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# Hot-mode accretion and the physics of thin-disk galaxy formation

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## ABSTRACT

We use FIRE simulations to study disk formation in $z \sim 0$, Milky-Way-mass galaxies, and conclude that a key ingredient for the formation of thin stellar disks is the ability for the accreting gas to exchange angular momentum and develop a narrowly-aligned angular momentum distributions prior to joining the galaxy. Among central galaxies with a high fraction ($> 70\%$) of young stars in a thin disk ($h/R \sim 0.1$) we find that: (i) hot, virial-temperature gas dominates the inflowing gas mass on halo scales ($\gtrsim 20$ kpc), with radiative losses offset by compression heating as the gas moves in toward the central galaxy; (ii) this hot accretion proceeds until angular momentum support stalls inward motion, at which point the gas cools to $\lesssim 10^4$ K directly onto the galaxy; (iii) concurrent with cooling, the accreting gas transitions from a hot quasi-spherical configuration to a cool, flattened, disk-like configuration, with a tightly aligned angular momentum distribution. We further show that the existence of this "rotating cooling flow" accretion mode is strongly correlated with the fraction of thin disk stars in the central galaxy, among a sample of 17 $z \sim 0$ FIRE galaxies spanning a halo mass range of $10^{10.5} M_\odot \lesssim M_{\rm h} \lesssim 10^{12} M_\odot$. Notably, central galaxies with a thick disk or irregular morphology do not show any correspondence between cooling and flattening of accreted gas. Our results suggest that rotating cooling flows (or, more generally, rotating subsonic flows), which become coherently angular-momentum supported prior to direct deposition onto the galaxy, are likely a necessary condition for the formation of thin, star-forming disk galaxies in a LCDM universe.

**Key words:** galaxies: disk – galaxies: evolution – galaxies: halos – cosmology: theory

## 1 INTRODUCTION

Our present picture for the formation of galactic disks can be largely traced to analytic ideas first explored by Fall & Efstathiou (1980), where a galaxy's angular momentum is intimately tied to the corresponding properties of its host dark matter halo. Collapsing structures in an otherwise expanding universe will be spun up by the large-scale matter field (Peebles 1969); this can deliver enough angular momentum to allow (at least some) galaxies to have significant angular-momentum support (e.g. Mo et al. 1998). While these ideas have provided foundational insights into the origin of disk galaxies in a LCDM universe, our understanding of disk formation, and thin-disk galaxy formation in particular, remains incomplete. While dark matter halos of all masses have similar angular momentum distributions (e.g. Barnes & Efstathiou 1987), disk fraction varies noticeably as a function of galaxy mass (Bernardi et al. 2010; Moffett et al. 2016, e.g.[). Moreover, the detailed properties of disks formed in cosmological simulations cannot be explained by the dark matter spin alone (e.g. Sales et al. 2012; Garrison-Kimmel et al. 2018a).

Given what we know about the angular momentum distribution in galactic halos, it is somewhat surprising that so many galaxies are dominated by *thin* disks, with scale heights and vertical velocity dispersions that are small compared to their scale radii and circular speeds $h/R \sim \sigma_z/V_c \sim 0.1$ (Kregel et al. 2002). We know, for example, that the angular momentum distribution of dark matter (Bullock et al. 2001; Lian et al. 2018) and gas (Stewart et al. 2013; DeFelippis et al. 2020) in galactic halos is quite broad. This means that in order for a tightly-ordered thin disk to emerge, the gas must become coherently aligned along a single plane *after* being part of the quasi-spherical extended galactic halo and *before* forming stars. This suggests that the process by which gas is deposited from the galactic halo into the galaxy, and how this process affects the angular momentum distribution, is an essential aspect of thin disk formation.

The process by which gas is deposited into a galaxy from the circumgalactic medium (CGM) has been the subject of considerable exploration (e.g. Kereš et al. 2005; Dekel & Birnboim 2006; Kereš et al. 2009b; Anglés-Alcázar et al. 2017; Martin et al. 2019) with broadly two paths to galaxy fueling

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**Figure 1.** Mock Hubble images of four $z = 0$ galaxies in the FIRE-2 simulations. Halo masses are noted in the panels, together with the fraction of young ($< 1$ Gyr) stars which reside in a thin disk. The Milky-Way-mass galaxies have thin disk morphologies (top, bottom-left), while the lower mass galaxy has an irregular morphology (bottom-right).

identified: hot mode and cold mode. In the cold-mode case, gas is deposited into the galaxy without ever virializing; this occurs typically in lower mass halos, where the gas cooling time is shorter than the infall time. In hot mode accretion, which dominates for massive halos at late times (e.g. Van de Voort et al. 2011; Van de Voort & Schaye 2012; Joung et al. 2012; Murante et al. 2012; Nelson et al. 2013), gas first shock-heats to the halo virial temperature, and then radiates its gravitational and thermal energy prior to accreting onto the galaxy. Our own Milky Way (MW) is one such galaxy for which hot mode accretion is expected to dominate. As discussed above, we expect the mode of gas delivery, and the precise means by which gas mixes, cools, and accretes should have a substantial baring on the ability to form thin, coherently rotating disks.

In cold mode accretion, cool, $T \sim 10^4$ K cosmological filaments travel into the galaxy from the IGM (e.g. Kereš et al. 2005; Dekel & Birnboim 2006; Kereš et al. 2009b; Martin et al. 2019), often along with embedded satellite galaxies (e.g. Hafen et al. 2019; Esmerian et al. 2021). This mode is expected to dominate the mass inflow rate at high-redshift ($z \gtrsim 2$; e.g. Kereš et al. 2009a; Dekel et al. 2009; Huscher et al. 2021). It is unclear however if the cool filaments remain intact down to the galaxy, or rather heat up and dissolve into the surrounding hot phase (e.g. Nelson et al. 2016; Mandelker et al. 2016, 2018, 2020), in which case hot accretion onto the galaxy would also be important at high redshift. While cool halo inflow of this kind typically contains more specific angular momentum (in total) than either hot gas or dark matter (Stewart et al. 2017), the tendency for such gas to reach the galactic region prior to mixing may hinder the ability to develop a thin, coherently aligned structure prior to star formation. The fact that thin disk galaxies are common only among fairly massive systems $L \sim 0.1 L_\star - L_\star$ at lower redshift (e.g. Kranz et al. 2003; Kassin et al. 2006; Bizyaev et al. 2021; Kassin et al. 2012b; Simons et al. 2015, 2017), is roughly consistent with the idea that cold-mode delivery is not conducive to thin disk formation.

An alternative possibility is that hot mode accretion, believed to dominate in more massive halos at lower redshift, is more favorable to thin-disk formation. This depends on the specific mechanics of this accretion mode, and on whether the hot gas manages to cool and accrete rather than being reheated by galactic feedback processes. One possible subset of hot-mode accretion is instability-driven accretion, wherein gas precipitates out of the hot halo due to thermal instabilities, forming cool clouds which lose buoyancy and accrete onto the galaxy (e.g. Maller & Bullock 2004; McCourt et al. 2012; Voit et al. 2015; Armillotta et al. 2016; Gronke & Oh 2020; Voit 2021). Alternatively, radiative cooling in the hot CGM can cause the entire hot phase to flow inward. In this latter scenario, the inward flow occurs at a rate where compression heating of the hot phase roughly balances radiative losses, so the hot gas roughly retains its temperature. This type of hot accretion has been termed a 'cooling flow' in the context of galaxy cluster studies (Mathews & Bregman 1978; Cowie et al. 1980; Fabian et al. 1984; Balbus 1988; Bertschinger 1989, see McNamara & Nulsen 2007 for a review), and was recently revisited by Stern et al. (2019) in the context of galaxy-scale halos. Stern et al. (2020) then further explored the interplay between angular momentum and thermodynamics in these solutions, using steady-state calculations and idealized hydrodynamic simulations. In the present paper we demonstrate that such cooling flows with

angular momentum ('rotating cooling flows') are the primary mode of gas accretion onto disky Milky Way-mass galaxies at $z \sim 0$ in the FIRE cosmological simulations (Hopkins et al. 2018), and may be a necessary condition for the formation of thin star-forming disks.

The analysis here follows Stern et al. (2021), which showed that the formation of disks in FIRE is closely connected to the formation of a virialized and stable hot CGM. Yu et al. (2021) subsequently showed that the emergence of an inner virialized CGM in FIRE simulations correlates specifically with a transition from *thick*-disk to *thin*-disk formation. The conditions necessary for stars to be born in a well-aligned plane on circular orbits appears to correlate with the conditions necessary for the onset of hot accretion modes such as cooling flows. This observation partially motivates the exploration that follows.

Modern cosmological simulations provide a means to understand the characteristics, prevalence, and mechanics of different accretion modes. These simulations include a combination of cosmological environment and galactic physics, which has allowed simulators to investigate accretion while accounting for both its cosmological nature and its interaction with galaxies and their CGM (e.g. Oppenheimer et al. 2010; Stewart et al. 2011; Fernández et al. 2012; Ford et al. 2014; Anglés-Alcázar et al. 2017; Hafen et al. 2019, 2020; Ho et al. 2019; Röttgers et al. 2020; Trapp et al. 2021). Of special note are "zoom-in" simulations that focus on resolving a single halo and its environment, enabling high resolution while preserving cosmological structure (e.g. Katz & White 1993; Oñorbe et al. 2014; Wang et al. 2015; Agertz et al. 2021). Among these the FIRE simulations (Hopkins et al. 2014, 2018)[1] are a set of zoom-in simulations that resolve stellar feedback on the scale of giant molecular clouds in the ISM, producing winds that naturally expand into the CGM and interact with accreting gas (Muratov et al. 2015, 2017; Hafen et al. 2019, 2020). The resultant galaxies are broadly consistent with the stellar mass-halo mass relation (Hopkins 2017), the mass-metallicity relation (Ma et al. 2016), satellite galaxy populations (Wetzel et al. 2016; Garrison-Kimmel et al. 2019), and can have thin-disks consistent with Milky Way-like galaxies (Ma et al. 2017; Garrison-Kimmel et al. 2018b; El-Badry et al. 2018b; Yu et al. 2021).

Here we use the FIRE simulations to study gas accretion onto $z \sim 0$ galaxies and its relation to thin disk morphology. Our approach uses the methodology developed in Hafen et al. (2019, 2020) to explore the mechanics of rotating cooling flows near the disk-halo interface where angular momentum support is substantial. This goes beyond 1D steady-state solutions developed in classic ICM studies (e.g. Cowie et al. 1980), and extends the idealized 3D simulations in Stern et al. (2019) to a more realistic cosmological setting.

This paper is structured as follows. In §2 we describe our sample of FIRE simulations and the sample of accreting particles selected from the simulations. In §3 we analyze the characteristics and mechanics of gas accretion onto $z \sim 0$ galaxies in FIRE, and their relation to thin disk morphology in the central galaxy. We discuss our results in §4 and conclude in §5.

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## 2 METHODS

### 2.1 Simulations

We analyze the hydrodynamical cosmological zoom-in simulations produced as part of the FIRE project (Hopkins et al. 2014). The simulation sample, listed in Table 1, were run with the FIRE-2 version (Hopkins et al. 2018) of the gravity and hydrodynamics code GIZMO[2] (Hopkins 2015). The simulations were produced using the meshless finite-mass ("MFM") mode of GIZMO, a Lagrangian method with no inter-element mass flux. This enables use to track the history of each resolution element. The full details of simulations produced with the FIRE-2 code are available in Hopkins et al. (2018). The FIRE simulations include detailed prescriptions for star formation and stellar feedback. Each star particle contributes to the simulation momentum from radiation pressure; energy, momentum, mass, and metals from Type Ia and II supernovae and stellar winds; and photo-ionization and photo-electric heating. Star formation is limited to self-gravitating, molecular, self-shielding gas with a density of at least $n_{\rm SF} = 1000$ cm$^{-3}$. In the simulations and throughout our analysis we use a standard flat ΛCDM cosmology with $\Omega_{\rm m} \approx 0.32$, $\Omega_\Lambda = 1 - \Omega_{\rm m}$, $\Omega_{\rm b} \approx 0.049$, and $H_0 \approx 67$ km s$^{-1}$ Mpc$^{-1}$ (e.g., Planck Collaboration et al. 2018).

Figure 1 shows edge-on mock Hubble images (with no dust attenuation) for the $z = 0$ snapshots of four of our simulated galaxies. The top and bottom-left panels show three MW-mass galaxies (`m12i`, `m12b`, and `m12c`) while the bottom-right panel shows a $M_\star \sim 5 \times 10^9 M_\odot$ galaxy, `m11d`. As noted in previous studies (Garrison-Kimmel et al. 2018b; El-Badry et al. 2018b) MW-mass galaxies in FIRE typically have thin disk morphologies, while lower mass galaxies show a thick disk / irregular morphology. We quantify this trend using $f_{\rm thin\,disk,\,recent}$, defined as the fraction of stars with age $< 1$ Gyr (at $z = 0$) that have $j_z/j_c(E) > 0.8$. Here $j_z$ is the specific angular momentum in the $z$ direction and $j_c(E)$ is the angular momentum the star would have if it had the same energy but was in a circular orbit. The $z$ axis is defined as the direction of the total angular momentum vector of stars inside the galaxy. This definition of the thin disk is the same definition used in Yu et al. (2021). Values of $f_{\rm thin\,disk,\,recent} > 0.8$ correspond to height to size ratios $h/R \sim 0.1$ and rotation to dispersion ratios $v_\phi/\sigma \sim 10$, and correlate strongly with the observed thin disk fraction in the r band (appendix A). The values of $f_{\rm thin\,disk,\,recent}$ are noted in Fig. 1 and listed in Table 1.

### 2.2 Analysis

For each galaxy we use the particle tracking method described in Hafen et al. (2019, 2020) to select all resolution elements (particles) that have accreted onto the central galaxy during the last Gyr prior to $z = 0$. To select such particles, we require that they are (1) within the galaxy radius $r_{\rm gal}$ at $z = 0$, either in stars or in gas with density $n_{\rm H} > 0.13$ cm$^{-3}$, and (2) within the CGM (gas at $0.1 - 1 r_{\rm vir}$) in the snapshot corresponding to 1 Gyr prior to $z = 0$. Throughout the paper we use $r$ for the 3D distance. We define $r_{\rm gal} = 4 r_{\star,0.5}$ following Hafen et al. (2019, 2020). For each selected particle we retrieve the

[2] http://www.tapir.caltech.edu/~phopkins/Site/GIZMO.html

**Table 1.** Simulation parameters.

| Name | $f_{\rm thin\,disk,\,recent}$ | $M_{\rm vir}$ $M_\odot$ | $M_\star$ $M_\odot$ | $R_{\rm vir}$ kpc | $\Delta f_{\rm aligned}$ | Physics | Reference |
|---|---|---|---|---|---|---|---|
| m12i | 0.83 | $1.1\times10^{12}$ | $7.3\times10^{10}$ | 268 | 0.34 | hydro+ | Wetzel et al. (2016) |
| m12b | 0.8 | $1.3\times10^{12}$ | $1.0\times10^{11}$ | 286 | 0.35 | hydro+ | Garrison-Kimmel et al. (2019) |
| m12i_core | 0.79 | $1.1\times10^{12}$ | $8.0\times10^{10}$ | 274 | 0.34 | no MD | Hopkins et al. (2018) |
| m12c | 0.72 | $1.3\times10^{12}$ | $6.8\times10^{10}$ | 283 | 0.25 | hydro+ | Garrison-Kimmel et al. (2019) |
| m12f | 0.72 | $1.5\times10^{12}$ | $9.7\times10^{10}$ | 302 | 0.24 | hydro+ | Garrison-Kimmel et al. (2017) |
| m12m | *0.37 | $1.5\times10^{12}$ | $1.4\times10^{11}$ | 298 | 0.26 | no MD | Hopkins et al. (2018) |
| m12w | 0.33 | $9.5\times10^{11}$ | $6.5\times10^{10}$ | 253 | 0.15 | hydro+ | Samuel et al. (2020) |
| m11h | 0.24 | $1.8\times10^{11}$ | $3.9\times10^{9}$ | 146 | 0.047 | hydro+ | El-Badry et al. (2018a) |
| m11b | 0.2 | $4.4\times10^{10}$ | $1.2\times10^{8}$ | 92.4 | 0.12 | no MD | Chan et al. (2018) |
| m12r | 0.16 | $1.0\times10^{12}$ | $2.4\times10^{10}$ | 257 | 0.11 | hydro+ | Samuel et al. (2020) |
| m12z | 0.073 | $8.0\times10^{11}$ | $2.5\times10^{10}$ | 242 | 0.052 | hydro+ | Garrison-Kimmel et al. (2019) |
| m11e | 0.05 | $1.5\times10^{11}$ | $1.6\times10^{9}$ | 136 | 0.044 | hydro+ | El-Badry et al. (2018a) |
| m11i | 0.023 | $7.0\times10^{10}$ | $1.0\times10^{9}$ | 106 | 0.013 | hydro+ | El-Badry et al. (2018a) |
| m11a | 0.018 | $4.1\times10^{10}$ | $1.3\times10^{8}$ | 90.3 | -0.022 | no MD | Chan et al. (2018) |
| m11c | 0.015 | $1.4\times10^{11}$ | $9.5\times10^{8}$ | 137 | 0.0068 | no MD | Hopkins et al. (2018) |
| m11d | 0.0097 | $2.9\times10^{11}$ | $4.9\times10^{9}$ | 169 | 0.0026 | hydro+ | El-Badry et al. (2018a) |
| m11q | 0.0058 | $1.5\times10^{11}$ | $7.4\times10^{8}$ | 138 | 0.0045 | hydro+ | Hopkins et al. (2018) |

Properties at $z=0$ of the sample of FIRE galaxies analyzed in this work. The value of $f_{\rm thin\,disk,\,recent}$ is the fraction of stars formed in the last Gyr prior to $z=0$ that are in a thin disk configuration ($j/j_c(E)>0.8$; e.g. Yu et al. 2021). Note that the `m12m` galaxy has a sizable bar, which forms secularly at late times and drives the thin-disk fraction lower by our adopted definition (marked by *). The value of $\Delta f_{\rm aligned}$ is a measure of the relation between cooling and circularization in accreted gas (§3.3). The "hydro+" simulations include fiducial FIRE physics, while the "no MD" simulations exclude a prescription for subgrid metal diffusion.

full history of the particle (including temperature, density, and metallicity). We discard a small fraction ($<2\%$) of the particles since over time their mass increases by a factor of over two due to mass deposition by stellar feedback. These particles pose a problem for our tracking method because the history of the additional mass is not recorded.

A key time for our analysis is the last time a particle cools prior to entering the galaxy. For a given particle, we define this time as:

$$t_{10^5\,\rm K} \equiv t\left(\text{last snapshot outside galaxy with } T>10^5\,\rm K\right)\,, \tag{1}$$

i.e., the last snapshot the particle was hot prior to entering the galaxy (according to the galaxy definition above). For gas that cools as it accretes, $t_{10^5\,\rm K}$ occurs as the gas passes through the galaxy-halo interface. Below we analyze the statistical properties of all accreting particles as a function of time relative to their cooling time ($t-t_{10^5\,\rm K}$).

## 3 RESULTS

To characterize gas accretion we analyze the central galaxy and its CGM from $z=0$ to one Gyr prior. Figure 2 shows a visual overview of how gas accretes onto `m12i` – a MW-mass galaxy that forms a substantial thin disk ($f_{\rm thin\,disk,\,recent}=0.83$). The top and right panels plot the temperature and spatial evolution of accreting gas versus time prior to cooling ($t-t_{10^5\,\rm K}$), while the bottom-left panel plots three representative trajectories for accreting gas elements. The trajectories were visualized using the Firefly visualization software (Geller & Gurvich 2018). [3] Red, white, and blue indicates $T=10^6$ K, $10^5$ K, and $10^4$ K, respectively. The figure shows that at early times relative to cooling ($t-t_{10^5\,\rm K}\sim-1000$ Myr) the accretion is hot ($\approx10^6$ K) and contracts quasi-spherically. Then, around the time of cooling the geometry of accreting gas transitions from quasi-spherical at $t-t_{10^5\,\rm K}=-150$ Myr to a cool disk at $t-t_{10^5\,\rm K}=+150$ Myr A quantitative analysis of this transition follows in sections 3.1–3.5.

### 3.1 Gas inflow is hot through the CGM

Figure 3 plots various characteristics of accreting gas on the `m12i` thin disk galaxy, as a function of time relative to the accretion's last cooling time ($t-t_{10^5\,\rm K}$). In each panel solid lines and shaded regions mark the medians and 16th to 84th percentile ranges of all particles accreted within $0.5-1$ Gyr prior to $z=0$. The lower limit on the time range applied in this figure is to ensure that particles are present for most of the time displayed after $t_{10^5\,\rm K}$. In the temperature panel (A) we exclude from the distribution particles that have converted into stars.

Panel (A) demonstrates that during the 500 Myr prior to cooling, the inflow is predominantly hot ($\gtrsim10^5$ K), with a median temperature of $4-8\times10^5$ K, similar to the halo virial temperature of $T_{\rm vir}(z=0)=6.5\times10^5$ K. During this time prior to cooling the accreting gas is inflowing toward the galaxy (panel B), from a median $r=55$ kpc at $t-t_{10^5\,\rm K}=-500$ Myr, to a median $r\approx18\,{\rm kpc}\approx1.4r_{\rm gal}$

[3] See the Firefly homepage at `galaxies.northwestern.edu/firefly`. A 3D version of the trajectories is available online at `zhafen.github.io/rotating-cooling-flows`.

**Figure 2.** Gas accretion onto a Milky-Way-mass disk galaxy in FIRE, `m12i`, near $z \approx 0$. **Top and right panels:** Temperature and spatial evolution of accreting gas with respect to $t_{10^5\,\mathrm{K}}$, defined as the last time at which the gas cools below $10^5$ K prior to accreting onto the galaxy. Red, white, and blue indicates $T = 10^6$ K, $10^5$ K, and $10^4$ K respectively. **Bottom-left panel:** Three representative trajectories for accreting gas elements. The panels show that accretion is hot ($\approx 10^6$ K) and contracts quasi-spherically at early times relative to the cooling time. At the time of cooling the geometry of accreting gas transitions from a quasi-spherical distribution at $t - t_{10^5\,\mathrm{K}} < -150$ Myr to a cool disk at $t - t_{10^5\,\mathrm{K}} > 150$ Myr.

at $t = t_{10^5\,\mathrm{K}}$, after which time the inflow stalls. The characteristic inflow velocity of $v_r \approx -70$ km s$^{-1}$ (Panel D) is substantially lower than the circular velocity of $170 - 200$ km s$^{-1}$, indicating significant pressure support in the accreting gas of $1 - (v_r/v_c)^2 \approx 85\%$. This radial velocity is also smaller than the median sound speed of $100 - 130$ km s$^{-1}$, indicating a subsonic flow.

A similar hot inflow is seen in other thin disk galaxies in our sample (appendix C). Thus, accretion from the CGM onto $z = 0$ thin disks in FIRE is dominated by the inflow of hot, virial temperature gas. We show below that this accretion flow corresponds to a 'cooling flow', similar to the classical solution envisioned for the ICM (e.g., Mathews & Bregman 1978). Also, we emphasize that this hot accretion mode, in which the entire hot phase inflows, is qualitatively different from 'precipitation' in which gas clumps cool at halo scales, lose buoyancy and subsequently accrete (e.g. Maller & Bullock 2004; Voit et al. 2017). The dominance of hot accretion over precipitation in MW-like galaxies simulated in FIRE has previously been noted by Esmerian et al. (2021).

### 3.2 Accretion cools and stalls at the galaxy-halo interface

Panel (A) in Fig. 3 demonstrates that at $t = t_{10^5\,\mathrm{K}}$ the temperature drops quickly from $\sim 10^6$ K to $\sim 10^4$ K. Panel (B) shows that this cooling occurs just outside the galaxy, at $r(t_{10^5\,\mathrm{K}}) \approx 10 - 30$ kpc, equivalent to $\approx 0.7 - 2.5 r_{\mathrm{gal}}$[4]. Less than 10% of particles cool beyond $\sim 40$ kpc. At this point, the temperature further drops to ISM temperatures of $100 - 10^4$ K and stars start to form at a rate of $\approx 10\%$ per

[4] Note that gas can have $r(t_{10^5\,\mathrm{K}}) < r_{\mathrm{gal}}$ if it is under-dense relative to the galaxy when it crosses $r_{\mathrm{gal}}$ ($n_{\mathrm{H}} < 0.13$ cm$^{-3}$), see section 2.2.

**Figure 3.** Properties of gas accretion onto a $z \sim 0$ thin disk galaxy in FIRE, versus time relative to the final cooling time ($t - t_{10^5\,\rm K}$). In each panel solid lines and shaded regions mark the medians and 16th to 84th percentile ranges of all particles accreted within 1 Gyr prior to $z = 0$. **A:** Temperature. During the 500 Myr prior to cooling, the inflow is predominantly hot ($\gtrsim 10^5$ K), with a median temperature approaching $T_{\rm vir} \approx 10^6$ K. At $t = t_{10^5\,\rm K}$ the gas cools (by definition), and achieves ISM temperatures or forms stars at later times. **B:** 3D distance from halo center. Cooling occurs at $10 - 30$ kpc, corresponding to $0.7 - 2.5\,r_{\rm gal}$. Prior to cooling the gas forms an inflow while after cooling the inflow stalls. **C:** Absolute height from the disk plane. Most of the gas collapses into a disk upon cooling, with a median $|z| \approx 2$ kpc at $t = t_{10^5\,\rm K}$. **D:** Velocity components of accretion (colored lines and band), relative to circular velocity at the median radius (dash-dotted line). The gas reaches full rotational support upon cooling. **E:** Fraction of gas converted into stars. Star formation starts after cooling, at a rate of $\sim 10\%$ per 100 Myr.

100 Myr (panel E), roughly equal to the average rate in the galaxy ISM.

Panel (D) in Fig. 3 demonstrates that cooling at the galaxy scale is further associated with a change in accretion kinematics. The radial inflow velocity $|v_r|$ starts decelerating $\approx 40$ Myr prior to cooling, and almost completely stalls ($\lesssim 10$ km s$^{-1}$) after cooling. This stalling is associated with $v_\phi$ reaching $v_c$, indicating a transition from pressure-support in the hot CGM to rotational support in the cool ISM. Note that deceleration prior to accretion is possible due to the subsonic nature of the hot flow. Similar results are seen for accretion onto other thin-disk galaxies in our sample (appendix C). Specifically, the majority of accretion onto $z \sim 0$ thin disk galaxies in FIRE is a hot inflow which cools and stalls just outside the galaxy. This is *not* the case for galaxies that lack thin disks in our sample (appendix B). Galaxies that are dominated by thick/irregular morphology demonstrate no such stalling behavior.

### 3.3 Cooling of accreted gas is concurrent with circularization

Panel (C) in Fig. 3 plots the distance $z$ above the disk plane as a function of time. We see that as the gas collapses, it becomes increasingly flattened in the disk plane. The horizontal line shows $r_{\rm gal}$ for reference. At the time of cooling, the gas has median height of $\approx 2$ kpc, indicating a disk geometry with height to radius ratio of $|z|/r_{\rm gal} \approx 0.2$, consistent with the transition to rotation support indicated by panel (D). Panel (E) in Fig. 3 emphasizes that all of the star formation occurs after rotation support is achieved and the disk geometry is in place.

This correspondence between a transition to disk geometry and cooling is further explored in Figure 4, which plots the geometry of accreting gas at different times relative to $t_{10^5\,\rm K}$, for the four galaxies shown in Fig. 1. Times prior to cooling are colored in red, while times after cooling are plotted in blue. All particles with $t - t_{10^5\,\rm K}$ within $\pm 30$ Myr of the value noted in the legend are included in the distribution. The curves show the PDF of $\cos\theta = z/r$, i.e. $\theta$ is the angle between the gas element position and the total angular momentum vector of stars in the galaxy. A spherical distribution of accreted gas would have a flat PDF with a value of 0.5, while the PDF of an infinitely thin disk would be a $\delta$-function centered at $z/r = 0$. The figure shows that gas accreting onto the three thin disk galaxies transitions from being distributed quasi-spherically at $t = t_{10^5\,\rm K} - 200$ Myr to being distributed in the galaxy plane at $t = t_{10^5\,\rm K} + 200$ Myr. This indicates that cooling and flattening of the accreted gas occurs simultaneously in these galaxies, consistent with the conclusion from Figs. 2 and 3. In contrast, in the irregular galaxy shown in the bottom-right, there is no association between cooling and flattening. Rather, the geometry of accreting gas is quasi-spherical both before and after cooling.

Figure 5 extends the analysis in Fig. 4 to the full sample. We parametrize the extent to which flattening and cooling

**Figure 4.** Angular distribution of accreting gas, as a function of time relative to the last cooling time. In thin disk galaxies (top and bottom-left panels) the angular distribution of accreting gas evolves significantly at the time of cooling, from a quasi-spherical distribution prior to cooling to a disk-like configuration after cooling. In contrast, in the irregular galaxy (bottom-right) accreting gas is roughly spherical both prior to and after cooling.

**Figure 5. Left:** Mass fraction of accreting gas aligned with the disk ($|z/R < 0.1|$, see Fig. 4) before and after cooling, for our sample of 17 FIRE halos. The horizontal axis plots the fraction of young stars in the central galaxy that are in a thin disk. **Right:** Change in aligned mass fraction during the ±200 Myr around cooling time shown in the left panel. A large $\Delta f_{\rm aligned}$ indicates that circularization is concurrent with cooling. Color indicates virial mass. The value of $\Delta f_{\rm aligned}$ is strongly correlated with the fraction of young stars in a thin disk.The square point that is circled on the right is `m12m`. This galaxy has developed a sizable secular bar at late times, which gives rise to a lower than expected thin disk fraction by our definition.

are concurrent via a parameter $f_{\rm aligned}$ (spatial aligned accretion), which corresponds to the fraction of accreting gas mass aligned with the disk plane ($|z/R| < 0.1$, marked by dashed vertical lines in Fig. 4). This range of angles contains $\approx 60\%$ of stars in thin disks [5]. The left panel of Fig. 5 shows the evolution of $f_{\rm aligned}$ from 200 Myr before $t_{10^5\,{\rm K}}$ (red) to 200 Myr after $t_{10^5\,{\rm K}}$ (blue), while the right panel shows the difference in $f_{\rm aligned}$ between these two epochs. The horizontal axes plot the fraction of young stars in a thin disk $f_{\rm thin\,disk,\,recent}$. For most halos the accreting gas is largely unaligned prior to cooling, with aligned mass fractions $f_{\rm aligned} \sim 0.1 - 0.2$ comparable to $f_{\rm aligned} = 0.1$ expected for an isotropic distribution. Upon cooling, the alignment of accreting gas sharply increases in halos with $f_{\rm thin\,disk,\,recent} > 0.5$ — in most cases $\gtrsim 50\%$ of mass collapses to $|z/R| < 0.1$ during this time. In contrast, in halos with $f_{\rm thin\,disk,\,recent} \approx 0$ there is practically no change in $f_{\rm aligned}$ upon cooling. Intermediate cases with $f_{\rm thin\,disk,\,recent} \approx 0.2 - 0.4$ typically show a modest increase in $f_{\rm aligned}$ and are further discussed in appendix F. The right panel of Fig. 5 demonstrates the strong correlation between the change in $f_{\rm aligned}$ when the gas cools and the fraction of young stars in a thin disk. The halo circled in the right panel, `m12m`, is of special note: gas accretes onto the halo as a rotating cooling flow, but subsequent evolution in the ISM and/or stellar population produces a stellar bar. Fig. 5 thus demonstrates, for our entire FIRE sample, that circularization is concurrent with cooling in accretion onto thin-disk galaxies, while no such association exists for accretion onto irregular / thick disk galaxies.

### 3.4 Angular momentum coherence in accreted gas

Figure 6 shows the cumulative distribution function of $j_z/|\vec{j}|$ in the accreted gas, weighted by mass, for the four simulations shown in Figure 4. This distribution quantifies the level of alignment of angular momentum in the accreted gas with respect to the rotation axis of the stars. For reference, perfectly co-rotating gas has $j_z/|\vec{j}| = 1$, while perpendicular and counter-rotating gas have $j_z/|\vec{j}| = 0$ and $-1$, respectively. An isotropic distribution of angular momentum would appear as a diagonal line in this plot. Each curve corresponds to a different range of $t - t_{10^5\,{\rm K}}$ as noted in the legend. Outlined in black are the CDFs for the three times plotted in Fig. 5: $t - t_{10^5\,{\rm K}}$ = -200, 0, 200 Myr.

In gas accreting onto thin disk galaxies (top and bottom-left panels of Fig. 6) the angular momentum distribution becomes increasingly coherent with time relative to $t_{10^5\,{\rm K}}$. At $t - t_{10^5\,{\rm K}} = -1$ Gyr the angular momentum distribution is marginally coherent, with only $\approx 50\%$ of accreting gas co-rotating, with $j_z/|\vec{j}| > 0.5$. In contrast at $t - t_{10^5\,{\rm K}} = +500$ Myr the distribution is highly coherent, with $j_z/|\vec{j}| > 0.9$ for $\gtrsim 90\%$ of accretion. The majority of the evolution in coherence occurs over $\lesssim 400$ Myr centered on $t_{10^5\,{\rm K}}$, as seen by the differences between the outlined CDFs. This increase in coherence allows the accreting gas to collapse into a thin disk as shown in Figs. 4–5. Furthermore, this result shows that accreting gas is almost entirely co-rotating with the galaxy *prior* to cooling, i.e., while the accretion is still part of the galactic 'hot corona'. Close comparison with Fig. 4 shows that angular momentum coherence is achieved just prior to spatial flattening.

In stark contrast with thin disk galaxies, the irregular galaxy `m11d` shown in the bottom-right panel of Fig. 6 experiences only a very mild evolution in angular momentum coherence — angular momentum remains only marginally co-rotating both before and after cooling.

In Fig. 7 we show the evolution of angular momentum alignment across the full sample, as Fig. 5 did for spatial alignment. In this case, spin alignment is defined as the fraction of gas with $j_z/j > 0.9$. As was the case for spatial alignment, a greater increase in spin alignment during cooling correlates with a greater thin disk presence.

The evolution of angular momentum in accretion onto thin disks is further explored in Figure 8, for the example case of `m12i`. Panel (A) shows the median and 16th-84th percentiles in $j_z/|\vec{j}|$ for individual particles as a function of $t - t_{10^5\,{\rm K}}$. The dashed line plots this ratio for the *sum* of all particles at a given $t - t_{10^5\,{\rm K}}$; the closer the dashed line and shaded region are, the more coherent the spin. Note that the ratio of the total $j_z/|j|$ is not identically equal to unity because the $z$ direction is with respect to the central galaxy and *not* the gas itself. Consistent with Fig. 6, at $t - t_{10^5\,{\rm K}} = -500$ Myr the ratio $j_z/|\vec{j}|$ spans a large range of $\approx -0.3 - 0.9$, while by $t_{10^5\,{\rm K}}$ nearly all the accreting gas has $j_z \approx |\vec{j}|$, indicating all hot accreting gas particles are co-rotating. On the other hand, the ratio $j_z/|\vec{j}|$ of the total angular momentum vector is nearly constant with time prior to accretion. These trends indicate that components unaligned with the net angular momentum are canceling out due to interaction in the hot halo.

Figure 8 panel (B) shows the magnitude of the specific angular momentum ($|\vec{j}|$; green) and the z-component of the specific angular momentum ($j_z$; purple). The median value $|\vec{j}|$ decreases prior to cooling, from $\approx 5000$ kpc km s$^{-1}$ to $\approx 3000$ kpc km s$^{-1}$, in contrast with $j_z$ which remains constant. The nearly constant $j_z$ indicates the inflow conserves angular momentum in this direction, and is not subject to significant torques. The value of $j_z \approx 2500$ kpc km s$^{-1}$ is comparable to the average specific angular momentum of $j_{\rm DM} \simeq \sqrt{2}\lambda r_{\rm vir} v_{\rm vir}$ expected in dark matter halos due to tidal torques (e.g. Bullock et al. 2001). Using a typical dimensionless spin parameter $\lambda \simeq 0.035$, and the virial radius $r_{\rm vir} = 270$ kpc and virial velocity $v_{\rm vir} = 130$ km s$^{-1}$ of this halo, we get $j_{\rm DM} \approx 1750$ kpc km s$^{-1}$, i.e. the expected average value of the dark matter is within 30% of the net angular momentum of accreting hot gas shown in Fig. 8. [6]

The dashed line in panel (B) of Fig. 8 plots the specific angular momentum necessary for gas to be fully supported by angular momentum at a given radius, i.e. $v_c(r)r$, where we use the median $r$ at the relevant $t - t_{10^5\,{\rm K}}$ for this calculation. The accretion attains significant angular momentum support as it proceeds through the inner CGM, consistent with other analyses of CGM rotational support (Oppenheimer 2018). The values of $j_z$ and $v_c(r)r$ converge shortly after $t = t_{10^5\,{\rm K}}$, indicating that cooling and a transition to rotational support occur almost simultaneously, as indicated also by Fig. 3.

[5] by 'thin disk' we mean stars with $j_z/j_c > 0.8$

[6] The fact that the gas has slightly more angular momentum than naively expected for the dark matter is consistent with previous findings that gas typically has a slightly higher spin than dark matter (e.g. Stewart et al. 2017).

**Figure 6.** Angular momentum distribution of accreting gas, as a function of time relative to the last cooling time. Curves show the fraction of mass above a given $j_z/|\vec{j}|$. In the thin-disk galaxies (top and bottom-left panels) the angular momentum distribution becomes more coherent and aligned with the central galaxy with time, mainly during the ±200 Myr around the time of cooling. In the irregular galaxy (bottom right) the angular momentum distribution is quasi-spherical both before and after cooling.

**Figure 7.** Angular momentum-space equivalent of Fig. 5. **Left:** Mass fraction of accreting gas aligned with the disk before and after cooling, defined in this figure as the fraction with $|j_z/|j| > 0.9$ (see Fig. 6). **Right:** Change in aligned mass fraction during the ±200 Myr around cooling time shown in the left panel. The greater the extent to which accretion becomes coherent as it cools, the greater the fraction of young stars in a thin disk.

**Figure 8.** Angular momentum and energetics of gas accreting onto a $z \sim 0$ thin disk galaxy in FIRE, versus time relative to the final cooling time ($t - t_{10^5\,\mathrm{K}}$). In each panel solid lines and shaded regions mark the medians and 16th to 84th percentile ranges of all particles accreted within 1 Gyr prior to $z = 0$. **A:** The ratio of $j_z/\mid\vec{j}\mid$. The dashed line shows this ratio for the sum total angular momentum of all accreted particles. The shaded region shrinks as gas flows inward, indicating the flow becomes more coherent and that angular momentum unaligned with the total angular momentum is cancelled out, as suggested by Fig. 6. **B:** The magnitude of the specific angular momentum of particles ($\mid\vec{j}\mid$, green) and the component of angular momentum aligned with the galaxy disk ($j_z$; purple). The dashed line shows the angular momentum necessary for rotational support. Cooling occurs when angular momentum support becomes significant, as expected in subsonic cooling flows (Cowie et al. 1980; Stern et al. 2019). **C:** Baryon number density. Prior to cooling the gas density increases due to the inflow. As the gas cools the density sharply increases, due to the stalling of the inflow at the galaxy scale and the collapse into a disk geometry. **D:** Energy loss from radiative cooling (blue) and heating from $PdV$ work on the gas particles (red). Prior to cooling, compression heating offsets radiative cooling yielding the flat temperature profile seen in Fig. 3, as expected in a cooling flow. Compression heating plummets after the inflow is stalled by angular momentum support. **Change $Rv_c(R)$ to lowercase.**

This result is consistent with 1D steady-state cooling flow solutions which include angular momentum. These solutions demonstrate that the hot inflow cools to $\sim 10^4$ K at the radius where $j_z = rv_c(r)$, as long as the flow remains subsonic down to this radius (Cowie et al. 1980; Stern et al. 2019).

There is small-but-noticeable increase in $j_z$ at $t \approx t_{10^5\,\mathrm{K}}$. This increase is not the focus of our analysis, but we note that it may be a result of a difference in orientation and/or amplitude between the angular momentum of the galaxy and the angular momentum of the accreting gas (e.g. Danovich et al. 2012; DeFelippis et al. 2017), which forces the accreting gas to co-rotate with the galaxy. The explicit mechanism to increase $j_z$ may be exchange of angular momentum via gravitational torques (e.g. Danovich et al. 2015) or via collisional interactions. Any angular momentum gained is expected to be lost by other particles, driving inflow of existing gas particles in the galaxy or galaxy-halo interface (e.g. Mayor & Vigroux 1981; Pezzulli et al. 2017). We note that the median increase in $j_z$ upon accretion and cooling shown in Fig. 8 is quantitatively consistent with the observed 30% difference between the rotation velocity of the the Milky Way disk and its hot CGM (Hodges-Kluck et al. 2016).

### 3.5 Energetics of accreting gas

Figure 8 panel (C) shows the distribution of the accreting gas number density versus time relative to cooling. Prior to cooling the gas density increases steadily due to the inflow, reaching $\approx 10^{-3}$ cm$^{-3}$ just before cooling at $t \lesssim t_{10^5\,\mathrm{K}}$. This density is comparable to observational estimates of the hot gas density just outside the Milky Way disk (e.g., Li & Bregman 2017). At $t \approx t_{10^5\,\mathrm{K}}$, the gas density sharply increases, reaching 0.1 cm$^{-3}$ within $\approx 50$ Myr, due to the deceleration induced by the stalling of the inflow upon accretion (Fig. 3), and due to the collapse from a quasi-spherical geometry into a disk geometry.

In Figure 8 panel (D) we assess the energetics of the gas to determine why it cools. We study the energetics through two types of change in specific energy: radiative cooling (blue lines) and compression heating (red lines). Radiative cooling per unit mass for an individual particle is calculated as $n_{\mathrm{H}}^2\Lambda/\rho$, where $n_{\mathrm{H}}$ is the Hydrogen density, $\rho$ is the mass density, and $\Lambda$ is the cooling function, which we take from Wiersma et al. (2009). Compressive heating per unit mass for an individual particle is calculated as $P\frac{dV}{dt} \approx \frac{P}{\rho^2}\frac{\Delta\rho}{\Delta t}$, where $P = nk_BT$, $\Delta\rho$ is the change in density from one snapshot to the next, and $\Delta t$ is the snapshot time spacing. Because accreting gas elements interact with other accreting gas elements thermodynamically we show the mean specific energy tracks of all gas elements binned into 100 Myr bins of $t_{10^5\,\mathrm{K}}$. To focus on the behavior of the majority of the particles we do not bin the 1% of particles with the highest change in specific energy. Some $t_{10^5\,\mathrm{K}}$ bins contain much more accreting gas than others, and to reflect this we set the darkness of the lines proportional to the number of particles in the bin.

At $t - t_{10^5\,\mathrm{K}} = -500$ Myr the radiative cooling rate is $\approx 0.006$ erg s$^{-1}$ g$^{-1}$, corresponding to a cooling time of 400 Myr for the median temperature of $T = 4 \times 10^5$ K at this epoch (see Fig. 3, panel A). At $t - t_{10^5\,\mathrm{K}} = -500$ Myr the cooling time is thus comparable to the accretion time of $\approx 500$ Myr. At later $t - t_{10^5\,\mathrm{K}}$ but still prior to cooling, the radiative cooling rate increases due to the increase in gas density.

The panel however shows that this energy loss to radiation is nearly completely offset by compressive heating, explaining the roughly flat temperature profile at $t < t_{10^5\,\mathrm{K}}$ (Fig. 3). These equalities between the cooling time and the accretion time, and between radiative cooling and compressive heating, are defining characteristics of classic cooling flows in which angular momentum support can be neglected (Mathews & Bregman 1978; McNamara & Nulsen 2007; Stern et al. 2019).

Around $t_{10^5\,\mathrm{K}}$ the cooling rate and compressive heating diverge. This can be understood by noting that the radiative cooling rate per unit mass scales as $\propto \rho\Lambda$, while the compressive heating rate scales as $\propto \epsilon d\log\rho/dt$ where $\epsilon$ is the specific thermal energy. The deceleration of the hot inflow prior to accretion onto the galaxy causes $\rho$ to increase faster than $d\log\rho/dt$, causing the temperature to decrease. This in turn increases $\Lambda$ and decreases $\epsilon$, which further accelerates the drop in temperature. The result is gas that cools from $\approx 10^6$ K to $\approx 10^4$ K over the course of $\lesssim 50$ Myr.

## 4 DISCUSSION

In this paper we analyze the properties of gas accreting onto $z \sim 0$ galaxies simulated in FIRE, focusing on Milky-Way mass galaxies in which new stars form in a thin disk. We find that thin disk galaxies in FIRE accrete via 'rotating cooling flows', a mode of 'hot accretion' in which the quasi-spherical $T \sim T_{\mathrm{vir}}$ CGM phase inflows towards the galaxy, remaining hot down to the radius where its angular momentum is sufficient to provide rotational support. At this radius ($\gtrsim 4R_{1/2}$, just outside the galaxy radius) the hot inflow both decelerates and becomes coherently rotating, and then simultaneously cools and collapses into a rotating cool disk. Our results thus extend classic cooling flow theory by demonstrating their applicability in realistic cosmological simulations, and by exploring the mechanics of cooling flows with angular momentum, a subject which has not yet been studied extensively (c.f. Cowie et al. 1980; Stern et al. 2019). Moreover, we find a strong correlation between the prevalence of this accretion mode and the fraction of stars in the central galaxies that form in a thin disk, potentially indicating that a rotating cooling flow is a necessary condition for the formation of a thin star-forming disk. In this section we discuss several interpretations, caveats, and implications of our results.

### 4.1 Why are rotating cooling flows conducive to thin disk formation?

Our analysis identifies two properties of rotating cooling flows that likely promote the formation of thin star forming disks in the central galaxy. These include the tendency of rotating cooling flows to become coherently rotating prior to cooling and accretion onto the galaxy (Fig. 6 and panels A–B in Fig. 8), and their tendency to decelerate before accretion (panel D in Fig. 3). Combined, these two properties indicate that upon cooling the accretion flow forms a thin disk with $v_\phi \approx v_{\mathrm{c}}$ and $v_r, v_\theta \ll v_{\mathrm{c}}$. Though any accreting collisional medium is expected to eventually equilibriate into such a coherently rotating disk, in rotating cooling flows this coherence is achieved *prior* to cooling and accretion onto the ISM. This both implies that the accretion process does not stir turbulence in the ISM (in contrast with cold flows as discussed in Dekel et al. 2009), and that star formation commences only after the accreting gas forms a thin gaseous disk morphology (Fig. 3). In contrast, in other accretion modes some stars may succeed in forming while the accreting gas morphology is still a thick disk or irregular. Such stars will inject feedback momentum and energy into their surroundings which could further delay the equilibration process, allowing even more stars to form outside of a thin disk.

Why do hot inflows decelerate and rotate coherently prior to accretion? We argue here that these characteristics are a result of the subsonic nature of the flow, though defer a formal derivation to future work. In a subsonic flow gradual deceleration prior to accretion is expected since the inflow is 'forewarned' (via changes in pressure) of the transition to rotational support at the galaxy scale. This is in contrast with supersonic accretion modes where the accreting gas is expected to shock and halt abruptly at the galaxy scale. The subsonic nature of hot inflows may also induce the angular momentum coherence achieved near the rotational support radius (Fig. 8, panel A). This follows since at the rotational support radius the mean rotational velocity $\langle v_\phi \rangle$ equals the circular velocity $v_{\mathrm{c}}$ (by definition), while $v_{\mathrm{c}}^2 \approx c_{\mathrm{s}}^2$ in hot flows where $c_{\mathrm{s}}$ is the sound speed. Thus, the mean Mach number in the $\phi$ direction approaches unity at the rotational support radius, and any velocity fluctuations around this mean would lead to speeds which approach or exceed the sound speed. Since such supersonic fluctuations will rapidly shock and convert their kinetic energy into thermal energy, we expect any velocity fluctuations induced by a broad distribution of angular momentum to rapidly die out when the hot flow approaches the rotational support radius, yielding a coherent accretion flow.

### 4.2 When and where do we expect thin disks?

The scenario suggested by this paper, that thin star forming disks are a result of accretion via rotating cooling flows, allows us to predict at which halo masses and redshifts we expect thin disks to form. Cooling flows are expected only following the formation of a time-steady and pressure-supported 'virialized CGM', which occurs when the cooling time of hot shocked CGM gas $t_{\mathrm{cool}}^{(s)}$ exceeds the free-fall time $t_{\mathrm{ff}}$ at halo masses above a threshold of $\sim 10^{11} - 10^{12}\mathrm{M}_\odot$ (White & Rees 1978; White & Frenk 1991; Birnboim & Dekel 2003). Even in the presence of such a virialized CGM, cooling flows may be subdominant to cold flows that penetrate the hot halo, especially at $z > 1$ (e.g., Kereš et al. 2005; Dekel & Birnboim 2006; Dekel et al. 2009), or could be disrupted by heating from feedback as envisioned in 'thermal-balance' models of the CGM (e.g., McCourt et al. 2012; Sharma et al. 2012; Voit et al. 2017; Faerman et al. 2017, 2020). Furthermore, Stern et al. (2019) demonstrated that even if a virialized CGM exists in the outer halo and heating by feedback can be neglected, the resulting cooling flow may go through a sonic point and reach the galaxy as cool supersonic accretion. Thus, to produce cooling flows which remain hot and subsonic down to the galaxy scale as found above for thin disk galaxies, a more specific condition should be satisfied, namely that $t_{\mathrm{cool}}^{(s)}$ exceeds $t_{\mathrm{ff}}$ at an inner CGM radius of $\approx 0.1 r_{\mathrm{vir}}$. In FIRE, this latter condition is met and the inner CGM indeed virializes at $M_{\mathrm{vir}} \approx 10^{12}\mathrm{M}_\odot$, roughly independent of redshift (Stern et al. 2021).

**Figure 9.** Fraction of young stars in a thin disk versus $M_{\rm vir}$ and $t_{\rm cool}^{(s)}/t_{\rm ff}$ evaluated at $0.1R_{\rm vir}$. Color indicates change in the fraction of accreted gas which is aligned with the central galaxy, during $-200\,{\rm Myr} < t - t_{10^5\,{\rm K}} < 200\,{\rm Myr}$ (see Fig. 5). For $M_{\rm vir} < 10^{12} M_\odot$ both the thin disk fraction and $\Delta f_{\rm aligned}$ are small. In more massive galaxies these quantities span a large range. The square point that is circled on the right is `m12m`. This galaxy has developed a sizable secular bar at late times, which gives rise to fairly low thin-disk fraction by our definition.

Figure 9 shows the relationship between thin disk fraction and virial mass (left panel), stellar mass (middle), and $t_{\rm cool}^{(s)}/t_{\rm ff}$ at $0.1r_{\rm vir}$ (right panel), in our sample of $z \sim 0$ FIRE galaxies. Markers are colored by $\Delta f_{\rm aligned}$, a measure of the dominance of rotating cooling flows in accreting gas (Fig. 5). The figure shows that thin disks and rotating cooling flows appear at $M_{\rm vir} \approx 10^{12}{\rm M}_\odot$ and $t_{\rm cool}^{(s)}/t_{\rm ff}(0.1r_{\rm vir}) > 1$, consistent with the expectation noted above that cooling flows and hence thin disks commence only when the inner CGM virializes. This mass scale for thin disk formation is however larger than in $z \sim 0$ observations, as further discussed in the next section.

We note that accretion via a rotating cooling flow does not ensure a thin disk forms. A merger, strong feedback event, or other disruption may take a thin gaseous disk and disturb it, preventing stars from forming in a thin disk. Simulation `m12m` provides evidence of this: it has rotating cooling flow accretion comparable to thin disk galaxies ($\Delta f_{\rm aligned} \approx 0.25$), but has a relatively small $f_{\rm thin\,disk,\,recent} \approx 0.4$ (yellow square in Fig. 5). However, the strong correlation seen in Fig. 5 between the prevalence of rotating cooling flow accretion (quantified via $\Delta f_{\rm aligned}$) and the thin disk fraction $f_{\rm thin\,disk,\,recent}$ suggests that such events are relatively rare.

The result in Fig. 9 that cooling flows occur when $t_{\rm cool}^{(s)} > t_{\rm ff}$ at $0.1r_{\rm vir}$ and the inner CGM virializes indicates that any heating of the CGM by stellar feedback in FIRE is insufficient to disrupt the cooling flow. This is consistent with the weak outflows at this mass and redshift scale in the FIRE simulations (Muratov et al. 2015, 2017; Stern et al. 2021; Pandya et al. 2021) and in observations (e.g., Heckman & Thompson 2019). The potential effects of AGN feedback, not implemented in the FIRE sample used in this work, are further discussed in § 4.4.

How does thin disk formation depend on redshift? While the threshold of inner CGM virialization is roughly independent of redshift, the importance of cold flows penetrating the hot halo does is expected to be redshift-dependent, and thus if thin disks form as a result of hot accretion we expect them to be rarer at high redshift. This expectation is realized in FIRE, where disks that form following virialization at $z \gtrsim 2$ tend to be thicker ($V_{\rm rot}/\sigma_z \approx 2-3$, see fig. 14 in Stern et al. 2021) than their low-redshift counterparts discussed in this work ($V_{\rm rot}/\sigma_z \approx 7-10$). This trend is also qualitatively consistent with other simulations which show relatively thick disks at high redshift (e.g., Pillepich et al. 2019; Dekel et al. 2019) and with the thicker disks seen in high-redshift observations (e.g. Tadaki et al. 2017).

We note that while the thickness of massive disks and the dominance of cooling flows in FIRE appear to depend on redshift, other transitions associated with inner CGM virialization appear to be redshift-independent. These include the suppression of stellar-driven outflows on CGM scales and the transition from rapidly fluctuating ('bursty') star formation to time-steady star formation (Stern et al. 2021; Yu et al. 2021, Gurvich et al., in prep). These transitions may hence be tied more directly to a different effect of inner CGM virialization, such as the confinement of outflows (see Stern et al. 2021).

### 4.3 Analogous accretion in cosmic ray-dominated halos

In Fig. D1 in the appendix we plot the properties of accreting gas in a simulation which includes cosmic ray physics (Chan et al. 2019; Hopkins et al. 2020), thus providing a window into the differences in gas accretion modes in simulations with non-thermal support. The accretion onto the central galaxy in this simulation (`m12i_cr`) is similar to rotating cooling flows

in many aspects: accreting gas gains coherence in the halo, becomes rotationally supported at the galaxy edge (with a decreased radial velocity), and subsequently collapses into a disk. These properties were highlighted also by Trapp et al. (2021), who performed a phenomenological-focused analysis on the accretion of gas onto MW-mass disk galaxies with CR-dominated halos. However, panels A and I of Fig. D1 demonstrates that accreting gas in CR-dominated never shocks to a temperature $T \sim T_{\rm vir} \sim 10^{5.5}$ K and the radiative cooling is not offset by compression heating, i.e. the accretion is not a cooling flow. This is because `m12i_cr` is dominated not by thermal pressure, but by cosmic ray (CR) pressure that provides support against gravity without significantly heating the gas (Ji et al. 2020).

Increased coherence and decreased radial velocity prior to accretion, the two properties of rotating cooling flows we identify as promoting thin disk formation (§4.1), are clearly present in `m12i_cr` (Fig. D1). Consistent with this, `m12i_cr` has a high thin disk fraction, $f_{\rm thin\,disk,\,recent} = 0.71$. In §4.1 we argue that the coherent co-rotation and deceleration of rotating cooling flows is a result of its subsonic nature. Consistent with this, the accreting gas in the CR-dominated halo is also effectively subsonic, wherein gas elements interact via CR pressure rather than thermal pressure. The qualitatively similar behavior between both rotating cooling flows and accretion in CR-dominated halos suggests these accretion modes are a subset of a more general form of *disk-conducive subsonic accretion*.

### 4.4 Caveats

In our MW-mass halos the average SFR over $z = 0 - 0.5$ is SFR$\approx 3 - 10\,M_\odot$/yr, while the observationally-based average SFR for $M_{\rm vir} \sim 10^{12} M_\odot$ halos over the same redshift range is SFR$\approx 0.7 - 6\,M_\odot$/yr (Behroozi et al. 2013). Since the SFR is expected to be regulated by the CGM accretion rate $\dot{M}_{\rm CGM}$, this potential discrepancy may be a result of an elevated $\dot{M}_{\rm CGM}$ relative to the real accretion rate.

The CGM accretion rate may be reduced if the cooling flow is disrupted by additional physics implemented in separate suites of FIRE simulations, including cosmic rays (Chan et al. 2019; Hopkins et al. 2020, 2021a,c) and AGN feedback (Wellons et al. in prep.). It is however unclear whether either of these processes can disrupt the cooling flow in the CGM, given the uncertainties in the assumed CR transport model which is uncertain especially in the CGM (Hopkins et al. 2021b; Quataert et al. 2021a,b), and given that it is uncertain whether the coupling between AGN feedback and the CGM is sufficiently high. Moreover, if AGN feedback is intermittent, a rotating cooling flow is expected to reform quickly when AGN feedback is off, roughly on a cooling timescale which is $\approx 100$ Myr in the inner CGM.

An alternative solution to the elevated accretion rate problem is that the cooling flow is not disrupted, but just weaker than in FIRE since the CGM mass or metallicity are overpredicted in FIRE at $z \sim 0$. This follows since in a cooling flow $\dot{M}_{\rm CGM} \propto M_{\rm CGM}^2 \Lambda(Z)$, where $M_{\rm CGM}$ is the CGM mass and $\Lambda$ is the cooling function. Thus, if the CGM mass is overpredicted by a factor of two then $\dot{M}$ and the SFR would be overestimated by a factor of four. Both the CGM mass and metallicity are a result of the integrated enrichment and depletion of the CGM by outflows over cosmic time, and thus are uncertain (e.g., Davies et al. 2021; Kelly et al. 2021). A lower CGM mass than found in FIRE would also be more consistent with several studies of X-ray emission from the MW which find $M_{\rm CGM}/f_b M_{\rm vir} \approx 0.1$ (Li et al. 2018; Bregman et al. 2018), where $f_b M_{\rm halo}$ is the cosmological baryon fraction multiplied by the halo mass. This is in contrast with $M_{\rm CGM}/f_b M_{\rm vir} \approx 0.2 - 0.4$ for similar-mass FIRE halos (Hafen et al. 2019), though note that other studies deduce $M_{\rm CGM}/f_b M_{\rm halo} = 0.3$ based on the same X-ray data (Faerman et al. 2020).

A lower CGM mass in units of the halo baryon budget may also help alleviate the discrepancy between $z \sim 0$ FIRE galaxies in which a rotation-dominated disk appears only above $M_\star \sim 10^{10}{\rm M}_\odot$, in contrast with observations which find rotation-dominated disks above $M_\star \sim 10^9{\rm M}_\odot$ (El-Badry et al. 2018a,b, see also Peebles 2020). This follows since a lower $M_{\rm CGM}$ both implies a lower SFR and hence lower $M_\star$ for a given halo mass, and a lower halo mass threshold for inner CGM virialization, since $t_{\rm cool}^{(s)}$ is larger when $M_{\rm CGM}$ is lower. The latter effect would cause the onset of cooling flows and the formation of thin disks to occur at lower halo masses than suggested by Fig. 9. Stern et al. (2021) showed that at $z \sim 0$ a factor of a few increase in $t_{\rm cool}^{(s)}$ relative to that in FIRE would decrease the threshold halo mass in which the inner CGM virializes to $M_{\rm vir} \sim 10^{11}{\rm M}_\odot$, corresponding to a threshold stellar mass of $M_\star \sim 10^9{\rm M}_\odot$ for thin disk formation.

### 4.5 Comparison to observations

Hodges-Kluck et al. (2016) analyzed the velocity shifts of OVII absorption lines originating in the Milky-Way halo, observed with XMM-Newton towards an ensemble of AGN. They deduced that the hot inner CGM of the Milky Way (or 'Galactic corona') is rotating at $180 \pm 40$ km s$^{-1}$, corresponding to $60-90\%$ of the rotation velocity of the disk. This result is consistent with a rotating cooling flow, in which the hot CGM spins up as it flows inward, and achieves a significant rotational speed just outside the galaxy (Fig. 3). It would thus be useful to make quantitative predictions for X-ray absorption and emission line observations in the halos of the Milky-Way and nearby massive disks, assuming they are fed by rotating cooling flows as found above in FIRE. Comparing these predictions with existing and future observations (e.g. with Lynx, Team 2018) will allow to test whether local massive disks are indeed fed by rotating cooling flows.

While cool gas in the CGM is more accessible to observations than the hot CGM, in rotating cooling flows the accreting gas becomes cool only when it has no significant spatial or kinematic offset from the galaxy, and would thus be challenging to detect beyond $z \sim 0$. Rotating cooling flows thus constitute a type of 'quiet accretion' (Putman et al. 2012). Consistent with quiet accretion, Sancisi et al. (2008) and Binney et al. (2009) argue that the accretion implied by cool gas observed in the halos of massive disks is insufficient to sustain star formation. We defer to future work making predictions for hot gas cooling just outside the galaxy and comparing with observations of the Milky-Way and nearby disks (e.g., Zheng et al. 2017).

## 5 SUMMARY

In this paper we use the particle-tracking method developed in Hafen et al. (2019, 2020) to study how gas accretes onto $z \sim 0$ galaxies in the FIRE-2 cosmological zoom simulations (Hopkins et al. 2018), focusing on Milky-Way mass galaxies in which stars form in a thin disk. Our main results are as follows.

(i) **Mechanics of rotating cooling flows:** We find that gas accretion onto thin disk galaxies in FIRE is dominated by rotating cooling flows, wherein the hot $T \approx T_{\rm vir}$ CGM forms a subsonic and angular momentum-conserving inflow down to the galaxy-halo interface, at which it cools to $T \lesssim 10^4$ K (Figs. 3 and 8). Cooling occurs at the radius where rotational support in the flow becomes substantial, and is concurrent with flattening of the flow, i.e. the flow transitions rapidly from a quasi-spherical hot medium into a cool thin disk (Figs. 2 and 4). Prior to cooling and flattening the hot flow decelerates and becomes coherently rotating with a narrow angular momentum distribution (Figure 6), properties which we attribute to the subsonic nature of the flow (§ 4.1). Our results thus extend classic cooling flow theory by demonstrating rotating cooling flows are a primary accretion mode for many cosmologically-simulated galaxies, and by further exploring the mechanics of cooling flows with angular momentum beyond previous studies (Cowie et al. 1980; Stern et al. 2019).

(ii) **Relation between rotating cooling flows and thin stellar disks:** We find that across a sample of 17 galaxies spanning $10^9 M_\odot < M_\star < 10^{11} M_\odot$, there is strong correlation between the dominance of cooling flow accretion and the fraction of stars formed in a thin disk in the central galaxy (Figs. 4–5, Fig 7). This expands the result of Stern et al. (2021), which found a relation between the formation of disks and the virialization of the inner CGM in FIRE, where the latter is a necessary condition for the onset of cooling flows. We theorize that rotating cooling flows are conducive to the formation of thin disks since these flows achieve coherent, purely rotating kinematics prior to cooling to $\lesssim 10^4$ K, and thus before any star-formation in the accreting gas takes place (Fig. 3, §4.1). If rotating cooling flows are indeed a requirement for forming thin disks, then we expect thin disks mainly in relatively massive star-forming galaxies in which the CGM has virialized or is composed of subsonic gas, and at low redshift where cold flows are not expected to dominate the accretion. These trends are qualitatively consistent with observations which shows that thin disk morphologies are prevalent mainly in high mass and low-redshift star forming galaxies (Kassin et al. 2012a; Simons et al. 2017).

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This research used the Python programming language and the following modules: Firefly (Geller & Gurvich 2018), Numpy (Harris et al. 2020), Matplotlib (Hunter 2007), pytest (Krekel et al. 2004), Jug (Coelho 2017), h5py (Collette 2013), SciPy (Virtanen et al. 2020), pandas (McKinney 2010; Reback et al. 2020), palettable (`https://github.com/jiffyclub/palettable`), and Numba (Lam et al. 2015).

## REFERENCES

Agertz O., et al., 2021, Monthly Notices of the Royal Astronomical Society, 503, 5826
Anglés-Alcázar D., Faucher-Giguère C.-A., Kereš D., Hopkins P. F., Quataert E., Murray N., 2017, Monthly Notices of the Royal Astronomical Society, 470, 4698
Armillotta L., Fraternali F., Marinacci F., 2016, Monthly Notices of the Royal Astronomical Society, 462, 4157
Balbus S. A., 1988, The Astrophysical Journal, 328, 395
Barnes J., Efstathiou G., 1987, ApJ, 319, 575
Behroozi P. S., Wechsler R. H., Conroy C., 2013, The Astrophysical Journal, 770, 57
Bernardi M., Shankar F., Hyde J. B., Mei S., Marulli F., Sheth R. K., 2010, MNRAS, 404, 2087
Bertschinger E., 1989, The Astrophysical Journal, 340, 666
Binney J., Nipoti C., Fraternali F., 2009, Monthly Notices of the Royal Astronomical Society, 397, 1804
Birnboim Y., Dekel A., 2003, Monthly Notices of the Royal Astronomical Society, 345, 349
Bizyaev D., Makarov D. I., Reshetnikov V. P., Mosenkov A. V., Kautsch S. J., Antipova A. V., 2021, arXiv:2105.11855 [astro-ph]
Bregman J. N., Anderson M. E., Miller M. J., Hodges-Kluck E., Dai X., Li J.-T., Li Y., Qu Z., 2018, The Astrophysical Journal, 862, 3
Bullock J. S., Dekel A., Kolatt T. S., Kravtsov A. V., Klypin A. A., Porciani C., Primack J. R., 2001, The Astrophysical Journal, 555, 240
Chan T. K., Kereš D., Wetzel A., Hopkins P. F., Faucher-Giguère C.-A., El-Badry K., Garrison-Kimmel S., Boylan-Kolchin M., 2018, Monthly Notices of the Royal Astronomical Society, 478, 906
Chan T. K., Kereš D., Hopkins P. F., Quataert E., Su K.-Y., Hayward C. C., Faucher-Giguère C.-A., 2019, Monthly Notices of the Royal Astronomical Society, 488, 3716
Coelho L. P., 2017, Journal of Open Research Software, 5, 30
Collette A., 2013, Python and HDF5. O'Reilly
Cowie L. L., Fabian A. C., Nulsen P. E. J., 1980, Monthly Notices of the Royal Astronomical Society, 191, 399
Danovich M., Dekel A., Hahn O., Teyssier R., 2012, Monthly Notices of the Royal Astronomical Society, 422, 1732
Danovich M., Dekel A., Hahn O., Ceverino D., Primack J., 2015, Monthly Notices of the Royal Astronomical Society, 449, 2087
Davies J. J., Crain R. A., Pontzen A., 2021, Monthly Notices of the Royal Astronomical Society, 501, 236
DeFelippis D., Genel S., Bryan G. L., Fall S. M., 2017, The Astrophysical Journal, 841, 16
DeFelippis D., Genel S., Bryan G. L., Nelson D., Pillepich A., Hernquist L., 2020, ApJ, 895, 17
Dekel A., Birnboim Y., 2006, Monthly Notices of the Royal Astronomical Society, 368, 2
Dekel A., et al., 2009, Nature, 457, 451
Dekel A., Lapiner S., Dubois Y., 2019, arXiv:1904.08431

El-Badry K., et al., 2018a, Monthly Notices of the Royal Astronomical Society, 473, 1930

El-Badry K., et al., 2018b, Monthly Notices of the Royal Astronomical Society, 477, 1536

Esmerian C. J., Kravtsov A. V., Hafen Z., Faucher-Giguère C.-A., Quataert E., Stern J., Kereš D., Wetzel A., 2021, Monthly Notices of the Royal Astronomical Society, 505, 1841

Fabian A. C., Nulsen P. E. J., Canizares C. R., 1984, Nature, 310, 733

Faerman Y., Sternberg A., McKee C. F., 2017, The Astrophysical Journal, 835, 52

Faerman Y., Sternberg A., McKee C. F., 2020, ApJ, 893, 82

Fall S. M., Efstathiou G., 1980, Monthly Notices of the Royal Astronomical Society, 193, 189

Fernández X., Joung M. R., Putman M. E., 2012, The Astrophysical Journal, 749, 181

Ford A. B., Davé R., Oppenheimer B. D., Katz N., Kollmeier J. A., Thompson R., Weinberg D. H., 2014, Monthly Notices of the Royal Astronomical Society, 444, 1260

Garrison-Kimmel S., et al., 2017, Monthly Notices of the Royal Astronomical Society, 471, 1709

Garrison-Kimmel S., et al., 2018b, Monthly Notices of the Royal Astronomical Society, 481, 4133

Garrison-Kimmel S., et al., 2018a, MNRAS, 481, 4133

Garrison-Kimmel S., et al., 2019, Monthly Notices of the Royal Astronomical Society, 487, 1380

Geller A. M., Gurvich A., 2018, Astrophysics Source Code Library, p. ascl:1810.021

Gronke M., Oh S. P., 2020, Monthly Notices of the Royal Astronomical Society, 494, L27

Hafen Z., et al., 2019, Monthly Notices of the Royal Astronomical Society, 488, 1248

Hafen Z., et al., 2020, Monthly Notices of the Royal Astronomical Society, 494, 3581

Harris C. R., et al., 2020, Nature, 585, 357

Heckman T. M., Thompson T. A., 2019, arXiv:1701.09062 [astro-ph]

Ho S. H., Martin C. L., Turner M. L., 2019, The Astrophysical Journal, 875, 54

Hodges-Kluck E. J., Miller M. J., Bregman J. N., 2016, The Astrophysical Journal, 822, 21

Hopkins P. F., 2015, Monthly Notices of the Royal Astronomical Society, 450, 53

Hopkins P. F., 2017, Monthly Notices of the Royal Astronomical Society, 466, 3387

Hopkins P. F., Keres D., Onorbe J., Faucher-Giguere C.-A., Quataert E., Murray N., Bullock J. S., 2014, Monthly Notices of the Royal Astronomical Society, 445, 581

Hopkins P. F., et al., 2018, Monthly Notices of the Royal Astronomical Society, 480, 800

Hopkins P. F., et al., 2020, Monthly Notices of the Royal Astronomical Society, 492, 3465

Hopkins P. F., Chan T. K., Squire J., Quataert E., Ji S., Kereš D., Faucher-Giguère C.-A., 2021a, Monthly Notices of the Royal Astronomical Society, 501, 3663

Hopkins P. F., Chan T. K., Ji S., Hummels C. B., Kereš D., Quataert E., Faucher-Giguère C.-A., 2021b, Monthly Notices of the Royal Astronomical Society, 501, 3640

Hopkins P. F., Squire J., Chan T. K., Quataert E., Ji S., Keres D., Faucher-Giguere C.-A., 2021c, Monthly Notices of the Royal Astronomical Society, 501, 4184

Hunter J. D., 2007, Computing in Science Engineering, 9, 90

Huscher E., Oppenheimer B. D., Lonardi A., Crain R. A., Richings A. J., Schaye J., 2021, Monthly Notices of the Royal Astronomical Society, 500, 1476

Ji S., et al., 2020, Monthly Notices of the Royal Astronomical Society, 496, 4221

Joung M. R., Putman M. E., Bryan G. L., Fernández X., Peek J. E. G., 2012, The Astrophysical Journal, 759, 137

Kassin S. A., de Jong R. S., Weiner B. J., 2006, The Astrophysical Journal, 643, 804

Kassin S. A., Devriendt J., Fall S. M., de Jong R. S., Allgood B., Primack J. R., 2012a, Monthly Notices of the Royal Astronomical Society, 424, 502

Kassin S. A., et al., 2012b, The Astrophysical Journal, 758, 106

Katz N., White S. D. M., 1993, The Astrophysical Journal, 412, 455

Kelly A. J., Jenkins A., Deason A., Fattahi A., Grand R. J. J., Pakmor R., Springel V., Frenk C. S., 2021, arXiv:2106.08618 [astro-ph]

Kereš D., Katz N., Weinberg D. H., Davé R., 2005, Monthly Notices of the Royal Astronomical Society, 363, 2

Kereš D., Katz N., Fardal M., Davé R., Weinberg D. H., 2009a, Monthly Notices of the Royal Astronomical Society, 395, 160

Kereš D., Katz N., Davé R., Fardal M., Weinberg D. H., 2009b, Monthly Notices of the Royal Astronomical Society, 396, 2332

Kranz T., Slyz A., Rix H.-W., 2003, The Astrophysical Journal, 586, 143

Kregel M., Van Der Kruit P. C., De Grijs R., 2002, Monthly Notices of the Royal Astronomical Society, 334, 646

Krekel H., Oliveira B., Pfannschmidt R., Bruynooghe F., Laugher B., Bruhin F., 2004, pytest 3.4, `https://github.com/pytest-dev/pytest`

Lam S. K., Pitrou A., Seibert S., 2015, Proceedings of the Second Workshop on the LLVM Compiler Infrastructure in HPC - LLVM '15, pp 1–6

Li Y., Bregman J., 2017, The Astrophysical Journal, 849, 105

Li J.-T., Bregman J. N., Wang Q. D., Crain R. A., Anderson M. E., 2018, ApJ, 855, L24

Lian J., Thomas D., Maraston C., Goddard D., Comparat J., Gonzalez-Perez V., Ventura P., 2018, Monthly Notices of the Royal Astronomical Society, 474, 1143

Ma X., Hopkins P. F., Faucher-Giguère C.-A., Zolman N., Muratov A. L., Kereš D., Quataert E., 2016, Monthly Notices of the Royal Astronomical Society, 456, 2140

Ma X., Hopkins P. F., Wetzel A. R., Kirby E. N., Anglés-Alcázar D., Faucher-Giguère C.-A., Kereš D., Quataert E., 2017, Monthly Notices of the Royal Astronomical Society, 467, 2430

Maller A. H., Bullock J. S., 2004, Monthly Notices of the Royal Astronomical Society, 355, 694

Mandelker N., Padnos D., Dekel A., Birnboim Y., Burkert A., Krumholz M. R., Steinberg E., 2016, Monthly Notices of the Royal Astronomical Society, 463, 3921

Mandelker N., van Dokkum P. G., Brodie J. P., van den Bosch F. C., Ceverino D., 2018, The Astrophysical Journal, 861, 148

Mandelker N., Nagai D., Aung H., Dekel A., Birnboim Y., van den Bosch F. C., 2020, Monthly Notices of the Royal Astronomical Society, 494, 2641

Martin D. C., et al., 2019, arXiv

Mathews W. G., Bregman J. N., 1978, The Astrophysical Journal, 224, 308

Mayor M., Vigroux L., 1981, Astronomy and Astrophysics, vol. 98, no. 1, May 1981, p. 1-8., 98, 1

McCourt M., Sharma P., Quataert E., Parrish I. J., 2012, Monthly Notices of the Royal Astronomical Society, 419, 3319

McKinney W., 2010, in Python in Science Conference. Austin, Texas, pp 56–61, doi:10.25080/Majora-92bf1922-00a

McNamara B. R., Nulsen P. E. J., 2007, Annual Review of Astronomy and Astrophysics, 45, 117

Mo H. J., Mao S., White S. D. M., 1998, MNRAS, 295, 319

Moffett A. J., et al., 2016, MNRAS, 457, 1308

Murante G., Calabrese M., De Lucia G., Monaco P., Borgani S., Dolag K., 2012, The Astrophysical Journal Letters, 749, L34

Muratov A. L., Keres D., Faucher-Giguere C.-A., Hopkins P. F., Quataert E., Murray N., 2015, Monthly Notices of the Royal

Astronomical Society, 454, 2691
Muratov A. L., et al., 2017, Monthly Notices of the Royal Astronomical Society, 468, 4170
Nelson D., Vogelsberger M., Genel S., Sijacki D., Kereš D., Springel V., Hernquist L., 2013, Monthly Notices of the Royal Astronomical Society, 429, 3353
Nelson D., Genel S., Pillepich A., Vogelsberger M., Springel V., Hernquist L., 2016, Monthly Notices of the Royal Astronomical Society, 460, 2881
Oñorbe J., Garrison-Kimmel S., Maller A. H., Bullock J. S., Rocha M., Hahn O., 2014, MNRAS, 437, 1894
Oppenheimer B. D., 2018, Monthly Notices of the Royal Astronomical Society, 480, 2963
Oppenheimer B. D., Davé R., Kereš D., Fardal M., Katz N., Kollmeier J. A., Weinberg D. H., 2010, Monthly Notices of the Royal Astronomical Society, 406, 2325
Pandya V., et al., 2021, arXiv
Peebles P. J. E., 1969, ApJ, 155, 393
Peebles P. J. E., 2020, Monthly Notices of the Royal Astronomical Society, 498, 4386
Pezzulli G., Fraternali F., Binney J., 2017, Monthly Notices of the Royal Astronomical Society, 467, 311
Pillepich A., et al., 2019, Monthly Notices of the Royal Astronomical Society, 490, 3196
Planck Collaboration et al., 2018, arXiv:1807.06209
Putman M., Peek J., Joung M., 2012, Annual Review of Astronomy and Astrophysics, 50, 491
Quataert E., Thompson T. A., Jiang Y.-F., 2021b, arXiv:2102.05696 [astro-ph]
Quataert E., Jiang Y.-F., Thompson T. A., 2021a, arXiv:2106.08404 [astro-ph]
Reback J., et al., 2020, Pandas-Dev/Pandas: Pandas 1.0.3, Zenodo, doi:10.5281/zenodo.3715232
Röttgers B., Naab T., Cernetic M., Davé R., Kauffmann G., Borthakur S., Foidl H., 2020, Monthly Notices of the Royal Astronomical Society, 496, 152
Sales L. V., Navarro J. F., Theuns T., Schaye J., White S. D. M., Frenk C. S., Crain R. A., Dalla Vecchia C., 2012, Monthly Notices of the Royal Astronomical Society, 423, 1544
Samuel J., et al., 2020, Monthly Notices of the Royal Astronomical Society, 491, 1471
Sancisi R., Fraternali F., Oosterloo T., van der Hulst T., 2008, Astronomy and Astrophysics Review, 15, 189
Sharma P., Mccourt M., Quataert E., Parrish I. J., 2012, Monthly Notices of the Royal Astronomical Society, 420, 3174
Simons R. C., Kassin S. A., Weiner B. J., Heckman T. M., Lee J. C., Lotz J. M., Peth M., Tchernyshyov K., 2015, Monthly Notices of the Royal Astronomical Society, 452, 986
Simons R. C., et al., 2017, The Astrophysical Journal, 843, 46
Stern J., Fielding D., Faucher-Giguère C.-A., Quataert E., 2019, Monthly Notices of the Royal Astronomical Society, 488, 2549
Stern J., Fielding D., Faucher-Giguère C.-A., Quataert E., 2020, Monthly Notices of the Royal Astronomical Society, 492, 6042
Stern J., et al., 2021, ApJ, 911, 88
Stewart K. R., Kaufmann T., Bullock J. S., Barton E. J., Maller A. H., Diemand J., Wadsley J., 2011, The Astrophysical Journal Letters, 735, L1
Stewart K. R., Brooks A. M., Bullock J. S., Maller A. H., Diemand J., Wadsley J., Moustakas L. A., 2013, The Astrophysical Journal, 769, 74
Stewart K. R., et al., 2017, The Astrophysical Journal, 843, 47
Tadaki K.-i., et al., 2017, The Astrophysical Journal, 834, 135
Team T. L., 2018, arXiv:1809.09642 [astro-ph]
Trapp C., et al., 2021, arXiv:2105.11472 [astro-ph]
Van de Voort F., Schaye J., 2012, Monthly Notices of the Royal Astronomical Society, 423, 2991
Van de Voort F., Schaye J., Booth C. M., Dalla Vecchia C., 2011, Monthly Notices of the Royal Astronomical Society, 415, 2782

**Figure A1.** Fraction of recent stars in a thin disk versus Sloan-r-band-weighted thin disk fraction, showing that the thin disk fraction of young stars closely tracks the observationally-motivated luminosity-weighted thin disk fraction.

Virtanen P., et al., 2020, Nat Methods, 17, 261
Voit G. M., 2021, The Astrophysical Journal, 908, L16
Voit G. M., Donahue M., O'Shea B. W., Bryan G. L., Sun M., Werner N., 2015, The Astrophysical Journal, 803, L21
Voit G. M., Meece G., Li Y., O'Shea B. W., Bryan G. L., Donahue M., 2017, The Astrophysical Journal, 845, 80
Wang L., Dutton A. A., Stinson G. S., Macciò A. V., Penzo C., Kang X., Keller B. W., Wadsley J., 2015, Monthly Notices of the Royal Astronomical Society, 454, 83
Wetzel A. R., Hopkins P. F., Kim J.-h., Faucher-Giguère C.-A., Kereš D., Quataert E., 2016, The Astrophysical Journal, 827, L23
White S. D. M., Frenk C. S., 1991, The Astrophysical Journal, 379, 52
White S. D. M., Rees M. J., 1978, Monthly Notices of the Royal Astronomical Society, 183, 341
Wiersma R. P., Schaye J., Smith B. D., 2009, Monthly Notices of the Royal Astronomical Society, 393, 99
Yu S., et al., 2021, arXiv e-prints, 2103, arXiv:2103.03888
Zheng Y., Peek J. E. G., Werk J. K., Putman M. E., 2017, The Astrophysical Journal, 834, 179

## APPENDIX A: OBSERVATIONALLY-MOTIVATED THIN DISK FRACTION

Figure A1 shows the relationship between the fraction of stars with $j/j_c(E) > 0.8$ at $z = 0$ ($f_{\rm thin\,disk,\,recent}$) and the same fraction of stars weighted by their Sloan r band luminosity-weighted. The thin disk metric used throughout our analysis, $f_{\rm thin\,disk,\,recent}$ is closely related to the observationally-motivated luminosity-weighted thin disk fraction.

## APPENDIX B: ACCRETION ONTO HALOS ABSENT THIN DISKS

Figure B1 shows characteristic accretion onto a halo with a small (in this case nearly zero) thin disk fraction. Such halos do not show the features of rotating cooling flows, as also seen in Figures 5 and 7.

## APPENDIX C: ACCRETION ONTO OTHER MW-MASS HALOS

Figures C1 and C2 show the combined equivalent of Figures 3 and 8 for two other Milky Way-mass halos. The behavior is qualitatively very similar to each other and `m12i`. This is summarized for additional simulations in Figures 5 and 7.

## APPENDIX D: ACCRETION IN COSMIC RAY-DOMINATED HALOS

Figure D1 shows the combined equivalent of Figures 3 and 8 for the same halo, but with an implementation of cosmic ray feedback Chan et al. (2019); Hopkins et al. (2020). Note that we center the trajectories on the time of first accretion instead of $t_{10^5\,\mathrm{K}}$ because in CR-dominated halos much of the gas is never heated beyond $T = 10^5$ K. This does not significantly affect the result, as accretion is largely concurrent with cooling in the halos without CRs. This halo forms a thin disk ($f_{\mathrm{thin\,disk,\,recent}} = 0.71$, which we argue may be a general feature of rotating subsonic flows (§4.1, §4.3).

## APPENDIX E: INSTANTANEOUS MASS FLOW

In this section we analyze if inflow is dominated by hot or cold gas, which allows us to distinguish a hot inflow from the accretion of cool clouds (formed, e.g., via instabilities). Figure E1 shows the mass inflow rate versus radius for hot gas (red curves; $T > 10^5$ K) and for cool gas (blue curves; $T < 10^5$ K), for the four simulations shown in Fig. 1. We calculate the mass inflow rate at a given radius as

$$\dot{M}(r) = \frac{\int_{\mathrm{shell}} v_r dm}{\Delta r} = \frac{M_{\mathrm{shell}}}{\Delta r} \langle v_r \rangle_{\mathrm{mass\,weighted}} \tag{E1}$$

where $\Delta r = 0.05\,\mathrm{dex}$ is the shell thickness, and the integration is done on all particles with centers within the shell which satisfy the appropriate temperature cut.

In the three MW-mass galaxies with a large thin disk fraction, at halo scales of $r > 20$ kpc the inflow is dominated by hot gas, where in `m12i` and `m12b` $\dot{M}$ of the hot gas is larger by a factor of $\gtrsim 4\times$ than that of cool gas. The greater mass flux of hot gas indicates that the dominant form of accretion is an inflowing hot phase, rather than cold flows or cool clouds precipitating from the hot phase. In contrast, in the lower mass galaxy shown in the bottom right the inflow is dominated by cool gas, while the hot gas is outflowing out to $\approx 50$ kpc. Fig. E1 also shows that the inflow rate of hot gas in the MW-mass galaxies drops within $r_{\mathrm{gal}}$, reflecting the cooling of the hot inflow at the galaxy-halo interface, as shown in §3.2.

## APPENDIX F: NOTES ON INDIVIDUAL GALAXIES

The halos with $0.1 \lesssim f_{\mathrm{thin\,disk,\,recent}} < 0.5$ have varying levels of circularized cooling flow accretion. Four of these six halos, `m12z`, `m12r`, `m12w`, and `m12m`, have $M_{\mathrm{vir}} \sim 10^{12} M_\odot$. `m12z` has a chaotic halo with a number of ongoing mergers. `m12r` has some ongoing thin disk formation, but is undergoing a major merger during the last Gyr that dominates the accreting gas supply and disrupts the galaxy structure. This merger is relatively well-aligned with the disk, with $f_{\mathrm{aligned}} \approx 0.3 - 0.4$, and the aligned mass fraction does not change significantly as the gas cools past $t_{10^5\,\mathrm{K}}$. `m12w` is a galaxy with its inner CGM is only just virializing at $z = 0$ (Yu et al. 2021), and the majority of the gas accretes with angular momentum perpendicular to the galaxy angular momentum. Of these four the one with the highest thin disk fraction, `m12m`, is galaxy undergoing significant rotating cooling flow accretion, but absent a high thin disk fraction. Visual inspection reveals that `m12m` has a prominent stellar bar. `m12m` may be evidence that if rotating cooling flows are a condition for disk formation, they are a necessary-but-not-sufficient condition (§4.1). `m12m` is one of the few MW-mass halos that does not include metal diffusion, which may play a role in its morphology. The $M_{\mathrm{vir}} \sim 10^{11} M_\odot$ halos are `m11h` and `m11b` — galaxies that are beginning to form disks despite their lower virial mass. Much of their accretion is still isotropic, but alignment increases mildly post-cooling.

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**Figure B1.** Temperature and geometry of gas accreting onto a $z \sim 0$ galaxy in FIRE that *does not* form a thin disk, versus time relative to the final cooling time ($t - t_{10^5\,\rm K}$). In each panel solid lines and shaded regions mark the medians and 16th to 84th percentile ranges of all particles accreted within 1 Gyr prior to $z = 0$. **A:** Temperature. The final cooling tends to occur shortly after the gas is heated beyond $T = 10^5$ K. **B:** 3D distance from halo center. **C:** Absolute height from the disk plane. **D:** Velocity components of accretion (colored lines and band), relative to circular velocity at the median radius (dash-dotted line). **E:** Fraction of gas converted into stars. Star formation proceeds shortly after cooling, well before gas orients into a disk. **F:** The ratio of $j_z / |\vec{j}|$. The dashed line shows this ratio for the sum total angular momentum of all accreted particles. The coherence of the gas does not change before/after cooling. **B:** The magnitude of the specific angular momentum of particles ($|\vec{j}|$, green) and the component of angular momentum aligned with the galaxy disk ($j_z$; purple). The dashed line shows the angular momentum necessary for rotational support. Rotational support occurs $\gtrsim$ 300 Myr after $t_{10^5\,\rm K}$, at which time inward movement stalls and gas velocity decreases. **C:** Baryon number density. **D:** Energy loss from radiative cooling (blue) and heating from $PdV$ work on the gas particles (red). Radiative cooling exceeds compression heating with the exception of when the gas is heated, shortly before cooling.

**Figure C1.** Same as Figure B1, but for a MW-mass halo with a thin disk, `m12b`.

**Figure C2.** Same as Figure B1, but for another MW-mass halo with a thin disk, `m12c`.

**Figure D1.** Same as Figure B1, but for a cosmic ray-dominated MW-mass halo, `m12i_cr`. The accretion in cosmic ray-dominated halos is qualitatively similar to rotating cooling flows. The exceptions are the temperature (panel A) and the energy balance (panel B): nonthermal support from cosmic rays (CRs) produces a $T \sim 10^4$ K, diffuse halo absent cooling flows. As with rotating cooling flows accreting gas in this halo becomes coherently aligned *prior to accretion*, a key mechanism that enables thin disk formation.

**Figure E1.** Average mass inflow rate over the course of one Gyr prior to $z = 0$ in the same halos as in Figure 1, by gas temperature. The galaxy radius $r_{\rm gal} = 4r_{\star,0.5}$ and fraction of stars in a thin disk are marked in the panels. Hot accretion ($T > 10^5$ K) dominates the mass inflow onto thin-disk galaxies at $r \gtrsim r_{\rm gal} \sim 10 - 20$ kpc. Cold accretion ($T < 10^5$ K) dominates within the galaxy in thin disk galaxies, and in the halo of the lower-mass irregular galaxy shown in the bottom-right panel.