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Cold Torquing as a Mechanism for Radial Redistribution in FIRE Simulations of Milky Way-mass Galaxies

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ABSTRACT

Cold torquing is a poorly understood mechanism for radial redistrubtion, which does not leave easily detectable dynamical traces in a star's kinematics. We study the extent to which cold torquing has shaped the stellar distributions of 6 FIRE simulations of Milky-Way mass galaxies by comparing their orbits at formation to the present day, and find that cold torquing makes up nearly half of all radial redistribution for younger stars. We also find a previously undiscussed phenomenon in which the orbits of stars get colder after formation, which we call colder torquing. We find that colder torquing comprises up to forty percent of all radial redistribution, and that it is particularly prevalent for older stars formed before disk settling.

1. INTRODUCTION

Spiral disks such as the Milky Way are relatively young galaxies in which stars are constantly forming out of the gas and dust in the galactic disk, known as the interstellar medium (ISM). Throughout the main-sequence portion of their lives, stars fuse hydrogen and helium into heavier elements broadly referred to as metals, which are scattered back into the ISM when stars die. This process enriches the ISM for the next generation of stars, steadily increasing the metallicity of the ISM over the course of a galaxy's life. Galactic evolution models also predict that galaxies form from the inside out, suggesting that the metallicity of the ISM should be highest near the center of the disk and decrease outwards as a function of galactic radius—a trend which has been observed in the Milky Way (Wilson & Rood 1994), as well as other disk galaxies (Henry & Worthey 1999). Naively, it follows that the elemental distribution of stars throughout a galaxy should match that of the ISM they are born in: young stars should be more metal-rich than older stars at a given radius, and the metallicity of stars at a given age should decrease as a function of radius. However Edvardsson et al. (1993) find no such correlation between age and metallicity in our solar neighborhood, and Lehmann et al. (2024) even find stars with metallicities higher than the local ISM throughout the Milky Way. This suggests that some stars move from their birth radii, changing their orbits in a process which we will comprehensively refer to as *Radial Redistribution*.

There are two main processes by which stars can be perturbed from their orbits. *Heating* occurs by many dynamical processes such as scattering off molecular clouds, and is called such because it increases the velocity dispersion, and thus the entropy of a star's orbit. Because stars are generally assumed to form on circular orbits, it is fairly straightforward to identify whether a star has undergone heating. However, the radial redistribution caused by heating alone is insufficient to explain the observed lack of correlation between age and metallically. A second mechanism for radial redistribution was proposed by the seminal paper Sellwood & Binney (2002), which suggested that co-rotation resonances with spiral arms can allow stars to undergo significant changes in orbital radius while remaining on a circular orbit. This mechanism, which was later demonstrated by Vera-Ciro et al. (2014) in N-body simulations, is most often referred to as churning or radial migration. However, we will refer to it specifically as *Cold Torquing* to avoid ambiguity, as this term more clearly conveys the idea that it does not leave significant dynamical signatures in the kinematics of the affected stellar population in the way that heating does. Consequently, cold torquing is far more difficult to detect, and the true extent to which it has shaped the stellar distributions we observe today is not well understood. A better understanding of the role it plays in radial redistribution is necessary to accurately reconstruct stellar histories and develop our understanding of galactic evolution.

As galaxies evolve on a timescale far longer than we can observe, the study of galactic evolution was once limited to performing galactic archaeology on observed stellar populations. In recent decades however, advances in computational technology have given rise to increasingly high-precision cosmological simulations of galaxy formation which model a variety of physical processes across immense scales. The FIRE (Feedback in Realistic Environments) project has developed and released numerous high-resolution cosmological zoom-in simulations of galaxy simulation which directly resolve the structure of the ISM, while modeling the main processes of stellar evolution and feedback (Wetzel et al. 2023).

This project studies the prevalence of cold torquing within 6 Milky-Way mass galaxies from the FIRE-2 public data release by analyzing the orbits of stars, both at their formation and today. In Section 2, we present a parameter which quantifies the dynamical coldness of a star's orbit, along with definitions for other relevant terms. Section 3 contains our main results and discussion, which are followed by a conclusion and a summary of future work in Section 4.

2. DEFINITIONS

To study how much of an effect cold torquing has on a stellar population, we consider (1) how much of the total stellar population experiences radial redistribution, and (2) how much of all radial redistribution occurs via cold torquing. In this section, we quantitatively define these values and the relevant parameters in terms of a the instantaneous kinematics of a star particle.

2.1. *Circularity*

The entropy of a star's orbit, or the amount of random (non-azimuthal) motion in the orbit, is directly reflected in the circularity of the orbit. While eccentricity is the classical orbital element corresponding to circularity, the circularity parameter η is often used in its place as it is easier to measure from a single snapshot of the orbit's kinematics. It is defined as $\eta = j/j_{\rm circ}(E)$, where j is the particle's instantaneous specific orbital angular momentum, and $j_{\rm circ}(E)$ is that of a particle on a circular orbit with the same energy. In order to obtain the particle's total energy however, it is necessary to compute the potential of the entire galaxy. While this can be reasonably done for a single snapshot, it becomes far more expensive to find the circularity of every star at formation, which would require information on the potential over the galaxy's entire history. We therefore approximate $j_{\rm circ}(E)$ as the specific angular momentum of a circular path with the same kinetic energy, which gives $\eta \approx v_\phi/v_{\rm tot}$. where v_ϕ is the azimuthal component of the particle's total velocity, $v_{\rm tot}$. η is also related to eccentricity by $e = \sqrt{1-\eta^2}$ for a Keplerian orbit, which we use to define the approximate eccentricity of an orbit:

$$e' = \frac{v_{ZR}}{v_{\rm tot}}. \quad (1)$$

Here, v_{ZR} is the sum in quadrature of the axial and radial velocity components. e' has the advantage of depending only on a particle's instantaneous velocity, and is a reasonable approximation for the particle's true eccentricity at high circularities. For conciseness, all future references to eccentricity will refer to this approximation. It is also worth noting that e' is equivalent to the fraction of the total velocity that is non-azimuthal, which agrees with our physical intuition of circularity.

e'	η
0	1
0.1	0.995
0.2	0.980
0.3	0.954
0.4	0.917
0.5	0.866
0.6	0.800
0.7	0.714
0.8	0.600
0.9	0.436
1	0

Table 1: Corresponding values of e' and η as defined in Section 2.1 for the full range of circularities, $0 < e' < 1$.

Table 1 displays the corresponding values of η for the full range of eccentricities. Notably, η is weighted towards higher eccentricities such that the entire range of reasonably circular orbits ($0 < e' < 0.4$) translates to the far smaller range $1 < \eta < 0.9$. For this reason, we use e' as our metric for an orbit's dynamical coldness in our main investigation.

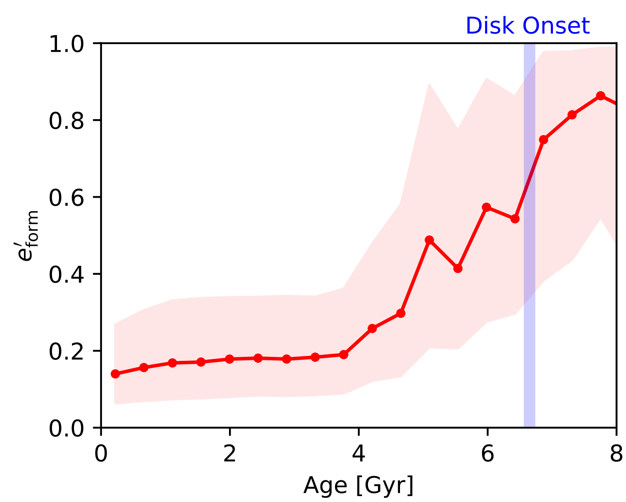

Figure 1: Median formation eccentricity versus age in m12i. The shaded regions show the 68th percentile scatter, and the blue shaded bar indicates the disk onset time (McCluskey et al. 2023). The trend of increasing eccentricity with age suggests that older stars that formed before or around disk onset tend to form on less circular orbits.

We argue that e' is a suitable circularity metric for the scope of this work, despite the fact that its accuracy as an approximation for eccentricity depends on assumptions of circularity which do not hold for less circular orbits. This is because we limit our main investigation to stars that form on highly circular orbits, and we are primarily interested in the subset of them that remain circular as candidates for cold-torquing. This choice is supported by Figure 1, which shows median formation eccentricity as a function of age for the simulation m12i. The onset of disk settling, defined as the time when stars began to form with rotationally-dominated kinematics such that $(v_\phi/\sigma_{\rm tot})_{\rm form} > 1$, is taken from McCluskey et al. (2023). We find that the majority of young stars form on close to circular orbits, and that stars formed on eccentric orbits are likely to be older stars formed before or within a couple Gyr of disk-onset. Our choice to focus on stars with high formation circularity is further supported by Vera-Ciro et al. (2014), who find that cold torquing preferably occurs for stars already close to circular orbits, which they reason is because these stars spend the most time in the disk plane where they would experience the strongest azimuthal perturbations. However, we also investigate the effect of cold torquing on this population of stars forming on non-circular orbits in Section 3.2.

We consider a star to have formed on a circular orbit if $e'_{\rm form} < 0.2$. Note that in Figure 1, the median formation circularity of stars formed during the Late Disk Era falls under this cutoff, which we further justify in Section 3.3.

2.2. *Cold Torquing*

We are specifically interested in the prevalence of cold torquing in the population of stars that have experienced significant radial redistribution. To this end, we measure radial redistribution through fractional changes in orbital angular momentum, which is related by $j \propto r^{1/2}$ to orbital radius for a Keplerian orbit. We then measure the resulting change in the dynamical coldness of its orbit using the eccentricity approximation e' introduced in Section 2.1. We say a star has been cold torqued if it meets the following criteria:

1. It has experienced significant radial redistribution, such that $|\Delta j/j_{\rm form}| > 0.2$.
2. Its orbit is not significantly heated during its redistribution, such that $|\Delta e'| < 0.1$.

We explore the effects of adjusting these cutoff values in Section 3.3. These definitions allow us to measure the prevalence of both radial redistribution and cold torquing as a simple fraction of the relevant stellar population. For convenience, we will refer to the fraction of total stars formed on circular orbits that experience radial redistribution as $f_{\rm RR}$. We will also refer to the fraction of radially redistributed stars that also experience cold torquing as $f_{\rm CT}$.

2.3. *Colder Torquing*

When we include stars which form on highly eccentric orbits in our investigation, which is summarized in Section 3.2, we find a significant population of stars whose orbits actually become *colder* after radial redistribution. Figure 2 shows the distribution of $\Delta e'$ across the population of radially redistributed stars, along with the median and 68th percentile scatter. Note that the lower bounds of this scatter extends to negative values of $\Delta e'$, and that the peak of the distribution is skewed left of the positive median, close to zero, which corresponds to cold torquing as defined in the previous section. As this phenomenon has not been previously defined in the literature, we refer to it as *Colder Torquing*, and define it as a decrease in eccentricity such that $\Delta e' < -0.1$. We will refer to the fraction of radially redistributed stars which also experience colder torquing as $f_{\rm CRT}$. It is also important to note that because we do not impose a formation circularity cutoff, $f_{\rm RR}$ in our investigation of colder torquing refers to the fraction of *all* stars that experience radial redistribution.

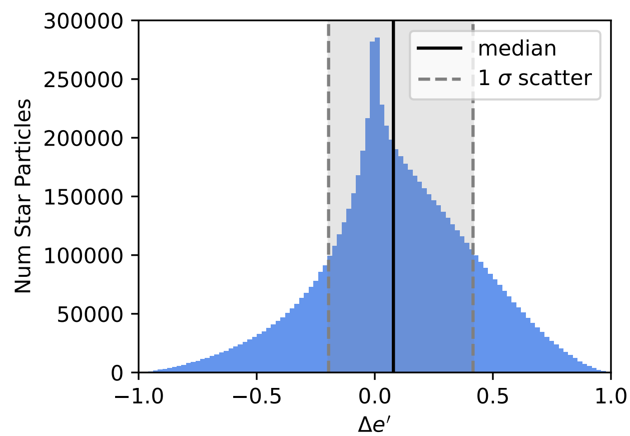

Figure 2: The distribution of $\Delta e'$ over the population of all stars that undergo significant radial redistribution in m12i, with no restriction on formation circularity. The black line indicates the median, and the shaded gray region corresponds to the 68th percentile scatter from the median.

3. RESULTS AND DISCUSSION

3.1. *Cold Torquing*

Using the metrics for cold torquing and radial redistribution defined in Section 2.2, we investigate their dependence on a number of parameters across all 6 Milky way-mass FIRE-2 simulations. Figure 3 shows both $f_{\rm CT}$ and $f_{\rm RR}$ as functions of radii, for stellar populations of three different age groups corresponding to the main phases of a galaxies life. The first takes place before the onset of disk settling, and the latter two indicate the time at which the velocity dispersion of the galaxy stopped decreasing. The average of these times for all the Milky-Way mass Fire-2 Simulations are taken from McCluskey et al. (2023) as 4 Gyr and 8 Gyr respectively. Radial redistribution appears to decrease with

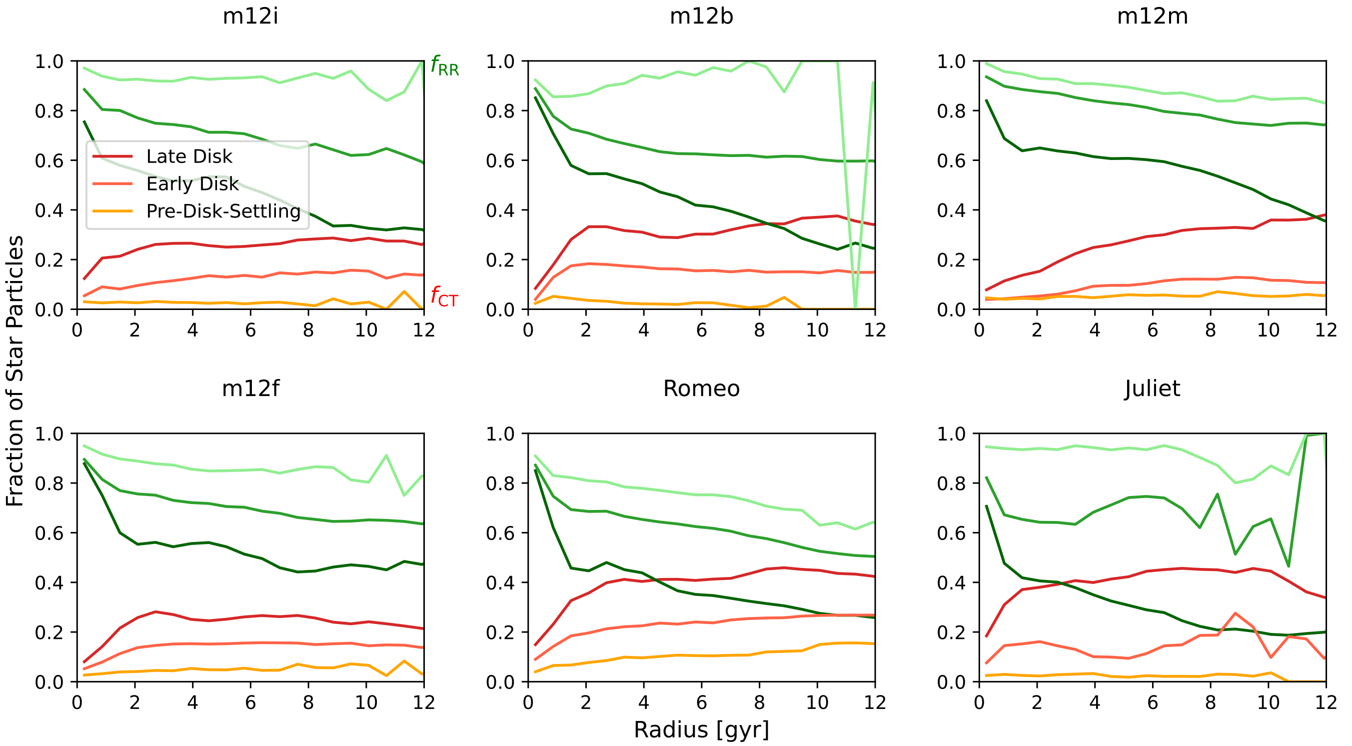

Figure 3: $f_{\rm RR}$ and $f_{\rm CT}$ as functions of formation radius for all 6 simulations, plotted in green and red, respectively. $f_{\rm RR}$ is the fraction of total stars formed on circular orbits that experience radial redistribution, and $f_{\rm CT}$ is the fraction of radially redistributed stars that also experience cold torquing. Both are shown for 3 age populations corresponding to the 3 main stages of galactic evolution, taken from McCluskey et al. (2023). Darker colors correspond to later stages.

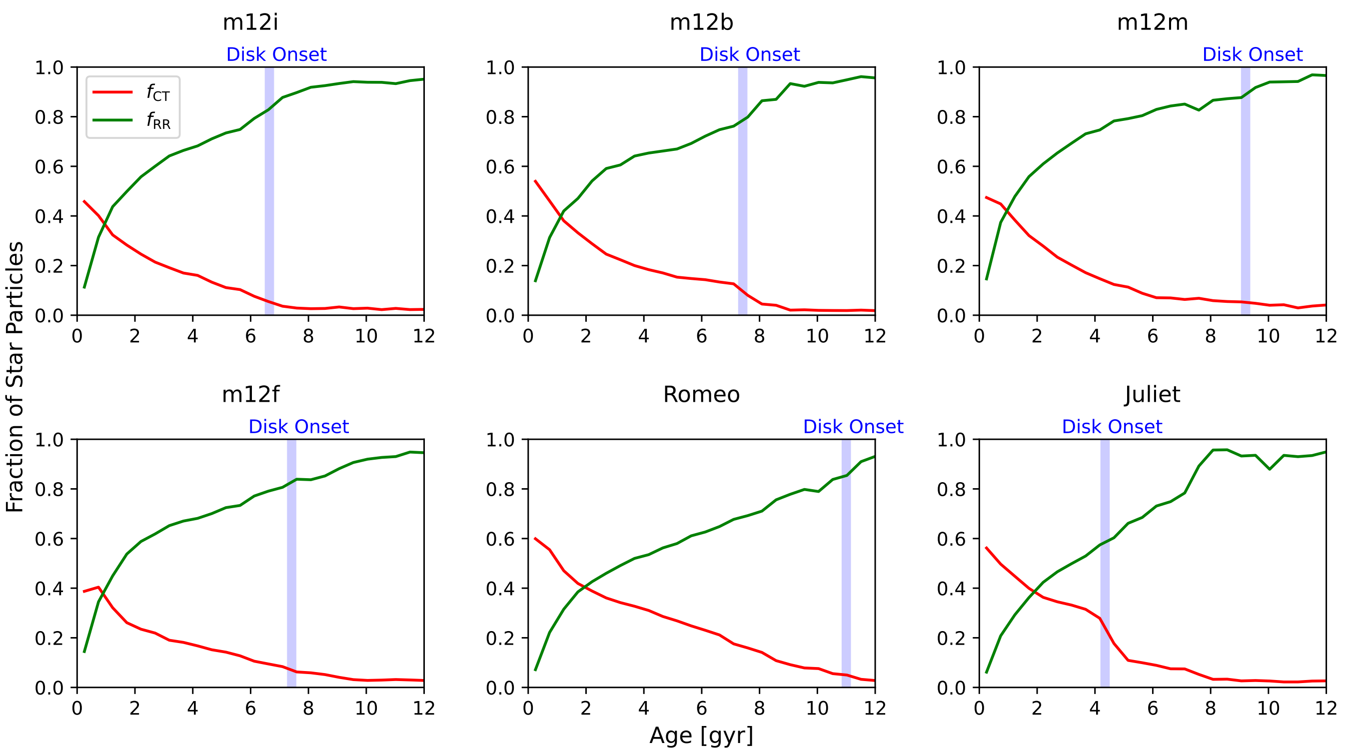

Figure 4: $f_{\rm CT}$ and $f_{\rm RR}$ as functions of age for all 6 simulations, plotted in red and green, respectively. The disk onset times of each galaxy is indicated by the blue line.

as formation radii increases, such that stars that form at the center of the galactic disk are more likely to move than those near the edge, and that this trend appears to strengthen with the age of the stellar population. This is not surprising, as the density of matter is highest near the center of the galaxy, which also contains more asymmetric structures such as bars and spiral arms leading to strong perturbing forces. Furthermore, as galaxies form from the inside out, older stars are more likely to have formed closer to the galactic center and moved outwards as the galaxy settled into a thin disk. However, cold torquing does not appear to be significantly affected by formation radius, apart from a slight increasing trend with radius in m12m and Romeo, our two earliest settling galaxies.

Generally, we find that both radial redistribution and cold torquing are more significantly affected by age in Figure 6. We observe that radial redistribution increases with age across all galaxies, from close to 10% of very young stars to more than 80% of stars formed before disk onset. This is not surprising, as newly formed stars are far less likely to have experienced many perturbations that would heat their orbits. On the other hand, the population of stars formed before the galaxy began settling into a thin disk must by definition been born with a high velocity dispersion, which later decreased as the angular momenta of their orbits collapsed along the galactic axis. We also observe a decreasing trend in $f_{\rm CT}$ with stellar age. Cold torquing makes up around half of all radial redistribution for the youngest stars, but almost none for stars formed before disk onset. This is also reasonable, as younger stars have had less time to scatter off molecular clouds and heat up their orbits, but could experience cold torquing far earlier if they were born into a co-rotation resonance with a spiral arm. Similarly, nearly all stars older than the disk settling time were formed on highly eccentric orbits as shown in Figure 1, indicating that e' is a less accurate approximation for their true eccentricity. This also agrees with Vera-Ciro et al. (2014)'s result that stars on less circular orbits are less likely to be cold torqued. It is notable that $f_{\rm CT}$ is usually less than 0.5 even in younger populations, indicating that cold torquing almost never dominates the radially redistributed population.

3.2. *Colder Torquing*

As galaxies settle into a disk, the angular momenta of their star particles collapse along a single axis, which we expect to cause an overall decrease in velocity dispersion which may actually reduce the eccentricity of some orbits. We investigate the prevalence of colder torquing in the full population of star particles without any restriction on formation circularity, using the parameters defined in Section 2.3.

Figure 5 plots $f_{\rm CRT}$ against radius for the same three age populations described in Section 3.1, and shows no significant correlation between the two for any age group. However, we observe several significant trends in Figure 5, which shows both $f_{\rm CRT}$ and $f_{\rm RR}$ as a function of age. $f_{\rm RR}$ increases with age in an overall similar trend to the one observed for the population of stars formed on circular orbits in Figure 6. However, we see a sharp increase in radial redistribution during disk onset in Juliet, our earliest forming galaxy, and m12b, which is not present in Figure 6.

Colder torquing seems to be slightly less prevalent than cold torquing in most of our galaxies, ranging from between five to forty percent of all radial redistribution in all of them except Juliet. We also find that colder torquing actually tends to increase with age, especially after disk onset, although this trend is not as strong as the one observed for cold torquing.

3.3. *Sensitivity to Cutoff Parameters*

We explore the sensitivity of our cold torquing parameter, $f_{\rm CT}$, to each of the parameters used in its definition: $e_{\rm form}$, Δe, and $\Delta j/j_{\rm form}$ in Figures 7, 8, and 9, respectively, for the same age groups described in Section 3.1. We also show the sensitivity of our radial redistribution parameter, $f_{\rm RR}$, to $e_{\rm form}$ and $\Delta j/j_{\rm form}$ in Figures 7 and 9.

Figure 7 shows the prevalence of both cold torquing and radial redistribution as functions of $e'_{\rm form}$ for stars formed during the three main stages of the galaxy's evolution. For stars formed during the Late Disk Era, we find that cold torquing has the largest effect on orbits which are relatively circular at formation with $e'_{\rm form} \approx 0.2$. We also find that stars formed on highly eccentric orbits are more likely to be radially redistributed, but that this trend is less distinct in older populations.

Figure 8 plots $f_{\rm CT}$ as a function of the maximum Δ'_e cutoff described in Section 2.2. All three age populations display a similarly increasing trend, which follows the logic that the prevalence of cold torquing will increase as the definition of "cold" is loosened. Finally, Figure 9 shows the prevalence of both cold torquing and radial redistribution as functions of the minimum $\Delta j/j_{\rm form}$ cutoff described in Section 2.2. As expected, we also see that the prevalence of radial redistribution increases as we loosen the definition of what constitutes significant redistribution for all age groups, although the relationship is fairly linear for older stars and more of an exponential decrease for young stars. However, the prevalence of cold torquing in all radially redistributed populations appears to be nearly constant, regardless of the cutoff used to define them.

4. FUTURE WORK

Colder torquing is a relatively unexplored phenomenon that plays a significant role in shaping stellar populations. More investigation into the mechanisms behind it, such as disk settling and angular momentum collapse, as well as its prevalence in the stellar population.

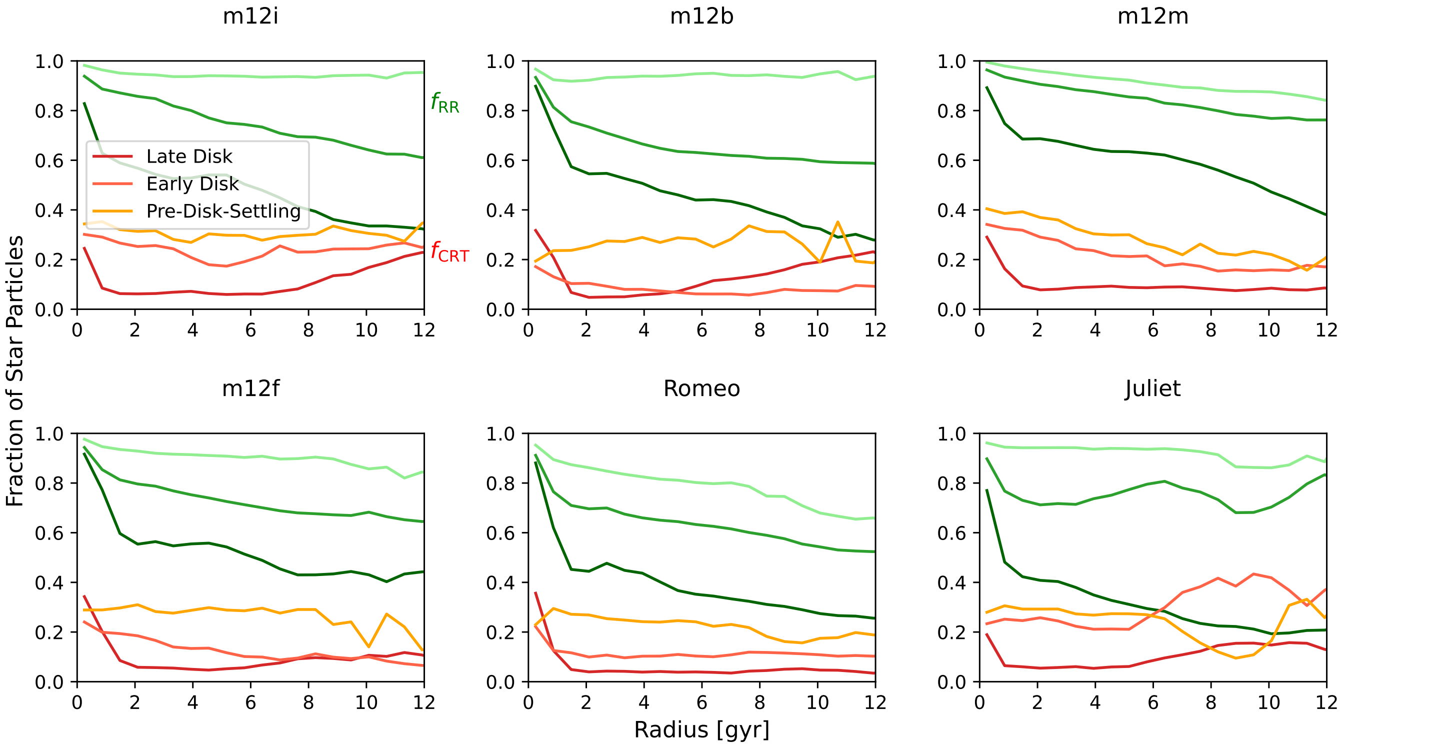

Figure 5: f_{CRT} and f_{RR} as a function of formation radius for all six simulations, plotted in green and red respectively. Unlike Figure 3, we impose no restriction on formation circularity such that f_{RR} corresponds to the fraction of *all* stars which undergo radial redistribution, and f_{CRT} corresponds to the fraction of stars in this population that also experience *colder* torquing.

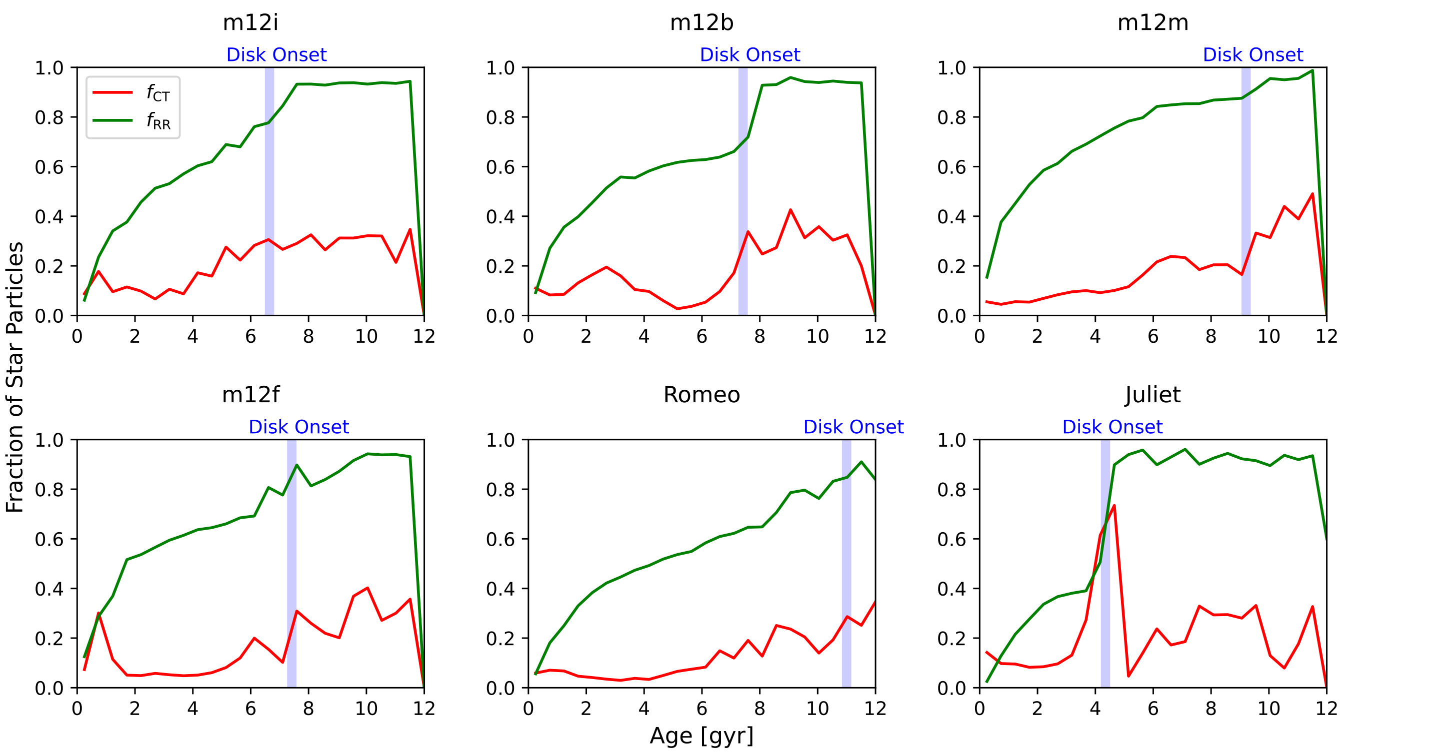

Figure 6: f_{CRT} and f_{RR} as functions of age for all six simulations, plotted in red and green, respectively. As in Figure 5, f_{RR} is a fraction of the total population of stars, with no restriction on formation circularity. The disk onset times of each galaxy is indicated by the blue line.

An archaeological approach to studying cold torquing may also be helpful in comparing results from the FIRE-2 simulations to observed stellar populations. We investigated cold torquing using a forward approach, by observing how the orbits of stars change after their formation, but focusing more on how characteristics of the current day population are affected by cold torquing may also give more valuable insight. Finally, we investigated both cold torquing and radial redistribution with a rather crude cutoff that fails to capture many more subtle trends. Future investigations might find it more useful to more quantitatively consider the dynamical coldness of a star's orbit rather than selecting a simple cutoff values.

ACKNOWLEDGMENTS

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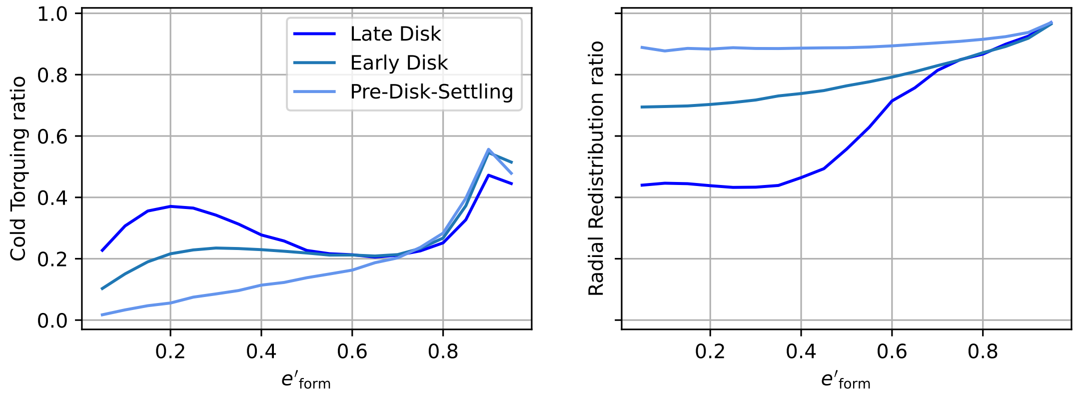

Figure 7: Cold torquing (left) and radial redistribution (right) as a function of formation circularity in m12i. Both graphs show trends for three different age populations, corresponding to the main phases of a galaxy's life.

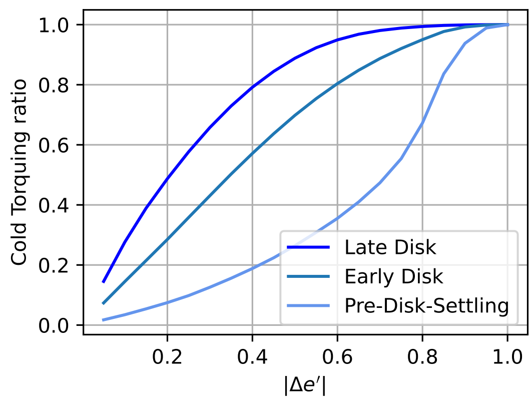

Figure 8: Cold torquing as a function of the maximum $\Delta e'$ cutoff used to define cold torquing in m12i. The three different age populations on the graph correspond to the main phases of a galaxy's life.

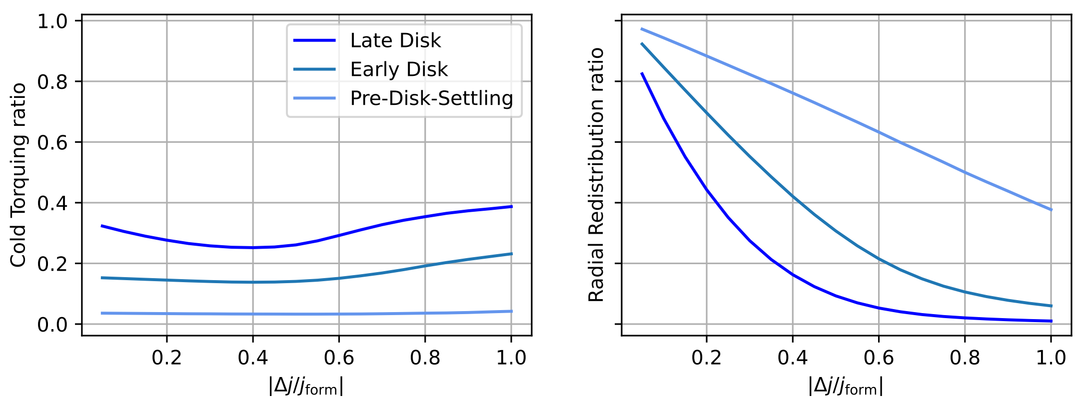

Figure 9: Cold torquing (left) and radial redistribution (right) as a function of the minimum $\Delta j'$ cutoff used to define radial redistribution in m12i. Both graphs show trends for three different age populations, corresponding to the main phases of a galaxy's life.