The difficulties simulating Milky Way-mass galaxies in cosmological volumes

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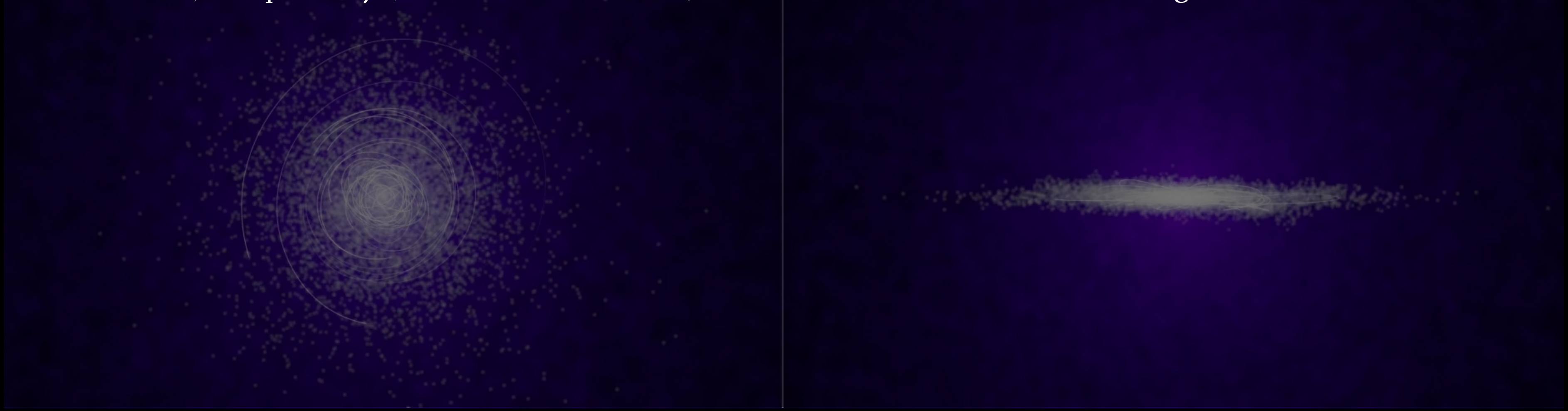

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Collisional relaxation of simulated galaxies and halos

Preliminaries…

Binney & Tremaine, 2008

The "relaxation time" for a *collisional* system of N particles is

$$\frac{t_{\rm rel}}{t_{\rm cr}} \simeq \frac{N}{8\ln N}$$ where $$t_{\rm cr} = \frac{r}{v}$$

$$\Delta(v^2) \simeq v^2$$ at $$t = t_{\rm rel}$$

$\Rightarrow$ The relaxation time of galaxies and halos is ***long***…
…even for relatively low-mass galaxies

Simulations must emulate this behaviour with much smaller N

For cosmological simulations…

$$N_i = \frac{M}{m_i}$$ so… $$\frac{t_{\rm rel}}{t_{\rm cr}} \propto \frac{M}{\ln M}$$

The relaxation time for simulated halos can, in principle, be short, but will *always decrease with decreasing halo/galaxy mass*

Collisional relaxation of simulated galaxies and halos

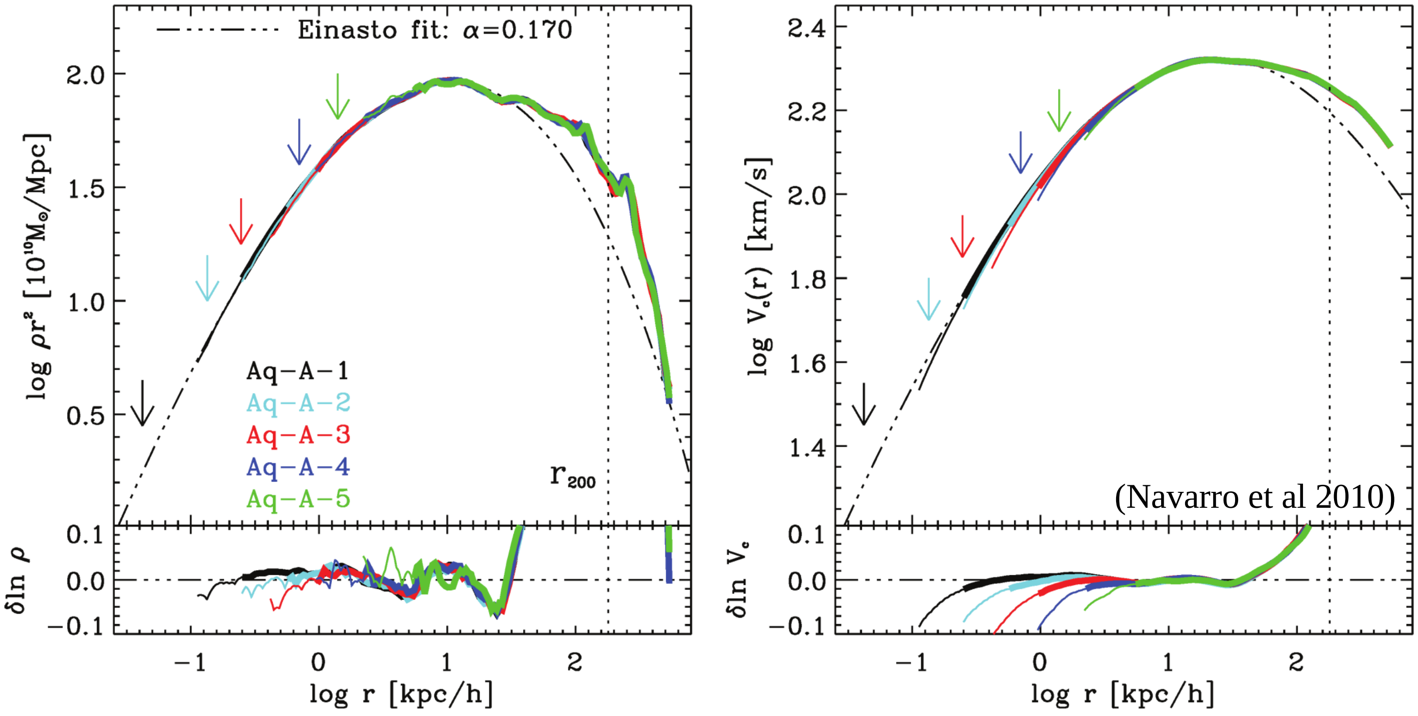
“Convergence radius” of DM halos:
(e.g. Power et al, 2003)

$$\kappa(r) = \frac{N}{8\ln N}\frac{r/V_c}{r_{200}/V_{200}} = \frac{\sqrt{200}}{8}\frac{N(r)}{\ln N(r)}\left[\frac{\overline{\rho}(r)}{\rho_{\rm crit}}\right]^{-1/2}$$

$\kappa(r)$ is defined as the relaxation time expressed in units of a Hubble time

Better convergence is obtained for higher values of $\kappa(r)$

N_{200} [10^6]	r_{conv} [kpc]
1074	*0.35*
134	*0.79*
37	*1.32*
4.7	*3.12*
0.6	*7.60*



Collisional heating of simulated galaxies and halos

Multi-component collisional systems tend toward energy equipartition:

$$m_\star \, \sigma_\star^2 \approx m_{\rm DM} \, \sigma_{\rm DM}^2 \quad \Longrightarrow \quad \left(\frac{m_\star}{m_{\rm DM}}\right)\left(\frac{\sigma_\star^2}{\sigma_{\rm DM}^2}\right) \approx 1$$

For a typical galaxy in a cosmological simulation $m_\star \sigma_\star^2 \ll m_{\rm DM} \sigma_{\rm DM}^2$

$$\frac{m_{\rm DM}}{m_\star} = \frac{\Omega_{\rm DM}}{\Omega_{\rm bar}} \approx 5 \qquad \text{and} \qquad \frac{\sigma_\star}{\sigma_{\rm DM}} \ll 1$$

(cosmological simulations typically sample Lagrangian density fields with equal numbers of DM and baryonic particles)

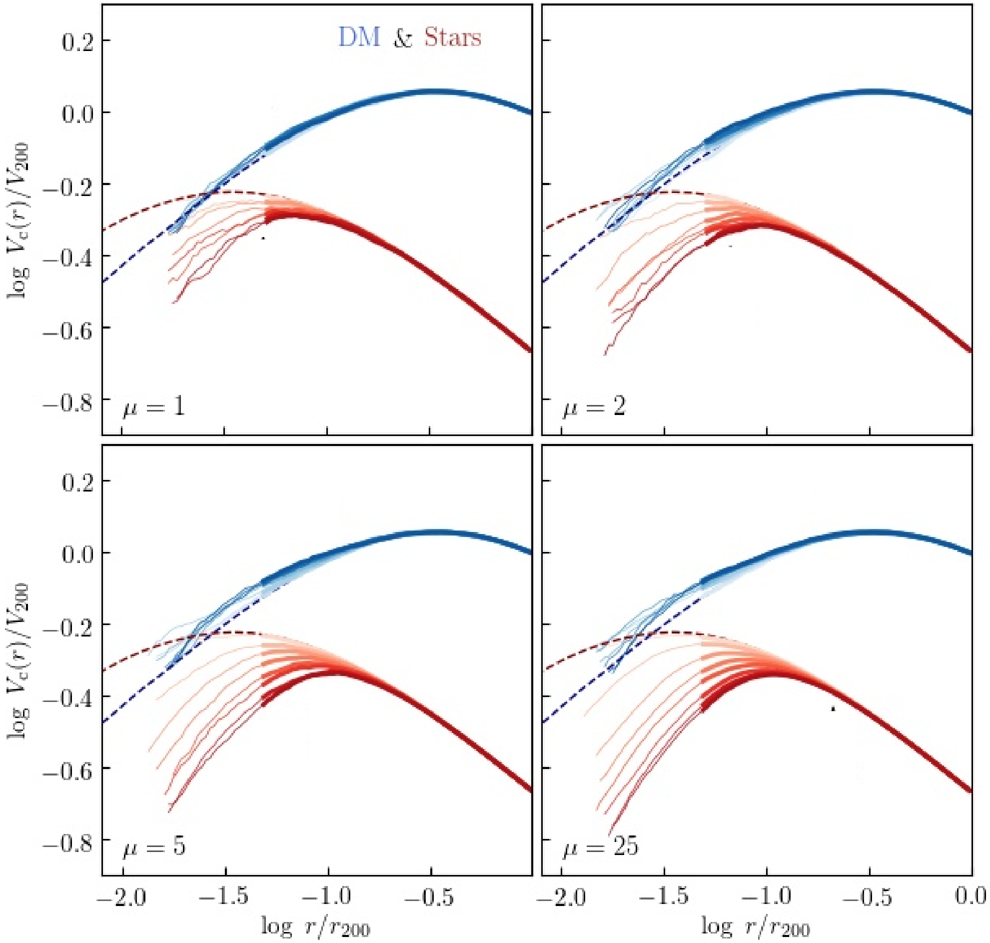
(galaxies – particularly disk galaxies – are “colder” than their surrounding DM haloes)

Collisional heating of simulated galaxies and halos

Example: "idealized" elliptical galaxies

(Ludlow et al, 2019)

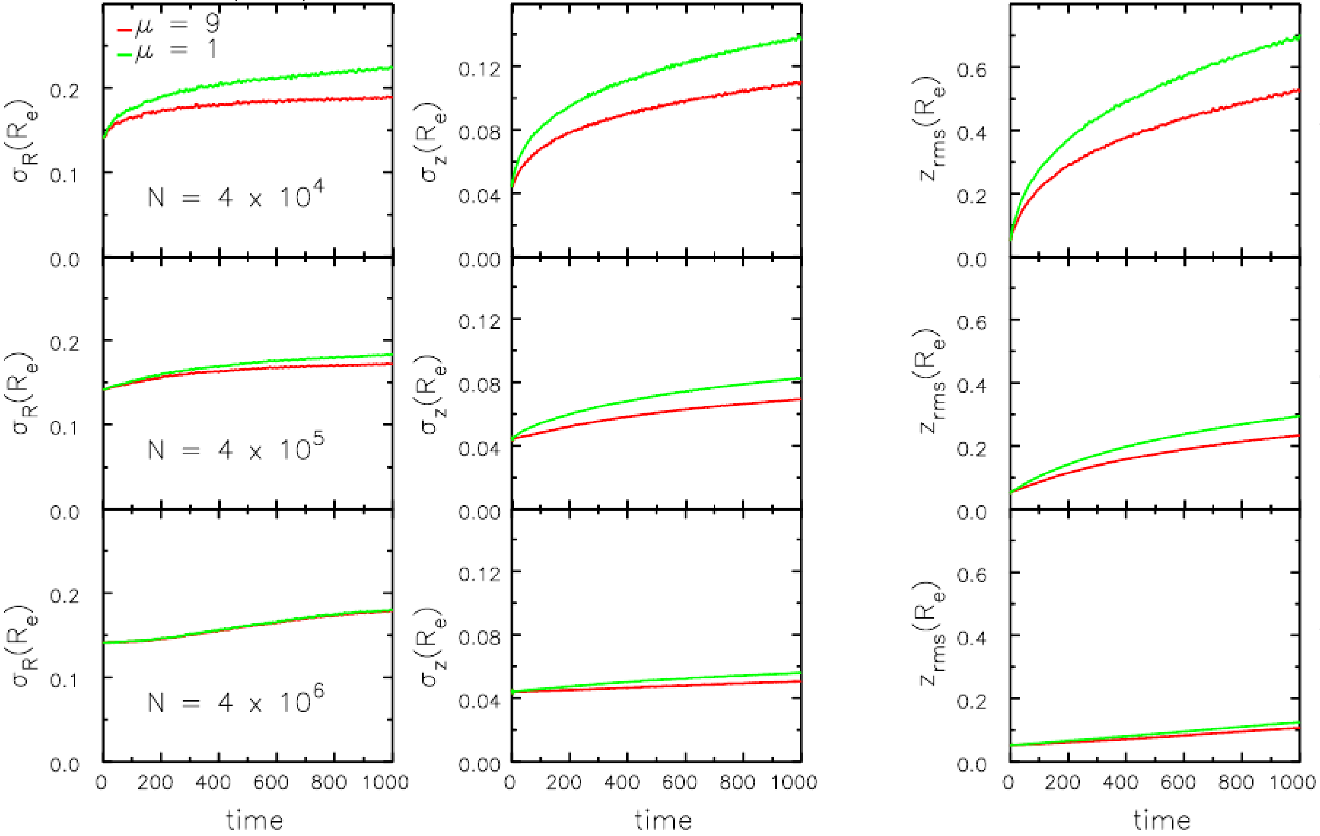
$$\left(\frac{m_\star}{m_{\rm DM}}\right)\left(\frac{\sigma_\star^2}{\sigma_{\rm DM}^2}\right) \ll 1$$



Spurious collisional heating of simulated disk galaxies

Increasing mass resolution

Sellwood (2013)



Stable (Mestle) disk, free from instabilities

Rigid (i.e. smooth) dark matter halo…

Heavy and *light* stellar particles

The segregation of two "collisionless" particle species of different mass is a faithful indicator of collisional relexation

Spurious collisional heating of the Milky Way's disc

$$\frac{\Delta\sigma_i^2}{\Delta t} = \sqrt{2}\pi G^2 \ln\Lambda \frac{\rho_{\rm DM} m_{\rm DM}}{v_{\rm DM}} f_i\langle ...\rangle$$

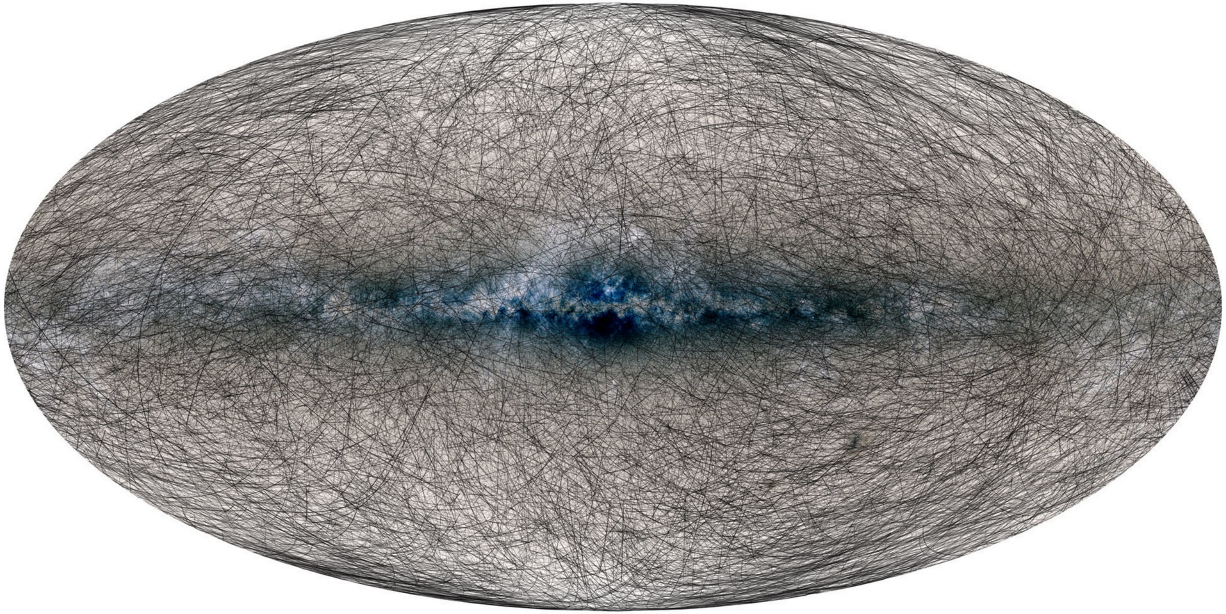
Disk heating rates calculated analytically by Lacey & Ostriker (1985)

Assumed that black holes were plausible candidates for dark matter

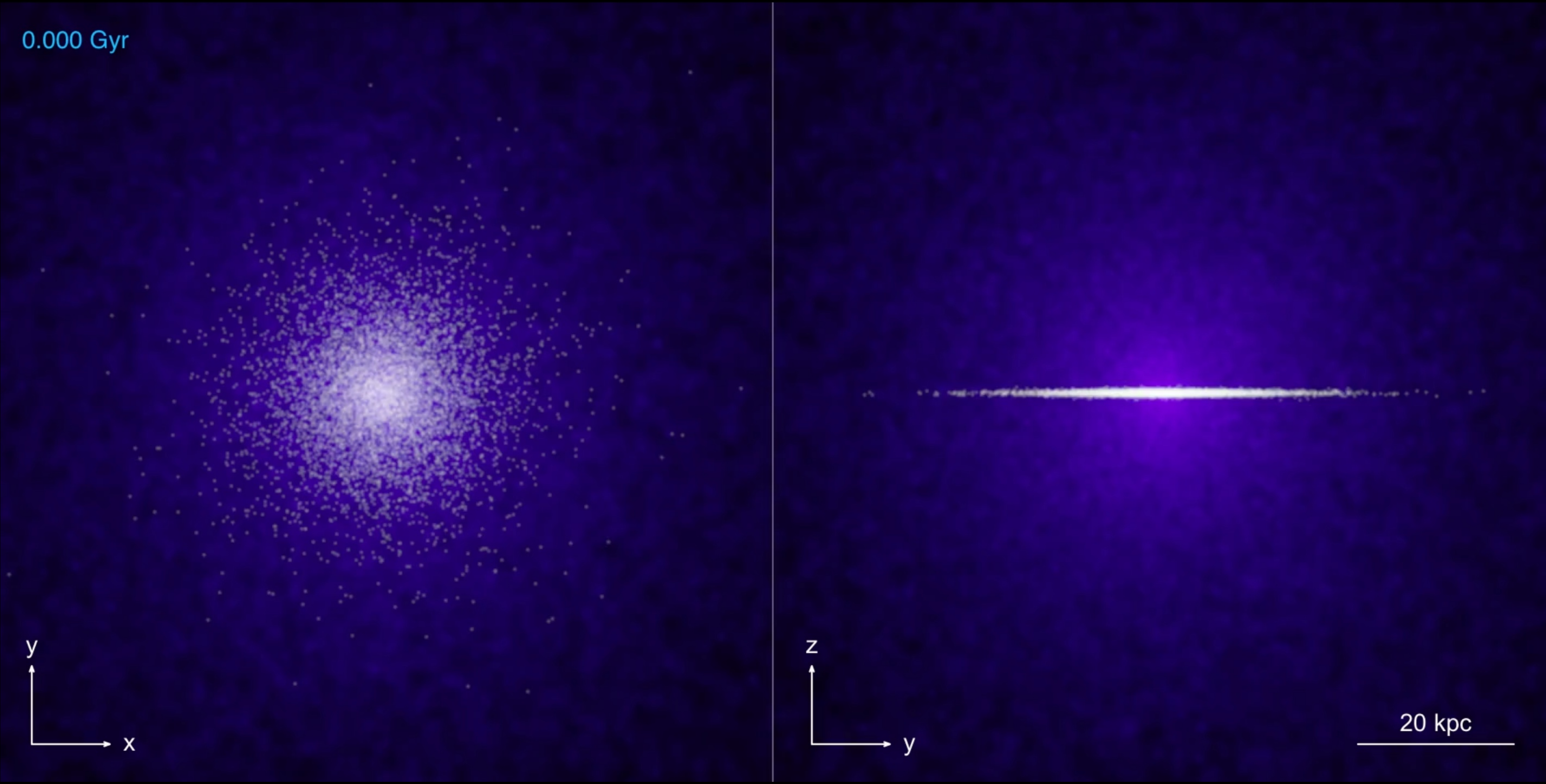
BHs cannot be more massive than

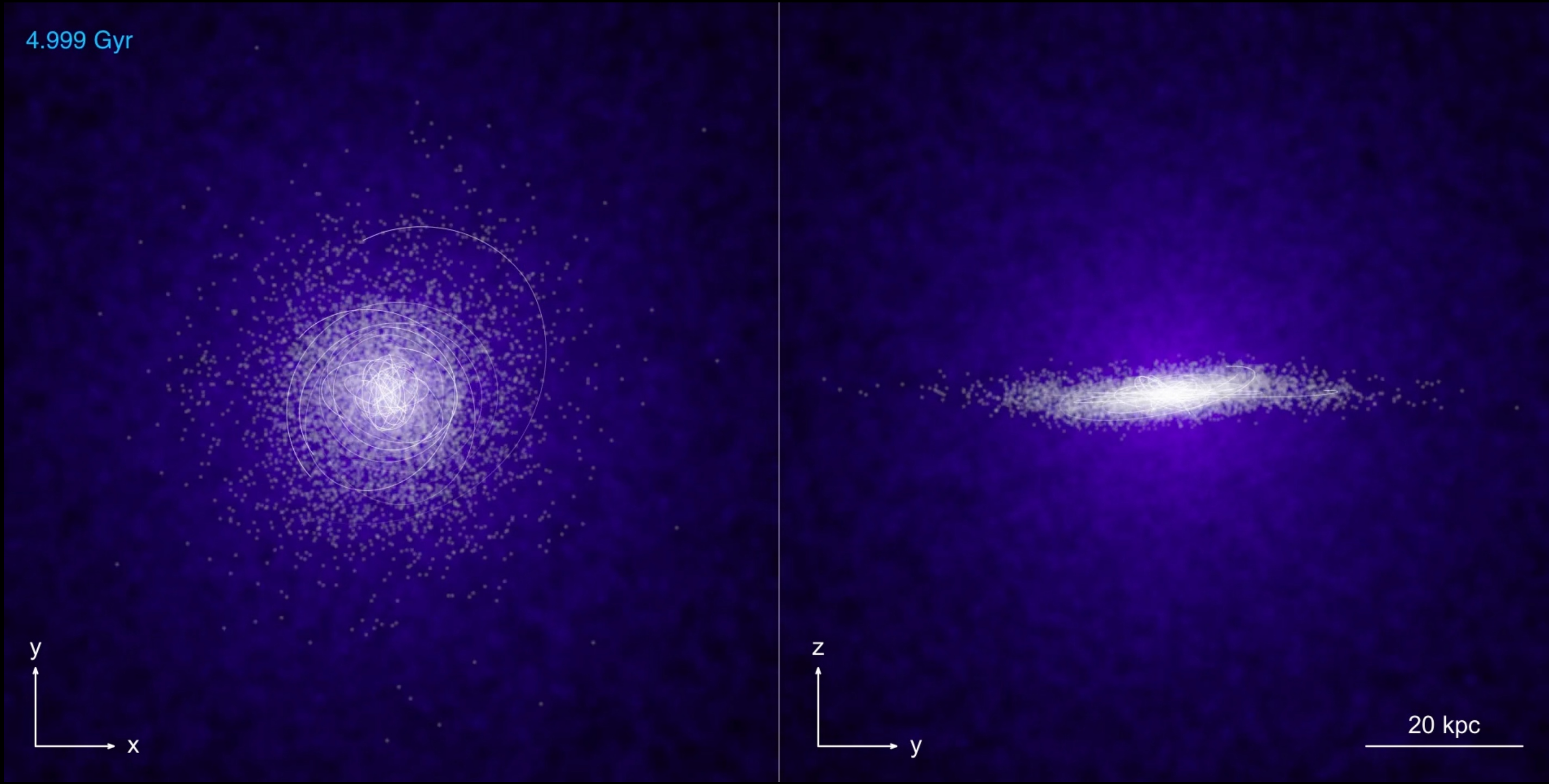
$$M_{\rm BH} \approx 10^6\,{\rm M}_\odot$$

or the Milky Way's disc would be hotter and thicker than it is observed to be



High Resolution Simulations


0.000 Gyr
y
x
z
y
20 kpc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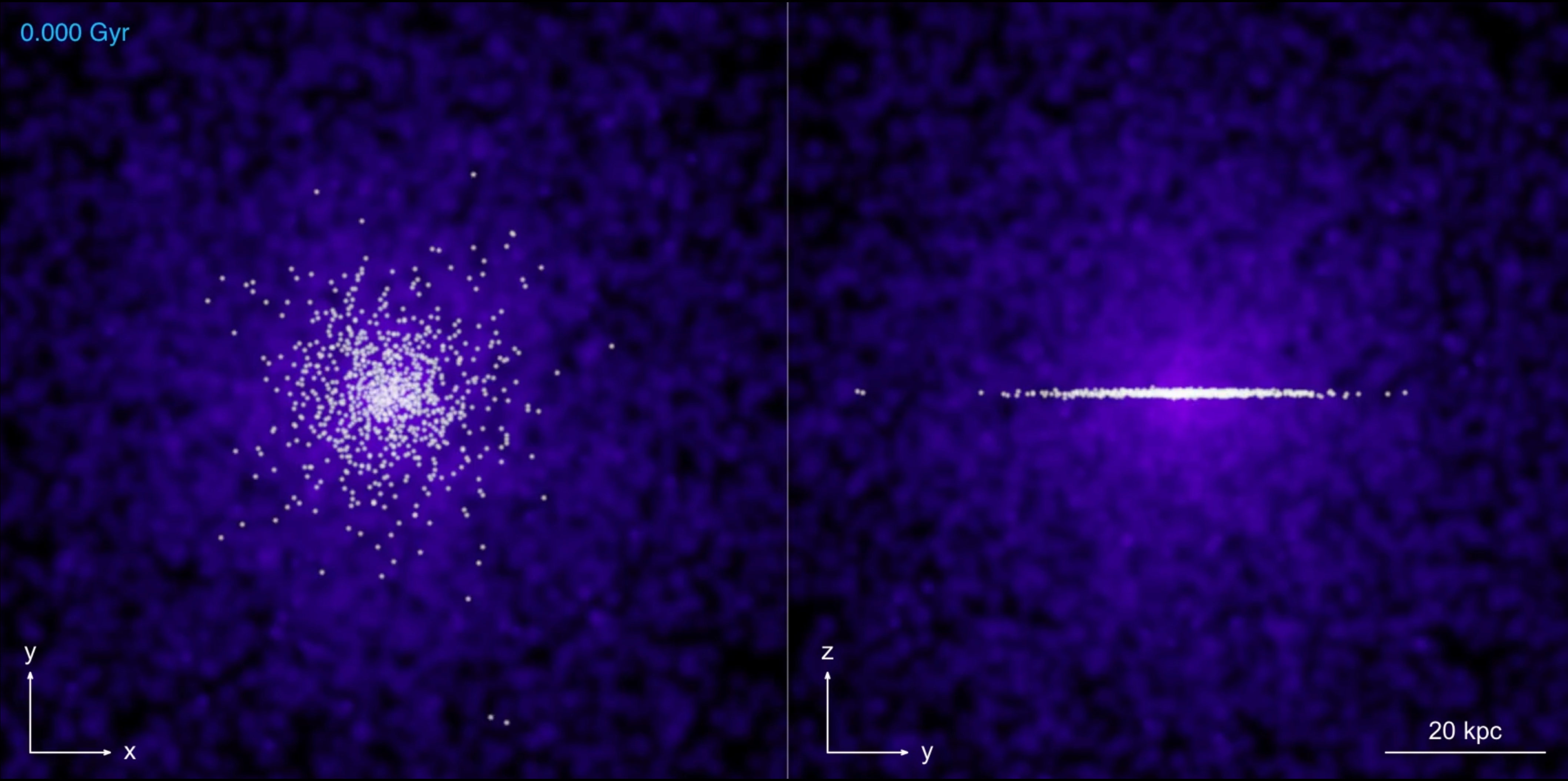
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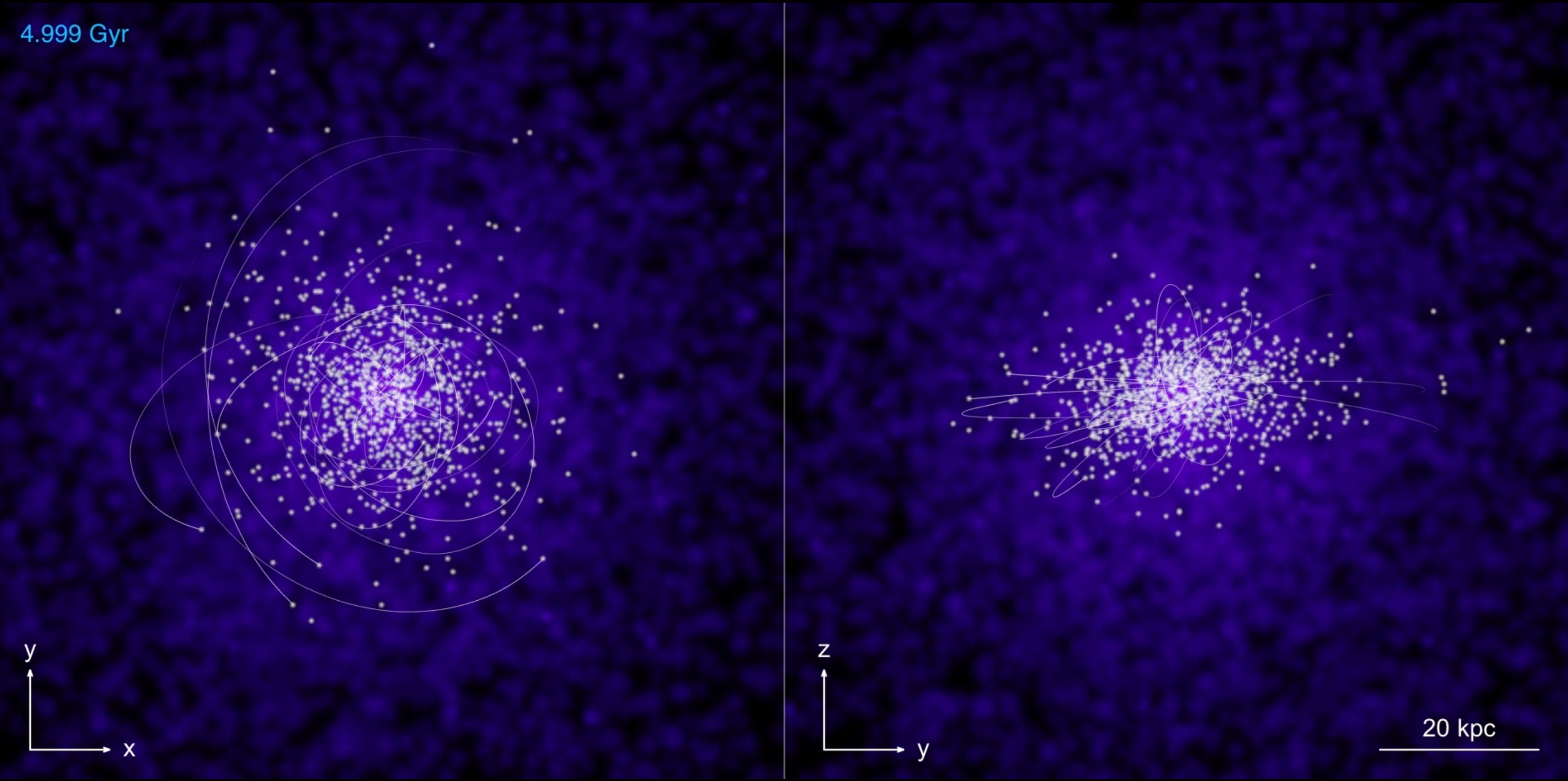

4.999 Gyr
y
x
z
y
20 kpc

The impact of spurious collisional heating on disc galaxies

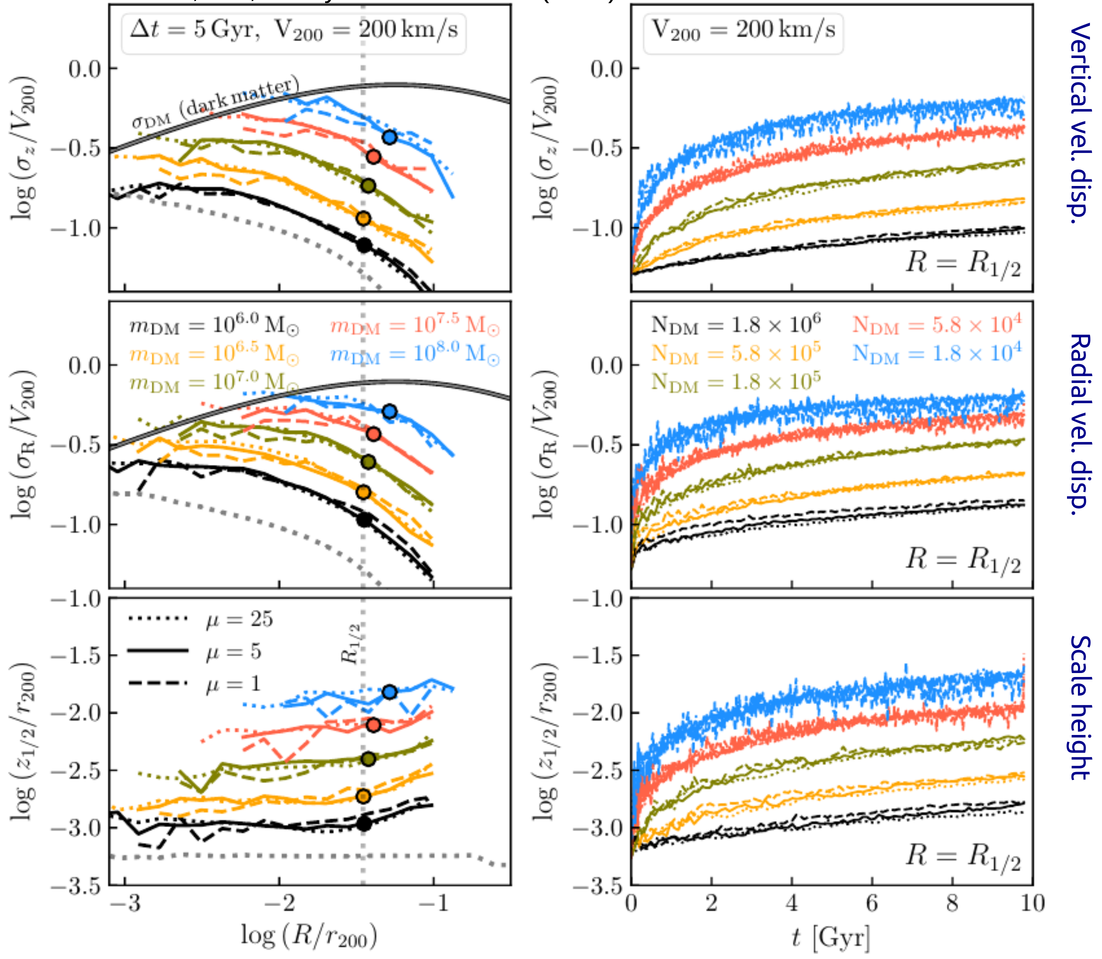
The evolution of stable equilibrium stellar disks in coarse-grained DM halos betrays the effects of spurious collisional heating:

1) Disks become hotter and thicker as a function of time
2) The effects are more pronounced at lower resolution
3) Disks are heated/thickened at all radii (but more in the centre)

Different line styles in these plots show different stellar particle masses

(See Matt Wilkinson's talk and Wilkinson et al (2022) for an assessment of how spurious heating affects disc morphology)

Ludlow, Fall, Schaye & Obreschkow (2021)



The impact of spurious collisional heating on disc galaxies

Disk heating rates can however be modelled
(e.g. Chandrasekhar 1960, Lacey & Ostriker 1985)

$$\frac{\Delta\sigma_i^2}{\Delta t} = \sqrt{2}\pi G^2 \ln\Lambda \frac{\rho_{\rm DM} m_{\rm DM}}{v_{\rm DM}} f_i \langle ... \rangle$$

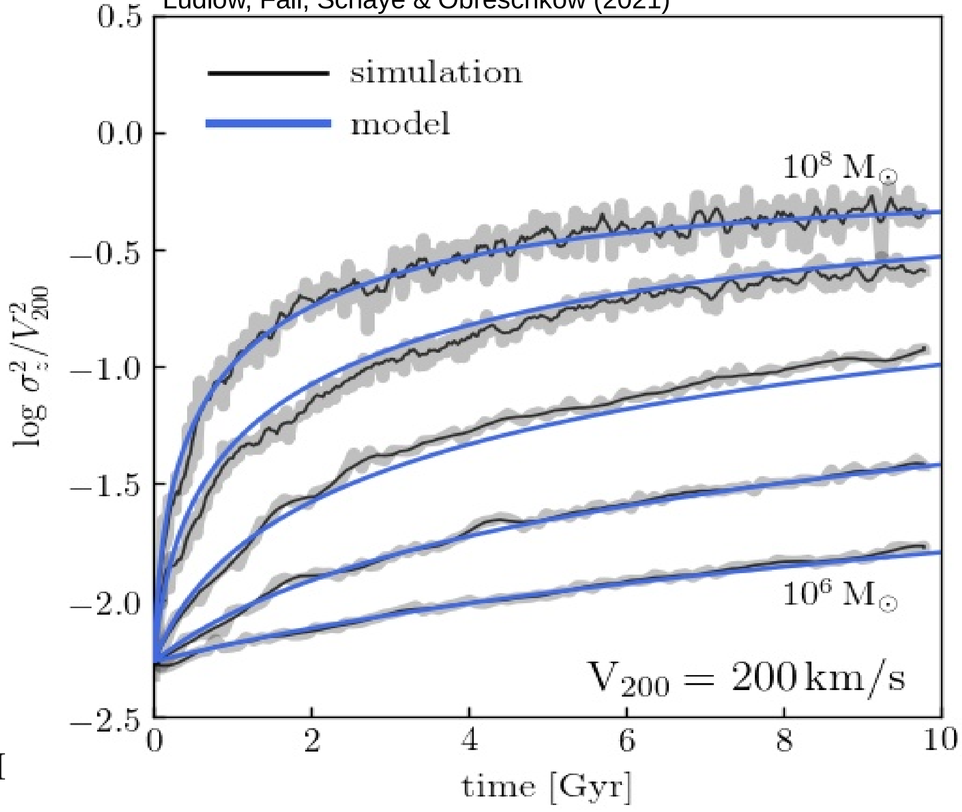
In practice…

$$\sigma_i^2(t) = \sigma_{\rm DM}^2 \left[1 - \exp\left(- \frac{(t + t_0)}{t_{\rm vir}} \right) \right]$$

t_0 sets the initial velocity dispersion

$t_{\rm vir}$ timescale for maximal heating, i.e. $\sigma_i = \sigma_{\rm DM}$

Ludlow, Fall, Schaye & Obreschkow (2021)



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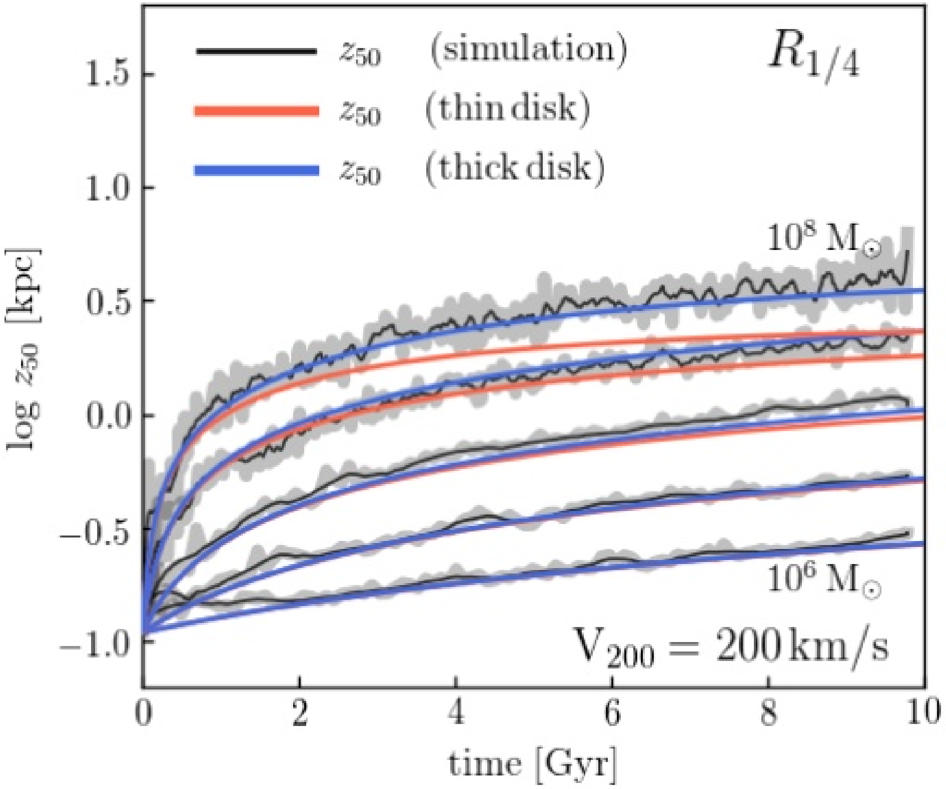
Scale-heights from the hydrostatic eq. Equation:

$$\frac{\sigma_z^2}{\rho_{\rm D}} \frac{\partial \rho_{\rm D}}{\partial z} = -\frac{\partial}{\partial z}(\Phi_{\rm DM} + \Phi_{\rm D})$$

Ludlow, Fall, Schaye & Obreschkow (2021)



Implications for cosmological simulations of galaxy formation

It is important to assess these effects in cosmological simulations of galaxy assembly

We carried out 2 **EAGLE** simulations that differ only in the mass of DM particles:

$$m_{\rm DM} = 9.7 \times 10^6 \, {\rm M}_\odot, \;\; m_{\rm gas} = 1.8 \times 10^6 \, {\rm M}_\odot, \;\; \mu = 5.3$$

$$m_{\rm DM} = 1.4 \times 10^6 \, {\rm M}_\odot, \;\; m_{\rm gas} = 1.8 \times 10^6 \, {\rm M}_\odot, \;\; \mu = 0.8$$

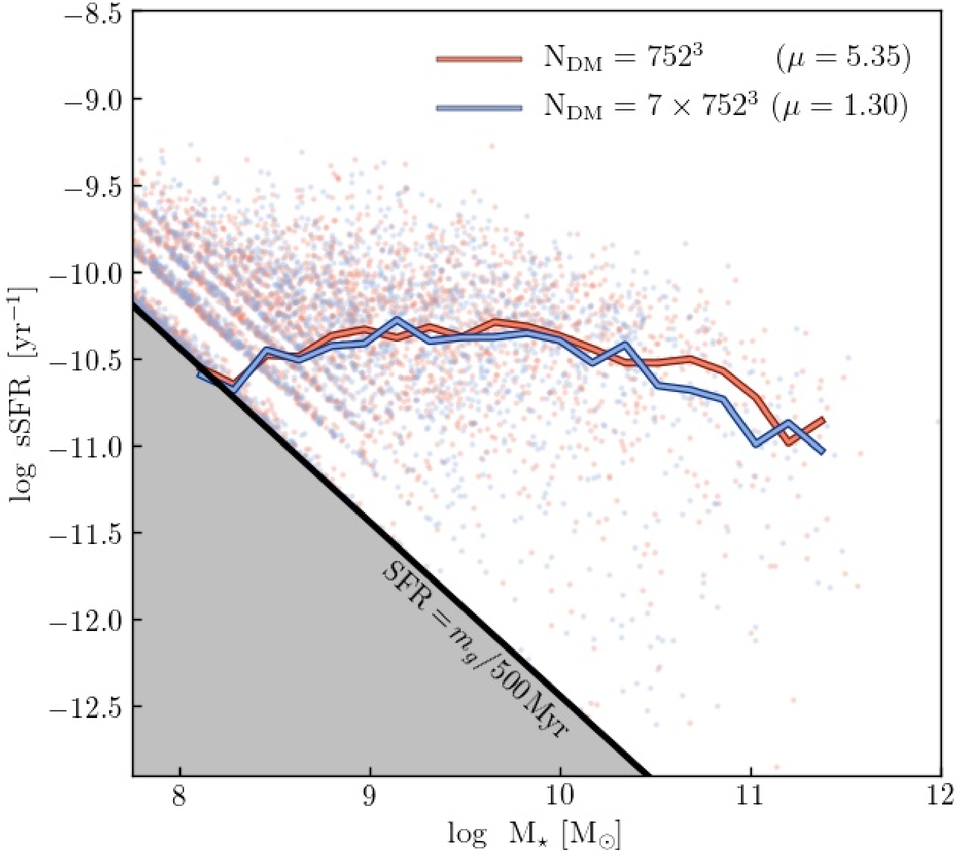
The subgrid physics models, force and baryon mass resolution, and numerical parameters are identical

Implications for cosmological simulations of galaxy formation

Does the DM mass resolution affect the basic galaxy population statistics?

- Star formation rates
- Star formation histories
- Stellar and halo mass functions
- Stellar-halo mass relations

Ludlow, Fall, et al in prep.



$\mu = 5.3$
$\mu = 0.8$

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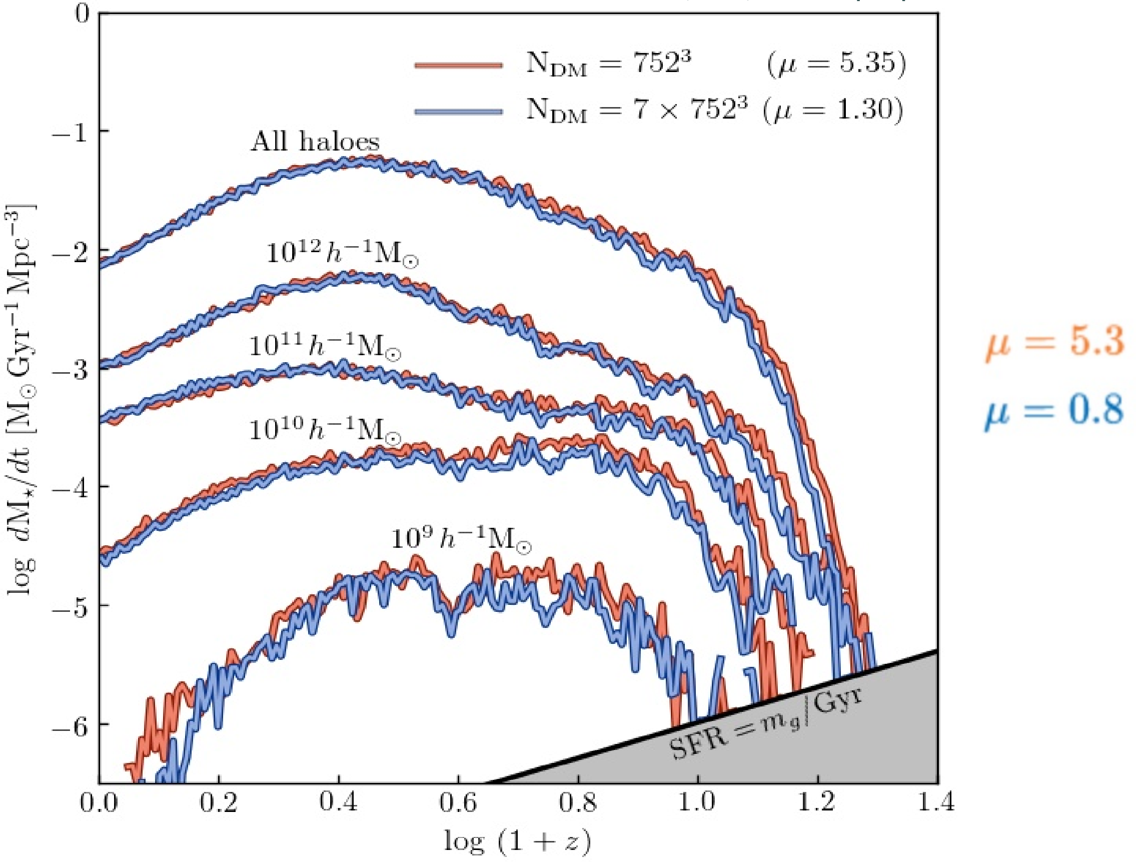

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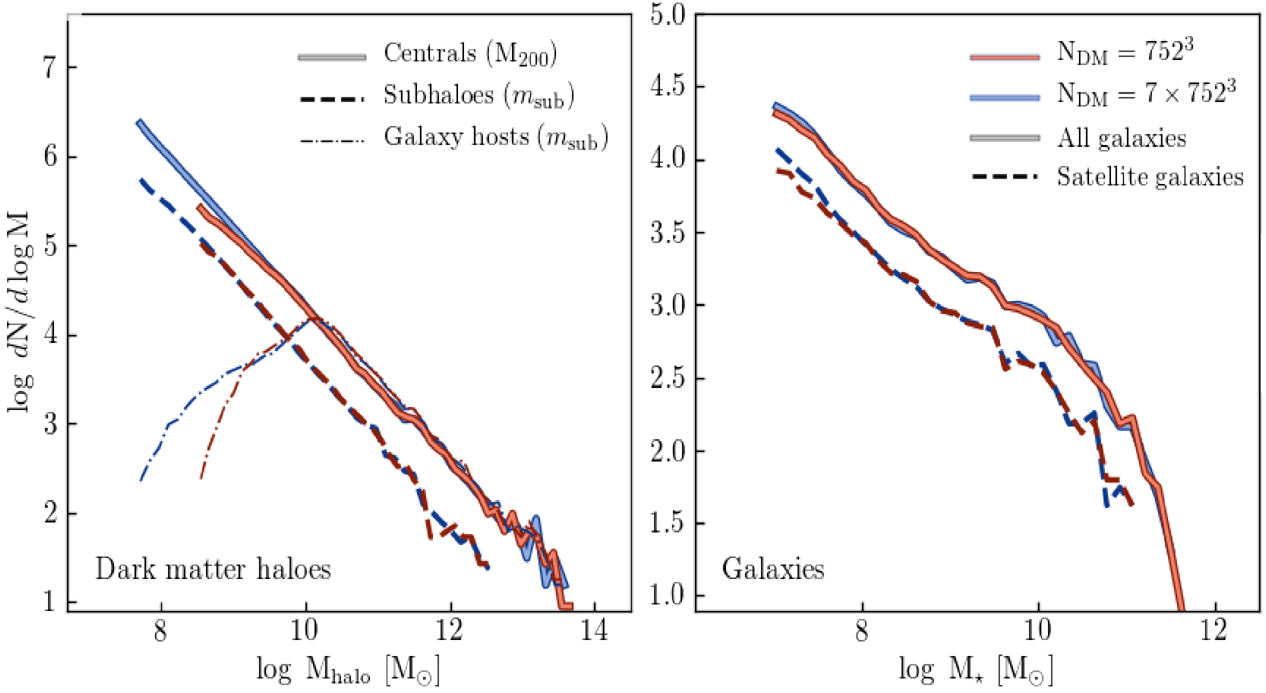

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Implications for cosmological simulations of galaxy formation

Does the DM mass resolution affect the basic galaxy population statistics?

- Star formation rates
- Star formation histories
- Stellar and halo mass functions
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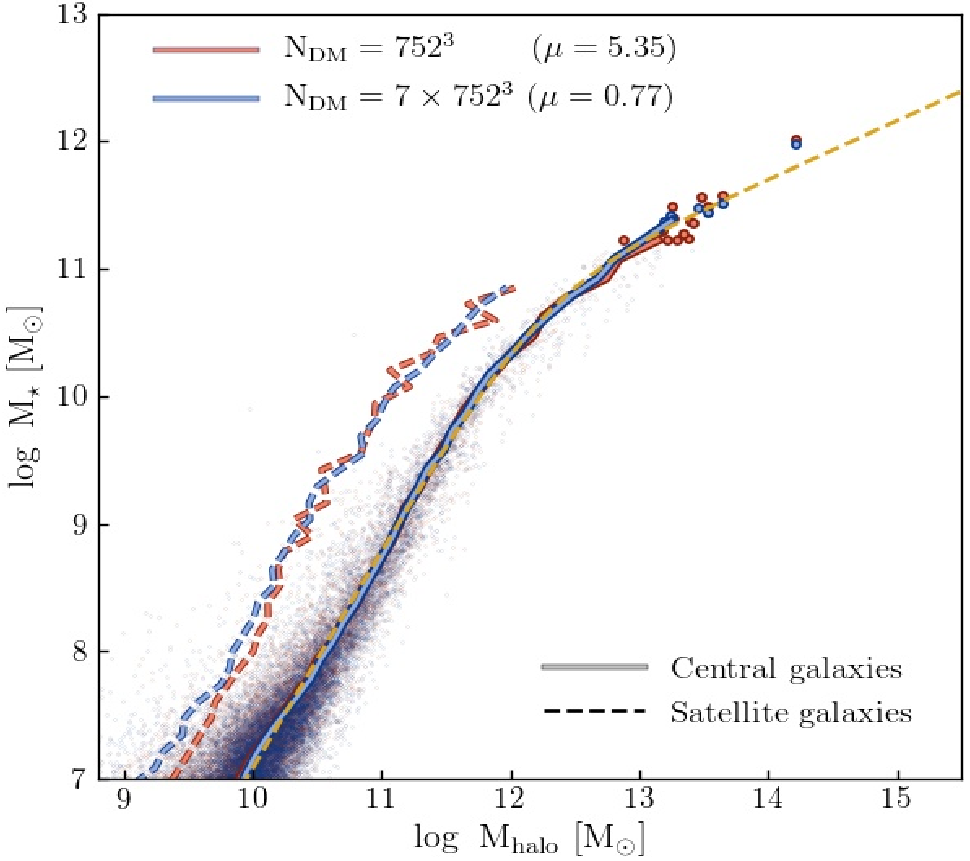
This is good…

Collisional heating *does not* affect some of the basic predictions of hydrodynamical simulations

Steinmetz & White (1996): spurious heating of gas particles problematic as well, but requires DM particle masses a few orders of magnitude larger Than those adopted for most recent simulations

Ludlow, Fall, et al in prep.



$\mu = 5.3$

$\mu = 0.8$

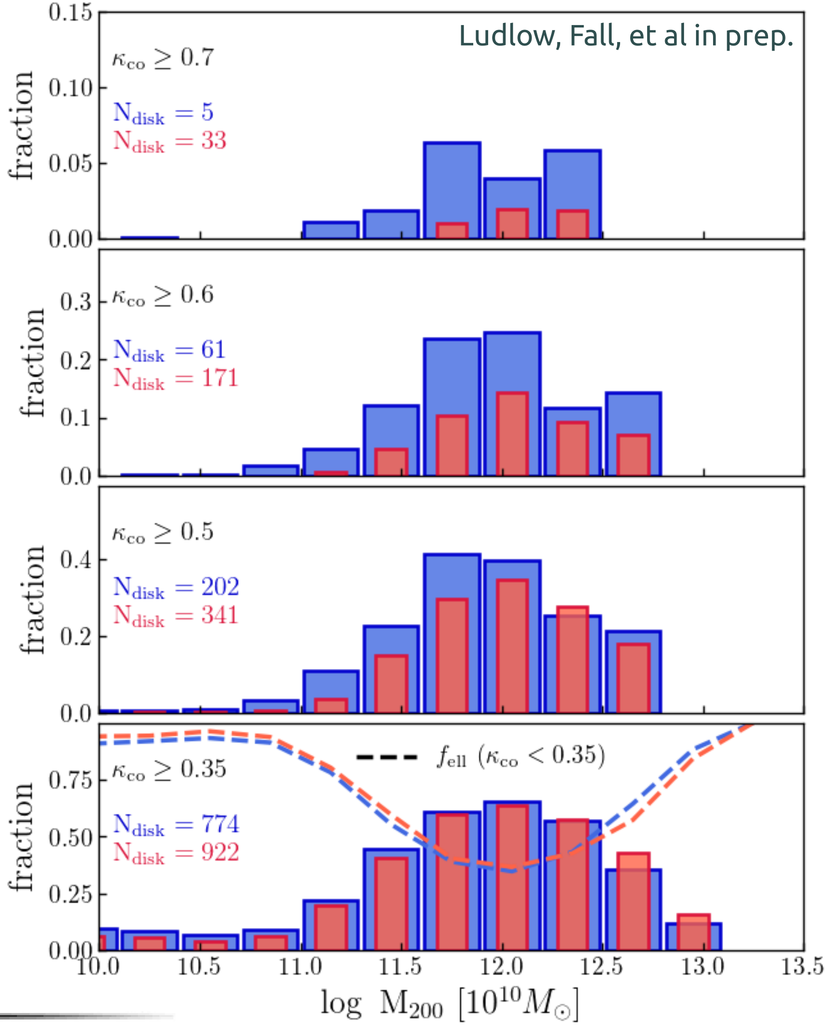
Implications for cosmological simulations of galaxy formation

But what about the structural and kinematic properties of galaxies?

- Morphologies: *Disky galaxies are more prevalent when the resolution of the DM component is increases*

  …e.g. there are roughly 70% more "disks" in our HRDM with $\kappa_{\rm co} \geq 0.5$

$$\kappa_{\rm co} = \frac{1}{2\,K} \sum_{L_{z,i}>0} m_i \left(\frac{L_{z,i}}{m_i\,R_i}\right)^2$$



Implications for cosmological simulations of galaxy formation

But what about the structural and kinematic properties of galaxies?

- Stellar velocity dispersion

Reasonable convergence in stellar velocity dispersions provided the intrinsic dispersion exceeds that expected due to collisional heating, i.e.

$$\sigma_{\rm coll}(M,R,t) \lesssim \sigma_\star(M,R,t)$$

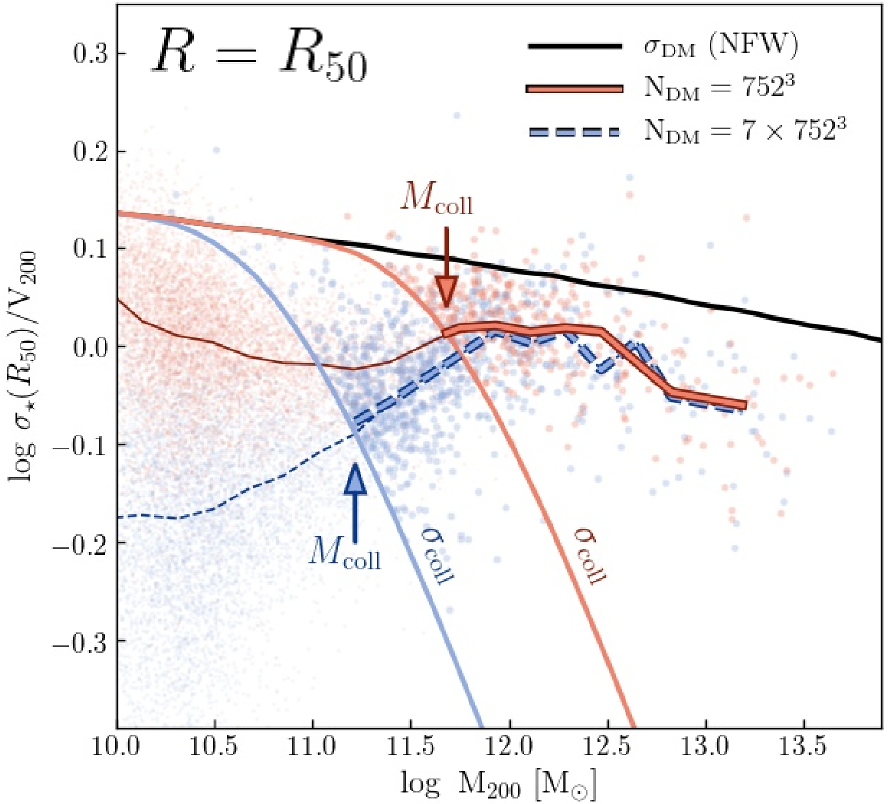
For **EAGLE**...

$$M_{\rm coll} \simeq 4.8 \times 10^{11}\,{\rm M}_\odot$$

or with high-res DM...

$$M_{\rm coll} \simeq 1.6 \times 10^{11}\,{\rm M}_\odot$$

Ludlow, Fall, et al in prep.



Implications for cosmological simulations of galaxy formation

But what about the structural and kinematic properties of galaxies?

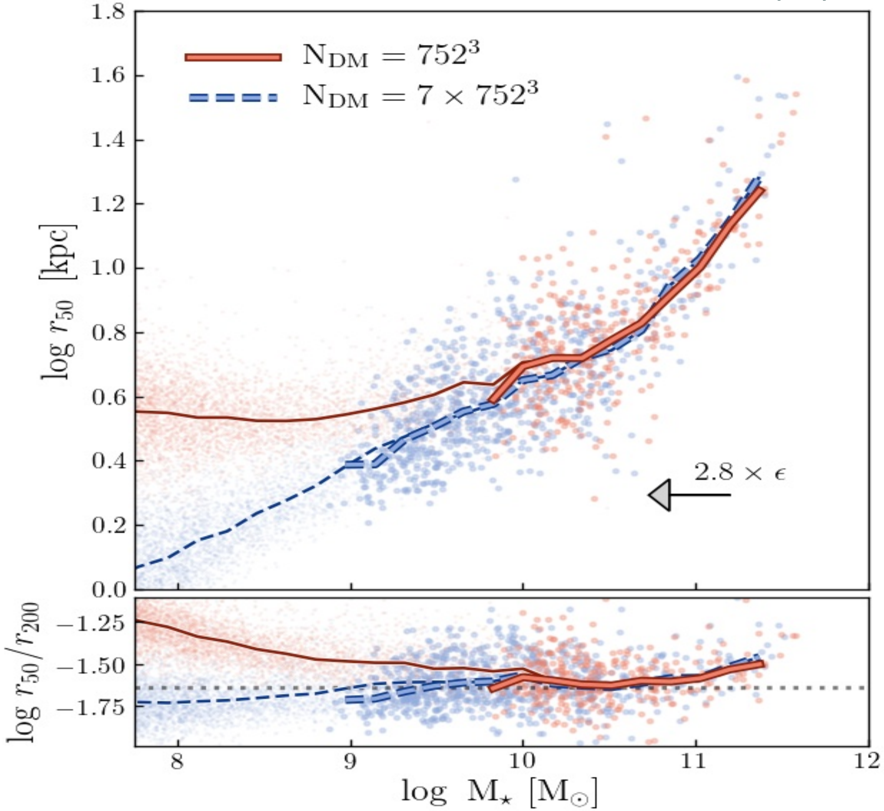
- Galaxy sizes

  Reasonable convergence in galaxy sizes provided the intrinsic velocity dispersion exceeds that expected due to collisional heating, i.e.

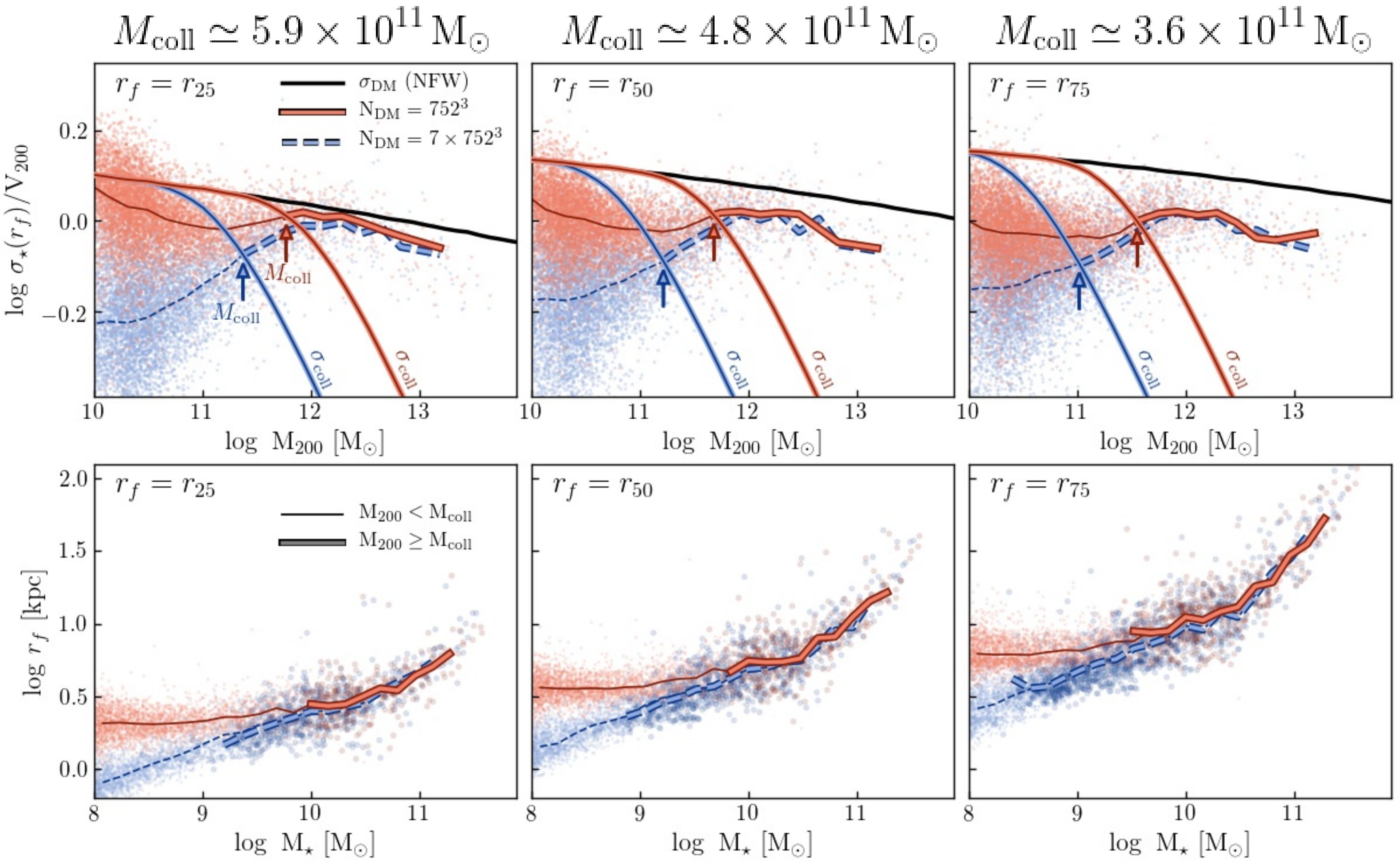
$$\sigma_{\rm spur}(R) \lesssim \sigma_\star(R)$$

(Note that the flattening of the size-mass relation at low stellar masses is also present in simulations other than **EAGLE**)

Ludlow, Fall, et al in prep.

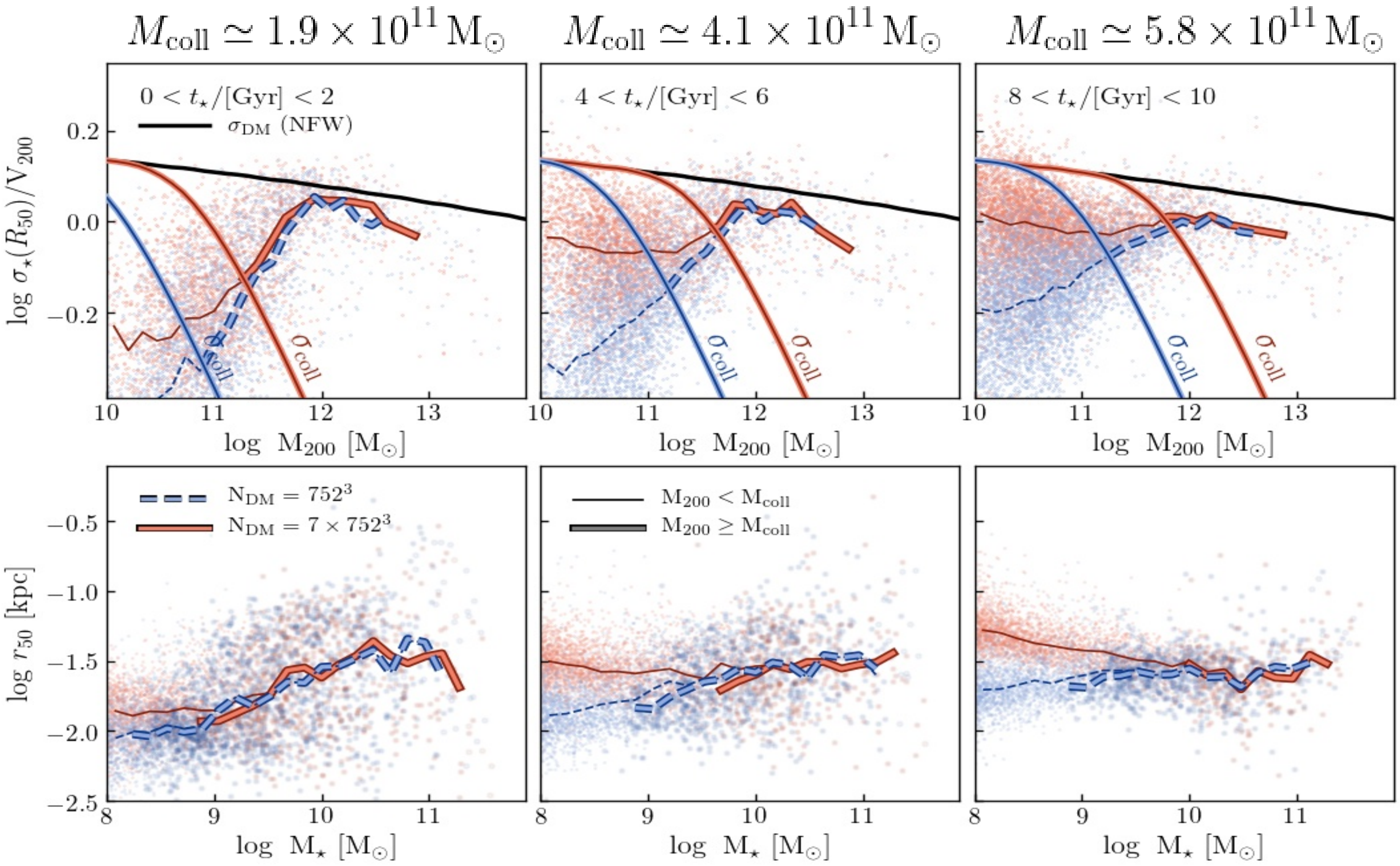


Implications for cosmological simulations of galaxy formation



Ludlow, Fall, et al in prep.

Implications for cosmological simulations of galaxy formation



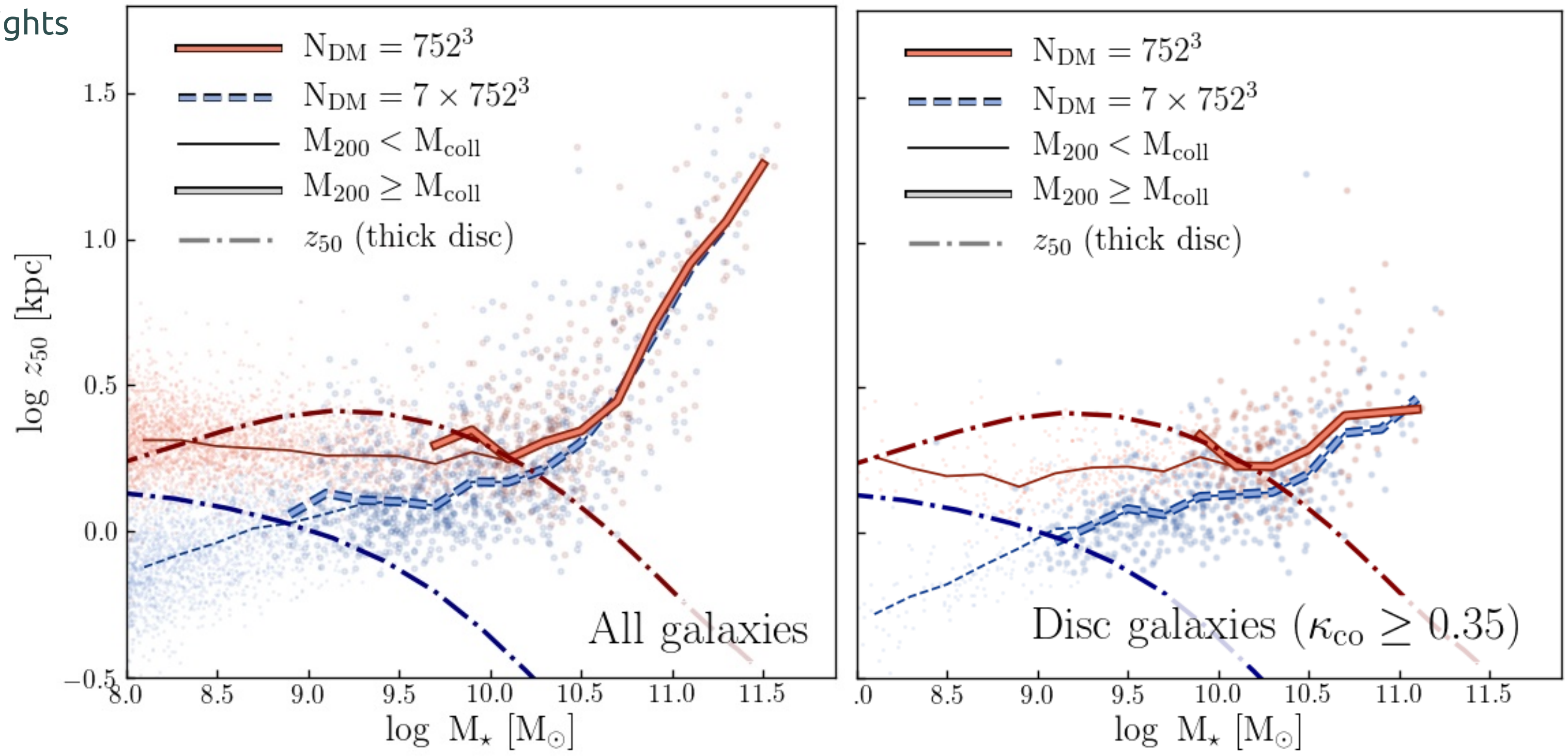
Ludlow, Fall, et al in prep.

Implications for cosmological simulations of galaxy formation

But what about the structural and kinematic properties of galaxies?

Ludlow, Fall, et al in prep.

- Galaxy disc scale heights

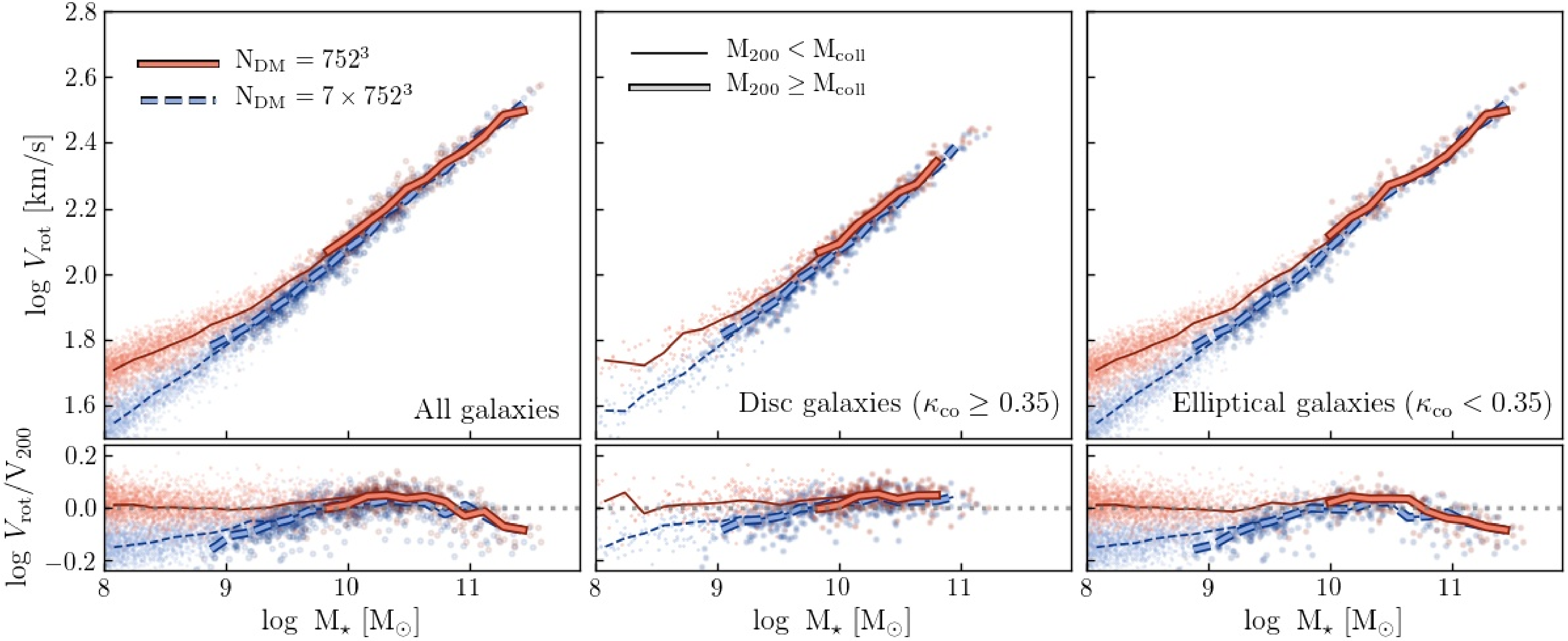


Implications for cosmological simulations of galaxy formation

But what about the structural and kinematic properties of galaxies?

- Rotation Velocities: The Tully-Fisher relation

Ludlow, Fall, et al in prep.



Summary

This stellar disks can be heated by a number of physical processes (spiral arms, GMCs, globular clusters, substructure, local disk instabilities, etc)…

But simulated disks are also heated *numerically*

1) Collisional heating of disks is largely driven by the properties of their host halos (star-star collisions less important)
2) It affects all galacto-centric radii (but affects the centre more than the outskirts)
3) It alters the (vertical, radial, and azimuthal) kinematics of stars, and the scale heights of galaxies
4) It is largely independent of the baryonic (stellar) mass resolution; determined primarily by DM mass resolution
5) Can be modelled, which allows useful "convergence criteria" to be developed for hydrodynamical simulations