SIDM on FIRE

Robyn Sanderson, UPenn • SIDM in Valencia

What we have simulated so far

ALL have CDM counterparts with identical baryonic physics

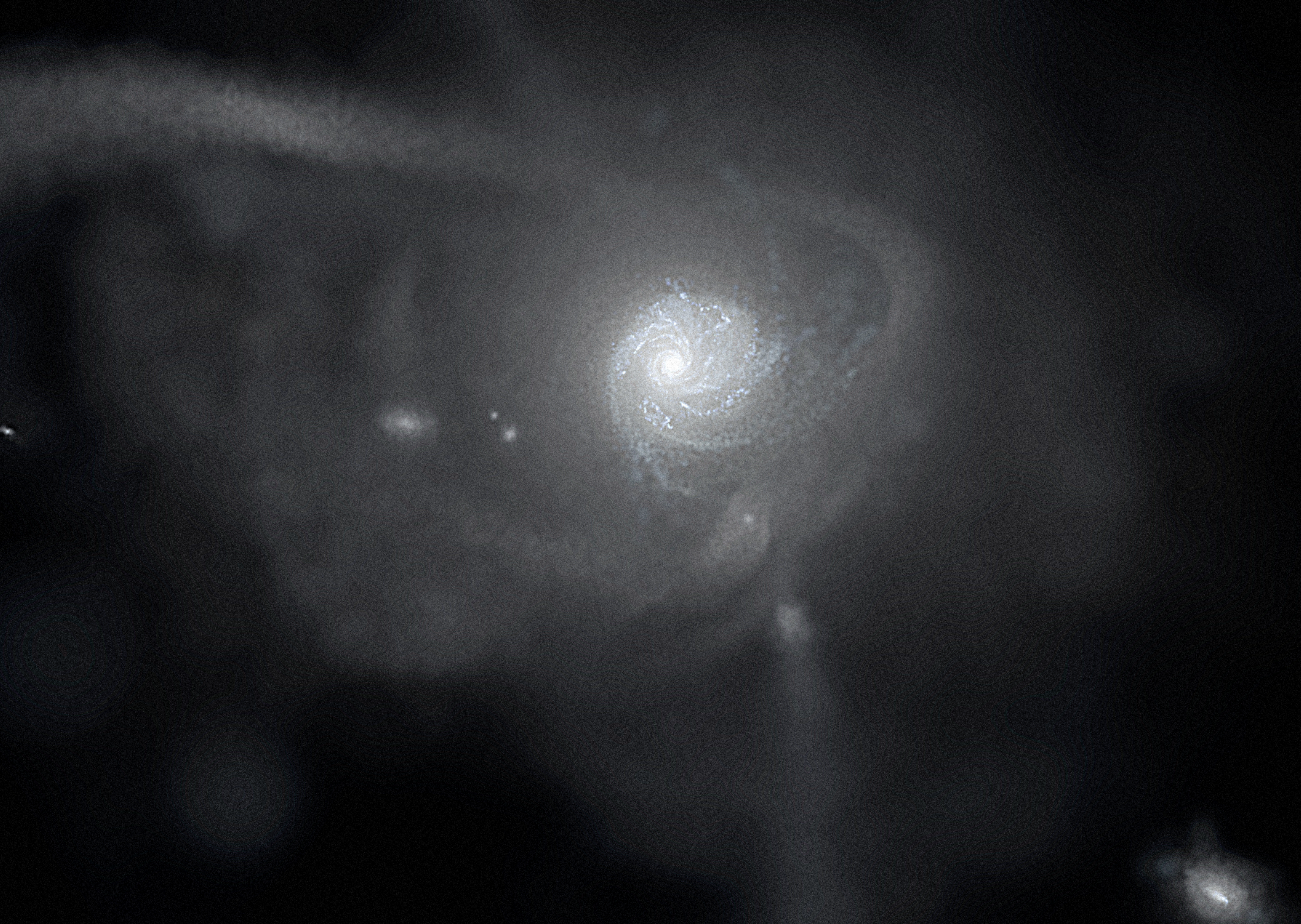
- 4 MW-mass host galaxies (10^12 Msun) with **constant**, **isotropic** cross sections between 0.1 and 10 cm^2/g + **elastic** scattering
  - Resolution: 7e3 Msun/particle gas/stars, 5.7e4 Msun/particle DM
  - All 4 simulated at 1 cm^2/g, other cross sections vary per halo
  - Sameie+2021, Vargya+2022, Baptista+2023, Arora+2024, Arora, RES et al in prep
- Range of masses from 10^9 to 10^12 with **constant**, **isotropic** cross sections between 0.1 and 10 cm^2/g + **dissipative** scattering
  - Resolution: 5.7e4 Msun/particle gas/stars, 4.5e5 Msun/particle DM @ 10^12 Msun
  - Shen+2021,2022

What we have simulated so far

ALL have CDM counterparts with identical baryonic physics

- 8 small halos (10^10 Msun) with 1 cm^2/g **constant, isotropic** cross section + **elastic** scattering
  - Resolution: 500 Msun/baryon particle, 2500 Msun/DM particle
  - Rocha+2017, Fitts+2018
- **DM-only** isolated small halos (10^10 Msun) with **constant, isotropic** cross sections 30, 70, and 140 cm^2/g + **elastic** scattering
  - Resolution: 1500 Msun/particle
  - **Baryonic** runs **in progress**
  - Silverman et al in prep

Latte: Cosmological Milky-Way-mass systems



$m_{baryon} = 7070\ M_\odot$ (init)

$m_{DM} = 35000\ M_\odot$

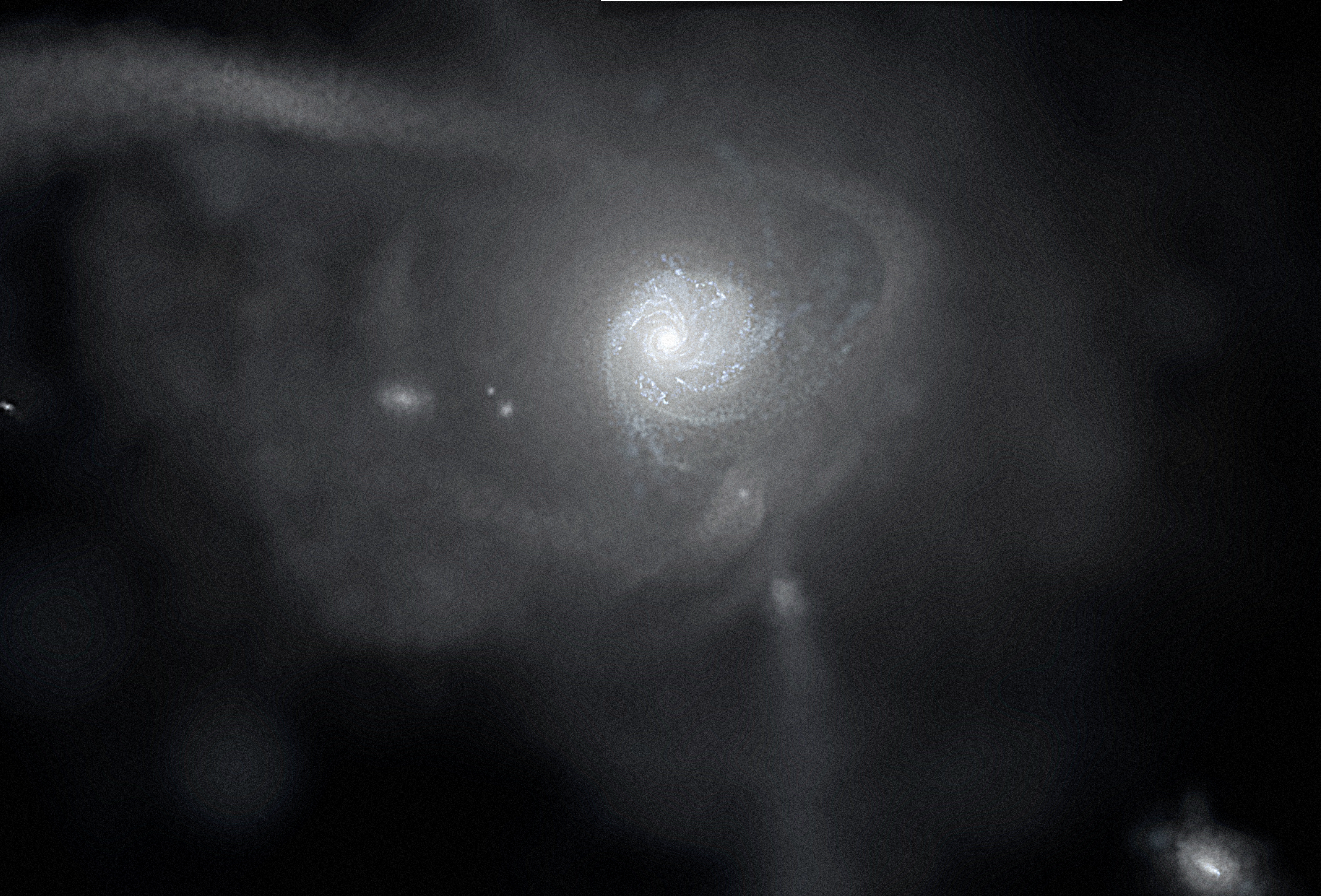
FIRE-2 feedback model
(Hopkins et al. 2018)

10 chemical elements

stars form in dense gas
($n > 1000\ pc^{-3}$)

min softenings:
1pc (gas)
4pc (stars)
20pc (DM)

Latte: Cosmological Milky-Way-mass systems



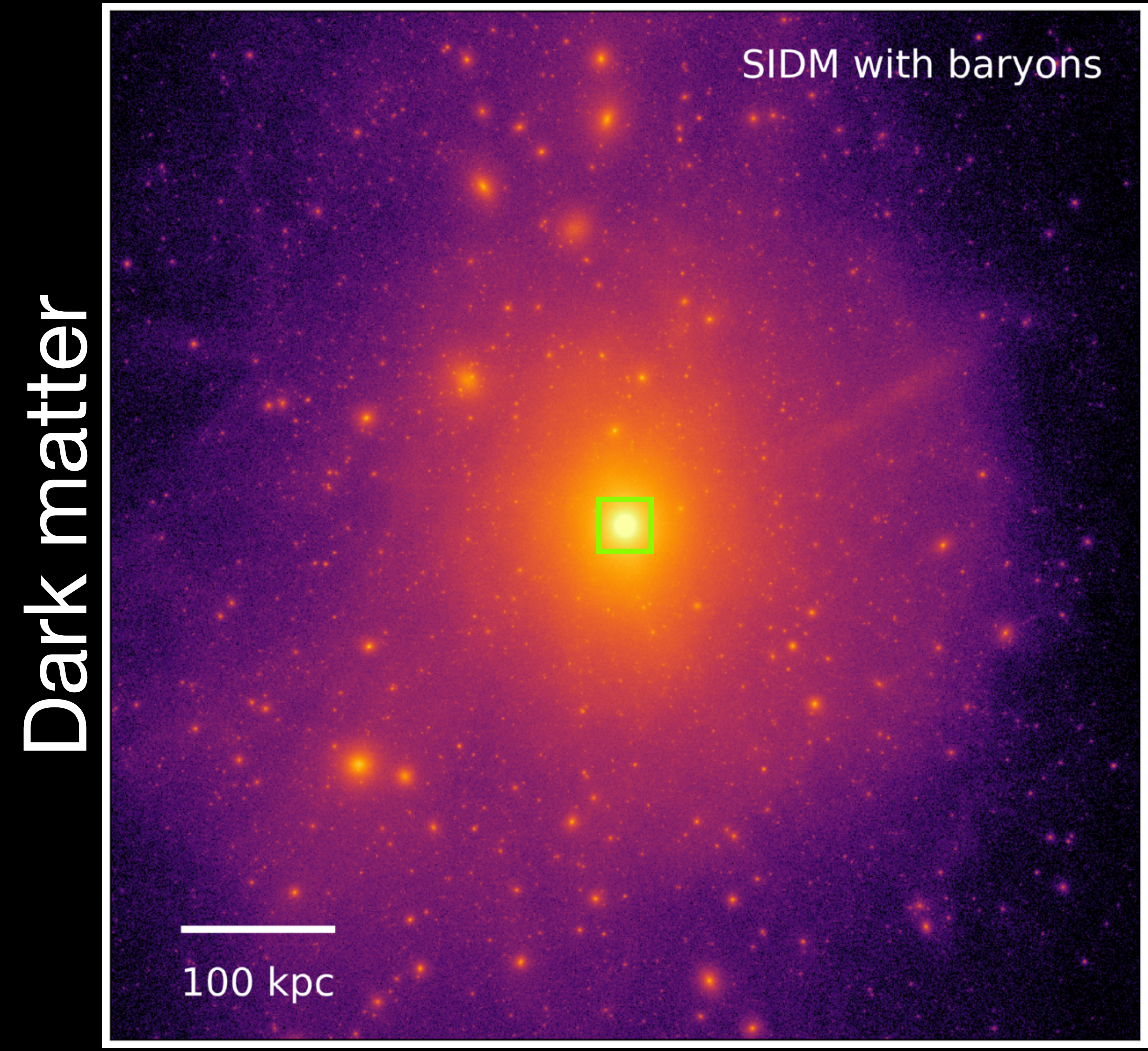
M_{halo} = 1-2 x 10^{12} M_{sun}

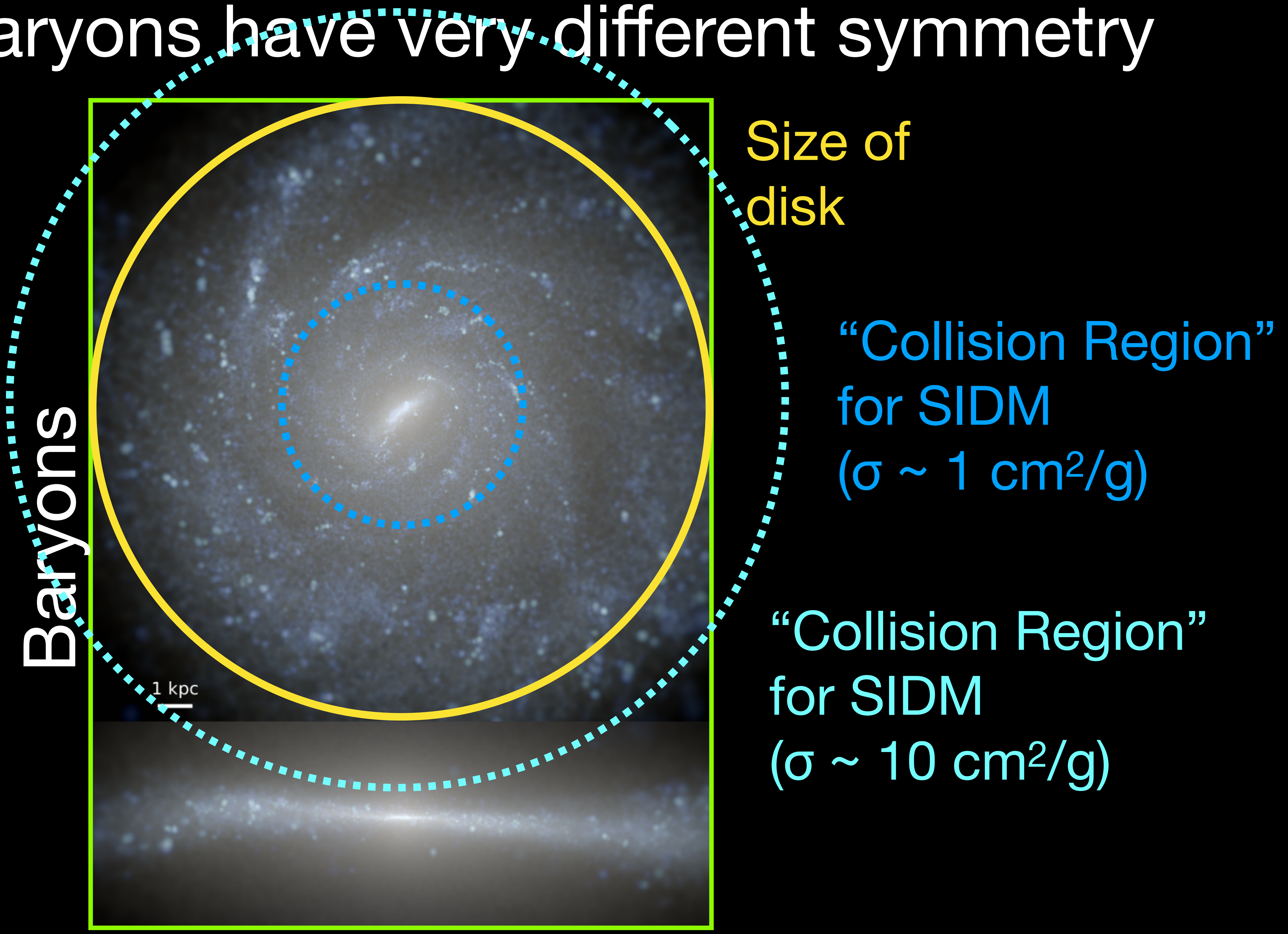
Isolated: no massive neighbor in ~5 Mpc

Selections made on CDM-only simulation

Self-Interacting Dark Matter + Galaxy Formation

- All the particles we know of interact with *something*
- Self-interactions allow greater *gravitational* response of DM to baryons
    - In disk galaxies (like MW) DM and baryons have very different symmetry





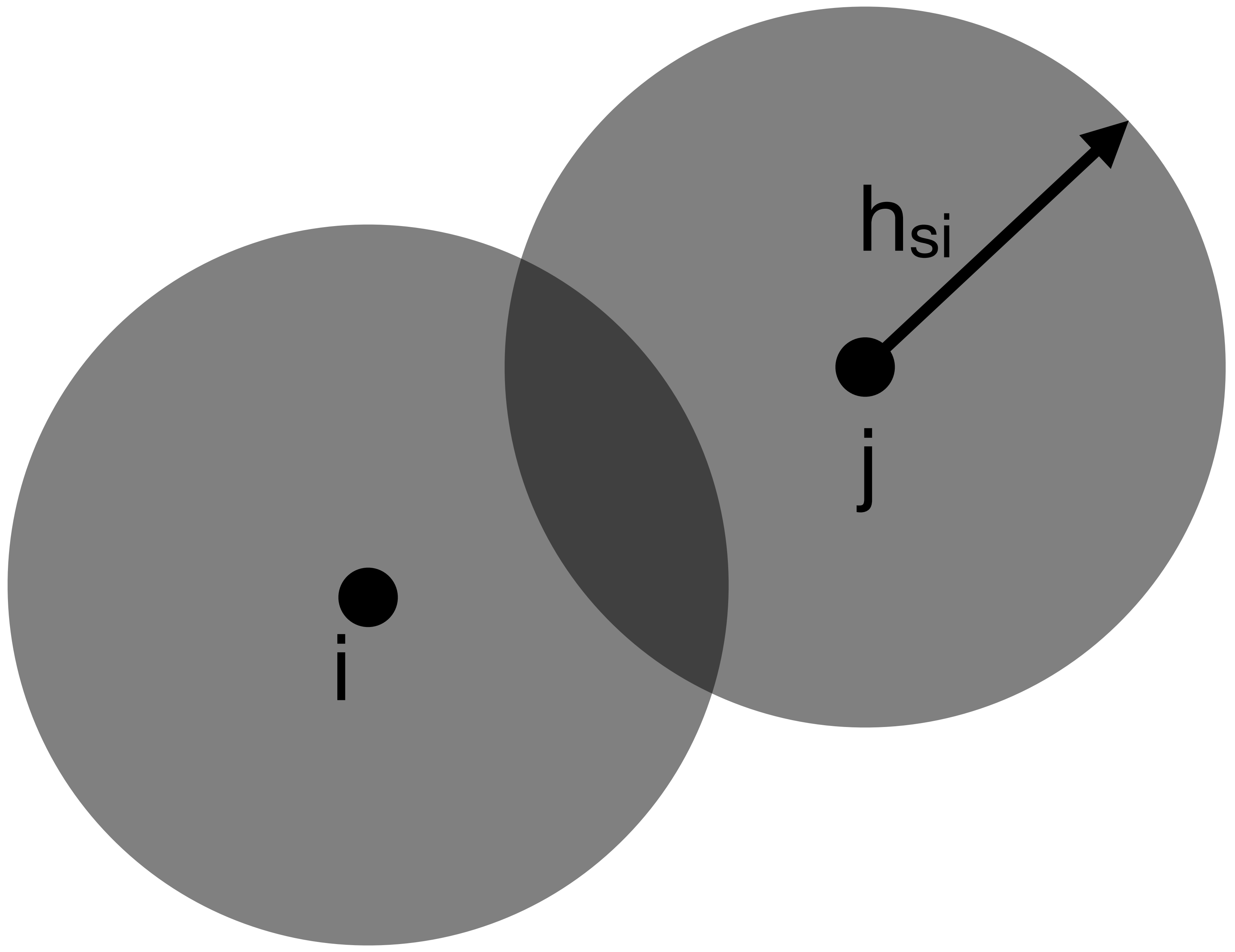
Self-Interacting Dark Matter + Galaxy Formation

- All the particles we know of interact with *something*
- Self-interactions allow greater *gravitational* response of DM to baryons
  - In disk galaxies (like MW) DM and baryons have very different symmetry
- New length scale in problem: size of “collision region”
  - Can be larger or smaller than disk scale
- Naively, a growing galaxy in SIDM should:
  - Have larger central density of DM than CDM
  - Flatten the halo perpendicular to the disk axis

How we simulate SIDM

Follows Rocha+2013

h_{si} set **globally** by choosing $1/h_{si}^3$ st $\Gamma >> H$
Look at particles whose h_{si} regions overlap
choose δt so that $P\ \delta t << 1$



- Compute Γ_{ij} and P_{ij} using "**coarse-grained**" collisional Boltzmann treatment
- Symmetrize over pairs of macroparticles
- If $P_{ij} > 0$:
    - Determine whether collision occurs via "rejection sampling" (compare a random number to P)
    - Collisions are hard-sphere elastic scattering
    - Determine velocity kicks to re-distribute particles in phase space by MC sampling **isotropic** distribution

comparing cosmological hydro simulations

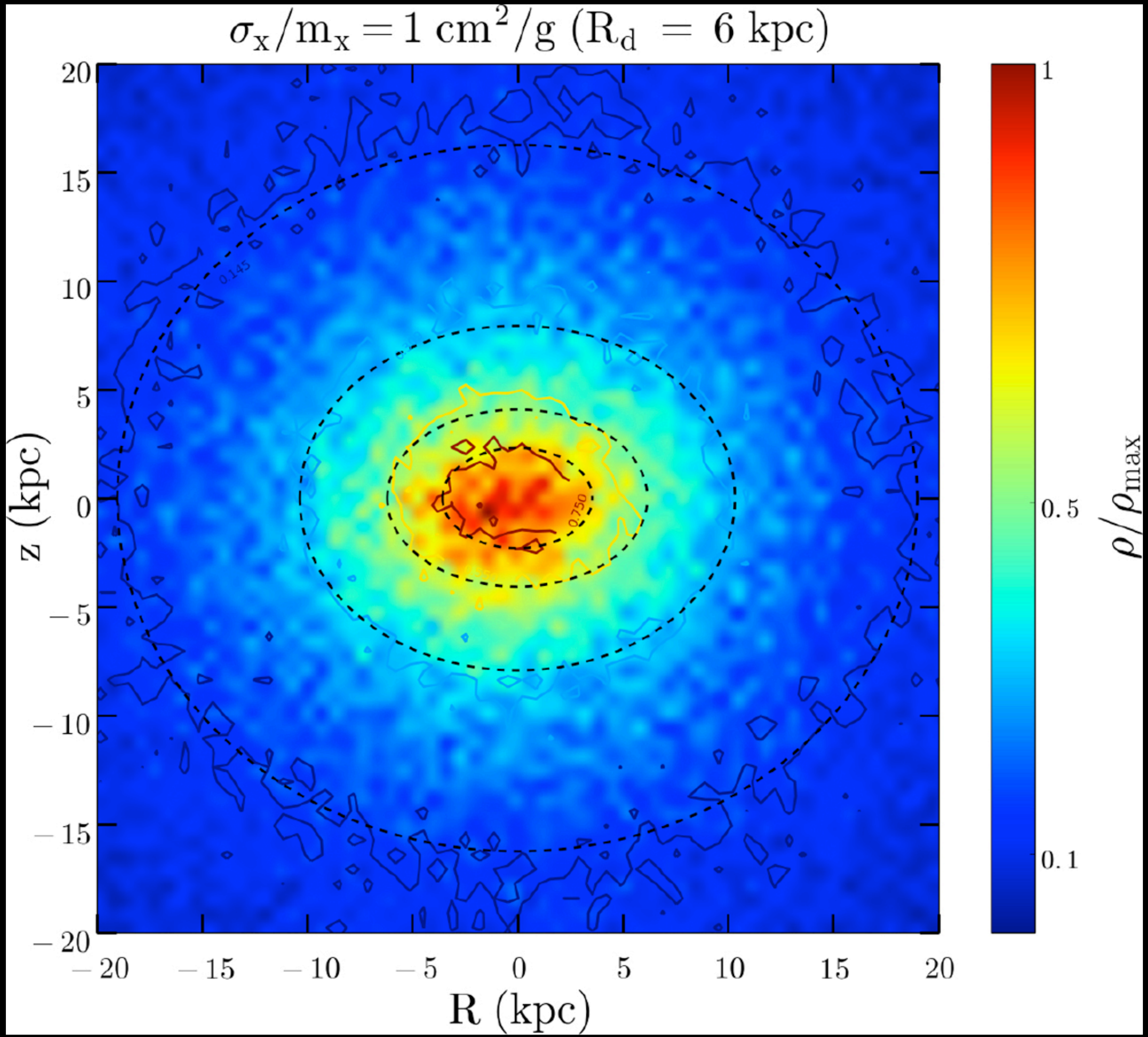
What is held constant

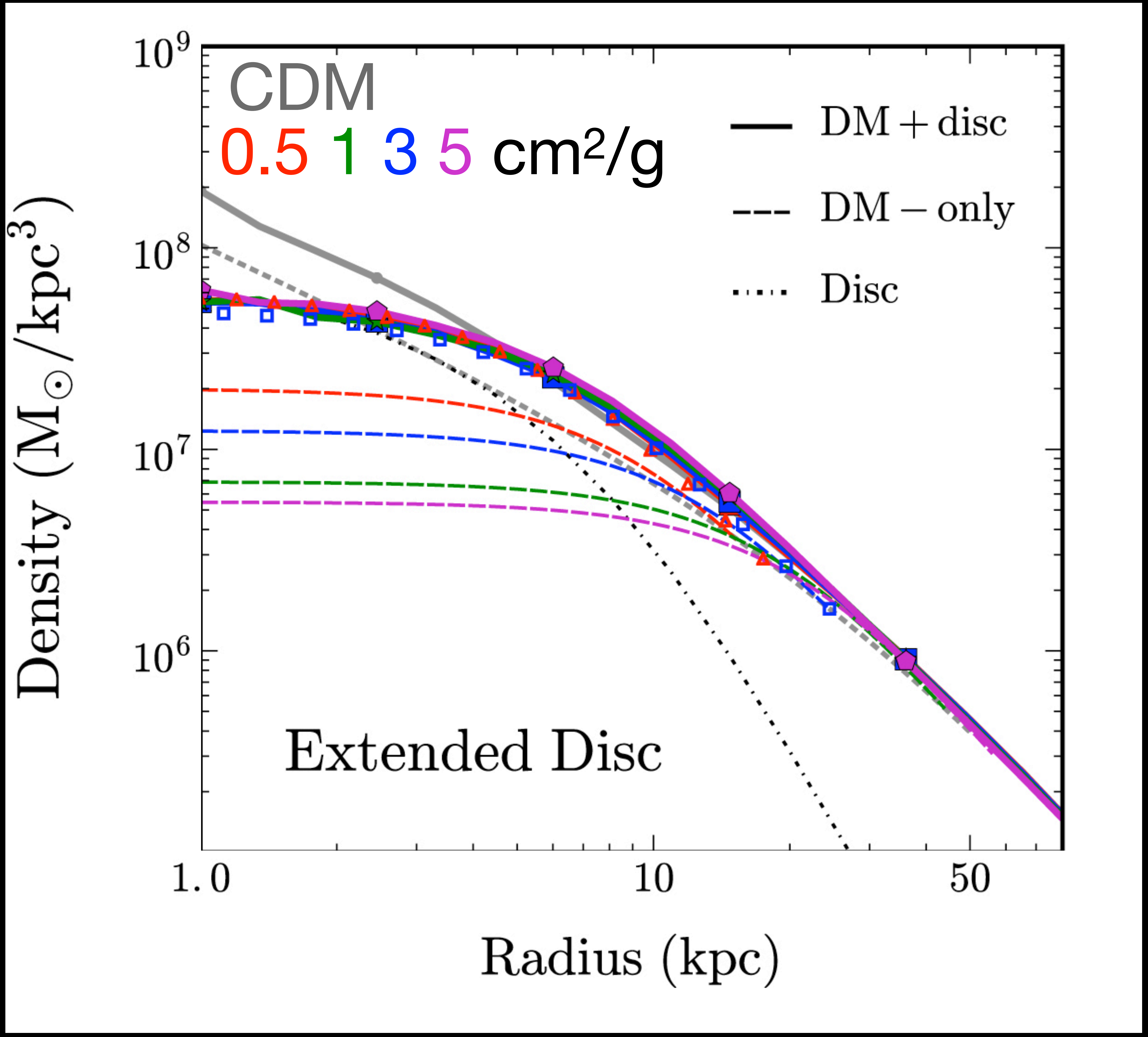
- Initial conditions
- Cosmology
- Hydrodynamics
- Gravity
- Numerics (softening, timesteps, etc)
- Feedback prescriptions & treatment
- Physics of gas cooling/heating

What varies between runs

- **Dark matter**
- *Timing* of supernovae =>
  - Star formation histories
  - Stellar mass (varies less for larger systems)

MW-mass Halos: Intuition from DM-only models
SIDM should produce MW-mass galaxies with different density profiles than CDM

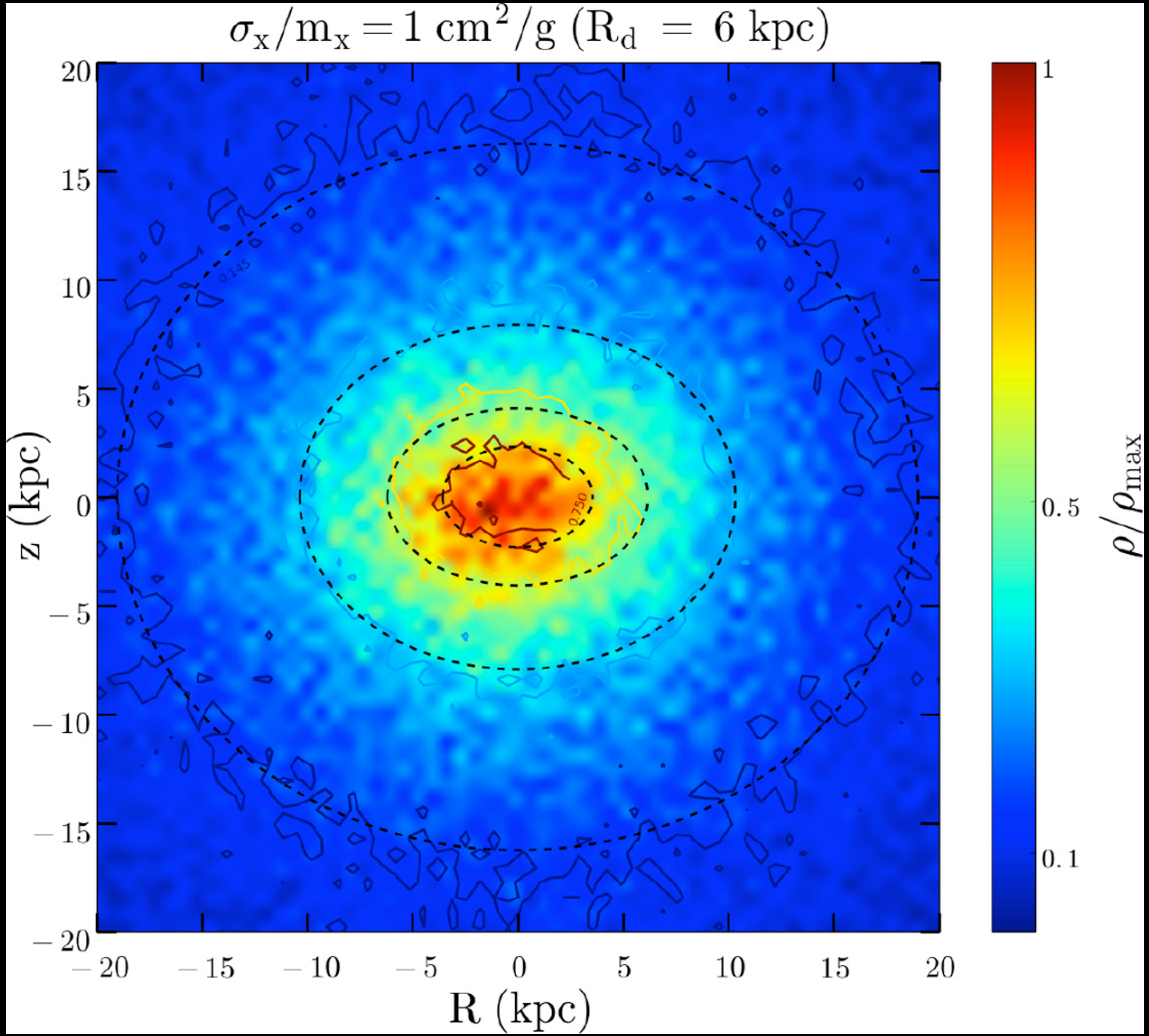


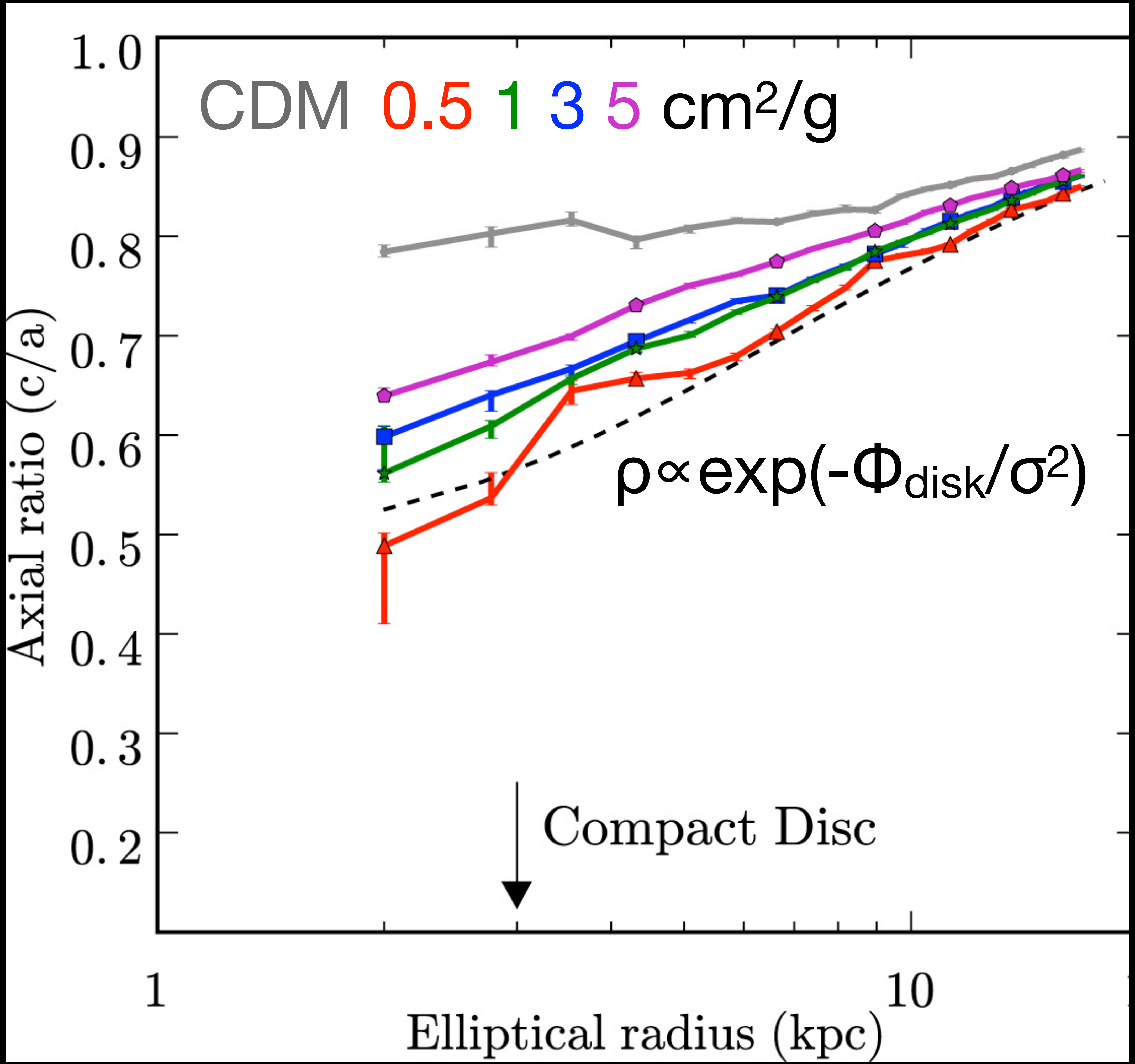


Isolated DM-only simulation with analytic disk

Sameie+2018

MW-mass Halos: Intuition from DM-only models
SIDM should produce MW-mass galaxies with different shapes than CDM

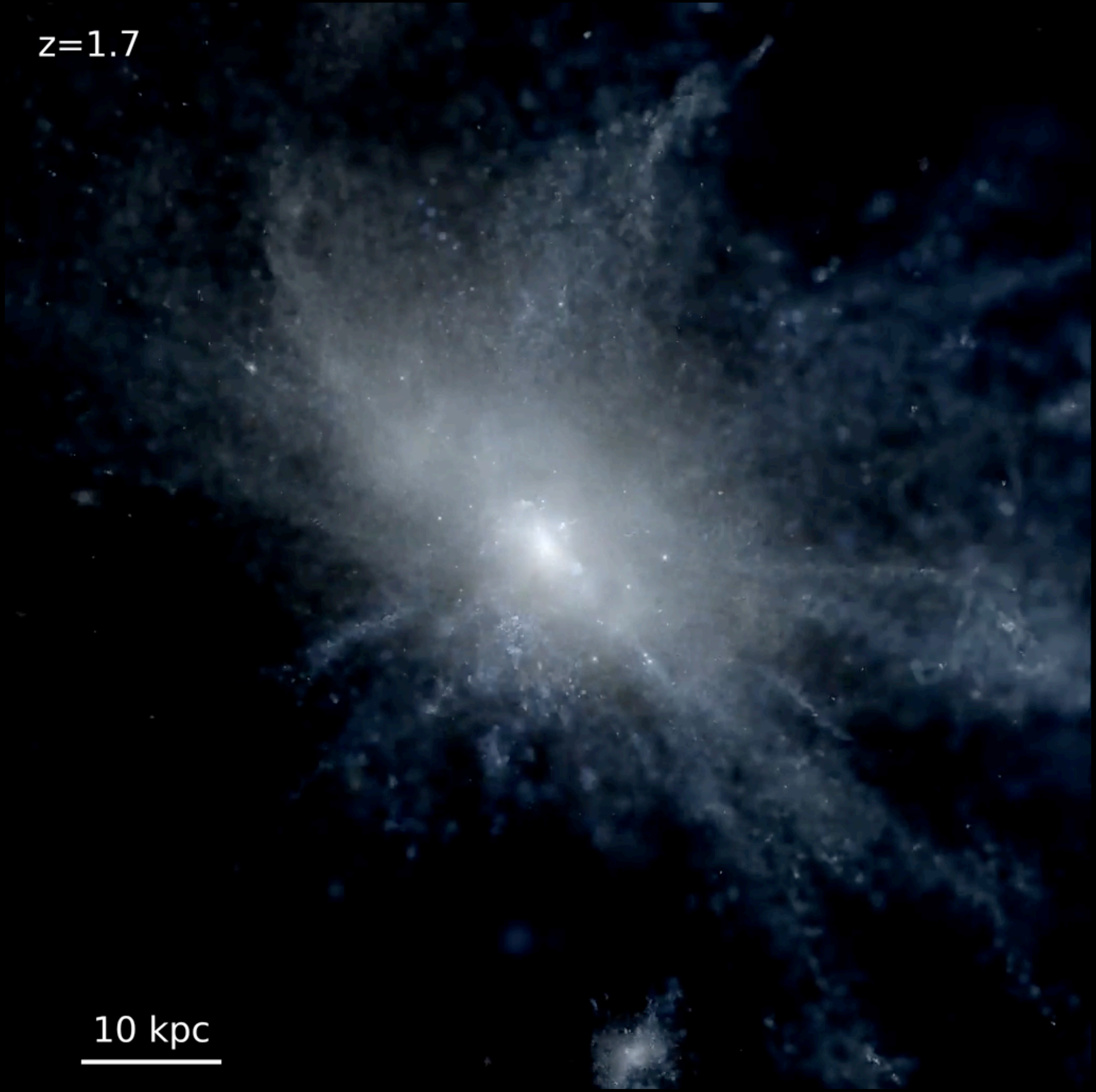




Isolated DM-only simulation with analytic disk

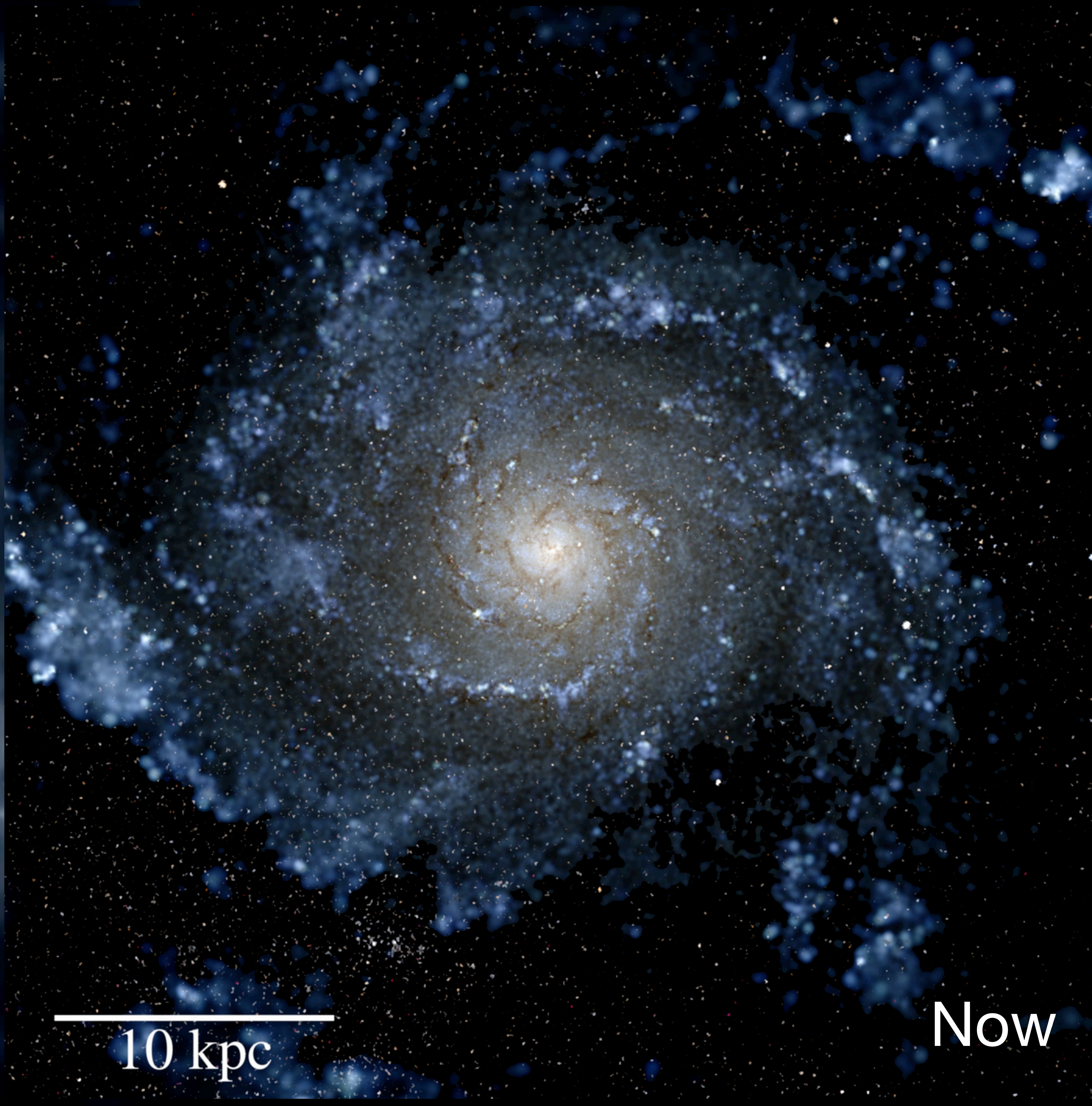
Sameie+2018

But…

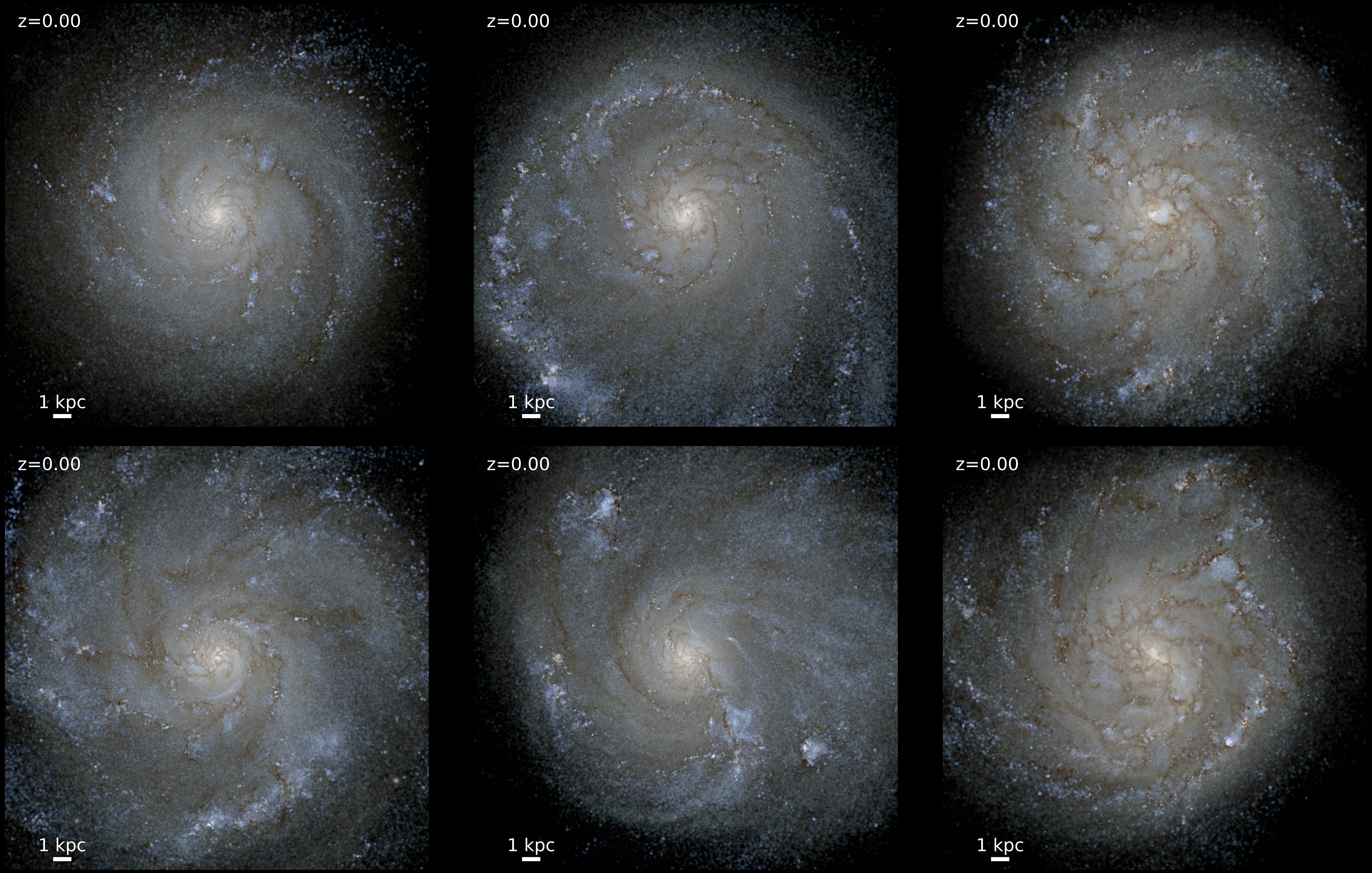


But…

Disks usually begin assembling ~8 Gyr ago & are rotationally supported by ~4 Gyr ago (McCluskey+2023)



SIDM produces MW-mass galaxies



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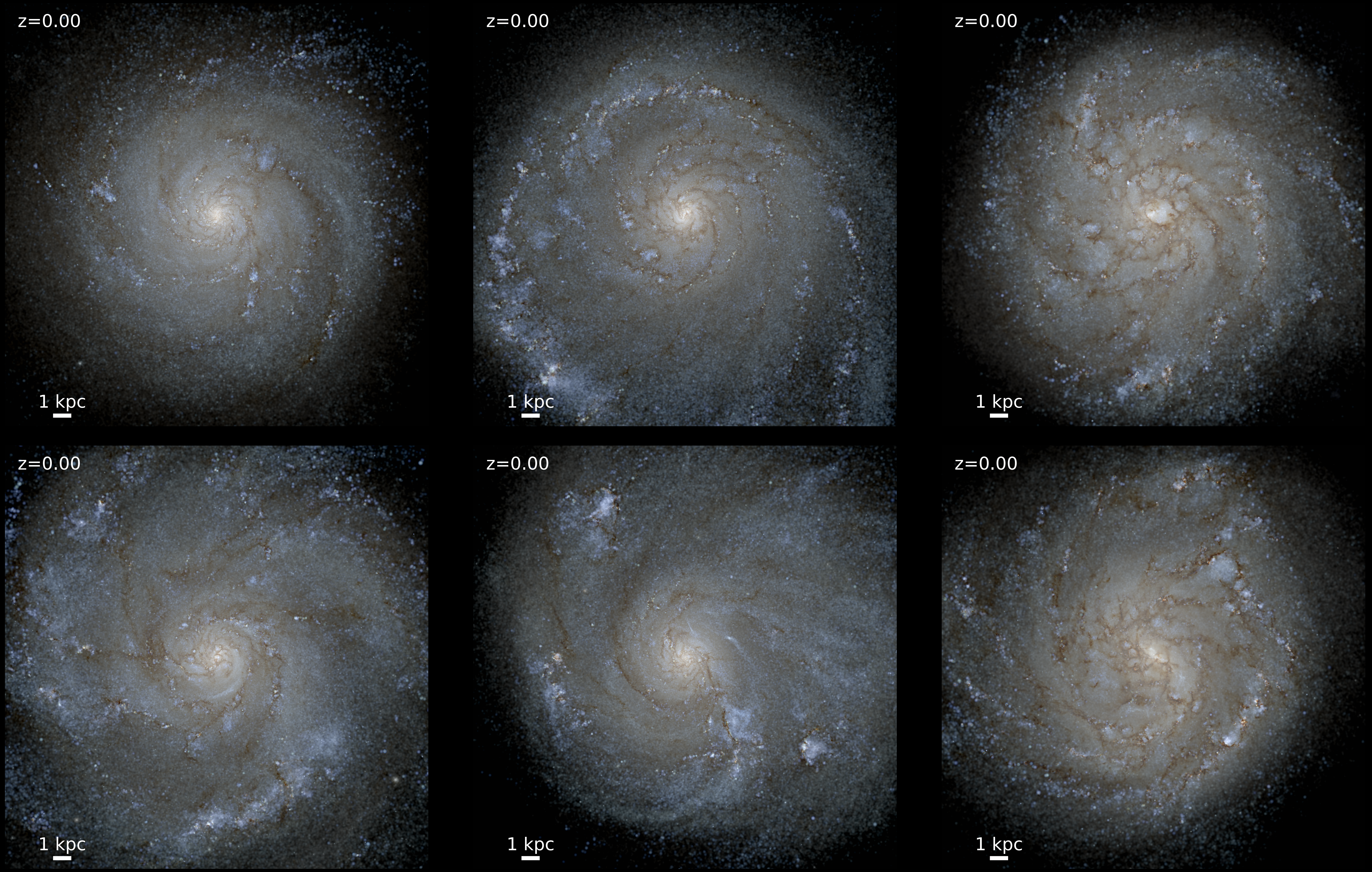
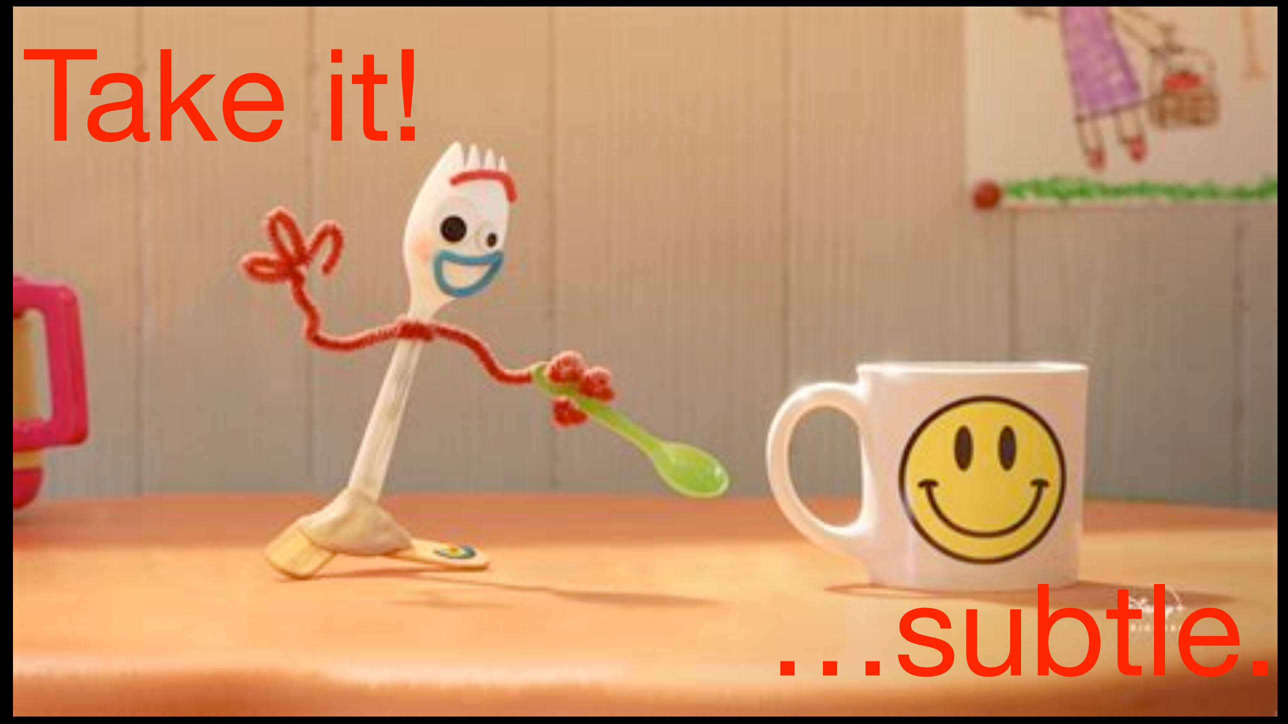


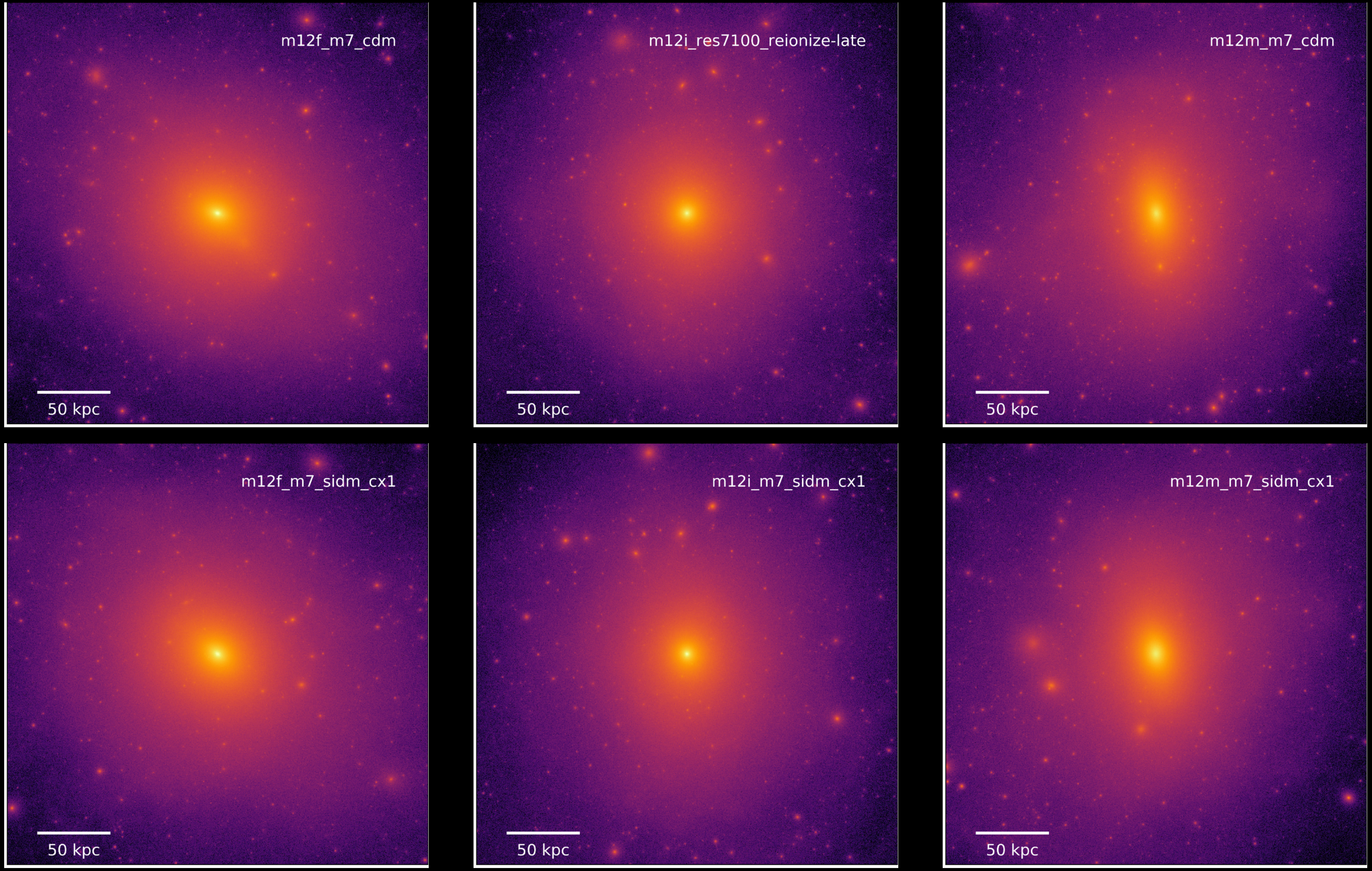
CDM

SIDM

Sameie+2021, Vargya+2022

SIDM effects are pretty subtle



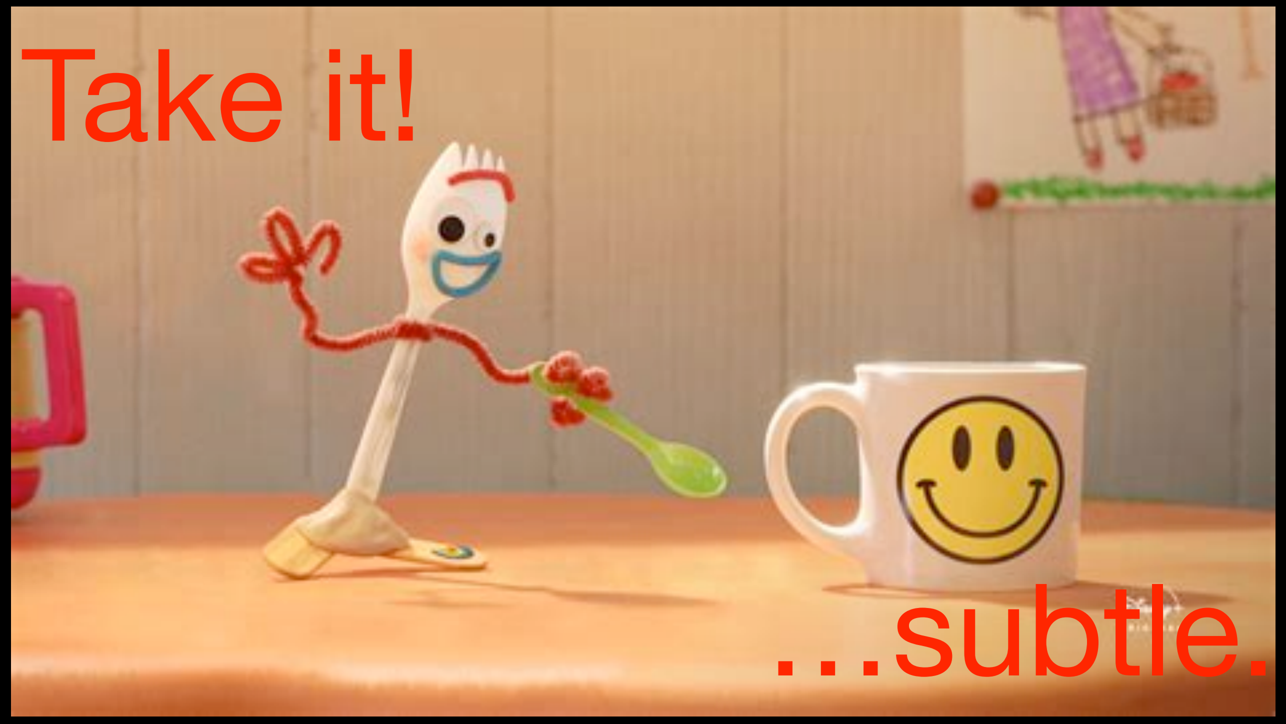


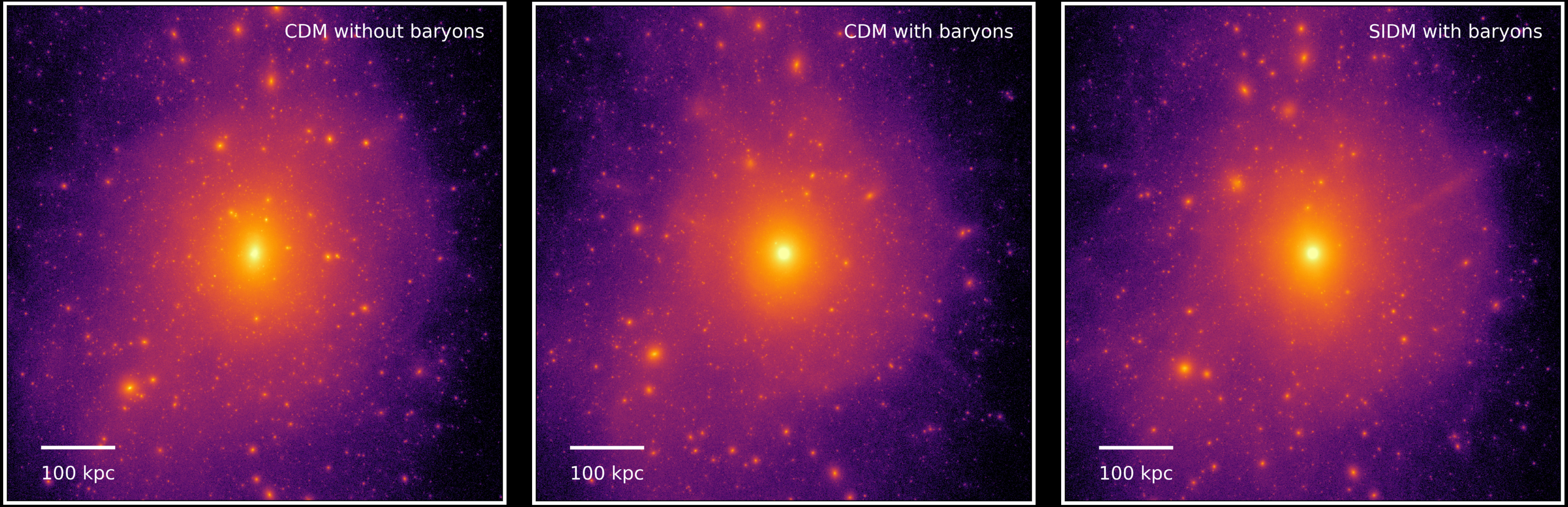
CDM

SIDM

Sameie+2021, Vargya+2022

SIDM effects are pretty subtle…
Especially relative to baryons



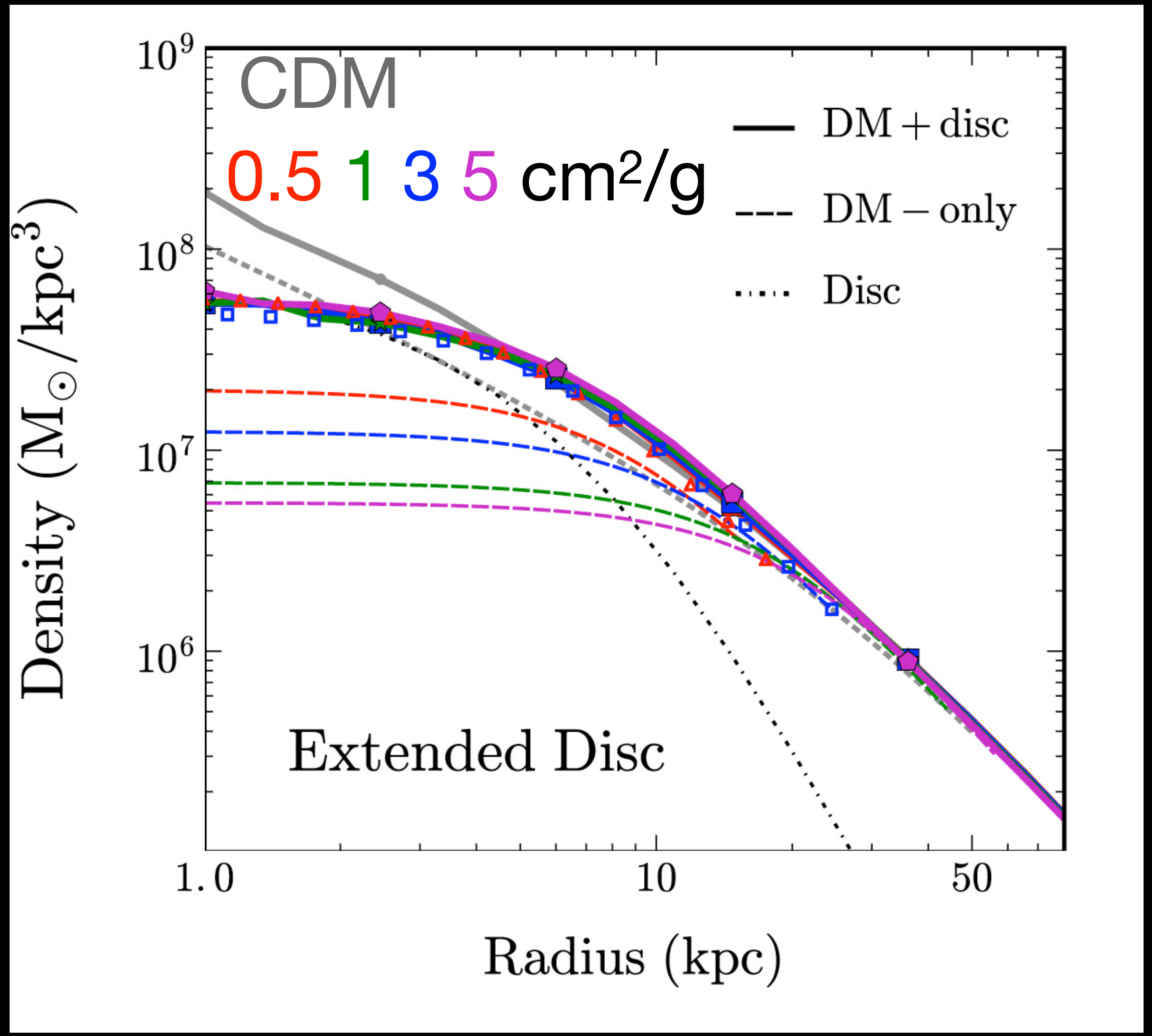


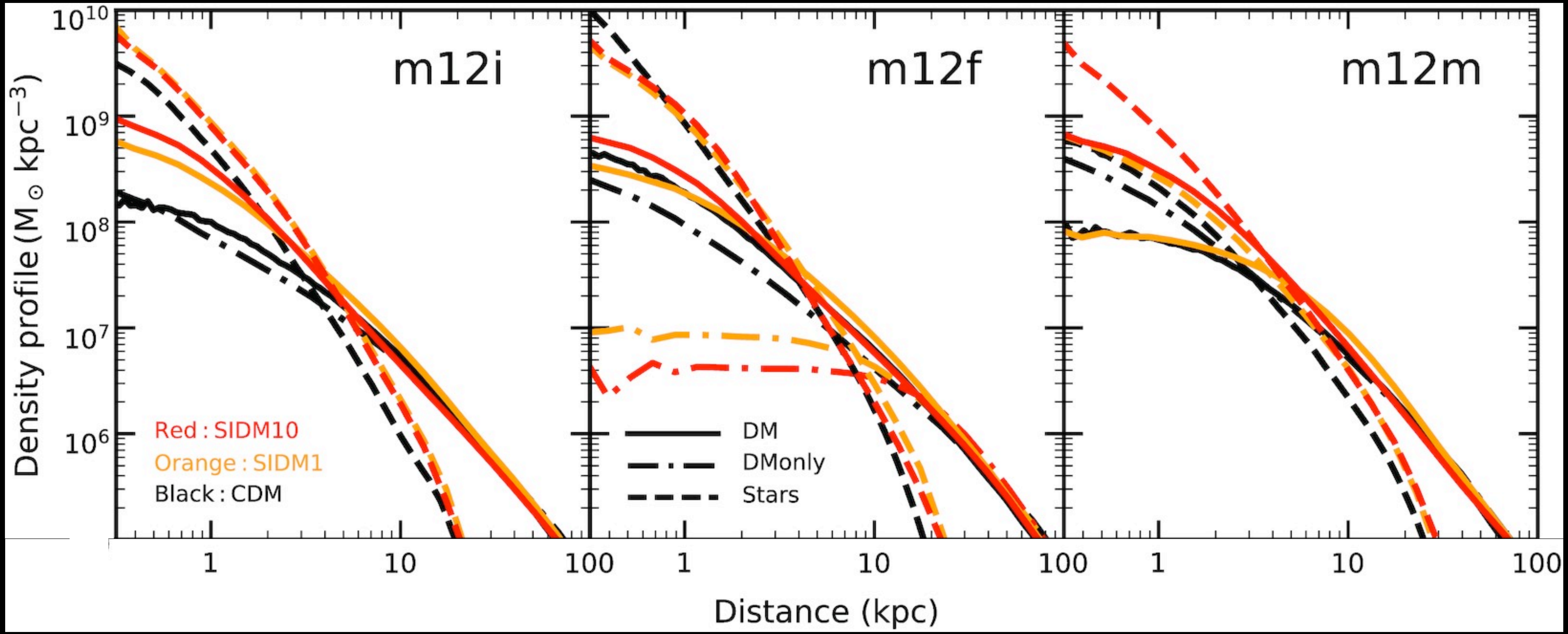
Sameie+2021, Vargya+2022

SIDM produces MW-mass galaxies with different density profiles/shapes than CDM

Sameie+2021 (See also Rose, Vogelsberger, & O'Neil 2023)

Cross-talk between baryons and DM creates "diversity" *beyond* predictions from semi-analytic approaches





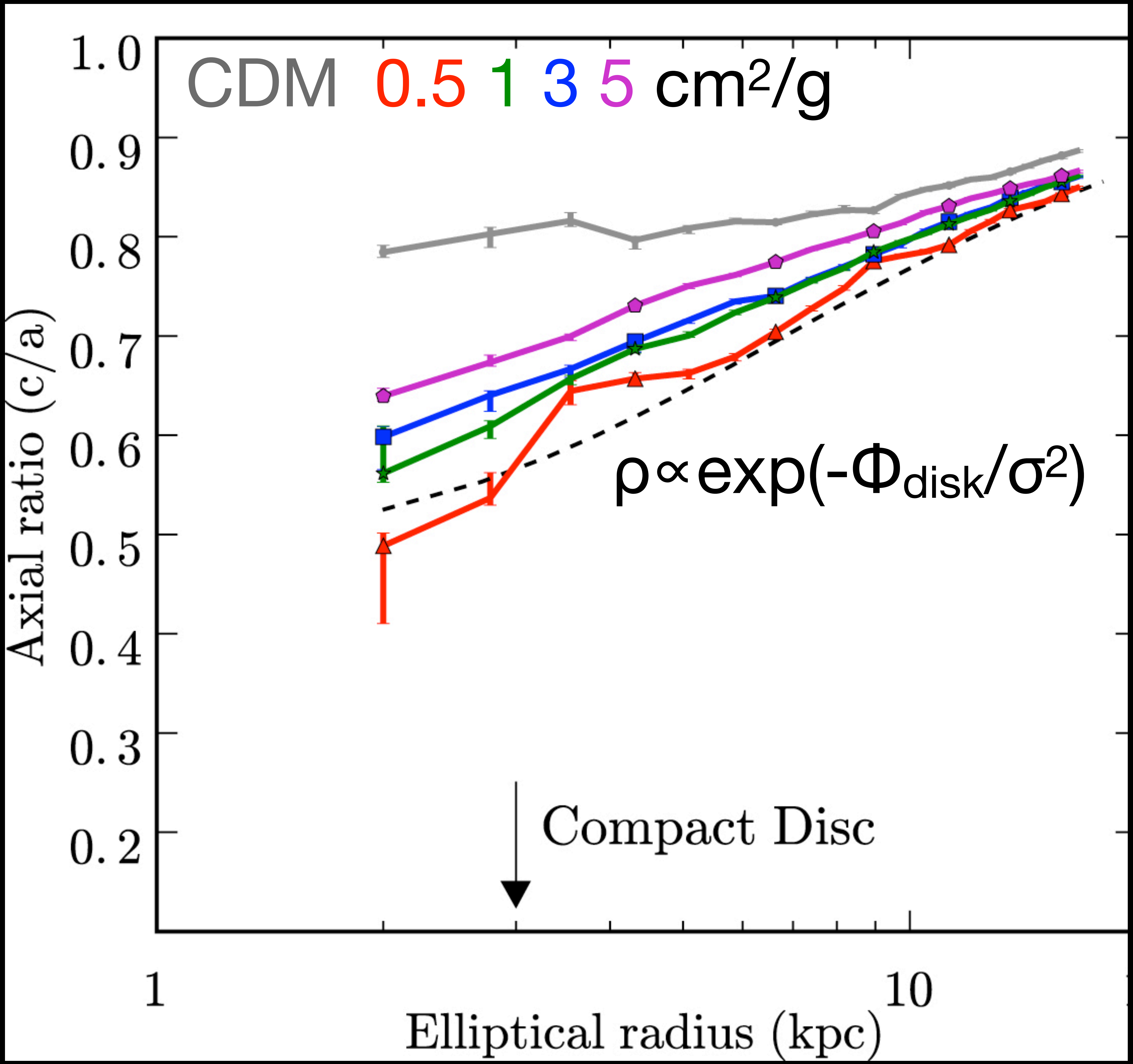
Sameie+2018

Sameie+2021

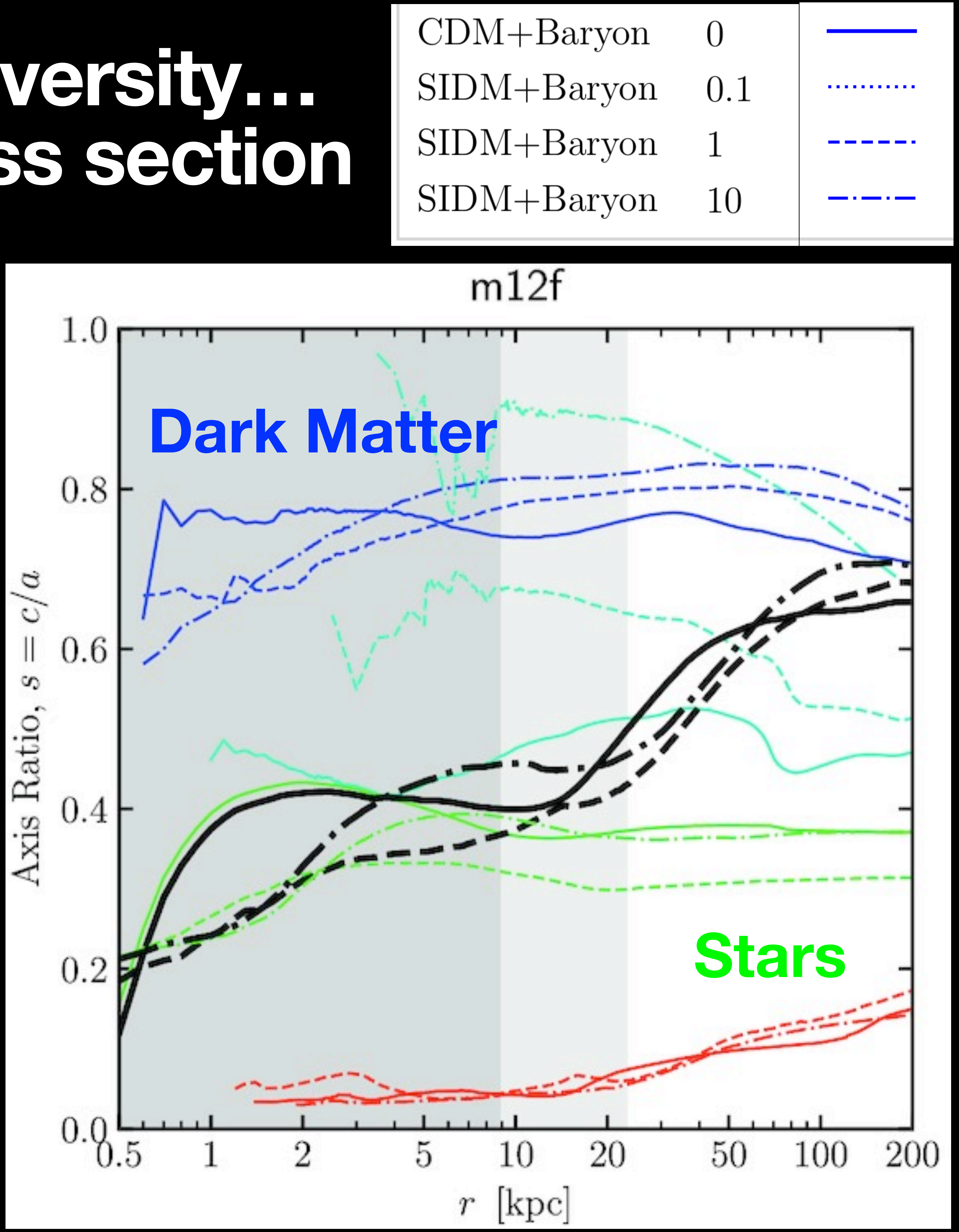
SIDM produces MW-mass galaxies with different density profiles/shapes than CDM

Vargya+2021

Again, gravitational crosstalk creates diversity… variations can occlude scaling with cross section

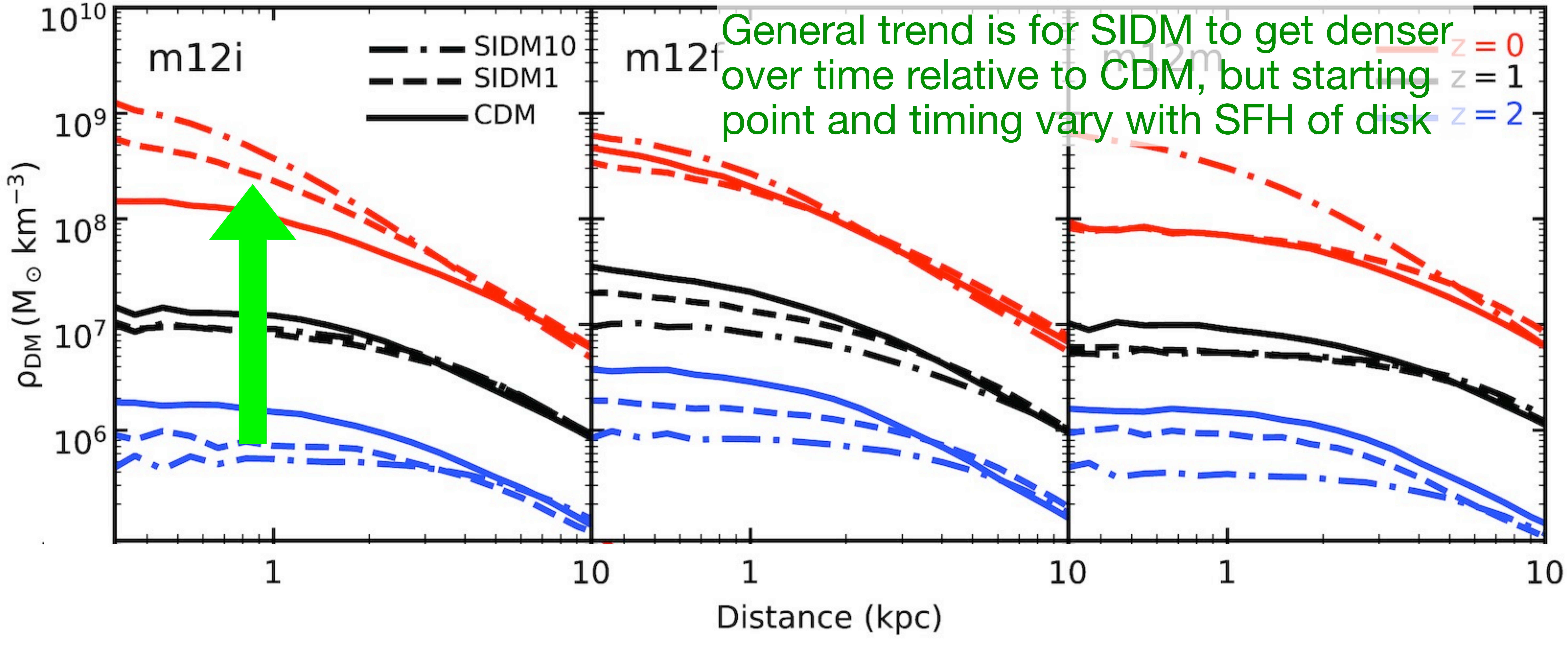


Sameie+2018



Vargya, RES+2022

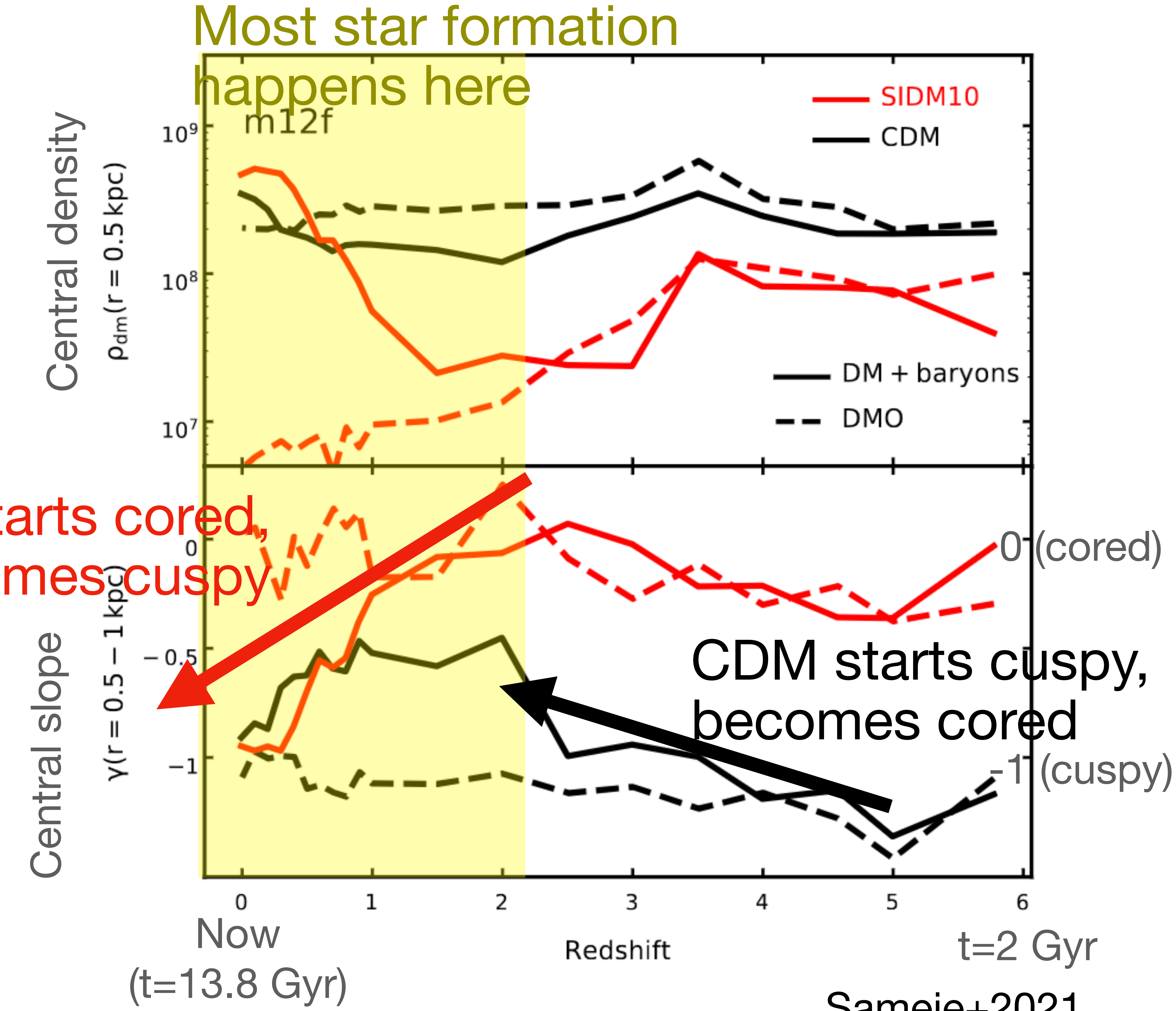
Diversity is the result of long-term co-evolution of the halo and its galaxy



Sameie+2021

Diversity is the result of long-term co-evolution of the halo and its galaxy

- "the **concentration** of the stellar distribution is more important than the total disc mass in creating diverse SIDM density profiles." - Sameie+2020
- At late times (z>~2) galaxy formation, not DM, is the dominant determinant of the density profile in MW-mass halos
- SIDM amplifies this effect (it's more responsive to the stars than CDM) to solve the diversity problem



Sameie+2021

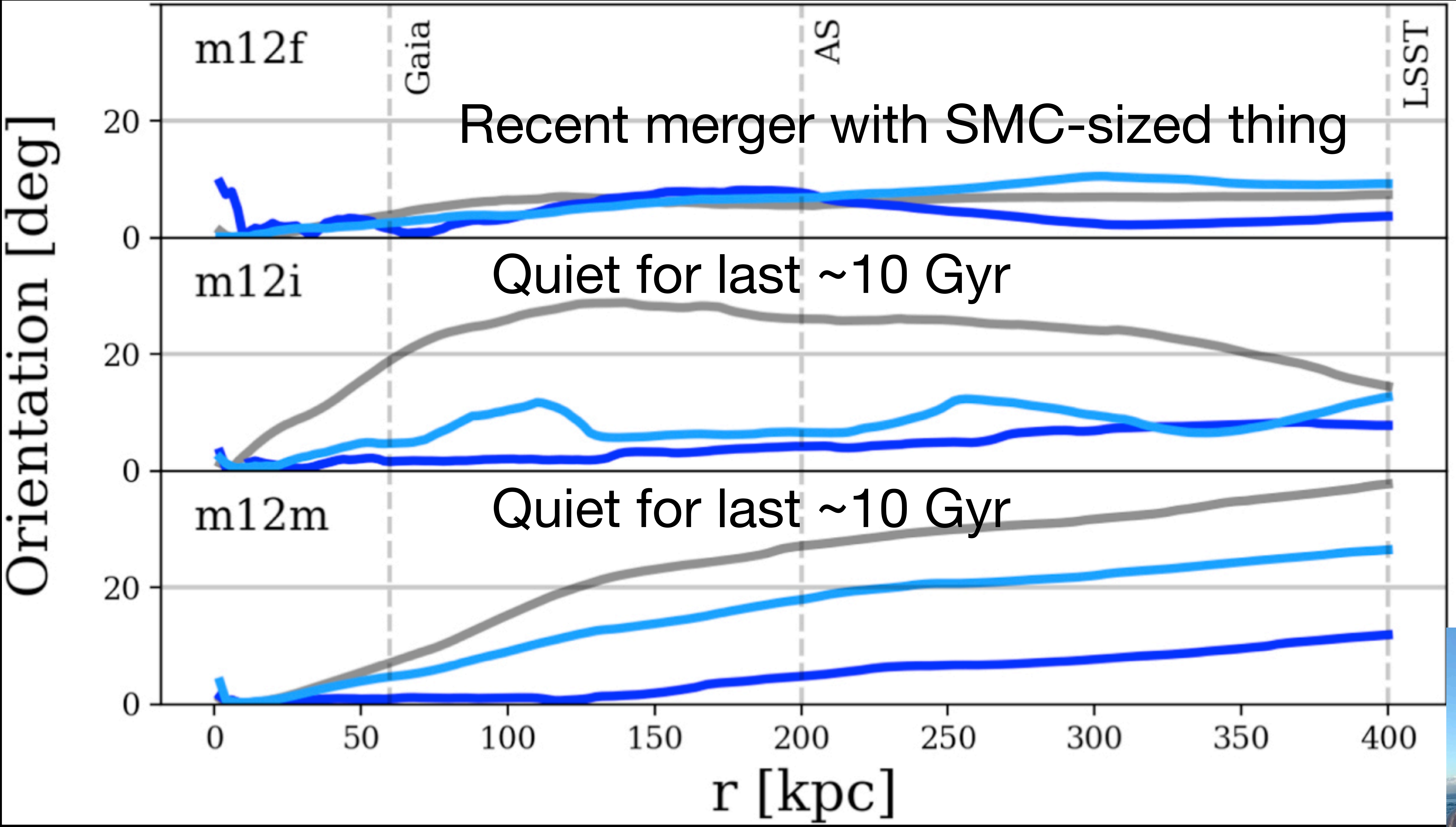
Individual galaxies *cannot* tell us if they have CDM or SIDM just by accurately mapping the baryons

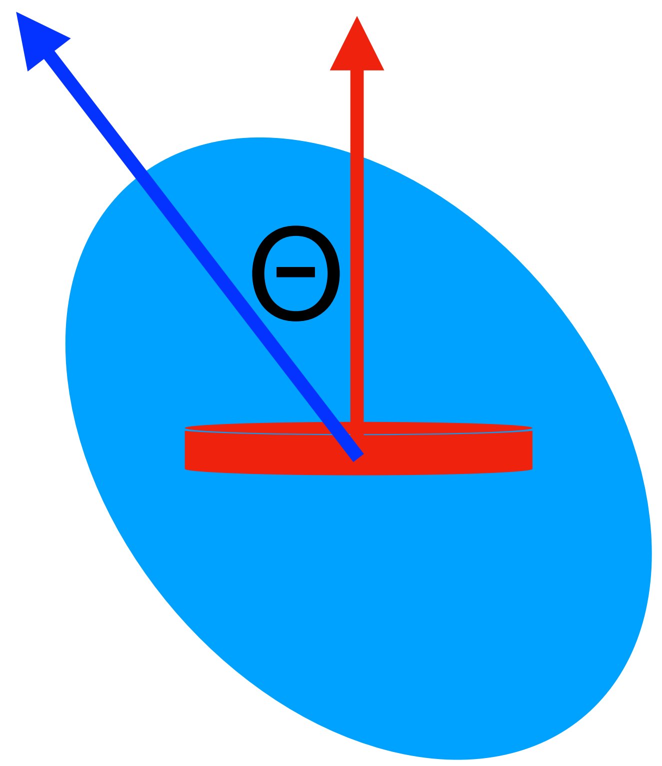
Arora, RES, Chakrabarti +2024

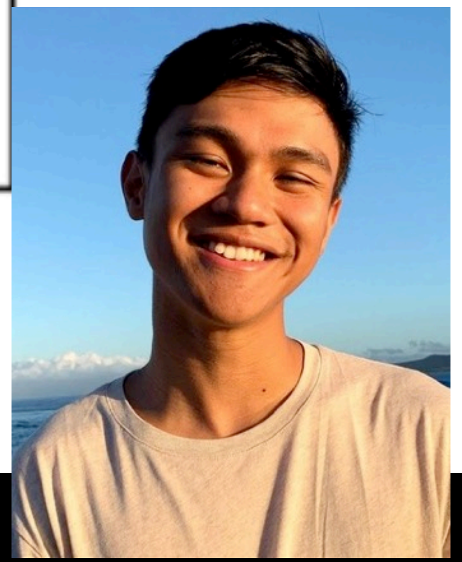
So…what do we do?

Dynamical tests can tell us more

SIDM halos seem to be better aligned with their galactic disks (modulo merger history)

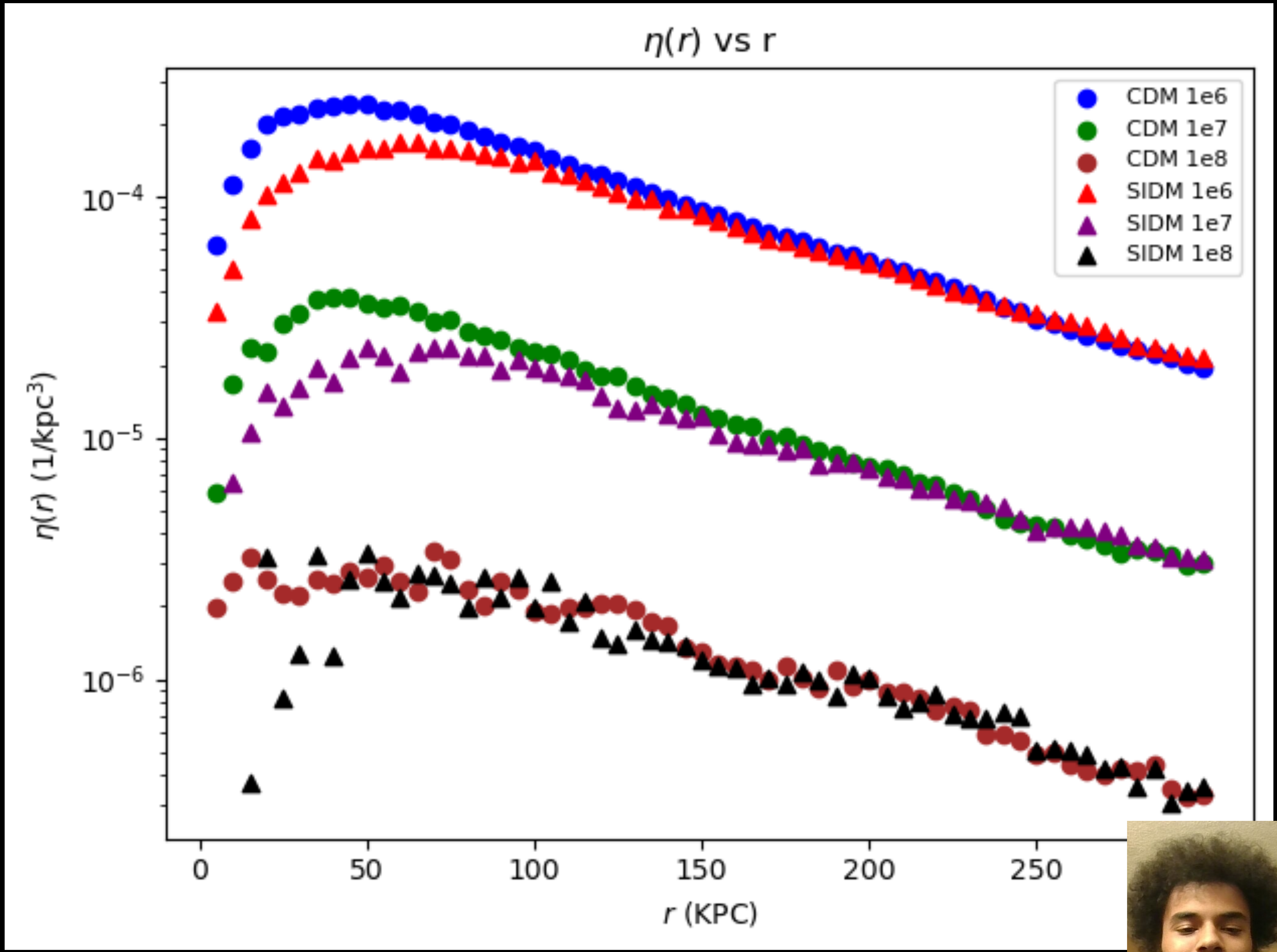






Baptista, RES et al 2023

SIDM halos seem to be better at destroying their subhalos



Number density η of subhalos is depleted in SIDM relative to CDM

Why?

- It's not *primarily* SIDM effects in subhalos (σ = 1 cm^2/g, see Fitts+2018)
- It's not *entirely* missing subhalos in SIDM rel to CDM (avg of 3 sims, 2 with similar central ρ in both)
- Is i

Central galaxy is 2 more massive in SID

Ford, Singh, RES et al. in prep

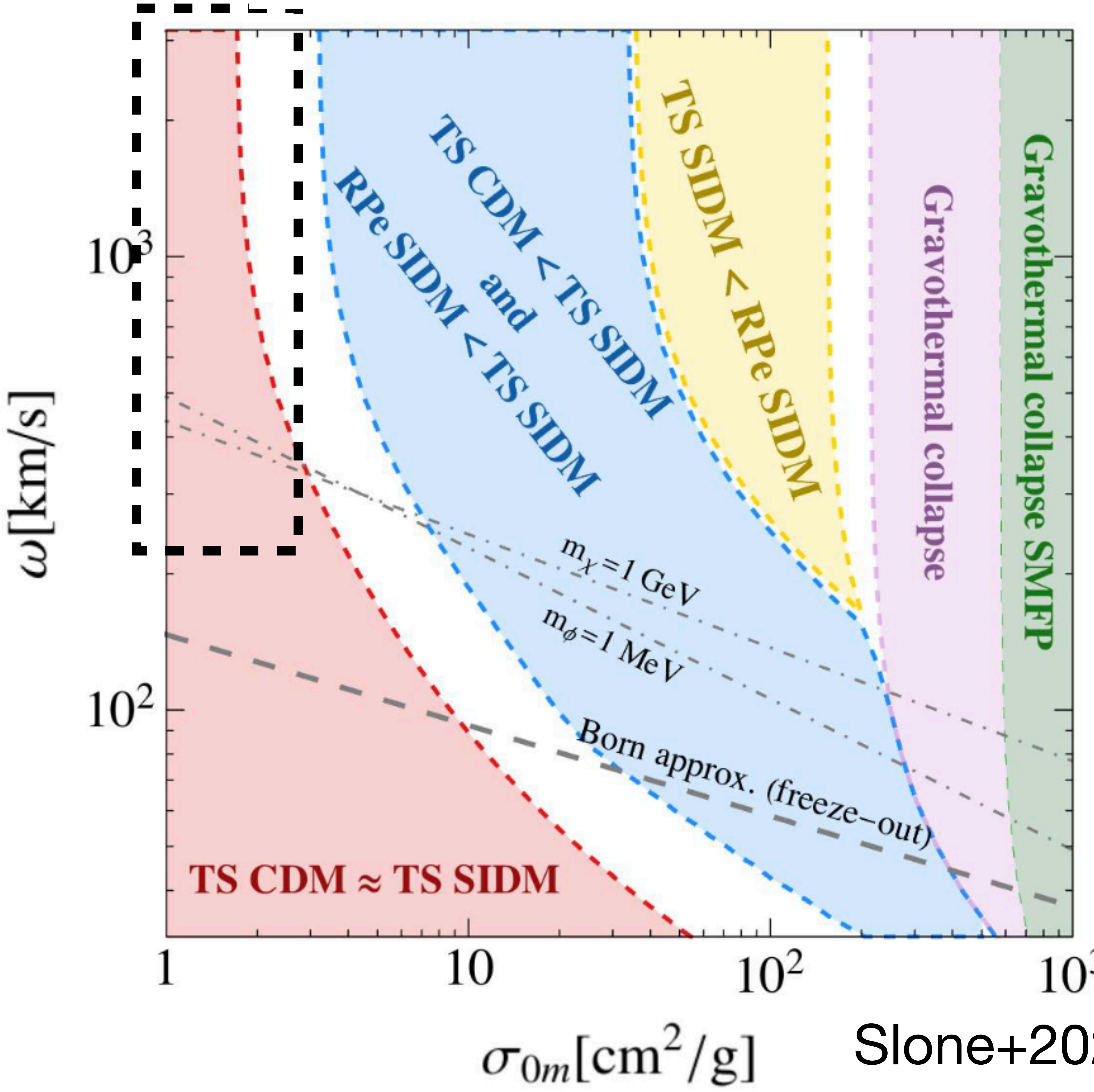
Tidal stripping: intuition from analytic models

- All else equal, we should expect similar tidal stripping in our CDM and SIDM simulations, based on Slone+2021

- However their tests used small satellites (max $m_i = 10^{10.5}$)…

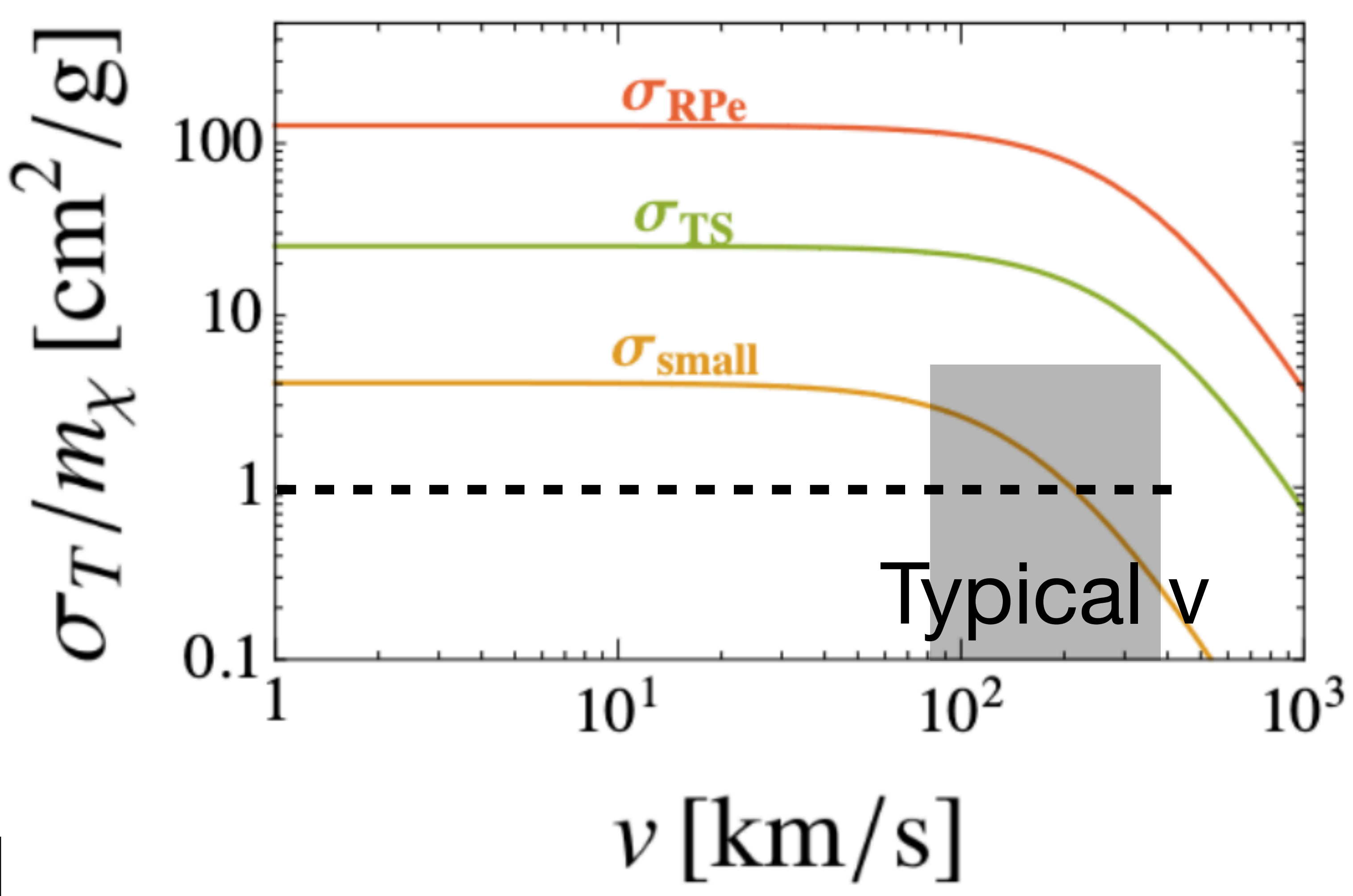
- …and no explicit baryonic physics

$$\frac{d\sigma}{d\theta} = \frac{\sigma_0 \sin\theta}{2\left[1 + \frac{v^2}{\omega^2}\sin^2\frac{\theta}{2}\right]^2}$$

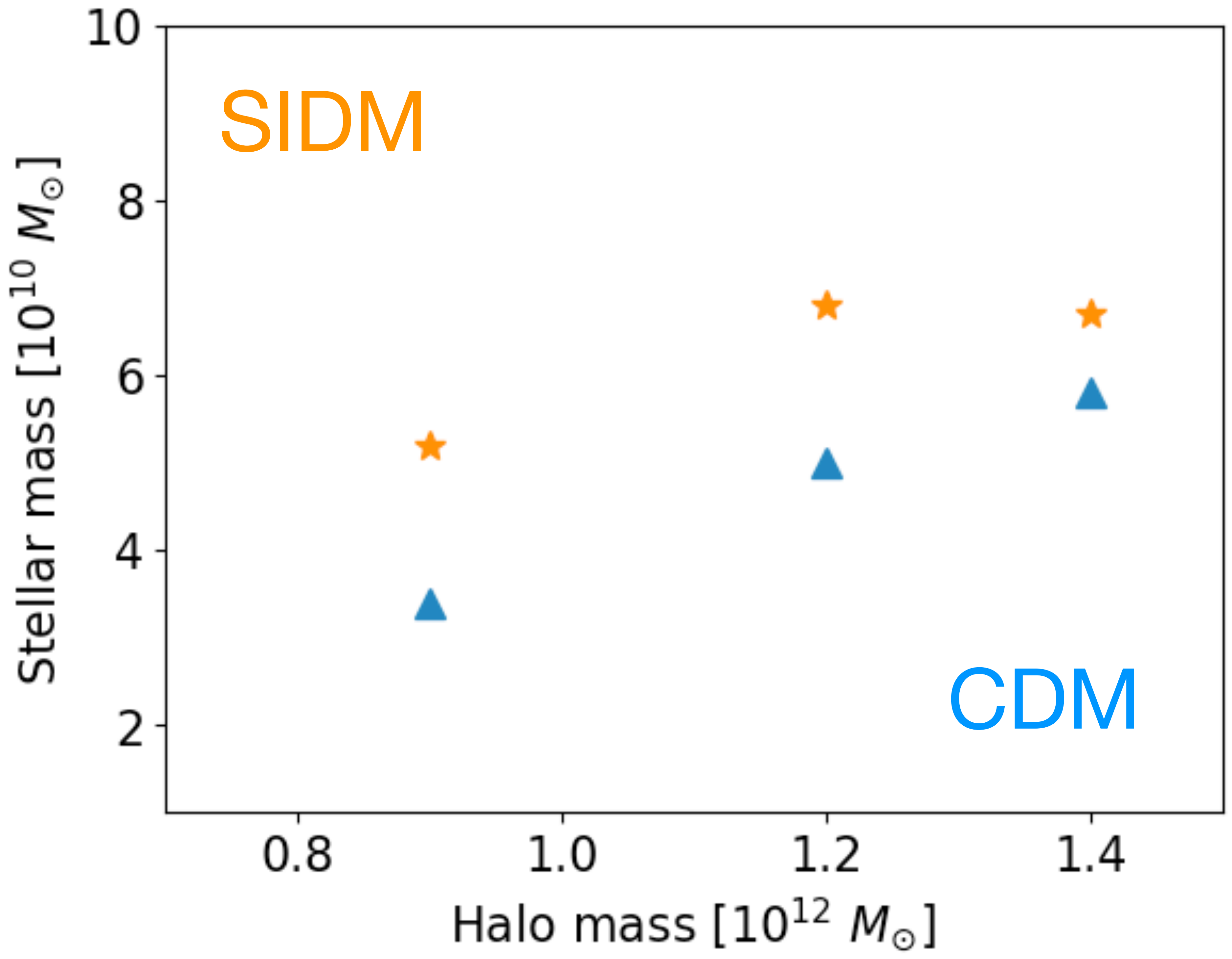


Slone+2021

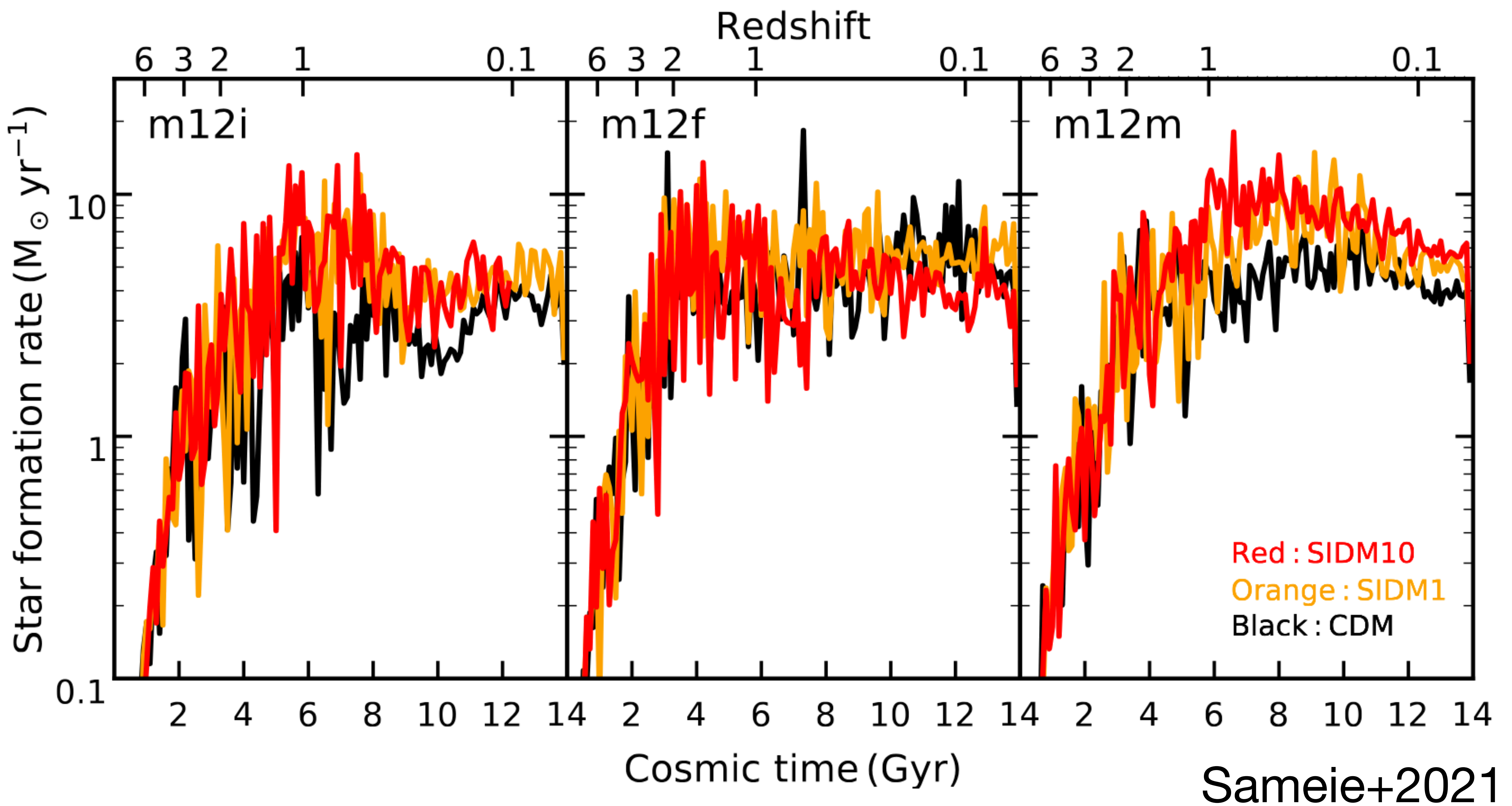
Our model is ~ σ_{small}



SIDM halos systematically have higher stellar mass than their CDM counterparts

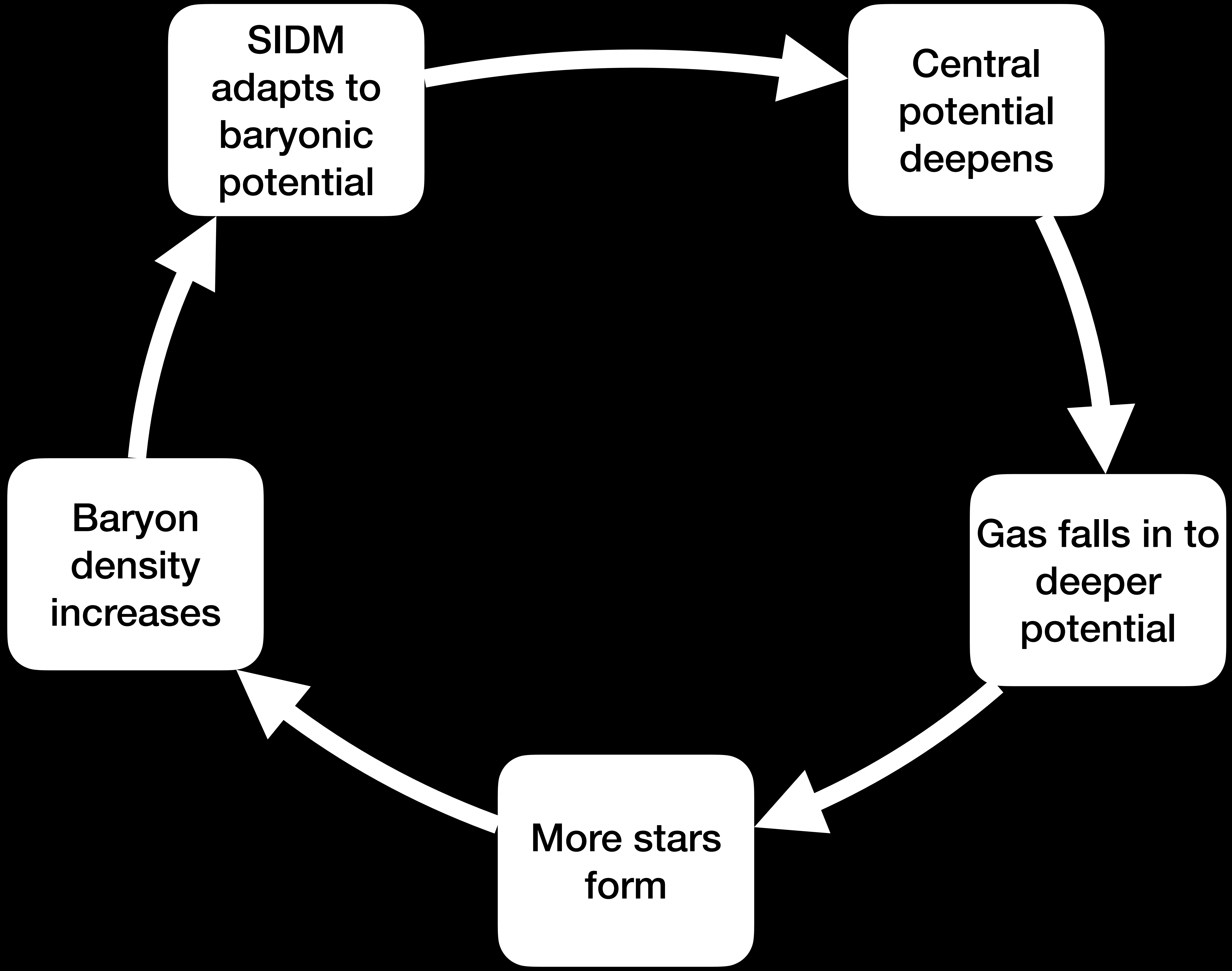


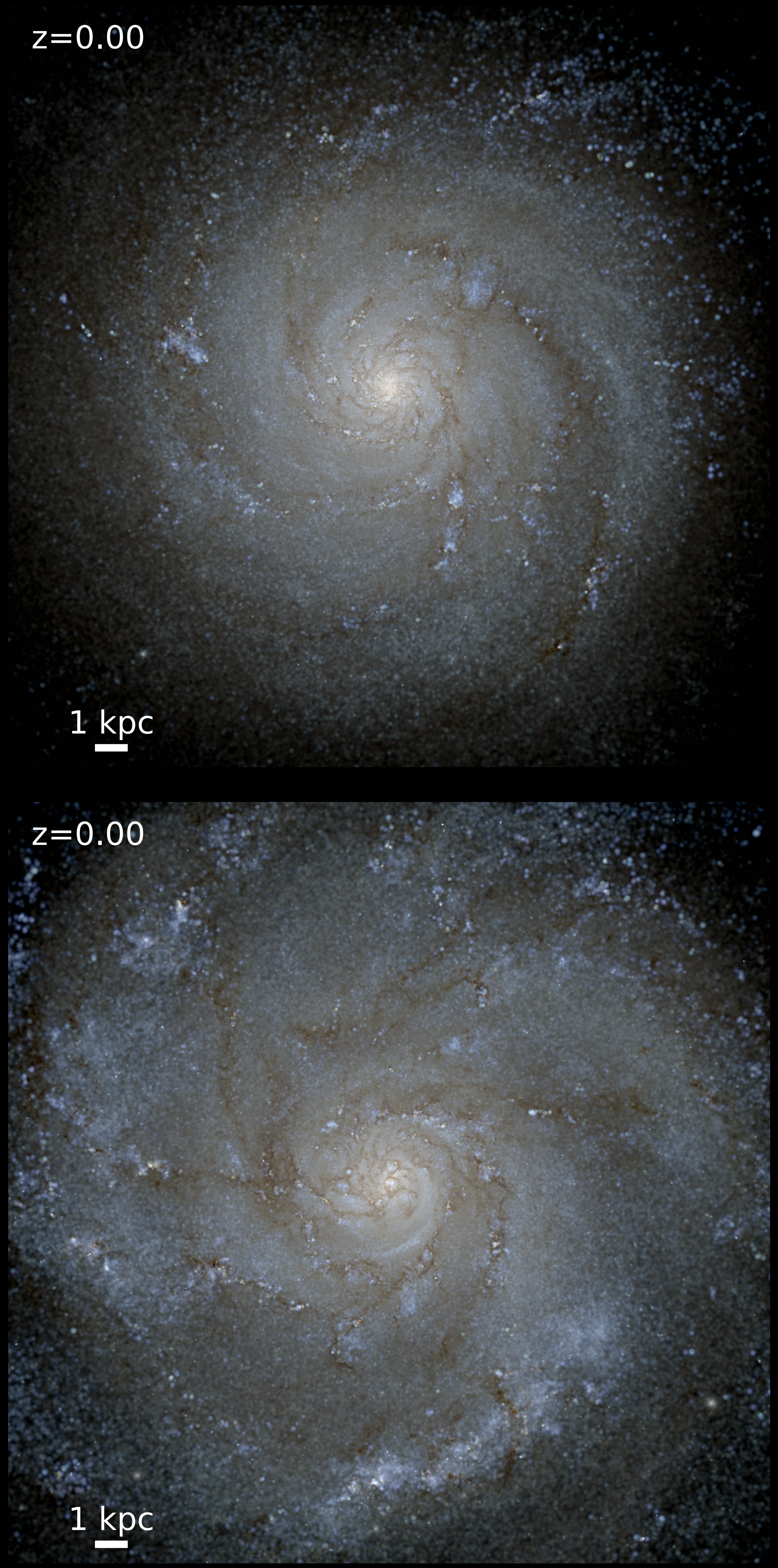
This is because they sustain higher star formation rates for longer



Sameie+2021

SIDM can amplify small changes in galaxy growth





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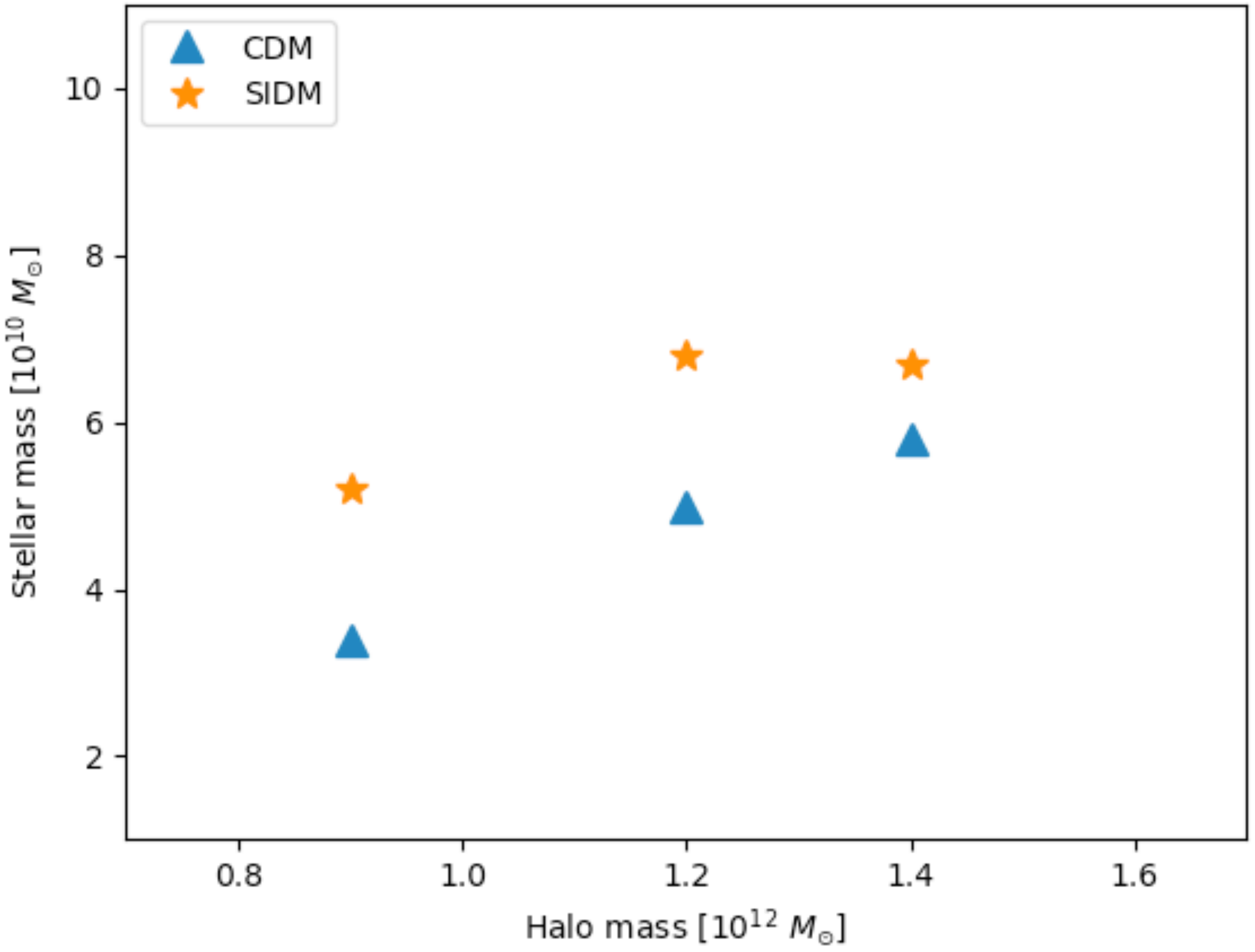
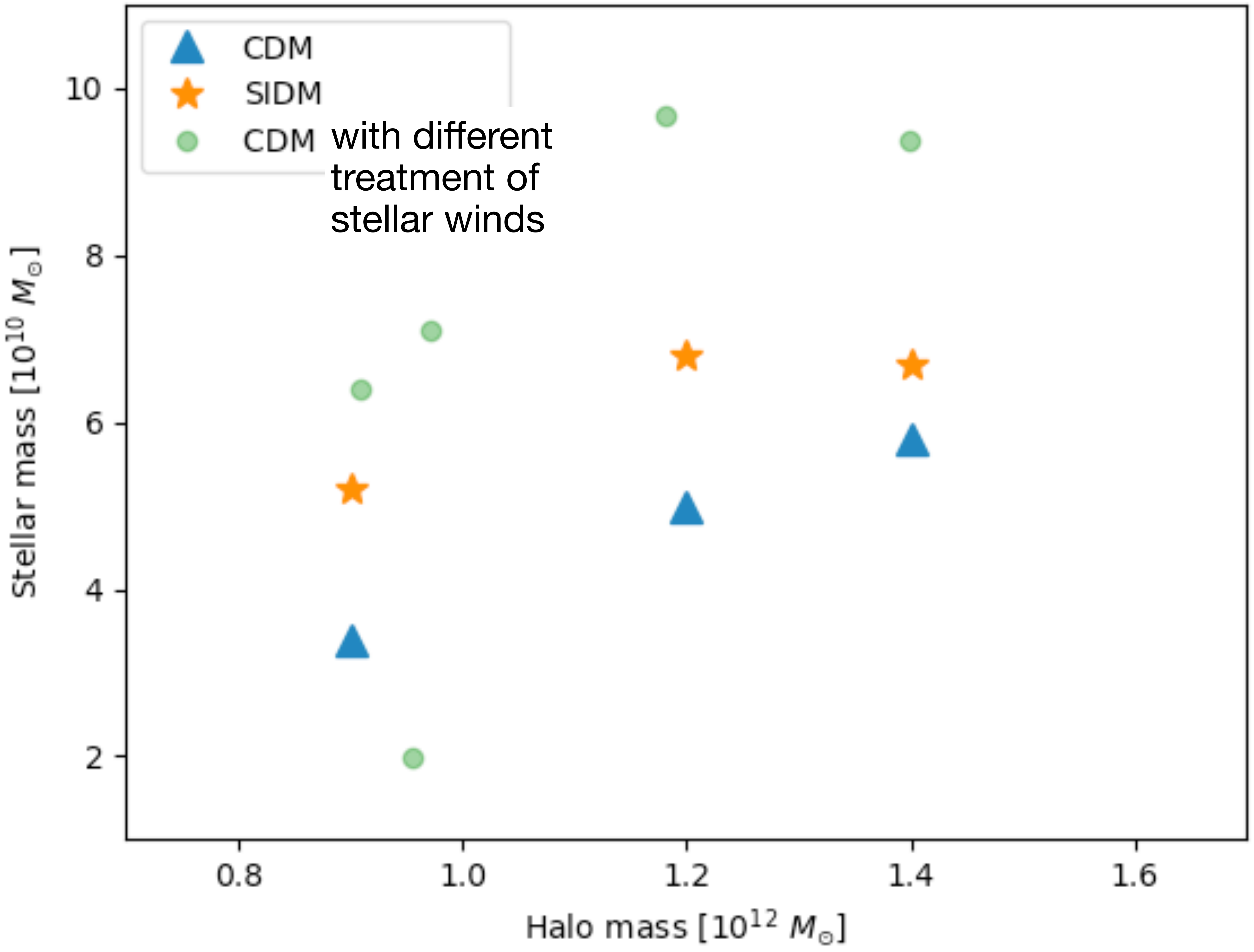


SIDM halos systematically have higher stellar mass than their CDM counterparts

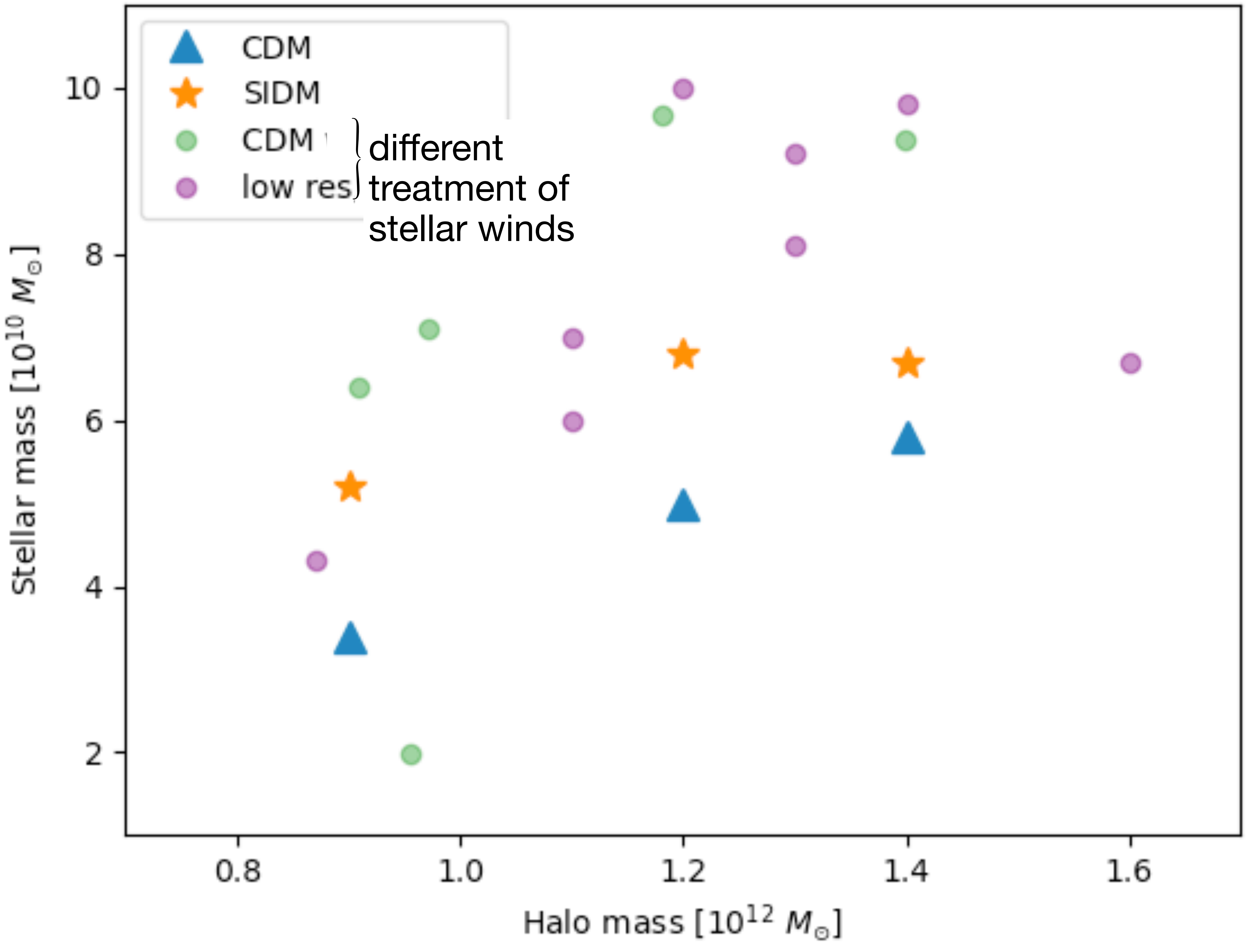
…by an amount similar to changing the baryonic physics



SIDM halos systematically have higher stellar mass than their CDM counterparts

…by an amount similar to changing the baryonic physics

…but more than resolution effects

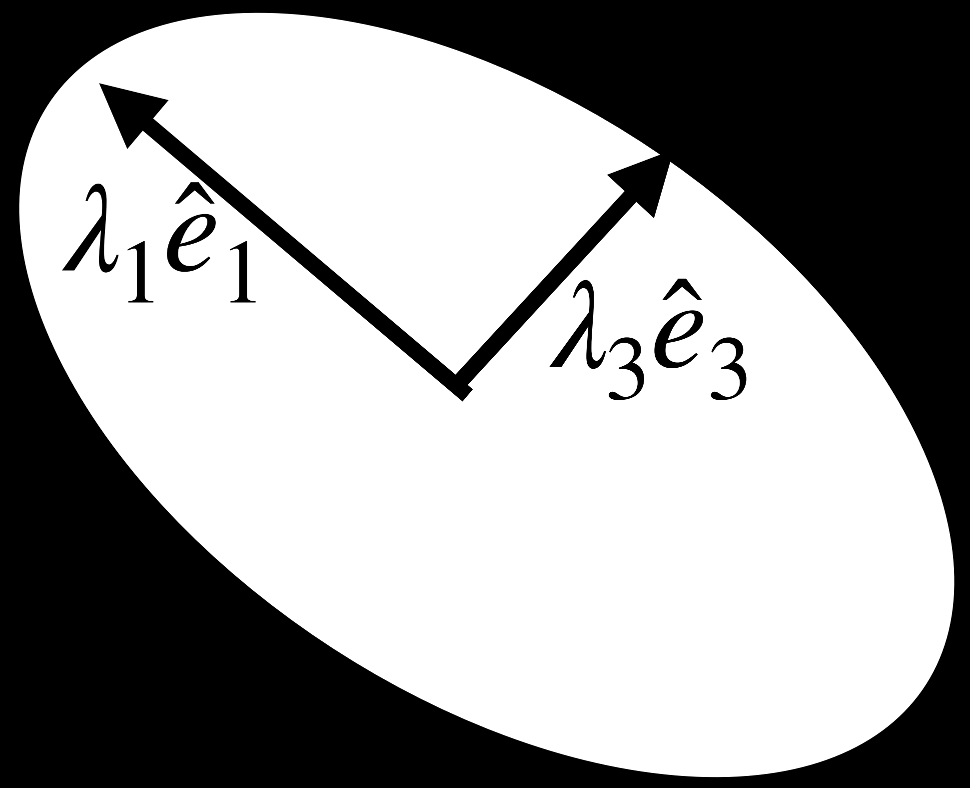


Measuring the "disruption power" of a halo

Tidal tensor:

$$\tilde{T}_{ij} = \frac{\partial^2 \Phi}{\partial x_i \partial x_j} \qquad T_{ij} = \tilde{T}_{ij} - \frac{1}{3}\tilde{T}_{ii}$$

Find eigensystem:



λ_1 : Max tidal strength in any direction

λ_1 / λ_3 : Tidal shear

Disruption is fastest when *both* strength and shear are large:

$$\Lambda \equiv \lambda_1 \times \left(\frac{\lambda_1}{\lambda_3}\right) = \frac{\lambda_1^2}{\lambda_3}$$

Note for nerds: this arises from the fact that the phase-space diffusion tensor in a potential Φ evolves as

$$\dot{D}_{\mu\nu} = T_{\mu\beta} D_{\beta\nu}$$

where T includes the traceless tidal tensor above, and D ~ λ (see e.g. Vogelsberger et al 2008).

At present day, tides are similar in SIDM and CDM (if anything, CDM tides are a bit stronger)

Ford, Singh, RES et al. in prep

But at z=1….

Ford, Singh, RES et al. in prep

So are there more streams?

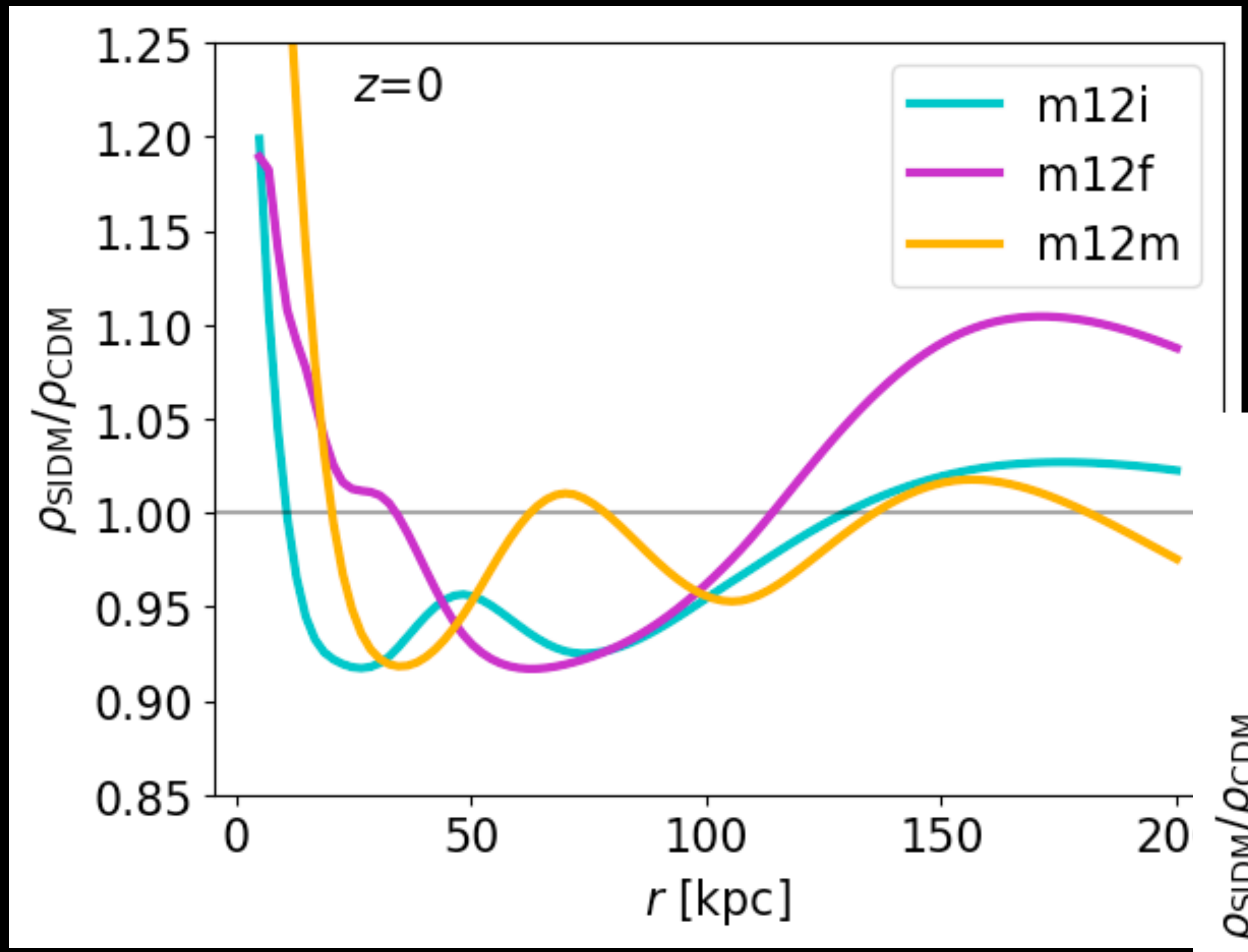
So are there more streams?

So are there more streams?

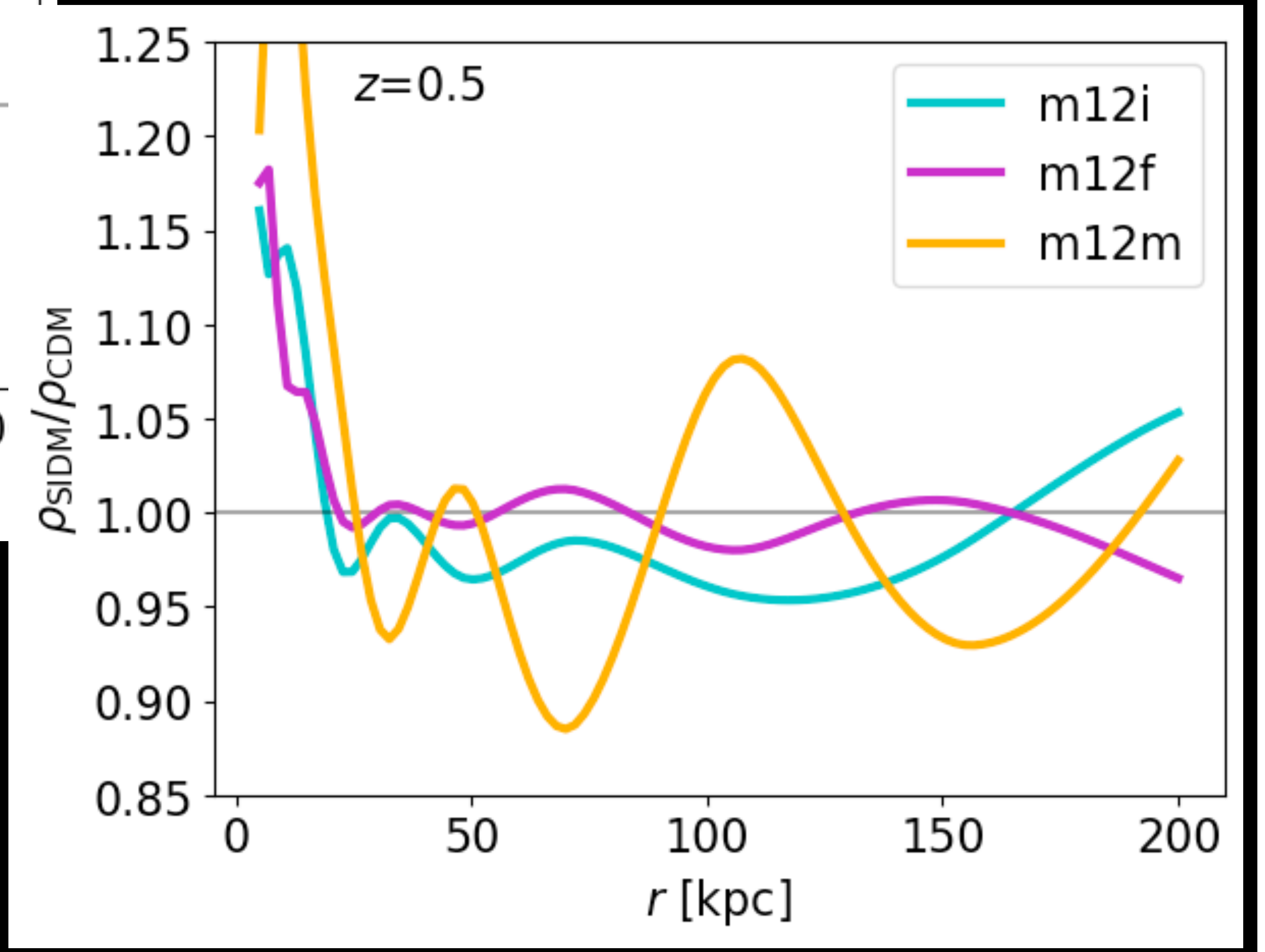
Main points

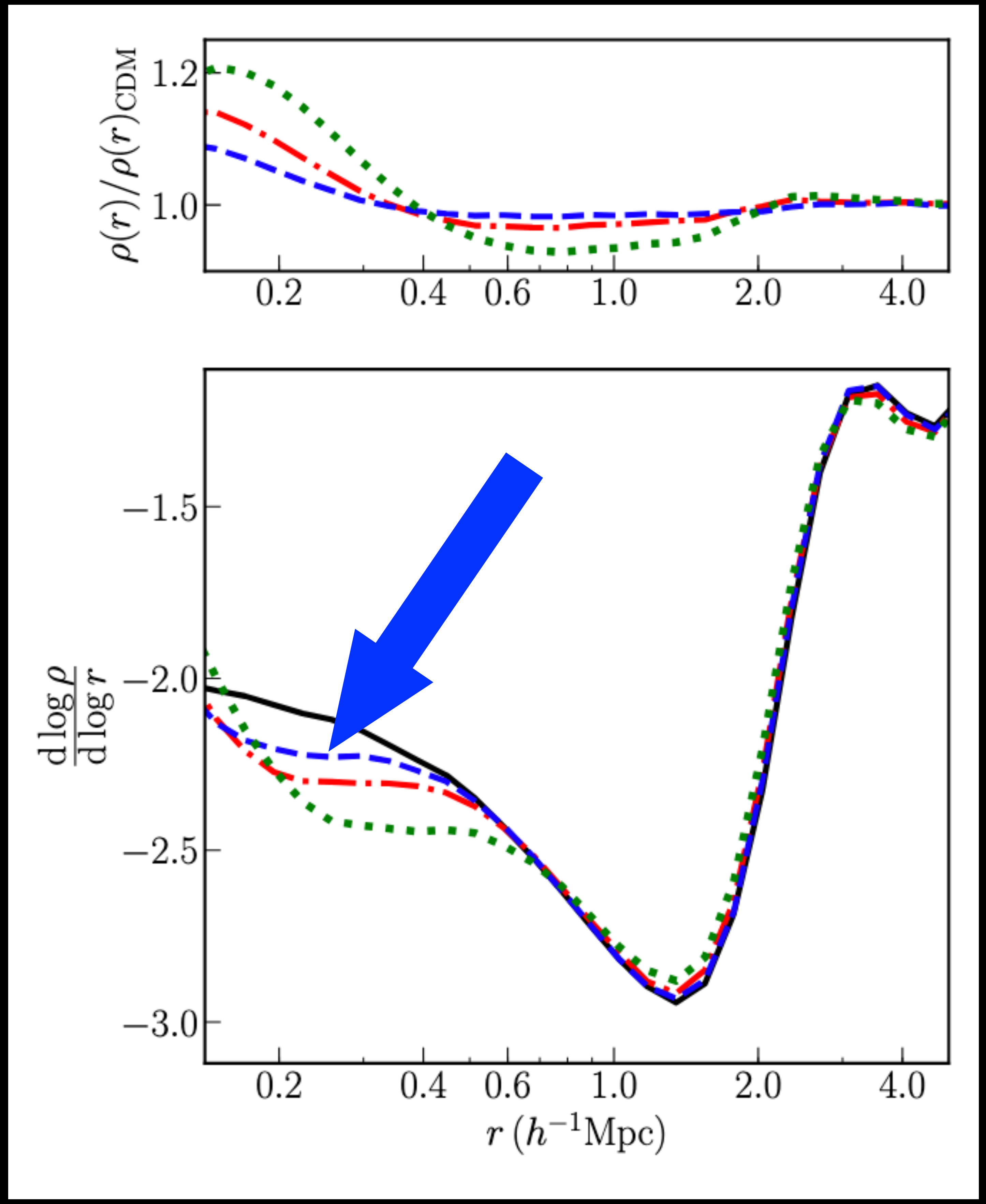
- Cosmological-hydrodynamical simulations of galaxy formation in individual halos (“zooms”) allow us to confront models with realism
- Testing models of DM that respond more efficiently than CDM to baryonic matter requires new, different approaches:
  - Are inner densities of MW-like systems *statistically* too high for CDM?
  - Are galaxies too well aligned to their halos for CDM?
  - Are there fewer bound substructures than expected? More streams?

SIDM rearranging the halo density profile



FIRE SIDM, Mh~10^12 Msun
(cosmo-baryonic)





Effect is larger than in DM only thanks to presence of galaxy

Banerjee+2020, Mh~10^14 Msun
(DM only)

Once the disk is formed it governs most of the subsequent shape evolution at radii relevant for tidal stripping.
Response from the SIDM halo is there, but is weak