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From Formation to Fossil Record:
Tracing Galaxy Evolution Through Stellar Dynamics in Cosmological Simulations

By

FIONA MCCLUSKEY
DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

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DAVIS

Approved:

Andrew Wetzel, Chair

David Wittman

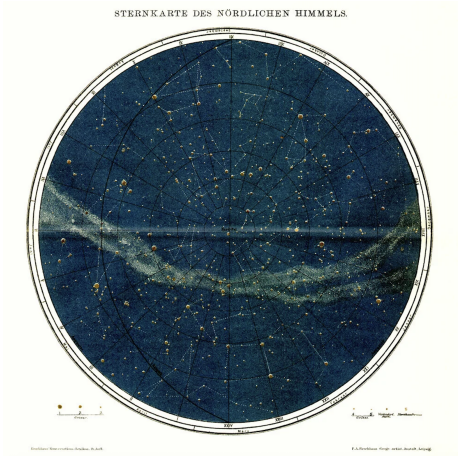
Tucker Jones

Committee in Charge

2026

FROM FORMATION TO FOSSIL RECORD: TRACING GALAXY EVOLUTION
THROUGH STELLAR DYNAMICS IN COSMOLOGICAL SIMULATIONS

FIONA MCCLUSKEY



We say the dreams of night

Are within us

As blood within flesh

As spirit within substance

As the oneness of things

As from the dust of pigeons

The white light of wings

Rebecca Elson, "The Last Animists"

Dedicated to my parents, I love you

ABSTRACT

How disk galaxies, including our own Milky Way (MW), formed and evolved over cosmic time remains an outstanding question in astrophysics. A powerful approach is to treat a galaxy’s stellar populations as an archaeological record, one in which the present-day kinematics of stars retains a memory of their galaxy’s past dynamical state. In particular, the age–velocity dispersion relation, $\sigma(\tau)$, has long served as a probe of stellar dynamical evolution, reflecting both the kinematics with which stars formed—set by the star-forming interstellar medium—and the dynamical processes that have since altered their orbits. However, interpreting $\sigma(\tau)$ is inherently ambiguous: similar present-day trends can arise from stars forming with different initial kinematics or from cumulative dynamical heating over time.

I use cosmological zoom-in simulations from the FIRE-2 project to disentangle these effects. I find that disk assembly proceeds through three distinct eras, during which stars form with systematically evolving kinematics as galaxies transition from turbulent, dispersion-dominated systems to dynamically cold, rotationally supported disks. Although the strength and character of dynamical heating vary across these eras, I show that, for all but the oldest stellar populations, present-day velocity dispersions are largely set at formation rather than acquired through subsequent evolution. I further find that galaxies that form disks earlier host systematically colder star-forming gas at late times, linking present-day conditions to the timing of disk assembly.

Recent observations have extended measurements of $\sigma(\tau)$ well beyond the solar neighborhood, enabling comparisons across a growing sample of nearby disk galaxies. I compile these measurements and use simulations to quantify how observational systematics – such as aperture size, galactocentric radius, and age uncertainties – affect the inferred $\sigma(\tau)$, placing these data on a common footing. In this framework, the simulations broadly reproduce the kinematics of external systems, while the MW exhibits systematically colder stellar populations than our simulations and all but one observed galaxy. This suggests that the MW, long used as the benchmark for disk evolution and for testing simulations, instead appears to be a kinematic outlier with an atypical dynamical history.

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Part I

INTRODUCTION

I

INTRODUCTION

From a nearly uniform beginning, the Universe has spent nearly 14 billion years building islands of light – or, more accurately, gravitationally bound baryonic structures embedded in dark-matter halos; or, more simply, galaxies – lots of them.

This dissertation examines the formation and evolution of Milky Way (MW) mass galaxies using cosmological simulations that follow their growth across cosmic time. It focuses on the kinematics that stars acquire at birth and the processes that subsequently modify those orbits. By comparing these simulated histories to the stellar motions observed in the MW and in nearby galaxies, this work links the internal dynamics of disks to the broader goals of galactic archaeology. In particular, it asks how the present structure of a galaxy records the conditions under which it formed.

For centuries, every star we could see belonged to the MW and for much of that time the MW was the Universe. Only in the 1920s did astronomers grasp that the observed spiral nebulae were themselves vast “island universes”, that is, galaxies, in their own right (Hubble, 1929). Our view of the cosmos has since deepened, yet our observations still favor what is close and bright, so the story of galaxy formation was long built from the present backward, working from nearby systems to infer how they once began.

That said, we are no longer beholden to this historical view. With the theoretical scaffolding of physical cosmology, we can now place galaxy formation within the history of the Universe itself; from the hot, dense beginnings of the Big Bang to the assembly of dark-matter halos and the galaxies that inhabit them. Thus, although my fascination began with the stars of our own Galaxy, this introduction begins with the cosmological paradigm, that is, the broader history through which galaxies, and the MW among them, came to be. It begins with an outline of the cosmological context most relevant to the emergence of galaxies. It then summarizes key observational results on how galaxy populations evolve with redshift and the physical processes that regulate that evolution. I next give a brief overview of the Milky Way, including its main components and its history. With this foundation in place, I discuss cosmological simulations and describe how they model galaxy growth by coupling the formation of large-scale structure to the physics of gas, stars, and feedback.

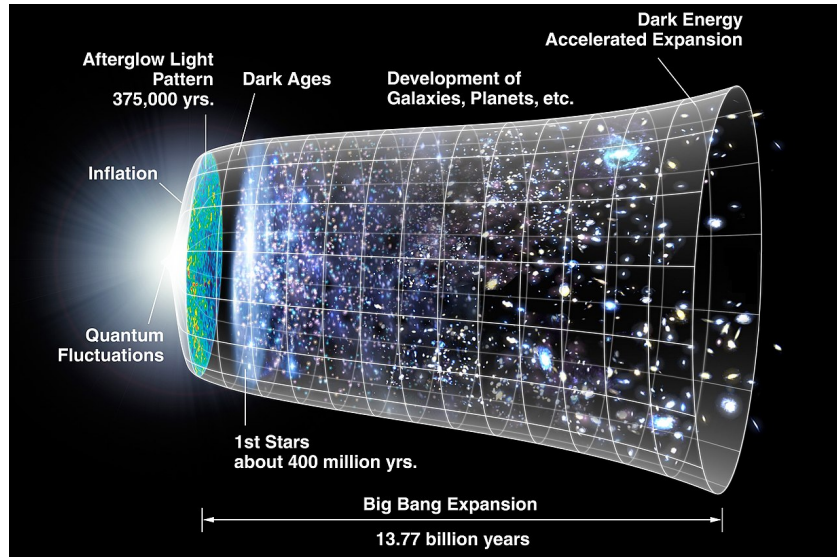


Figure 1: **A simplified timeline of the Universe:** a representation of the evolution of the Universe over the past 13.7 Gyr, showing how the expansion of the initially hot, dense early Universe gave way to stars and small and frequently-merging galaxies, and eventually the present-day galaxy population. Credit: NASA / WMAP Science Team

1.1 A BRIEF HISTORY OF THE UNIVERSE

Our current understanding of galaxy formation rests on the Λ CDM model, the prevailing paradigm of modern cosmology. It assumes that, on sufficiently large scales, the Universe is homogeneous and isotropic, and that its evolution is governed by Einstein’s general theory of relativity, which relates the geometry of space–time to its matter and energy content. Within this framework, cold dark matter (CDM) supplies the gravitational backbone for the growth of structure, while dark energy (typically associated with the cosmological constant, Λ) drives the accelerated expansion of the cosmos. Despite the unknown physical nature of these dark components, Λ CDM has become a remarkably successful concordance model, underpinning the era of “precision cosmology” and reproducing with striking accuracy the large-scale distribution of matter, the fluctuations of the cosmic microwave background, and the hierarchical formation of galaxies over cosmic time.

In this Λ CDM framework, the Universe began with the Big Bang: an initial state of extraordinary heat, density, and simplicity from which space itself expanded and cooled over the next 13.8 billion years. In its earliest moments, the cosmos was a “primeval fireball”, a brilliant, almost uniform sea (or “primordial soup”) of electrons, baryons, and photons, coupled so tightly that matter and radiation moved as one. Its homogeneity was remarkable, but, luckily, not perfectly so. Quantum fluctuations produced during inflation – an initial period of extremely rapid expansion – provided tiny density irregularities that would go on to seed future structure (Guth, 1981).

As expansion proceeded, the Universe cooled through a series of generally well-understood transitions: Figure 1 provides a visual overview of our Universe’s evolution from the Big Bang to the present.

Within the first ~ 100 seconds after the Big Bang, light elements such as hydrogen, helium, and traces of lithium formed through primordial nucleosynthesis, setting the initial chemical composition of the cosmos.

Initially, radiation dominated over matter, and the pressure of the relativistic plasma resisted gravitational collapse, keeping density fluctuations small. However, as the Universe expanded, radiation thinned more rapidly than matter, and the balance of its energy density gradually tipped in matter's favor at $z \sim 3600$ (approximately 47,000 years after the Big Bang). Once matter dominated the mass-energy budget, gravity could amplify perturbations and begin to assemble structure. Unaffected by radiation pressure, dark matter condensed first. However, “normal” baryonic matter, remained coupled to radiation via frequent Thompson scattering, and could not follow dark matter's collapse.

The temperature of the Universe continued to fall as it expanded, eventually cooling to a balmy ≈ 3000 K at a redshift of $z \sim 1100$ (approximately 370,000 years after the Big Bang). At this record low temperature (for the time), protons and electrons could readily combine into neutral hydrogen¹, which is essentially immune to the scattering that relentlessly plagued the lives of its constituent electrons and protons. This epoch of recombination made the Universe transparent: photons decoupled from matter and streamed freely through space, continuously “redshifting” with the expanding cosmos. We view these photons today as a steady barrage of microwave photons originating from all parts of the sky, referred to as the Cosmic Microwave Background (CMB).

Figure 2 shows a map of the CMB measured from the Planck spacecraft, detailing how its temperature differs across the sky (Planck Collaboration et al., 2020). From first impressions, the map seems to show great variety – those orange regions certainly have a very different color than those blue regions. However, the temperature difference between the very hottest orange regions and the very coldest blue regions is .0006 K, meaning that the CMB temperature (≈ 2.73 K) is the same to 1 part in 10^5 in every region of the sky. Put in a slightly more dissertation-appropriate manner, the CMB is a near perfect blackbody that is faintly speckled by temperature variations of one part in 10^5 . However, these faint anisotropies are immensely important because they capture the density and velocity structure of the Universe at the time of recombination and thus bear the gravitational imprint of the early DM-halo scaffolding that would later grow into the cosmic web of galaxies and clusters.

After recombination, baryons could decouple from cosmic expansion and collapse into the gravitational wells of DM halos. Surely the time following recombination marked a frenetic, exciting chapter of the Universe's history? Not quite yet. This period marks the beginning of the cosmic “Dark Ages”.

Dark matter (to the best of our knowledge) is collisionless and dissipationless. As it gravitationally collapses, potential energy is converted into random motion that cannot be radiated away, so while it forms gravitationally bound halos, these structures remain fairly diffuse and pressure-supported. Baryons, in contrast, *can* dissipate energy. As gas accretes onto dark-matter halos, it also shock-heats to the halo's virial temperature. In principle, this shocked gas can cool radiatively and further collapse. In practice, this was difficult in the early Universe,

¹ This transition is generally referred to as recombination, which, even in a field full of lamentable terminology, stands out as particularly poorly named given that electrons and protons had never been combined into atoms previously.

because neutral atomic hydrogen is a notoriously poor coolant (at temperatures below 10^4K) and primordial gas lacked the metals and molecules that dominate gas cooling at low temperatures.

That said, give the Universe about 300 million years, and particularly dense regions of primordial gas can reach sufficient densities to form stars. The first metal-free stars, known as Population III stars, likely began to form at $z \sim 30\text{--}20$ in DM “minihalos” of $M_{\text{vir}} \sim 10^{5-6} M_{\odot}$. The formation of the first Population III stars marked the end of the cosmic dark ages. Their intense radiation and supernovae began the Universe’s first episode of stellar feedback: forging the earliest heavy elements, ionizing and heating neutral gas, driving outflows that excavated shallow potential wells and, thus, regulating the assembly of the first galaxies.

However, the first stars predated the first galaxies, albeit only slightly. The minihalos that hosted the first stars were massive enough to collect enough dense gas, but ultimately the potential wells there were not deep enough to retain this gas in the face of rampant stellar feedback. Over time, halos gained more mass, and the first bona fide galaxies began to form in halos of $M_{\text{vir}} \sim 10^{7-8} M_{\odot}$. The emergence of the first long-lived galaxies marked a new stage in cosmic evolution, as systems assembled in dark-matter halos deep enough to retain gas heated above 10^4K and to survive both photoionization and supernova-driven outflows.

Remarkably, we can now glimpse some of these early galaxies. The Hubble Space Telescope (HST) first pushed the frontier to redshift $z \sim 11$ (Oesch et al., 2016). The advent of the James Webb Space Telescope (JWST), with its larger mirror and mid-infrared capabilities, brought a deluge of even higher-redshift candidates. Many studies reported massive, surprisingly bright systems within weeks of JWST’s first observations (Castellano et al., 2022; Robertson et al., 2023). Spectroscopic confirmation remains ongoing, but several galaxies have been verified at $z \gtrsim 12$ (Maiolino et al., 2024) and even $z \gtrsim 14$ (Carniani et al., 2024; Naidu et al., 2025). These objects are rare and extreme, likely destined to evolve into massive ellipticals at the center of the most massive galaxy clusters. Still, their existence tells us that by $z \sim 14$, barely 300 Myr after the Big Bang, the Universe was in the galaxy making business.²

1.2 GALAXY FORMATION AND EVOLUTION

In the previous section, we discussed how the first galaxies emerged in the early Universe. We now discuss how these galaxies continued to form and evolve over the past ~ 13 Gyr.

The ideas introduced in the previous section continue to hold true: Structure forms hierarchically, or “bottom-up”, with small structures forming first and combining to form larger structures. Such structure formation is largely

² Many pre-JWST models underpredicted the number of very bright sources at $z > 10$ by more than two orders of magnitude. Their surprising luminosities may stem from bursty star formation (and thus high UV variability), unusually high star formation efficiencies, increased mass-to-light ratios (as expected from a top-heavy IMF or dust-poor environments), or, if you prefer a more sensational, headline-ready explanation, the end of ΛCDM as we know it.

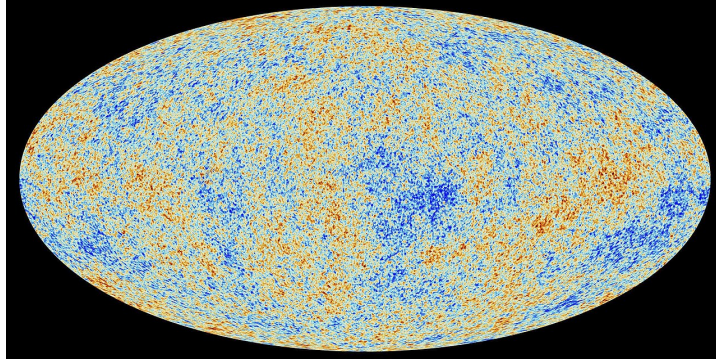


Figure 2: **A map of the cosmic microwave background radiation (CMB)**, showing tiny temperature fluctuations that correspond to slight differences in density imprinted during the epoch of recombination. These small perturbations seed the growth of structure, ultimately resulting in our present-day distribution of galaxies. Credit: ESA and the Planck Collaboration.

dictated by DM with gas following suit (on large scales). That is, DM builds the scaffolding of the cosmic web, dictating where (and when) galaxies form. Matter in galaxies (be it dark or baryonic) gains angular momentum via tidal torques (Peebles, 1969). If all goes well, gas collapses into DM halos and forms stars (White and Rees, 1978).

The "dark side" of galaxy formation is comparatively well understood, with theory/simulation providing a robust/consistent description of the abundances, clustering, sizes, etc. of DM halos and their evolution over cosmic time (on $>kpc$ scales) (Wechsler and Tinker, 2018). The formalism of CDM structure formation, which describes the formation and growth of DM halos over cosmic time, can be readily extended to galaxy formation via theoretical and/or (semi-)analytical modeling. In classical models, disk galaxies readily formed from dissipative gas collapse, provided that the gas retained its initial angular momentum (Dalcanton, Spergel, and Summers, 1997; Fall and Efstathiou, 1980; Mo, Mao, and White, 1998). Alas, real galaxies are not so simple.

Broadly speaking, there are two main (distinct but complementary) approaches for observationally studying how galaxies form and evolve. One approach is to observe a large number of galaxies at low resolution across a range of redshifts (given that with the finite speed of light allows us to look back in cosmic time) to understand how broad galaxy populations evolve. The other approach is to study nearby galaxies in greater detail and, via galactic archeology, disentangle their young and old stellar populations to reconstruct their formation history.

With the launch of HST, high-redshift galaxies could be resolved, showing that high-redshift galaxies differ from their low-redshift descendants, exhibiting disturbed, irregular morphologies in contrast to the thin disk and spheroidal structural dichotomy of the present day. Ground-based observatories, increasingly aided by adaptive optics, soon complemented the picture revealed by HST, offering spectroscopy (and thus kinematic measurements). Other surveys – such as GOODS and COSMOS – also combined observations from other space-based observatories (Infrared from Spitzer and Herschel, X-Ray from Chandra and XMM), to provide a fuller picture of the state of high-redshift galaxies. Indeed, high-redshift galaxies are not just morphologically peculiar but exhibit larger (gas)



Figure 3: **Images showing the evolution of MW-like galaxies over cosmic time** from CANDELS. Galaxies transform over cosmic time, evolving from compact, irregular systems to thin disks. This upside-down and inside-out transformation occurs alongside changes in star formation and the formation of internal structures like bars and spiral arms. Credit: NASA, ESA, C. Papovich, H. Ferguson, S. Faber, and I. Labbé

velocity dispersions, produce stars at higher rates/surface densities, and commonly contain massive star-forming clumps.

Figure 3 shows a sequence of galaxies observed with HST as part of the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS). Each panel shows a galaxy that, in the present day, would likely be comparable in mass to the MW.³ The sequence proceeds from right to left, tracing how such galaxies have evolved over the past ~ 11 Gyr.

At the earliest epochs ($z \sim 3$; rightmost panel), MW progenitors appear as compact, gas-rich systems that form stars at extraordinary rates. Their reddish appearance is a product of redshift; in their rest frame, they would shine in ultraviolet light, dominated by massive, short-lived stars. These galaxies are kinematically hot, with velocity dispersions comparable to their rotational speeds, and morphologically irregular, clumpy structures stirred by high gas fractions, gravitational instabilities, and mergers (e.g. Förster Schreiber and Wuyts, 2020a; Genzel et al., 2011).

By $z \sim 2$ (third from right), the galaxies have grown in both size and mass, yet still appear as bright, turbulent “blobs.” Star formation remains vigorous, consistent with this epoch marking the peak of the cosmic star-formation history (Madau and Dickinson, 2014). These systems may be in the early stages of disk formation: despite their disordered appearance and high gas turbulence, their underlying kinematics could already exhibit coherent rotation not evident from morphology alone. However, such ordered motion is by no means ubiquitous at this stage.

A significant transition occurs by $z \sim 1.3$ (center panel). The galaxy has flattened, its light now tracing a nascent disk rather than a central blob. Spiral features begin to appear, and star formation becomes more diffuse and organized along the outer disk. Kinematically, such galaxies exhibit rising v_ϕ/σ , indicating that ordered rotation has begun to dominate random motion (e.g. Kassin et al., 2012; Simons et al., 2016).

³ Ultimately, it is impossible to say whether any of these individual galaxies resemble the MW today, but we can say that each of these galaxies have observed stellar masses similar to expectations for the typical progenitors of today’s MW-mass galaxies.

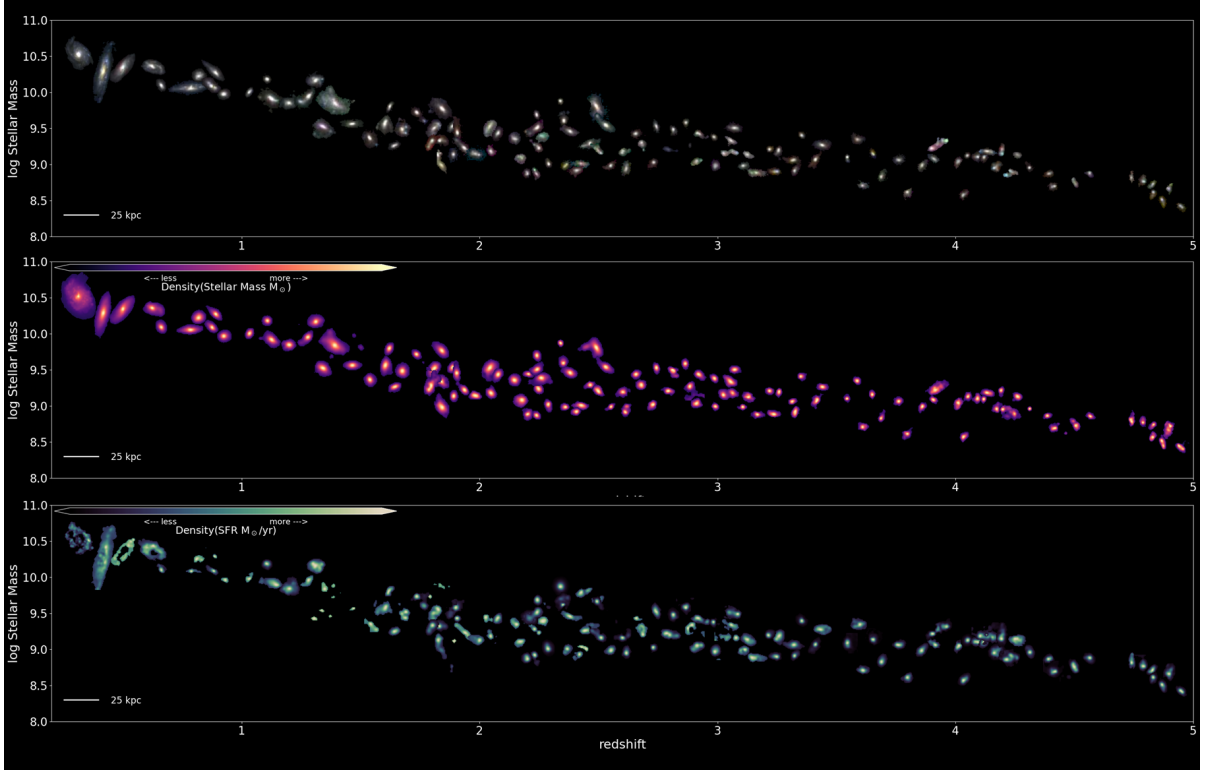


Figure 4: Color images (top), stellar mass maps (middle) and SFR maps (bottom) of MW-analog progenitors in CANUCS, from Tan et al. (2024).

By $z \sim 0.65$ (second from left), the transformation is well advanced. The disk has expanded and the light is dominated by older, redder stellar populations, signaling the gradual decline of star formation. In the left panel ($z \sim 0.26$), the transformation is complete. The galaxy exhibits a thin, extended disk with well-defined spiral arms and a luminous central bulge. Although the overall star formation rate is modest, it remains evident in the bright H_{II} regions distributed along the spiral arms, each a compact, ionized pocket illuminated by recently formed massive stars.

Similarly, Figure 4 – taken from Tan et al. (2024) – shows color images (top), stellar mass maps (middle), and SFR maps (bottom) of 119 MW-analog progenitor galaxies from the Canadian NIRISS Unbiased Cluster Survey (CANUCS) as a function of each galaxy’s redshift. Thin, extended disks are limited to recent times: at high and intermediate redshifts, progenitors regularly disturbed, gnarled morphologies, and star formation is restricted to the innermost regions.

These images help to highlight some key points in our current understanding of galaxy formation and evolution.

Galaxies do not pop into existence as disks, much less thin, radially-extended disks. The earliest galaxies, being low-mass, recurrently merging systems, were likely clumpy and irregular. Furthermore, at higher redshifts, disk galaxies are consistently thicker, clumpier, and more turbulent than local disks (for example Birkin et al., 2023; Förster Schreiber et al., 2009), which likely relates to their higher gas fractions and star-formation, accretion,



Figure 5: **Illustrations and images highlighting three key drivers of galaxy evolution:** environmental interactions including gas accretion (left), star formation (center), and galaxy mergers (right). Left: A diagram of the CGM and the processes that cycle gas in and out of galaxies, Credit: Tumlinson, Peeples, and Werk (2017). Center: Composite infrared and radio image of 30 Doradus, Credit: ESO, ALMA (ESO/NAOJ/NRAO)/Wong et al., ESO/M.-R. Cioni/VISTA Magellanic Cloud survey. Right: Composite image of Arp 107 from combined JWST NIRCам and MIRI data, Credit: NASA, ESA, CSA, STScI

and merger rates (Conselice, Blackburne, and Papovich, 2005; Förster Schreiber and Wuyts, 2020b; Swinbank et al., 2012; Tacconi et al., 2013). Importantly, disk galaxies "settle" over cosmic time, such that their gaseous disks become progressively less turbulent and more rotationally-supported (Kassin et al., 2012). As the disk settles, successive generations of stars form on progressively "thinner" (kinematically colder) orbits, such that disk galaxies are commonly said to form "upside-down". Prior to disk settling, star formation predominantly occurs at smaller radii (near the galaxy center). As the disk settles and grows, star formation also occurs at progressively larger radii, such that disk galaxies are said to form "inside-out" (Bird et al., 2013). With this inside-out and upside-down formation in place, much of the late-time evolution of the disk's structure and kinematics is governed by steady, secular (internal) processes (to be discussed in later sections) (Sellwood, 2014).

This kinematic and morphological evolution is intimately connected to the physical processes governing a galaxy's mass growth, gas supply, and star formation.

Galaxies are not isolated "island universes", but are embedded within the greater cosmic web, continuously interacting with and accreting gas from the intergalactic medium (IGM). Put simply, galaxy evolution is essentially the story of how galaxies acquire gas from this web and turn that gas into stars. In a simple picture, extragalactic gas accretes from the cosmic web, acquires angular momentum, shock heats, cools down via radiation, and finally enters the galaxy proper, where it settles into a rotationally supported disk and forms stars (Mo, Mao, and White, 1998).

Unsurprisingly, this simple picture has limitations. For one, the nature of this gas accretion depends on the mass of the galaxy, and thus can change over a galaxy's lifetime. In lower mass halos ($M_{\text{halo}} \lesssim 10^{12} M_{\odot}$), the free-fall time exceeds the gas-cooling time. In turn, shocked gas can cool rapidly, and this loss of thermal pressure support allows gas to barrel into the galaxy via supersonic filamentary cold flows. This "cold mode" accretion is essentially a barrage of gas with random orientations (that can regularly shock upon impact), which promotes an irregular,

highly turbulent ISM in addition to potentially reorienting/flipping (if not outright destroying) existing disks (Dekel et al., 2009; Kretschmer, Dekel, and Teyssier, 2022). In contrast, in higher mass halos, the gas cooling time exceeds the free-fall time. Now, the infalling gas has sufficient time to self-align, such that it coherently accretes along the disk’s edges with subsonic velocities, smoothly and continuously building the disk (Hafen et al., 2022). Recent theoretical work also shows that this change in the primary mode of gas accretion broadly coincides with the virialization of the galaxy’s inner circumgalactic medium (CGM) (Stern et al., 2021).

Gas accretion provides the fuel for star formation, but this process is remarkably inefficient. Feedback processes – that is, energy/momentum injection from stars, supernovae (SN), and active galactic nuclei (AGN) – play an immense role in galaxy formation. In particular, SN feedback from dying massive stars regulates star formation within galaxies, and perhaps even more importantly, drives large-scale multi-phase outflows that expel gas (and metals) out of galaxies. The fate of the expelled material varies – it can fall back into the galaxy (be reaccreted), or can escape the galaxy’s gravitational pull and abscond to the IGM. Figure 5 (right) shows an image of the Tarantula Nebula (also called 30 Doradus), a H II region in the Large Magellanic Cloud (LMC) and the most luminous and active star-forming region in the Local Group (LG).⁴ While certainly an extreme example, this image shows that star formation is strongly clustered, and that feedback from massive stars drives substantial amounts of energy and ionizing radiation into their surrounding environments. Eventually, core collapse SN will go off and gas will be evacuated, and star formation will cease in the nebula.

On galaxy scales, the nature of star formation also evolves over time. At high redshift, the progenitors of MW-like galaxies exhibit higher star formation rates that are largely time-variable, i.e., “bursty”, such that star formation rates fluctuate by order(s)-of-magnitude on 10-100 Myr timescales (Sparre et al., 2017; Weisz et al., 2014). In contrast, higher mass galaxies, like the MW, trudge along and steadily make stars. Over their lifetimes, galaxies transition from having primarily bursty star formation rates to steady star formation rates, a transition that typically corresponds with the growth of thin disks (and potentially a change in how gas is accreted onto the galaxy (Gurvich et al., 2023; Yu et al., 2021).

It has long been recognized that galaxies interact with each other: local observations seemingly catch galaxies in the act, with tidal tails and bridges seen between galaxies (Toomre and Toomre, 1972), and indeed Λ CDM establishes mergers as a ubiquitous (or perhaps inescapable) consequence of hierarchical structure formation. Mergers are more frequent at early cosmic times, when the Universe was smaller and denser (Conselice, 2014; Hammer et al., 2005) (and also when galaxies were typically gas rich). Often, these mergers are fairly one-sided, with a more massive galaxy accreting many different lower-mass galaxies. Although this may induce some minor enhancements in star formation or slight morphological deviations, the more massive galaxy is generally relatively unbothered, while the less-massive galaxy is destroyed. Nevertheless, mergers can have profound effects on galaxies – igniting star formation, fueling AGN, generating bars, building classical bulges, thickening if not destroying disks, and forming “red and dead” ellipticals. However, in contrast to classical expectations, some

⁴ The Tarantula Nebula is also home to SN 1987a, the closest SN to Earth since the invention of the telescope, and many of the most massive stars ever observed, having over a dozen stars with masses greater than 100 $M_{\odot}$.

mergers can also *foster* disk formation (though at the expense of heating pre-existing populations) (Hopkins et al., 2009). Indeed, the outcome of mergers seems strongly dependent not just on the mass ratio of the galaxies but also on their gas content, with gas-rich mergers enhancing disk formation while gas-poor mergers regularly destroy disks.

All of these processes – star formation, gas accretion, and mergers – work together to shape galaxies over their lifetimes. However, it is hard to disentangle exactly what impact each has on the galaxy at present. In particular, because when we look back across redshift, we are not tracking the evolution of any individual galaxy, but rather a whole population, each with their own distinct histories.

Key Takeaways for this Dissertation

- Galaxies evolve over cosmic time. In the early Universe, galaxies are consistently smaller and clumpier, have higher gas fractions, and experience intense, bursty star formation, with disk morphologies being comparatively rare.
- As the Universe ages, disks become increasingly common. However, early gas disks are (predominately) thicker and dynamically-hotter than those observed today. Gas disks become progressively thinner towards present-day: disks settle over cosmic time.
- A galaxy’s structure and kinematics is shaped by its mass-accretion, star-formation, and merger histories, with chaotic gas accretion, star bursts, and major mergers hindering or disrupting disk formation and settling.
- At fixed mass and redshift, there is substantial scatter in galaxy kinematics, indicating that today’s disks galaxies experienced a wide range of formation histories.

1.3 THE MILKY WAY

Thus far, we have discussed galaxies as the consequences of hierarchical structure formation, gas accretion, star formation, and feedback. But before there was a Universe of billions (potentially trillions) of galaxies, there was a Universe of a single galaxy.

In the MW, we can observe the inner workings of a galaxy in unprecedented detail, obtaining detailed censuses of stars and clusters (Zucker et al., 2023). However, our internal perspective gives an incomplete picture of the Galaxy as a whole. For example, the most recent data release from ESA’s Gaia mission provided parallaxes and proper motions for almost 1.5 billion stars in the MW (Gaia Collaboration et al., 2023). However, we have yet to reach a consensus on the number or location of the spiral arms of the MW (Hunt and Vasiliev, 2025), remain uncertain about whether the MW’s disk is unusually compact (Lian et al., 2024), and continue to debate its basic

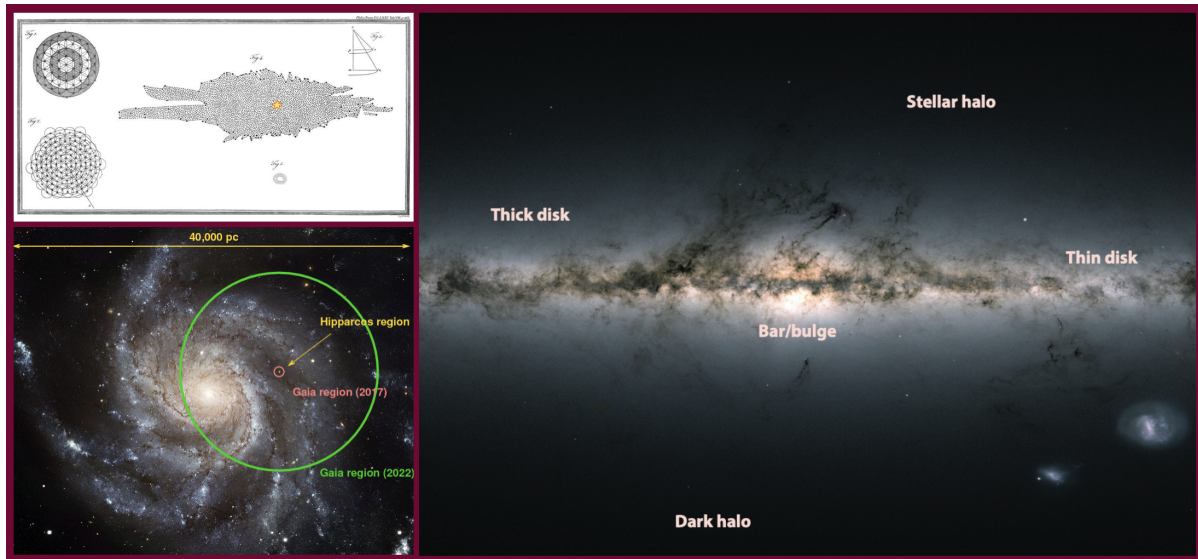


Figure 6: **Different representations of the Milky Way.** Top Left: Map of William Herschel. Bottom Left: Bird's-eye view of a Milky-Way like galaxy, showing the regions probed by the Hipparcos and Gaia astrometric surveys; Credit: Michael Richmond; background image of M101 courtesy of NASA/ESA. Right: Image of the Milky Way's center from the Gaia mission; Credit: Figure from Helmi (2020), adapted from Gaia/DPAC/ESA (CC BY-SA 3.0 IGO).

global properties, with recent work suggesting that the MW's total stellar mass is nearly a factor of two lower than long assumed (Lian et al., 2025). That is to say, linking the richly resolved physics of the solar neighborhood to the global structure and evolution of the MW is far from straightforward.

Figure 6 shows different views of our Galaxy. The upper-left corner shows the first published map of the MW, which was painstakingly constructed by William Herschel (with the help of his sister, Caroline) between 1784 and 1785 from star count measurements across 683 regions of the sky. The dramatic rise in star counts along the MW's band and decline toward the poles led Herschel to (rightfully) conclude that the MW is strongly flattened (as far as its stars are concerned), and his map of the MW can generously be considered as a disk (albeit one with a particular amoeba-like quality). That said, Herschel also concluded that we are at the center of the MW, which was reasonable given that he saw roughly equal numbers of stars in each direction along the disk plane.⁵

The true location of the Sun is more reliably represented in the bottom-left panel of Figure 6, where now the MW is represented by an image of M101.⁶ This image highlights the Sun's position in the outer disk – approximately 8 kpc from the galactic center – and its placement between two spiral arms, as well as our expanding view of our Galaxy thanks to the Gaia mission.

⁵ This heliocentric view persisted until the 1920s, when Harlow Shapley showed that the MW's globular clusters centered not around the Sun, but around some unfamiliar location, now known to be the Galactic center; indeed, we had previously neglected the effects of dust, as is often the case in astronomy.

⁶ M101 is also known as “The Pinwheel Galaxy”, or, if you are feeling less whimsical, NGC 5457.

Launched in 2013, the Gaia mission has ushered in a golden age of MW studies: Its data cover the whole sky, are open to the entire community, and are unprecedented in both quantity and precision. Conceived as the successor to Hipparcos, an earlier European Space Agency mission that measured parallaxes and proper motions for roughly 118,000 bright stars (Perryman et al., 1997) Gaia was designed first and foremost as an astrometric survey. By tracking exquisitely small shifts in stellar positions on the sky, Gaia measured proper motions and trigonometric parallaxes for 1.5 billion stars (Gaia Collaboration et al., 2023). Crucially, these trigonometric parallaxes can be used to calculate reliable distances. Gaia is not solely an astrometric mission, however, but also obtains photometry and low-resolution spectroscopy. Although fairly coarse, this spectroscopy yielded radial velocities for ≈ 33 million stars in Gaia’s third data release, which can be combined with Gaia’s astrometry to obtain full 6D phase space information (that is, 3D positions and velocities). In parallel, large-scale, ground-based spectroscopic surveys, including APOGEE (Majewski et al., 2017), GALAH (Buder et al., 2018; De Silva et al., 2015), LAMOST (Cui et al., 2012), and most recently the Milky Way Mapper (SDSS Collaboration et al., 2025), now provide enormous, high-quality datasets replete with radial velocities and physical properties – including detailed elemental abundances – for hundreds of thousands to millions of stars.

These datasets allow us to observe our galaxy – and understand its structure and history – in unprecedented detail. The right-panel of Figure 6, taken from Helmi (2020), shows Gaia’s view of the MW and its various (conveniently labeled) components: the thin and thick disks, bar/bulge, stellar halo, and dark halo.

1.3.1 STRUCTURAL COMPONENTS

1.3.1.1 THE DISK

The stellar disk of the Milky Way is, by most reasonable measures, its defining component: it contains the bulk of the Galaxy’s stellar mass and effectively all of its cold gas (and thus star formation).

THICK AND THIN DISKS

The MW’s stellar disk is often divided into two main components – typically designated as the “thin” and “thick” disks. The idea that the MW hosts a distinct thick disk was popularized by Gilmore and Reid (1983), who showed, using star counts toward the South Galactic Pole, that the MW’s vertical stellar density profile is inconsistent with a single exponential and is instead well fit by the sum of two exponentials with different scale heights.⁷ This two-component picture has largely persisted, and the vertical stellar density (at the solar radius) is now commonly described as a thin component with scaleheight 300 ± 50 pc and a thick component with 900 ± 180 pc (Bland-Hawthorn and Gerhard, 2016; Jurić et al., 2008).

⁷ Thick disks were first detected in external (S0/lenticular) galaxies by Tsikoudi (1979) and Burstein (1979), with Burstein (1979) coining the term “thick disk” to describe their secondary disk component.

The thick disk differs from the thin disk in more than just its vertical extent. Thick disk stars are typically old ($\sim 9\text{--}11$ Gyr), relatively metal-poor (with mean $[\text{Fe}/\text{H}] \sim -0.5$ to -0.7 dex)⁸, and enhanced in α -elements, while the thin disk is dominated by younger populations ($\sim 4\text{--}6$ Gyr on average) with near-solar metallicity (Bensby, Feltzing, and Lundström, 2003; Bensby et al., 2011; Fuhrmann, 1998; Hayden et al., 2015). Perhaps unsurprisingly, the differences between thick and thin disks also extend to kinematics: the thick disk is “dynamically hot”, with larger velocity dispersions ($\sigma_z \approx 50$ km/s) and a measurable rotational lag, while the thin disk is comparatively cold ($\sigma_z \approx 25$ km/s) and rotates close to the local circular speed (Bland-Hawthorn and Gerhard, 2016; Sanders and Binney, 2015; Soubiran, Bienaymé, and Siebert, 2003; Soubiran et al., 2008). That said, the two disks are not always cleanly distinguishable; for example, a young star in the outer disk may reach seemingly “thick” heights above the plane, while an old, metal-poor star interior to the Solar radius may remain on a cold, ostensibly “thin” orbit. Nevertheless, studies often treat the thin and thick disks as distinct components, distinguishing populations using various geometric, kinematic, age-based, or abundance-based criteria, which often involve ambiguous (arguably arbitrary) boundaries and select different populations.

For example, it has become increasingly common to distinguish the two disks *chemically* based on the stars’ locations on the $[\alpha/\text{Fe}]$ plane (e.g. Mackereth et al., 2019a; Miglio et al., 2021). Elemental abundances (measured from absorption line features in a star’s spectra) are particularly valuable because they remain largely unchanged over a star’s lifetime (in contrast to positions or kinematics, which can change substantially), meaning they essentially “freeze in” information on the ancient star-forming ISM, with the $[\alpha/\text{Fe}]$ ratio encoding information on the relative contribution of core-collapse and white dwarf supernovae to the ISM’s enrichment and thus the star formation timescale. Stars that form early or in regions with short, intense star-formation episodes tend to be α -enhanced, while stars that form later, after substantial Type Ia enrichment, exhibit lower $[\alpha/\text{Fe}]$ ratios.⁹ In turn, the high- $[\alpha/\text{Fe}]$ disk is believed to have formed rapidly early in the MW’s history, during a phase when the Galaxy was radially-compact, vertically-thick, and gas rich, whereas the low- $[\alpha/\text{Fe}]$ disk formed later in a calmer (that is, less bursty and less rapidly star-forming), more radially-extended, thin gaseous disk. Although the correspondence between different disk definitions is not exact, the high- $[\alpha/\text{Fe}]$ disk broadly resembles the classical thick disk, being predominantly old, kinematically hot and vertically extended. Similarly, the low- $[\alpha/\text{Fe}]$ disk, being younger, dynamically colder, and radially extended, is closely associated with the thin disk (Rix and Bovy, 2013). That said, the high- $[\alpha/\text{Fe}]$ disk is frequently noted to be particularly radially concentrated, having a radial scale length of just ~ 2 kpc whereas the low- $[\alpha/\text{Fe}]$ disk has a scale length of ~ 2.6 kpc Bland-Hawthorn and Gerhard (2016) and Bovy et al. (2012a). In contrast, the classical (geometric) thick disk has a scale length of 3.5–4 kpc (Jurić et al., 2008). Theoretical work suggests that this discrepancy reflects the flaring of low- $[\alpha/\text{Fe}]$ populations: as the disk grows, younger populations can form at progressively larger radii, where they subsequently flare given the lower

⁸ $[\text{Fe}/\text{H}] \equiv \log_{10} \left(\frac{N_{\text{Fe}}}{N_{\text{H}}} \right)_{\star} - \log_{10} \left(\frac{N_{\text{Fe}}}{N_{\text{H}}} \right)_{\odot}$

⁹ After a star formation event, core-collapse supernovae enrich the ISM with α elements (along with other elements including Fe, though in comparatively meager amounts) almost immediately, whereas type Ia supernovae contribute large amounts of Fe (and negligible α elements) but require longer ~ 100 Myr timescales.

density (and thus weaker gravitational pull) in the outer disk (Martig et al., 2016; Minchev et al., 2015). Thus, young, low- $[\alpha/\text{Fe}]$ populations can reside high above the midplane, “infiltrating” the geometric thick disk.

SPIRAL ARMS

The MW contains multiple spiral arms, which are large-scale non-axisymmetric over-densities of gas, stars, and dust that serve as predominant regions of star formation. Although controversial, there is tenuous acceptance that the MW has four main spiral arms – the Scutum–Centaurus and Sagittarius–Carina arms interior to the Solar circle and the Perseus and Norma–Outer arms exterior – but their exact shapes, strengths, and pattern speeds (among various other properties) remain deeply uncertain (Castro-Ginard et al., 2021; Drimmel et al., 2025; Reid et al., 2019; Shen and Zheng, 2020).

The confusion regarding spiral structure is not restricted to the MW’s arms, as there is still remarkably little consensus regarding many (seemingly basic) theoretical aspects of spiral structure. Foundational questions, including how long spiral arms persist, what mechanism initiates or sustains them, and even their fundamental nature remain subjects of active debate. The canonical framework, Lin–Shu density-wave theory (Lin and Shu, 1964), posits that spirals originate from long-lived, quasi-stationary density waves that organize gas and stars into coherent overdensities over many rotation periods. A contrasting view, rooted in Toomre’s swing-amplification framework (Toomre, 1977), and reinforced by modern N-body simulations (Fujii et al., 2011; Sellwood, 2011), envisions spiral arms as transient, recurrent features that wind, shear, and reform on dynamical timescales. Despite decades of study, neither theory has been conclusively “proven” over the other. Furthermore, some spirals may be triggered by bars (through non-linear mode coupling) (Minchev and Famaey, 2010) or tidal interactions (Pettitt, Tasker, and Wadsley, 2016; Purcell et al., 2011), and it is unclear how these spirals correspond to those formed in non-barred, isolated galaxies. The observed diversity of spiral morphologies, ranging from symmetric grand-design systems to flocculent, “swirling hotch-potch[es] of pieces of spiral arm” (Goldreich and Lynden-Bell, 1965), suggests that no single mechanism dominates universally, and the physical origin of this variety remains incompletely understood.

Despite our lack of understanding regarding the nature of spiral arms, it is well established that spiral arms can significantly alter stellar kinematics. Perhaps the most widely discussed dynamical consequence of spiral structure is “radial migration”, whereby stars near the corotation resonance of a spiral arm experience considerable changes in angular momentum, and thus guiding center radius, *without* any corresponding increases in random energy (Minchev et al., 2012; Roškar et al., 2008; Sellwood and Binney, 2002). Spirals can also increase the random motions of stars, either through direct scattering or through the cumulative interaction of multiple patterns (Aumer, Binney, and Schönrich, 2016; Binney and Tremaine, 2008; Carlberg and Sellwood, 1985).

1.3.1.2 BULGE

In addition to the disk, the MW’s center contains a more spheroidal “bulge” component. This component is the next most massive stellar component after the disk, with an estimated mass of $(1.4 - 1.7) \times 10^{10} M_{\odot}$, such that the bulge to total stellar mass ratio is 0.3 ± 0.06 (Bland-Hawthorn and Gerhard, 2016). The MW’s bulge typically contains more older stars than the disk, but it is not exclusively old, also including intermediate-aged and also young stars.

Bulge-like structures are commonly observed in massive galaxies, and much work has focused on distinguishing between the “classical bulges” observed in elliptical galaxies and “pseudobulges” like the one in our MW. Likely, classical bulges formed primarily via mergers, while pseudobulges formed primarily via secular processes like bar formation and buckling. More specifically, the MW’s pseudobulge is designated as a “boxy/peanut bulge”, named for the shape of the orbits dominating its structure. This pseudobulge can be considered to be the inner, vertical extension of the MW’s bar.

BAR

The MW, like the majority of disk galaxies in the present-day Universe, hosts a central bar: an elongated, rotating overdensity of stars that dominates the stellar distribution of the inner galaxy (Erwin, 2018).¹⁰ For decades, it was believed that the MW lacked a stellar bar, but by the mid-90’s, observations of non-axisymmetric gas flows (Binney et al., 1991), star count studies (Stanek et al., 1994, 1997), and, crucially, near-IR photometry from the COBE satellite (Dwek et al., 1995; Weiland et al., 1994), gradually betrayed our bar’s existence. Subsequent spectroscopic and photometric studies, and ever-growing samples of red-clump stars, mapped the 3D structure of the MW’s bulge and bar, revealing an X-shaped/boxy-peanut structure indicative of a past bar-buckling event and thus a disk-origin for much of the bulge (e.g. McWilliam and Zoccali, 2010; Ness and Lang, 2016; Wegg, Gerhard, and Portail, 2015).

Estimates of the bar’s mass and dynamical properties remain uncertain and model dependent (see Gaia-era reviews of Hunt and Vasiliev, 2025; Shen and Zheng, 2020); however, recent studies applying kinematic modeling to stars in either the inner-disk/bulge or solar neighborhood generally favor a long (~ 5 kpc), slow ($\Omega_p \sim 35 - 45 \text{ km s}^{-1} \text{ kpc}^{-1}$) bar for the MW. Similarly, while age-dating the bar remains fraught with difficulties, most post-Gaia studies find that the bar is fairly old, forming $\gtrsim 8$ Gyr ago (Bovy et al., 2019; Haywood et al., 2024; Sanders et al., 2024; Zhang et al., 2024).

Bars exert a substantial dynamical influence on their host galaxies. This influence is particularly strong over the course of the bar’s initial formation and subsequent early growth (and slow-down), with simulations finding

¹⁰ The exact bar fraction depends on the adopted definition of “barred”. When all bars, including weak bars are included, the barred fraction is $\sim 60\text{-}70\%$ (for disk galaxies in the local Universe), but this fraction drops to $\sim 30\%$ when restricted to just strong bars (Masters et al., 2011; Sheth et al., 2008). Furthermore, the bar fraction evolves over cosmic time, with bars being increasingly rare towards higher redshift: recent JWST observations indicate that only 10-15% of disk galaxies hosted bars at $z=2\text{-}3$ (Géron et al., 2025; Le Conte et al., 2024).

that bar formation can cause stars from the inner galaxy to move outward by $\gtrsim 4$ kpc, with initially eccentric orbits becoming circular (in contrast to most other dynamical processes)(Haywood et al., 2024; Khoperskov et al., 2020). While their dynamical impact may be strongest early on, bars, being massive, non-axisymmetries in the gravitational potential, continuously/perpetually perturb stellar orbits (and increase their random motions) throughout their lifetimes. In fact, simulations find that the strength of the bar is well correlated with the degree of snapshot to snapshot heating, particularly for young stars (Grand et al., 2016). Furthermore, bar resonances can non-linearly couple with those of spiral arms, which can in turn heat stellar orbits (rather substantially) and induce rapid angular-momentum redistribution on short timescales (Minchev et al., 2012).

The very center of our galaxy hosts a supermassive black hole, in line with expectations for nearly all massive galaxies. With an estimated mass of $(4.2 \pm 0.2) \times 10^6 M_\odot$, the MW’s black hole seems to be less massive proportionally compared to supermassive black holes in other disk galaxies (Savorgnan et al., 2016). Given the well-established connection between galaxy mergers and supermassive black hole growth (Di Matteo et al., 2008; McAlpine et al., 2017) this low mass suggests that the MW had a comparatively quiescent merger history, which is indeed consistent with our current understanding of the MW’s history.

1.3.1.3 STELLAR HALO

With a total stellar mass of $(1.4 \pm 0.4) \times 10^9 M_\odot$ (Deason, Belokurov, and Sanders, 2019), the stellar halo comprises only $\sim 2 - 3\%$ of the MW’s total stellar mass.¹¹ The mass-fraction of the MW’s stellar halo is on the lower end of values reported for external galaxies and simulations, which is consistent with it experiencing its last major merger early in its lifetime (Hammer et al., 2007).

Although the stellar halo makes up only a small fraction of the MW’s stellar mass, it offers particularly rich insight into the MW’s accretion history. The stellar halo is rich with debris and stellar streams from accreted systems, but also contains a roughly-spheroidal swarm of older stars, believed to have formed in-situ. Because dynamical times are long in the stellar halo, it retains our best record of our Galaxy’s merger history, hosting the Sagittarius dwarf spheroid galaxy and its associated stream, and as shown more recently, a preponderance of evidence for a massive merger occurring 10 Gyr ago.

1.3.2 GALACTIC ARCHAEOLOGY

We see the Milky Way only in its current state, after more than 13 Gyr of evolution, and we cannot replay how it assembled. Instead, we can use its stars to infer that history. Long-lived stars preserve the chemical conditions of the interstellar medium at their birth, and their present-day orbits carry the imprint of where they formed and how

¹¹ Historically, the inferred halo mass was even lower, at $2-4 \times 10^8 M_\odot$ (Bell et al., 2008; Deason, Belokurov, and Evans, 2011).

they were perturbed. By combining these chemical and dynamical records, we can attempt to disentangle how the Milky Way formed and evolved.

In one of the first – and most influential – implementations of Galactic archaeology, Eggen, Lynden-Bell, and Sandage (1962) (ELS) presented a model for the formation of the Galaxy based on observations of ~ 200 metal-poor stars in the solar neighborhood. ELS observed that stars with large ultraviolet excesses (indicating lower metallicity) tended to have large orbital eccentricities and vertical velocities, while metal-rich(er) stars followed more circular, disk-like orbits.

On the basis of these observations, ELS argued that the life of our Galaxy began with the rapid collapse of an enormous ball of primordial gas. Amidst this collapse, individual gas clouds formed stars, some of which enriched the (still infalling) gas with metals. These early forming stars would have low metallicities and highly eccentric orbits. Upon reaching the Galaxy center, newly enriched gas clouds readily collide and dissipate away their gravitational energy, settling into a rotationally supported disk and forming stars with higher metallicities and circular orbits. In total, ELS estimates that this entire process took ~ 200 Myr.

Searle and Zinn (1978) challenged the ELS view by focusing on the chemical and structural properties of the Galactic halo, arguing that its stellar populations could not have formed in a single rapid collapse. Their analysis suggested that the halo formed over an extended period through stochastic, hierarchical growth rather than through a single coherent contraction, and it established one of the earliest observational arguments for a merger-driven assembly history of the MW.

These two papers – now 64 and 48 years old – underscore the persistent complications of Galactic archaeology. In the words of Eggen, “We had opened a can of worms, and when different people look into a can of worms, they see different worms” (Croswell, 1996).

With the advent of Gaia, our view of the MW’s history has been increasingly refined. Multiple recent works agree that the nascent “proto-MW” developed into a thick but continuously settling disk sometime between 9-13 Gyr ago, experienced a major merger, the Gaia-Sausage-Enceladus or GSE merger¹² (Belokurov et al., 2018; Helmi et al., 2018) between 8-11 Gyr ago, and then formed a thin disk between 7-9 Gyr ago (Belokurov and Kravtsov, 2022; Conroy et al., 2022; Xiang and Rix, 2022). Nevertheless, many crucial details about the GSE merger remain blurry or even completely unconstrained.

Galactic archaeology is challenging. Observations within the MW show that the youngest stars share the kinematics of the gas from which they formed: in the present-day solar neighborhood, stars form on nearly circular

¹² The dual name of the Gaia-Sausage-Enceladus merger stems from it being first reported in two different works. The “sausage” moniker derives from the fact that its stars form a sausage shape in velocity space. Helmi et al. (2018) named the debris “Enceladus” after a giant in Greek mythology, the son of Gaia and Uranus (the sky). Upon his defeat by the Gods, he was buried under Mount Etna, whose seismic activity was blamed on his his entombed tossing and turning. Similarly, the merged dwarf galaxy was buried beneath the MW, “puffing up” the MW’s disk just as the mythical Enceladus caused tremors and volcanic eruptions.

orbits with total velocity dispersions $\sigma_{\text{tot}} \approx 25 - 30$ km/s (Casagrande et al., 2011; Edvardsson et al., 1993). However, the star-formation environment of the Galaxy’s youth likely provided a much more tumultuous nursery.

Ideally, we could use the present-day orbits of stars as a function of age to study exactly how the MW’s disk settled over cosmic time. However, the disk’s evolution is obfuscated by processes that alter the orbits of stars after they formed. In particular, via “kinematic heating” stars gain additional random orbital over time due to gravitational interactions with asymmetric structures from inside the galaxy, such as giant molecular clouds (GMCs) (Lacey, 1984; Spitzer and Schwarzschild, 1951; Wielen, 1977), spiral arms (Barbanis and Woltjer, 1967; Carlberg and Sellwood, 1985; Minchev and Quillen, 2006), and bars (Grand et al., 2016), and from outside the galaxy, such as accreting gas inflows, mergers, and satellites (for example Brook et al., 2004; Quinn, Hernquist, and Fullagar, 1993; Villalobos and Helmi, 2008), among various additional processes.

The varied formation and heating histories of stars nevertheless result in the present-day kinematic structure of the Galaxy. In the solar neighborhood, the velocity dispersion increases monotonically with age (for example Casagrande et al., 2011; Strömberg, 1946; Wielen, 1977). Nordström et al. (2004) and Holmberg, Nordström, and Andersen (2009) argued that this observed trend is consistent with MW stars forming on ‘disky’ orbits that then underwent dynamical heating by the combination of GMCs and spiral arms. Mackereth et al. (2019a) and Ting and Rix (2019) extended this analysis to include stars located outside the solar neighborhood ($R = 3 - 14$ kpc) and found similar results: the observed relations are consistent with stars younger than ≈ 8 Gyr having formed with a low, constant dispersion and subsequently being heated by both GMCs and spiral arms. However, as before, the observed dispersions of older stars (age $\gtrsim 8$ Gyr) are higher than those predicted by heating models (Mackereth et al., 2019a). This discrepancy could arise if old stars were born kinematically hotter, or if their dynamical heating differed from what current models predict. Likely, both factors contribute, but disentangling this remains challenging.

There is an inherent degeneracy in the galactic archaeological record, in that kinematics can reflect both how stars form and also how they subsequently evolved. Undoing this degeneracy is one of the key goals of galactic archaeology. Simulations allow us to track an individual galaxy throughout its lifetime, allow us to run the cosmic clock forward and backward. Of course, for simulations to be a useful tool, they need to at least in some way match the reality of how galaxies actually form. In truth, accurately simulating galaxies in a fully cosmological context is no easy feat, as we will now discuss.

Key Takeaways for this Dissertation

- The MW provides a remarkable laboratory for studying galaxy formation and evolution, because it is the only galaxy for which we can obtain ages, positions, kinematics, and abundances for large samples of individual stars.
- By studying the kinematics of stars as a function of age, we can attempt to understand the MW's history, including the formation of its thick and thin disk and possible mergers.
- Various dynamical processes alter the orbits of stars over their lifetimes. In particular, gravitational interactions with spiral arms, bars, GMCs, and merging galaxies can increase the velocity dispersion of stars.
- A major challenge for understanding the MW's history is our inability to distinguish the velocity dispersion that stars formed with from that they gained via subsequent interactions.

1.4 SIMULATING GALAXIES

Simulations have long provided a laboratory for studying disk galaxies. Early N-body simulations, and later more sophisticated methods that added gas dynamics, star formation, and feedback, typically began by imposing a rotationally supported disk and then following its subsequent evolution. These studies were invaluable for clarifying internal disk physics; however, as discussed in Section 1.2, galaxies cannot be easily separated from their greater cosmological context because hierarchical structure formation and gas accretion drive much of a galaxy's formation and evolution, particularly at early times. Therefore, cosmological simulations attempt to directly model this greater cosmic environment, adopting a cosmological model (typically Λ CDM) and initial conditions (density perturbations). A full and robust theory of galaxy formation in Λ CDM should begin with the initial conditions of Λ CDM and the building block of gravity, evolving them forward in time to match the observed distribution and properties of galaxies over time.

The left panel of Figure 7 (taken from the review of Vogelsberger et al. (2020) on cosmological galaxy simulations) highlights some of the many different cosmological simulations in the literature, grouping them into 4 categories based on spatial scale and physics modeled. The bottom panel of Figure 7 (left) highlights large volume simulations. These simulations encompass a large volume – $4,110^3$ (comoving) Mpc^3 and $11,628^3 \text{ Mpc}^3$ for the DM-only simulations Millenium-XXL and DarkSky, respectively, and $\approx 100^3 \text{ Mpc}^3$ for hydrodynamical simulations Eagle and Illustris TNG100 – providing information on a large statistical sample of halos/galaxies, but computational cost ultimately restricts the resolution.

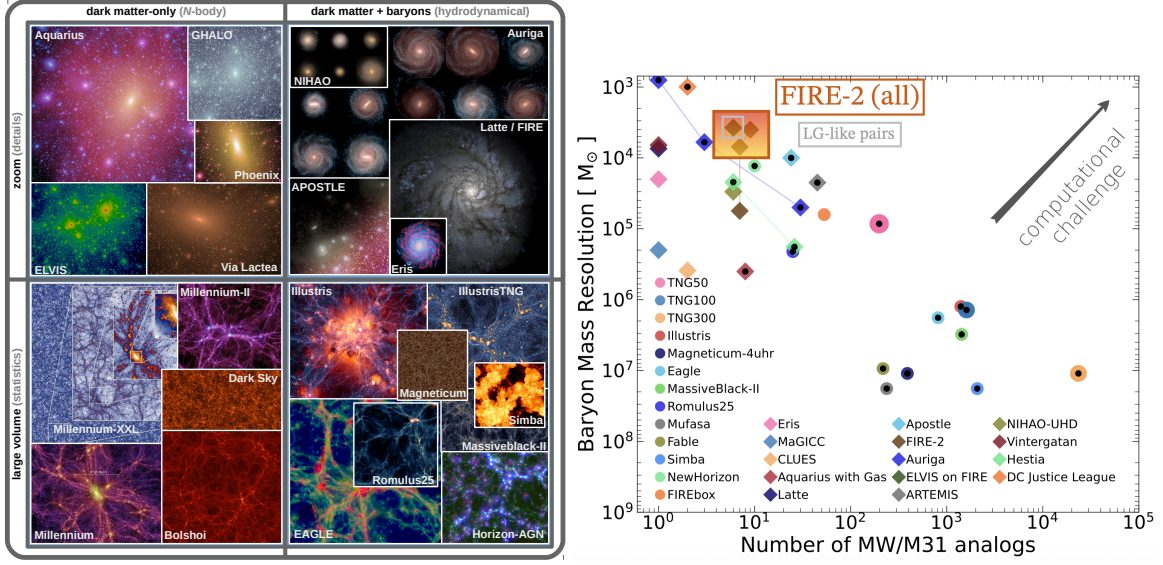


Figure 7: **Overview of Different Cosmological Simulations:** The left panel, taken from Vogelsberger et al. (2020), shows visual representations of cosmological structure and galaxies from a variety of recent simulations. Importantly, modern cosmological zoom-in simulations, featured in the top-right corner, generate galaxies that largely resemble observed galaxies, exhibiting extended disks with spiral structure. The right panel, (slightly) adapted from Pillepich et al. (2024), highlights the necessary trade-off between statistics and resolution: the increased computational expense of high resolution simulations limits the resulting sample size. Nevertheless, the FIRE-2 simulation suite (highlighted in orange) contains 14 galaxies simulated at state-of-the-art resolution.

The upper half of Figure 7 shows simulations that focus on small regions of the cosmos. These "zoom-in" simulations start from large-scale, DM-only simulations, and pick a particular halo of interest. This region is then re-simulated with much higher resolution, either with or without hydrodynamics/baryonic physics. With this approach, these simulations can reach a much higher resolution than their large-volume counterparts. For example, the FIRE-2 simulations can reach resolutions of ≈ 1 pc¹³ in the star-forming ISM while popular large-volume simulations such as IllustrisTNG and Eagle can reach ~ 200 pc and 350 pc.

This dissertation focuses mainly on the type of simulations shown in the upper right panel: zoom-in simulations that directly model gas and stars – and their complicated physics – alongside dark matter.

Historically, simulators struggled to generate galaxies that resembled observed disks. Early simulations included dissipative gas but neglected star formation (and consequently, stellar feedback), resulting in galaxies that were significantly more compact than observed systems. This “over-cooling” problem resulted from the catastrophic collapse of gas into the centers of DM halos. Later simulations modeled star formation and its associated stellar feedback; however, even with this new stellar component, the over-cooling problem persisted, with gas rapidly

¹³ Specifically, the minimum adaptive force softening length for gas cells (which for FIRE, is equivalent to the hydrodynamic smoothing kernel) is $\epsilon = 1$ pc in the isolated “m12” simulations and $\epsilon = 0.400$ in the “ELVIS on FIRE” simulations of LG-like galaxy pairs. That said, this represents the *minimum* softening length. The softening length is fully adaptive and set by the gas density, with values being ~ 4 pc at typical star-forming densities ($n \sim 4000 \text{ cm}^{-3}$) and ~ 20 –40 pc at typical ISM densities ($n \sim 1 \text{ cm}^{-3}$).

converting into stars and forming bulge-dominated systems. In systems that did form disks, the resulting stellar disks were too small or had too low of a mass fraction (and often both). However, by the early 2010's, cosmological hydrodynamic simulations were finally able to generate fairly realistic disk galaxies owing to improvements in resolution, and perhaps more importantly, new methods of implementing stellar feedback (Governato et al., 2012; Guedes et al., 2011).

I now briefly discuss the key ingredients of cosmological baryonic simulations (gravity, hydrodynamics, gas physics, star formation, and feedback processes) including how they are typically modeled in modern baryonic zoom-in simulations.

1.4.1 GRAVITY

In cosmological simulations, stars and dark matter are both typically modeled as collisionless particles that interact only through gravity.¹⁴ In the continuum limit, the dynamics of these collisionless components are governed by the collisionless Boltzmann equation, which describes how the phase-space distribution function evolves under the influence of gravity. The gravitational potential itself is determined by the Poisson equation, which links the mass density to the gravitational potential.

In principle, N-body simulations are straightforward: find the gravitational force acting on a particle and update its 3D position and velocity accordingly. Here, one needs only to integrate the $6N$ ordinary differential equations that describe the motion of N particles under Newtonian gravity. However, straightforward does not mean practical, or even computationally possible. Because each particle interacts gravitationally with each other, the computational cost of a direct integration grows as $O(N^2)$. Modern simulations routinely follow millions (or even billions) of particles, making such a computational cost utterly infeasible. Instead, simulators adopt different methods to improve computational efficiency when solving for gravity.

One popular approach is tree methods, which group distant particles together and approximate their collective influence through multipole expansions (Barnes and Hut, 1986). Another approach is particle mesh methods, which map the particle distribution to a spatial mesh and solve for the potential in Fourier space using fast Fourier transforms. Both tree and particle mesh methods can achieve computational scalings of $O(N \log(N))$. More recently, different hybrid methods have been developed, including the popular Tree-PM method, which uses the tree method for short range gravitational interactions and particle mesh for long range interactions (Bagla, 2002). Such Tree-PM methods form the basis of the popular GADGET (Springel, 2005; Springel, Yoshida, and White,

¹⁴ This assumption is well justified for stars and cold, non-relativistic dark matter, though alternative self-interacting dark matter models have been implemented in large-volume and zoom-in simulations, both with and without baryons/hydrodynamics (Burger et al., 2022; Correa et al., 2022; Despali et al., 2025; Robertson et al., 2019). See also (Robles et al., 2017; Vargya et al., 2022) for implementations of SIDM in the FIRE-2 hydrodynamic zoom-in simulations.

2001), GIZMO (Hopkins, 2015), and AREPO (Springel, Pakmor, and Weinberger, 2019) codes (with GIZMO being the code used in the FIRE-2 simulations analyzed throughout this work).

1.4.2 HYDRODYNAMICS

Unlike DM and stars, gas cannot be treated as a collisionless fluid. Instead, its evolution is governed by the hydrodynamic equations, which in astrophysical contexts reduce to the Euler equations for an ideal, inviscid, conducting medium. Because these equations admit no closed-form solutions for galactic flows, simulations must discretize the gas to evolve it forward in time. Hydrodynamic solvers typically fall into two classes: Lagrangian, particle-based approaches that discretize mass and track moving fluid elements, and Eulerian, grid-based approaches that discretize space and solve the fluid equations on a grid.

The most commonly used Lagrangian method is smoothed particle hydrodynamics (SPH). Here, the fluid is represented by particles that carry mass, energy, and entropy and interact through kernel-smoothed estimates of their neighbors’ properties. Because SPH elements move with the flow, the method naturally adapts its resolution to dense regions, conserves mass and momentum by construction, and interfaces cleanly with N-body gravity. Its grid-free nature also makes it easy to handle irregular geometries. Yet traditional, “vanilla” SPH comes with well-known shortcomings. Capturing shocks requires artificial viscosity, which can broaden discontinuities, introduce spurious heating, and degrade angular-momentum conservation. Standard formulations also struggle with fluid instabilities, mixing, and contact discontinuities (Agertz et al., 2007), limiting their accuracy in various regimes – strong shocks, turbulent media, and cold streams – commonly encountered during galaxy formation. As a result, modern simulations rely on improved SPH variants (for example Hopkins, Narayanan, and Murray, 2013; Price and Monaghan, 2007; Wadsley, Keller, and Quinn, 2017) that mitigate these issues, and the original formulation is now rarely used in state-of-the-art cosmological work.

The second major approach are Eulerian methods, in which the fluid equations are solved on a spatial grid rather than following individual mass elements. The hydrodynamic variables live on mesh cells that cover the simulation volume, and fluxes between neighboring cells, computed using exact or approximate Riemann solvers, update the fluid state. As a result, Eulerian methods capture shocks and contact discontinuities accurately (unlike traditional Lagrangian schemes). However, because grid resolution is spatially fixed, Eulerian methods lack the built-in adaptivity of Lagrangian schemes. In order to capture the range of scales involved in cosmological galaxy formation, modern Eulerian codes employ methods like adaptive mesh refinement (AMR). In AMR codes, cells that meet chosen criteria (e.g. gas mass or density) are recursively subdivided, allowing resolution to follow structure and making the approach effectively quasi-Lagrangian. AMR enables high-resolution studies of shocks, ionization fronts, and the multiphase CGM, but its irregular grids are memory-intensive. Furthermore, even with AMR, Eulerian schemes do not strictly conserve angular momentum, which can be problematic for rotating

systems (like galaxies), and gas moving rapidly across the grid frequently suffers from excess numerical mixing and advection errors.

More recently, different groups have developed hybrid approaches to capture the benefits of both SPH and AMR techniques. For example, FIRE-2 uses the hybrid Meshless Finite-Mass (MFM) method. This method is both Lagrangian (move with the fluid flow) and meshless, allowing continuous and automatic adaptive resolution and deformation with the flow, while being simultaneously second-order accurate and manifestly (machine-accurate) conservative of mass, momentum, and energy.

1.4.3 GAS PHYSICS AND STAR FORMATION

To generate realistic galaxies, simulators must also model (some degree of) the baryonic physics that governs the evolution of gas and stars. Crucially, gas can dissipate away its internal energy via various radiative processes, including collisional excitation and ionization, metal-line, fine-structure, and molecular cooling, and inverse Compton, recombination, and free-free emission. Such gas cooling is perhaps the most important process in galaxy formation: via cooling, gas escapes (at least temporarily) from the cosmic web and makes it home in a galaxy where, through yet more cooling, it can reach sufficient densities to gravitationally collapse and form stars. The rate of gas cooling is not a one-size-fits-all prescription but depends sensitively on the gas density, temperature, metallicity, and ionization fraction. Typically, simulations adopt cooling rates (and ionization fractions) from precomputed cooling tables (generally from large-scale spectral synthesis codes, such as CLOUDY), often accounting for ionization from local radiation sources and a uniform meta-galactic UV background.

Stars form from dense gas. Thus, how simulations implement star formation will depend on how they model and resolve the ISM. Generally, the simulation’s resolution sets a limit on the maximum density that gas particles/cells can reach, with spatial resolutions of a few hundred pc corresponding to maximum densities on the order of $n = 0.1 \text{ cm}^{-3}$. Oftentimes, simulations model star formation following a type of Kennicutt-Schmidt law, where gas particles/cells that meet certain eligibility criteria convert to stars at a rate proportional to the gas density. Star formation thresholds are often set to be slightly less than the maximum reachable gas density, since stars (simulated and real) only form from the densest gas. That said, at any given time in a real galaxy, the fraction of gas with densities above many of these thresholds is much higher than the fraction of gas that will form stars within a free-fall time, requiring simulators to tune star formation efficiency or timescale parameters such that star formation follows observed rates. For example, simulations often parameterize the star formation density as $\rho_{\text{sf}} = \epsilon_{\text{sf}} \frac{\rho}{t_{\text{sf}}}$, where ϵ_{sf} is the efficiency at which gas converts to stars on the star formation time scale t_{sf} , which is empirically calibrated.

In contrast, the FIRE-2 simulations – which are the subject of this dissertation – resolve the multi-phase structure of the ISM, including the collapse of gas into GMCs. The FIRE-2 simulations adopt comparatively

stringent requirements: For gas to become eligible for star formation, it must be locally self-gravitating, Jeans-unstable, molecular – following (Krumholz and Gnedin, 2011) – and dense ($n > 1000 \text{ cm}^{-3}$) (Hopkins et al., 2018). In FIRE-2, gas cells are converted to star particles at an efficiency of 100% per local free-fall time. However, this does not imply that the global star formation efficiency is 100% within a GMC (or across larger scales), as self-regulated feedback limits star formation to $\sim 1\text{--}10\%$ per free-fall time (Orr et al., 2018). Such high SFR density thresholds lead to local and global galaxy properties that are more in line with observed properties than lower thresholds (Buck, Dutton, and Macciò, 2019; Dutton et al., 2019).

Star particles in simulations are necessarily much more massive than actual stars. For example in the FIRE-2 simulations that I analyze in this work, a newly formed star particle has a typical mass of $7070 M_{\odot}$ (although stellar mass loss results in star particles having masses around $5000 M_{\odot}$ at the end of the simulation). These star particles represent single stellar populations, with total/combined masses and metallicities inherited from their progenitor gas cells.

1.4.4 FEEDBACK

Stars are not passive: they inject energy, momentum, mass, and metals into their surrounding gas, thus enriching and disrupting the star-forming ISM.

Stellar feedback from core-collapse supernovae is particularly crucial to galaxy evolution; however, accurately modeling this process remains a persistent challenge (Keller, Kruijssen, and Chevance, 2022; Stinson et al., 2013) (see Dale, 2015; Naab and Ostriker, 2017, for review). Young stars, and the core-collapse supernovae they produce, form in dense, star-forming regions of the ISM, where high gas densities result in rapid radiative cooling. Consequently, the energy injected by supernovae dissipates quickly, limiting its ability to drive turbulence, regulate star formation, or launch large-scale galactic outflows (Bournaud et al., 2011; Katz, 1992).

To overcome this “over-cooling problem”, simulators adopt a range of ad-hoc sub-grid methods. Popular strategies include delayed cooling models (Guedes et al., 2011; Stinson et al., 2006), where gas cooling is temporarily turned-off in gas surrounding the newly formed star particles, modified thermal injection schemes, such as stochastic thermal feedback (Dalla Vecchia and Schaye, 2012) and (decoupled) wind models, where gas cells are converted into wind particles, decoupled from hydrodynamics, and launched into less dense regions far from the supernova site (Schaye et al., 2010; Springel and Hernquist, 2003). With the appropriate calibration of (fine-tuned) model parameters, these different sub-grid methods yield galaxies with properties much more in line with observations (albeit at the cost of diminished predictive power). A more physically-motivated approach is to explicitly model feedback from young stars, including stellar winds, radiation pressure, and photoelectric heating. This early feedback can clear the dense gas *before* the first supernovae detonate, essentially paving the way for more efficient supernova feedback (Agertz, Romeo, and Grisdale, 2015; Hopkins, Quataert, and Murray, 2012).

On galaxy scales, this prompt stellar feedback prevents the early onset of star formation that builds overly massive bulges (Stinson et al., 2013).

While earlier simulations necessarily adopted simplified (and often non-physical) sub-grid methods to model physical processes, more recent simulations, such as the FIRE simulations, now attempt to form realistic galaxies without fine-tuning. The FIRE-2 feedback model does not limit itself to just thermal energy from core collapse SNe, but also momentum and energy from SNe Types Ia and II, stellar winds (young star and AGB), local photoionization and photoelectric heating, and radiation pressure from UV and IR photons. Importantly, all of these feedback quantities (energy, momentum, mass, and metals) are taken directly from the STARBUST99 stellar population synthesis models of Leitherer et al. (1999) (assuming a Kroupa (2001) IMF) with no tunable parameters.

With these ingredients – gravity, hydrodynamics, gas physics, star formation, and stellar feedback – simulations now self-consistently generate galaxies – in a fully cosmological setting – that strongly resemble observed galaxies. This work focuses on a suite of 11-14 MW-mass galaxies from the (now oft mentioned) FIRE-2 simulation group. These simulated galaxies not only resemble the MW and M31 in a broad sense, having similar stellar, gas, and halo masses, radii, and morphologies, but also generally agree well in detail, having star-formation histories, metallicity gradients, and satellite populations, among other properties, similar to observations.

By modeling the formation of galaxies across cosmic time, simulations inform how the present state of a galaxy connects to its formation history. In particular, we can disentangle what properties of stellar disks were imprinted at formation versus subsequent evolution. Importantly we are not limited to one galaxy and one history, but a(-n ideally) representative sample of galaxies to compare to the MW and other observed galaxies and to help understand how these observed systems came to be.

Key Takeaways for this Dissertation

- Zoom-in simulations allow us to model galaxy formation in a fully cosmological context without sacrificing resolution.
- To form realistic galaxies, hydrodynamic simulations must model stellar feedback. While the majority of simulations adopt ad-hoc subgrid models to capture feedback effects, the FIRE-2 simulations model all major channels of stellar feedback, with all feedback quantities tabulated directly from stellar evolution models.
- The FIRE-2 simulations directly resolve (and rigorously) model the star-forming ISM, making them particularly compelling theoretical tools for understanding how stars in disk galaxies form and evolve over cosmic time.

1.5 MOTIVATIONS AND DISSERTATION OVERVIEW

Thus far, this Introduction has provided a broad overview of different topics underscoring this Dissertation work, ranging from the Λ CDM model, observations of high redshift galaxies, the detailed structure of the Milky Way, and the historical pitfalls and recent successes of cosmological simulations. In truth, I enjoy each of these topics and would be remiss to ignore them, and they provide a fuller background on the central topic of this work: the evolution of stellar kinematics in real and observed disk galaxies.

As previously mentioned, the formation histories of galaxies are encoded in stellar kinematics and, in particular, stellar velocity dispersions, because stellar populations largely retain the dispersions with which they formed. This “remembered” birth dispersion can be subsequently augmented by dynamical heating processes, owing to interactions with structures within and outside the galaxy. Therefore, stellar kinematics contains valuable information on two crucial but poorly understood aspects of galactic physics: the formation and settling of (gas) disks and the nature of dynamical heating over cosmic time.

As of writing, the formation of disks (never mind the added complexities of thick and thin disks) is rather contentious. Over the past few decades, observations from HST and large ground-based observatories converged on a picture of where disks formed recently, at $z < 2$ (Kassin et al., 2012; Übler et al., 2019; Wisnioski et al., 2015). However, more-recent observations from JWST and ALMA have discovered numerous well-ordered disk galaxies at $z > 4$, with reports even suggesting that the majority of star-forming galaxies have disk morphologies until $z \sim 5$ (Ferreira et al., 2023; Lelli et al., 2021; Nelson et al., 2023; Rizzo et al., 2020; de Graaff et al., 2024). In tandem with the upheaval regarding high redshift disks, MW studies – newly aided by Gaia and spectroscopic surveys – reported that the MW’s thick disk formed very early in its history, some 10 to 12 Gyr ago (Belokurov and Kravtsov, 2022; Conroy et al., 2022), with some studies suggesting that it formed as early as 13 Gyr ago (Xiang et al., 2025).

Compared to disk formation, the topic of dynamical heating has attracted less attention (and debate) in recent years; but like disk formation, it remains poorly understood. Dynamical heating is predominantly studied numerically, using either analytical models or simulations, with a rich literature extending back to Spitzer and Schwarzschild (1951). These works have yielded a theoretical picture in which σ increases with age ^{β} (with typical values of $\beta_R \sim 0.3 - 0.5$ and $\beta_Z \sim 0.25 - 0.35$) due to scattering interactions with GMCs and spiral arms (Aumer, Binney, and Schönrich, 2016; Carlberg and Sellwood, 1985; Jenkins and Binney, 1990; Sellwood, 2014). However, it is unclear how these theoretical findings apply to actual galaxies, especially at high redshift, given that canonical studies assume stars always form on circular orbits in MW-mass galaxies and frequently neglect gas (much less star formation and feedback).

These outstanding questions regarding the formation and evolution of galactic disks motivates the work presented in Chapter 2. Here, we study the kinematics of stars both at their formation and today within 14 MW-mass

galaxies from the FIRE-2 cosmological zoom-in simulations. In particular, we quantify the relative importance of cosmological disk settling and post-formation dynamical heating on the current kinematics of disk stars, and also quantify when disks begin to form in our simulations.

Towards the end of Chapter 2, we briefly compare the cold gas kinematics in our simulations to that observed by ALMA in 19 nearby galaxies, and stellar kinematics to those observed in MW, M31, M33, and (the same) 19 galaxies as observed by MUSE. Overall, we find that our kinematics are consistent with observations, with the strong exception of the MW, which exhibits substantially colder kinematics.

This discrepancy naturally raises the question: why do the MW’s kinematics differ so significantly (both from our simulations and from other observations)? One possibility is that the MW is a kinematic outlier, with particularly cold kinematics compared to other disk galaxies? (Which then raises the even more interesting question: Why is the MW so kinematically-cold?) Another possibility is that observations of MW stars are taken differently than those in other galaxies, and this discrepancy (at least partially) stems from methodological differences.

This finding motivates the work of Chapter 3. Here we place the kinematics of the FIRE-2 simulations (and thus the findings of Chapter 2) and the MW in observational context. First, we use our simulations to assess how various observational effects impact the measured velocity dispersion in disk galaxies. We then compare the age-velocity dispersion relationships of stellar disks in the FIRE-2 simulations with literature observations of nearby disk galaxies, accounting for each work’s respective aperture size, radial selection, inclination angle, and age-binning. We also performed a deeper dive on observations within the MW, compiling age-velocity dispersion relationships from 11 studies in the literature, and comparing them to measurements for other nearby star-forming disk galaxies.

Lastly, in Chapter 4 we summarize our results and consider future directions of study that follow from the work presented in previous chapters.

Part II

RESULTS

2

DISK SETTling AND DYNAMICAL HEATING: HISTORIES OF MILKY WAY-MASS STELLAR DISKS ACROSS COSMIC TIME IN THE FIRE SIMULATIONS

2.1 ABSTRACT

We study the kinematics of stars both at their formation and today within 14 Milky Way (MW)-mass galaxies from the FIRE-2 cosmological zoom-in simulations. We quantify the relative importance of cosmological disk settling and post-formation dynamical heating. We identify three eras: a Pre-Disk Era (typically $\gtrsim 8$ Gyr ago), when stars formed on dispersion-dominated orbits; an Early-Disk Era ($\approx 8 - 4$ Gyr ago), when stars started to form on rotation-dominated orbits but with high velocity dispersion, σ_{form} ; and a Late-Disk Era ($\lesssim 4$ Gyr ago), when stars formed with low σ_{form} . σ_{form} increased with time during the Pre-Disk Era, peaking ≈ 8 Gyr ago, then decreased throughout the Early-Disk Era as the disk settled and remained low throughout the Late-Disk Era. By contrast, the dispersion measured today, σ_{now} , increases monotonically with age because of stronger post-formation heating for Pre-Disk stars. Importantly, most of σ_{now} was in place at formation, not added post-formation, for stars younger than ≈ 10 Gyr. We compare the evolution of the three velocity components: at all times, $\sigma_{\text{R,form}} > \sigma_{\phi,\text{form}} > \sigma_{\text{Z,form}}$. Post-formation heating primarily increased σ_{R} at ages $\lesssim 4$ Gyr but acted nearly isotropically for older stars. The kinematics of young stars in FIRE-2 broadly agree with the range observed across the MW, M31, M33, and PHANGS-MUSE galaxies. The lookback time that the disk began to settle correlates with its dynamical state today: earlier-settling galaxies currently form colder disks. Including stellar cosmic-ray feedback does not significantly change disk rotational support at fixed stellar mass.

2.2 INTRODUCTION

The present-day kinematics of stars encode a galaxy’s dynamical history. A star’s orbit is set by both its initial dynamics, as inherited from the star-forming interstellar medium (ISM) at its formation, and all post-formation

dynamical perturbations that the star experienced over its lifetime. Thus, stellar kinematics provide dual insight into the past state of the ISM and the dynamical processes that shaped the galaxy. However, the extent to which a star’s current motion results from its initial state *or* from post-formation perturbations remains poorly understood. The inability to reliably disambiguate these two remains a significant obstacle in connecting the kinematics and morphology of a galaxy today to its formation history (for example Naab and Ostriker, 2017; Somerville and Davé, 2015).

Overcoming this ambiguity requires understanding the kinematics with which stars formed throughout the entire lifetime of a galaxy. In the solar neighborhood, the youngest stellar populations share the kinematics of the gas disk from which they formed: young stars are on nearly circular orbits with total velocity dispersions, $\sigma_{3D} \approx 25 - 30 \text{ km s}^{-1}$ (Casagrande et al., 2011; Edvardsson et al., 1993). However, the kinematics of stars that formed at earlier times are likely different from those forming in the Milky Way (MW) today, based on observations of high-redshift galaxies, which provide statistics on how the initial state of stars evolved over cosmic time. Such observations reveal that MW-like thin disks today are the endpoint of a metamorphosis: galactic disks at higher redshifts ($z \gtrsim 1 - 2$) were thicker, clumpier, and more turbulent than their thin counterparts at lower redshifts (for example Birkin et al., 2023; Förster Schreiber et al., 2009; Stott et al., 2016) (though see Rizzo et al., 2020). The high turbulence of MW-mass progenitors probably resulted from the combination of stellar feedback, given their higher star formation rates (SFRs) (for example Förster Schreiber and Wuyts, 2020b; Madau and Dickinson, 2014), gravitational instabilities (for example Dekel et al., 2009; Elmegreen et al., 2007; Lehnert et al., 2009), and higher merger and accretion rates, leading to higher gas fractions and surface densities (for example Genzel et al., 2015; Tacconi, Genzel, and Sternberg, 2020).

Thus, high-redshift observations show that disk galaxies ‘settled’ over cosmic time (Kassin et al., 2012), becoming less turbulent and more rotationally supported since $z \sim 1 - 2$ (for example Johnson et al., 2018; Wisnioski et al., 2015). Specifically, the velocity dispersion, σ , of gas disks decreased while their rotational velocity, v_ϕ , increased. Although most works used emission lines from ionized gas to measure high-redshift kinematics, recent works indicate that the dispersions of atomic and molecular gas, while $\approx 15 \text{ km s}^{-1}$ lower, evolved similarly (for example Girard et al., 2021; Übler et al., 2019). Thus, stars, which are born from cold dense gas, formed with larger dispersions at earlier times when turbulence was higher, and later formed with progressively lower dispersions as turbulence decreased and the galaxy’s disk settled.

Alongside understanding how stars kinematically formed, it is equally important to understand how they evolved post-formation. Over their lifetimes, stars undergo repeated scattering interactions with perturbations within the disk, such as giant molecular clouds (GMCs) (Lacey, 1984; Spitzer and Schwarzschild, 1951; Wielen, 1977), spiral arms (Barbanis and Woltjer, 1967; Carlberg and Sellwood, 1985; Minchev and Quillen, 2006), and bars (Grand et al., 2016; Saha, Tseng, and Taam, 2010). Stars are effectively collisionless and dissipationless, and thus these interactions result in enduring increases to their random orbital energy, or ‘dynamical heating’. In turn, a stellar population’s σ increases over its lifetime. Additional heating may arise from feedback-driven outflows and potential fluctuations (El-Badry et al., 2016), the galaxy’s global asymmetries – including torquing from the

misalignment of the stellar and gaseous disk (Roškar et al., 2010) – cosmic accretion, mergers, and interactions with satellites (for example Belokurov et al., 2018; Brook et al., 2004; Quinn, Hernquist, and Fullagar, 1993; Villalobos and Helmi, 2008). However, the relative impact of each mechanism remains uncertain.

Furthermore, the scattering environment of the disk evolves across cosmic time. At earlier times, a galaxy’s gas fraction and gas surface density were higher (for example Shapley, 2011; Swinbank et al., 2012; Tacconi, Genzel, and Sternberg, 2020), such that scattering by GMCs was likely more frequent. Before the formation of a disk, galaxies generally lacked strong spiral structure, and thus spiral-driven heating (for example Margalef-Bentabol et al., 2022). On the other hand, certain processes that can drive non-adiabatic rapid heating were more prevalent earlier, including mergers (for example Conselice, Blackburne, and Papovich, 2005) and feedback-driven outflows (for example Genzel et al., 2015).

One can understand the relative strength of these heating mechanisms by comparing the observed relationship between velocity dispersion and stellar age with predictions from various heating models. The magnitude of each component of σ (along R , ϕ , or Z) provides insight into the relative strength of different mechanisms: spiral structure increases the in-plane dispersion but is generally inefficient at increasing the vertical, whereas GMCs heat stars more isotropically and can redirect in-plane heating (for example Carlberg and Innanen, 1987; Jenkins and Binney, 1990; Sellwood, 2013).

The MW is an ideal test-bed for such comparisons because it offers unparalleled access to the 3D motions, positions, and ages of individual stars. In particular, the observed monotonic increase in velocity dispersion with age for stars in the solar neighborhood provides an important benchmark (for example Casagrande et al., 2011; Strömberg, 1946; Wielen, 1977). Nordström et al. (2004) and Holmberg, Nordström, and Andersen (2009) argued that this observed trend is consistent with MW stars forming on ‘disky’ orbits that then underwent dynamical heating by the combination of GMCs and spiral arms. Mackereth et al. (2019a) and Ting and Rix (2019) extended this analysis to include stars located outside the solar neighborhood ($R = 3 - 14$ kpc) and found similar results: the observed relations are consistent with stars younger than ≈ 8 Gyr having formed with a low, constant dispersion and subsequently being heated by both GMCs and spiral arms. However, as before, the observed dispersions of older stars (age $\gtrsim 8$ Gyr) are higher than those predicted by heating models (Mackereth et al., 2019a). This discrepancy could arise if old stars were born kinematically hotter, or if their dynamical heating differed from what current models predict. Likely, both factors contribute, but disentangling this requires insight into the MW’s early history.

Fortunately, recent MW observations now allow us to characterize this bygone era. Astrometric data from Gaia (Gaia Collaboration et al., 2016) along with stellar properties from large spectroscopic surveys, such as APOGEE (Majewski et al., 2017), GALAH (Buder et al., 2018; De Silva et al., 2015), and LAMOST (Cui et al., 2012), now provide 6D kinematics and elemental abundances for stars throughout the Galaxy. Most notably, this data revealed that the MW underwent a massive merger – the Gaia-Sausage-Enceladus (GSE) – ≈ 8 to 11 Gyr ago (for example Belokurov et al., 2018; Helmi et al., 2018). The GSE merger, probably the most major merger of the MW,

contributed most of the stars in the MW’s stellar halo, and it likely dynamically heated MW stars to more eccentric halo-like orbits, and potentially it triggered intense star-formation and even the formation of the MW’s low- α disk (for example Bonaca et al., 2020; Das, Hawkins, and Jofré, 2020; Gallart et al., 2019; Haywood et al., 2018; Mackereth et al., 2019b). Recent works suggest that the MW developed this thick – but continuously-settling – disk early in its history, with estimates for the onset of coherent rotation ranging from ≈ 10 to 13 Gyr ago (Belokurov and Kravtsov, 2022; Conroy et al., 2022; Xiang and Rix, 2022), and that the MW’s thin-disk began to form later, $\approx 8 - 9$ Gyr ago. However, post-formation dynamical heating leads to ambiguity about the nature and timing of these transitions, highlighting the difficulties innate to separating birth kinematics from post-formation dynamical heating, especially for old, metal-poor stars.

Cosmological simulations of the formation of MW-mass galaxies provide important tools for understanding the relative impacts of cosmological disk settling and post-formation dynamical heating (see Naab and Ostriker, 2017; Vogelsberger et al., 2020, for recent reviews). Cosmological zoom-in simulations provide the high resolution needed to model a galaxy’s internal structure, including the multi-phase ISM that sets the birth kinematics of stars and thus the dynamical structure of the disk, within an accurate cosmological context, allowing for non-equilibrium dynamical perturbations, mergers, mass growth, and so forth. Many works used such cosmological zoom-in simulations to show that (1) MW-like galaxies form radially ‘inside-out’ and vertically ‘upside-down’, transitioning from a thick, turbulent galaxy at early times to a thin, rotationally dominated disk at later times, and (2) the present-day kinematics of stars result from their kinematics at birth and subsequent dynamical heating, both of which change over cosmic time (for example Agertz et al., 2021; Bird, Kazantzidis, and Weinberg, 2012; Bird et al., 2021; Bonaca et al., 2017; Brook et al., 2012; Buck et al., 2020; Ceverino et al., 2017; Grand et al., 2016; Ma et al., 2017; Martig, Minchev, and Flynn, 2014).

We build upon a series of papers that used FIRE-2 simulations to study the formation of galactic disks. Stern et al. (2021) found that virialization of the inner circumgalactic medium (CGM), that is, the onset of a stable hot halo, coincided with the formation of a thin disk, a change from ‘bursty’ to ‘steady’ star formation, and the suppression of gaseous outflows; the presence of a hot halo can allow infalling gas to align coherently with a galaxy’s disk *before* it accretes onto the disk (Hafen et al., 2022). Additional works found that the virialization of the inner CGM and the associated transition from bursty to steady star formation coincided with the transition from ‘thick-disk’ to ‘thin-disk’ formation Yu et al. (2021, 2022) and the emergence of a rotationally-supported thin gaseous disk from a previously quasi-isotropic ISM (Gurvich et al., 2023). More recently, Hopkins et al. (2023) investigated the physical causes of such transitions. While the initial formation of a disk depends on the development of a sufficiently centrally concentrated mass profile, the transition from bursty to smooth star formation generally arises later, when the absolute depth of the gravitational potential (within the radius of star formation) crosses a critical threshold. This threshold is similar to the threshold for inner CGM virialization.

In this work, we use the FIRE-2 cosmological zoom-in simulations to study cosmological disk settling and dynamical heating across the formation histories of MW-mass galaxies. We study the kinematics of stars both at birth and today, emphasizing different phases of disk-galaxy formation. We examine how stellar formation

kinematics manifest themselves today, that is, how post-formation dynamical heating alters the initial orbits of stars. By doing so, we aim to understand how the current kinematics of the MW and nearby galaxies relate to their formation histories.

2.3 METHODS

2.3.1 FIRE-2 SIMULATIONS

We analyze 14 cosmological zoom-in simulations of MW/M31-mass galaxies from the Feedback in Realistic Environments (FIRE) project¹, which include both dark matter and baryons (gas and stars). The simulations use the GIZMO gravity plus hydrodynamics code (Hopkins, 2015) with the meshless finite-mass (MFM) Godunov method, which provides adaptive spatial resolution while maintaining excellent conservation of energy and (angular) momentum.

We ran these simulations using the FIRE-2 physics model (Hopkins et al., 2018). FIRE-2 models the dense, multi-phase ISM and incorporates metallicity-dependent radiative cooling and heating processes for gas across temperatures $10 - 10^{10}$ K, including free-free, photoionization and recombination, Compton, photoelectric and dust collisional, cosmic ray, molecular, metal-line, and fine structure processes. The simulations self-consistently generate and track 11 elements (H, He, C, N, O, Ne, Mg, Si, S, Ca, Fe), including a model for sub-grid mixing/diffusion via turbulence (Escala et al., 2018; Hopkins et al., 2018; Su et al., 2017). FIRE-2 also includes photoionization and heating from a spatially uniform, redshift-dependent UV background (Faucher-Giguère et al., 2009) that reionizes the Universe at $z \approx 10$.

Crucially for this work, FIRE-2 simulations resolve the phase structure in the ISM, allowing gas to collapse into giant molecular clouds and form stars (Benincasa et al., 2020; Guszejnov et al., 2020). Star formation occurs in locally self-gravitating, Jeans-unstable, dense ($n_{\text{SF}} > 1000 \text{ cm}^{-3}$), molecular (following Krumholz and Gnedin, 2011) gas. After reaching these criteria, a gas cell probabilistically converts to a star particle in a local free-fall time. Our simulations, like all simulations, have a finite resolution. As such, our star-formation model is an extrapolation of the collapse below the resolution scale. That said, numerous resolution tests carried out in Hopkins et al. (2018) indicate that uncertainties induced by our resolution limit are minor; for example, the GMC mass function and the relation between internal gas velocity dispersion and GMC size for these simulations are both independent of resolution.

¹ FIRE project web site: <http://fire.northwestern.edu>

Each star particle represents a single stellar population sampled from a Kroupa (2001) initial mass function, with mass and metallicity inherited from its progenitor gas cell. Once formed, star particles follow stellar evolution models that tabulate feedback event rates, luminosities, energies, and mass-loss rates from STARBURST99 v7.0 (Leitherer et al., 1999). FIRE-2 implements the major channels for stellar feedback, including core-collapse and white-dwarf (Ia) supernovae, stellar winds, radiation pressure, photoionization, and photoelectric heating.

We generated cosmological zoom-in initial conditions at $z \approx 99$ using MUSIC (Hahn and Abel, 2011). Each zoom-in region is embedded within a cosmological box of side length $70.4 - 172$ Mpc. The simulations use a flat Λ CDM cosmology with parameters broadly consistent with Planck Collaboration et al. (2020): $h = 0.68 - 0.71$, $\Omega_\Lambda = 0.69 - 0.734$, $\Omega_m = 0.266 - 0.31$, $\Omega_b = 0.0455 - 0.048$, $\sigma_8 = 0.801 - 0.82$ and $n_s = 0.961 - 0.97$.

Our simulation set consists of 14 MW/M31-mass galaxies: 8 isolated galaxies from the *Latte* suite, and 6 galaxies from the *ELVIS on FIRE* suite of Local Group (LG)-like pairs of galaxies. The *Latte* suite, with the exception of m12z, has an initial baryon particle mass of $7070 M_\odot$, although stellar mass loss leads to star particles having typical masses $\approx 5000 M_\odot$, and dark matter particle mass of $3.5 \times 10^5 M_\odot$. m12z has initial baryon and dark matter particle masses of $4200 M_\odot$ and $2.1 \times 10^5 M_\odot$, respectively. The *ELVIS on FIRE* suite has a mass resolution $\sim 2\times$ better than the *Latte* suite: Romeo & Juliet have initial baryon particle masses of $3500 M_\odot$, while Romulus & Remus and Thelma & Louise have $4000 M_\odot$.

Both star and dark-matter particles have fixed gravitational force softenings (comoving at $z > 9$ and physical thereafter) with a Plummer equivalent of $\epsilon_{\text{star}} = 4$ pc and $\epsilon_{\text{dm}} = 40$ pc. Gas cells have fully adaptive gravitational softenings that match the hydrodynamic kernel smoothing: softening lengths are $\approx 20 - 40$ pc at typical ISM densities ($n \sim 1 \text{ cm}^{-3}$) and < 1 pc in the densest regions.

Certain aspects of the FIRE-2 ISM model have been subject to scrutiny within the literature. In particular, Kim et al. (2023) and Wibking and Krumholz (2023) argued that the equilibrium gas cooling in FIRE-2 transitions between the warm and cold phase in the neutral ISM at unphysically low pressures and densities due to our order of too-low free-electron fraction at a given gas density. This implies that the diffuse ISM in FIRE-2 is entirely in the cold neutral phase. However, their idealized tests did not encompass how FIRE-2 simulations actually implement gas cooling; instead, they only tested one aspect of gas cooling in FIRE-2 and only in the presence of a metagalactic UV background, with no local sources. The free-electron fraction and ISM phase structure in actual FIRE-2 simulations agree much better with the observations presented in those works.² Furthermore, the specifics of the ISM cooling model are largely inconsequential for the properties that we examine here, because the thermal pressure essentially never dominates over the turbulent pressure in the cold, dense ISM resolved in these simulations. Indeed, as Hopkins et al. (2018) showed, dramatic changes to the assumed ISM cooling rates lead to only minor effects on most galaxy dynamical properties. Indeed, we tested re-simulating one of our simulations

² The FIRE collaboration has made numerous improvements to the gas cooling model in recent years: the default cooling in FIRE-2 since 2020, and in FIRE-3, includes all terms claimed to be missing from earlier FIRE models. See the GIZMO user guide: http://www.tapir.caltech.edu/~phopkins/Site/GIZMO_files/gizmo_documentation.html

(m12i) over the last 500 Myr using the newer FIRE-3 model (Hopkins et al., 2023), which includes numerous updates to gas cooling, and this results in nearly identical velocity dispersions for cold gas and stars.

For our main results (Sections 2.4.1, 2.4.3, 2.4.4, and 2.4.5), we present properties averaged across our galaxy sample, not including the lower-mass galaxies m12r and m12z or Juliet from the *ELVIS on FIRE* suite. However, in Sections 2.4.6, 2.4.7 and 2.4.8, where we explore dependence on galaxy mass, we include all 14 galaxies. m12r and m12z have stellar masses of 1.8 and $1.5 \times 10^{10} M_{\odot}$, lower than the MW’s and M31’s stellar masses of $\approx 5 \times 10^{10}$ and $\approx 10^{11} M_{\odot}$, respectively. Furthermore, m12r and m12z have stellar kinematics that are weakly or never dominated by disk-like motion. Juliet has a stellar mass closer to the MW’s, at $3.3 \times 10^{10} M_{\odot}$, and disk-dominated kinematics at $z = 0$, but we exclude it, because a rapid gas accretion event late in its history leads to anomalous properties that skew the sample-averaged properties towards trends unique to Juliet. We will examine these cases in more detail in future work.

2.3.2 MEASURING STELLAR DYNAMICS TODAY AND AT FORMATION

Motivated primarily by measurements of the MW, we select stars that are in each galaxy’s ‘solar annulus’: $R = 6 - 10$ kpc and $|Z| < 3$ kpc today. In future work, we will examine trends with radius, to understand the drivers of post-formation dynamical heating and their application to MW observations in greater detail; briefly, we find that the dispersion today generally decreases with R today, but that neither the dispersion at formation nor the dispersion today depend on R at $R \gtrsim 1 - 2$ kpc. The effect of the vertical selection on our results is minimal, as we show in Appendix 2.6.1.

For all of our results besides those in Section 15, we show ‘disk-wide’ (or more aptly, ‘annulus-wide’) kinematics. That is, we compute median velocity and velocity dispersions using all the stars (in a given age bin) within the ‘solar annulus’. However, in Section 15, we show ‘local’ kinematics, meaning we compute the median velocity and dispersion within smaller patches (of diameter 150 or 500 pc) spanning an annulus centered at 8 kpc, and then average across all patches.

A key advantage of simulations is their ability to study properties both today and when stars formed. In both cases, we select stars on the basis of their *current* coordinates. However, when determining properties at formation, we only include stars that formed in situ, which we define following Bellardini et al. (2022) as forming within a total distance of 30 kpc comoving from the galactic center. We do not apply this in-situ selection when measuring properties today, to more directly compare with observations. Across our simulations, ex-situ stars comprise only $\sim 4\%$ of all stars currently within the disk ($R < 20$ kpc and $|Z| < 3$ kpc), but they can make up a non-trivial percentage within our oldest age bins: we show the effect of our in-situ selection on velocity dispersion versus age in Appendix 2.6.2.

We compute stellar positions and velocities relative to the galaxy’s center. We determine the orientation of the galaxy at each snapshot (independently) by computing the rotation tensor and axis ratios of the principal axes of the stellar disk, which we define via the moment of inertia tensor of the 25% youngest star particles inside a radius enclosing 90% of the total stellar mass within 10 kpc physical. We compute properties at formation using the galaxy’s orientation at that time, not at $z = 0$.

Our simulations store 600 snapshots from $z = 99$ to 0, with a time between snapshots of 20 – 25 Myr, and the past 20 Myr (immediately before today) includes 10 snapshots spaced by 2 Myr. We measure a star’s ‘formation’ properties at the first snapshot after it formed, so a star particle on average experienced ≈ 10 Myr of evolution when we record its properties. This limits to some extent our ability to measure the earliest dynamical evolution, especially because, in our simulations, stars are born clustered in GMCs (for example Benincasa et al., 2020; Guszejnov et al., 2020), where they can be subject to various gravitational interactions on short timescales. Thus, ‘formation’ properties in our analysis necessarily refer to the combination of birth properties and early dynamical evolution.

When computing the velocities of a stellar population, we select star particles using 250 Myr bins of age, which corresponds to the dynamical/orbital time at the solar annulus today. When plotting velocities, we use the mass-weighted median velocity of all star particles within a given age range; we find nearly identical results using the mass-weighted mean instead. To ensure that outlier stars do not skew our results, we compute the velocity dispersion by finding half of the difference between the mass-weighted 16th and 84th-percentile velocities of all stars in a given age range, which is equivalent to the standard deviation for normal distribution. We compute these quantities (in each age bin) individually for each galaxy and then show the mean and standard deviation across our 11 galaxies.

Name	$M_{\star}^{90}$ [$10^{10} M_{\odot}$]	v_{ϕ}^{disk} [km/s]	σ_Z^{disk} [km/s]	$\sigma_{3D}^{\text{disk}}$ [km/s]	σ_Z^{local} [km/s]	$\sigma_{3D}^{\text{local}}$ [km/s]	$t_{\text{lb}} \left[\left(\frac{v_{\phi}}{\sigma_{3D}} \right)_{\text{form}} > 1 \right]$ [Gyr]	$t_{\text{lb}} \left[\left(\frac{v_{\phi}}{\sigma_{3D}} \right)_{\text{now}} > 1 \right]$ [Gyr]	$t_{\text{lb}} \left[\left(\frac{v_{\phi}}{\sigma_Z} \right)_{\text{now}} > \sqrt{3} \right]$ [Gyr]	$t_{\text{lb}}^{\text{burst}}$ [Gyr]
m12m	10.0	288	16.7	50.1	13.3	33.1	9.21	6.90	7.68	3.81
Romulus	8.0	265	20.4	55.9	16.6	41.8	7.42	7.16	7.16	4.90
m12b	7.3	272	17.9	56.6	13.1	37.5	7.42	7.42	7.42	6.32
m12f	6.9	256	19.9	74.9	13.5	31.6	7.42	6.39	6.39	5.01
Thelma	6.3	230	21.2	62.8	19.4	43.9	4.35	4.35	4.25	2.57
Romeo	5.9	249	14.1	40.3	12.2	31.3	11.0	10.2	10.2	6.52
m12i	5.3	238	20.1	52.4	12.8	27.5	6.65	6.39	6.39	3.14
m12c	5.1	240	23.1	62.8	19.5	38.4	6.49	6.14	6.39	3.70
m12w	4.8	163	16.6	83.9	5.5	29.8	4.09	4.6	5.89	0
Remus	4.0	216	13.9	40.3	10.7	25.0	7.93	7.93	7.93	5.88
Juliet	3.3	211	16.6	45.6	15.0	32.6	4.35	4.61	4.61	4.40
Louise	2.3	177	14.6	37.5	11.0	26.1	7.16	6.9	7.16	5.56
m12z	1.8	92.6	21.4	67.6	19.0	39.0	0.51	-	-	-
m12r	1.5	127	17.4	47.1	7.3	15.4	5.9	0.26	2.3	-
mean	6.0	236	18.0	56.1	13.5	32.4	7.19	6.76	6.98	4.31

Table 1: **Stellar properties at $z = 0$ of the FIRE-2 simulations of MW/M31-mass galaxies that we analyze**, in order of decreasing stellar mass. The first column lists the galaxy name: ‘m12’ indicates an isolated galaxy; otherwise the galaxy is in a Local Group-like pair. M_{star}^{90} is the stellar mass within R_{star}^{90} , the radius enclosing 90% of the stellar mass within 20 kpc. v_{ϕ}^{disk} , σ_Z^{disk} , and $\sigma_{3D}^{\text{disk}}$ are the *disk-wide* median azimuthal velocity, vertical velocity dispersion, and total velocity dispersion, respectively, of stars younger than 250 Myr in a cylindrical radius $R = 6 - 10$ kpc and $|Z| < 3$ kpc from the midplane. σ_Z^{local} and $\sigma_{3D}^{\text{local}}$ are the *local* vertical and total velocity dispersion of stars younger than 100 Myr measured in 500 pc patches centered at $R = 8$ kpc. The first 3 lookback times are the onset of disk formation, defined as the oldest age/lookback time that stars permanently passed above a disk-wide threshold: $v_{\phi}/\sigma_{3D} > 1$ at formation, $v_{\phi}/\sigma_{3D} > 1$ measured at present, and $v_{\phi}/\sigma_Z > 1.8$ measured at present. The last column lists the lookback time when the galaxy transitioned from bursty to steady star formation from Yu et al. (2021). The last row shows the average quantities for our sample (excepting m12r, m12z, and Juliet, see text).

2.4 RESULTS

2.4.1 STELLAR KINEMATICS VERSUS AGE

2.4.1.1 DEFINING THE ERAS OF DISK EVOLUTION

Motivated by the kinematic trends that we explore and by previous analyses of these galaxies (for example Faucher-Giguère, 2018; Garrison-Kimmel et al., 2018; Gurvich et al., 2023; Ma et al., 2017; Yu et al., 2021), we divide our galaxies’ histories into three eras, which we term the ‘Pre-Disk’, ‘Early-Disk’, and ‘Late-Disk’ Eras. Each of our galaxies began in the Pre-Disk Era, when the gas lacked coherent rotation, such that stars formed on nearly isotropic orbits. Then, each galaxy formed a stable, coherent disk and transitioned into the Early-Disk Era. Specifically, the start of the Early-Disk Era marks the time when all subsequent generations of stars that formed with rotationally-dominated kinematics, with $(v_\phi / \sigma_{3D})_{\text{form}} > 1$. Table 1 lists the lookback time, t_{lb} , that each galaxy transitioned into the Early-Disk Era, $t_{\text{lb}} [(v_\phi / \sigma_{3D})_{\text{form}} > 1]$.

These disks were kinematically hot, with a high σ , at the start of the Early-Disk Era, but became increasingly settled, with increasingly cold and rotationally-dominated kinematics, throughout it. As a result, $(v_\phi / \sigma_{3D})_{\text{form}}$ grew most rapidly throughout this era. Eventually, the growth of $(v_\phi / \sigma_{3D})_{\text{form}}$ slowed and the galaxies transitioned into the Late-Disk Era, when the kinematics at formation did not evolve much as stars formed on highly rotational orbits in a dynamically cold disk. On average, galaxies in our sample transitioned from the Pre-Disk to the Early-Disk Era ≈ 8 Gyr ago and from the Early-Disk to the Late-Disk Era ≈ 4 Gyr ago, though with significant galaxy-to-galaxy scatter in these ages.

Hopkins et al. (2023) argued that two aspects of the galaxy’s gravitational potential drive the transitions between these eras. The *shape* of the potential, specifically the formation of a sufficiently centrally-concentrated mass profile, drives the initial formation of a disk, that is, the Pre-Disk to Early-Disk transition. Separately, the *absolute depth* of the potential (within the radius of star formation) drives the transition from bursty to smooth star formation, which roughly coincides with the transition from the Early-Disk to Late-Disk era, although this connection may be less direct. Similarly, our Pre-Disk and Early-Disk Eras generally correspond to the ‘bursty star formation’ phase, in Stern et al. (2021), Gurvich et al. (2023) and Yu et al., 2021, while our Late-Disk Era corresponds to their ‘steady star formation’ phase.

2.4.1.2 MEDIAN VELOCITY VERSUS AGE

We start by analyzing the general dynamic evolution of our simulated galaxies. Figure 8 (top) shows the sample-averaged azimuthal, radial, vertical, and total median velocities at formation (dashed lines) and at present (solid

lines) versus stellar age. We label the Late-, Early-, and Pre-Disk Eras on the top of each column, and we mark the start of the Early and Late-Disk Eras with shaded bars. The time that one era ended and another began is not exact, in part because Figure 8 shows sample-averaged quantities, so the shaded bars represent the approximate transition time and not an instantaneous boundary.

Figure 8 (top left) shows the median azimuthal (rotational) velocity, v_ϕ , versus age. For most of the Pre-Disk Era, stars formed with $v_{\phi,\text{form}} \approx 0 - 20 \text{ km s}^{-1}$: in the early galaxy, stars did not coherently rotate. Eventually, $v_{\phi,\text{form}}$ began to increase as the disk began to settle, and the galaxy transitioned into the Early-Disk Era. The slight growth of $v_{\phi,\text{form}}$ towards the end of the Pre-Disk Era arises because we average over multiple galaxies, so earlier-transitioning galaxies bias the sample’s mean: within individual galaxies, the rise of $v_{\phi,\text{form}}$ is generally (but not always) sharp and coincident with the transition to the Early-Disk Era (see Figure 10). $v_{\phi,\text{form}}$ strongly rose throughout the Early-Disk Era, but its growth weakened once the galaxy transitioned into the Late-Disk Era ($\approx 4 \text{ Gyr}$ ago), likely because the total mass within our radial range changed little during this period (Garrison-Kimmel et al., 2018). $v_{\phi,\text{now}}$ primarily follows the same trends with age as $v_{\phi,\text{form}}$. However, stars that formed in the Pre-Disk Era have significantly larger v_ϕ now than at formation, because they were torqued onto more coherent rotational orbits as the disk subsequently formed and settled. Likely, gas-rich mergers that seeded the disk’s orientation also torqued up these existing stars (for example Santistevan et al., 2021). Bellardini et al., in preparation, show that this increase in v_ϕ corresponds to an increase in specific angular momentum for these pre-existing stars, that is, they were indeed torqued. In contrast, stars that formed in the Late-Disk Era on nearly circular orbits now have slightly smaller v_ϕ now than at formation because of dynamical heating/scattering.

Figure 8 (top row, column 2 and column 3) shows the median radial velocity, v_R , and the median vertical velocity, v_Z , versus stellar age. Previous work analyzing FIRE simulations found that bursty star formation in the Pre-Disk galaxy drove significant gaseous outflows (for example Anglés-Alcázar et al., 2017; Feldmann et al., 2017; Muratov et al., 2015; Pandya et al., 2021; Sparre et al., 2017; Stern et al., 2021). These outflows sometimes remained star-forming and produced stars that inherited their progenitor’s outflowing dynamics (El-Badry et al., 2016; Yu et al., 2021). We find complementary results: stars that were born in the Pre-Disk Era had positive (outward) $v_{R,\text{form}}$, indicating the presence of star-forming outflows, and $v_{Z,\text{form}}$ that rapidly fluctuated around 0. Once the early disk formed, $v_{R,\text{form}}$ decreased to 0, in part because feedback-driven outflows declined and eventually ceased: throughout the rest of the Early-Disk and Late-Disk Eras, stars had $v_{R,\text{form}} \approx v_{Z,\text{form}} \approx 0$.

At present, both $v_{R,\text{now}}$ and $v_{Z,\text{now}} \approx 0$ for stars that formed in *all* eras, meaning that old stars’ subsequent dynamical evolution overrode any preference for outward/upward/downward motion. This difference also reflects our selection of stars that remain within the disk today. Our galaxies largely formed radially ‘inside-out’ (for example Garrison-Kimmel et al., 2018), such that old in-situ stars typically formed inside of our current radial range of $6 - 10 \text{ kpc}$, and as El-Badry et al. (2016) and Ma et al. (2017) discussed for the FIRE simulations, old in-situ stars typically reside at larger radii today, compared to when they formed, because bursts of feedback-driven outflows generated large fluctuations in the gravitational potential at early times that moved these stars outward. We note that this change in radius for old stars is distinct from ‘radial migration’, in that the vast majority of

these stars have moved coherently outward, while radial migration entails a roughly equal number of inward and outward moving stars. As such, old stars in our sample are more likely than young stars to be near their apocenters, and as a result, have $v_{R,\text{now}}$ closer to 0. Bellardini et al., in preparation will examine this radial redistribution in detail.

Figure 8 (top right) shows the median total velocity, v_{3D} , versus age. The growth of the galaxy’s mass drove much of the evolution of v_{3D} , because the underlying gravitational potential determines its virial velocity. In turn, the evolution of $v_{3D,\text{form}}$ indicates that the galaxy’s mass increased over time, most rapidly in the Pre-Disk Era and only minimally in the Late-Disk Era. The evolution of $v_{3D,\text{form}}$ largely resembles that of $v_{\phi,\text{form}}$, with the exception of the Pre-Disk Era, when $v_{3D,\text{form}}$ grew steadily, while $v_{\phi,\text{form}}$ remained near 0. This is not surprising: v_{3D} depends only on the magnitude of each component, while v_{ϕ} also depends on the sign. In the Pre-Disk Era, stars rotated, just not coherently, such that the median $v_{\phi,\text{form}} \approx 0$ while $\sqrt{v_{\phi,\text{form}}^2} > 0$. However, once the galaxy transitioned into the Early-Disk Era, stars had larger and larger fractions of their (increasing) $v_{3D,\text{form}}$ in rotation. At present, v_{3D} has almost no dependence on age, with all stars near $v_{3D,\text{now}} \approx v_{\text{virial}} \approx 200 - 240 \text{ km s}^{-1}$, as a result of virialization and dynamical heating.

2.4.1.3 VELOCITY DISPERSION VERSUS AGE

Figure 8 (bottom) shows the azimuthal, radial, vertical, and total stellar velocity dispersion, σ , versus age, at both the time of the star’s formation and at present. All components exhibit similar trends with age, albeit with different normalizations. Here we focus on general trends with age; we compare the 3 components in Section 2.4.3.

σ_{form} reflects the turbulence in star-forming gas and shows distinct behavior in each kinematic era. The oldest stars formed with the lowest σ , reflecting their low $v_{\text{tot,form}}$ in the low-mass galaxy progenitor at early times. As the galaxy grew during the Pre-Disk Era, σ_{form} grew, reflecting the deepening of the gravitational potential in addition to an increase in absolute gas turbulence, from accretion, mergers, bursty and more vigorous star formation, and outflows (for example El-Badry et al., 2018a; Flores Velázquez et al., 2021; Hung et al., 2019; Ma et al., 2017).

σ_{form} reached a maximum during the transition to the Early-Disk Era. This peak in σ_{form} reflects the competing effects of the galaxy continuing to become more massive (increasing $v_{\text{tot,form}}$) but also starting to settle into a disk, decreasing the relative contribution to σ_{form} . σ_{form} steadily decreased throughout the Early-Disk Era as the disk settled. This steady decrease in turbulence could occur only after the initial onset of the disk, when it could self-regulate to maintain a turbulent Toomre $Q \sim 1$ in star-forming gas (for example Faucher-Giguère, Quataert, and Hopkins, 2013; Gurvich et al., 2020; Hopkins, Quataert, and Murray, 2012; Krumholz et al., 2018; Orr et al., 2020; Wisnioski et al., 2015). As such, equilibrium models imply that a gas disk maintains $\sigma/v_{\phi} \approx M_{\text{gas}}(< r)/M_{\text{tot}}(< r) \approx f_{\text{gas}}$, so σ reduced as f_{gas} did.

Finally, upon the transition to the Late-Disk Era, σ_{form} reached a floor and remained nearly constant, reflecting the plateauing gas fraction and correspondingly steady and low turbulence and SFR during this era (Garrison-Kimmel et al., 2018; Gurvich et al., 2023; Hung et al., 2019; Ma et al., 2017; Yu et al., 2021).

While σ_{form} shows distinct trends in each era, σ_{now} shows markedly different behavior, monotonically increasing with age across all eras. *Thus, the additional dispersion from post-formation dynamical heating, in combination with σ_{form} , produces the observed continuous increase in dispersion with stellar age; neither process alone explains it. This also means that σ_{now} does not directly and simply reflect the formation history of the galaxy.* This difference is most evident for stars that formed in the Pre-Disk Era, which have the highest values of σ_{now} today but formed with the smallest values of σ_{form} . By contrast, stars forming in the Early-Disk Era exhibit an age evolution that follows a similar slope at formation and at present, modulo a normalization offset. Finally, stars that formed in the Late-Disk Era have σ_{now} increasing with age their while σ_{form} is constant. We examine the age dependence of post-formation dynamical heating in detail in Section 2.4.4.

In conclusion, the age dependence of σ_{form} differed in the Pre-Disk, Early-Disk, and Late-Disk Eras, reflecting the distinct kinematics of these eras. At present, σ_{now} increases monotonically with age, with a relation to σ_{form} that differs for each era.

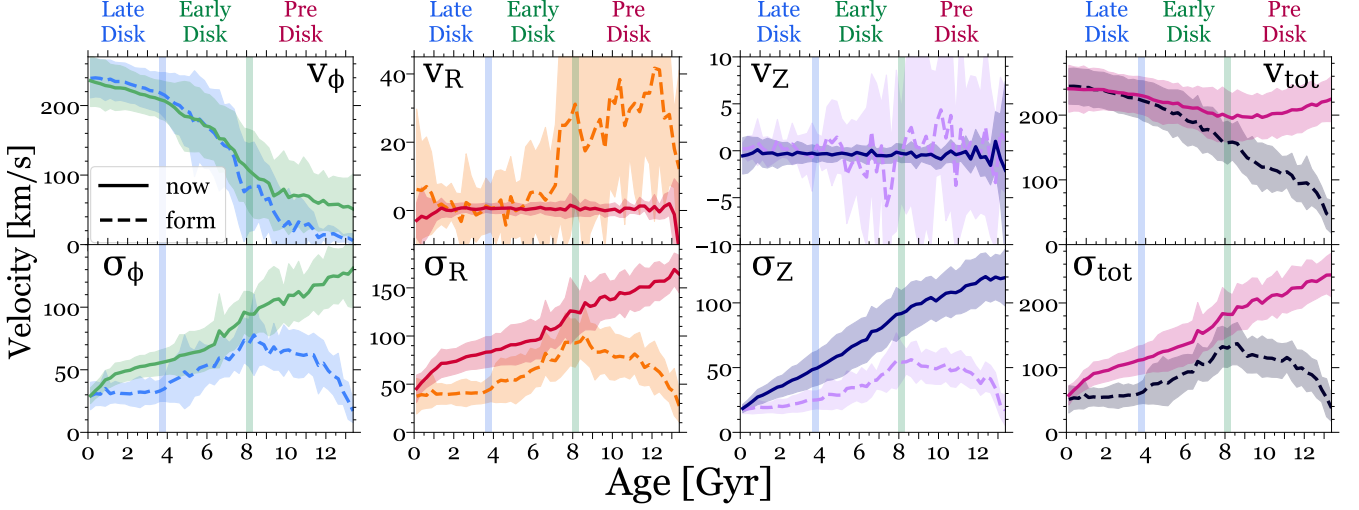


Figure 8: **Median velocities and velocity dispersions for stars versus age**, within cylindrical $R = 6 - 10$ kpc and $|Z| < 3$ kpc at $z = 0$.

Age bins have a width of 250 Myr. The lines show the average and the shaded regions show the standard deviation across 11 **MW!** (MW!) mass galaxies, with velocities measured at $z = 0$ (solid) and at the time of formation (dashed, including only in-situ stars). The shaded vertical bars show when our galaxies transitioned from the Pre-Disk to the Early-Disk Era (≈ 8 Gyr ago) and the Early-Disk to the Late-Disk Era (≈ 4 Gyr ago), on average: we define these eras in Section 2.4.1.1. **Top row:** Median velocity versus age. For most of the Pre-Disk Era, stars formed with little net rotation, but $v_{\phi, \text{form}}$ rapidly increased in the Early-Disk Era when the disk initially formed, and it increased at a lower rate in the Late-Disk Era when the disk further settled. Stars that formed in the Pre-Disk Era have $v_{\phi, \text{now}} > v_{\phi, \text{form}}$ from dynamical torquing after formation, whereas stars that formed in the Late-Disk Era now have slightly smaller $v_{\phi, \text{now}}$ than at formation from post-formation dynamical heating. v_R and v_Z fluctuated at formation in the Pre- and Early-Disk Eras, because of frequent mergers, rapid accretion, bursty star formation, and gaseous outflows, but today they are 0 across all ages. $v_{\text{tot}, \text{form}}$ steadily increased at all times, but $v_{\text{tot}, \text{now}}$ is nearly independent of age, because all stars have been dynamically heated to orbit near the virial velocity. **Bottom row:** Velocity dispersion versus age. All 3 components and the total show the same trends with age. σ_{form} increased throughout the Pre-Disk Era as the galaxy grew, peaking ≈ 8 Gyr ago, but decreased throughout the Early-Disk Era and remained constant throughout the Late-Disk Era. By contrast, σ_{now} monotonically increases with stellar age because of the dynamical heating of stars after their formation. Thus, *the kinematics of stars today do not simply reflect their kinematics at formation.*

2.4.1.4 ROTATIONAL SUPPORT VERSUS AGE

The ratio v_ϕ/σ is a dimensionless measure of the degree of rotational support, that is, how ‘disky’ or ‘dynamically cold’ a disk is. Figure 9 (top) shows the ratio of median v_ϕ to σ_Z and σ_{tot} , versus stellar age, averaged across our 11 galaxies. We do not show the ratios with σ_R or σ_ϕ , because they exhibit qualitatively similar trends as σ_{tot} , albeit with higher normalizations.

In the Pre-Disk era, $(v_\phi/\sigma_{\text{tot}})_{\text{form}} < 1$ (by definition). When $v_{\phi,\text{form}}$ permanently exceeded $\sigma_{\text{tot,form}}$ (≈ 8 Gyr ago on average), a galaxy transitioned into the Early-Disk Era, when successively younger populations were born with increasing $(v_\phi/\sigma_{\text{tot}})_{\text{form}}$ and $(v_\phi/\sigma_Z)_{\text{form}}$. After the galaxy transitioned into the Late-Disk Era (≈ 4 Gyr ago on average), $(v_\phi/\sigma_{\text{tot}})_{\text{form}}$ grew only slightly, so stars during this era formed with the same degree of total rotational support. By contrast, $(v_\phi/\sigma_Z)_{\text{form}}$ continued to increase throughout the Late-Disk Era, with only slightly slower growth than in the Early-Disk Era, reflecting the more significant reduction in $\sigma_{Z,\text{form}}$ over time. Thus, we find more significant *vertical* ‘settling’ during the Late-Disk Era.

Relative to formation, stars have lower v_ϕ/σ as measured today. To better understand how the post-formation change in v_ϕ/σ depends on age, Figure 9 (bottom) shows the ratio $(v_\phi/\sigma)_{\text{form}}/(v_\phi/\sigma)_{\text{now}}$ versus age. This ratio indicates how ‘disky’ a stellar population formed relative to how diskly it is today, from the combined effect of post-formation dynamical heating and coherent torquing.

Younger stars, which formed in the Late-Disk Era, became increasingly less diskly with age, as post-formation dynamical heating increased their dispersion. Stars older than ≈ 2 Gyr exhibit ratios near 2, meaning that they are currently half as diskly as when they formed. For stars that formed in the Early-Disk Era, this trend *reverses*, as the post-formation change in diskiness *lessens* with age, and the oldest stars in this era are now equally diskly as when they formed. This occurs because $(v_\phi/\sigma)_{\text{form}}$ decreased with age *faster* than the post-formation change in v_ϕ/σ increased. Now, the ratio with σ_{tot} exhibits behavior nearly identical to that of the ratio with σ_Z , indicating that both ‘3D diskiness’ and ‘vertical diskiness’ evolved after formation identically relative to their values at formation.

Stars that formed in the Pre-Disk Era have values of $(v_\phi/\sigma)_{\text{form}}/(v_\phi/\sigma)_{\text{now}}$ that fluctuate around 1. Some stars have higher v_ϕ/σ now than when they formed, from post-formation torquing from events like mergers. Also, the division of intrinsically small velocity values amplifies the fluctuations.

2.4.2 CASE STUDIES

While Figures 8 and 9 show trends averaged across 11 galaxies, Figure 10 shows these trends for 3 individual galaxies: m12f (blue), m12m (pink), and Romeo (green).

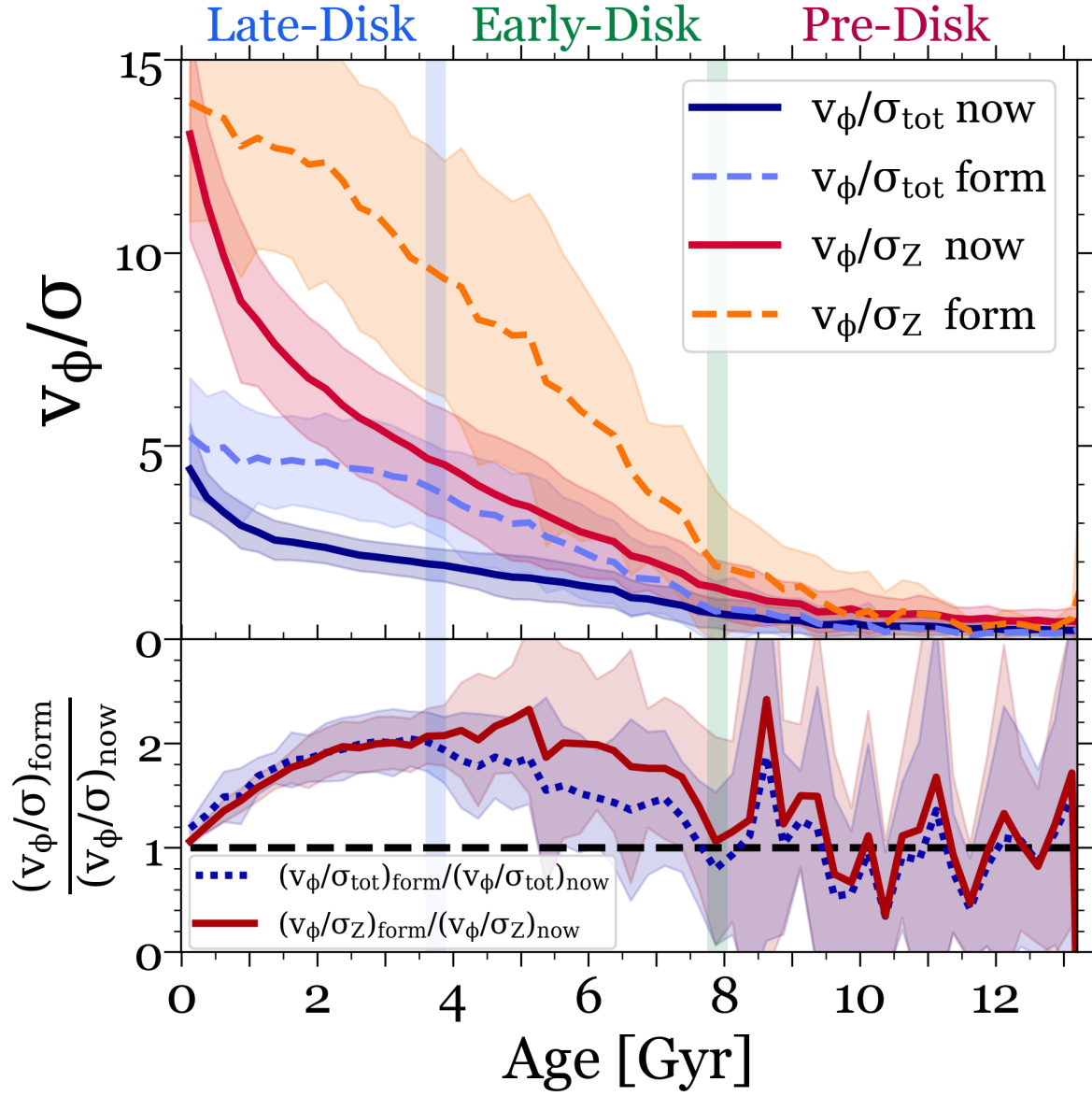


Figure 9: **Top:** The ratio of median v_ϕ to σ , that is, how rotationally supported or ‘disky’ the stars are, versus age. We average across 11 galaxies, and the shaded region shows the galaxy-to-galaxy standard deviation. The solid purple line shows $(v_\phi/\sigma_{\text{tot}})_{\text{now}}$, while the red shows $(v_\phi/\sigma_Z)_{\text{form}}$. The dashed light-purple and orange lines show the same but measured when the star formed. In the Pre-Disk Era, stars formed with $v_\phi/\sigma \approx 0$, but once the disk began to form, $(v_\phi/\sigma_Z)_{\text{form}}$ rapidly increased until today, so vertical settling continued until today. By contrast, $(v_\phi/\sigma_{\text{tot}})_{\text{form}}$ also initially increased rapidly during the Early-Disk Era, but it remained roughly constant in the Late-Disk Era. **Bottom:** $(v_\phi/\sigma)_{\text{form}} / (v_\phi/\sigma)_{\text{now}}$ for σ_{tot} (dotted navy) and σ_Z (solid red), which measures how ‘disky’ stars were when they formed relative to today. Both ratios have similar values and exhibit similar trends with age. Stars that formed in the Early- and Late-Disk Eras have ratios above 1 (and near 2 for most ages), because post-formation dynamical heating increased their dispersions. Pre-Disk stars have $(v_\phi/\sigma)_{\text{now}} \approx (v_\phi/\sigma)_{\text{form}} \approx 0$, with fluctuations from mergers/accretion and feedback.

Romeo is one of our closest analogues to the MW today, residing in a LG-like pair and having a stellar mass of $5.9 \times 10^{10} M_{\odot}$, similar to the MW. Furthermore, recent observational analysis suggests that the MW’s disk began to form ≈ 12 Gyr ago (Belokurov and Kravtsov, 2022; Conroy et al., 2022; Xiang and Rix, 2022), and as we quantify further below, of all our galaxies, Romeo’s disk began to form the earliest and thus nearest in time to this estimate for the MW, likely because of its forming in LG-like environment (Garrison-Kimmel et al., 2018; Santistevan et al., 2020). Figure 10 (left) shows that Romeo’s $v_{\phi, \text{form}}$ rapidly increased and its $(v_{\phi}/\sigma_z)_{\text{form}}$ began to rise ≈ 12 Gyr ago and it transitioned into its Early-Disk Era ≈ 11 Gyr ago. Although Romeo transitioned the earliest, its evolution largely follows the same trends as most of our other galaxies.

m12f highlights the effect of major mergers on stellar kinematics. Its $v_{\phi, \text{form}}$ and $(v_{\phi}/\sigma_z)_{\text{form}}$ began to increase ≈ 10 Gyr ago, during its transition to the Early-Disk Era. However, both decreased ≈ 8 Gyr ago, when a galaxy flew by and torqued its disk. After this, $v_{\phi, \text{form}}$ and $(v_{\phi}/\sigma_z)_{\text{form}}$ increased again. m12f then experienced a major merger ≈ 6.9 Gyr ago. Although the dispersion was high during the merger, afterwards $\sigma_{z, \text{form}}$ sharply decreased while $(v_{\phi}/\sigma)_{\text{form}}$ increased. Thus, a major merger led to a more rotationally-supported disk and may have triggered its transition to the Late-Disk Era. This agrees with previous work that found that gas-rich mergers can trigger the settling of galactic disks, particularly if they occur when the potential is sufficiently deep to prevent outflows after bursts of merger-triggered star formation (for example He et al., 2023; Hopkins et al., 2009; McElroy et al., 2022; Moreno et al., 2021; Santistevan et al., 2021).

At present, the high dispersion during the merger and the sharp decline afterward remain discernible. Although the merger more dramatically impacts the in-plane components of the dispersion (notably, at present spikes from 60 km s^{-1} to 150 km s^{-1} back down to 55 km s^{-1} within 1 Gyr during the merger), for consistency, we display only the vertical component. Thus, the present-day kinematics of stars, specifically ‘spikes’ in the velocity dispersion versus age, can reveal past merger events, as we will explore in future work. After its disk began to settle, m12f underwent a smaller, prograde merger ≈ 1.5 Gyr ago that triggered a significant burst of star formation (Yu et al., 2021), increased σ_{form} , and decreased $(v_{\phi}/\sigma)_{\text{form}}$. Thus, certain mergers occurring in the Pre- or Early-Disk Eras increased the galaxy’s rotational support, while mergers occurring in the Late-Disk Era decreased the disk’s rotational support.

We next highlight m12m, whose evolution deviates from our other galaxies. m12m has the largest stellar mass at $z = 0$ in our sample, $\approx 10^{11} M_{\odot}$, more similar to M31. Furthermore, m12m underwent numerous early mergers, including two particularly massive mergers ≈ 10 and 9 Gyr ago, but it had a quiescent merger history over the past 8 Gyr.

m12m has our second earliest transition into the Early-Disk Era: its $(v_{\phi}/\sigma_{\text{tot}})_{\text{form}}$ permanently surpassed unity ≈ 9 Gyr ago. Despite this, m12m has yet at $z = 0$ to transition fully into its Late-Disk Era: its $v_{\phi, \text{form}}$ continues to increase (albeit only slightly), all but its vertical component of σ_{form} have yet to become constant, and $(v_{\phi}/\sigma_{\text{tot}})_{\text{form}}$ continues to strongly increase. This may be because m12m began to develop a bar ≈ 4.8 Gyr ago, leading to a bar-buckling event that formed a significant X-shaped bulge composed primarily of younger stars (age < 4.8 Gyr)

(Debattista et al., 2019). m12m’s kinematics are also unique at present; most notably, its $v_{\phi,\text{now}}$ exhibits no significant decrease for old stars; instead, all ages have $v_{\phi,\text{now}} \gtrsim 160 \text{ km s}^{-1}$, which is almost $3\times$ faster than our sample’s average, likely as a result of its multiple major mergers. Of our 3 case studies, m12m generally had the lowest $\sigma_{Z,\text{form}}$ for stars older than $\approx 8 \text{ Gyr}$, but at present m12m has the highest $\sigma_{Z,\text{now}}$ at almost all ages, because its stars have been more dynamically heated.

Comparing these case studies provides useful context and caution for interpreting population-wide trends. First, the dispersion of young stars does not necessarily reflect the dispersion of older stars: across the three galaxies, the difference in $\sigma_{Z,\text{now}}$ is only a few km s^{-1} for the youngest stars (age $< 250 \text{ Myr}$), but jumps to 14 km s^{-1} at 1 Gyr old and 57 km s^{-1} at 6 Gyr old. In fact, the rate at which σ_{now} increases with age varies between galaxies. On a related note, how σ_{form} compares between galaxies may be different from how σ_{now} does. That is, stars of a certain age may now have larger/smaller dispersions than those in another galaxy despite forming with smaller/larger dispersions. For example, Romeo generally had the highest values of $\sigma_{Z,\text{form}}$ for stars older than 6 Gyr , while m12m had the lowest. However, this ordering flips at present: today, σ_Z in m12m is higher than in Romeo. Thus, the dispersion with which stars formed does not set their present dispersion, because the amount and age dependence of post-formation heating can differ significantly between galaxies.

On the contrary, v_{ϕ}/σ_Z provides a similar comparison between galaxies at both formation and present-day. $(v_{\phi}/\sigma_Z)_{\text{now}}$ maintains its relative ordering between galaxies from formation and even largely preserves the trends with age exhibited by each individual galaxy: Romeo still has the highest values for stars younger than $\approx 10 \text{ Gyr}$, m12f and m12m still have similar values for intermediate-aged stars, and m12f still has the lowest values for young stars. Although the differences between each galaxy’s v_{ϕ}/σ_Z are less pronounced today than at formation, *present day observations of $(v_{\phi}/\sigma)_{\text{now}}$ (versus age) give a better representation of a galaxy’s formation history than σ_{now} and $v_{\phi,\text{now}}$ alone.*

2.4.3 COMPARING VELOCITY COMPONENTS

All three spatial components of velocity dispersion share similar trends with age, but we now compare them in detail. Figure 11 shows the radial, azimuthal, and vertical velocity dispersions, averaged across the 11 galaxies, at formation (left) and at present (right).

Figure 11 (top row) compares the dispersions. The relative order of the components at formation is constant with age: $\sigma_{R,\text{form}} > \sigma_{\phi,\text{form}} > \sigma_{Z,\text{form}}$. At present, $\sigma_{R,\text{now}}$ dominates at all ages. However, $\sigma_{Z,\text{now}}$ now matches $\sigma_{\phi,\text{now}}$ for stars that formed in the Early- and Pre-Disk Eras. Thus, the similarity between $\sigma_{Z,\text{now}}$ and $\sigma_{\phi,\text{now}}$ for intermediate-aged and old stars arises from vertical post-formation dynamical heating, not from formation. Measurements of σ_{now} in the Solar neighborhood find $\sigma_R > \sigma_{\phi} > \sigma_Z$ (for example Dehnen and Binney, 1998; Nordström et al., 2004; Wielen, 1977). Although our results agree for stars that formed in the Late-Disk Era,

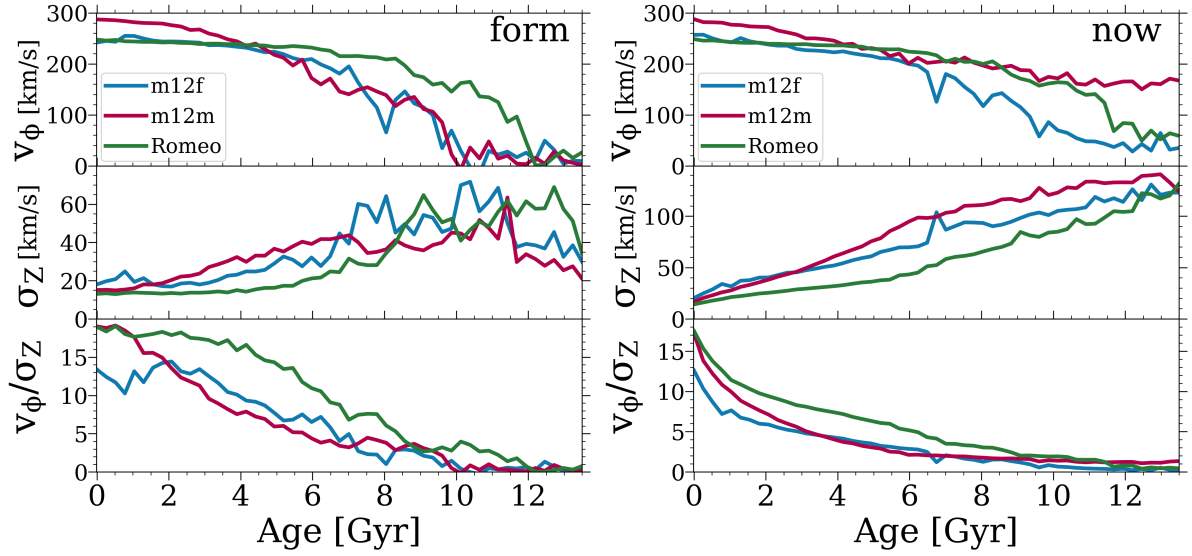


Figure 10: **Median azimuthal velocity and velocity dispersion of stars versus age for 3 galaxies:** m12f (blue), m12m (pink), and Romeo (green). Left shows velocities at the time of formation, while right shows velocities today. **Top:** Median azimuthal velocity, v_ϕ . Romeo is the earliest settling galaxy in our sample; it exhibited rapid growth in v_ϕ at formation ≈ 2 Gyr before m12m or m12f. However, by $z = 0$ the later-settling m12m exhibits higher v_ϕ at almost all ages, including its oldest stars. *Thus, kinematics at a given age as measured today do not necessarily indicate those at formation.* **Middle:** Vertical velocity dispersion, σ_Z . At formation, all of the galaxies show large fluctuating velocity dispersions for old stars, which peaked at different times, but this peak does not reflect itself in the current velocity dispersion versus age, at right. m12f underwent a major merger ≈ 7 Gyr ago, corresponding to a spike in the velocity dispersion in both panels. **Bottom:** Ratio of median azimuthal velocity to vertical velocity dispersion, as a measure of rotational support. Romeo is the most rotationally supported galaxy at all ages, measured both today and at formation, although m12m catches up for young stars today. Despite differing histories, all 3 galaxies have similar velocity dispersions for young stars today, although they are more separated in v_ϕ/σ_Z .

we find that $\sigma_{\phi,\text{now}} \approx \sigma_{Z,\text{now}}$ for stars that formed in the Early and Pre-Disk Eras, potentially indicating that post-formation heating of σ_Z is greater for older stars in our galaxies than in the MW.

Figure 11 (second row) shows the ratio of each component's σ^2 to the total σ^2 at that age, which compares each component's contribution to the overall kinetic energy in dispersion. Because $\sigma_{\text{total}}^2 \equiv \sigma_R^2 + \sigma_\phi^2 + \sigma_Z^2$, the sum of this ratio in all three components is 1. Remarkably, the ordering and relative value of each component at the time of formation are independent of age. That is, σ_{form} was distributed across its 3 components the same way throughout the galaxy's entire formation history, with $\sigma_{R,\text{form}}^2$, $\sigma_{\phi,\text{form}}^2$, and $\sigma_{Z,\text{form}}^2$ accounting for $\approx 51\%$, 32% , and 17% of $\sigma_{\text{tot,form}}^2$, on average. This roughly constant partitioning across cosmic time is striking, given that it persists across the eras of disk formation, including the transition from dispersion-dominated to rotation-dominated orbits, from bursty to steady star formation, and the abatement of galactic outflows. Given this consistent partitioning at formation during both early and late times, we posit that the drivers of (star-forming) gas dispersion common in the early galaxy, such as star-burst driven outflows, and those common in the later galaxy, such as spiral arms, have similar impacts on how the energy in dispersion at formation is partitioned between components. However, we welegate testing this hypothesis to future work.

Currently, $\sigma_{R,\text{now}}^2$ dominates in all ages, as Figure 11 (top) shows. However, unlike at formation, the relative contributions of $\sigma_{R,\text{now}}^2$ and $\sigma_{Z,\text{now}}^2$ are constant with age only for stars older than ≈ 6 Gyr, which formed in the Pre-Disk Era and the beginning of the Early-Disk Era. $\sigma_{R,\text{now}}^2$ still contributes $\approx 50\%$ of the random kinetic energy of these old stars, while $\sigma_{\phi,\text{now}}^2$ and $\sigma_{Z,\text{now}}^2$ both contribute $\approx 25\%$.

For stars younger than 6 Gyr, the relative contribution of $\sigma_{R,\text{now}}^2$ increases for younger stars, even surpassing its contribution at formation, because young stars have been heated most strongly along their radial component, as we show below. In contrast, the relative contribution of $\sigma_{Z,\text{now}}^2$ decreases for younger stars, more directly reflecting the low $\sigma_{Z,\text{form}}$ of these young stars. Interestingly, stars of all ages have approximately 25% of their random kinetic energy from $\sigma_{\phi,\text{now}}^2$, slightly less than when they formed.

We define σ_0 as the dispersion of our youngest stars (age < 250 Myr at $z = 0$). To examine the degree of self-similarity in the evolution of the different velocity components, Figure 11 (third row) shows $\sigma - \sigma_0$, the *absolute change* in the velocity dispersion with age. All velocity components have more similar evolution in $\sigma - \sigma_0$ than in σ . This is most self-similar at formation, but it also holds to a lesser degree at present. In particular, $\sigma_{R,\text{form}}$ exhibits a greater absolute change only for intermediate-aged stars ($\approx 6 - 10$ Gyr), whereas $\sigma_{R,\text{now}}$ has a greater absolute change at all ages, because $\sigma_{R,\text{now}}$ had the largest amount of dispersion added by post-formation dynamical heating for all but intermediate-aged stars, as we discuss below.

Figure 11 (bottom row) shows σ/σ_0 , the *fractional change* in the velocity dispersion with age, relative to today. At formation, this exhibits significant self-similarity, with all components showing near identical evolution for stars that formed in the Early- and Late-Disk Eras. In particular, at the onset of the Early-Disk Era, stars formed with $\approx 3\times$ the dispersion as young stars today for all velocity components. However, the striking self-similarity at formation does *not* hold at present. Although all components evolve relatively similarly for ages $0 - 3$ Gyr,

the vertical component increasingly dominates for older stars, with the oldest stars having vertical dispersions $\approx 7 \times \sigma_{Z,0}$. Because σ_Z had similar fractional evolution at formation, its distinctive behavior at present must arise from a greater fractional amount of post-formation heating for stars that formed in the Early- and Pre-Disk Eras, which we explore next.

2.4.4 DISK SETTLING VERSUS POST-FORMATION HEATING

As we have shown, both disk settling and dynamical heating shape the relation between σ_{now} and stellar age. We now quantify the relative importance of these two processes versus age.

Figure 12 shows the absolute and fractional impact of post-formation dynamical heating on the present-day radial, azimuthal, vertical, and total velocity dispersion of stars versus age. Most notably, both absolute and fractional post-formation dynamical heating follow distinct trends with age for stars that formed in each of our three kinematic eras.

Figure 12 (top) shows the difference between dispersion at present and formation, $\sigma_{\text{now}} - \sigma_{\text{form}}$, versus age, which directly conveys the amount of dispersion added post-formation. We focus primarily on the total dispersion, noting that the radial and azimuthal components show similar behavior. However, we discuss the vertical dispersion separately below, because it shows qualitatively different behavior.

For stars that formed in the Late-Disk Era, the amount of dispersion added post-formation increases with age, but at a declining rate, consistent with the idea that post-formation dynamical heating from scattering processes causes the observed increase in σ_{now} with age (for example Spitzer and Schwarzschild, 1951). However, stars that formed in the Early-Disk Era have been dynamically heated by the same total amount, $\approx 50 \text{ km s}^{-1}$, regardless of age. Considering the monotonic increase of σ_{tot} in Figure 8, one may not intuitively expect this plateau. For example, stars that formed at the start of the Early-Disk Era ($\approx 8 \text{ Gyr}$ ago) currently have $\sigma_{\text{tot,now}}$ that is almost 80 km s^{-1} higher than stars born at the end of the Early-Disk Era ($\approx 4 \text{ Gyr}$ ago), but have 5 km s^{-1} less σ_{tot} added post-formation. Thus, *the monotonic increase of $\sigma_{\text{tot,now}}$ with age for stars that formed in the Early-Disk Era ($\approx 4 - 8 \text{ Gyr}$ ago) arose not from the dependence of post-formation heating on age, but rather, from the amount of disk settling in σ_{form} versus age.*

Once a disk started to form, scattering with structures within the now well-defined disk plane likely drove most post-formation heating, though interactions with satellite galaxies likely also contributed. As stars were dynamically heated, they experienced larger radial and vertical oscillations. Larger vertical oscillations decrease the amount of time that stars spend near the midplane and increase their vertical velocities when passing through the midplane. In turn, the ability of stars to be heated along the in-plane direction decreases as vertical oscillations increase. Similarly, stars with large radial eccentricities encounter spiral structure at different orbital phases; the effects of these varied encounters tend to average out, so that spiral-driven heating becomes progressively weaker

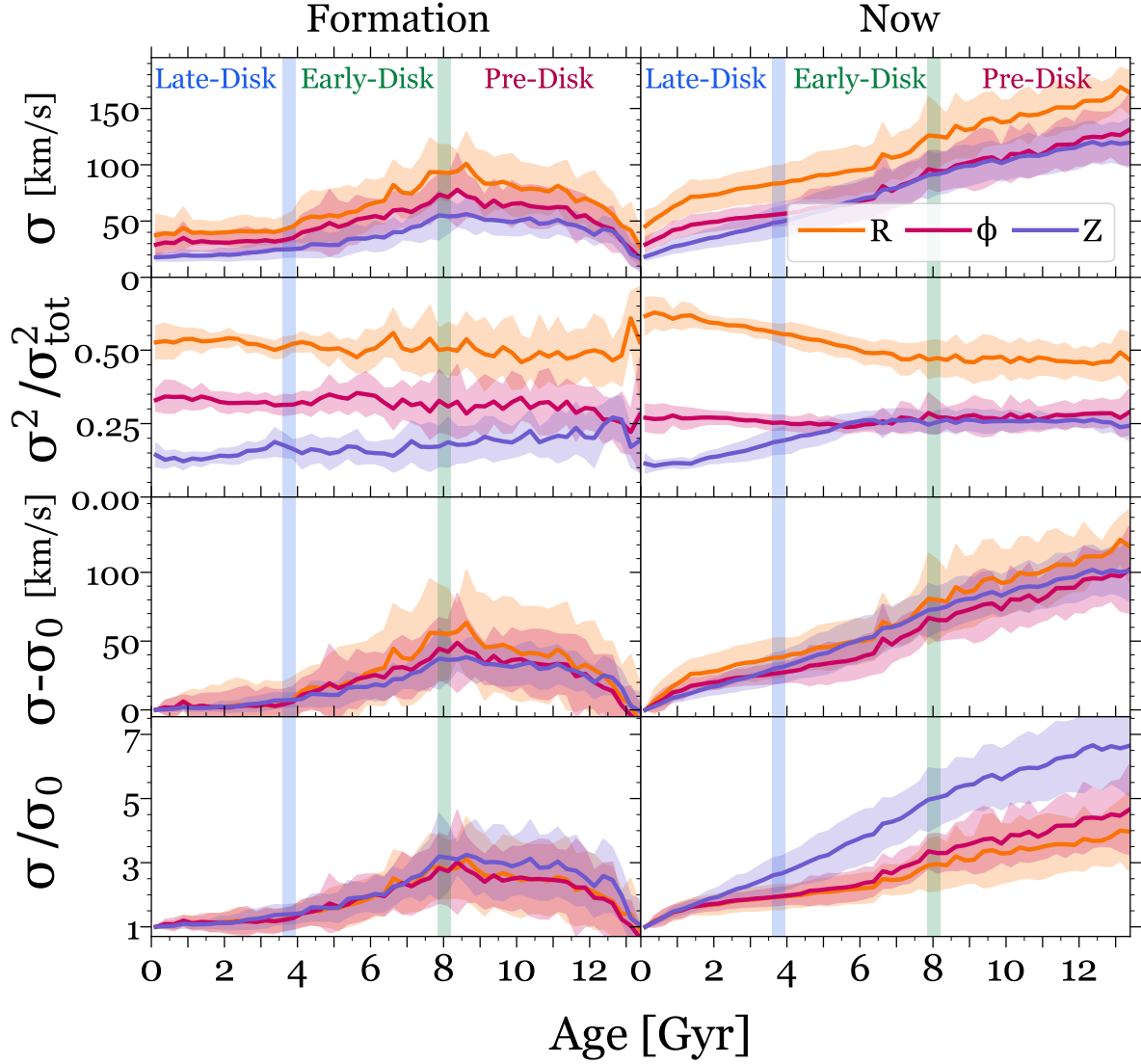


Figure 11: **Comparing the evolution of the 3 components of velocity:** lines show the radial (orange), azimuthal (pink), and vertical (purple) velocity dispersion at formation (left) and today (right) versus age. We average across 11 galaxies, and the shaded regions show the galaxy-to-galaxy standard deviation. **Top row:** Velocity dispersion, σ . At formation, all components exhibit constant ordering, with $\sigma_R > \sigma_\phi > \sigma_Z$, and similar dependence on age. Today, σ_R dominates at all ages, while σ_ϕ and σ_Z are near identical for older stars. However, σ_Z falls below σ_ϕ for stars that formed in the Late-Disk Era. **Second row:** Ratio of each component's σ^2 relative to the total at that age, as a metric of the relative kinetic energy in each component. At both formation and today, σ_R^2 dominates the kinetic energy. At formation, kinetic energy partition is nearly independent of age, while today, it is nearly independent for ages > 6 Gyr, but because of post-formation heating, the importance of σ_Z^2 decreases while σ_R^2 increases for younger and younger stars. **Third row:** Absolute change in the velocity dispersion relative to σ_0 , the dispersion of the youngest stars (age < 250 Myr at $z = 0$) for each component. At formation and today, all components are nearly self-similar, indicating that each component changes with age by about the same absolute amount (although at present, the radial component is slightly higher, because of its stronger post-formation heating). **Bottom row:** Velocity dispersion normalized by its value for the youngest stars, which quantifies the fractional change in σ over time. At formation, all components display similar values and age dependence, such that intermediate-age stars formed with 3 times higher σ than the youngest or oldest stars did. As measured today, σ_Z exhibits the strongest fractional dependence on age, despite it showing the weakest absolute dependence on age in the top panels, as a result of post-formation heating.

for increasingly eccentric orbits (Binney and Tremaine, 2008). Thus, stars that formed with low dispersions in the Late-Disk Era were initially efficiently heated. However, this efficiency decreased accordingly as their dispersions increased over their lifetimes, explaining their near-exponential behavior for $\sigma_{\text{tot,now}} - \sigma_{\text{tot,form}}$ shown in the upper row of Figure 12. Similarly, because stars that formed in the Early-Disk and Pre-Disk Eras had large dispersions at birth, they likely underwent little post-formation heating over the course of the Late-Disk and Early-Disk Era (though old stars likely experienced significant heating within the Pre-Disk Era).

On the other hand, post-formation *vertical* heating shows different trends than in-plane heating throughout the Late and Early-Disk Eras. The amount of σ_z added post-formation never plateaus, but instead monotonically increases with age by $\approx 7 \text{ km s}^{-1}$ per Gyr. Therefore, *post-formation vertical heating is likely a steady, continuous process*, implying a different dynamical origin than in-plane post-formation heating. In future work, we will pursue a detailed analysis of the origin of in-plane and vertical heating.

For stars that formed in the Pre-Disk Era, the amount of post-formation heating increases steadily with age for all components, including vertical. Older stars have more dispersion added post-formation, not only because they have had more time to be heated, but also because the early galaxy experienced the most frequent mergers, starbursts, and potential fluctuations that increased the dispersion of existing stars (for example El-Badry et al., 2018b). Likely, this phase accounted for most of the heating of stars that formed in the Pre-Disk Era. In later eras, more localized, temporally-stable processes (that is, scattering by non-axisymmetric structures within the disk) primarily heated the stars.

Figure 12 (bottom) shows the ratio of dispersion at present to dispersion at formation, $\sigma_{\text{now}}/\sigma_{\text{form}}$, versus age, which quantifies the fraction of the present dispersion that existed at formation versus arose from post-formation heating. Values of $\sigma_{\text{now}}/\sigma_{\text{form}} > 2$ indicate that post-formation heating contributes more to the current dispersion than the dispersion from formation, while values < 2 indicate that most of the dispersion was in place at the time of formation.

The evolution of the total dispersion largely matches that of the radial and azimuthal components. $\sigma_{\text{now}}/\sigma_{\text{form}}$ has an ‘S’-shaped dependence on age, somewhat different from that in the top panel. Post-formation heating increases rapidly with age for stars that formed in the Late-Disk Era. The oldest stars of this era have current (radial, vertical, and total) dispersions with approximately equal contributions from heating and formation. Furthermore, stars that formed ≈ 4 Gyr ago, during the transition to the Late-Disk Era, experienced the largest fractional increase from post-formation heating of all stars younger than 10 Gyr (for all but the vertical dispersion). These stars formed in a dynamically-settled thin disk with low dispersion and had more time to experience dynamical heating than stars that formed afterward.

However, this dependence on age strikingly *reverses* in the Early-Disk Era, when $\sigma_{\text{now}}/\sigma_{\text{form}}$ decreases with age. As Figure 12 (top row) showed, the absolute amount of dispersion added post-formation is constant throughout this era. However, as Figure 8 showed, σ_{form} increases with age throughout this era. Thus, the fractional contribution of σ_{form} at birth became increasingly important with age in this era. Besides stars younger than ≈ 1 Gyr, the

oldest stars from the Early-Disk Era have the lowest dependence on post-formation heating, with only 40% of their current σ_{tot} from post-formation heating, corresponding to their maximum σ_{form} and comparatively low amount of post-formation heating. In essence, stars were not able to be dynamically heated efficiently during this Early-Disk Era, because they already were born with high dispersions.

For stars that formed in the Pre-Disk Era, $\sigma_{\text{now}}/\sigma_{\text{form}}$ increases rapidly with age, because σ_{form} decreases with age (given the galaxy's lower mass), while the amount of post-formation heating (and thus σ_{now}) increases with age (from mergers, starbursts, and strong outflows). Thus, *the current total dispersion of stars is primarily due to post-formation heating for stars older than ≈ 11 Gyr, and is primarily inherited at formation for stars younger than 11 Gyr.*

The evolution of the vertical component largely resembles that of the other components for stars that formed in the Late-Disk Era. However, while $\sigma_{\text{now}}/\sigma_{\text{form}}$ of the in-plane components noticeably decrease with age for stars that formed in the Early-Disk Era, the vertical component remains relatively constant near 2. In fact, $\sigma_{Z,\text{now}}/\sigma_{Z,\text{form}} \approx 2$ for stars with ages between 2 – 10 Gyr, meaning that the current vertical dispersions of stars with ages 2 – 10 Gyr have equal contributions from post-formation heating and formation. Thus, *for most stars, the fractional impacts of vertical post-formation heating and vertical disk settling are about the same.* For stars younger than 2 Gyr, $\sigma_{Z,\text{form}}$ is more important, while for stars older than 10 Gyr, vertical post-formation heating is.

In summary, the monotonic rise of the current velocity dispersion with stellar age arises from the *combined* effects of *both* cosmological disk settling and the dynamical processes that heat stars after they form. In understanding the origin of the current *shape* of the relation between the total velocity dispersion and age, we conclude that: (1) *post-formation heating dominates the dispersion for stars that formed in the Late-Disk Era* (age $\lesssim 3.5$ Gyr), when the dispersion at formation was flat with age, (2) *disk settling dominates for stars that formed in the Early-Disk Era* (age $\approx 4 - 8$ Gyr), when post-formation heating was flat with age, and (3) *post-formation heating strongly dominates for stars that formed in the Pre-Disk Era* (age $\gtrsim 10$ Gyr). Overall, post-formation dynamical heating only dominates the current dispersion for stars that formed ≈ 3 Gyr before the disk started to form, or, equivalently, *the stellar velocity dispersion at present is primary inherited at formation and not from post-formation dynamical heating* for stars younger than ≈ 10 Gyr.

Our results agree with Yu et al. (2022), who also analyzed these FIRE-2 galaxies and found that most stars currently on ‘thin-disk-like’, ‘thick-disk-like’, or ‘spheroid-like’ orbits were born that way, that is, the type of orbit a star is currently on primarily reflects its formation orbit, not its post-formation evolution.

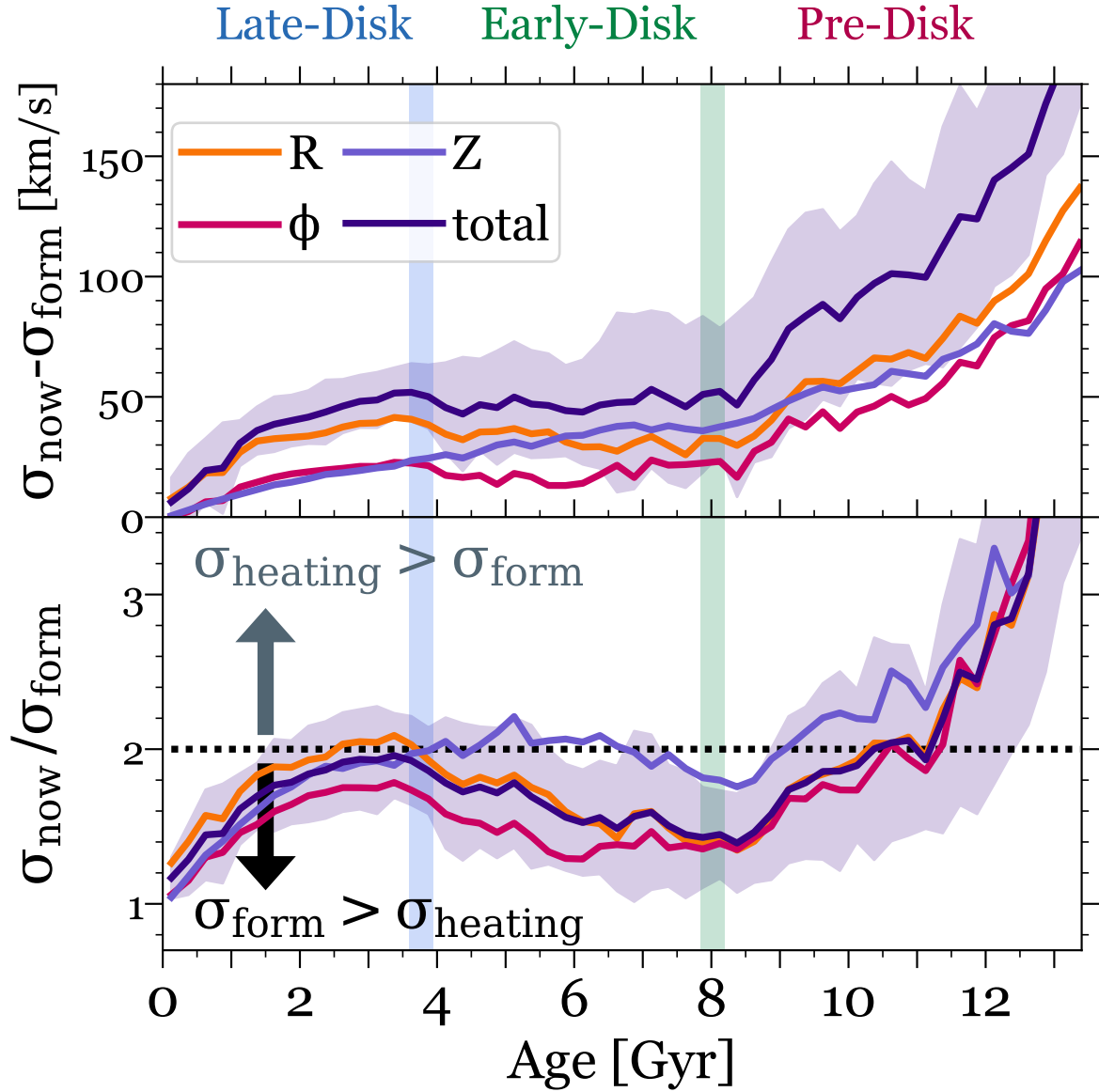


Figure 12: **Comparison between the velocity dispersion today versus at formation, which quantifies the amount of post-formation dynamical heating, versus age**, for different components of velocity. We average across 11 galaxies, and the shaded region shows the galaxy-to-galaxy standard deviation. **Top:** Absolute change in dispersion from formation to today. The amount of heating increases with age. However, for all components except σ_Z , the heating is constant for ages $\approx 3 - 8$ Gyr, and thus intermediate-age stars were heated by a similar amount. **Bottom:** Ratio of dispersion today relative to that at formation, which shows an ‘S’-shaped dependence on age. The dotted horizontal line at 2 divides stars whose current dispersion is primarily from formation (below) versus post-formation (above). The combination of small dispersions at birth and rapid post-formation heating leads to a steadily increasing ratio with age up to ≈ 2 Gyr. Intermediate-age stars have a present dispersion mostly inherited from formation, because they formed when the intrinsic dispersion within the galaxy was highest. The oldest stars have the largest contribution from post-formation heating. *For stars younger than 10 Gyr, most of their dispersion was in place at formation, although σ_Z shows nearly equal contributions from formation and subsequent heating at ages 4 – 8 Gyr.*

2.4.5 EFFECTIVE RATE OF POST-FORMATION HEATING

Stars that formed in the Pre-Disk Era have the most dispersion added post-formation, as Figure 12 (top) shows. One might assume (naively) that the amount of heating simply scales with age because older stars have had more time to be heated. However, Figure 12 (top) showed that the amount of post-formation heating does not necessarily increase with age in all eras. For example, stars 8 Gyr old have experienced the same absolute amount of post-formation heating as stars 4 Gyr old. To provide more insight, we examine the ‘effective’ rate that stars today experienced post-formation heating, on average, via $(\sigma_{\text{now}} - \sigma_{\text{form}})/\text{age}$. This quantity is *not* the actual instantaneous rate of increase in dispersion. Rather, it represents the overall time-averaged rate at which the dispersion increased since formation. Thus, one can think of this effective rate as the amount of post-formation heating normalized to the stellar populations’ age.

Figure 13 shows this effective rate versus stellar age, for radial, vertical, azimuthal, and total dispersions. First, we focus on the total dispersion: $(\sigma_{\text{tot,now}} - \sigma_{\text{tot,form}})/\text{age}$. The youngest stars experienced the largest effective rate of increase, which rapidly decreases with age for stars that formed during the Late-Disk Era. For stars that formed in the Early-Disk Era, the effective rate was low, reaching a minimum near the transition to the Pre-Disk Era. This strong age dependence implies that, for stars that formed in a disk, most dynamical heating occurred shortly after birth, and their heating rate slowed as they became progressively dynamically hotter (excepting the vertical component). By contrast, stars that formed in the Pre-Disk Era had effective rates of heating that *increase* with age, likely because more dramatic, galaxy-wide, non-equilibrium perturbations like mergers and accretion, starbursts, and galactic winds were more prominent. The number of these perturbation events that stars in the Pre-Disk era experienced increases with stellar age, such that the oldest stars have experienced the most cumulative heating.

Furthermore, for stars that formed in the Late-Disk Era, the increase in σ_R strongly dominates over the other components, so radial heating dominates the total heating. For example, the youngest stars have effective rates near 10 km/s/Gyr for σ_ϕ and σ_Z , but above 30 km/s/Gyr for σ_R , which may indicate that heating by spiral arms and/or bars dominates most early heating for stars forming in the Late-Disk Era. However, the effective radial rate decreases with age, while the other components remain more constant. Thus, stars that formed in the Early- and Pre-Disk Eras have nearly identical rates for all components of σ , indicating that *heating was more isotropic in the early galaxy*. Thus, *post-formation heating operated differently over cosmic time*. Any model of post-formation heating thus should treat early cosmic times (prior to the initial formation of the disk) and later cosmic times (after the formation of the disk) separately.

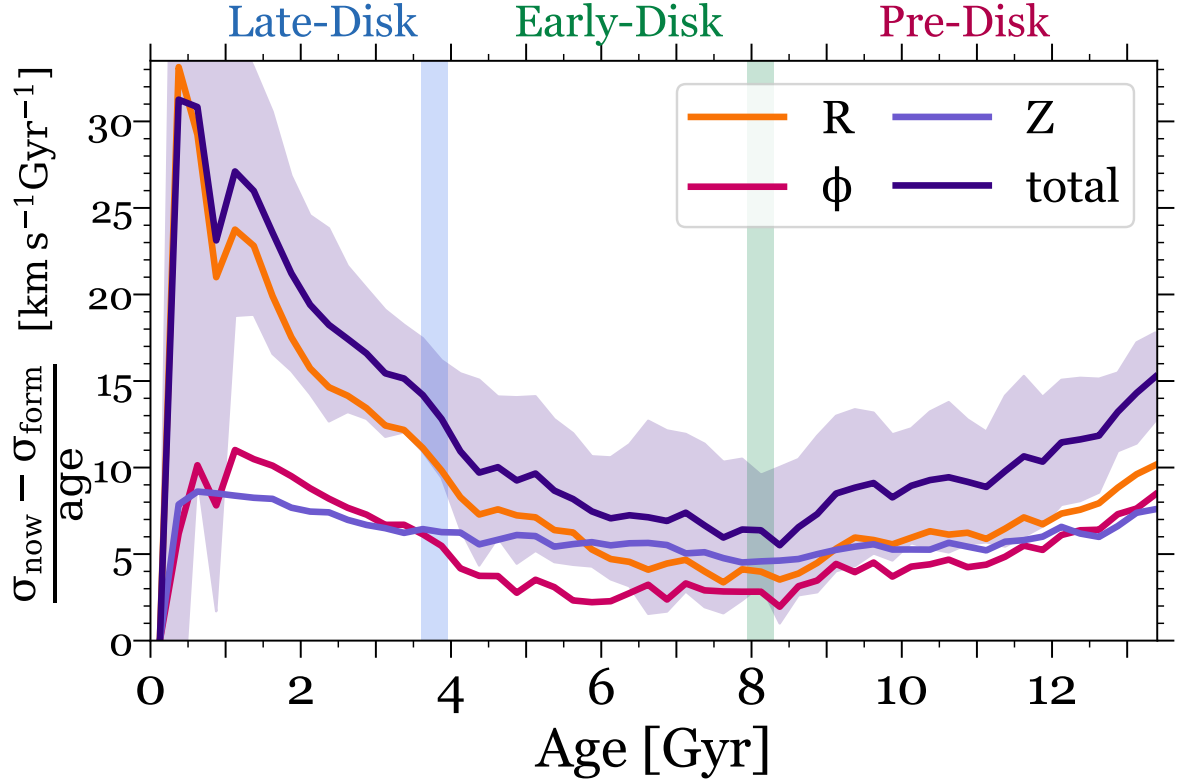


Figure 13: **The effective rate of dynamical heating since formation, $(\sigma_{\text{now}} - \sigma_{\text{form}})/\text{age}$, versus stellar age**, for each component of velocity. We average across 11 galaxies, and the shaded region shows the galaxy-to-galaxy standard deviation. The youngest stars have the highest effective rate of heating, implying that the rate of dynamical heating was most rapid immediately after stars formed and became more gradual over time. Increases in σ_R strongly dominate for stars that formed in the Late-Disk Era, but all components exhibit broadly similar effective rates for stars that formed in the Early- and Pre-Disk Eras.

2.4.6 DISK KINEMATICS VERSUS GALAXY MASS

So far, we showed trends averaged across our 11 galaxies that are similar to the MW in stellar mass. Now, we analyze all 14 galaxies in our sample individually, including the lower-mass m12r, m12z, and Juliet to expand the mass range (see Table 1 for details).

Figure 14 shows how stellar kinematics depend on the current stellar mass (within R_{90}) of a galaxy. We focus on σ and v_ϕ/σ , as before. Although we do not show it, v_ϕ increases strongly with stellar mass, which follows from the deeper gravitational potential of more massive galaxies (see also Hopkins et al., 2023). We show the isolated galaxies from the *Latte* suite as circles, and the galaxies in LG-like pairs from the *ELVIS on FIRE* suite as stars.

Figure 14 (top panels) shows σ_Z (top row) and v_ϕ/σ_Z (second row), for stars of all ages. If we exclude the two lowest-mass galaxies, m12r and m12z, whose disks have yet to or have just begun to settle, σ_Z increases with stellar mass. This trend is remarkably strong among LG-like galaxies, with the exception of Thelma, which underwent the most major mergers and has a higher σ_Z than galaxies of similar or higher mass. Unlike σ_Z , v_ϕ/σ_Z of all stars does not depend on mass at $> 2 \times 10^{10} M_\odot$. Interestingly, galaxies in LG-like pairs have lower dispersions and more rotational support than isolated galaxies on average. These colder kinematics likely relate to the fact that on average our LG-like galaxies formed discs earlier than our isolated galaxies did, as we show below.

Figure 14 (bottom panels) shows the same, but for stars younger than 250 Myr, which more closely reflects the current dynamical state of the ISM and is less affected by a galaxy’s integrated merger and heating histories. For young stars, σ_Z does not depend on stellar mass, while v_ϕ/σ_Z increases modestly with mass, implying that more massive galaxies have more vertically settled gas disks.

Although we do not show it, we performed an identical analysis for σ_R , σ_ϕ , and σ_{tot} . The kinematics of all stars show nearly identical trends for all components; however, the in-plane and total kinematics of young stars depend more weakly on stellar mass than the vertical kinematics do. Ultimately, we conclude that the stellar mass of a galaxy has little effect on the current velocity dispersion of young stars in the solar annulus and at most a modest effect on v_ϕ/σ in the mass range we explore.

2.4.7 COMPARISONS WITH OBSERVATIONS

Thus far, we have focused on our galaxies’ *disk-wide* kinematics, that is, the median velocities and dispersions for all stars (in a given age bin) within our simulated ‘solar annulus’ of $R = 6 - 10$ kpc and $|Z| < 3$ kpc at $z = 0$. However, observational measurements of nearby external galaxies typically measure kinematics in smaller-scale ‘patches’ and then average over these spatial patches to discuss trends with age within the galaxy. Similarly, most

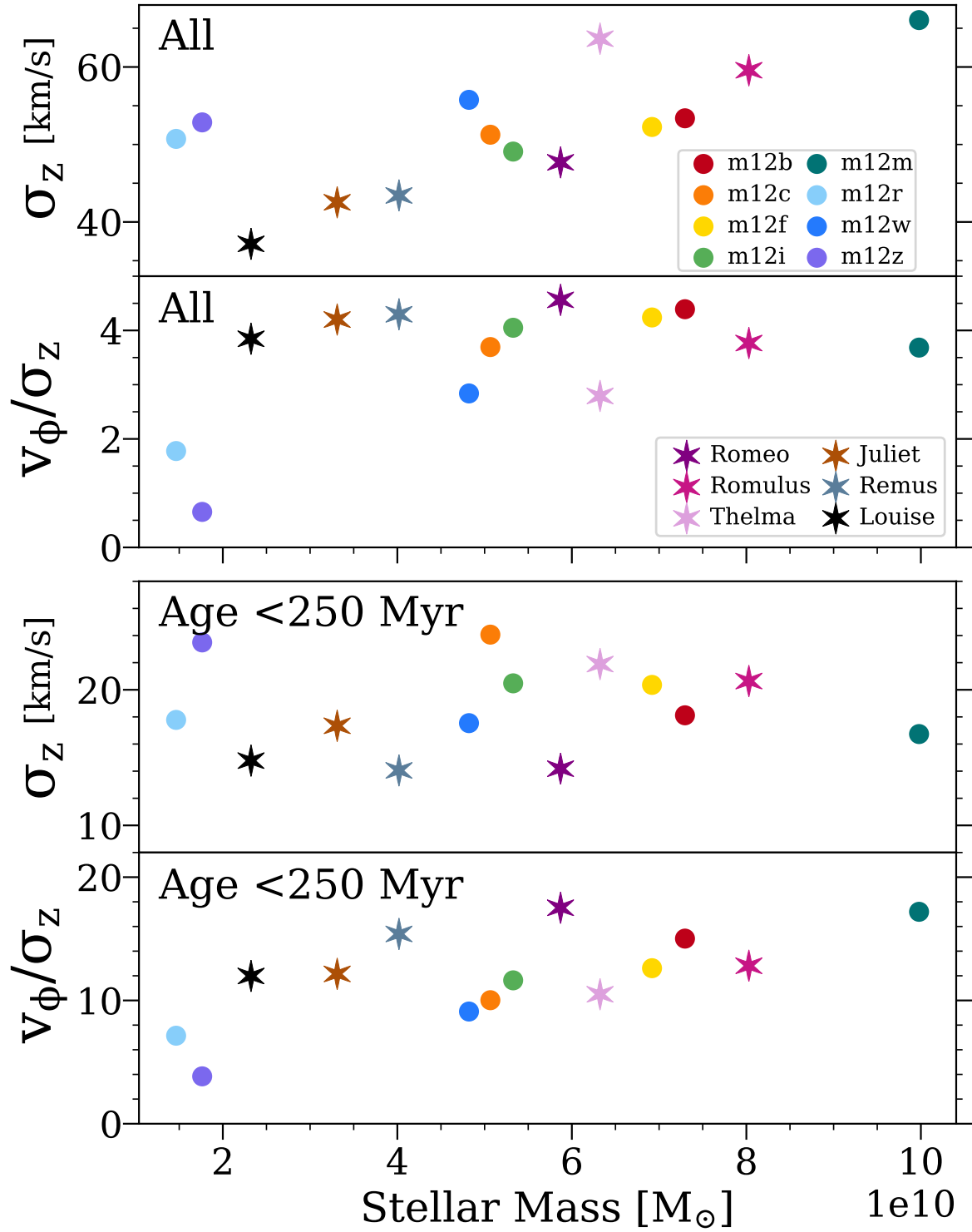


Figure 14: **Vertical velocity dispersion, σ_z , and v_ϕ/σ_z today versus stellar mass** for 14 galaxies. We show the isolated (m12) galaxies via circles and LG-like paired galaxies via stars. **Top panels:** stars of all ages in the galaxy. The dispersion for our disk-dominated galaxies increases with mass. All galaxies have approximately constant v_ϕ/σ_z regardless of mass, excepting m12r and m12z. **Bottom panels:** stars with ages < 250 Myr. Here, σ_z does not correlate with mass, though v_ϕ/σ_z is slightly higher in at higher mass. Overall, galaxies in LG-like pairs tend to have lower dispersions and more rotational support at a given mass; however, this difference is more evident for all stars than for young stars.

published dispersion values for the MW are for stars within one ‘patch’ – the solar neighborhood. We now examine how the type of measurement – ‘disk-wide’ or ‘local’ – impacts our measured velocity dispersions.

We measure a *local* velocity dispersion within annular bins of side length 150 pc, motivated by the typical ALMA-resolution scale for nearby galaxies, and then compute the average across the annulus at a given radius. For more context of our results on velocity dispersions of young stars, we also determine the local dispersions of cold and dense gas, $T < 300$ K and $n > 10\text{cm}^{-3}$, as a proxy for molecular gas, following Orr et al. (2018).

Figure 15 shows the average vertical (top) and total (bottom) dispersion of cold dense gas at present (left) and young (age < 250 Myr) stars at formation (right), averaged over 14 galaxies, for both *local* dispersions (light blue) and *disk-wide* dispersions (magenta). Our disk-wide dispersions use the same geometric selection as all of our previous analyses, while our local dispersions are the annulus-averaged dispersion in patches of side length 150 pc centered at $R = 8$ kpc. However, for the local dispersion of cold gas, we instead averaged between the dispersion within annuli centered at $R \approx 3.5$ and $R \approx 4.9$ kpc (corresponding to 1/3 and 2/3 of our observational radial range), to match the radial range of the PHANGS observations we compare against (see below). The cold gas velocity dispersions measured at $R = 8$ kpc are $\approx 72\%$ of those at $R \approx 4.2$ kpc in our simulations.

As the results for σ_Z (top) show, cold gas in FIRE-2 galaxies have 1D local velocity dispersions of $\sigma_{1D} \approx 8.4 \text{ km s}^{-1}$ at $R \approx 4.2$ kpc (as shown, and $\approx 6 \text{ km s}^{-1}$ at $R \approx 8$ kpc not shown) – much lower than the typical disk-wide dispersions in our previous results. We compare against ALMA-measured dispersions of molecular gas CO(2–1) on ≈ 100 pc scales in PHANGS galaxies from Sun et al. (2020), where we restrict the observed sample to the 19 galaxies that also have resolved stellar kinematics in Pessa et al. (2023). We include only gas observations within $R = 4.2 \pm 2$ kpc, and we measure the local dispersion of cold gas in our FIRE-2 galaxies at concordant radii (≈ 3.5 and 4.9 kpc). We measure the mean σ_{LOS} for each PHANGS galaxy and assume isotropy to convert to a 3D σ_{tot} . Figure 15 (bottom left) shows the PHANGS-ALMA sample’s full range of mean σ_{tot} as a shaded light-blue region and 1σ scatter in darker blue. Although our FIRE-2 galaxies have local velocity dispersions in cold gas somewhat higher than typical in PHANGS, all of our FIRE-2 galaxies fall within the observed range. Although a rigorous comparison would require synthetic CO observations, our comparison here indicates that velocity dispersions in cold gas are broadly consistent with those of molecular gas in nearby galaxies.

Most importantly, Figure 15 shows that the dispersion of cold gas in our simulations is significantly larger (≈ 3 times) if we measure it disk-wide rather than locally. Similarly, stars at formation have disk-wide σ_Z and σ_{tot} that are ≈ 2 times larger than their local values at $R = 8$ kpc. These values broadly agree with those from Orr et al. (2020) ($\approx 15 - 30 \text{ km/s}$), who examined the spatially-resolved dispersion of neutral gas in 7 of our isolated (m12) simulations. This motivates the need to use local velocity dispersions to compare against spatially-resolved observations of nearby galaxies.

Finally, the *local* σ_Z and σ_{tot} for young stars at formation are 1.5 and 1.9 times larger, respectively, than for cold gas (at $R \approx 8$ kpc). On the other hand, young stars at formation have a *disk-wide* σ_{tot} that is about the same as cold dense gas, while the *disk-wide* σ_Z is lower for stars at formation than for cold dense gas. The higher local

dispersion for stars than for cold gas is expected, given that we typically measure them ≈ 12 Myr after formation. However, the weaker (and even negative) change from cold gas to stars at formation for the disk-wide dispersion suggests that rapid dynamical heating has less of an effect on the galaxy-wide dispersion, which may be more influenced by spiral arms, warps, etc. We defer a more detailed investigation to future work.

Figure 14 showed that the *disk-wide* vertical velocity dispersion of young stars in FIRE-2 galaxies is $\approx 15 - 25 \text{ km s}^{-1}$ higher than the MW's $\approx 10 \text{ km s}^{-1}$ (Anders et al., 2023; Casagrande et al., 2011; Nordström et al., 2004). However, there are key differences in the spatial scales on which we measured our dispersions in Figure 14 versus the scales used for MW observations. Given the non-trivial differences between the disk-wide and local velocity dispersions shown in Figure 15, we now revisit our previous comparison between galaxy kinematics and stellar mass from Figure 14, and now include observed values from the MW and nearby galaxies. This more detailed comparison between stellar kinematics in our simulations, in the MW, and in nearby galaxies is especially important because detailed MW observations lay the bedrock for much of our understanding of disk formation and dynamical heating. However, the MW is only one galaxy, and it remains unclear how representative the MW is of similarly-massive galaxies.

For these comparisons, we compute the average *local* velocity dispersion of our galaxies, as opposed to the *disk-wide* dispersion of our previous results. Specifically, motivated by the typical measurement scales of the observations that we compare against here, we measure the ‘local’ velocity dispersion within annular bins centered at 8 kpc and then compute the average across the annulus.

Figure 16 shows the *local* σ_{tot} (top) and $v_{\phi}/\sigma_{\text{tot}}$ (bottom) for young (age < 100 Myr) stars versus stellar mass. We also show the observed velocity dispersion of young stars from Casagrande et al. (2011) for the MW, Dorman et al. (2015) for M31 (Andromeda), Quirk et al. (2022) for M33 (Triangulum), and Pessa et al. (2023) for 19 galaxies from PHANGS-MUSE. We show velocity dispersions for only young stars; in McCluskey et al. (in prep.), we will pursue a more rigorous comparison of the full relation between velocity dispersion and age using mock observations.

An important caveat is that each of these observational works measured stellar populations and velocity dispersions somewhat differently. In particular, the M31, M33, and MW measurements used individual stars, but the PHANGS-MUSE measurements used integrated spectra from regions of size ≈ 100 pc, which may include some contribution from older stars, leading to larger velocity dispersions. Nevertheless, the larger sample from PHANGS-MUSE provides an important statistical context for both our simulations and the Local Group. M31 and M33 observations measure resolved stars in multiple apertures of radius ≈ 760 and 350 pc, respectively, while the MW measurement includes stars within 60 pc of the Sun, so this represents only a single region of the MW. As a compromise to matching all of these works, and to limit numerical noise in our simulations, we use an intermediate aperture of diameter 250 pc (unlike in Figure 15, where we used smaller 150 pc patches to better match ALMA’s resolution). Using a larger region in our simulations increases the measured dispersion, but this effect is minimal for regions $\lesssim 1$ kpc.

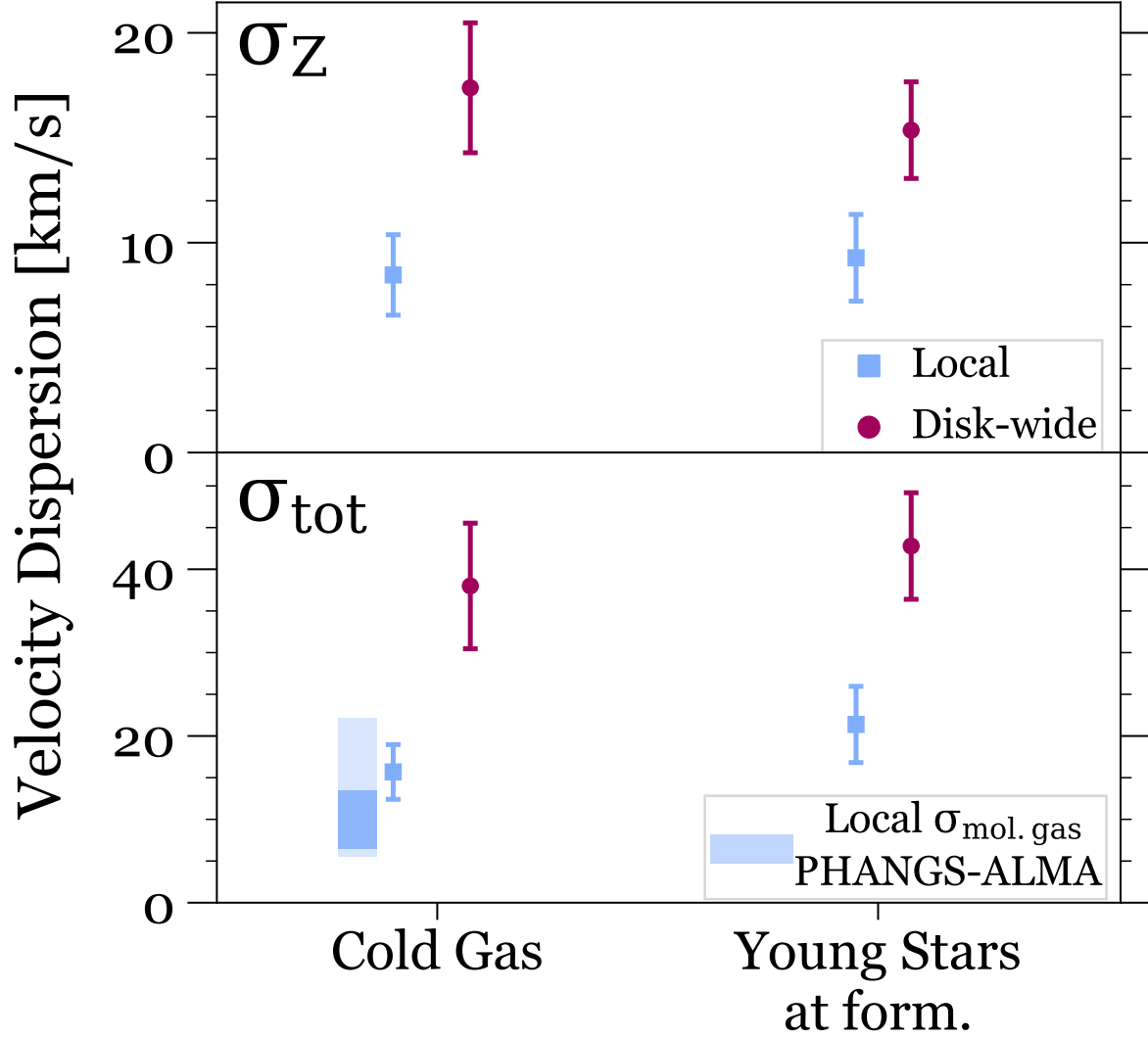


Figure 15: **Comparison of velocity dispersion, for a disk-wide versus local measurement, for cold dense gas and young stars:** specifically, σ_Z (top) and σ_{tot} (bottom) of cold ($T < 300$ K) and dense ($n > 10\text{cm}^{-3}$) gas at present (left) and young (age < 250 Myr) stars at formation (right). The points show the mean across all 14 galaxies, while the error bars show the standard deviation. Magenta circles show the dispersion of gas or stars within $R = 6 - 10$ kpc and $|Z| < 3$ kpc, identical to our previous analyses. The blue squares show the local velocity dispersion, within 150 pc patches, with cold gas patches centered at ≈ 4 kpc and young star patches centered at 8 kpc (see the text for a further explanation). The shaded region shows the total dispersion of molecular gas in 19 PHANGS-ALMA galaxies: light blue shows the sample's full range, while darker blue shows the sample's 16th-84th percentile range.

Moreover, we show the youngest stellar population from each work, but their age binning varies: the average age is 100 Myr for the MW, 30 Myr for M31, 80 Myr for M33, and 100 Myr for PHANGS-MUSE. Therefore, for this comparison only, we measure stars in our simulations today younger than 100 Myr. This reasonably matches the MW and PHANGS-MUSE, but these younger stars in M31 and M33 may have undergone somewhat less post-formation heating than in the MW, PHANGS-MUSE, or our simulations.

Finally, full 3D kinematics are available only for the MW: measurements of M31, M33, and the PHANGS-MUSE sample are limited to line-of-sight dispersions, σ_{LOS} . To estimate a total 3D dispersion, we assume isotropy such that $\sigma_{\text{tot}}^2 = 3\sigma_{\text{LOS}}^2$, given the wide variety of observed inclination angles across these observations. This is a simplification, given that our simulated galaxies show σ that is not isotropic, with $\sigma_{\text{R}} > \sigma_{\text{φ}} > \sigma_{\text{Z}}$. As such, our assumption may underestimate the total dispersion of galaxies observed with smaller inclinations (more face-on), including the PHANGS-MUSE sample, which generally has inclinations $\approx 25 - 55^\circ$, while our assumption likely overestimates the total dispersion of highly-inclined galaxies, such as M31 at 77° .

Our 14 FIRE-2 galaxies have an average *local* $\sigma_{\text{tot,now}} \approx 32 \text{ km s}^{-1}$ for young stars, with isolated and LG-like galaxies exhibiting similar values, on average. Although our average $\sigma_{\text{tot,now}}$ is slightly higher than the MW and M33’s values of ≈ 26.3 and 27.5 km/s , it is considerably lower than M31’s value of $\approx 55 \text{ km/s}$. However, the local total velocity dispersion of young stars shows a slight increase with galaxy mass, unlike the disk-wide vertical dispersion in Figure 14. In turn, the high dispersion of M31 is likely (at least in part) due to its higher stellar mass. We emphasize that MW’s value of $\sigma_{\text{tot,now}}$ is lower than that of all but 1 of the 21 galaxies in this PHANGS-MUSE sample. That said, 5 of our galaxies exhibit dispersions within 5 km/s of the MW’s value, while 9 lie within 10 km/s, and 3, the fairly low-mass m12r, Remus, and Louise, have even lower dispersions than the MW at ≈ 15.5 , 25.0 , and 26.1 km/s , respectively.

Sanderson et al. 2020 (Figure 2) also compared three FIRE-2 galaxies—m12i, m12f, m12m—against observations of the MW and M31; but for M31, they compared the *disk-wide* total (3D) dispersion in FIRE-2 against just the *local* line-of-sight (1D) dispersion of M31. Therefore, our comparison is more accurate and shows better agreement between FIRE-2 and the MW and M31.

Figure 16 (bottom) compares $v_{\text{φ}}/\sigma_{\text{tot}}$, which is a better dimensionless metric of ‘diskiness’ and the degree of rotational support. For each of the PHANGS-MUSE galaxies, we used their maximum $v_{\text{φ}}$ in Lang et al. (2020), which they determined using PHANGS-ALMA measurements of CO (2–1) emission. We note that Lang et al. (2020) do not include $v_{\text{φ}}$ values for 3 of the PHANGS galaxies; as such, we do not show these 3 galaxies in the bottom panel. As above, we emphasize that this observational compilation shows that *young stars in the MW are kinematically colder, in terms of both σ_{tot} and $v_{\text{φ}}/\sigma_{\text{tot}}$, than those in all but 1 of 21 nearby galaxies*, including M31 and M33. Specifically, young stars in the MW have $v_{\text{φ}}/\sigma_{\text{tot}} \approx 9$, while M31, M33, and the average PHANGS galaxy have values of ≈ 4.8 , 3.4 , and 3.4 . In turn, this initial comparison indicates that the MW is a kinematic outlier compared to similar-mass nearby galaxies; however, we will test this hypothesis more rigorously in McCluskey et al. (in prep.).

Secondly, young stars in FIRE-2 galaxies show a range of $v_\phi/\sigma_{\text{tot}}$ that is *consistent* with the range of the observed sample: all FIRE-2 galaxies reside within the observed range. The average $v_\phi/\sigma_{\text{tot}}$ of FIRE-2 is ≈ 6.4 , with LG-like and isolated galaxies having similar values. If anything, the typical FIRE-2 galaxy is kinematically colder than M31, M33, and the typical galaxy in PHANGS-MUSE. Although none of the FIRE-2 galaxies have $v_\phi/\sigma_{\text{tot}}$ quite as high as the MW’s value (≈ 9), two galaxies, Remus and m12m, are within 10% of the MW’s value, at 8.3 and 8.2, respectively. Thus, this tentative comparison indicates that *young stars in FIRE-2 have statistically realistic/representative values of σ_{tot} and $v_\phi/\sigma_{\text{tot}}$* , provided that we measure both on spatial scales comparable to those of observations.

2.4.8 TIME OF DISK ONSET

Galaxies transitioned from their Pre-Disk to their Early-Disk Era at their ‘time of disk onset’, which marks the *start* of the *continuous* process of disk settling. Most of our galaxies transitioned 4 – 8 Gyr ago, although Romeo transitioned particularly early, ≈ 11 Gyr ago. We now examine the time of disk onset across our sample, including how it relates to a galaxy’s stellar kinematics today. We also reiterate that, unlike in the previous subsection, all values are now *disk-wide* quantities, just as in the first 6 subsections of our results.

We defined the transition to the Early-Disk Era as when all stellar populations that formed after this time had $(v_\phi/\sigma_{\text{tot}})_{\text{form}} > 1$. Of course, v_ϕ/σ measured today may differ from its formation value. To examine how transition times derived using present-day kinematics compare to our fiducial formation-based times, we also measure the age when $(v_\phi/\sigma_{\text{tot}})_{\text{now}}$ permanently exceeds 1. Furthermore, we show that σ_z evolved somewhat differently post-formation than the other components, so we additionally test this by also finding the oldest age after which $(v_\phi/\sigma_z)_{\text{now}}$ permanently exceeds $\sqrt{3}$, under the simplifying (and in detail incorrect) approximation of isotropy. For all of these metrics, we tested a range of threshold values, and while this shifts the exact lookback time that a galaxy transitioned, it has little effect on the relative ordering within our sample, which is our primary metric of interest. We also tested transition times determined using only v_ϕ (both at formation and today) and found that they broadly agree with our v_ϕ/σ derived times, differing by $\lesssim 1$ Gyr for thresholds above ≈ 100 km/s. However, we limit our analysis to v_ϕ/σ -based metrics, because, unlike v_ϕ alone, v_ϕ/σ is dimensionless, largely independent of galaxy stellar mass in this mass range, and has a logical threshold ($v_\phi > \sigma$).

In summary, we use three thresholds to measure the time of disk onset that defines the transition from the Pre-Disk to Early-Disk Era:

- $v_\phi/\sigma_{\text{tot}} > 1$ at formation
- $v_\phi/\sigma_{\text{tot}} > 1$ as measured today
- $v_\phi/\sigma_z > \sqrt{3} \approx 1.73$ as measured today

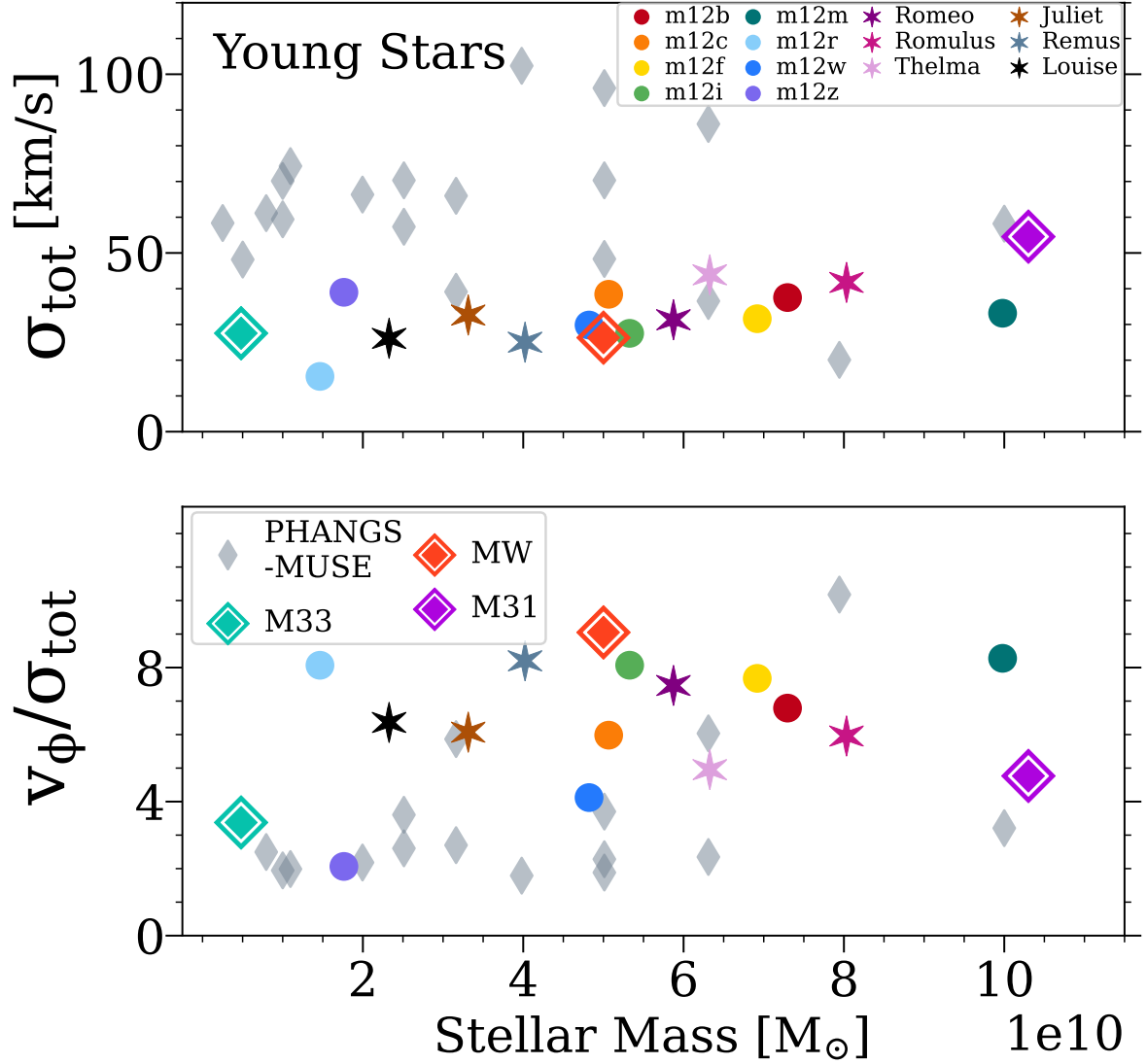


Figure 16: **Total present-day velocity dispersion, σ_{tot} , and median $v_{\phi}/\sigma_{\text{tot}}$, today for young (age < 100 Myr) stars versus stellar mass** for 14 galaxies. As before, we show the isolated (m12) galaxies via circles and LG-like paired galaxies via stars. We also show observations of young stars in the Local Group: the MW (Casagrande et al., 2011), M31 (Dorman et al., 2015), and M33 (Quirk et al., 2022), and in 19 nearby star-forming disk galaxies from the PHANGS-MUSE survey (Pessa et al., 2023). Young stars in FIRE-2 galaxies have kinematics that broadly agree with most observed galaxies; their $v_{\phi}/\sigma_{\text{tot}}$ are slightly lower than the MW, but two galaxies are within 10% of the MW. Young stars in the MW are kinematically colder than those in M31, M33, and all but one of the 19 galaxies in PHANGS-MUSE.

Table 1 lists the lookback times/ages of disk onset for each galaxy.

These three metrics give times within $\approx 0.5 - 1$ Gyr of each other for most galaxies. Times based on $(v_\phi/\sigma_z)_{\text{now}}$ and $(v_\phi/\sigma_{\text{tot}})_{\text{now}}$ agree best with each other. Thus, the present vertical and total kinematics of stars provide similar insights into the disk’s formation. However, lookback times from the kinematics at formation are generally earlier, because dynamical heating tends to decrease v_ϕ/σ of stars post-formation. A few galaxies yield substantially different times for different metrics. Notably, formation kinematics indicate that m12r transitioned 5.9 Gyr ago, while current kinematics indicate that it settled only 0.26 Gyr ago, because m12r experienced a merger with an LMC-mass galaxy ≈ 0.5 Gyr ago, which significantly heated existing stars. This lends caution to using present-day kinematics to infer the exact timing of events in a galaxy’s formation history.

As Figure 9 shows, once our galaxies transitioned to the Early-Disk Era, their stars formed on progressively cooler orbits as the disk continuously settled. If, after the time of disk onset, $(v_\phi/\sigma)_{\text{form}}$ grew at a broadly similar rate in each galaxy, then galaxies that had earlier times of disk onset would have higher $(v_\phi/\sigma)_{\text{form}}$ today, simply because they had more time to settle.

Figure 17 tests this idea, showing the time of disk onset versus v_ϕ/σ_z of stars younger than 250 Myr for our 14 galaxies. The three rows show our three thresholds in v_ϕ/σ for the onset of disk settling, which all show similar trends. We show isolated galaxies as circles and galaxies in LG-like pairs as stars, as in Figure 14. Figure 17 shows that the time of disk onset was $\approx 4.5 - 8$ Gyr ago ($z \approx 0.4 - 1$) for most of our galaxies, although Romeo (see Section 2.4.2) has the earliest time of disk onset, $\approx 10.2 - 11$ Gyr ago ($z \approx 2$).

Figure 17 shows that galaxies that experienced earlier disk onset have young stars (age < 250 Myr) with larger v_ϕ/σ_z today, that is, they currently form stars on dynamically cooler orbits. Although we do not show it, we find similarly strong correlation between the time of disk onset and the average v_ϕ/σ_z and $v_\phi/\sigma_{\text{tot}}$ for both all and young stars. Table 2 lists the Pearson correlation coefficients, which are close to 0.9, and their corresponding p-values, which are $\sim 10^{-5} - 10^{-6}$, indicating a strong correlation. We find similar results using instead the Spearman rank coefficients.

We also examined correlations with other galaxy properties. Surprisingly, the time of disk onset does not correlate much with the galaxy’s current stellar mass within our sample. It also does not correlate with any component of σ , for all or young stars. However, the time of disk onset *does* correlate with the median v_ϕ of all or young stars, with Pearson coefficients ranging between 0.75 and 0.85 for all stars and between 0.73 and 0.80 for young stars. Despite the lack of correlation with σ , each threshold has its highest correlations with v_ϕ/σ , *not* with v_ϕ alone, further supporting that $(v_\phi/\sigma)_{\text{now}}$ is a more fundamental (and dimensionless) metric than σ_{now} to compare different galaxies’ formation histories.

The strong correlation with the v_ϕ/σ of young stars today is particularly striking, considering that it only moderately correlates with v_ϕ of young stars. This correlation implies that, after disk onset, these disks settled

metric	v_ϕ/σ_Z young	$v_\phi/\sigma_{\text{tot}}$ young	v_ϕ/σ_Z all	$v_\phi/\sigma_{\text{tot}}$ all
	corr. coeff. (p-value)	corr. coeff. (p-value)	corr. coeff. (p-value)	corr. coeff. (p-value)
$v_\phi/\sigma_{Z,\text{now}} > 1.8$	0.90 (1.3×10^{-6})	0.91 (8.1×10^{-6})	0.86 (6.7×10^{-5})	0.92 (3.3×10^{-6})
$v_\phi/\sigma_{\text{tot},\text{now}} > 1$	0.91 (6.1×10^{-6})	0.86 (8.8×10^{-5})	0.87 (5.1×10^{-5})	0.93 (2.4×10^{-6})
$v_\phi/\sigma_{\text{tot},\text{form}} > 1$	0.89 (1.7×10^{-5})	0.89 (2.4×10^{-5})	0.81 (4.0×10^{-4})	0.88 (3.00×10^{-5})
t_{burst}	0.78 (3.0×10^{-3})	0.70 (0.011)	0.55 (0.067)	0.63 (0.028)

Table 2: **Pearson correlations and p-values between the degree of rotational support of stars and different lookback times of galaxy transitions.** The first three rows are the lookback times of the onset of disk settling, using the three different metrics discussed in Section 2.4.8, while the fourth row is the lookback time corresponding to the galaxy’s transition from bursty to steady star formation from Yu et al. (2021). *All three times of disk onset show strong correlations with the degree of rotational support: earlier-forming disks are kinematically colder, both for young stars and for all stars, than later-forming disks.*

at relatively similar rates, in order to preserve rank ordering. In particular, after disk onset, mergers and internal processes tend not to significantly alter the overall Hubble-time-averaged rate of disk settling.

In general, galaxies in LG-like pairs experienced earlier disk onset than isolated galaxies. This follows from Section 2.4.6, where LG-like galaxies had lower disk-wide σ and higher disk-wide v_ϕ/σ than isolated galaxies of similar (current) stellar mass, consistent with their larger radii (Bellardini et al., 2022). The earlier settling times for galaxies in LG-like environments follows from the fact that such galaxies assemble (form stars) earlier than those in isolated environments, which in turn follows from the fact that their dark-matter halos formed earlier (Garrison-Kimmel et al., 2019; Santistevan et al., 2020). Thus, galaxies in LG-like environments, despite ending up at a stellar mass similar to that of galaxies in isolated environments, formed stars earlier, their disks started to settle earlier, and their disks are radially larger and dynamically cooler today.

This dependence on the LG-like environment provides important insight into the assembly history of the MW (and M31) compared to other galaxies of similar mass today. As discussed in Section 2.4.7, young stars in the MW are dynamically colder than those in other nearby galaxies. If we naively extrapolate and place the MW’s (local) $v_\phi/\sigma_{\text{tot}} \approx 8$ along the relation in Figure 17, the trends within our simulated sample indicate that the MW disk began to settle earlier than our galaxies’ disks ($\gtrsim 11$ Gyr ago). Remarkably, this simple extrapolation agrees with recent estimates of the age of the MW’s thick disk: recent work has argued that its coherent rotation may have begun $\approx 12 - 13$ Gyr ago (Conroy et al., 2022; Xiang and Rix, 2022). We postulate that this dependence on the LG environment provides critical insight into this seemingly early assembly of the MW.

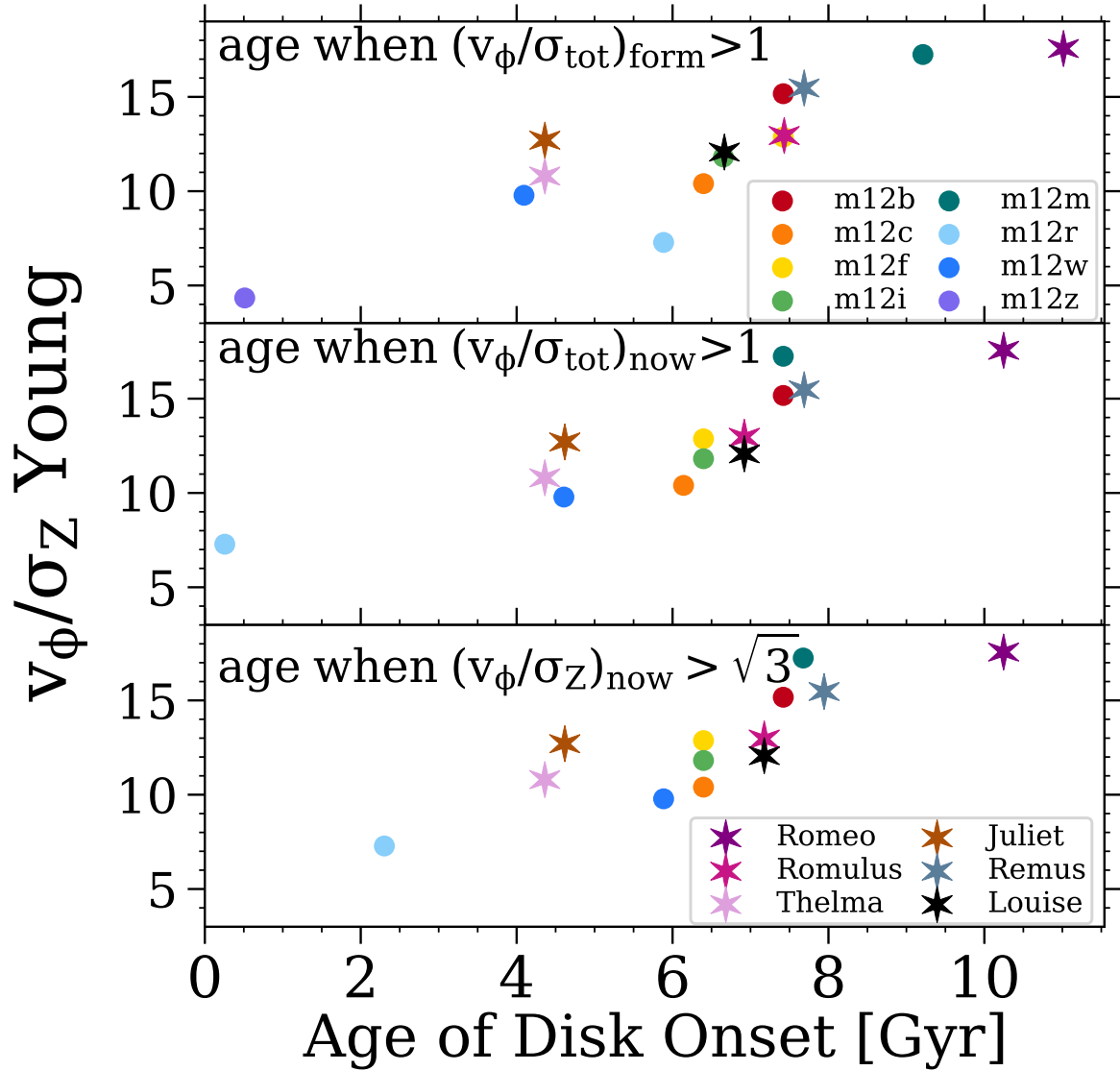


Figure 17: **Degree of rotational support, v_ϕ/σ_Z , for young stars (age < 250 Myr) versus the lookback time of disk onset.**

Circles show isolated (m12) galaxies, and stars show galaxies in LG-like pairs. We examine 3 metrics to determine the time that each galaxy's disk started to settle, which yield similar but occasionally different times and ordering between galaxies. **Top:** disk onset time defined as age when $v_\phi/\sigma_{\text{total}}$ at formation permanently exceeded 1. **Middle:** disk onset time defined age as when $v_\phi/\sigma_{\text{total}}$ as measured today permanently exceeded 1. **Bottom:** disk onset time defined age as when v_ϕ/σ_Z as measured today permanently exceeded 1.8. Overall, using kinematics at formation versus today or measuring different velocity components all lead to similar times of disk onset. *All 3 metrics show that disks that started to settle earlier currently form stars on more rotationally supported orbits, which implies that the MW, which is unusually dynamically cold today, started to settle unusually early.*

2.5 SUMMARY AND DISCUSSION

2.5.1 SUMMARY OF RESULTS

We summarize the main results from our analysis of stellar disks across the formation histories of 14 MW-mass galaxies from the FIRE-2 simulations. Most importantly, *the kinematics of stars today do not simply reflect their kinematics at formation, but neither do they simply reflect post-formation dynamical heating; both processes are important.* In particular, although the present-day dispersion of stars, σ_{now} , increases monotonically with age, σ_{form} does not.

We identified **Three Eras of Disk Formation**, when stars formed with different kinematics and experienced different degrees of post-formation dynamical heating:

1) Pre-Disk Era (typically $\gtrsim 8$ Gyr ago): stars formed on dispersion-dominated orbits, with $(v_\phi/\sigma_{\text{tot}})_{\text{form}} < 1$ and $v_\phi \lesssim 20 \text{ km s}^{-1}$. σ_{form} increased over time, reflecting the deepening of the gravitational potential. Thus, the oldest stars formed with the *lowest* dispersion. However, the present-day dynamics versus stellar age do not reflect this trend: σ_{now} increases monotonically with age, meaning that the oldest stars now have the *highest* dispersion. Thus, post-formation dynamical heating is most important during this era. Furthermore, the typical $v_{\phi,\text{now}} \approx 60 \text{ km s}^{-1}$, so the oldest stars often have been ‘spun up’ since formation. As a result of both of these trends, $(v_\phi/\sigma_{\text{tot}})_{\text{now}}$ remains below 1, similar to formation.

2) Early-Disk Era (typically $\approx 4 - 8$ Gyr ago): began at the time of disk onset, when $v_\phi/\sigma_{\text{tot}} > 1$ and grew rapidly, and ended when the growth of v_ϕ/σ slowed significantly. Similarly, σ_{form} peaked at the beginning of this era, and decreased steadily throughout, reaching a minimum by the end of the era. The amount of dispersion added by post-formation heating was constant with age throughout this era, so the slope of σ_{now} with age is unchanged from that at formation. The majority of σ_{now} for these stars was in place at formation, not added via post-formation dynamical heating.

3) Late-Disk Era (typically $\lesssim 4$ Gyr ago): began when the growth of $(v_\phi/\sigma_{\text{tot}})_{\text{form}}$ slowed. The stars formed with a nearly constant $\sigma_{\text{tot,form}}$. $\sigma_{\text{tot,now}}$ increases monotonically with age, because post-formation dynamical heating increases with age, and the oldest stars in this era have σ_{now} with an equal contribution from post-formation heating and formation.

We examined the evolution of the three different components of the velocity. At formation, $\sigma_{\text{R,form}} > \sigma_{\phi,\text{form}} > \sigma_{\text{Z,form}}$ for all ages. Remarkably, across all eras and ages, the relative amount in each component is relatively unchanged. At present, $\sigma_{\text{R,now}}$ continues to dominate at all ages, but $\sigma_{\text{Z,now}} \approx \sigma_{\phi,\text{now}}$ for stars that

formed in the Early- and Pre-Disk Eras (ages $\gtrsim 4$ Gyr). *Post-formation dynamical heating* primarily increased σ_R at ages $\lesssim 4$ Gyr but acted nearly isotropically for older stars.

We examined the dependence of stellar kinematics on galaxy stellar mass. σ_{now} of all stars increases with galaxy stellar mass, but $(v_\phi/\sigma)_{\text{now}}$ of all stars is nearly constant. Young stars (age < 250 Myr) exhibit opposite trends: σ_{now} is independent of mass, while $(v_\phi/\sigma)_{\text{now}}$ increases with mass.

We compared disk-wide and local ($\lesssim 250$ pc) velocity dispersions for cold gas and young stars at formation: local dispersions are ≈ 3 times lower than disk-wide dispersions for cold gas and ≈ 2 times lower for stars at formation. Thus, the velocity dispersion strongly depends on the spatial scale measured over, which is critical for observational comparisons.

We compared locally-measured kinematics in our 14 simulated galaxies to those observed in 3 Local Group galaxies and nearby star-forming galaxies, compiling measurements of σ and v_ϕ/σ for young stars (age $\lesssim 100$ Myr) in the MW, M31, M33, and 19 galaxies from PHANGS-MUSE. *The MW is significantly kinematically colder than both M31 and M33, and all but one of the PHANGS galaxies.* For young stars, all of our simulations show broad agreement with observations, with 3 of our galaxies even exhibiting lower locally-measured σ_{tot} than the MW.

We quantified the time of disk onset, the lookback time that each galaxy’s disk began to settle, using thresholds in v_ϕ/σ , measured both today and at formation. *The degree of rotational support of young stars today correlates strongly with the time of disk onset: earlier-settling galaxies currently form colder disks.* Most of our galaxies began to settle $\approx 4 - 8$ Gyr ago, with galaxies in LG-like environments generally starting to settle earlier than isolated galaxies. Romeo, a galaxy in an LG-like pair, began to settle the earliest, $\approx 10 - 11$ Gyr ago, likely the closest to the MW.

In Appendix 2.6.3, **we examine the impact of including self-consistent cosmic-ray injection/transport from stars,** assuming a constant diffusion coefficient, which in the FIRE-2 simulations leads to galaxies with lower stellar masses, lower rotational velocities, and lower dispersions. *Overall, the inclusion of cosmic rays does not change significantly v_ϕ/σ at a given stellar mass.*

2.5.2 DISCUSSION

2.5.2.1 CAVEATS

We first discuss key limitations and caveats to our analysis of 14 MW-mass galaxies from the FIRE-2 simulations.

First, we reiterate the selection function of our simulated sample. We selected isolated or LG-like paired dark-matter halos from dark-matter-only simulations at $z = 0$ with $M_{200\text{m}} \approx 1 - 2 \times 10^{12} M_{\odot}$, without additional selection based on galaxy properties or merger/formation history, etc. Thus, we did not choose our galaxies specifically to be analogues of the MW (or M31 or M33). As such, our galaxy-averaged results represent randomly sampled formation histories of MW-mass galaxies, which should fairly sample the cosmological scatter in formation histories.

Second, these FIRE-2 simulations do not model all of the physics that may be relevant for disk formation, in particular, AGN feedback from black holes. The degree to which AGN may impact stellar dynamics in the solar annuli of MW-mass galaxies (which in this work we define as $R = 6 - 10$ kpc and $|Z| < 3$ kpc) is unclear. Although AGN feedback is likely most crucial for more massive galaxies and most significantly alters stellar dynamics in the galaxy’s innermost regions (Dubois et al., 2013; Mercedes-Feliz et al., 2023; Weinberger et al., 2017; Wellons et al., 2023), growing evidence from simulations indicates that AGN can directly and indirectly affect the kinematic and structural properties of MW-mass and low-mass galaxies (Dashyan et al., 2018; Irodotou et al., 2022; Koudmani, Henden, and Sijacki, 2021). For example, Grand et al. (2017) found that the primary effect of AGN in MW-mass galaxies was to suppress central star formation, which in turn prevents the formation of overly massive bulges. Indeed, Grand et al. (2017) found that a simulation of a MW-mass galaxy reran from $z = 1$ without AGN feedback had a smaller fraction of stars on disc-like orbits (defined as having orbital circularities > 0.7), more dominant bulges, and enhanced star formation in the outer disk leading to a more extended disk component compared to versions run with AGN feedback.

Furthermore, our analysis of birth kinematics has limitations. We determined a star particle’s position and velocity relative to the galaxy’s major axes, which are stable and well-defined at present, but not necessarily at earlier times, when accretion and mergers were more significant, and even the notion of a single main galaxy progenitor can be ill-defined (Giocoli et al., 2007; Santistevan et al., 2020; Wechsler et al., 2002). Thus, cleanly separating the R , ϕ , and Z components is difficult at early times. However, all components of the dispersion at formation display similar trends as σ_{tot} , which is independent of the determination of the axes, implying that the impact of this limitation on our overall qualitative results is likely minor.

Furthermore, as we discussed in Section 3.3.2, our simulations store snapshots every 20 – 25 Myr, so our star ‘formation’ properties include this additional ≈ 12 Myr of post-formation dynamical evolution, on average. This early heating can be significant: using an idealized simulation of an isolated MW-like galaxy with sub-parsec resolution (0.05 pc), Renaud et al. (2013) found that stars that formed with $\sigma_{\text{tot,form}} \approx 10 \text{ km s}^{-1}$ were heated to 15 km s^{-1} in just 10 Myr. Similarly, our Figure 13 shows that σ_{tot} increased rapidly by $\approx 30 \text{ km s}^{-1}$ in the first ≈ 125 Myr after formation. We tested whether this early evolution could change our conclusions about the relative importance of ‘formation’ dispersion versus post-formation heating. For stars younger than 10 Gyr, $\sigma_{\text{tot,now}}/\sigma_{\text{tot,form}} < 1.95$ for all but ≈ 3.5 Gyr old stars, meaning that post-formation heating is less than 95% of their $\sigma_{\text{tot,form}}$. If we assume that stars were heated at the same effective rate as the youngest stars in Figure 13 for ≈ 12 Myr, our revised $\sigma_{\text{tot,now}}/\sigma_{\text{tot,form}}$ still remains below 1.95 for the same ages. Even if we assume an initial

effective heating rate that is $4\times$ larger, $\sigma_{\text{tot,now}}/\sigma_{\text{tot,form}}$ remains less than 2 for the same ages. Thus, our results about the relative importance of post-formation heating remain unchanged.

Lastly, our analysis did not account for uncertainties in stellar age. Stellar ages are difficult to accurately measure, and uncertainties about stellar ages for large populations are generally $\gtrsim 20 - 30\%$ (for example Soderblom, 2010), although the synergy of astrometric and spectroscopic surveys with asteroseismological data has driven tremendous progress in the past decade (for example Mackereth et al., 2019a; Silva Aguirre et al., 2018). Previous work showed that the inclusion of observationally-motivated age uncertainties of 20 - 30% in simulations can (1) obscure features from mergers in the age-velocity dispersion relationship (Buck et al., 2020; Martig, Minchev, and Flynn, 2014), and (2) decrease inferred exponential heating rates via the ‘smearing’ of age bins (Aumer, Binney, and Schönrich, 2016). In McCluskey et al. (in prep.) we will examine the kinematic trends of our simulations versus age at $z = 0$, incorporating realistic age uncertainties, which will allow us to compare to observational trends in much more detail.

2.5.2.2 DISK GALAXY FORMATION IN FIRE SIMULATIONS

As we discussed in the Introduction, our work builds upon a series of analyses of FIRE simulations that studied the formation histories of MW-mass galaxies, in particular, the co-evolution of their stellar and gaseous dynamics, morphology, star formation burstiness, metallicity spatial variations, and virialization of the inner CGM (Bellardini et al., 2022; Garrison-Kimmel et al., 2018; Gurvich et al., 2023; Hafen et al., 2022; Hopkins et al., 2023; Ma et al., 2017; Stern et al., 2021; Trapp et al., 2022; Yu et al., 2021, 2022). We further quantified the notion that MW-mass disk galaxy formation occurred in distinct phases, showing that stellar kinematics, both at formation and at present, follow broadly contemporaneous evolutionary phases.

In particular, what we define as the transition from the Early-Disk to the Late-Disk Era coincides with the virialization of the inner CGM (Stern et al., 2021), the transition from bursty to steady star formation (Yu et al., 2021), and a transformation in the energetics and angular momentum of both accreted gas (Hafen et al., 2022) and the ISM (Gurvich et al., 2023). During this stage of steady star formation in the Late-Disk Era, σ_{form} was low and constant, with the gas turbulence reaching a floor maintained by the thermal and turbulent pressure of the warm neutral/ionized medium (for example Leroy et al., 2008), stellar feedback, and spiral arms.

Yu et al. (2021) quantified the lookback time that star-formation transitioned from bursty to steady – the ‘burst time’ or t_b – for 12 of the 14 galaxies that we analyze. Table 1 lists each galaxy’s t_b from Yu et al. (2021). The transition to steady star formation typically occurred ≈ 2 Gyr after our ‘time of disk onset’, when stellar $v_\phi/\sigma_{\text{tot}} > 1$. Nominally, this implies that star formation remained bursty for a while during the Early-Disk Era, in agreement with our finding that σ_{form} remained high (but declining) throughout this era. However, our times of disk onset are based on stellar dynamics within the solar annulus today ($R = 6 - 10$ kpc and $|Z| < 3$ kpc) and only moderately correlate with t_b , having Spearman coefficients between 0.75 – 0.78. On the contrary, Yu et al. (2021)

included all stars that formed within 20 kpc physical of the galactic center. If instead we extend our radial range to $R < 12$ kpc, this yields times that (1) are on average 1.2 Gyr later than our original times, because of the hotter kinematics of the inner region, and (2) more strongly correlate with t_b , with Spearman coefficients between 0.94 and 0.96 for our three dynamical thresholds. Thus, these estimates for when a galaxy’s disk began to form/settle can depend on the selection of stars today, with stars in the solar neighborhood yielding earlier settling times. We will investigate radial trends in these simulations in future work.

Using the same FIRE-2 simulations, Yu et al. (2022) argued that they can subdivide their bursty star-formation era into two eras: an early bursty and chaotic phase, when stars formed with irregular morphology, and a subsequent bursty phase, when stars formed with disk morphology. These bursty star-formation eras generally correspond to our Pre-Disk and Early-Disk eras. Yu et al. (2022) also studied how both the birth and present-day orbits of stars reflect the era when they formed, classifying stars as belonging to the thin-disc, thick-disc, and isotropic spheroid based on their orbital circularity at both formation and at $z = 0$. They found that, in general, a star’s orbital classification at formation reflects the era in which it formed: stars primarily formed on isotropic spheroid orbits in the early bursty star-formation phase, thick-disc orbits in the later bursty star-formation phase, and thin-disc orbits in the steady star-formation phase. However, Yu et al. (2022) noted that this is not a one-to-one mapping: $\approx 34\%$ of stars that formed with thin-disc orbits now have thick-disc orbits, while a similar fraction of stars that formed with thick-disc orbits now have isotropic spheroid orbits. Furthermore, the fraction of stars that were born ‘thin’ but are now ‘thick’ increases with age. Our results agree with theirs, and we further quantify the degree of post-formation heating/perturbations that stars experienced.

2.5.2.3 COMPARISON TO OTHER COSMOLOGICAL ZOOM-IN SIMULATIONS

Various works have used different cosmological zoom-in simulations to study the formation histories of MW-mass galaxies (for example Agertz et al., 2021; Bird, Kazantzidis, and Weinberg, 2012; Bird et al., 2021; Brook et al., 2012; Buck et al., 2020; Grand et al., 2016; Martig, Minchev, and Flynn, 2014). Across a wide range of different numerical implementations of hydrodynamics, star formation, and feedback, cosmological simulations consistently agree that the dynamical history of a MW-mass disk arises from *both* cosmological disk settling and post-formation dynamical heating; one cannot neglect one or the other. As we discuss below, most current-generation zoom-in simulations of MW-mass galaxies also broadly agree in both the *typical* disk-wide velocity dispersion of young stars at $z \approx 0$ and the shape/magnitude of the stellar age dependence, as measured today.

Our results agree with the VINTERGARTEN simulation (Ageritz et al., 2021), which used the same initial conditions as m12i but simulated with the adaptive mesh refinement code RAMSES (Teyssier, 2002). Their $\sigma_{Z,\text{now}}$ versus age (Figure 14 of Agertz et al., 2021) is nearly identical to ours for m12i, both in value and shape: both of our simulations show near-exponential increases in $\sigma_{Z,\text{now}}$ with age for stars younger than 6 Gyr and a jump at 6 Gyr. Our results also agree well with the NIHAO-UHD suite (Buck et al., 2020): their 5 galaxies, which span $M_{\text{star}} = 1.5 - 16 \times 10^{10} M_{\odot}$, have $\sigma_{Z,\text{now}} \approx 20 - 35 \text{ km s}^{-1}$ for young stars, and $\approx 60 - 120 \text{ km s}^{-1}$ for stars 12

Gyr old, similar to ours. Any difference in the exact age dependence of each galaxy’s dispersion follows from its unique formation history.

Grand et al. (2016) analyzed 16 MW-mass galaxies from the Auriga simulations, also finding broadly similar disk-wide $\sigma_{Z,\text{now}}$ and $\sigma_{Z,\text{form}}$ as we do. Similarly to FIRE, NIHAO-UHD, and VINTERGARTEN, Auriga simulations have typical disk-wide $\sigma_{Z,\text{now}} \approx 20 - 25 \text{ km s}^{-1}$. They also concluded that cosmological disk settling was generally the primary effect that set the relation between the velocity dispersion and the age of stars today. However, Grand et al. (2016) found that bars were the strongest contributor to vertical dynamical heating. This seemingly contradicts our results, because stars in *all* of our galaxies had significant post-formation increases to their disk-wide σ_Z , including stars in unbarred or weakly-barred galaxies. Furthermore, even our galaxies that do house significant bars near $z = 0$ (such as m12m) did not at early times, and our results indicate that heating is most significant for stars that formed in the Pre-Disk Era. Although we do not study the effect of bars in this work, Ansar et al., (in prep.) quantifies the incidence of bars in the FIRE-2 simulations, and in future work we will address the drivers of dynamical heating in our simulations, including bars.

Our results may differ from those of Grand et al. (2016) due to numerical differences. First, Auriga uses the subgrid model from Springel and Hernquist (2003), treating the ISM as a two-phase medium with an effective equation of state that inhibits the formation of dense gas, so that star formation occurs at much lower density, $n > 0.13 \text{ cm}^{-3}$, compared to $n > 1000 \text{ cm}^{-3}$ in FIRE-2. House et al. (2011) found that low thresholds in density impose a dispersion ‘floor’ in σ_{form} , even in high-resolution simulations (50 pc), because stars form from higher-temperature gas. House et al. (2011) find that this floor effectively disappears if one increases the star-formation threshold from $n = 0.1$ to 1000 cm^{-3} (see also Kumamoto, Baba, and Saitoh, 2017; Martig, Minchev, and Flynn, 2014). That said, given that Grand et al. (2016) find that σ_{form} decreases over time, this dispersion ‘floor’ may have little effect on their results.

Second, certain mechanisms that induce dynamical heating in our simulations may be different (and less significant) in the Auriga simulations. The simulations in Grand et al. (2016) had baryonic mass resolution of $4 \times 10^4 M_{\odot}$, 8 – 10 times larger than ours, and they used lower spatial resolution, with gravitational force softenings of 375 pc physical for stars and gas (which is comparable to the thin-disk scale height of the MW), while our FIRE-2 simulations use 2.7 – 4 pc for star particles and ≈ 1 pc minimum and ~ 4 pc ISM-averaged for gas cells. Thus, Auriga simulations do not resolve the dense ISM, including important dynamical structures like GMCs that likely heat star particles after their formation in FIRE. Furthermore, the modeling of stellar feedback in Auriga is markedly different: supernovae launch ‘wind particles’ that are temporarily decoupled from the hydrodynamics until the particle encounters sufficiently low-density gas, which does not couple that feedback directly to dense gas in a star-forming region. In turn, our simulations may exhibit more gas turbulence. That said, the Auriga simulations do model certain physics that these FIRE-2 simulations do not include, most importantly, AGN feedback.

Grand et al. (2016) also found that spiral arms did not considerably heat the disk, while we proposed that spiral arms are probably responsible for the significant increase in $\sigma_{\text{tot,now}}$ of young stars, in part because σ_R dominates the overall dispersion (see also Orr et al., 2022). However, Grand et al. (2016) only considered *vertical* heating. Because the Auriga simulations do not resolve GMCs, spiral arms likely have negligible effects on the vertical dispersion, but may have more significant impacts on the in-plane dispersions. For example, while the FIRE-2 simulations resolve GMCs, young stars in FIRE-2 have vertical effective heating rates that are $\approx 4\times$ lower than their radial rates, as Figure 13 showed. Many previous works – both observational and theoretical – only examined the vertical velocity dispersion. However, vertical post-formation dynamical heating operates differently than total and in-plane heating. For example, Figure 2.4.4 (top) shows that the amount of vertical dispersion added post-formation increases approximately linearly across all ages, while in-plane heating plateaus for Early-Disk stars. Similarly, Figure 2.4.4 (bottom) shows that the present-day vertical dispersion has the largest relative impact from post-formation heating: the dispersion added from heating typically begins to equal (or exceed) the dispersion from formation at ≈ 4 Gyr for the vertical component, but does not rival the in-plane dispersions from formation until ≈ 11 Gyr. Furthermore, the vertical dispersion typically exhibits the smallest values. For these reasons, we do not recommend using vertical heating to draw inferences regarding total heating.

As we discussed above, nearly all current cosmological zoom-in simulations form MW-mass galaxies with typical *disk-wide* $\sigma_{Z,\text{now}} \gtrsim 20 \text{ km s}^{-1}$, not as dynamically cold as the (solar-neighborhood) measurements of MW today. However, Bird et al. (2021) analyzed a single MW-mass galaxy, h277, selected from the *g14* suite of simulations (Christensen et al., 2012), generated using the parallel N -body+SPH code GASOLINE (Wadsley, Stadel, and Quinn, 2004). That simulation had *disk-wide* $\sigma_{Z,\text{now}} < 10 \text{ km s}^{-1}$, measured within an annulus of $R = 8 - 10 \text{ kpc}$, for stars younger than 1 Gyr, similar to (primarily locally-measured) values for the MW (for example Mackereth et al., 2019a; Nordström et al., 2004).

The cold disk-wide kinematics of h277 likely reflect its formation history: its disk began to settle early, ≈ 9 Gyr ago, and it had no major mergers since $z \approx 2$. That said, one of our galaxies, Romeo, has a similar time of disk onset and merger history as h277 but has a larger (disk-wide) $\sigma_Z \approx 16 \text{ km s}^{-1}$ for stars 1 Gyr old today. However, we note that Romeo has a local $\sigma_Z \approx 12 \text{ km s}^{-1}$, which is closer, albeit still higher, than MW measurements. Therefore, differences in our simulations’ physical and numerical modeling likely contribute to our unequal dispersions. Although the baryonic mass resolution, modeling of dense ISM, and molecular-based star-formation criteria are broadly similar between our FIRE-2 simulations and h277, key numerical differences exist between our simulations: h277 used SPH for the hydrodynamics solver (instead of MFM); used larger gravitational force softening of 173 pc for all particle species; used the ‘blastwave’ feedback model for core-collapse supernovae in which cooling is turned off for gas within the blast wave radius to mimic the adiabatic expansion of a remnant (Stinson et al., 2006); used only thermal energy injection for white-dwarf (Type Ia) supernovae; and did not include stellar winds or radiative feedback. Although it is unclear how any of these individual aspects affect or do not affect their results, differences in feedback modeling may contribute to their lower dispersions to some extent. FIRE-2 accounts for energy and momentum injection for both core-collapse and white-dwarf supernovae,

and includes stellar winds, radiation pressure, and photo-ionization. This feedback launches starburst-induced star-forming outflows at early times (see the top-right panel of our Figure 8 and El-Badry et al. (2018a)), which Bird et al. (2021) notes are absent in their simulation. As such, it is possible that our additional feedback channels contribute to larger gas velocity dispersions and subsequently larger σ_{form} values in our simulations, although it is unclear if this persists to later cosmic times. Similarly, Hopkins, Quataert, and Murray (2012) and Agertz et al. (2013) both show that the structure of the ISM can non-trivially vary depending on the feedback model used. Despite any differences, we again emphasize that both the disk-wide $\sigma_{\text{Z,form}}$ and $\sigma_{\text{Z,now}}$ exhibited similar trends with age in h277 and our FIRE-2 simulations.

2.5.2.4 CONNECTIONS TO THE EARLY FORMATION OF THE MW

As we discussed in Sections 2.4.6 and 2.4.8, the cold kinematics of MW stars may indicate that the MW’s disk began to settle unusually early in its history. For example, using our predicted result that the disk-wide kinematics of young stars today correlates with when the disk began to settle, and placing the MW’s value of $v_{\phi}/\sigma_{\text{tot}} \approx 8$ along the relation from our simulations in Figure 17, this implies that the MW’s time of disk onset was $\gtrsim 11$ Gyr ago, which agrees with recent estimates from observations (for example Belokurov and Kravtsov, 2022; Conroy et al., 2022; Xiang and Rix, 2022). Thus, our analysis of disk settling times in cosmological simulations and its relation to present-day kinematics complements and augments these works.

That said, measurements of the MW’s kinematics are largely restricted to one local patch: the solar neighborhood. As we show in Figure 15, locally-measured velocity dispersions in our simulations (at formation) are typically ≈ 2 times smaller than disk-wide measurements. In turn, while all of our disk-wide dispersions are larger than the MW’s, 3 of our galaxies have present-day local dispersions lower than the MW’s. Furthermore, the galaxy-to-galaxy scatter in the relation between disk-wide and local kinematics is significant. For example, stars today younger than 100 Myr in one of our most MW-like galaxies, Romeo, have disk-wide σ that is 1.1 – 1.2 times higher than its local value, while m12i, which is otherwise similar to Romeo, has disk-wide values that are 1.5 – 1.7 times higher than local values. More work is needed to determine how the MW’s disk-wide dispersion compares to its local dispersion, and if these differences affect its placement on our disk onset - young stellar kinematics relation. In McCluskey et al. (in prep.) we will more rigorously compare our simulations to the MW as well as other observed galaxies.

We now discuss connections with some of these recent observational works. Conroy et al. (2022) combined Gaia astrometry and H3 Survey spectroscopy to posit that the MW disk formed in three dynamical eras, broadly consistent with our Pre-Disk, Early-Disk, and Late-Disk Eras. Conroy et al. (2022) proposed that the MW began in a ‘simmering phase’, during which the star formation efficiency was low and stars formed kinematically hot, but that $\approx 12 - 13$ Gyr ago the MW transitioned into a ‘boiling phase’, during which the SFE strongly increased and stars formed with increasingly ‘disky’ dynamics, marking the ‘birth of the Galactic disk’. This thick disk continued to grow and settle in a ‘boiling phase’ for $\approx 3 - 4$ Gyr (from $z \approx 4$ to $z \approx 1$) until the Gaia-Sausage-Enceladus

(GSE) merger, after which the star formation efficiency decreased and stars formed in a dynamically-colder, thin disk until today.

Similarly, Belokurov and Kravtsov (2022) combined Gaia astrometry with spectroscopy from the APOGEE Data Release 17. Although Belokurov and Kravtsov (2022) lacked empirical age estimates, their general picture agrees with ours: old, metal-poor, in-situ stars were born in a ‘messy’ phase, then the MW ‘spun-up’ as stars rapidly became metal-rich and rotational earlier than ≈ 8 Gyr ago. Belokurov and Kravtsov (2022) posited that this rapid formation of the MW’s disk took place over 1 - 2 Gyr, with the GSE merger occurring after the initial formation of a thick-disk, such that the merger heated disk stars onto halo-like orbits.

On the other hand, Xiang and Rix (2022) conclude that the formation of the in-situ halo and thick-disk overlapped. In this picture, the GSE merger then occurred ≈ 11 Gyr ago, 1 - 2 Gyr earlier than previous estimates, and did not strongly heat pre-existing disk stars, or cause a transition to a thin-disk, but instead enhanced thick-disk formation.

Our results help connect these present-day observations to understanding the MW’s formation history. In particular, *the presence of coherent rotation in a stellar population today does not necessarily indicate the presence of coherent rotation at the time of formation*. Observations show that older, more metal-poor stars in the MW rotate slower than younger stars, but they still display some coherent rotation. In our simulations, this is not primarily the result of these Pre-Disk stars being born with coherent rotation, but rather, this tends to arise from post-formation torquing (see Figure 8), for example, caused by mergers (see Bellardini et al. in preparation). m12m provides an illustrative example: it experienced several major mergers at early times, broadly similar to estimates of when the GSE merger occurred. As Figure 10 shows, m12m has old stars with $v_{\phi, \text{now}} \approx 200 \text{ km s}^{-1}$, despite having $v_{\phi, \text{form}} \approx 0 - 50 \text{ km s}^{-1}$. Thus, mergers like the GSE merger could have torqued old stars in the MW onto more coherently-rotating orbits.

Ultimately, the MW’s kinematics reflect its individual formation history. While the MW provides a useful benchmark, the fact that most current cosmological simulations form galaxies with hotter kinematics than the MW may speak to the MW’s early settling time rather than to limitations of the simulations. Indeed, the comparison of the MW to M31 and M33 in Figure 14 affirms that the MW may be an outlier among galaxies at its mass. Therefore, future works that study the kinematics of stars and their relation to stellar ages in external galaxies will provide excellent opportunities to place the MW in a statistical context, to study the combination of cosmological disk settling and dynamical heating across a range of formation histories (Dorman et al., 2015; Leaman et al., 2017; Quirk et al., 2022).

2.6 APPENDICES

2.6.1 EFFECT OF VERTICAL SELECTION

By default, we select stars currently at $|Z| < 3$ kpc, which includes stars in both the thin and thick disk, to sample disk stars at all ages in an unbiased manner and avoid assumptions about thin- versus thick-disk dynamics. Figure 18 shows the effect of the vertical selection on $\sigma_{Z,\text{now}}$ and $\sigma_{\text{tot},\text{now}}$ versus stellar age, specifically, the fractional change relative to our fiducial selection of $|Z| < 3$ kpc. We also examined the effect on $\sigma_{R,\text{now}}$ and $\sigma_{\phi,\text{now}}$ and they show trends nearly identical to $\sigma_{\text{tot},\text{now}}$ so we do not show them separately.

At most ages, our vertical selection has minimal impact on any component of the dispersion, $\lesssim 3\%$. This is because most disk stars lie well within $|Z| < 1$ kpc, so they dominate regardless of vertical selection. Thinner vertical selection does yield slightly higher $\sigma_{\text{tot},\text{now}}$, although with significant scatter. Interestingly, thinner selection only yields higher $\sigma_{Z,\text{now}}$ for stars older than ≈ 8 Gyr, and instead yield slightly *lower* values of $\sigma_{Z,\text{now}}$ for younger stars. The youngest population formed near the mid-plane and experienced ≈ 125 Myr of post-formation heating, on average, so most are still near the mid-plane and have low dispersions. Any that are above $|Z| = 0.25 - 1$ kpc likely experienced an atypical amount of heating. Again, all of these effects are at the level of $\lesssim 3\%$, where non-equilibrium effects like disk warping and asymmetries may become important.

If instead we measure the dispersion for the galaxy overall (not in age bins) as in Section 14, larger vertical selections non-trivially increase the dispersion. Vertical dispersions within $|Z| < 3$ kpc are 10 - 35% larger than within $|Z| < 1$ kpc, because larger vertical selections include a higher fraction of older, higher-dispersion stars.

2.6.2 EFFECT OF IN-SITU SELECTION

By default, we select only stars that are at $R = 6 - 10$ kpc and $|Z| < 3$ kpc at present. We include all of these stars when measuring present-day kinematics, but when measuring kinematics at formation, we select only in-situ stars that formed within 30 kpc comoving of the galactic center. Figure 19 shows the effect of also including this in-situ selection on the *current* velocity dispersion versus stellar age. As above, we only show $\sigma_{Z,\text{now}}$ and $\sigma_{\text{tot},\text{now}}$, because $\sigma_{R,\text{now}}$ and $\sigma_{\phi,\text{now}}$ exhibit the same trends as $\sigma_{\text{tot},\text{now}}$. Overall, our in-situ selection has no effect on stars younger than ≈ 6 Gyr, because almost all of them formed in situ. However, the effects of in-situ selection become increasingly significant for older stars, when a more significant fraction formed ex situ. Not surprisingly, including those older ex-situ stars increases the dispersion. That said, this effect is $\lesssim 10\%$ for all but the oldest stars (see El-Badry et al., 2018b, for analysis of these ancient stars).

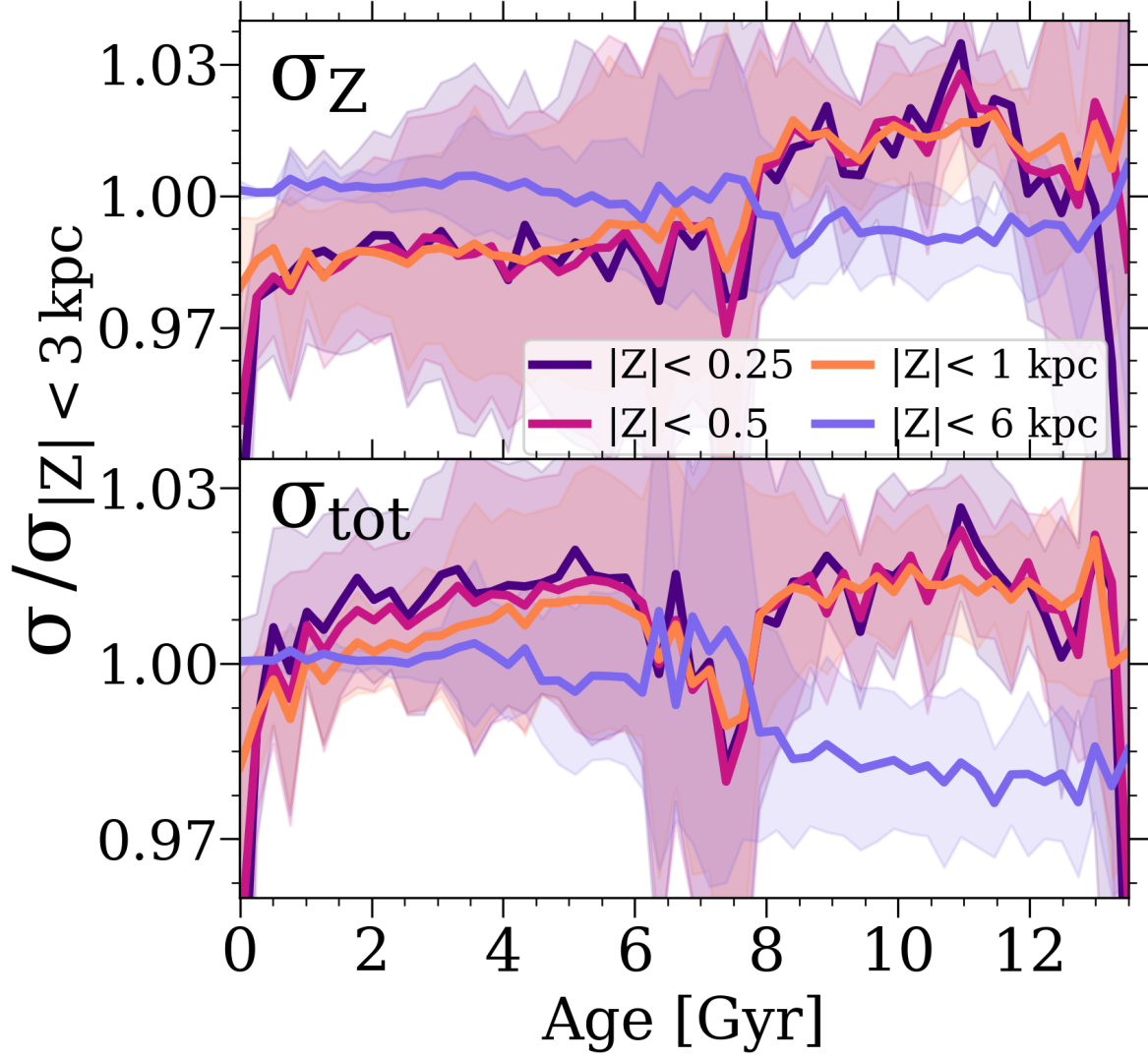


Figure 18: **Effect of vertical selection on σ_Z (top) and σ_{tot} (bottom):** present-day velocity dispersion for stars selected within 4 vertical ranges, divided by the dispersion for our fiducial range of $|Z| < 3$ kpc, versus stellar age. We select all stars at $R = 6 - 10$ kpc. Thinner vertical selections lead to slightly higher σ_Z and σ_{tot} for stars older than ≈ 8 Gyr, but slightly *lower* σ_Z and *higher* σ_{tot} for stars younger. However, different vertical selections change the dispersion by $\lesssim 3\%$, with the exception of the oldest and youngest stars, which have $\approx 5\%$ lower dispersions for thinner vertical ranges.

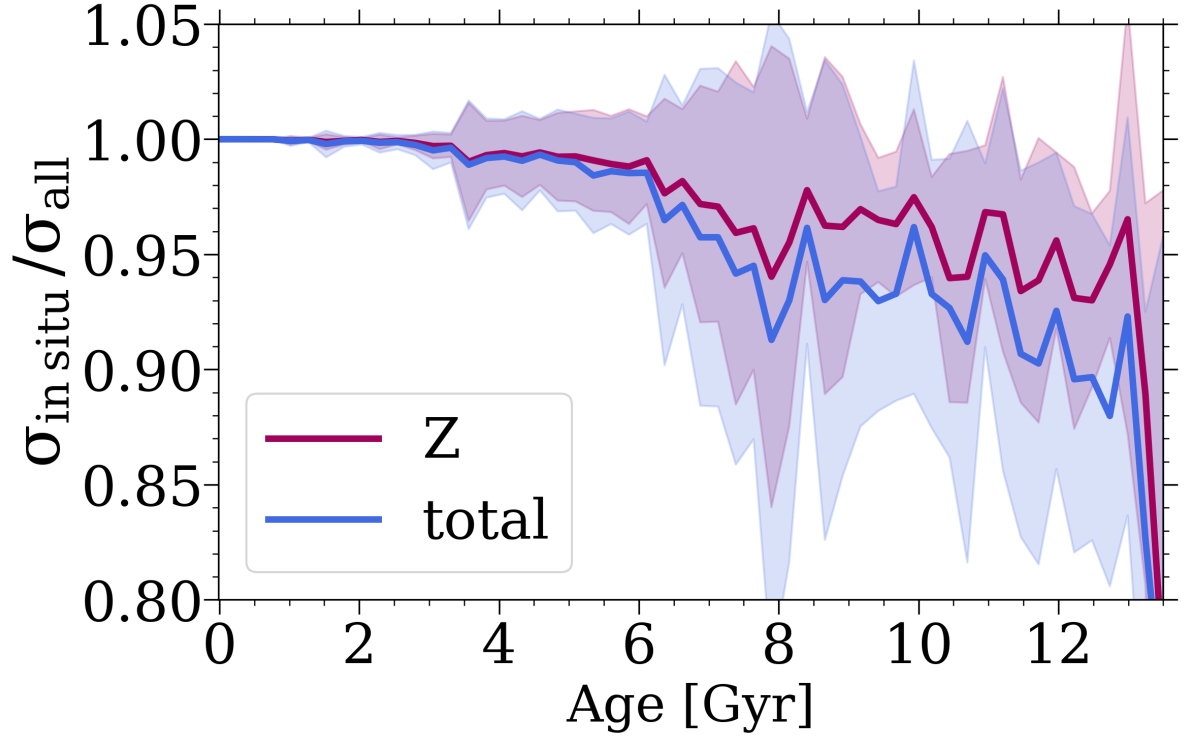


Figure 19: **Effect of excluding ex-situ stars on the present-day velocity dispersion:** $\sigma_{Z,\text{now}}$ (top) and $\sigma_{\text{tot},\text{now}}$ (bottom) of only stars that formed in situ divided by that of all (in-situ + ex-situ) stars, versus age, averaged across 11 galaxies. Stars with ages $\lesssim 6$ Gyr show no significant difference, because almost all young disk stars formed in situ. Older than 6 Gyr, the dispersion of in-situ stars relative to all stars decreases with age, because the fraction of ex-situ stars increases with age, and ex-situ stars have larger present-day dispersions. However, at almost all ages that we investigate, the difference in velocity dispersion is $\lesssim 10\%$.

2.6.3 EFFECT OF COSMIC-RAY FEEDBACK

The fiducial FIRE-2 simulations that we examine do not include self-consistent cosmic ray (CR) injection and transport. However, CRs may be important in regulating the dynamical state of the ISM, and therefore the resultant stellar populations, because in the solar neighborhood the CR energy density is comparable to the gas thermal and turbulent energy densities (for example Boulares and Cox, 1990).

Here, we explore the effects of CR feedback from stars on the dynamical state of our MW-mass disks. One proposed way to form kinematically colder disks in cosmological simulations is the inclusion of previously neglected feedback channels, including CRs, because they can provide a spatially and temporally smoother form of feedback and potentially launch cooler galactic winds. Previous work using FIRE-2 simulations found that the inclusion of magnetic fields, anisotropic conduction, and viscosity has no appreciable effects on any bulk galaxy properties, but that the inclusion of CRs, within reasonable uncertainty for the treatment of the CR diffusion coefficient, significantly can alter galaxy properties (Hopkins et al., 2020; Su et al., 2017). FIRE-2 simulations with CRs also include anisotropic CR transport with stream and advection / diffusion (with constant parallel diffusivity, $\kappa = 3 \times 10^{29} \text{cm}^2 \text{s}^{-1}$), CR cooling (hadronic and Compton, adiabatic, and streaming losses), CR injection in supernova shocks, and CR–gas coupling (see Chan et al., 2019, for details of the numerical implementation of CRs in these simulations).

Hopkins et al. (2020) showed in the FIRE-2 simulations that the primary effect of CR feedback is to prevent the accretion of halo gas into the galaxy, leading to lower star formation and stellar mass by $\approx 2 - 4\times$ in MW-mass galaxies at $z \lesssim 2$. Furthermore, Chan et al. (2021) found that the inclusion of CRs in FIRE-2 leads to lower velocity dispersions in gas, which might suggest dynamically cooler disks, although they did not examine v_ϕ/σ . We show here that the *opposite* is true for young stars when considering v_ϕ/σ , that is, the inclusion of CRs leads to dynamically hotter stellar disks.

Figure 20 shows the effect of CRs on present-day stellar kinematics versus age. We include only the isolated galaxies from the *Latte* suite, which have versions with CR feedback. We also include the lower-mass galaxies m12r and m12z, because our goal is only to examine the differential effects of including CRs. Figure 20 (top) shows the current median azimuthal velocity, $v_{\phi, \text{now}}$, versus stellar age, averaged across the same galaxies in the CR simulations and the fiducial simulations. At all ages, galaxies with CR feedback have lower v_ϕ , with the largest absolute difference for the youngest stars, which arises primarily because of their lower stellar masses.

Figure 20 (middle) shows the present vertical velocity dispersion, σ_z , versus age. The CR simulations have lower σ_z at all ages, except for the youngest stars, which may arise from the effects of CRs on the ISM and halo gas occurring over long timescales. We also examined σ_R , σ_ϕ , and σ_{tot} and found qualitatively similar results. Overall, the inclusion of CR feedback leads to lower velocity dispersions in stars, consistent with analyses of gas in these simulations (Chan et al., 2021; Hopkins et al., 2020).

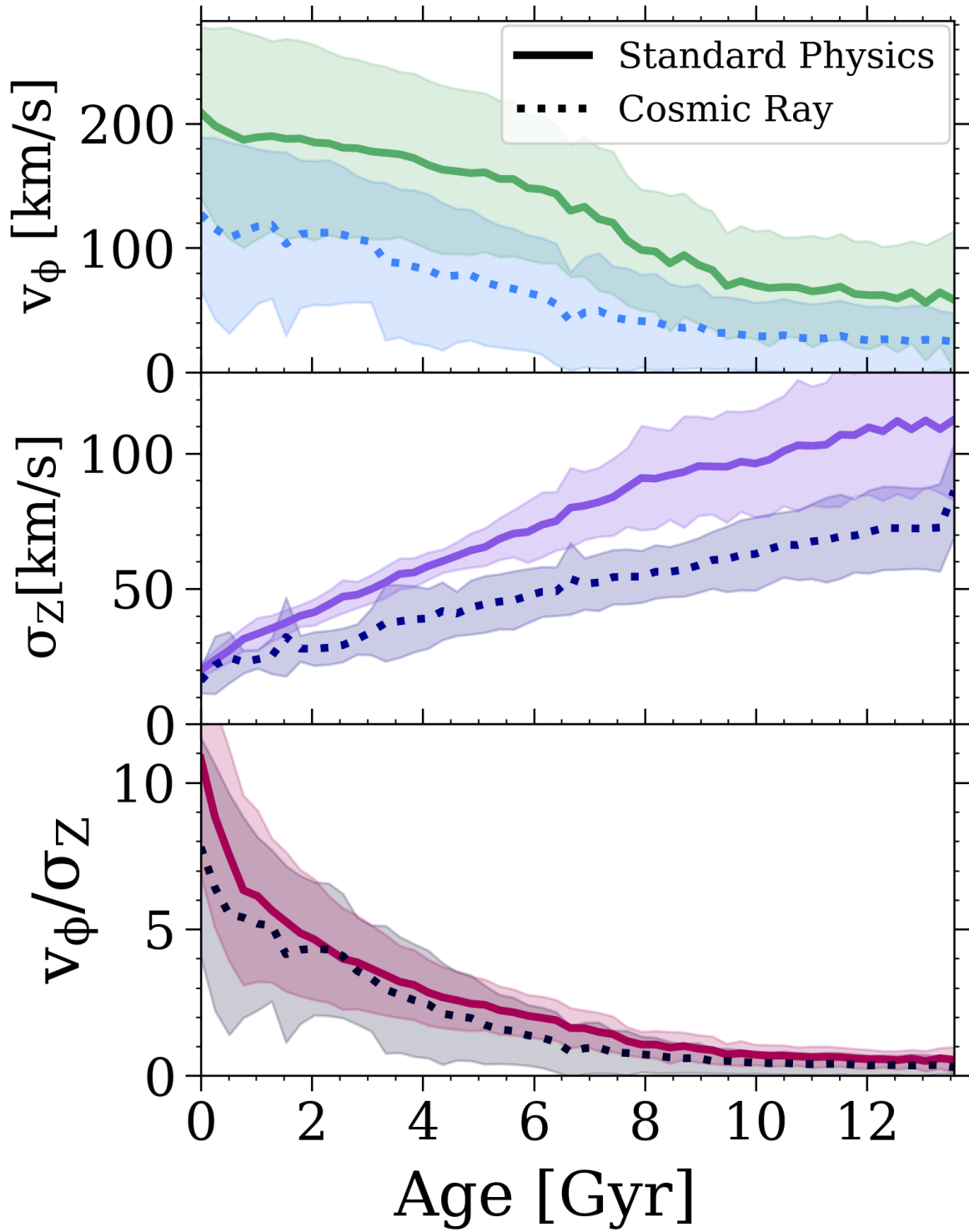


Figure 20: **Effects of cosmic-ray feedback on disk dynamical history:** current stellar kinematics versus age, averaged across 8 isolated MW-mass galaxies simulated with fiducial FIRE-2 physics (solid) and additionally including cosmic ray (CR) injection and transport from stars (dotted), assuming a constant effective diffusion coefficient $\kappa = 3 \times 10^{29} \text{cm}^2 \text{s}^{-1}$. The shaded regions show the galaxy-to-galaxy standard deviation. **Top:** median azimuthal velocity, v_ϕ . The addition of CR feedback reduces overall star formation, leading to lower-mass galaxies with lower velocities at all ages. **Middle:** vertical velocity dispersion, σ_z . Given their lower stellar mass, the CR simulations have lower velocity dispersions, though the CR simulations converge to the fiducial simulations for the youngest stars. **Bottom:** median v_ϕ/σ_z , as a measure of rotational support and ‘diskiness’. Given the reduction of both v_ϕ and σ_z in the CR simulations, v_ϕ/σ_z is similar at nearly all ages for the fiducial and CR simulations. For the youngest stars, the CR simulations are fractionally dynamically hotter and less rotationally supported. We find similar trends for the other velocity components and the total dispersion.

Figure 20 (bottom) shows the sample-averaged v_ϕ/σ_z versus age. For most ages, stars in the CR simulations have slightly *less* rotational support than in the simulations without CR feedback; the youngest stars show the most significant reduction at $\approx 30\%$. Thus, including CR feedback leads to fractionally dynamically hotter galaxies, despite their lower absolute velocity dispersions. However, Figure 21 shows that CR feedback leads to galaxies with $\approx 3\times$ lower stellar mass at present, as Hopkins et al. (2020) showed.

Figure 21 (top row) shows v_ϕ/σ_z for all stars versus stellar mass, while Figure 21 (bottom row) shows the same but for young stars (age < 250 Myr). We show our 6 fiducial LG-like galaxies (as black stars) to clarify our fiducial sample’s mass-relation across this entire mass range, given that none of our fiducial isolated simulations have masses within $2 - 4 \times 10^{10} M_\odot$, the range containing half of their CR counterparts. That said, we advise against making direct comparisons between any individual fiducial LG-like simulations and CR isolated simulations, because each galaxy has its own unique history and our fiducial LG-like simulations generally have slightly colder kinematics than our isolated simulations. We emphasize that Figure 21 shows the same trends with stellar mass as for our fiducial simulations without CR feedback in Figure 14. Thus, the inclusion of CR feedback primarily acts to reduce a galaxy’s stellar mass and correspondingly shifts its v_ϕ and v_ϕ/σ_z along the existing relation. This leads to galaxies that are slightly less disky, with slightly lower v_ϕ/σ_z . We conclude that the inclusion of CR feedback, at least as implemented in FIRE-2 and assuming a constant diffusion coefficient, does not lead to dynamically colder disks.

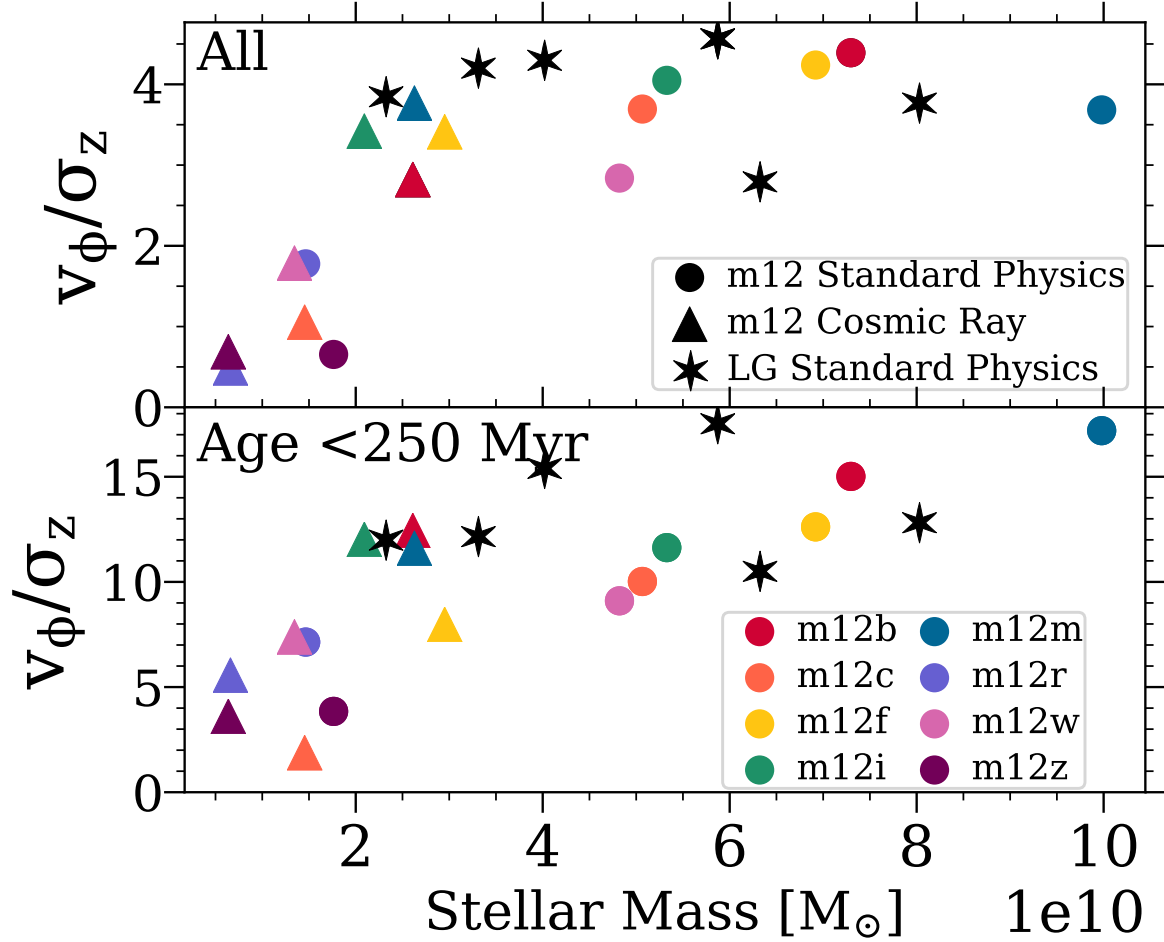


Figure 21: **Effects of cosmic-ray feedback on current stellar v_ϕ/σ_z versus stellar mass**, across 8 isolated MW-mass galaxies simulated with fiducial FIRE-2 physics (circles) and additionally with CR injection and transport (triangles). Black stars show LG-like galaxies simulated with fiducial physics; although these galaxies lack CR counterparts, we include them in order to illustrate our fiducial sample’s v_ϕ/σ_z - stellar mass relation. CR feedback leads to galaxies with ≈ 3 times lower stellar mass. **Top row:** v_ϕ/σ_z for stars of all ages. The CR simulations have lower σ_z but also lower stellar masses, leading them to land on a similar relation in v_ϕ/σ_z . **Bottom row:** same but for young stars with ages < 250 Myr. CR simulations have slightly lower v_ϕ/σ_z for 7 of the 8 galaxies, though again, they remain on a similar scaling relation. *Adding CR feedback does not lead to dynamically colder disks; it primarily reduces the stellar mass formed and moves galaxies along a similar relation.*

3

STELLAR VELOCITY DISPERSION VERSUS AGE: CONSISTENCY ACROSS OBSERVATIONS AND SIMULATIONS, WITH THE MILKY WAY AS AN OUTLIER

3.1 ABSTRACT

Within disk galaxies, the velocity dispersion, σ , of stars increases with age, τ , as measured in the Milky Way (MW) and nearby galaxies. This relation provides a key window into galactic formation history, tracing both the kinematics of stars at birth and the dynamical heating of stars after birth. We compile and compare observational measurements of the MW, M31, M33, and 16 galaxies from the PHANGS survey. The MW exhibits significantly colder stellar kinematics, with 2-3 times lower $\sigma(\tau)/v_{\phi,0}$ at a given age, than all but one other observed galaxy. Therefore, the MW is a kinematic outlier. To assess how measurement effects influence $\sigma(\tau)$, we analyze the FIRE-2 cosmological simulations, quantifying the impact of uncertainties in stellar age, aperture size, galactocentric radius, and galaxy inclination. Aperture size and galactocentric radius affect $\sigma(\tau)$ by up to a factor of ≈ 2 for stars younger than 100 Myr, with milder effects on older stars. Age uncertainties up to 40% change the *value* of $\sigma(\tau)$ at a given age by $\lesssim 20\%$ but can reshape the relation with age and erase merger signatures. We compare $\sigma(\tau)/v_{\phi,0}$ in FIRE-2 simulations with observations. FIRE-2 agrees well with M31 and M33 at all measured ages, and with PHANGS for stars older than ≈ 500 Myr. The average $\sigma(\tau)/v_{\phi,0}$ in FIRE-2 is about two times higher than the MW at most ages, but the youngest stars show better agreement. The velocity ratios (σ_ϕ/σ_R , σ_Z/σ_ϕ , σ_Z/σ_R) in FIRE-2 broadly agree with the MW. We conclude that $\sigma(\tau)$ in FIRE-2, and most cosmological zoom-in simulations, reasonably matches observed nearby galaxies, but matching the MW is rare, because it is a kinematic outlier.

3.2 INTRODUCTION

Galactic discs form and grow over cosmic time, and the stars within them retain a lasting record of this dynamical evolution. Nowhere is this stellar record richer than in the Milky Way (MW), and much work has focused on

measuring the velocity dispersion, σ , as a function of stellar age, τ , in the solar neighborhood.¹ Almost all works agree that σ typically increases with age, that is, young stars are kinematically cold, exhibiting tidally circular orbits, while older stars are on less coherently circular orbits and therefore have higher σ . However, despite decades of extensive study, a fundamental question persists: What is the physical origin of σ_τ ?

The present-day orbits of stars, including σ of a population at a given age, reflect two key aspects of a galaxy’s formation history: the conditions of the (star-forming) interstellar medium (ISM) over time, which sets the initial orbits of stars at birth, and their subsequent dynamical evolution. Both processes affect $\sigma(\tau)$, but their relative contributions remain uncertain.

In the canonical picture of Spitzer and Schwarzschild, 1951, stars form with the same low σ at all ages, but repeated scattering interactions with (then undetected) giant molecular clouds (GMCs) gradually increase σ as a stellar population ages. However, analytical models of GMC-driven heating failed to match observation, motivating the study and acceptance of additional dynamical heating processes, such as transient spiral arms (Barbanis and Woltjer, 1967; Carlberg and Sellwood, 1985; Minchev and Quillen, 2006), bars (Saha, Tseng, and Taam, 2010), perturbations by satellite galaxies (Bird, Kazantzidis, and Weinberg, 2012; Carr et al., 2022; D’Onghia et al., 2016), and galaxy mergers (Abadi et al., 2003; Villalobos and Helmi, 2008). The current consensus is that perturbations from transient spiral structure efficiently increase the in-plane σ , while GMC scattering acts more isotropically and redirects motions out of the plane (Binney and Tremaine, 2008; Sellwood, 2013). Yet, standard heating models fail to reach the high σ observed for the MW’s older stars. This discrepancy is unsurprising, because traditional models assume that the MW’s present-day conditions are representative of its earlier states, such that stars formed with the same low σ over cosmic time and subsequently experienced the same dynamical heating processes.

In contrast, nearly all recent observations and theoretical models of galaxy formation find that the dynamical state of the ISM evolves substantially over cosmic time. At higher redshifts ($z \gtrsim 1$), disk galaxies are consistently thicker, clumpier, and more turbulent than local disks (for example Birkin et al., 2023; Förster Schreiber et al., 2009), probably due to their higher gas fractions and star-formation, accretion, and merger rates (Conselice, Blackburne, and Papovich, 2005; Förster Schreiber and Wuyts, 2020b; Genzel et al., 2017; Stott et al., 2016; Swinbank et al., 2012; Tacconi et al., 2013). Spatially resolved studies of ionized gas kinematics find that v_ϕ/σ , which measures the degree of rotational-support or diskiness, is often as high as 10 – 20 in the local Universe but decreases with increased redshift, with average values of ≈ 2 at $z = 3$ (see recent compilation in Danhaive et al., 2025). Similarly, σ increases from $\approx 20 \text{ km s}^{-1}$ in disk galaxies today to $\approx 50 \text{ km s}^{-1}$ at $z = 3$ (Kassin et al., 2012; Simons et al., 2016; Übler et al., 2024; Wisnioski et al., 2015, 2019). These works indicate that disks “settled” over cosmic time, such that their gaseous disks became progressively less turbulent and more rotationally supported. Theoretical models, including cosmological simulations, strongly support these observations, generally finding that the progenitors of MW-mass galaxies typically formed long-lived disks at $z \lesssim 1 - 2$, with such disks growing radially “inside-out” and vertically “upside-down” (for example Bird, Kazantzidis, and Weinberg, 2012; Pillepich et al., 2019).

¹ While this age velocity dispersion relation is often abbreviated as “AVR”, we refer to it as $\sigma(\tau)$ throughout this paper.

This observational picture indicates that stars form with different dynamics over cosmic time, given that stars inherit their initial kinematics from their progenitor gas. That said, the same conditions that drive increased ISM turbulence – including substantial gas fractions, higher merger rates, and burstier star formation – also affect post-formation dynamical heating. For example, feedback-driven outflows and the resulting potential fluctuations can inject additional energy into the stellar component, leading to rapid, non-adiabatic heating that further amplifies stellar velocity dispersions (El-Badry et al., 2018a). Such ISM conditions also increase the prevalence of scattering from long-lived massive gas clumps and GMCs (for example Bournaud et al., 2014; Johnson et al., 2018; Price et al., 2020). Disentangling the degree to which present-day velocity dispersions reflect hotter birth conditions versus cumulative dynamical heating is challenging, as both processes can yield similar observational signatures. For example, Ting and Rix (2019) argue that the MW’s vertical $\sigma(\tau)$ is consistent with stars forming with a constant, low σ over the past 8 Gyr, but experiencing stronger GMC-driven dynamical heating at these earlier times.

This already tangled picture has recently been further complicated, as some recent observations now challenge our understanding of (gaseous) disk evolution. ALMA has revealed cold, rotationally supported molecular gas discs out to $z \sim 7$, including systems with $v/\sigma_0 \gtrsim 4$ (Lelli et al., 2021; Pope et al., 2023; Rizzo et al., 2020), and even as high as $v/\sigma_0 \sim 11$ at $z = 7.3$ (Rowland et al., 2024). JWST now extends this picture to ionized gas, detecting kinematically cold discs across a broad range of stellar masses and star formation rates (Nelson et al., 2023; Nelson et al., 2024; Robertson et al., 2023; Tohill et al., 2024; de Graaff et al., 2024). Although these findings suggest that dynamically cold disks can form, at least temporarily, in gas, an open question is how representative these disks are at early times. For example, Danhaive et al., 2025 showed that almost all of these early disks are massive, $M_{\text{star}} > 10^{10} M_{\odot}$, and thus not representative of a typical MW-mass progenitor at these redshifts.

A key limitation of high-redshift studies is that they generally only provide a statistical view of galaxy populations and cannot reveal how any individual galaxy continuously evolved across cosmic time. In contrast, detailed measurements of resolved stars (or stellar populations) in nearby galaxies can provide a view of the entire formation history of a galaxy. In particular, the advent of Gaia (Gaia Collaboration et al., 2016), along with large spectroscopic surveys, such as APOGEE (Majewski et al., 2017), GALAH (Buder et al., 2018; De Silva et al., 2015), and LAMOST (Cui et al., 2012), now provides up to 6D orbital phase-space coordinates and elemental abundances for millions of stars throughout the Galaxy. In parallel, the growth of asteroseismology (Miglio et al., 2021; Pinsonneault et al., 2018), in combination with high-quality spectroscopic measurements and data-driven models (Ho et al., 2017; Ness et al., 2016; Queiroz et al., 2023; Sharma et al., 2018), has driven remarkable progress in our ability to measure the ages of stars. Such progress enables measurements of $\sigma(\tau)$, which was historically limited to the immediate solar neighborhood and beholden to unclear systematics and age uncertainties (Casagrande et al., 2011; Holmberg, Nordström, and Andersen, 2007; Nordström et al., 2004), to large swathes across the disk with unprecedented precision (for example Anders et al., 2023; Kordopatis et al., 2023; Lagarde et al., 2021).

These advancements have revolutionized our view of the MW’s formation history. Indeed, a general picture has emerged that the MW began as a turbulent galaxy, subject to a bombardment of mergers and bursts of star formation (Chandra et al., 2023; Myeong et al., 2019; Rix et al., 2022). It then rapidly “spun up”, forming a coherently rotating disk ≈ 12 Gyr ago (Belokurov and Kravtsov, 2022; Conroy et al., 2022; Xiang and Rix, 2022; Xiang et al., 2025). The young disk then faced, and ultimately survived, a head-on collision with a massive satellite $\approx 8 - 11$ Gyr ago: this event, the “Gaia-Sausage-Enceladus” (GSE) merger (Belokurov et al., 2018; Helmi et al., 2018), scrambled and “splashed” the pre-existing disk, but also brought in fresh fuel for star formation and potentially seeded the formation of the thin disk (Belokurov et al., 2020; Grand et al., 2020, for example). While many aspects of the GSE merger, including its impact on the MW’s disk and $\sigma(\tau)$, remain unclear (for example Di Matteo et al., 2019; Fernández-Alvar et al., 2025; Skúladóttir et al., 2025), it is generally agreed to be the MW’s last major merger to date (though see Donlon et al., 2024, about the timing of this event).

Furthermore, there is growing consensus that certain aspects of the MW’s formation history – namely its early disk formation and quiescent merger history since $z \sim 2$ – are atypical among present-day disk galaxies (Evans et al., 2020; Hammer et al., 2007; Kruijssen et al., 2019b; Mackereth et al., 2018; Semenov et al., 2024a). Given how much of our understanding of galaxy formation, and in particular post-formation dynamical heating, is benchmarked against the MW, it is imperative to understand whether the MW is indeed an outlier or simply appears so due to observational bias remains an open question. Because we view it from the inside, we cannot measure it using the same methods applied to other galaxies, complicating efforts to draw meaningful comparisons (though see Fielder et al., 2021; Wang et al., 2024).

One of the best ways to distinguish these possibilities is via spatially resolved measurements of $\sigma(\tau)$ in nearby disk galaxies. M31 and M33, the only other disk galaxies in the Local Group (LG), provide our best opportunities, motivating surveys by the Hubble Space Telescope (HST) (Dalcanton et al., 2012; Williams et al., 2021) and ground-based observatories (Bhattacharya et al., 2019; Guhathakurta et al., 2006; McConnachie et al., 2009, 2018). In many ways, M31 is similar to the MW: a slightly more massive disk galaxy with a central bar, spiral arms, and modest star formation (Mutch, Croton, and Poole, 2011; Yin et al., 2009). In other ways, M31 is a foil to the quiescent MW: it likely experienced a major ($\approx 4:1$) merger ≈ 2.5 Gyr ago (D’Souza and Bell, 2018; Hammer et al., 2018), resulting in a thicker overall disk (Dalcanton et al., 2023; Gibson et al., 2024). While M31 allows us to compare the MW to a more massive, recently-interacting galaxy, its most massive satellite, M33, provides a view of a disk in the lower-mass regime. With a stellar mass of $4.8 \times 10^9 M_\odot$, M33 occupies the mass scale at which thin disks emerge (for example Dekel et al., 2009; Simons et al., 2016), and its flocculent spiral structure and recent bursts of star formation provide valuable insights into the dynamical evolution of the ISM and post-formation heating processes (Peltonen et al., 2024; Smercina et al., 2023). Importantly, observations of M31 (Dorman et al., 2015) and M33 (Quirk et al., 2022) have provided our first view of $\sigma(\tau)$ for a star-forming disk galaxy other than the MW.

Beyond the LG, integral-field spectroscopy (IFS) provides an intermediate view between galaxy-wide integrated properties and individual stars. While many IFS surveys, including MANGA (Bundy et al., 2015), SAMI (Croom

et al., 2012), and CALIFA (Sánchez et al., 2012), strike a middle ground between survey scope and depth, measuring spatially resolved kinematics for up to 10,000 galaxies at intermediate resolution (0.5 – 1 kpc), some surveys focus on higher-resolution ($\lesssim 100$ pc) measurements for smaller samples. The PHANGS-MUSE survey (Emsellem et al., 2022) obtained stellar kinematics for 19 star-forming galaxies at cloud-scale ($\approx 50 - 100$ pc) resolution, measuring $\sigma(\tau)$ in disk galaxies outside the LG for the first time (Pessa et al., 2023). These results, along with those of other MUSE surveys, including MAD (den Brok et al., 2020), TIMER (Gadotti et al., 2019), and GECKOS (van de Sande et al., 2024), allow us to place the detailed dynamical record of the MW (and the LG) in a greater cosmological context.

Cosmological baryonic simulations are valuable tools for interpreting observations of stellar kinematics, as they now produce realistic disk galaxies spanning a wide range of formation histories (for reviews see Crain and van de Voort, 2023; Naab and Ostriker, 2017; Vogelsberger et al., 2020). Zoom-in simulations, in particular, contain both cosmological nonequilibrium perturbations like mergers and mass growth, with the resolution needed to model the multiphase ISM, enabling star formation and feedback to be treated self-consistently in a broad context. Notably, these simulations resolve both global galaxy properties (e.g., morphology, disk dynamics) and the smaller-scale structures (e.g., GMCs, spiral arms, bars) that drive post-formation dynamical heating (Ansar et al., 2025; Benincasa et al., 2020; Yu et al., 2022). This enables detailed analysis of the evolving strength and balance between birth kinematics and subsequent heating across cosmic time. By tracing galaxy evolution across time and comparing simulated galaxies with each other and with observations, these models reveal how present-day kinematics reflect both birth conditions and cumulative dynamical processes imprinted on $\sigma(\tau)$.

In this work, we focus on $\sigma(\tau)$ in the MW and nearby disk galaxies of similar mass, using FIRE-2 simulations (described in §3.3) as a comparison baseline. Although some of these works (for example Dorman et al., 2015) note that the observed $\sigma(\tau)$ in M31 differs from that of the MW, no work has compiled and compared all available measurements of $\sigma(\tau)$ in nearby MW-mass disk galaxies. In this work, we aim to (1) put these observations on more equal footing, and (2) provide a cogent view of the state of the literature.

In §3.4, we assess how measurement considerations, including aperture size, galaxy inclination, age uncertainties, and galactocentric radius, affect the inferred $\sigma(\tau)$. In §3.5, we compile existing observations, focusing exclusively on star-forming disk galaxies; we exclude non-disk low-mass systems such as the LMC, SMC, and other MW satellites (for example Cole et al., 2005; Leaman et al., 2017; Olsen and Massey, 2007), as well as lenticular/S0 galaxies (Poci et al., 2021; Poci et al., 2019). We summarize and interpret these results in the discussion (§3.6).

3.3 METHODS

3.3.1 FIRE-2 SIMULATIONS

We study the stellar disks of 11 simulated MW-mass galaxies from the Feedback in Realistic Environments (FIRE) project², including 5 isolated galaxies from the *Latte* suite (Wetzel et al., 2016) and 3 LG-like pairs from the *ELVIS on FIRE* suite (Garrison-Kimmel et al., 2018). These baryonic cosmological simulations model the physics of stars and gas (in addition to dark matter) in a “zoom-in” region embedded within a lower-resolution cosmological background. Crucially, this zoom-in method enables these simulations to reach the resolution needed to resolve the multiphase ISM and GMCs.

These simulations use the zoom-in technique to simulate MW-mass galaxies at high resolution within a fully cosmological context. We first run dark-matter-only cosmological simulations within a periodic volume of side length 70.4 – 172 Mpc, assuming a flat Λ CDM cosmology with parameters broadly consistent with Planck Collaboration et al. (2020): $h = 0.68 - 0.71$, $\Omega_\Lambda = 0.69 - 0.734$, $\Omega_m = 0.266 - 0.31$, $\Omega_b = 0.0455 - 0.048$, $\sigma_8 = 0.801 - 0.82$ and $n_s = 0.961 - 0.97$. After selecting a region centered on a halo (or pair of halos) of interest at $z = 0$, we use MUSIC (Hahn and Abel, 2011) to identify the particles within the region, trace them back to $z \approx 99$, and regenerate the initial conditions for that region at higher resolution and including baryons.

For the *Latte* suite, halo selection is based solely on their mass at $z = 0$ ($M_{200m} \approx 1 - 2 \times 10^{12} M_\odot$) and relative isolation from similarly massive halos. The *ELVIS on FIRE* suite selection is a pair of neighboring ($d < 600 - 1000$ kpc), massive ($M_{200m} \approx 1 - 3 \times 10^{12} M_\odot$) halos approaching each other, to mimic the LG. We emphasize that the selection of these halos was agnostic to any halo properties beyond mass (and LG-like environment), including formation history, concentration, spin, or satellite population. That is, there was no attempt to recreate the MW, or any other individual galaxy, or the larger-scale environment (beyond the LG). We exclude three galaxies (m12r, m12w, and m12z) from our analysis, because they lack coherent (rotationally-dominated) stellar disks, making them poor analogs for the observed disk galaxies we compare against.

We ran the simulations using GIZMO³, a multimethod gravity plus (magneto)hydrodynamics code, in its meshless finite-mass (MFM) mode. This mesh-free Lagrangian Godunov method combines the advantages of smoothed-particle hydrodynamics methods and grid-based adaptive mesh refinement schemes while avoiding many of their drawbacks: this method allows automatically adaptive resolution, accurate gravitational coupling, and reduced advection errors, all while accurately capturing instabilities and shocks and maintaining exact mass, energy, and momentum conservation and excellent angular momentum conservation (for extensive tests see Hopkins, 2015, 2017; Hopkins and Raives, 2016). For gravity, GIZMO couples hydrodynamics to an improved

² FIRE project web site: <http://fire.northwestern.edu>

³ <http://www.tapir.caltech.edu/~phopkins/Site/GIZMO.html>

version of the N -body TreePM solver from GADGET-3 (Springel, 2005) using fully adaptive and conservative gravitational force softenings, so that the gravitational force softening for gas always matches the hydrodynamic smoothing length, following Price and Monaghan, 2007.

The *Latte* suite has a dark-matter particle mass of $3.5 \times 10^5 M_\odot$ and an initial baryon particle mass of $7070 M_\odot$, although stellar mass loss causes star particles to have typical masses $\approx 5000 M_\odot$ today. Gas cells have fully adaptive gravitational softenings that match the hydrodynamic kernel smoothing: softening lengths are $\approx 20 - 40$ pc at typical ISM densities ($n \sim 1 \text{ cm}^{-3}$) but reach ≈ 1 pc in the densest regions. In contrast, dark-matter and star particles have fixed gravitational force softenings, comoving at $z > 9$ and physical thereafter, with a Plummer equivalent of $\epsilon_{\text{dm}} = 40$ pc and $\epsilon_{\text{star}} = 4$ pc (corresponding to the typical interparticle spacing in star-forming gas). The *ELVIS on FIRE* suite has a mass resolution $\sim 2\times$ better than the *Latte* suite: Romeo & Juliet have initial baryon particle masses of $3500 M_\odot$, while Romulus & Remus and Thelma & Louise have $4000 M_\odot$.

The simulations incorporate metallicity-dependent radiative cooling and heating processes for gas across temperatures $10 - 10^{10}$ K, including free-free, photoionization and recombination, Compton, photoelectric and dust collisional, cosmic ray, molecular, metal-line, and fine structure processes. Combined with their high resolution, the FIRE-2 simulations can resolve key phase structures in the ISM, allowing gas to collapse into GMCs (Benincasa et al., 2020; Guszejnov et al., 2020). The simulations self-consistently generate 11 elements (H, He, C, N, O, Ne, Mg, Si, S, Ca, Fe), including a model for sub-grid mixing/diffusion via turbulence (Escala et al., 2018; Hopkins, 2016; Su et al., 2017).

Star formation occurs in gas that is dense ($n > 1000 \text{ cm}^{-3}$), self-gravitating (following Hopkins, Narayanan, and Murray, 2013), self-shielding and molecular (following Krumholz and Gnedin, 2011), and Jeans unstable. If all of these criteria are met, a gas cell probabilistically converts to a star particle in a local gravitational free-fall time. Each star particle represents a single stellar population sampled from a Kroupa (2001) initial mass function, with mass and metallicity inherited from its progenitor gas cell. Once formed, star particles follow stellar evolution models that tabulate feedback event rates, luminosities, energies, and mass-loss rates from STARBURST99 v7.0 (Leitherer et al., 1999). FIRE-2 implements all of the major channels for stellar feedback, including core-collapse and white-dwarf (Type Ia) supernovae, stellar winds, radiation pressure, photoionization, and photoelectric heating. FIRE-2 also includes photoionization and heating from a spatially uniform, redshift-dependent UV background (Faucher-Giguère et al., 2009) that reionizes the Universe at $z \approx 10$.

3.3.2 SELECTING STARS AND MEASURING VELOCITY DISPERSION

We measure all positions and velocities in galactocentric cylindrical coordinates (R, ϕ, Z). To determine the center of each galaxy – and thus our coordinate system – we iteratively compute the mean center-of-mass position of all stars using the “shrinking spheres” method until the spherical radius drops below 10 pc. We then align our

coordinate system with the principal axes of the stellar disk, as defined by the moment-of-inertia tensor of the 25% youngest stars inside a radius that encloses 90% of the total stellar mass within 10 kpc. Although we define our coordinate system using the disk-scale properties of young stars, we measure stellar kinematics on local apertures, which in principle can have distinct alignments relative to other apertures and the galaxy as a whole. However, we found that our results are insensitive to the specifics of our coordinate system, for example, if we instead assign our axes using just the young stars within that aperture, or if we use gas or different definitions for young stars.

McCluskey et al., 2024 showed that, in these FIRE-2 simulations, σ of cold gas and young stars at formation strongly depend on the spatial scale over which one measures them. Specifically, when measured in apertures of radius 250 pc, σ of cold gas and young stars at formation are 3 times and 2 times *lower* than when measured across an entire galactocentric annulus. We now extend this analysis to the present-day σ of stars of various ages.

Within each aperture, we compute the velocity dispersion, σ , for a given velocity component (v_R , v_ϕ , or v_Z), as half of the mass-weighted 16^{th} – 84^{th} inter-percentile range, which is equivalent to the standard deviation for normal distribution. From these we also compute the “total” 3-D velocity dispersion, $\sigma_{3D} \equiv \sqrt{\sigma_R^2 + \sigma_\phi^2 + \sigma_Z^2}$. We then compute the median σ across the aperture at a given galactocentric radius, R , where we only include apertures that contain at least seven star particles within our desired age range. Unless otherwise specified, these are cylindrical apertures of radius 250 pc and vertical height $|Z| < 3$ kpc that span an annulus centered at $R = 8$ kpc.

By default we show the “total” σ_{3D} , because the individual velocity components generally show trends similar to σ_{3D} (or σ_{LOS}) and each other. In some cases we show individual components, either because this allows us to compare the FIRE-2 simulations to the MW, as in Section 3.5.4, or because nontrivial differences exist between different components, as in Section 3.4.1.

We tested how each of the parameters for apertures impacts our results. Using the mean σ of the apertures across an annulus instead of the median typically produces identical results. Similarly, the median (or mean) σ across an annulus is largely insensitive to the minimum number of star particles, provided $N_{\min} \gtrsim 3$. That said, σ within individual apertures occasionally depends on this threshold, with higher $N_{\min}$ restricting our results toward denser apertures, which are generally (but not exclusively) biased towards larger σ .

For our fiducial parameters ($R = 8$ kpc, $|Z| < 3$ kpc, and $r_{ap} = 250$ pc) the median number of star particles within our age bins centered at ≈ 400 Myr, 2 Gyr, and 6 Gyr typically exceeds 100 for the ELVIS simulations and 50 for the Latte simulations (given their differing mass resolutions). The narrow range of our youngest age bin (0 – 100 Myr) can reduce this median to 10 – 20 particles. Ultimately, we use a threshold of a minimum of 7 star particles to include an aperture, as a balance against Poisson noise within individual apertures and against small-number statistics and density-biasing across a galactic annulus.

Our results depend on the spatial parameters of the aperture, specifically its size and its galactocentric radius, as we explore in Sections 3.4.2 and 3.4.3. We also examined the impact of the vertical extent of an aperture, finding

that it has negligible effects, given that the majority of stars are close to the disk midplane, in agreement with the tests shown in McCluskey et al., 2024.

3.3.3 AGE BINNING

In Section 3.4, we show results for stars in five representative age ranges: $0 - 0.1$, $0.1 - 0.6$, $1.75 - 2.25$, $5.75 - 6.25$, and $10.75 - 11.75$ Gyr. We choose these age ranges to sample the full dynamical history of the disk and also to complement observations of resolved stars and stellar populations in nearby galaxies.

The youngest age bin, $0 - 100$ Myr allows us to study the kinematics of stars near birth and thus probe the dynamical state of the star-forming ISM. Although stars inherit the kinematics of their progenitor gas cells, dynamical heating of stars quickly can increase and decouple the (effectively dissipationless) stars from the (dissipational) gas. This narrow age range also allows us to compare with observations of young stars in nearby galaxies.

The youngest age bins probed by observations of M31 and M33 have mean ages of 30 and 80 Myr, while P23 presented $\sigma(\tau)$ of stellar populations in PHANGS galaxies with luminosity-weighted ages < 100 Myr.

Our second age bin is $100 - 600$ Myr. While still young, these stars have evolved over 1-3 disk dynamical times, so they provide a window into the internal heating processes that shape stellar dynamics in the disk. This age range also overlaps with the youngest age bins used in MW observations, and it bookends the ages of young AGB stars in M31 (which have a mean age of 400 Myr), and exactly matches the “intermediate” age bin of P23 for PHANGS galaxies.

For the three older age bins, we chose age ranges that correspond to the typical midpoints of the disk dynamical eras that we presented for the FIRE-2 simulations in McCluskey et al., 2024. Briefly, McCluskey et al., 2024 found that the formation of stellar disks – as traced by the v_ϕ/σ of newly formed stars – proceeded in three distinct phases. Stars in the “Pre-Disk” Era formed on non-disk, dispersion-dominated orbits. Next, the “Early-Disk” Era commenced once stars began to form (permanently) on rotation-dominated orbits. These early disks were thick and kinematically hot, with high σ . Subsequent generations of stars formed on increasingly rotationally dominated orbits, and eventually the galaxies settled into their “Late-Disk” Era, forming stars on consistently dynamically cold orbits. Although the exact timing and length of these transitions vary across the sample, these simulations typically transitioned to the Early-Disk Era 8 Gyr ago and the Late-Disk Era 4 Gyr ago, such that stars with ages of $1.75 - 2.25$, $5.75 - 6.25$, and $10.75 - 11.25$ Gyr formed predominantly in the Late-, Early-, and Pre-Disk Eras, respectively.

Simulation	$M_{\star,90}$	$v_{\phi,0}$	σ_Z	σ_{3D}	τ_{disk}
Name	[$10^{10}M_{\odot}$]	[km/s]	[km/s]	[km/s]	[Gyr]
m12m	10.0	288	13.3	33.1	9.2
Romulus	8.0	265	16.6	41.8	7.4
m12b	7.3	272	13.1	37.5	7.4
m12f	6.9	256	13.5	31.6	7.4
Thelma	6.3	230	19.4	43.9	4.4
Romeo	5.9	249	12.2	31.3	11.0
m12i	5.3	238	12.8	27.5	6.7
m12c	5.1	240	19.5	38.4	6.5
Remus	4.0	216	10.7	25.0	7.9
Juliet	3.3	211	15.0	32.6	4.4
Louise	2.3	177	11.0	26.1	7.2
Average	6.0	236	13.5	32.4	7.2

Table 3: Stellar properties today for the FIRE-2 simulations of MW/M31-mass galaxies that we analyze. We list galaxies by decreasing stellar mass. The first column lists the galaxy name: ‘m12’ indicates an isolated galaxy; otherwise the galaxy is in a Local Group-like pair. $M_{\star,90}$ is the stellar mass within $R_{\text{star},90}$, the radius enclosing 90% of the stellar mass within 20 kpc. $v_{\phi,0}$, σ_Z and σ_{3D} are the median rotational velocity, vertical velocity dispersion, and total 3D velocity dispersion of stars younger than 100 Myr, as measured in cylindrical apertures of radius of 250 pc around an annulus centered at $R = 8$ kpc. τ_{disk} is the lookback time when the galaxy formed a long-lived disk and all stars formed with $v_{\phi}/\sigma_{3D} > 1$, from McCluskey et al., 2024. The bottom row shows the mean across the 11 galaxies.

3.4 MEASUREMENT EFFECTS

In this section, we use the FIRE-2 simulations to investigate how uncertainties, systematics, and measurement choices impact the measured stellar velocity dispersions. We seek to provide guidance for interpreting observations, comparing them against each other, and comparing them against simulations.

3.4.1 AGE UNCERTAINTIES

Stellar ages are difficult to measure precisely, and their uncertainties are generally $\gtrsim 20 - 30\%$ (for example Soderblom, 2010). Fortunately, the synergy of astrometric and spectroscopic surveys with asteroseismological data has driven tremendous progress in the past decade (for example Mackereth et al., 2019a; Silva Aguirre et al., 2018). Nevertheless, stellar-age uncertainties continue to hinder our ability to accurately reconstruct the formation history of the MW and nearby galaxies, both by obscuring merger features (Buck et al., 2020; Martig, Minchev, and Flynn, 2014) and by decreasing inferred dynamical heating (Aumer, Binney, and Schönrich, 2016).

We explore the impact of age uncertainties on the measured $\sigma(\tau)$. To model this, we generate new ages for each star particle, randomly drawing “measured” ages from Gaussian distributions centered on the true age with standard deviations corresponding to 10, 20, 30, and 40% (fractional) uncertainties. We then recompute σ in each age bin using these ages.

The degree to which age uncertainties influence $\sigma(\tau)$ depends mainly on the steepness and shape of the true dependence on age. In general, if $\sigma(\tau)$ is smooth and slowly varying, modest age uncertainties do little to distort the overall trend. However, by mixing populations across age bins, uncertainties generally lead to an inferred dependence on age that is shallower than truth. Furthermore, if $\sigma(\tau)$ exhibits sharp features – such as spikes or breaks in slope – age uncertainties can smear these signatures by mixing stars across bins with different intrinsic kinematics. The impact also varies with age: for a fixed fractional age uncertainty, absolute uncertainties are smaller at younger ages. Accordingly, we expect minimal effects from age errors at young ages, even when the slope is steep, and more noticeable smoothing at older ages, where the population size is limited, absolute uncertainties are larger, and slopes are (occasionally) steep.

3.4.1.1 CASE STUDIES

Figure 22 shows the total stellar velocity dispersion, σ_{3D} , versus stellar age, τ in four of our galaxies: m12m (top left), m12f (top right), Romeo (bottom left), and Louise (bottom right). We selected these galaxies to bracket the mass range of the observed systems that we compare against in Section 3.5 – namely the MW, M31, and M33 –

and to serve as useful analogs: Louise is comparable in mass to M33, Romeo resembles the MW, and m12m is a comparable stellar mass to M31. We also include m12f to illustrate a merger-driven spike in its $\sigma(\tau)$ and to demonstrate how such features are affected by age uncertainties.

All galaxies show a characteristic rise in $\sigma(\tau)$ with age, the result of disk settling and post-formation dynamical heating, as (McCluskey et al., 2024) explored for these galaxies. The youngest stars exhibit the most rapid increase, because heating is most efficient for dynamically cold populations (Binney and Tremaine, 2008). However, the exact shape of $\sigma(\tau)$ reflects the unique history of each galaxy and, because of this, age uncertainties impart different effects on each galaxy.

With a stellar mass of $10^{11} M_{\odot}$, m12m is our most massive galaxy and the closest to M31’s stellar mass of $10.3 \pm 2.3 \times 10^{10} M_{\odot}$ (Sick et al., 2015). In m12m, σ rises steadily with age between 1 and 7 Gyr, which in this case primarily reflects the continued settling of the star-forming ISM (McCluskey et al., 2024). For stars younger than 6 Gyr, the impact of age uncertainties is weak, while for older ages, age uncertainties reduce σ and flatten its age dependence.

m12f highlights the dramatic impact that a gas-rich merger can have and the equally dramatic impact that age uncertainties have on the observability of this feature. m12f underwent a merger (of stellar mass ratio $\approx 1:13$) ≈ 6.9 Gyr ago, after it entered its Early-Disk Era, but before it settled into a thin disk ≈ 4.6 Gyr ago. This merger led to a significant spike in the *present-day* σ of stars formed around that time. When measured with perfect age precision, this spike is dramatic, and it would provide a direct way to age-date the merger. However, even 10% age uncertainties reduce this spike to a gentle bump, and 20% age uncertainties wash it out entirely.

Not all mergers drive such spikes in σ today. m12f underwent another merger ≈ 500 Myr ago with an LMC-mass satellite. This merger was by no means negligible: for example, Necib et al., 2019 shows that this merger accounts for 53% of the accreted stellar mass in the solar circle, while Yu et al., 2021 show that this merger triggered a significant burst of star formation. Nevertheless, $\sigma(\tau)$ remains comparatively smooth, even in the absence of age uncertainties. Thus, merger signatures in $\sigma(\tau)$ depend on the timing and orbit of the merger. The fact that mergers that coincide with (and perhaps facilitate) disk formation can lead to spikes in $\sigma(\tau)$ is particularly relevant for the MW, given that its disk formation was potentially coincident with the GSE merger (for example Conroy et al., 2022). Correctly characterizing such merger signatures require age uncertainties of $\lesssim 10\%$, with the earlier timing of GSE (≈ 10 Gyr ago) potentially necessitating even tighter constraints within an already enigmatic age regime.

Romeo is our earliest-forming galaxy, both in terms of stellar mass assembly and the onset of disk formation, which occurred ≈ 11 Gyr ago (McCluskey et al., 2024). Thus, in many ways, it provides our best MW analog, in terms of an early-forming disk (Belokurov and Kravtsov, 2022; Xiang and Rix, 2022), being in an LG-like environment, and having a stellar mass of $5.9 \times 10^{10} M_{\odot}$. In the absence of age uncertainties, Romeo’s σ_{3D} increases steadily with age, and with a sharper rise ≈ 8 and 12 Gyr ago, which is the steepest relation for old stars among our sample. Thus, for Romeo, *fractional* age uncertainties significantly reduce σ in older stars by up to

$50 - 75 \text{ km s}^{-1}$. Given that Romeo is our best dynamical analog to the MW, this suggests particular caution in interpreting σ of old stars in the MW.

Louise is the lowest-mass galaxy in our sample, with $M_{\text{star}} \approx 2.3 \times 10^{10} M_{\odot}$, and is thus closest to approaching the even lower mass of M33 – $4.8 \times 10^9 M_{\odot}$ (Corbelli et al., 2014). For Louise, σ rises gradually with age up to 6 Gyr, but σ increases rapidly between ≈ 6 and 9 Gyr ago, reflecting the rapid settling of its disk. However, increasing age uncertainties shift this rapid rise to occur more recently, by up to 2 Gyr. In contrast, at ages $\gtrsim 9$ Gyr, the flatness of $\sigma(\tau)$ leads to only minor effects for age uncertainties.

Ultimately, the impact of age uncertainties varies between galaxies and depends on a galaxy’s formation history. Age uncertainties can change our inference about the ISM settling history and dynamical heating of old stars (weakly for m12m, strongly for Romeo), the merger history (m12f), and the disk formation/settling time (Louise).

3.4.1.2 TRENDS ACROSS ALL SIMULATIONS

Figure 23 shows how uncertainties in stellar age affect $\sigma(\tau)$ on average across 11 FIRE-2 galaxies. Because the impact varies by velocity component, we show radial, tangential, and vertical σ separately. For each galaxy, we compute $\sigma(\tau)$ with and without age uncertainties in individual apertures, normalize by the median value for that galaxy, and then average across the sample. This normalization allows for more meaningful comparisons across galaxies with varying stellar masses, star formation histories, and disk structures. Shaded regions denote the 16th–84th percentile range, illustrating the degree of galaxy-to-galaxy scatter, which is particularly prominent for young stars. For context, shaded bars along the top of the figure indicate the average lookback times when these galaxies transitioned between the Pre-Disk, Early-Disk, and Late-Disk Eras (see Section 3.3.3).

Figure 23 shows that the impact of age uncertainties varies depending on when the stars formed relative to the disk eras. In general, age uncertainties *increase* σ for stars formed in the Late-Disk and Early-Disk Eras and decrease σ for stars formed in the Pre-Disk Era. For Late-Disk stars, age uncertainties of 20% increase σ by $\lesssim 2\%$, while uncertainties of 40% increase σ by $\lesssim 10\%$. However, age uncertainties increase σ for Early-Disk stars more significantly. In particular, σ_{ϕ} shows the strongest increase with age uncertainty, up to 30%, during the Early-Disk Era. In contrast, σ_R increases by up to $\approx 10\%$, and σ_Z changes by $\lesssim 5\%$. The disproportionate impact on σ_{ϕ} results from the fact that v_{AE} shows the strongest time evolution (both across all components and ages) throughout the Early-Disk Era due to the (generally rapid) onset of disk formation. Although the median v_R and v_Z of ~ 4 and 8 Gyr old stars are usually broadly similar at $\sim 0 \text{ km/s}$, the median v_{ϕ} can differ by up to $\sim 200 \text{ km/s}$. Thus, the faulty inclusion of older, non-disky stars artificially increases σ_{ϕ} . Lastly, age uncertainties reduce σ by up to 10 – 20% for Pre-Disk stars, with σ_{ϕ} exhibiting the weakest decrease.

Overall, age uncertainties most significantly impact σ_{ϕ} , inflating its value by up to 30% at intermediate ages (4 – 8 Gyr old). In comparison, the effects on σ_R and σ_Z are generally weaker. Ultimately, the effect of age uncertainties on the total σ_{3D} is generally $\lesssim 15\%$ at any given age. However, we repeat that these are the *average*

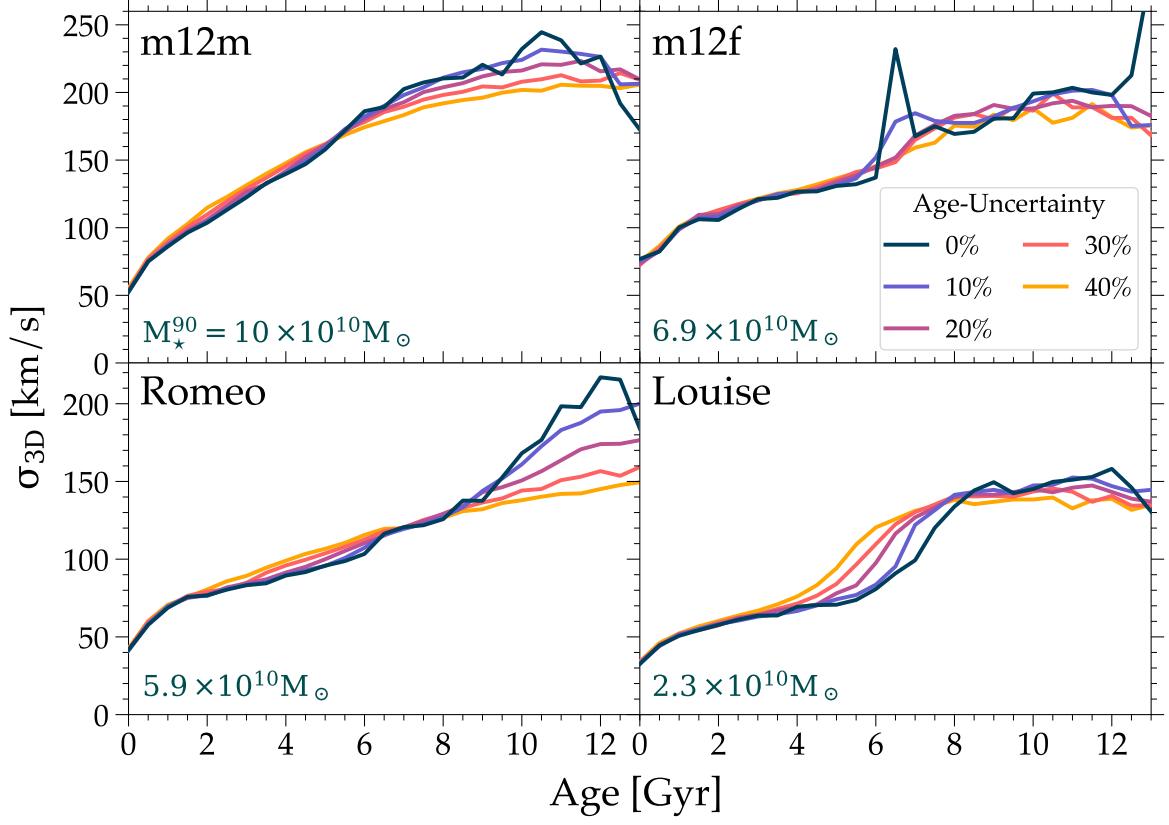


Figure 22: **Stellar 3D velocity dispersion versus age in 4 representative galaxies**, with M_{star}^{90} today in each corner. We measure σ_{3D} at $R = 8$ kpc, imposing fractional uncertainties on stellar ages of 0%, 10%, 20%, 30% and 40%. σ_{3D} generally increases with age, reflecting the disk settling over time *and* the dynamical heating of stars after birth. **m12m (top left)** show a nearly linear relation, largely unaffected by age uncertainties at ages $\lesssim 6$ Gyr, but the relation flattens at ages > 6 Gyr, with larger uncertainties leading to progressively flatter slopes. **m12f (top right)** shows dramatic behavior: a major merger ≈ 7 Gyr ago caused a spike, but age uncertainties $\gtrsim 20\%$ erase this. **Romeo (bottom left)** is our closest analog to the MW. Age uncertainties have mild effects up to ≈ 9 Gyr, before which the strong increase with age becomes increasingly flattened for larger uncertainties. **Louise (bottom right)** is our lowest-mass galaxy. The rapid rise in $\sigma_{3D} \approx 7$ Gyr ago reflects its rapid disk formation and settling, but increasing age uncertainties shift this feature to younger ages. Ultimately, the impact of age uncertainties varies between galaxies, changing our inference about the ISM settling history and dynamical heating of old stars (weakly for m12m, strongly for Romeo), the merger history (m12f), and the disk formation/settling time (Louise).

shifts in σ at fixed age across our galaxy sample. Within individual galaxies, the effect of age uncertainties can be more dramatic, shifting the inferred ages of certain kinematic features (as shown in Figure 22).

3.4.2 APERTURE SIZE

Next, we study how measurements of $\sigma(\tau)$ depend on physical scale. The long-known size-linewidth relation, that $\sigma_{\text{GMC}} \propto l^{0.5}$ (Larson, 1981), indicates that σ of molecular gas increases with the size of the region, often as a power law (Heyer and Dame, 2015; Leroy et al., 2025; Rice et al., 2016; Rosolowsky et al., 2021). This arises because the star-forming ISM is supersonically turbulent, and GMCs reflect this hierarchical turbulent structure. The FIRE-2 simulations show this behavior in the ISM, with various works confirming that star-forming gas and GMCs in the simulations follow the observed size-linewidth relation (hopkins18; hung19; Guszejnov et al., 2020).

Stars form from dense gas and thus inherit the clustered distribution of their natal ISM. In turn, σ of newly-formed stars is correspondingly scale-dependent (Krumholz, McKee, and Bland-Hawthorn, 2019; Lada and Lada, 2003; Maschmann et al., 2024). However, this inherited scale dependence rapidly evolves and is erased on timescales of ≈ 100 Myr, as stellar orbits mix and evolve (Grasha et al., 2019; Peltonen et al., 2023).

McCluskey et al., 2024 showed in these FIRE-2 simulations that σ of young stars (and cold gas) increased by $\approx 2\times$ when measured across an annulus versus when measured in small (150 pc) apertures, in part because larger apertures incorporate later-scale disk dynamical structures such as spiral arms, bars, and warps. This aperture dependence provides an important context for interpreting and comparing observational work. Historically, many studies of the MW focused on stars within a few 10's of pc of the Sun, while more recent surveys extended to a few kpc. In M31 and M33, where observations span considerable swaths of the disk, observations use smoothing techniques to measure σ within apertures of radius ≈ 0.5 kpc. Furthermore, high-resolution studies of nearby galaxies, such as PHANGS-MUSE, derive σ from integrated spectra of $100\sim 200$ pc spaxels.

To quantify the impact of the aperture radius, Figure 24 (top) shows the ratio of σ_{3D} measured in a cylindrical aperture of radius r_{ap} to its value when measured within $r_{\text{ap}} = 2$ kpc, for five representative age ranges. In general, the impact of aperture radius is weak: for all but the youngest stars, apertures of 50 pc yield $\sigma \approx 80\%$ as large as those in 2 kpc apertures, while apertures of 150 pc and 250 pc yield σ that are 90% and 95% as large, respectively. Ultimately, aperture radii larger than ≈ 500 pc do not matter. These results indicate that stars older than 100 Myr are well phase-mixed in the FIRE-2 simulations. Furthermore, we interpret the sharp downturn below 200 pc for stars older than ≈ 200 Myr as reflecting the numerical limits from resolution in the FIRE-2 simulations, so we use 250 pc as our fiducial aperture radius throughout.

That said, the youngest stars (ages $\lesssim 100$ Myr) show stronger aperture dependence. Aperture radii of 50 and 250 pc yield median $\sigma \approx 45\%$ and 70% of their value at 2 kpc, and they only reach 90% at 1.25 kpc. This gradual

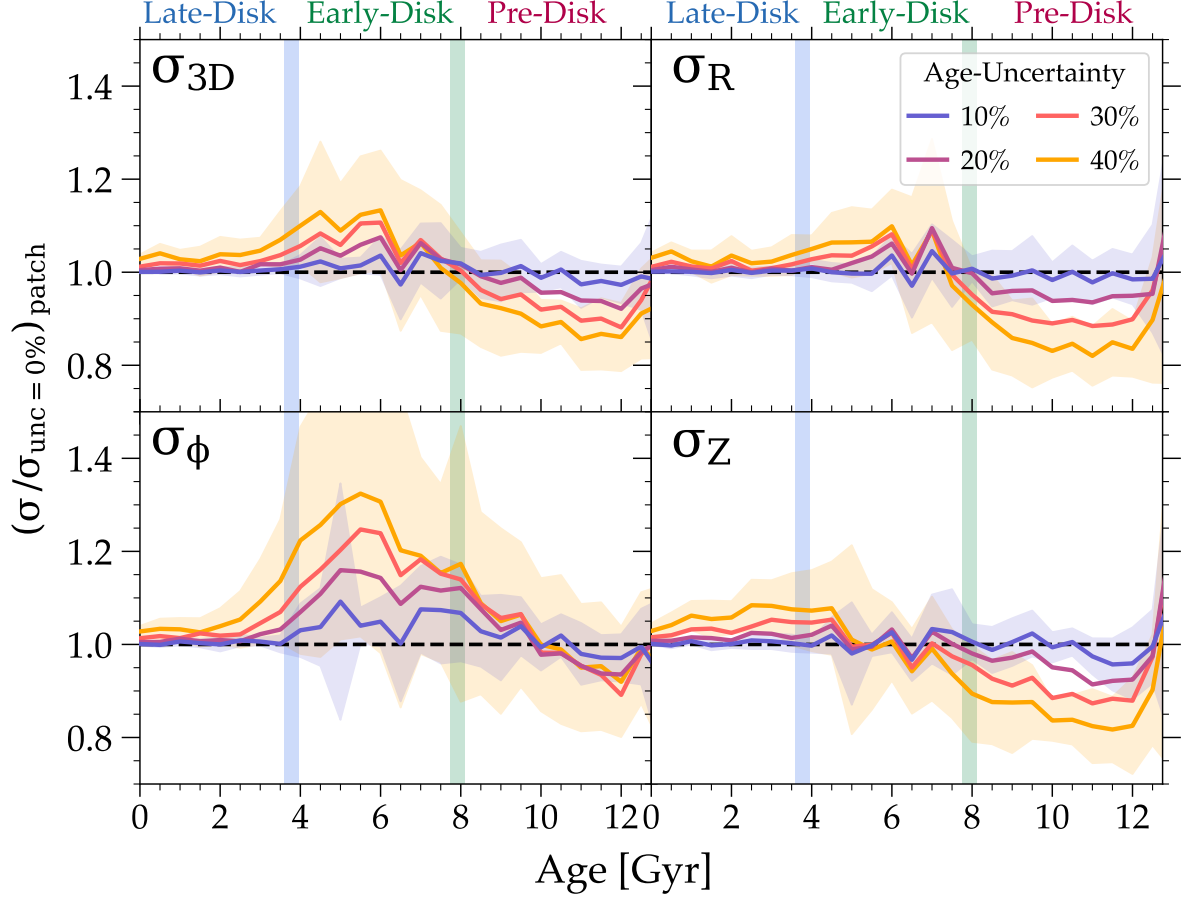


Figure 23: **The impact of stellar age uncertainties on the measured velocity dispersion.** The ratio of σ using different age uncertainties to its value without any age uncertainty, for σ_{3D} , σ_R , σ_ϕ , and σ_Z . Lines show the average across our 11 galaxies, and shaded regions show their corresponding 16-84th percentile range (for 10% and 40% age uncertainties). The shaded vertical bars indicate when these galaxies transitioned, on average, from the Pre-Disk to the Early-Disk Era (≈ 8 Gyr ago) and from the Early-Disk to the Late-Disk Era (≈ 4 Gyr ago). Overall, age uncertainties have only a minimal impact on σ of Late-Disk stars, with 40% uncertainties leading to $\lesssim 10\%$ increases. For Early-Disk stars, σ_R and σ_Z continue to be only minimally impacted, while σ_ϕ noticeably increases – on average, 20 and 40% age uncertainties cause σ_ϕ of 6 Gyr old stars to be overestimated by 15 and 30%, reflecting the (usually) rapid growth of the disk during this period. For Late-Disk stars, age uncertainties lead to lower σ on average, although this effect is within 10% for uncertainties $\lesssim 30\%$. Ultimately, age uncertainties have only a minor impact on the *value* of σ at a given age: on average, σ_{3D} remains within 20% of its true value, even for age uncertainties of 40%.

increase of σ with aperture radius, out to scales $\gtrsim 1$ kpc, highlights the *physical effects* of clustered star formation and gas turbulence. However, the absence of this scale dependence for stars 100–600 Myr old suggests that newly formed stars rapidly diffuse through phase space, with clusters dispersing on the order of a dynamical time. Thus, one should exercise caution in comparing results that measure σ of young stars across different spatial extents.

Figure 24 (bottom) quantifies how aperture size affects the aperture-to-aperture *scatter* in the measured σ_{3D} at fixed R . It shows the *fractional scatter* via the ratios of the scatter (the 68th percentile width) of σ_{3D} , relative to σ_{med} , around an annulus for a given stellar population. For all but the youngest stars, $\sigma_{\text{scatter}}/\sigma_{\text{med}}$ is remarkably scale-independent at $r_{\text{ap}} \gtrsim 250$ pc, being $\approx 10\%$, 5% , and 2% of the typical σ_{3D} at ages 400 Myr, 2 Gyr, and $\gtrsim 6$ Gyr. As above, the aperture-to-aperture scatter is most significant for young stars: σ_{3D} within $r_{\text{ap}} = 250$ pc varies by $\approx 50\%$ across the annulus, and remains as high as 20% even for $r_{\text{ap}} = 2$ kpc.

These results help to contextualize how the stellar σ varies within different apertures and “solar neighborhoods” of a galaxy. For example, as we will show in Section 3.5.3, the MW exhibits significantly colder kinematics than other galaxies. Individual 250 pc regions can have σ for *young* stars that are up to 40% lower than the galaxy’s average at a given R , which may be a limiting systematic in interpreting the MW. That said, such aperture-to-aperture variations do *not* provide a key systematic uncertainty for *older* stars.

3.4.3 GALACTOCENTRIC RADIUS

Observations show that σ decreases with galactocentric radius, R , in both external disk galaxies (for example Bottema, 1993; Kregel, van der Kruit, and Freeman, 2005) and the MW (for example Bovy et al., 2012b; Dehnen, McLaughlin, and Sachania, 2006). A classical explanation for this decrease follows from $\Sigma(R) \propto \sigma_Z^2/h_Z$ for a disk in equilibrium, where $\Sigma(R)$ is the surface density and h_Z is the disk scale height. To the extent that $h_Z(R)$ does not change significantly with radius, while $\Sigma(R)$ falls off rapidly with R (often as an exponential), this implies that σ_Z should decline with R .

Figure 25 shows σ_{3D} , measured in cylindrical apertures of $r_{\text{ap}} = 250$ pc and vertical extent $|Z| < 3$ kpc, versus R for stars of different ages. We limit our analysis to $R = 2 - 12$ kpc, neglecting the innermost region where the tangled contributions from the bulge, bar, and inner halo complicate interpreting the disk component; as well as the outer disk, where the number of older star particles is limited. σ increases with age at all R , and this is the primary dependence. Thus, to isolate trends with R , in Figure 25 we normalize the σ at each age to its value at $R = 12$ kpc. We have verified that our results are not sensitive to this normalization, as even in the (potentially warped) outer disk, the dispersion depends just on the relative motion of stars in that patch.

At all ages, σ decreases with R : stars in the inner galaxy have hotter kinematics. Such behavior is expected, given that previous work confirmed that the gas mass, stellar mass, and star formation surface densities in these simulations decrease with R (Gurvich et al., 2020; Orr et al., 2020). The strength of this radial dependence exhibits

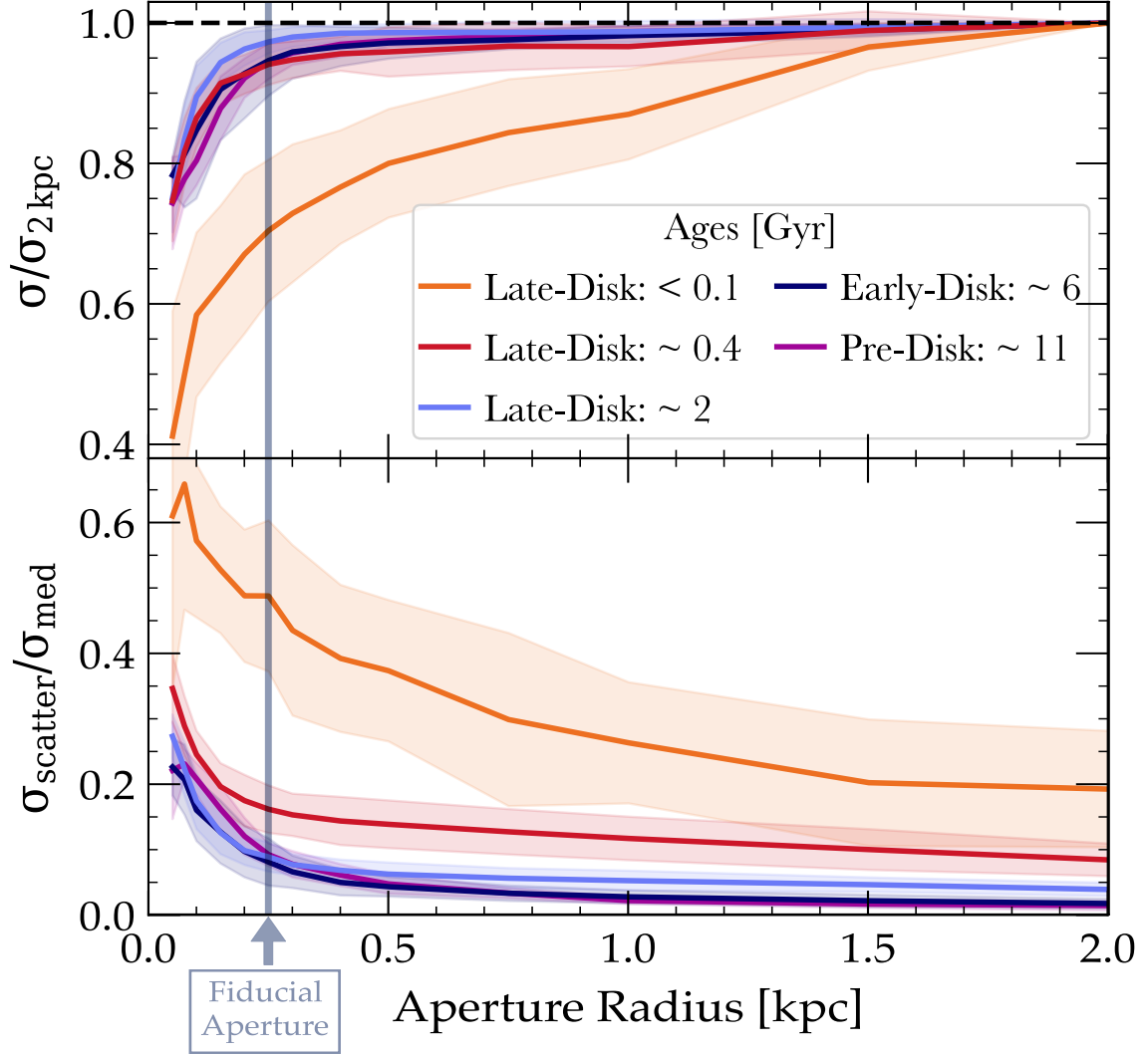


Figure 24: **Effect of aperture radius, r_{ap} , on the measured 3D velocity dispersion, $\sigma_{3\text{D}}$.** We measure $\sigma_{3\text{D}}$ in cylindrical apertures of radius r_{ap} and $|Z| < 3$ kpc across an annulus centered at $R = 8$ kpc. We average across 11 FIRE-2 galaxies, and the shaded region shows the galaxy-to-galaxy standard deviation. **Top:** The median of $\sigma_{3\text{D}}$ versus r_{ap} for stars of different ages, normalized by the value for a large aperture of $r_{\text{ap}} = 2$ kpc. The dashed horizontal lines indicates 100% of the dispersion value for $r_{\text{ap}} = 2$ kpc. $\sigma_{3\text{D}}$ is nearly independent of the aperture size at $r_{\text{ap}} \gtrsim 0.25$ kpc for all but the youngest stars (age $\lesssim 100$ Myr). For these stars, $r_{\text{ap}} < 0.25$ kpc leads to σ that are $\approx 50\%$ of those measured with $r_{\text{ap}} = 2$ kpc. **Bottom:** The fractional aperture-to-aperture scatter in σ around the annulus, normalized by the median σ . $\sigma_{\text{scatter}}/\sigma_{\text{med}}$ increases with smaller aperture radius, especially at $r_{\text{ap}} \lesssim 0.25$ kpc. The youngest stars have the largest relative contribution from σ_{scatter} . For $r_{\text{ap}} = 250$ pc, these σ vary by $\approx 50\%$ across the annulus. Older stars exhibit small scatter, indicating these populations are well mixed across the annulus.

a complicated relationship with age: the youngest stars (age < 100 Myr) have the strongest radial dependence, while stars of ages ≈ 6 Gyr, 11 Gyr, 400 Myr, and 2 Gyr show progressively weaker radial gradients.

The youngest stars (age < 100 Myr) show the strongest radial dependence: young stars in the inner galaxy have nearly twice the σ as their cohorts in the outer galaxy. This strong radial dependence is largely – though not exclusively – inherited from the star-forming ISM. In these FIRE-2 simulations, the gas surface density, Σ_{gas} , generally decreases by an order of magnitude between $R = 2 - 12$ kpc (Graf et al., 2024). This outward radial decline in σ also results from radially-dependent post-formation heating, and post-formation dynamical heating may be stronger in the inner galaxy (Aumer, Binney, and Schönrich, 2016; Schönrich and Binney, 2009).

These trends also reflect the radial redistribution of these populations. Stars do not necessarily remain at the R where they formed, but, via various dynamical processes, can redistribute across multiple kpc (for example Daniel and Wyse, 2018; El-Badry et al., 2018a; Frankel et al., 2020; Roškar et al., 2012; Sellwood and Binney, 2002; Vera-Ciro et al., 2014). In contrast to dynamical heating, post-formation radial redistribution has a negligible effect on stars younger than ≈ 100 Myr. This is not necessarily the case for older stellar populations. Indeed, 400 Myr and 2 Gyr old stars show the *weakest* radial dependence, despite forming with a radial dependence similar to that of 100 Myr old stars, due to radial redistribution. While stars from the cold outer disk exhibit a net inward redistribution, stars from the hot inner disk exhibit a net outward distribution (Bellardini et al. in prep.). In turn, this mixing subsequently weakens the strong radial dependence inherited at formation.

Stars 6 and 11 Gyr old exhibit a stronger radial dependence than those 400 Myr and 2 Gyr old. This might seem to contradict our earlier claim, given that these stars had more time to redistribute and weaken any initial radial dependence. However, when these stars formed, these galaxies were more radially compact, vertically thick, and highly turbulent (for example El-Badry et al., 2018b; Horta et al., 2024). Over time, these galaxies grew and formed disks, with subsequent generations of stars forming in increasingly thin and radially extended disk (Bellardini et al., 2022; Carrillo et al., 2023; Yu et al., 2022). Thus, while Late-Disk stars formed throughout this radial range ($R = 2 - 12$ kpc), older stars predominantly formed in the (now) inner galaxy.

The stronger radial dependence exhibited by stars that formed in the Early-Disk and Pre-Disk Eras compared with those that formed in the Late-Disk Era (save the youngest population) agrees with observations. For example, Aniyan et al., 2018 shows that in the nearby spiral galaxy, NGC 628, stars older than 3 Gyr exhibit a $\approx 50\%$ stronger radial dependence than their younger counterparts.

3.4.4 GALAXY INCLINATION ANGLE

The MW is the only galaxy where we can directly measure all three velocity components; in external galaxies, observations are typically limited to the 1D line-of-sight velocity, v_{LOS} . Because v_{LOS} is a projection of the intrinsic 3D velocity, its value depends on inclination, with different viewing angles amplifying or suppressing

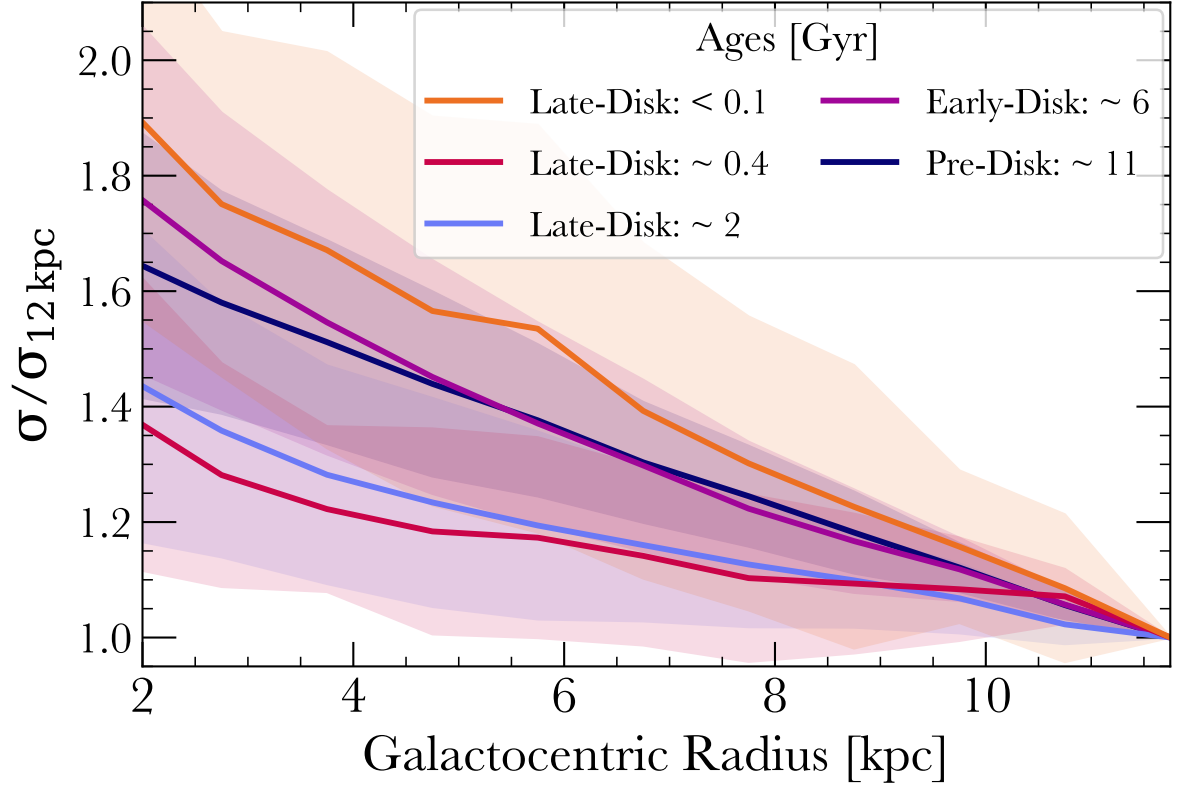


Figure 25: **Effect of galaxy radial selection on the measured 3D velocity dispersion.** σ_{3D} , normalized to its value at $R = 12$ kpc, for stars of different ages. σ_{3D} increases towards the inner galaxy, with the youngest stars (age $\lesssim 100$ Myr) having the strongest radial dependence, followed by Early- and Pre-Disk stars, and finally the older Late-Disk populations, indicating that though the star-forming ISM is more turbulent at small radii, subsequent radial mixing of young stars mitigates this dependence.

individual velocity components. The inclination dependence of σ_{LOS} complicates our ability to directly compare galaxies, and may obscure (or erroneously suggest) intrinsic differences in their kinematics.

For example, McCluskey et al. (2024) examined the evolution of these components in these FIRE-2 simulations and found that $\sigma_R > \sigma_\phi > \sigma_Z$ at all ages, both at formation and today. At birth, the radial component accounted for about half of the total energy in σ , with the azimuthal and vertical components contributing $\approx 32\%$ and $\approx 17\%$, respectively. Over time, post-formation heating amplified these differences, with young stars experiencing stronger radial heating, likely due to bar and spiral structure, while vertical heating remained more constant. As a result, while σ_Z shows the weakest absolute increase with age, it exhibits the strongest fractional evolution.

Rather than deriving full corrections for inclination effects – where dust extinction and beam smearing introduce additional complexities – we isolate the geometric influence of inclination, specifically how σ_{LOS} changes due to the shifting contributions of σ_R , σ_ϕ , and σ_Z (see Ejdetjärn et al., 2022 for discussion on additional inclination effects on gas dispersions). Most importantly, we show how this effect varies with stellar age, providing insight for comparing $\sigma(\tau)$ across different galaxies.⁴

Figure 26 shows σ_{LOS} , normalized to its value for a face-on projection, versus inclination for stars of different ages. At each age, we mark the value of σ_R with a triangle on the right, because σ_R is the largest, so it sets an upper limit on σ_{LOS} . We also indicate the inclination where $\sigma_{\text{LOS}} = \sigma_{3D}/\sqrt{3}$ with circles, in part to aid in our later comparisons to the MW, for which we assume isotropy in comparing with other observed galaxies.

At all ages, σ_{LOS} increases with inclination. This is unsurprising: in face-on galaxies, σ_{LOS} reflects only vertical motions, while at edge-on inclinations, it is entirely independent of σ_Z . Because σ_Z is smaller than the in-plane σ in disk galaxies, higher inclinations amplify the contribution of the dominant in-plane components to σ_{LOS} .

Inclination effects depend on stellar age: σ_{LOS} of 400 Myr and 2 Gyr old stars shows the strongest dependence on inclination, with edge-on σ_{LOS} exceeding face-on σ_{LOS} by a factor of ≈ 2 . By comparison, young stars (age < 100 Myr) show a weaker dependence on inclination. The stronger inclination dependence after just a few 100 Myr reflects the nature of early dynamical heating of these stars: rapid and strongly in-plane. σ_{3D} increases from 30 km s^{-1} at 100 Myr to 75 km s^{-1} at 1 Gyr, with σ_R accounting for 60% of this increase, σ_ϕ by 30%, and σ_Z just under 10% (see Figure 32). This radially-biased dynamical heating becomes weaker over time, while vertical heating persists, as Early-Disk and Late-Disk stars exhibit weaker inclination dependencies and thus more isotropic σ (see Section 3.5.4.2).

Although many methods for inclination correction exist (for example Westfall et al., 2019), they typically assume a homogeneous stellar population, applying the same correction across all stars regardless of age. However, Figure 26 shows that the inclination affects stellar populations of different ages in distinct ways. A one-size-fits-all

⁴ Our spatial selection does not account for inclination-induced projection effects: we define cylindrical apertures consistently across all inclinations, ensuring that each aperture always contains the same stars. This effectively selects apertures as if viewing the galaxy face-on, where a single line of sight corresponds to an aperture along the annulus. In reality, at higher inclinations, each line of sight cuts through a cylindrical stripe of the disk, so an aperture includes stars from a range of galactocentric radii and azimuthal positions.

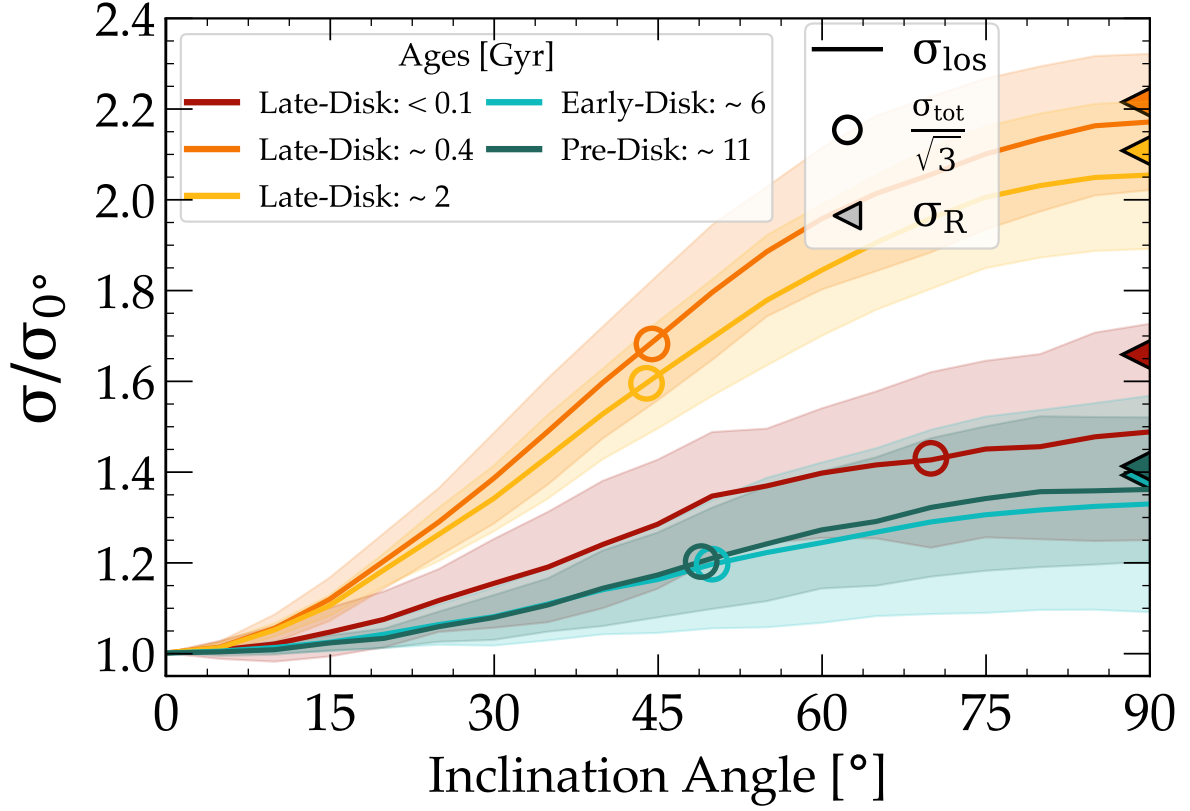


Figure 26: **The impact of galaxy inclination angle on the line-of-sight velocity dispersion.** σ_{LOS} , normalized to its value for a face-on galaxy (0°), versus inclination angle for stars of various ages. Circles show where $\sigma_{\text{LOS}} = \sigma_{\text{3D}}/\sqrt{3}$. For reference, triangles at right mark σ_R , which is the largest component, at each age. For all ages, σ_{LOS} increases with inclination, equaling σ_Z at 0° but remaining slightly subdominant to σ_R at 90° . Older stars generally show weaker dependence on inclination, reflecting their less circular orbits, while 0.4 and 2 Gyr old stars show the strongest dependence, such that their edge-on σ are $\gtrsim 2\times$ of their face-on values. Interestingly, the inclination dependence of the youngest stars (age $\lesssim 100$ Myr) is intermediate to the older Late-Disk and Early/Pre-Disk populations, indicating that the star-forming ISM is more isotropic and that early heating is primarily in-plane.

correction can misrepresent the intrinsic kinematics by overestimating σ of younger stars (400 Myr to 2 Gyr) relative to both the youngest and older stars. Overall, one must apply age-dependent corrections before interpreting trends such as dynamical heating or other evolutionary processes.

3.5 OBSERVATIONAL COMPARISONS

Thus far, we used FIRE-2 simulations to investigate how age uncertainties, aperture size, galactocentric radius, and galaxy inclination influence measurements of stellar velocity dispersion. These results provide us with a

Galaxy	$M_{\star}$ [$10^{10}M_{\odot}$]	$v_{\text{FE},0}$ [km/s]	r_{ap} [pc]	Inclination [$^{\circ}$]	Reference
Milky Way	$5 \pm 1^{\text{a}}$	238^{a}	250	-	See Table 5
M31	$10.3 \pm 2.3^{\text{b}}$	260	760	77	Dorman et al., 2015
M33	$0.48 \pm 0.06^{\text{c}}$	93	420	54	Quirk et al., 2022
PHANGS median (range)	3.63 (0.25 - 9.3)	$182(137 - 230)^{\text{d}}$	100	38.5 (8.9 - 57.3)	Pessa et al., 2023

Table 4: Properties of nearby disk galaxies with measured stellar velocity dispersion versus age: Values without superscripts are from the listed reference, while superscripted values are from: a: Bland-Hawthorn and Gerhard, 2016, b: Sick et al., 2015, c: Corbelli et al., 2014, and d: Lang et al., 2020. $v_{\phi,0}$ refers to the maximum circular velocity of the gaseous or young stellar disk (see text for more details). 0° inclination is face-on, 90° is edge-on.

framework for combining and comparing disparate observations of $\sigma(\tau)$ in observed galaxies. We now compile observations from the literature, including the MW, M31, M33, and PHANGS galaxies, and we compare $\sigma(\tau)$ in these galaxies. We then use these observations to benchmark how well the FIRE-2 simulations model $\sigma(\tau)$.

3.5.1 M31, M33, AND PHANGS

In this section, we outline three works that measured σ_{tau} in disk galaxies other than the MW: the studies of M31 by Dorman et al. (2015) (hereafter D15), M33 by Quirk et al. (2022) (hereafter Q22), and 19 PHANGS-MUSE galaxies by Pessa et al. (2023) (hereafter P23). Here we provide a broad overview of the observations and briefly discuss certain key details of each work’s method, and we discuss these observations in greater detail in Appendix 3.7.2. Table 4 lists these galaxies’ stellar masses, circular velocities, inclinations, and the typical aperture radius used by each study.

M31’s proximity (785 kpc), nearly edge-on inclination (77°), and low foreground extinction (Schlafly and Finkbeiner, 2011) provide a relatively clear view of its entire disk and halo, while also allowing observations of many individually resolved stars. Like the MW, M31 hosts a central bar and an extended stellar disk. However, multiple lines of evidence indicate that our massive neighbor had a more extended and active accretion history. For example, M31’s stellar halo is $\approx 10\times$ more metal-rich and $\approx 10\times$ more massive than the MW’s, containing significant tidal debris and a metal-rich component consistent with belonging to a “kicked-up” disk population (Dorman et al., 2013; Escala et al., 2023). Similarly, M31’s disk appears thicker than the MW’s, with RGB stars having a scale height of ≈ 770 pc (Dalcanton et al., 2023). Simulations indicate that these properties are consistent with M31 experiencing a major ($\approx 4 : 1$) merger ≈ 2.5 Gyr ago (D’Souza and Bell, 2018; Hammer et al., 2018),

which is likely related to M31’s contemporaneous global burst of star formation (for example Williams et al., 2015).

Much of this knowledge of M31 results from large-scale surveys of resolved stellar populations throughout M31’s disk and halo. Two notable surveys of M31’s disk are the Panchromatic Hubble Andromeda Treasury (PHAT) survey (Dalcanton et al., 2012; Williams et al., 2014), a Hubble Space Telescope (HST) MultiCycle Treasury program that provided six-filter photometry for 138 million stars, and the Spectroscopic and Panchromatic Landscape of Andromeda’s Stellar Halo (SPLASH) survey (Dorman et al., 2012; Gilbert et al., 2012; Guhathakurta et al., 2006), which obtained Keck/DEIMOS spectra for $\approx 10,000$ stars. These two surveys allowed for the first measurements of $\sigma(\tau)$ in a disk galaxy other than the MW.

M31’s largest satellite, M33, allows us to study a disk at lower masses. Lying 859 kpc from the MW, M33 offers a holistic view and resolved stellar populations. With a stellar mass of $3 \times 10^{10} M_{\odot}$, M33 provides a crucial perspective on the formation of galactic disks, as this is precisely the “mass of disk formation”, that is, the mass where the observed (stellar mass) Tully-Fisher relation transitions (Simons et al., 2015). HST provided six-filter photometry for millions of disk stars, here for ≈ 22 million stars via the Panchromatic Hubble Andromeda Treasury: Triangulum Extended Region (PHATTER) survey (Williams et al., 2021), while complementary spectroscopic surveys provide line-of-sight velocities for a small fraction of the photometric sample. For example, the TRiangulum EXtended Survey (TRESX) survey (Quirk et al., 2022, hereafter) measured spectra for ≈ 7000 stars across the disk of M33. Importantly, these two surveys allowed Q22 to measure $\sigma(\tau)$ in M33 using ≈ 3000 stars.

Within the LG, we can resolve *individual* stars, but the number of disk galaxies is limited. Fortunately, integral-field spectroscopy (IFS) of nearby galaxies offers a compelling new window, with IFS instruments like MUSE on the VLT providing spatially resolved spectra of stellar populations on ≈ 100 pc scales. Recently, P23 used MUSE to measure $\sigma(\tau)$ in the 19 star-forming galaxies comprising the PHANGS-MUSE sample. These galaxies lie within $\lesssim 20$ Mpc of the MW, have low to moderate inclinations ($< 60^\circ$), and have stellar masses of $\log(M_{\star}/M_{\odot}) = 9.4 - 11.0$, with a median of $\log(M_{\star}/M_{\odot}) = 10.5$. Although P23 measured $\sigma(\tau)$ for all 19 of these galaxies, we only include results from the 16 that also have reported rotational velocity measurements from Lang et al. (2020). An important caveat for interpreting the results of this work is that these σ from MUSE are likely overestimated at small intrinsic values (and thus at young ages), as we discuss in Section 3.5.3.

3.5.2 THE MILKY WAY

We now present a compilation from the literature of observational measurements of $\sigma(\tau)$ of the MW. We restrict our compilation to results published after the release of *Gaia* DR1, with the exception of three commonly cited studies based on the (pioneering and pivotal) Geneva-Copenhagen Survey (GCS). Table 5 summarizes the key

properties of the observational datasets we include. As for the above galaxies, we provide additional details in Appendix 3.7.2.4.

Figure 27 shows the radial, azimuthal, vertical, and 3D velocity dispersions in the MW from 13 analyses. While some works present all 3 velocity components, many present only one or two. Consequently, each panel of Figure 27 includes different subsets of observations. Specifically, while σ_Z contains data from all 13 works, σ_R , σ_ϕ , and σ_{3D} include data from 9, 7, and 8 works, respectively. Secondly, 5 of these works split their sample into separate high- and low- α populations and did not present σ for their combined sample. For these works, we show the low- α data as filled markers and the high- α data as unfilled.

In addition to showing σ reported by each of these works (scatter points), Figure 27 also shows the mean of the sample (solid lines) and its maximum-minimum range (shaded regions). To standardize the age-binning of these different observations, we used a 1-D linear interpolation method to fit each work’s data into 250 Myr-wide age bins spanning 0.25 – 13.25 Gyr. For works that distinguished between high- and low- α stars, we treated the data of the two populations separately. We then found the mean/minimum/maximum σ of our interpolated sample in each age bin, excluding data for high- α populations for ages < 8 Gyr and low- α populations for ages > 8 Gyr.

We make this cut in α -element populations for two reasons. First, the relative fractions of high- and low- α stars are almost always far from equal at any given age. Given that the vast majority of high- α stars have ages $\gtrsim 8$ Gyr while most low- α stars exhibit ages spanning 0 – 10 Gyr, this cut provides a broadly sensible distinction. That said, a significant number of stars seemingly depart from the simple heuristic that high- α stars are old and low- α stars are young. Much debate has surrounded the nature of reportedly young (age < 6 Gyr) high- α stars, with a general consensus that these stars are not genuinely young, but are instead the product of binary evolution, having gained mass through mergers or accretion (for example Grisoni et al., 2024; Jofré et al., 2023; Miglio et al., 2021). On the other end, the nature of old (> 10 Gyr) low- α stars remains unclear, potentially because the formation of these populations truly overlapped (Silva Aguirre et al., 2018), or because significant older high-alpha stars are subject to significant age uncertainties (Haywood et al., 2013). See Buder et al. (2019) for further discussion. Nevertheless, the mean σ for stars with ages $\gtrsim 8$ Gyr is largely unaffected by this cut, with the inclusion or exclusion of old low- α stars changing the mean σ by $\lesssim 5\%$.

In Figure 27, all three components (σ_R , σ_ϕ , σ_Z) exhibit a broadly similar age dependence: a steady rise for stars younger than ≈ 8 Gyr followed by a shallower slope at older ages. This flattening is most apparent in σ_R and σ_ϕ , whereas σ_Z continues to increase with age more noticeably, albeit more gradually than it does at younger ages. Across all ages, the radial component dominates, with the mean σ_R exceeding the means of both σ_ϕ and σ_Z by at least 50%. For stars younger than ≈ 8 Gyr, $\sigma_\phi > \sigma_Z$, while the two components become roughly comparable for older populations. These trends – σ_Z ’s continued rise, σ_R ’s dominance, and σ_ϕ and σ_Z ’s convergence at old ages – are in remarkable agreement with the results of McCluskey et al. (2024) for FIRE-2 (see their Figure 4). We further explore the physical drivers of the relative strength and evolution of each component of σ in Section 3.5.4.2.

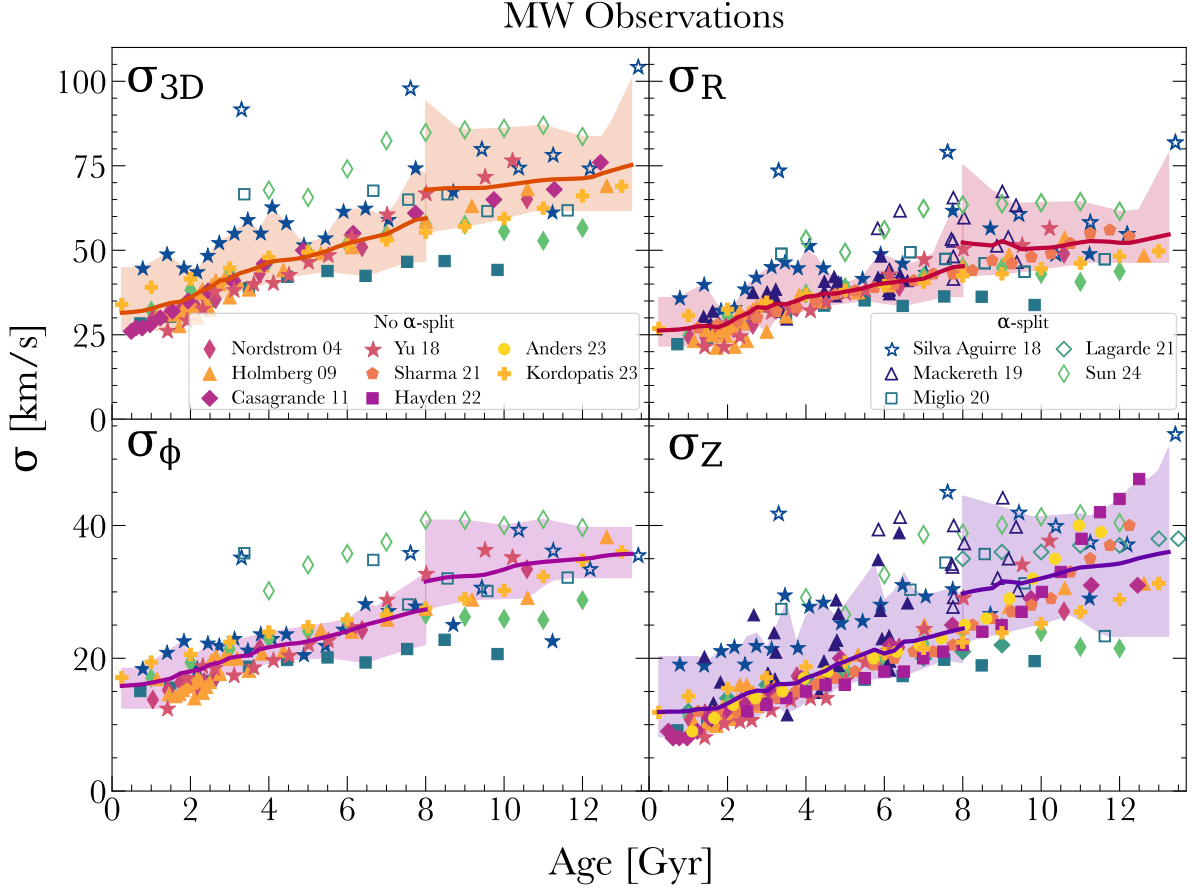


Figure 27: **Compilation of stellar velocity dispersion versus age observed for the Milky Way.** “Warm” colored points show works that included all stars, while “cool” colored points show works that separated stars into high- α (unfilled markers) and low- α (filled markers). Solid lines show the mean, and shaded region shows the full range, across the observations, see §3.5.2 for details and caveats, including the origin of break in the mean relation. All works agree that each component of σ increases with age, but these works show substantial scatter for both the normalization and shape of the observed relation. σ_R unambiguously dominates: the mean σ_R is at least 50% greater than the mean σ_ϕ and σ_Z at all ages. For ages $\lesssim 8$ Gyr, $\sigma_\phi > \sigma_Z$, while $\sigma_\phi \approx \sigma_Z$ for ages > 8 Gyr.

Despite the general agreement among the different observational datasets that each component of σ increases with age, there is considerable scatter in both the normalization and slope of the relation. Even after discounting potentially biased measurements from high- or low- α samples, the total 3D velocity dispersion at fixed age can vary by $\approx 25\%$, with σ_Z alone varying by up to 50%. Nevertheless, none of the observational trends show evidence of a factor of two increase in σ over the age range.

Reference	Survey(s) Used	Stellar Type	Age Method	Spatial Selection [kpc]	Velocity Components	α -element Split?
Nordström et al., 2004	GCS	F+G dwarfs	Isochrone	$d < 0.1$	U, V, W	-
Holmberg, Nordström, and Andersen, 2009	GCS	F+G dwarfs	Isochrone	$d < 0.1$	U, V, W	-
Casagrande et al., 2011	GCS	F+G dwarfs	Isochrone	$d < 0.1$	W, 3D	-
Silva Aguirre et al., 2018	APOGEE DR10, Kepler, Gaia DR1	RC/RGB	Asteroseismic	$d < 2 \quad Z < 1$	U, V, W	yes
Yu and Liu, 2018	LAMOST DR3, Gaia DR1	SGB/RGB	Isochrone	$d < 1 \quad Z < 0.27$	R, ϕ, Z	-
Mackereth et al., 2019a	APOGEE DR14, Gaia DR2	RC/RGB	Spectroscopic		R, Z	yes
Lagarde et al., 2021	APOGEE DR14, Kepler, Gaia DR2	RC/RGB	Asteroseismic	$R = 7.5 - 8.5 \quad Z < 1.2$	R, ϕ, Z	yes
Miglio et al., 2021	APOGEE DR14, Kepler, Gaia DR2	RC/RGB	Asteroseismic	$d < 1 - 2$	Z	yes
Sharma et al., 2021	GALAH iDR3, Gaia DR2	MSTO	Spectroscopic	$R = 6 - 10 \quad Z < 0.6$	R, Z	-
Hayden et al., 2022	GALAH DR3, Gaia DR2	All	Chemical	$R = 7.1 - 9.1 \quad Z < 0.5$	Z	-
Anders et al., 2023	APOGEE DR17	RGB	Spectroscopic	$R = 7 - 9$	Z	-
Kordopatis et al., 2023	Gaia DR3	MSTO	Isochrone	$d < 1$	R, ϕ, Z	-
Sun et al., 2024	LAMOST DR4, Gaia EDR3	RC	Asteroseismic	$R = 7 - 9 \quad Z < 1$	R, ϕ, Z	yes

Table 5: Compilation of Observational Analyses of the MW in our Comparison: All distances in kpc. For the reported spatial selection, d is the total 3D distance from the Sun, while R and Z refer to Galactocentric radial and vertical coordinates. For the reported components of σ , U , V , and W are Galactic space-velocities, where U points towards the Galactic center, V the direction of rotation, and W the north Galactic pole, while R , ϕ , Z are Galactocentric cylindrical coordinates. Works that report all 3 velocity components necessarily provide the 3D total dispersion as well (either directly or indirectly), but we do not include 3D in the listed reported components, with the exception of works that report the total dispersion sans the three components.

3.5.3 COMPARING OBSERVED GALAXIES

Figure 28 shows $\sigma(\tau)$ for the MW, M31, M33, and PHANGS galaxies. For the MW, we show the mean and range of the 13 observations from Figure 27 (top left), and we convert the MW’s total 3D σ to a 1D value by assuming isotropy: $\sigma_{1D} = \sigma_{3D}/\sqrt{3}$. Some such conversion is necessary, given that the other observations show inherently 1D σ_{LOS} . That said, stars in the MW are generally not isotropic but instead typically have $\sigma_R > \sigma_\phi > \sigma_Z$. However, we assume isotropy for this comparison to account for the wide range of inclinations of the other observed galaxies. Figure 26 shows that $\sigma_{3D}/\sqrt{3}$ typically matches σ_{LOS} at inclinations $45 - 50^\circ$, but over/underestimates σ_{LOS} at smaller/larger inclination. However, these estimates are typically within 25% and 10% of the proper value for young stars and old stars, respectively. In turn, inclination effects, or the faulty assumption of isotropy, cannot cause a factor of 2-3 difference between galaxies.

Direct comparisons between galaxies are complicated by the different age binning employed by these works. First, data for external galaxies are limited to 3 or 4 age bins of unequal width, whereas most MW datasets use narrower and more uniform bins. Second, the youngest age bins for external galaxies are $0 - 100$ Myr but are $250 - 500$ Myr in the MW. MW datasets rarely include the youngest ages easily probed in external galaxies, because MW observations are limited by the scarcity of young stars in the solar neighborhood and subject to different biases introduced by survey design and selection criteria. For example, GCS excludes blue stars entirely, whereas other surveys remove stars with poorly constrained ages, a common issue for younger RGB stars. This gap between the youngest age bins in external galaxies and the MW can be partially addressed by including blue stars with imprecise ages, as in Aumer and Binney, 2009, who found $\sigma_{3D}/\sqrt{3} \approx 8 \text{ km s}^{-1}$. Alternatively, young star clusters provide well-dated populations, as demonstrated by Tarricq et al., 2021, who measured $\sigma_{3D}/\sqrt{3} \approx 5.2$ and 7.3 km s^{-1} for clusters aged 15 Myr and 100 Myr. Including these other populations further suggests that the MW is particularly kinematically cold.

Figure 28 (top) shows σ_{1D} versus stellar age. The MW and M33 show significant overlap at all ages, and while some PHANGS galaxies reach similarly low values, most PHANGS galaxies have σ that are twice as large. Furthermore, although M31 falls within the 68% scatter of the PHANGS sample at ages $\lesssim 1$ Gyr, by 4 Gyr its σ towers over that of the other galaxies, reaching values that are approximately $2\times$ that of the typical PHANGS galaxy and $4\times$ those of M33 and the MW. However, we caution against taking this comparison of σ_{1D} at face value because it does not account for the order-of-magnitude range in these galaxies’ stellar masses.

Figure 28 (bottom) shows a more robust comparison, where we now scale each galaxy’s measured $\sigma_{1D}(\tau)$ by its measured circular velocity today, $v_{E,0}$, as obtained from the literature. For M31 and M33, we adopt the maximum rotational velocity of the youngest stars from D15 and Q22, respectively. For each PHANGS-MUSE galaxy, we use the peak velocity of the CO-based rotation curve, as determined in Lang et al. (2020) using PHANGS-ALMA observations. Lastly, for the MW, we adopt the circular velocity at the solar position from the literature review of Bland-Hawthorn and Gerhard (2016). We list these $v_{E,0}$ values, and their respective sources, in Table 4. Ideally, our

adopted $v_{E,0}$ values would rely on identical methods for each galaxy; that said, these different methods generally yield values within a few percent of each other, which would have little impact on our main conclusions.

Figure 28 (bottom) shows a clear contrast between the MW and nearby galaxies. External galaxies, although constrained to broad age bins with only partial overlap with MW data, exhibit $\sigma/v_{\phi,0}$ that are almost all higher than the MW. Compared to the MW, $\sigma/v_{\phi,0}$ is higher in M31 by $2.3 - 3.3\times$ (depending on age), is higher in M33 by $2.4 - 2.8\times$, and is higher than the average PHANGS galaxy by $2.7 - 3\times$. Furthermore, 15 of 16 PHANGS galaxies exceed the MW’s value by at least a factor of 1.5, while the 68th percentile range for PHANGS is consistently double that of the MW. The MW’s relation becomes even more striking when compared to the remarkable uniformity of M31, M33, and the average PHANGS galaxy, whose $\sigma/v_{\phi,0}$ vary by no more than 20%, provided that we exclude the likely overestimated σ at the youngest ages in PHANGS.

Although PHANGS galaxies exhibit a mean $\sigma/v_{\phi,0}$ that is more than double that of the MW, we emphasize that one galaxy (NGC 1433) has values nearly identical to the MW’s. This is an important benchmark, given the different methodologies of measuring σ in the MW versus in nearby galaxies: NGC 1433 shows that at least one other disk galaxy has measurable stellar kinematics similar to that of the MW. NGC 1433’s low σ may reflect (partially) the galaxy’s low inclination (28.6°), because, as Figure 26 shows, such inclinations lead to measured dispersions that are $10 - 25\%$ lower than isotropic predictions (which we assumed for the MW in Figure 28. However, low inclination alone cannot explain NGC 1433’s low dispersions, because other PHANGS galaxies exhibit similar, if not smaller, inclinations. NGC 1433’s properties provide further explanations for its cold kinematics. Its stellar mass, $7.9 \times 10^{10} M_\odot$ —the second highest in the PHANGS sample—aligns with theoretical predictions from McCluskey et al., 2024 that link higher galaxy masses with more vertically settled disks. Moreover, the galaxy’s subdued star formation rate of $1.1 M_\odot \text{yr}^{-1}$, comparable to the MW’s $\approx 2 M_\odot \text{yr}^{-1}$ (Elia et al., 2022), places it 0.36 dex below the star-forming main sequence, the largest offset in the PHANGS sample. With lower SFRs comes lower stellar feedback and thus a less turbulent ISM, allowing stars to form with colder kinematics than those in more turbulent galaxies. These shared traits of NGC 1433 and the MW – moderately high stellar masses and low SFR – provide useful information in understanding how comparatively cold stellar kinematics relates to a galaxy’s recent and cumulative star formation history. We further discuss potential explanations for why the MW is kinematically colder than the majority of these observed galaxies in Section 3.6.2.1.

3.5.4 COMPARING FIRE-2 WITH OBSERVATIONS

We now compare the $\sigma(\tau)$ of these observed galaxies to those of FIRE-2 simulations. We separately compare each observed galaxy (or galaxy sample in the case of PHANGS), so that we match the aperture size, radial selection, inclination angle, and age-binning of each work. For all of these comparisons, we scale each (observed and simulated) galaxy by its $v_{\phi,0}$, which for FIRE-2 we define as the azimuthal velocity of stars with age $< 100 \text{ Myr}$

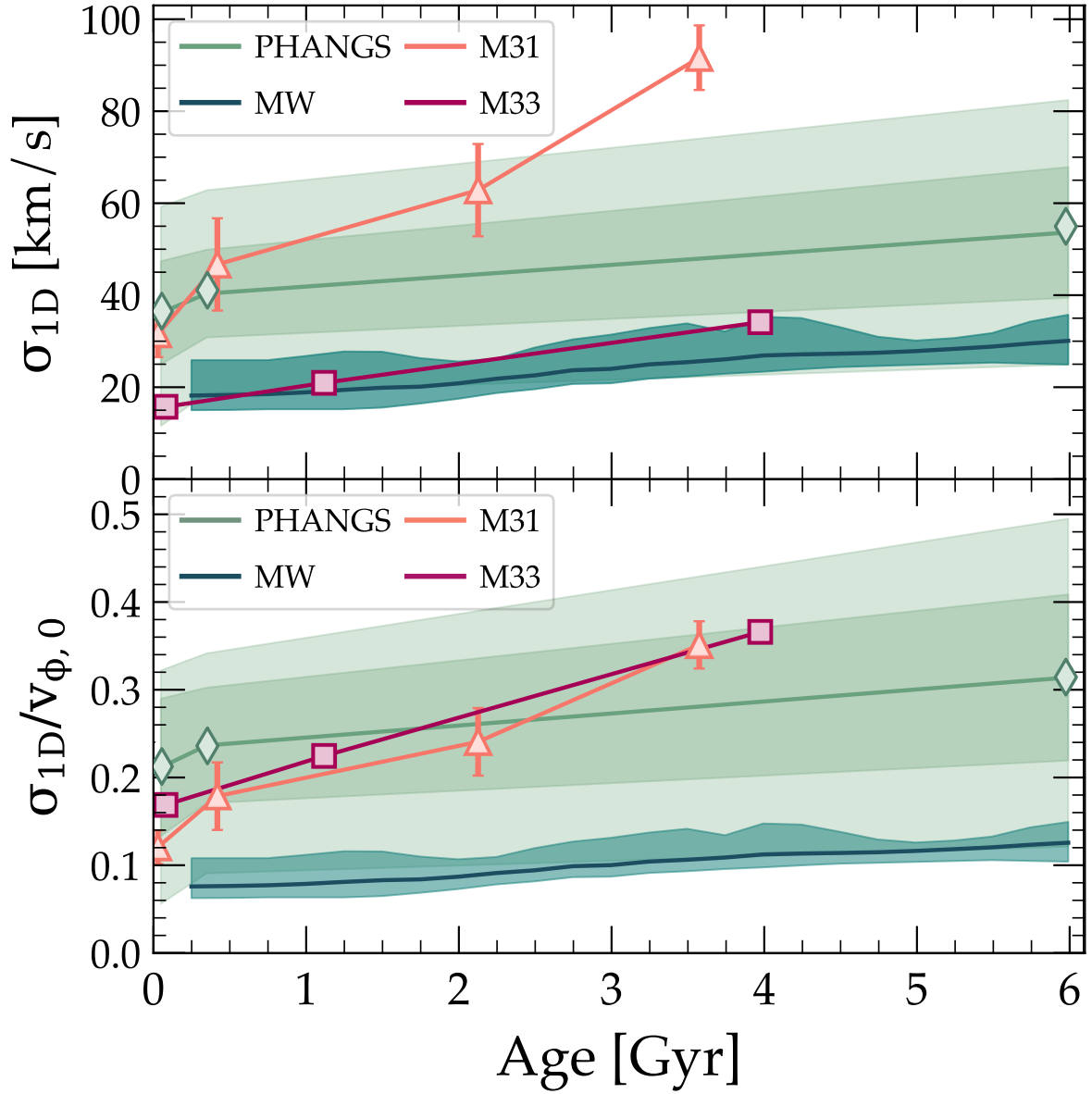


Figure 28: **Comparison of stellar velocity dispersion versus age in nearby galaxies.** **Top:** The line-of-sight (1D) velocity dispersion of stars, σ_{1D} , versus age, as observed in the MW, M31 (Dorman et al., 2015), M33 (Quirk et al., 2022), and 16 nearby galaxies from the PHANGS survey (Pessa et al., 2023). For the MW, the teal line and shaded region show the mean and full scatter across the observational works in Figure 27 for $\sigma_{1D} = \sigma_{3D}/\sqrt{3}$. The light green line and shaded regions show the median, 68% scatter, and full range across the PHANGS sample. **Bottom:** Same, but scaled to each galaxy’s rotational velocity, $v_{\phi,0}$, for young stars today, to provide a dimensionless metric of dynamical coldness that is more comparable across these different-mass galaxies. σ_{1D} and $\sigma_{1D}/v_{\phi,0}$ increase with age for all galaxies and at all ages, *though at differing rates with age*. M31 and M33 have broadly similar $\sigma_{1D}/v_{\phi,0}$, which also agrees with (lies within the 68% scatter) of PHANGS. However, among this total sample of 19 galaxies, *the MW is an outlier*, being dynamically colder in terms of $\sigma_{1D}/v_{\phi,0}$ than all but one galaxy from PHANGS.

measured in apertures of $r_{\text{ap}} = 250$ pc across the annulus at $R = 8$ kpc, although these values exhibit little dependence on the exact age and aperture size. We adopt age uncertainties of 20% when measuring $\sigma(\tau)$ in FIRE-2, reflecting the lower end of typical observational age uncertainties.

3.5.4.1 FIRE-2 VERSUS M31, M33, AND PHANGS

We first compare FIRE-2 simulations to M31, M33, and PHANGS.

For our M31 comparison, we adopt an inclination angle of 77° and an aperture radius of 760 pc – the mean r_{ap} used by D15. The age bins in D15 have fairly broad and overlapping age distributions, but each binned distribution showed a distinct peak. To compromise between “broad and overlapping” and “clearly defined” age bins, we use bins that span 0 – 0.1 Gyr, 0.1 – 1 Gyr, 0.5 – 3.17 Gyr, and 1 – 10 Gyr (where $3.17 \approx \sqrt{10}$). We measure σ across annuli centered at $R = 5, 8, 11$, and 14 kpc broadly to match the radial range probed by D15 while accounting for the fact that our stellar disks do not extend as far as M31’s and thus suffer from poor sampling at $R \gtrsim 16$ kpc.

For our M33 comparison, we use an inclination of 56° , $r_{\text{ap}} = 420$ pc (the median aperture in Q22), and age bins of 0.02 – 0.18 Gyr, 0.56 – 2.2 Gyr, and 1.4 – 9 Gyr, corresponding to the 16 – 84th percentile ranges given for the age distributions in Q22. We measure σ across annuli centered at $R = 1.5, 4, 6.5$, and 9 kpc, because these four equally spaced values bracket the radial range probed in Q22.

For our PHANGS comparison, we use $r_{\text{ap}} = 100$ pc, age bins of 0–0.1, 0.1–0.6, and 3 – 10 Gyr (the same as used by P23), and $R = 3, 5$, and 7 kpc. As before, we find the median σ across the 3 annuli, which we then average across. We repeat this for each of the 16 inclinations of the PHANGS sample ($8.9 - 57.3^\circ$). We then average over these 16 measurements for each simulated galaxy, before ultimately computing the mean across our 11 simulations.

Figure 29 (left) compares observations of M31 from D15 with the M31-like apertures applied to FIRE-2. FIRE-2 shows remarkable agreement with M31, especially at younger ages. This agreement at young ages is encouraging, because M31’s large dispersions (relative to the MW) are generally attributed to a major merger approximately 2.5 Gyr ago for example D’Souza and Bell, 2018; Hammer et al., 2018. Although such a merger likely had dramatic effects on M31’s dynamical state, both now and at the time of the merger, its ability to *directly* heat stars that formed more than 2 Gyr later is clearly circumspect at best. Similarly, the majority of FIRE-2 galaxies lack significant late-time mergers (though we note that m12f experienced a fairly massive merger less than a Gyr ago), such that our young stars’ deviations from MW-like kinematics can not be handily ascribed to (or, perhaps more accurately, blamed on) merger events. Thus, FIRE and M31’s agreement at young ages implies that non-MW-like kinematics can occur without the need for mergers. That said, although M31’s oldest age sample lies within the full distribution of FIRE-2, M31 falls at the high end of the FIRE-2 distribution, hinting that merger driven heating plays a non-negligible role at older ages in M31 (and at least some of our simulations).

Similarly, Figure 29 (middle) compares $\sigma(\tau)$ measured in FIRE-2 using “M33-like apertures” with the actual relation observed for M33 by Q22. Overall, FIRE-2 agrees well with M33, although the youngest stars in M33 exhibit slightly higher σ than FIRE-2. Considering the marked similarity between M31 and M33’s $\sigma_{\text{LOS}}/v_{\phi,0}$ in Figure 28, it is perhaps not too surprising that FIRE-2 – having just been seen to agree with M31 – also agrees fairly well with M33. However, Figure 28 simply reports the values reported in the literature and does not account for the different radial ranges, aperture sizes, and inclinations of these observations.

Lastly, Figure 29 (right) compares the average (and sample scatter) of $\sigma(\tau)$ observed in the PHANGS-MUSE sample of 16 nearby galaxies with FIRE-2. At first glance, the agreement is weaker than with M31 and M33, with the typical $\sigma_{\text{LOS}}/v_{\phi,0}$ of the youngest stars being $4\times$ higher in PHANGS than in FIRE-2. However, this discrepancy at young ages likely results from the fact that the observed σ_{LOS} in PHANGS is overestimated, for two reasons.

First, the true velocity dispersion, σ_{true} , of young populations is typically lower than the spectral resolution of the MUSE instrument, $\sigma_{\text{inst}} \approx 62 \text{ km s}^{-1}$ (Emsellem et al., 2022). If $\sigma_{\text{true}} < \sigma_{\text{inst}}$, the observed line profile is dominated by the spectrograph’s line-spread function, effectively masking the intrinsic broadening of the narrower σ_{LOS} . The tendency of Penalized Pixel Fitting (pPXF) to systematically overestimate σ when σ_{true} is close to or near instrumental dispersions is well studied (for example Cappellari et al., 2011; Falcón-Barroso et al., 2017; Varidel et al., 2020; van de Sande et al., 2017): various works found that this bias increases as σ_{true} decreases but largely disappears as σ_{true} exceeds the instrumental resolution.

Second, PHANGS measurements are not for individual stars, but for aggregate stellar populations within $\approx 100 \text{ pc}$ apertures. For each aperture, the reported age is the luminosity-weighted average age of its constituent stars; moreover, because young stars dominate the light, these ages are biased by younger, brighter populations. Thus, even apertures deemed very young could include a significant number of older stars. In turn, the PHANGS measurement will overestimate σ of “young populations”, because even though older stars contribute negligibly to the light, they can contribute substantially to the line broadening (Wang et al., 2024). Together, these results indicate that σ is typically overestimated by $\gtrsim 10 \text{ km s}^{-1}$ relative to its true value in the youngest age bin, with the intermediate age bin likely showing weaker, but non-zero, systematic biases, while the oldest age bin is unaffected. Therefore, one should take the observed values at the youngest ages shown in Figure 29 (right) with a grain of salt, and to the extent that they are lower in reality, they would agree better with FIRE-2. At the oldest ages, where these instrumental effects are less important, FIRE-2 and PHANGS agree well.

Overall, $\sigma(\tau)$ in the FIRE-2 simulations exhibits remarkable similarity to those observed in M31 and M33, and is largely consistent with those in PHANGS galaxies, considering measurement effects. This concordance goes against the standard lore that cosmological simulations have hotter kinematics than observed galaxies (for example House et al., 2011). However, as we will show, this newfound harmony between (the stellar disk dynamics in) FIRE-2 and observations is not replicated for the MW.

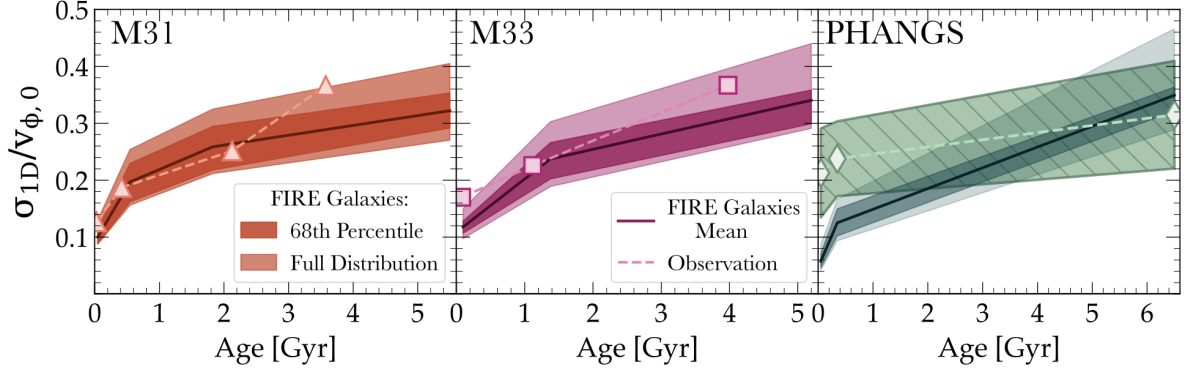


Figure 29: **Comparison of stellar $\sigma_{1D}/v_{\phi,0}$ versus age in the FIRE-2 simulations against observations of M31, M33, and 16 galaxies from the PHANGS-MUSE survey.** We emphasize that while σ_{1D} depends on stellar age, $v_{\phi,0}$ is constant: In measuring FIRE-2, we match the inclination angle, radial selection, spatial aperture size, and age binning of each corresponding observational sample, as in §3.5.4. The solid lines and shaded regions show the median, 68 percent scatter, and full range scatter across 11 FIRE-2 galaxies. The dashed lines with markers are from Figure 28 (bottom), showing observations of M31 (Dorman et al., 2015), M33 Quirk et al., 2022, and 16 galaxies from PHANGS-MUSE (Pessa et al., 2023). *The trends for these 11 FIRE-2 galaxies are broadly consistent with those measured across this sample of 18 nearby galaxies, with the key exception being young stars in PHANGS, which have higher σ than FIRE-2.*

3.5.4.2 FIRE-2 VERSUS THE MILKY WAY

Finally, we compare the FIRE-2 simulations with the MW. As we mentioned in Section 3.5.2 and discussed in detail in Appendix 3.7.2.4, observational works measured the MW’s $\sigma(\tau)$ using different stellar samples. While some works measure stars in the immediate solar neighborhood ($d \lesssim 60$ pc), others push towards the inner and outer disk ($d \lesssim 3$ kpc). We choose a middle ground for our comparison, measuring stars within apertures of $r_{\text{ap}} = 250$ pc spanning an annulus centered at $R = 8$ kpc. We adopt the same “standardized” age bins that we previously used to determine the mean (and range) among the assorted MW observations, that is, 250 Myr-wide age bins spanning 0.25 – 13.25 Gyr. Furthermore, we also include a younger age bin (0 – 0.25 Gyr) to highlight the rapid dynamical evolution of the youngest stars in FIRE-2 simulations. That said, we caution against comparing results from this youngest FIRE-2 age bin with MW observations, given the lack of comparable MW data in this age range. We note that unlike in previous sections, we do not compute the median σ across the annulus of each galaxy. Instead, we consider each aperture as a distinct measurement, which allows us to show the full range of “solar neighborhoods” in FIRE-2, not just the range of medians.

In Figure 30, we compare $\sigma(\tau)/v_{\phi,0}$ from the FIRE-2 simulations to the MW. Following the format of Figure 27, we display the 3D, radial, azimuthal, and vertical velocity dispersion components separately. The FIRE-2 average appears in white, with dark and light shaded regions marking the 68% and full simulation ranges, respectively.

We overlay MW observations from Figure 27, using dashed lines for the mean and gray shading to indicate the total observed scatter.

In general, all components show similar trends: the typical $\sigma(\tau) v_{\phi,0}$ is ≈ 3 times larger in FIRE-2 than in the MW across all ages, except for the youngest stars, which suggests that post-formation dynamical heating is a driver the discrepancy between FIRE-2 and the MW. However, comparing with young stars in the MW is difficult, because observational works have not yet measured ages and σ for a large population of young stars (though see Zari, Frankel, and Rix, 2023). Interestingly, some individual apertures at a given age agree with the MW. However, no *individual* aperture matches the MW across *all* ages. Having a low σ at some ages does not necessarily indicate a low σ at all ages for a particular region.

σ_R agrees the best with the MW, followed by σ_Z and then σ_ϕ . This may reflect that the MW’s thin disk began to form earlier than almost all galaxies in FIRE-2. This means that at intermediate ages (4 – 8 Gyr), MW stars likely formed and subsequently evolved in a thin disk, whereas in FIRE-2 these stars formed in a thicker and more turbulent disk.

We now examine the ratios of the components of σ , which are often considered to be key diagnostics of the relative contributions of different dynamical heating mechanisms (Sellwood, 2013; Smith, Whiteoak, and Evans, 2012; though see Pinna et al., 2018; Walo-Martín et al., 2021). Figure 31 shows three ratios – σ_ϕ/σ_R , σ_Z/σ_ϕ , and σ_Z/σ_R – versus stellar age, comparing FIRE-2 (mean and 1σ range) to the observed mean and range in the MW. As mentioned, many MW studies either provide all 3 components or only σ_Z . One study, Mackereth et al., 2019a, included σ_Z and σ_R but not σ_ϕ . Therefore, our comparisons for σ_ϕ/σ_R and σ_Z/σ_ϕ include values from the 6 works that include all 3 components for the MW, whereas σ_Z/σ_R includes values from these seven in addition to data from Mackereth et al., 2019a. We compute the ratio for each work, interpolate as discussed in Figure 27, and then find the mean and range across all the works. We confirmed that our results are not affected by the use of this subset of observational works, because this reduced sample yields average ratios nearly identical to those from the sample-averaged means of Figure 27.

Figure 31 (left) shows σ_ϕ/σ_R versus stellar age. In the MW, σ_ϕ/σ_R is nearly constant with age, with a mean between 0.6 and 0.7. In contrast, the mean in FIRE-2 shows a more complicated age dependence: σ_ϕ/σ_R is roughly constant at 0.7 between 0.25 – 5 Gyr, steadily increases from 0.7 to 0.9 between 5 and 8 Gyr, and finally remains constant at 0.9 for ages above 8 Gyr. The fact that FIRE-2 is flat at the youngest epoch while the MW is flat across all ages likely reflects the dominance of the thin disk throughout the MW’s history. However, as the 1σ scatter shows, some FIRE-2 galaxies have age dependence as flat as the MW.

For the case of nearly circular orbits, σ_ϕ and σ_R are theoretically coupled via the epicyclic approximation, with a flat rotation curve predicting $\sigma_\phi/\sigma_R = \sqrt{2}/2 \approx 0.71$ (Binney and Tremaine, 2008). Of course, the epicyclic approximation might not hold, because stellar orbits can be eccentric and/or the underlying gravitational potential can be non-axisymmetric or in disequilibrium. However, we note that both for the entirety of the ages for the MW and for the youngest epoch for FIRE-2, the values are consistent with what is expected from the epicyclic

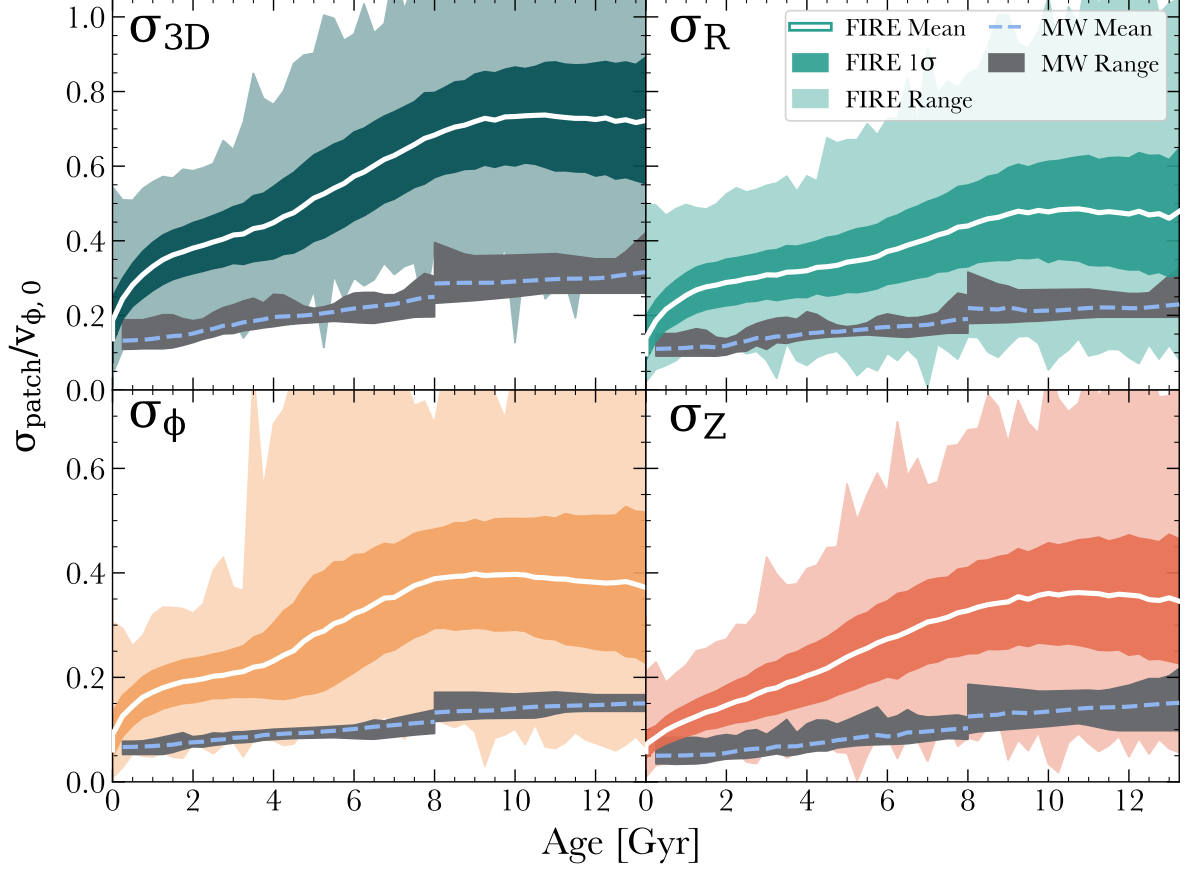


Figure 30: **Comparing stellar $\sigma(\tau)/v_{\phi,0}$ versus age, τ , in the FIRE-2 simulations against observations of the MW for σ_{3D} , σ_R , σ_ϕ , and σ_Z .** The solid white lines show the mean $\sigma(\tau)/v_{\phi,0}$, assuming 20% age uncertainties, across all "solar neighborhood" apertures in 11 simulations, while the dark and light shaded regions show the 68% and full scatters across these apertures. For the MW, we show the mean and full scatter of $\sigma(\tau)/v_{\phi,0}$ from the observational works in Figure 27. In general, FIRE-2 has significantly hotter stellar kinematics than the MW, with the exception of the youngest stars. This offset is most pronounced for σ_{3D} and σ_ϕ , while σ_R shows better agreement. That said, these FIRE-2 galaxies do have some (rare) apertures that are as kinematically cold as the MW.

approximation, whereas for older ages in FIRE-2, the approximation does not hold, as expected for stars on non-circular orbits.

Figure 31 (center) shows σ_Z/σ_ϕ versus age. Here, the averages for FIRE-2 and the MW are quite consistent. In the MW, σ_Z/σ_ϕ increases from 0.75 to 0.9 for low- α stars and remains between 0.9 and 1 for high- α stars. This initial increase and subsequent flattening also occur in FIRE-2, with σ_Z/σ_ϕ increasing from 0.7 to 1 for Late-Disk stars (0 – 4 Gyr) and flattening/decreasing for Early-Disk stars (4 – 8 Gyr). The fact that these transitions occurred at younger ages in FIRE-2 (≈ 4 Gyr) compared to the MW (8 Gyr) probably reflects the earlier formation of the MW’s disk, as discussed above. Furthermore, unlike in the MW, FIRE-2 shows a third trend for the oldest stars, with σ_Z/σ_ϕ steadily rising from 0.9 to 1.1 for Pre-Disk stars. This behavior for the oldest stars likely reflects the shorter Pre-Disk period of the MW and, correspondingly, the lack of Pre-Disk (halo) stars in the local sample. However, we cannot exclude the possibility that FIRE-2 galaxies experienced stronger vertical heating in the Pre-Disk Era than the MW. We also note that previous work found that this ratio is particularly sensitive to selection effects (Aumer, Binney, and Schönrich, 2016; McMillan, 2011).

Lastly, Figure 31 (right) shows σ_Z/σ_R versus age. In FIRE-2, σ_Z/σ_R shows a strong increase with age, reflecting the increasing significance of vertical heating (relative to radial heating) over time. This agrees with the results of McCluskey et al., 2024, who found that the amount of post-formation vertical heating increased linearly with stellar age in these simulations, while in-plane heating plateaued at intermediate ages, and that σ_Z had the largest relative impact from post-formation heating. In comparison, the MW’s trend is relatively flat, with only a modest increase with age. This may indicate that FIRE-2 experienced more intense or extended vertical heating than the MW.

The ratio σ_Z/σ_R has been studied extensively in the literature. Hänninen and Flynn, 2002 showed that it depends on the number density of GMCs, with larger densities yielding larger σ_Z/σ_R . At early times, the higher mass and number density of GMCs rendered them particularly efficient heating agents. However, this effectiveness decreased over cosmic time, because the relative mass contribution of GMCs decreased. In contrast, large-scale spiral structure, being associated with the self-gravity of the stellar disc, increased in strength as the disk grew. The fact that the MW exhibits lower values (and a flatter age dependence) may indicate that it sustained spiral structure for a larger fraction of its lifetime. However, as with the left panel, the 1σ scatter shows that some FIRE-2 galaxies have age dependence as flat as the MW.

Across all panels, the youngest stars exhibit large values for these ratios, as the rapid rise of the white line towards the left edge of each panel shows. However, these values decline rapidly within a few 100 Myr, driven by a rapid increase in the in-plane components, particularly σ_R . Specifically, in the first Gyr, σ_{3D} more than doubles, increasing from 30 km/s to 75 km/s, with σ_R accounting for 60% of this heating, σ_ϕ accounting for 30%, and σ_Z accounting for just under 10%.

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Figure 31: Comparing the ratios of different components of the velocity dispersion versus age in FIRE-2 and the MW.

Each white line shows the mean across all “solar neighborhood” apertures in the 11 simulations, and each shaded region shows the 68% aperture-to-aperture scatter. Dashed lines show the corresponding ratios for the MW, which we calculate using the mean σ of the observational works in Figure 27. **Left:** In FIRE-2, the average σ_ϕ/σ_R exhibits different behavior for young ($\lesssim 4$ Gyr), intermediate-aged (~ 4 –8 Gyr), and old ($\gtrsim 8$ Gyr) stars. In contrast, σ_ϕ/σ_R in the MW remains flat with age at 0.6 until ≈ 9 Gyr ago, before which it weakly increases. The average value for MW lies below the mean from FIRE-2 mean, but the MW falls within the simulations’ 68% scatter at nearly all ages. **Center:** σ_Z/σ_ϕ in FIRE-2 is consistent with the MW, growing from ≈ 0.75 at 1 Gyr to ≈ 1 at 13 Gyr in both. **Right:** In both FIRE-2 and the MW, σ_Z/σ_R generally increases with age, reflecting the growing importance of σ_Z at older ages. Although FIRE-2 and the MW agree at young ages, FIRE-2 exhibits a stronger increase with age at 1 – 6 Gyr, such that the mean in FIRE-2 is typically 30% larger than the MW. Nevertheless, the MW falls within the 68% scatter in FIRE-2.

In summary, these ratios of the components of σ in FIRE-2 agree with the MW, in that the 1σ scatter in FIRE-2 almost always overlaps with the mean of the MW. However, the average FIRE-2 galaxy is higher than the MW for σ_Z/σ_R and σ_ϕ/σ_R , primarily because of the stronger increase with age in FIRE-2.

3.6 SUMMARY AND DISCUSSION

3.6.1 SUMMARY OF RESULTS

We investigated the stellar age velocity (dispersion) relation, $\sigma(\tau)$, which is a key tracer of both stellar birth conditions (from the star-forming ISM) and subsequent dynamical heating of stars in disk galaxies. We used a suite of 11 MW-mass galaxies from the FIRE-2 cosmological zoom-in simulations to assess how various observational effects influence the measured $\sigma(\tau)$, finding:

- Age uncertainties of up to 40% alter σ by typically $\lesssim 20\%$ at any given age. However, age uncertainties can significantly affect the slope of the relation between σ and τ , and age uncertainties $>10\%$ can erase sharp features of major mergers.
- For young stars (age $\lesssim 100$ Myr), σ increases significantly with the measured aperture radius, r_{ap} , out to > 1 kpc, reflecting turbulence in the star-forming ISM. However, for stars older than this, σ is essentially independent (to within a few percent) of aperture radius, at least at $r_{\text{ap}} \gtrsim 250$ pc, where FIRE-2 simulations spatially resolve σ at that age.

- σ increases with decreasing galactocentric radius at all ages, by a factor of $1.5 - 2$ from $R = 12$ to 2 kpc. The youngest stars have the strongest radial dependence: stars are born dynamically hotter towards the galactic center. However, slightly older stars (≈ 400 Myr old) show the weakest dependence, likely from radial redistribution, while progressively older stars show somewhat stronger radial dependence.
- Galaxy inclination affects measured line-of-sight dispersion, σ_{LOS} , by up to a factor of 2, with larger σ_{LOS} for inclinations $> 50^\circ$ compared to face-on observations. This is because generally $\sigma_R > \sigma_\phi > \sigma_Z$, so a face-on disk generally leads to the smallest σ_{LOS} . This effect is the largest for fairly young stars ($0.4 - 2$ Gyr) but weaker for newly-formed stars (ages $\lesssim 100$ Myr are affected up to 40%). Stars $\gtrsim 6$ Gyr old, being the most isotropic, are affected by at most 25-30%.

We compiled observational measurements of $\sigma(\tau)$ from the literature: 13 analyses of the MW and analyses of M31, M33, and 16 PHANGS galaxies. We compared them primarily in terms of $\sigma(\tau)/v_{\phi,0}$, where $v_{\phi,0}$ is the rotation velocity today, because this dimensionless ratio provides the most robust way to compare these galaxies that span over an order of magnitude in stellar mass. We found:

- All analyses of the MW show an increase in σ with age for all velocity components (v_R , v_ϕ , v_Z), by a factor of $2 - 3$ over the last ≈ 13 Gyr. However, these works show substantial scatter ($\approx 50\%$), in both the normalization of σ at fixed age, and shape of the relation of σ with age. Within the MW, σ_R dominates, being at least 50% greater than σ_ϕ and σ_Z at all ages.
- M31, M33, and the average PHANGS galaxy exhibit remarkably consistent values of $\sigma(\tau)/v_{\phi,0}$. M31 and M33 are nearly identical and generally within the 1σ range of the PHANGS sample.
- Thus, among this sample of 19 nearby disk galaxies, the MW is a strong kinematic outlier. The MW is dynamically colder than M31, M33, and 15 of the 16 PHANGS galaxies. The MW is similar to one PHANGS galaxy, NGC 1433, so importantly, it is possible to measure at least one other nearby galaxy as dynamically cold as the MW.

Finally, we compared $\sigma(\tau)/v_{\phi,0}$ in the FIRE-2 simulations against these observations, accounting for the observational effects that we explored. We found:

- FIRE-2 galaxies show good agreement with M31 and M33 across all measured ages. FIRE-2 matches PHANGS galaxies at older ages, but at the youngest ages ($\lesssim 100$ Myr), $\sigma/v_{\phi,0}$ is lower in FIRE-2 by a factor of 4. However, this discrepancy is likely not physical, but instead reflects the (well-known) limitations of measuring small σ with MUSE.
- FIRE-2 galaxies show $\sigma(\tau)/v_{\phi,0}$ typically $2 - 3\times$ higher than the MW at a given age. The youngest stars show the best agreement, indicating that post-formation dynamical heating is more rapid in FIRE-2 than in the MW.

- The ratios of components of σ in FIRE-2 agree with the MW within the 1σ scatter, though there are offsets in the average relations. In both FIRE-2 and the MW, $\sigma_R > \sigma_\phi > \sigma_Z$ at essentially all ages.

3.6.2 DISCUSSION

3.6.2.1 THE MILKY WAY AS AN OUTLIER AMONG OBSERVATIONS

One of our most important results is that the MW is a kinematic outlier, with an unusually low $\sigma/v_{\phi,0}$ by a factor of 2 – 3 at all measured ages, as compared with observed nearby disk galaxies. A possible concern is systematics in comparing measurements of σ based on individual stars in the Solar neighborhood of the MW to σ measured across many apertures of nearby galaxies. However, our exploration of measurement effects in Section 3.4, using FIRE-2 simulations, indicates that these effects alone are unlikely to be strong enough to explain why the MW is a kinematic outlier. We also emphasize that one galaxy (out of 16) from the PHANGS-MUSE sample, NGC 1433, has $\sigma(\tau)/v_{\phi,0}$ similar to the MW. Thus, measuring σ as low as in the MW is *possible* in nearby galaxies, despite our external view. That is to say, the existence of a similarly cold galaxy actually strengthens the classification of the MW as a kinematic outlier.

Furthermore, recent observational works arrive at similar conclusions regarding the MW’s typicality. Bershady et al., 2024 estimated $\sigma(\tau)$ for 500 star-forming disk galaxies in the MANGA survey by parameterizing their observed asymmetric drift, σ_{AD} , which is the lag between the tangential speeds of stars and gas. Bershady et al., 2024 also derived analogous σ_{AD} relations for the MW, M31, and M33 from literature data, finding that while M31 and M33 are broadly consistent with the typical trends in MANGA, the MW falls far below the standard relation. These findings also provide further insight on the origin of the MW’s discrepancy, because Bershady et al., 2024 parameterized their exponential heating model via both the radial σ of young stars and a heating index or “stratification rate”. These results indicate that although young stars in the MW are atypically cold, with similarly-massive MANGA galaxies exhibiting radial σ nearly 3 times higher – the *rate* of heating in the MW (over the past few Gyr) is well within the range of observed values.

The unusual stellar kinematics of the MW likely relates to its unique history, mainly, its early forming disk and paucity of major mergers. As we discuss below (and tritely summarize now), these factors allowed the majority of the MW’s stars to form “disky” and subsequently stay (reasonably) “disky” throughout the Galaxy’s lifetime.

The earliest epoch of the MW’s history has been the subject of extensive recent study (for reviews see Deason and Belokurov, 2024; Helmi, 2020). Such studies primarily focus on the orbit and abundance distributions of the Galaxy’s oldest, and thus, most metal poor, stars. Notably, Belokurov and Kravtsov, 2022 identify a large sample of in-situ stars from APOGEE DR17 and Gaia EDR3 that span iron abundances down to $[\text{Fe}/\text{H}] = -1.5$, and show that the mean v_ϕ of these stars rapidly increased from $[\text{Fe}/\text{H}]$ of -1.2 to -1 . They argue that this increase traces the

MW’s transition from a protogalaxy with negligible net rotation to a coherent disk with $v_\phi \approx 150 \text{ km s}^{-1}$ within $1 - 2 \text{ Gyr}$. Subsequently, Conroy et al., 2022 used the H3 survey to extend this analysis to even lower metallicities, and by measuring the ages of these stars, argued that the disk formed $\approx 10 - 12 \text{ Gyr}$ ago. On the other hand, Xiang and Rix, 2022 and Xiang et al., 2025 studied 250,000 subgiant stars in LAMOST (with a remarkably low typical age uncertainty of $\approx 8\%$) and concluded that the MW’s disk emerged $\gtrsim 13 \text{ Gyr}$ ago, formed a total stellar mass of $3.7 \times 10^9 M_\odot$ by 13 Gyr ago, and then further experienced a 2-3 Gyr period of intense star formation.

Indeed, the exact timing of the formation of the MW’s disk remains rather uncertain (for example Horta and Schiavon, 2025; Viswanathan et al., 2024; Zhang, Arderm-Arentsen, and Belokurov, 2024). For example, age uncertainties of 10% can shift inferred disk formation times to 1-2 Gyr earlier than in reality (Zhang et al., 2024), and accreted stars can masquerade as in-situ disk populations (Mardini et al., 2022; Santistevan et al., 2021). Furthermore, the stellar orbits that we measure today do not necessarily reflect those at birth, especially for the oldest stars: McCluskey et al. (2024) showed that stars need not form with disk-like kinematics to exhibit significant coherent rotation today, given possible subsequent torquing by mergers, satellite interactions, or bars (see also Chandra et al., 2024). Nevertheless, most works agree that the MW’s (long-lived) disk probably formed no later than $9 - 10 \text{ Gyr}$ ago.

This places the MW at the earliest end of the distribution of disk formation, at least within cosmological simulations. Only $\approx 10 - 13\%$ of the MW-mass analogs in the TNG50 and Artemis simulations form disks in stars at such low metallicities (Dillamore et al., 2024; Semenov et al., 2024a), and this is only 6% among the E-MOSAICS simulations (Kruijssen et al., 2019a). We note that some high redshift simulations form coherent disks even earlier, at $z = 4 - 7$ (Kohandel et al., 2024; Tamfal et al., 2022; van Donkelaar et al., 2024); however, many of these are already massive at these early times, with $M_{\text{star}} \gtrsim 10^{10} M_\odot$, and thus are not representative of the typical MW-mass progenitors. Furthermore, when comparing against the MW and nearby galaxies, it is critical to compare with simulations that have been run to the present day and thus include the effects of long-term dynamical heating of stars.

The MW’s early disk formation likely reflects its rapid early mass assembly.⁵ Works based on the MW’s reconstructed SFH (Snaith et al., 2014) and globular cluster properties (Kruijssen et al., 2019a; Trujillo-Gomez et al., 2021) consistently predict that our Galaxy assembled 50% of its $z=0$ stellar mass by 10-10.5 (± 1.5) Gyr ago. In contrast, typical MW-mass halos reached 50% of their final stellar mass $2 - 3 \text{ Gyr}$ later than this, based on semi-empirical models (Behroozi et al., 2019), abundance matching of observed galaxy populations (Papovich et al., 2015), and reconstructing star-formation histories of low-redshift galaxies (Pacifci et al., 2016).

Once a disk forms, it tends to self-regulate near Toomre $Q \approx 1$, enabling subsequent generations of stars to form with progressively colder kinematics, provided its gas fraction declines (as expected) (for example Gurvich

⁵ Theoretical works indicate that galactic disks tend to emerge once their host halos exceed $\approx 10^{11} M_\odot$ and/or a stellar mass of $\approx 10^9 - 10^{10} M_\odot$ (El-Badry et al., 2018a; Hopkins et al., 2023; Pillepich et al., 2019), although the exact link between mass assembly and disk formation remains debated (Dekel et al., 2009; Hafen et al., 2022; Semenov et al., 2024b; Stern et al., 2021).

et al., 2020). For example, McCluskey et al. (2024) showed that FIRE-2 galaxies with earlier disk formation times tend to *form* stars with colder present-day kinematics than those with later-forming disks (see also Semenov et al., 2024a).

Forming a disk is only half the battle; preserving it is equally critical. Once disks have formed, mergers act to dynamically heat existing stellar populations, potentially reorienting and even destroying pre-existing disks (for example Semenov et al., 2024c). In the limit that disks are maintained, simulations consistently show that mergers induce noticeable increases in stellar velocity dispersion and imprint discontinuities in $\sigma(\tau)$ (Grand et al., 2020; Khoperskov et al., 2023; Martig, Minchev, and Flynn, 2014). The MW likely underwent a major merger ≈ 10 Gyr ago (Belokurov et al., 2018; Helmi et al., 2018). Since then, its merging history has been atypically tranquil for a galaxy of its present-day mass (Hammer et al., 2007): for example, Evans et al., 2020 found that only 5% of MW-mass galaxies in the large-volume EAGLE simulation experienced an early major merger with no subsequent massive mergers since $z=1$ (which reduces to 0.65% if an LMC-like satellite is also required).⁶

The MW’s unique formation history likely relates to its group environment, because galaxies in proto-group (that is, cosmically dense) environments experience more rapid mass accumulation at early times e.g., Gallart et al., 2015; Santistevan et al., 2020. Furthermore, the LG’s unique cosmographic landscape and quiet Hubble flow likely facilitated the MW’s early disk formation and quiescent merger history, as various works find earlier formation and last major merger times for simulations constrained to match the LG’s larger environment (for example Carlesi et al., 2020; Forero-Romero et al., 2011). These constrained simulations also help us to understand the differences between the MW and M31, since even though M31-mass and MW-mass galaxies formed similarly quickly at early times, M31 analogues exhibited more late-time mass growth and essentially shielded their lower-mass (MW-analogue) neighbors from later mergers (Wempe et al., 2025).

These theoretical works are in agreement with our understanding of both the MW and M31’s merger histories. M31 appears to have experienced a recent major merger – possibly as significant as a 1:4 mass ratio – approximately 2.5 Gyr ago (Bhattacharya et al., 2023; D’Souza and Bell, 2018; Hammer et al., 2018; Tsakonas et al., 2024). That said, M33’s merger history is more ambiguous. Its warped stellar and HI disks, coupled with a burst of star formation in both M31 and M33 roughly 2–3 Gyr ago, have long been interpreted as signatures of a past fly-by interaction with M31 (Bernard et al., 2012; Corbelli and Burkert, 2024; McConnachie et al., 2009; Williams et al., 2017). However, recent observations and orbital modeling strongly suggest that M33 is on its *first* infall into the Local Group and has yet to undergo a close pericentric passage with M31 (Patel, Besla, and Sohn, 2017; Patel, Garavito-Camargo, and Escala, 2025; van der Marel et al., 2019).

Lastly, we note that the MW’s cold kinematics, early formation, and quiescent merger history are only a few of its potentially atypical properties. For example, many works argue that the MW is abnormally compact for its

⁶ The MW’s atypically rapid early assembly and similarly atypical subsequent calm are likely two sides of the same coin: galaxies with rapid early mass assemblies that then go on to experience more typical (less quiescent) merger histories wind up more massive than the MW, whereas galaxies with similarly minor late-time mass growth cannot reach MW masses unless they also reached similarly high masses early on.

stellar mass, having a remarkably short disk scale radius (Bland-Hawthorn and Gerhard, 2016; Licquia, Newman, and Bershadsky, 2016; Rix and Bovy, 2013). However, recent work argues that the MW’s size is actually typical, and that its apparent compactness reflects the faulty assumption that its disk follows a simple exponential profile (Lian et al., 2024). When (Lian et al., 2024) fitted the MW’s surface brightness profile nonparametrically, the Galaxy’s measured half-light radius doubles, and its disk size is consistent with the overall galaxy population. However, this increased disk size makes the MW even more of an outlier in terms of its (abnormally) steep radial gradient in metallicity (Boardman et al., 2020; Lian et al., 2023).

3.6.2.2 CAVEATS ABOUT FIRE-2 SIMULATIONS

We next discuss some key limitations of the FIRE-2 simulation and other caveats to our results.

$\sigma(\tau)$ in FIRE-2 agrees well with M31 and M33, partially with PHANGS galaxies, and is systematically higher than the MW. We emphasize that the FIRE-2 simulations are not designed to recreate any individual galaxy, including the dynamically cold MW. FIRE-2 represents halos (or LG-like pairs of halos) selected based only on their dark-matter mass at $z = 0$, agnostic to the halos’ additional properties and formation/merger history. Thus, the FIRE-2 results should represent *random and representative* histories of MW-mass galaxies. As such, it may not be surprising that among 11 FIRE-2 MW-mass galaxies, none of them agrees well with the normalization of $\sigma(\tau)$ in the MW, while they age better with larger samples of observed galaxies. As McCluskey et al. (2024) discussed, and consistent with our discussion in the previous subsection, the LG-like FIRE-2 simulations tend to form disks earlier (in particular, Romeo), so they tend to have lower $\sigma(\tau)/v_{\phi,0}$ today and thus among the sample are closest to the MW.

That said, the FIRE-2 simulations in this paper do not model all the physics that could be relevant. These simulations do not model magnetohydrodynamics (MHD) nor self-consistent cosmic-ray injection, transport, and feedback. Hopkins et al., 2020 show that including cosmic rays in these simulations can lower the stellar mass (growth) of the galaxy, especially at late times, although the strength of the effect depends sensitively on the details of the assumed diffusion/transport of cosmic rays. Cosmic-ray feedback can reduce a galaxy’s present-day stellar mass and SFR, which can lead to a lower σ in gas (Chan et al., 2021). However, McCluskey et al., 2024 show that this also leads to a slight *reduction* in the degree of rotational support of these galaxies, in terms of v_{ϕ}/σ , because this shift occurs primarily along the existing stellar mass-kinematics relation (see Figure A2 in McCluskey et al., 2024). Thus, cosmic-ray feedback, as implemented in FIRE-2, does not make these disks meaningfully dynamically colder.

Potentially more important is that these FIRE-2 simulations do not model supermassive black holes and feedback via active galactic nuclei (AGN), although some recent FIRE simulations have (Mercedes-Feliz et al., 2023; Wellons et al., 2023). Although AGN feedback is most critical for more massive galaxies, growing work finds that AGN can affect the structural and dynamical properties of MW-mass galaxies (for example Irodotou

et al., 2022). The lack of AGN feedback may explain how these FIRE-2 galaxies display high average SFR: the average SFR in these FIRE-2 simulations today is $\approx 5 - 10 M_{\odot} \text{ yr}^{-1}$, higher than most (although not all) observational inferences at these masses (Gandhi et al., 2022). In particular, the central regions of FIRE-2 galaxies display intense star formation stemming from strong gas inflows. In real galaxies, these gas inflows would also feed the central black hole, and the resulting AGN feedback would regulate further inflows and star formation in the central regions. Indeed, Marasco et al., 2025 argue that the lack of AGN feedback in FIRE-2 causes them to exhibit more complex and broader HI line profiles than in most observed galaxies.

Given the intimate connection between bar formation and gas dynamics in the inner galaxy (for example Athanassoula, Machado, and Rodionov, 2013; Fragkoudi et al., 2025; Fraser-McKelvie et al., 2020), the lack of AGN feedback may also affect bars in these simulations. For example, high gas fractions and star formation in the inner galaxy can drive fluctuations of the gravitational potential that disrupt bars as they form (Weinberg, 2024). Bars do form in about half of these FIRE-2 simulations, but they are generally weaker, more ellipsoidal, and shorter-lived than in observed galaxies (Ansar et al., 2025). Bars can affect stars throughout the galaxy and can be a driver of post-formation dynamical heating, either directly (for example Grand et al., 2016), or through resonant overlap with spiral structure (Marques et al., 2025; Minchev and Famaey, 2010). As such, stronger bars might increase σ , especially σ_{ϕ} (Asano et al., 2022; Dillamore et al., 2023; Fillion et al., 2023; Khoperskov and Gerhard, 2022).

Lastly, much of our analysis focused on quantifying the impact of measurement effects – age uncertainties, aperture radius, galactocentric radius, and inclination angle – applied to the “truth” of the FIRE-2 simulations. However, we did not use synthetic observations that modeled observable photometry and spectroscopy, including magnitude limits, dust, etc. In future work we will explore in more detail how both synthetic measurements of resolved stars and of IFS-like synthetic measurements of stellar population affect these results.

3.6.2.3 COMPARISON TO OTHER SIMULATIONS

We now discuss our results from the FIRE-2 simulations in relation to other cosmological zoom-in simulations of MW-mass galaxies. We identified six other studies reporting $\sigma(\tau)$, spanning 48 MW-mass galaxies: 16 from Auriga (Grand et al., 2016), 19 from RaDES (Few et al., 2012; Ruiz-Lara et al., 2016), five from NIHAO-UHD (Buck et al., 2020), one from VINTERGATAN (Agertz et al., 2021), one (h277) from the g14 suite (Bird et al., 2021), and 6 from HESTIA (Khoperskov et al., 2023). We also included results for 11 FIRE-2 galaxies. *A critical point that we emphasize: among these 59 cosmological zoom-in simulations of MW-mass galaxies across seven suites, only a single galaxy, h277, matches the MW’s $\sigma(\tau)$. In contrast, these simulated galaxies generally agree better with the larger sample of M31, M33, and PHANGS.*

We first note important caveats to this statement. As mentioned, we limit this comparison to *cosmological zoom-in simulations of MW-mass galaxies*, meaning we do not include results for isolated (non-cosmological)

simulations (for example Kumamoto, Baba, and Saitoh, 2017; van Donkelaar, Agertz, and Renaud, 2022), non-hydrodynamic simulations, including those using sticky-particle algorithms (for example Martig, Minchev, and Flynn, 2014), larger-volume simulations (for example Pillepich et al., 2019, 2024), or simulations targeting significantly different masses than the MW (for example Brook et al., 2012). Second, the galaxies for which the authors measure $\sigma(\tau)$ in the above simulation suites sometimes represent only a subset of the entire suite. HESTIA features 13 LG-like pairs (Libeskind et al., 2020), Auriga encompasses 30 galaxies (Grand et al., 2017), and the g14 suite includes about a dozen otherwise well-studied galaxies (for example Brooks et al., 2017; Christensen et al., 2016; Kassin et al., 2014; Loebman et al., 2012; Munshi et al., 2013), of which h277 has by far the smallest $\sigma(\tau)$.

Also striking is that nearly all of these different simulation suites (FIRE-2, Auriga, NIHAO-UHD, VINTERGATAN, HESTIA, RaDES) show remarkable quantitative consistency among them for their average $\sigma(\tau)$, all of which increases (generally monotonically) with age. Most of these 59 galaxies have $\sigma_Z \approx 15 - 20$ km/s for the youngest stars and 60-70 km/s for stars aged ≈ 6 Gyr, with some galaxies scattering to higher values. This quantitative agreement may be surprising, given the diversity of models for the ISM, star formation, and feedback used across these simulation suites and their diversity of initial conditions, and thus formation histories. These σ_Z values generally match M31, M33, and (at least for stars older than ≈ 1 Gyr) PHANGS. In contrast, σ_Z in the MW is only ≈ 12 and 20 km/s at the same ages. Therefore, tension with the MW is somewhat stronger at older ages, which may reflect the MW’s quiescent merger history and early-forming disk. However, these explanations do not obviously apply to younger stars, which in almost all simulations formed in non-merging, rotationally-dominated disks.

The key exception is h277, which, as Bird et al., 2021 show, exhibits a $\sigma(\tau)$ similar to that of the Solar neighborhood of the MW. Furthermore, as Bird et al., 2021 noted, h277 is unusual among the larger g14 simulation suite of over a dozen galaxies. Brooks et al., 2009 introduced h277, and Zolotov et al., 2009 notes its particularly quiescent merger history. However, the original version of h277 did *not* stand out kinematically: House et al., 2011 showed that it had the highest σ_Z (≈ 28 km s⁻¹) among young stars in their simulated sample. The updated version of h277 analyzed in Bird et al., 2021 had twice better spatial resolution (173 pc), eight times better mass resolution ($5800 M_\odot$), and updated ISM and star formation models from Christensen et al., 2012, which directly link star formation to H₂.

Bird et al., 2021 argues that the low $\sigma_Z \approx 7$ km s⁻¹ today arose primarily from their updated star-formation prescription, which limits star formation to dense gas ($n > 100$ cm⁻³). The connection between star formation thresholds and σ of stars at birth may account for unrealistic kinematics in earlier simulations (House et al., 2011). However, the relationship between high-density star formation thresholds and low σ in newly formed stars is not clear across different simulations. For example, the FIRE-2 simulations we analyze here adopt a minimum density for star formation of $n = 1000$ cm⁻³, along with a requirement of gas being self-gravitating. An alternative expectation is that higher density thresholds combined with a self-gravitating criterion lead to more clustered star formation, which increases the impact of stellar feedback and dynamical perturbations on short timescales

(Fielding, Quataert, and Martizzi, 2018; Martizzi, 2020; Orr et al., 2022). An even broader explanation is that while stars form from the densest self-gravitating gas, this gas is still not as kinematically cold as the gas in the MW (or h277).

The cold kinematics of h277 likely relate to the simulation’s MW-like, yet cosmologically rare, early formation history and absence of late-time mergers. This is coupled with h277’s relatively low SFR, $\approx 1 \text{ M}_\odot \text{ yr}^{-1}$, over the last 6 Gyr, which is broadly consistent with observational estimates of the MW’s star-formation history (Ruiz-Lara et al., 2020; Smith, Whiteoak, and Evans, 2012), because star formation and its associated feedback drive turbulence in the ISM, increasing σ in gas. The FIRE-2 galaxies we analyze have an average SFR today of $\approx 5 - 10 \text{ M}_\odot \text{ yr}^{-1}$ (Gandhi et al., 2022). (See also Figure 9 of Iyer et al., 2020, for a comparison of SFRs in m12m, m12f, and h277). Indeed, among the sample of cosmological zoom-in simulations we discuss above, most have higher SFRs than the MW and h277: for example, 60% of Auriga galaxies have SFRs of $5-10 \text{ M}_\odot \text{ yr}^{-1}$, though individual galaxies occasionally have $1-2 \text{ M}_\odot \text{ yr}^{-1}$. Few simulations exhibit such low SFR over a long ($\gtrsim 6$ Gyr) timescale, potentially indicating that this may be necessary to reproduce the MW’s $\sigma(\tau)$. Reinforcing this idea is that the one PHANGS galaxy with MW-like kinematics, NGC 1433, has a recent SFR of $1.1 \text{ M}_\odot \text{ yr}^{-1}$, the lowest among the PHANGS-MUSSE sample.

We thus conclude that, based only on observational comparisons, the MW is a kinematic outlier with unusually low $\sigma(\tau)/v_{\phi,0}$ among this sample of 19 observed nearby galaxies. As such, it may not be surprising that among the sample of 59 cosmological zoom-in simulations with published $\sigma(\tau)$, only one (h277) matches the MW, while most simulations reasonably match the much larger sample of M31, M33, and (at least for stars older than ≈ 500 Myr) PHANGS. This highlights the potential dangers in benchmarking simulations only against the MW, but this also highlights the remarkable value of ongoing measurements of stellar kinematics and their histories within nearby galaxies.

3.7 APPENDICES

3.7.1 APPENDIX: COMPARING FIRE-2 SIMULATIONS AND OBSERVATIONS WITHOUT SCALING

In Section 3.5.4, we compared $\sigma(\tau)$ in the FIRE-2 simulations against observed galaxies, scaling each galaxy by its rotational velocity, $v_{\phi,0}$, such that we compare $\sigma(\tau)/v_{\phi,0}$. This dimensionless metric provides a fairer comparison of galaxy samples that span a factor of 10 in stellar mass. However, many studies examine only $\sigma(\tau)$. Therefore, here we show versions of Figure 32 and Figure 30 unscaled by $v_{\phi,0}$. Note that the scaled versus unscaled versions differ only in normalization, not in shape, because $v_{\phi,0}$ is rotational velocity today and does not vary with age. The results are qualitatively similar, because these FIRE-2 galaxies have stellar masses (and thus rotational

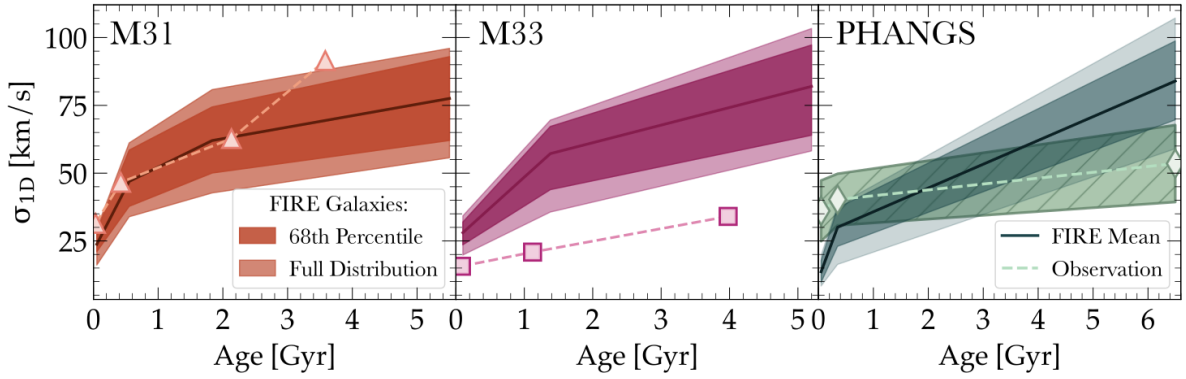


Figure 32: Same as Figure 29, comparing FIRE-2 against M31, M33, and 16 galaxies from PHANGS, but *without* scaling each galaxy’s line-of-sight σ to its rotational velocity for young stars today, $v_{\phi,0}$. As a result, these σ_{1D} are sensitive to the mass (gravitational potential) of the galaxy, in addition to its dynamical state. In particular, σ_{1D} for M33 is now much lower than FIRE-2. However, given that M31 has a stellar mass more similar to most of these FIRE-2 galaxies, FIRE-2 still agrees with M31 about as well as in Figure 29. The typical galaxy in the PHANGS has slightly lower stellar mass than in our FIRE-2 sample, so its normalization is slightly lower relative to FIRE-2 than in Figure 29. We show these results for σ_{1D} for completeness, but we consider the comparison against the dimensionless $\sigma_{1D}/v_{\phi,0}$ in Figure 29 more robust, because this normalizes out each galaxy’s mass and therefore overall velocity scale.

velocities) similar to the MW, M31, and the median mass of the PHANGS-MUSE sample. The primary difference is for M33, given its much lower stellar mass.

3.7.2 APPENDIX: OBSERVATIONS OF NEARBY GALAXIES

3.7.2.1 OBSERVATIONS OF M31

We now discuss the observations of Dorman et al. (2015) (D15) in detail. D15 measured the line-of-sight $\sigma(\tau)$ relation across the northern half of M31’s disk using a sample of ≈ 5800 individual stars with combined SPLASH spectroscopy and PHAT photometry. The photometric accuracy and precision afforded by deep HST observations allow clean color-magnitude-based separation of RGB, AGB, and MS stars. In turn, D15 split stars from their sample into 4 broad age bins based on their position on the optical CMD; these age bins have distinct mean ages (0.03, 0.4, 2, and 4 Gyr) despite their overlapping age distributions. For each star, D15 first measured σ in a surrounding circular patch of radius ≈ 760 pc. If the patch contained at least 15 stars in the same age bin, they calculated σ from the second moment of the velocity distribution (of same-aged stars) using a kernel density estimator, while patches with fewer than 15 same-aged neighbors were ignored. The final reported σ is the mean of all aperture-based σ in each age bin.

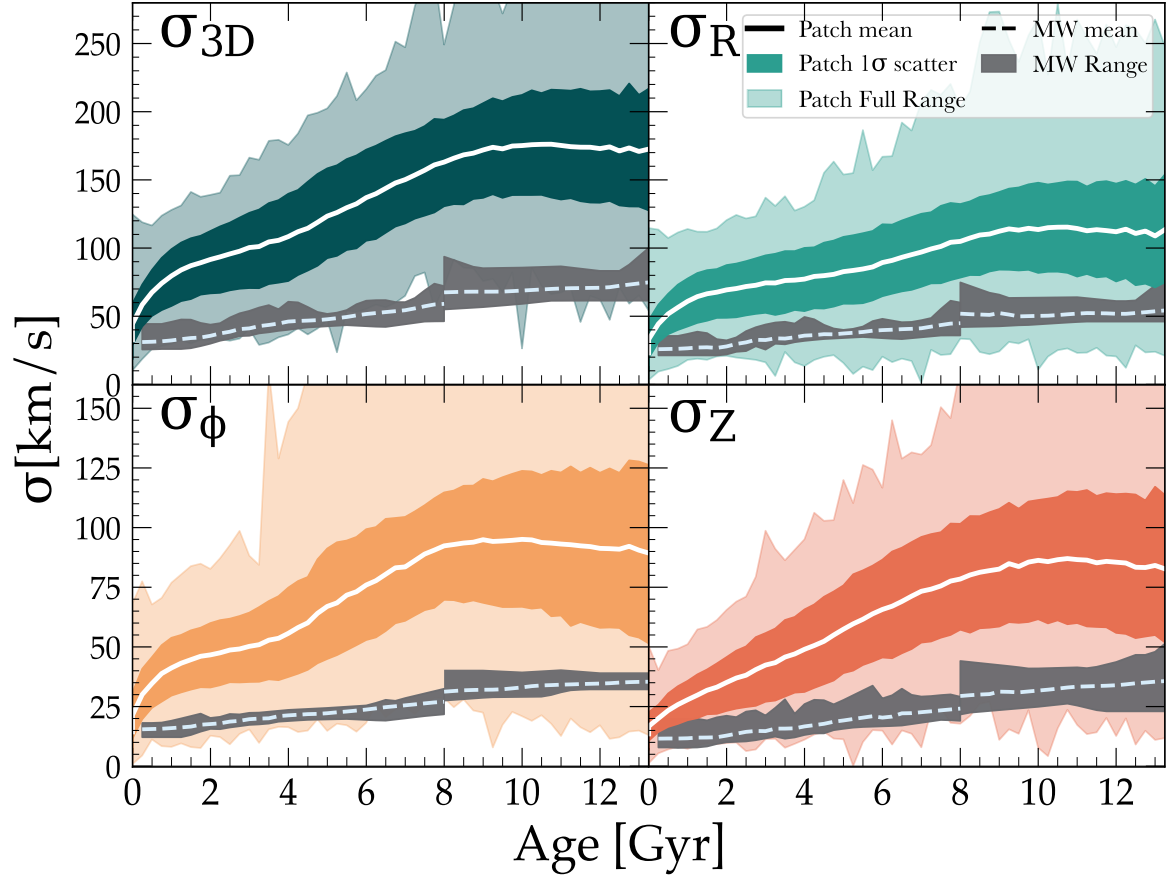


Figure 33: Same as Figure 30, comparing FIRE-2 and the MW, but *without* scaling σ to each galaxy’s rotational velocity today, $v_{\phi,0}$. This yields nearly identical results: σ in FIRE-2 simulations are typically larger than those measured in the MW, but they do agree for rare apertures. This negligible difference when not scaling by $v_{\phi,0}$ arises because the median (or mean) $v_{\phi,0}$ of our FIRE-2 sample ($\approx 240 \text{ km s}^{-1}$) is nearly identical to the value we use for MW (238 km s^{-1}).

3.7.2.2 OBSERVATIONS OF M33

Similarly, we now discuss the observations of M33 by Quirk et al. (2022) (Q22) in more depth. The procedure of Q22 largely followed that of D15, although their exact parameters necessarily differed. Specifically, Q22 divided their sample into 3 age bins with corresponding mean ages of ≈ 0.08 , 1, and 4 Gyr. As in D15, the age distributions within each bin are broad and overlap, having 16th–84th percentile ranges of $\approx 20 - 180$ Myr, 0.56–2.2 Gyr, and 1.4–9 Gyr. Furthermore, the aperture/patch radius over which Q22 measured σ differed between age groups, with median values of ≈ 350 , 500, and 420 pc for the young, intermediate, and old populations, respectively.

Crucially, Q22 presented two $\sigma(\tau)$ relations for M33: one in which they removed “halo” stars, defined as stars whose v_{LOS} are not consistent with belonging to a dynamically cold component, and one in which they did not. Although this dynamically hotter component only accounts for $\approx 14\%$ and 23% of the initial intermediate-age and old-age populations, respectively, its inclusion significantly impacts the measured σ . When the hotter component is excluded, $\sigma(\tau)$ is *flat* with age, with all age bins having $\sigma \approx 16 \text{ km s}^{-1}$. However, including the hotter component resulted in $\sigma(\tau)$ that increases monotonically with age. Specifically, σ is unchanged for the youngest age bin, while the intermediate and oldest bins have σ of ≈ 21 and 35 km/s – nearly 1.4 and 2 times larger than their “uncontaminated” values. Nevertheless, given that neither D15 nor Pessa et al., 2023 made similar dynamical cuts for M31 and PHANGS galaxies, we use the measurements from Q22 that do not remove dynamically-hot stars for consistency. This choice is further justified by the results of Beasley et al., 2015, who found a monotonically rising $\sigma(\tau)$ relation in M33 using observations of ≈ 80 star clusters. Interestingly, this cluster-based relation exhibited a higher normalization and a stronger age dependence than the “halo-contaminated” relation of Q22. We emphasize that regardless of the sample used, $\sigma(\tau)/v_{\phi,0}$ is always $\gtrsim 2\times$ larger in M33 than in the MW.

3.7.2.3 PHANGS-MUSE SURVEY

We now discuss – in greater detail – the PHANGS-MUSE sample and the procedure that Pessa et al. (2023) (P23) used to measure $\sigma(\tau)$ in 19 galaxies. The PHANGS-MUSE sample lies within $\lesssim 20 \text{ Mpc}$ with low to moderate inclinations ($< 60^\circ$) and stellar masses of $\log(M_\star/M_\odot) = 9.4 - 11.0$, with a median of $\log(M_\star/M_\odot) = 10.5$.

As we discuss, one way to better compare the kinematics of different galaxies is to scale the dispersion by the galaxy’s rotational velocity, $v_{\phi,0}$. Although P23 does not measure $v_{\phi,0}$, earlier work by Lang et al., 2020 provided rotation curves for 67 galaxies in the larger PHANGS-ALMA sample using high-resolution CO (2-1) maps. By parameterizing these rotation curves with smooth analytic fits, Lang et al., 2020 determined the maximum (asymptotic) rotational velocities; however, three of the PHANGS-MUSE galaxies (NGC 2835, NGC 5068, and IC 5332) lacked robust smooth fits, leaving their maximum rotational velocities unreported. Consequently, our analysis focuses on the remaining 16 PHANGS-MUSE galaxies, which we hereafter refer to as the “PHANGS galaxies/sample”.

Unlike the previously mentioned observations, these measurements are for stellar populations across ≈ 100 pc scales, not individual stars. To extract stellar properties and kinematics, P23 used the popular Penalized PiXel-Fitting (PPXf) code introduced by Cappellari and Emsellem, 2004 and significantly upgraded by Cappellari (2017). To measure stellar kinematics, they fit the observed Voronoi-binned spectrum to stellar templates (here the E-MILES templates of Vazdekis et al., 2012 and their young extensions from Asa'd et al., 2017) convolved with a line-of-sight velocity distribution parameterized by a Gauss-Hermite expansion assuming a single stellar kinematic component.

The high spatial resolution and wide coverage of the PHANGS survey allowed P23 to study stellar populations across multiple galactic environments separately. To more fairly compare different galaxies and account for radial and environmental trends, the $\sigma(\tau)$ relations in P23 included only disk stars within $0.25 - 0.30R_{25}$, where R_{25} is the 25th magnitude isophotal B-band radius. For this sample, R_{25} ranges from 7 – 34 kpc with a mean value of ≈ 15 kpc, such that $0.25 - 0.30R_{25}$ corresponds to $\approx 3.75 - 4.25$ kpc. After making this geometric selection, P23 calculated the mean for populations with luminosity-weighted ages within three age bins: young (< 100 Myr), intermediate ($100 - 600$ Myr), and old (≥ 3 Gyr).

3.7.2.4 OBSERVATIONS OF THE MILKY WAY

Finally, we describe the 13 works that we compiled that measured $\sigma(\tau)$ of the MW. Nordström et al., 2004 introduced the Geneva-Copenhagen Survey (GCS). The GCS combined Stromgren photometry and radial velocity measurements with Hipparcos proper motions and parallaxes to measure late-type stars in the Solar neighborhood, ultimately creating an all-sky, kinematically-unbiased catalog of $\approx 16,500$ F and G stars that is volume complete within 40 pc of the Sun.

Since Nordström et al., 2004, the GCS catalog has undergone multiple revisions. First, Holmberg, Nordström, and Andersen, 2007 used new temperature and metallicity calibrations to update the metallicities and ages. Second, Holmberg, Nordström, and Andersen, 2009 implemented newly revised Hipparcos parallaxes to significantly improve distance measurements, resulting in improved kinematics and ages as well. Lastly, Casagrande et al., 2011 adopted a corrected effective temperature scale to provide more accurate and precise metallicities and ages. These updated ages are generally ≈ 1 Gyr younger than their earlier values, with the oldest ages often decreasing by $\approx 3 - 6$ Gyr. However, a substantial number of stars previously deemed young (age < 1 Gyr) now have ages ranging between 0.5 – 10 Gyr (see Figure A2 of Casagrande et al., 2011). Despite these changes, all of these works show similar $\sigma(\tau)$. We include Nordström et al., 2004, Holmberg, Nordström, and Andersen, 2009, and Casagrande et al., 2011 in our compilation, given their prevalence in the literature, and to show how different age determinations impact the measured $\sigma(\tau)$ for the same stellar sample.

All of the GCS analyses used the Galactic coordinate system and a heliocentric Cartesian system, so they quoted σ in Galactic space-velocities (U,V,W), where U points towards the Galactic center, V the direction of

rotation, and W the north Galactic pole. However, with the exception of Silva Aguirre et al., 2018, the other works (including our own) used the Galactocentric coordinate system (R, ϕ, Z). We tested how using the Galactic coordinate system impacts the σ measured in FIRE-2, and we found that for aperture-based measurements, the median vertical (W) and 3D σ were generally unchanged, as expected. However, the median σ in U is typically $\approx 15 - 20\%$ lower than σ in v_R , while V is typically $\approx 20 - 25\%$ higher than σ in v_ϕ , across all ages. Although the in-plane components of σ are not exactly analogous for the two coordinate systems, we show the U and V velocity dispersions as σ_R and σ_ϕ in Figure 27 for consistency.

We now discuss works that measured $\sigma(\tau)$ in the Gaia era, grouping similar works together rather than adopting a purely chronological ordering. Yu and Liu, 2018 analyzed a sample of $\approx 3,500$ SGB/RGB stars that have LAMOST spectroscopy and Gaia DR1 astrometry (stars in the Tycho-Gaia Astrometric Solution catalog). Following the likelihood technique of Liu et al. (2015), Yu and Liu, 2018 estimated stellar ages by comparing the observed stellar parameters with theoretical isochrones, leading to typical age uncertainties of $\approx 30\%$. This sample is fairly local: requiring reliable astrometric measurements limits the sample to within 1 kpc of the solar neighborhood. Furthermore, Yu and Liu, 2018 divided their sample into two equal populations based on the stars' distance from the mid-plane: ≈ 1780 stars with $|Z| < 270$ pc and 1780 with $|Z| > 270$ pc. Both populations exhibit similar 3D and radial σ , with the population at $|Z| < 270$ pc having a larger azimuthal σ and a smaller vertical σ at most ages. For brevity, we include only the population at $|Z| < 270$ pc.

Kordopatis et al., 2023 derived stellar parameters, including orbital properties, masses, and isochrone ages, for ≈ 5 million stars with radial velocities from Gaia-EDR3, by combining Gaia-EDR3 spectroscopy, photometry, and astrometry with 2MASS infrared photometry. Kordopatis et al., 2023 presented $\sigma(\tau)$ for RGB and MSTO stars within 1 kpc of the Sun. They claim that their stellar ages are most reliable for MSTO stars, with all but the least-massive MSTO stars having age errors $\lesssim 50\%$. Therefore, we include only their MSTO data, sampling their trendline every 0.5 Gyr in Figure 27.

Sharma et al., 2021 compared the results of multiple complementary surveys, including GALAH, LAMOST, APOGEE, Kepler, and Gaia, to explore how the $\sigma(\tau)$ depends on age, angular momentum, metallicity, and $|Z|$. However, Sharma et al., 2021 mainly presented (dimensionless) normalized σ , in part to compare the relative profiles of these different works. That said, they presented raw σ from GALAH DR3 for $\approx 100,000$ MSTO stars in the extended solar neighborhood, defined via $|R - R_\odot|$ and $|Z|$, which we sample every 0.5 Gyr. The GALAH+ DR3 catalog (Buder et al., 2021) provides stellar ages estimated using the Bayesian Stellar Parameter Estimation code from Sharma et al., 2018, which provides a Bayesian estimate of stellar parameters from (PARSEC-COLIBRI) isochrones. When we adopt the same quality cuts as Sharma et al., 2021, we find an average age uncertainty of 16.7%. Interestingly, Sharma et al., 2021 compared $\sigma(\tau)$ of RGB and MSTO stars in GALAH DR3 and LAMOST DR4, finding that while RGB stars from both surveys and MSTO stars in LAMOST had σ that significantly flattened or even decreased with age above 8 Gyrs, σ of MSTO stars from GALAH continued to increase monotonically with age. The authors posited that this behavior may stem from the lower age uncertainties of the GALAH MSTO sample.

Also using GALAH DR3 results, Hayden et al., 2022 derived new ages for $\approx 215,000$ stars using their measured elemental abundances and overall metallicities. They quote typical age uncertainties for their abundance-based ages of $\approx 1 - 2$ Gyr. However, unlike for other methods, these uncertainties are largely age-independent, so older stars have more accurate ages than younger stars. Hayden et al., 2022 showed $\sigma(\tau)$ for stars at $R = 7.1 - 9.1$ kpc and $|Z| < 0.5$ kpc. We sample the σ of their “All GALAH Stars” population every 0.5 Gyr.

Silva Aguirre et al., 2018 combined optical and infrared photometry, APOGEE spectroscopy, and Kepler astroseismology to construct a photometrically complete sample of ≈ 1200 stars across 2 kpc of the solar annulus. The sample has a median age uncertainty of 28.5%. Silva Aguirre et al., 2018 also used the Galactic coordinate system.

Miglio et al., 2021 and Lagarde et al., 2021 considered overlapping samples of red-giant-branch (RGB) stars with reliable constraints from Kepler astroseismology, APOGEE spectroscopy, and Gaia astrometry. However, each work further refined their sample and determined stellar properties, in particular stellar ages, differently. Miglio et al., 2021 selected only giant stars with robust mass measurements, producing a final sample of $\approx 3,300$ stars with a median random age uncertainty of 23%. From this sample, Lagarde et al., 2021 further selected for stars in the APOKASC catalog, yielding a final sample of $\approx 2,800$ giant stars. Both works divided their sample into high- and low- α populations, with Lagarde et al., 2021 further dividing their low- α population by $[\text{Fe}/\text{H}]$. We show both populations from Miglio et al., 2021, and we show the low- α and the metal-poor high- α populations from Lagarde et al., 2021, omitting their metal-rich high- α population for brevity, given that its σ lie between those of the other populations.

As in Yu and Liu, 2018, Sun et al., 2024 also combined LAMOST and Gaia observations. However, the improved proper motions that Gaia DR2 and EDR3 provided allow them to measure red clump stars throughout much of the disk, with a sample of $\approx 130,000$ stars spanning $R = 6 - 15$ kpc and $|Z| < 3 - 4$ kpc. They determined stellar ages from a machine-learning model trained on a sample of thousands of red clump stars in the LAMOST-KEPLER field with accurate astroseismic ages (following Huang et al. (2018)), leading to a typical age uncertainty of $\approx 30\%$. In their analysis, Sun et al., 2024 subdivided their entire sample into various spatial and population bins, providing 3D kinematic maps and $\sigma(\tau)$ for each. For this comparison, we use their “thin” and “thick” disk measurements for stars within $R = 7 - 9$ kpc and $|Z| < 1$ kpc (shown in the bottom-left panels of their Figure 9), where they determined the low- α and high- α disk populations using an empirical cut in the $[\text{Fe}/\text{H}]-[\alpha/\text{Fe}]$ plane.

Similarly, Mackereth et al., 2019a also provided a comprehensive dissection of the low- and high- α disks using stars with spectra from APOGEE DR14 and ages determined using machine learning models trained on APOGEE stars that have robust asteroseismic ages from Kepler. As in Sun et al., 2024, the improved astrometry of Gaia DR2 allowed Mackereth et al., 2019a to probe stars throughout a large volume of the disk: $R = 4 - 13$ kpc and $|Z| < 2$ kpc. Mackereth et al., 2019a presented $\sigma(\tau)$ for stars across $R = 6 - 11$ kpc. We make no further radial selection and include their data for all mean radii, because we cannot determine these stars’ *current* radii from their *mean* radii. However, low- and high- α populations generally have slightly different radial ranges, with the low- α

data spanned the entire radial range, while the high- α data had mean radii limited to $R \approx 6 - 7$ kpc. Interestingly, σ_R showed little dependence on the mean orbital radius, while σ_Z increased with increasing mean radius at a fixed age. The final sample of $\approx 66,000$ stars has a median age uncertainty $\approx 30 - 35\%$, though the authors note that for stars older than 10 Gyr their ages are likely to be underestimated and subject to large uncertainties.

Recently, Anders et al., 2023 provided a catalog with precise stellar ages for $\approx 180,000$ RGB stars from APOGEE. They used a supervised machine learning method trained on $\approx 3,000$ RGB stars with existing ages from both APOGEE spectra and Kepler asteroseismic ages. They claim that the catalog has a median age uncertainty of 17%. Adopting distances and velocities from the StarHorse value-added catalog from APOGEE DR17 (Queiroz et al., 2023), which combined APOGEE DR17 spectra, broad-band photometric data, and Gaia EDR3 parallaxes to derive astrophysical parameters for APOGEE stars, Anders et al., 2023 presented $\sigma(\tau)$ for stars with $|Z| < 1$ kpc across multiple R . To maintain consistency with the other MW observations, we present their data for $R = 7 - 9$ kpc.

Part III

SUMMARY AND OUTLOOK

4

SUMMARY AND OUTLOOK

4.1 SUMMARY

In Chapter 2, I examined how MW-like galaxies evolve in a cosmic context: transforming from turbulent proto-galaxies bombarded with numerous mergers into cold, thin disks whose stars nevertheless recall their dynamical origins. Some key results from this paper were:

- The histories of MW-like galaxies can be divided into three distinct eras. First, galaxies begin in a Pre-Disk Era (typically $\gtrsim 8$ Gyr ago), where (as the name implies) they lack well-defined, long-lived stellar disks. At these times, stars form on dispersion dominated orbits. Next, galaxies transition into an Early-Disk Era ($\approx 8 - 4$ Gyr ago), where they form stars on rotation-dominated orbits. Although these galaxies are now “disky”, these disks are thicker and more turbulent than the thin disks seen in nearby galaxies, such that stars form with high velocity dispersion σ_{form} . Lastly, galaxies enter a Late-Disk Era ($\lesssim 4$ Gyr ago), when they form stars on highly disk-dominated orbits. Now, stars form with low σ_{form} , similar to observations of nearby disk galaxies.
- Although these eras directly correspond to differences in the formation kinematics of stars, stars born in different eras also exhibit different amounts of post-formation heating. In fact, the amount of post-formation heating exhibits different trends with age in each of these three eras. In the Pre-Disk Era, the amount of heating continuously increases with age. In the Early-Disk Era, stars of all ages have been heated by the same amount, on average. In the Late-Disk Era, the amount of heating increases with age but at a decreasing rate.
- The combination of formation dispersion and post-formation dynamical heating results in a monotonically increasing age-velocity dispersion relation at $z=0$.
- Heating operates differently for the different velocity components. Post-formation heating primarily increased σ_R at ages $\lesssim 4$ Gyr but acted nearly isotropically for older stars.

- The lookback time that the disk began to settle correlates with its dynamical state today: earlier-settling galaxies currently form colder disks.
- Including stellar cosmic-ray feedback does not significantly change disk rotational support at fixed stellar mass.

In Chapter 3, I compared these simulations with observations in detail, determining how selection and observation effects can lead to different kinematic measurements in the same galaxy.

The main conclusions that we found in this paper are as follows:

- To assess how measurement effects influence $\sigma(\tau)$, we analyze the FIRE-2 cosmological simulations, quantifying the impact of uncertainties in stellar age, aperture size, galactocentric radius, and galaxy inclination. Aperture size and galactocentric radius affect $\sigma(\tau)$ by up to a factor of ≈ 2 for stars younger than 100 Myr, with milder effects on older stars. Age uncertainties up to 40% change the *value* of $\sigma(\tau)$ at a given age by $\lesssim 20\%$ but can reshape the relation with age and erase merger signatures.
- We compile and compare observational measurements of the MW, M31, M33, and 16 galaxies from the PHANGS survey. The MW exhibits significantly colder stellar kinematics, with 2-3 times lower $\sigma(\tau)/v_{\phi,0}$ at a given age, than all but one other observed galaxy, suggesting that it is a kinematic outlier.
- We compare $\sigma(\tau)/v_{\phi,0}$ in FIRE-2 simulations with observations. FIRE-2 agrees well with M31 and M33 at all measured ages, and with PHANGS for stars older than ≈ 500 Myr. The average $\sigma(\tau)/v_{\phi,0}$ in FIRE-2 is about two times higher than the MW at most ages, but the youngest stars show better agreement. The velocity ratios (σ_ϕ/σ_R , σ_Z/σ_ϕ , σ_Z/σ_R) in FIRE-2 broadly agree with the MW. We conclude that $\sigma(\tau)$ in FIRE-2, and most cosmological zoom-in simulations, reasonably matches observed nearby galaxies, but matching the MW is rare, because it is a kinematic outlier.

4.2 FUTURE DIRECTIONS

4.2.1 DISK ERAS

In Chapter 2, we found that the histories of MW-like galaxies proceed in three (relatively distinct) phases, which we termed the Pre-Disk, Early-Disk, and Late-Disk Eras. That galaxy evolution occurs in “phases” is certainly not a new finding, but this Disk-Era framework has proven to be a useful (and fairly straightforward) approach for understanding the histories of disk galaxies. Indeed, as emphasized in Chapter 2, σ_{form} , and $\sigma_{\text{now}} - \sigma_{\text{form}}$ exhibit different normalizations and trends with age in each era. Furthermore, this three-phase picture of disk formation

is not unique to our simulations; for example, analogous eras have been identified for the MW’s history (Chandra et al., 2024), and more recently, analytical models of disk formation have adopted complementary frameworks (Semenov, 2026).

One of the most interesting findings of Chapter 2 was that a galaxy’s present-day dynamical state strongly correlated with the time its disk began to settle, that is, when it transitioned from the Pre-Disk to the Early-Disk Era. As mentioned, Pearson and Spearman correlation tests showed that the time of disk onset (determined using each of our three different metrics) was strongly correlated with v_ϕ/σ for both all and young (age < 250 Myr) stars, with correlation coefficients of ~ 0.9 (and p-values of $10^{-5} - 10^{-6}$). The correlation between disk settling time and v_ϕ/σ of all stars is perhaps unsurprising: one would expect galaxies with earlier forming disks to be dynamically colder overall, given that (1) stars formed on colder orbits for more of the galaxy’s history, and (2) certain vigorous dynamical heating processes pervasive prior to disk formation (such as burst-driven potential fluctuations, “spin-flips” from misaligned gas accretion, or “baryon sloshing”) occurred over less of the galaxy’s history.

However, the (often stronger) correlation between disk onset time and v_ϕ/σ of very young stars is less trivial. Future work is needed to understand this correlation between the disk formation time and the present-day dynamical state of the ISM (which sets v_ϕ/σ of young stars). A dynamically-colder ISM suggests weaker turbulence, which is thought to be sourced by some combination of stellar feedback, gravitational instability, and mass accretion, although the importance of these mechanisms remains debated. A very preliminary investigation indicates that, in the FIRE-2 simulations, earlier forming disks typically have lower specific star formation rates at present, although this correlation is comparatively weak. Additionally, much of the work in Chapter 2 focused on annulus-wide kinematics. A clear next step would be to verify if this correlation persists when considering locally-measured stellar kinematics.

Furthermore, although we determined when each of our galaxies transitioned from their Pre-Disk to Early-Disk Eras, we did not define corresponding times for the Early-Disk to Late-Disk transition. We formally define this transition in Steele et al. (in prep.), where we analyze cold torquing in the FIRE-2 simulations using the Disk-Era framework, adopting a threshold of $(v_\phi/\sigma_{3D})_{\text{form}} > 3$. The typical Late-Disk transition time is ~ 4 Gyr, in agreement with the findings of this dissertation. Interestingly, these Late-Disk times exhibit striking similarity with the burst times of (Yu et al., 2021), with times for most galaxies differing by $\lesssim 250$ Myr. Also interesting is the substantial variation between the duration of the Late-Disk Era for different galaxies: on average, the Late-Disk transition occurs 2-3 Gyr after the Early-Disk transition, but ranges from ~ 5.5 to 1 Gyr across the galaxy sample. Interestingly, preliminary work indicates that $(v_\phi/\sigma$ of young stars correlates more strongly with the Pre-Disk to Early-Disk transition than the Early-Disk to Late-Disk transition: future work is needed to understand the origin of these correlations (and their respective differences).

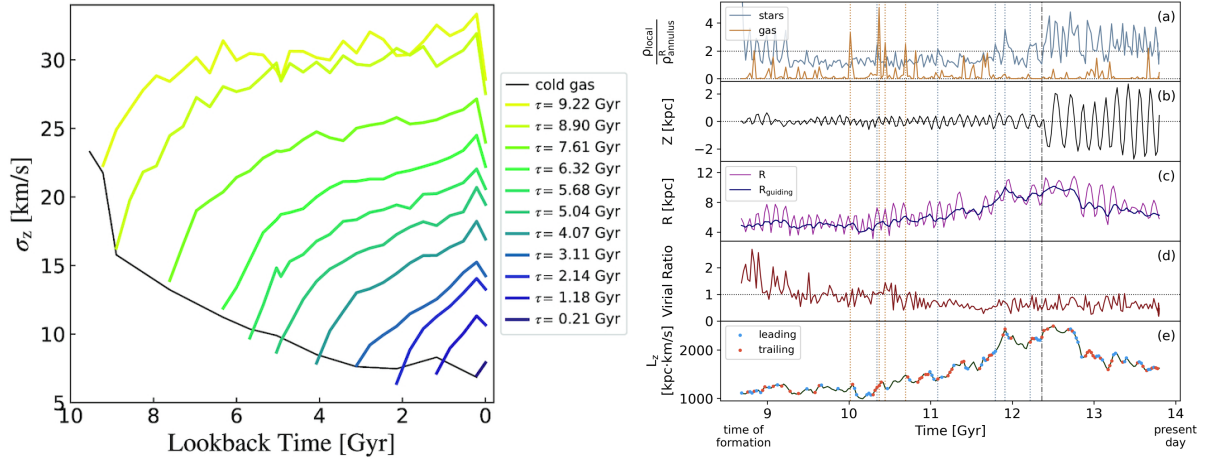


Figure 34: Left: Example of work that tracks heating histories of mono-age populations in the h277 simulation from Bird et al. (2021). Right: Figure from Wiggins et al. (2025) tracking the orbit and evolution of a long-lived open cluster in the FIRE-2 m12f simulation. The cluster experiences significant changes in orbital angular momentum and guiding radius, without an associated increased in random vertical motion, indicating it undergoes cold torquing.

4.2.2 DYNAMICAL HISTORIES

HEATING HISTORIES

Thus far, we have discussed heating only by comparing the velocity dispersion of populations at birth and at present. However, this heating does *not* occur steadily over a star’s lifetime. Generally, a substantial amount of heating occurs very early in a star’s life, when it is kinematically-coldest (and thus most susceptible to perturbations) and is necessarily in a dense environment (close to other newly formed stars and clusters, which can be distributed along spiral arms). That said, particular events in a galaxy’s history can also drive substantial, coherent heating of pre-existing stars, including mergers, satellite interactions, and bar formation and buckling.

The clear next step for future analysis to take is to track star particles throughout their lifetimes. By tracking star particles, we can identify when (and perhaps where) heating takes place and relate this to the presence of non-axisymmetric structures and/or galaxy-wide events.

The left panel of Figure 34 shows the results of a similar analysis by Bird et al. (2021) for stars in the particularly MW-like h277 simulation. As expected, older populations are born dynamically hotter than younger ones, and the fastest rate of heating occurs immediately after formation, with most populations exhibiting relatively similar (but by no means identical) heating rates throughout their lifetimes.

Future work could also be done to correlate such heating with long-lived non-axisymmetric structures in the simulations. A previous work has identified the dominant spiral modes in the FIRE-2 simulations (Quinn et al.,

2025). In turn, future work could test whether there is a correlation between spiral strength and increased heating, both in newly formed stars and in the overall stellar population.

TRACKING RADIAL REDISTRIBUTION

One could also consider orbital changes outside of heating, that is, changes to stellar positions and actions (such as the azimuthal action, better known as angular momentum). This is particularly relevant for studying radial migration (or “cold torquing”), in which stars experience substantial changes in angular momentum (and thus guiding center radius), without experiencing dynamical heating, owing to resonant interactions at the corotation radius of transient spiral arms (Sellwood and Binney, 2002). This dynamical process is particularly “nefarious” as it leaves little dynamical evidence. Therefore, constraining radial migration is of tantamount importance for interpreting the MW’s dynamical record (along with the archeological record of other galaxies, like M31 and M33).

For example, Wiggins et al. (2025) tracked the orbital changes of an open star cluster in the FIRE-2 m12f simulation. This open cluster is particularly long-lived, surviving until the end of the simulation, a full 5.13 Gyr after its formation, while other similarly massive open clusters typically dissolve on $\lesssim 100$ Myr timescales (in our simulations and in observed galaxies). As shown in the right panel of Figure 34, this simulated cluster experiences radial migration, such that its guiding center radius changes from ≈ 4 kpc to 12 kpc (panel c) after passing through a particularly gas-rich region (panel a), while its random motion (and thus vertical oscillations around the midplane) remains unchanged (panel b).

This tracking can be further complemented by work studying the changes in stars’ orbital radii over cosmological time across our simulation suite. In the current literature, it is often assumed that stellar populations experience negligible net inward or outward motion, and that their changes in radius can be well-approximated by a diffusion in angular-momentum space that steadily increases with age (Sanders and Binney, 2015; Sellwood, 2014; Sharma, Hayden, and Bland-Hawthorn, 2021).

Figure 35 (left) shows the median change in the guiding center radius¹ and the (half-width of the 68%) scatter of this change for stars in the FIRE-2 simulations from Bellardini et al. (in prep.) (in which I am co-author). Importantly, this figure compares the results of the FIRE-2 simulations (solid colored solid lines) with empirically estimated results for the MW of Ratcliffe et al. (2025) (dashed colored dashed lines) and Frankel et al. (2020) (black dotted line). Here, Ratcliffe et al. (2025) determines the change in radius directly by estimating birth radii using the ISM’s metallicity gradient and its scatter (following the method of Lu et al. (2022), which is itself based on the method of Minchev et al. (2018)), while Frankel et al. (2020) fits the multiparameter data assuming that the change in radius follows a $\tau^{1/2}$ relation. In FIRE-2, older stars show a net movement outward, and this tendency increases steadily with age (top panel). However, in FIRE-2, the diffusion around birth radius increases with age

¹ Specifically, the guiding center radius, R_j , is the radius of a circular orbit with the same angular momentum, defined as $R_{\text{circ}}(j) = j^{2/3} \left[\frac{d\Phi(R)}{dR} \right]_{R=R_{\text{circ}}(j)}^{-1/3}$.

only up to $\sim 2\text{--}4$ Gyr, after which it essentially saturates (if not slightly decreases). Interestingly, FIRE-2 shows remarkable agreement with the empirical results of Ratcliffe et al. (2025) for the MW, but disagrees with the parameterized MW results of Frankel et al. (2020). Although works like Bellardini et al. (in prep.) do not track individual star particles (or clusters), they are crucial for understanding how stars actually evolve in MW-like galaxies overtime, and for testing assumptions about how such orbital changes “should” occur.

ORIGIN OF EARLY HEATING

In Chapters 2 and 3, we found that stars form with fairly cold kinematics in FIRE-2, but are rapidly heated after their birth (as evidenced, for example, by the difference between ~ 250 Myr old populations at birth and today in the lower panels of Figure 8). Although much of the (post-formation dynamical) heating in our simulations is physical, reflecting “true” dynamical perturbations, some heating may very well be numerical, that is, reflecting spurious interactions due to the finite mass-resolution of the simulations. In future work, one could investigate the origins of this (potentially non-physical) heating.

In FIRE-2 (and reality) star formation is highly clustered, and gravitational interactions between nearby co-natal star particles could overestimate heating (given the larger masses of star particles compared to actual stars). Furthermore, strong feedback may also drive local potential fluctuations that overly heat stars (that said, such strong feedback would quickly disperse star clusters and limit nearby gravitational interactions). A useful avenue for future work would be to conduct a dedicated numerical investigation of feedback strength, gravitational softening, and other numerical parameters, testing how sensitive our results, including stellar kinematics at birth and $\approx 10\text{--}250$ Myr after formation, are to our numerical/computational choices.

4.2.3 MORE SIMULATIONS

TAILORED MW SIMULATIONS

The FIRE-2 simulations are far from exact MW analogs, in part because they were not chosen to be MW analogs². For that reason, their differences from the MW are in some part expected. In order to simulate galaxies that match the MW’s cold kinematics, it seems necessary to capture certain aspects of the MW’s particular formation history, likely including both its early mass assembly (and thus disk formation) and quiescent merger history (and thus perhaps its particular larger-scale cosmic environment). Future work could try to identify initial conditions that are particularly MW-like in these regards. Fortunately, there has been some headway on this, with an early-forming MW-analog identified in FIRE-3. Running this simulation, along with other possible “evolutionary MW-analogs”, down to $z=0$ at full resolution will help us better understand if the disconnect between our simulated galaxies (and

² That said, the 6 Elvis on FIRE runs were chosen to be Local Group analogs (defined as two massive galaxies within $600 - 1000$ kpc of each other), and m12r and m12w were chosen to have LMC analogs.

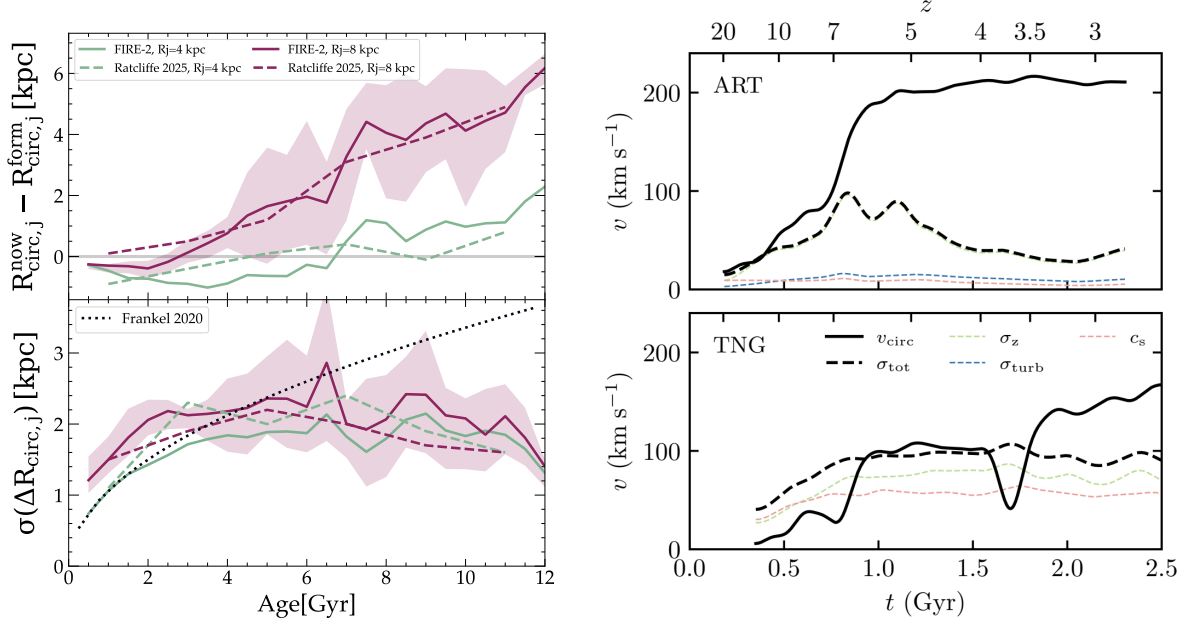


Figure 35: Left: Example of work that studies radial redistribution in the FIRE-2 simulations from Bellardini et al. (in prep.).

Right: Figure from Semenov et al. (2024c), comparing the dynamical histories of the same MW-like galaxy ran with the TNG50 code and the ART code.

nearly all other simulations) and the MW stems from the MW’s unique history or from some underdeveloped aspect of the simulations.

SIMULATION CONSISTENCY: AN ASIDE

Chapter 3 discussed results from other zoom-in simulations: a future edition of the work will include a figure presenting the different age velocity dispersion relationships directly, to better highlight the remarkable conformity between the different simulations (and the outlier status of h277).

This comparison will use the data from these groups’ published relations, but different works adopt different spatial and kinematic selections making the comparison less exact. Luckily, most of the published results select stars to be in solar-neighborhood-like locations, making broadly similar vertical selections (although as shown in the appendix of Chapter 2, this impact of vertical selection is typically mild), though this is not true for all works. Some of these simulations, like Auriga (and FIRE-2) are publicly available, allowing more detailed comparisons beyond literature results.

In Chapter 3, we primarily framed this consistency between simulations as support for the outlier-status of the MW (and, by implication, for the reliability of our simulations). But in truth, this consistency – although not necessarily a demerit against the reliability of FIRE-2 – is slightly disconcerting.

$\sigma(\tau)$ is set by the kinematics of stars at birth – as inherited from the star-forming ISM – and subsequent dynamical heating processes, sourced by non-axisymmetric structures within the disk, including spiral arms, bars,

and GMCs, with additional influence from external perturbers like merging galaxies and satellites. However, different simulation groups employ vastly different modeling approaches, which significantly impacts how star formation, feedback, and dynamical heating operate in these galaxies.

For example, some of these simulations adopt highly simplified ISM and thus star-formation models: in Auriga and HESTIA, the ISM is modeled using an effective equation of state, with stars forming stochastically above gas densities of $n=0.13 \text{ cm}^{-3}$ on a time-scale of 2.2 Gyr. In turn, stars form at very low gas densities, and the simulation is unable to resolve GMCs. In contrast, FIRE-2 directly resolves the multi-phase ISM including GMCs, and star formation occurs at a mean gas density of $n=3400 \text{ cm}^{-3}$. This suggests that different mechanisms act to generate similar birth dispersions and different scattering agents act to generate similar amounts of heating.

SIMULATION RE-RUNS

A useful direction for future work would be to re-run other initial conditions with FIRE-2 (or FIRE-3) code. Of particular interest would be h277, which is the simulation with the most MW-like AVR. This approach is similar to that of Semenov et al. (2024c), who re-ran the initial conditions of a particularly early-forming MW in TNG50 with the higher-resolution ART code. Figure 35 (right) shows the evolution (since the start of the simulation) of the circular velocity (black solid lines) and velocity dispersion (black dashed lines) for gas in the galaxy. Importantly, a disk only forms once the circular velocity exceeds the velocity dispersion. In the high resolution AMR code ART, this happens within 1 Gyr, but in the same simulation, run with the lower resolution TNG50 code, a disk forms a full Gyr later (and with less rotational support). Interestingly, this same disk was later destroyed by a merger in the ART run, while in the TNG50 run, the disk – despite being later forming and weaker – survived. Thus, different physics implementations can have drastically different results for the same initial conditions. Initial conditions that yield age-velocity dispersion relations as cold as the MW may be rare, but they may also require advanced (and computationally expensive) physics implementations.

SYNTHETIC OBSERVATIONS

In Chapter 3 (and to a lesser degree in Chapter 2), we compared our simulations with various observations; however, we have not generated proper synthetic observations. Clearly, a potential avenue for future work is to create mock IFU data cubes for the FIRE-2 simulations, which could be achieved using existing packages like GALCRAFT (Wang et al., 2024), which would allow for a more "apples to apples" comparison between our simulations and the results of PHANGS-MUSE.

4.2.4 MORE OBSERVATIONS

In Chapter 3, we argued that the MW is a kinematic outlier among star-forming, disk-dominated galaxies in the local Universe. However, this comparison was based on a sample of just 19 systems, which span a factor of ~ 50

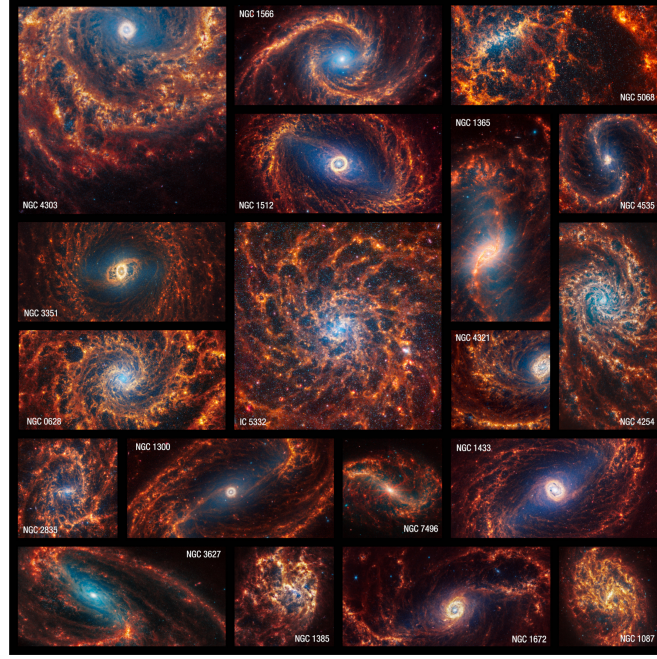


Figure 36: Mosaic of 19 face-on galaxies in the PHANGS sample, as seen by JWST in near- and mid-infrared. NGC 1433 - shown towards the lower right corner - is the only galaxy in the sample to have colder kinematics than the MW. Image Credit: NASA, ESA, CSA, STScI, PHANGS Team, Janice Lee (STScI), Thomas Williams (Oxford); Designer: Elizabeth Wheatley (STScI)

in stellar mass. Ideally, we will be able to obtain age velocity dispersion relations for a larger sample of galaxies. Although measuring age velocity dispersions is immensely challenging because it requires deep, high resolution observations, it is necessary to understand how dynamical heating operates across different systems. In particular, it may be useful to prioritize observations of close MW-analogs, that is, particularly thin/rotationally dominated systems (perhaps close to the green valley).

Figure 36 shows (rather stunning) JWST images of 19 nearby galaxies in the PHANGS sample, including the 16 PHANGS galaxies that we included in our observational comparison in Section 3. Importantly, in Chapter 3, we showed that NGC 1433 - pictured towards the bottom right corner of Figure 36 - is the only galaxy of our 18 galaxy observational sample that is colder than the MW. The origin of this systems cold kinematics may reflect the fact that it is (slightly) more massive ($7.9 \times 10^{10} M_{\odot}$) than the MW; that it is below the star formation main sequence (being the furthest from the main sequence in the PHANGS-MUSE sample); that it is a Seyfert galaxy, indicating recent AGN activity; or that (like the MW) it resides in a group environment. Understanding the similarities (and differences) between NGC 1433, the MW, and our simulations will be immensely helpful in disentangling how particular formation histories result in present-day dynamics.

Recently, different works have combined high resolution IFU spectroscopy with dynamical modeling - specifically Schwarzschild's orbit-superposition method. These population-orbit superposition methods distinguish distinct kinematic components/orbital families within the galaxy and assign mean stellar ages and metallicities to each

of these components. In turn, we can now recover the orbital, age, and metallicity distributions within different galaxies. Although most works have applied these methods to lenticular/S0 galaxies (Poci et al., 2021; Poci et al., 2019; Zhu et al., 2022), recent work extended the method to a nearby barred-disk galaxy (Tahmasebzadeh et al., 2024). Furthermore, recent work has applied these methods to our own MW, while other works have applied these methods to mock data from simulations (Khoperskov et al., 2025a,b). Ideally, such works will be used to provide (at long last) a true apples-to-apples comparison between the MW, external galaxies, and simulations, and even allow us to fully disentangle the drivers of disk formation and evolution.

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