

# **Bridging the Scales of Star Formation: Embedded Clusters to Galactic Histories**

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**Abstract**

Bridging the Scales of Star Formation: Embedded Clusters to Galactic Histories

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Chair of the Supervisory Committee:  
Professor Benjamin F. Williams  
Astronomy

Stars are the fundamental tracers of how galaxies form, evolve, and enrich the Universe. They produce much of the visible light we observe from galaxies, synthesize and redistribute heavy elements, and preserve records of the physical conditions under which they formed. In this thesis, I study star formation across a wide range of physical scales, from the emergence of individual young stars from dusty molecular clouds to the recent star formation histories of entire galactic disks. Across these chapters, I use simulations, synthetic observations, and resolved stellar population measurements from nearby galaxies to ask how stars form, when they become observable, and how their present-day properties encode their birth environments.

I begin by examining the transition from embedded to exposed star formation using the STAR-FORGE simulations. By tracking the evolution of embeddedness in simulated star-forming clouds, I find that the transition from embedded to exposed is rapid for individual stars, occurring within 1.3 Myr after each star reaches its maximum mass. Massive stars dominate this transition. They remain highly obscured while accreting, emerge when their feedback overcomes the local inflow, and then drive local gas clearance through pre-supernova feedback. Because these stars dominate the luminosity of young populations, their rapid emergence controls how stellar light escapes from dust.

I then move from individual star-forming regions to young stellar clusters by measuring the high-mass stellar initial mass function in Local Group galaxy M33. Using resolved *Hubble Space Telescope* photometry of young clusters, I probabilistically model the optical color-magnitude di-

agrams of each cluster and infer the distribution of high-mass mass-function slopes. For nine clusters more massive than  $\log(M/M_{\odot}) = 3.6$ , I find an ensemble high-mass slope of  $\bar{\Gamma} = 1.49 \pm 0.18$ , with no significant intrinsic scatter. This result is consistent with a universal IMF and shows no clear dependence on local star formation rate or galactocentric radius within M33.

At larger scales, I use resolved stellar populations to reconstruct the recent star formation history of M31. Using HST optical imaging from the Panchromatic Hubble Andromeda Southern Treasury, I fit color-magnitude diagrams in more than 6500 spatial regions across the southern disk and recover star formation histories over the last  $\sim 500$  Myr. Combined with existing measurements from the northern third of the M31 disk, these data provide homogeneous, spatially resolved star formation histories across two-thirds of M31's star-forming disk. The resulting maps trace the ringed structure of the galaxy and reveal a clear decline in the recent star formation rate, with a pronounced drop over the last  $\sim 40$  Myr. The decline is strongest in the star-forming rings and in regions near M32, suggesting that M31 is in the late stages of a longer-term wind-down from a more active state.

Motivated by this result, I finally examine how reliably FUV luminosity traces recent star formation when the star formation history is evolving. FUV luminosities are commonly interpreted as star formation rates averaged over the last  $\sim 100$  Myr, but that calibration assumes a constant recent star formation history. By modeling a range of idealized histories, I show that many different recent star formation histories can produce the same present-day FUV luminosity. When the star formation rate is not constant, the FUV becomes increasingly uncertain as a constraint on the true average rate beyond  $\sim 35$  Myr. Across rising and declining histories, averaging timescales of  $\sim 25$ – $40$  Myr provide better agreement between the FUV-inferred and true input star formation rates than the traditional 100 Myr average.

Together, these results from the four chapters of this thesis connect the physics of star formation to the stellar populations that survive as observable records.

# DEDICATION

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*No such thing as a life that's better than yourz.*

– Jermaine Cole

For my Mom and Dad. My support system, my inspiration, and my friends.

# ACKNOWLEDGMENTS

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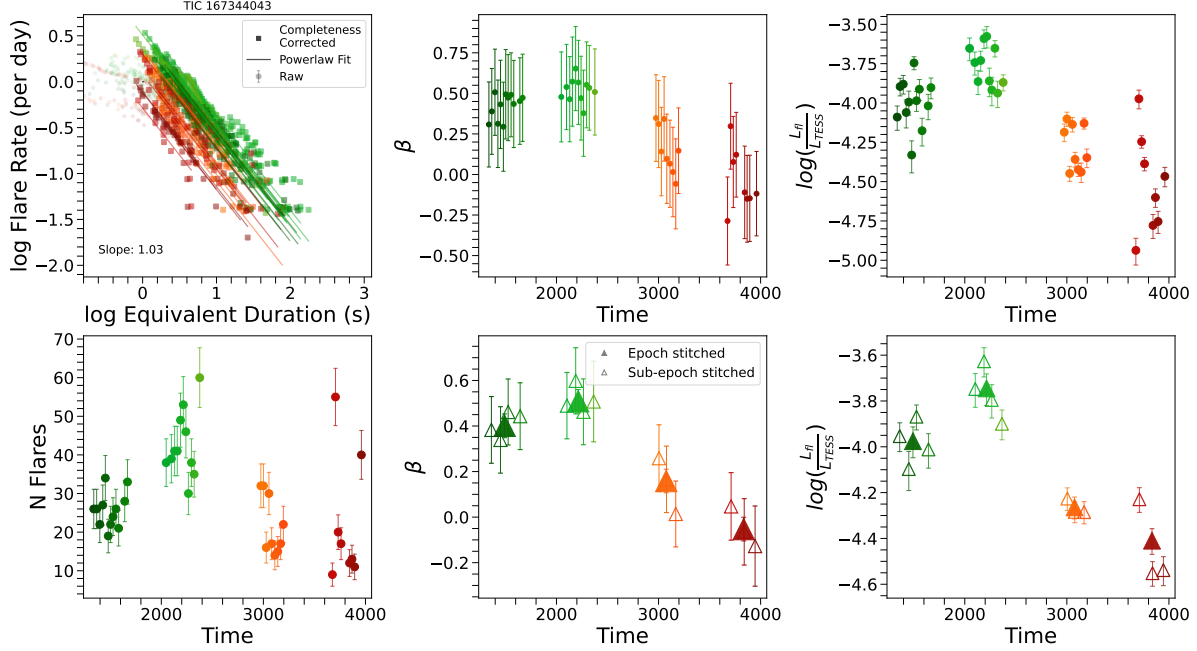
When I first came to the university of Washington 4 years ago, I was admitted off the wait-list at the last minute, with less than a day to make a decision about which coast I wanted to attend graduate school. After much turmoil, and consideration I had a had an overwhelming sense that UW was the placed where I belonged. Over the last four years, while there were many trials along the way, with lessons both in science and inter-personal relations, I can confidently say that decision made with my gut was correct.

While I had conviction in that decision, I never could have imagined was how much collaboration would come from my time here. Among UW faculty, I have been on papers 7 of the highest esteemed members of the scientific community. Emily Levesque, Eric Bellm, Nora Shipp, and Željko Ivezić; as well as my advisors Ben Williams, Julianne Dalcanton, and James Davenport.

On projects that are not covered in this thesis, there has been no one I have collaborated with more than James Davenport. Over the last four years, we have worked on a series of papers using stellar flares observed by TESS to search for long-term magnetic activity cycles (Wainer et al., 2024a, 2026a). In our first paper, we reanalyzed Kepler and TESS observations of TIC 272272592 and found that comparing flare samples across missions is far more subtle than it first appears. Differences in bandpass, cadence, and signal-to-noise can masquerade as astrophysical change, and even dramatic short-term variations can arise from sampling a power-law flare distribution over a limited observing window.

Our follow-up work expanded that idea from one star to more than 14,000 stars in the TESS continuous viewing zone. After building a flare search, injection-recovery tests, completeness corrections, and time-resolved flare diagnostics, we identified 17 stars with evidence for long-term changes in flare activity (Wainer et al., 2026a). These candidates are not the slowly rotating, solar-type stars that have traditionally anchored the activity-cycle literature. Many are rapidly rotating, highly active stars, including possible fully convective M dwarfs and the super-flaring G-dwarf TIC 167344043, whose flare activity shows one of the clearest solar-like patterns in our sample (As seen in Figure 0.1). These systems suggest that organized, cycle-like magnetic variability may be detectable in a younger and more active regime than is usually probed by classical activity-cycle studies. Working on this series of projects with Dr. Davenport helped shaped how I think about time-domain stellar astrophysics, statistical caution, and the value of turning a qualitative impression into a measurable diagnostic, all skills that were used extensively in this thesis, and I will continue to use throughout my career.

In addition to the UW faculty who I collaborated with, even more important to me are the collaborations that I built with other graduate students. More than anyone else, Tom Wagg has appeared on 4 of my papers (Wainer et al., 2024a, 2026a, 2023a,b), including the development of `elk`, and who has taught me much about coding and productivity. Additionally, Meredith Durbin essentially produced, or was involved with nearly all of the photometry used in this thesis, and Margaret Lazzarini lended her code enabling much of the star formation history work. Lupita Tovar Mendoza has been a key collaborator on all of the flare work, and an invaluable academic sounding



**Figure 0.1:** Diagnostic figure for TIC 167344043, a G4 superflare star with a rotation period of  $\sim 2.9$  days, from [Wainer et al. \(2026a\)](#). The flare activity peaks around BTJD  $\sim 2200$  and then undergoes a sustained decline, suggesting a possible activity-cycle period of at least  $\sim 9$  years. TIC 167344043 is one of the clearest solar-like activity-cycle candidates in our TESS continuous-viewing-zone search, despite rotating much faster and producing much more energetic flares than the Sun.

board for all things related to the flare world. Andy Tzanidakis and I co-mentored an undergraduate student, Giovanni Gollotti, looking at two very interesting, asymmetric dips in a TESS light curve ([Gollotti et al., 2024](#)). Debby Tran produced an fantastic work on clusters in the Fireworks galaxy ([Tran et al., 2026](#)), which also included Bo-Eun Choi, while my research note on from the Rubin observatory’s DP1 ([Wainer et al., 2025](#)), included grad students Gray Thoron, and David Wang, and I was a co-author on David’s paper on X-ray binaries ([Wang et al., 2026](#)). Finally, there are also 2 papers in prep, one from Myles McKay, and one from Charlie Willard that I hope will be published very soon. Collaborating with each one of these amazing colleagues absolutely made my experience at UW, and taught me a lot.

Additionally, I would like to thank the PHAT/PHATTER/PHAST/PHATTEST research group that I have had the privilege of being apart of. We host group meetings on Fridays, and it feels like every week I can show up, and listen to what my truly amazing colleagues are up to, and every week, is the perfect cap to the week. Whether it’s learning what amazing analysis Zhuo Chen is up to, what new JWST proposal Adam Smercina has won, or how Margaret Lazzarini somehow continues to produce great science while teaching a multitude of classes, or simply being a sponge to soak up the wisdom of Ben Williams and Julianne Dalcanton, the postdocs and faculty in the group are inspirational, and being able to bounce ideas off of them every week absolutely made me a better scientist.

Outside of the science, the graduate students in the department played a undeniable role in my experience here at UW. New friendships were forged, and the comradery from David, Tom, Sam,

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Hector, Jake, Rudy, and Andy truly meant the world to me. There are so many grads that that made my experience here at UW a positive one, specifically Lauryn, Oge, Sam, Pip, J.F., Dino, Tyler, Debby, all made coming into the office, or whine-time amazing.

I would also like to thank my entire mentoring community. At UW: Ben Williams, Julianne Dalcanton, James Davenport, and Jess Werk. Each played a pivotal role in my development as a scientist, mentor, colleague, collaborator, and man. I am truly in debt to them, and am grateful everyday for the opportunity that I've had to learn from them. I hope that I can continue to work with them for years to come. Next, my mentors from before I began graduate school, Anil Seth, Cliff Johnson and Gail Zasowski. And Finally, Kristy McQuinn, who is giving me an opportunity, and I hope to learn from her and live up to the challenge.

I now thank and acknowledge my family. My parents Sam and Heidi Wainer, who this thesis is dedicated to. The amount of love and support they have given me my entire life is truly what made this work possible. My brother Kai, and my extended family Josh, Suz, Isaac, and Em, and the matriarch of the family, and a woman who holds such a special place in my heart, Mumpa.

And while not family by blood, I would not be here without the kinship from my closest friends: Chandler, Jared, Steph, Kam, and most importantly, my best friend, Alec. As Barney once said, "whatever you do in this life, it's not legendary, unless your friends are there to see it". I am so blessed to have such amazing friends, who are willing to come and support me doing this crazy thing of getting a PhD.

And Finally, I want to take a moment here and acknowledge a man who made a great difference in my life, Hal Adams. I believe that one of the reasons I was able and confident in my decision to not attend law school, and instead choose the underpaid route of astronomy research, was because of the impact this man had on my life.

I harbor a lot of love for all those mentioned here in the acknowledgments, and am truly grateful to each of them.

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# CHAPTER 1

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## INTRODUCTION

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# 1 Where We Come From

*The surface of the Earth is the shore of the cosmic ocean. Some part of our being knows this is where we came from. We long to return, and we can, because the cosmos is also within us. **We're made of star stuff.***

– Carl Sagan

The question of, “where do we come from?” is one that is as old as civilization itself. For millennia, it belonged to myth, philosophy, and religion, where origin stories explained not only the beginning of the world, but also humanity’s place within it. Ancient cosmogonies gave the question narrative and spiritual form, while philosophers asked whether the cosmos could be understood through reason and underlying principles (Anaximander, 1983; Hesiod, 1914). Plato’s *Timaeus*, for example, treated the structure and origin of the cosmos as questions that could be examined and explained, rather than only inherited through myth (Plato, 1871). Across these traditions, the question carried both intellectual and emotional weight. Our common origin story gave structure to the unknown.

Modern astronomy has transformed this ancient question, without diminishing its emotional force. Carl Sagan wrote that, “By far the best way I know to engage the religious sensibility, the sense of awe, is to look up on a clear night” (Sagan, 2006). This same sense of awe is not in any way different from the scientific purpose of this thesis, but one of its deepest motivations.

When we look up at the night sky, it is stars that first give the Universe its visible form. With a few notable exceptions of solar system objects<sup>1</sup>, nearly all the light visible to the unaided eye is a star. For centuries, it has been clear that the Milky Way galaxy was composed of stars (e.g., Herschel, 1785). The same remains true beyond the limits of human vision. In the optical, the galaxies we observe across the Universe are seen primarily through the accumulated light of their stellar populations (e.g., Review by Walcher et al., 2011), and stars themselves were pivotal in determining that there were such things as “other” galaxies (Hubble, 1929). These little twinkling points of light are therefore both the objects that inspire the most immediate sense of cosmic wonder, and one of the physical tracers that make the Universe observable.

The visible light of stars is only the most immediate way they connect us to the cosmos. Their compositions provide another, deeper connection. Stars are made primarily of hydrogen and helium (Payne-Gaposchkin, 1925), the two lightest elements, but they also contain small amounts of heavier elements that encode the history of earlier generations of stellar evolution (Burbidge et al., 1957).

During the main sequence evolution of a star, hydrogen nuclei fuse into helium in the stellar core, releasing energy that supports the star against gravitational collapse. As stars evolve, their cores contract and heat, allowing more massive stars to ignite successive stages of nuclear burning. Helium fusion produces carbon and oxygen, while later burning stages in massive stars build elements such as neon, magnesium, silicon, sulfur, calcium, and eventually, iron (e.g., Chabrier & Baraffe, 1997; Clayton, 1968; Wallerstein et al., 1997; Weaver et al., 1978). Fusion releases

---

<sup>1</sup>While I mention these objects are exceptions for the purpose of arguments sake, my office-mate, Jake Kurlander, likes to remind me that solar system objects like the moon, planets, and asteroids, all reflect sun-light, and are therefore also only visible to us because of star-light.

energy up to the iron peak, but building nuclei heavier than iron requires different processes, because further fusion no longer provides a net source of energy (e.g., [Woosley et al., 2002](#)). Stars therefore provided the physical sites where simple nuclei can be fused into more complex ones, and stellar deaths provided the mechanisms by which those products could be released back into space ([Cameron, 1962](#)). Each generation of stars therefore changes the material available for the next.

The deaths of massive stars are especially important for redistributing and extending this chemical complexity. Core-collapse supernovae occur when massive stars can no longer support their cores against gravity, producing an explosion that ejects material enriched by both the star's prior evolution and explosive nucleosynthesis during the supernova itself ([Nomoto, 1984, 1987](#); [Nomoto et al., 2006](#)). These events are major sources of alpha elements such as oxygen, magnesium, silicon, sulfur, calcium, and titanium, and they inject energy and metals into the interstellar medium on short timescales after star formation ([Matteucci, 2012](#); [Matteucci & Greggio, 1986](#); [Matteucci & Recchi, 2001](#); [Woosley & Weaver, 1995](#)). Type Ia supernovae, which arise from thermonuclear explosions of white dwarfs, contribute a large fraction of the iron-peak elements and enrich galaxies on a broader range of delay times ([Matteucci & Greggio, 1986](#); [Nomoto et al., 1984](#)). Together<sup>2</sup>, supernovae then transform the products of stellar interiors into the raw material for future stars, planets, and life.

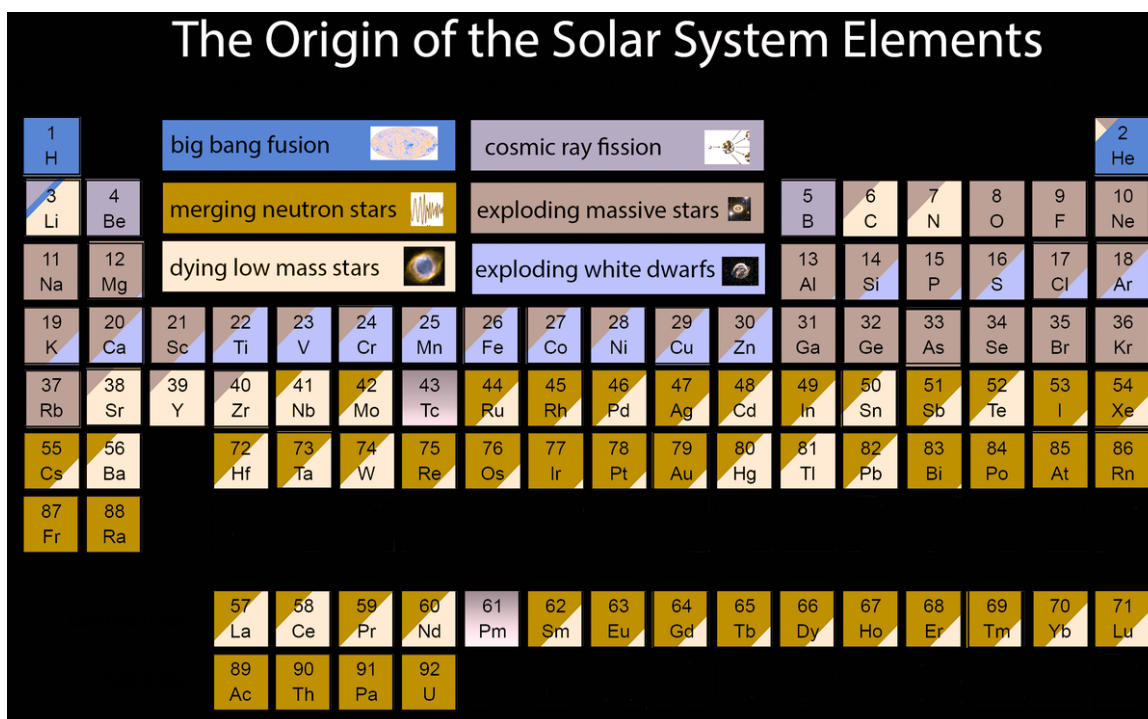
This chemical history is what is summarized visually in Figure 1.1, adopted from [Johnson \(2019\)](#). Each element in the periodic table carries information about the astrophysical environments that produced it. Some elements, including hydrogen and helium, trace the earliest moments of the Universe. Others were assembled in the interiors of stars, in the winds of evolved stars, in the explosions of massive stars and white dwarfs, or in compact-object events capable of producing the heaviest nuclei. These concepts, visualized Figure 1.1 provide tangible evidence to the idea that the material world is a product of cosmic history. The carbon in organic molecules, the oxygen in water, the silicon in rock, the calcium in bone, and the iron in blood were not present in their present abundance at the beginning of the Universe. They were produced and redistributed through generations of star formation, stellar evolution, and stellar death. Therefore, asking where we come from is, at its essence, asking where the stars come from.

In this thesis, over the course of my graduate studies, I have worked to help answer this question. While all of star formation is far too broad a topic to cover and synthesize in one introduction, my work spans a broad range of topics, all intertwined by this common theme. This introduction attempts to focus on the pieces most relevant to the chapters that follow, with a particular bias towards topics and papers that I want to learn more about about this current moment in time.

## 2 From Gas to Stars

Let us begin by covering some of the basic, current theory of how stars form. To ask how stars form, we must first understand the material from which they form. Stars do not appear from empty space, but condense out of the gas and dust that make up galaxies. The basic physical story of star formation therefore begins with the interstellar medium. This section introduces some of the

<sup>2</sup>along with contributions from stellar winds, asymptotic giant branch stars, and neutron-capture processes, ([Arlandini et al., 1999](#); [Busso et al., 1999](#))



**Figure 1.1:** The origin of the Solar System elements, color-coded by dominant nucleosynthetic production channel. Figure adapted from J. A. Johnson’s SDSS visualization of the origins of the elements in the Solar System (Johnson, 2017); see also Johnson (2019) and Johnson et al. (2020) for reviews of the nucleosynthetic processes represented here.

fundamental properties of interstellar gas, and follows that gas into molecular clouds, and their subsequent gravitational collapse.

The material from which stars form is the interstellar medium: the diffuse mixture of gas, dust, cosmic rays, radiation, and magnetic fields that fills the space between stars. The interstellar medium exists in multiple phases, spanning hot ionized gas, warm neutral and ionized gas, cold atomic gas, and dense molecular gas (Ewen & Purcell, 1951; Field et al., 1969; McKee & Ostriker, 1977; Reynolds, 1984). Each phase is shaped by cooling, heating, turbulence, magnetic fields, cosmic rays, stellar feedback, and the gravitational potential of the galaxy (Draine, 2011; Spitzer, 1978).

Star formation is associated most directly with the coldest and densest parts of this medium (Kennicutt & Evans, 2012; Lada et al., 2010; McKee & Ostriker, 2007; Shu et al., 1987). At sufficiently low temperatures and high densities, gas can cool, shield itself from dissociating radiation, and form molecules (Bergin & Tafalla, 2007; Glover & Clark, 2012; Hollenbach & Tielens, 1999). Large-scale motions in galaxies, including spiral arms, turbulence, expanding shells, and gravitational instabilities, can help collect this cool, shielded gas into denser, potentially self-gravitating

regions, called molecular clouds (Goldreich & Kwan, 1974). As the density increases, the gas cools more efficiently and dust grains shield the interior from dissociating ultraviolet radiation, allowing molecular hydrogen to form and survive. (Elmegreen, 1993a; Hartmann et al., 2001; Hennebelle & Chabrier, 2008).

Once formed, molecular clouds carry the turbulent, hierarchical, and filamentary structure from the ISM. These sub-structures in clouds span from giant molecular clouds tens to hundreds of parsecs across down to dense cores less than a parsec in size (Ballesteros-Paredes et al., 2020; Elmegreen, 1993b; Williams et al., 2000). Early observations showed that when viewed as a whole, molecular clouds obey approximate correlations between size, velocity dispersion, and density, suggesting that internal motions and structure are linked across scales (Larson, 1981). More recent infrared and submillimeter surveys have emphasized that much of the dense gas in nearby molecular clouds is organized into filaments (André et al., 2014; Hacar et al., 2018; Molinari et al., 2010; Sanhueza et al., 2019).

Once sufficiently dense structures form within molecular clouds, gravity can begin to dominate their subsequent evolution (Jeans, 1902). Star formation begins when localized regions become gravitationally unstable and collapse under their own self-gravity (Krumholz et al., 2007; McKee & Ostriker, 2007). This collapse is not generally an isolated, all-at-once process. Molecular clouds are hierarchical, and their collapse is hierarchical as well. Large-scale filaments and flows gather gas into and hubs, while smaller-scale clumps and cores collapse within the larger structures (Gómez & Vázquez-Semadeni, 2014; Treviño-Morales et al., 2019). Star formation then proceeds through nested levels of collapse and accretion, with dense cores drawing material from filaments, filaments feeding clumps, and clumps assembling groups or clusters of young stars (Vázquez-Semadeni et al., 2017, 2019). The initial conditions for individual stars are therefore tied to the larger cloud environment in which they form.

Fragmentation is one of the key consequences of this hierarchical collapse. Because small variations in density, velocity, temperature, magnetic field strength, and angular momentum can be amplified as the gas contracts, collapse naturally breaks into substructures (Goodwin et al., 2004; Joos et al., 2013). Regions that become locally self-gravitating can collapse on their own, producing substructure within larger collapsing clouds. Fragmentation can occur across many scales, from filaments and clumps to dense cores and protostellar disks, and it helps determine whether a star-forming region produces a single star, a multiple system, or a clustered population (Hacar et al., 2023; Offner et al., 2023; Zhang et al., 2015). The amount of fragmentation depends on the balance between gravity and the processes that resist or reshape collapse, including thermal pressure, turbulence, magnetic fields, rotation, and radiative feedback (e.g., Krumholz et al., 2007).

Individual protostars form within this larger, fragmented environment. In the simplest local picture, a dense core collapses to form a central protostar, while surrounding material continues to accrete inward through an envelope and, later, through a circumstellar disk (Dunham et al., 2014; Shu et al., 1987). Conservation of angular momentum naturally leads to disk formation, while magnetic fields and accretion processes help launch bipolar outflows that remove mass and angular momentum from the system (McKee & Ostriker, 2007). The young star therefore grows through accretion while simultaneously interacting with and reshaping the material from which it formed. The final stellar mass is then determined by the competition between accretion and feedback, as outflows, radiation, winds, and ionization regulate how much of the surrounding gas remains available for further growth, and setting the characteristic stellar mass scale (Guszejnov et al., 2021, 2022; Neralwar et al., 2024; Offner et al., 2014).



The earliest observable products of this process are young stellar objects (YSOs), i.e., protostars still embedded in their natal gas and dust (Lada & Lada, 2003). During this phase, the forming star grows by accreting material from its surrounding envelope and disk, while outflows and jets interact with the cloud from which the star is forming (Bachiller, 1996; Frank et al., 2014; Grudić et al., 2022; Offner & Chaban, 2017). As feedback disperses the surrounding material<sup>3</sup>, the young star's accretion rate declines as the available envelope and disk reservoir is depleted and, in massive stars, as radiation pressure, ionization, winds, and outflows increasingly oppose, redirect, or expel the inflowing gas (Kahn, 1974; Krumholz et al., 2009a; Kuiper et al., 2010, 2011; Wolfire & Cassinelli, 1987; Yorke & Sonnhalter, 2002; Zinnecker & Yorke, 2007).

The sequence from molecular cloud structure to protostars is summarized schematically in Figure 1.2. In this picture, dense gas is organized into a turbulent, magnetized filamentary network, which fragments into clumps and cores. Collapse within those structures produces protostars, disks, and outflows, while feedback from young stars begins to reshape and eventually disperse the surrounding cloud.

## 3 Stars as Populations

Up to this point, we have followed the physical path from interstellar gas to young stars. For clarity, I centered that description on local collapse, accretion, and the growth of individual protostars. In reality, however, star formation is rarely (if ever) limited to one star at a time. Molecular clouds fragment across many scales, so a single star-forming region can produce many stars with related ages, motions, and chemical compositions (Elmegreen & Lada, 1977; Lada & Lada, 2003). Most stars are therefore born as members of groups, associations, clusters, or broader hierarchical stellar populations (Bressert et al., 2010; Krumholz et al., 2019). These shared properties are what allow stars to be studied not only as individual objects, but as stellar populations.

### 3.1 The Simplest Stellar Population

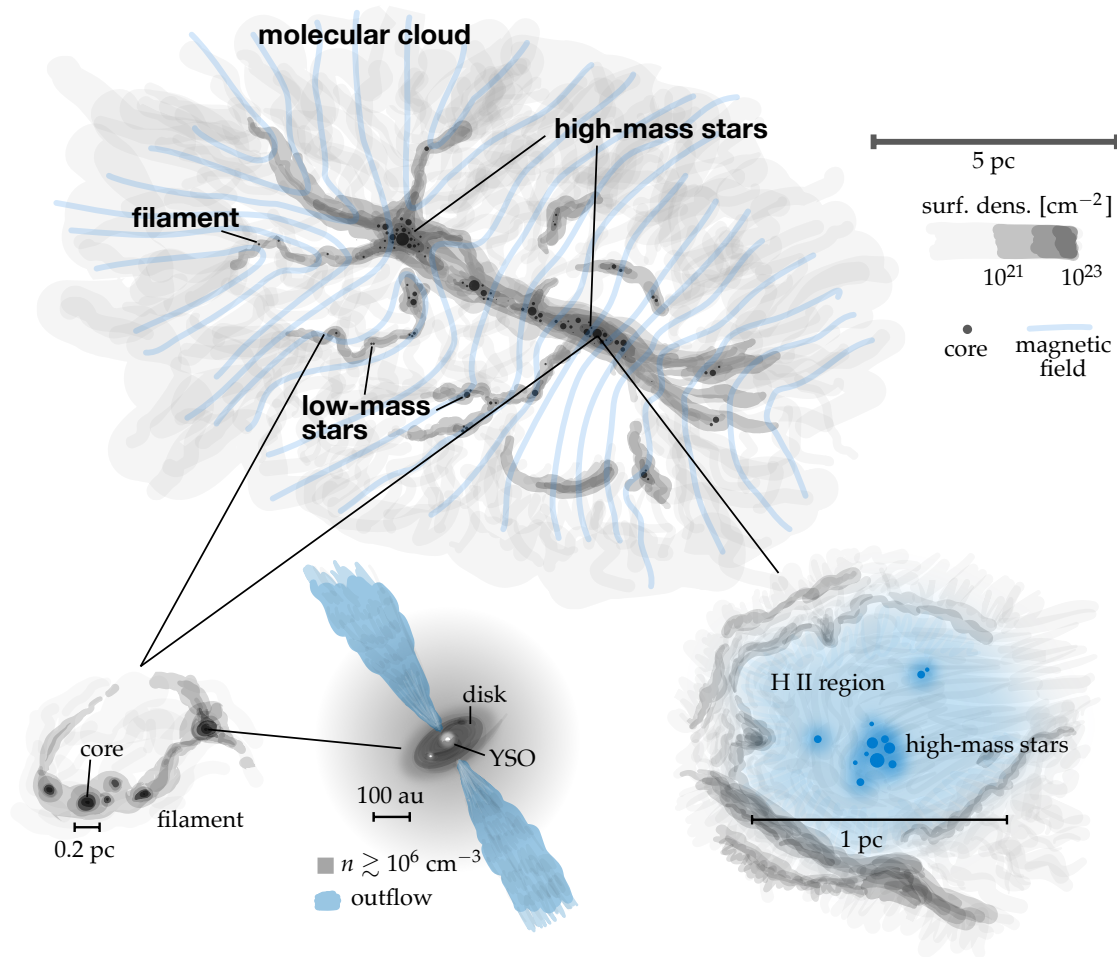
The simplest form of a stellar populations is a star cluster. In an idealized picture, a star cluster is a group of stars that formed at approximately the same time, from the same parent cloud, with the same initial chemical composition, with all the stars equal distance from the observer. These assumptions make stellar clusters particularly clean laboratories for stellar population studies; a population whose differences are driven primarily by stellar mass and stellar evolution is particularly useful for the development stellar models, where observed properties do not primarily reflect differences in age, distance, metallicity or extinction (Girardi et al., 2020; Renzini & Fusi Pecci, 1988). As such, star clusters have long served as anchors for stellar evolution models, stellar population synthesis, and the connection between star formation and the stars that are ultimately observed (e.g., Adamo et al., 2020).

In practice, however, star clusters are not so simple. The stars in an observed cluster are drastically affected by binary evolution (Eldridge et al., 2017; Sana et al., 2012), with other notable degeneracies in: differential extinction (Anders et al., 2004; Hillenbrand, 1997), mass segregation (Spitzer, 1969), dynamical evolution (Baumgardt & Makino, 2003), and the stochasticity of how

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<sup>3</sup>A careful distinction can be made here, that this does not necessarily have to be feedback from the star itself. It very well could be feedback from a neighboring star.





**Figure 1.2:** Sketch of a star-forming complex taken from a Review article by [Beuther et al. \(2025\)](#), illustrating a unified view in which turbulent, magnetized molecular gas fragments into filaments, clumps, and cores, which then form protostars, disks, jets/outflows, and feedback structures. The figure was originally created by André Oliva, and inspired by both observational and numerical data from ([Grudić et al., 2023](#); [Oliva & Kuiper, 2023](#); [Soler, 2019](#)), and a Hubble image of Orion (credit: NASA, C.R. O’Dell and S.K. Wong).

many stars of a given mass form during a single event ([Cerviño & Luridiana, 2004](#); [Fouesneau & Lançon, 2010](#)). Each of these effects reshape the cluster over time, entangling the records of its formation. Additionally, even the assumption of a single age or a single formation event may be only an approximation, as the formation can extend over timescales comparable to the ages being inferred ([Bally, 2008](#); [De Marchi et al., 2011](#); [Kerr et al., 2024](#)). These effects can complicate the interpretation of clusters, but importantly do not diminish the value of the star clusters being approximately simple stellar populations.

Specifically, despite these complications the power of the idealized assumption that all the stars were born at the same time becomes even more evident in the context of how stars of different masses evolve. In a coeval population, stellar mass becomes the main clock. Massive stars burn

through their nuclear fuel quickly and evolve away from the main sequence, while lower-mass stars remain comparatively unevolved for much longer (e.g., [Iben, 1967](#); [Lamers & Levesque, 2017](#)). For individual, isolated stars, age is notoriously difficult to constrain (e.g., [Soderblom, 2010](#)); however, because of this mass dependent evolution, stellar clusters provide one of the most important empirical routes to age-dating stars (e.g., [Portegies Zwart et al., 2010](#)). The ordered pattern of luminosities and colors in a coeval population can be used to infer the age of the cluster as a whole, and that age can then be assigned to the individual stars it contains.

## 3.2 The Color-Magnitude Diagram as a Diagnostic Tool

One observational tool available for inferring ages from patterns of luminosities and colors is the color-magnitude diagram (CMD). A CMD plots the brightnesses of stars against their colors, using color as an observational proxy for stellar temperature. The distribution of the stars reflects the underlying physics of stellar evolution, as stars of different masses evolve at different rates and therefore occupy different regions of the CMD at a given age and composition ([Russell, 1914](#); [Sandage, 1953](#)).

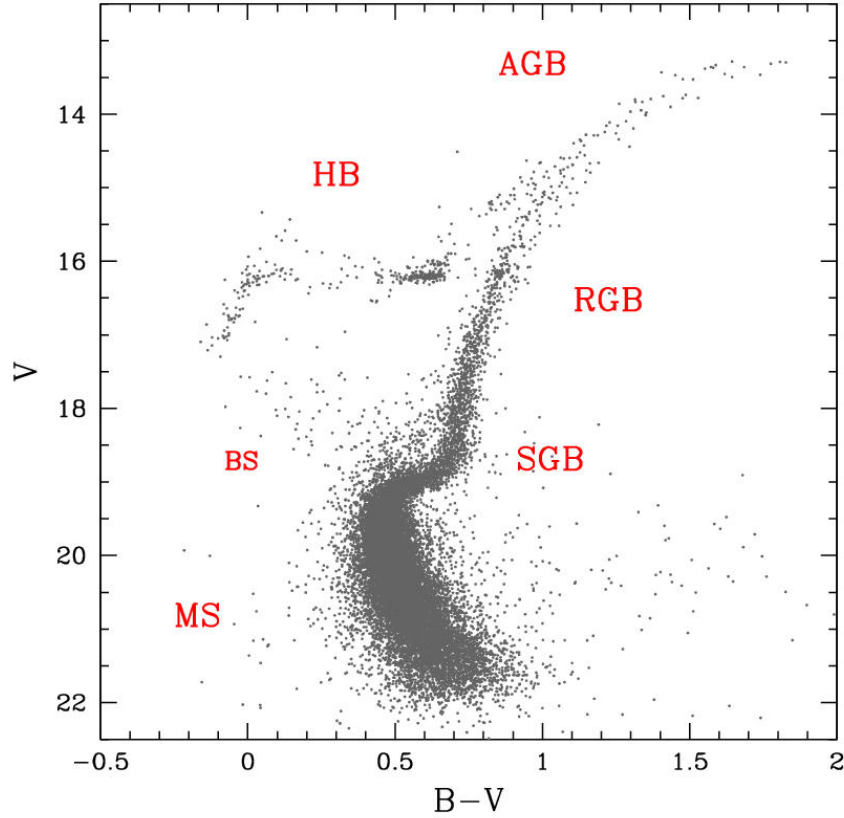
For a simple stellar population (i.e., a star cluster), the CMD provides a direct quantitative record of stellar evolution. Low-mass stars remain on the main sequence for long periods of time, while higher-mass stars exhaust their core hydrogen more quickly and evolve toward later evolutionary phases. The point where stars begin to leave the main sequence, the main-sequence turnoff, a function of a stars given mass, and therefore provides one of the most important age diagnostics. As a cluster ages, progressively lower-mass stars reach the end of their main-sequence lifetimes, causing the turnoff to move to fainter luminosities and redder colors (e.g., [Renzi & Buzzoni, 1986](#); [Renzi & Fusi Pecci, 1988](#)). The location and shape of the turnoff therefore provide a way to translate the stellar population approximation into a measurable age. Based on the relative number counts of stars across the CMD, one can also infer the mass, and measure the IMF ([Kroupa, 2001](#); [Salpeter, 1955](#)).

Figure 1.3 illustrates these features in the CMD of the globular cluster NGC 1851 ([Maraston, 2003](#); [Piotto et al., 2002](#))<sup>4</sup>. The main sequence is visible as the broad, dense diagonal sequence extending from faint ( $V \sim 22$  mag), red stars (around  $B - V \sim 0.75$ ), toward brighter, bluer stars up and to the left. Near  $B - V \sim 0.6$  and  $V \sim 19$ , the sequence turns away from the main sequence, where stars of the corresponding mass have exhausted their core hydrogen and begun to evolve toward later phases. Above the turnoff, stars populate the subgiant branch and then the red giant branch, while the horizontal branch and asymptotic giant branch trace shorter-lived post-main-sequence stages. The locations, relative numbers, and widths of these features depend on age, chemical composition, distance, extinction, binaries, and observational uncertainties ([Charlot & Bruzual A, 1991](#); [Gallart et al., 2005](#)). Together, the culmination of information encoded in these features provide a set of evolutionary clocks, which can yield estimates of cluster properties, such as age.

Quantitative CMD fitting formalizes this visual description. In classical cluster studies, ages were often inferred by fitting theoretical isochrones to overlap the locations of observed main sequence, turnoff, and evolved sequences, or by measuring age-sensitive CMD features such as the

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<sup>4</sup>While there is mounting evidence that globular clusters are not “simple” stellar populations ([Bastian & Lardo, 2018](#); [Gratton et al., 2004](#)), and the width of the main sequence here suggests as much, this is one of the more beautiful, and descriptive CMDs I have found to date.



**Figure 1.3:** CMD taken from [Maraston \(2003\)](#). Shown is the globular cluster NGC 1851, observed and published by [Piotto et al. \(2002\)](#). Annotated are the different evolutionary phases: i.e. Main Sequence (MS); Sub Giant Branch (SGB); Red Giant Branch (RGB); Horizontal Branch (HB); Asymptotic Giant Branch (AGB); and Blue Stragglers (BS). Each phase occupy distinct regions of the CMD because stars of different initial masses evolve at different rates.

luminosity and color of the main-sequence turnoff ([Sandage, 1953](#); [Vandenbergh, 1983](#)). One could therefore infer the age and other physical properties of a cluster by shifting isochrones for distance and extinction and comparing their morphology to the observed main sequence, turnoff, and evolved phases ([Bertelli et al., 1994](#); [Choi et al., 2016](#); [Dotter, 2016](#); [Girardi et al., 2000](#)). Later methods made this comparison increasingly rigorous by minimizing distances between observed stars and model sequences in color-magnitude space or by maximizing the likelihood of the observed CMD under a model population ([Monteiro et al., 2010](#); [Naylor & Jeffries, 2006](#)). More detailed approaches use Bayesian or synthetic-cluster frameworks to infer age, distance, extinction, metallicity, binary fraction, and cluster membership simultaneously ([Perren et al., 2015](#); [von Hippel et al., 2006](#)).

One notable<sup>5</sup> approach for resolved stellar populations is statistical fitting of model CMDs to observed ones. One of the most heavily employed software packages for doing this is MATCH, which compares observed and synthetic CMDs in Hess-diagram space ([Dolphin, 2002](#)). Rather than fitting a single isochrone to a single-age population, MATCH models the observed CMD as

<sup>5</sup>I use “notable” semi facetiously, as it is (mostly) notable only in the sense that it is the one I use.

a linear combination of synthetic CMDs with different ages and metallicities, while incorporating assumptions about the IMF, binary fraction, distance, extinction, photometric uncertainties, and completeness. Because the observed number of stars in each CMD bin is Poisson-distributed around the expectation value for the model, CMD-fitting methods often compare observed and model Hess diagrams using a Poisson likelihood or likelihood-ratio statistic. If  $n_i$  stars are observed in CMD bin,  $i$ , and the model predicts  $m_i$ , the likelihood for the binned CMD is

$$\mathcal{L} = \prod_i \frac{m_i^{n_i} e^{-m_i}}{n_i!}. \quad (1.1)$$

Equivalently, one can minimize the Poisson likelihood-ratio statistic,

$$\Upsilon = 2 \sum_i \left[ m_i - n_i + n_i \ln \left( \frac{n_i}{m_i} \right) \right], \quad (1.2)$$

which is argued to be more accurate than classic likelihood estimates such as  $\chi^2$ , which implicitly assume Gaussianity (Dolphin, 2002).

Given this rich evolutionary information, and our ability to statistically model it, the CMD preserves the fossil records of a stellar population, long after it has formed. The methods shown here to interpret simple stellar populations are relatively straight forward. However, for an entire galaxy, the same diagnostic contains the overlapping signatures of many generations of star formation. Interpreting these signatures requires the same basic ingredients introduced here, stellar evolution models, observational effects, and statistical comparison between data and synthetic populations, but applied to a population whose history is no longer simple, as I discuss in the following section.

### 3.3 Stellar Populations as Records of Galaxy Evolution

Although most stars form in clustered or grouped environments, most stars are not found in bound clusters today. Studies suggest that the vast majority of embedded clusters are not long lived, and are instead disrupted during, or shortly after their formation (e.g., Ascenso, 2018). This disruption has long been well characterized, where only a small fraction of stars formed in a given event will remaining in a gravitationally bound cluster (e.g., Geyer & Burkert, 2001; Kruijssen, 2012). Initial studies showed that to have enough binding mass present after the dispersal of gas, the star formation efficiency must be high, such that there is enough stellar mass to have and a gravitationally bound cluster (e.g., Elmegreen, 1983; Lada et al., 1984). The formation mechanisms for bound stellar clusters are highly uncertain (e.g., Zhou et al., 2025), but favor high density and high star formation efficiency (Krumholz & McKee, 2020).

Given this high rate of cluster destruction, the vast majority of stellar populations that were born together, disperse into the galactic field. The field population of a galaxy is therefore the accumulated remnant of many star-forming events whose original spatial structure has been partly or completely erased. Rather than a single coeval population, the stellar populations of a galaxy are composite, built from many generations of star formation that occurred at different times, in different environments, and from gas with different chemical enrichment histories.

In a galactic context, the CMD becomes more than an age-dating tool for a single cluster; it becomes a time-resolved description of an entire galaxy. Figure 1.4 illustrates this contrast using a CMD containing both the Small Magellanic Cloud (SMC) dwarf galaxy, and the Milky Way

globular cluster 47 Tuc (Figure taken from [Wainer et al., 2025](#), similar analysis was conducted by [Choi et al. 2025](#)). These data were taken from Data Preview 1 of the Vera C. Rubin Observatory ([Vera C. Rubin Observatory, 2025](#)), using its very large field of view, which can capture the extended stellar population of the SMC while also including 47 Tuc in the field of view. The cluster appears as a comparatively narrow and coherent sequence, consistent with a population that is close to coeval and chemically self-similar. Its main sequence, turnoff, and evolved phases occupy well-defined regions of color-magnitude space. The SMC, by contrast, fills a different region of the CMD. While the SMC is much ( 5 mags) farther away, some of the differences are due to the fact that the 47Tuc stars in the CMD are intrinsically much fainter and lower mass than the SMC ones; however, its stars span a wider range of colors and magnitudes because the galaxy contains many stellar populations formed over different times, with different metallicities, extinctions, and evolutionary states. The same CMD features that allow a cluster to be dated therefore become, in a galaxy, the overlapping record of many generations of star formation ([Gallart et al., 2005](#); [Sarajedini, 2024](#); [Tolstoy et al., 2009](#)).

However, recovering these records requires extending the simple-population logic introduced above. A galaxy’s CMD, needs to be modeled as the sum of many simple stellar populations, each with its own age and metallicity (e.g., [Aparicio & Hidalgo, 2009](#); [Dolphin, 2002](#)). Each component populates particular regions of the CMD depending on the star formation rate and chemical composition at that particular time. Young populations uniquely contribute bright main-sequence and helium-burning stars, intermediate-age populations contribute red clump and asymptotic giant branch stars, while old populations contribute faint main-sequence turnoffs, subgiant branches, red giant branches, and horizontal branches, each chemically unique from similarly long lived, but younger late type stars ([Tolstoy et al., 2009](#)). The relative contribution of different age components then encodes the star formation history (SFH), the rate at which stars formed as a function of time, often together with the chemical enrichment history ([Holtzman et al., 1999](#); [Skillman, 2005](#)).

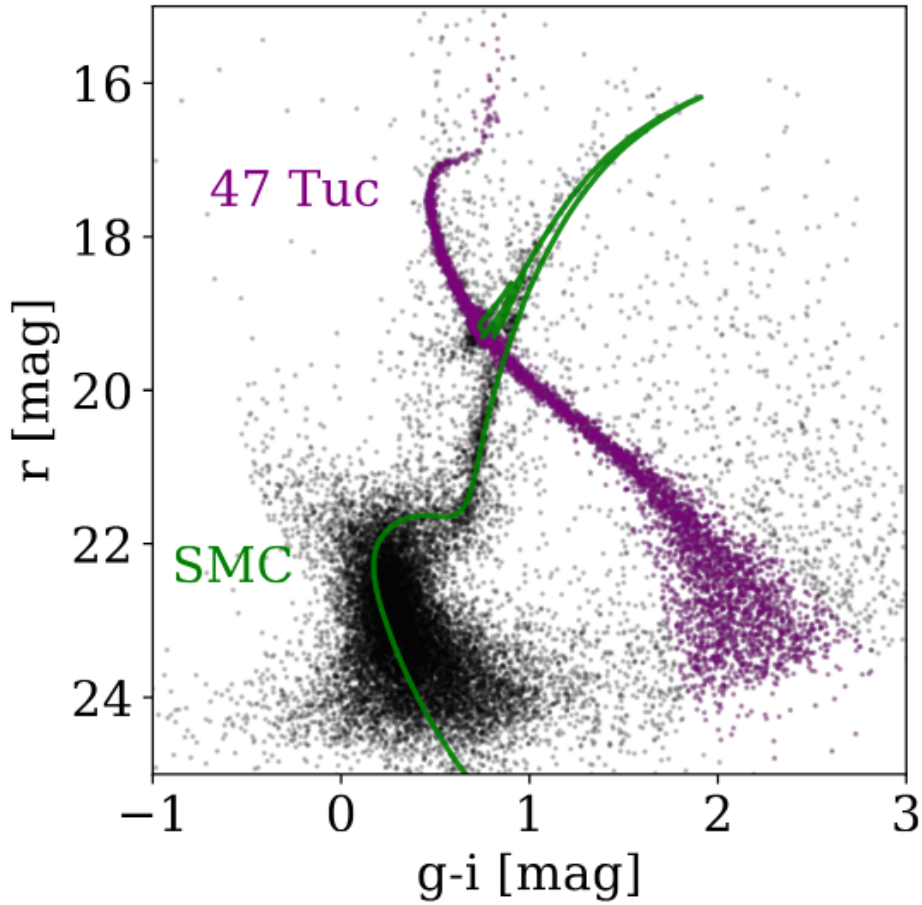
The resulting SFH is then a way of translating the present-day stellar population into a record of past galaxy growth, showing when the galaxy assembled its stellar mass, whether that growth was steady or bursty, and how different stellar generations contributed to the population observed today (e.g., [McQuinn et al., 2010](#); [McQuinn et al., 2010](#); [Weisz et al., 2014, 2011](#)). When CMDs are modeled in different locations within a galaxy, the models can connect changes in star formation to galactic structure, environment, and interaction history ([Harris & Zaritsky, 2004, 2009](#); [Lewis et al., 2015](#)). The resolved stellar populations then provide a direct link between the physics of individual stars and the evolution of galaxies as systems.

### 3.4 The Nearby Universe as a Resolved Star Laboratory

Fundamentally, the power of the diagnostics we have discussed thus far depends on the ability to measure individual stars, and each of the techniques described above are therefore limited to the nearby Universe, where stellar populations can be resolved into their constituent stars rather than observed only through their integrated light. Proximity, is therefore a fundamental observational advantage. In the Milky Way, nearby star-forming regions have provided the most detailed laboratories for connecting young stars to the gas and dust from which they formed ([Evans, 1999](#)).

In Orion, optical and near-infrared studies of the Orion Nebula Cluster have been used to measure the stellar population, infer ages and masses, characterize the IMF, and connect young stars to nebular gas, disks, and externally illuminated protoplanetary systems ([Hillenbrand, 1997](#); [O’Dell,](#)





**Figure 1.4:** CMD of globular cluster 47 Tuc (purple), and the SMC (black), taken from [Wainer et al. \(2025\)](#), from Data Preview 1 of the Vera C. Rubin Observatory ([Vera C. Rubin Observatory, 2025](#)). The narrow purple sequence of 47 Tuc reflects a population with a comparatively small spread in age, distance, and chemical composition, while the broader black distribution of SMC stars contains a compilation of stellar populations formed over an extended history and much further away.

2001). In Taurus-Auriga, the relative isolation of low-mass star formation has made it a benchmark for studying pre-main-sequence stars, multiplicity, disks, jets, and outflows in a comparatively sparse molecular-cloud environment ([Kenyon et al., 2008](#)). In Perseus, embedded YSOs are present across the molecular cloud, linking protostellar evolutionary classes and star formation rates to the distribution of dense gas ([Dunham et al., 2014](#); [Evans et al., 2009](#)). More massive Galactic regions such as Carina and Cygnus X extend this connection to environments dominated by high-mass stars, where young stellar populations, molecular clouds, ionized gas, winds, and feedback-driven structures can be studied together ([Comerón et al., 2020](#); [Preibisch et al., 2011a,b](#); [Smith et al., 2010](#); [Wright et al., 2010](#)).

Figure 1.5 shows one example of these nearby star-forming laboratories: the Orion Nebula (Figure from [European Southern Observatory, 2010](#)). On the left is visible light, where much of the light is dominated by bright ionized gas, illuminated cloud surfaces, and dark dust lanes that



**Figure 1.5:** The Orion Nebula, shown in different wavelengths from [European Southern Observatory \(2010\)](#) with ground-based observatories. The left panel shows visible light, while the right is VISTA near-infrared. Orion illustrates why nearby Galactic regions provide powerful laboratories for connecting young stars to their natal environments. Image credit: ESO/J. Emerson/VISTA; Cambridge Astronomical Survey Unit, R. Gendler.

shape the visible morphology of the region. In contrast, in the near-infrared, the obscuring effect of dust is reduced, revealing a larger fraction of the young stellar population embedded within and behind the cloud. The comparison between optical and near-infrared imaging shown in Figure 1.5 illustrates how different wavelengths trace different components of the same star-forming complex. Features that appear as dark structure in the optical become part of the stellar environment in the infrared, directly linking the exposed nebula to the younger stars still emerging from it.

The same approach extends across other nearby Galactic star-forming regions. Much of modern star formation theory has been built from observations that place resolved young stars in direct context with the gas, dust, and feedback structures that shape their formation. In these regions, stellar ages, masses, disks, accretion signatures, and spatial clustering can be compared directly to molecular gas, dust extinction, ionization fronts, and feedback-driven structures ([Lada & Lada, 2003](#)). While mitigated by improvements with Gaia ([Collaboration et al., 2021](#)), the tradeoff is that the Milky Way is difficult to view in entirety. Our position inside the disk introduces projection effects, uncertain distances, variable extinction, and line-of-sight confusion. Nearby external galaxies therefore provide a complementary laboratory. Wide-field ground-based surveys of the Magellanic Clouds ([Cioni et al., 2011](#); [Zaritsky et al., 2002](#)), M31 and M33 (e.g., [Massey et al., 2006](#)), and other Local Group systems have shown that resolved stellar populations can be mapped

across coherent galactic structures, from bars and disks to halos, tidal debris, and dwarf satellites (McConnachie, 2012).

The Magellanic Clouds are especially important examples of this bridge between Galactic and extragalactic star formation. The Large Magellanic Cloud hosts 30 Doradus, one of the most massive and active star-forming complexes in the Local Group, where the young massive cluster R136, surrounding OB associations, ionized gas, and feedback-driven structures can be studied in a common environment (Crowther et al., 2010; Walborn, 1991). More broadly, the LMC and SMC provide resolved stellar populations at lower metallicities than the Milky Way, and with interaction histories that have shaped their recent star formation (Harris & Zaritsky, 2009; Nidever et al., 2011; Zaritsky et al., 2002).

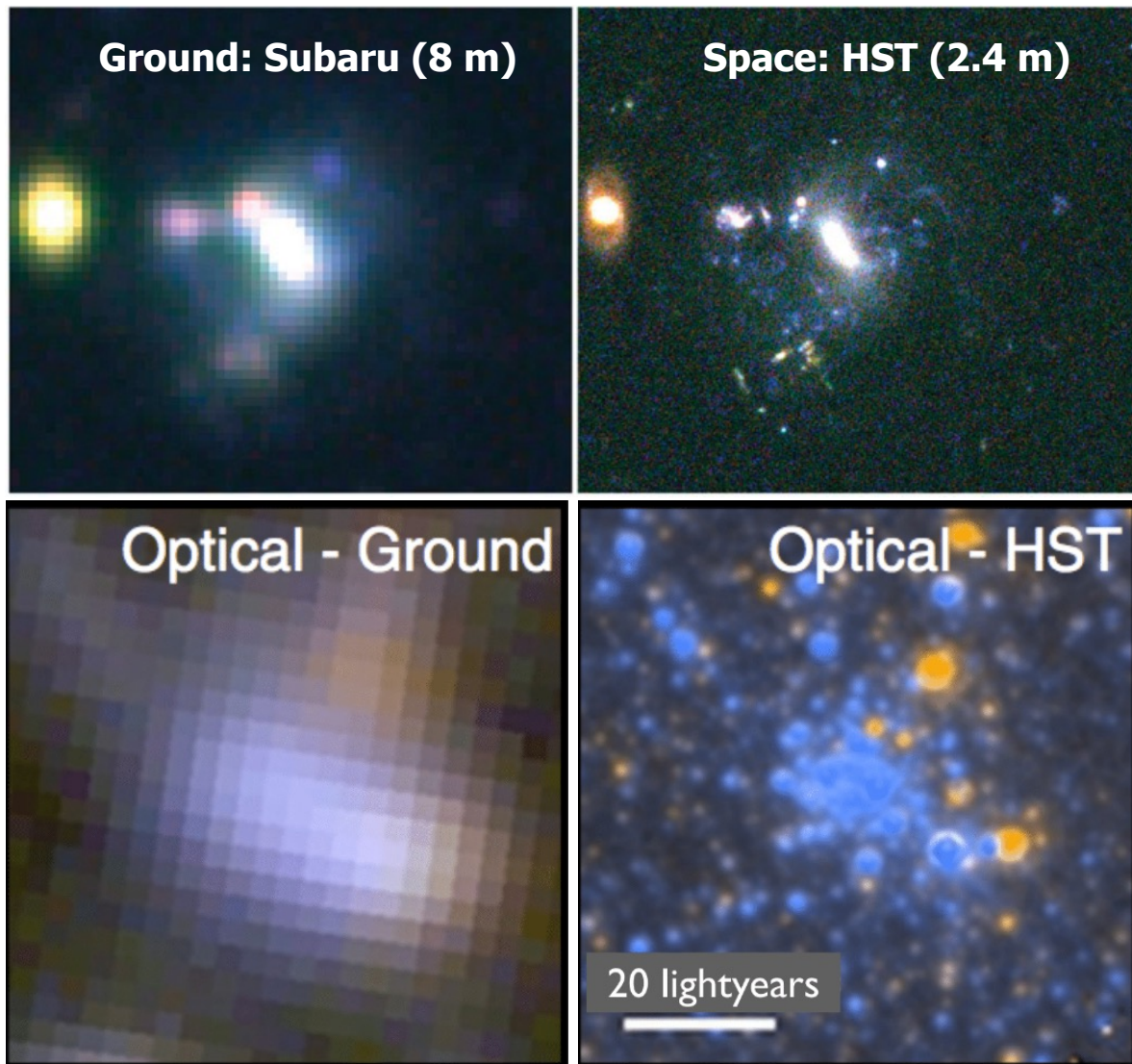
The step from Galactic regions to nearby galaxies does not require a new conceptual framework so much as a more demanding observational one. Beyond the Milky Way the most diagnostic stars are faint, crowded, and easily blended with their neighbors. The surveys discussed in this section demonstrated that stellar populations can be mapped across Local Group galaxies, but the depth and angular resolution needed for precise crowded-field photometry pushed against the limits imposed by the atmosphere. This observational bottleneck set the stage for the Hubble Space Telescope (HST), which we discuss in more detail in the next section.

### 3.5 The HST Legacy

HST truly transformed resolved stellar population work by removing one of the primary limitations faced from the ground: the blurring imposed by Earth’s atmosphere. For nearby galaxies, where the most informative stars are often faint and projected against crowded stellar backgrounds, angular resolution is not a technical detail but a scientific requirement. Figure 1.6 illustrates this point directly. In ground-based imaging, even from large telescopes, neighboring stars can blur together into diffuse structure, limiting the ability to measure accurate colors and magnitudes for individual stars. In contrast, HST resolves the same regions into much sharper stellar sources, turning blended light into measurable stellar populations. The lower panel illustrates this the same principle in an M31 star cluster (Johnson et al., 2012, 2015), showing the impact for the stellar populations discussed throughout this work. The improvement in angular resolution separates stars that would otherwise be confused in a crowded field. This capability made it possible to construct precise CMDs in environments where ground-based observations blend many stars together, extending resolved-star methods from nearby clusters and the brightest stellar populations to crowded regions across the Local Group and nearby Universe (Dalcanton, 2009).

A major part of this legacy has come from large HST imaging programs designed to resolve nearby galaxies into individual stars and star clusters. These surveys used optical and ultraviolet photometry to measure stellar populations across a wide range of environments, from dwarf galaxies and galaxy halos to spiral disks, star-forming complexes, and interacting systems. Programs such as ANGST (Dalcanton et al., 2009), PHAT (Dalcanton et al., 2012; Williams et al., 2014), PHATTER (Williams et al., 2021), PHAST (Chen et al., 2025), ISLAndS (Skillman et al., 2017), the M31 Satellites Treasury (Savino et al., 2022), LEGUS (Calzetti et al., 2015), HTTP (Sabbi et al., 2013), LUVIT (Gilbert et al., 2025), Scylla (Murray et al., 2024), and GULP (Sabbi et al., 2026) have produced homogeneous catalogs, deep CMDs, cluster samples, and spatially resolved star formation histories for many of the nearest galaxies. Together, these programs established HST imaging as one of the central observational foundations for connecting individual stars to the





**Figure 1.6:** Comparison of ground-based and HST imaging, illustrating the effect of angular resolution on resolved stellar population studies. The top panels show the same distant galaxy observed from the ground with the Subaru 8-m telescope and with HST; atmospheric blurring in the ground-based image blends neighboring stars and small-scale structure, while HST resolves the galaxy into sharper individual sources. The bottom panels show the same effect for a star cluster in M31 (Johnson et al., 2012), where HST separates stars in a crowded field that are blended at lower angular resolution. The top panels are adapted from Dalcanton (2009); the bottom panels are courtesy of Anil Seth, private communication.

histories of their host galaxies.

The legacy of these surveys lies not only in the large and comprehensive resolved stellar catalogs they produced, but in what those stars can tell us about each galaxy's evolutionary history. In nearby dwarf galaxies, HST CMDs have shown that galaxies with similar present-day masses can have very different formation histories, ranging from predominantly ancient systems to galaxies with extended or bursty star formation over much of cosmic time (McQuinn et al., 2010; Weisz

et al., 2014, 2011). In the LMC, SMC, and M31, this approach transformed from a global measurement into a spatially resolved one, mapping recent star formation across the disk and linking it to coherent structures such as spiral arms and the 10 kpc ring, while deeper CMD fitting constrained the older stellar mass assembly of the disk (Harris & Zaritsky, 2004, 2009; Lewis et al., 2015; Williams et al., 2017).

In addition to the star formation histories of entire galaxies, studies of the stellar populations within a galaxy, namely clusters, have also improved with HST. Homogeneous HST imaging has produced large samples of resolved star clusters across a range of nearby galaxies, providing a powerful basis for testing how clusters form, evolve, and trace the broader process of star formation. These studies have allowed some of the best constraints on the initial mass function of stars to date (Escher Jung et al., 2023; Fillion et al., 2024; Gennaro & Robberto, 2020; Gennaro et al., 2018a,b; Liu et al., 2009; Weisz et al., 2015, which we revisit in Chapter 3 of the thesis), as well as the best statistics on how massive clusters can be themselves, and the amount of stars they form (Adamo et al., 2015, 2017; Jordan et al., 2007; Linden et al., 2017; Tang et al., 2024; Whitmore et al., 1999; Zhang & Fall, 1999), with a link between how many stars a galaxy forms and how large it's clusters can be (Johnson et al., 2017; Larsen, 2009; Wainer et al., 2022).

HST observations have also reshaped the interpretation of star clusters themselves. Earlier, star clusters were taken as the cleanest approximation to a simple stellar population – i.e., a group of stars with a common age, distance, and initial composition. However, high-precision HST photometry has shown that this approximation is incomplete for many globular clusters. Instead of a single narrow evolutionary sequence, many clusters show split or broadened main sequences, subgiant branches, red giant branches, and horizontal branches, indicating the presence of multiple stellar populations with distinct chemical abundance patterns (Clontz et al., 2024; Milone & Marino, 2022; Milone et al., 2012, 2017, 2018). These results turned globular clusters from simple calibration objects into laboratories for testing formation channels in the early universe, chemical enrichment, and the early dynamical evolution of dense stellar systems (Marchuk et al., 2026; Wallace et al., 2005).

The observational leverage of HST that helped lead to these discoveries in both clusters and SFHs came in part from the ability to obtain precise photometry in crowded fields and in filters that isolate the signatures of different stellar populations. Ultraviolet and blue photometry are especially sensitive to light-element abundance variations, while narrow-band  $H\alpha$  imaging can identify emission-line sources, accretion signatures, and interacting or unusual stellar systems within clusters (Cohen et al., 2021; Dondoglio et al., 2022). Additionally, HST imaging of young stellar populations has also connected these different interfaces. Particularly regarding clusters, associations, massive stars, and feedback-shaped gas in actively star-forming environments, including 30 Doradus discussed in the previous section, and nearby spiral galaxies (Cook et al., 2019; Peltonen et al., 2023; Sabbi et al., 2013).

HST and the studies discussed within this section established the framework for studying resolved stars as a way to recover not only *when* galaxies formed stars, but where that star formation occurred and how it related to galactic structure and environment. Ultraviolet imaging remains especially important for these studies because hot, massive stars emit strongly at UV wavelengths, making UV light one of the classical tracers of recent star formation (Kennicutt & Evans, 2012; Kennicutt, 1998; Leitherer et al., 1999). For resolved stellar populations, combining UV and optical photometry also increases the temperature baseline of the CMD, improving the separation of young main-sequence stars from evolved blue helium-burning populations that are used to re-

construct recent star formation histories (Dalcanton et al., 2012; Dohm-Palmer & Skillman, 2002; Dohm-Palmer et al., 2002). As long as HST remains available, its ultraviolet sensitivity and stable high-resolution imaging continue to provide a capability that is difficult to replace from the ground.

## 4 The Current Frontier

The legacy of HST is not only historical. As the chapters of this thesis show, HST remains central to resolved stellar population work, and its ultraviolet and optical imaging continue to provide measurements that cannot simply be replaced by any other current facility. At the same time, the framework built by HST has made the present moment especially rich for studies of star formation with new facilities. In particular, the James Webb Space Telescope (JWST) extends HST's successes into the infrared, revealing younger and more embedded phases of star formation that are difficult or impossible to access in the optical, and with better spatial resolution at shorter wavelengths. These new observations do not stand alone, however. As the data become deeper, sharper, and more multi-wavelength, the interpretation increasingly depends on simulations that can connect physical models of gas, stars, dust, feedback, and dynamics to the observables measured by telescopes. The current frontier described in this section explores these two linked advances: new facilities that reveal star formation in regimes previously hidden from view, and increasingly realistic models that allow those observations to be interpreted in physical terms.

### 4.1 JWST Is Challenging Existing Pictures of Star Formation

JWST is changing our understanding of the balance between stars, dust, and gas. Many of the youngest stellar populations are difficult to interpret at optical wavelengths because they remain embedded in their natal material, where extinction hides young stars and reshapes the light that escapes. JWST's near- and mid-infrared imaging reaches into these dusty environments, revealing embedded sources, warm dust, PAH emission, shells, filaments, and feedback-carved structures that were previously inaccessible or unresolved in nearby galaxies (Lee et al., 2023; Rodríguez et al., 2023; Sandstrom et al., 2023a; Thilker et al., 2023). At wavelengths where both HST and JWST observe, JWST's larger mirror provides finer angular resolution than HST, while its infrared sensitivity opens a view of star formation that is complementary to HST's ultraviolet and optical strengths. The result is not simply a sharper picture, but a more complete census of the star formation process.

Figure 1.7 shows this shift from optical to infrared diagnostics in the nearby spiral galaxy NGC 628. This comparison is analogous to the optical and near-infrared view of Orion shown in Figure 1.5, but now applied across an entire galaxy. In the HST optical image in the bottom right portion of the figure, dust appears primarily as dark lanes where visible starlight is absorbed, while young stars and HII regions stand out in blue, purple, and pink. In the JWST image in the upper left, which combines near- and mid-infrared light, the same dust is seen in emission, tracing in red and orange the spiral filaments, knots, and cavities throughout the disk. The two views therefore trace different components of the star formation cycle. HST emphasizes exposed stars and ionized gas, while JWST reveals the dusty structures, embedded regions, and infrared-bright material associated with ongoing and recent star formation.





**Figure 1.7:** Comparison of JWST and HST views of the nearby spiral galaxy NGC 628. The upper-left portion shows JWST near- and mid-infrared imaging, where dust emits brightly in red and orange and traces spiral filaments, knots, and cavities. The lower-right portion shows HST visible-light imaging, where the same dust appears mainly as dark lanes that absorb starlight, while young stellar populations and HII regions appear in blue, purple, and pink. This galaxy-scale comparison echoes the optical/infrared contrast shown for Orion in Figure 1.5, but extends the multi-wavelength view to an entire nearby galaxy. Image credit: NASA, ESA, CSA, STScI, and the PHANGS Team; visualization by Amy Moran. Reproduced from NASA SVS ID 31290.

NGC 628, shown in Figure 1.7, was observed as part of PHANGS-JWST, a multi-facility program designed to connect the small-scale physics of star formation to the larger-scale structure and evolution of nearby galaxies (Lee et al., 2023). PHANGS combines high-resolution observations from ALMA, VLT/MUSE, HST, and JWST, bringing together molecular gas, ionized gas, exposed stellar populations, star clusters, and infrared dust emission in the same galaxies. The JWST component extends this framework into the near- and mid-infrared, with imaging from roughly 2 to 21  $\mu\text{m}$ , where dust obscuration is reduced and warm dust and PAH emission become visible. In this way, PHANGS-JWST adds the obscured and dusty phases of recent star formation to the optical view established by HST (Lee et al., 2023).

Several early PHANGS-JWST studies show how this multi-wavelength view is already being used to test the timing and environment of star formation. In NGC 628 (Figure 1.7), JWST imaging has been used to measure the duration of the embedded phase of massive star formation, demonstrating that this measurement can now be extended well beyond the few nearest galaxies accessible with earlier infrared facilities (Kim et al., 2023). In the same galaxy, JWST, ALMA, and MUSE observations of spiral-arm spurs show that some young star-forming regions cannot be explained

simply as material that formed in the spiral arm and then drifted downstream, pointing instead to localized star formation within spurs themselves (Williams et al., 2022). In barred environments, PHANGS-JWST observations of NGC 1365 connect massive young clusters, molecular gas lanes, and a central star-forming ring, showing how gas inflow and rapidly evolving dense gas structures can shape intense circumnuclear star formation (Schinnerer et al., 2023).

Additional PHANGS-JWST results focus on the dusty ISM itself, revolutionizing how dust is used in studies of star formation. Near-infrared extinction mapping in the Milky Way, enabled on large scales by 2MASS, established dust as a tracer of molecular-cloud column density and structure rather than only an obscuring screen (Lada et al., 1994; Lombardi & Alves, 2001; Lombardi et al., 2006; Skrutskie et al., 2006). JWST now extends this view to external galaxies, where infrared emission maps reveal dust as a structured component of the star-forming ISM. PAH emission traces small grains illuminated by nearby stellar populations, while warm dust emission reveals filaments, knots, shells, holes, and bubble-like structures across spiral disks (Sandstrom et al., 2023a,b). The strength and morphology of this emission vary between star-forming regions, diffuse emission, spiral arms, and inter-arm environments, linking the dusty ISM to both local radiation fields and larger galactic structure (Thilker et al., 2023). These infrared maps connect recent star formation to the surrounding medium, showing where young stars have heated, cleared, or reshaped the gas and dust around them (Chastenet et al., 2023).

JWST is also beginning to shape resolved star formation history work. The JWST Resolved Stellar Populations Early Release Science program demonstrated that NIRCarn and NIRISS can obtain precise crowded-field photometry in Local Group systems spanning very different distances, luminosities, and surface brightnesses, including the globular cluster M92, the ultra-faint dwarf Draco II, and the star-forming dwarf galaxy WLM (Weisz et al., 2023). In these local dwarfs, JWST/NIRCarn reached below the oldest main-sequence turnoff and produced the first SFH and age-metallicity relation derived from resolved stellar populations observed with JWST (McQuinn et al., 2024a). The resulting SFH agreed well with overlapping HST-based measurements, validating near-infrared CMD fitting as a tool for galaxy archaeology (McQuinn et al., 2024b). More recently, spatially resolved JWST and HST measurements of WLM have mapped stellar age gradients across the galaxy, connecting the timing of star formation to structure and environment within a dwarf galaxy (Cohen et al., 2025). These resolved star studies emphasize that JWST is not only revealing embedded star formation, but also extending the resolved-star methods developed with HST into new wavelength regimes and more obscured or crowded environments.

These recent JWST results allow us to sharpen the questions that we can ask. Infrared imaging now reveals which young populations remain hidden from optical surveys, how long stars and clusters stay embedded in their natal material, and how feedback reshapes the surrounding dust and gas before those populations become visible. At the same time, spatially resolved star formation histories continue to show that recent star formation is tied to galactic structure rather than distributed uniformly across disks. These themes run through the chapters that follows in this thesis.

## 4.2 Connecting Observations and Theory with Simulations

The observations described above reveal what can be measured across the nearby Universe at the present moment. By comparing regions and galaxies at different evolutionary stages, we can infer how stars form, emerge from their natal material, and assemble into larger stellar populations. Those inferences, however, are built from snapshots. Simulations provide a complementary

view by following the same physical system continuously through time. They allow the processes inferred from resolved observations, including collapse, fragmentation, accretion, feedback, and dispersal, to be tested in controlled numerical experiments where the full evolutionary sequence can be tracked directly.

Computer simulations have become essential for translating the theory of star formation into quantitative predictions. Early and modern calculations alike have shown that gravitational collapse, turbulence, rotation, magnetic fields, radiative transfer, and feedback cannot be treated as isolated ingredients, because their effects are coupled across many spatial and temporal scales (Boss, 2009; McKee & Ostriker, 2007). In particular, numerical studies of turbulent molecular clouds have shown how turbulent structure seeds fragmentation and regulates the formation of dense cores and stars (Federrath, 2015). As computational power and numerical methods have improved, simulations have become increasingly capable of following the formation of stars and clusters within turbulent molecular gas while including the effects of outflows, radiation, winds, and stellar feedback (Krumholz et al., 2019). This progress makes simulations a central counterpart to resolved observations, providing a way to ask which physical processes can reproduce the stellar populations, gas structures, feedback signatures, and embedded phases being measured in nearby galaxies.

The relevant simulations span a wide range of scales. Cosmological and galaxy-scale calculations follow the growth of galaxies within their large-scale environments, including gas accretion, mergers, chemical enrichment, feedback, and the buildup of stellar mass over cosmic time (Hopkins et al., 2023; Pillepich et al., 2018). Zoom-in simulations push this connection further by concentrating resolution on a single galaxy or region, making it possible to study how inflow, satellite interactions, feedback, and environmental evolution shape the star formation history of a particular system (Hopkins et al., 2014; Wetzel et al., 2016). These simulations provide the natural theoretical counterpart to spatially resolved SFHs. Observations recover when and where stars formed, while simulations test which physical processes could have produced those patterns.

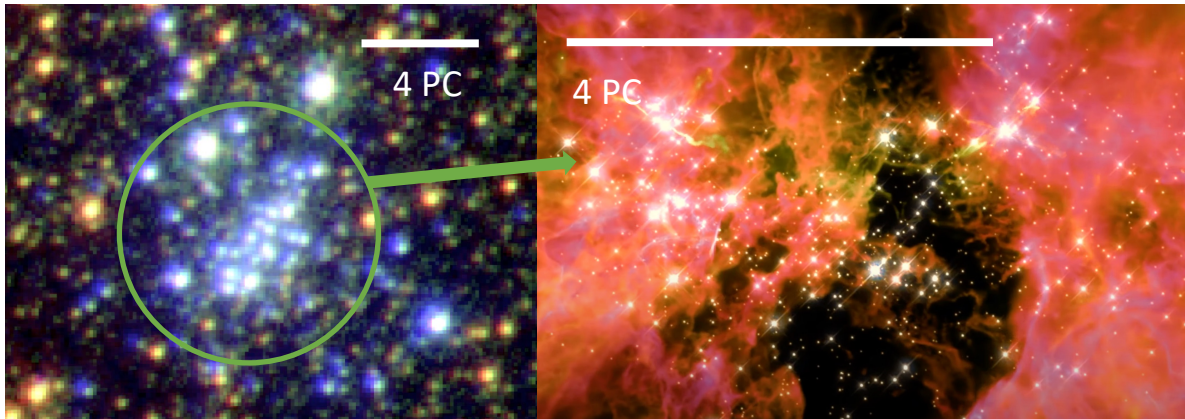
A complementary approach focuses on the internal evolution of molecular clouds and young stellar systems. These calculations give up cosmological volume in order to resolve the dense gas, fragmentation, accretion, and stellar dynamics that shape individual star-forming regions. At this scale, the formation of stars can be followed alongside protostellar outflows, radiation, winds, and supernova feedback within the same evolving cloud (Bate, 2009a,b; Grudić et al., 2020; Offner et al., 2009a), while the resulting stellar population depends on the initial conditions of the cloud (Bate, 2009c; Grudić et al., 2023; Grudić & Hopkins, 2019). This class of resolution has emphasized that star formation is hierarchical and time-dependent, as stars form in clustered structures within turbulent gas, while accretion, feedback, and dynamical evolution proceed simultaneously rather than as separate stages (Dale et al., 2014; Grudić et al., 2018, 2022; Offner et al., 2009a).

One particularly inspiring<sup>6</sup> example of this cloud-scale approach is the STARFORGE project, a suite of simulations designed to follow star formation within giant molecular clouds while resolving the formation and accretion of individual stars (Grudić et al., 2021). The STARFORGE framework combines self-gravity, magnetohydrodynamics, gas thermodynamics, radiative transfer, protostellar jets, stellar radiation, winds, and supernova feedback, allowing multiple feed-

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<sup>6</sup>I have a particular affinity for STARFORGE for several reasons. First and foremost is because of my amazing experience working within the collaboration. But also because of their truly sensational visualizations, which, as an undergraduate studying star clusters, mesmerized me. Other examples of cloud scale simulations exist in the literature, but frankly, not in my heart.





**Figure 1.8:** Left: HST/JWST combined 3 color (F090W, F200W & F336W) image of young star cluster LGCS 45 in Local Group galaxy M33 (Johnson et al., 2022). Shown in green is the cluster radius from Johnson et al. (2022), with the scale bars indicating the same area covered in the STARFORGE simulation. Right: snapshot of a STARFORGE simulation (Grudić et al., 2021), highlighting the precision and compatible physical scales between Local Group resolved stellar population studies and cloud-scale simulations.

back channels to act together during cloud collapse and dispersal (Grudić et al., 2021, 2022). In these simulations, stars, clusters, filamentary gas structure, and feedback-carved cavities form self-consistently, making it possible to study how young stellar populations emerge from dusty star-forming environments (Grudić et al., 2022). Subsequent STARFORGE work has used this framework to examine how feedback and environment shape the IMF, star formation efficiency, stellar multiplicity, and cluster assembly (Guszejnov et al., 2021, 2022, 2023).

The connection to resolved stellar population work is especially clear in the physical scales involved. The same parsec-scale structures that nearby-galaxy observations can now resolve, including young clusters, associations, compact star-forming regions, and the gas and dust surrounding them, are also the scales followed directly in high-resolution cloud simulations. Figure 1.8 illustrates this overlap. The left panel shows a young stellar population in M33 (Johnson et al., 2022; Wainer et al., 2022) observed with combined HST and JWST imaging, while the right panel shows a snapshot from a STARFORGE simulation on a comparable physical scale. In both cases, the relevant structures are only a few parsecs across. This comparability makes STARFORGE a natural theoretical counterpart to the HST and JWST observations discussed above.

Throughout this section, I have argued how the temporal information of simulations provide a bridge to interpreting star formation in a way infeasible for even the best observations. Additionally, by post-processing simulations and applying the same observational limitations that affect real images, simulations can be used to ask which stars would be visible, which would remain hidden, how the surrounding dust would appear, and how long different phases of star formation would be observable. Simulations can therefore be a tool for interpreting what our observational constraints and biases are.

The current frontier in resolved stellar population studies is therefore defined by the combination of new observations and physically motivated models. HST has established the ability to measure individual stars across nearby galaxies, while JWST is revealing embedded stellar populations and dusty star-forming structures that were previously difficult to access. At the same time, modern



simulations now follow the formation and emergence of young stellar populations on comparable physical scales. The chapters that follow sit within this combined observational and theoretical landscape. In this thesis, I examine how young stars emerge from dusty environments, how recent star formation is distributed across galactic structure, how resolved stellar populations can be used to infer the physical conditions under which stars formed, and test our analytical ability to measure star formation from different tracers.

## 5 Thesis Outline

In this outline, I introduce each work using the abstracts from the respective papers. Within this thesis, I choose to move through the scales of star formation, first beginning with the smallest scales, and progressing to galaxy scales. Because these works were conducted in collaboration with others, I transition to the inclusive “we” throughout.

### 5.1 Chapter 2 Summary

In Chapter 2, we study the theory behind the first moments of star formation, and the interplay between embedded, and emerging stars. Specifically, the timing and physical mechanisms that govern the transition from deeply embedded to exposed stars remain uncertain. Using the STARFORGE simulations, we analyze the evolution of “embeddedness”, identifying what drives emergence. We find the transition from embedded to exposed is fast for individual stars, within 1.3 Myr after the star reaches its maximum mass. This rapid transition is dominated by massive stars, which accrete while remaining highly obscured until their feedback eventually balances, then overcomes, the local accretion. For these massive stars, their maximum mass is reached simultaneously with their emergence. Once these stars are revealed, their localized, pre-supernova feedback then impacts the cloud, driving gas clearance. Because massive stars dominate the luminosity, their fast, local evolution dominates the light emergence from the dust. We calculate the dependence of these processes on the mass of the cloud and find that emergence always depends on when massive stars form, which scales with the cloud’s free-fall time. We also measure the evolution of dust and  $H\alpha$  luminosities, where for  $\sim 2$  Myr, these tracers outshine the emerging stellar continuum, reaching their peak when gas and dust remain tightly coupled to the massive stars. These results closely resemble observationally observed lifetimes, tying the observable dust and line emission directly to the same localized processes that drive stellar emergence, evidence that our simulated de-embedding physics is representative of real star-forming regions.

### 5.2 Chapter 3 Summary

In Chapter 3, we then try and quantify how many stars are formed in a given star forming event. To do this, we measure the high-mass stellar initial mass function (IMF) from resolved stars in M33 young stellar clusters. Leveraging *Hubble Space Telescope*’s high resolving power, we fully model the IMF probabilistically. We first model the optical CMD of each cluster to constrain its power-law slope  $\Gamma$ , marginalized over other cluster parameters in the fit (e.g., cluster age, mass, and radius). We then probabilistically model the distribution of MF slopes for a highly strict cluster

sample of 9 clusters more massive than  $\log(\text{Mass}/M_{\odot})=3.6$ ; above this mass, all clusters have well-populated main sequences of massive stars and should have accurate recovery of their MF slopes, based on extensive tests with artificial clusters. We find the ensemble IMF is best described by a mean high-mass slope of  $\bar{\Gamma} = 1.49 \pm 0.18$ , with an intrinsic scatter of  $\sigma_{\Gamma}^2 = 0.02_{0.00}^{+0.16}$ , consistent with a universal IMF. We find no dependence of the IMF on environmental impacts such as the local star formation rate or galactocentric radius within M33, which serves as a proxy for metallicity. This  $\bar{\Gamma}$  measurement is consistent with similar measurements in M31, despite M33 having a much higher star formation rate intensity. While this measurement is formally consistent with the canonical Kroupa ( $\Gamma = 1.30$ ) IMF, as well as the Salpeter ( $\Gamma = 1.35$ ) value, it is the second Local Group cluster sample to show evidence for a somewhat steeper high-mass IMF slope. We explore the impacts a steeper IMF slope has on a number of astronomical sub-fields.

### 5.3 Chapter 4 Summary

In Chapter 4, we move to galactic scales, and study star formation in the Andromeda galaxy, our nearest spiral neighbor. We use *Hubble Space Telescope* optical imaging from the Panchromatic Hubble Andromeda Southern Treasury (PHAST) to measure the spatially resolved recent star formation history (SFH) across the southern disk of M31. We fit color–magnitude diagrams (CMDs) of over 6500 individual  $0.01 \text{ kpc}^2$  regions to measure SFHs over the last  $\sim 500 \text{ Myr}$ . The resulting maps show coherent structure which trace the ringed morphology of the disk. We find a clear global decline in the recent star formation rate (SFR), with a pronounced drop in the last  $\sim 40 \text{ Myr}$  that is most evident in the region closest to M32. Combining PHAST and PHAT measurements, we now cover two-thirds of M31’s star forming disk with homogeneous SFHs derived with the same technique, yielding the highest resolution spatially resolved SFHs of M31 measured with resolved stars. Inside the joint footprint, we measure a mean SFR of  $0.445 \pm 0.006 M_{\odot} \text{ yr}^{-1}$  over the last 100 Myr, and  $0.285 \pm 0.014 M_{\odot} \text{ yr}^{-1}$  over the last 20 Myr, implying a total disk SFR of  $\sim 0.67 M_{\odot} \text{ yr}^{-1}$  and  $\sim 0.43 M_{\odot} \text{ yr}^{-1}$  respectively when extrapolated to the full star-forming disk. The observed decline is interpreted to be the late stages of a multi-Gyr wind-down from a previously more active state. Because recent star formation in M31 is concentrated primarily in the rings, the observed global decline is driven mainly by decreasing activity within those features. We also compare the CMD-based SFR surface densities to those inferred from FUV+24  $\mu\text{m}$  prescriptions and find that the FUV-based calibration underestimates the CMD-based 100 Myr average by a factor of  $\sim 2.1$ . However, the PHAST SFHs produce a synthetic *GALEX* FUV image that agrees well with observations, indicating that the CMD-derived SFHs provide an accurate description of recent star formation. The mismatch with the FUV+24  $\mu\text{m}$  estimates underscores that tracers implicitly averaged over  $\sim 100 \text{ Myr}$  are not reliable when the recent SFR is evolving.

### 5.4 Chapter 5 Summary

Given this uncertainty with FUV star formation tracers that we observe in Chapter 4, in Chapter 5, we move to analytically characterize the reliability of the FUV when the recent SFH is evolving. More specifically, FUV luminosities are broadly used commonly interpreted as tracers of star formation averaged over the last  $\sim 100 \text{ Myr}$ . However, this timescale is usually calibrated under the assumption of a constant recent SFH. This assumption may be appropriate when averaged over slowly evolving massive galaxies, but may not apply when the SFR is changing rapidly, or,

when analyzing increasingly small subregions of galaxies that approach the size of star forming gas clouds. We therefore revisit the effective timescale of FUV-based SFRs when relaxing the requirement that the SFH is constant. Because the FUV mass-to-light ratio changes rapidly with time, many different star formation histories can produce the same present-day FUV luminosity, and the FUV measurement becomes increasingly uncertain as a constraint on the true average SFR beyond  $\sim 35$  Myr if the SFH is not constant. Further, across a grid of different idealized rising and declining SFHs, we find that averaging timescales of  $\sim 25$ – $40$  Myr provide the best agreement between the FUV-inferred SFR and the true input SFR. We then compare nearby galaxies with published CMD-based SFHs and FUV-based SFR estimates, finding that CMD averages over  $25$ – $32$  Myr bring M31, M33, into closer agreement with the FUV-based measurements than the traditional  $100$  Myr averages. Additionally, we find that calibration and IMF choices introduce systematic shifts in FUV-based SFRs at the  $\sim 20\%$  level. These results suggest that when recent SFHs are evolving, FUV-based SFRs are better interpreted as luminosity-weighted averages over the last few tens of Myr rather than as universal tracers of a fixed  $100$  Myr interval.

### 5.5 Chapter 6 Summary

In Chapter 6, I briefly describe some of the immediate next steps for the work completed in this thesis, and offer some concluding remarks.

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## CHAPTER 2

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# THE TIMESCALES OF EMBEDDED STAR FORMATION AS OBSERVED IN STARFORGE

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## 1 Introduction

It is widely accepted that stars are born during the gravitational collapse of turbulent molecular clouds (e.g., Lada & Lada, 2003, for review). These stars eventually emerge from the cloud, through a variety of feedback processes that clear the surrounding gas, leaving a largely unobscured view of the newly-formed stars (Krause et al., 2020; Pineda et al., 2023).

Early on, however, accreting protostars remain enshrouded in their dusty natal clouds. These young stars are typically shielded by heavy layers of dust, making them largely invisible at optical wavelengths. At longer wavelengths however, they can be detected – either directly as individual stars, or, indirectly through their heating of the surrounding dust. In this early phase, these collections of enshrouded stars and protostars are known as embedded clusters and are some of the earliest windows onto the star formation process (Ascenso, 2018).

This embedded stage concludes when gas is expelled from the region, exposing the stars, and consequently destroying the GMC (See reviews Chevance et al., 2020; Krumholz, 2014; Schinnerer & Leroy, 2024, and references within). The primary mechanisms for this gas removal are through accretion-driven bipolar jets and outflows, radiation, and stellar winds from protostars (Grudić et al., 2022; Guszejnov et al., 2022).

Two primary parameters are thought to determine the evolution of an emerging embedded cluster: the star formation efficiency and the timescales of gas dispersal (Lada & Lada, 2003). Specifically, gas removal, and the timescales on which it occurs, is critical to star formation models. Once material is removed from the system, star formation is quenched, not only regulating star formation locally, but on a galactic scale (e.g., Krumholz et al., 2019, 2005).

Despite its importance, the underlying mechanism which govern how, and when, gas is cleared – and the associated observability of the embedded phase – remains poorly constrained. There remain ongoing conversations about the timescales over which this gas removal takes place, how long the newly formed stars remain embedded observationally, and what physical processes drive the clearance and its timescales (e.g., Chevance et al., 2022; McLeod et al., 2021; McQuaid et al., 2024).

Efforts to constrain embedded cluster lifetimes have historically relied on associating young stellar clusters with their parent molecular clouds. Early studies found that clusters younger than  $\sim 5$  Myr were often still embedded, while older ones were not, suggesting gas is typically cleared on  $\sim 5$  Myr timescales (e.g., Lada & Lada, 2003; Leisawitz et al., 1989; Whitmore & Zhang, 2002). More recent work extended this method to external galaxies using HST to detect young clusters and using ALMA observations to trace molecular gas or  $H\alpha$  to trace ionized gas (e.g., Grasha et al., 2018; Hannon et al., 2022; Whitmore et al., 2011, 2025). These larger samples often yield shorter inferred timescales of 1–2 Myr across diverse galactic environments.

However, a central limitation is that optical and UV studies are blind to the most deeply em-



bedded phases. The stars must already be clearing their surroundings to be observable at these wavelengths, meaning that these methods trace when clusters become visible, not when star formation starts or gas dispersal begins. The resulting timescales are therefore biased toward later, more exposed stages.

Infrared (IR) observations fill part of this gap. Dust emission in the mid- and far-IR can trace embedded clusters before their stellar populations emerge in the optical or UV. When individual stars are resolved, their ages provide constraints on how long dust and gas remain detectable (e.g., [Getman et al., 2014](#)). Using this approach, studies with *Spitzer* and *Herschel* generally recover longer embedded lifetimes of  $\sim 3-5$  Myr (e.g., [Battersby et al., 2017](#); [Chevance et al., 2022](#); [Kim et al., 2021](#); [Morales et al., 2013](#)), reflecting their sensitivity to earlier stages of cluster formation.

However, IR observations face their own challenges. Dust emission is not exclusive to embedded clusters; contamination from field stars and unrelated star-forming regions can lead to false positives ([Ascenso, 2018](#)). Without high-resolution imaging and multi-wavelength context, it's difficult to determine whether a dusty region truly corresponds to an embedded system ([Johnson et al., 2022](#)).

The capabilities of JWST are beginning to resolve this ambiguity. For the first time, we can spatially disentangle embedded structures in external galaxies, simultaneously tracing both stellar content and dust emission at sub-parsec resolution (e.g., [Lee et al., 2023](#); [Rodríguez et al., 2023, 2025](#)). In particular, polycyclic aromatic hydrocarbons (PAHs) serve as a powerful tracer of cluster emergence, illuminating photodissociation regions (PDRs) as UV radiation escapes young stars ([Knutas et al., 2025](#); [Rodríguez et al., 2023](#); [Whitmore et al., 2023](#)). These signatures enable detailed mapping of the de-embedding process; but critically, they still require stellar ages to anchor timescales.

While there is general consensus that the de-embedding process takes less than 5 Myr ([Portegies Zwart et al., 2010](#); [Schinnerer & Leroy, 2024](#)), the process is complex. Importantly, the interpretation of this timescale varies depending on the observable—whether it is CO, dust, PAH, or  $H\alpha$  emission. Different tracers probe different phases of feedback and dispersal ([Kruijssen et al., 2018](#)), and different techniques emphasize different parts of the sequence ([Leisawitz et al., 1989](#)). Moreover, mounting evidence suggests that the embedded lifetime may not be fixed, but instead varies with the mass and environment of the parent cloud ([Knutas et al., 2025](#); [Leroy et al., 2025](#); [McQuaid et al., 2024](#)).

Theoretically, it is likely that the lifetime of the embedded phase is closely tied to the formation and evolution of massive stars. Winds and radiation from massive stars dominate the stellar feedback, so the timing of their formation is likely to be coupled to the timing of gas removal (e.g., [Kim et al., 2021](#); [Lewis et al., 2023](#)). However, measuring these formation timescales directly is extremely challenging, with the largest source of uncertainty being how stellar ages are measured ([Getman et al., 2014](#)). Additionally, it is unclear when embedded massive stars can be detected individually as protostars, or how long it takes for high mass stars to form (e.g., [Backs et al., 2024](#)).

To address these challenges, simulations provide a valuable alternative. With complete knowledge of stellar properties and gas dynamics, simulations can isolate the physical mechanisms that regulate embedded lifetimes and test how different tracers respond to them. As a proven laboratory for testing star formation models, the recent increase in high performance computing has allowed simulation studies to make large leaps in the models of cluster growth (e.g., [Karam & Sills, 2022](#); [Lahén et al., 2020](#)), embedded cluster morphology, and N-body dynamics (e.g., [Cournoyer-Cloutier et al., 2023](#)).

One of the simulation suites pushing the envelope in resolution is STARFORGE (Grudić et al., 2021). With a mass resolution of  $10^{-3}M_{\odot}$ , STARFORGE fully models individual star formation, incorporating stellar processes including all major forms of feedback along with global properties of gravity and magnetic fields to create a self-consistent model of star formation.

Recent analysis of the STARFORGE simulations has measured the gas removal timescales for several different initial conditions, finding that the gas removal occurs rapidly, taking between 0.7 and 1.7 Myr and around 0.5 cloud free-fall times (Farias et al., 2024). In this work, we build on these measurements, focusing primarily on how this gas removal impacts the embedded cluster’s observability in a variety of ways.

Specifically, we leverage the high resolution of the STARFORGE simulations to investigate the timescales that proto-clusters remain embedded. To do this, we investigate the governing processes of gas removal, the timing and duration of these mechanisms, the drivers of these processes, and the observable signatures of different stages of this process. We perform this measurement for the stellar region as a whole, considering the global ensemble of properties, as well as for individual stars.

This paper is structured as follows. We first introduce the STARFORGE simulations in Section 2. We then describe our methodology for measuring stellar properties (Section 3.1), and extinction (Section 3.2), and present the evolution of embeddedness in Sections 4.1, 4.3. We then present different wavelength observations of the simulation in Section 5, highlighting timescales in Section 5.4. We then discuss the implications of these measurements in Section 6.1.

## 2 STARFORGE Simulations

We analyze a set of 3D radiative magnetohydrodynamical (MHD) STARFORGE simulations (Grudić et al., 2021), which account for all key ingredients needed to describe the dynamics of gravity, MHD, chemistry, radiative cooling, stellar dynamics, and all forms of stellar feedback. Briefly, STARFORGE uses the GIZMO code Hopkins (2015), and the “full” STARFORGE physics setup of Grudić et al. (2022) which includes numerical methods for sink particles, stellar feedback, and evolution, as described in Grudić et al. (2021). These simulations have sufficient mass resolution to resolve the stellar initial mass function (IMF) down to a  $\sim 0.1M_{\odot}$ , enabling resolution of individual protostellar core-collapse, accretion, and feedback flows.

STARFORGE solves the ideal MHD equations using the GIZMO Meshless Finite Mass MHD solver (Hopkins & Raives, 2016), with a constrained-gradient  $\nabla \cdot \mathbf{B}$ -minimization scheme (Hopkins, 2016), and a fixed Lagrangian mass resolution typically set to  $10^{-3}M_{\odot}$ . The time-dependent, frequency-integrated radiation hydrodynamics equations are solved by the GIZMO mesh-free finite-volume solver assuming the M1 closure (Hopkins & Grudić, 2019; Hopkins et al., 2020), with a reduced speed of light of  $90 \text{ km s}^{-1}$ , in five frequency bands ranging from the Lyman continuum to the far IR. The different bands couple to matter through photoionization, photodissociation, photoelectric heating, and dust absorption, accounting for photon momentum. Dust, gas, and radiation temperatures are evolved independently, and self-consistently with the IR band of the RT solver, while radiative heating and cooling from all major molecular, atomic, nebular, and continuum processes using the cooling module of the FIRE-3 simulations (Hopkins et al., 2023).

In STARFORGE, a gas cell forms a sink particle once it satisfies a list of criteria designed to identify the centers of runaway collapse (see Grudić et al. 2021). The newly formed sink particle

can then accrete gas based on the criteria of [Bate et al. \(1995\)](#), which include the gas gravitational boundedness, its proximity to the sink particle, angular momentum, and density. Once a particle has become a sink, its equation of motion includes only gravity and the back-reaction of local momentum conservation during accretion. Binary and higher-order multiple systems can form through the dynamics of distinct sinks (e.g., [Guszejnov et al., 2023](#)), but we do not resolve multiplicity for separations below  $\sim 20$  au and each sink is treated as a single star for the purposes of this work.

Each sink hosts a single model protostar and an internal gas “reservoir”. Resolved accretion moves gas from the simulation domain into the sink by merging the discrete gas cells, and unresolved accretion then transfers mass from the reservoir onto the protostar, providing a continuous accretion rate in this regime ([Grudić et al., 2021](#))<sup>1</sup>. The protostar, and its properties such as luminosity and radius evolves through standard pre-collapse and protostellar phases to the main sequence ([Offner et al., 2009b](#)). We approximate the emergent spectrum as a blackbody with  $T_{\text{eff}} = 5780 \text{ K} (L_*/L_\odot)^{1/4} (R_*/R_\odot)^{-1/2}$ . Protostars can continue to accrete after reaching the main sequence, which we discuss further in Section 3.1.

Feedback is tied directly to this evolving protostar: protostellar outflows scale with the accretion rate, while radiative feedback and line-driven winds scale with the stellar mass and luminosity ([Grudić et al., 2021, 2022](#)). There is thus no single discrete “onset” of feedback; mechanical feedback is present from the moment a sink forms and radiative/wind feedback strengthen as massive stars grow. Self-gravity is solved on a finite, non-periodic domain whose size is  $\sim 10$  times the initial cloud radius, so the cloud evolves as an effectively isolated object rather than in a periodically replicated volume.

In this work, we primarily focus on a fiducial simulation<sup>2</sup>, which begins with a molecular cloud of uniform density. The cloud has a mass of  $2000 M_\odot$ , a radius of 10pc, in a 100pc periodic box filled with an ambient medium  $1000\times$  less dense than the original cloud. The flow is initialized as a Gaussian random velocity field with a  $k^{-2}$  power spectrum and scaled to obtain an initial virial parameter of 2, such that the cloud is marginally bound. The initial magnetic field is uniform and scaled so that the magnetic pressure is 10% of the turbulent ram pressure ([Miville-Deschênes et al., 2017](#)). The mass resolution is  $10^{-3} M_\odot$  for gas cells, and  $10^{-4} M_\odot$  for protostellar jets and stellar wind gas cells. In section 4.4, we also analyze a second simulation<sup>3</sup>, which has a mass of  $20000 M_\odot$ , and a radius of 30pc but the same governing physics as the fiducial model.

### 3 Quantifying the Properties of Embedded Stars in STARFORGE

In our subsequent analysis, we analyze the time evolution of the properties of the proto-cluster stars, as they form and move out of the embedded phase. However, doing so requires quantifying a number of stellar properties in a consistent fashion. For stellar masses, it is simple; we chose to associate each star with its eventual final mass after accretion ends, even when considering it at an earlier time in its evolution. However, for age and extinction, there is more nuance in the

<sup>1</sup> See Figure 4 in [Grudić et al. \(2021\)](#) for a complete picture of the sink, star, reservoir, and resulting feedback.

<sup>2</sup> named: M2e4\_R10

<sup>3</sup> named: M2e5\_R30

definitions, and we discuss the specific choices in the subsequent subsections.

### 3.1 Quantifying Stellar Ages

As the simulated cloud evolves, the initial turbulent motions seed dense clumps and filaments. These high density clumps and filaments have shorter dynamical times, which can accelerate star formation locally. As a result, there can be a significant age spread for the formation times of protostars in the cluster. Moreover, protostars can continue accreting gas from the cloud, making the exact “formation time” of the final star ambiguous.

We demonstrate these effects and show the resulting age spread in Figure 2.1. In the bottom panel, for each star we compare the simulation time when each protostar begins its protostellar phase (on the X-axis) to the time when the star reaches its final mass (on the Y-axis), color-coded by the final mass. The histogram in the upper panel shows the age distribution for the start of the protostellar phase, for all stars (red) and for the subset of more massive stars ( $> 1 M_{\odot}$ ; blue)<sup>4</sup>. The middle panel shows the total duration of the protostars’ mass-accretion stage for the same mass bins.

The density distribution histograms of stellar age, and range of points in the upper panel of Figure 2.1 clearly demonstrates the extended nature of star formation in the cloud. Protostars begin to form within 2 Myrs of the start of the simulation, and while the formation peaks at 4–6 Myr, new protostars continue to form until well after 10 Myr, such that over  $\sim 40\%$  of stars form after 6.5 Myr, and the rms in the stellar formation times is 6.7 Myr.

In addition to the scatter in proto-star formation times, the accretion time to reach the final mass can be significant. In the bottom panel of Figure 2.1, for each point, this accretion time is the integrated distance between the star, and the black dashed line, while in the middle panel, this time is shown on the y-axis. Of particular interest is the accretion time for stars more massive than  $1 M_{\odot}$ , which may take upwards of 3 Myr to reach their final masses (Grudić et al., 2022), depending on the availability of the gas supply. At early times, gas is ample, leading to longer accretion times for early-forming stars, on average.

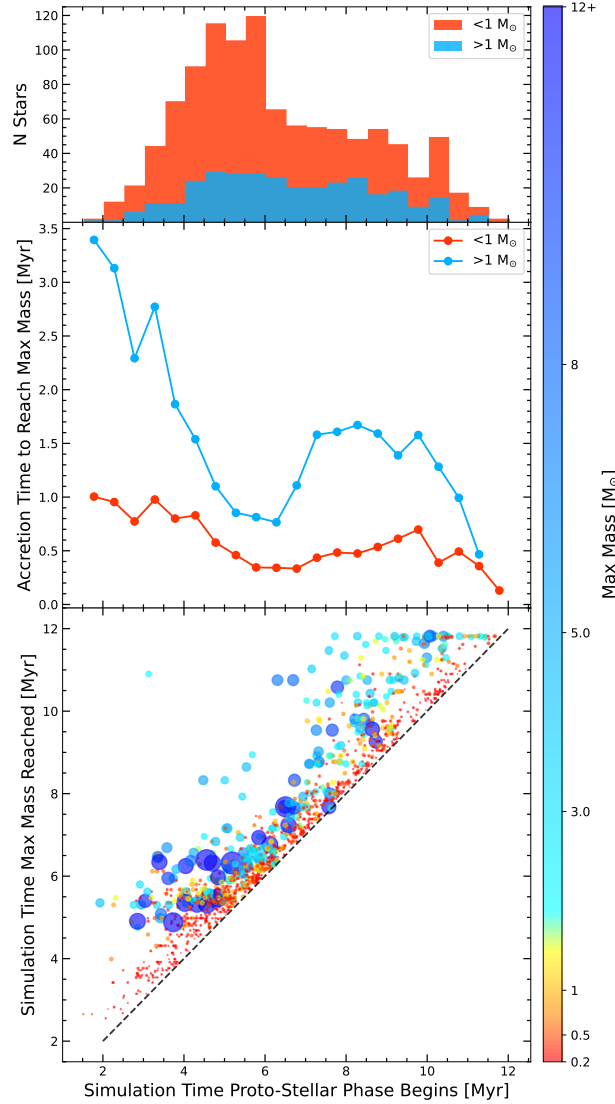
We note, however, the accretion time does not decrease monotonically with time. This variation is driven by substructure in the cloud, such that the gas supply varies as a function of position. Some parts of the cloud may collapse at later times, in regions with less local feedback and thus larger local gas reservoirs. These local gas pockets can fuel on-going accretion, explaining the second period where accretion rates for stars more massive than  $1 M_{\odot}$  rise above  $1 M_{\odot}$  between 7–10 Myr.

#### 3.1.1 Stellar Age Definition

Because the stars in our simulations form over an extended period, we cannot assume a single, shared formation time. Instead, we define each star’s “zero age” as the moment it reaches its maximum mass. This choice avoids two problematic alternatives: the time when a sink particle first forms, which is highly stochastic due to varying accretion times; or the time the star reaches the main sequence, as massive stars can continue to accrete after reaching the main sequence. Specifically, massive stars in our simulations continue to accrete for a median of 0.27 Myr after

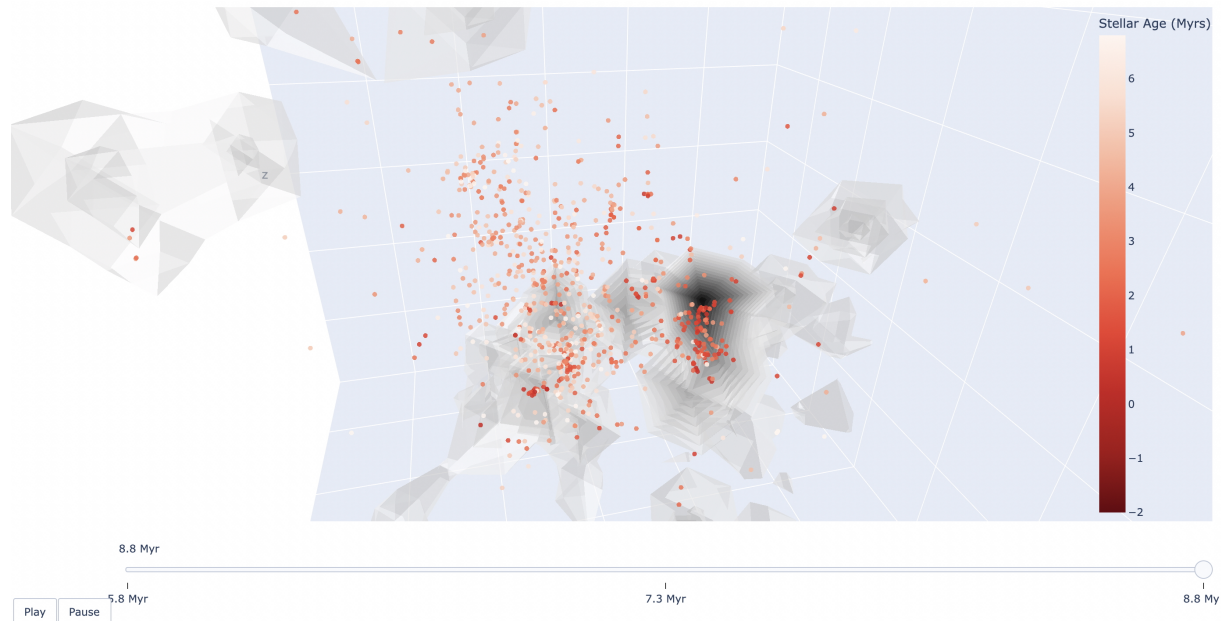
<sup>4</sup>We explored further binning the stars, but found that all bins above  $1 M_{\odot}$  behaved the same.

reaching the main sequence, and in some cases for as long as 2 Myr, meaning that main sequence arrival does not mark the end of mass growth or feedback onset. While our definition lacks a direct observational analog, it more closely reflects the physical endpoint of a stars formation and provides a consistent, replicable anchor which uniquely describes the timescales probed in this study.



**Figure 2.1:** The simulation time where a sink particle begins to accrete and how long it takes for that particle to reach its maximum mass, which we take to be the zero-point of a star’s age. The top panels shows the distribution of stellar formation times, split into two bins, one for stars below  $1 M_{\odot}$ , and one for stars larger than  $1 M_{\odot}$ . The middle panel then shows the average time it takes for the stars in these two bins to achieve their maximum mass. In both bins, but specifically for the larger stars, the accretion time depends on simulation time, which encodes the gas density. The bottom panel then shows each individual star, colored and sized by its final mass, where the y-axis shows the simulation time where each star reaches its maximum mass. The accretion time is then vertical distance above the dashed one-to-one line.





**Figure 2.2:** Interactive figure showing stellar and gas locations at three simulation snapshots, mapped to the middle panels of Figure 2.4. The red scatter points indicate stellar locations, where the points are colored by stellar age as defined in Section 3.1 where negative ages (darker red colors) are stars that are still undergoing accretion. The gray contours depict the gas density at that location. The white lines on the grid mark 5 pc. The still snapshot shown is at 8.8 Myr, and demonstrates that the ongoing star formation is for a localized sub-clump in the right part of the image. The interactive version of the plot [available in the online journal](#), includes 5.8 Myr, as well as 7.3 Myr, where readers can rotate around simulation space and zoom in/out.

### 3.1.2 Exploring Stellar Age and Location

As the system dynamically evolves throughout the simulation, the location of both the stars, and the gas are constantly changing. As discussed in Section 3.1, we see a large age spread as different sub-clumps within the cloud collapse and form stars. In this section, we quantify the location of the stars with respect to their age.

Throughout the simulation, the stars form in meaningfully different locations. Initially, the cloud spans 20 pc and then collapses, which leads to stars forming centrally. However at later times, the cloud expands and formation occurs on the outskirts. Therefore, the median formation location for stars that form before 6.5 Myr is 4.1 pc away from the median location of formation for stars after 6.5 Myr. This distance is also demonstrated in Figure 2.2 where the youngest stars are noticeably offset from the older stars.

The clumpy nature of the stars and gas is demonstrated in the interactive Figure 2.2. Shown in red are the 3 dimensional locations of stars, colored by their age (as defined in Section 3.1), where older stars are whiter, and the youngest stars still undergoing accretion are darker. We can clearly see that the youngest stars are tightly clustered in the bottom right corner of the still image. Readers are encouraged to rotate around simulation space and view the location of stars from several angles.

In addition to the stellar locations, the gray contours show gas density. At 8.8 Myr, we see small pockets of gas on the outskirts of the stellar association. Importantly, the location of the youngest

stars directly corresponds to where the gas is the densest. This correlation between pockets of gas and newly formed stars demonstrates the sub-clump nature of the star formation in the model, and explains the large spread in stellar ages discussed in Section 3.1, where parts of the cloud collapse at different times.

One way to describe this correlation quantitatively is to measure the median distance to all other stars. This stellar density also can be compared between frames of the interactive Figure 2.2. Stars that form before 6.5 Myr are tightly clustered in physical space, with a median distance to other stars of 3.5pc . However, when we consider stars that form between 6.5 Myr, and 10 Myr, the median distance to other stars almost doubles to 6.8pc . This latter increased distance to other stars is consistent with a more-distributed mode of star formation that ensues when the already expanding cloud also begins disruption. This increased distance is also clearly seen in the interactive Figure 2.2 by adjusting the slider between times; the stars become less tightly clustered as time progresses.

### 3.2 Quantifying Extinction

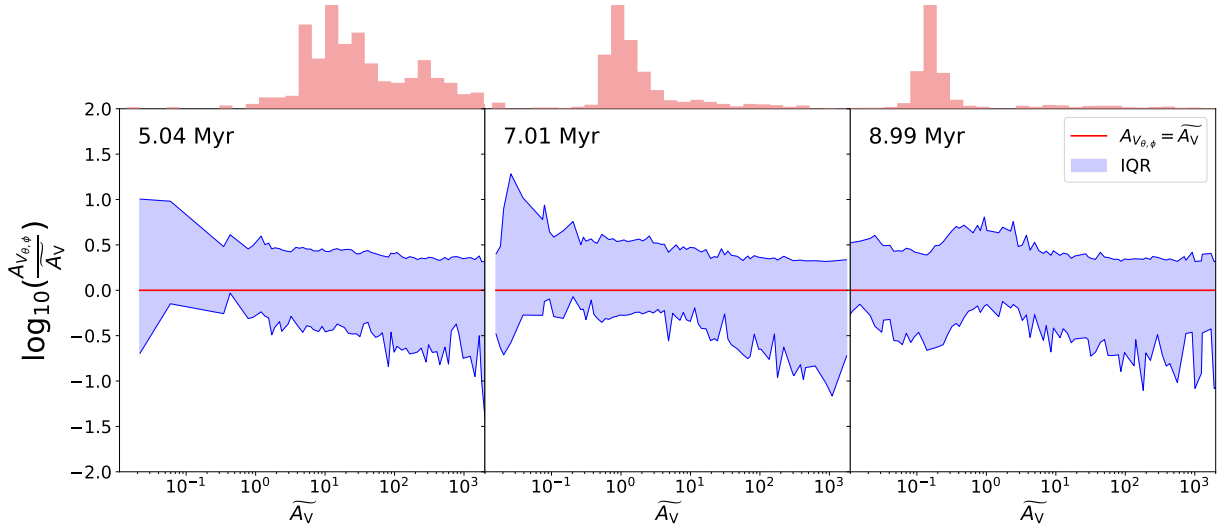
Quantifying the extinction associated with individual stars, or with the proto-cluster as a whole, is a critical part of assessing “embeddedness”. However, like age or mass, there are a range of possible choices one could conceivably make.

We start by assuming that gas and dust are well-mixed and that intrinsic dust properties are uniform, so that dust extinction is determined solely by the gas column density along the line of sight. We compute the gas column density by summing the column densities of gas elements along each stellar line-of-sight. We then convert to the optical extinction  $A_V$  using the conversion  $A_V = 4.52 \times 10^{-22} \text{cm}^2 N_H$  from Güver & Özel (2009), which was derived via x-ray measured column densities with respect to optical extinctions. We take  $N_H$  to be the number column density of H nuclei (i.e. not distinguishing between ISM phases).

The extinction,  $A_V$ , to an individual star depends strongly on the complex, 3-dimensional structure of the surrounding gas cloud. As such, the extinction is a strong function of viewing angle, and any one line-of-sight measurement of  $A_V$  is not necessarily representative of the overall embeddedness.

We therefore characterize the “typical” extinction to a star by recalculating the line-of-sight extinction,  $A_{V,\theta,\phi}$ , for 60 unique viewing angles. These directions are distributed quasi-uniformly over the sphere using a Fibonacci lattice, with step sizes in spherical coordinates where  $\phi = \pi(3 - \sqrt{5})$  and  $\theta = \phi \cdot i$ , where  $i$  indexes the viewing direction. This yields a well-sampled distribution of extinctions for each star at a given timestep. We adopt the median of these values,  $\widetilde{A}_V$ , as a representative metric for describing a star’s overall level of embeddedness. This analysis is repeated every 8th simulation snapshot (i.e., approximately every 0.2 Myr), which we find to be fine-enough sampling to accurately describe the simulation for the present analysis.

Figure 2.3 shows the resulting distribution of extinctions at different viewing angles, for three different time steps in the simulation. The  $x$ -axis shows the value of the median extinction  $\widetilde{A}_V$ , in a running bin space evenly in log space. The  $y$ -axis shows the interquartile range (in blue) of the values of the individual orientation measurements  $A_{V,\theta,\phi}$ , normalized by the median. The total number of stars at each median extinction  $\widetilde{A}_V$  is plotted as a red histogram above the plotting window, and shifts from high  $\widetilde{A}_V$  to low as the gas in the cluster is consumed or expelled.



**Figure 2.3:** Interquartile ranges (IQR) for the  $\log$  ratio of stellar  $A_V$ s at different viewing angles,  $A_{V_{\theta,\phi}}$ , and a function of the median extinction  $\widetilde{A}_V$ , shown for three different times in the simulation. Shown in red is the one-to-one line where  $A_{V_{\theta,\phi}}$  is equal to  $\widetilde{A}_V$ , while the blue shaded region shows inner quartile range. The histograms above are the number density of stars at a given  $\widetilde{A}_V$  at that time, showing how many stars are contributing to the IQR.

In the left most panels of Figure 2.3, the interquartile range is relatively constant in log space, which is consistent with the log-normal nature of most ISM density fields. We find that it typically spans around  $0 \pm 0.5$  in the log, independent of the median extinction, or the timestep.

We note, however, the distribution shifts from being heavy-tailed towards high densities for weakly embedded stars (low  $\widetilde{A}_V$ ), to being skewed towards low densities for highly embedded stars (high  $\widetilde{A}_V$ ). This tail is largely an artifact of “reversion to the mean”. Statistically, when a star has an extreme level of  $\widetilde{A}_V$ , it is far more likely that there will be a tail to more “typical” levels of extinction for the association, which explains the characteristic asymmetry.

The behavior of the distribution of  $A_{V_{\theta,\phi}}$  is somewhat more complex at late times (rightmost panel of Figure 2.3). Rather than the skew shifting steadily from low to high  $\widetilde{A}_V$ , instead, the characteristic change in skew occurs twice, once at low median extinctions and again at high  $\widetilde{A}_V$ . This behavior likely reflects the presence of a residual dense substructure within a cloud that has largely been dissipated by feedback. The bulk of the stars have median extinctions of  $\widetilde{A}_V \sim 0.2$ , but there is a long tail with extinctions greater than 1. Specifically, there are 1004 stars with an  $\widetilde{A}_V < 1$ , and only 170 with an  $\widetilde{A}_V > 1$ . The overall distribution of  $A_{V_{\theta,\phi}}$  is therefore the sum of two distributions – one that is characteristic of stars that live in the surviving dense substructure, and one that is characteristic of the stars that occupy the largely evacuated cloud. For the stars in the tail of this distribution, the IQR is therefore more stochastic since it is based on a small number of sources.

## 4 The Evolution of Embeddedness During Formation

With our extinction measurements in hand, we can now track how stars transition from being deeply embedded to fully exposed over time. In the following section, we apply this framework to quantify the changing embeddedness of both the stellar population as a whole and individual stars. We begin by characterizing the global evolution of embeddedness over time, then identify the key physical mechanisms that drive this evolution. We also explore embeddedness for individual stars, and investigate the strong mass dependencies in how long stars remain embedded. Finally, we examine how the overall timescales of embeddedness vary across two clouds of different mass.

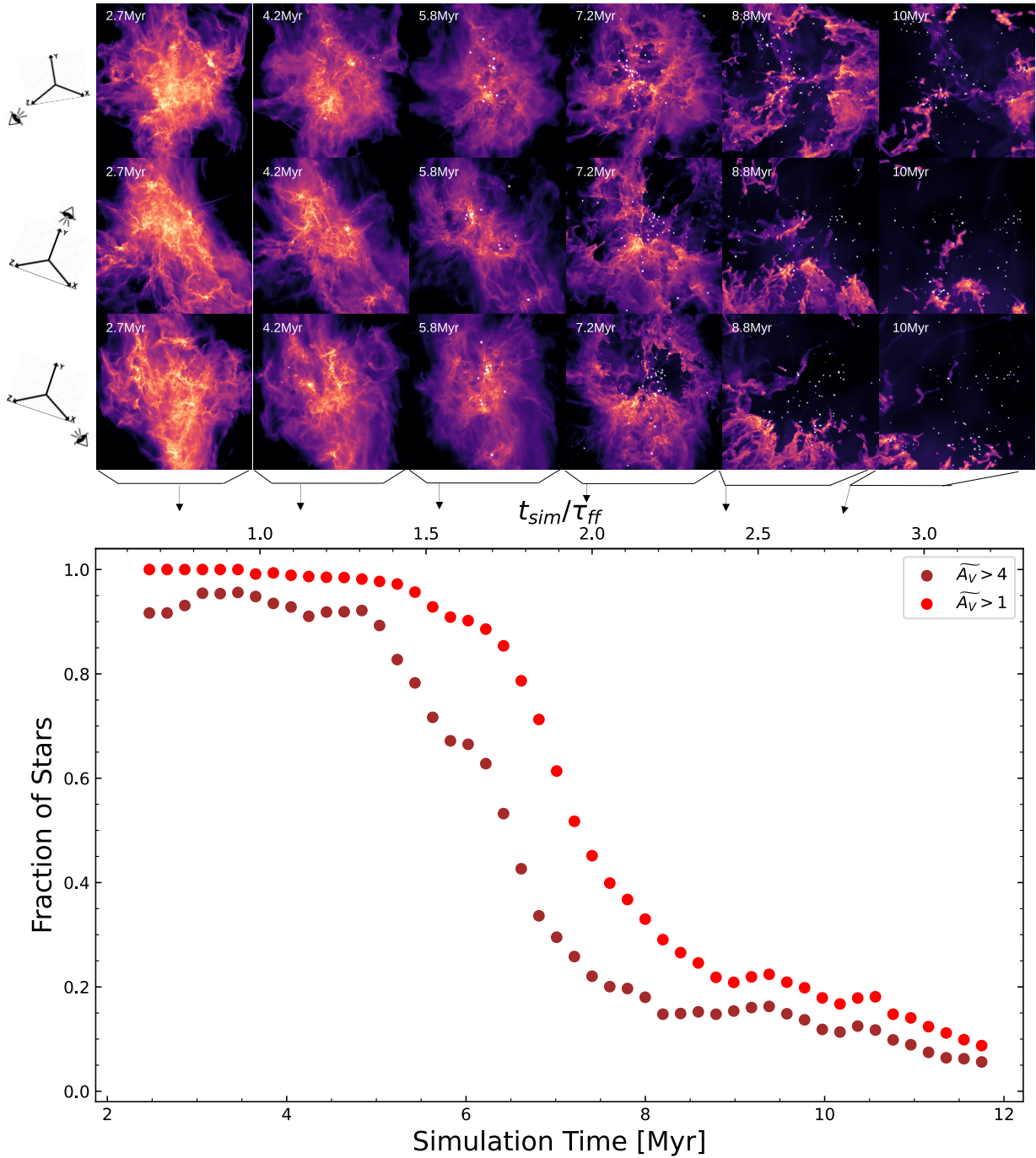
### 4.1 The Overall Evolution of Embeddedness

The expectation from models of stellar feedback is that stars form from dense gas within dusty molecular clouds, but that the evolution of these stars eventually destroys and/or removes the molecular gas, through the cumulative impacts of jets, winds, and radiation, and eventually supernova. Within this framework, stars that form early should be deeply embedded in the dusty gas, leading to high  $\widetilde{A}_V$ . In contrast, by the end of the cloud's evolution, most stars occupy regions that are free of gas, and thus should be visible along largely clear lines-of-sight. The only exception would be any newly formed stars, which may still occupy dense dusty sub-clumps that happened to survive to late times.

We can see this evolution in the top panels of Figure 2.4, which plots snapshots of the gas and stars in the fiducial STARFORGE simulation as a function of increasing time (from left to right, spanning from 2.7-10 Myr) and three different viewing angles (from top to bottom); the gas density is shown in the color map along with individual stars (in white) that are convolved with the HST point spread function. In this sequence of images, one can see the expected transition from gas-rich with few visible stars (<5 Myr), through a transition period with a mix of stars occupying evacuated regions within the cloud and dense gas that is likely to still be forming stars ( $\sim$ 5-8 Myr), to finally a late stage where most of the molecular cloud has been destroyed, leaving the majority of stars visible from most viewing angles, outside of a few residual dense gas clumps (>8 Myr).

We quantify this evolution in the bottom panel of Figure 2.4, where we show the fraction of stars that are deeply embedded ( $\widetilde{A}_V > 4$  mag; brown) or weakly embedded ( $\widetilde{A}_V > 1$  mag; red), as a function of time. These limits were chosen because in solar-metallicity, photo-dissociation models,  $A_V \sim 1$  mag is the approximate threshold for forming molecular hydrogen (Franco & Cox, 1986; Krumholz et al., 2009b; Sternberg et al., 2014), where  $A_V \sim 4$  mag is a threshold within which carbon recombination takes place, and corresponds to HCN line emission (e.g., Hollenbach & Tielens, 1997; Kauffmann et al., 2017). The small vertical arrows connecting the top panels to the bottom plot indicate the times corresponding to the snapshot images. The times are given both in terms of the time since the start of the simulation ( $t_{sim}$ ; bottom axis), and  $t_{sim}$  scaled by the free-fall time of the initial gas cloud ( $\tau_{ff}$ ; top axis, calculated as  $\tau_{ff} = 3.7$  Myr). Every point on the bottom plot includes all stars formed at or before  $t_{sim}$ , not just the stars forming at that particular timestep.

Figure 2.4 shows that stars emerge from their natal cloud relatively quickly. Specifically, there is a steep decline in the fraction of stars with a  $\widetilde{A}_V > 1$  occurring over a rapid  $\sim 2.5$  Myr period. At a simulation time 6 Myr, 90% of stars have a  $\widetilde{A}_V > 1$ , but only 2.5 Myr later, fewer than 25% of stars have even this relatively modest level of extinction.



**Figure 2.4:** *Top:* Snapshots from six simulation times each box covering 30pc: different rows correspond to three different viewing angles. Gas surface density is shown in the color map, and stars rendered with a standard HST PSF. Stellar magnitudes are determined by considering the line of sight gas column density. *Bottom:* Scatter plot showing the fraction of stars with a  $A_V$  greater than 4 (brown), and 1 (red) as a function of simulation time, where the median is defined by 60 different viewing angles. The stars in the formation event emerge from their natal cloud relatively quickly, with a steep decline in the fraction of stars that are highly extinguished occurring over a  $\sim 1$  Myr period at 6 Myr. It is also important to note that this model does not produce a gravitationally bound stellar cluster. Rather, the association disperses entirely by 10 Myr, which can be seen in the right most panel of simulation snapshots.



Although the overall emergence of stars is rapid, a reservoir of dense gas persists for much longer, even after half the stars have  $\widetilde{A}_V > 1$  (at  $t_{sim} = 7.3$  Myr; see the top panel of Figure 2.4). This reservoir consists of dense pockets of gas that still continue to form stars. While some viewing angles (such as the bottom row at late times) have sufficiently cleared enough local gas to open an unobstructed viewing window, other viewing angles (such as the top row) still have some lines of sight where there is some degree of gas for nearly all the stars.

From the last two columns of Figure 2.4, where nearly all stars are largely un-embedded, it is also apparent that the simulation does not produce a gravitationally-bound stellar cluster. Instead, when the gas disperses, so do the stars, due to the low star formation efficiency of the system (e.g. Hills, 1980; Tutukov, 1978), leaving no long-lasting remnant of the star formation. Even as soon as 11 Myr after the initial collapse, while small pockets of gas are still producing a handful of stars, the stars from this event are not meaningfully coupled in any kind of longer-lived quasi-bound structure.

Also shown on the secondary axis of the scatter plot is the time in units of the cloud free-fall time  $\tau_{ff}$ . We can see that the  $\widetilde{A}_V$  first begins to decrease around  $\sim 1.5 \tau_{ff}$ . We further discuss the timescales driving the emergence in the following subsections.

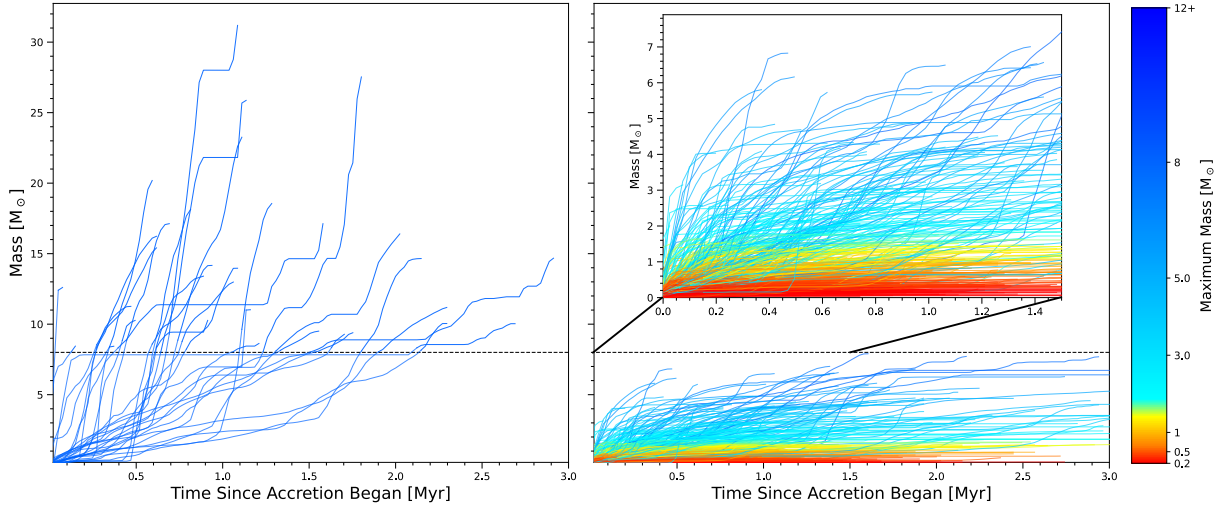
## 4.2 Drivers of Embeddedness Evolution

Empirically, the rapid emergence of stars from a dusty gas cloud is quite clear from the plots in Figure 2.4. Broadly, this change can be ascribed to “stellar feedback”, but exactly what aspect of feedback drives the evolution? Is it early jets, which deposit kinetic energy into the gas? Is it the momentum deposition from stellar winds? Is it radiation pressure and/or dissociation from ultraviolet photons? All of these processes are potentially important in young star-forming regions — as supported by an extensive literature examining these questions theoretically and observationally (e.g., Grudić et al., 2019; Kim et al., 2018; Krumholz & Matzner, 2009; Lopez et al., 2011, 2014; Olivier et al., 2021), all of which are likely stronger for massive stars.

A full analysis of feedback is well outside the scope of this paper (e.g., Neralwar et al., 2024), but we can attempt to identify whether any of the above processes are associated temporally with the rapid changes in the median stellar extinction. We specifically look at quantities that trace the formation of stars in general (the total number of stars, and the total bolometric luminosity of all stars and protostars), and quantities that trace the subset of massive stars that are likely to drive cloud evolution (the total number of stars with masses  $> 8 M_\odot$ , and the number of ionizing photons).

When calculating the above quantities, we: (1) count stars during their formation, rather than from the time they stop accreting mass, to better capture effects from protostellar feedback; (2) calculate the bolometric luminosity using the effective temperature of the star as defined by its mass and radius for its stellar evolutionary phase; (3) and calculate the number of ionizing photons by assuming a blackbody stellar SED and integrating over ionizing wavelengths shorter than 91.1 nm. We also plot the time evolution of these quantities normalized by their peak value over the simulation.





**Figure 2.5:** Accretion histories for stars in the simulation, colored by their final maximum mass, mapped to Figure 2.1. Tracks for individual stars are only plotted until the point where the star reaches its maximum mass. The horizontal dashed line at  $8 M_{\odot}$  represents portions of the evolution considered in the massive star counter. Stars in the left panel are the 31 stars with a final masses greater than  $8 M_{\odot}$ , while all other stars are in the right panel. We show an zoomed-in axis range in the right panel only going to  $8 M_{\odot}$  on the y axis, and 0 to 1.5 Myr on the x-axis.

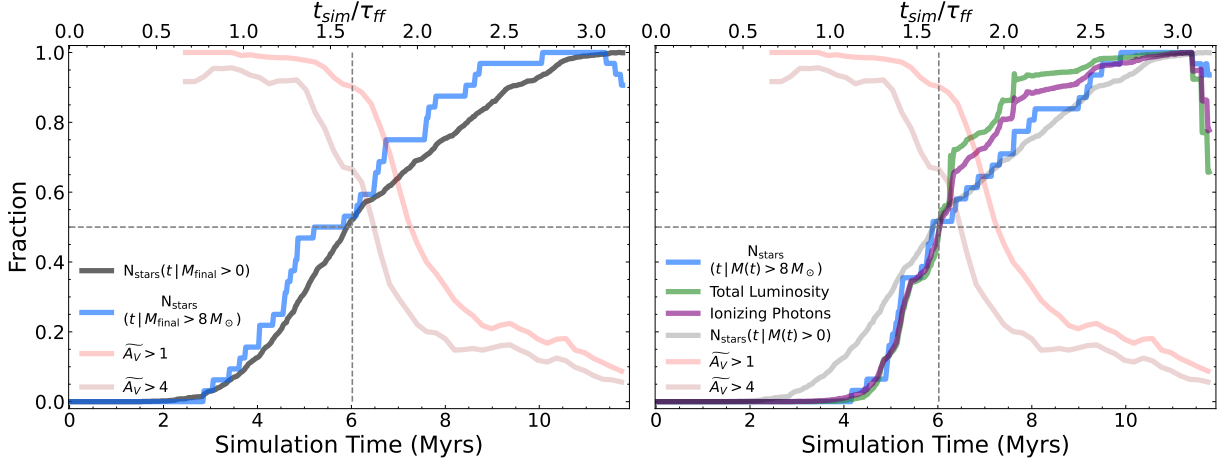
#### 4.2.1 The Accounting of High-Mass Stars

There is an additional subtlety to consider when counting stars. Specifically, in most models of feedback, massive stars have a greater impact, due to their higher luminosities, harder spectra, and higher average accretion rates during the protostellar phase (e.g., Dale, 2015; Lewis et al., 2023). We therefore choose to track low- and high-mass stars separately during their evolution.

However, during their early evolution, future high-mass stars can have the same masses as a future low-mass star. In STARFORGE, the strength of the instantaneous protostellar feedback is proportional to the mass accretion rate, which depends on the current mass of the protostar, as well as the local gas supply. As such, the impact of protostellar feedback may not strictly depend on the final mass of the star, during the star’s early evolution.

We help clarify this subtlety in Figure 2.5, where we plot the mass evolution as a function of time for a sample of stars from our simulation, with stars with final masses greater than  $8 M_{\odot}$  in the left panel and all other stars on the right. Lines are color-coded by the eventual maximum mass of the star (according to Figure 2.1), and the thick lines indicate the portion of the evolution where the mass is greater than  $8 M_{\odot}$ , respectively. The accretion rate, proportional to the strength of protostellar feedback, is indicated by the slope of the tracks, such that steep, rapid increases in stellar mass will be associated with strong instantaneous feedback.

For the majority of stars, the first  $\sim 0.3$  or so Myr of each star’s accretion in Figure 2.5 looks similar, where massive stars may not immediately “know” that they are destined to be massive. However, the eventually-massive protostars are then distinguished by having either: a rapid burst of accretion, or a systematically more sustained accretion rate over their lifetime – as is needed to reach a higher final mass. It is this rapid and/or extended accretion that leads to higher protostellar feedback for massive stars.



**Figure 2.6:** *Left:* Distributions of the fraction of stars which have formed (black), as well as the fraction of stars larger than  $8 M_{\odot}$  (blue) which have begun accretion as a function of time. Both fractions are a ratio of the number at the current time step compared to the total amount that formed. Also shown is the fraction of stars with a  $\bar{A}_V$  greater than 1 (transparent red) and 4 (transparent brown) from Figure 2.4 for comparison to the association embeddedness. In each panel, we show gray dashed lines at 50% and at 6 Myr, the point where  $\bar{A}_V > 1$  begins to steeply drop. *Right:* Bolometric stellar luminosity at each time step is shown in the dashed green line, and the number of ionizing photons is shown in dashed-dotted purple line, both normalized by the maximum value at any time. We see the fractional luminosity and the fraction of ionizing photons closely track the number of massive stars that have formed. Noticeably, each of the quantities converges to 50% around the same time.

We note however, that the high accretion rates seen for some massive stars in the left-hand panel (primarily at  $< 5$  Myr) are also observed for some of the low-mass stars in the zoomed-in version of the figure in the right panel. However, the rapid accretion that these stars experience is not as sustained as for the massive stars in the left-hand panel. This systematic difference in the absolute accretion rate and/or its duration should lead to weaker protostellar feedback for the low-mass stars.

In order to isolate the low-mass and high-mass phases of protostar evolution we count stars in two regimes: (1) any star that is currently less than  $8 M_{\odot}$ , regardless of its final mass; and (2) any star that is currently greater than  $8 M_{\odot}$ , regardless of its final mass.

#### 4.2.2 The Time Evolution of Drivers

With the definition of “high mass” now settled, in Figure 2.6 we compare the time evolution of the embeddedness to the time evolution of a variety of possible drivers of stellar feedback to look for possible correlations. In both panels, we plot the time evolution of the embeddedness, tracked using the fraction of stars that are heavily embedded ( $\bar{A}_V > 4$ ; brown) or lightly embedded ( $\bar{A}_V > 1$ ; red), reproduced from Figure 2.4 and discussed in Section 4.1.

In the left panel, we compare the change in the fraction of embedded stars to the fraction of stars which have begun their protostellar phase, for both stars with high final masses ( $M_{final} > 8 M_{\odot}$ ; dark blue), and all stars regardless of their final mass (black line). We count massive stars from

the time accretion begins until the time they explode and normalize the curves by the maximum number of stars in each category at any point during the simulation. Note that this normalization leads to a downturn in the fraction of massive stars at  $\sim 11$  Myr in Figure 2.6, when SNe begin.

Comparing the number of stars to the embeddedness shows the expected impact of stellar feedback, namely that the stellar extinction (highly transparent red and brown lines) drops systematically as more stars form. However, a surprisingly large amount of star formation occurs before we see any clear decline in extinction. Specifically, the  $\widetilde{A}_V > 4$  remains above 90% until  $\sim 4.7$  Myr, and  $\widetilde{A}_V > 1$  remains above 90% until  $\sim 6.0$  Myr, when both begin to decline more rapidly. Quantitatively, at  $\sim 4.7$  Myr, only 25% of all stars have already begun forming. Perhaps more strikingly, close to 50% of eventually massive stars have begun forming by  $\sim 6.0$  Myr, when there is a significant drop in the typical embeddedness.

### 4.2.3 Only Considering Massive Stars Once they are Massive

This unexpected result can be explained by considering how the stars are being counted. The top panel counts stars from the time they begin accretion, but it is clear from Figure 2.5 that even “eventually massive” stars can exist upwards of 2 Myr before they are meaningfully more massive than the other stars. As such, there is no appreciable difference between the blue and black curves in the left panel of Figure 2.6, and no guarantee that any of the stars contributing to the curves currently have high mass, early in the simulation.

In contrast, we see very different behavior in the right panel of Figure 2.6, where we choose to only consider massive stars once they surpass the  $8 M_\odot$  threshold (i.e., above the dashed line in the left panel of Figure 2.5). With this choice, we are only counting massive stars once they are massive enough to have had either, significant mass accretion rates (i.e., significant protostellar feedback), or prolonged accretion events, such that they have large luminosities.

With this different choice of how to define “massive”, we see a different correlation with the  $\widetilde{A}_V > 4$  embeddedness that tracks dense gas. In contrast to the left panel, the decrease in extinction now appears to be more tightly related to the onset of massive stars (at  $\sim 4$ -5 Myr) rather than star formation in general (comparing the blue and grey curves). In other words, the drop in significant stellar embeddedness is driven by effects produced by stars as they reach a significant mass.

While the observed correlation strongly suggests that massive stars are driving the drop in extinction, there are multiple possible mechanisms at work. We consider one of these mechanisms in the right panel of Figure 2.6, where we assess the role of radiation, which is dominated by the population of hot massive stars. We plot the time evolution of the bolometric stellar luminosity (green) and the number of ionizing photons (purple), each normalized by their maximum value throughout the simulation<sup>5</sup>.

As expected, both the luminosity and the number of ionizing photons increase along with the number of stars. Even more striking is the degree to which both quantities track the subset of massive ( $> 8 M_\odot$ ) stars, rising in lockstep until 6 Myr, which is roughly the time by which half of all stars (massive and otherwise) have formed, half the sight-lines are no longer highly embedded (transparent brown  $\widetilde{A}_V > 4$  curve), and the fraction of lightly embedded stars begins to decline (transparent red  $\widetilde{A}_V > 1$  curve). At later times, the total stellar luminosity and the number of

<sup>5</sup>For reference, the maximum number of ionizing photons is  $10^{48.09}$  photons, and the maximum stellar luminosity is  $10^{5.92} L_\odot$ .

ionizing photons grow even faster, presumably as a subset of stars reach masses higher than the  $8 M_{\odot}$  threshold used as the mass limit for the blue curve.

The impact of the most massive stars on the total luminosity is also seen in the downturn in the luminosity after the two supernova explosions at  $\sim 11$  Myr. Specifically, in the last simulation snapshot, the fractional luminosity is only  $\sim 60\%$  of its maximum luminosity, before the two supernova. Importantly, the stellar association is nearly entirely un-embedded by the time the first supernova explosion occurs. Therefore, pre-supernova feedback is efficient to de-embed most stars and remove dusty sight lines, as noted in Grudić et al. (2022); Guszejnov et al. (2022).

We also highlight the convergence of each of the properties considered here around the 6 Myr mark, highlighted by the gray line. At this time, each of the fractional measurements are all right around 50%. While the common thread is clearly “the emergence of genuinely massive stars”, more detailed analysis is needed to isolate the relative importance of the luminosity, the ionizing photons, and the protostellar feedback (e.g., Grudić et al., 2022).

### 4.3 Tracking the Evolution of Formation Time and Embeddedness for Individual Stars

In the previous section, we presented a connection between the number of massive stars, and the overall extinction of the stellar association. From Figure 2.4, it is clear that pre-supernova feedback from massive stars is responsible for de-embedding the stars overall. In this section, we turn to tracking the behavior of individual stars’ embeddedness rather than the ensemble. Specifically, we consider the evolution of a star’s typical extinction  $\widetilde{A}_V$  as a function of their mass and age, calculated in reference to the time when they reach their maximum mass.

We present these results in Figure 2.7, which shows the value of  $\widetilde{A}_V$  as a function of stellar age, in four simulation snapshots; a movie for all snapshots is available as supplementary material<sup>6</sup>. Each star is plotted as a point that is colored and scaled in size by the star’s maximum mass, using the same color bar as Figure 2.1, such that a star keeps a consistent color and size across all plots. The dashed vertical line indicates zero age, when a star’s host sink particle reaches maximum mass and stops accreting; stars to the left of this line (negative age) are accreting sink particles. The grey area on the right of each panel indicates times longer than the run-time of the simulation at each timestep.

The density distribution histograms on the top and right axes track the bulk distributions in stellar age and  $\widetilde{A}_V$ , respectively. The top plots all stars (blue), and the subset of massive stars ( $> 8 M_{\odot}$ ; purple). The vertical gold line in the histogram (and associated triangle) indicates the median age of the stars that exist at that timestep, which is typically much less than the simulation age (c.f., the median age at  $t_{sim} = 7$  Myr is only 1.35 Myr). These histograms reinforce the general trend shown in Figure 2.4 — extended star formation and a shift towards lower extinction with increasing time.

We first focus on the overall timing of star formation throughout the simulation, best seen in the age histograms on the top of each plot. As discussed in previous STARFORGE works (e.g., Grudić et al., 2022; Millstone et al., 2023) and in Section 3.1, stars form across essentially the entire duration of the simulation. There is a clear peak at  $t_{sim} \approx 5 - 6$  Myr, but it is both preceded and followed by on-going star formation, as can best be seen in the blue histogram for the oldest

<sup>6</sup>We also include a link to the online movie here: <https://zenodo.org/records/17156032>

timestep (bottom right, as well as Figure 2.1). This extended star formation is consistent with persistence of residual dense gas, as was clearly visible in the snapshot images in Figure 2.4.

We now turn to the joint distributions of age and extinction, as traced by individual stars. We encourage readers to view the movie version of Figure 2.7, where one can track each star in higher snapshot fidelity than is possible in the 4 panel still shots. Throughout the simulation, young stars first appear in dense gas with high characteristic  $\widetilde{A}_V$ , consistent with forming inside of dense molecular gas. Therefore, as stars form, they appear in the upper left corner of the plot. However, over time they become orders of magnitude less obscured (moving down the y-axis), typically with a notable transition near the time they stop accreting mass, at the zero-age boundary. This pattern repeats for stars formed throughout the simulation. There is also a more gradual, but steady decrease in the typical extinction of the post-accretion ( $t_{age} > 0$ ) stars, due to the on-going loss of dense dusty gas throughout the cloud.

The transition in extinction at zero age is to some degree expected, because we have defined zero age to be the moment the sink particle is no longer accreting. In many cases, this transition marks a natural inflection point. When accretion ends, local gas supply has likely diminished, and stellar feedback becomes more effective at clearing the surrounding material. As a result, extinction tends to peak around this time and then decline, although the precise timing of that decline appears to depend on the stars properties.

#### 4.3.1 Mass-dependence of $\widetilde{A}_V(t_{age})$

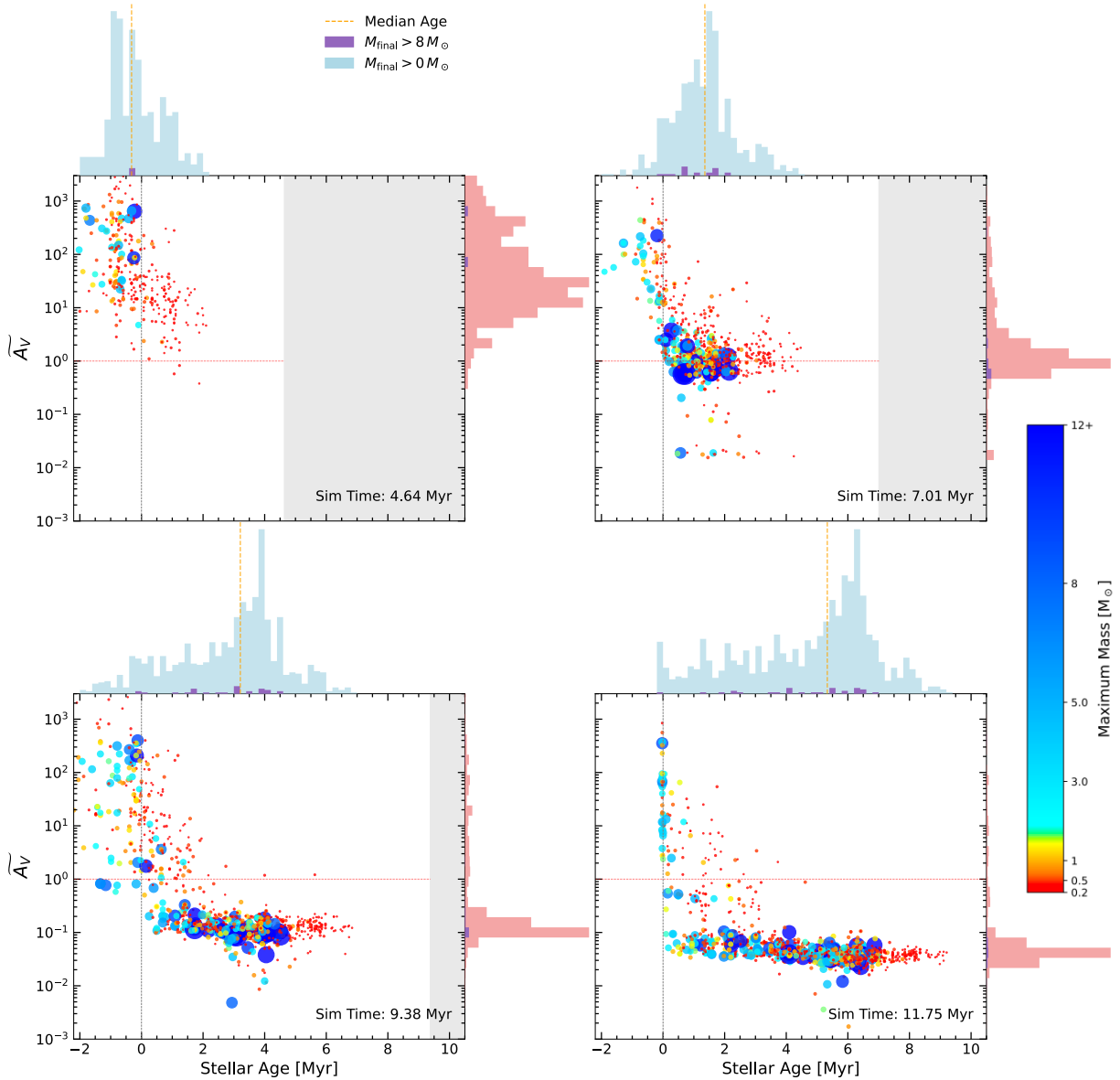
Visual inspection of Figure 2.7 suggests that the general correlation between the drop in a star's embedding and the end of its mass accretion may also depend on the star's final mass. There is a significant population of low mass stars (red points;  $< 0.5 M_\odot$ ) that remains highly embedded even after accretion stops (upper right quadrant), at all time steps. In contrast, there are essentially no higher mass stars found in the upper right quadrants, at any time step. This difference strongly suggests that low and high mass stars do not become un-obscured through identical mechanisms.

We explore this possibility more quantitatively in Figure 2.8, where we calculate the median value of  $\widetilde{A}_V$  as a function of stellar age for all stars in given mass bin, with colors mapping to those in Figure 2.7 and Figure 2.1. These lines track the typical trajectory of stars in the panels of Figure 2.7, tracing their obscuration over their lifetimes, no matter when they were formed.

All of the trajectories in Figure 2.8 show broadly similar behavior, in line of expectations from Figure 2.7. Namely, stars are highly embedded for the majority of their protostellar accretion phase, and then emerge from the dusty gas. However, we also now see clear mass trends in how long stars stay heavily embedded, and how sharply their embedding drops as they reach their maximum mass.

Regardless of their mass, stars in Figure 2.8 start at similar levels of embedding. However, the low and high mass stars emerge from dusty sight-lines at different rates. High mass stars ( $> 8 M_\odot$ ) stay deeply embedded for longer, up until the moment they reach their maximum mass, but then become un-embedded much faster — dropping by  $\Delta\widetilde{A}_V \sim 200$  in a fraction of a Myr. In contrast, low mass stars ( $< 1 M_\odot$ ) have more gradual evolution, de-embedding well before they reach their maximum mass, and then typically taking another  $\sim 1.20$  Myr to reach  $\widetilde{A}_V < 1$ , roughly 2 times longer than that for massive stars.

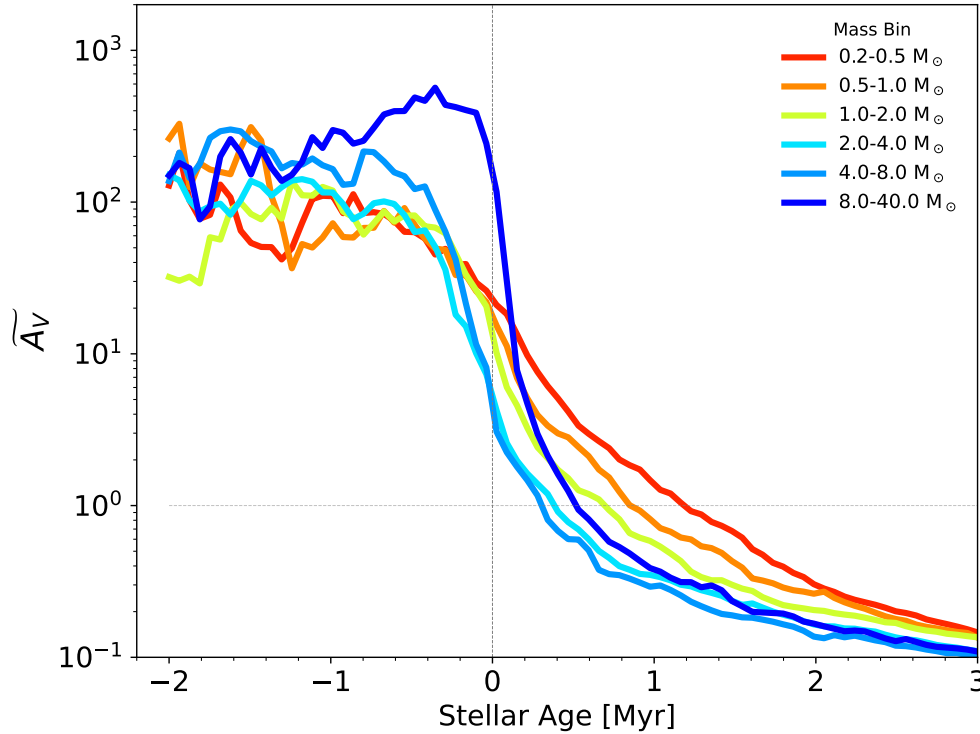




**Figure 2.7:** Each star’s extinction as a function of stellar age, for four simulation snapshots. A movie showing each snapshot can be found in the online version of the manuscript. The extinction is taken to be the median value across all viewing angles, and age zero corresponds to the time the star reaches its maximum mass (Figure 2.1) which is shown by the dashed vertical line. The horizontal red line at  $\bar{A}_V = 1$ , corresponds to the red points in Figure 2.4. In each snapshot, the extinction decreased exponentially, with a precipitous decay around the time the star reaching its maximum mass. Additionally, the time a star remains heavily embedded appears to depend on stellar mass, where most red points stay above the  $\bar{A}_V = 1$  line well after their zero age, compared to stars greater than  $8 M_\odot$  that tend to fall below this threshold right around this zero age. We discuss this trend further in Figure 2.8.

Top histograms are number counts for stars of different ages with blue being all stars and purple representing stars larger than  $8 M_\odot$ . Side histograms are number counts of stars at a given extinction. We see star formation occurring across the entire duration of the simulation, and high mass stars form throughout. The movie can also be found at

[doi:https://doi.org/10.5281/zenodo.17156032](https://doi.org/10.5281/zenodo.17156032).



**Figure 2.8:** Stellar extinction tracks as a function of stellar age, binned by final mass. Lines represent the median values of stars in the mass bin, with colors corresponding to the final stellar mass in Figure 2.1. There is a clear trend with when a stars begins decrease in  $\widetilde{A}_V$  and the final mass of the star, as well as how long it takes that star to become un-embedded.

#### 4.3.2 What is Driving the Mass-dependence of $\widetilde{A}_V(t_{\text{age}})$ ?

There are three general classes of mechanisms that might drive stars’ emergence from deep obscuration: (1) global feedback; (2) local feedback; and (3) drift. In the first, stars may become systematically less extinguished because of the global loss of dusty gas from the cluster, due to the cumulative effects of feedback. In the second “local” scenario, most of the embedding is actually from dust close to an individual star, where it can be cleared out by a star’s own feedback. In the final “drift” scenario, some of the emergence from embeddedness may be due to stars and gas clumps moving apart, because of velocity differences and/or the changing structure of the turbulent gas. In this scenario, even modest relative velocities can move a star out of a dense gas cloud in a short time, provided the cloud is small.

The plots in Figures 2.7 & 2.8 strongly suggest that for massive stars, emergence from embedding is driven by their own feedback into their local natal gas. Almost every massive star (i.e, dark blue) plummets in  $\widetilde{A}_V$  almost exactly when they reach their maximum mass, and reach  $\widetilde{A}_V < 1$  by a median 0.6 Myr after the maximum mass is reached. This behavior remains consistent across time and is independent of the extinction of the overall association, strongly suggesting that the transition is driven by local, rather than global, feedback. Dense gas is needed for the massive star to form, but the removal of that gas is largely controlled by the star itself.

Not only do the massive stars drive their own emergence from the dusty gas, they also appear to

control their early evolution as well. Unlike the majority of stars in the simulation, the most massive stars’ obscuration initially *increases* with time, presumably due to gravitational contraction of the surrounding gas cloud. This contraction provides fuel for the massive star’s on-going gas accretion (left panel of Figure 2.5), up until the star’s own feedback shuts off the accretion and prevents any further increase in the star’s mass. The fact that the embedding plummets at exactly the same time strongly suggests that, for these massive stars at least, the majority of their line-of-sight extinction is extremely local.

The behavior of the low-mass stars is quite different, however. These stars will have limited ability to drive stellar feedback, given that the available energy during the pre-main sequence phase is strongly mass dependent (Section 4.2), and their final luminosities are low. It therefore is unlikely that their reduction in embeddedness is feedback driven.

However, low-mass stars are not entirely passive in shaping their local environments. Even though their radiative output is minimal, these stars can drive powerful collimated outflows during the protostellar phase (e.g., Frank et al., 2014), which have been shown to efficiently expel nearby gas on small scales (e.g., Offner & Chaban, 2017). Because the outflow momentum and radiative output are directly to the stellar mass (Offner & Chaban, 2017), low-mass protostars inject substantially less momentum per unit time than their high-mass counterparts, meaning that any reduction in extinction proceeds more slowly and may not reach large enough scales to fully de-embed the star. Indeed, in Figure 2.8, we see the evolution of extinction for low-mass stars takes place over a longer timescale, with no strong features in  $\bar{A}_V$  associated with reaching their maximum mass.

The evolution of embeddedness for low-mass stars is therefore shaped by a combination of this limited local feedback, and external environmental factors. While outflows may partially clear nearby gas, these low-mass stars lack the ability to regulate their broader surroundings. Instead, their emergence can then reflect either drift relative to dense filaments, changes in the gas structure driven by turbulence, or the cumulative influence of more massive neighbors. Interestingly, this empirically leads to a situation where it is the lower mass stars that remain embedded for longer, well-past the time that the massive stars have become unobscured; this is in contrast to scenarios where the formation of massive stars clears out the obscuration for all stars.

While we have stressed the strong impact of local embeddedness and feedback for massive stars, there are global effects as well. The distributions of individual stars in Figure 2.7, along with the red histograms of  $\bar{A}_V$  on the right axes, show that after  $\sim 6$  Myr there is a population of weakly-embedded stars that have reached their maximum mass, and that all have similar median embeddedness. These are stars that are currently outside of any dense gas clump (and thus no longer accreting mass), whose line-of-sight extinctions are now set by the overall extinction properties of the global gas distribution. The median extinction of this population decreases steadily with time, due to the global evolution of gas in the system due to on-going feedback. As such, in Figure 2.8 the late time evolution of  $\bar{A}_V$  for most stars looks quite similar, particularly for the more massive stars that have eliminated any local sources of obscuration, and are now subject only to the statistical properties of extinction in the cluster as a whole.

In summary, the change of embeddedness is local to the high mass stars. For massive stars, the energy required to overcome the accretion is larger due to larger gravitational potential of the larger system. Once accretion stops, the large radiation pressure then helps to clear out the region around the star. In contrast, the outflows from low-mass stars take place on longer time-scales, and the stars are free to move relative to the gas, and can therefore de-embed in part through geometry, regardless of the overall gas reservoir in the system.

#### 4.4 How is the Time Evolution of Embeddedness Impacted by Cloud Mass?

There are a number of timescales we expect to operate during cluster formation, including the free-fall time  $\tau_{ff}$  for gravitational collapse, the gas accretion timescale for protostars, and the stellar evolution timescales associated with feedback (i.e., the emergence of jets, ionizing radiation, and supernovae). The latter of these timescales are connected closely to the properties of individual stars, and should be relatively similar from cluster to cluster, at fixed metallicity. In contrast, the free-fall and gas accretion times are both dependent on the initial properties of the molecular cloud as a whole, including its mass.

Here, we investigate the empirical mass-dependence of the timescale for cluster embedding. As discussed in Section 4.1, the fiducial STARFORGE simulation is based on a  $2 \times 10^4 M_\odot$  cloud, 10pc in radius. The free-fall time depends on the initial cloud density  $\rho_0$  as  $\tau_{ff} = (3\pi/32G\rho_0)^{1/2}$ , which for the fiducial model corresponds to 3.7 Myr. We now compare the timescales of the fiducial simulation to a second, more massive cloud simulation beginning with  $2 \times 10^5 M_\odot$  and a 30pc radius. The initial density of this higher mass simulation is a factor of  $2.7\times$  smaller than the low mass simulation, leading to a  $1.6\times$  longer free-fall time for the massive cloud. Both simulations have identical initial virial parameters, such that their crossing times at the characteristic velocity dispersions scale linearly with the free-fall time. We therefore expect that the more massive cloud should take longer to collapse, and should have gas available for accretion over a longer timescale.

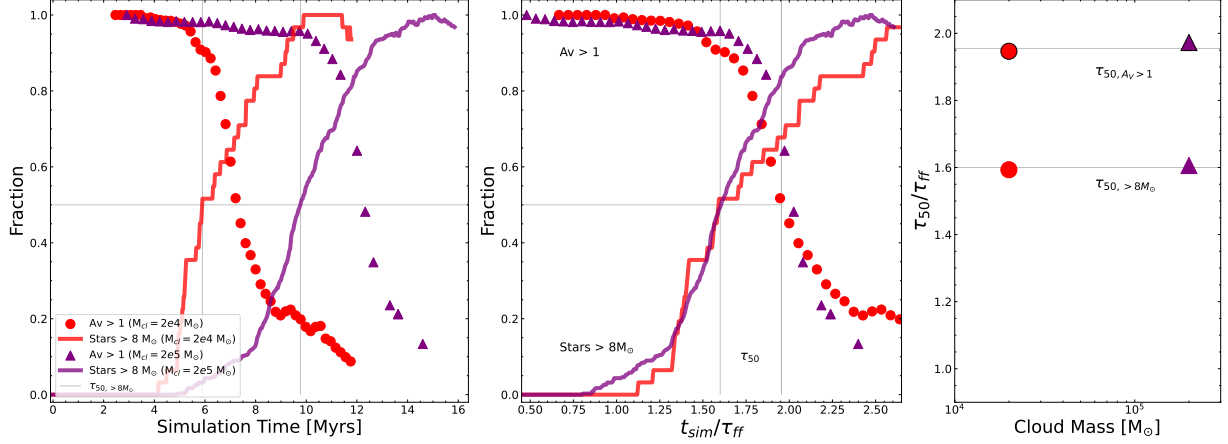
We test this assumption in Figure 2.9 by generating plots similar to the bottom of Figure 2.4 for both the low mass (red) and high mass (purple) simulations. The filled points indicate the time evolution of the fraction of stars with  $\bar{A}_V > 1$ , which for both simulations starts at one (all stars highly obscured) and declines to small values (little net extinction) by the end of the simulation. The solid lines indicate the fraction of high mass ( $> 8 M_\odot$ ) stars  $f_{>8M_\odot}$  at each timestep (same accounting as right hand panel in Figure 2.6<sup>7</sup>) as a function of time, which increases from zero to one for both the low mass (red) and high mass (purple) cluster simulations, and decreases as stars explode and undergo supernovae.

The left-hand panel of Figure 2.9 shows the evolution of the embedded and the high mass star populations in raw simulation time. As expected from the initial free-fall time calculations, the characteristic formation timescale of the high mass cluster is significantly longer. Massive stars take longer to form, and all stars take longer to emerge from the dust.

The fact that all the curves in Figure 2.9 have similar shapes suggests that they may scale with the free-fall time. We test this possibility in the center panel, where we rescale the simulation time by  $\tau_{ff}$ . We find that the bulk of the evolution in  $f(\bar{A}_V > 1)$  and  $f(> 8 M_\odot)$  is quite similar, once the scaling in the free-fall time is removed. We note that we do not expect the trends for the two clouds to be in perfect agreement, given that there will be second-order effects from specifics in the cloud substructure, and that some feedback timescales such as "time to first supernova after a massive star forms" are not going to be affected by the overall cluster dynamics.

We quantify the scaling with free-fall time by calculating the times at which the fractions  $f(\bar{A}_V > 1)$  and  $f(> 8 M_\odot)$  reach 50%, as indicated by the thin grey lines in the left and center panels. We then plot these two quantities as function of cloud mass in the right most panel of Figure 2.9. When considering the scaling of the cloud free fall time, we find that the point that 50% of the massive

<sup>7</sup>We note that we could have chosen to measure the fraction of high mass stars which have reached their maximum mass, consistent with the age zero from Section 3.1. If we had made this distinction,  $\tau_{50, > 8 M_\odot}$  in the Fiducial model increases slightly to  $1.72 \tau_{ff}$ .



**Figure 2.9:** Comparison between two STARFORGE simulations, differing in molecular cloud mass. The fiducial  $2 \times 10^4 M_\odot$  cloud is shown in red, while the  $2 \times 10^5 M_\odot$  cloud is shown in purple. The left panel correspond to Figure 2.4, with points showing the fraction of stars with  $\widetilde{A}_V$  greater than 1, while the solid lines show the fraction of stars greater than  $8 M_\odot$  which have begun their proto-stellar stage. The middle panel shows the same as the left, but is normalized by the respective cloud free-fall times,  $\tau_{ff}$ , demonstrating that the start of emergence is related to initial cloud mass and density. The vertical gray lines correspond to  $\tau_{50, > 8 M_\odot}$  and  $\tau_{50, A_V > 1}$ , which denote the time where 50% of of the stars greater than  $8 M_\odot$  have begun their proto-stellar stages, and the time when 50% of of the stars have a  $\widetilde{A}_V$  greater than one. These metrics are also shown in the right panel. In both simulations, the extinction is tied to the point in the star-forming event where the high-mass stars form.

stars form ( $\tau_{50, > 8 M_\odot}$ ) occurs at  $1.6 \tau_{ff}$  in both clouds.

In addition to  $\tau_{50, > 8 M_\odot}$  being consistent between the two clouds, we also find the point where 50% of stars have an  $\widetilde{A}_V$  greater than 1 ( $\tau_{50, A_V > 1}$ ), to also scale with the cloud free fall time. We measure  $\tau_{50, A_V > 1}$  to be  $1.97 \tau_{ff}$  for the  $2 \times 10^5 M_\odot$  cloud and  $1.94 \tau_{ff}$  in the  $2 \times 10^4 M_\odot$  cloud. Given that the  $\tau_{50, > 8 M_\odot}$  in both clouds is  $1.6 \tau_{ff}$ , this slight difference in  $\tau_{50, A_V > 1}$  between the two simulations means that the emergence occurs slightly faster in the lower mass cloud than in the high mass cloud.

We note that the exact scaling of 1.6 free-fall times is likely to change with different initial conditions, or different chemical prescriptions. While the exact scaling may change, we expect the overall correlation to hold. Physically, we demonstrate the onset of massive star formation, and the subsequent feedback associated with them, to be the driving mechanism of gas clearance. While the formation time of massive stars is likely dependent on the initial conditions of the simulation, given the spread in stellar age seen here, the length of this formation time should still scale with the free fall time of the cloud.

This result once again re-enforces that de-embedding is governed by the local impact of massive stars. Once a massive star forms, their feedback – ionization, radiation pressure, and winds – rapidly evacuates its immediate surroundings, regardless of the mean cloud density. In this regime, the de-embedding timescale reflects the time required to form the massive stars themselves, not the efficiency of subsequent large-scale feedback. For the two cloud masses explored here, this local



mechanism dominates, yielding a nearly self-similar emergence time in units of  $\tau_{\text{ff}}$ . However, more analysis is needed for other simulations with different cloud masses and different initial conditions. At significantly higher densities or metallicities, we expect this balance may shift, but within our parameter space, the onset of de-embedding is tightly linked to the timing of massive star formation.

## 5 Observational Measures of Embeddedness

Throughout this work, we have focused on measures of embeddedness from the lens where we know the intrinsic properties of all aspects of the simulation. This framework has allowed us to probe the relationships between newly formed stars, their feedback, and the timescales of embeddedness. However, these ground truths are not a luxury afforded to those in the observational community. We therefore now approach the simulation from another angle, re-framing our analysis to mirror the observational approach.

In the previous section, this framework led us to conclude that individual stars transition from deeply embedded to exposed very rapidly once they reach their maximum mass, and that this transition is driven primarily by local feedback from massive stars rather than by global gas removal (Section 4). To connect this physical picture to what observers actually measure, we must determine whether such locally driven emergence would be imprinted in the diagnostics used to infer embedded lifetimes. We therefore model the standard tracers used to infer embedded timescales and star-formation rates from our simulation, and measure how long each tracer is dominant, peaks, and fades relative to the physically defined de-embedding of the stars presented in the previous section. By comparing these synthetic timescales to those inferred from real systems, we can test both whether the short, local emergence phase around massive stars leaves a clear imprint on the luminosity evolution and whether the STARFORGE model is capturing the same physics that governs observed embedded clusters.

While trying to observe star formation, there are specific times throughout the process where different tracers dominate the emission from the region (e.g., [Kim et al., 2021](#); [Kruijssen et al., 2018](#)). These different tracers can then lead to different measured embedded timescales, depending on how long each tracer is viable. In this section, we discuss three main observational tracers often used: 1) IR emission from irradiated dust, 2)  $\text{H}\alpha$  emission from hydrogen re-combination, and 3) UV/Optical emission from stars. We will then compare the timescales for which different wavelength regimes are observable.

### 5.1 Infrared Emission

When stars are obscured, their light is absorbed by the surrounding dust. The warmed dust then re-emits this energy as thermal emission at mid- and far-infrared (MIR/FIR) wavelengths. This dust emission therefore has become widely used as a way to find young, but shrouded, stellar clusters early in their evolution. In this section, we calculate this emission from warm dust, and the fraction of reprocessed stellar luminosity as a function of time, with the goal of measuring the timescales over which MIR/FIR emission might be detected for young clusters.

To model the emergent radiation from the dust in our simulation, we perform post-processing radiative transfer calculations using the *SKIRT* code ([Baes et al., 2011](#); [Camps & Baes, 2015](#),

2020). SKIRT is a three-dimensional Monte-Carlo radiative transfer code that tracks the propagation, absorption, scattering, and re-emission of photon packets through arbitrary dusty geometries. SKIRT includes both stellar and background sources, and computes self-consistent dust heating and emission assuming local thermodynamic equilibrium and stochastic heating (Baes & Camps, 2015).

The primary radiation is provided by both stellar particles and a diffuse interstellar radiation field (ISRF). Stellar sources are imported from STARFORGE outputs as individual particles, each with a position, velocity, mass, age, and metallicity. We then assign each star an SED drawn from the Bruzual & Charlot (2003) simple stellar population models. In addition to the stars, we include a spherical background radiation field that approximates the ISRF, following the multi-component modified blackbody model from Zucconi et al. (2001) as updated by Bate & Keto (2015).

The absorbing and emitting medium consists of the gas cells in the simulation, which are imported into SKIRT. Each cell provides a position, mass, metallicity, and dust temperature, where SKIRT then internally computes the dust mass assuming a fixed dust-to-metals ratio of 0.4. We adopt the Draine & Li (2007) dust mixture, and the dust is discretized onto a Voronoi mesh with 500,000 sites, where photon packets are propagated through the grid. For accuracy, we include dust heating by the CMB, though it has a negligible effect. For emission, we adopt a logarithmically spaced wavelength grid from 0.1 to 2000  $\mu\text{m}$  with 200 bins, ensuring accurate coverage of both stellar and IR re-emission peaks.

The dust luminosity is calculated internally by SKIRT as the total bolometric energy absorbed, and subsequently re-emitted by dust grains. Specifically, SKIRT determines the absorbed luminosity in each spatial cell  $m$  by integrating the product of the radiation field, absorption opacity, and path length over all wavelength bins  $\ell$ :

$$L_{\text{bol},m}^{\text{abs}} = \sum_{\ell} k_{\ell,m}^{\text{abs}} (L\Delta s)_{\ell,m}, \quad (2.1)$$

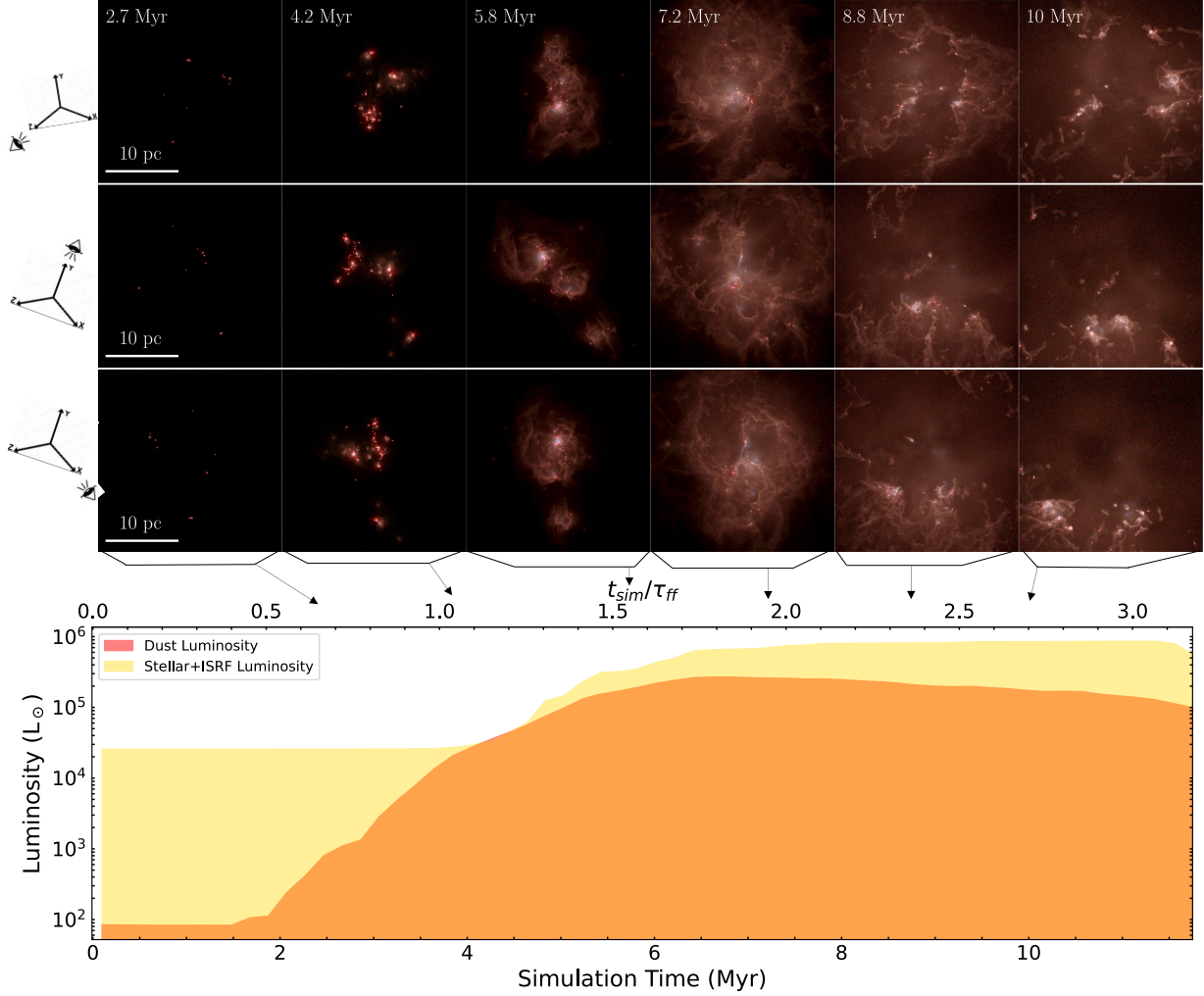
where  $k_{\ell,m}^{\text{abs}}$  is the absorption opacity in cell  $m$  at wavelength bin  $\ell$ , and  $(L\Delta s)_{\ell,m}$  is the path-integrated packet luminosity accumulated in that bin. The total dust luminosity is then obtained by summing over all cells.

While SKIRT includes the capability of including separate contributions from primary and secondary emission cycles (Camps & Baes, 2015), in this work we choose to focus on the dust luminosity resulting from the absorption of light from stars and the ISRF, and all dust luminosities presented are those of the primary emission cycles. Therefore, while the luminosity values presented here represent a lower limit, the overall shape and timescales of the dust luminosity, are representative of the total infrared emission.

Based on the absorbed energy, dust properties, and the local radiation field, `skirt` calculates the dust emissivity spectrum  $j_{\nu}(\vec{r})$  in each cell. Photon packets are then emitted according to this emissivity distribution. The total emergent dust luminosity is given by:

$$L_{\text{dust}} = \int_V \int_{\nu} j_{\nu}(\vec{r}) d\nu dV, \quad (2.2)$$

where  $j_{\nu}(\vec{r}) = \kappa_{\nu}\rho(\vec{r})B_{\nu}(T_d(\vec{r}))$  for grains in thermal equilibrium, or is derived from the full temperature probability distribution for stochastically heated grains (Baes et al., 2011; Camps & Baes, 2015; Verstocken et al., 2017). The resulting  $L_{\text{dust}}$  includes the integrated emission from all dust species and temperatures present in the simulation volume.



**Figure 2.10:** Top: three-color (R: 80-120  $\mu\text{m}$ , G: 6-13  $\mu\text{m}$  B: 20-30  $\mu\text{m}$ ) composite images of the STARFORGE simulation viewed from 3 different angles at 500 pc with time increasing left to right. Bottom: time evolution of the total dust luminosity in solar lumens (red) compared to the luminosity from stars and the ISRF (yellow). We include a larger, high-resolution image of one viewing angle from the 7.2 Myr snapshot in Appendix B.

### 5.1.1 Total Dust Luminosity

The time evolution of the total dust luminosity across our simulation snapshots is shown in bottom panel of Figure 2.10. Shown in red is the total luminosity, while yellow shows the combined luminosity of the ISFR and stars. At the start of the simulation when stars have yet to form, the energy budget is dominated by the ISRF, and the total dust luminosity is  $\sim 80L_{\odot}$ . This initial dust luminosity remains relatively constant until the first stars begin to form and heat the dust. The dust luminosity then increases gradually as more stars form, and peaks at 6.8 Myrs ( $1.68 \tau_{ff}$ ) with the formation of large numbers of massive stars (see upper right panel of Figure 2.7).

For visualization purposes, we also generate synthetic images of dust luminosity calculated by `skirt` in the STARFORGE simulation, which are shown in the top panel of Figure 2.10. These

images are generated from the same simulation snapshots as in Figure 2.4, with time increasing from left to right, and each row presenting the same simulation output viewed at a different orientation. Each image spans 25 pc in the x and y direction, covered by 25 Megapixels. For these images, we set a distance of 500 pc to the source, giving an angular resolution of  $\sim 2$  arcseconds per pixel, roughly consistent with JWSTs instruments (Rieke et al., 2015; Wright et al., 2023). The three-color composite images- R: 80-120  $\mu\text{m}$ , G: 6-13  $\mu\text{m}$  B: 20-30  $\mu\text{m}$ - were chosen to best represent the SED, where red is the peak of the SED showing cold dust, green shows the primary PAH features, and blue shows the features arising from hot dust. We also include one larger, high-resolution image of the 7.2 Myr snapshot in Appendix B to best showcase the filamentary dust structure that emerges in STARFORGE.

Images were created using `ds9` (Joye, 2019). Each channel was scaled such that they are equally-weighted by integrated luminosity in the snapshot, and to compensate for the evolving total dust luminosity across snapshots (see Figure 2.10, bottom panel; i.e. 2360 has the highest maximum scaling, while 1080 has the lowest). Each channel was logarithmically-scaled, with a varying log-exponent (ranging from 3000-10,000), depending on the dynamic range of the image, such that a higher exponent was used for snapshots with a large amount of fine structure at low-surface brightness.

In these composite images, the different colors reveal distinct physical processes and evolutionary stages within the dusty star-forming region. The bright red knots, which dominate early in the evolution, represent dense, cold dust concentrated around young protostars still deeply embedded in their natal gas. These compact structures correspond to the regions of highest extinction, and their prominence reflects ongoing accretion and gravitational collapse. In contrast, the blue regions trace hot dust that has been heated by the intense radiation of recently formed massive stars. This emission, arising primarily in the 20–30  $\mu\text{m}$  range, is characteristic of photodissociation regions (PDRs) where stellar UV radiation heats and erodes surrounding material. As the system evolves, these blue features become more spatially extended, marking the emergence of heated cavities and expanding shells. The green channel highlights mid-infrared emission from PAHs, which are also clustered around regions of recent massive star formation. Together, these evolving color patterns offer a visual narrative of how feedback transforms the structure of the cloud, progressing from dense, cold star-forming cores to dispersed, UV-irradiated PDRs.

This evolving color structure reflects not only changes in local conditions but also tracks the global evolution of dust luminosity over time. As more stars form and begin heating their surroundings, the total dust luminosity increases steadily, peaking around 6.8 Myr ( $1.84\tau_{\text{ff}}$ ), coinciding with the appearance of large numbers of massive stars (see Figure 2.7). This trend closely parallels the decline in median extinction shown in Figure 2.4, underscoring how star formation and dust heating go hand in hand during the embedded phase.

Beyond the overall rise and fall in brightness, the morphology of the dust emission undergoes a dramatic transformation. Early on, emission is confined to compact, embedded clumps, but by 10 Myr, the gas has largely been dispersed and the stars themselves have begun to drift apart. The remaining dust appears far more diffuse, but continues to emit due to localized heating from residual star-forming activity. These late-time clumps stand out clearly in the upper panels of Figure 2.10, marking the final, spatially fragmented stages of clustered star formation.



### 5.1.2 $24\mu\text{m}$ Emission

In addition to the bolometric dust luminosity presented above, we also choose to highlight  $24\mu\text{m}$  emission, which has become widely used as a tracer of embedded star formation since the launch of *Spitzer* (e.g., Schinnerer & Leroy, 2024). This mid-infrared band is dominated by emission from warm, large dust particles, with little emission from more fragile polycyclic aromatic hydrocarbons (PAHs) (Whitcomb et al., 2023) making the  $24\mu\text{m}$  emission easier to interpret. Scattering is also negligible at  $24\mu\text{m}$ , with an albedo of only  $4.6 \times 10^{-4}$ , making Eq. 2.2 a good approximation. Additionally, the F2100W filter on JWST serves a similar purpose, and tends to track the same physical processes (Ramambason et al., 2025).

Using the same framework used to make the images, and calculate the dust luminosity in Section 5.1, we make mock  $24\mu\text{m}$  observations of the simulation using *skirt*. Here, we adopt the *Spitzer*  $24\mu\text{m}$  pass-band which ranges from 20.8 to 26.1 microns, integrating the dust SED only across these wavelengths to determine the  $24\mu\text{m}$  luminosity, as observed by *Spitzer*.

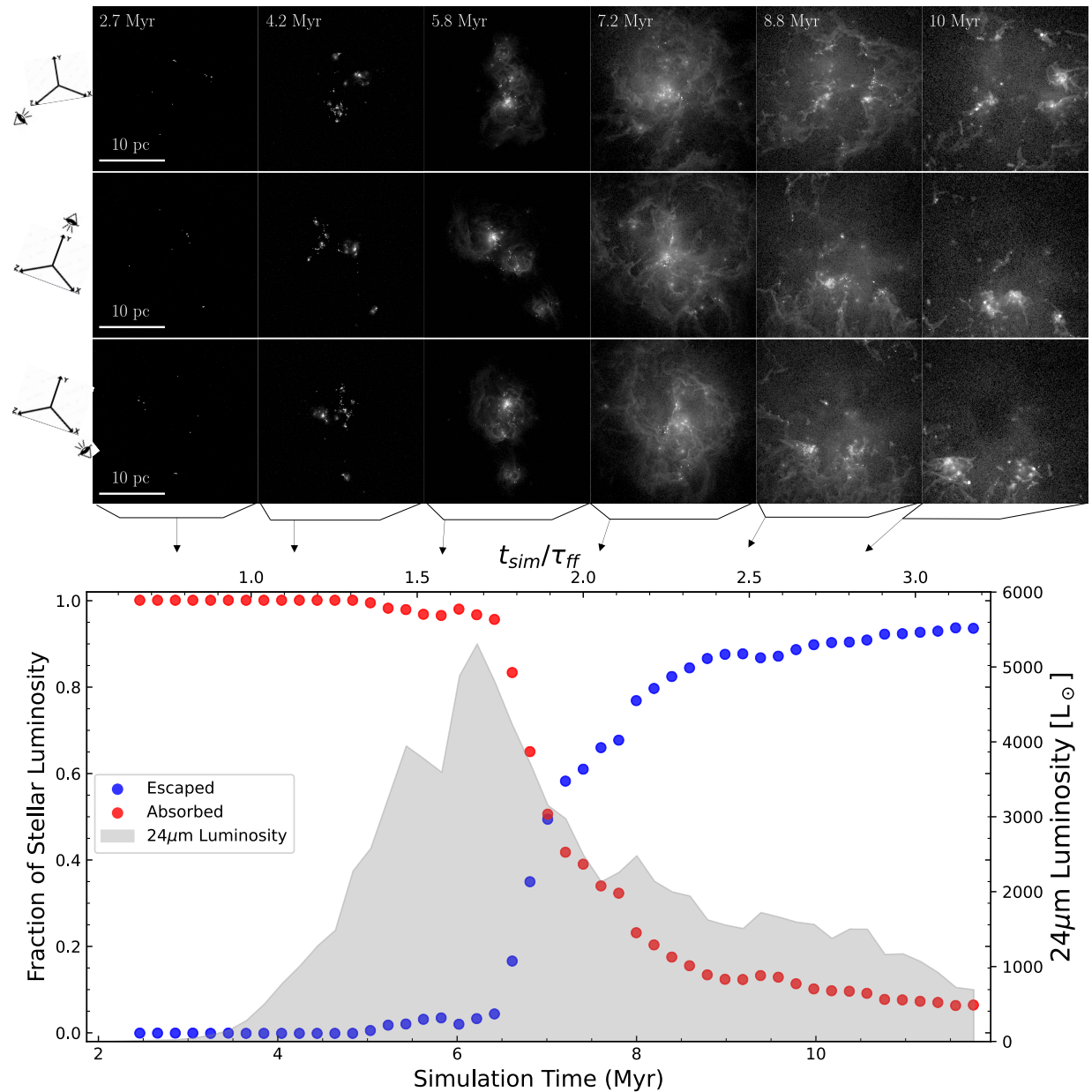
In the top panels of Figure 2.11, we show a time sequence of  $24\mu\text{m}$  images, generated from the same simulation snapshots as in Figure 2.4, with time increasing from left to right, and each row presenting the same simulation output viewed at a different orientation. The gray shaded region in the bottom panel is the integrated  $24\mu\text{m}$  luminosity of the region as a function of time, while the red and blue points show the fraction of the emitted V-band stellar luminosity that is absorbed by the dust and how much escapes, respectively. The absorbed fraction is derived from the fractional, cumulative stellar  $A_{V,\theta,\phi}$ , integrated over all angles, where the amount escaped is simply the inverse of how much is absorbed.

Overall, the evolution in Figure 2.11 is quite similar to that seen for the overall dust luminosity. However, while the  $24\mu\text{m}$  luminosity increases gradually as more stars form just like the overall dust luminosity, the  $24\mu\text{m}$  luminosity peaks earlier, at 6.2 Myr ( $1.68 \tau_{ff}$ ) compared to the peak at 6.8 Myr seen in Section 5.1. Additionally, in contrast to the relatively smooth decline in luminosity seen in Figure 2.10, the decline in  $24\mu\text{m}$  luminosity from the peak is much more pronounced. In fact, by 6.8 Myr when the total dust luminosity is peaking, the  $24\mu\text{m}$  luminosity is already at 70% of its maximum.

When the  $24\mu\text{m}$  begins to decrease, in the bottom panel of Figure 2.11 we can see that over 95% of the optical stellar luminosity is being absorbed, warming the dust and powering the  $24\mu\text{m}$  emission. However, during the period of time between  $\sim 6$  and 8 Myr the fraction of significantly extincted stars is steadily dropping (bottom panel of Figure 2.4), and the  $24\mu\text{m}$  luminosity drops as the star light becomes less coupled to the dust and a larger fraction of the light escapes (blue points in Figure 2.11). This low level  $24\mu\text{m}$  emission seen here after the peak in star formation is consistent with that seen in Kim et al. (2021), who measure diffuse emission for up to 9 Myr after star formation ceases.

In total, the upper and lower panels of Figure 2.11 confirm that compact, high-intensity  $24\mu\text{m}$  emission is a signature of the embedded phase of star formation. Within STARFORGE, the  $24\mu\text{m}$  luminosity is high for only a brief window of  $\sim 2$ -3 Myr, corresponding to the period where the emission is truly embedded. There is also a fainter, but extended tail of  $24\mu\text{m}$  emission that persists for an additional  $\sim 5$ -6 Myr. However, during this long tail, the existence of  $24\mu\text{m}$  emission alone does not necessarily imply the association is in the embedded phase, particularly when there is not enough spatial resolution to discern the morphology of the emission.





**Figure 2.11:** *Top:*  $24\mu\text{m}$  luminosity from the *Spitzer* band-pass, visualized at the same viewing angles and time steps as Figure 2.4. *Bottom:* Fraction of stellar luminosity absorbed (red), and escaped (blue). On the secondary axis and shown in gray is the total  $24\mu\text{m}$  luminosity of the region as a function of time. The  $24\mu\text{m}$  luminosity from dust emission peaks before 20% of the stellar luminosity escapes and is visible.

## 5.2 Gas Density and H $\alpha$ Emission

Later in their evolution, young clusters can be identified through their H $\alpha$  emission at 656 nm (e.g., Kennicutt, 1998; Rydgren, 1979), which arises from recombination of hydrogen (HII) that has been ionized by young massive stars or shocks (e.g., Kennicutt, 1998; Kennicutt & Kent, 1983; Schinnerer & Leroy, 2024; Strömgren, 1939; Tacchella et al., 2022). H $\alpha$  emission is therefore a direct indicator of the presence of short-lived massive stars, and thus offers constraints on the age of a stellar cluster. Its morphology is also a useful indicator of the evolutionary state of gas clouds, which can range from “tracing a dense reservoir of ionized gas” to “tracing recent photodissociation along extended surfaces of a disrupting turbulent molecular cloud” (e.g., Hannon et al., 2022; Whitmore et al., 2011).

Here, we calculate the H $\alpha$  luminosity and morphology for the evolving stellar association. For each gas cell, we derive the H $\alpha$  luminosity from the number density of protons ( $n_p$ ) and electrons ( $n_e$ ), using the recombination rate  $\alpha$  such that,

$$L_{\text{H}\alpha} = 2.86 \alpha_{\text{H}\beta}^{\text{eff}} n_p n_e \frac{hc}{\lambda_{\text{H}\alpha}} \cdot \frac{m}{\rho}, \quad (2.3)$$

where  $\alpha_{\text{H}\beta}^{\text{eff}}$  is the effective recombination coefficient for H $\beta$  emission, scaled by the H $\alpha$ /H $\beta$  line ratio of 2.86, at 10000 K, taken from Osterbrock & Ferland (2006).

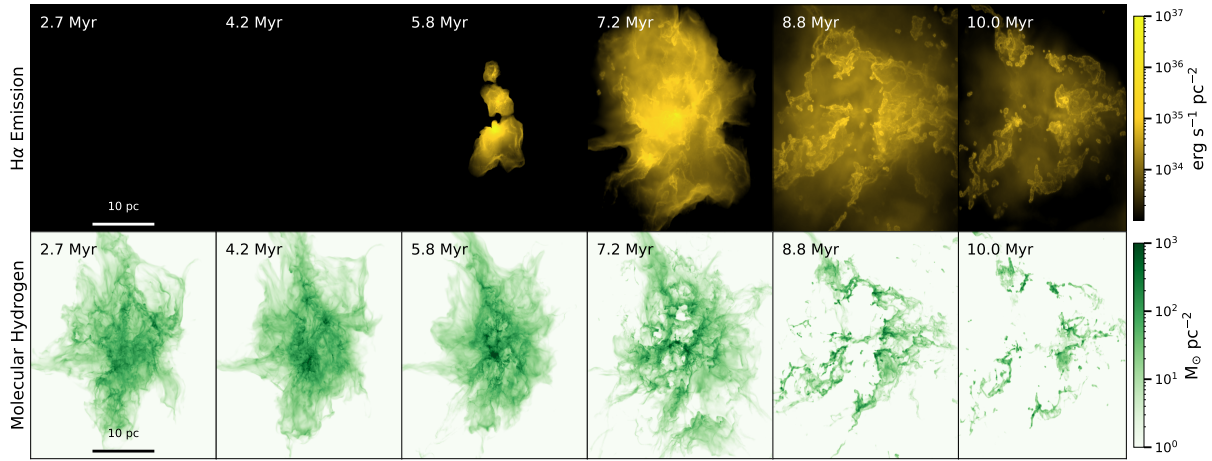
The proton number density  $n_p$  is given by the product of the ionized hydrogen fraction  $x_{\text{HII}}$  and the total hydrogen number density  $n_{\text{H}}$ , while the electron number density  $n_e$  is computed in STARFORGE. The hydrogen number density itself is derived from the gas density  $\rho$  using  $n_{\text{H}} = \rho/(\mu_{\text{H}} m_p)$ , where  $m_p$  is the proton mass and  $\mu_{\text{H}}$  is the hydrogen mass fraction, measured for each gas particle based on metallicity.

The energy emitted in H $\alpha$  is then computed as  $hc/\lambda_{\text{H}\alpha}$ , where  $h$  is Planck’s constant,  $c$  is the speed of light, and  $\lambda_{\text{H}\alpha} = 656 \text{ nm}$  is the rest-frame wavelength of the H $\alpha$  line. The final factor  $m/\rho$  represents the physical volume associated with each gas particle, effectively integrating the local emissivity over that volume. The result is the total H $\alpha$  luminosity per gas particle, expressed in units of  $\text{erg s}^{-1}$ .

Figure 2.12 shows the resulting maps of H $\alpha$  emission at the same time steps and orientations as the top row in Figure 2.4. The colorbar represents the surface brightness of the emission, where yellow corresponds to brighter regions. To provide context, we also show maps of the molecular gas surface density in the bottom row, where shades of green depict the gas density in solar masses per square parsec. Together, these maps allow for direct comparison of where ionized and molecular gas coexist, separate, and evolve over time.

The H $\alpha$  emission is initially insignificant but rises quite quickly after a significant fraction of stars reach high stellar masses, roughly 5 Myr into the simulation (Figure 2.6); similar behavior is seen in the  $24\mu\text{m}$  emission maps (Figure 2.11).

Initially, the H $\alpha$  emission is relatively smooth and compact, akin to the classical Stromgren sphere (Strömgren, 1939). In this phase, the emission is largely from dense cavities of ionized gas around massive stars. Beyond 8 Myr, however, these cavities have expanded and the ionized gas density has dropped, suppressing the smooth component of H $\alpha$  (whose recombination emission goes as density squared). Instead, the H $\alpha$  emission becomes extended and highly structured. Its structure also becomes highly correlated with the remnants of the dense molecular gas. This correspondence suggests that at late times the high-surface density H $\alpha$  emission is primarily from



**Figure 2.12:** Surface brightness of  $H\alpha$  emission (yellow color map; top) and the surface density of molecular hydrogen (bottom; green), as a function of simulation time. The densest regions of the molecular gas are the locations of star formation, which is traced by the  $H\alpha$  in the top panel. The  $H\alpha$  emission also mirrors that seen in the  $24\mu\text{m}$  in Figure 2.11.

ionization of dissociation fronts on the dense surfaces of the remnants of the original molecular reservoir, which by now has been disrupted or dispersed, leaving behind only a few regions that have survived the cumulative effects of massive star feedback.

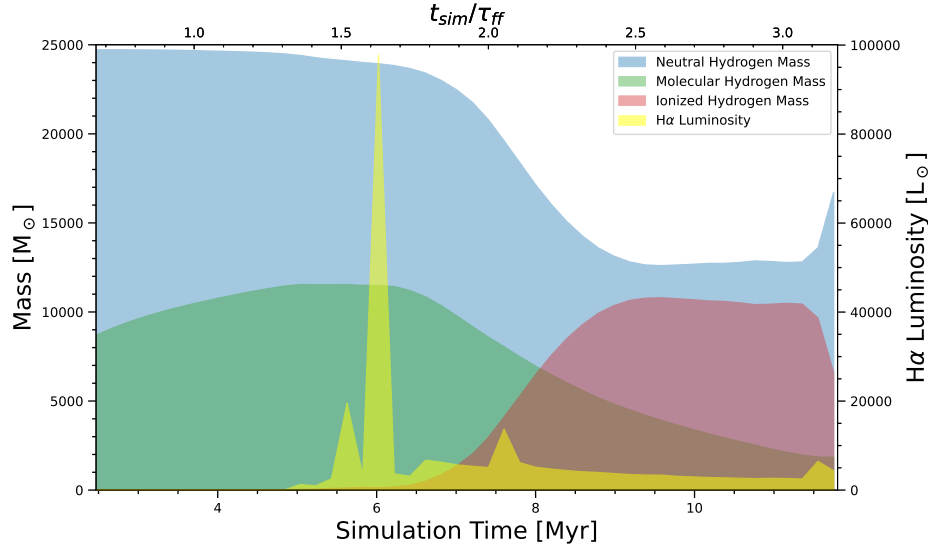
Interestingly, the morphology of the  $H\alpha$  emission at early times resembles the  $24\mu\text{m}$  mid-infrared emission shown in Figure 2.11. This similarity is not coincidental; both tracers are powered by radiation from the same population of embedded massive stars. The mid-IR emission arises from irradiated dust heated near the photoionization front, which are the same locations responsible for the strongest  $H\alpha$  emission.

We also quantify the global evolution of the  $H\alpha$  emission in Figure 2.13, in context with the various gas phases present in the simulation as a function of time. We plot the time evolution of the total  $H\alpha$  luminosity (yellow curve, right axis), along with the total mass in molecular (green), neutral (blue), and ionized (red) hydrogen gas (left axis). Together, these curves display the interplay between gas phase transitions and emergent emission.

Confirming the visual impression from Figure 2.12, the  $H\alpha$  luminosity remains negligible during the early stages of star formation (2.5–4.5 Myr), despite a growing population of low-mass protostars. The first strong rise occurs around 5 Myr, peaking sharply at 6 Myr, corresponding with the onset of significant massive stars. Following the brief peak, the luminosity declines more gradually, punctuated by brief secondary spikes at 7.7 Myr and 11.5 Myr. The former likely reflects a small burst of massive star formation, while the latter coincides with the first supernova event.

From 5 Myr to 6 Myr, the time-evolution of the  $H\alpha$  emission fluctuates rapidly. While the full analysis for determining the exact cause of the large peak in the  $H\alpha$  luminosity at 6 Myr should be the focus of future studies, one possibility could be collisionally-ionized shocked regions from jets or winds. Another possibility is that the  $H\alpha$  variability reflects short-timescale variability in the accretion of massive stars.

We also compare the evolution of the  $H\alpha$  luminosity to the overall evolution of different gas



**Figure 2.13:** Time evolution of the gas mass in neutral (blue), and molecular hydrogen (green). The secondary axis shows the time evolution of the  $H\alpha$  emission in  $L_{\odot}$ .

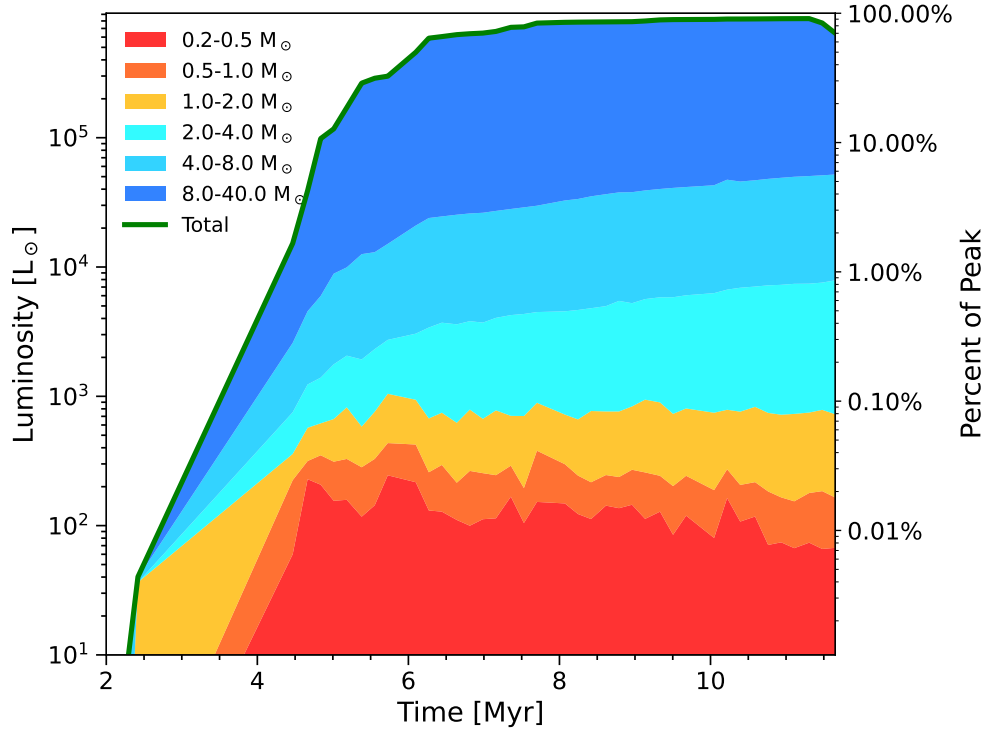
phases in the simulation. Early on, the neutral gas mass steadily declines as material is converted into stars or accreted onto sink particles. Around 6 Myr, the decline in neutral gas accelerates as feedback begins to ionize the cloud. This trend is mirrored by a rapid increase in the ionized gas mass, with the two phases clearly anti-correlated. In parallel, the molecular gas mass initially increases due to the collapse and cooling of the gas cloud, even as stars begin to accrete the dense gas. This growth continues until 6.2 Myr, at which point the molecular reservoir begins to deplete after feedback from massive stars becomes significant. Some molecular gas does survive to late times, however, fueling a low level of residual star formation throughout the simulation.

We note that, surprisingly, the strongest  $H\alpha$  emission actually precedes the formation of a significant ionized gas component in the cloud. As seen in Equation 2.3, recombination-driven  $H\alpha$  depends on the square of the gas density, which is highest earlier in the simulation. At later times, there is more ionized gas, but most of that gas is now diffuse, with a much lower recombination rate, and thus a lower  $H\alpha$  luminosity. This behavior echoes the picture developed in Section 4.2, where  $H\alpha$  is brightest when massive stars are still tightly coupled to localized gas, and fades once their feedback evacuates their immediate surroundings, even as global ionization of the cloud continues to grow.

### 5.3 Optical and UV Emission from Stars

As gas and dust are cleared by stellar feedback, the direct emission from stars begins to escape, allowing optical and ultraviolet light to emerge. These bands not only mark the transition from embedded to exposed phases of stellar formation, but also offer critical age constraints on the system. To evaluate how this starlight evolves and eventually becomes observable, we begin by computing the bolometric luminosity of each star, based on its mass and radius at each evolutionary stage (Section 4.2).

In Figure 2.14, we decompose the total bolometric luminosity into contributions from stars in



**Figure 2.14:** Bolometric luminosity of stars as a function of time. The green curve shows the total luminosity, while shaded regions indicate contributions from different stellar mass bins (same as in Figure 2.8). The right axis shows luminosity as a percentage of the peak total. Once they gain sufficient mass, around 4.2 Myr (Figure 2.6), high-mass stars clearly dominate the luminosity the system.

different mass bins. The green curve shows the total stellar output, while the stacked colored curves reflect how stars of different masses contribute over time (same bins and color scheme as Figure 2.8). These results reaffirm the key insight from Figure 2.6: once massive stars form—especially after  $\sim 4.5$  Myr—they quickly dominate the cluster’s light budget, accounting for the majority of stellar luminosity well before the system is optically revealed.

While bolometric luminosity captures the full stellar energy output, what is detectable is shaped by dust attenuation and filter throughput. Therefore, we map the intrinsic stellar luminosities into synthetic observations of two filters frequently used to identify young stars: the *GALEX* far-ultraviolet (FUV; 135–175 nm) and the *HST* F555W optical band (458–620 nm). For each star, we integrate the stellar spectral energy distribution across the filter bandpasses.

To account for extinction, we determine the dust attenuation using the viewing angle-averaged  $\widetilde{A}_V$  values from Section 3.2. Extinction in each band is then scaled according to the Cardelli et al. (1989) extinction law, with UV extinction taken to be  $3.85 \times \widetilde{A}_V$ .

## 5.4 The Relative Timing of Observational Indicators

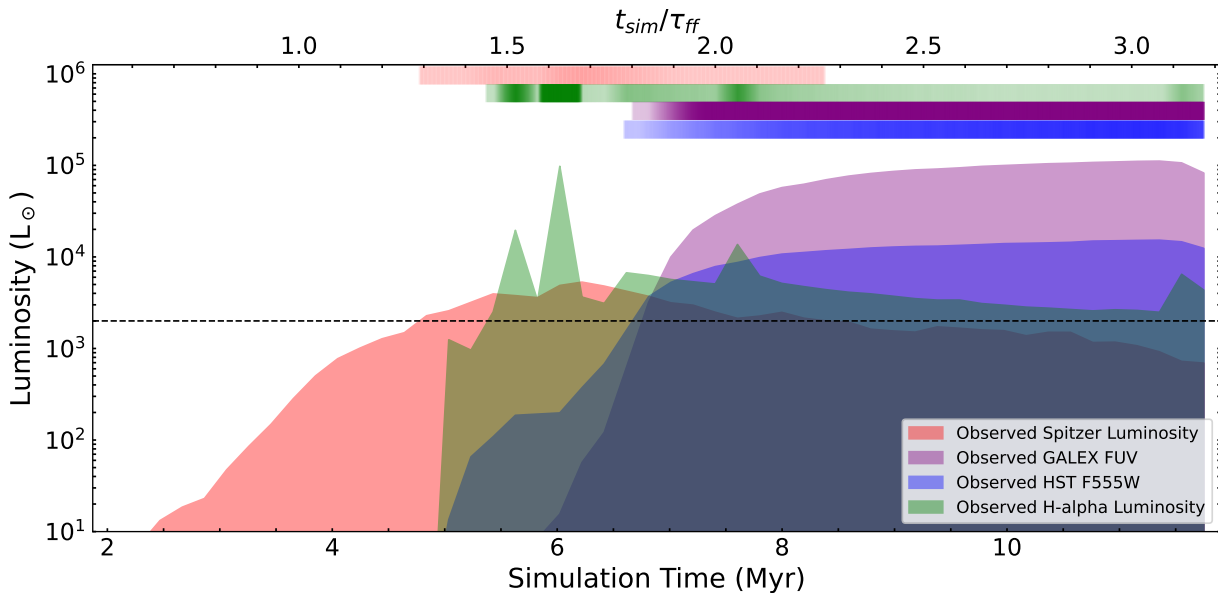
Having established how different star formation tracers emerge over the course of the simulation, we now turn to comparing their characteristic timescales. Each wavelength regime becomes visible



on different timescales and persists for a different duration, depending on both the physical state of the cloud and the presence of massive stars. In this section, we compare when each tracer first appears, how long it dominates the association emission, and when it fades, providing a direct comparison between the observable windows offered by wavelength regimes.

To do this comparison, we consider quantities discussed throughout this section; dust luminosity (Section 5.1),  $H\alpha$  luminosity (Section 5.2), and the stellar luminosity as viewed in the optical and UV (Section 5.3). We present this comparison for potentially observed luminosities, where each quantity is measure through the specific telescope band pass with the corresponding wavelength attenuation.

We summarize the evolution of emission across wavelength regimes in Figure 2.15, which shows the observed luminosity from stars (blue and purple), dust (red), and ionized gas (green) as a function of time.



**Figure 2.15:** Observed luminosities in different telescope pass bands as determined by the median of 60 viewing angles. Red is  $24\ \mu\text{m}$  emission observed in the *Spitzer* band pass. Green is  $H\alpha$  emission, while blue is optical light observed in the HST F555W filter, and purple is UV as observed by the GALEX FUV filter. The black dashed line at  $2000\ L_{\odot}$  represents our threshold for “onset” timing, and the bars depict the times and relative brightness of each tracer with respect to this threshold. The mid-IR emission is most dominant for the first few Myr, until the onset of massive star formation, when the  $H\alpha$  emission dominates for  $\sim 1\text{Myr}$ . There is a brief period of  $\sim 0.5\text{Myr}$  where all tracers are present and bright, before the stellar luminosity becomes the dominant feature.

Each tracer becomes prominent on a characteristic timescale, reflecting the physical conditions required for it to emerge. To make this comparison more concrete, Table 2.1 lists the onset time, peak, and duration of each tracer’s dominance in the simulation. We define the onset to be when the luminosity crosses  $2000\ L_{\odot}$ . This relatively arbitrary threshold was chosen to best differentiate between when a tracer is present, and when it is clearly visible. While this threshold is unique to our current simulation, it adequately characterizes the intrinsic timescales for each tracer.

| Tracer                                        | Onset (Myr) | Onset ( $\tau_{\text{ff}}$ ) | Duration (Myr) | Duration ( $\tau_{\text{ff}}$ ) |
|-----------------------------------------------|-------------|------------------------------|----------------|---------------------------------|
| <i>Spitzer</i> 24 $\mu\text{m}$ Dust Emission | 4.8         | 1.29                         | 3.6            | 0.97                            |
| 656 nm $\text{H}\alpha$ Emission              | 5.4         | 1.45                         | >6.4           | >1.72                           |
| HST F555W Optical                             | 6.6         | 1.78                         | >5.2           | >1.39                           |
| GALEX FUV                                     | 6.7         | 1.8                          | >5.1           | >1.37                           |

**Table 2.1:** Approximate emission timescales for each tracer, defined as the period above  $2000 L_{\odot}$ . Times in  $\tau_{\text{ff}}$  use the fiducial  $\tau_{\text{ff}} = 3.7$  Myr.

The 24 $\mu\text{m}$  emission from irradiated dust appears first, describing the truly embedded phase of formation. It builds throughout and peaks around 6.2 Myr, remaining prominently observable for nearly 3 Myr.  $\text{H}\alpha$  emission emerges slightly later around 5 Myr, and peaks rapidly, overlapping with the IR for about 1 Myr before declining as gas is cleared.

Although future work will be needed to determine the origin of this unexpectedly early peak in the  $\text{H}\alpha$  luminosity, it winds up being nearly contemporaneous with the peak in the 24 $\mu\text{m}$  emission. This correspondence is surprising, given that the typical view is that the MIR/FIR traces a purely embedded phase that precedes any visible signatures of massive stars that later manifest in the  $\text{H}\alpha$ . Instead, both tracers have similar early peaks, and long tails.

This unexpected behavior for the time-evolution of  $\text{H}\alpha$  and 24 $\mu\text{m}$  emission again highlights the importance of local properties within the evolving cloud. Both luminosities will be strongly enhanced by having dense gas close to massive stars, although for different physical mechanisms – i.e., recombination versus higher dust temperatures, to a degree that frequently dominates over the global evolution of the majority of the gas<sup>8</sup>.

In contrast, optical and UV stellar light becomes dominant only after localized feedback has substantially cleared gas from the highest mass stars which dominate these wavelengths. This transition is rapid, occurring over just  $\sim 0.5$  Myr. By 7.0 Myr, over half of the intrinsic stellar light escapes without being absorbed, and direct starlight becomes the primary observable tracer.

We note that the specific values are subject to change with different decisions made throughout (i.e, threshold, dust-luminosity from secondary-emission), and therefore the derived timescale values should not be taken as ground truth. However, the overall evolution of these tracers are independent of these decisions, and the primary results of characteristic timescales are robust to the accuracy of the exact values.

Together, these results reaffirm that dominant emission phases are not neatly sequential, but overlapping and are often controlled more by local feedback conditions than global cloud properties.

## 6 Discussion

### 6.1 Contextualizing STARFORGE and Observations

Several previous works, both observational and theoretical, have attempted to quantify the timescales of the embedded stage of star formation. Compared to observation, one unique advantage of the

<sup>8</sup>Note the degree to which the high surface brightness 24 $\mu\text{m}$  emission in Figure 2.11 is actually highly localized in small clumps, likely tracing associated young bright stars.

work here is the plethora of information available in the STARFORGE simulations. Here we explore some notable differences between the two landscapes that should be kept in mind, discussing particularly relevant observations as examples, as well as ways that the results presented here can translate into the analysis of observations.

### 6.1.1 The Timing and Sequence of Star Formation

The model of star formation presented in the STARFORGE simulations indicates that stellar associations are not necessarily single age populations. We measure stars forming throughout all times of the simulations, with a standard deviation of 2.14 Myr and an rms of 6.7 Myr (Section 3.1). Moreover, there is a clear mass progression in star formation, with low mass stars forming first, up to 1 Myr before high mass stars ( $>8$  Myr) begin to form. We also note that some of the extended star formation is localized to a long-lasting and/or late-forming high-density gas region in the turbulent, but largely dissociated molecular gas cloud (Section 3.1.2).

However, most observational studies of embedded timescales typically assume stars form nearly instantaneously (e.g., [Hannon et al., 2022](#); [Portegies Zwart et al., 2010](#); [Rodríguez et al., 2025](#); [Whitmore et al., 2023](#)). However, this assumption is increasingly challenged across a wide range of mass and spatial scales. In the most comprehensive studies of individual clusters like 30 Doradus (e.g., [De Marchi et al., 2011](#)), or Orion (e.g., [Bally, 2008](#); [Kounkel et al., 2018](#)), often find evidence for extended star formation. Additionally, age spreads remain common when considering smaller associations and clusters (e.g., [Kerr et al., 2024](#)). Similarly, the extended star formation seen in STARFORGE echoes this broader observational trend, and is advocated in other theoretical works in both turbulence supported clouds (e.g., [Krumholz & McKee, 2020](#)), and collapse driven models (e.g., [Vázquez-Semadeni et al., 2024b](#)). Together, these results suggest that the assumption of near instantaneous star formation may be an oversimplification in many systems.

While the single age stellar population is not an appropriate model for the behavior of the STARFORGE simulations as a whole, it is true that some of the extended star formation is spatially segregated from the earliest star formation (Section 3.1.2, [Guszejnov et al. \(2022\)](#)). In an observational context, these sub-regions might be analyzed as independent regions, for which single age assumptions might be more appropriate approximations. However, in distant galaxies, these sorts of sub-regions are indistinguishable with current resolution, and cannot be analyzed independently. In such cases, it may be worth considering SED and spectral fits that allow a more extended or complex recent star formation history. Additionally, the simulations presented here use a limited set of initial conditions, and it may well be that the simultaneous, synchronous star formation assumption is more appropriate in other conditions.

We see some of these different approaches with respect to region size in the current literature. In some cases, there is sufficient resolution available to identify sub-regions that could behave like more traditional single age populations ([Knutas et al., 2025](#); [Linden et al., 2024](#); [Rodríguez et al., 2025](#)). In others, there is more of an attempt to characterize populations of entire star forming regions (e.g., [Chevance et al., 2022](#); [Kerr et al., 2021](#); [Kim et al., 2022, 2023](#); [Pan et al., 2022](#); [Ramambason et al., 2025](#)), which may contain a range of ages, more closely mimicking the behavior of the entire association presented here. These complementary approaches may well manifest in different inferred timescales for embeddedness, that can be brought into agreement by considering the different spatial scales and likely level of coherence in the analyzed regions.

Also pertaining to the sequence of star formation is the specific timing of the massive star for-

mation, where quasi-instantaneous massive star formation is used in most timescale measurements (Schinnerer & Leroy, 2024). However, the timing of massive star formation is currently an open question in the field (e.g., Kumar et al., 2006; Rosen et al., 2020). The massive stars forming after the smaller stars observed here has also been seen in other simulations (Vázquez-Semadeni et al., 2024a). This timing supports the mode of formation where smaller cores form first, and high mass cores are a scaled up version of these smaller cores.

### 6.1.2 Interpreting Measures of Embeddedness for Individual Stars

In analyzing the STARFORGE simulations, we identified two main pathways through which the embeddedness evolves. The first is the more traditional large scale gas clearance from the association (Section 4.1), driven by massive stars; within STARFORGE, this process has been analyzed in detail by Farias et al. (2024) across a range of cloud properties. The second is through highly localized feedback in the immediate neighborhood of individual massive stars (Section 4.3). This latter process acts such that as embedded massive stars reach their maximum mass and luminosity (i.e., ending the accretion phase of their formation), their typical extinction drops dramatically, within less than 1 Myr. The emergence of low mass stars from the dust is much more gradual, more closely tracking the overall evolution of the cloud and their drift from regions of high gas density, rather than local feedback.

This behavior has some potentially interesting implications when analyzing embeddedness of individual stars. Typically, one measures spectra or spectral energy distributions, and uses stellar models to infer the line of sight extinction to the star. If massive stars are typically responsible for clearing out their own very local gas supply, they should rarely be seen with high extinctions outside of their initial accretion phase. Indeed, this has been seen in Lindberg et al. (2024), where populations of massive stars in M31 had a mean  $A_V$  of 1, independent of environment. We note, however, that the measures of embeddedness here are based on finding the median extinction over  $4\pi$  steradians, which still allows individual stars to be highly embedded over up to  $2\pi$  of all viewing angles. As such, appropriate comparisons are with large enough samples that a range of viewing angles are represented.

Another aspect that may differ when making observational assessments of stellar embedded timescales is the lifetime at the point of observation. In STARFORGE, we have complete access to the evolution of each individual star, including the entire proto-stellar phase (Figure 2.13). For massive stars, this phase terminates when gas accretion ends, which is also when the star becomes rapidly less embedded, synchronized through feedback that shuts off the local gas supply. As such, the lifetime of the protostar phase is roughly equivalent to the embedded timescale for massive stars, which is much shorter than the gas clearance timescale of the association as a whole. Therefore, the light from these stars will escape the system, and be visible at shorter wavelengths, even before gas clearance takes place.

### 6.1.3 Interpreting Measures of Embeddedness for Semi/Un-resolved Association and Star Forming Regions

In the absence of resolved stellar populations, clusters and associations are typically analyzed through their integrated spectral energy distributions. In STARFORGE, we find the expected sequence of emission that moves from luminous in the mid-IR, to a mixture of  $H\alpha$  and mid-IR

emission, to a brief window where optical stellar luminosity is comparable to the other tracers before the optical and UV light becomes dominant (Section 5.4). The timescales associated with these transitions are largely in agreement with those measured in external galaxies (Kim et al., 2021; Knutas et al., 2025; Linden et al., 2024; Ramambason et al., 2025; Rodríguez et al., 2025).

This agreement suggests that the same physical processes that govern light emergence in our simulations here are the same as those in the observed clusters. In particular, the simulations reveal that de-embedding is a highly local process, driven primarily by the feedback from massive stars disrupting their immediate surroundings, rather than the result of global cloud dispersal. Because such fine-grained spatial information is inaccessible in unresolved systems, the results presented here serve as a valuable calibration tool, offering physical insight into what integrated tracers are actually measuring. Observed timescales for light emergence can therefore be interpreted as reflecting the timing and locality of massive star formation, rather than a synchronized, global clearance of dust and gas.

For embedded clusters, there has been recent discussion about the embedded timescales of cluster formation being linked to cloud properties (Dinnbier & Walch, 2020; Knutas et al., 2025; McQuaid et al., 2024; Ramambason et al., 2025, Pedrini et al. *in prep*). Specifically, McQuaid et al. (2024) and Knutas et al. (2025) find the time a cluster stays embedded is inversely proportional to mass, where smaller systems stay embedded longer.

We find that the overall timescales for formation and emergence scale strongly with the initial free fall time, such that the larger mass cloud has a larger characteristic timescales. We note however, that the simulations analyzed here only consider two masses with extremely similar initial conditions, such that the main difference is cloud mass and density. We also note that these timescales reflected the association as a whole, and that one might well derive different timescales when analyzing distinct sub-regions. In fact, when considering the embeddedness of individual stars in both clouds, we see the behavior of smaller stars staying embedded longer than massive stars (Section 4.3). More instantaneous formation of stars would then manifest in the more massive complexes (i.e., higher number of massive stars) having shorter embedded timescales.

## 6.2 Model Limitations

For numerical simulations to be computationally viable, certain trade off are made. A detailed discussion of the compromises in STARFORGE is available in Grudić et al. (2021). In this section we discuss the specific ways in which this work is subjected to model limitations.

First, the initial conditions within our STARFORGE model are an isolated, spherical cloud. Recent trends in the star formation literature tend to focus on the topic of triggered star formation, including cloud-to-cloud interaction, where gas is continually being deposited into the region where star formation is occurring (e.g., Fujita et al., 2021; Fukui et al., 2021; Luisi et al., 2021; Wall et al., 2020; Zucker et al., 2020). This scenario would likely increase the gas removal time scale as more gas is being introduced to the system. Consequentially, the embedded timescales would likely be longer, allowing for more stars to form, and further increase the spread in stellar ages.

Additionally, this interactive model of star formation has been argued as a potential formation mechanism of gravitationally bound star clusters (e.g., Sakre et al., 2023; Wurster & Bonnell, 2023; Xu et al., 2020). Because the model used in this work is of an isolated cloud, and does not form a gravitationally bound cluster, we cannot comment on the embedded timescales of such systems.



Similarly, because the cloud in our model is isolated, we cannot comment on any potential galactic environmental dependencies on variations to embedded timescales. Recent work has suggested environment impacts the effectiveness of stellar feedback (e.g., [Chevance et al., 2022](#); [Della Bruna et al., 2022](#); [Kim et al., 2022](#); [McLeod et al., 2021](#)). Increased feedback would decrease the time stars stay embedded, and shorten the transition time while the inverse is true for decreased feedback.

Similarly with regards to the galactic context, the simulations do not include a background galactic potential or vertical stratification, and therefore lack the additional confining weight and external pressure present in real galactic discs. In vertically stratified disc simulations, feedback-driven bubbles evolve in balance with the vertical weight of the ISM, and their ability to clear gas locally depends on this balance (e.g., [Faucher-Giguère et al., 2013](#); [Ostriker & Kim, 2022](#)). As such, stronger vertical gravity or higher ambient pressure can prolong the time that gas remains bound and dense, potentially lengthening the embedded phase. Our results should be viewed as characterizing the locally driven de-embedding physics, with the understanding that large-scale galactic context can modulate the absolute timescales.

We also dutifully acknowledge that the free fall time of the cloud is difficult to measure observationally, especially in dynamic environments. In these environments where one cloud can feed into another, the free fall time is an ever changing measurement, which may actually increase over time as mass is added to the system. Additionally, the free fall time is only a measure for the initial cloud. Once fragmentation occurs, each sub-clump has its own free fall time, which changes with time as gas is consumed and expelled. While flawed, the free fall time presents the best mode the isolated cloud simulations in STARFORGE.

Despite these limitations, the work presented here is a reasonable model. STARFORGE presents one of the best star formation simulations due to its physical realism achievable with the high resolution. Importantly, it has been demonstrated to reproduce key phenomena such as star formation efficiency measurements and the IMF ([Guszejnov et al., 2022, 2023](#)). While modeling star formation as an interactive process in conjunction with environmental surroundings is a realistic scenario, it also introduces an additional layer of complexity to the model, and there is still much to be learned about the formation process from extremely high resolution simulation of isolated clouds.

## 7 Conclusion

In this work, we measure the mechanisms which drive the embeddedness stages of star formation in the high resolution STARFORGE simulation. We look at the stellar extinction levels of both individual stars, and of the association as a whole. We also assess the time evolution of dust and  $H\alpha$  emission, frequently used to identify embedded star formation. We find the following results:

- The overall drop in extinction is driven by transitions experienced by individual stars. We show that stars all begin their lives with a high level of extinction, due to being embedded within their surrounding molecular cloud. The stars then experience a sharp, rapid decline in their typical extinction  $A_V$  when they reach their maximum mass and stop accreting. Most notable is that this behavior persists no matter when a star forms. As a result, the overall evolution of association embedding is a reflection of this individual evolution, convolved with the history of star formation within the association.

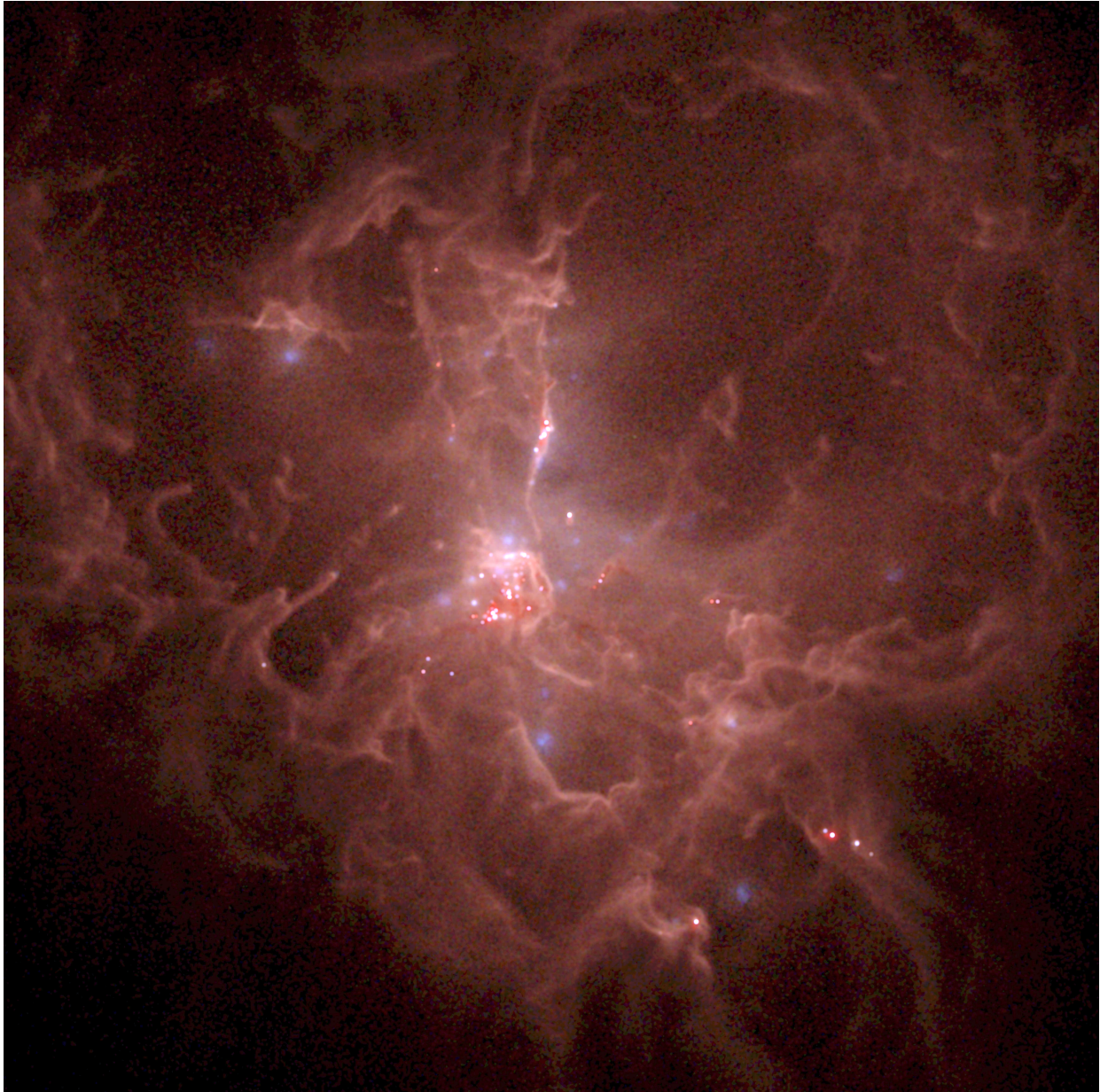
- This transition in extinction is particularly sharp for massive stars, where the decrease to low extinction ( $\widetilde{A_V} < 1$ ) happens in less than half a free-fall time. For these massive stars, their maximum mass is reached simultaneously with their emergence from dust, as they continue to accrete up until their feedback overcomes the local accretion. Once these stars halt accretion, their localized, pre-supernova feedback then impacts the cloud as a whole, de-embedding lower mass stars in their vicinity. Therefore, the local feedback takes individual stars  $\widetilde{A_V}$  from 100 to 1, then the collective action of massive stars takes  $\widetilde{A_V}$  from one to zero as gas is cleared from the association as a whole.
- Because of this effect the massive stars have on the association embeddedness, when massive stars form is particularly relevant for any measured timescale. We find the fraction of highly embedded stars begins to drop precipitously at the point where  $\sim 50\%$  of the massive stars form, which equates to  $1.6 \tau_{ff}$  independent of cloud mass. After this drop in extinction begins, almost all stars are un-obscured within  $\sim 3$  Myr.
- We find a large age spread for when the stars formed in the simulation, with both low- and high-mass stars forming throughout the simulation, with a standard deviation of 2.14 Myr, and rms of 6.7 Myr. The star formation does have a well-defined peak, but there is also a long tail to late times, where star formation is sustained in dense sub-clumps that have survived earlier feedback.
- Overall, the fully embedded stage is brief, lasting only a few Myrs. While  $24 \mu\text{m}$  emission is present before any other tracer, the peak in  $\text{H}\alpha$  luminosity actually coincides with the peak of  $24 \mu\text{m}$  luminosity. Transversely, the transition period where all tracers are visible and sufficiently bright occurs for  $0.49 \tau_{ff}$  (1.8 Myrs for fiducial cloud). Therefore overall, while IR wavelengths are an excellent tracer of star formation, the timescale where it is expected compared to other tracers is comparatively short.
- Both  $24 \mu\text{m}$ , and  $\text{H}\alpha$  emission are brightest during the short interval when dense gas and dust remain tightly coupled to massive stars. At later times, dust and  $\text{H}\alpha$  luminosities decline even as the ionized gas mass grows, enforcing the local clearing produced by high-mass stars as the dominant mechanism in setting embedded timescales. Additionally, the duration of the  $24 \mu\text{m}$  dominance agrees well with observationally inferred embedded timescales, reinforcing that the simulations correspond to the same physics that governs embedded tracers in real systems.

These results offer a new perspective on the evolution of embeddedness and the timescales at which stars remain enshrouded in their natal clouds, as viewed through stellar extinction, and multi-wavelength observation. Most notable deviations from previous studies include the age spread of stars, the effect localized feedback of massive stars has on embeddedness, and how the timing of when high mass stars form connects to the embedded timescale as a whole.

*Software:* `astropy` (Astropy Collaboration et al., 2013, 2018, 2022), `Jupyter` (Kluyver et al., 2016), `matplotlib` (Hunter, 2007a), `numpy` (Harris et al., 2020), `python` (Van Rossum & Drake, 2009), `scipy` (Gommers et al., 2024; Virtanen et al., 2020a), `h5py` (Collette, 2013; Collette et al., 2023), `skirt` (Baes et al., 2011; Camps & Baes, 2015), `openai` (OpenAI, 2023)

## Appendix A. Supplementary Mock Image

We include a large, high resolution image of the dust luminosity from Figure 2.10 to highlight key features and provide the reader with the best visual representation of the data. Shown in Figure 2.16 is the snapshot at 7.2 Myr, seen from the y-direction.



**Figure 2.16:** 7.2 Myr snapshot from the y-direction from Figure 2.10, demonstrating the resolution available in the dust luminosity images. The full-high resolution version of this Figure can be found at [doi:10.5281/zenodo.17667459](https://doi.org/10.5281/zenodo.17667459)

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## CHAPTER 3

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# THE HIGH-MASS STELLAR INITIAL MASS FUNCTION OF M33

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## 1 Introduction

The stellar initial mass function (IMF) plays a central role in both observational and theoretical astrophysics. Formally, the IMF is the distribution of the masses of stars formed in a single event. Of particular interest is the stellar IMF for stars greater than  $1 M_{\odot}$ . Because such stars evolve over cosmologically short timescales to become supernovae and asymptotic giant branch stars that energize and enrich galaxies, their relative numbers affect a wide range of astrophysics.

Observationally, the high-mass IMF impacts interpretations of stellar populations of galaxies (e.g., Arrabal Haro et al., 2023; Bell et al., 2003), cosmic reionization (e.g., Ouchi et al., 2009), and star formation efficiency (e.g., Alves et al., 2007; Hennebelle & Chabrier, 2008). Theoretically, the IMF dictates prescriptions in numerical simulations of galaxy formation (e.g., Kim et al., 2014), chemical yields in simulations (e.g., Buck et al., 2021), modeling the frequency of core-collapse supernovae (e.g., Heger et al., 2003), and constraining stellar evolution models (e.g., Kroupa, 2001; Krumholz, 2014; Massey, 1998).

The formation of high-mass stars has also been shown to affect the overall star forming process for other stars in the same region (e.g., Grudic et al., 2023). Specifically, the formation of a massive star early or late in the star formation process can have important impacts on the overall star formation in a molecular cloud (Dinnbier et al., 2022; Lewis et al., 2023). Thus, quantifying the number of high mass stars created is vital for a comprehensive understanding of the entire star formation process.

Given these widespread impacts, the high-mass IMF has long been of great interest (see review by Bastian et al., 2010). Most recently, theoretical studies of the IMF have attempted to quantify the impact that different physical and environmental effects, such as metallicity and star formation rate, have on the high-mass IMF (e.g., Grudic et al., 2023; Grudić et al., 2023; Li et al., 2023; Marks et al., 2012; Parravano et al., 2018; Smith et al., 2023; Zhang et al., 2018). These studies have further increased the motivation for observational measurements of the high-mass IMF across a range of environments.

Historically, the IMF was first measured in the 1950's by counting stars in the solar neighborhood (Salpeter, 1955), and modeled with a two part power law ( $dN/dM \propto M^{\Gamma_i}$ ) where  $\Gamma_i$  denotes the slopes of the two power laws, with a break at  $1 M_{\odot}$ . Early studies focused mainly on the universality of the IMF (e.g., Lequeux, 1979; Miller & Scalo, 1979) and whether it was possible to observe any considerable variations from the canonical Salpeter (1955) IMF. This led some to argue that there does not appear to be a systematic IMF dependence on environment or initial star-forming conditions (e.g. Bastian et al., 2010; Offner et al., 2014), although other studies present evidence for a top-heavy IMF in the galactic center (e.g., Lu et al., 2013). These studies, however,



did not explain the observed scatter in measured IMF slopes, contradicting a picture where the IMF was universal across environments. However, [Weisz et al. \(2013\)](#) showed that  $> 75\%$  of IMF studies significantly underestimated uncertainties, detailing how difficult it is to untangle systematic effects from intrinsic IMF variability.

Due to these limitations, our understanding of the high-mass IMF is incomplete. In spite of the uncertain observational evidence, within the field there has been an adoption of a “universal” IMF for theoretical predictions. This typically assumes either the Kroupa ( $\Gamma = +1.3$ ; [Kroupa, 2001](#)) or Salpeter ( $\Gamma = +1.35$ ; [Salpeter, 1955](#)) slope for stars more massive than  $1 M_{\odot}$ , assuming no variations, despite persistent controversy over the universality of the IMF since the first studies (e.g., [Kroupa, 2002](#); [Scalo, 1998, 1986](#)).

Current observational approaches to measure the high-mass IMF and its applicability fall primarily into two large classes. The first approach uses stellar systems where individual stars are not resolvable. Studies have characterized galactic-wide stellar mass functions for unresolved sources through integrated light techniques (e.g., [Cheng et al., 2023](#); [Conroy & van Dokkum, 2012](#); [Dib, 2022](#); [Lee et al., 2009](#); [Meurer et al., 2009](#)). These studies require substantial assumptions due to degeneracies between dust, age, metallicity, and stochastic sampling of the IMF itself. As such, it remains undetermined whether integrated light measurements will provide a new avenue for reliably characterizing the IMF (e.g., [Calzetti et al., 2010](#); [Weidner et al., 2014](#); [Weisz et al., 2013](#)).

In contrast to “unresolved” approaches to measure the high-mass IMF, our current best constraints come from studying resolved stellar populations in the Milky Way and nearby galaxies. One notable study is that of [Weisz et al. \(2015, hereafter W15\)](#), who measured the IMF for 85 star clusters in the north-east third of M31 using data from the Panchromatic Hubble Andromeda Treasury (PHAT) data ([Dalcanton et al., 2012](#)). This study remains one of the best extragalactic IMF measurements, yielding one of the most robust high-mass IMF measurements to date. They found a universal high-mass IMF unlikely to be the best representation in the Local Group. Instead they find a slightly steeper high-mass IMF where  $\Gamma = 1.45^{+0.03}_{-0.06}$ . Although similar to the traditional values of the [Salpeter](#) IMF, the deviation makes a considerable difference in the number of high mass stars formed and in the values obtained from common star formation rate prescriptions.

The tension in the debate between a perfectly known, universal IMF, and an IMF dependent on environment and chemical properties, remains high, as discussed in the recent review article by [Lee et al. \(2020\)](#) (and complementary articles, e.g., [Baumgardt et al., 2023](#); [Escher Jung et al., 2023](#); [Marks et al., 2012](#); [Pouteau et al., 2022](#); [Zhang et al., 2018](#)). Deviations from a universal IMF could manifest in both bottom-heavy (e.g., [Smith, 2020](#); [Spiniello et al., 2012](#)) IMFs of low mass stars ( $< 1 M_{\odot}$ ), and top-heavy (e.g., [Marks et al., 2012](#); [Pouteau et al., 2022](#)) IMFs of massive stars discussed in this work. Due to the observed cluster-to-cluster variance of the IMF, a large, homogeneous survey of individually resolved young, massive stars is required to reliably resolve these debates ([W15](#)). Thus, the need for additional IMF studies in galaxies where we can resolve individual stars is required for our ability to understand if there is a universal high-mass IMF.

One of the best targets for such a study is the Local Group spiral M33. M33 is a nearby galaxy to us with a relatively face on inclination of  $55^{\circ}$  ([Koch et al., 2018](#)), and also has lower line-of-sight dust attenuation compared to M31. With a distance modulus of 24.67 ([de Grijs & Bono, 2014](#)), it is possible to resolve individual stars down to at least  $1 M_{\odot}$ . However, compared to M31, M33 has a lower metallicity, and a higher SFR intensity, making it a natural target for identifying any environmentally driven variations in the high-mass IMF.

In M33, the high-mass IMF has been studied through inferences of integrated properties (e.g.,

Corbelli et al., 2011; Grossi et al., 2010), as well as single cluster IMF characterizations (e.g., González Delgado & Pérez, 2000; Jamet et al., 2004). However, the high-mass IMF has not previously been measured across star clusters with resolved stars, the most reliable characterization. We follow the methodology of W15, measuring the IMF from resolved stars above  $1M_{\odot}$  probabilistically. We model the optical CMD of each cluster to constrain its power law slope,  $\Gamma$ , of the present-day high-mass MF, marginalized over other cluster parameters (i.e., cluster age, mass, and radius).

This paper is structured as follows. In Section 2, we describe the PHATTER photometry, define our cluster sample, and describe our synthetic cluster sample. In Section 3, we lay out the probabilistic approach for MF fitting and the inference of the IMF from these measurements. We present our results in Section 4 and discuss implications in Section 6.

## 2 Data

Our cluster data is drawn from the Local Group Cluster Search (LGCS) cluster catalog (Johnson et al., 2022), which was created using data from the PHATTER survey (Williams et al., 2021). The PHATTER survey uses the *Hubble Space Telescope* (HST) Advanced Camera for Surveys (ACS) and Wide Field Camera 3 (WFC3) to image the inner 5 kpc of M33’s disk in six filters from UV to IR. The Johnson et al. (2022) catalog presents 1214 star clusters identified through a crowd-sourced, visual search of the optical PHATTER data (F475W & F814W), facilitated by the LGCS project<sup>1</sup>, a citizen science effort hosted on the Zooniverse<sup>2</sup> platform. We adopt the recommended cluster catalog threshold (the minimum weighted fraction of identifications as a cluster,  $f_{\text{cluster}, W} > 0.674$ ), which limits the contamination rate to  $\lesssim 4\%$  for the cluster sample. Cluster properties for this sample were derived through CMD modeling in Wainer et al. (2022).

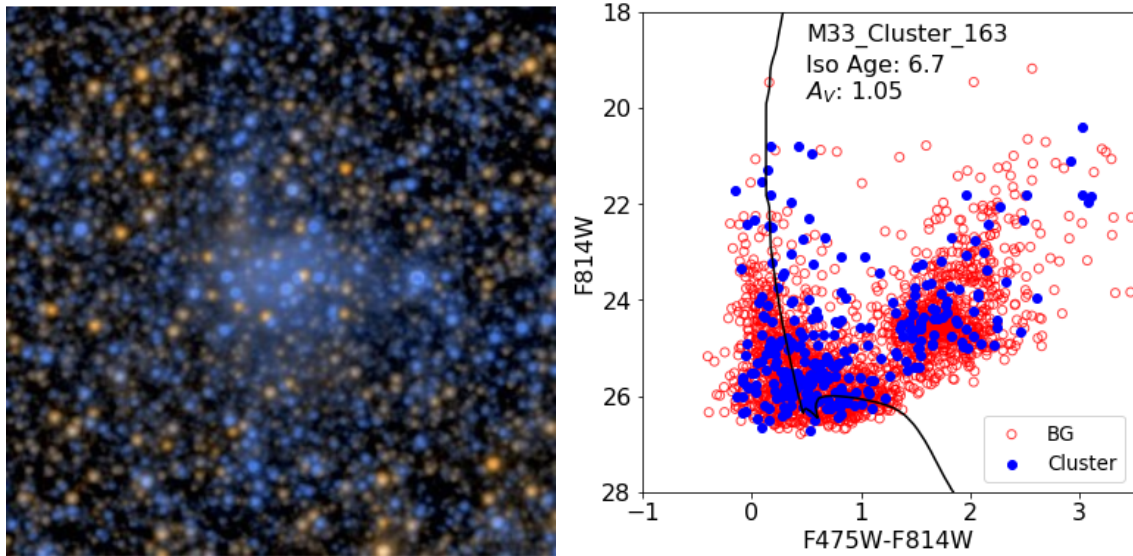
For this study, we follow the methodology of W15 and select an initial, inclusive sample of clusters younger than 25 Myr, more massive than  $10^3 M_{\odot}$ , and having half-light radii larger than 1.66 pc. These threshold limits were explicitly adopted due to the synthetic cluster analysis presented in Sections 3.4, and represent the range of parameters where we can best recover the input IMF, which will be discussed further in Sections 3.4. These clusters have ages of order  $\sim 0.1$  relaxation times, largely mitigating the effects of mass segregation or cluster dissolution, because these effects take place on longer time scales, making them the ideal sample to probe the high mass IMF (W15). The lower mass limit excludes clusters that will not have sufficient stars to add meaningful constraints to the IMF. Selecting clusters with larger half-light radii limits the impacts of stellar crowding in the densest clusters.

The M33 cluster sample from these selection cuts contains 34 clusters<sup>3</sup>, compared to the 85 clusters analyzed in W15. The largest reason for this difference is the much larger survey area of PHAT in M31 compared to PHATTER in M33. In addition, there are subtle differences in our cluster selection. We include clusters with half-light radii greater than 1.66 pc as opposed to the 2.0 pc threshold used in W15. This difference in selection criterion includes eight additional clusters

<sup>1</sup><https://www.clustersearch.org>

<sup>2</sup><https://www.zooniverse.org>

<sup>3</sup>We note that this sample does not include a few popular M33 targets. Most notably, NGC 604 is classified as an emission region opposed to a cluster in Johnson et al. (2022), and NGC 588 which is not within the PHATTER footprint.



**Figure 3.1:** On the left is a F475W, F814W combined color image for M33 cluster 163 identified by [Johnson et al. \(2022\)](#) clearly showing resolved stars. On the right is the best fit isochrone to stellar photometry from [Wainer et al. \(2022\)](#), highlighting the level of photometric depth available in the CMD. The blue dots are stars that fall within the photometric aperture, while the open red circles are stars within the background annulus (see text for details), illustrating the input data to MATCH.

which would be excluded if we impose a 2.0 pc threshold. Including these clusters increased our sample by  $\sim 30\%$ , allowing for a more precise measurement. We have performed extensive tests with synthetic clusters, and used these to determine our optimal cluster sub-sample, which we discuss in detail in Section 3.4.

For the purposes of this work, we use only the optical (F475W and F814W) resolved stellar photometry from PHATTER, which contain the most information about the IMF slope due to having the deepest photometry, reaching F475W  $\sim 28$  mag, sufficient to detect  $1.3M_{\odot}$  stars as seen in Figure 3.3, which we will further discuss in Section 3. The photometry of the PHATTER clusters was performed with `dolphot` ([Dolphin, 2016, 2000](#)), using the HST specific modules described in [Williams et al. \(2014\)](#). An example of the photometry is shown in the optical color image of M33 cluster 163, the left hand panel of Figure 3.1. The right hand panel has the CMD and best fit isochrone determined by [Wainer et al. \(2022\)](#).

The uncertainty, bias, and completeness of the resolved stellar photometry in each cluster is thoroughly tested with artificial star tests (ASTs), where artificial stars with known parameters are injected into the data and then recovered. Following the principles in [Williams et al. \(2021\)](#), the artificial stars are generated with the `fake` utility of MATCH ([Dolphin, 2002](#)). For each cluster, we insert and recover 50,000 ASTs to ensure accurate characterization of photometric completeness and noise, as was done in [W15](#). Input positions for the ASTs are distributed following the light profile of the cluster, based on the [Johnson et al. \(2022\)](#) half-light radii and assuming a [King \(1962\)](#) profile.

To quantify the SFR of the surrounding region associated with each cluster in our sample, we use the SF maps of [Lazzarini et al. \(2022\)](#) who fit color magnitude diagrams to resolved stars in

2005,  $\sim 100$  parsec regions. Based on the cluster location, we adopt the [Lazzarini et al. \(2022\)](#) SFR value between 0-100 Myr ago as the cluster's local SFR. We normalize the value given in [Lazzarini et al. \(2022\)](#) by the area in order to estimate the  $\Sigma_{\text{SFR}}$ , a value more comparable to galactic samples in the literature. We also compute the angular galactic radius of each cluster assuming a common distance modulus.

### 3 Analysis

Following [W15](#), we first measure the stellar probability distribution function (PDF) of the present day MF for each young cluster. We then fit the ensemble of the PDFs for the MF slopes to infer the intrinsic IMF slope for the ensemble of clusters<sup>4</sup>. We discuss each of these steps in detail below.

#### 3.1 Measuring Each Cluster's Stellar Mass Function

We use the MATCH software package ([Dolphin, 2002, 2012, 2013](#)) to characterize the stellar MF for a young star cluster. For a given evolution library, MATCH constructs a simple stellar population which is then convolved with completeness, noise, and photometric biases derived from artificial stars tests (ASTs). The resulting synthetic CMD is then linearly combined with a suitable CMD of foreground/background populations and scaled to best reproduce the observed cluster CMD. The fit quality is calculated according to a Poisson likelihood, fit over a large grid of parameters, including IMF, to fully cover all likelihood space.

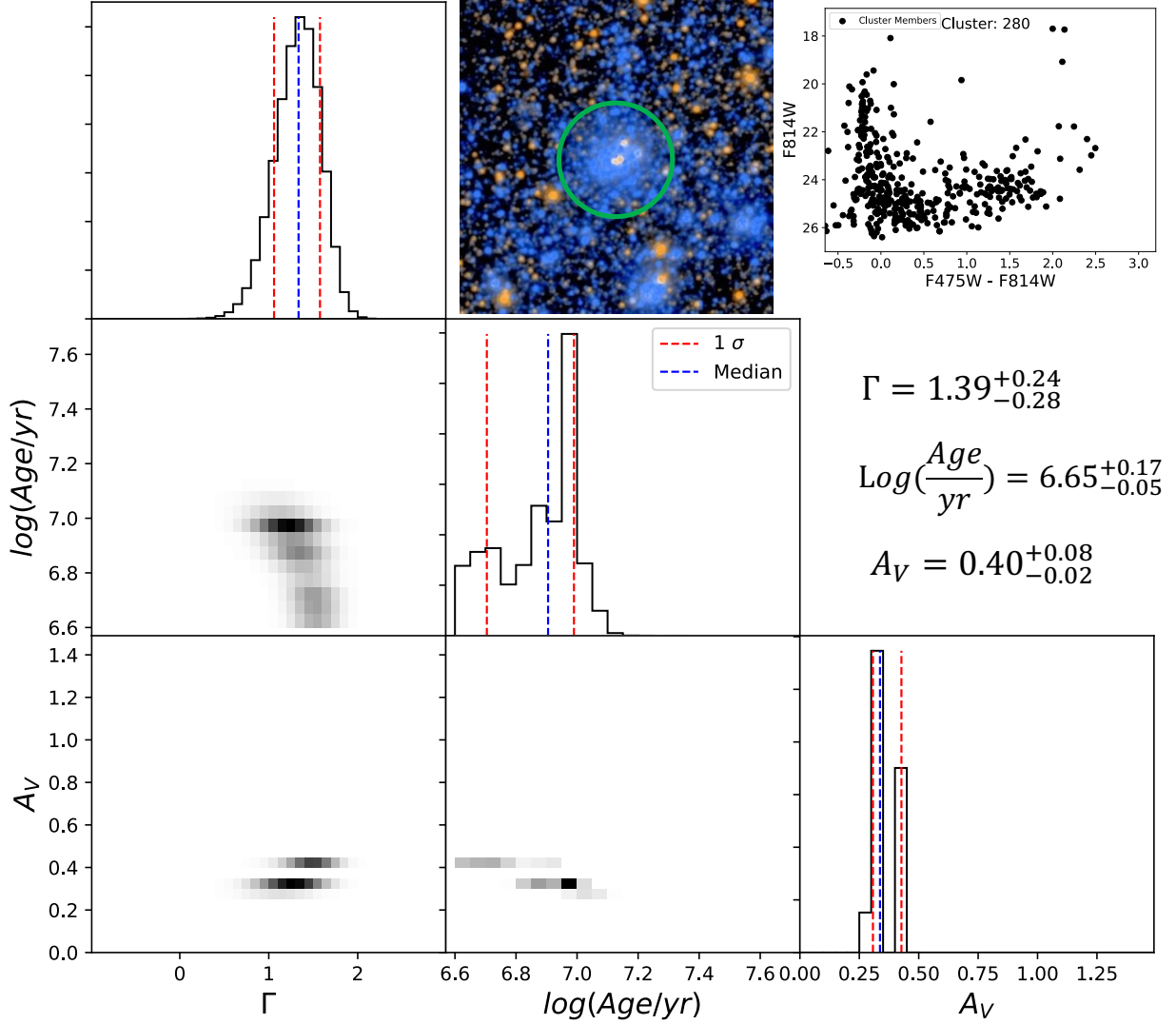
For this analysis, we adopt Padova stellar evolution models ([Girardi et al., 2010; Marigo et al., 2008, 2017](#)), and a binary fraction of 0.35 where the mass ratio of the stars is drawn from a uniform distribution. This assumed binary fraction is within reasonable uncertainties for consistency with studies on binary fraction in clusters ([Albrow & Uluse, 2022; Elson et al., 1998](#)). While recent studies suggest binary fraction increases with stellar mass ([Offner et al., 2023](#)), we do not have the infrastructure available to adequately incorporate this dependence into our study. Additionally, changes in the binary fraction have shown to have little effect on IMF slopes measured with the CMD modeling used here ([W15](#)). We experimented with binary fractions ranging from 0.2 to 0.6, and our results were not significantly different.

We adopt a distance modulus of 24.67 ([de Grijs & Bono, 2014](#)), and assume a metallicity  $[M/H]$  of  $-0.05 \pm 0.15$  consistent with the range of present-day gas phase metallicity in M33 (e.g., [Rogers et al., 2022](#)). To model the non-cluster background stars, we adopt the practice of [Johnson et al. \(2022\)](#) and construct an empirical CMD from an annulus around the cluster extending from 1.2–3.4 times the photometric aperture. These sky annuli robustly characterize the sky flux levels and associated uncertainties with stellar contaminants.

We model the cluster parameters as follows: MF slope ( $\Gamma$ ) for stars  $\geq 1 M_{\odot}$  from  $-1.2$  to  $5.0$  with a step-size of 0.2 dex,  $\log(\text{Age/yr})$  from 6.6 to 9.0 with a step-size of 0.1 dex, extinction ( $A_V$ ) from 0.0 to 2.5 mag with a step-size of 0.05 mag, and metallicity from  $-0.2$  to  $0.1$  with a step-size of 0.1 dex. Resulting model CMDs are then compared to observed CMDs to determine the likelihood ([Dolphin, 2002](#)).

<sup>4</sup>Throughout the rest of this paper, we will use "IMF" to indicate the ensemble, while individual cluster fits will be referred to as "MF".





**Figure 3.2:** The marginalized PDF for M33 Cluster 280 showing the the posterior PDFs for  $\Gamma$ , age, and extinction. We also include the F475W and F814W combined color image with the 2.33 arcsecond radius visualized by the green circle. We also show the CMD, and best-fit age and  $A_V$  estimates, along with the uncertainties, from [Wainer et al. \(2022\)](#) in the text which are interesting to compare to our full PDFs. We also show in the text the measured  $\Gamma$ . In the upper left, middle, and lower right panels, the blue line represents the median of the marginalized PDF, and the red lines correspond to the 16th and 84th percentiles. The bin sizes in the PDFs correspond to the grid with which each parameter was fit over, as described in the text.

In Figure 3.2, we plot the joint and marginalized PDFs for three cluster parameters,  $\Gamma$ , age, and  $A_V$ . While this methodology does not account for every source of systematic uncertainty the parameters are tightly constrained, and the posterior probabilities give a reliable estimate of the uncertainty in the measured IMF ([Weisz et al., 2013](#)).

Figure 3.2 also shows that the IMF slope and the cluster age have correlated and non-Gaussian PDFs. We also see that the  $A_V$  distribution is bimodal, which results from the combination of the



common degeneracy between age and extinction and from the discreteness of the color distribution of stars in the cluster CMD. However, because we marginalize over age and  $A_V$ , the uncertainty driven by such correlations are incorporated into the total uncertainty on the IMF slope (upper left plot). This propagation of uncertainty is a particular strength of our technique, which accounts for degeneracies among several cluster properties.

The fitted CMDs are comprised of all stars inside the [Johnson et al. \(2022\)](#) photometric aperture, which are modeled as a combination of cluster stars and background field stars. The magnitude range of the fitted CMD is determined based on cluster specific photometric completeness results derived from ASTs. We tested a wide range of completeness limits, from 5% to 80%. From 20% to 60% completeness, our resulting  $\Gamma$  remains unchanged. We find below 20% completeness, the artifacts present in the photometry have a significant impact on the CMD and resulting IMF, while above 60% there are too few stars to accurately constrain the IMF. We adopt the 20% completeness limit which for synthetic clusters, was able to the best recover the input mass of the clusters. These completeness limits are presented in Figure 3.3, along with the corresponding main sequence stellar mass limit. From Figure 3.3, we can see a clear trend between photometric completeness and cluster mass. This trend is unsurprising as the more massive clusters have more stellar crowding, making resolving individual stars difficult. Note that the equivalent main sequence mass completeness limits for all clusters are  $>1 M_\odot$ , which is consistent with the assumption of a single high-mass power-law slope over the fitted mass range, whereas any turnover in the IMF (e.g., [Kroupa, 2001](#)) occurs at smaller stellar mass.

### 3.2 Inferring the IMF Slope from the Distribution of CMFs

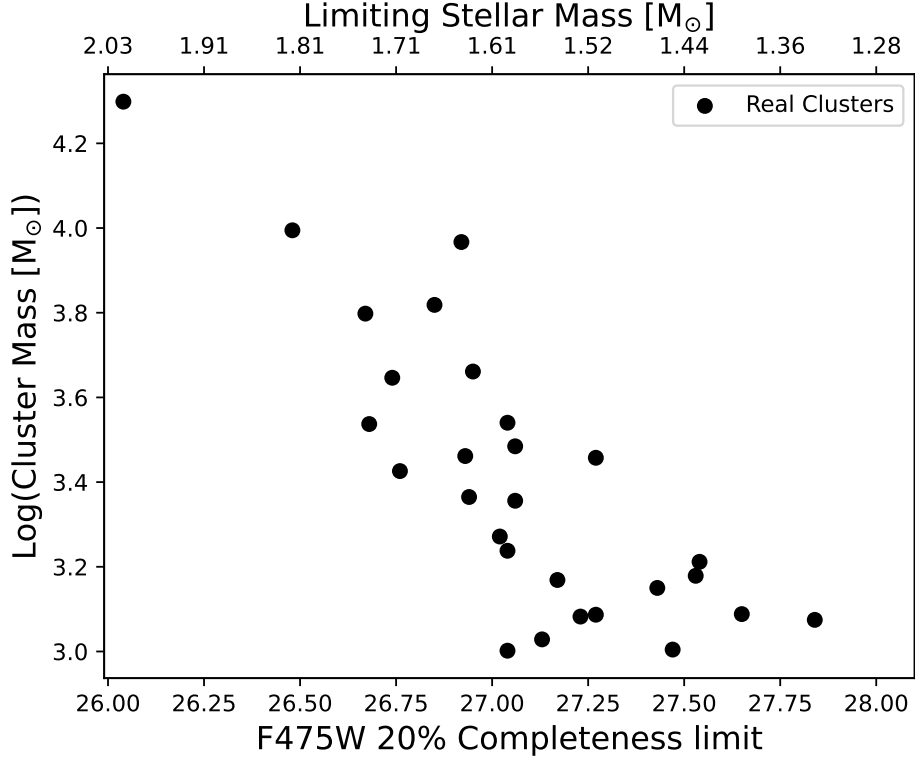
In this section we describe how we model the mean slope of the IMF,  $\bar{\Gamma}$ , and the intrinsic scatter in that slope,  $\sigma_\Gamma$  from the ensemble of cluster MFs, obtained in Section 3.1. This step is to infer population-wide characteristics of the distribution of MF slopes,  $\bar{\Gamma}$ . To fit a Gaussian mixture model likelihood function for the MF of the clusters, we follow the approach laid out in [Hogg et al. \(2010\)](#) and [Foreman-Mackey et al. \(2014\)](#), using the affine invariant ensemble Markov chain Monte Carlo (MCMC) program EMCEE ([Foreman-Mackey et al., 2013](#)). We closely follow the implementation of this methodology by [W15](#), and a brief explanation follows.

The Gaussian mixture model framework allows us to consider that each data point has an associated probability of actually being a cluster,  $Q_i$ . We can then write down a Gaussian mixture model likelihood function for the MF of  $i$  clusters, mitigating the impacts of questionable cluster candidates<sup>5</sup>. Specifically, the mixture model can be written as

$$p(\Gamma_i|\theta, Q_i) = Q_i \exp\left(-\frac{(\Gamma - \Gamma_i)^2}{2\sigma_\Gamma^2} - 0.5 \log(2\pi\sigma_\Gamma^2)\right), \quad (3.1)$$

where  $\Gamma_i$  is the marginalized PDF for the MF of the  $i$ th cluster, and  $\Gamma$  and  $\sigma_\Gamma^2$  represent the mean and variance of the Gaussian that characterizes the high-mass slope.  $\bar{\Gamma}$  is the mean slope for the true distribution, and  $\sigma_\Gamma$  characterizes the intrinsic spread, such that small values of  $\sigma_\Gamma$  indicate the IMF is more consistent with a universal IMF, with the sample variance being driven by observed

<sup>5</sup>We note that the exclusion of this parameter, giving each cluster equal weight, has very little impact on the resulting  $\Gamma$  because of the high statistical probability that all of the clusters in our sample are truly clusters. We choose to include it to best replicate [W15](#).



**Figure 3.3:** The 20% F475W photometric completeness limit, as determined by ASTs, as a function of stellar mass. The secondary axis corresponds to the limiting main sequence stellar mass probed at this magnitude.

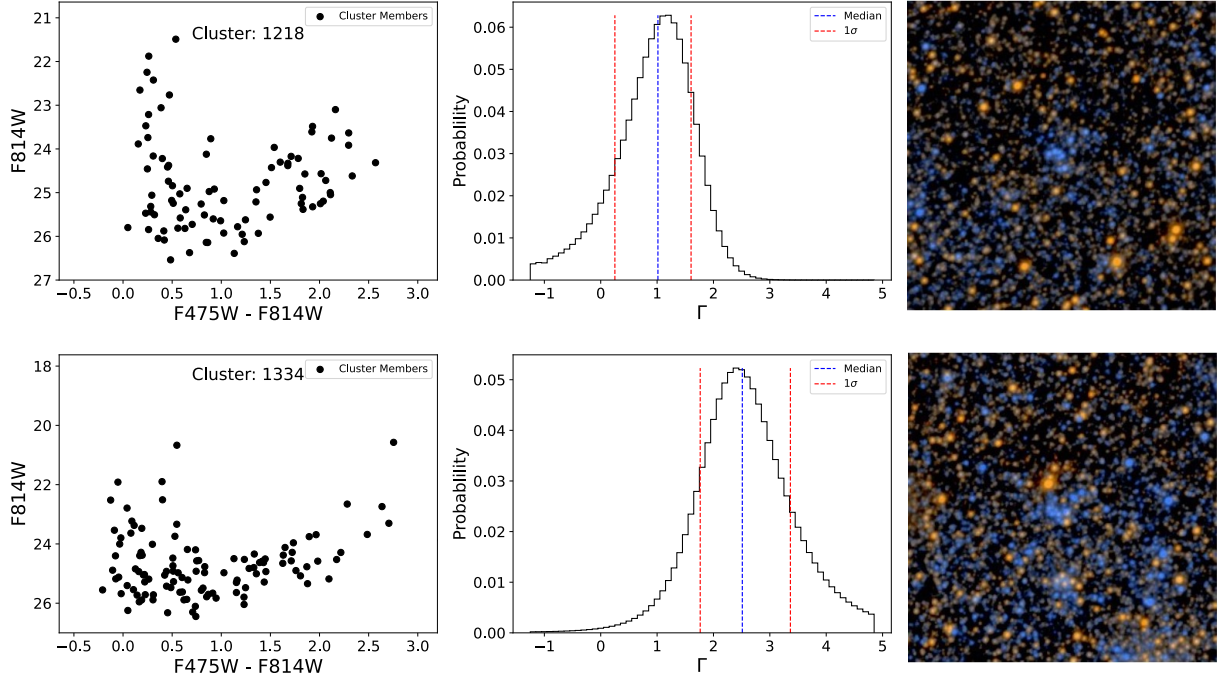
uncertainty. This model allows us to not make any assumptions about the structure of the PDFs, considering the likelihood at all values, and incorporating the degeneracies from all grid runs.

From this model, we can test the dependence of the MF slope on cluster properties such as age, mass, and radius. In order to test potential environmental dependencies on the IMF, we add two additional properties compared to [W15](#), the local SFR in the region of the cluster, and the clusters galactic radius. The generalized model takes the form

$$\begin{aligned} \Gamma(T_i, M_i, R_i) = & \bar{\Gamma} + a_m \log\left(\frac{M_i}{M_c}\right) + a_t \log\left(\frac{T_i}{T_c}\right) \\ & + a_r \log\left(\frac{R_i}{R_c}\right) + a_{sfr} \log\left(\frac{SFR_i}{SFR_c}\right) + a_{gr} \log\left(\frac{Gr_i}{Gr_c}\right) \end{aligned} \quad (3.2)$$

where  $T_i$ ,  $M_i$ , and  $R_i$  are the most likely age mass and radius of the  $i$ th cluster according to the [Wainer et al. \(2022\)](#) fits.  $SFR_i$  and  $Gr_i$  are calculated for each cluster using the [Lazzarini et al. \(2022\)](#) SFR maps, and the angular galactic radius assuming a common distance modulus.  $T_c$ ,  $M_c$ ,  $R_c$ ,  $SFR_c$  and  $Gr_c$  are the mean of the full cluster sample in each case. Each parameter ( $\bar{\Gamma}, \sigma_{\Gamma}^2, a_t, a_m, a_r, a_{sfr}, a_{gr}$ ) are assumed to have flat priors over the ranges reported in Section 3.1, where  $\sigma_{\Gamma}^2$  must be greater than zero, and  $a_t, a_m, a_r, a_{sfr}, a_{gr}$  must be less than one. These parameters are then sampled with the affine invariant ensemble MCMC program EMCEE ([Foreman-Mackey et al., 2013](#)).

For our MCMC calculation, we use 100 walkers, each performing 5000 steps, of which we



**Figure 3.4:** Shown are cluster CMDs, the  $\Gamma$  marginalized PDFs, and the F745W and F814W color images for two low-mass clusters: clusters 1218 and 1334. The left panels are CMDs as reported in [Johnson et al. \(2022\)](#), where the black points are cluster members. The middle panels are the marginalized  $\Gamma$  PDFs for each cluster, where the blue line is the median and the red lines represent the 16th and 84th percentiles.

discard the first 200 burn-in steps. We assess convergence of our chains according to the autocorrelation time, estimated to be  $\sim 60$  steps, which is exceeded by the burn-in period. In Section 4 we report the median value of the marginalized posterior probability function for each of the seven parameters in the mixture model.

### 3.3 Reliability of Techniques, and Testing the Robustness of Results

In addition to running our full analysis on a set of synthetic clusters, we test critical steps of our technique through a quality test.

First, we generate distributions of fake cluster PDF's and test the Gaussian Mixture methodology from Section 3.2. We generate PDF's with medians randomly drawn between 0.35, and 2.35, with  $1\sigma$  widths between 0.1 and 1.0 dex to represent with the typical observed uncertainty in  $\Gamma$ , and center the distribution of PDF's at  $\Gamma$  values of 0.5, 1.3, and 2.0. For each case, we are able to recover the input value of the distribution within the uncertainties, demonstrating the mixture model technique is robust to different  $\Gamma$  values.

As mentioned above, MATCH incorporates a background CMD into the fitting, and therefore should be reliable against single star outliers. To test this assumption, we perform a second experiment to quantify the impact a single massive star has on our results. Because the impact of single star outliers will be most pronounced in low mass clusters, we select two low mass clusters, clus-

ters 1218 and 1334, with  $\log(M/M_{\odot})$  of 3.08 and 3.00, respectively. Both cluster 1218 and 1334 are of similar ages with  $\log(\text{Age/yr}) = 7.35$  and  $7.15$  (Wainer et al., 2022). However, the range in measured median MF slopes for these clusters spans more than 1.5 dex. These clusters are shown in Figure 3.4, where the left panel shows the CMDs, and the middle panel is the marginalized  $\Gamma$  PDF, along with the color image of each cluster.

For these low mass clusters, we perform an experiment testing this assumption, adding and subtracting a single bright star from the observed CMD, and investigate the results. For each cluster, we remove the brightest star in F814W. To add a bright star, we give the new star a F475W-F814W color equal the the brightest star in the cluster, and make the star 0.5 magnitudes brighter in F814W than the brightest star in the cluster. We find neither adding nor removing a star has an impact of  $\Delta\Gamma > 0.04$  on the median measured MF. These results suggest that our measurements are not driven by the presence or absence of a single high mass star, but rather encompass the uncertainty in CMD scatter, and potential cluster contaminants.

We also note the degeneracy between the fit cluster age and  $\Gamma$ , as seen in Figure 3.2. At the lowest cluster masses, there are typically larger age uncertainties, and a single high mass star can have an impact on the fit age, and thus effecting the  $\Gamma$  likelihoods. However, this experiment indicates that even in the presence of this degeneracy, the age uncertainty is typically well incorporated in the  $\Gamma$  PDF, and a single star won't have a statistically significant effect of the resulting  $\Gamma$  measurement.

### 3.4 Synthetic Clusters

To test the end-to-end reliability of our analysis, we repeated our entire fitting technique (Section 3) for a set of synthetic clusters with known ages, masses, radii, and IMF slopes. Using MATCH, we generated 76 synthetic clusters spanning a range across the age, mass, and radii ranges of the real clusters. Individual stars for the synthetic clusters were drawn from a Kroupa (2001) IMF with a 0.35 binary fraction, with stellar properties using Padova stellar evolution models (Girardi et al., 2010; Marigo et al., 2008, 2017), and spatial positions drawn from a King (1962) profile.

We place the 76 synthetic clusters selected for analysis in a PHATTER field (B02-F08) where the number density of main sequence stars equals the median found for the sample of real clusters described in Section 2 ( $N_{\text{MS}} \sim 2000$  for surrounding region; see Section 2.3 from Wainer et al. 2022). This is notably higher than the average for the PHATTER footprint ( $N_{\text{MS}} \sim 700$ ), which is not surprising as the youngest clusters are likely to be located in more dense star-forming regions. The insertion was performed by DOLPHOT into the optical F475W and F814W exposures that were used for cluster photometry, and run through the same photometry routines as the original data. The synthetic clusters were positioned by hand to avoid existing clusters, chip gaps, foreground stars, and background galaxies. The photometry catalogs were then processed the same way as for the real data, with cluster photometry being extracted from within an user-defined photometric aperture sized to mimic that of the real clusters. The surrounding field population is sampled using an annulus that spans 1.2–3.4 times the photometric radius, 10 times the area of the cluster. Upon visual inspection of the inserted synthetic clusters, we removed 17 clusters that were not visually distinguishable from the field as they would not be in our real cluster sample which was determined from a visual search.

These synthetic clusters facilitated a variety of tests of our analysis routines. First, we take the populated isochrones of the synthetic clusters, and before inserting them into the images, we run our fitting technique on the isochrones and recover  $\bar{\Gamma} = 1.30^{+0.02}_{-0.02}$ , which is consistent with the input

Kroupa IMF. This test demonstrates our ability to accurately measure the MF without observational noise, and the reliability of our methods described in Section 3.2. It is also important to note that not every isochrone had a median MF slope equal to the input Kroupa IMF (16th to 84th percentile spread of 0.97 dex<sup>6</sup>), and only from looking at the ensemble of MF slopes were we able to fully recover the input. This result demonstrates that even in a regime without measurement uncertainty, Poisson statistics make drawing conclusion from single cluster measurement difficult.

From this point forward, the synthetic clusters are analyzed with the same software and in the same way as the real clusters. The individual MF results for the 45 synthetic clusters that passed the selection criteria from Section 2 are shown in Figure 3.5. It is clear from the figure that our analysis routine introduces a dependence on the recovered MF slope with the input mass of the cluster. When fitting the ensemble for the full swath of synthetics, we verify this dependence by recovering a  $3\sigma$   $a_m$  of  $-0.21 \pm 0.07$ . The figure shows a clear systematic bias toward measuring higher  $\Gamma$  at low masses.

We investigate different mass regimes where we can reliably recover the input Kroupa IMF. From Figure 3.5, we divide the synthetic sample into two sub-samples, above and below  $\log(\text{Mass}/M_\odot)$  of 3.6 (26 and 19 clusters, respectively), and find the lower mass sample shows a significant offset to a higher slope value, with an ensemble value of  $\bar{\Gamma} = 1.76^{+0.10}_{-0.11}$ .

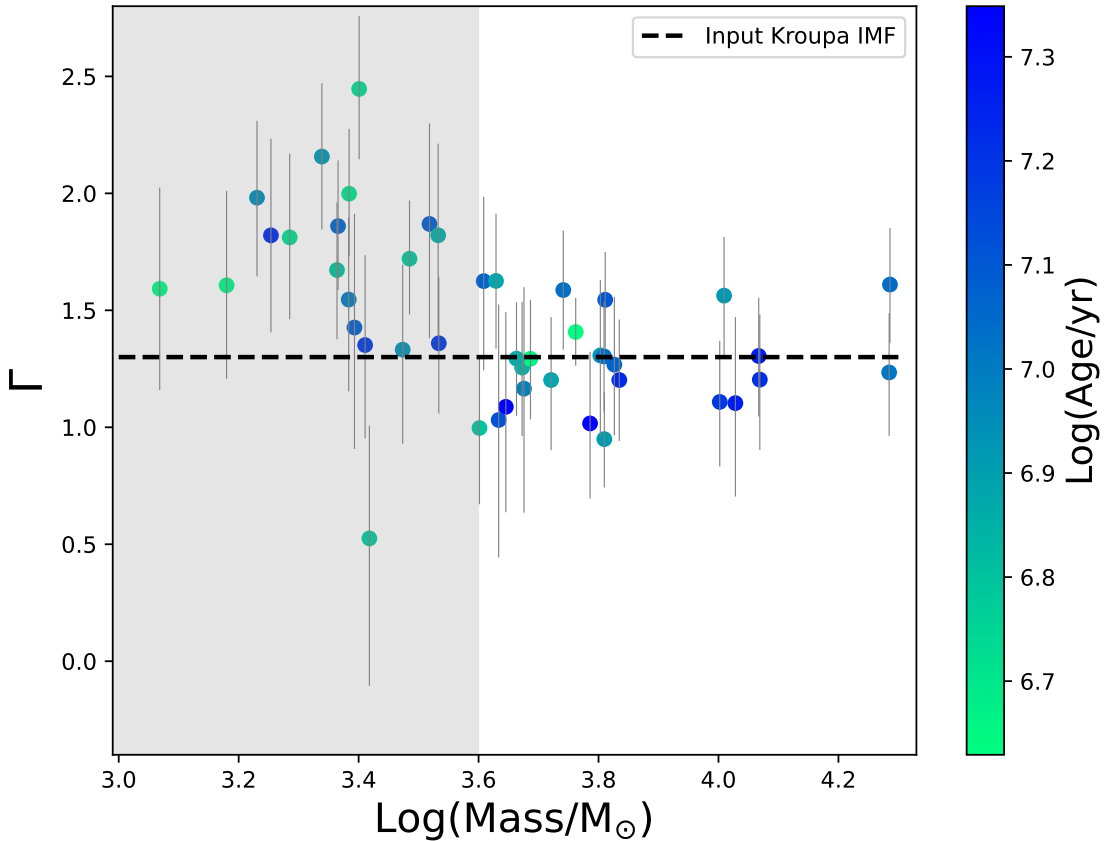
We have extensively tested this bias to high  $\Gamma$  for low-mass clusters: performing quality tests on our ASTs, distributing ASTs according to an empirical effective radius opposed to the half light radius, adjusting photometric radii, fitting over different magnitude ranges, using a fixed the limiting magnitude for the fitted CMD, and inserting the synthetic clusters in less dense regions. However, the bias at low masses persists. We conclude that at lower masses, the scatter in MF slopes is more drastic, and the synthetic cluster results suggest that fitted  $\Gamma$  values have the potential to be biased high. For low mass clusters, the increased scatter in fitted MF slopes is likely due to the decreasing ratio of cluster stars to field stars, leading to confusion in the faint regions of the CMD and degeneracies in the fitting. In M33, the field is significantly more dense than in M31, with the average number of main sequence stars in PHATTER images a factor of 5 greater than in PHAT (Johnson et al., 2022). For low mass clusters, where star counts are smallest, the background component becomes more significant, and may therefore be at least partially to blame for the bias seen in the synthetic clusters results which was not seen in W15.

However, for clusters more massive than  $\log(\text{Mass}/M_\odot)$  of 3.6, we find our methods accurately recover the input IMF. In the synthetic sample, there are 26 clusters above the mass limit. The results for these synthetic 26 clusters in this range are shown in Figure 3.6. This higher mass sample recovers a mean IMF slope of  $\bar{\Gamma} = 1.34 \pm 0.07$  that is consistent with the input IMF and shows no significant dependencies, as presented in Figure 3.6. Therefore, we establish a "gold" sample, which represents clusters above  $\log(\text{Mass}/M_\odot)$  of 3.6, where we expect little to no mass dependence in our results. These results demonstrate that for  $\log(\text{Mass}/M_\odot)$  above 3.6, we are able to corroborate our results against synthetic clusters, and verify the reliability of our analysis techniques.

In the M33 cluster sample (Section 2), we find there are 9 clusters more massive than the synthetic-derived "gold" reliability threshold of  $\log(\text{Mass}/M_\odot)$  of 3.6. To better quantify the effect that small number statistics of this "gold" sample have on the robustness of our results,

<sup>6</sup>The spread in median cluster  $\Gamma$  is larger for lower mass clusters:  $\sim 1.3$  for clusters smaller than  $\log(\text{Mass}/M_\odot)$  of 3.6, and  $\sim 0.6$ , for those larger, demonstrating more uncertainty at smaller masses.

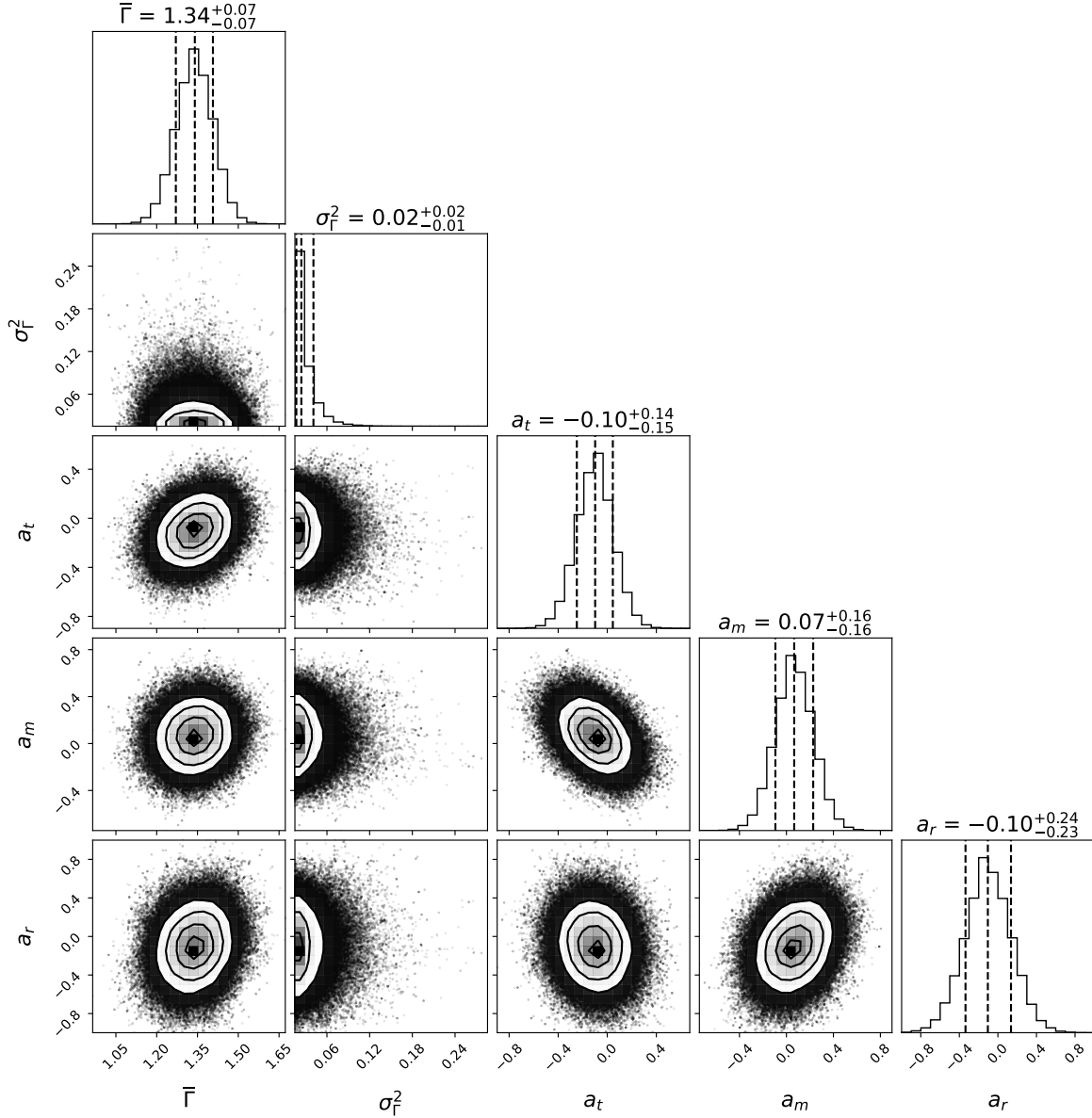




**Figure 3.5:** MF recovery for 45 synthetic clusters using the analysis techniques described in Section 3. The x-axis is the input mass of the synthetic cluster, and each point is colored by the input  $\log(\text{Age}/\text{yr})$  of the synthetic cluster. The black line represents the input Kroupa IMF slope. We can see a clear gradient in recovered  $\Gamma$  with Mass, lower mass clusters recovering higher  $\Gamma$  values. The grey region in the plot signifies the break at  $\log(\text{Mass}/M_{\odot})$  of 3.6, where the synthetics recover the input IMF.

we perform a final test on the synthetic sample. In order to test if there is an implicit bias from selecting a subsample of clusters from a parent distribution, we randomly selected 9 of the 26 synthetics above  $\log(\text{Mass}/M_{\odot})$  of 3.6 to match the number of real clusters we observe above. We perform 1000 draws without replacement in each trial selecting a sub-sample of 9 synthetic clusters. For the 1000 trials, we find the median bootstrapped  $\bar{\Gamma} = 1.34 \pm 0.07$ , with each trial having an ensemble uncertainty of  $0.27 \pm 0.02$ , around  $4\times$  larger than the uncertainty for the sample of 26 clusters, which is consistent with our expectations based on the scaling of uncertainty with  $N_{\text{clusters}}$  from W15. Moreover, the dependence parameters  $a_l$ ,  $a_m$ , and  $a_r$ , have median values of  $0.00 \pm 0.18$ ,  $0.00 \pm 0.017$ , and  $0.00 \pm 0.022$  respectively for the 1000 trials.

These results are consistent with the ensemble values we recovered for the larger sample of 26 clusters shown in Figure 3.6, demonstrating that having a sub-sample of only 9 clusters does not introduce additional biases from the ensemble values of a larger sample. These results also validate the  $\sigma_{\Gamma}$  value reported in Figure 3.6, indicating that over this gold sample of synthetics there is little intrinsic spread in MF values, consistent with a universal IMF. This is reassuring, as all synthetic

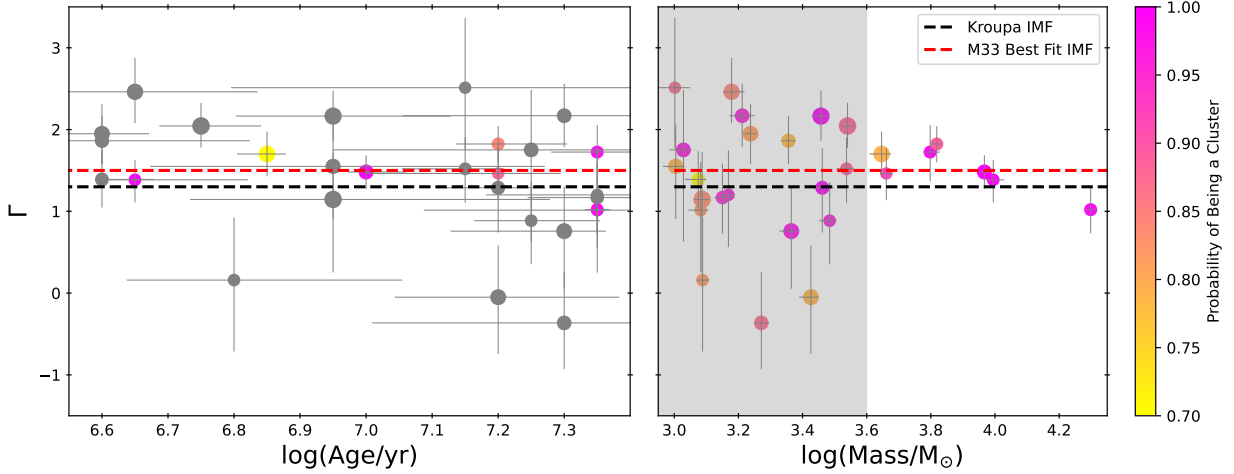


**Figure 3.6:** The joint and marginalized distributions for the distribution of synthetic cluster MF for 26 synthetic clusters with masses larger than  $3.6 \log(\text{Mass}/M_{\odot})$ . In all panels, the dashed lines represent the 16th, 50th, and 84th percentiles of each marginalized distribution.

clusters were generated with the same IMF, and establishes a floor for our ability to detect a truly universal IMF in the real data.

## 4 Results

In this section, we present the results for the IMF in M33, described by the two steps in Section 3. First, we present the present-day MF slopes for our full sample of 34 clusters, and then discuss the results for the 9 clusters in the gold sample range described in Section 3.4.



**Figure 3.7:** The MF slope for each cluster compared to the best fit cluster age (left) and mass (right) from the [Wainer et al. \(2022\)](#) fits. Each point size is scaled by the cluster radius and colored by the probability of being a cluster based on the weighting system of [Johnson et al. \(2022\)](#). The black dashed line is at the Kroupa IMF of  $\Gamma = 1.3$ , and the red line shows the median IMF result from this work of  $\Gamma = 1.49$ . The greyed region represents the region of mass space where our synthetic clusters suggest a potential for bias. The left panel has points that are lower than  $3.6 \log(\text{Mass}/M_\odot)$  greyed out.

The individual MF results for our full sample of clusters are shown in Figure 3.7. In this figure, we compare the fitted MF slope versus the cluster age and mass as presented in [Wainer et al. \(2022\)](#). The black line in the figure represents the [Kroupa](#) IMF slope of  $\Gamma = 1.30$ . The greyed out region in the right panel represents the range of masses where our synthetic clusters indicate a potential for bias. Below this limit of  $\log(\text{Mass}/M_\odot)$  of 3.6, we can visually see the spread in MF values increase; however there does not appear to be a systematic bias to higher values as we saw for the synthetic clusters. While the reason for the lack of mass-dependent behavior in the observed sample is unclear, it suggests there could be fundamental differences between real and synthetic clusters, such as unrealistic synthetic photometry of cluster members or the cluster’s spatial profile. All 34 cluster MFs are presented in Table 3.1, along with all the properties which go into Equation 3.2.

In the second step of our analysis, we present the results for the Gaussian mixture model, reporting the results for the seven parameters of the model: the mean MF slope  $\bar{\Gamma}$ , the intrinsic dispersion  $\sigma_\Gamma$ , and the linear trend with the data against the cluster properties, cluster age  $a_t$ , mass  $a_m$ , cluster radius  $a_r$ , local SFR  $a_{sfr}$ , and galactocentric radius  $a_{gr}$ . These results are shown in Figure 3.8.

As seen in Figure 3.8, the mean IMF slope is  $\bar{\Gamma} = 1.49 \pm 0.18$ . These results are consistent at the  $1\sigma$  level with the [Kroupa](#) IMF of  $\Gamma = 1.3$  and the [Salpeter](#) IMF of  $\Gamma = 1.35$ , but they are closer to the results from young clusters in M31, which were also steeper than these standard values [W15](#).

While we report the median and  $1\sigma$  uncertainty of the  $\sigma_\Gamma^2$  value in Figure 3.8 for consistency with other parameters, the distribution is highly un-Gaussian, and limited by 0. Therefore, we follow the procedure of [W15](#), and characterize  $\sigma_\Gamma^2$  with the mode of the distribution, and quantify its uncertainty by the 68th percentile. With this nomenclature, we find the intrinsic scatter of the distribution  $\sigma_\Gamma^2$  to be  $0.02^{+0.16}_{-0.00}$ . As demonstrated by [W15](#), the ensemble uncertainty scales as

$\propto 1/N_{clusters}$ . Because our gold cluster sample is small, with only 9 PHATTER clusters, a larger sample of clusters would provide a tighter constraint on the M33 IMF.

Within the gold sample, we find no dependence of the IMF with cluster age, cluster radius, local SFR, or galactic radius, but do see a slight dependence with cluster mass at the  $\sim 1\sigma$  level, where  $a_m$  is  $-0.47^{+0.37}_{-0.30}$ . However, this mass dependence can easily be explained by the very limited number of clusters in the gold sample. Primarily, this correlation is driven by the single cluster at  $\log(\text{Mass}/M_\odot) = 4.3$ . Given the small number statistics, and without any additional data above  $\log(\text{Mass}/M_\odot) = 4.0$ , any correlation depends heavily on this single cluster's  $\Gamma$  measurement. Therefore, while the gold sample has a small dependence on cluster mass, we believe it is likely not a physical effect, but rather a result of small number statistics, and more clusters are required to make any significant claims.

In addition to the gold sample, we also calculate the ensemble IMF for the full sample of 34 clusters. For the full sample, we find  $\bar{\Gamma} = 1.45 \pm 0.10$ , consistent with the result for the gold sample. Importantly, over the full range of cluster masses, we find no mass dependence with  $a_m = -0.01 \pm 0.11$ . We also note that in the left hand panel of Figure 3.7, there appears to be a dependence on cluster age. In fact, when considering the the full sample of 34 clusters, there is a slight age dependence of  $a_t = -0.27 \pm 0.17$ . However, as seen in Figure 3.8, the gold sample of 9 clusters shows evidence of no age dependence with an  $a_t = 0.00^{+0.30}_{-0.29}$ . Moreover, when considering the slight age dependence in the full 34 clusters, it is important to note that it is driven by clusters which are less massive than the high-confidence threshold of  $\log(\text{Mass}/M_\odot)$  of 3.6. We iterate that more clusters are needed to make claims about any potential dependence.

While the mass-limited gold sample was conservatively chosen to avoid possible fitting biases revealed by synthetic cluster tests, we reiterate that  $\Gamma$  results for the full observed sample show no evidence for cluster mass-dependent biases. We conclude there is no evidence that ensemble constraints on  $\bar{\Gamma}$  depend on cluster sample selection, and that the full sample could benefit from improved precision due to larger number statistics, but adopt results for the gold sample as this work's primary result out of an abundance of caution.

**Table 3.1:** Individual Cluster MF Results

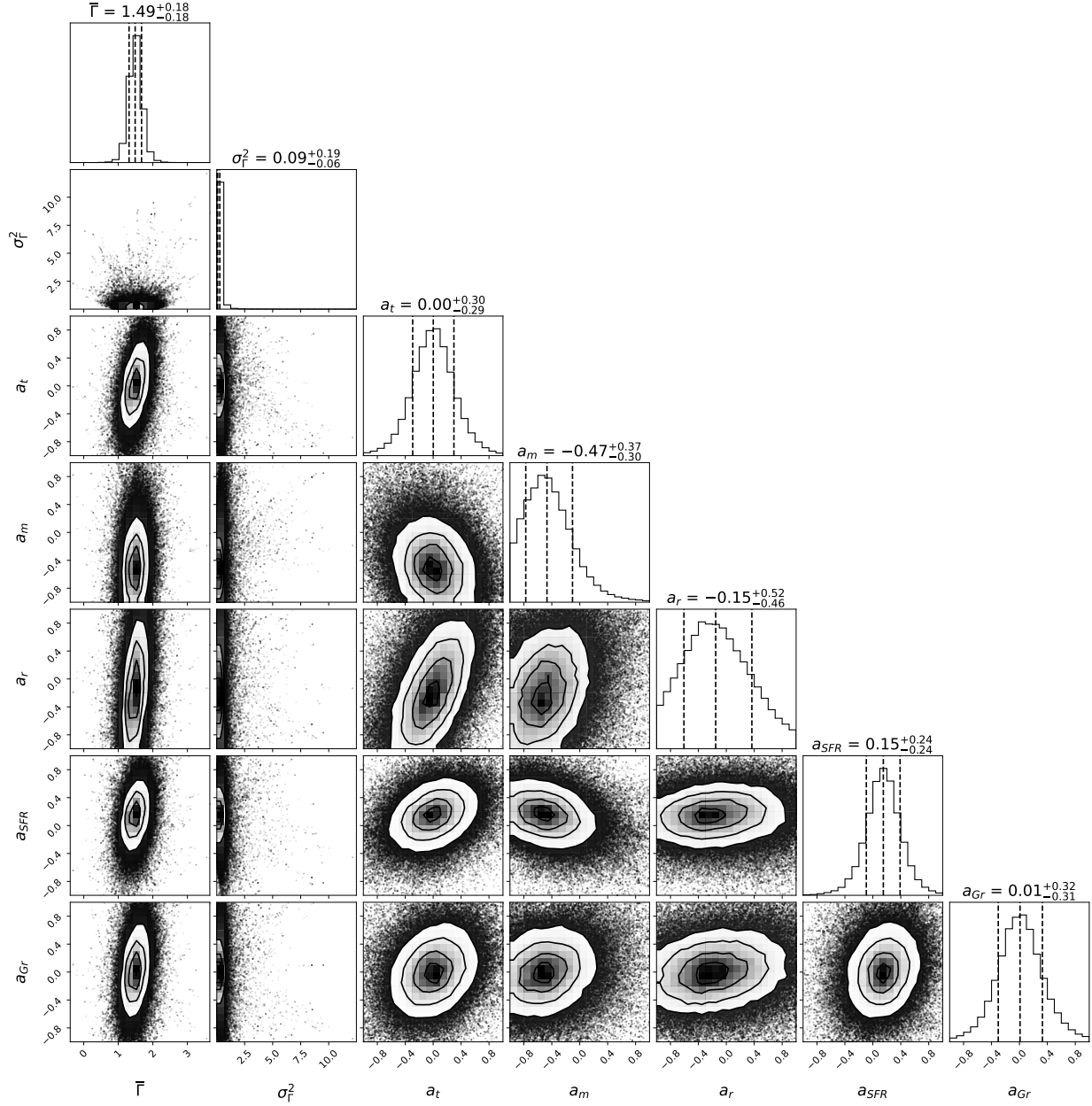
| ID  | Gamma 16 | Gamma 50 | Gamma 84 | Age <sup>a</sup><br>[log(Age/yr)] | Mass <sup>a</sup><br>[log(Mass/ $M_\odot$ )] | AV <sup>a</sup><br>[mag] | Clst Radius <sup>b</sup><br>[parsec] | SFR <sup>c</sup><br>[log( $M_\odot$ yr <sup>-1</sup> kpc <sup>-2</sup> )] | Gal Radius<br>[kpc] |
|-----|----------|----------|----------|-----------------------------------|----------------------------------------------|--------------------------|--------------------------------------|---------------------------------------------------------------------------|---------------------|
| 45  | 1.22     | 1.43     | 1.64     | 7.0                               | 3.97                                         | 0.35                     | 2.73                                 | -3.61                                                                     | 0.7                 |
| 163 | 2.03     | 2.41     | 2.83     | 6.65                              | 3.18                                         | 1.05                     | 3.32                                 | -3.43                                                                     | 2.47                |
| 179 | 1.32     | 1.67     | 2.0      | 7.35                              | 3.8                                          | 0.4                      | 1.97                                 | -3.5                                                                      | 1.09                |
| 200 | 1.08     | 1.41     | 1.72     | 7.2                               | 3.66                                         | 0.45                     | 1.76                                 | -3.98                                                                     | 1.32                |
| 280 | 1.06     | 1.34     | 1.58     | 6.65                              | 3.99                                         | 0.4                      | 1.89                                 | -3.15                                                                     | 1.69                |

*Note.* Table 3.1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

<sup>a</sup> Estimates in the table represent the “Best-fit” parameters from Wainer et al. (2022).

<sup>b</sup> Estimates in the table represent the half-light radius ( $R_{\text{eff}}$ ) from Johnson et al. (2022).

<sup>c</sup> Estimates in the table are area-normalized values of the SFR from 0–100 Myr from Lazzarini et al. (2022).



**Figure 3.8:** The joint and marginalized distributions for the distribution of cluster MF, described by Equations 3.1 and 3.2. In all panels, the dashed lines represent the 16th, 50th, and 84th percentiles of each marginalized distribution. Parameters are the mean slope of the IMF,  $\bar{\Gamma}$ , and the intrinsic scatter in that slope,  $\sigma_{\Gamma}$  from the ensemble of cluster MFs, and well and parameters testing for dependencies on cluster properties: cluster age  $a_t$ , mass  $a_m$ , cluster radius  $a_r$ , local SFR  $a_{sfr}$ , and galactocentric radius  $a_{gr}$ , as described in the text.

## 5 Discussion

While our measurements of the IMF in M33 clusters is of interest for M33-specific studies, it is also of interest for constraining the dependence of the IMF on environment. Below, in Section 5.1,



we discuss the cluster to cluster variance of the IMF, illustrating the need to perform IMF analysis on as large a sample of clusters as possible. We then explore environmental impacts on the IMF in Section 5.2, and discuss the broader implications a steeper IMF has on the number of high-mass stars created, and how that impacts the broader astronomical research enterprise in Section 5.3.

## 5.1 Cluster to Cluster Variance of the IMF

In M33, for our gold sample, we report an ensemble scatter in MF slopes of  $0.02^{+0.16}_{-0.00}$  (visualized in Figure 3.8), which is consistent with a universal IMF as determined by the synthetic clusters. However, when considering the more inclusive sample that extends down to  $\log(\text{Mass}/M_{\odot})$  of 3.0, we find there is more scatter, with an ensemble scatter of  $0.04^{+0.13}_{-0.00}$ , higher than what we expect from the synthetic cluster results. This scatter is also visible in Figure 3.7, where in particular, the low mass clusters have a much higher spread in  $\Gamma$  values. There is a well documented history of intrinsic scatter within the compilation of IMF slope measurements from individual clusters (Kroupa, 2002; Lee et al., 2020). We also see scatter from cluster to cluster in the IMF slope, which emphasizes the need for determining IMF properties from an ensemble of clusters, rather than single clusters.

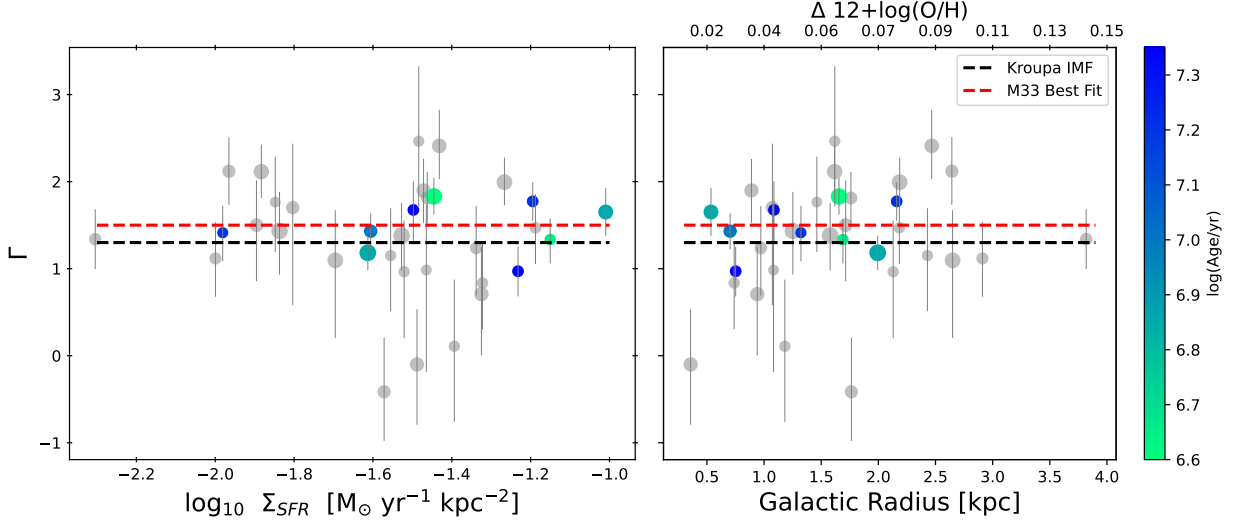
This variance is highlighted in our sample by the two clusters shown in Figure 3.4. Despite the two clusters being very close in age and mass, the number of high-mass main sequence stars is visibly different in the two CMDs, and the resulting  $\Gamma$  values are therefore different.

To explore the observed variation with respect to our uncertainties, we quantify the scatter in the distribution of MF slopes by determining the reduced  $\chi^2$ . For the full sample of 34 clusters, we find  $\chi^2$  to be 1.98, while for the gold sample,  $\chi^2$  is 1.33. This result demonstrates that the scatter in the sample at smaller masses is larger than the uncertainties would predict, which suggests intrinsic IMF scatter across the cluster sample. However, when we compare this distribution of  $\chi^2$  values to a normal distribution through a Kolmogorov-Smirnov (KS) test, we recover a K-S statistic of 0.20 and a p-value of 0.21. Therefore, we are unable to conclusively claim that the variance between clusters is more than what would be expected from stochastic sampling of the IMF. This work highlights the need for large samples of clusters in order to make substantial claims about the IMF. We emphasize that drawing galactic, or universal, claims about the IMF from single clusters is extremely difficult.

## 5.2 Exploring Environmental Impacts on the IMF

As discussed through this paper, one of the most pressing questions in studies of the high-mass IMF is the universality of the IMF, or whether there are significant environmental effects which impact the number of high-mass stars formed (e.g., Lee et al., 2020). Most notably, there has been recent evidence to support an IMF which is variable in extreme star forming environments or environments with different metallicities (Li et al., 2023; Marks et al., 2012; Rautio et al., 2023; Weidner et al., 2011; Zhang et al., 2018). We have discussed cluster to cluster variations of the IMF in our study (Section 5.1), and in this section, we will investigate potential impacts the local cluster environment, such as SFR and metallicity, has on the measured cluster MF, and inferred IMF.

On a galactic scale, The  $\bar{\Gamma} = 1.45^{+0.03}_{-0.06}$  measured in M31 by W15 serves as the tightest systematically constrained measurement of a galactic high-mass IMF from resolved stars. The M33



**Figure 3.9:** Cluster  $\Gamma$  as a function of cluster  $\Sigma_{SFR}$ , and galactic radius, which serves as a proxy for metallicity. The  $\Sigma_{SFR}$  is measured for a  $\sim 0.01 \text{ kpc}^2$  region containing the cluster, calculated by Lazzarini et al. (2022) from 0-100 Myrs. Each point is colored by the  $\log(\text{Age}/\text{yr})$  of the cluster and is scaled by the radius of the cluster to easily map to Figure 3.7, and greyed out if it is below  $\log(\text{Mass}/M_\odot)$  of 3.6. These results show no trend in IMF with either  $\Sigma_{SFR}$ , or galactic radius. The secondary axis for galactic radius is the change in  $12+\log(\text{O}/\text{H})$  abundance gradient with radius according to Rogers et al. (2022).

ensemble IMF results of  $\bar{\Gamma} = 1.49 \pm 0.18$  of our gold sample, as well as the  $\bar{\Gamma} = 1.46^{+0.11}_{-0.12}$  from the more inclusive sample, presented in Section 4 are consistent with the M31 value, and adds an additional galactic data point using multiple clusters across galactic environments. This consistency between the derived  $\Gamma$  values for M33 and M31 is of particular interest as M33 is a more active star forming galaxy, with an average star formation rate surface density  $\log(\langle \Sigma_{SFR} \rangle / (M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}))$  of  $-2.04^{+0.16}_{-0.18}$  (Lazzarini et al., 2022; Wainer et al., 2022), nearly four times higher than M31 ( $\log(\langle \Sigma_{SFR} \rangle / (M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}))$  of  $-2.68^{+0.26}_{-0.38}$  (Johnson et al., 2017; Lewis et al., 2015). Because of the higher  $\Sigma_{SFR}$ , M33 is able to make slightly more massive clusters than M31 (Johnson et al., 2017; Wainer et al., 2022). Despite the difference in cluster masses and  $\Sigma_{SFR}$  between the two galaxies, the measured IMFs are the same. This consistency supports the universality of the mean high-mass IMF in the Local Group.

On an individual cluster scale, we investigate potential impact local cluster environments could have on a clusters MF. To quantify the SFR associated with each cluster in our sample, we use the SF maps of Lazzarini et al. (2022) who fit color magnitude diagrams to resolved stars in 2005,  $\sim 100$  parsec regions. Based on the cluster location, we adopt the Lazzarini et al. (2022) SFR value between 0-100 Myr ago as the cluster SFR. We normalize the value given in Lazzarini et al. (2022) by the area in order to estimate the  $\Sigma_{SFR}$ , a value more comparable to galactic samples in the literature.

The individual cluster MF results are shown in the left panel of Figure 3.9. As we can see, there is no significant trend with the cluster neighborhood SFR. Moreover, for the 9 clusters in our gold sample, visualized in Figure 3.8, we find no significant trends in our Gaussian mixture model

with a  $a_{\text{SFR}} = 0.15 \pm 0.24$ . These results show no dependence of the IMF on the SFR in the region around the cluster.

It is no surprise that the majority of the newest formed star clusters are located in environments with higher than average  $\Sigma_{\text{SFR}}$ . Therefore, while the increased  $\Sigma_{\text{SFR}}$  in these regions covers a wide range of the galactic  $\Sigma_{\text{SFR}}$  presented in Leroy et al. (2021), (from  $-2.3 \leq \Sigma_{\text{SFR}} \leq -1.0$ ) even the most extreme star forming regions in M33 are not representative of the extreme environments suggested to create a more top-heavy IMF (Zhang et al., 2018). While we do not see any IMF dependence on the  $\Sigma_{\text{SFR}}$  in our sample, due to its smaller mass, the galactic M33  $\Sigma_{\text{SFR}}$  of  $\sim -2$  (Leroy et al., 2019; Wainer et al., 2022) is small compared to the majority of galaxies in the PHANGS survey (Leroy et al., 2021). It would be of significant interest to the community to measure the IMF for a large sample of clusters with resolved stars in a star-bursting galaxy.

The other primary environmental effect which has been discussed in the literature to affect the IMF is metallicity. While there is a gas phase metallicity gradient across the M33 disk, the PHATTER footprint is constrained to the five innermost kpc, and the metallicity does not begin to significantly change until the outer regions of the galaxy (Rogers et al., 2022). While within the PHATTER footprint the metallicity is fairly constant with a measured  $12+\log(\text{O}/\text{H})$  abundance gradient of  $-0.037 \pm 0.007 \text{ dex kpc}^{-1}$  (Rogers et al., 2022), we nevertheless show the cluster  $\Gamma$  results against galactic radius, which serves as a proxy for metallicity. These results are shown in the right hand panel of Figure 3.9.

From the measured  $12+\log(\text{O}/\text{H})$  gas phase abundance gradient of  $-0.037 \pm 0.007 \text{ dex kpc}^{-1}$ , the majority of our clusters are between 0.5 and 3 kpc, and therefore, across our sample of clusters, we expect a change of  $\sim -0.1 \text{ dex}$ . Similarly, for the 9 clusters in our gold sample, we only see a difference of  $\sim 1.5 \text{ kpc}$  in Galactic radius, which is only a  $\sim -0.06 \text{ dex}$  difference in metallicity. The results for the gold sample are shown in Figure 3.8, and we do not see a trend in our Gaussian mixture model with  $a_{\text{gr}} = 0.01^{+0.32}_{-0.31}$ , showing no significant dependence of the IMF on the galactic radius. It would be very interesting to have a survey covering the entirety of the M33 disk, and be able to have clusters in different metallicity environments. We also note that when measuring the environmental statistics for the full sample of clusters which extends to  $\log(\text{Mass}/M_{\odot})$  of 3.0, we do not see any dependencies, and values of  $a_{\text{sfr}}$  and  $a_{\text{gr}}$  are consistent with those of the gold sample.

Recent theoretical work has proposed additional tests of environmentally-dependent IMF behavior, however in practice these tests are not observationally feasible – even with a high-quality dataset like PHATTER. For example, Grudić et al. (2023); Grudić et al. (2023) proposes a comparison between the maximum stellar mass found in a cluster and the total number of cluster stars. In practice, both the maximum mass and the total cluster mass are difficult to constrain due to observational magnitude and crowding limits. Moreover, both the number of stars in a cluster and the number of stars above  $8 M_{\odot}$  are age-dependent measurements. While we have preferentially selected the youngest clusters to probe the initial state of the cluster, it is very difficult to differentiate between an evolved system where the most massive stars have already evolved away and one where those most massive sources were never formed (e.g., Schneider et al., 2015). Observers have also used indirect tracers of massive stars to place constraints on the upper IMF (e.g., Jung et al., 2023), however this path is also difficult.

In this study, we do not see any dependence on the IMF with  $\Sigma_{\text{SFR}}$  or  $12+\log(\text{O}/\text{H})$ . As noted above, the change in these two parameters across the PHATTER survey is relatively small. However, the outer regions of M33 see a significant extended HI disk that reaches far beyond the visible

stellar disk (Koch et al., 2018). Additionally, the metallicity gradient throughout the disk may affect the cooling efficiency of gas, which in turn influences the rate of star formation. Given the uncertainty scaling of the IMF with number of clusters in W15, if a high mass slope difference exists for different environments, of order  $\sim 40$  clusters is needed for a  $3\sigma$  detection. Extended coverage of the M33 disk would provide substantial evidence for any potential impact SFR or metallicity has on the high mass IMF.

### 5.3 Implications of a Steeper IMF

The work presented in this paper is formally consistent with the canonical Kroupa and Salpeter values for the high mass slope of the IMF. However, it is also consistent with other results in the literature with steeper IMF slopes. Most notably, the W15  $\bar{\Gamma}$  value of  $1.45^{+0.03}_{-0.06}$  for M31, but also the Kennicutt IMF ( $\Gamma = 1.5$ ; Kennicutt (1983)), the Miller & Scalo IMF from  $1-10M_{\odot}$  and the high-mass Scalo IMF ( $\Gamma = 1.6$ ; Scalo (1986)) above  $4M_{\odot}$ . This potentially steeper IMF could have drastic ramifications in the number of high-mass stars produced, which would have far reaching impacts to nearly every aspect of astronomy. Due to these high impacts, in this section, we will explore some of these implication a steeper IMF slope could have.

Because of the homogeneity and high-precision of the measurement in M31, Weisz et al. (2015), recommend the community adopt the modified Kroupa IMF which takes the form,

$$\xi(m) = cm^{-(\Gamma+1)} \begin{cases} \Gamma = 0.3 & \text{for } 0.08 < m < 0.5M_{\odot} \\ \Gamma = 1.3 & \text{for } 0.5 < m < 1.0M_{\odot} \\ \Gamma = 1.45^{+0.03}_{-0.06} & \text{for } 1.0 < m < 100M_{\odot} \end{cases} \quad (3.3)$$

This modified IMF is extrapolated from  $2 M_{\odot}$  down to  $1M_{\odot}$ , and up to  $100 M_{\odot}$ , allowing for a fair comparison to conventional definitions in the literature with effects less than a few percent. Assuming this modified Kroupa IMF, we replicate the calculations from W15 of number of stars expected relative the the traditional Kroupa IMF. Because the IMF measured here in M33 is statistically consistent with that of M31, the implications are the same as Section 5.3 of W15. Here, we highlight the largest impacts from W15, and include new estimates for astronomical fields which have become more refined in the time since W15.

Most notably, the modified Kroupa IMF predicts the formation of fewer stars than Kroupa at all masses, and fewer high-mass stars than a Salpeter IMF for masses  $> 2M_{\odot}$ . For the most massive stars, the modified Kroupa model predicts  $\sim 25\%$  fewer stars with masses above  $8M_{\odot}$  compared to a Kroupa IMF. The smaller number of these most massive stars has the largest impacts for the field, as the  $8M_{\odot}$  stars are believed to be the progenitors for core collapse supernovae (e.g., Smartt, 2009). These supernovae serve as a primary mechanism for alpha enhancement, and thus our ability to correctly model chemical enrichment (e.g., Buck et al., 2021).

These stars with masses greater than  $8M_{\odot}$  are believed to be the progenitors for neutron stars and stellar mass black holes (e.g., Heger et al., 2003), and are the progenitors for the newly detected gravitational waves (e.g., Abbott et al., 2017, 2020). The number of available progenitors decreasing by even a factor of a few will have drastic impacts on the inferred merger-rates (Abbott et al., 2023), and the number of expected gravitational wave detections, impacting the open questions such as the black hole mass gap (Farmer et al., 2019).

On a similar thread, fewer massive stars will decrease the number of expected Gamma-Ray-Bursts (GRBs) (Heger et al., 2003). GRBs have been used to infer star formation histories at both high and low redshifts (e.g., Taggart & Perley, 2021; Wang & Dai, 2011). Adapting the Wang & Dai (2011) GRB rates, 25% fewer expected GRBs will under-predict the inferred star formation histories in high  $z$  galaxies by as much as a factor of  $\sim 1.2$ . This additional steepness of the IMF also requires more than the factor of 0.77 correction on the cosmic star formation history scale factor of Hopkins & Beacom (2006), providing additional evidence of an evolving IMF throughout cosmic time, where the number of massive stars created today is different than the earliest generations of stars. The number of high-mass stars is also imperative to help answer some of the outstanding questions on whether massive stars form through direct collapse or mergers (e.g., Bally & Zinnecker, 2005).

W15 also discuss the implications for common SFR indicators like the luminosity to SFR relation, and  $H\alpha$  tracers (Conroy et al., 2009, 2010; Kennicutt & Evans, 2012; Kennicutt, 1998). Specifically, for a fixed luminosity, the SFRs assuming the modified Kroupa IMF are a factor of  $\sim 1.3 - 1.5$  larger.

Another possible explanation for the steeper IMF slope could be that observational measurements of cluster stars have been impacted by high-mass stars being preferentially ejected from clusters within the first few Myr of a clusters life. Oh & Kroupa (2016) have shown that the W15 slope could be consistent with such a model, but we cannot distinguish this possibility from a steeper IMF with the present study. It would be of interest to look for additional observational tracers that high-mass stars that have been ejected in simulations, and see if that evidence is present in the data.

## 6 Summary

We measure the high-mass IMF in Local Group galaxy M33 using data from the PHATTER survey (Williams et al., 2021). For the purest sample of 9 young stellar clusters identified by Johnson et al. (2022), the best fit IMF is inferred to be  $\bar{\Gamma} = 1.49 \pm 0.18$ , formally consistent with the canonical Kroupa and Salpeter values. We do not find a robust trend of MF slope on the cluster’s age, mass, cluster radius, galactic radius, or SFR around the cluster location.

The results presented here are in agreement with that of M31 (W15). If this increased steepness is confirmed, it has drastic ramifications in the number of high-mass stars produced and will have far reaching impacts to nearly every aspect of astronomy.

*Facilities:* HST(ACS, WFC3)

*Software:* emcee (Foreman-Mackey et al., 2013), corner (Foreman-Mackey, 2016), astropy (Astropy Collaboration et al., 2013, 2018, 2022), numpy (Harris et al., 2020), scipy (Virtanen et al., 2020b), matplotlib (Hunter, 2007b)



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# CHAPTER 4

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## THE SPATIALLY RESOLVED RECENT STAR FORMATION HISTORY IN M31

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## 1 Introduction

One key tracer of a galaxy’s formation and evolution is its star formation history (SFH). This simple metric of how much stellar mass has formed each year constrains the galaxy’s mass assembly and chemical evolution, offering clues about the astrophysical phenomena that have influenced its evolution (e.g., Conroy, 2013; Holtzman et al., 1999; Lazzarini et al., 2022; Lewis et al., 2015; Skillman, 2005; Tolstoy et al., 2009; Weisz et al., 2014). Focusing on the recent ( $<1$  Gyr) SFH, we can directly measure the connection between local star formation events and the surrounding dust and gas, allowing us to study the physics of star formation and feedback (e.g., Cannon et al., 2011; Christensen et al., 2024). However, this detailed level of analysis can only be done for nearby galaxies with resolved stellar photometry, where we can spatially resolve the SFH for a specific region using samples of the stars that were formed (e.g., Lewis et al., 2015, 2017; McQuinn et al., 2012). This distance limitation is particularly acute for massive galaxies, due to their high intrinsic stellar density.

A precise method that can be used to measure SFHs with the highest time resolution is color magnitude diagram (CMD) fitting. In this method, the number of stars of various ages and masses is counted directly, and the distribution of stars on the CMD is used to infer time-resolved star formation rates (SFRs) that would produce the observed population (e.g., Dolphin, 2002; Weisz et al., 2008; Williams et al., 2011). A spatially-resolved SFH can be constructed by using CMD-fitting to measure the SFH independently in multiple spatial regions across a galaxy, which can then be tiled together to form a cohesive map of recent star formation (Lazzarini et al., 2022; Lewis et al., 2015; Tran et al., 2023).

Like all methods used to measure a galaxy’s SFH, CMD analysis relies on assumptions about stellar evolution, binary populations, the initial mass function (IMF), and the distribution and amount of dust (Dolphin, 2013). CMD derived SFHs also have better time resolution at younger ages opposed to older ages. Small changes in stellar population age produce large changes in the color-magnitude distribution of stars, particularly in the well-populated, well-understood main sequence. In contrast, older populations are constrained more heavily by evolved phases such as the red clump and horizontal branch, where the age sensitivity is weaker and the modeling is less certain (e.g., Dib et al., 2025; Dolphin, 2002; Gallart et al., 2005; Tolstoy et al., 2009).

CMD-based spatially resolved SFHs have been wildly successful in mapping nearby galaxies, which offer the most dynamic range of age sensitive CMD features. Examples include the SMC (Cohen et al., 2024a; Harris & Zaritsky, 2004), LMC (Cohen et al., 2024b; Harris & Zaritsky, 2009), M33 (Lazzarini et al., 2022), and M31 (Lewis et al., 2015; Williams, 2003); as well as more

distant systems such as M81 (Choi et al., 2015), NGC 300 (Gogarten et al., 2010), NGC 2403 (Williams et al., 2013), and NGC 6946 (Tran et al., 2023).

M31 is an especially powerful laboratory for this kind of work. At a distance assessed to be 785 kpc (McConnachie et al., 2005), M31 is the nearest massive  $L_*$  spiral that can be resolved into individual stars. As a result, its recent SFH has been the focus of numerous resolved-star studies in selected fields (Bernard et al., 2012; Brown et al., 2006, 2007, 2008; Davidge et al., 2012; Williams, 2002, 2003). These studies established that M31 has a complex and spatially varying SFH, most notably that the galaxy appears to have a lower SFR at more recent look-back times, compared to times larger than 1 Gyr. However, these studies also reflected the usual trade-off between photometric depth, which improves age resolution and helps reduce age–metallicity degeneracies (e.g., Gallart et al., 2005), and spatial coverage. Thus, early studies had limited spatial coverage and heterogeneous sampling of the disk, making it difficult to connect temporal variations in the SFR to galaxy-wide structure.

However, M31’s deep photometric coverage was greatly improved when a significant portion of the galaxy was observed with *HST* as a part of the Panchromatic Hubble Andromeda Treasury (PHAT) (Dalcanton et al., 2012). PHAT spans the near-UV through the near-IR, providing resolved stellar photometry for over 100 million stars. The survey’s combination of depth and contiguous spatial coverage made it possible to connect M31’s local stellar populations to larger-scale disk structure in a way that had not been feasible in earlier targeted-field studies.

One notable study which used these data is that of Lewis et al. (2015, hereafter L15), which provided the first spatially resolved SFH for a significant portion of M31. L15 divided the 0.5 square degree area in the northern third of the disk covered by PHAT into roughly 9000 regions measuring 100 pc by 100 pc. They optimized their fits for recent star formation, accurate within the last  $\sim 500$  Myr, focused on reconstructing the blue half of the CMD, which is populated almost entirely by young main sequence stars.

The results from L15 have been incredibly valuable in precisely characterizing M31. For galactic structure and evolution, the L15 SFH maps have helped establish how long-lived the 10 kpc ring is, and that the PHAT region in M31 had a modest burst of star formation  $\sim 100$  Myr ago, in addition to the large burst seen  $\sim 2$  Gyr ago (Williams et al., 2014) most likely in the aftermath of a recent merger (D’Souza & Bell, 2018; Hammer et al., 2018).

The maps have also been used to better calibrate various SFR indicators, via direct comparison with the CMD-based SFRs (Lewis et al., 2017). For stellar astrophysics, Díaz-Rodríguez et al. (2018) used the L15 SFH maps to measure the progenitor mass distribution for core collapse supernovae. Additionally, the maps have been used to measure the age distribution of high-mass X-ray binaries (Lazzarini et al., 2018, 2021; Williams et al., 2018). For gas and dust studies, the L15 maps are an important indicator of local densities of young stars (e.g., Eknath, 2024; Lindberg et al., 2024). They also provide a key observational constraint for theoretical simulations of galactic dynamics (e.g., Feng et al., 2024; Hammer et al., 2025).

In contrast to the well-studied region of M31 covered by the PHAT survey, the southern disk has not yet been as well characterized, despite being notably different and more complex than the northern half. The largest, and arguably the most interesting, feature distinguishing the southern half of the disk is the presence of M32, just 5 kpc from the center of the M31 disk in projection, although with unknown distance to the disk itself (e.g., McConnachie, 2012). Due in part to this distance uncertainty, and equally large kinematic uncertainties, the exact history of interaction between M32 and M31 is unknown. Some models suggest that M32 is the stripped remnant of

a recent merger (Bekki et al., 2001; Dierickx et al., 2014; D’Souza & Bell, 2018; Escala et al., 2025), and the prevailing theory is that M32 is currently impacting the M31 disk (e.g., Gordon et al., 2006; Patel et al., 2025).

Whether due specifically to M32 or otherwise, the southern half of the M31 disk appears to be more perturbed by its merger history than the northern half (D’Souza & Bell, 2018; Gordon et al., 2006; Hammer et al., 2018). Additional unique features in the southern half of the M31 disk include the giant southern stream (Ibata et al., 2001, 2007), and NGC 206, M31’s largest star forming region (Brinks, 1981; Odewahn, 1987). The galaxy’s largest stellar clusters are in the south (Perina et al., 2009), which could be evidence of a higher star formation rate surface density ( $\Sigma_{SFR}$ ) (Johnson et al., 2017; Wainer et al., 2022).

Each of these features may either influence the local SFH or reflect a distinct evolutionary history relative to the northern disk. Thus, the southern disk is a natural target for a detailed modeling of the recent SFH, which could yield valuable clues to the relationship between M31 and M32, and link the prominent structures seen today to M31’s global evolutionary history. Spatially resolving the SFH makes that connection especially meaningful by tracing these southern structures in both space and time.

The opportunity to study the southern disk with deep, high precision photometry is now available with the Panchromatic Hubble Andromeda Southern Treasury (PHAST) survey (Chen et al., 2025), obtained using the *Hubble Space Telescope* (HST). With over 90 million resolved stars covering  $0.45 \text{ deg}^2$  of the star forming disk, PHAST presents reliable optical photometry down to  $\sim 27$  magnitude corresponding to an absolute magnitude of  $\sim 2.5$ . This depth is more than adequate for precisely measuring the star formation activity over the past 500 Myr in M31 with excellent time resolution (see Section 3.5 for more details). With this comprehensive data set, we seek to follow the methodology of L15 and measure the spatially resolved SFH within the PHAST footprint, using CMD fitting to describe the SFH in  $100 \times 100 \text{ pc}$  regions.

By combining the PHAT and PHAST surveys, we gain access to resolved-stellar photometry for roughly 0.2 billion stars. Together, these homogeneous *HST* data sets provide contiguous coverage of roughly two-thirds of the star-forming disk, enabling the highest-resolution galaxy-scale SFH map of M31 yet measured from resolved stars, and the only such detailed map of any  $L_*$  galaxy. Combining the SFH maps created with both the PHAT (L15) and PHAST surveys enables the first truly galaxy-scale analysis of the recent SFH in M31. With this combined coverage, we can directly test asymmetries between the northern and southern disk, connect local star-forming structures to global trends, and trace how star formation has evolved across M31 over the last  $\sim 500 \text{ Myr}$ .

This paper is structured as follows. We describe the PHAST data in Section 2 and describe the CMD based SFH fitting in Section 2. We present the SFH for PHAST in Section 4, and combine the PHAT and PHAST results in Section 5. We then compare the SFRs derived from our CMD based analysis to other indicators in Section 7. Finally, we compare the northern and southern disk, and discuss the M31 SFH in the context of galaxy evolution in Section 6, including consideration of specific sub-regions such as the vicinity of M32, and the inner arm, in Section 6.2.

## 2 PHAST Data

Our analysis is based on imaging from the PHAST survey (Chen et al., 2025), a large HST program targeting the southern disk of M31 (GO-16778 and 16796–16801; PI: Williams). A full description



of the survey, along with figures of the survey strategy can be found in [Chen et al. \(2025\)](#), a brief summary follows.

PHAST builds upon the strategy of the PHAT ([Dalcanton et al., 2012](#)) and PHATTER ([Williams et al., 2021](#)) surveys, providing contiguous four-band coverage in the F275W, F336W, F475W, and F814W filters using single-orbit observations from ACS/WFC and WFC3/UVIS. Our work here only uses the optical F475W and F814W wavelengths due to their depth and our focus on young stars, as discussed more in Section 2. The survey extends  $\sim 13$  kpc along the southern major axis of M31, covering a total area of  $\sim 1640$  arcmin<sup>2</sup>.

Observations were conducted at two orientations separated by  $180^\circ$ , which placed the parallel ACS/WFC exposures over the location of primary WFC3/UVIS exposures. Each pointing received one orbit of exposure time, with two dithered exposures in each filter to mitigate detector artifacts and improve sampling. The footprint of PHAST, combined with PHAT, covers approximately two-thirds of the far-ultraviolet (FUV) flux from M31’s disk, based on comparison with *GALEX* imaging ([Martin et al., 2005](#)).

## 2.1 Photometry and Catalogs

Stellar photometry was measured using the DOLPHOT package ([Dolphin, 2016, 2000](#)), following procedures established in PHAT and PHATTER. For a full description of the intricacies of deriving the PHAST photometry, refer to [Chen et al. \(2025\)](#). Here we provide a brief synopsis.

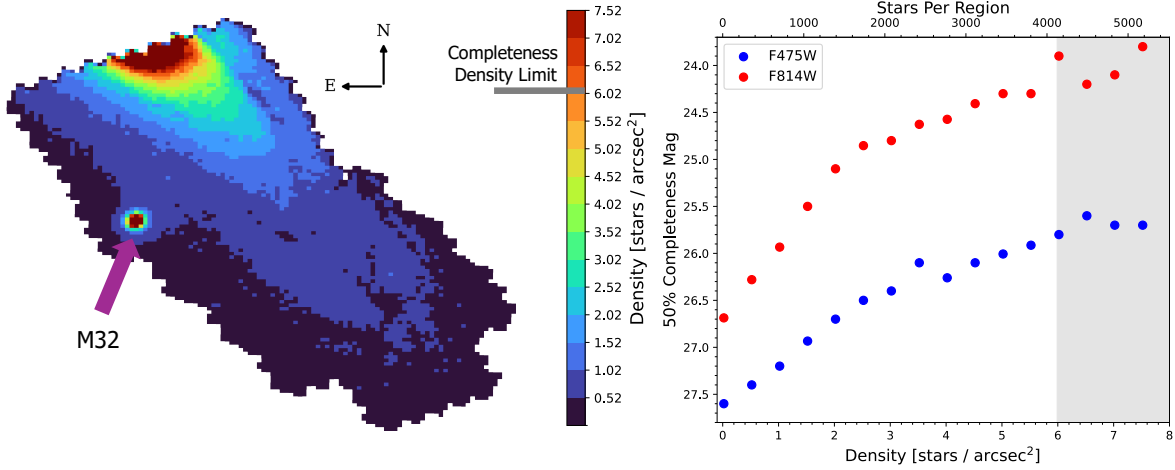
Photometry was carried out using PSF fitting across stacked subregions containing all overlapping exposures. The photometry pipeline incorporates cosmic-ray masking, pixel area maps, PSF and aperture corrections, and produces calibrated magnitudes for all stars detected in any band. Each subregion includes overlapping exposures from adjacent bricks and fields, ensuring consistent depth and reducing edge artifacts. The final PHAST catalog contains  $\sim 91$  million sources with full 4-band photometry, signal to noise estimates, crowding and sharpness diagnostics, and quality flags. We use the `gst` subset of the catalog, which includes only stars with reliable photometry in each band ( $S/N > 4$ ,  $\text{sharpness}^2 < 0.2$ , and  $\text{crowding} < 2.25$ ). This catalog forms the basis for CMD fitting in this work.

## 2.2 Region Size and Stellar Density Determination

Each region in our spatial grid spans  $\sim 26$  arcsec per side, binned by RA and Dec. At the distance of M31 at 785 kpc, this corresponds to square pixels that equate to 100 pc per side. However, due to the inclination of the galaxy ( $i = 77^\circ$ ; [Walterbos & Kennicutt 1988](#)), projection makes each region larger by a factor of  $1/\cos(i)$ . Throughout the rest of this work, when we consider the area of each region, we refer to the de-projected area, or  $0.0445$  kpc<sup>2</sup>. This region size balances the need for resolved structures (e.g., OB associations, H II regions) with sufficient CMD sampling to constrain the SFH (e.g., [Simones et al., 2014](#)).

We characterize the stellar density following the [Chen et al. \(2025\)](#) prescription. Specifically, stellar density is determined by the number of `gst` stars per square arcsecond with  $21.5 < F814W < 23$ . This density across the footprint is shown in the left panel of Figure 4.1, where density is binned by steps of  $0.5$  stars per arcsec<sup>2</sup>. As expected, there is a clear gradient of decreasing density moving from the dense center of the galaxy down and to the right along the disk. Notably however, there is a very prominent dense region near the survey edge, which is M32.

We note that in our analysis we only includes regions where that are fully covered by the PHAST imaging. Because our grid was done in RA and Dec, any regions that lie on the perimeter of the survey only have partial coverage, and therefore incorrect density estimates, and are excluded.



**Figure 4.1:** *Left:* Stellar density in the PHAST survey, as defined by stars per square arcsecond with  $21.5 < F814W < 23$ . *Right:* 50% completeness limits as determined by ASTs as a function of local stellar density, estimated from bootstrapped sampling of across the PHAST footprint. Completeness declines at higher stellar densities due to crowding. The gray shaded region in the right panel, and illustrated on the color bar of the left panel, indicates regions not included in the current study (Section 3.5).

## 2.3 Artificial Star Tests

A standard way to characterize photometric uncertainties, completeness, and bias due to crowding, is to use artificial star tests (ASTs) inserted throughout the survey area (Chen et al., 2025; Dalcanton et al., 2012; Dolphin, 2002; Williams et al., 2021). We follow this common approach, inserting fake stars to survey fields individually, covering a range of magnitudes and colors, and processing the image through the same photometric pipeline as the original imaging data to assess recovery. To quantify this dependence, we compute completeness curves using ASTs drawn from bins in stellar density, and identify the magnitude at which 50% of inserted stars are recovered within 1 mag and 2 pixels (See Figure 4.1).

In the PHAST survey (Chen et al., 2025), five regions along the southern major axis of the disk were initially selected for ASTs. These regions were chosen to span the full dynamic range of Red Giant Branch (RGB) stellar densities observed throughout the survey area. To refine our completeness model for the current work, we expanded this sample by conducting identical AST procedures on seven additional sub-regions chosen to specifically supplement areas of density space.

Our AST library therefore spans twelve representative fields, and creates a high-fidelity lookup foundation from which the subsequent density-dependent sampling can be confidently performed for any observed region on the disk. Together, this constitutes a library of 670,000 ASTs in total, each with an associated local density, providing the necessary empirical framework for the SFH modeling described in this work.

We adopt the 50% completeness limit of our ASTs as the faintest magnitude used in our CMD fitting. These limits vary across the survey as a function of local stellar density, with denser regions towards the center of the galaxy having brighter 50% completeness limits, as seen in the right panel of Figure 4.1. We choose bin widths of 0.5 stars per square arcsec, sampled from densities of 0 to 8 stars per square arcsec, and randomly select 50,000 ASTs for each density bin. To better reflect the CMD structure of each region, we supplement the straight density-based AST selection with an additional subset drawn from the magnitudes ranges specifically populated in observed CMD morphology (i.e., we draw 15,000 more ASTs for the color and magnitude ranges where we explicitly observe stars in each region). For each density bin, we repeat the completeness calculation 15 times using bootstrap resampling of 65,000 ASTs per trial, and adopt the mean 50% completeness magnitude in F475W and F814W. The right panel of Figure 4.1 shows the median 50% completeness magnitude. We can see a clear trend in 50% completeness magnitude as a function of stellar density. These 50% completeness magnitudes correspond to specific ages for the main sequence turnoff, which is visualized in Figure 4.3, and discussed further in Section 3.5.

To test for any bias introduced by the selection of ASTs we performed a series of sensitivity tests by assessing how varying choices for our standard procedure affect the measured 50% completeness limits, and subsequent SFH. We describe these tests below, and for each test, we found that the SFH changed by less than the  $1\sigma$  uncertainties. Specifically, we: 1) increase the width of density bins we draw the AST from to be within 0.5, and 1 stars per square arcsec, 2) only select ASTs entirely from the density bin higher and lower than the current region, and 3) change the number of ASTs to range from 50,000 to 100,000. In each case, the resulting SFH varied by much less than the  $1\sigma$  uncertainty. These tests suggest the 65,000 ASTs well sample the population within the region, and the SFH is robust to minor fluctuations in stellar density. Additionally, while the 50% completeness curve is not perfectly smooth between density bins, these small changes do not impact the SFH results.

### 3 Methods

We derive spatially resolved recent SFHs across the PHAST footprint using the `MATCH` CMD-fitting package (Dolphin, 2002), following the established approach introduced by L15 and later applied across a range of galaxies (Lazzarini et al., 2022; Tran et al., 2023). A detailed description of the methodology can be found in L15, while we provide a brief overview here.

#### 3.1 Derivation of the SFHs

We reconstruct the time-dependent star formation rate for a given region by statistically comparing observed optical CMDs to synthetic CMDs generated from stellar evolution models, convolved with photometric uncertainties and completeness from artificial star tests (ASTs). The likelihood of each model is computed using a Poisson maximum likelihood statistic, and the best-fit SFH corresponds to the model CMD with the highest likelihood.

Our analysis uses HST photometry in the F475W and F814W filters (Section 2), which provides the deepest coverage and the greatest leverage on recent star formation. We focus on the young stellar populations, following the practices of L15 and Lazzarini et al. (2022), by excluding regions of the CMD dominated by older stars by removing sources with  $F475W - F814W > 1.25$

and  $F475W > 21$ , a color-magnitude cut that minimizes contamination from the RGB and red clump while preserving reddened massive stars and helium-burning phases. This exclusion region is shown as a gray region outlined by a dashed box when we plot CMDs (see Figures 4.3 and Figure 4.4). These limits include young red and blue He burners in our fits which are useful for age dating at young ages (e.g., Dohm-Palmer et al., 1997; McQuinn et al., 2012).

We fit the CMD using the following choices for MATCH. The stellar population models are drawn from the Padova 2006 isochrones (Marigo et al., 2008) with CO ratio support (Girardi et al., 2010), and the Girardi (2016) translations. We assume a Kroupa IMF (Kroupa, 2001), a binary fraction of 0.35 with uniformly distributed secondary masses, and a fixed distance modulus of 24.47. We assume metallicity increases with time, with  $[M/H]$  ranging from  $-2.3$  to  $+0.1$ . The SFH is solved in 34 logarithmic time bins from  $\log(\text{age/yr}) = 6.6$  to  $10.15$ , with 0.1 dex spacing except for the final bin which spans  $\log(\text{age/yr}) = 9.9$ - $10.15$ .

### 3.2 Correcting for IMF Integration Limits

The SFHs used throughout this work were derived with MATCH, assuming a Kroupa (2001) IMF. As noted by Telford et al. (2020), MATCH normalizes the IMF by integrating over the full mass range from 0 to  $\infty$ , rather than over the more commonly adopted finite stellar-mass limits of  $0.1$ – $100 M_{\odot}$ . This choice does not affect the relative distribution of stars across the CMD, but it does affect the conversion between the fitted number of stars and the total stellar mass formed. As a result, the SFRs reported directly by MATCH are systematically offset from those corresponding to the same IMF evaluated over finite stellar-mass limits.

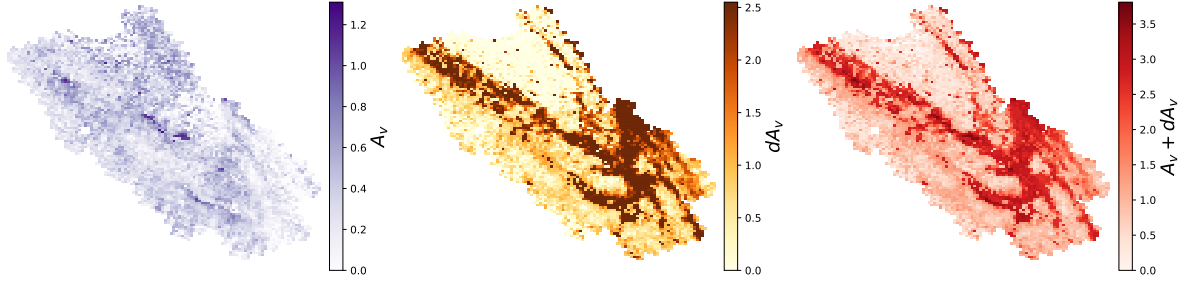
Using the same IMF slopes adopted in the MATCH fits, we compute the ratio between the IMF normalization over  $0.1$ – $100 M_{\odot}$  and that obtained over the effectively unbounded mass range assumed internally by MATCH. We then apply a uniform correction to all reported SFRs so that they correspond to a Kroupa IMF integrated from  $0.1$  to  $100 M_{\odot}$ .

This correction yields a multiplicative correction factor of  $f_{\text{IMF}} = 0.799$ , corresponding to a  $-20.096\%$  decrease in all SFR values. We apply this correction uniformly to every SFH time bin and to all derived SFR quantities reported in this paper. This correction only changes the absolute normalization of the SFHs, and does not affect any of the relative temporal or spatial trends discussed below.

### 3.3 Extinction

The stars within any given PHAST region are subject to a range of line-of-sight extinctions, which leads to differential attenuation imprinted directly on the morphology of the observed CMD. To recover reliable recent SFHs, we must therefore model the impact of both foreground and internal dust.

When modeling the effects of dust on the CMD, foreground dust is treated as a screen with total extinction  $A_V$  that affects all stars equally, shifting all features to redder colors and fainter magnitudes. Internal dust is fundamentally more complicated, as it depends on the details of the star-gas geometry, which can be different depending on the ages and locations of a particular stellar sub-population. For the young stars that we focus on here, we adopt a “uniform slab” model where young stars are assumed to be evenly mixed within a uniform layer of dust of total extinction  $dA_V$ , such that some stars near the front of the slab have little additional extinction, and those near the



**Figure 4.2:** Spatial distribution of recovered extinction parameters across the PHAST footprint, as determined by the CMD-fitting procedure in each analysis region. Left panel shows the foreground extinction  $A_V$ , while the middle panel shows the differential extinction  $dA_V$ , and the right panel shows the total extinction  $A_V + dA_V$ . Regions are color-coded by extinction, with darker values indicating higher total extinction. Elevated extinction values trace prominent dust structures which correspond to arms and active star-forming regions (refer to color image in Figure 4.4). The spatial coherence of this morphology provides confidence in the CMD-based recovery of dust attenuation across the disk.

back experience the full  $dA_V$ . This two component  $A_V + dA_V$  model is flexible enough to reproduce the observed broadening and dimming of stars across the CMD.

Specifically, our adopted model of dust attenuation has two free parameters per region: a uniform extinction  $A_V$  to model for foreground dust, and a differential extinction component  $dA_V$ , which introduces a spread in extinction values across the stellar population, equivalent to assuming the stars are uniformly distributed within a layer of dust. The foreground extinction,  $A_V$ , shifts the CMD redward and fainter, while the differential component,  $dA_V$ , broadens and differentially dims the main sequence, but keeps the blue edge fixed. This approach follows the implementation in L15, where the total extinction is applied as a tophat distribution between  $A_V$  and  $A_V + dA_V$ .

This extinction model is appropriate for young stellar populations (ages  $\lesssim 1$  Gyr), which are confined to the disk and tend to experience relatively uniform extinction on the scales probed here (Dolphin et al., 2003; Weisz et al., 2014). In MATCH, the application of  $A_V$  and  $dA_V$  in a uniform distribution across all stars provides an effective first-order treatment of reddening for young stars, though notable departures are seen for older stellar populations that are not confined to the scale height of the dusty ISM (e.g., Choi et al., 2018; Dalcanton et al., 2015).

We determine the best-fit extinction values by evaluating the SFH over a grid of  $A_V$  and  $dA_V$  combinations. We initially sample  $A_V$  in the range  $[0.0, 1.5]$  and  $dA_V$  in the range  $[0.0, 2.5]$ <sup>1</sup> using a coarse grid with spacing of 0.2 in each parameter. We then refine the solution by constructing a finer grid with spacing of 0.05 around the best-fit  $(A_V, dA_V)$  pair, limited to the region within  $2\sigma$  of the minimum fit statistic. This two-step grid search allows us to efficiently locate the best-fitting extinction parameters while assessing uncertainty in the dust distribution.

We measure modest foreground extinction values across the PHAST regions, ranging from  $A_V \approx 0.1$  mag up to 1.2 mag, consistent with the values from L15. Each region’s best fit  $A_V$  is seen in the left panel of Figure 4.2. While there is some slight structure in the  $A_V$  map, these values are mostly uniform across the disk, representing the foreground extinction. The values recovered

<sup>1</sup>See Appendix B in L15 for a discussion on why these limits were chosen.



here are also broadly consistent with the [Schlegel et al. \(1998\)](#) and [Schlafly & Finkbeiner \(2011\)](#) E(B-V) maps in the regions near M31. However, some of the residual structure indicates regions where some of M31’s complex gas distribution might create a “foreground” that is associated with M31, not the Milky Way.

In contrast, our inferred differential extinction ( $dA_V$ ) extends to higher values, demonstrating a wider dynamic range across the disk. Elevated  $dA_V$  is frequently associated with dense star-forming structures, especially along spiral arms, as expected for an approximately uniform dust-to-gas ratio. When plotted spatially, the dust morphology, traced from the  $A_V + dA_V$ , maps out known galactic structure, reinforcing the reliability of our extinction mapping, which is done independently in each region, but produces coherent, physically sensible maps.

This spatial structure is shown in Figure 4.2, which shows the best-fit  $A_V + dA_V$  values across the PHAST footprint. The recovered extinction morphology tracks expected features of M31’s disk, such as the outer spiral arms and active star-forming ring, with elevated  $dA_V$  appearing in dense, or visible dusty regions. The overall structure, and dynamic range, of extinction across PHAST regions appear consistent with known patterns of star formation and dust. Moreover, visual inspection of CMDs and recovered SFHs in high-extinction regions reveals no signs of inadequate fits, suggesting the CMD-based extinction solutions are robust even in dusty regions.

### 3.4 Uncertainties

Uncertainties in our SFH measurements primarily arise from a combination of statistical, systematic, and extinction-related effects. We follow the uncertainty estimation procedures described in [Dolphin \(2013\)](#), adopting the same techniques used in previous applications of this method ([L15](#); [Lazzarini et al. \(2022\)](#); [Tran et al. \(2023\)](#)).

#### 3.4.1 Random Uncertainties

Statistical uncertainties are estimated using the hybrid Markov Chain Monte Carlo (MCMC) routine built into `MATCH`. This sampler efficiently explores high-dimensional parameter space and generates 10,000 SFH realizations per region, with the density of samples proportional to the posterior probability. The  $1\sigma$  confidence interval is determined by identifying the region that contains 68% of the realizations, even in bins where the best-fit SFR is zero.

Dust-related uncertainties are introduced by the degeneracy between reddening and stellar age, as well as our choice of spacing between  $(A_V, dA_V)$  grid points. To account for this uncertainty, we marginalize over all SFH solutions within  $2\sigma$  of the best-fit extinction parameters  $(A_V, dA_V)$ , weighting each solution by the likelihood relative to the best fit. This weighting follows a Gaussian likelihood kernel (i.e.,  $e^{-0.5n^2}$ ), where  $n$  is the number of standard deviations above the minimum fit statistic.

We note that our assumed binary fraction (0.35) may be inconsistent with studies showing a dependence of multiplicity fraction on stellar mass ([Offner et al., 2023](#)). In `MATCH`, the adopted binary fraction is not independent of the companion mass-ratio distribution, which is assumed to be uniform from 0 to 1. As a result, some differences in the true binary population could manifest as differences in the mass-ratio distribution rather than the overall binary fraction. In practice, previous tests show that reasonable variations in the adopted binary fraction have negligible impact on the recovered SFH compared to uncertainties from dust and photometric noise ([L15](#)).

### 3.4.2 Systematic Uncertainties from Stellar Evolution Models

In addition to the random and dust-related uncertainties discussed above, there is a further source of systematic uncertainty associated with our choice of stellar evolution models, and the fixed [Kroupa \(2001\)](#) IMF. We discuss both of these additional assumptions here.

In [Lazzarini et al. \(2022\)](#), a comparison between Padova and MIST isochrones for the full PHATTER survey showed that the two model sets generally agree within the measured uncertainties for most time bins older than  $\sim 20$  Myr, while the largest discrepancies appear at the youngest ages. At ages  $\lesssim 15$  Myr, they found that the inferred SFRs from different model sets can differ by up to a factor of two.

To assess the impact of these model choices in PHAST, we repeated the entire SFH fitting for a representative subset consisting of roughly a third of our regions using the MIST ([Choi et al., 2016](#)) isochrones in place of the Padova ([Girardi et al., 2010](#); [Marigo et al., 2008](#)) tracks. The comparison sample spans a wide range of stellar densities and recent SFRs, capturing the diversity of conditions present in the full survey. For each region in this subset we compared the recovered SFHs from the Padova and MIST fits in the same logarithmic time bins used throughout this work.

We find that for most of time bins in our analysis, the Padova and MIST SFHs agree to within the formal random uncertainties, and never exceed  $2\sigma$  deviation. We note however, that the residuals are not symmetric. Across the sample, across all time bins the MIST models find a median  $\sim 30\%$  increase relative to the Padova models.

The other source of systematic uncertainty we consider is the choice of a fixed [Kroupa \(2001\)](#) IMF. There has been recent evidence to support that the high-mass IMF slope in nearby galaxies is steeper than this canonical value ([Wainer et al., 2024b](#); [Weisz et al., 2015](#)). Specifically, using the PHAT data in M31, [Weisz et al. \(2015\)](#) measured a high mass slope of  $\Gamma = 1.45^{+0.03}_{-0.06}$ . To determine the impact this difference has on our derived SFHs, we repeated the entire SFH fitting for the same representative subsample with the [Weisz et al. \(2015\)](#) IMF slope. We find that the derived SFHs are equivalent within the uncertainties, with the higher IMF slope systematically recovering  $\Sigma_{\text{SFR}}$  values only 2% higher than the baseline model, a much smaller deviation than that found between the stellar models. This result likely indicates that the systematic errors from stellar evolutionary models are less than the age-to-age differences in the recovered SFHs.

We note that in both the IMF and isochrone model analysis, the spread in recovered  $A_V + dA_V$  values is larger than the consistency in  $\Sigma_{\text{SFR}}$  might suggest. For the comparison between MIST and Padova, the standard deviation of the squared difference  $[(A_V + dA_V)_{\text{Padova}} - (A_V + dA_V)_{\text{MIST}}]^2$  is 0.14 mag, and it is 0.17 mag for the IMF comparison. However, the best-fit likelihood values are extremely similar in both tests. This implies that differences between the model choices are largely accommodated by small shifts in the best-fit extinction parameters, with minimal change in the likelihood. Importantly, despite this flexibility in  $(A_V, dA_V)$ , the recovered  $\Sigma_{\text{SFR}}$  values remain statistically consistent between model choices, suggesting that the dominant effect of these differences is to adjust dust parameters, rather than to change the inferred recent star formation rate.

We do not fold this model dependence into the reported uncertainties on our SFHs, which represent the random uncertainties from the CMD fitting. Instead, we treat the model differences as an additional systematic uncertainty, particularly affecting the absolute normalization of the SFR. The detailed values of the SFR bins should therefore be interpreted with an additional slight systematic uncertainty of order  $\sim 10\%$ , while the spatial patterns and longer-timescale trends remain robust.

### 3.5 Reliable Age Range of SFH Measurements

While the full MATCH time binning extends to several Gyr, the reliability of SFH recovery is fundamentally limited by the photometric depth in each region. Main-sequence turnoff stars dominate age sensitivity for young populations, but become increasingly faint and rare at older ages. Although useful age information can still be extracted from CMDs that do not reach the main-sequence turnoff, the resulting age constraints are generally less precise and less secure than those obtained from turnoff-resolved photometry.

Following L15, we adopt a uniform 500 Myr lookback time as the threshold for reliable star formation constraints across the PHAST footprint. Imposing a consistent limit ensures spatial uniformity and avoids over-interpretation, though we note that low-density or dust-free regions can reliably probe somewhat older ages (Appendix B).

To empirically justify this threshold, we use the Padova stellar evolution models to trace the main-sequence turnoff as a function of age. For each isochrone in our grid, we consider the transition point from the hydrogen-burning main sequence to the subgiant branch from the model, and extract its F814W magnitude. Figure 4.3 shows the full set of isochrones in CMD space, color-coded by age, with black stars marking the turnoff points.

The top panel summarizes the turnoff magnitude as a function of age, with a horizontal line indicating  $F814W = 24$  mag which corresponds to the turnoff for the  $\log(\text{Age})=8.7$  ( $\sim 500$  Myr) isochrone. From Figure 4.1, we can see that regions with densities smaller than  $\sim 6$  stars per  $\text{arcsec}^2$  have F814W 50% completeness limits fainter than 24th mag.

We therefore adopt 500 Myr as a conservative and physically motivated boundary for the time range of reliable SFH recovery, and choose to only consider regions where the stellar density is below 6 stars per  $\text{arcsec}^2$ . From Figure 4.1, we can see that this density threshold only cuts off the very center of the galaxy ( $r < \sim 1$  kpc), and M32.

## 4 PHAST Star Formation Histories

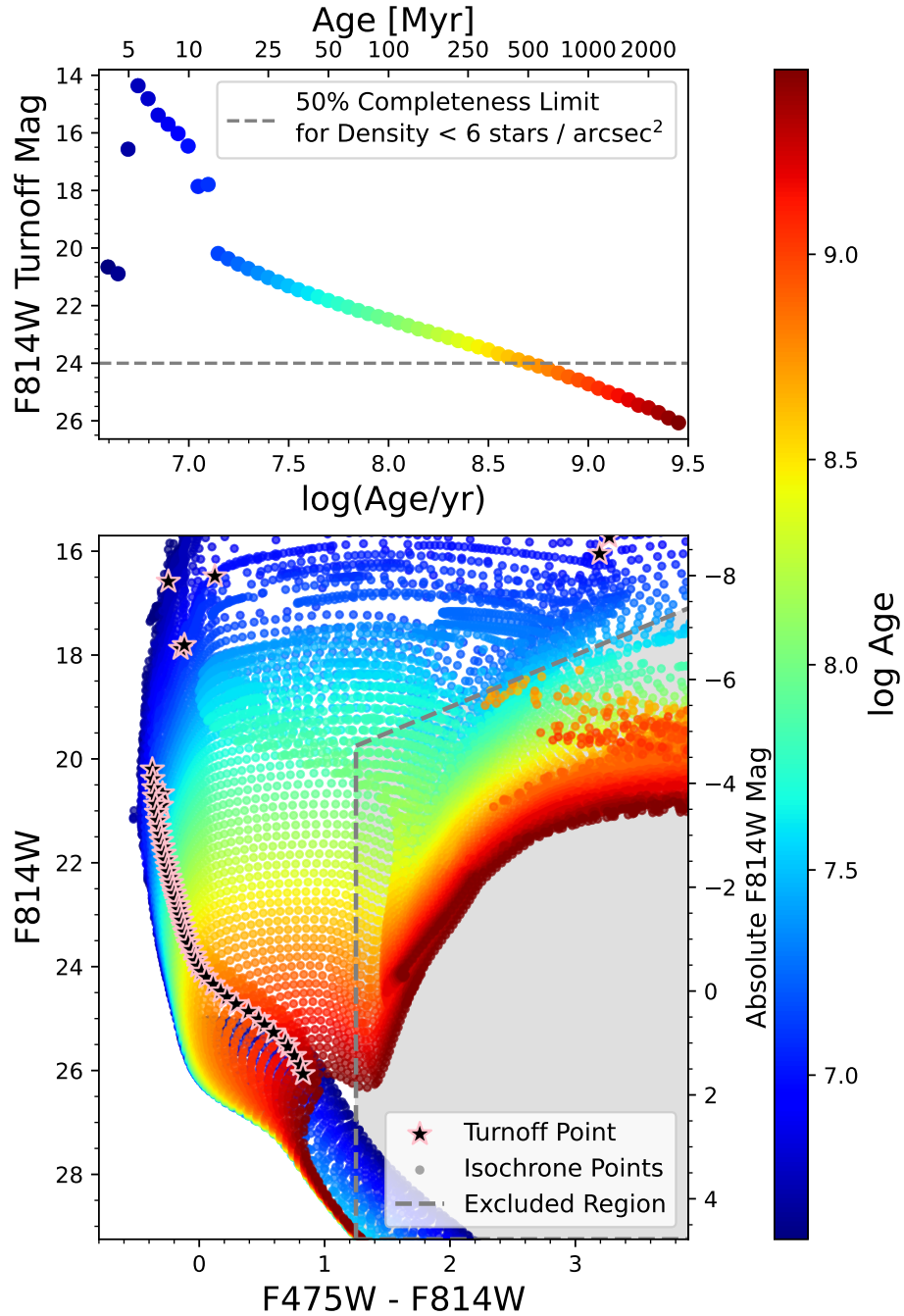
In this section, we present the integrated and spatially resolved SFH for the PHAST survey. Full SFH results for each spatial region are presented in Table 4.1<sup>2</sup>.

Figure 4.4 showcases three representative regions that illustrate the range of stellar densities and environments captured in the survey. The top left shows a color mosaic<sup>3</sup> of the southern M31 disk with PHAST coverage, highlighting Regions 6068, 835, and 2284. These regions span a range of stellar densities from sparse outskirts to more crowded inner disk structures. Region 6068 lies near M32 and the 10 kpc ring, Region 835 sits along a well-defined dust lane, and Region 2284 is a high-density region ( $\sim 4.1$  stars per  $\text{arcsec}^2$  as defined in Figure 4.1). For each region, we show the observed CMD, the corresponding image cutout, and the derived SFH.

From the color images, we can see that each of the regions is visually quite distinct. Region 2284 has a higher density of stars, and the general color is much redder than the other highlighted regions. Region 835 has a clear dust region in the center of the cutout, while Region 6068 has a

<sup>2</sup>We note there are 15 spatial regions towards the very center of the galaxy that exceeded the available compute resources due to density and increased extinction. For these regions we note a -99 in the  $A_V$ ,  $dA_V$  and fitvalue columns of Table 4.1. We mask these regions in our analysis, and fill in 0 SFR in the spatial maps.

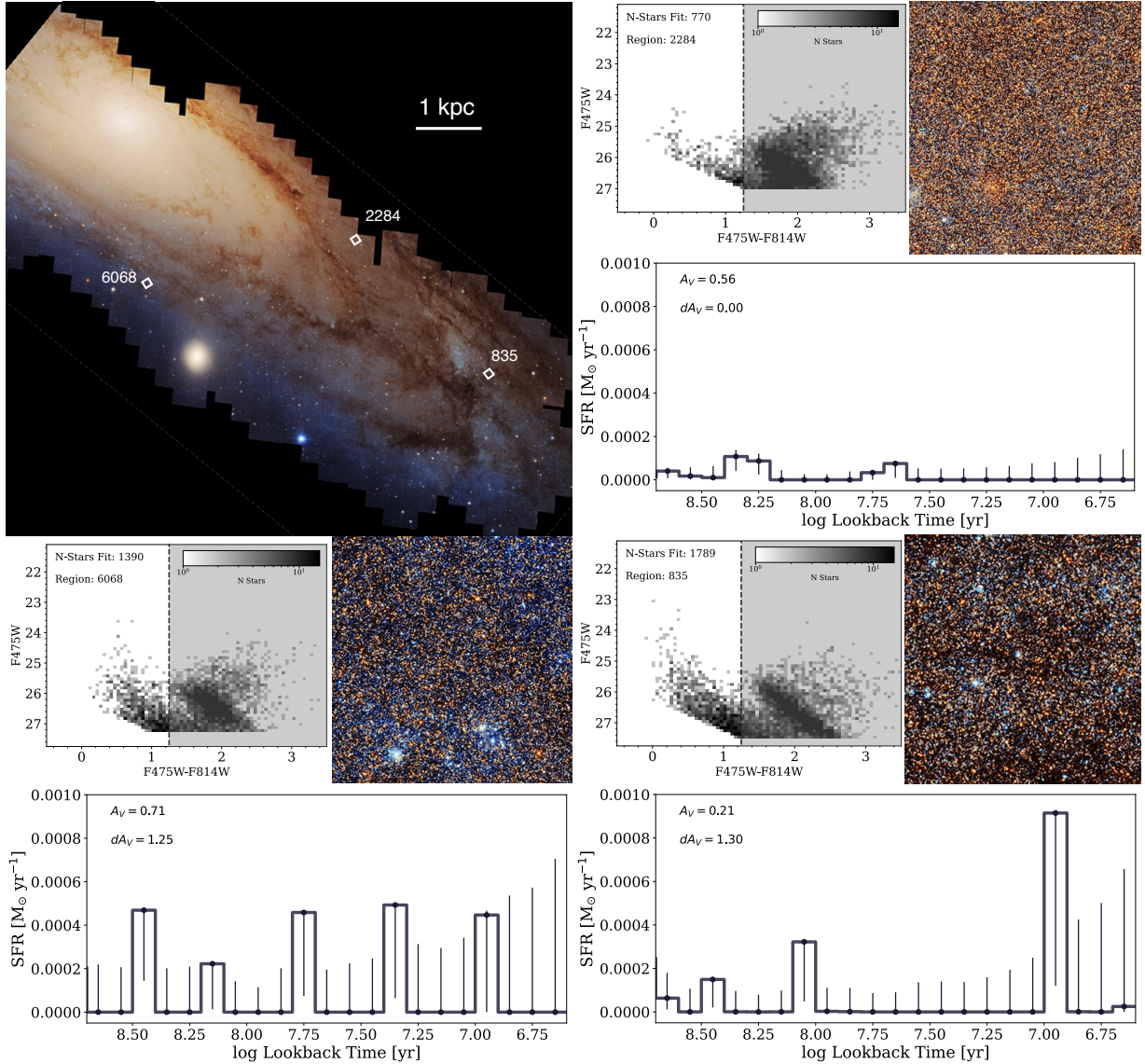
<sup>3</sup>Image credit: NASA, ESA, Benjamin F. Williams (University of Washington), Zhuo Chen (University of Washington), L. Clifton Johnson (Northwestern); Image Processing: Joseph DePasquale (STScI).



**Figure 4.3:** Padova stellar isochrones spanning  $\log(\text{Age}/\text{yr}) = 6.6\text{--}10.2$  plotted in CMD space ( $F_{475W}\text{--}F_{814W}$  vs.  $F_{814W}$ ), color-coded by age. Black stars mark the main-sequence turnoff point for each isochrone, defined as the transition from core hydrogen burning to the subgiant phase. The gray shaded region shows the excluded region described in Section 3.1. The secondary axis to the right shows the absolute F814 magnitude.

The top panel shows the F814W magnitude of the turnoff as a function of age, with a horizontal dashed line at  $F_{814W} = 24$  mag indicating the shallowest 50% completeness limit across the PHAST survey. This provides a basis for our adopted 500 Myr threshold for reliable SFH measurements.





**Figure 4.4:** Overview of three representative PHAST regions spanning a range of stellar densities and environments. *Upper Left:* A color mosaic of the southern disk of M31, and the three selected regions (6068, 835, and 2284) highlighted (not perfectly to scale). For each region, we show: (upper left) the observed CMD used in SFH fitting, with excluded areas shaded in gray; (upper right) a color cutout of the region from the mosaic; and (bottom) the derived recent SFH. These examples highlight the diversity of star-forming environments in the PHAST footprint and demonstrate the robustness of our CMD-fitting methodology across varying crowding and extinction conditions.

number of bright blue stars in the two stellar clusters towards the bottom of the cutout. Each of these observations are also present in the CMDs, and SFHs. In contrast, the denser, redder Region 2284, has little star formation in the last 100 Myr, while for Region 835, there is quite a bit of star formation, and a well-populated upper main sequence in the CMD.



**Table 4.1:** Star Formation Histories for PHAST Regions

| Region ID                                           | RA <sub>BR</sub> | Dec <sub>BR</sub> | Density | A <sub>V</sub> | dA <sub>V</sub> | SFR(8.7–8.6)                              | SFR(8.3–8.2)                              | SFR(7.7–7.6)                      | SFR(7.1–7.0)                      | SFR(6.7–6.6)                      | SFR <sub>0–100</sub>                      |
|-----------------------------------------------------|------------------|-------------------|---------|----------------|-----------------|-------------------------------------------|-------------------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-------------------------------------------|
| [10 <sup>−5</sup> M <sub>⊙</sub> yr <sup>−1</sup> ] |                  |                   |         |                |                 |                                           |                                           |                                   |                                   |                                   |                                           |
| 7                                                   | 9.887189         | 40.660532         | 0.247   | 0.360          | 0.350           | 4.279 <sup>+0.075</sup> <sub>−1.919</sub> | 1.104 <sup>+0.083</sup> <sub>−1.104</sub> | 0 <sup>+1.197</sup> <sub>−0</sub> | 0 <sup>+3.001</sup> <sub>−0</sub> | 0 <sup>+6.809</sup> <sub>−0</sub> | 0 <sup>+1.568</sup> <sub>−0</sub>         |
| 8                                                   | 9.887189         | 40.667822         | 0.267   | 0.410          | 0.650           | 5.136 <sup>+1.677</sup> <sub>−2.560</sub> | 0 <sup>+1.492</sup> <sub>−0</sub>         | 0 <sup>+1.824</sup> <sub>−0</sub> | 0 <sup>+4.026</sup> <sub>−0</sub> | 0 <sup>+8.880</sup> <sub>−0</sub> | 0.113 <sup>+2.139</sup> <sub>−0.113</sub> |
| 9                                                   | 9.887189         | 40.675113         | 0.245   | 0.060          | 0.800           | 0 <sup>+2.134</sup> <sub>−0</sub>         | 0 <sup>+0.594</sup> <sub>−0</sub>         | 0 <sup>+0.929</sup> <sub>−0</sub> | 0 <sup>+2.744</sup> <sub>−0</sub> | 0 <sup>+6.094</sup> <sub>−0</sub> | 0 <sup>+1.195</sup> <sub>−0</sub>         |
| 10                                                  | 9.887189         | 40.682404         | 0.270   | 0.110          | 0.750           | 3.035 <sup>+0.126</sup> <sub>−2.420</sub> | 0 <sup>+0.531</sup> <sub>−0</sub>         | 0 <sup>+1.077</sup> <sub>−0</sub> | 0 <sup>+2.760</sup> <sub>−0</sub> | 0 <sup>+6.317</sup> <sub>−0</sub> | 0.394 <sup>+1.002</sup> <sub>−0.370</sub> |
| 14                                                  | 9.896828         | 40.645950         | 0.296   | 0.160          | 0.800           | 0 <sup>+1.454</sup> <sub>−0</sub>         | 0 <sup>+0.860</sup> <sub>−0</sub>         | 0 <sup>+1.165</sup> <sub>−0</sub> | 0 <sup>+2.901</sup> <sub>−0</sub> | 0 <sup>+6.670</sup> <sub>−0</sub> | 0 <sup>+1.429</sup> <sub>−0</sub>         |

*Note.* Excerpt of the machine-readable table of recent star formation histories for individual PHAST regions. RA<sub>BR</sub> and Dec<sub>BR</sub> give the J2000 coordinates of the bottom-right corner of each region. SFR values are reported in units of 10<sup>−5</sup> M<sub>⊙</sub> yr<sup>−1</sup>, with asymmetric uncertainties written as  $x^{+err_{hi}}_{-err_{lo}}$ . SFR<sub>0–100</sub> gives the average SFR over the last 0–100 Myr. The full machine-readable table includes all logarithmic age bins from  $\log(t/\text{yr}) = 8.7\text{--}6.6$ , the corresponding upper and lower uncertainties, and the coordinates of all four corners of each region.

## 4.1 PHAST SFH Maps

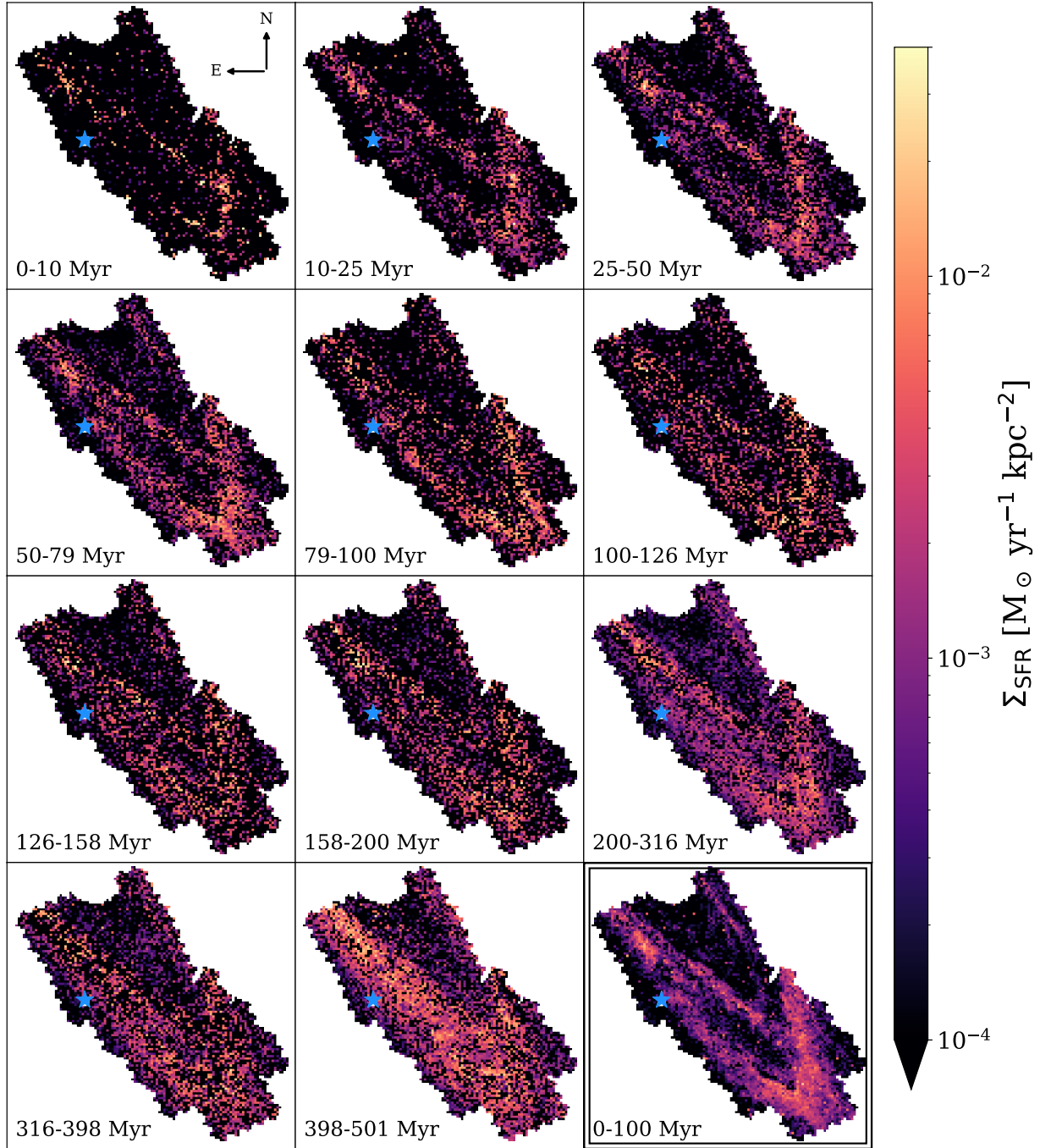
We visualize how recent star formation is distributed across the M31 disk by constructing spatially resolved maps of the SFR in multiple time bins. These maps serve as a key tool for identifying the locations, durations, and propagation of recent star-forming activity, such as spiral arms, and ring-like structures, that may not be evident from the summed SFHs alone.

Figure 4.5 shows the SFR surface density,  $\Sigma_{\text{SFR}}$  in each region for a series of time intervals, with the age range labeled in the bottom-left corner of each panel. For each time bin, the region SFR is determined by the total stellar mass formed divided by the time duration, and then normalized by the de-projected area of each region; for the youngest ages ( $< 100$  Myr), we combine adjacent time bins into broader  $\sim 25$  Myr intervals to improve signal-to-noise and reveal coherent spatial features. The resulting SFHs are then used to color-code each single spatial region in the given time bin. Regions shown in black have SFRs below  $10^{-4} M_{\odot} \text{ yr}^{-1}$ , a threshold comparable to the typical uncertainty in low-activity regions. As discussed further in Section 6, the maps reveal strong spatial and temporal variations in star formation across the PHAST footprint. For reference, we also include a map of the SFR integrated over a 100 Myr baseline, which is often used as a canonical timescale for broad-band SFR indicators (bottom right panel). The location of M32 is shown as a blue star in all panels.

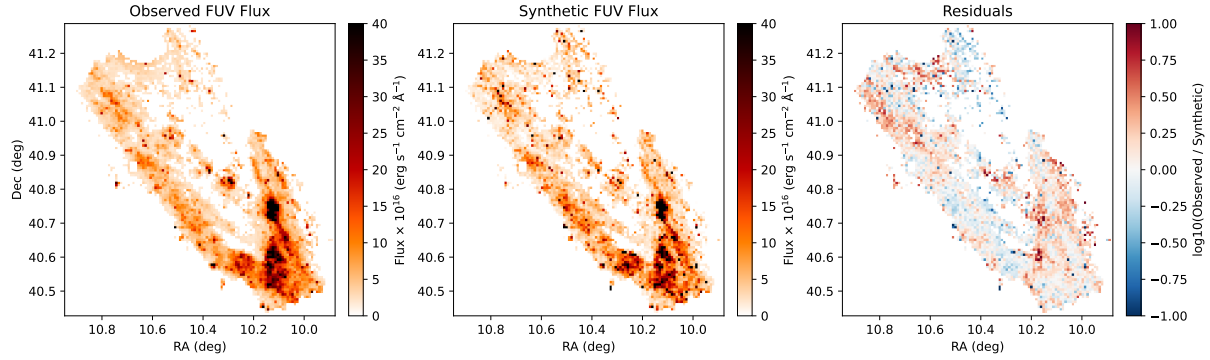
## 4.2 Stress-testing the PHAST CMD-derived SFHs’ Consistency with Observed FUV Fluxes

One way to test the validity of the CMD-based SFH methods is to use the derived SFHs to forward-model a synthetic FUV image and compare it directly to the observed *GALEX* map, as was done with great success in [Lewis et al. \(2017\)](#). In this section, we replicate the methodology of [Lewis et al. \(2017\)](#) to produce a synthetic FUV image, and compare to the *GALEX* map of [Martin et al. \(2005\)](#). To generate synthetic UV fluxes for each PHAST region, we use the *FSPS* population synthesis code ([Conroy & Gunn, 2010](#); [Conroy et al., 2009, 2010](#)), following the technique described in detail in Appendix A.

We present our derived synthetic FUV image, and the comparison, pixel-matched observed *GALEX* image in Figure 4.6. The left panel displays the observed *GALEX* FUV map, re-gridded to match the PHAST analysis regions. The middle panel shows the synthetic FUV image constructed from the CMD-derived SFHs. The right panel presents the residuals, defined as the ratio of observed to synthetic flux.



**Figure 4.5:** PHAST SFH maps over the indicated timescales in terms of lookback time. The top rows are the most recent epochs, and the subsequent rows look at older lookback times. Each pixels represents one  $100 \text{ pc}^2$  region, colored by the star formation rate surface density  $\Sigma_{\text{SFR}}$  in units of  $M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ . In each panel, we denote the location of M32 with a blue star. In the bottom right panel, we also include the average SFR over the last 100 Myr, which we refer to throughout the manuscript as  $\Sigma_{\text{SFR}_{\text{CMD},100}}$ .



**Figure 4.6:** Comparison between the observed and synthetic FUV emission in the PHAST footprint. Left: observed *GALEX* FUV image, reprojected to the PHAST spatial grid. Middle: synthetic FUV map constructed by forward-modeling the CMD-derived SFHs with FSPS following the methodology of [Lewis et al. \(2017\)](#), including a two-component extinction model based on the [Cardelli et al. \(1989\)](#) law. Right: residual map showing the ratio of observed to synthetic FUV flux. The synthetic map reproduces the major UV-bright structures in the disk and matches the observed FUV fluxes to within a factor of a few over most of the area, indicating that the CMD-based SFHs provide a consistent description of the recent star-forming population. This result is particularly important given the offset in SFR with respect to FUV+24  $\mu\text{m}$  calibrations.

At this level of comparison, the agreement is striking. The synthetic map reproduces the major UV-bright structures, including the 10 kpc ring, the inner arm feature, and many of the smaller-scale star-forming complexes. The residuals are typically within a factor of a few across most of the disk, with larger discrepancies confined to a small subset of regions. There is no systematic offset in the residuals, which while structured, appear as likely to be high as they are to be low.

To quantify the degree of agreement between the synthetic and observed FUV maps, we computed the MAD of the squared residuals between the observed and synthetic fluxes. We find this to be 1.8 in our adopted flux units of  $10^{16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$ . The fractional residual distribution,  $[(\text{synthetic} - \text{observed}) / \text{observed}]$  is centered at -0.11 with a 25th percentile of -0.37 and an 75th percentile of 0.21. Therefore, there is a tendency for the synthetic image to under predict the flux by about 10%. Although there is scatter, the vast majority of regions agree markedly well within the  $\sim 20\%$  uncertainty associated with UV emission from older stellar populations (e.g., [Johnson et al., 2013](#)).

This test provides strong internal validation of the CMD-derived SFHs. Given the combined uncertainties in dust attenuation, UV stellar population modeling, and the CMD-based SFH recovery itself, some level of region-to-region scatter is expected. And yet, despite these uncertainties, the synthetic map successfully reproduces both the observed FUV morphology and the overall flux normalization across the PHAST footprint. This successful replication indicates that the recent SFHs inferred from the CMDs capture the dominant stellar populations responsible for the UV emission.

### 4.3 Attaching PHAT SFH Maps to PHAST

To place the PHAST results in the broader context of M31’s recent star formation history, we combine the SFH measurements from the PHAT survey (L15) to generate a SFH map that spans the full disk of M31.

In Figure 4.7, we show the spatially resolved map of the SFR surface density,  $\Sigma_{\text{SFR}}$ , for different time bins, combining both the PHAST and PHAT footprints, following Section 4.1 for calculating the SFR used to color-code the maps. The PHAST data representing the southern half of the disk is shown on the left. The PHAT data in the north was taken from Lewis et al. 2015. The position of M32 and the center of the M31 bulge are marked with a blue star and a red "×", respectively.

We note that the original SFRs reported by L15 do not include the IMF normalization correction described in Section 3.2. For consistency, we apply the same correction to the PHAT SFHs before combining them with the PHAST results. In practice, we multiply the L15 SFR in region by the multiplicative factor of 0.779 derived in Section 3.2. This places both surveys on the same IMF normalization and ensures that any differences seen in the combined maps reflect real spatial variations in the recent SFH rather than a mismatch in the absolute SFR scale. We further note that the PHAT SFHs were derived using an earlier generation of stellar evolution libraries than those adopted here. Specifically, the Girardi (2016) transitions for the Padova 2006 isochrones used in this work were not available to L15, although the impact on the recent SFHs considered here is expected to be small.

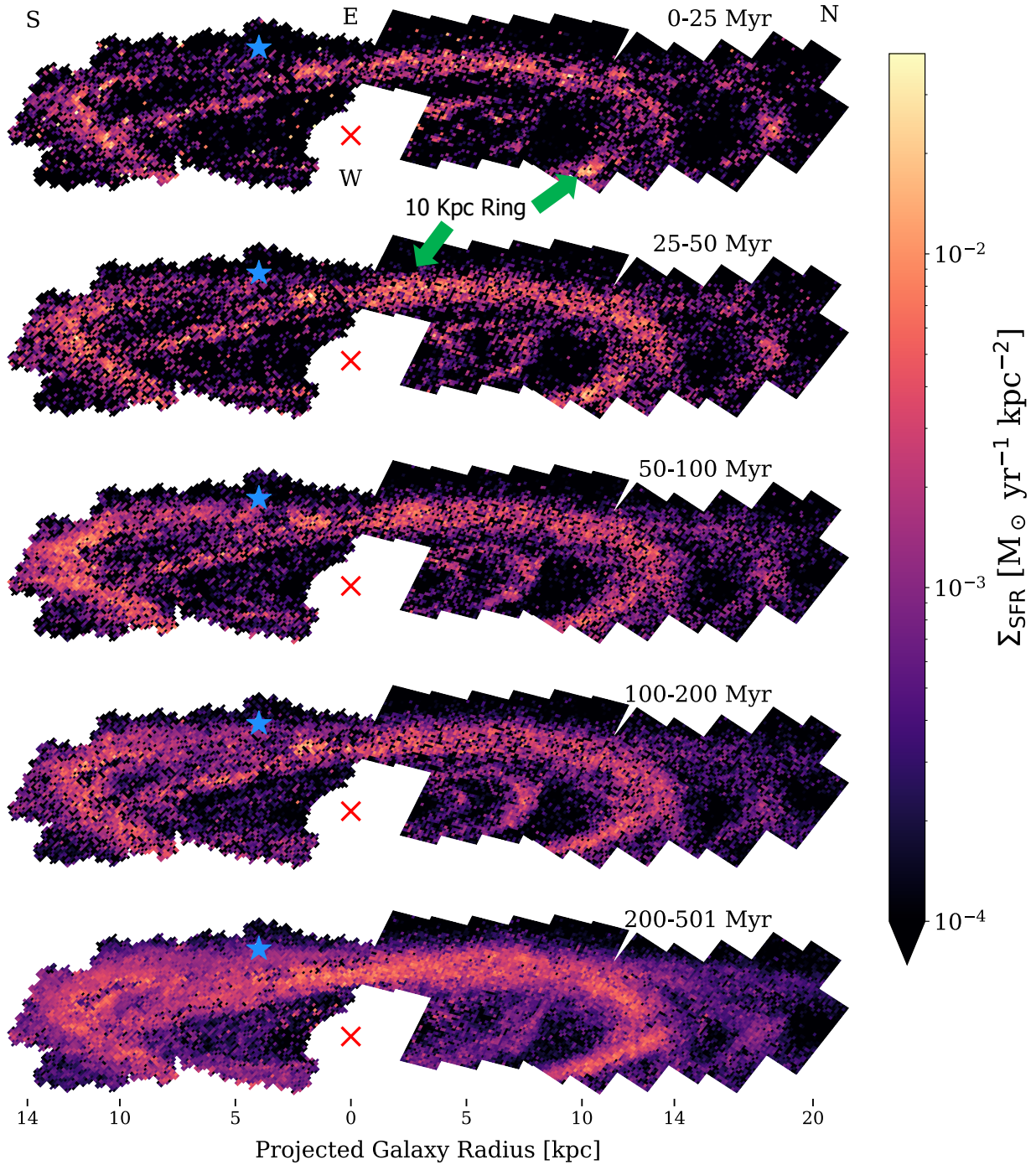
Additionally, the pixel grids for the PHAST and PHAT SFH maps have the same physical pixel size, but are not identically aligned on the sky. The PHAT regions were defined brick-by-brick following the survey layout, whereas the PHAST regions were constructed on a uniform RA–Dec grid and then filtered to retain only cells with full imaging coverage. As a result, the survey boundaries differ in shape, the PHAT survey boundary is straight along the bricks while PHAST appears more jagged. The two footprints overlap only over a handful of pixels from each survey ( $\sim 10$ ). In this limited overlap area, the recovered SFHs are consistent, but the pixels are not co-spatial because of the different grid definitions. We therefore stitch the two surveys by plotting the PHAT map directly over the PHAST map in the overlap region, without attempting an additional re-gridding step. Given the very small area involved, any double counting has a negligible effect on the SFRs or spatial trends discussed here.

The time bins shown in Figure 4.7 are broader than those in Figure 4.5, and the native age resolution used in the SFH fitting. At that time resolution, the spatial maps appear noisier, with more cell-to-cell variation due to the larger uncertainties in individual bins. Averaging over slightly wider time intervals improves the signal-to-noise and makes the large-scale spatial features easier to identify. We therefore show the maps in these broader age bins to emphasize the coherent structures in the recent SFH. We also note that the 0-100 Myr average is shown in the bottom panel of Figure 4.10, as opposed to one of the panels in Figure 4.7. An animated version of the maps at the full native time resolution is available in the online material.

## 5 Full M31 Results: Combining PHAT and PHAST

The maps shown in Figure 4.7 offer the highest resolution spatially-resolved SFH of M31 measured with resolved stars. Together, these two datasets provide contiguous coverage of two thirds of the





**Figure 4.7:** Full M31, PHAT and PHAST combined SFH maps over the indicated timescales. Five time bins are shown moving to older lookback times downward in the plot. The left side of the images is the PHAST region, shown in Figure 4.5, while the right side is PHAT taken from L15. Each pixel is colored by the star formation rate surface density  $\Sigma_{\text{SFR}}$  in units of  $\text{M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ . In each panel, we denote the location of M32 with a blue star, and the center of the galaxy with a red x. Green arrows in the top two panels point to the 10 Kpc ring. An annotation of this Figure, with the time resolution of Figure 4.5 is available in the online version.



star-forming disk, enabling a panoramic view of the past  $\sim 500$  Myr of star formation in M31.

At a high level, the maps emphasize a number of features that were previously known about M31. First, much of M31's recent star formation is concentrated in the "10 kpc ring" (e.g., [Gordon et al., 2006](#); [Lewis et al., 2015](#)), which stands out particularly strongly in the north as a coherent, nearly continuous structure traced by active star-forming regions. In the southern PHAST survey region, the ring becomes a more complex mixture of the ring and spiral features, with both a bifurcation and a reduction in strength near M32.

Second, there is an overall decline in the SFR towards the present, which has been previously noted for the PHAT survey area by [Williams et al. \(2015\)](#). The same effect is seen in the southern PHAST survey area as well. We note, however, that this impression is largely created by the ring, which dominates the bulk of the star formation. We discuss this decline in Section 6.1.

Third, the SFH map highlights large-scale asymmetries in the spatial distribution of star formation across the M31 disk. This asymmetry suggests that different regions of the disk may be responding to distinct dynamical or environmental influences. We explore this further by examining subsets of the disk in Section 6.2.

Finally, we note that our decision to match the PHAST SFH calculation to that used previously by [Lewis et al. \(2015\)](#) for PHAT has produced seamless maps despite different observing strategies and depths of the two surveys. In addition, the emergence of coherent structure across thousands of independently-analyzed spatial regions further reinforces the reliability of the measurement technique.

We discuss these above points in more detail below.

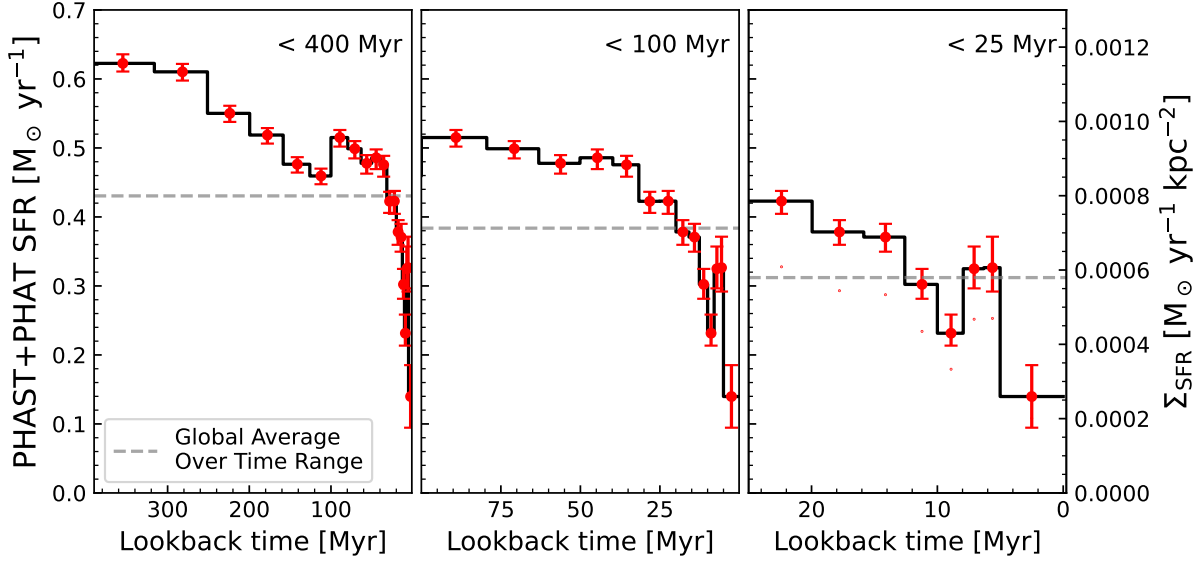
## 5.1 The Total Recent Star Formation Rate of M31

We first consider what the combined PHAT+PHAST SFHs imply for the total star formation rate of M31. We initially choose to integrate our CMD-based SFHs over the last 0–100 Myr, which is taken as a canonical timescale for widely used extragalactic star formation rate indicators such as FUV+24 $\mu$ m (e.g., [Kennicutt et al., 2009](#)).

Across the union of the two surveys, we measure a total mean SFR of  $0.445 \pm 0.006 M_{\odot}, \text{yr}^{-1}$ . The uncertainty is derived from adding each regions uncertainty in quadrature, although a larger uncertainty ( $\sim 0.03$ ) could be considered when factoring in additional systematic uncertainty. Scaling the SFR from the combined footprint by the fraction of the galaxy's FUV  $D_{25}$  flux (obtained from [Martin et al., 2005](#)) enclosed within the footprint implies a total disk-averaged SFR of  $\sim 0.67 M_{\odot}, \text{yr}^{-1}$  over the last 100 Myr. The footprint of PHAT+PHAST now covers roughly two-thirds of the actively star-forming disk, so only about one-third of the disk area requires extrapolation.

We note that while this updated extrapolated value for the total M31 SFR is similar to that derived by [L15](#) based on extrapolating from the PHAT footprint ( $\sim 0.7 M_{\odot}, \text{yr}^{-1}$ ) over the same 0–100 Myr interval, that estimate did not incorporate the IMF correction (Section 3.2), and is therefore slightly overestimated. Additionally, the star formation intensity is higher in the south (discussed more in Section 5.3), which would lead an extrapolation based on the north alone to be a slight underestimate. This updated value also relies far less on extrapolation now that a majority of the star-forming disk is directly constrained by CMD-based SFHs.

These estimates fit comfortably within the range of previous measurements for M31. Other previous studies have examined the global SFR using resolved stars ( $\sim 1 M_{\odot}, \text{yr}^{-1}$ ; [Williams, 2003](#)),



**Figure 4.8:** The star formation history of M31 from the PHAT+PHAST as a function of lookback time, where the most recent time is to the right. The black line is the mean SFR per given time bin, while the red lines show the uncertainty for each bin. In each panel, the gray dashed line shows the average SFR over the plotted time baseline. We show both the SFR, and the  $\Sigma_{\text{SFR}}$  on the right axis. X-axis ranges were chosen to match the complimentary Figure 11 in L15. The panels progressively zoom in on the x axis, while the data is the same per bin. We see a pronounced, global decline in the SFR in M31, especially over the last 40 Myr.

$8\ \mu\text{m}$  emission ( $0.4\ M_{\odot}, \text{yr}^{-1}$ ; Barmby et al., 2006), FUV emission ( $0.6\text{--}0.7\ M_{\odot}, \text{yr}^{-1}$ ; Kang et al., 2009),  $\text{H}\alpha$  ( $\sim 0.3\ M_{\odot}, \text{yr}^{-1}$ ; Tabatabaei & Berkhuijsen 2010;  $0.44\ M_{\odot}, \text{yr}^{-1}$ ; Azimlu et al. 2011), FUV+ $24\ \mu\text{m}$  ( $0.25\ M_{\odot}, \text{yr}^{-1}$ ; Ford et al., 2013), and a combination of several ( $\sim 0.4\ M_{\odot}, \text{yr}^{-1}$ ; Rahmani et al., 2016).

We note, however, that pinning the “current” SFR to the 0-100 Myr average paints an incomplete picture, due to M31’s declining recent SFR. Figure 4.8 presents the total SFR as a function of lookback time, over all PHAST and PHAT regions. While the individual SFHs of each region exhibit significant diversity – particularly in the 10 kpc ring and inner disk – the combined SFH smooths over these fluctuations, revealing robust global trends. We plot this integrated recent SFR on three different timescales to highlight both the longer-term and shorter-term trends.

In all cases, we find a steady decline in the total SFR over the past  $\sim 500$  Myr (see also Figure 4.15 and discussion in Appendix B), the origins of which we will further discuss in Section 6.1. This decline makes the integrated SFR a strong function of exactly which time interval one chooses to integrate over. For example, if we average the SFR only over the last 20 Myr, we measure a mean SFR of  $0.285 \pm 0.014\ M_{\odot}, \text{yr}^{-1}$ , which then implies a total disk-averaged SFR of  $\sim 0.43\ M_{\odot}, \text{yr}^{-1}$  — roughly  $\sim 40\%$  lower than the 0-100 Myr average. This lower SFR agrees better with the literature measurements based on  $\text{H}\alpha$  and/or  $8\ \mu\text{m}$  emission, which are expected to have shorter associated timescales.

We also note that the existence of an overall declining SFR will change how one interprets quantities averaged over longer baselines like the FUV flux. Such quantities are calculated assuming a

constant SFR, which clearly does not apply to M31 as a whole. As such, a FUV based SFR (even corrected with  $H\alpha$ , or  $24\ \mu\text{m}$  flux) will likely underestimate M31's true SFR over the adopted time interval. We make this comparison explicitly in Section 7.1 below.

## 5.2 Spatial Dependence of Global Trends

The recent star formation in M31 is not distributed uniformly across the disk. As shown in Figure 4.7, the CMD-based SFR maps exhibit strong spatial structure, with star formation concentrated prominently in the ringed-features, and varying across the surveyed area. This is consistent with the PHAT analysis of L15, who found that the 10 kpc ring dominated the recent SFH in the northern disk and hosted roughly 60% of the star formation over the last 400 Myr. The expanded PHAT+PHAST coverage now allows us to revisit this type of analysis over both sides the galaxy and examine how the recent SFH depends on spatial location throughout the disk.

To compare the spatial structure independently of the changing global normalization, we return to the maps in Figure 4.7 and compute, for each age bin, the offset of every region's SFR surface density from the disk-wide mean at that same timestep. This relative normalization highlights whether a given part of the disk is forming stars above or below the mean at a given epoch, instead of simply reflecting the overall decline in the average SFR. We restrict the comparison to spatial cells with a mean  $\Sigma_{\text{SFR}}$  over the last 0–500 Myr greater than  $6 \times 10^{-4}\ M_{\odot}\text{yr}^{-1}\text{kpc}^{-2}$ , so that the normalization is set by regions contributing meaningfully to the recent SFH rather than by the large number of quiescent cells.

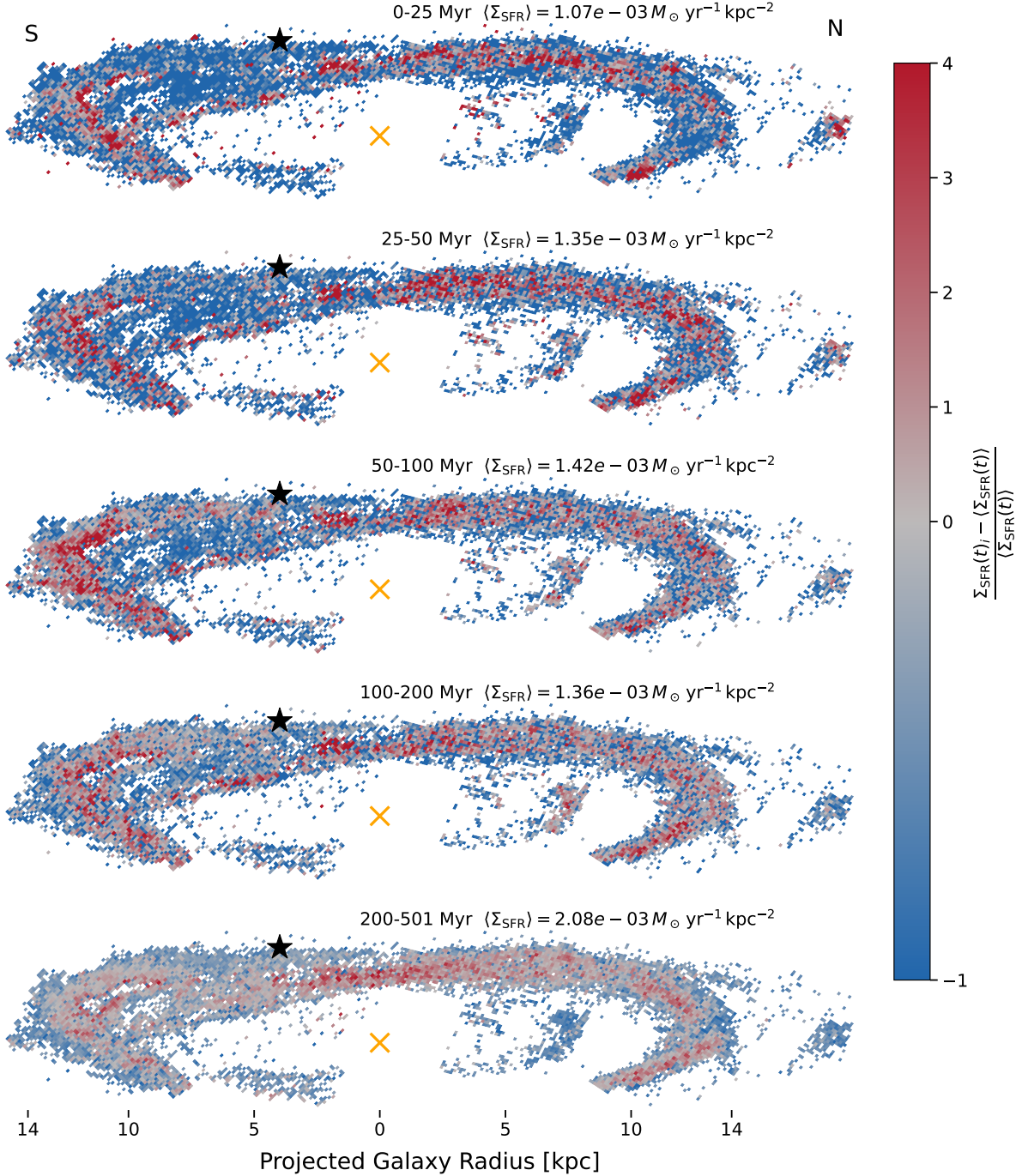
For each time interval, we then calculate  $(\Sigma_{\text{SFR}}(t)_i - \langle \Sigma_{\text{SFR}}(t) \rangle) / \langle \Sigma_{\text{SFR}}(t) \rangle$ , where  $\Sigma_{\text{SFR}}(t)_i$  is the SFR surface density in an individual spatial region and  $\langle \Sigma_{\text{SFR}}(t) \rangle$  is the mean over all cells passing our 0–500 Myr star-forming threshold.

The results are shown in Figure 4.9. Gray depicts a region that is forming close to the global average at each timestep,  $\langle \Sigma_{\text{SFR}}(t) \rangle$ , while red regions mark locations forming stars above the mean at a given epoch, and blue regions indicate regions below the mean.

Even before considering the relative offsets, restricting the sample to regions with  $6 \times 10^{-4}\ M_{\odot}\text{yr}^{-1}\text{kpc}^{-2}$  over the last 500 Myr highlights the strongly structured distribution of recent star formation across M31. In the north, the regions with any recent star formation in the last 500 Myr (i.e, included in this plot), are contained almost entirely to the rings, with distinct gaps in between. However, in the south, the regions that have recent star formation are less distinct, and create a much smoother feature.

This difference in the masked morphology is only part of the picture. Among the regions that remain actively star forming, the strength of the spatial contrast also changes with age. In the oldest time bin, spanning 200–501 Myr, the contrast relative to the disk-wide mean is weaker than at younger ages. However, the map is not spatially uniform, and large-scale asymmetric structure is still clearly present. The persistence of this structure shows that the signal has survived orbital mixing on large scales. Even so, because this broad age bin spans a substantial fraction of the disks dynamical timescale, the present-day positions of these stars are not precise tracers of their birth sites. The most robust interpretation is therefore that the 200–501 Myr map retains information about the large-scale distribution of past star formation, while any finer spatial localization has been blurred by the combination of stellar motions and the wide temporal averaging of the bin.

At younger lookback times, the spatial contrast becomes much stronger and easier to interpret. By 100–200 Myr, and especially 50–100 Myr, the ring structures stand out as the dominant sites



**Figure 4.9:** the spatial distribution of recent star formation in M31 as a fractional offset from the disk-wide mean SFR surface density in each age interval. In each panel we plot  $(\Sigma_{\text{SFR}}(t)_i - \langle \Sigma_{\text{SFR}}(t) \rangle) / \langle \Sigma_{\text{SFR}}(t) \rangle$ , where  $\Sigma_{\text{SFR}}(t)_i$  is the SFR surface density in an individual spatial cell and  $\langle \Sigma_{\text{SFR}}(t) \rangle$  is the mean over all cells with  $\langle \Sigma_{\text{SFR}} \rangle_{0-500 \text{ Myr}} > 6 \times 10^{-4} M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ . This mask restricts the comparison to regions contributing meaningfully to the recent SFH. Red regions are forming stars above the mean at that epoch, while blue regions are below the mean. The black star marks the center of M32, and the orange cross marks the center of M31. In all age bins, the strongest positive offsets are concentrated in the ring structures, especially the 10 kpc ring. An animated version of this Figure with higher fidelity time steps is available in the online journal.



of above-average star formation. In the youngest bins, the distribution becomes increasingly heterogeneous, with a smaller number of localized regions, primarily within the rings, accounting for a growing share of the remaining star formation and driving the global average. At the same time, there are some parts of the rings that fall below the global mean, most noticeably around M32, which we will discuss further in Section 6.2.1.

The fractional-offset maps make clear that the strongest enhancements in recent star formation remain concentrated in the ring structures over the last  $\sim 500$  Myr. Having established that relative spatial pattern, we next ask how it translates into the recent SFH budget of the disk, and how the temporal trends that we see in Figure 4.8 depend on galactic radius. To do so, we analyze the radial dependence of the SFH using radially selected areas on both the northern and southern sides of M31.

We define two matched comparison regions in the northern and southern disk, each with the same projected size, shape, and orientation, and placed along the same axis to sample comparable galactocentric radii on opposite sides of M31. Each region is subdivided into four equal bins, and we then sum the CMD-based SFHs of all spatial cells within each bin. This approach allows a direct comparison of how the recent SFH varies with position through the disk and across the ring structure as a function of galactocentric.

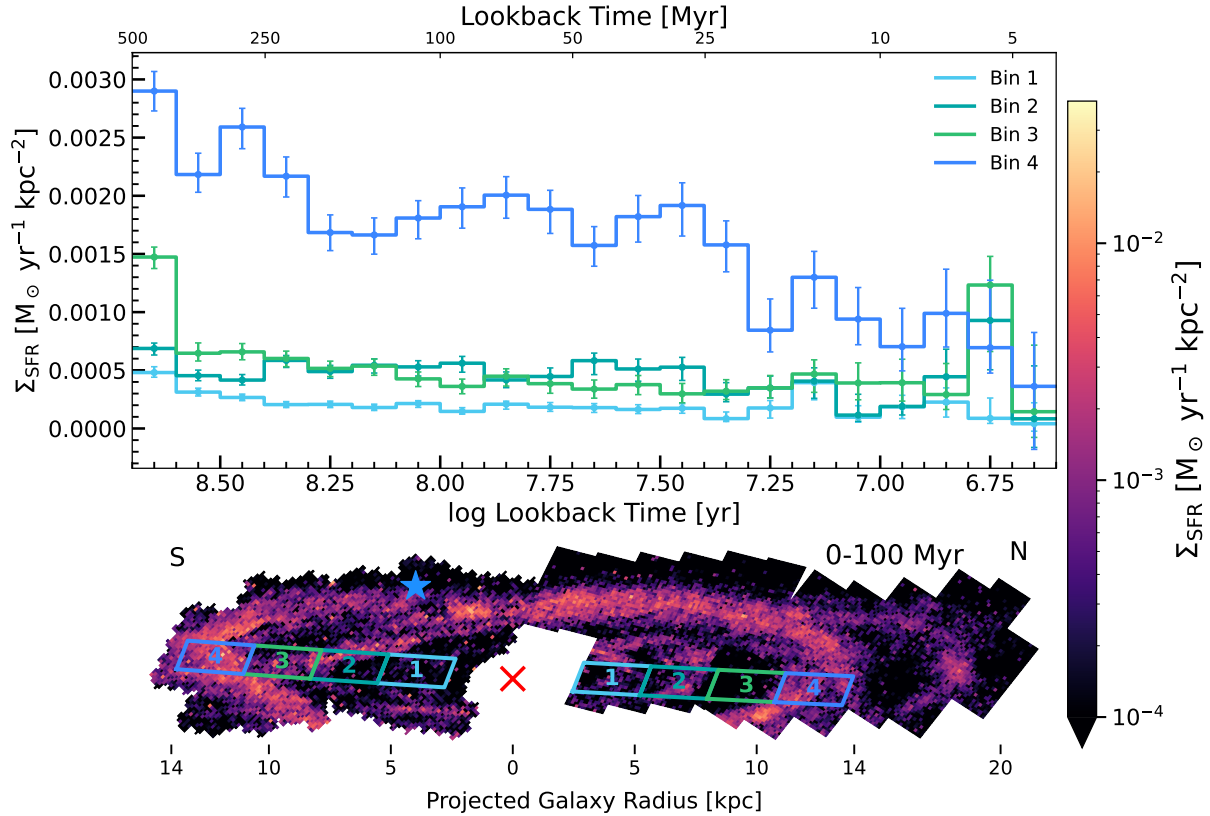
Figure 4.10 shows a clear and consistent pattern on both sides of the galaxy. Bin 4, which overlaps the 10 kpc ring structure in the north and the south (bottom panel), coincides with the regions of highest  $\Sigma_{\text{SFR}}$ . As we expect, the top panel shows that bin 4 dominates the recent SFH, with substantially elevated  $\Sigma_{\text{SFR}}$  relative to the bins interior to the ring. Bin 4 also show the largest temporal variations, where the  $\Sigma_{\text{SFR}}$  5 Myr ago is  $\sim 5\times$  smaller than it was 500 Myr ago. In contrast, bins interior to the ring remain at much lower  $\Sigma_{\text{SFR}}$  and evolve more gradually.

Therefore, the global recent SFH shown in Figure 4.8 is strongly shaped by the evolution of rings. Because the majority of the recent star formation occurs in the rings, the disk-averaged decline seen in Figure 4.8 is driven primarily by declining activity in the ring rather than by a uniform decrease at all radii. The recent wind-down of M31 is therefore best understood not as a featureless fading of the disk, but as a decline within the structures that dominate the star formation budget, and such regions are more spatially concentrated toward the present day.

### 5.3 North–South Comparison in the M31 Disk

While the global behavior across the disk is broadly consistent, with both halves showing the same decline in SFR over the last  $\sim 500$  Myr, the spatially resolved maps in Figure 4.7, and Figure 4.9 indicate that the distribution of recent star formation across M31’s disk is not entirely symmetric. In fact, PHAST covers key features which are distinctly different from the structures in the northern disk. These include the interface between M31 and M32, the interface between the disk and the giant southern stream, and the split-ring feature in the young populations (See Section 6.2). M31’s star-forming regions have a more complex morphology in the south, including key features of interest such as the largest star forming region in M31 (NGC 206; e.g., Brinks, 1981), the most massive young cluster in M31 (e.g., Perina et al., 2009), double the number of bright X-ray sources as the northern half (Trudolyubov et al., 2002; Vulic et al., 2016; Williams et al., 2004), and evidence that velocity dispersion of the southern disk is greater than that measured in the north (D. Grion Filho et al. 2026, in preparation). All of these features confirm the assertion that this half has been more recently or more violently disturbed (Gordon et al., 2006). In this



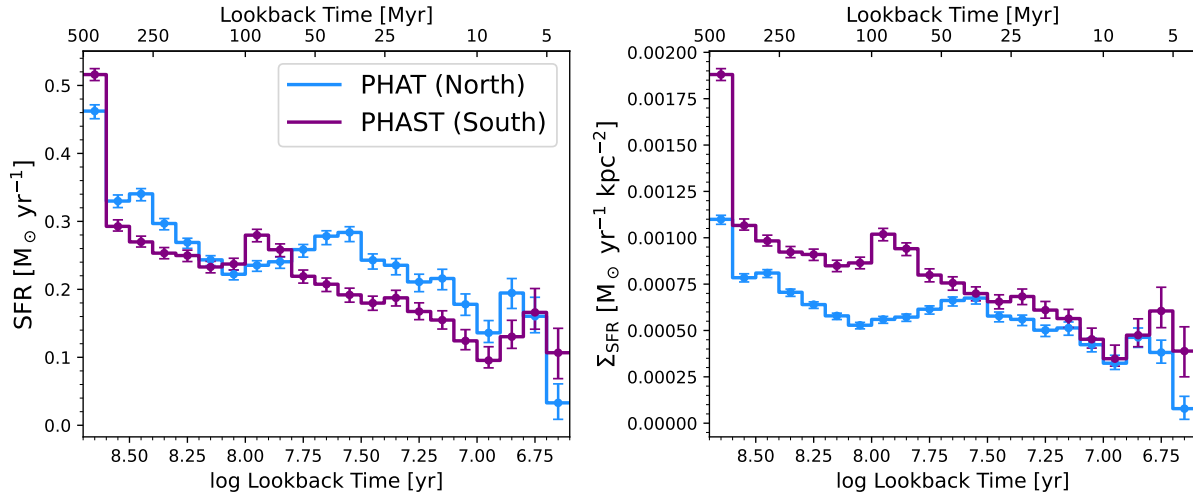


**Figure 4.10:** Shown is the radial dependence of the recent star formation history in M31. *Bottom:* map of the mean SFR surface density,  $\Sigma_{\text{SFR}}$ , averaged over the last 100 Myr across the combined PHAT+PHAST footprint. The blue star marks the center of M32, and the red cross marks the center of M31. Two matched comparison regions are overlaid on the northern and southern disk, each subdivided into four bins of equal size. *Top:* SFH each of the four radial bins. In both the north and south, the bins intersecting the 10 kpc ring dominate the recent star formation budget and show the strongest temporal variation, while bins away from the ring remain at substantially lower  $\Sigma_{\text{SFR}}$ , demonstrating that the recent, disk-averaged decline in star formation is driven primarily by declining activity in the ring rather than by a uniform decrease across all radii.

section we discuss how these primary differences are probed by their spatially-resolved recent SFHs.

The largest visual discrepancy between the northern and southern maps in Figure 4.7 occurs in the 10kpc ring. In the PHAT footprint, the ring is bright and continuous. While it does continue through the southern disk, it has several distinct gaps in the southern half, most noticeably near M32. However, since the PHAT survey footprint was explicitly designed to follow regions of high UV surface brightness and was truncated where the ring fades, the decline in recent star formation along this boundary is not necessarily surprising.

To describe the global differences seen in the north and south, Figure 4.11 compares the PHAT and PHAST SFHs directly. The blue curves show the PHAT results from L15 for the northeastern disk, while the purple curves show the PHAST SFHs presented here for the southern footprint. In the left panel we plot the SFR as a function of lookback time, and in the right panel we show the



**Figure 4.11:** Comparison of the SFHs for the North and South regions of the M31 disk. Left panel shows the SFR, while the right shows the SFR surface density  $\Sigma_{\text{SFR}}$  as a function of lookback time, where the most recent time is to the right. Blue shows the SFH from the PHAT survey in the North from L15, while the purple are the results presented here from the PHAST survey in the South. Both surveys are declining over the 500 Myr window, but the North saw a modest burst from  $\sim 100$ –40 Myr ago not seen in the South. We note that measured SFR of  $\sim 0.5 \text{ M}_{\odot} \text{ yr}^{-1}$  in the first bin at log age 8.7 to 8.6 is consistent with the ancient SFH of Williams et al. (2017) derived over the same age interval, and we believe this increase is real (See Appendix B).

corresponding SFR surface density,  $\Sigma_{\text{SFR}}$ , averaged over each survey area. The normalization of the curves differ partly because the PHAT footprint covers a larger deprojected area ( $\sim 420 \text{ kpc}^2$ ) than PHAST ( $\sim 274 \text{ kpc}^2$ ), so small differences in  $\Sigma_{\text{SFR}}$  translate into noticeable changes in the total mass formed.

Over the last 100 Myr, the two halves of the disk form stars at very similar absolute rates. Over this time baseline, we calculate the average SFR in the PHAT survey to be  $0.231 \pm 0.004 \text{ M}_{\odot} \text{ yr}^{-1}$ , when considering the IMF correction from Section 3.2, and adding each regions uncertainty in quadrature. For the PHAST region, we measure a mean SFR of  $0.213 \pm 0.004 \text{ M}_{\odot} \text{ yr}^{-1}$  over the same time interval, despite the smaller surveyed area. This leads to the southern disk having a somewhat higher  $\Sigma_{\text{SFR}}$ , specifically at lookback times of  $\sim 80$ –100 Myr, as seen in the right panel of Figure 4.11. This increased  $\Sigma_{\text{SFR}}$  in the south also agrees with theoretical predictions (Hammer et al., 2018).

However, over the last  $\sim 80$  Myr, the northern and southern disks converge to very similar SFR surface densities. The most noticeable difference in Figure 4.11 is that the PHAT region has a steady increase in star formation from 100 Myr to 40 Myr ago, from  $\sim 0.22 \text{ M}_{\odot} \text{ yr}^{-1}$  to  $\sim 0.29 \text{ M}_{\odot} \text{ yr}^{-1}$ , that has no clear analogue in the PHAST measurements. In contrast, the southern disk instead shows a smoother decline in the SFR from 100 Myr to the present.

Within the uncertainties, the PHAT and PHAST SFHs at  $\lesssim 40$  Myr are consistent with a shared picture in which the M31 disk has experienced a recent decline in star formation, superimposed on smaller-scale spatial variations. At the youngest ages however, both surveys show a modest upturn in SFR in the last  $\sim 10$  Myr relative to the 10–20 Myr bins. This feature is intriguing, but

should be interpreted with caution, since this is the regime with the highest systematic uncertainties (Section 3.4).

We also note that the SFR in the oldest bin of our recent-SFH measurement may appear unusually high, roughly 60% higher relative to the bins immediately below it. However, we believe this is a real feature in the M31 SFH. The measured SFR in the log-age 8.7–8.6 bin agrees with the ancient SFH of Williams et al. (2017) over the same interval, providing an important consistency check at the boundary between the two analyses. As discussed further in Appendix B and Section 6.1, the SFR at this time is also consistent with the SFH recovered in the regions where we can reliably probe to older ages, supporting the interpretation of a longer decline in M31’s SFH.

## 6 Insights into M31’s Evolution

The SFHs derived from the PHAST and PHAT surveys provide a coherent view of how recent star formation has unfolded across the M31 disk and open several avenues where these maps can be used as diagnostic tools. In this section we use the M31 SFH maps combining the PHAT and PHAST regions to discuss how the recent SFR has evolved globally, and to discuss possible mechanisms responsible for the observed decline. In addition, we highlight two intriguing subregions in the PHAST footprint: the M32 region and the inner arm structure, as case studies of how local environment shapes the SFH.

### 6.1 Assessing the Global Decline in the SFR

As shown in Figure 4.8, the full SFH for the PHAT+PHAST combined footprint shows a very distinct picture: M31 has experienced a clear decrease in SFR over the last 500 Myr, with a particularly steep drop in the last  $\sim 40$  Myr. When we integrate over the full PHAT+PHAST footprint, the average SFR declines from  $\sim 1 \text{ M}_{\odot} \text{ yr}^{-1}$  at lookback times of  $\sim 500$  Myr to  $\simeq 0.5 \text{ M}_{\odot} \text{ yr}^{-1}$  40 Myr ago.

The orbital timescale of M31’s star-forming disk is of order  $\sim 250$  Myr, so a coherent decline in SFR across most of the disk over only  $\sim 40$  Myr would appear, at face value, uncomfortably rapid. This makes it particularly important to ask whether part of the apparent decline could arise from systematics in the very youngest age bins, where stellar evolution models, dust treatment, and crowding effects introduce the largest uncertainties. However, multiple lines of evidence indicate that the decline is unlikely to be a methodological artifact, and is instead physical.

First, the downward trend is already present when we average the SFH over 40–500 Myr, well beyond the regime where massive-star evolutionary uncertainties and binary physics are most acute (e.g., Dolphin, 2002, 2013; Gallart et al., 2005) and where we see the largest mismatch between evolutionary models (Section 3.4). Second, the same MATCH-based fitting pipeline applied to M33 in the PHATTER survey recovers a recent SFH that is comparatively steady over the last 100 Myr and does not show an analogous global decline, even though the CMD depth, modeling assumptions, and extinction treatment are very similar (Lazzarini et al., 2022). This argues that the behavior we see in M31 is not a generic bias in the technique, but rather a feature of the galaxy. Finally, our extinction maps and CMDs do not show any abrupt change in dust geometry or fit quality at the lookback times where the SFR begins to drop, which would be expected if the decline were primarily driven by a breakdown in the dust modeling. For these reasons, we believe

the observed decline is a real feature of M31’s SFH history, and in this section, we discuss possible explanations.

### 6.1.1 Is M31 Running out of Gas?

From a gas-supply standpoint, a gradual decrease in SFR over several hundred Myr is compatible with the timescale of molecular gas depletion, of order 1–3 Gyr, seen in nearby star-forming disks (e.g., [Bigiel et al., 2011](#); [Schruba et al., 2011](#); [Sun et al., 2023](#)). However, it is important not to interpret this trend as a literal “running out of gas”. In both observations and simulations, galaxies like M31 do not exhaust their fuel reservoir in isolation unless an additional process suppresses accretion and/or prevents recycled material from re-cooling efficiently (e.g., [Bell, 2008](#); [Somerville & Davé, 2015](#)). Empirically, truly quenched bulge-less central galaxies are rare, which suggests that sustained suppression of star formation is linked to compact central structures and the physics associated with them ([Bell, 2008](#)).

This causality is explicit in modern galaxy-formation models where without super massive black-hole (SMBH) feedback, simulations generally fail to quench massive central galaxies and instead retain excessive late-time star formation (e.g., [Byrne et al., 2024](#)). In IllustrisTNG, for example, SMBH feedback is explicitly responsible for quenching galaxies in intermediate and high-mass halos ([Pillepich et al., 2018](#)), and across multiple simulation suites the most predictive parameter separating star-forming from quenched central galaxies is the SMBH mass, consistent with cumulative, integrated feedback ([Piotrowska et al., 2022](#)). Observationally, direct SMBH mass measurements similarly show that quiescence correlates strongly with  $M_{\text{BH}}$  at fixed stellar mass ([Terrazas et al., 2016, 2017](#)).

For M31, the central SMBH (M31\*) has  $M_{\text{BH}} \simeq 1.4 \times 10^8 M_{\odot}$  ([Bender et al., 2005](#)), but the nucleus today is extremely low luminosity ([Li et al., 2011](#)), so any direct, contemporaneous feedback on the disk is expected to be weak ([Li et al., 2009](#)). Constraints on past activity instead come from relic diagnostics. XMM–Newton/RGS spectroscopy of M31’s inner bulge has been interpreted as evidence for an AGN episode as recently as roughly 0.5 Myr ago ([Zhang et al., 2019](#)), and extended high-energy emission has been discussed as potentially consistent with past nuclear injection, though interpretations are not unique ([Pshirkov et al., 2016](#)). In addition, deep very long baseline interferometer (VLBI) observations indicate that the nuclear radio emission is intrinsically extended on milliarcsecond scales, consistent with a hot outflow/wind from the weakly accreting AGN ([Peng et al., 2023](#)). This evidence is qualitatively consistent with “maintenance-mode” feedback, in which energy and momentum injection keep the halo and inner-disk gas hot, turbulent, or otherwise unable to cool and condense efficiently (e.g., [Alexander et al., 2025](#); [Harrison & Ramos Almeida, 2024](#)). In such instances, star formation can decline without wholesale expulsion of the star-forming ISM, because the long-term resupply of cold gas is reduced and recycling times are lengthened.

These considerations motivate AGN-related maintenance feedback as a physically plausible contributor to M31’s long-term decline in SFR and central quiescence. However, establishing a direct causal link between AGN activity and a galaxy’s star-formation history is intrinsically difficult due to spatial and timescale mismatches (e.g., [Alexander et al., 2025](#); [Leung et al., 2026](#)).

### 6.1.2 Late Stages of a Longer Decline

A decline of a factor of a few over the last few hundred Myr is also consistent with what is expected for green valley galaxies like M31. Empirical reconstructions and large-survey analyses generally find that the post star-burst “wind-down” is not instantaneous, but proceeds over a range of characteristic timescales from several  $\times 10^8$  yr to a few Gyr, with galaxy-to-galaxy diversity (e.g., [Lin et al., 2026](#); [Martin et al., 2007](#); [Schawinski et al., 2014](#)).

When we place our measurements of the recent SFH in the broader context of M31’s evolution, the recent decline appears to be the continuation of a longer-term evolution of the M31 disk. The ancient SFH derived from the PHAT survey shows that M31 experienced a strong enhancement in star formation  $\sim 2$  Gyr ago, during which the global SFR reached upwards of  $6M_{\odot}, \text{yr}^{-1}$ , followed by a gradual decrease toward quiescence ([Williams et al., 2015, 2017](#)). In fact, when we consider the outermost regions of PHAST where we can trace out to ages of 1.2 Gyr with the main sequence turn-off (See Appendix B), we see a fairly constant decline in the SFR in the last 1.2 Gyr.

Our measurements here extend this picture to younger ages, showing that the disk has continued to evolve toward lower SFRs over the last 500 Myr, with a modest enhancement around 100 Myr, followed by the more pronounced decline in the last  $\sim 40$  Myr. In this view, the current low SFR is not the result of a sudden, synchronized shutdown across the disk, but rather the latest stage of a multi-Gyr relaxation from a previously more active phase.

In fact, the decline is not perfectly uniform across the disk. As discussed in Section 5.3, and seen in Figure 4.11, the PHAT region sees a modest increase in star formation from 100 Myr up until 40 Myr ago, which is not seen in the PHAST survey. More importantly, inspection of both Figure 4.7 and the radial analysis in Figure 4.10 show that most of the recent star formation is concentrated in the rings, which dominates the total star formation budget for the galaxy. The disk-averaged decline in Figure 4.8 is therefore driven primarily by declining activity in the ring, rather than by a uniform decrease across the disk.

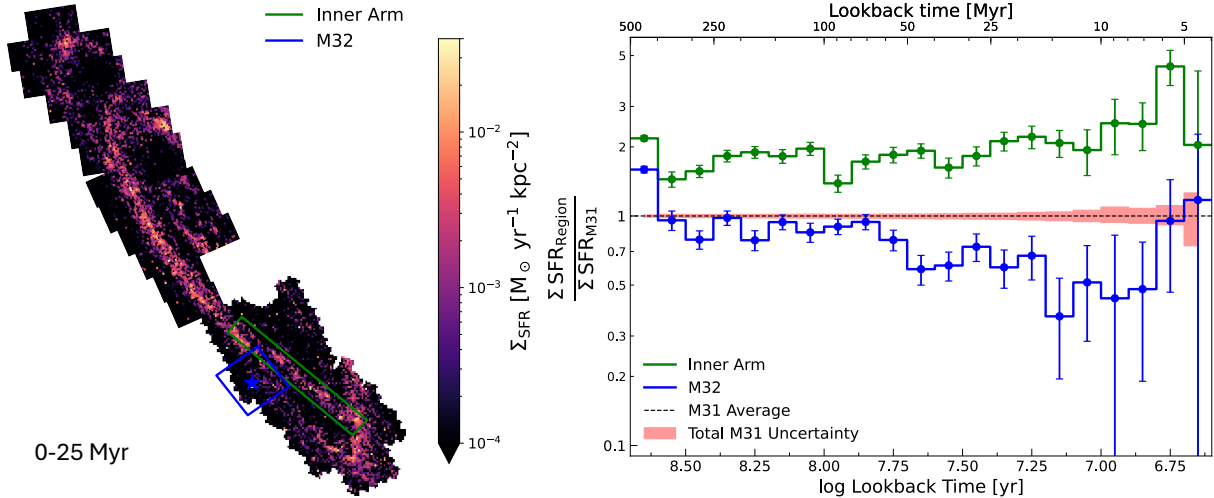
For the reduction in the 10 kpc ring, a plausible interpretation is that the recent decline reflects reduced fueling. In dynamical models, long-lived rings persist when gas replenishment balances inward transport and depletion by star formation, so a reduction in inflow can lower the SFR while leaving the ring morphology intact (e.g., [Dekel et al., 2020](#); [Seo & Kim, 2013](#)). This same balance also helps set the lifetime of the structure. Star-forming rings are generally expected to be transient, but may persist up to order-Gyr timescales when maintained by the underlying disk dynamics (e.g., [Buta & Combes, 1996](#); [Sellwood, 2011](#); [Sellwood & Masters, 2022](#)).

More broadly, M31 offers a stringent test for galaxy-evolution models. Any successful framework must reproduce not only the present-day global SFR, but the structure and longevity of the rings, the quiescent inner regions, and the recent decline over the last couple of Gyr. As a result, M31 serves as a key benchmark for simulations in evaluating how processes such as gas accretion, recycling, and maintenance-style AGN feedback combine to regulate star formation in massive disk galaxies transitioning through the green valley.

## 6.2 Specific Regions of Interest in the PHAST Survey

The complete SFH map for PHAST presented in Figure 4.5 show specific areas of the southern disk that stand out in contrast to the consistently structured north. Sub-selecting these more localized features and comparing the SFH of those regions to that of the global average offers additional





**Figure 4.12:** Subregions used to investigate local variations in the recent SFH. *Left:* SFR surface density map for the 0–25 Myr time bin from Figure 4.7, with the two subregions highlighted. The blue outline marks the M32 region and the green outline marks the inner-arm/bar region near the apparent spur connecting the inner and outer 10 kpc rings. *Right :* Ratio of the SFR in each subregion to the global SFR averaged over the combined PHAT+PHAST footprint as a function of lookback time. The horizontal dashed black line indicates parity with the global average; the red shaded band shows the uncertainty on the global SFH from Figure 4.8. The curves for the M32 and inner-arm regions illustrate how their recent SFHs diverge from the disk average, highlighting a recent suppression of star formation in the M32 region and distinct burst in the inner arm.

insight into the underlying physical drivers of the SFR. In this section, we highlight two distinct sub-regions within the PHAST footprint: the region surrounding M32, and a segment of the inner-arm region of the 10 kpc ring split where, in our projection space, there appears to be a connecting spur between the inner and outer rings. These regions were chosen for their distinct structural and environmental context, and for their contrasting recent SFH behavior. By examining them in more detail, we aim to link small-scale structure to the broader trends seen across the southern disk and, in the case of M32, to place its recent activity in the context of the satellite’s interaction history with M31.

These regions are shown in the left-hand panel of Figure 4.12, where we outline the selected areas on top of the 0–25 Myr SFR surface density map from Figure 4.7. The M32 region is outlined in blue and the inner-arm region in green, while M32 itself is marked with a blue star. While the exact boundaries of these regions were defined somewhat arbitrarily, we experimented with modestly larger and smaller apertures and found that the quantitative SFH behavior is stable within the uncertainties.

### 6.2.1 The M32 Region

The first area of interest, and arguably the most striking structure in the southern part of M31, is the region surrounding the compact satellite M32. In Figure 4.12, this subregion is outlined in blue. The aperture shape was chosen to encompass the area immediately surrounding M32 and the associated perturbation in the disk.

In the right hand panel of Figure 4.12, we compare the SFR within this region to the overall SFR across the PHAT and PHAST surveys as a function of lookback time. We take the ratio such that 1 is the galactic average, which is shown by the dashed black line. The red shaded region around this line is the uncertainty in this measurement, using the same error-bars from Figure 4.8.

From  $\sim 500$  Myr to  $\sim 60$  Myr ago, the M32 region is statistically consistent with the M31 average, with only mild fluctuations around unity. At younger ages, however, the behavior changes. Starting at  $\sim 60$  Myr, the SFR in this region drops significantly below the global average and remains suppressed. From  $\sim 50$  Myr ago, to  $\sim 20$  Myr ago, the region around M32 is quenched by  $\sim 40\%$  compared to the rest of the galaxy, reaching a minimum of roughly 65% of the mean disk SFR at a lookback time of  $\sim 15$  Myr. This pattern suggests a recent and localized reduction in star formation activity that is not mirrored across the galaxy as a whole. In fact, in Figure 4.9, this regions stands out as particularly quenched with respect to the rest of the 10 kpc ring.

The seemingly most plausible explanation for this localized quenching would be a response to an interaction with M32. Several studies have linked M32 to M31’s ring-like structure and disturbed recent SFH, but the interaction history remains uncertain (e.g., Block et al., 2006; Dierickx et al., 2014; Gordon et al., 2006). A long-standing limitation has been the lack of a well-constrained proper motion and an accurate line-of-sight distance for M32, leaving substantial freedom in orbital reconstructions. As a result, published models span a range of encounter geometries and epochs, including scenarios with a disk passage  $\sim 200$  Myr ago (Block et al., 2006) and alternatives that place the most recent strong interaction much more recently (Gordon et al., 2006).

Recent HST data have been obtained through GO-15658 (PI: S.T. Sohn) to directly address this issue, and measure the proper motion of M32 relative to that of M31’s for the first time. Preliminary evidence suggests that M32 is moving southward relative to M31 with significant velocity (Fardal et al. 2026, in prep.). Additionally, ongoing work to integrate the backwards orbit of M32 in a rigid M31 halo potential suggests that a passage through M31’s disk was possible  $\sim 20$  Myr ago (with uncertainties of  $\sim 10$  Myr). However, further analysis is needed to determine the effects of tidal stripping of M32, and the range of orbital uncertainties derived from considering a range of relative distances between M32 and M31 (Patel et al. 2026, in prep.). These proper motion results (Fardal et al. 2026, in prep), are consistent with the earlier model of Gordon et al. (2006), which suggest M32’s passage through M31’s disk occurred 10 Myr ago.

If the localized quenching seen in Figure 4.12 is driven by an interaction with M32, then the timing in our resolved SFH is more aligned with a relatively recent perturbation than with a passage  $\sim 200$  Myr ago. In particular, the lowest measured SFR in this region occurs at lookback times of order  $\sim 15$  Myr, and we measure a modest uptick in the last  $\sim 10$  Myr, qualitatively consistent with the timescales invoked in recent-interaction scenarios. At the same time, our uncertainties in these youngest age bins are the largest, and the measured SFRs remain formally consistent with continued quenching within the errors.

However, the SFH results presented here do not provide clear support for the very recent interaction scenario either. Importantly, the SFR suppression in this region begins earlier, at  $\sim 60$  Myr lookback time, before the epoch implied by the most recent-interaction models. This timing either implies that M32’s projected distance from the disk is an underestimate and it is actually further away, or a simple one-event explanation doesn’t capture the full SFH of this region. The early decline may reflect local evolution unrelated to M32, or it may indicate that multiple processes act together, with any M32-driven perturbation superposed on pre-existing changes in the local star-forming environment.

In either case, these resolved SFH constraints presented here should play a central role in future modeling of the M31–M32 system. A full hydrodynamical treatment that predicts the timing, amplitude, and spatial extent of the disk’s star-formation response to an M32 passage would provide a critical test to the degree to which an interaction could account for the quenching history we measure in this region.

### 6.2.2 The Inner Arm Region

In contrast to the quenched behavior of the M32 region shown above, the inner arm ring segment describes a different picture, despite only being a short distance away in projection from the M32 field. In Figure 4.12, the inner arm region is outlined in green, tracing a segment of the inner spiral structure where the projected morphology suggests a narrow bar that links the inner and outer portions of the 10 kpc ring.

Over the last  $\sim 500$  Myr, the inner-arm region sits systematically above the global average. This enhancement is consistent with the expectation that spiral arms and ring-like structures tend to host elevated star formation relative to the surrounding disk (e.g., Kennicutt, 1989, 1998; Querejeta et al., 2024). Notably however, this feature is not simply part of the main 10 kpc ring, but a distinct segment of the split southern morphology that sustains enhanced star formation for several hundred Myr. That persistence is significant because it extends beyond an orbital timescale, implying that the feature has avoided being erased by radial and azimuthal mixing over much of that interval. This inner-arm component therefore traces a genuine, long-lived dynamical structure in the southern disk, rather than a short-lived fluctuation or a purely projected connection between neighboring star-forming regions.

Within this long-lived ring structure, the inner-arm segment also shows a pronounced enhancement at the youngest ages.<sup>4</sup> This behavior stands in sharp contrast to the neighboring M32 region, where the SFR in the last 60 Myrs is suppressed relative to the disk average (Section 6.2.1). Additionally, the youngest ( $< 50$  Myr) panels of Figure 4.10 show the inner-arm segment appears to be forming stars more actively than the nearby portion of the 10 kpc ring at similar projected galactocentric radius. The juxtaposition of an actively star-forming inner arm and a locally quenched M32 region within a few kpc highlights the sensitivity of recent star formation to local dynamical and environmental conditions, even inside a long-lived ring structure.

Interestingly, the apparent simplicity of the inner arm in projection does not reflect the true three-dimensional structure of the gas and stars. In our SFH maps, this feature resembles a straight bar connecting the inner and outer rings in the PHAST footprint, and clearly seen by the massive dust lane in Figure 4.4. However, the underlying kinematics indicate a more complex configuration. The H I velocity structure in the vicinity of this inner-arm segment from the new VLA data from LGLBS (Koch et al., 2025) shows possible evidence for a coherent set of velocities that are distinct from the neighboring ring material, similar to the behavior identified in earlier H I studies of M31 (e.g., Braun, 1991). This pattern suggests that the inner arm is not simply a bridge between two rings. Instead, it likely traces a geometrically distinct ring or arm segment that is inclined

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<sup>4</sup>We note that the size of the segment shown here was chosen to try and avoid ambiguity in determining which exact features are a part of the inner-arm. Although the region we adopt includes the star-forming complex NGC 206 at its south–western edge, we tested smaller apertures focused solely on the inner–arm structure and found similar recent SFR enhancements within the uncertainties. The more spatial regions included increase the signal to noise and are therefore easier to interpret.

relative to the bulk of the disk and projected into an apparently straight feature on the sky.

These results paint a picture in which two nearby regions in projection space, may be more separated than initial indications suggest. The M32 region shows a significant decline in SFR over the past  $\sim 60$  Myr, while the inner arm region exhibits a persistent enhancement during the same period relative to the galaxy wide average. Importantly, the quenching mechanism of the M32 region, did not impact the inner arm region.

The fact that the inner arm appears to be a distinct dynamical structure, rather than a mere continuation of the outer ring, makes this contrast more illuminating. This SFH result point out that these seemingly nearby regions experienced very different recent evolutionary histories. This combination of elevated SFR and unusual geometry marks the inner arm as a particularly interesting site for probing how local dynamical structures and external perturbations shape the recent SFH of M31, and should be the focus of future studies.

## 7 Comparison to Other Star Formation Tracers

The CMD-derived SFHs provide a view of star formation that is conceptually different from that obtained with traditional integrated luminosity tracers, particularly those with additional empirical corrections for dust, such as FUV+24  $\mu\text{m}$ . In contrast to the CMD-based SFHs derived here, which reconstruct the distribution of stellar ages and masses over a grid of lookback times, while other tracers infer instantaneous SFRs from the luminosity of short-lived massive stars and dust re-radiation, implicitly assuming a steady SFH and a fixed dust geometry (e.g., [Boquien et al., 2016](#); [Kennicutt et al., 2009](#)).

Several recent studies have highlighted a systematic offset between these approaches, with FUV based SFR indicators yielding results that are smaller by factors ranging from 1.3 to 3 compared to those inferred from resolved stellar populations (e.g., [Lazzarini et al., 2022](#); [Lewis et al., 2017](#); [McQuinn et al., 2015](#))<sup>5</sup>. Since both methods are widely used and each rests on well-motivated assumptions about stellar populations, this mismatch has large impacts for the community.

In this section, we first compare FUV+24  $\mu\text{m}$  SFR surface densities to the CMD-based SFRs averaged over the last 100 Myr. We then test whether either FUV+24  $\mu\text{m}$  or CMD derived SFR values held constant over the last 100 Myr can produce a synthetic FUV image similar to the observed *GALEX* FUV emission.

### 7.1 CMD-based SFR Surface Density Compared to UV Luminosity Tracers

Star formation rates can be estimated in many different ways, including  $\text{H}\alpha$  emission, UV continuum, infrared emission, combined UV+IR recipes, or non-thermal synchrotron radio emission (e.g., [Calzetti, 2013](#); [Kennicutt & Evans, 2012](#); [Kennicutt, 1998](#)). The most direct external comparison to our CMD-based recent SFHs are the tracers that involve UV emission, as both are grounded in similarly young stellar populations (e.g., [Kennicutt & Evans, 2012](#)). In contrast,  $\text{H}\alpha$  emission

<sup>5</sup>We note that the [Lazzarini et al. \(2022\)](#) study did not include the finite IMF integration limits, and if we adopt the same IMF limits chosen here, the SFRs would be interpreted  $\sim 20\%$  lower than the published values. When taking into consideration this correction, the CMD based SFRs are brought closer into alignment with the FUV based SFR, but the CMD estimates are still a factor of 1.3 larger.

traces the ionized-gas response to the youngest, most massive stars, and is subject to much greater stochasticity and dependence on the properties of the ambient ISM.

We therefore compare our CMD-based SFHs to the FUV+24  $\mu\text{m}$  calibration from Leroy et al. (2008),

$$\Sigma\text{SFR}_{\text{FUV}+24\mu\text{m}} = \left( 8.1 \times 10^{-2} I_{\text{FUV}} + 3.2_{-0.7}^{+1.2} \times 10^{-3} I_{24} \right) \cos i, \quad (4.1)$$

where  $I_{\text{FUV}}$  and  $I_{24}$  are the FUV and 24  $\mu\text{m}$  intensities in  $\text{MJy sr}^{-1}$ . The  $\cos(i)$  term takes into account M31's inclination  $i$ , taken to be  $77^\circ$  (Walterbos & Kennicutt, 1988).  $\Sigma\text{SFR}_{\text{FUV}+24\mu\text{m}}$  is therefore a SFR surface density with units of  $\text{M}_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$ , directly comparable to the CMD analysis from Section 2. We calculate  $\Sigma\text{SFR}_{\text{FUV}+24\mu\text{m}}$  using the 24  $\mu\text{m}$  map from the *Spitzer*/MIPS observations of Gordon et al. (2006), and the FUV map from the *GALEX* imaging of Martin et al. (2005). We project both data sets onto the PHAST spatial grid by integrating the native-image flux over each PHAST region, weighting each pixel by the fraction of its area that falls inside the region, making sure flux is conserved. We then compute  $\Sigma\text{SFR}_{\text{FUV}+24\mu\text{m}}$  in each spatial bin.

We note two adjustments to the *GALEX* image, needed to derive  $I_{\text{FUV}}$  in a way consistent with the Leroy et al. (2008) study. First, we subtract a uniform background from the image based on a section of non-galaxy pixels, and second, we correct for foreground dust. We choose to correct for dust based on each region's best fit foreground  $A_V$  (Figure 4.2) from the CMD fits. Alternatively, we could have chosen a uniform dust correction based on the Schlegel et al. (1998) maps of nearby regions, rescaling them following Schlafly & Finkbeiner (2011); however, the region-by-region correction produced the best comparison to our CMD analysis.

For the CMD-based reference SFRs, in each region, we integrate the SFHs over the last 100 Myr to derive the mean SFR (Section 4.1). This timescale is chosen to match what is generally considered the characteristic sensitivity window of the FUV+24  $\mu\text{m}$  tracer (e.g., Kennicutt & Evans, 2012; Kennicutt, 1998) and to remain within the regime where the SFHs are best constrained. We also divide by the deprojected area to obtain a CMD-based SFR surface density,  $\Sigma\text{SFR}_{\text{CMD},100}$  as described in Section 2, giving a consistent de-projection to a face-on SFR intensity as also used in Equation 4.1.

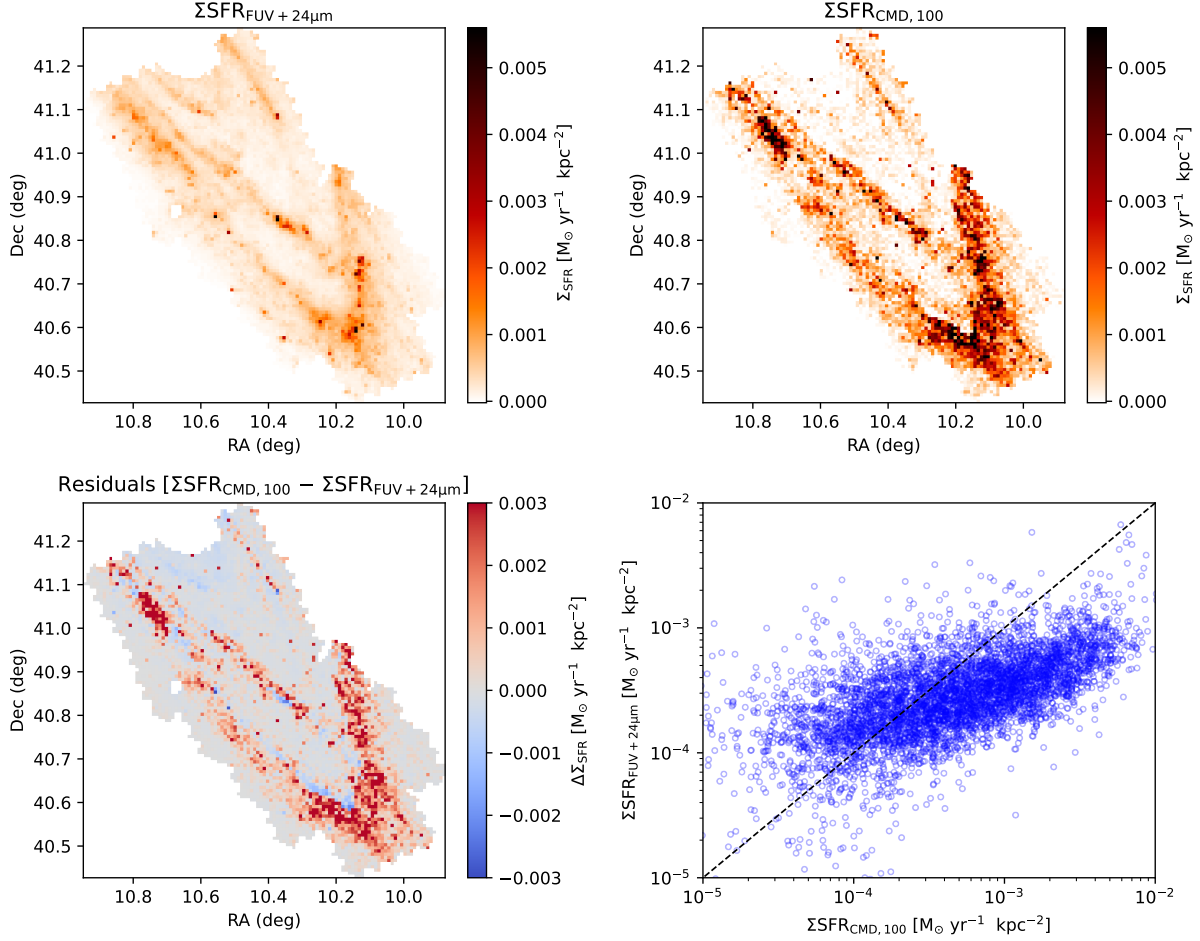
We compare the SFRs derived from these two methods in Figure 4.13. The top-left panel shows the  $\Sigma\text{SFR}_{\text{FUV}+24\mu\text{m}}$  map, and the top-right panel shows  $\Sigma\text{SFR}_{\text{CMD},100}$  over the same footprint and at the same spatial resolution. The bottom-left panel shows the residuals, and the bottom-right panel plots  $\Sigma\text{SFR}_{\text{CMD},100}$  versus  $\Sigma\text{SFR}_{\text{FUV}+24\mu\text{m}}$  for all spatial regions.

Comparing the top two panels, the overall morphologies are remarkably similar. The 10 kpc ring stands out prominently in both maps, as do the star forming region NGC 206 and many of the localized peaks associated with bright OB associations.

While the morphology of the SFR maps are similar between both methods, there is an obvious difference in scale. We find that the FUV+24  $\mu\text{m}$  SFR estimator yields systematically lower SFR surface densities than the CMD based SFRs. Specifically, we find that a multiplicative offset of 2.1 minimized the median absolute deviation (MAD) of squared residual (i.e.,  $(\Sigma\text{SFR}_{\text{CMD},100} - \Sigma\text{SFR}_{\text{FUV}+24\mu\text{m}})^2$ ) across the map as a whole.

Examining the residual map in the lower left panel of Figure 4.13, the bias towards lower FUV+24  $\mu\text{m}$  SFRs is clearest in the highest SFR regions in the ring structures. When we plot the direct region-by-region comparisons (bottom right panel), it is clear that the slope of the residuals does not follow the 1:1 relation. In fact, in log-log space as shown, a line of best fit has a slope





**Figure 4.13:** Comparison between SFR surface densities inferred from FUV+24  $\mu\text{m}$  emission and from the CMD-derived SFHs. Top left: SFR surface density map,  $\Sigma\text{SFR}_{\text{FUV}+24\mu\text{m}}$ , computed using the Leroy et al. (2008) calibration applied to the *GALEX* FUV and *Spitzer*/MIPS 24  $\mu\text{m}$  data (Gordon et al., 2006; Martin et al., 2005). Top right: mean SFR surface density over the last 100 Myr from the CMD-based SFHs,  $\Sigma\text{SFR}_{\text{CMD},100}$ , evaluated on the same spatial grid. Bottom left: the difference between the two metrics,  $\Sigma\text{SFR}_{\text{CMD},100} - \Sigma\text{SFR}_{\text{FUV}+24\mu\text{m}}$ , highlighting where the FUV+24  $\mu\text{m}$  predicts higher or lower SFRs than the CMDs. Bottom right: pixel-by-pixel comparison of  $\Sigma\text{SFR}_{\text{FUV}+24\mu\text{m}}$  versus  $\Sigma\text{SFR}_{\text{CMD},100}$ , with the dashed line indicating equality. The FUV+24  $\mu\text{m}$  systematically yields higher SFR surface densities, by factors of an order  $\sim 2.65$ , while preserving the same large-scale morphology seen in the CMD-based map.

of 0.34, where 1.0 would represent the 1:1 relation. Additionally, there is a significant scatter in the fractional residuals (defined to be  $[(\Sigma\text{SFR}_{\text{FUV}+24\mu\text{m}} - \Sigma\text{SFR}_{\text{CMD},100}) / \Sigma\text{SFR}_{\text{CMD},100}]$  where the interquartile range (IQR) is 0.21.

This structure leads to larger offsets for more intense star formation (large  $\Sigma\text{SFR}_{\text{CMD},100}$ ). Similarly, at the very lowest SFRs, there is a slight tendency for the FUV+24  $\mu\text{m}$  SFRs to be higher than those inferred from the CMDs, although with significant scatter. Fundamentally, the dynamic range of the CMD-based SFRs appears to be far greater than those derived from the FUV+24  $\mu\text{m}$  data, with the former spanning an additional order of magnitude in  $\Sigma_{\text{SFR}}$ . We explore potential

origins of this offset below.

## 7.2 The Only Way to Reproduce the Observed FUV Emission is With a Time Varying SFH

The offsets shown in Figure 4.13 reveal significant, systematic differences between the the CMD based 100 Myr average SFR, and SFRs derived from FUV+24  $\mu\text{m}$  emission. This pattern may indicate a mismatch in how the embedded, youngest star formation is treated in the two approaches, or, in the assumed timescales over which the SFR is being measured. We explore each of these possibilities in Appendix C, and conclude that a possible culprit for the offset appears to be the timescale sensitivity of the FUV in a rapidly evolving recent SFH.

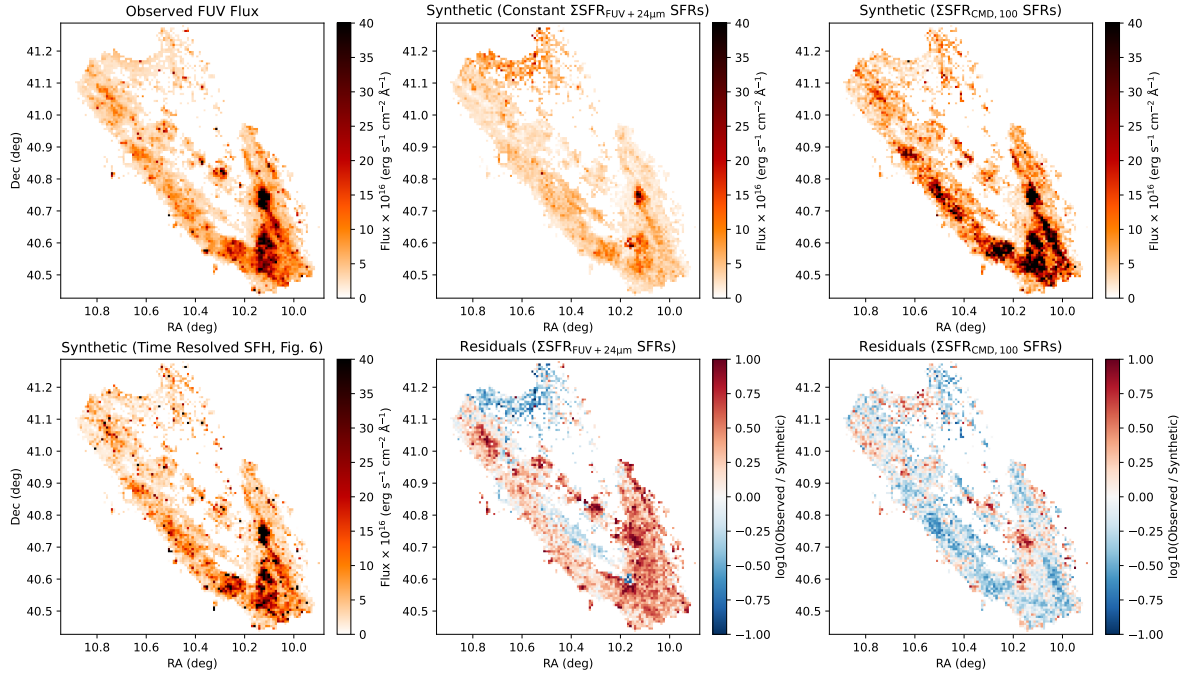
However, in Section 4.2, we showed that the CMD-derived SFHs can reproduce the observed *GALEX* FUV map across the PHAST footprint. In principle, that agreement might be reproduced by either of the constant SFRs presented in Section 7.1, even if the full time variability of the SFH is ignored. Here we test that possibility directly by comparing synthetic FUV images constructed from constant recent SFRs (Section 7.1) to the full time-resolved CMD-derived SFHs (Section 4.2). This comparison then also tests whether the FUV emission is governed by the average recent star formation, or the timing of that star formation over the last 100 Myr.

We perform this test by repeating the  $F_{\text{SPS}}$  based synthetic image generation described in Appendix A, but replace the last 100 Myr in each region with a constant SFR. We consider two choices for this constant value. In the first case, we adopt the CMD-based 100 Myr average,  $\text{SFR}_{\text{CMD},100}$ . In the second, we adopt  $\text{SFR}_{\text{FUV}+24\mu\text{m}}$  from Figure 4.13. For both instances, we treat dust extinction the same as we did in Section 4.2.

We present the results from these tests in Figure 4.14. The top-left panel shows the observed *GALEX* FUV map measured on the PHAST spatial grid, while the top-middle and top-right panels show synthetic FUV images constructed after replacing the recent SFH in each region with a constant SFR equal to  $\text{SFR}_{\text{FUV}+24\mu\text{m}}$  and the 0–100 Myr CMD-based average, respectively. For reference, the bottom-left panel reproduces the synthetic FUV map generated from the full time-resolved CMD-derived SFHs shown in Figure 4.6. The two residual panels then show how the constant-SFR experiments depart from the observations.

These results demonstrate that a time-varying SFH is required to reproduce the observed FUV flux. In both of these tests, we fail to recover a synthetic FUV flux that is consistent with observations. Using a constant SFR set from the  $\text{SFR}_{\text{FUV}+24\mu\text{m}}$  values leads to a MAD of the squared residuals of 4.71 from the true observed FUV map shown in the top left panel of Figure 4.14 (and in Figure 4.6). If the constant SFR is instead set to the (higher) average value from the CMD-based SFR over the past 100 Myr, the MAD of the squared residuals are 4.28, which is smaller, but only slightly. Both values are around  $2.5\times$  worse than the residuals obtained when the full time-varying SFH is used (Figure 4.6).

Although both constant-SFR experiments perform poorly, they fail in systematically different ways. Setting the constant rate at the CMD-based 100 Myr average provides too much FUV light because more of the star formation during the interval has been pushed to more recent times, where the younger stellar ages will have larger contributions to the FUV for a given stellar mass. In this case, the fractional residual distribution [ (synthetic - observed) / observed ] is centered at 0.24, indicating that the synthetic flux is typically too high.



**Figure 4.14:** Comparison between the observed FUV emission and synthetic FUV maps constructed under different assumptions for the recent SFH. *Top left:* observed *GALEX* FUV flux, background-subtracted and measured on the PHAST spatial grid. *Top middle:* synthetic FUV map generated by setting the SFR in the last 100 Myr in each region with a constant SFR equal to  $\text{SFR}_{\text{FUV}+24\mu\text{m}}$ . *Top right:* synthetic FUV map generated by by setting the SFR in the last 100 Myr in each region with a constant SFR equal to the 0–100 Myr CMD-based average,  $\text{SFR}_{\text{CMD},100}$ . *Bottom left:* synthetic FUV map generated from the full time-resolved CMD-derived SFHs, reproduced from Figure 4.6 for direct comparison. *Bottom middle:* residual map for the constant- $\text{SFR}_{\text{FUV}+24\mu\text{m}}$  case, shown as  $\log_{10}(\text{observed}/\text{synthetic})$ . *Bottom right:* residual map for the constant- $\text{SFR}_{\text{CMD},100}$  case, shown in the same way. Both constant-SFR prescriptions fail to reproduce the observed FUV distribution as well as the full time-resolved SFHs.

In contrast, setting the constant rate to that inferred from the FUV+ 24  $\mu\text{m}$  method (i.e.  $\text{SFR}_{\text{FUV}+24\mu\text{m}}$ ) provides too little FUV flux compared to what is observed. In this case, the synthetic image systematically under-predicts the observed FUV emission, with the fraction residual distribution centered at  $-0.38$ . The amplitude of this underestimate is roughly consistent with the factor of 2 under-prediction of the CMD-based SFR established earlier in Figure 4.13 (see Section 7.1).

Overall, the failure of either constant SFR model to explain the observed FUV emission is due to the fact that the FUV is sensitive not just to the averaged rate of star formation over some time interval, but also depends on the detailed timing of star formation within that interval. Physically, the FUV emission is weighted most strongly toward short lived O and B stars with lifetimes shorter than 100 Myr, with a strong weighting toward ages of 30–50 Myr (e.g., Kennicutt & Evans, 2012; Kennicutt, 1998; Oti-Flornes & Mas-Hesse, 2010). This makes the FUV especially sensitive to the star formation rate over the last few to few tens of Myr, when the mass-to-light ratio is lowest. In contrast, when the star formation is primarily biased to later times, it takes more star formation to drive the observed flux, due to the higher mass-to-light ratio.

In the specific case of M31, the CMD-based  $\text{SFR}_{\text{CMD},100}$  averaged over 0–100 Myr is higher than the actual SFR at any point during the last  $\sim 40$  Myr (Section 5.1). When a larger 100 Myr average is imposed as a constant recent SFR, the synthetic population contains too many young massive stars and therefore over-predicts the observed FUV flux.

The FUV+24  $\mu\text{m}$  SFR constant value moves in the opposite direction. Because the FUV+24  $\mu\text{m}$  SFR indicator assumes a constant SFR when setting the conversion factor from FUV flux to an un-obscured SFR, it naturally assumes the presence of a significant fraction of young, low mass-to-light ratio stellar populations. However, in M31, these populations are not actually prevalent, because of the rapidly declining SFR in the galaxy. Because the FUV+24  $\mu\text{m}$  SFR values are systematically lower than the CMD-based 100 Myr average, imposing them as a constant recent SFR produces too little recent star formation and therefore too little FUV emission. In that case the deficit is not limited only to the most massive O and B stars, but also reflects an underproduction of the broader young stellar population contributing to the UV over the full  $\sim 100$  Myr interval.

In summary, the observed FUV flux can only be reproduced from the CMD-derived SFHs in their full time resolution. These tests demonstrate that the observed FUV emission is sensitive not just to the amount of recent star formation, but to its detailed timing. Standard FUV-based calibrations implicitly assume a much steadier recent SFH than what our analysis recovers for M31, where the SFR has declined substantially over the last  $\sim 100$  Myr. M31 therefore provides a clear example of how time variability in the recent SFH can produce a substantial systematic offset between CMD-based and FUV-based SFR estimates.

However, this declining SFR is unlikely to be the only contributor to the observed offset. Other studies have found non-negligible discrepancies, at the level of at least  $\sim 50\%$  in predicted FUV flux, even in systems where the recent SFH appears comparatively steady over the last 100 Myr (Lazzarini et al., 2022; McQuinn et al., 2015). Additional effects, including uncertainties in stellar evolution models (Section 3.4.2), IMF assumptions, photometric completeness (Section 2.3), dust geometry and covering fraction, and assumptions about the fraction of UV light that is reprocessed into observable infrared emission, also contribute at a non-negligible level. These systematics imply that the shape of the recent SFH alone cannot explain the CMD verse FUV offset in every system. Our M31 results do however, clearly show that variations in the recent SFH can be a dominant source of systematic error when applying standard FUV-based SFR calibrations.

The tension between the CMD-based and FUV+24  $\mu\text{m}$  SFR calibrators in M31 therefore appears to arise from the timescale over which FUV emission traces a time-varying recent SFH. This result underscores that absolute SFR calibrations in nearby galaxies still carry systematic uncertainties at the level of factors of a few, and more investigation will be needed on modeling the SFR across systems where systematic differences can be ruled out. For applications of the SFR in M31, we encourage readers to consider the full time varying SFH, opposed to a single, time averaged value.

## 8 Summary

In this paper we have used HST photometry from the PHAST survey (Chen et al., 2025) to map the recent star formation history across the southern disk of M31 at  $\sim 100$  pc resolution. By fitting optical color-magnitude diagrams in more than 6500 regions, we recover spatially resolved SFHs over the past  $\sim 500$  Myr that reveal the ring and arm structure of the southern disk and quantify

how the recent SFR varies in both space and time.

Because the PHAST analysis follows the same MATCH-based methodology as the northern PHAT survey, we can combine the two data sets into a single, internally consistent view of recent star formation over roughly two thirds of M31's star-forming disk. We summarize our main results as follows:

- *PHAST SFR:* Across the PHAST footprint, which covers a deprojected area of  $\sim 2.7 \times 10^2 \text{ kpc}^2$  in the southern disk, the mean SFR over the last 100 Myr is  $0.213 \pm 0.004 \text{ M}_\odot \text{ yr}^{-1}$ , with most recent star formation concentrated in the 10 kpc ring, the inner arm structure, and NGC 206.
- *A unified view over two thirds of the M31 disk from resolved stars:* Within the joint PHAT+PHAST footprint, which covers roughly two thirds of M31's star-forming disk, we measure a mean SFR of  $0.445 \pm 0.006 \text{ M}_\odot \text{ yr}^{-1}$  over the last 100 Myr. Extrapolating this value to the full star-forming disk, implies a SFR of  $\sim 0.67 \text{ M}_\odot \text{ yr}^{-1}$  for M31's total SFR.
- *M31's global decline in star formation:* Both the PHAT and PHAST maps show that the recent SFH is not constant in time. The CMD-based SFHs indicate a clear, galaxy-wide decline in the mean SFR from  $1 \text{ M}_\odot \text{ yr}^{-1} \sim 500 \text{ Myr}$  ago, decreasing to an average of  $0.285 \text{ M}_\odot \text{ yr}^{-1}$  in the last 20 Myr. This decline appears to be the late stages of a multi Gyr decline in star formation from a more active state. Because the rings host the majority of the recent star formation, changes in their activity have a predominant impact on the disk-averaged SFH, and account for a substantial fraction of the observed decline.
- *Quenching of the M32 region relative to the global average:* Within the PHAST footprint, the region surrounding M32 shows a distinct recent SFH compared to the disk as a whole. From 500 Myr to  $\sim 60 \text{ Myr}$  ago, the M32 region is statistically consistent with the global average SFR. At lookback times younger than  $\sim 60 \text{ Myr}$ , however, the SFR in this region drops well below the disk average, reaching a suppression of roughly a factor of three around 10–15 Myr ago. This localized quenching, adjacent to regions that show enhanced recent activity (such as the inner arm segment), highlights the strong environmental variations in M31's recent SFH on kiloparsec scales, possibly related to interacting with M32.
- *Comparison to FUV+24  $\mu\text{m}$  tracers:* We compare the CMD-based SFR surface densities, averaged over the last 100 Myr, to those inferred from FUV+24  $\mu\text{m}$  calibrations. Consistent with previous work, we find that the FUV based tracer systematically underestimates the CMD-based SFRs by a factor of approximately 2.1. At the same time, when we forward-model the PHAST SFHs and extinction parameters into a synthetic GALEX FUV image, the resulting map reproduces the observed FUV morphology quite well, which cannot be done with a constant SFR. This agreement suggests that the CMD-derived SFHs provide a self-consistent description of where and when recent star formation has occurred. The mismatch with FUV+24  $\mu\text{m}$  estimates underscores that tracers implicitly averaged over  $\sim 100 \text{ Myr}$  are not reliable when the recent SFR is evolving over that time.

These results provide the most complete resolved-star view to date of recent star formation across M31, combining PHAT and PHAST into a nearly contiguous map over two thirds of the star-forming disk.



*Facilities:* HST(ACS, WFC3)

*Software:* `astropy` (Astropy Collaboration et al., 2013, 2018, 2022), `Jupyter` (Kluyver et al., 2016), `matplotlib` (Hunter, 2007a), `numpy` (Harris et al., 2020), `python` (Van Rossum & Drake, 2009), `scipy` (Gommers et al., 2024; Virtanen et al., 2020a), `h5py` (Collette, 2013; Collette et al., 2023), `MATCH` (Dolphin, 2002), `FSPS` (Conroy & Gunn, 2010) (OpenAI, 2023)

## Appendix A. Creating Synthetic FUV images with FSPS

In Sections 4.2, and 7.2, we use the population synthesis code `FSPS` to generate synthetic FUV images. Here we describe the procedure used to derive these images.

We feed the `MATCH`-derived SFHs directly into `FSPS` using its tabular SFH mode. The `MATCH` SFHs are specified as lookback-time bins, each with constant SFR. We convert these bins to an absolute-time grid, re-normalizing the youngest bin so that it extends to zero lookback while conserving the total stellar mass formed, and treat the SFR as piecewise constant in each interval. For each region we adopt a single metallicity equal to the SFR-weighted mean  $[M/H]$  over the last 100 Myr, or the metallicity of the most recent non-zero SFR bin, and assume this value for the full SFH. We then evaluate the `FSPS` model at  $t_{\text{age}} = 13.8$  Gyr to obtain integrated, dust-free *GALEX* FUV and NUV AB magnitudes. We note that in following Lewis et al. (2017), we use the full time resolution of our SFH fits out to  $\log(\text{age} / \text{yr})$  of 10.15, which is required to accurately model the UV flux given that  $\sim 20\% - 30\%$  of the FUV emission comes from stars that are older than our adopted 500 Myr reliability threshold. A full discussion of this decision can be found in Appendix A of Lewis et al. (2017).

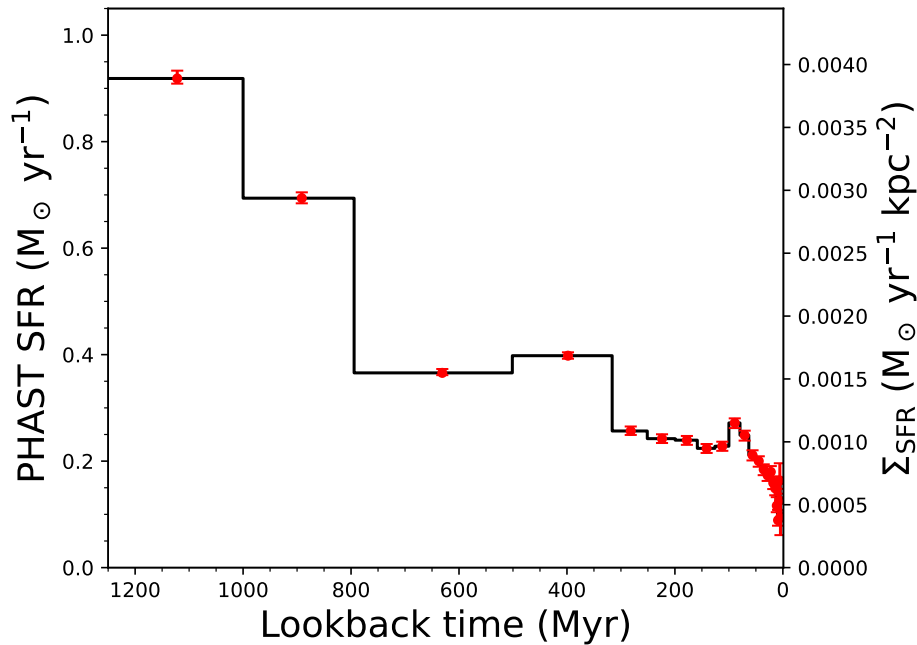
Dust attenuation is modeled using the Milky Way-like Cardelli et al. (1989) law with  $R_V = 3.1$ . To mimic the two-parameter extinction model used in the CMD fitting (Lewis et al., 2015, Section 2.2), we draw a set of 20 extinction values uniformly between  $A_V$  and  $A_V + dA_V$  (from Section 4.2), recompute the FUV and NUV magnitudes for each draw, convert each realization to  $f_\nu$ , and average in flux space. The resulting intrinsic and attenuated magnitudes are then converted to fluxes using the *GALEX* zero-points and placed on the PHAST spatial grid to construct synthetic UV images.

For the observed *GALEX* image, we subtract a uniform background/sky as described above. Before comparing the observed image to the simulated one, however, we choose to restrict our comparison only to well-measured image pixels, taken to be those that are more than  $3\times$  the background noise in the real *GALEX* image, when integrated over the area covered by the overlapping PHAST analysis region. We estimate an overall per-analysis-region  $1\sigma$  uncertainty from the global background root mean square, scaled by the effective number of observed *GALEX* image pixels covering the PHAST analysis region. We then compare this to the flux in the background-subtracted *GALEX* FUV image integrated over the matching simulated image pixel in the simulated PHAST image. We then only retained regions where the observed FUV flux exceeded the SNR=3 threshold.

## Appendix B. Pushing to Older Ages

Throughout this work, we have considered 500 Myr to be the limiting age where we can reliably recover the main sequence turnoff in our CMDs (Section 3.5). This threshold is the same limit used in L15, allowing for a seamless comparison between the analysis in the North and South. Additionally, this conservative limit allows us to maximize the amount of the disk we can reliably measure, and allows us to fully model the interior disk of M31 to look for Radial trends (Figure 4.10).

However, as we can see in Figure 4.1,  $\sim 89\%$  of the PHAST survey has a density lower than 1.5 stars per arcsecond<sup>2</sup>. From Figure 4.3, we can see that in these less dense regions, we can therefore reliably probe to somewhat older ages than what is considered in the main body of the manuscript.



**Figure 4.15:** The SFH for PHAST regions with a density less than 1.5 stars per arcsecond<sup>2</sup>, where our completeness limits allow us to probe older ages. Here we extend back to 1.2 Gyr, where we can reliably detect the MS turnoff above our completeness limit. We see a long decline in the SFR over this period of time.

Shown in Figure 4.15, are the SFH results for all PHAST regions with density lower than 1.5 stars per arcsecond<sup>2</sup>, extending back to 1.2 Gyr. These results are in striking agreement with the ancient SFH seen in PHAT (Williams et al., 2017). Additionally, these results help anchor Section 6.1, where we are observing a decline over several hundred Myr, extending back to the burst in SF M31 experienced 2-4 Gyr ago. What we observe in the last 500 Myr should then be interpreted as the tail of a longer decline.

## Appendix C. Testing Whether the Offset with FUV+ 24 $\mu\text{m}$ Tracers is Due in Part to the Handling of the IR and Dust Reprocessing

A natural explanation for the observed offset between the CMD derived 100 Myr average SFR, and FUV+ 24  $\mu\text{m}$  derived SFRs seen in Section 7 is that it arises in the infrared 24  $\mu\text{m}$  correction term, which is the component least directly constrained by the stellar populations measured in the CMD. The FUV+24  $\mu\text{m}$  calibration assumes that the 24  $\mu\text{m}$  emission provides a reliable correction for the UV light absorbed and reprocessed by dust. However, this assumption can break down when the SFR is changing. In particular, 24  $\mu\text{m}$  emission is dominated by dust heated by very young, deeply embedded massive stars and responds on timescales of only a few Myr (e.g., Kim et al., 2021; Kruijssen et al., 2018; Wainer et al., 2026b), whereas the CMD-derived SFRs are averaged over the last 100 Myr. In a system with a declining recent SFH, these two quantities are therefore not expected to match. In M31, where the SFR has declined significantly over the last  $\sim 40$  Myr, the IR-based correction term should naturally contribute less than what would be expected for a constant-SFR population, and be systematically lower than the 100 Myr-averaged SFR inferred from the resolved stellar populations, even if both methods are internally consistent. It is therefore possible that the FUV+24  $\mu\text{m}$  SFRs can become systematically offset from the CMD-based SFHs even when both are tied to the same recent stellar populations. Here we test this hypothesis directly.

First, we consider whether a simple recalibration of the FUV+24  $\mu\text{m}$  tracer could reconcile it with the CMD-based SFRs, we explored modifying the relative wavelength components in the Leroy et al. (2008) formula in Equation 4.1. Specifically, we re-fit the coefficients in Equation 4.1 to produce the CMD-based SFRs, while retaining its functional form. Equation 4.1 is then taken to be,

$$\Sigma\text{SFR}_{\text{FUV}+24\mu\text{m}} = \left( a_{\text{FUV}} I_{\text{FUV}} + a_{24} I_{24} \right) \cos i, \quad (4.2)$$

and we re-fit the coefficients  $a_{\text{FUV}}$  and  $a_{24}$ .

We find best-fit values of  $a_{\text{FUV}} = 0.36$  and  $a_{24} = 3.1 \times 10^{-3}$ . This refit substantially reduces the global normalization offset and improves the slope of the region-to-region residual, where the best-fit slope shifts to 0.42, closer to the 1.0 expected for the one-to-one relation, but still dramatically off base. Additionally, the improvement is mostly in the overall trend rather than in the local agreement. The MAD of the squared residuals is reduced by only  $\sim 3\%$  relative to the original Leroy et al. (2008) calibration, and the fractional residual distribution remains similarly broad, with an IQR of 0.165.

Therefore, refitting the coefficients improves the offset without addressing the underlying disagreement. In practice, the new coefficients bring the highest- $\Sigma_{\text{SFR}}$  regions into better agreement at the expense of over-predicting more of the lower- $\Sigma_{\text{SFR}}$  regions, and the remaining discrepancies appear as spatially coherent departures across the disk. This behavior argues against the offset being explained by a single missing scale factor or a simple renormalization of the FUV and 24  $\mu\text{m}$  terms. Instead, it suggests that the CMD-based and FUV based estimates are responding differently to the recent, time-variable SFH and to the local dust geometry.

Interestingly, the main change in the refit occurs in  $a_{\text{FUV}}$ , which increases by roughly a factor of four, while the best-fit  $a_{24}$  remains broadly consistent with the original calibration. This results points to the FUV term, rather than the 24  $\mu\text{m}$  term, as the dominant contributor to the mismatch,

a point we return to in Section 7.2. In fact, the regions with high levels of  $24\ \mu\text{m}$  emission are not the same as those with FUV emission, and any adjustment to the  $a_{24}$  terms results in notably worse scatter in the residuals.

Another possibility is that the problem lies specifically with the  $24\ \mu\text{m}$  band itself. If that were the case, one might try replacing the  $24\ \mu\text{m}$  term in Equation 4.1 with a longer-wavelength IR band or with a total-IR estimate (e.g., Boquien et al., 2016). However, a growing body of work suggests that both mid-IR and especially far-IR emission can be substantially powered by dust heated from evolved stellar populations rather than by the youngest massive stars (e.g., Bendo et al., 2012; Groves et al., 2012; Li et al., 2010; Whitcomb et al., 2023). In nearby spirals, analyses of the radial energy budget find that a significant fraction of the  $24\ \mu\text{m}$  flux, particularly in bulges and inner disks, arises from dust heated by older stars rather than embedded HII regions (e.g., Boquien et al., 2011; Leroy et al., 2012). At longer wavelengths, *Herschel* studies show that the bulk of the emission beyond  $\sim 160\ \mu\text{m}$  is often dominated by heating from the diffuse old stellar population, with only a minority of the far-IR luminosity directly linked to current star formation (e.g., Smith et al., 2012; Viaene et al., 2017).<sup>6</sup>

These results imply that simply switching from  $24\ \mu\text{m}$  to longer-wavelength IR, or to a total-IR term, would introduce an even larger and more spatially variable contribution from dust heated by old stars, rather than providing a clean fix to the discrepancy with CMD-based SFRs. Any attempt to recalibrate the FUV based indicators therefore has to explicitly account for both the timescale sensitivity of the FUV+IR combination and the local balance between young- and old-star dust heating, rather than assuming a single universal IR correction.

The tests shown here suggest that the offset observed between  $\Sigma\text{SFR}_{\text{CMD},100}$  and  $\Sigma\text{SFR}_{\text{FUV}+24\mu\text{m}}$  are not primarily caused by an incorrect treatment of embedded star formation traced by in the IR by dust-reprocessing. Although re-scaling the terms in Equation 4.1 can reduce the global normalization offset, it does not remove the spatially coherent residuals or substantially reduce the scatter. The primary culprit therefore appears to be the differing timescale sensitivity of the FUV in a rapidly evolving recent SFH.

<sup>6</sup>In M31 specifically, radiative-transfer modeling demonstrates that evolved stars dominate the heating of dust over most of the disk at  $\lambda \gtrsim 100\ \mu\text{m}$ , with young stars becoming energetically important only in the star-forming ring (e.g., Viaene et al., 2017).

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## CHAPTER 5

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# ON THE RELIABILITY OF THE FAR ULTRAVIOLET AS A TRACER OF STAR FORMATION IN THE FACE OF A EVOLVING STAR FORMATION RATE

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# 1 Introduction

The far-ultraviolet (FUV) luminosity of a galaxy is produced primarily by short-lived massive stars whose radiation dominates the integrated light at wavelengths near 1500 Å (e.g., Calzetti, 2013; Hao et al., 2011; Kennicutt & Evans, 2012; Kennicutt, 1998). As such, it has long been treated as one of the most direct tracers of recent star formation. Converting this luminosity into a star-formation rate (SFR), however, requires assumptions about the form of the recent star-formation history (SFH). Most commonly, this conversion factor assumes that the SFR has remained approximately constant. There is a natural timescale for the FUV emission, which is set by the lifetime of the young O and B stars that dominate the UV emission (e.g., Leroy et al., 2012; Madau et al., 1998). The FUV is therefore typically interpreted as tracing star formation over characteristic timescales of order  $\sim 100$  Myr (e.g., Boquien et al., 2014; Calzetti, 2013; Kennicutt & Evans, 2012; Kennicutt, 1998; Otí-Flóranes & Mas-Hesse, 2010), with theoretically calibrated factors explicitly calculating the FUV luminosity expected for constant star formation over the 100 Myr timescale.

In practice, the observed FUV luminosity is also strongly affected by dust attenuation (Buat et al., 2005; Burgarella et al., 2005; Kennicutt & Evans, 2012). A substantial fraction of the UV photons produced by young stars can be absorbed by dust and re-emitted at infrared wavelengths (Calzetti, 2013; Hao et al., 2011; Meurer et al., 1999). Therefore, hybrid prescriptions attempt to recover a more complete estimate of recent star formation by combining the detected FUV light with an additional correction for obscured SFR, based on the observed infrared emission in order to (Calzetti et al., 2007; Hao et al., 2011; Kennicutt et al., 2009). Among these, combinations of FUV and 24  $\mu\text{m}$ , FUV and total dust emission, have become especially common in nearby-galaxy and resolved studies (Boquien et al., 2016; Leroy et al., 2008, 2012, 2019).

However, even with corrections for dust, numerous studies have shown that SFRs inferred from the FUV are not always fully consistent with those derived from other recent star-formation diagnostics. Comparisons with  $\text{H}\alpha$  have long shown systematic differences between the two tracers, particularly in low-luminosity and low-SFR systems where the inferred  $\text{H}\alpha$  rates often fall below those derived from the FUV (e.g., Fetherolf et al., 2021; Lee et al., 2009; Padave et al., 2025; Tomičić et al., 2024). Realistic variations in the recent SFH can account for some, but not all of the offsets (Emami et al., 2019; Weisz et al., 2012). Similar tension also appears when FUV-based SFRs are compared with recent SFHs measured directly from resolved stellar populations, where the FUV based estimates tend to under-predict CMD based estimates by factors of 1.5 to 3 (Lazzarini et al., 2022; Lewis et al., 2015; McQuinn et al., 2015). These systematic offsets persist even after careful treatment of dust attenuation and explicit consideration of a non-evolving SFH (Lazzarini et al., 2022; McQuinn et al., 2015). These results emphasize the value of additional work to understand the biases and limitations of quantitative tracers of recent star formation. In this paper, we focus primarily on the FUV, and in particular, on the impact of the assumption of a constant SFR on 100 Myr timescale.

Previous work has also shown that departures from a constant recent SFH can affect the interpretation of UV-based SFR indicators, and the widely used constant-SFR approximation is itself an idealization (Cerviño et al., 2016). The central difficulty is that FUV emission is not produced by stars of a single age. Instead, the observed FUV luminosity reflects a weighted integral over the recent SFH, so variations over the last  $\sim 10$ –100 Myr can alter both the normalization and the effective timescale of the inferred SFR (Boquien et al., 2014; Flores Velázquez et al., 2021;

Johnson et al., 2013).

As a result, a standard FUV calibration does not recover a uniquely defined “recent SFR” when the underlying SFH is time-variable. The inferred value depends on how the true SFR has changed over the interval to which the FUV remains sensitive, and different SFH shapes can produce similar FUV luminosities while corresponding to a different true average over 100 Myr.

Highlighting the need for this revaluation is the fact that a broad range of observational and theoretical studies have shown that recent star formation can vary substantially on  $\sim 10$ –100 Myr timescales, both across entire galaxies and within smaller regions. At galaxy-wide scales, recent SFRs can decline as galaxies undergo longer timescale quenching or environmental suppression (e.g., Haines et al., 2015; Peng et al., 2015; Wetzel et al., 2013; Wright et al., 2019), while post-starburst systems provide a more extreme example of rapid recent evolution following an earlier episode of enhanced star formation (e.g., Chen et al., 2019; Wild et al., 2009, 2020). Recent SFRs can also rise or fluctuate, particularly when feedback-regulated gas cycling, renewed gas accretion, or bursty star formation drives short-timescale changes in the SFR (e.g., Davis et al., 2019; Faucher-Giguère, 2018; Hayward & Hopkins, 2017; Sparre et al., 2017).

At sub-galactic scales, the assumption of a constant recent SFR can break down even more dramatically. Individual regions may fade after a burst, respond to feedback-driven gas clearing, or reflect the short-lived evolution of molecular clouds and star-forming complexes (e.g., Chevance et al., 2020; Kruijssen & Longmore, 2014; Kruijssen et al., 2018, 2019). These local variations can produce discrepancies among SFR indicators that are different effective timescales, especially when comparing  $H\alpha$ , UV, and IR tracers on sub-kpc scales (e.g., Johnson et al., 2013; Lee et al., 2009; Simones et al., 2014).

Recent comparisons between resolved-star SFHs and integrated FUV-based SFRs suggest that this timescale issue may have already appeared in nearby galaxies. Lazzarini et al. (2022); Lewis et al. (2015, 2017) have shown large offsets between integrated CMD based SFHs averaged over 100 Myr, and FUV based SFR estimates in M31 and M33. Wainer et al. (2026c) recently argued that in M31, this offset was likely connected to the declining recent SFH. This result motivates a more general examination of what timescale an FUV-based SFR actually measures when the recent SFH is not constant.

In this work, we focus specifically on this problem by quantifying how a time-varying recent SFH changes the FUV luminosity and influences the SFR inferred from it. The FUV luminosity is not a snapshot of the instantaneous SFR. Instead, it is a luminosity weighted integral over the recent SFH, with the result that declining and rising histories can bias the inferred rate in different ways. The impact of bursts has recently been assessed using large scale galaxy simulations which find that the actual FUV timescale can be much shorter than the assumed 100 Myr, varying from  $\sim 10$  Myr to 100 for bursty systems (Flores Velázquez et al., 2021). Our goal is to build on these efforts, and explicitly quantify how strongly the inferred FUV SFR depends on the shape of the recent SFH, and over what range of timescales those effects become large enough to matter for practical measurements.

This paper is structured as follows. In Section 2, we describe our forward-modeling approach for generating synthetic stellar populations from an input SFH and converting the resulting FUV luminosity into an inferred SFR. In Section 3, we establish the baseline behavior of the FUV indicator for constant-SFR populations and quantify the systematic effects of different calibrations and IMF choices. In Section 4, we examine when the FUV flux is produced and use non-constant SFHs to identify the timescale over which the FUV luminosity most tightly constrains the recent

SFR. In Section 5, we test idealized rising and declining SFHs and compare the inferred FUV SFRs to true averages measured over different timescales. Finally, in Section 6, we discuss the implications for interpreting FUV-based SFRs in nearby and unresolved galaxies.

## 2 Methods

To isolate the impact of a changing recent SFH on the interpretation of FUV luminosity, we adopt a controlled forward-modeling approach. The goal of this experiment is to quantify the specific effect a non-constant SFH has on the FUV distribution in isolation, with the understanding that we are not reproducing the full complexity of observed galaxies. We therefore construct recent SFHs with known functional forms, and use stellar population synthesis to predict the intrinsic GALEX FUV luminosity produced by each history. We then apply a standard FUV-to-SFR calibration to recover the implied SFR. By comparing that recovered value to the known input history, we can directly measure how the shape of the recent SFH would affect the inferred FUV-based SFR.

This forward modeling approach is well suited to address the impact of time varying SFHs for two reasons. First, the analytic model isolates the temporal response of the FUV to the recent SFH without compounding effects from dust attenuation, dust geometry, metallicity evolution, or observational noise. Second, we can work in the deterministic limit of a fully sampled stellar population, so that any offsets between the recovered, and true SFRs, reflect the time dependence of the recent SFH alone rather than stochastic sampling of the stellar initial mass function. The work presented here is thus only intended to isolate the specific role of time-variable recent star formation, and not the additional layers of realism that could lead to additional bias and/or scatter in real world observations.

### 2.1 Synthetic UV Luminosities from FSPS

We compute synthetic UV luminosities using the Flexible Stellar Population Synthesis code (FSPS) (Conroy & Gunn, 2010; Conroy et al., 2009, 2010). FSPS provides a self-consistent framework for predicting the integrated light of a stellar population with an arbitrary recent SFH, while allowing the IMF, metallicity, and dust treatment to be held fixed. We use this framework to explore several complementary classes of recent SFHs, including constant star formation, smoothly rising and declining histories, and more irregular histories that fluctuate over the last 100 Myr.

For each of these models, we fix the stellar metallicity to solar. We do not include dust attenuation or dust re-emission, so all luminosities are intrinsic. Likewise, we do not include stochastic IMF sampling. Throughout this work adopt the FSPS default, Mist (Choi et al., 2016; Dotter, 2016) stellar evolution libraries. The resulting synthetic photometry is then interpreted as the expectation value for a fully sampled stellar population with the specified recent SFH.

Each model SFH is supplied to FSPS in tabular form, such that the SFHs is defined in look-back time bins spanning 0.2 Myr, and the stellar population is evaluated at each timestep. We then compute the GALEX FUV magnitudes for the simulated population at each time step. The FUV emission from the “present day” bin of each model history is set to denote what we would observe, and we convert these magnitudes to monochromatic FUV luminosities.

These synthetic FUV luminosity produced for a given SFH are then converted into an inferred SFR using the calibration of Kennicutt & Evans (2012) (See Section 3.3). Because the input

SFH is known exactly for every model, the comparison between recovered and truth can be made without ambiguity. The resulting offsets therefore reflect only the mismatch between the standard constant-SFR interpretation of the FUV and the time-dependent recent histories used to generate the synthetic luminosities.

### 3 Assessing Constant SFH Models

Before we can ask how a changing recent SFH biases the FUV, we first need to establish what the FUV flux produced from a truly constant-SFR actually predicts. In theory, recovering this baseline sounds straightforward. In practice; however, existing conversions which take observed FUV luminosity and convert to a SFR depend on several assumptions that are often folded into standard FUV calibrations without necessarily being made explicit. Those assumptions include the exact functional form used to convert FUV luminosity into SFR, the IMF used to define the underlying stellar population, and the finite time interval over which the population is assumed to have formed stars at a steady rate. Before introducing any time variation in the recent SFH, we therefore first explore the properties of current calibrations and the impact IMF has to simplest possible case, a population with a truly constant recent SFR.

#### 3.1 A Constant SFH, and When the FUV is Produced

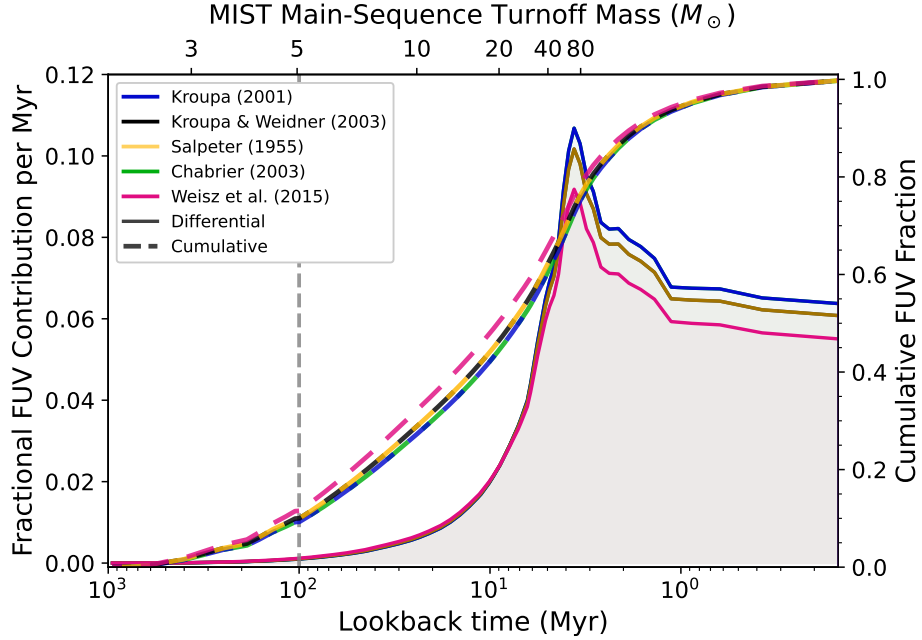
We begin by generating a  $1 M_{\odot}$  per year, constant-SFR models in FSPS evaluated every 0.25 Myr, from 1 Gyr ago to the present. The total formed mass is therefore  $10^9 M_{\odot}$ . For this baseline, we compute stellar populations using a variety of IMFs assumed in the literature, including: the Kroupa (2001) Salpeter (1955), Chabrier (2003) IMFs, and the Kroupa & Weidner (2003)<sup>1</sup> version. Additionally, recent evidence suggests that the high-mass IMF slope in nearby galaxies is steeper than these canonical values (Wainer et al., 2024b; Weisz et al., 2015).

Because the input SFH does not change, any age dependence in the emitted FUV light reflects the stellar-population response itself rather than variations in the recent SFR, providing a clean baseline for measuring how the FUV luminosity weights stars of different ages before introducing non-constant SFHs. Intrinsically, the present-day FUV luminosity is not produced uniformly by all stars formed over the last 100 Myr. Young massive stars contribute disproportionately to the FUV flux, while older populations contribute progressively less as the most massive stars leave the main sequence, and subsequently cease to exist.

We quantify this weighting by constructing the present-day FUV response as a function of lookback time,  $t$ . For each time bin in the constant-SFR model, we compute the fraction of the total present-day FUV luminosity contributed per Myr by stars formed at that lookback time. This differential response shows which stellar ages dominate the observed FUV flux. We also compute the cumulative contribution from stars older than  $t$ , such that at present day all the FUV flux is produced by stars older than  $t = 0$ .

The results are shown in Figure 5.1. The solid curves corresponding to the left axis shows the differential contribution to the present-day FUV luminosity, while the dashed line corresponding to the right axis shows the cumulative fraction of FUV luminosity contributed by stars older than  $t$ . As expected, the response is strongly weighted toward young populations peaking at 13 Myr, with

<sup>1</sup>We note that we use the form of the Kroupa & Weidner (2003) IMF as described in Kennicutt & Evans (2012).



**Figure 5.1:** Time dependence of the present-day FUV response for constant-SFR populations generated with different IMFs. Left axis: fractional contribution to the total FUV luminosity per Myr as a function of lookback time, shown with solid lines. Right: cumulative fraction of the total FUV luminosity contributed by stars younger than a given lookback time, shown with dashed lines. The FUV luminosity is dominated by young stellar populations, but a substantial fraction is contributed by stars formed from populations older than 10 Myrs, demonstrating that FUV-based SFRs are intrinsically weighted averages over the recent SFH.

fractional contributions of less than 1% per Myr coming from lookback times larger than 10 Myr. However for each of the IMF models, around 50% of the cumulative FUV luminosity is produced by stars older than  $t = 13$  Myr. Additionally, we see  $\sim 10\%$  contributions to the FUV flux from times older than 100 Myr.

### 3.2 IMF Dependence

The FUV-to-SFR calibration critically depends on the adopted stellar IMF. This dependence is especially important for the FUV emission because the luminosity is dominated by the most massive stars, so even modest changes in the high-mass IMF slope can alter the inferred SFR at a fixed UV luminosity. In this section, we quantify the effect the different IMF forms shown in Figure 5.1 have on the resulting FUV flux distribution. The results are summarized in Table 5.1. For the different forms of the IMF, we express each power-law segment as  $dN/dM \propto M^{-\alpha_i}$ , where  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_3$  apply over 0.1–0.5, 0.5–1, and 1–100  $M_\odot$ , respectively.

Despite the differences in IMF form, the normalized FUV response curves for each population show substantial overlap (Figure 5.1). The Kroupa (2001) and Chabrier (2003) forms produce nearly identical normalized age distributions because they have the same high-mass slope. Likewise, the Kroupa & Weidner (2003) and Salpeter (1955) curves overlap almost exactly: both have



| IMF                     | $\alpha_1$         | $\alpha_2$       | $\alpha_3$ | $\Delta L_{\nu, \text{FUV}} / L_{\nu, \text{FUV}}^{\text{KW03}}$ | $t_{20}$ [Myr] | $t_{50}$ [Myr] | $F(> 100 \text{ Myr})$ |
|-------------------------|--------------------|------------------|------------|------------------------------------------------------------------|----------------|----------------|------------------------|
|                         | $0.1 \leq M < 0.5$ | $0.5 \leq M < 1$ | $M \geq 1$ |                                                                  |                |                |                        |
| Kroupa & Weidner (2003) | 1.30               | 1.30             | 2.35       | 0.0%                                                             | 44.1           | 7.5            | 10.0%                  |
| Kroupa (2001)           | 1.30               | 2.30             | 2.30       | -12.0%                                                           | 40.1           | 7.0            | 9.2%                   |
| Salpeter (1955)         | 2.35               | 2.35             | 2.35       | -41.1%                                                           | 44.1           | 7.5            | 10.0%                  |
| Chabrier (2003)         | lognormal          |                  | 2.30       | -6.5%                                                            | 40.1           | 7.0            | 9.2%                   |
| Weisz et al. (2015)     | 1.30               | 2.30             | 2.45       | -32.2%                                                           | 52.7           | 9.0            | 11.5%                  |

**Table 5.1:** Dependence of the 0–1 Gyr FUV response on the adopted IMF. All three indices obey  $dN/dM \propto M^{-\alpha_i}$  over the mass ranges listed in the header, where masses are in units of  $M_\odot$ . In the alternative convention  $dN/d \log M \propto M^{-\Gamma}$ , the high-mass slope is  $\Gamma = \alpha_3 - 1$ . The Chabrier IMF is lognormal below 1  $M_\odot$  and therefore has no fixed  $\alpha_1$  or  $\alpha_2$ . We adopt the two-piece Kroupa–Weidner (2003) form presented by Kennicutt & Evans (2012); luminosity differences are measured relative to this model. The cumulative times satisfy  $F(> t_{20}) = 0.20$  and  $F(> t_{50}) = 0.50$ .

$\alpha = 2.35$  over the mass range that dominates the FUV emission, while their different low-mass behavior primarily changes the normalization per unit total stellar mass. The clearest change in shape occurs for the Weisz et al. (2015) IMF. Its steeper high-mass slope reduces the relative contribution from the youngest, most massive stars and shifts a larger fraction of the FUV emission toward older ages.

As a result of the similar functional form of each response curve, the cumulative timescales remain similar across the five models. We define  $t_{20}$  and  $t_{50}$  by  $F(> t_{20}) = 0.20$  and  $F(> t_{50}) = 0.50$ , where  $F(> t)$  is the fraction of the present-day FUV luminosity produced by stars older than lookback time  $t$ . The standard IMF prescriptions yield  $t_{20} = 40.1$ – $44.1$  Myr and  $t_{50} = 7.0$ – $7.5$  Myr, while the steeper Weisz et al. (2015) IMF increases these values to 52.7 and 9.0 Myr, respectively. Similarly, stars older than 100 Myr contribute 9.2–10.0% of the FUV luminosity for the standard forms and 11.5% for the Weisz et al. (2015) form. Thus, changing the IMF modifies the effective FUV timescale, but only modestly for the prescriptions considered here.

In contrast, the effect of the IMF on the total FUV luminosity is considerably larger than its effect on the response timescale. Relative to the adopted Kroupa & Weidner (2003) model, the final FUV luminosity of the 1 Gyr constant-SFH population is 12.0% lower for Kroupa (2001), 6.5% lower for Chabrier (2003), 41.1% lower for Salpeter (1955), and 32.2% lower for Weisz et al. (2015). Across the full set of models, the Chabrier (2003) population produces approximately 59% more FUV luminosity per unit SFR than the Salpeter (1955) population.

Because an FUV-based SFR is linear in the adopted luminosity conversion, these normalization differences map directly into systematic offsets when a calibration derived for one IMF is applied to a population described by another. Relative to the Kroupa & Weidner (2003) model, the mean absolute normalization offset among the IMF prescriptions considered here is approximately 18%, with an rms offset of approximately 24%. We therefore associate a characteristic systematic uncertainty of order 20% with the IMF dependence of the FUV-to-SFR conversion, while noting that individual IMF choices can produce offsets as large as approximately 40%.

### 3.3 Different FUV Calibrations

Having established the IMF dependence, we now ask how well each published FUV conversion recovers the constant SFH when evaluated on the most appropriate stellar-population scale available for that calibration. We first compare several standard FUV calibrations applied to synthetic

| Calibration              | Associated IMF          | $\log_{10} C_{\text{FUV}}$ | $\text{SFR}_{\text{FUV}, 100 \text{ Myr}}$ | $\text{SFR}_{\text{FUV}, 1 \text{ Gyr}}$ |
|--------------------------|-------------------------|----------------------------|--------------------------------------------|------------------------------------------|
| Salim et al. (2007)      | Chabrier (2003)         | -43.45                     | 0.761                                      | 0.839                                    |
| Leroy et al. (2019)      | Chabrier (2003)         | -43.42                     | 0.815                                      | 0.899                                    |
| Hao et al. (2011)        | Salpeter (1955)         | -43.17                     | 0.899                                      | 0.999                                    |
| Hao et al. (2011)        | Kroupa & Weidner (2003) | -43.35                     | 1.017                                      | 1.130                                    |
| Kennicutt & Evans (2012) | Kroupa & Weidner (2003) | -43.35                     | 1.017                                      | 1.130                                    |

**Table 5.2:** Recovery of an input constant SFR of  $1 \text{ M}_{\odot} \text{ yr}^{-1}$  after 100 Myr and 1 Gyr of continuous star formation, with each FUV conversion evaluated on its associated IMF or empirical SFR scale. Both recovered SFR columns are in  $\text{M}_{\odot} \text{ yr}^{-1}$ , and the rows are ordered by the 100 Myr result. The Leroy et al. (2019) coefficient is the median of the GSWLC (Salim et al., 2016) distribution; its quoted uncertainty is the 16th–84th percentile scatter and is not included in the tabulated central recovered SFRs.

constant-SFR models from Section 3, with the aim of identifying the prescription that most closely reproduces the input SFR for a constant 100 Myr reference case in our FSPS setup. For each calibration, we make sure to use the appropriate stellar-population generated from the IMF each specific calibration was calibrated against.

Several closely related FUV-to-SFR conversions are widely used in the literature, but they differ at a level that is non-negligible for the present problem. To place them on the same footing, we write each calibration in the form,

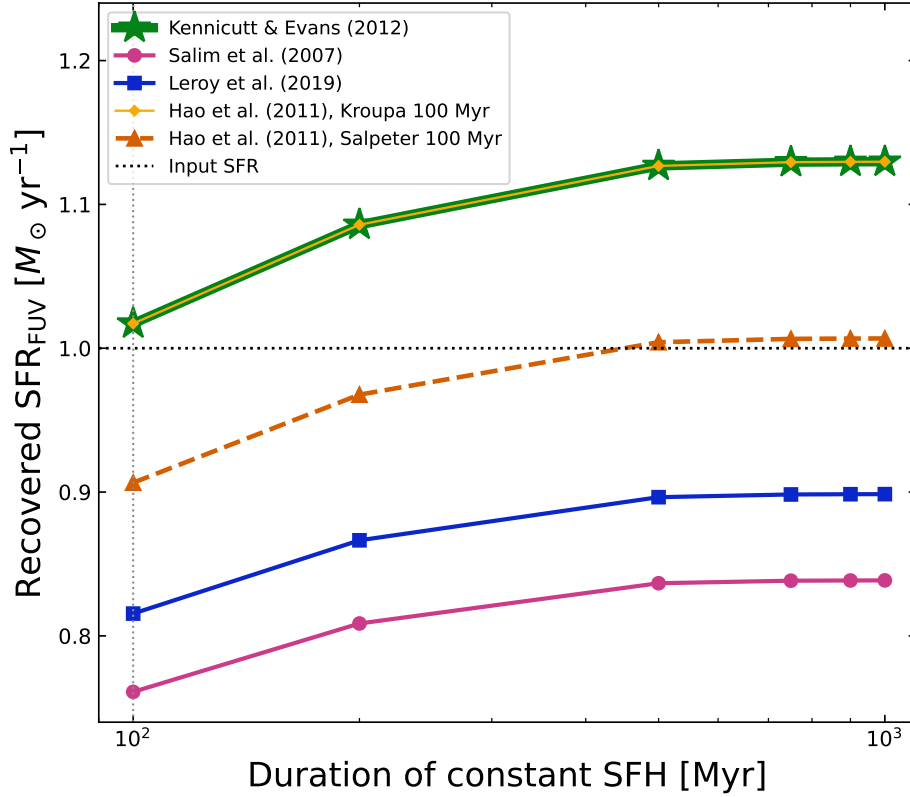
$$\text{SFR}_{\text{FUV}} = C_{\text{FUV}} \nu L_{\nu}, \quad (5.1)$$

where  $\nu L_{\nu}$  is the intrinsic FUV luminosity in  $\text{erg s}^{-1}$ , with  $\nu = c/\lambda_{\text{eff}}$  evaluated at the effective wavelength of the *GALEX* FUV band, which we adopt as  $\lambda_{\text{eff}} = 1516 \text{ \AA}$  (Martin et al., 2005). Defining  $\nu$  in this way ensures consistency with the FUV luminosities derived from our FSPS FUV-band luminosity density.

The prescriptions considered here are summarized in Table 5.2, where we list the adopted values of  $\log C_{\text{FUV}}$ , the IMF the model assumed, and the recovery over the last 100 Myr.

The recovery results from each of these conversions are shown in Figure 5.2. At 100 Myr, the recovered SFRs range from 0.761 to  $1.017 \text{ M}_{\odot} \text{ yr}^{-1}$ . The Kennicutt & Evans (2012) prescription most nearly reproduces the input constant SFR in our FSPS calculation, recovering  $1.017 \text{ M}_{\odot} \text{ yr}^{-1}$ , only 1.7% above the input value. The Kroupa-like Hao et al. (2011) conversion gives the same recovery when evaluated consistently at  $1516 \text{ \AA}$ , because the two prescriptions adopt the same FUV conversion coefficient. Across the full set of calibration–population pairings, we find the choice of FUV calibration introduces an approximately 25% systematic normalization range among the prescriptions considered here.

We note two nuances for the Hao et al. (2011) comparison. Hao et al. (2011) explicitly attribute the “Kroupa” model to Kroupa & Weidner (2003), not to Kroupa (2001), so here we associate it with the same adopted  $(\alpha_1, \alpha_2, \alpha_3) = (1.3, 1.3, 2.35)$  response used above, although the exact functional form of the Hao et al. (2011) model is not specified. Additionally, the values in Table 5.2 use  $\nu = 1516 \text{ \AA}$ , as in Equation 5.1. However, Hao et al. (2011) instead define their calibration using  $1528 \text{ \AA}$ . If we leave their tabulated  $C_{\text{FUV}}$  unchanged and alter only  $\nu$  to match their  $1528 \text{ \AA}$  definition, the corresponding recoveries are  $1.009$  and  $0.899 \text{ M}_{\odot} \text{ yr}^{-1}$  at 100 Myr and  $1.121$  and  $0.999 \text{ M}_{\odot} \text{ yr}^{-1}$  at 1 Gyr.



**Figure 5.2:** Recovered SFR from FUV flux produced for constant-SFR  $F_{\text{SPS}}$  models as a function of the duration over which the input SFR is held fixed. The horizontal dashed line marks the input SFR of  $1 \text{ M}_{\odot} \text{ yr}^{-1}$ . Calibration and IMF have a profound impact on the recovered SFR creating differences as large as  $\sim 20\%$  for the cases considered here. Extending the constant-SFR duration beyond 100 Myr increases the recovered SFR by a nearly common amount of  $\sim 10\%$  in all models relative to the 100 Myr value. Over 100 Myr intervals, we find the [Kennicutt & Evans \(2012\)](#) prescription most closely reproduces the input constant SFR, and adopt it throughout the rest of this work.

Because the main goal of this paper is to isolate the effect of time variability in the recent SFH, we adopt the [Kroupa & Weidner \(2003\)](#) IMF with the [Kennicutt & Evans \(2012\)](#) calibration normalization for the remainder of the analysis. We do not claim that this pairing is intrinsically more accurate than the other prescriptions considered here. Rather, it keeps the zeropoint of the constant 100 Myr control close to the input SFR, uses the same explicitly defined IMF response with the consistent  $\nu$  definition used in  $F_{\text{SPS}}$ .

From Figure 5.2, the [Leroy et al. \(2019\)](#) result is particularly informative because its calibration is derived from observations of real galaxies. Our primary comparison uses only their median coefficient. Propagating the quoted  $\pm 0.10$  dex interval would broaden the recovered 100 Myr SFR from the central value of  $0.815$  to  $0.648\text{--}1.027 \text{ M}_{\odot} \text{ yr}^{-1}$ . For the 1 Gyr population, the median coefficient recovers  $0.899 \text{ M}_{\odot} \text{ yr}^{-1}$ , making it the closest to unity at that duration. The better agreement at 1 Gyr is qualitatively interesting because the GSWLC ([Salim et al., 2016](#)) calibration is anchored to galaxies with possibly extended and composite SFHs, for which populations older

than 100 Myr can contribute to the observed FUV luminosity.

Additionally, for every calibration–population pairing, extending the constant-SFR duration beyond 100 Myr increases the recovered SFR because stars older than 100 Myr continue to contribute to the integrated FUV luminosity. By 1 Gyr, the recovered values have increased by approximately 10–11% relative to the 100 Myr case. This result is also expected given the percentages of FUV luminosity that comes from times older than 100 Myr from Table 5.1. This common duration dependence provides a useful reference for the contribution of populations outside the nominal 100 Myr interval and is consistent with earlier work showing that older stars can contribute meaningfully to the observed FUV emission (Johnson et al., 2013).

## 4 Multiple Paths the Same FUV Luminosity

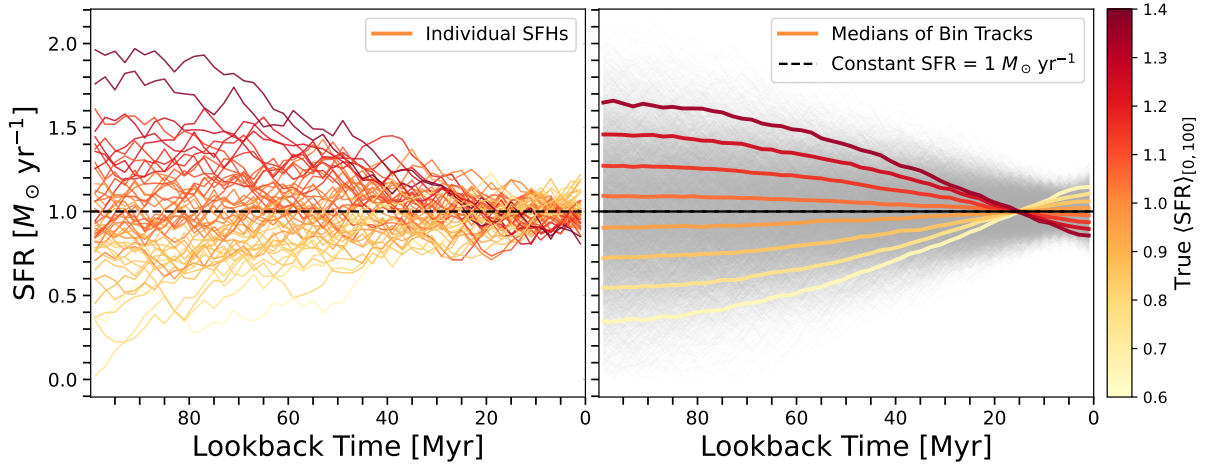
The previous section established the normalization of our FUV-based SFR measurements under the idealized assumption of a constant recent SFR. However, an additional relevant question is not only how much FUV luminosity is produced by a constant-SFR population, but rather *when* that luminosity was produced, and what impact this timing has on the inferred SFR. In this section, we answer this line of questions in a few contexts. First, for the constant SFH history described above, we quantify when the FUV luminosity was produced. We then discuss the ways in which that same FUV luminosity can be created from a non-constant SFH in the last 100 Myr, and measure timescales that minimize the uncertainty in the SFR estimation.

### 4.1 Degenerate SFHs

While constant SFR models are used for calibrating FUV-SFR conversions discussed in Section 3.3, many many different histories can produce nearly the same integrated FUV flux. To illustrate this point, we construct a large ensemble of synthetic SFHs that produce nearly the same FUV flux as our constant  $1 \text{ M}_{\odot}, \text{yr}^{-1}$  history over the last 100 Myr. Each SFH is divided into 50 bins of width 2 Myr. The starting SFR for each SFH is set to be between 0 and  $2.5 \text{ M}_{\odot}, \text{yr}^{-1}$ , with the additional constraint that adjacent bins cannot differ by more than  $0.1 \text{ M}_{\odot}, \text{yr}^{-1}$ . This produces smooth, but flexible recent SFHs that can rise, decline, or fluctuate over the 100 Myr interval. For each realization, we use the FUV response function from Figure 5.1 to compute the expected present-day FUV luminosity, and then generate 10,000 models whose total FUV luminosity is within 1% of the constant-SFR reference model. Thus, every synthetic SFH model would be assigned essentially the same FUV-inferred SFR, even though the underlying recent SFHs may differ substantially.

We present these SFHs in Figure 5.3, which emphasizes that the FUV constraint does not select a unique recent SFH, even when the models are required to reproduce the constant-SFR reference luminosity to within 1%. The left panel shows a random subset of SFHs, colored by their true 100 Myr average SFR,  $\text{True } \langle \text{SFR} \rangle_{[0,100]}$ , while the right panel shows the full ensemble of models in gray together with median SFH tracks for models grouped by  $\text{True } \langle \text{SFR} \rangle_{[0,100]}$ . In both panels, the dashed horizontal line marks the constant  $1 \text{ M}_{\odot}, \text{yr}^{-1}$  reference model.

Although each SFH would be measured at the same SFR from FUV luminosity alone, the underlying histories span a broad range of shapes. At larger lookback times, especially beyond  $\sim 25$  Myr, the envelope of allowed SFHs expands substantially. This increasing diversity emphasizes



**Figure 5.3:** Different recent SFHs that produce nearly the same present-day FUV luminosity. Left: 50 random SFHs, each with a total FUV luminosity within 1% of the constant  $1 M_{\odot}, \text{yr}^{-1}$  reference model, colored by the true average SFR over the 100 Myr history,  $\text{True } \langle \text{SFR} \rangle_{[0,100]}$ . Right: the gray lines shows all 10,000 SFH models, while the median values for groups of SFHs with different  $\text{True } \langle \text{SFR} \rangle_{[0,100]}$  are shown by the colored lines. In both panels, the dashed horizontal line marks the constant-SFR case. The model SFHs can have different true recent averages even though they would be assigned nearly the same FUV-inferred SFR, illustrating that a single FUV luminosity does not uniquely determine the recent SFH.

the point that the FUV luminosity does not necessarily indicate the SFH has remained close to  $1 M_{\odot}, \text{yr}^{-1}$  over the full 100 Myr interval. Additionally, the median tracks seen in the right panel all cross around a lookback time of  $\sim 13$  Myr, indicating that models with different 100 Myr averages can compensate for differences at older ages through corresponding, although smaller in amplitude, differences in their youngest populations. A single FUV luminosity therefore constrains an age-weighted recent average, but does not uniquely determine the detailed history past a few tens of Myr.

## 4.2 Timescales that Minimize Uncertainty

The degeneracy shown in Figure 5.3 indicates that the SFR inferred from FUV luminosity becomes more uncertain at larger lookback times, where significant departures in possible SFHs are prevalent. The most natural question is then: if not 100 Myr, over what timescale does the FUV luminosity provide the most reliable estimate of the true recent average SFR?

When considering different timescales, there is an inevitable tug of war between the two extremes. If the averaging window is too short, then a substantial fraction of the observed FUV light is produced by stars older than the window being measured. If the averaging window is too long, then the ensemble of SFHs that reproduce the FUV luminosity can have increasingly different true SFRs over that interval. The preferred timescale should therefore balance these two effects.

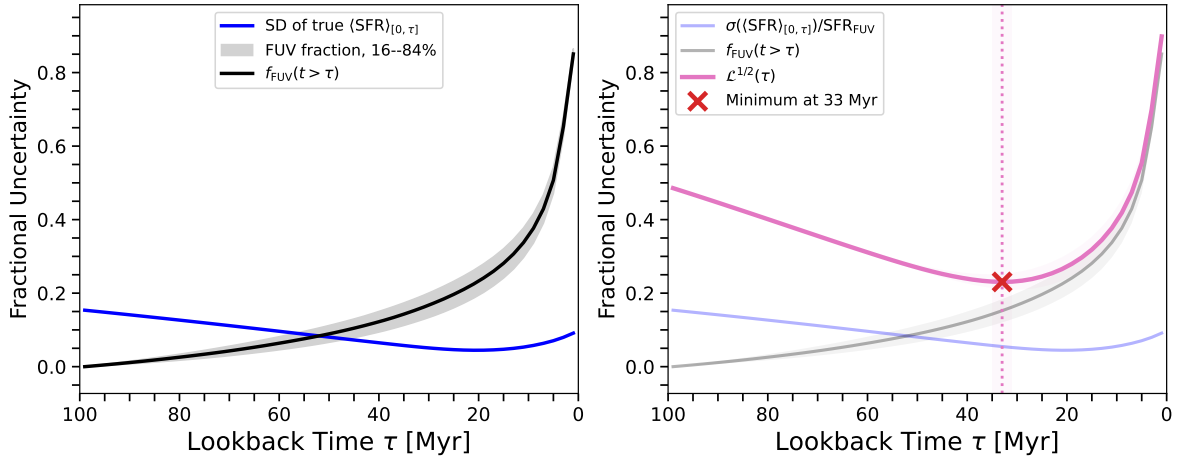
We attempt to quantify this balance by considering each component of uncertainty directly from the model SFHs in Figure 5.3. For each choice of  $\tau$ , we first compute the true average SFR over the interval from the present to that lookback time,  $\langle \text{SFR} \rangle_{[0,\tau]}$ , for every SFH. The width of



this distribution as a function of lookback time,  $\sigma(\langle \text{SFR} \rangle_{[0, \tau]})$ , measures how precisely the FUV luminosity constrains the True  $\langle \text{SFR} \rangle_{[0, \tau]}$ . A narrow distribution means that all SFHs have similar true averages over than time interval, while a broad distribution means that the FUV measurement is consistent with a wide range of underlying true averages.

Next, we compute the fraction of the total FUV luminosity produced by stars older than  $\tau$ ,  $f_{\text{FUV}}(t > \tau)$ . This term measures how much of the observed FUV light originates outside the averaging window being tested. Together, these two quantities provide a way to evaluate whether a chosen  $\tau$  is both well constrained by the model SFHs, and inclusive of the stellar populations that produce the FUV emission.

We quantify these two effects in left panel of Figure 5.4, which shows both terms as a function of averaging timescale  $\tau$ . The blue curve shows the model-to-model scatter in  $\langle \text{SFR} \rangle_{[0, \tau]}$ , normalized by the FUV-inferred SFR. The black curve shows the median value of  $f_{\text{FUV}}(t > \tau)$  across all SFH models, with the shaded region indicating the 16–84% range. The blue curve increases toward older lookback times because the model SFHs diverge more at at these lookback times. In contrast, the black curve decreases toward larger  $\tau$ , because longer averaging windows include more of the stellar populations responsible for the observed FUV light. Thus, short windows exclude larger portions of the FUV-producing population (increasing the uncertainty), while long windows suffer from increased SFH degeneracy.



**Figure 5.4:** Uncertainty diagnostics used to identify the averaging timescale over which the FUV luminosity most robustly constrains the recent SFR. Left: the blue curve shows the model-to-model scatter in the true average SFR measured over the interval  $[0, \tau]$ ,  $\sigma(\langle \text{SFR} \rangle_{[0, \tau]})$ , normalized by the FUV-inferred SFR. The black curve shows the median fraction of the total FUV luminosity produced by stars older than  $\tau$ ,  $f_{\text{FUV}}(t > \tau)$ , with the gray shaded region showing the 16–84% range across the accepted SFHs. Right: the same two dimensionless terms are combined into the empirical loss function,  $\mathcal{L}^{1/2}(\tau) = [10(\sigma(\langle \text{SFR} \rangle_{[0, \tau]}) / \text{SFR}_{\text{FUV}})^2 + f_{\text{FUV}}(t > \tau)^2]^{1/2}$ . The minimum in this loss function is marked by the red ‘x’, and occurs at  $\tau \approx 33$  Myr.

However, these two terms should not be interpreted as strictly equivalent sources of uncertainty. The older-FUV term represents the fraction of the luminosity produced outside the chosen window, but importantly, the impact of that light depends on how uncertain the SFH is at those older ages. If the SFH is tightly constrained at times older than  $\tau$ , then including additional FUV light from

those populations does not necessarily introduce a large uncertainty. Conversely, if the older SFH is poorly constrained, then contributions from these populations can complicate the interpretation of the FUV luminosity.

To reflect this distinction, we define an empirical loss function that gives primary weight to minimizing the scatter in the true averaged SFR, while still penalizing FUV emission produced by populations older than the chosen window,

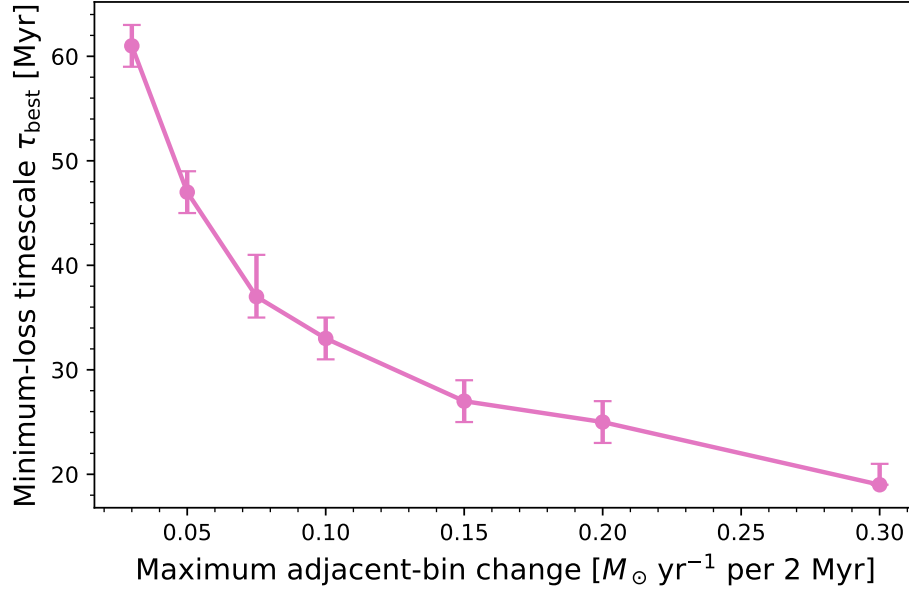
$$\mathcal{L}^{1/2}(\tau) = \left[ 10 \left( \frac{\sigma(\langle \text{SFR} \rangle_{[0,\tau]})}{\text{SFR}_{\text{FUV}}} \right)^2 + f_{\text{FUV}}(t > \tau)^2 \right]^{1/2}. \quad (5.2)$$

The  $\left( \frac{\sigma(\langle \text{SFR} \rangle_{[0,\tau]})}{\text{SFR}_{\text{FUV}}} \right)$  term penalizes timescales for which a broad range of SFHs can all produce the same FUV flux. The  $f_{\text{FUV}}(t > \tau)$  term then penalizes timescales for which a large fraction of the observed FUV luminosity is produced by stars older than the averaging window. The factor of 10 is a weighting choice rather than a universal calibration. While changing this weighting term changes the numerical output of the loss function, the interpretation remains the same. Functionally, this weighting encodes the purpose of the loss function, which is to identify the timescale over which the FUV luminosity most tightly predicts the true averaged SFR, while treating older-population FUV emission as a secondary penalty.

The right panel of Figure 5.4 shows the same two dimensionless uncertainty-components from the left panel, while the pink line shows our loss function,  $\mathcal{L}^{1/2}(\tau)$ . Within the framework of this experiment, the minimum of the loss function occurs at  $\tau \approx 33$  Myr, marked by the ‘x’. This result indicates that the averaging window that minimizes the combined uncertainty from out-of-window FUV emission and SFH degeneracy is much shorter than the canonical 100 Myr timescale.

However, this  $\sim 33$  Myr preferred averaging timescale is derived under the adopted SFH prior, FUV-matching tolerance, and loss-function weighting. In particular, the exact loss function minimum depends on how much structure we allow in the recent SFH. This dependence is, however, expected. If the SFHs are close to constant, then the true  $\langle \text{SFR} \rangle_{[0,\tau]}$  remains well constrained even at large  $\tau$ , and the contribution of FUV light from older stars becomes less problematic. In this constant, or near constant regime, the standard  $\sim 100$  Myr interpretation becomes increasingly appropriate. Conversely, as the allowed SFHs become more time-variable, the ensemble of histories that reproduce the same FUV luminosity can diverge more strongly at older lookback times. The loss function then shifts toward shorter averaging windows, closer to the timescale where the FUV response curve is most strongly weighted (i.e., Figure 5.1).

We test this dependence directly by repeating the experiment over a grid of maximum allowed SFR changes between adjacent 2 Myr bins. The results are shown in Figure 5.5, where the x-axis is the maximum step allowed, and the y-axis is the loss function minimum. As the allowed bin-to-bin variability increases, the minimum of the loss function moves to shorter timescales, demonstrating that within this framework, the “best” averaging window is sensitive to the assumed smoothness of the recent SFH.



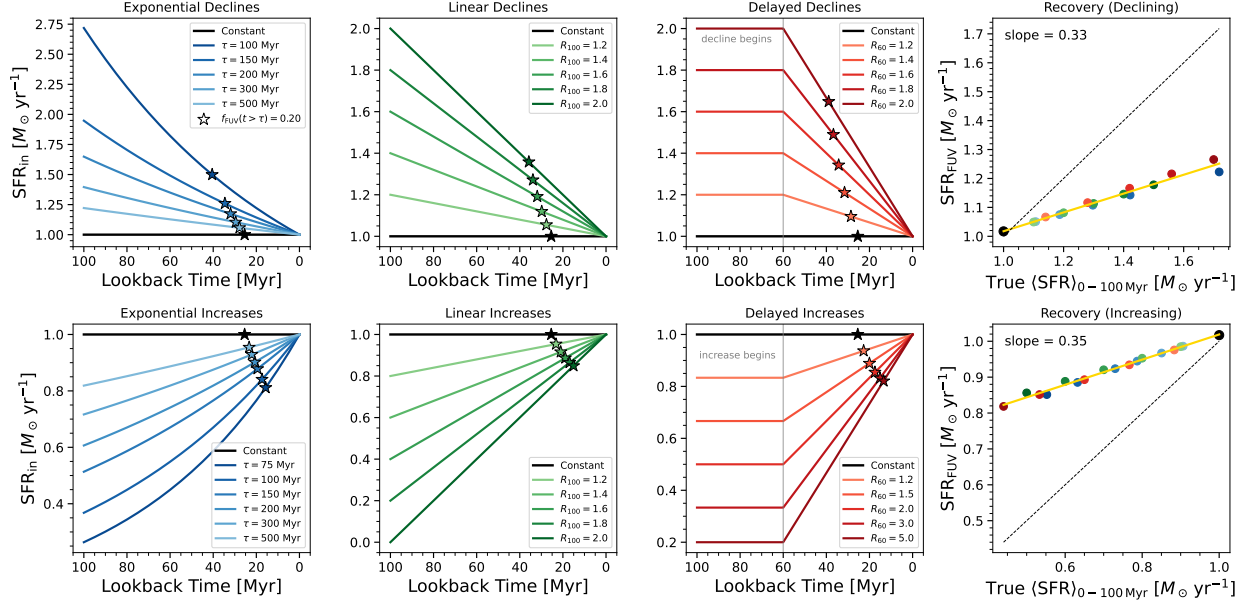
**Figure 5.5:** Effect of the amount of short-timescale variability on the best-fit minimum-loss timescale. The x-axis gives the maximum allowed change in SFR between adjacent 2 Myr bins, while the y-axis shows the minimum-loss value of  $\tau_{\text{best}}$ . Smaller allowed bin-to-bin changes force the model toward smoother SFHs and favor longer characteristic timescales, while larger allowed changes permit more rapid variability and shift the minimum-loss solution to shorter timescales. Error bars show the uncertainty on  $\tau_{\text{best}}$  assessed from monte-carlo style sampling of 10000 SFHs.

## 5 Considering a Different Timescale for Idealized, and Plausible Scenarios

The previous section demonstrated that when the recent SFH is varying, the FUV luminosity is most robustly interpreted over a timescale shorter than the canonical 100 Myr average. While that experiment was intentionally restrictive, (i.e., all accepted SFHs were required to produce nearly the same present-day FUV luminosity as the constant  $1 M_{\odot}, \text{yr}^{-1}$  reference model) in reality, SFHs with similar present day SFRs need not produce similar FUV luminosities. In this section, we now relax this constraint and ask how FUV-inferred SFRs compare to the true 100 Myr average when the recent SFR has evolved over the last 100 Myr such that the FUV luminosity is unique for a given SFH.

To perform this test, we construct a controlled grid of recent star-formation histories in order to isolate how different forms of declining or increasing SFRs over the last 100 Myr affect the interpretation of the FUV luminosity. These scenarios are intentionally idealized, but they are designed to capture physically motivated smoothed forms of recent evolution rather than arbitrary fluctuations. In each case, we fix the present-day SFR to  $1 M_{\odot}, \text{yr}^{-1}$  and vary the earlier SFR over the preceding 100 Myr.

The recent-SFH scenarios explored are shown in Figure 5.6. The top row shows declining histories, while the bottom row shows increasing histories. In each row, we consider exponential evolution, linear evolution, and delayed evolution, where the SFR remains at an earlier value be-



**Figure 5.6:** Idealized recent SFH scenarios and their FUV-inferred SFR estimate recovery. The top row shows declining histories, while the bottom row shows increasing histories. From left to right, we consider exponential evolution, and linear evolution over the full 100 Myr interval, and then delayed evolution in which the SFR remains at an earlier level before changing over the last 60 Myr. The black horizontal line marks the constant  $1 \text{ M}_{\odot} \text{ yr}^{-1}$  reference model. The rightmost panels compare the FUV-inferred SFR to the true average SFR over the last 100 Myr for the declining and increasing scenarios, where point color corresponds to the specific scenario in the left 3 columns. The dashed line marks one-to-one recovery, while the yellow line is the best fit line. In both cases, the recovery relation is substantially shallower than unity, with slopes of 0.33 for declining histories and 0.35 for increasing histories. In each panel, the stars denote the time when 20% of the total FUV luminosity is produced.

fore changing over the most recent 60 Myr interval. These models therefore probe not only the amplitude of the recent change, but also how rapidly the present-day SFR was reached and how long the system remained at a different level of star formation. The black horizontal line in each SFH panel marks the constant-SFR reference case.

For each scenario, we use the same FSPS framework described above to compute the resulting FUV luminosity. We define each SFH on a lookback-time grid covering the last 100 Myr with 0.2 Myr spacing, then convert this lookback-time history into a tabular FSPS SFH. The SFH is implemented as a piecewise-constant function in time, with zero dust attenuation, no nebular emission, solar metallicity, and the same Kroupa & Weidner (2003) IMF and Kennicutt & Evans (2012) calibration used in the baseline calibration tests.

The rightmost panels of Figure 5.6 show the recovery for these scenarios by comparing the FUV-inferred SFR,  $\text{SFR}_{\text{FUV}}$  to the True  $\langle \text{SFR} \rangle_{[0,100]}$ . The dashed one-to-one line marks perfect recovery of the 100 Myr average, while the yellow line shows the line of best fit for the recovery of different scenarios. In both the declining and increasing cases, the dynamic range of the FUV-inferred SFR is much less than the range of true 100 Myr averages. As the True  $\langle \text{SFR} \rangle_{[0,100]}$  moves farther from the present-day value of  $1 \text{ M}_{\odot} \text{ yr}^{-1}$ , the FUV estimate increasingly fails to recover

it. This behavior is expected from the FUV response function because the FUV luminosity is weighted toward younger populations.

Importantly, the recovery relations are shallow in both directions, with slopes of  $\sim 0.33$  for declining histories and  $\sim 0.35$  for increasing histories. Thus, over this set of idealized models, the FUV indicator recovers only about one third of the change in the true 100 Myr average. Interestingly, this 0.34 slope is and nearly identical to the slope found when comparing CMD-based 100 Myr averages to FUV+24  $\mu\text{m}$  SFR indicators in M31 in [Wainer et al. \(2026c\)](#), who suggested the offset is due to the declining SFR in M31, and the timescales over which the FUV is a reliable tracer of star formation. The agreement between those observations and the analytical recovery here provides further evidence that when recent SFH is evolving, the timescale associated with the FUV based SFR estimates might be less than 100 Myr.

This hypothesis can be easily tested. If the FUV-inferred SFR under-recovers changes in the 100 Myr average because the FUV luminosity is weighted toward younger populations, then the comparison should improve when the true SFR is averaged over a shorter interval. We therefore replace the fixed 100 Myr average with  $\langle \text{SFR} \rangle_{[0,\tau]}$  and ask whether there is a timescale  $\tau$  for which the FUV-inferred SFR and the true averaged SFR become mutually consistent.

We quantify the agreement in two complementary ways, shown in Figure 5.7. First, we compute the ratio between the true average SFR over each timescale and the FUV-inferred SFR,  $\langle \text{SFR} \rangle_{[0,\tau]} / \text{SFR}_{\text{FUV}}$ , for every model. The top panel shows the median ratio for the increasing (green) and declining (purple) scenarios, with shaded regions indicating the 16–84% range. A value of 1.0 means that the FUV-inferred SFR matches the true average over that timescale. Second, we fit the recovery relation between  $\text{SFR}_{\text{FUV}}$  and  $\langle \text{SFR} \rangle_{[0,\tau]}$  at each  $\tau$ . The bottom panel shows the resulting slope as a function of averaging timescale. A slope of 1.0 indicates that variations in  $\langle \text{SFR} \rangle_{[0,\tau]}$  are recovered one-to-one by the FUV luminosity.

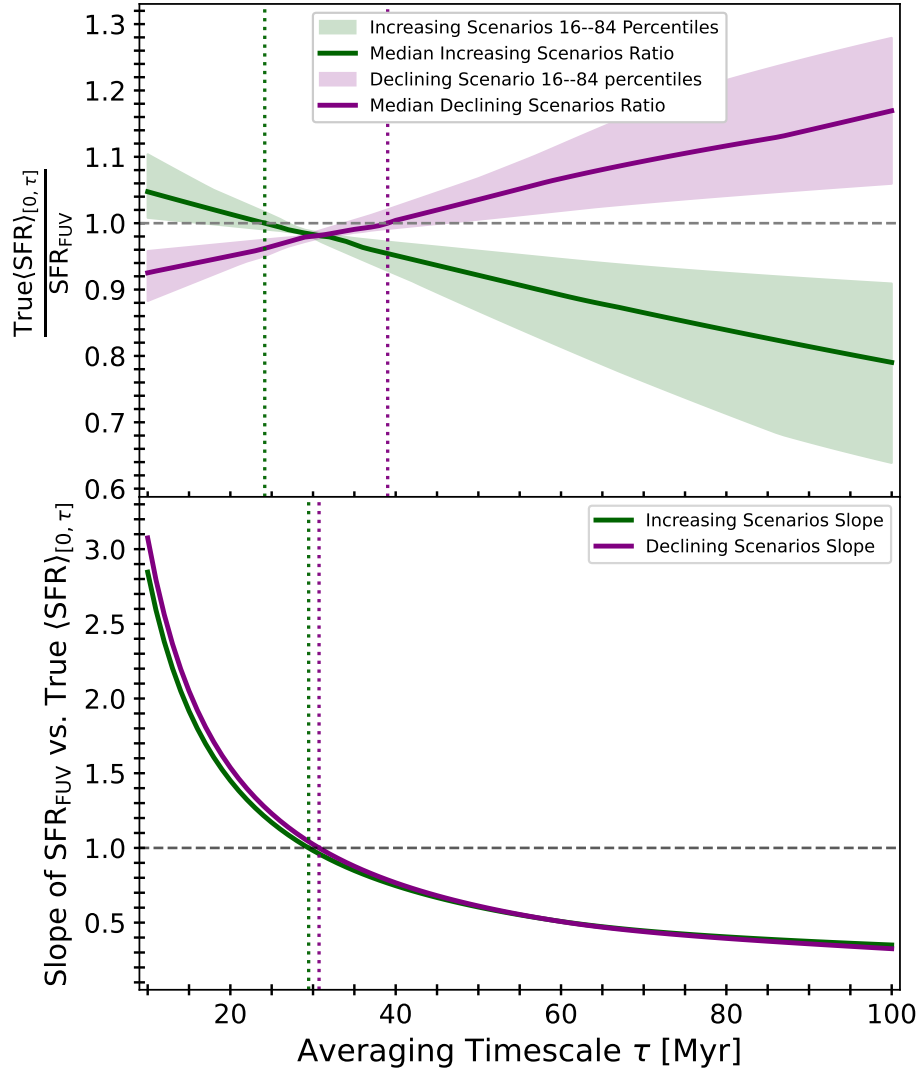
Both diagnostics point to averaging timescales of a few tens of Myr. In the top panel, the median ratio crosses unity between  $\sim 30$  and 40 Myr, with the increasing scenarios crossing at slightly shorter timescales than the declining scenarios. In the bottom panel, the fitted slopes for both sets of models reach unity at  $\sim 30$  Myr. At longer timescales, the slopes fall well below 1, reproducing the behavior seen in Figure 5.6, where the FUV luminosity responds only weakly to changes in the full 100 Myr average. At shorter timescales, the slopes exceed 1, indicating that the true average over very recent windows changes more strongly than the FUV-inferred SFR. The convergence of both diagnostics near  $\sim 30$ –40 Myr supports the interpretation from the loss-function analysis in Section 4.2 for evolving recent SFHs. Mainly, the FUV luminosity is more naturally associated with a timescale of a few tens of Myr compared to the full 100 Myr interval when the SFR is evolving over that time.

## 6 Discussion

### 6.1 Application to Real World Data

Throughout this work, we find evidence that when the SFH is evolving, the timescale for which the FUV most accurately traces the recent star formation is much closer to  $\sim 30$  Myr opposed to 100 Myr. We can test this empirically in nearby galaxies with resolved CMD-based SFHs, where the time resolved recent SFR can be averaged over different time intervals and compared to integrated





**Figure 5.7:** Top: median ratio of the true average SFR over  $0\text{--}\tau$  Myr to the FUV-inferred SFR,  $\langle \text{SFR} \rangle_{[0, \tau]} / \text{SFR}_{\text{FUV}}$ , with shaded regions showing the 16–84% ranges. Bottom: slope of the recovery relation between  $\text{SFR}_{\text{FUV}}$  and the true  $\langle \text{SFR} \rangle_{[0, \tau]}$  as a function of averaging timescale  $\tau$ . Dashed horizontal lines mark 1.0, where the FUV-inferred SFR matches the true average or recovers changes in the true average one-to-one. The vertical dotted lines mark the corresponding  $\tau$  where each metric equals 1. Both diagnostics indicate that the FUV luminosity is most consistent with true averages over timescales of  $\sim 30\text{--}40$  Myr, rather than the full 100 Myr interval.

FUV-based indicators. We focus particularly on M31 and M33, where offsets between CMD-based 100 Myr averages and FUV-based SFRs have been reported (Lewis et al., 2015, 2017; Wainer et al., 2026c). We also look at NGC 6946, whose CMD-derived SFH shows a factor of  $\sim 5$  decline in SFR over the last 25 Myr, and M81, who has a factor of  $\sim 3$  increase in the last 20 Myr, but has been comparatively steady over the last 150 Myr. Together, these systems test whether comparing FUV-based SFRs to shorter CMD averages brings the two methods into better agreement in real galaxies.

| Galaxy   | CMD SFR <sub>100</sub><br>(M <sub>⊙</sub> yr <sup>-1</sup> ) | CMD SFR <sub>32</sub><br>(M <sub>⊙</sub> yr <sup>-1</sup> ) | CMD SFR <sub>25</sub><br>(M <sub>⊙</sub> yr <sup>-1</sup> ) | FUV+WISE4 SFR<br>(M <sub>⊙</sub> yr <sup>-1</sup> ) | FUV-only SFR<br>(M <sub>⊙</sub> yr <sup>-1</sup> ) |
|----------|--------------------------------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|-----------------------------------------------------|----------------------------------------------------|
| M31      | 0.67 <sup>+0.03</sup> <sub>-0.03</sub>                       | 0.50 <sup>+0.03</sup> <sub>-0.03</sub>                      | 0.47 <sup>+0.03</sup> <sub>-0.03</sub>                      | 0.39 <sup>+0.23</sup> <sub>-0.14</sub>              | 0.60                                               |
| M33      | 0.59 <sup>+0.02</sup> <sub>-0.02</sub>                       | 0.47 <sup>+0.03</sup> <sub>-0.03</sub>                      | 0.45 <sup>+0.03</sup> <sub>-0.03</sub>                      | 0.32 <sup>+0.18</sup> <sub>-0.12</sub>              | 0.55 ± 0.10                                        |
| NGC 6946 | ...                                                          | ...                                                         | 10.5 <sup>+0.74</sup> <sub>-0.62</sub>                      | 6.17 <sup>+3.61</sup> <sub>-2.28</sub>              | 9.1                                                |
| M81      | 0.85 <sup>+0.15</sup> <sub>-0.09</sub>                       | 0.88 <sup>+0.15</sup> <sub>-0.11</sub>                      | 0.96 <sup>+0.15</sup> <sub>-0.09</sub>                      | 0.53 <sup>+0.32</sup> <sub>-0.20</sub>              | 0.35                                               |

**Table 5.3:** Comparison between CMD-based recent SFRs and FUV-based SFR estimates for nearby galaxies. CMD values have been corrected to a Kroupa IMF over 0.1–100 M<sub>⊙</sub> using the normalization correction discussed by [Telford et al. \(2020\)](#). For M31 and M33, the CMD-based SFRs have also been extrapolated from the survey footprint to the full  $D_{25}$  area. The FUV+WISE4 values are from [Leroy et al. \(2019\)](#). CMD SFR<sub>100</sub>, CMD SFR<sub>32</sub>, and CMD SFR<sub>25</sub> denote CMD-based averages over the last 100, 32, and 25 Myr, respectively. The M33 CMD values are based on [Lazzarini et al. \(2022\)](#); the M31 CMD values are based on [Lewis et al. \(2015\)](#); [Wainer et al. \(2026c\)](#); and the NGC 6946 CMD value is based on [Tran et al. \(2023\)](#); M81 are based on Rao et al. 2026 in preparation. FUV-only estimates are from [Kang et al. \(2009\)](#) for M31, [Verley et al. \(2009\)](#) for M33, [Botticella et al. \(2012\)](#) for NGC 6946, and Rao et al. 2026 in preparation for M81.

To make this comparison, we use the homogeneous FUV+WISE4 SFR estimates from [Leroy et al. \(2019\)](#). We adopt these values not because they necessarily provide the “definitive” SFR for each individual galaxy, but because they place the systems on a common observational and calibration footing. At the same time, the [Leroy et al. \(2019\)](#) estimates combine FUV emission with WISE4 emission to account for obscured star formation, while the experiments above focused specifically on the time response of the FUV luminosity. We therefore also compare to published FUV-only SFR estimates where available. These estimates provide a less homogeneous comparison due to differences in calibration, which as discussed in Section 3.3 can carry systematics at the 20% level. However, these estimates more directly isolate the FUV component and can help indicate whether any remaining offset is associated with the FUV timescale, or potentially in hybrid UV+IR calibration.

Additionally, before making this comparison, we place all of the CMD-based SFRs on a common IMF normalization. For these galaxies, the SFHs were derived with MATCH, assuming a Kroupa IMF. As discussed by [Telford et al. \(2020\)](#), MATCH normalizes the IMF over an effectively unbounded mass range rather than over the finite 0.1–100 M<sub>⊙</sub> interval commonly used in extragalactic SFR calibrations. Following [Telford et al. \(2020\)](#); [Wainer et al. \(2026c\)](#), we apply a uniform multiplicative correction of  $f_{\text{IMF}} = 0.799$  to the CMD-based SFRs.

For M31 and M33, the SFHs were derived from Hubble Space Telescope surveys (M31: PHAT-[Dalcanton et al. 2012](#) and PHAST-[Chen et al. 2025](#); M33 PHATTER-[Williams et al. 2021](#)) that did not cover the full extent as the FUV estimates. We therefore extrapolate the CMD-based SFRs from the survey footprint to the full  $D_{25}$  area of the galaxy, as was done in [Lazzarini et al. \(2022\)](#) and [Wainer et al. \(2026c\)](#).

The resulting comparison is shown in Table 5.3. The homogeneous [Leroy et al. \(2019\)](#) estimates are all lower than the CMD-based recent averages for all four galaxies. However, at the same time, the FUV+WISE4 values are also lower than the available FUV-only estimates, in each galaxy except M81.

This is somewhat counterintuitive, since adding an infrared term is usually expected to account for star formation that is obscured in the UV and therefore increase the inferred SFR relative to an uncorrected FUV estimate. One possible explanation is that the hybrid indicator is sensitive not only to the amount of obscured star formation, but also to the relative timescales traced by the FUV and mid-infrared emission. If the longer-wavelength emission peaks on a different timescale than the FUV, as suggested by [Kim et al. \(2021\)](#) and [Wainer et al. \(2026b\)](#), then the FUV+WISE4 calibration may not respond to recent changes in the SFH in exactly the same way as the FUV-only luminosity. Another possibility is the offset simply comes down to systematic differences. We have also shown in Section 3.3 that differences in IMF, and calibration can contribute systematic offsets at the 20% level, which could account for a large portion of the offsets.

Importantly however, for the galaxies where an offset between FUV-based SFRs and CMD-based 100 Myr averages has been reported (M31 and M33), averaging the CMD SFHs over shorter timescales brings the two measurements into closer agreement. In each galaxy, the CMD average over 32 or 25 Myr is within the 1 sigma uncertainty of FUV+WISE4 estimates. In M31 and M33, the CMD-based 100 Myr averages are both higher than the corresponding 25 or 32 Myr averages, as well as the FUV and FUV+WISE4 estimates. When the CMD SFHs are averaged over these shorter timescales, the CMD-based values move closer to both the FUV+WISE4 estimates and the available FUV-only measurements. NGC 6946 shows a similar behavior in a much more rapidly evolving system. These cases support the interpretation that FUV-based SFRs are more naturally associated with recent averages over the last few tens of Myr when the SFH is declining, rather than with a uniformly weighted 100 Myr average.

The one counter example is M81, whose SFR is actually lowest when averaged over 100 Myr. This is because there was a factor of three increase in the SFR over the last 25 Myr. It is particularly interesting then, that the FUV-only SFR estimate for M81 is the only estimate lower than FUV+WISE4. It is also interesting that the FUV emission does not reflect the recent burst seen in the CMD estimates.

These nearby galaxies provide an observational counterpart to the modeling experiments presented above. The constant-SFR models show that FUV luminosity can be calibrated to recover the input SFR under idealized conditions, but the response-function and synthetic-SFH tests show that the effective timescale changes when the recent SFH is not constant. The galaxy comparisons suggest that this effect is not only a feature of the idealized models. In systems with declining or otherwise evolving recent SFHs, part of the apparent discrepancy between CMD-based 100 Myr averages and FUV-based SFRs can be understood as a mismatch in the timescale being measured. The FUV luminosity remains a powerful tracer of recent star formation, but its interpretation depends on the recent SFH.

## 6.2 Implications of a Shorter FUV Timescale

Throughout this work, our results consistently indicate that FUV-based SFRs are not universal measurements of a fixed 100 Myr average, but instead trace an SFH-dependent, luminosity-weighted recent average that shifts toward the last  $\sim 25$ –40 Myr when the recent SFR is evolving. We emphasize that the interpretation is not that FUV-based SFRs are incorrect, but that their timescale should be treated as part of the measurement.

This interpretation is especially relevant for studies that compare FUV to shorter-timescale SFR indicators.  $H\alpha$ -to-FUV ratios have long been used to diagnose burstiness, stochasticity, IMF sam-

pling, and short-timescale SFH variations, particularly in low-mass galaxies (e.g., [Lee et al., 2009](#); [Weisz et al., 2012](#)). These comparisons often rely on the idea that  $H\alpha$  traces star formation over the last few Myr, while FUV traces a longer average over  $\sim 100$  Myr. Our results suggest that the FUV side of this comparison may itself shift to shorter effective timescales when the recent SFH is rapidly varying. This does not remove the diagnostic power of  $H\alpha$ /FUV ratios, but it changes how those ratios should be mapped onto burst amplitudes, durations, and duty cycles. In particular, the timescale separation between  $H\alpha$  and FUV may be smaller in bursty or recently quenched systems than is often assumed.

This SFH-dependent interpretation is especially important for galaxy populations whose recent SFHs are unlikely to be constant. Low-mass dwarf galaxies, outer disks, interacting systems, post-starburst or recently quenched galaxies, environmentally suppressed galaxies, and high-redshift galaxies with rapidly rising or stochastic SFHs are all cases where a fixed 100 Myr interpretation is least secure.

Our results also closely aligned with [Flores Velázquez et al. \(2021\)](#), who used bursty SFHs from the FIRE simulations to show that the timescales probed by  $H\alpha$  and FUV SFR indicators depend on the recent SFH rather than mapping onto universal averaging windows. Specifically, they find that the best-fit FUV timescale fluctuates between  $\sim 10$  and  $\sim 100$  Myr for bursty star formation. Our results provide an independent confirmation of that conclusion using controlled stellar-population experiments. Thus, offsets between FUV-based SFRs and other indicators may encode real recent SFH evolution, rather than dust-correction uncertainty, stochastic IMF sampling, or calibration differences.

This framework also provides guidance for future UV surveys. Upcoming facilities such as UVEX will greatly expand the availability of sensitive FUV and NUV imaging, including for low-mass, low-metallicity, and time-variable systems where recent SFHs may evolve rapidly ([Kulkarni et al., 2021](#)). Interpreting those data will require more than a single universal UV-to-SFR timescale. When independent information suggests an approximately constant recent SFH, the traditional  $\sim 100$  Myr calibration remains appropriate. When the SFH is rising, declining, bursty, or recently quenched, FUV-based SFRs should instead be compared to shorter-timescale averages or modeled with an explicit FUV response function. In this sense, the effective FUV timescale is not merely a nuisance parameter. It contains physical information about the recent SFH and can help connect unresolved UV measurements to the time-resolved star-formation histories now available for nearby galaxies.

## 7 Summary

UV luminosities are widely used to infer recent SFRs, often with the implicit interpretation that they trace star formation averaged over the last  $\sim 100$  Myr. In this work, we tested how that interpretation changes when the recent SFH is not constant. Using `FSPS` stellar-population models, we quantified the calibration-level systematics in FUV-based SFRs, measured the age dependence of the FUV response, and constructed controlled non-constant SFHs to determine the averaging timescales over which FUV-inferred SFRs best recover the true recent SFR. Our main conclusions are as follows.

- For constant-SFR populations, FUV-based SFRs are sensitive to calibration and IMF choices

at the  $\sim 20\%$  level. Using the same synthetic populations, different commonly adopted FUV-to-SFR conversions and IMF assumptions produce systematic shifts in the recovered SFR. These effects set an important baseline for interpreting FUV-based SFRs.

- The present-day FUV luminosity is strongly weighted toward young stellar populations, but it is not produced over a sharply defined timescale. In the constant-SFR reference model, the FUV luminosity is produced at young ages, with smaller contributions from older lookback times, although older populations continue to contribute non-negligibly to the total FUV flux. Therefore, FUV luminosities are best understood as age-weighted recent averages rather than measurements of a single fixed time interval.
- As a results, a single FUV luminosity does not uniquely describe a 100 Myr average SFR. We constructed ensembles of SFHs that reproduce the same present-day FUV luminosity and found that the range of allowed true averages grows substantially at longer lookback times. We find that the timescale which minimizes uncertainty is closer to  $\sim 30\text{--}40$  Myr than to 100 Myr for the variable SFHs.
- Idealized rising and declining SFHs show the same behavior. When compared the true 100 Myr average SFR, to the FUV-inferred SFR for different SFHs, only about one third of the change in the underlying SFH is recovered. However, when the true SFR is averaged over shorter windows, the FUV-inferred SFR becomes much more consistent with the input histories. Across these models, averaging timescales of  $\sim 25\text{--}40$  Myr provide the best agreement between the FUV-inferred SFR and the true recent average.
- Comparisons to nearby galaxies with resolved-star SFHs support this interpretation. In M31 and M33, where offsets between CMD-based 100 Myr averages and FUV-based SFRs have been reported, averaging the CMD SFHs over shorter timescales brings the measurements into closer agreement. NGC 6946, whose CMD-derived SFH declines strongly over the last 25 Myr, provides an additional example where the comparison to FUV-based indicators depends sensitively on the averaging timescale adopted for the resolved-star measurement.

*Software:* `astropy` (Astropy Collaboration et al., 2013, 2018, 2022), `Jupyter` (Kluyver et al., 2016), `matplotlib` (Hunter, 2007a), `numpy` (Harris et al., 2020), `python` (Van Rossum & Drake, 2009), `scipy` (Gommers et al., 2024; Virtanen et al., 2020a), `h5py` (Collette, 2013; Collette et al., 2023), `FSPS` (Conroy & Gunn, 2010) (OpenAI, 2023)



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## CHAPTER 6

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### FUTURE WORK AND CONCLUSIONS

|     |                                                           |     |
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# 1 Future Work

## 1.1 SFHs from the Nancy Grace Roman Space Telescope

The next major expansion of resolved stellar population work will come from the Nancy Grace Roman Space Telescope. Roman combines space-based image quality with a field of view far larger than HST, at the wavelengths of JWST, opening a new regime between the depth of targeted HST and JWST observations, and the wide-area coverage of ground-based surveys. For nearby galaxies, this combination is especially important. HST has shown that deep, precise photometry of individual stars can recover detailed star formation histories, but its small field of view makes wide-area mapping expensive. A single HST pointing can provide an exquisite CMD, but it may sample only one part of a galaxy, and that region may not represent the full system. Many of the scientific questions raised throughout this thesis depend not only on measuring individual stars, but on placing those stars in their full galactic context.

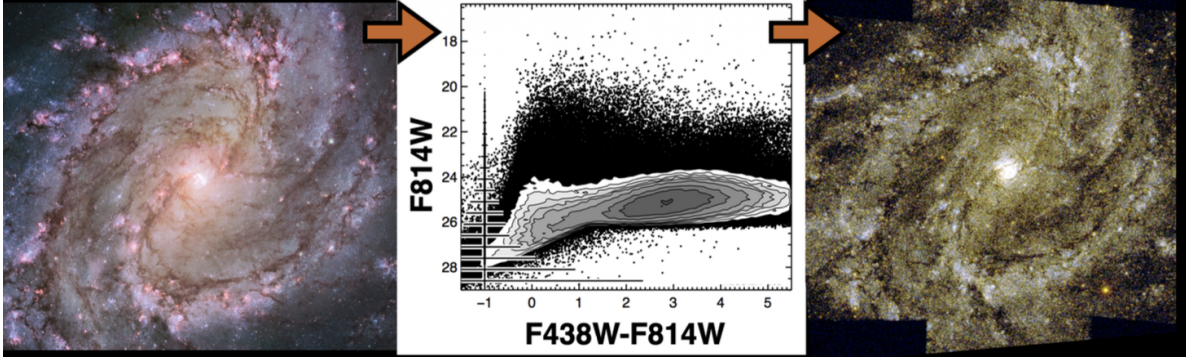
Roman’s wide field of view, near-infrared sensitivity, and stable space-based imaging will make it possible to map resolved stellar populations across much larger fractions of nearby galaxies than HST can cover efficiently. For example, Roman can produce maps comparable to the Panchromatic Hubble Andromeda Treasury [414 orbits of WFC3/IR integration; [Dalcanton et al. \(e.g., 2012\)](#); [Williams et al. \(e.g., 2023\)](#) and the PAndAS stellar halo survey [400 hours with CFHT; [Ibata et al. \(e.g., 2007, 2014\)](#)] for hundreds of nearby galaxies ([Karachentsev et al., 2013](#)), with just a handful of pointings. This coverage allows the SFH measuring techniques used in Chapter 4 to be extended to many more galaxies, pushing spatially resolved stellar population work beyond a few benchmark systems and into a much broader census of the nearby Universe.

This sample expansion is especially important for SFHs. HST has produced some of the most detailed SFHs available for nearby galaxies, particularly in dwarf systems where deep CMDs can reach old main-sequence turnoffs ([McQuinn et al., 2010](#); [Skillman et al., 2017](#); [Weisz et al., 2011](#)). Even in this regime, however, limited spatial coverage can complicate the interpretation of a galaxy-wide history, because different regions may have formed stars at different times or responded differently to feedback, interactions, gas accretion, and environmental effects ([Graus et al., 2019](#)). Roman will make it possible to measure these spatial variations across many more galaxies, linking resolved SFHs to internal structure and external assembly history.

A key tool for this study will be the use of simulated Roman images. In Figure 6.1 is an example simulation from HST observations of M83, where HST data were used to generate a star catalog that was then transposed to the Roman bands and applied as input for a simulated image. From these data, we will test crowding limits, which filter sets best recover SFHs, and other technical aspects that will allow science to be maximally produced as soon as real data becomes available.

## 1.2 Further Investigating the IMF

As discussed throughout this thesis, the stellar IMF governs the formation of massive stars and has ramifications in nearly every process in galaxies ([Bastian et al., 2010](#)). How many massive stars there are determines supernova rates, metal yields, and the fraction of stars that become compact remnants ([Bell, 2003](#); [Buck et al., 2021](#); [Grudić et al., 2023](#); [Hennebelle & Chabrier, 2008](#); [Krumholz, 2014](#)). Observations of the Milky Way suggest a broadly universal IMF ([Kroupa, 2001](#); [Offner et al., 2014](#); [Salpeter, 1955](#)), yet evidence from extreme environments may indicate



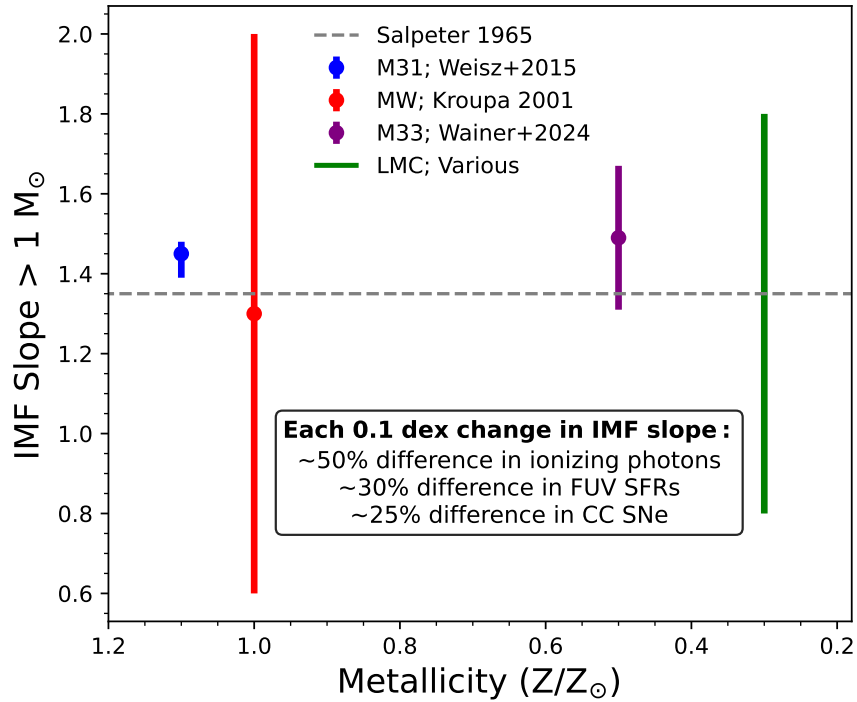
**Figure 6.1:** Roman simulated observation of M83. Left: HST 7-pointing UVIS mosaic of the nearby (5 Mpc) spiral galaxy M83. Center: Optical color-magnitude diagram of the stars measured in the mosaic. Right: Simulated 1 hour Roman image using transformed magnitudes for the stars in center.

otherwise, (Schneider et al., 2018). Additionally, deviations from canonical values have been proposed for chemically different regions (Escher Jung et al., 2023; Lee et al., 2020; Pouteau et al., 2022). However, due to statistical cluster-to-cluster variance in the IMF, individually resolving young, massive stars, homogeneously in galaxy wide surveys is the only reliable way to resolve this debate (Weisz et al., 2015).

Extragalactic observations provide essential constraints on the IMF and provide the best evidence for possible variations (Bastian et al., 2010). One simple probe of the IMF is to measure the mass distribution of individual stars in resolved clusters (Weisz et al., 2013). Yet, the Local Group is the *only* environment where resolved-star IMF measurements are currently possible with HST’s spatial resolution. Recent galaxy-wide studies in M31 (Weisz et al., 2015) and M33 (Chapter 3 of this Thesis; Wainer et al., 2024b) have measured systematically steeper high-mass IMF slopes than the canonical values (Kroupa, 2001; Salpeter, 1955), to the order of 25% fewer massive stars.

Importantly, this canonical IMF was established more than two decades ago using pre-Gaia data, simplified stellar models, and is affected by selection effects in distance, reddening, and completeness. In Figure 6.2, I show the only galaxy wide IMF measurements from resolved stars, and the uncertainties on them. The modern, resolved-star studies in the Local Group therefore represent an important opportunity to re-examine the high-mass IMF with updated data and methods. Extending such work to more diverse environments, and systematically testing against theoretical models is essential for determining if these variations reflect intrinsic changes in the star-formation process.

Four Local Group star-forming dwarf galaxies: IC 10, WLM, NGC 6822, and IC 1613 are particularly valuable in this context because of their low metallicity, and high enough SFR to form enough clusters for a statistically meaningful sample. Low-metallicity galaxies offer unique laboratories for testing how environment shapes star formation. Their reduced dust and metal content alter the thermodynamics of the interstellar medium (ISM) and the effectiveness of stellar feedback. With less efficient cooling and harder radiation fields, these systems develop hotter, more porous ISM structures and longer feedback-coupling timescales (e.g., Cormier et al., 2019; Hunter et al., 2024). Although such conditions are common throughout cosmic history (Madau & Dickinson, 2014; McQuinn et al., 2010; Weisz et al., 2012), the interplay between feedback, cloud



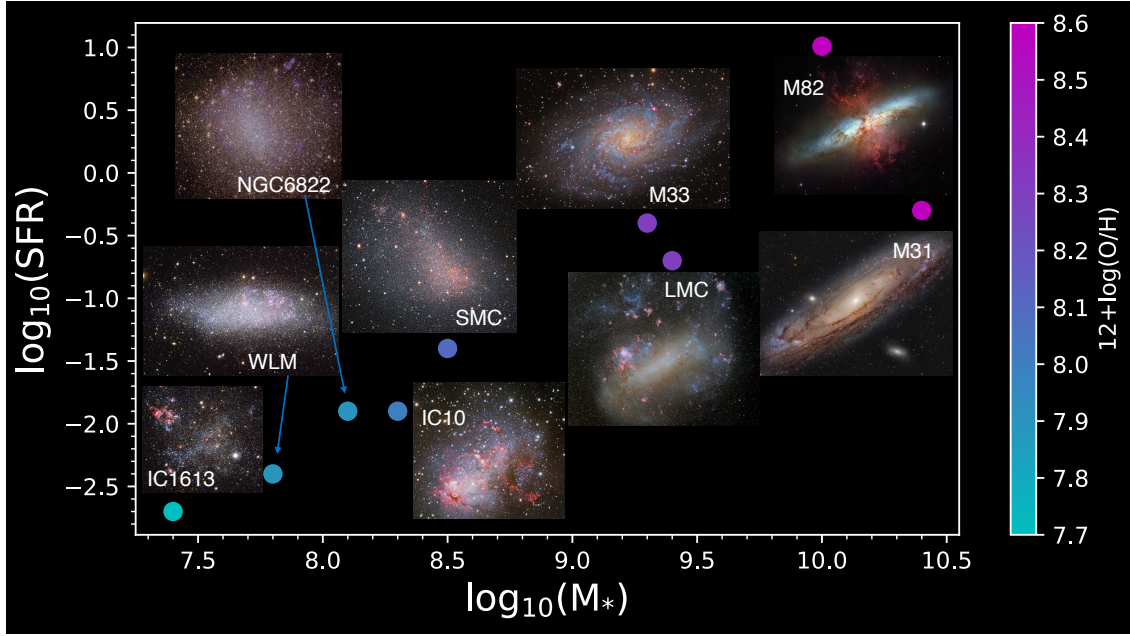
**Figure 6.2:** Compiled IMF measurements from the literature, highlighting the difference in uncertainty.

structure, and star formation in these regimes remains poorly understood.

On the other end of the spectrum, JWST now extends resolved-star imaging to distances of nearly 4 Mpc, where this critical analysis can finally move beyond the Local Group. The nearby starburst galaxy M82 offers the ideal counterpoint to the metal-poor dwarfs: an extreme, high-pressure environment where star formation proceeds at rates an order of magnitude higher than in any Local Group system (Davidge, 2008; Origlia et al., 2004). Its dense molecular disk, pervasive superwind, and extensive multi-wavelength coverage make it a uniquely powerful laboratory for testing how the IMF behaves under intense feedback and radiation fields. In M82, we can probe the opposite end of the environmental spectrum, providing a critical benchmark for understanding how massive-star formation scales from quiescent dwarfs to starburst galaxies.

JWST also has much greater angular resolution than HST. As discussed in Chapter 3, one of the limiting factors in the M33 IMF study was the inability to recover the input IMF for clusters less massive than  $\log(\text{Mass}/M_{\odot}) = 3.6$ . As a part of Cycle 5 JWST program lead by Eric Rosolowsky, I will redo this analysis with JWST data, also allowing us to probe younger clusters that are still embedded. When combined with the improved spatial resolution and separation of the ISM, the depth of the new data will allow existing studies of the stellar IMF in M33 to be extended from 9 to nearly 50 young stellar clusters, testing (Wainer et al., 2024b), while opening the ability to search for environmental variations across M33, and age-dependent variations using the new YSO data.

These galaxy targets span nearly three orders of magnitude in star-formation rate and stellar mass, and an order of magnitude in metallicity (Fig. 6.3), combining resolved star precision, and the range of metallicity and starburst regimes that dominate cosmic star formation. Literature samples suggest  $\sim 80$  clusters per dwarf (Howell et al., 2025) and over 3,000 in M82 (Levy et al., 2024), yielding 5–10 and  $\sim 100$  clusters young enough to use for my IMF study, respectively.



**Figure 6.3:** Stellar mass and star formation rates of galaxies for which I want to / will measure the IMF, colored by metallicity.

Even these modest counts are sufficient for galaxy-level IMF constraints, with uncertainties scaling inversely with the cluster number (Weisz et al., 2013). If there are fewer clusters than expected, I can combine samples across similar dwarfs. However, as the only local analogs of the low-metallicity, low-SFR environments ubiquitous throughout cosmic history, measuring the IMF in these systems is essential for characterizing star formation in the broader universe.

## 2 Conclusion

Over the last four years, I conducted several studies on the broader theme of star formation. These projects span different physical scales, from embedded stars in turbulent molecular clouds, to young clusters in M33, to the recent star formation history of M31, to the calibration of FUV light as a tracer of star formation. The common thread between them is they all ask how much physical meaning can be recovered from the quantities we measure.

A recurring lesson I have taken away from the works in this thesis is that star formation is difficult to describe with a single number. The embedded phase of star formation is not captured by one universal lifetime, because the transition from obscured to exposed depends on local accretion, feedback, and the formation of massive stars. The IMF may not be a universal, fixed, never changing slope. A galaxy’s star formation rate is not simply one global value, because recent star formation can vary strongly with position and can be tied to rings, spiral structure, interactions, and other galactic features. Even the FUV, one of the most widely used tracers of recent star formation, does not measure a single fixed timescale when the underlying star formation history is changing.

These complications are the physical content of the problem. A measurement becomes most useful when we understand what it averages over, what assumptions it carries, and what physical scales it is sensitive to. The work in this thesis has tried to make some of those dependencies ex-



plicit. The STARFORGE analysis connected the observability of young stars to the local feedback processes that clear gas and dust. The M33 cluster study tested whether the high-mass IMF varies across a nearby spiral galaxy and found results consistent with a nearly universal distribution, while still emphasizing the importance of probabilistic modeling and careful sample selection. The M31 study showed that spatially resolved CMDs can reveal coherent changes in recent star formation. The FUV analysis showed that integrated light can still be a powerful tracer, but only when its effective timescale is understood in relation to the recent SFH.

I think the broader impact of this work lies in that calibration between physical process and observable quantity. Astronomy often requires translating complicated histories into measurable diagnostics: a color, a luminosity, a slope, a rate, a map. Those diagnostics are powerful because they make the Universe measurable, but they can also become misleading when treated as universal. Nearby galaxies and resolved stellar populations give us one of the best ways to test these translations directly. They allow us to ask when a tracer works, when it fails, and what each of those outcomes reveals about the underlying physics.

The next generation of observations will make this problem even more important. JWST is revealing embedded clusters, dust structures, and feedback-shaped environments in nearby galaxies with unprecedented detail. Roman will expand resolved stellar population studies from a small number of benchmark systems to much larger samples across the nearby Universe. At the same time, simulations are becoming detailed enough to be observed synthetically, allowing models of star formation to be placed in the same observational space as real data. The challenge going forward will not be only to measure more stars, more clusters, or more galaxies. The challenge will be to understand what those measurements mean.

The work of describing star formation is therefore also the work of understanding dependencies. The answers depend on scale, environment, time, and tracer. The studies in this thesis help connect the physical processes at play. That connection is what allows stars to serve not only as points of light, but as records of how galaxies form, evolve, and become observable. There is still far more to understand than any single thesis could address. These questions are being pursued by a broad community of observers, theorists, simulators, instrument builders, and data analysts, and I am grateful to have contributed a piece to that larger effort.

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