Cosmological-hydrodynamical simulation of the Milky Way's interaction with the Large Magellanic Cloud in CDM and SIDM

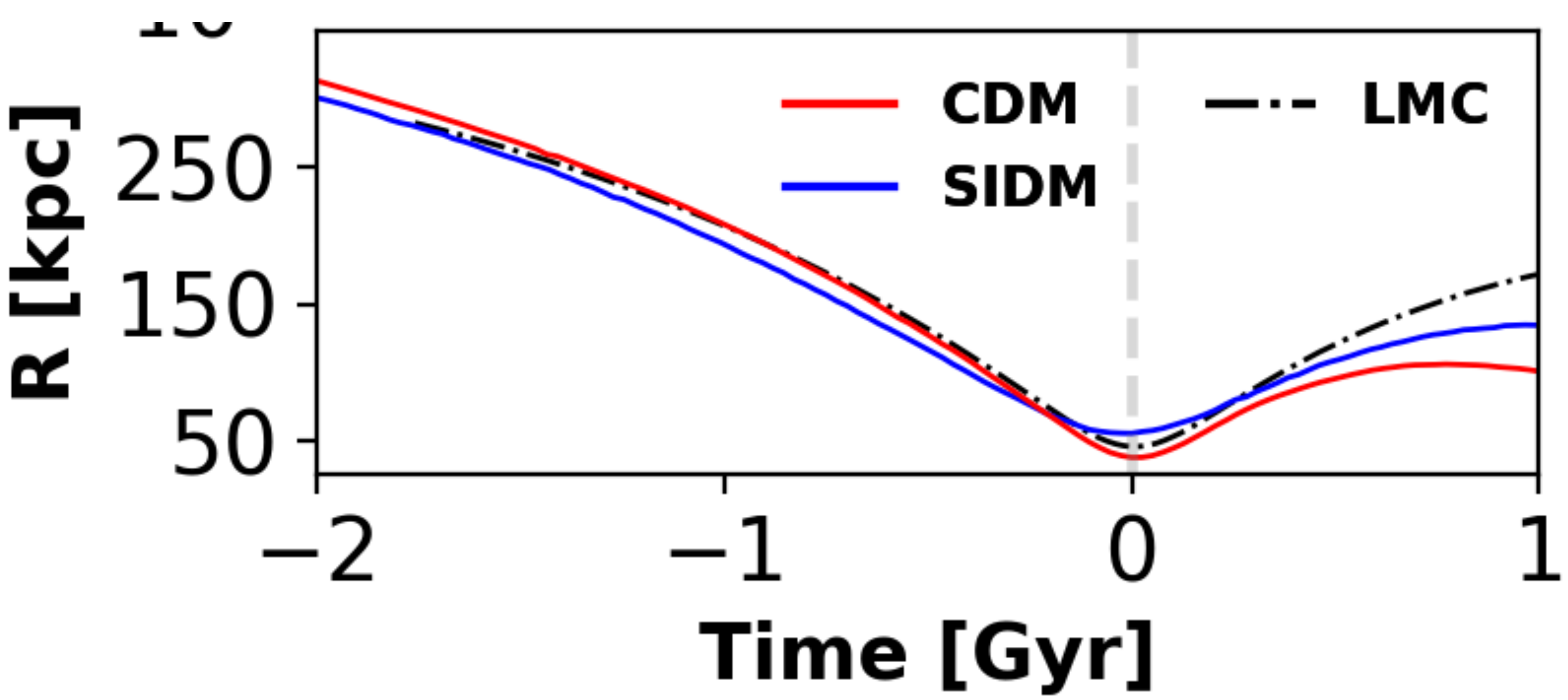
Robyn Sanderson & Arpit Arora, Penn

characteristics of the mw-lmc merger

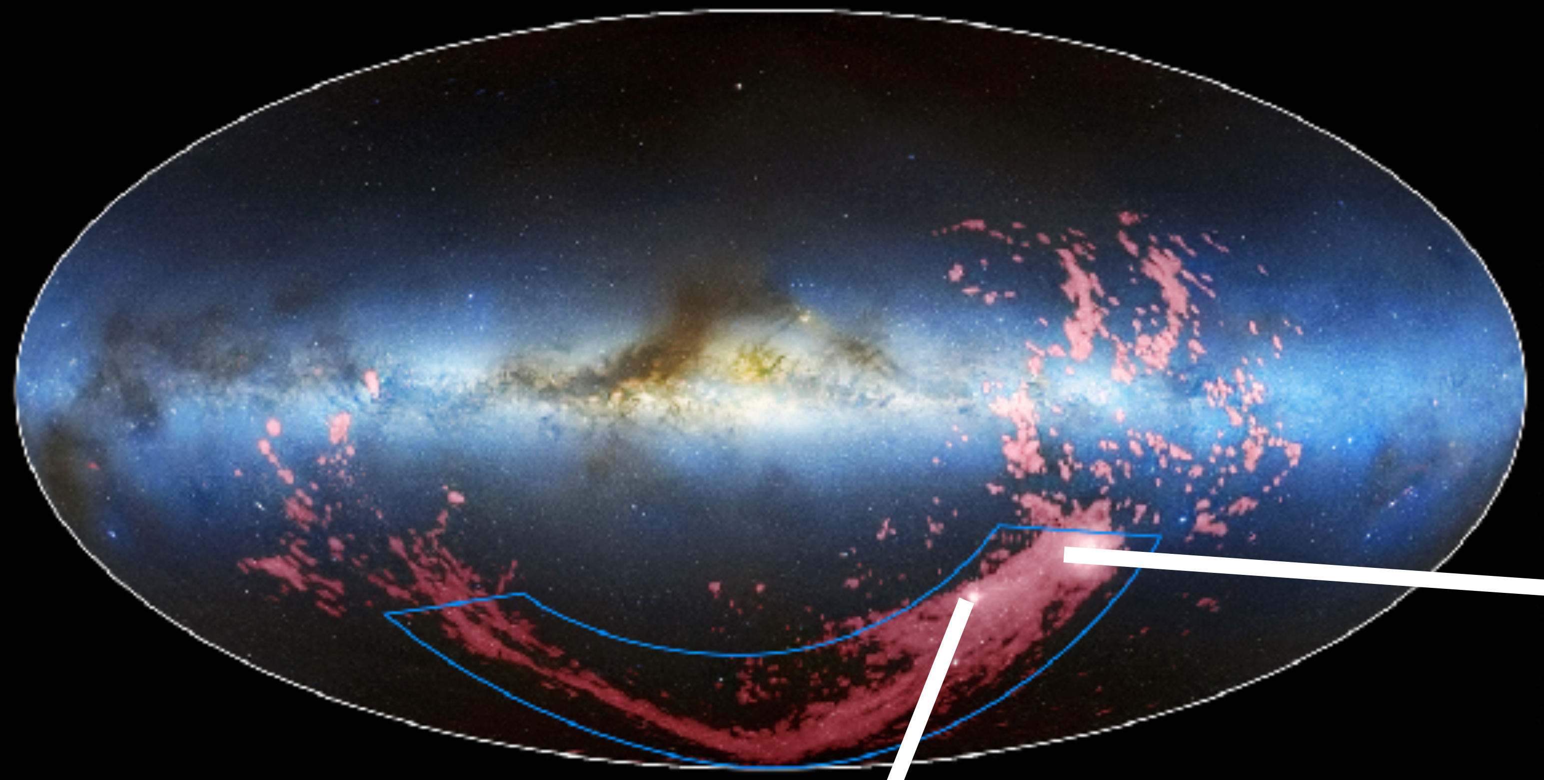
Quantity	LMC
M_{MW}/M_{LMC}	5—10
d_{peri} [kpc]	50
v_{tot} [km/s]	380
Tidal tensor [λ_{max}, 1/Gyr^2]	~23

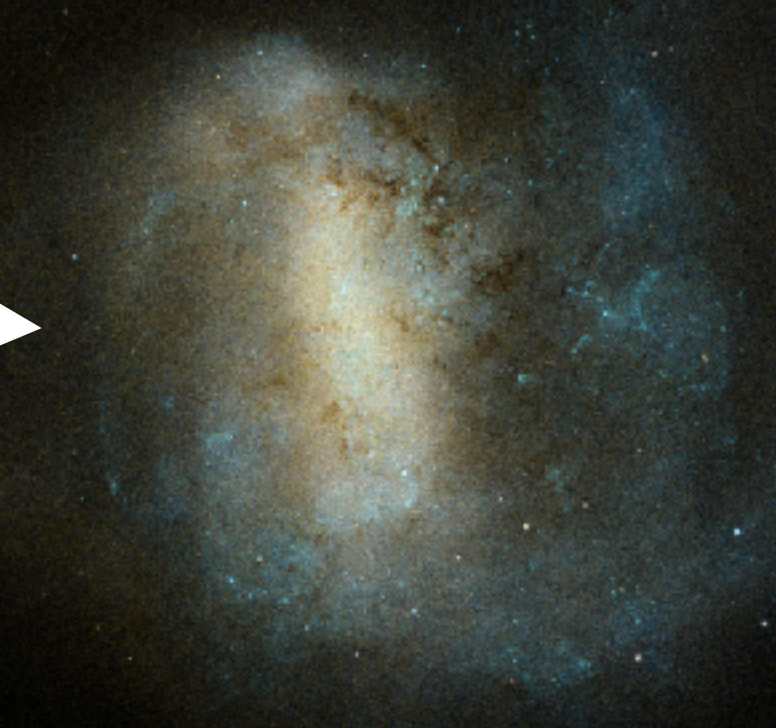
The LMC is thought to be on its first approach to the MW (Kallivayalil+2006, Besla+2007)

Its total mass is about 10-20% that of the MW (based on “reverse abundance matching”; Boylan-Kolchin+2010, Guo+2010).



Effects of the MW-LMC merger



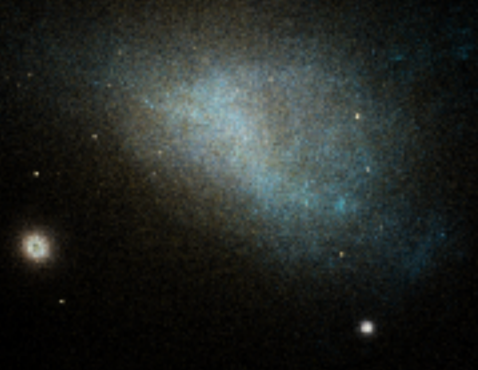


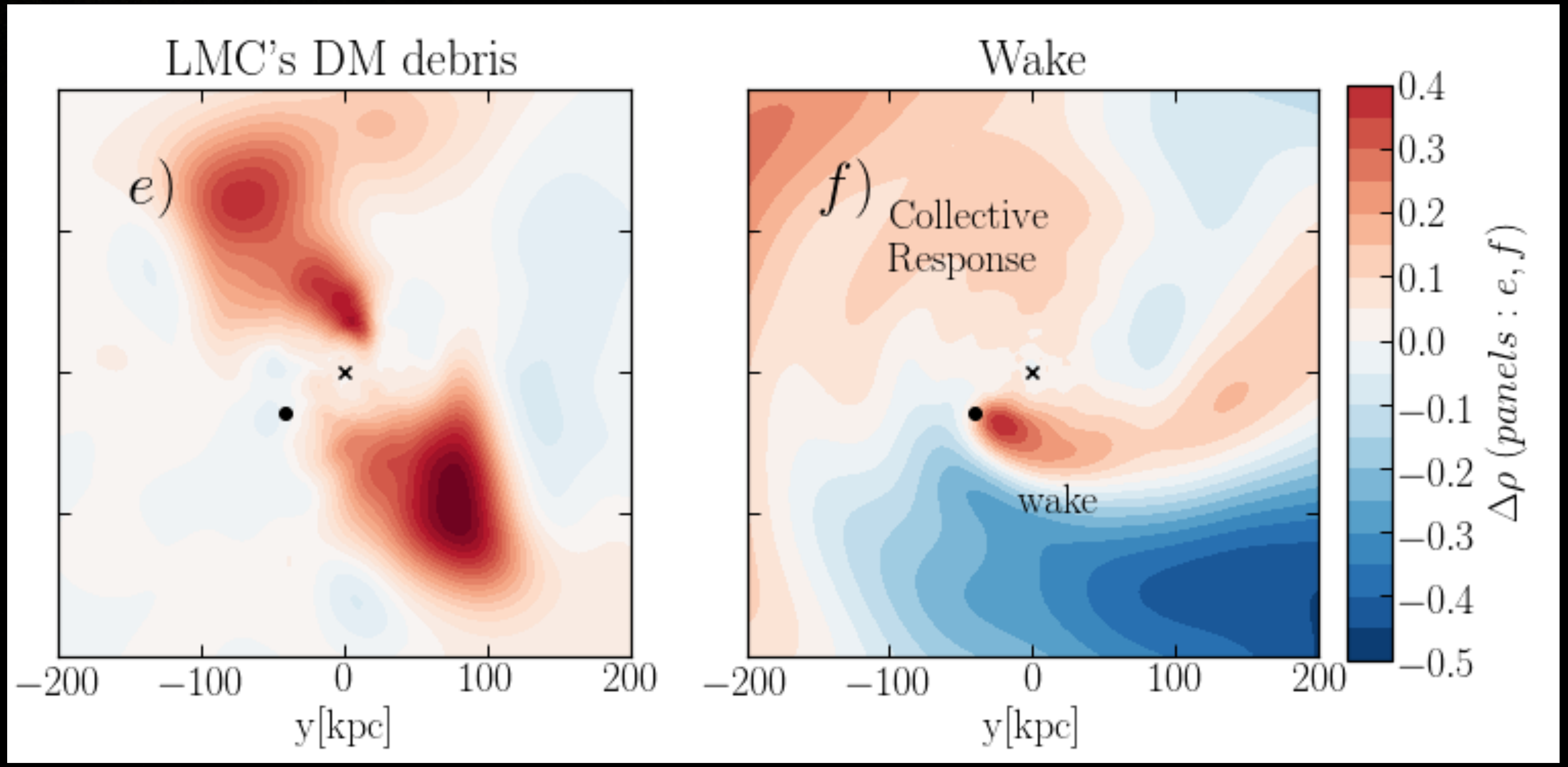
Large Magellanic Cloud (LMC) $M_{orig} \sim 10^{11}\,M_{Sun} = 0.1\,M_{MW}$

$(M_{now} \sim 10^{10}\,M_{Sun})$

D ~ 50 kpc
~ scale radius of MW DM halo
~ 5x edge of MW disk

Small Magellanic Cloud (SMC)
$M_{now} \sim 10^{9}\,M_{Sun}$

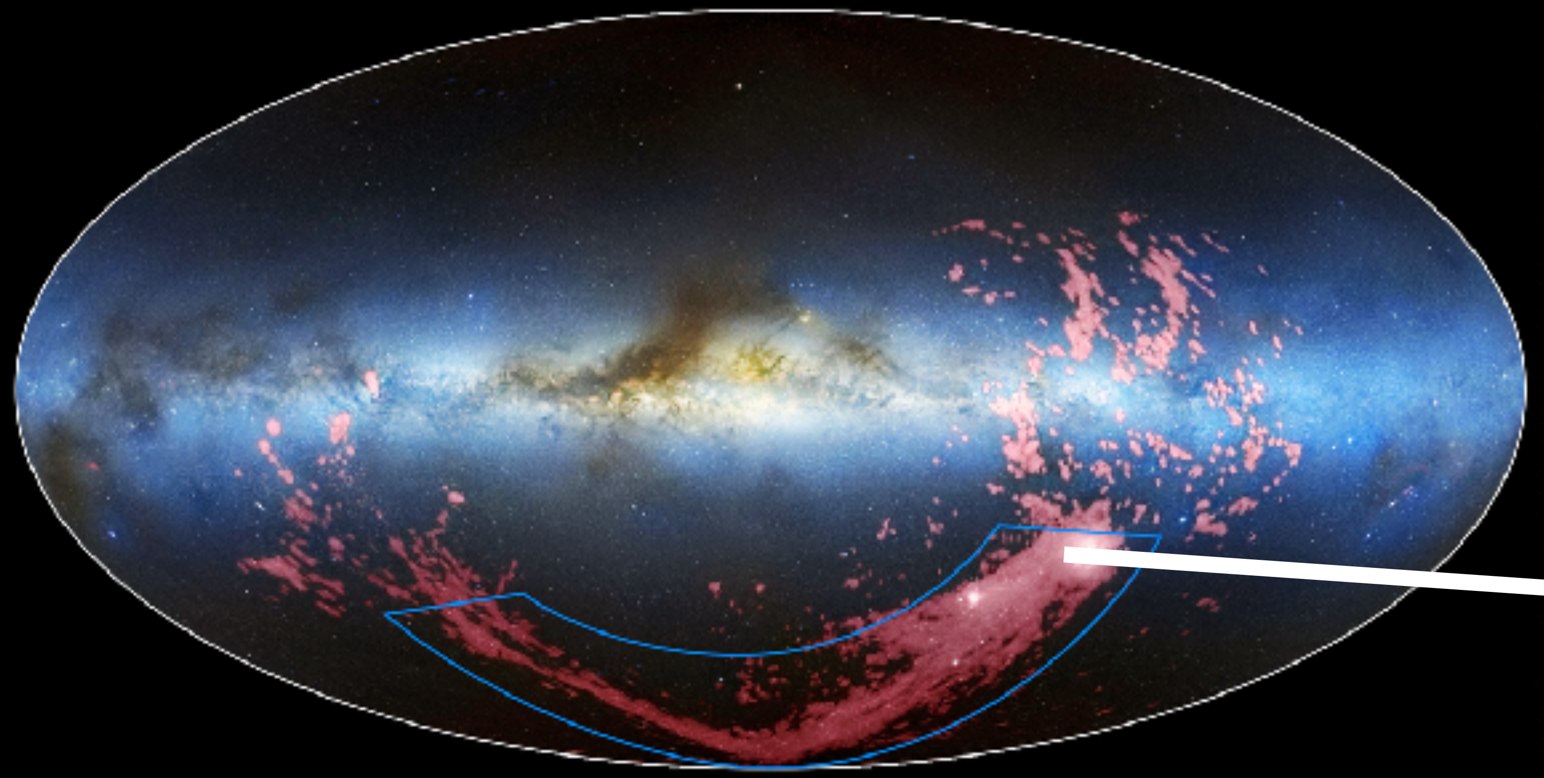




LMC and SMC from Gaia EDR3 - K. Loch

Garavito-Camargo+2020
See also Besla+2019

Effects of the MW-LMC merger



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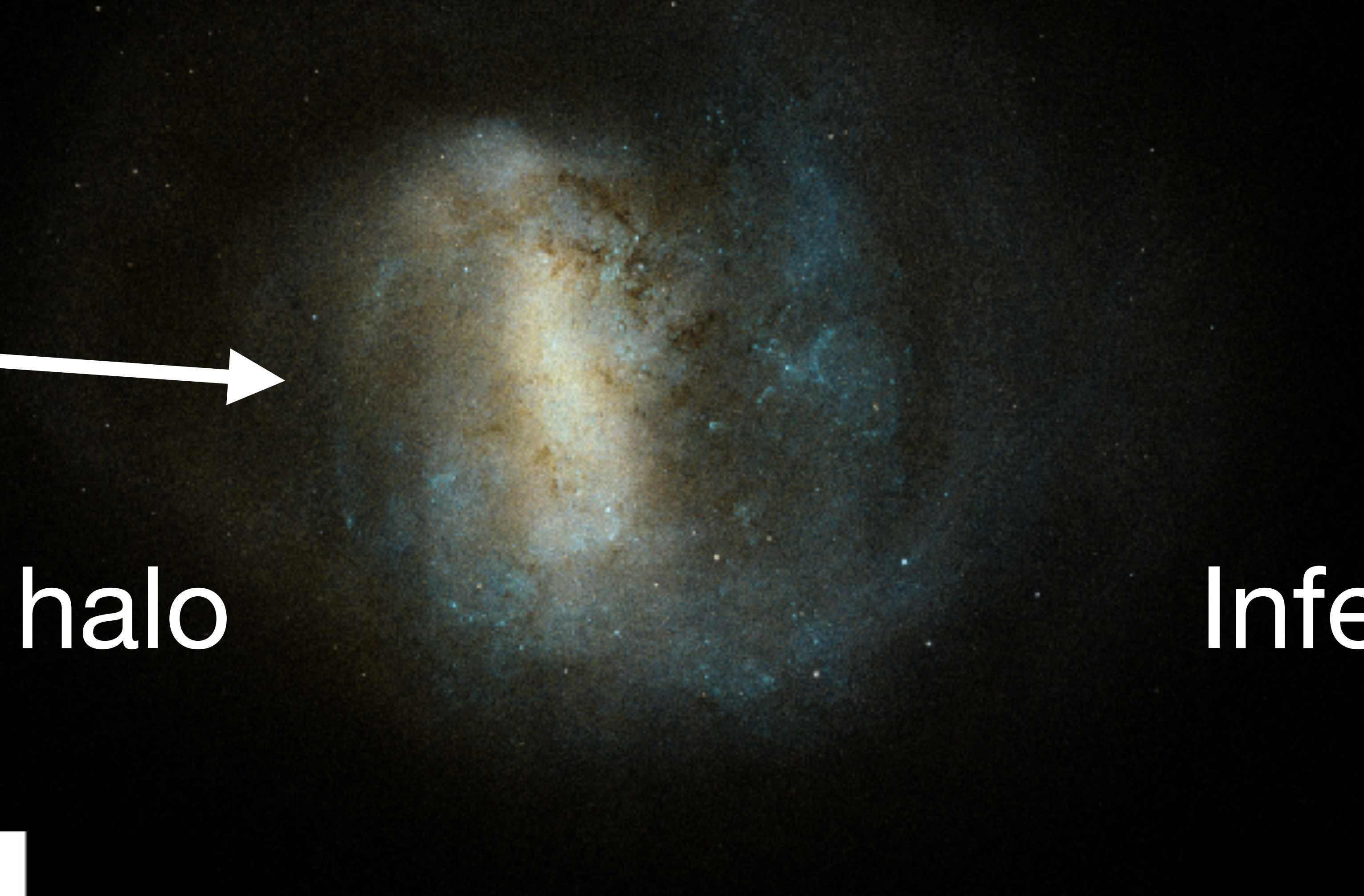
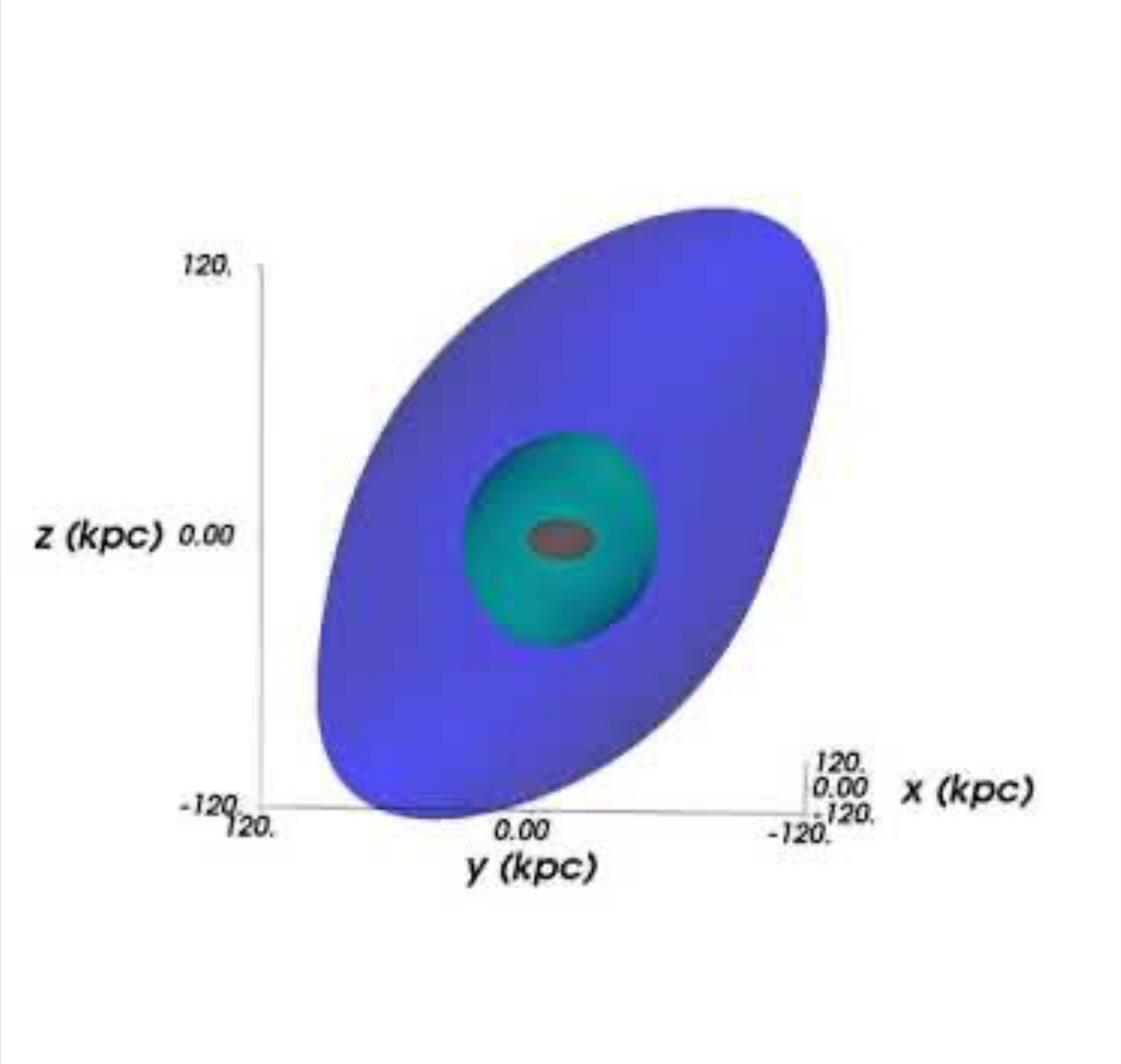
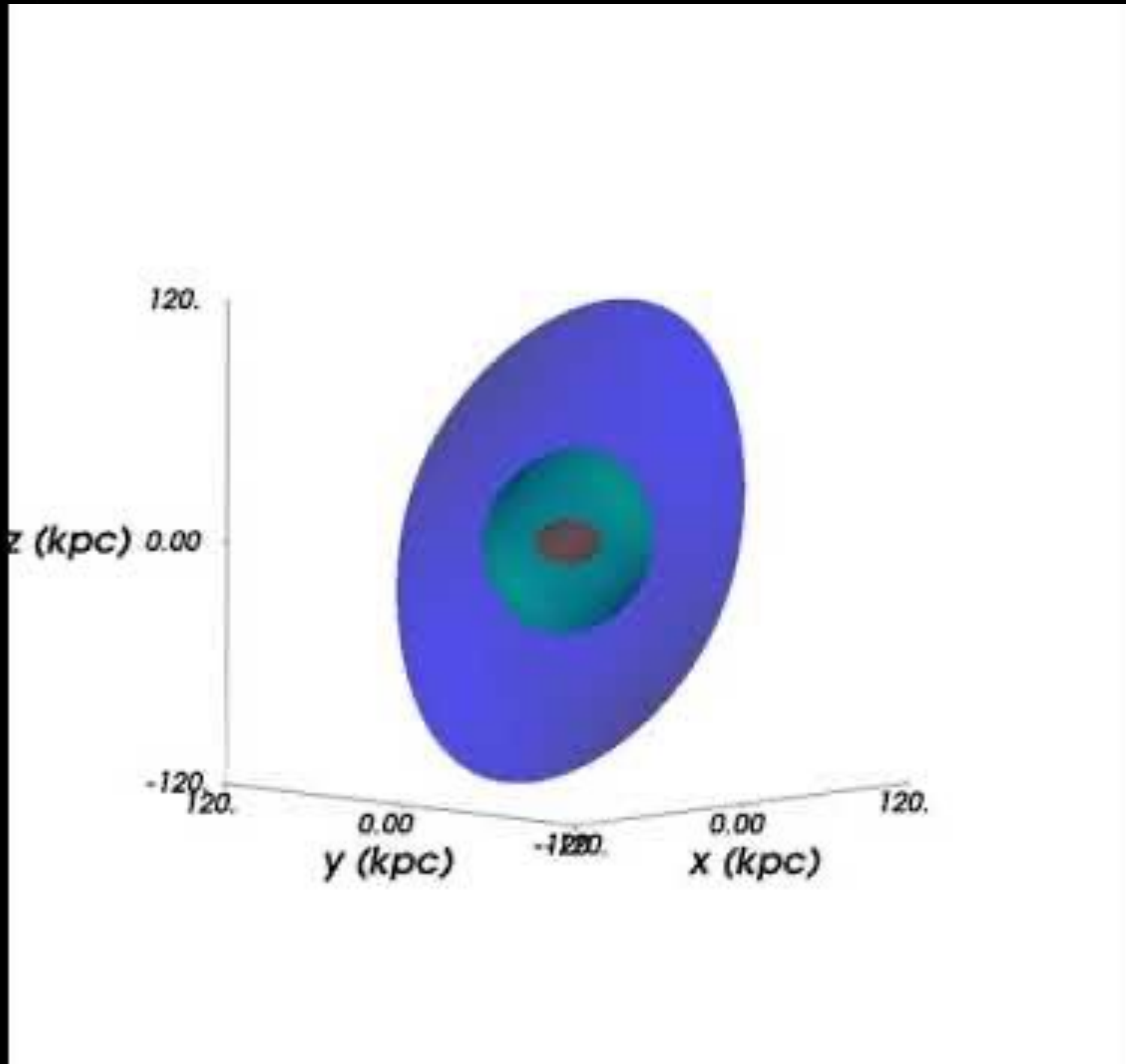


Inferred shape of MW dark halo if you **ignore** the LMC



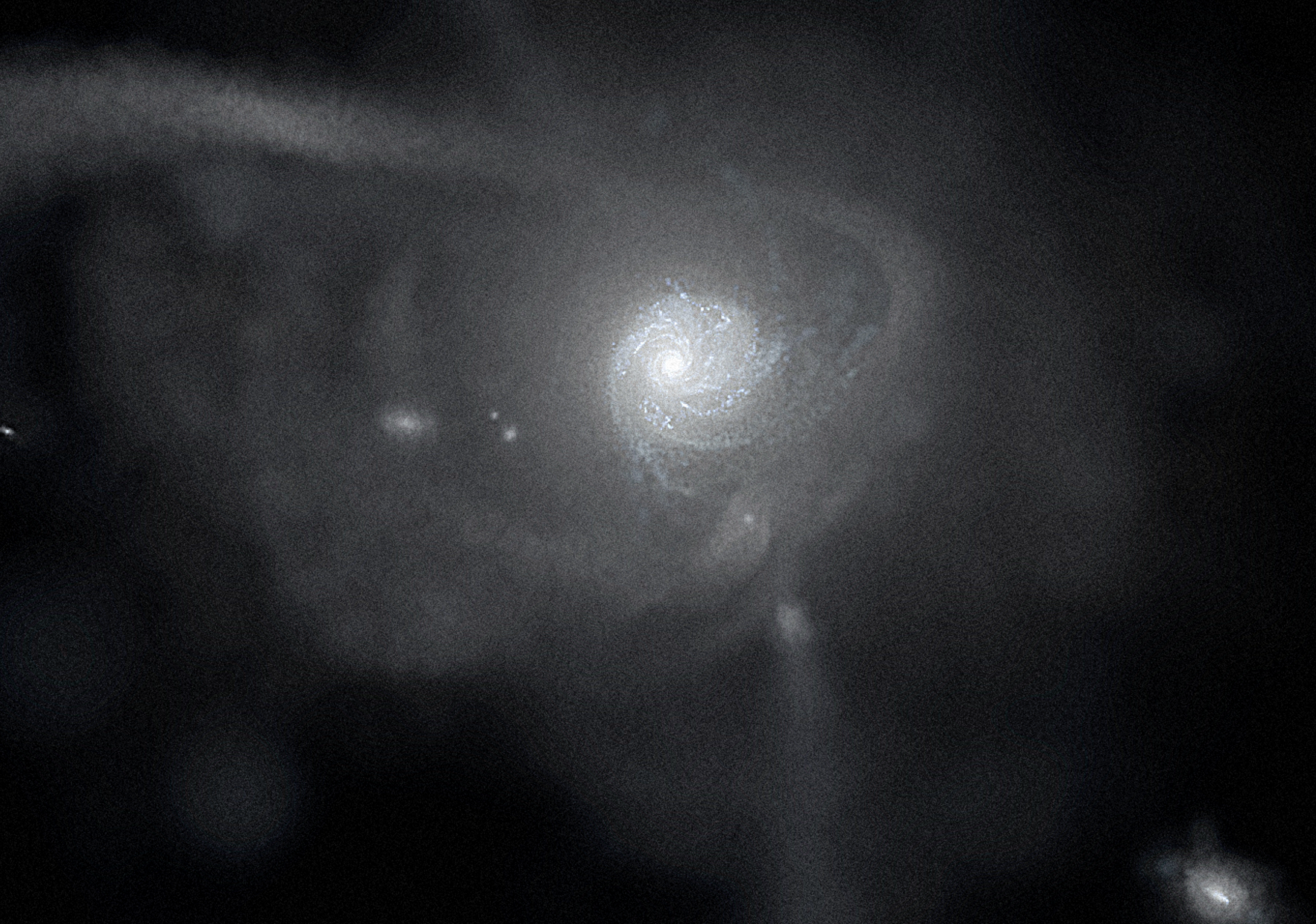
Inferred shape of MW dark halo if you **include** the LMC



Based on modeling Gaia observations of a tidal stream (Sagittarius)

Vasiliev+2021

Latte: Cosmological Milky-Way-mass systems



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

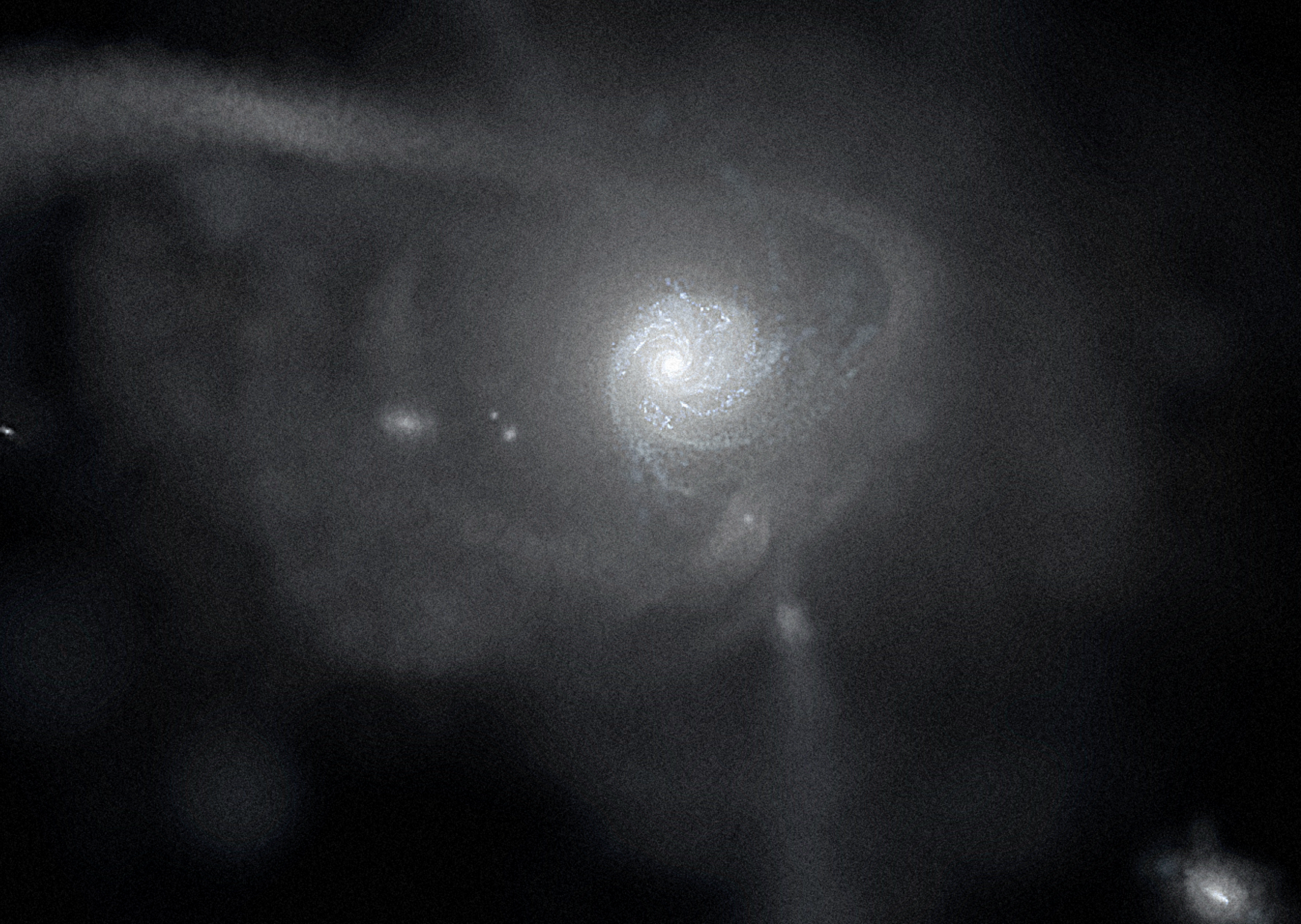
m_{DM} = 35000 $M_\odot$

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

10 chemical elements

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

Latte: Cosmological Milky-Way-mass systems



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10 chemical elements

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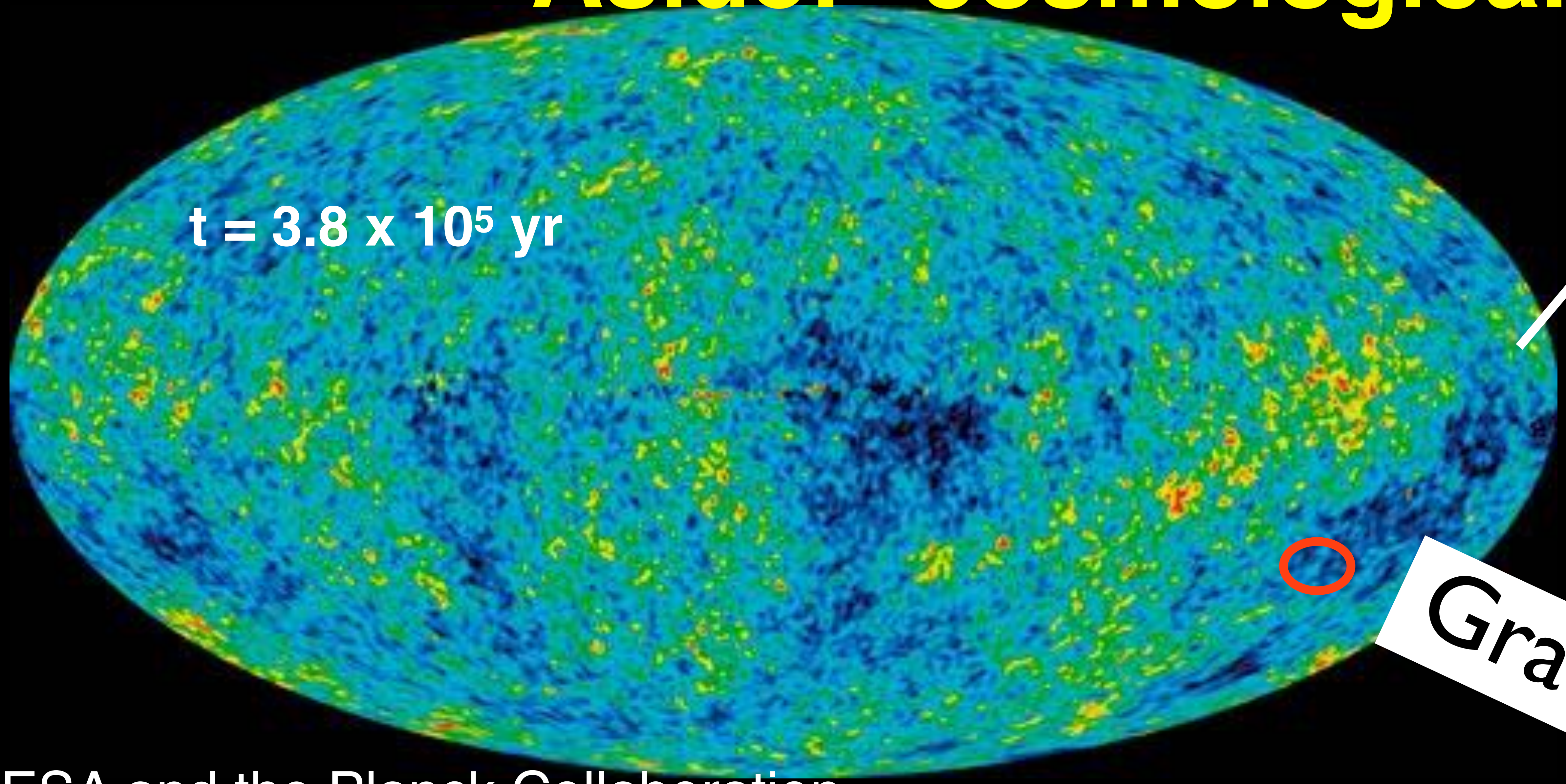
Aside: "cosmological simulation" means this:



t = 3.8 x 10^5 yr

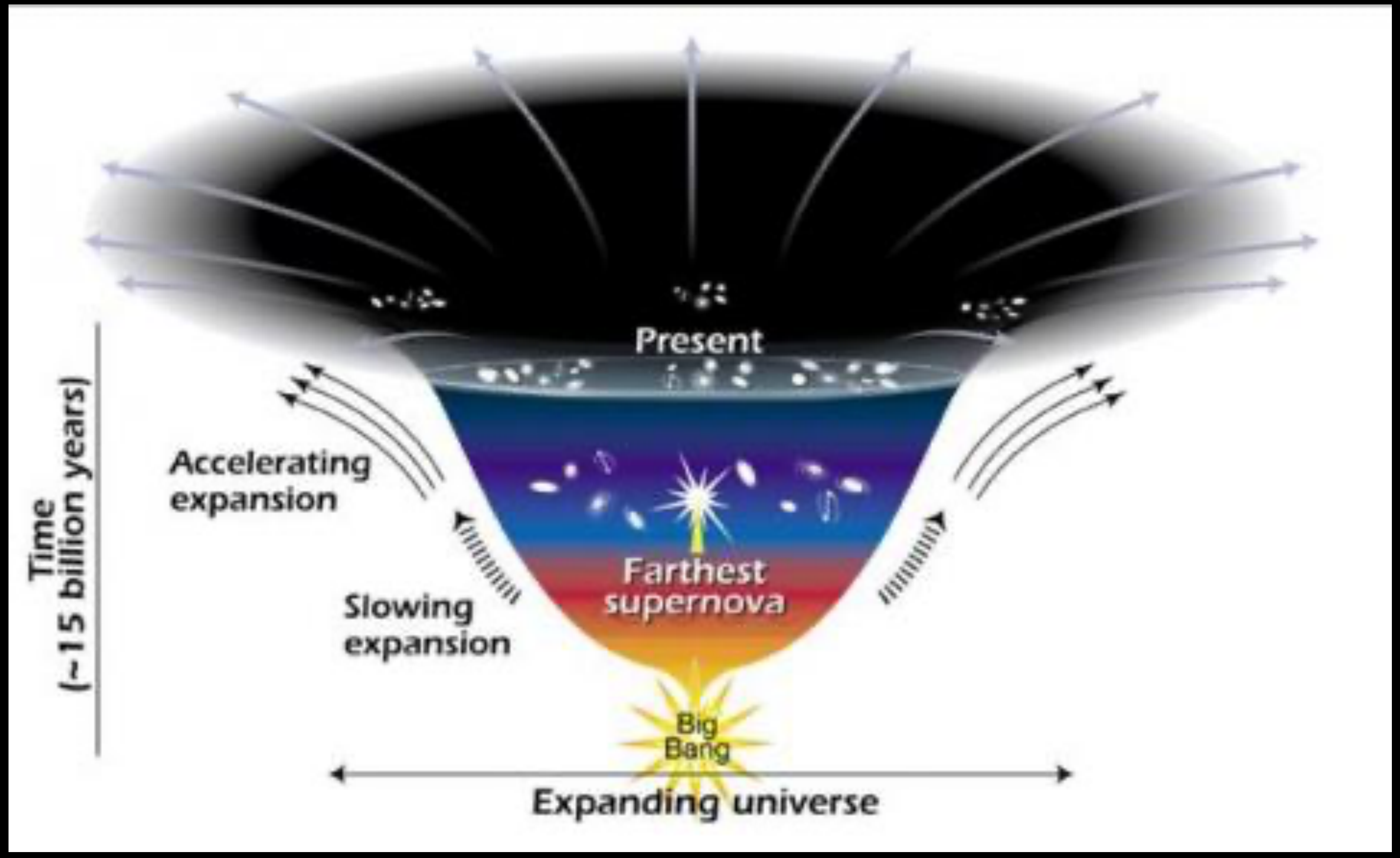
ESA and the Planck Collaboration

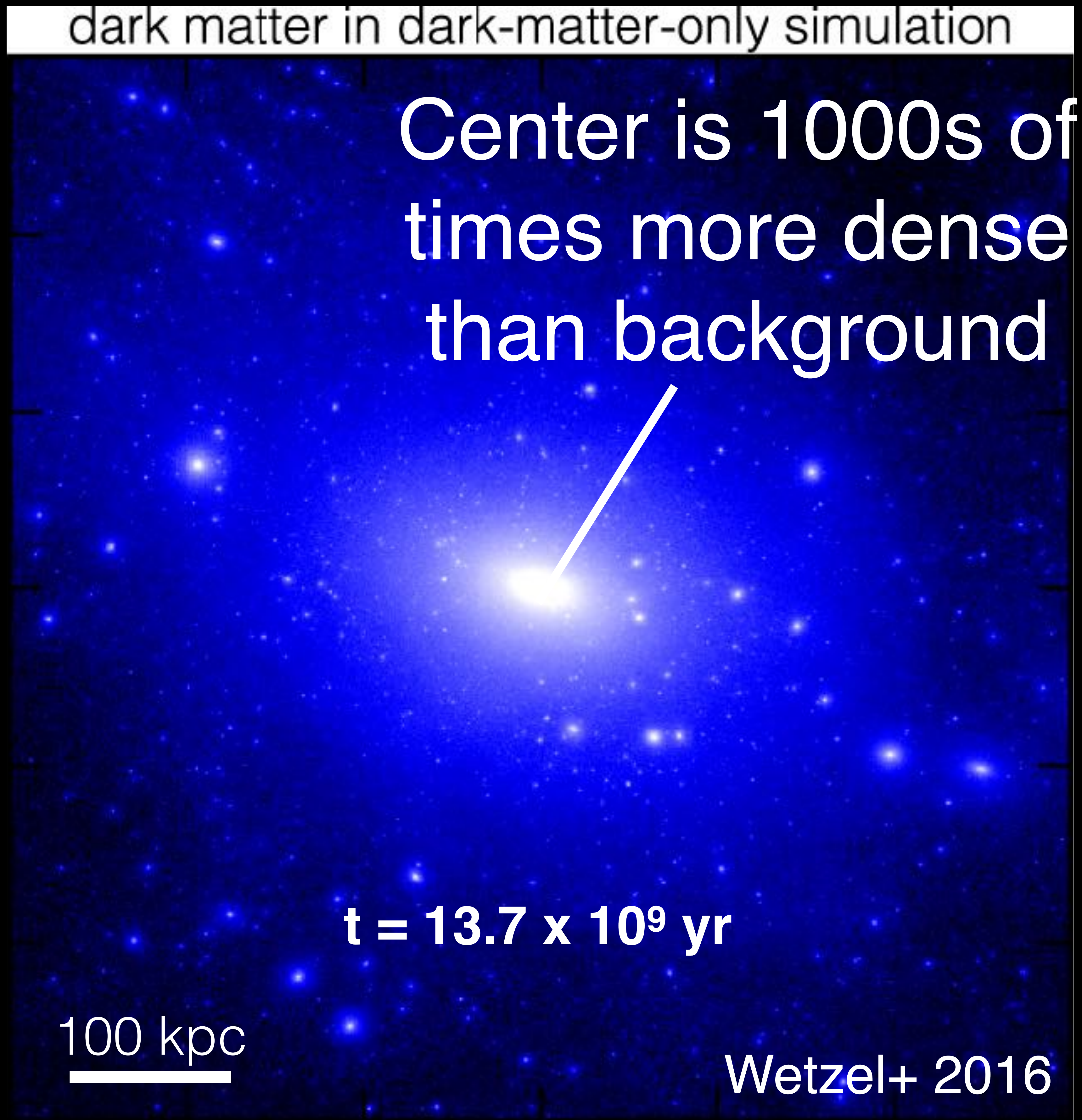
Density differences:
1 part in 100,000

DM-only: Hahn & Abel 2011

+baryons: Hahn, Rampf, & Uhlemann 2021

Gravity + Time



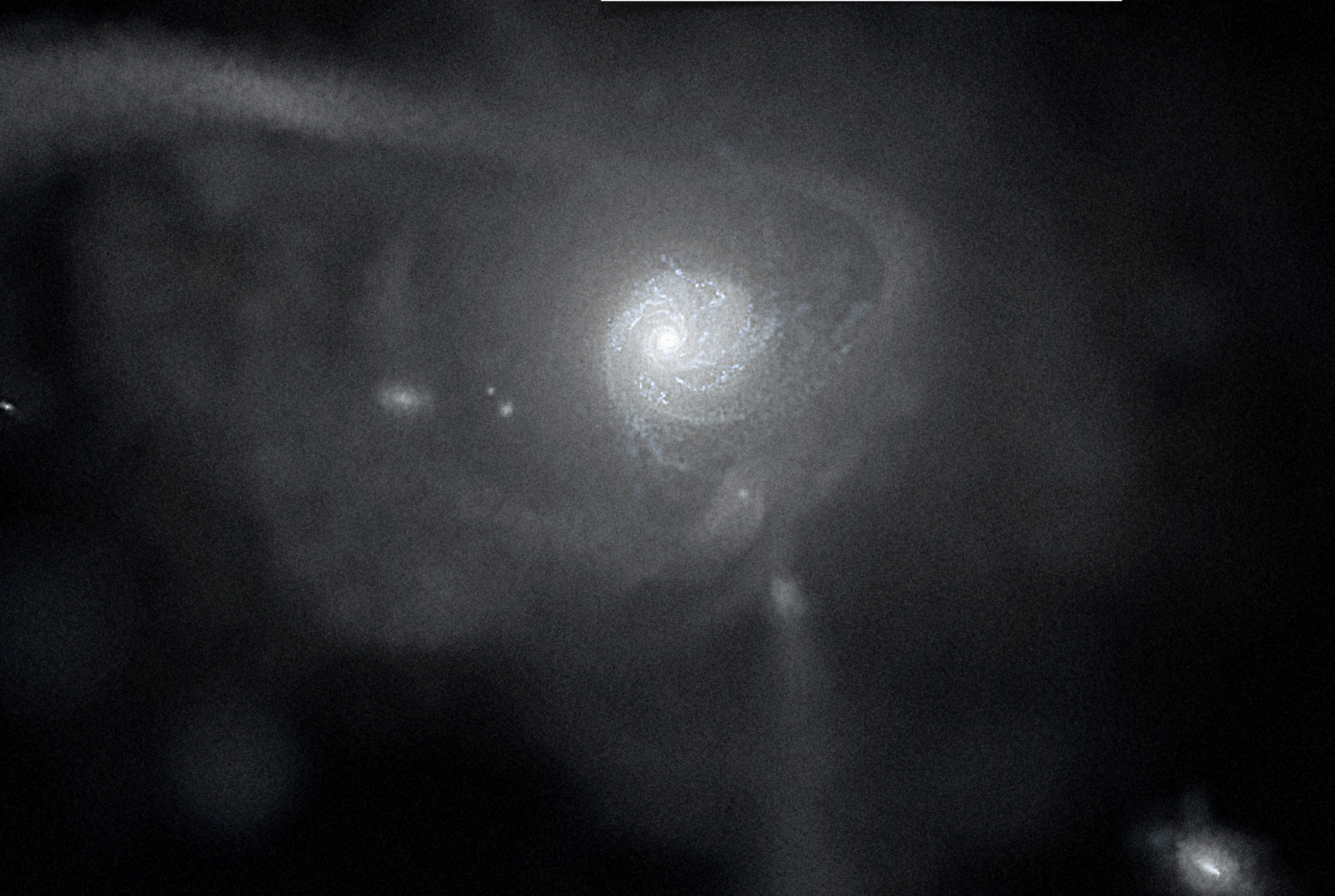


Center is 1000s of times more dense than background

t = 13.7 x 10^9 yr

Wetzel+ 2016

Latte: Cosmological Milky-Way-mass systems



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

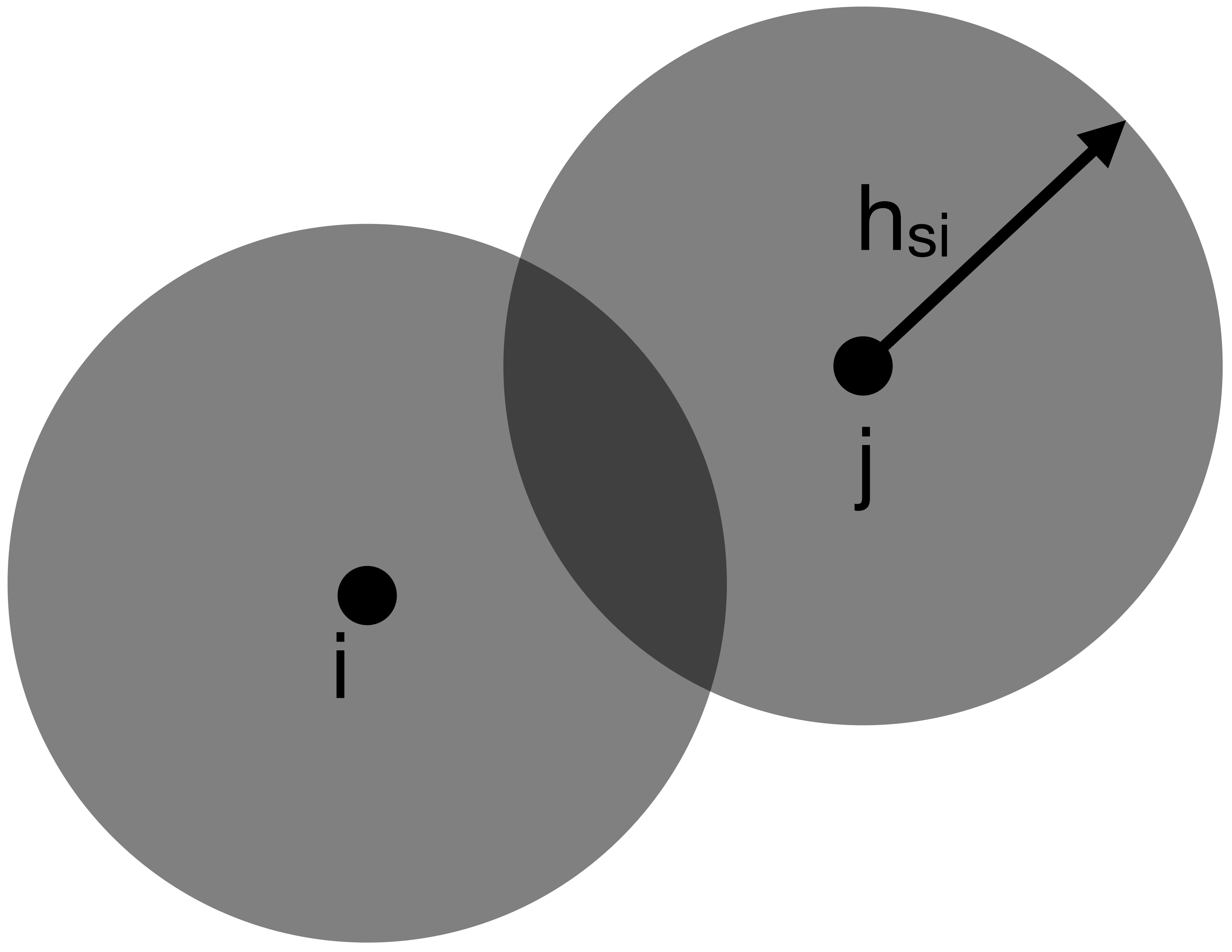
Isolated: no massive neighbor in ~5 Mpc

Selections made on DM-only simulation

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 $P\ \delta t << 1$

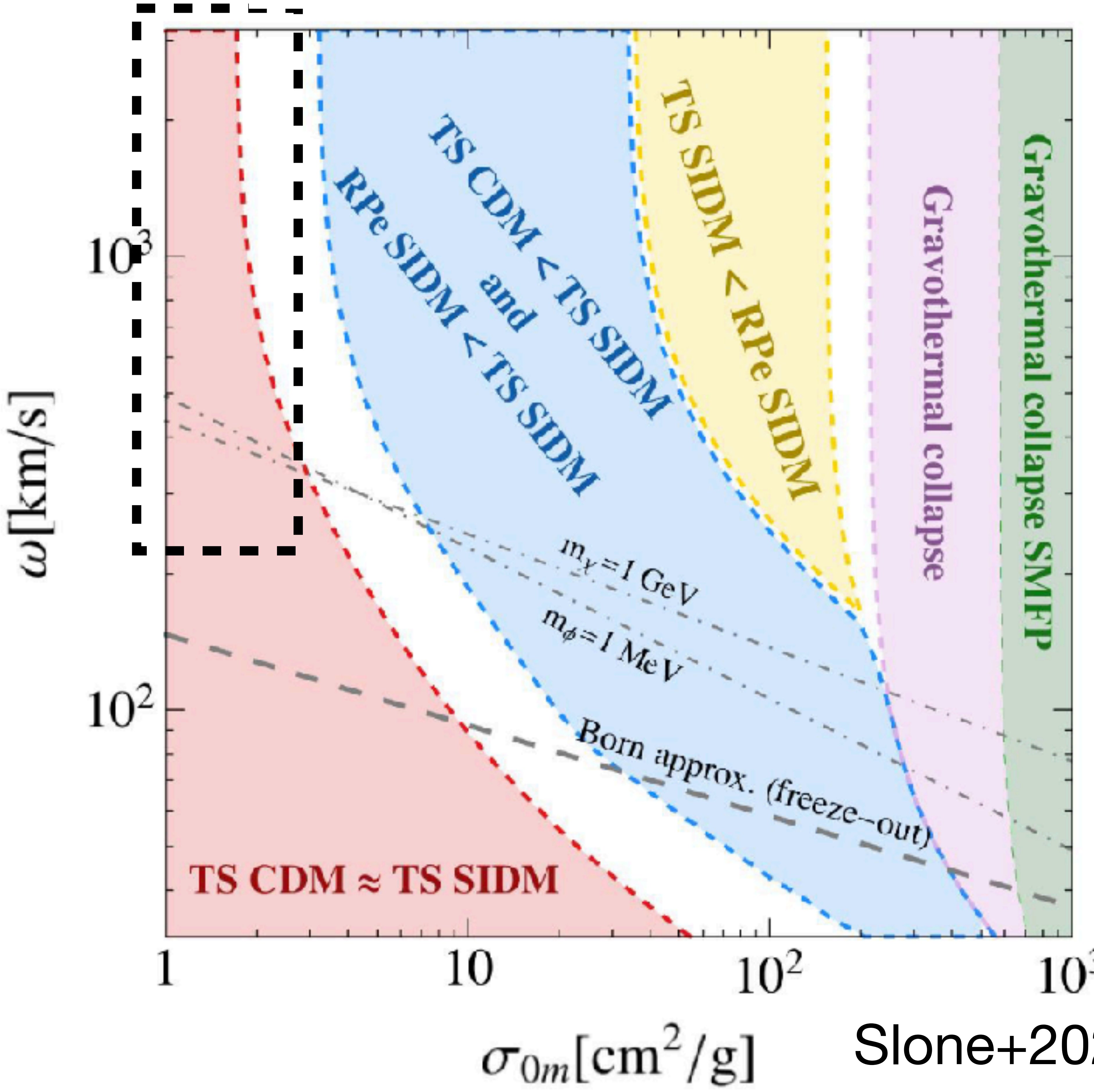


- Compute Γ_{ij} and P_{ij} using "**coarse-grained**" collisional Boltzmann treatment
- Symmetrize over pairs of macroparticles
- If $P_{ij} > 0$:
  - Determine whether collision occurs via "rejection sampling" (compare a random number to P)
  - Collisions are hard-sphere elastic scattering
  - Determine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

Intuition from analytic models

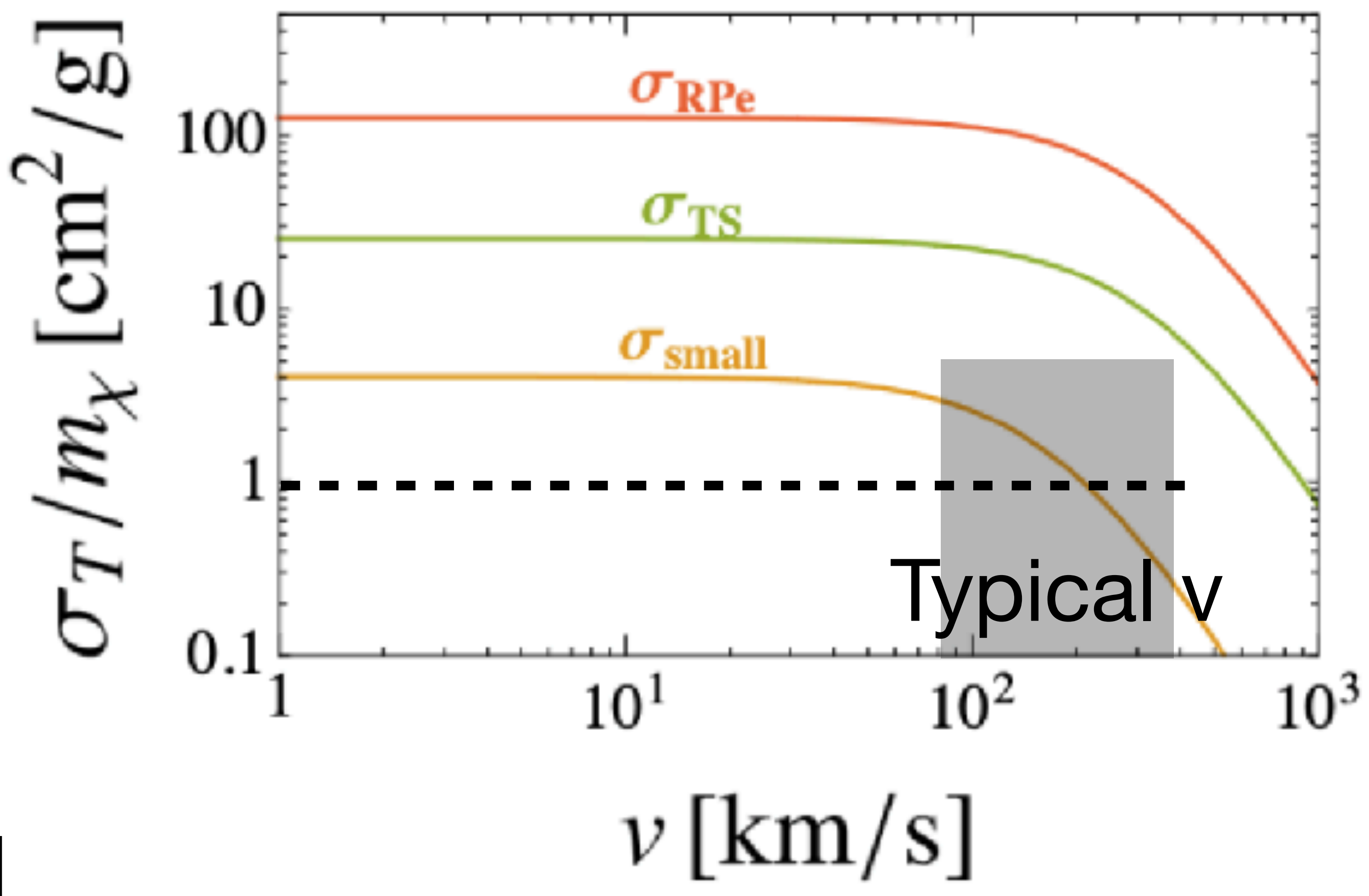
- All else equal, we should expect similar tidal stripping in our CDM and SIDM simulations, based on Slone+2021
- However their tests used less massive satellites (max $m_i = 10^{10.5}$)…
- …and no explicit baryonic physics

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



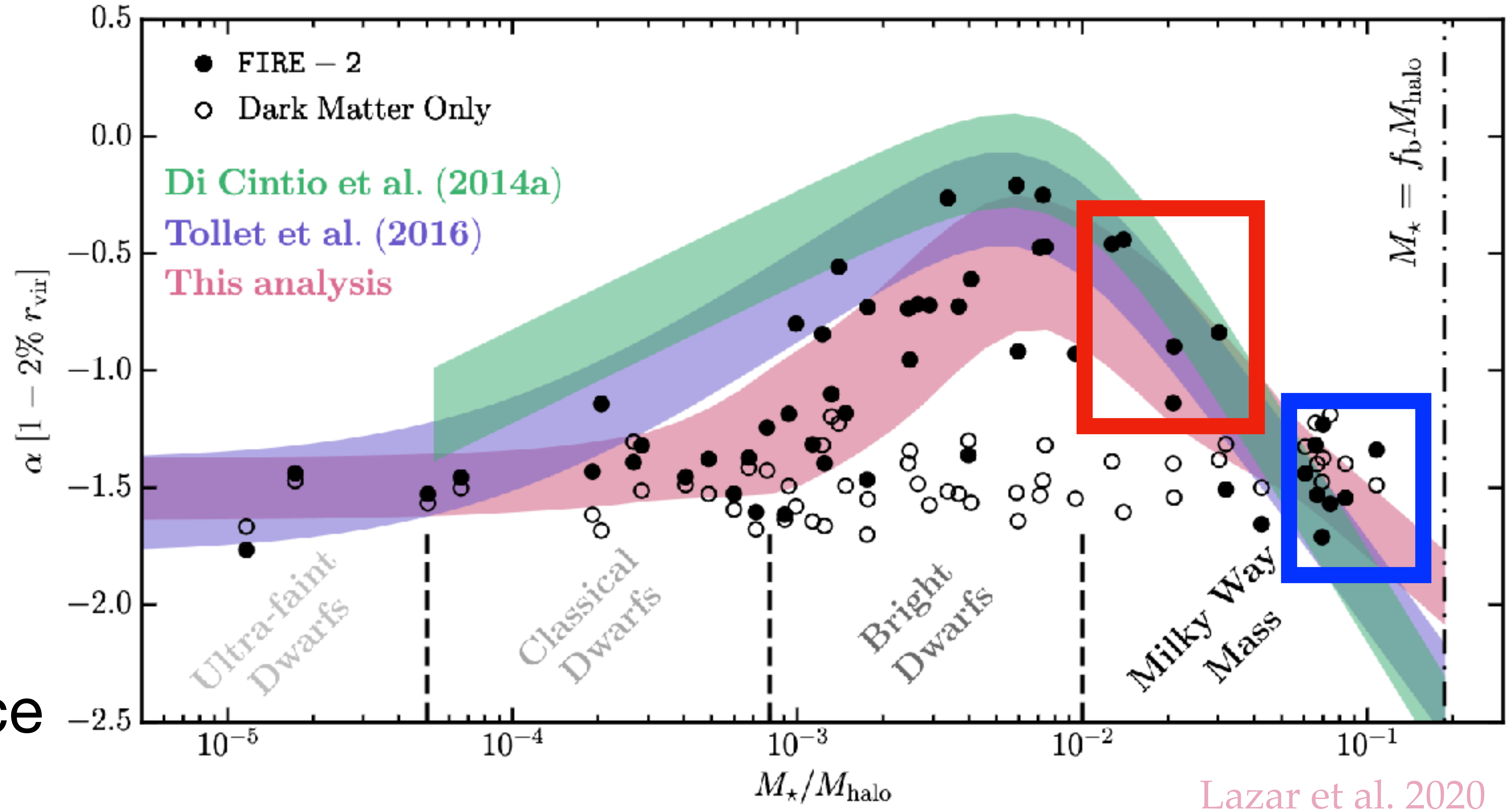
Slone+2021

Our model is ~ σ_{small}



Intuition from previous simulations

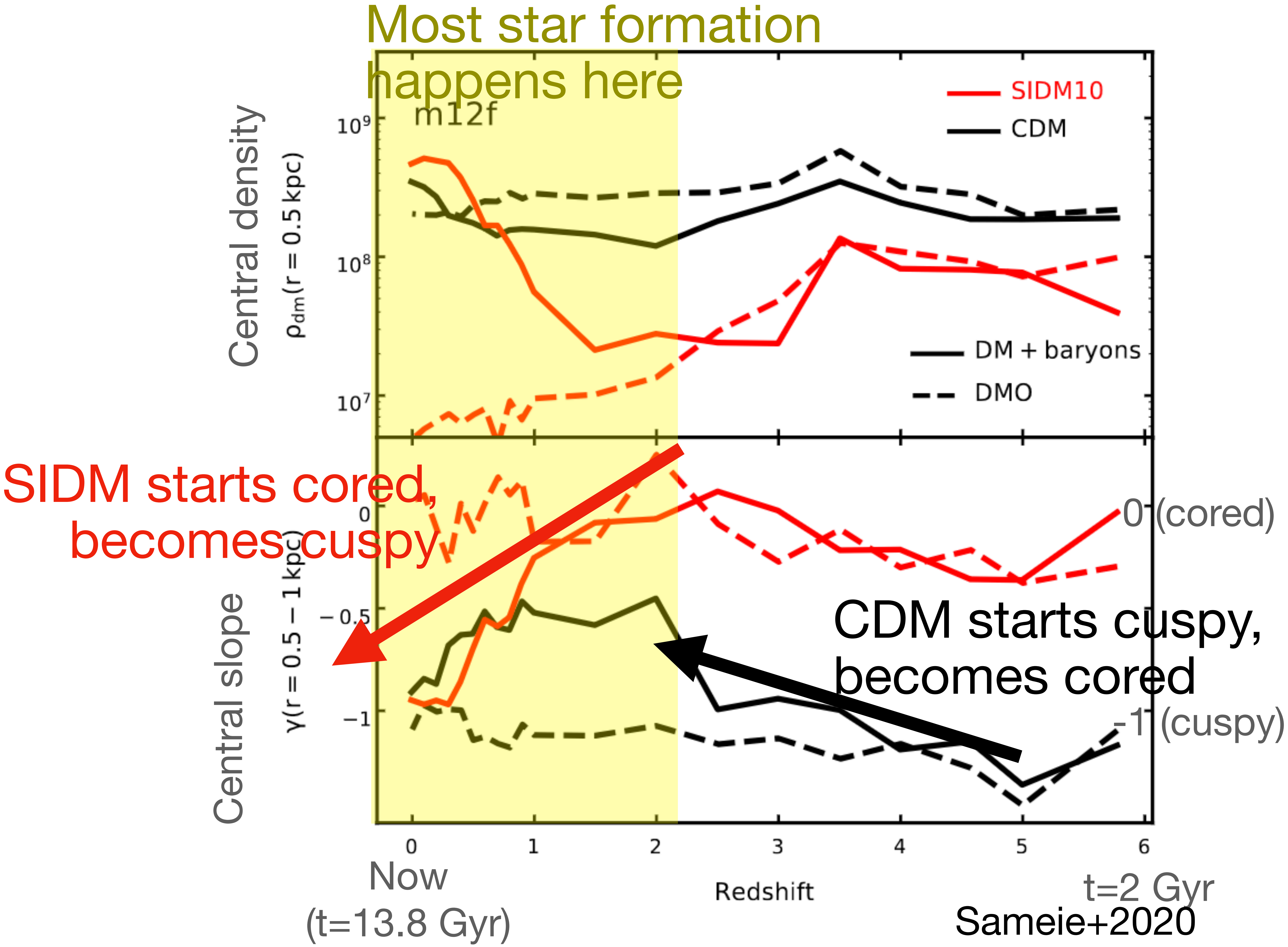
- *Absent SIDM effects* we expect:
  - The MW analog to be “cuspy” in the center, with α ~ -1.5
  - The LMC analog to be less cuspy, with α between -1.3 and -0.5, with a strong dependence on M*/Mhalo



Lazar et al. 2020

Intuition from previous simulations

- “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



comparing cosmological hydro simulations

What is held constant

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

What varies between runs

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

CDM

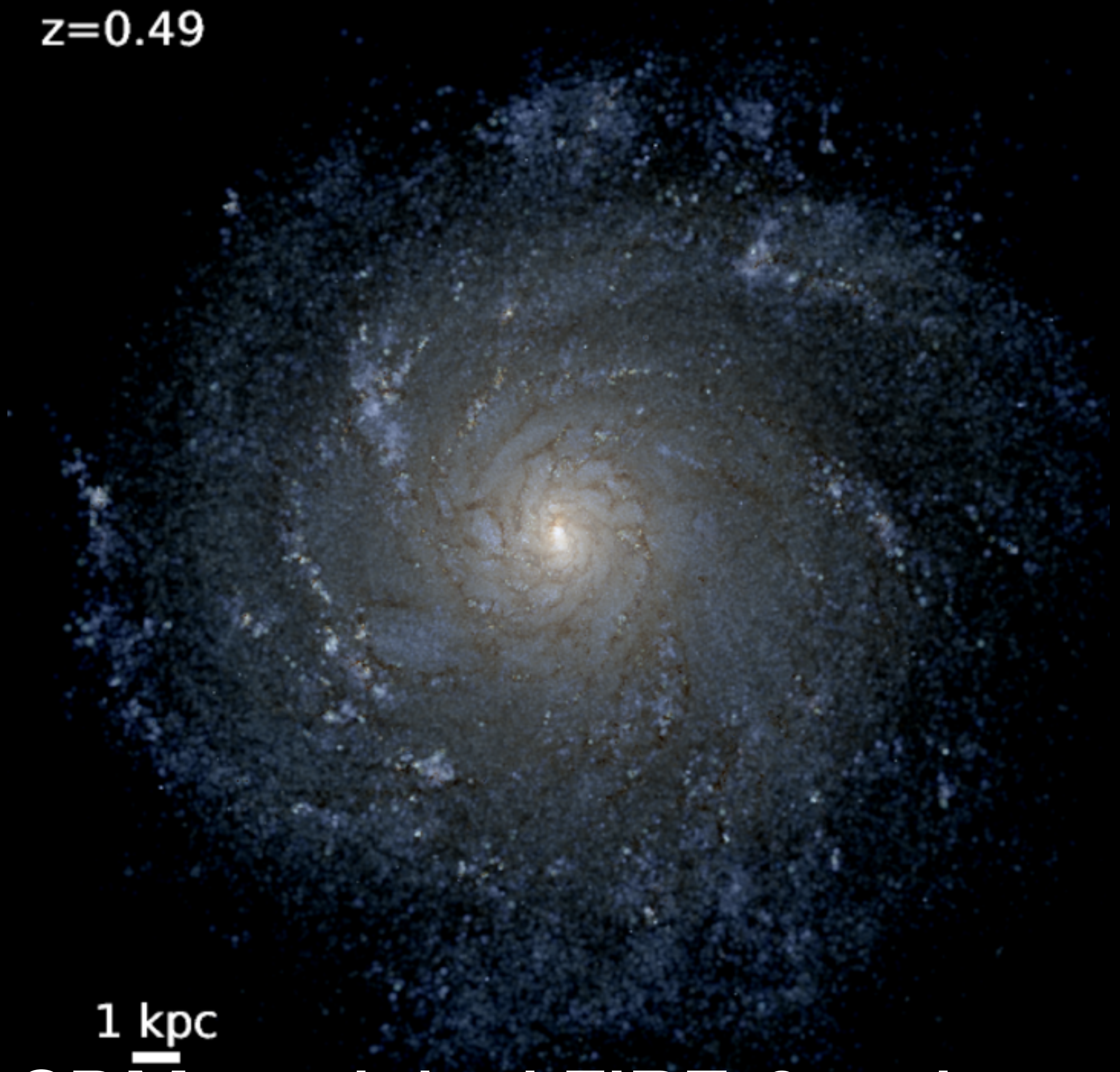
Arora, Sanderson et al in prep

SIDM

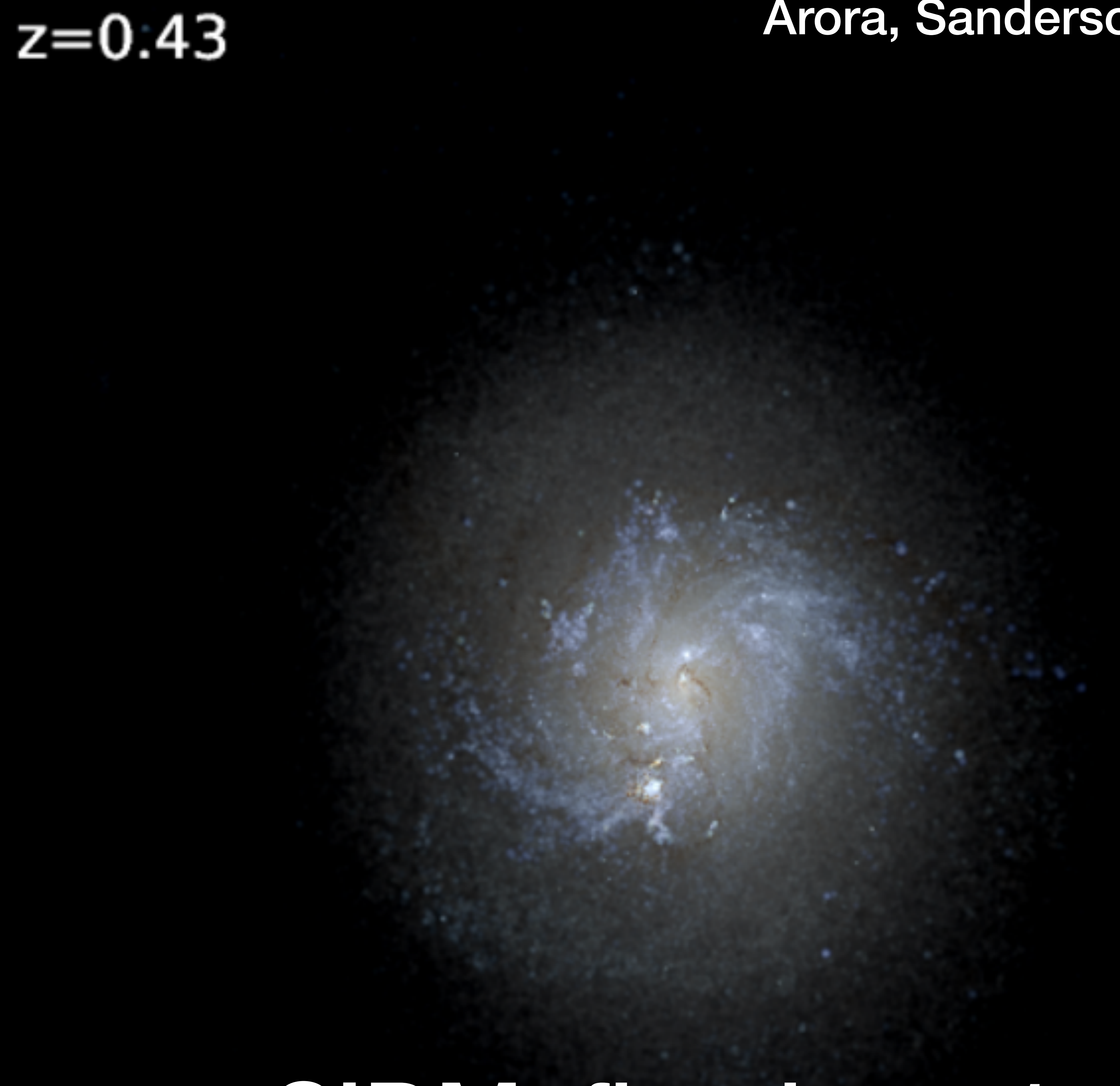
Arora, Sanderson et al in prep

Main galaxy: illustrating the role of fiddling with baryonic physics

Arora, Sanderson et al in prep



CDM + original FIRE-2 recipes

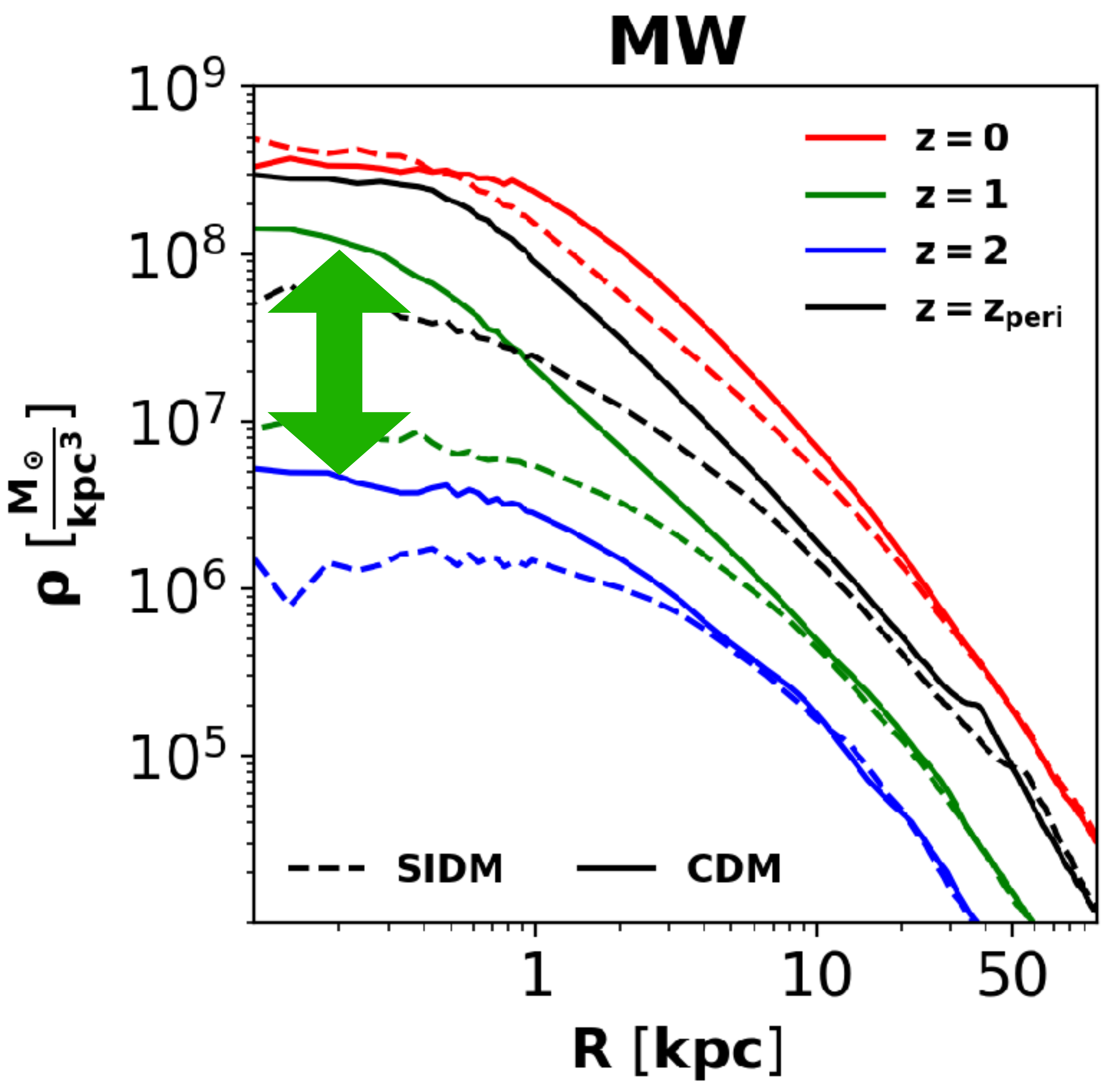


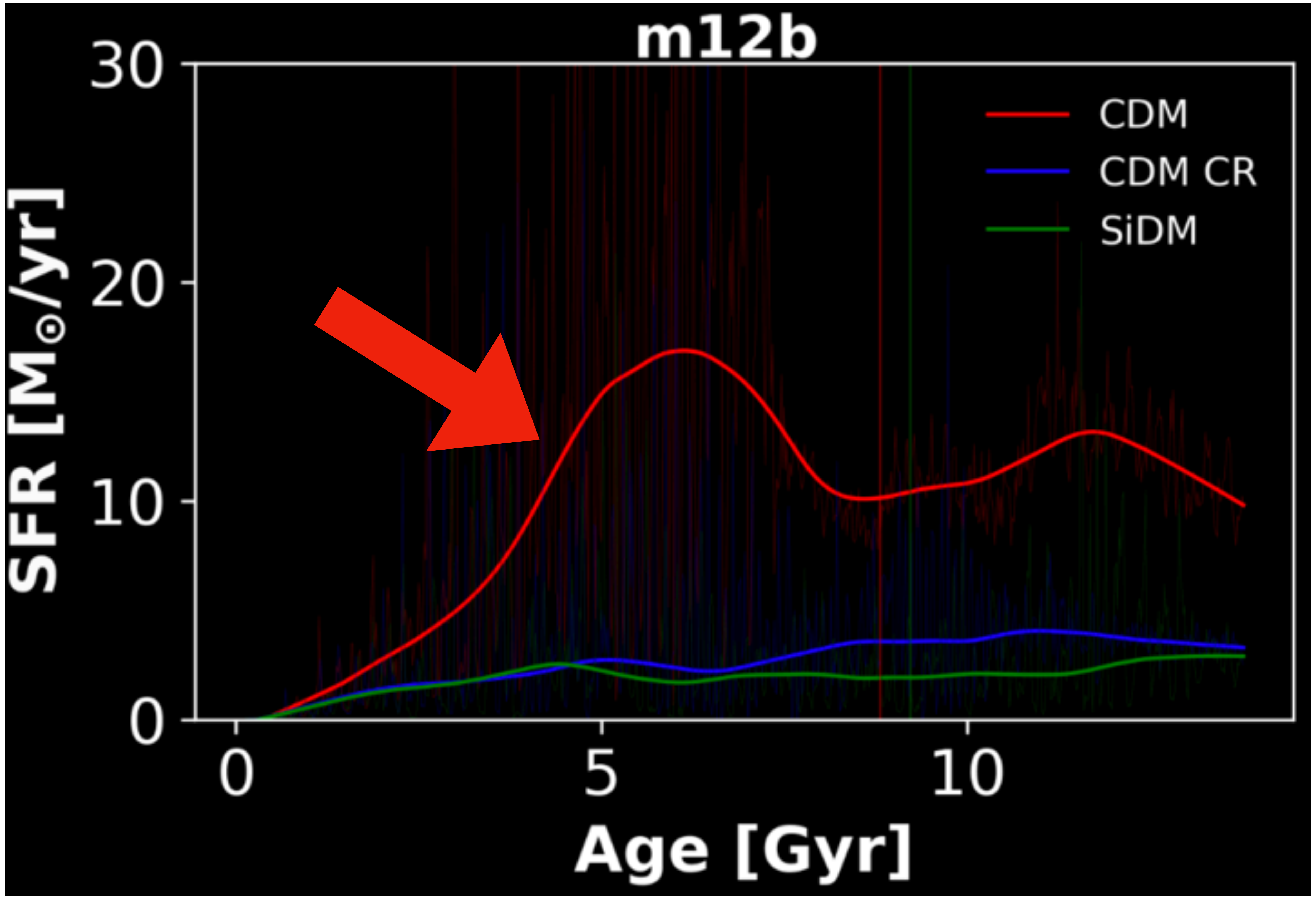
1 kpc

SIDM, fixed σ = 1 cm^2/g
+ modified FIRE-2 recipes
(cosmic ray heating)

Evolution of main galaxy in CDM/SIDM

Arora, Sanderson et al in prep





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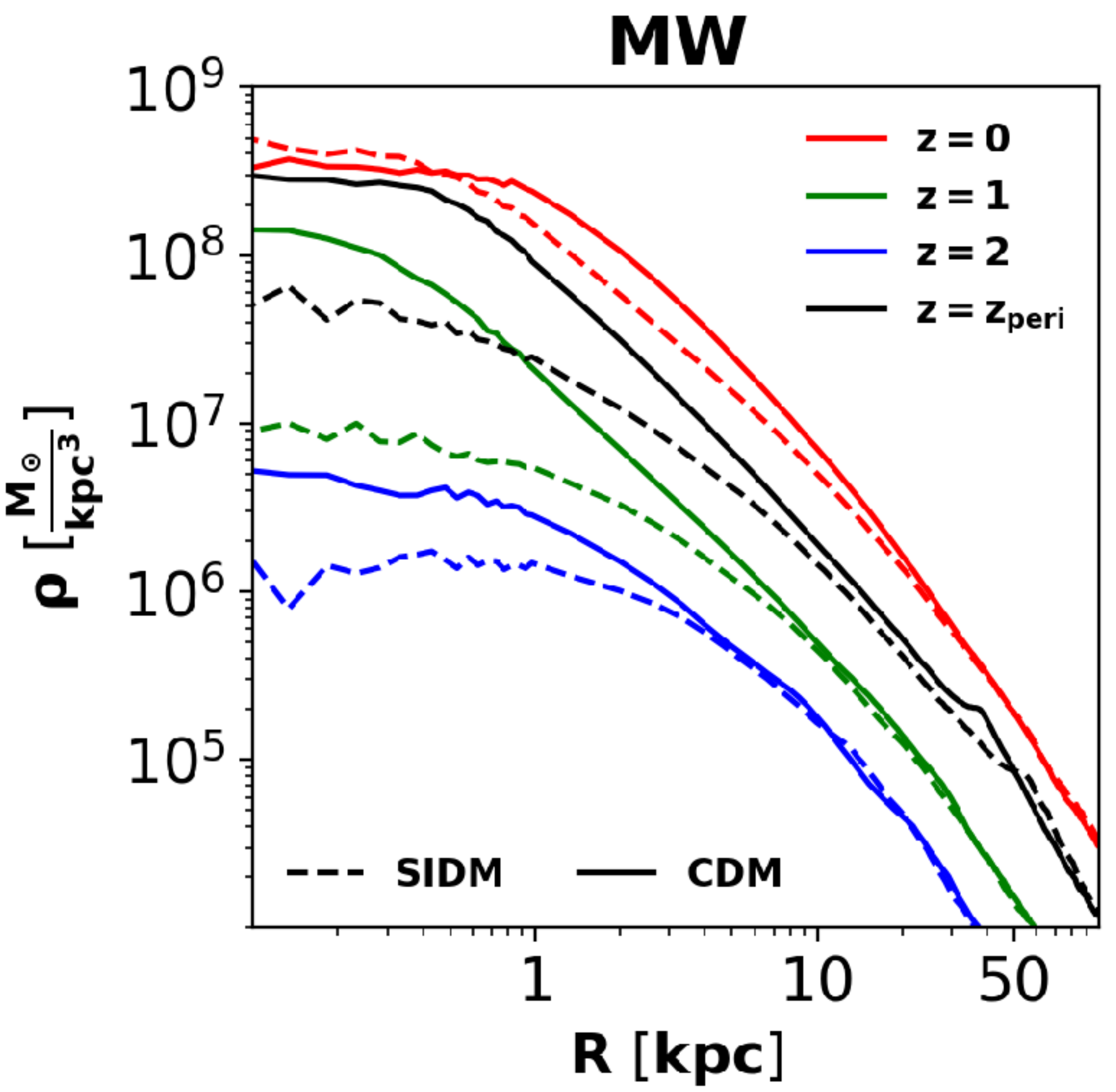

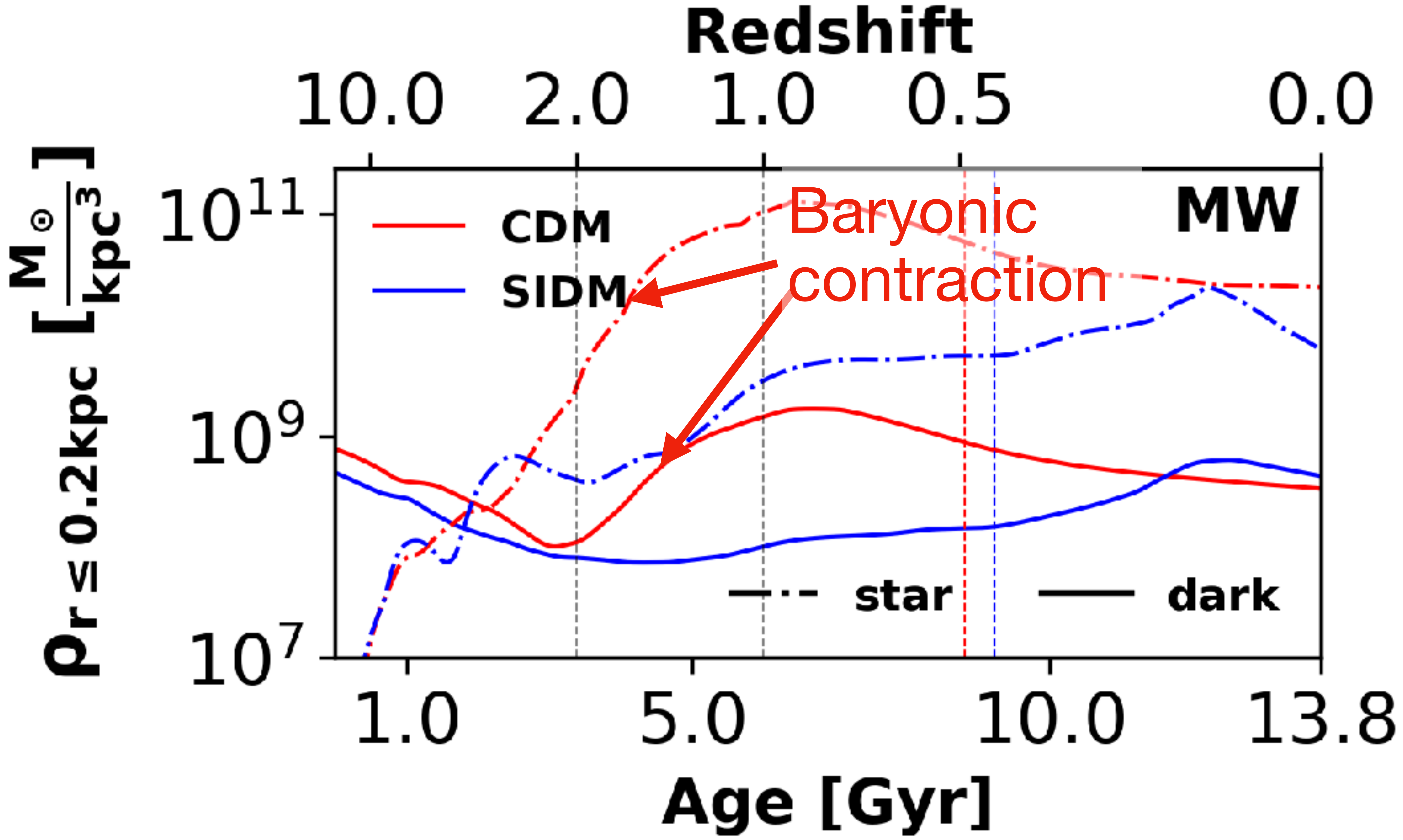

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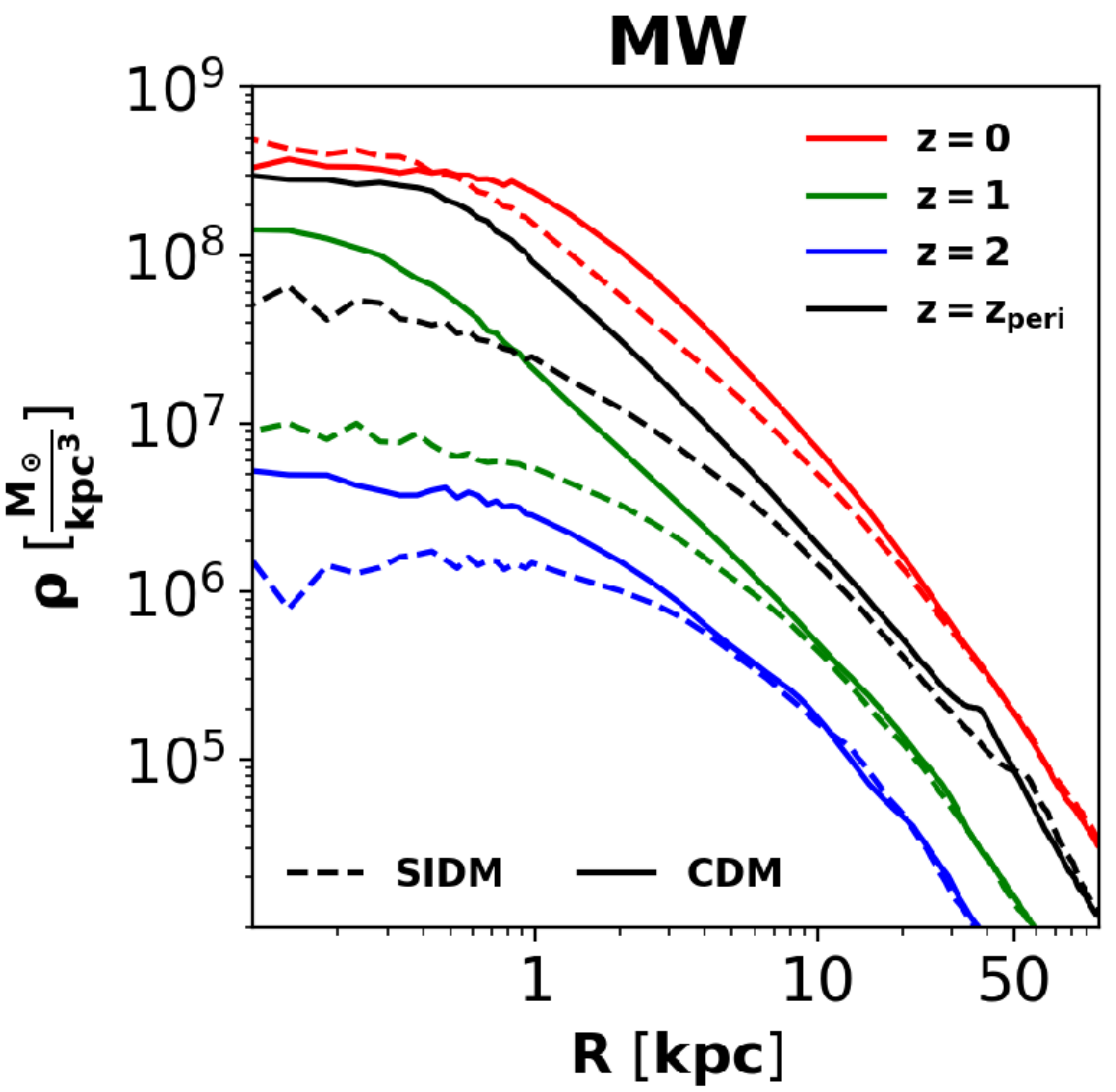
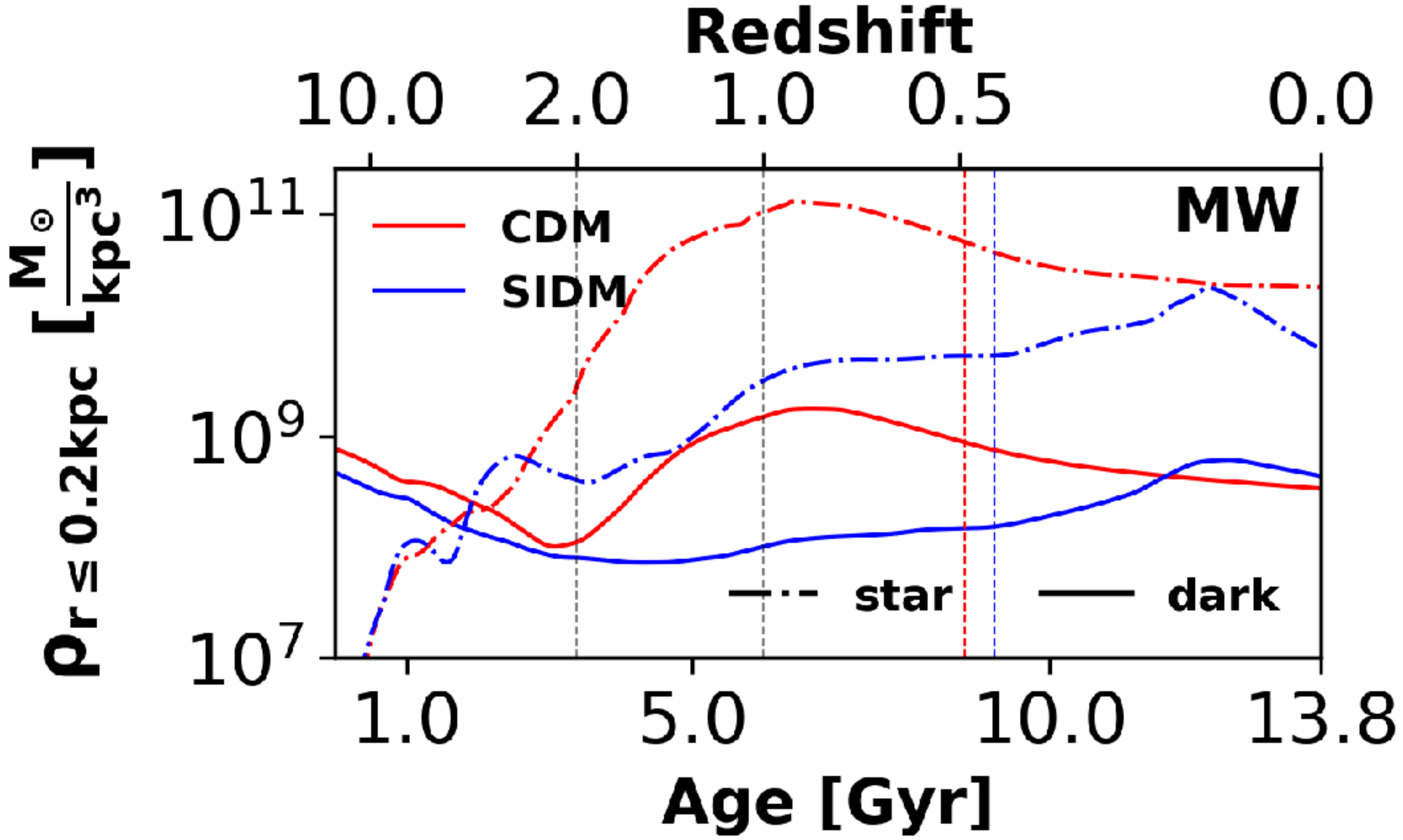
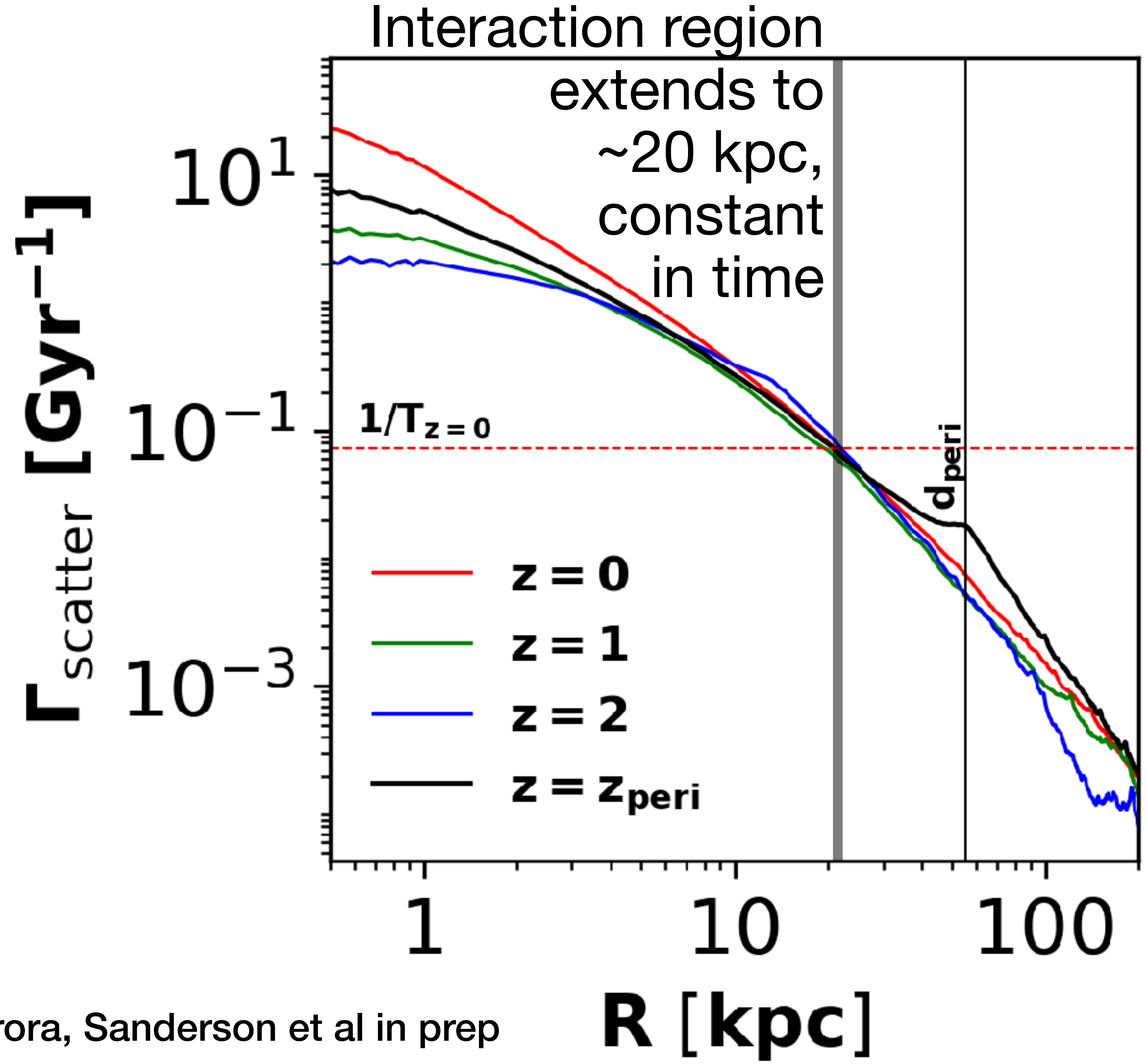
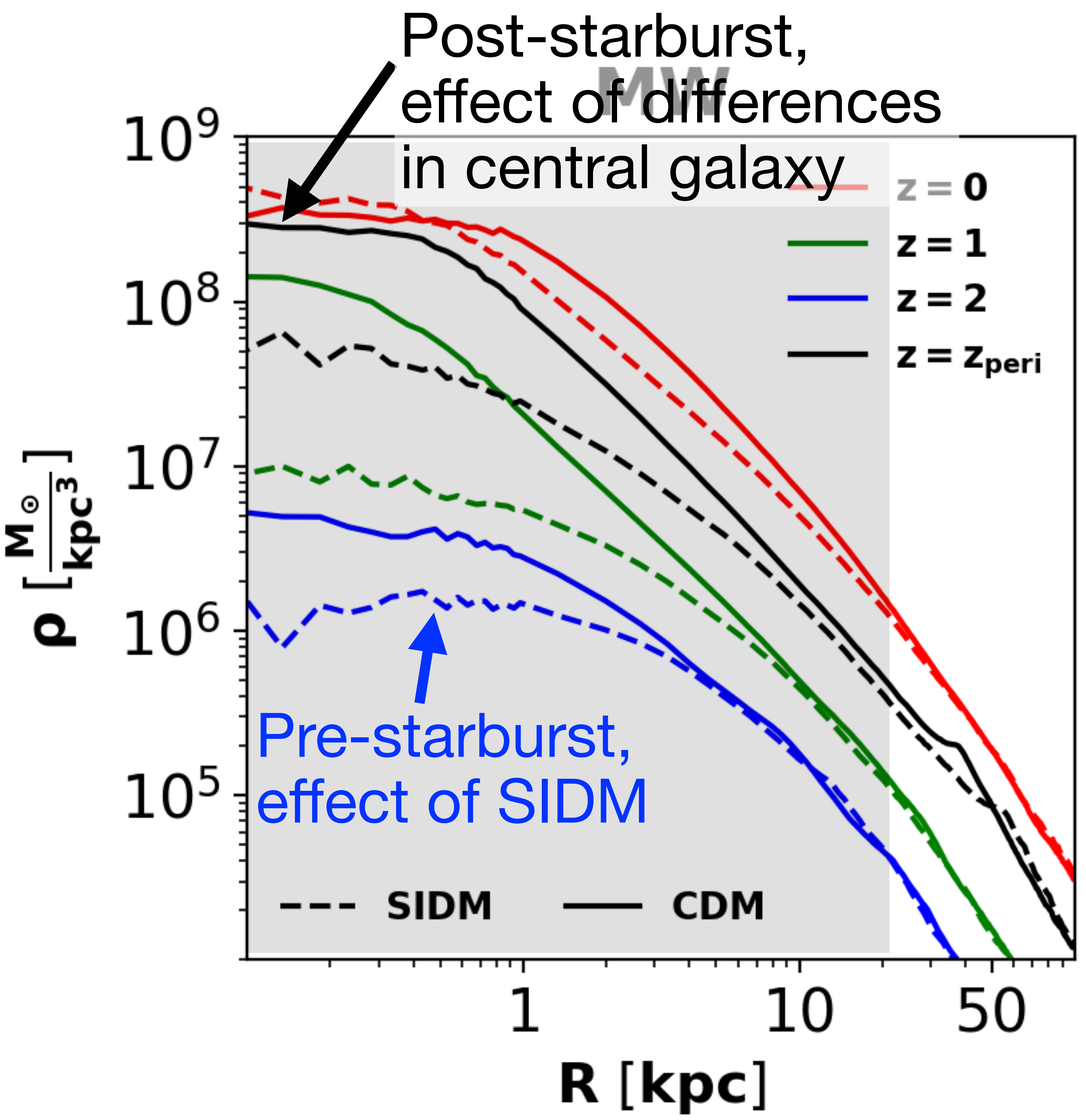




Baryonic contraction not as pronounced in SIDM sim (no starburst; lower stellar mass)

SIDM scattering rate in the main halo

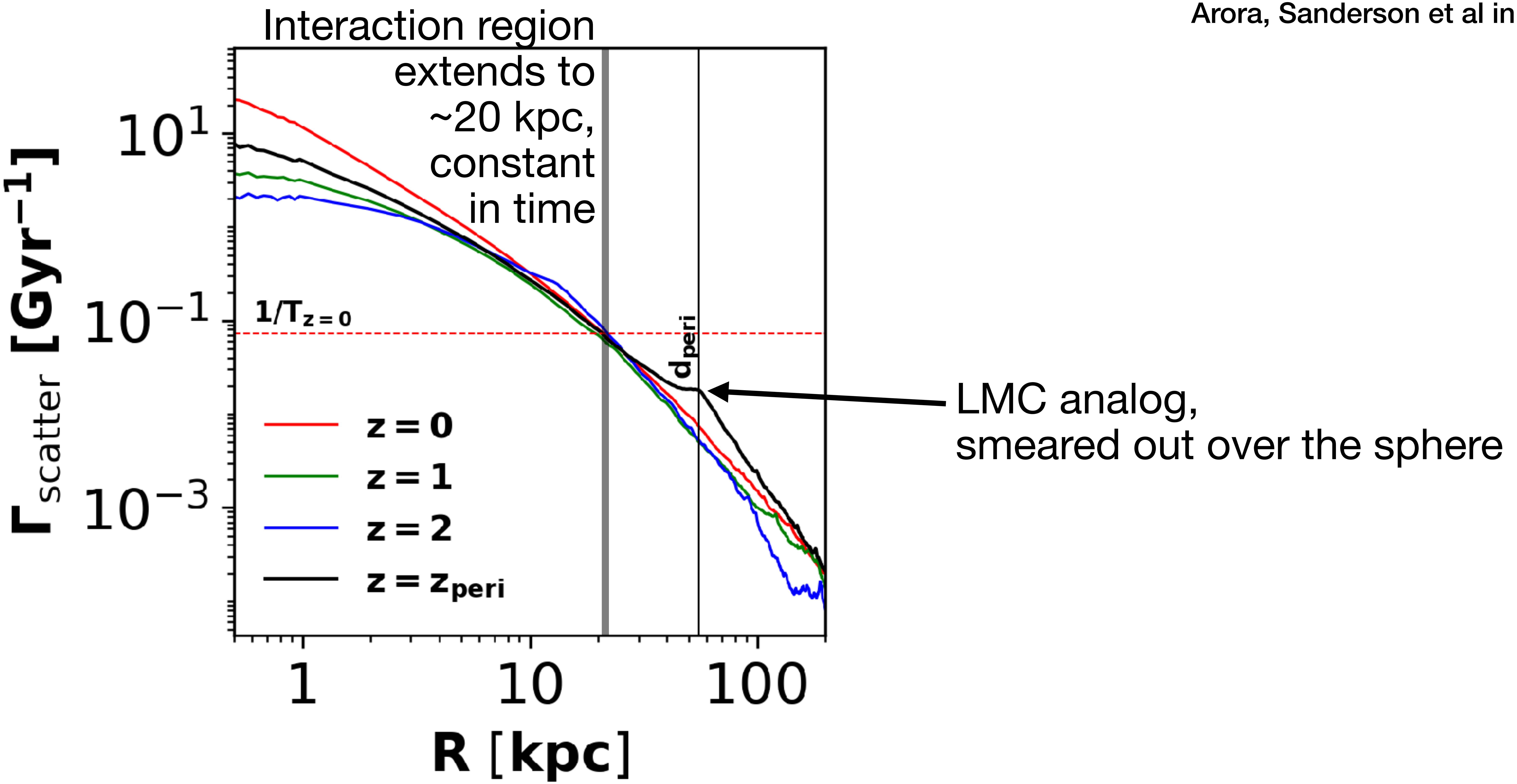


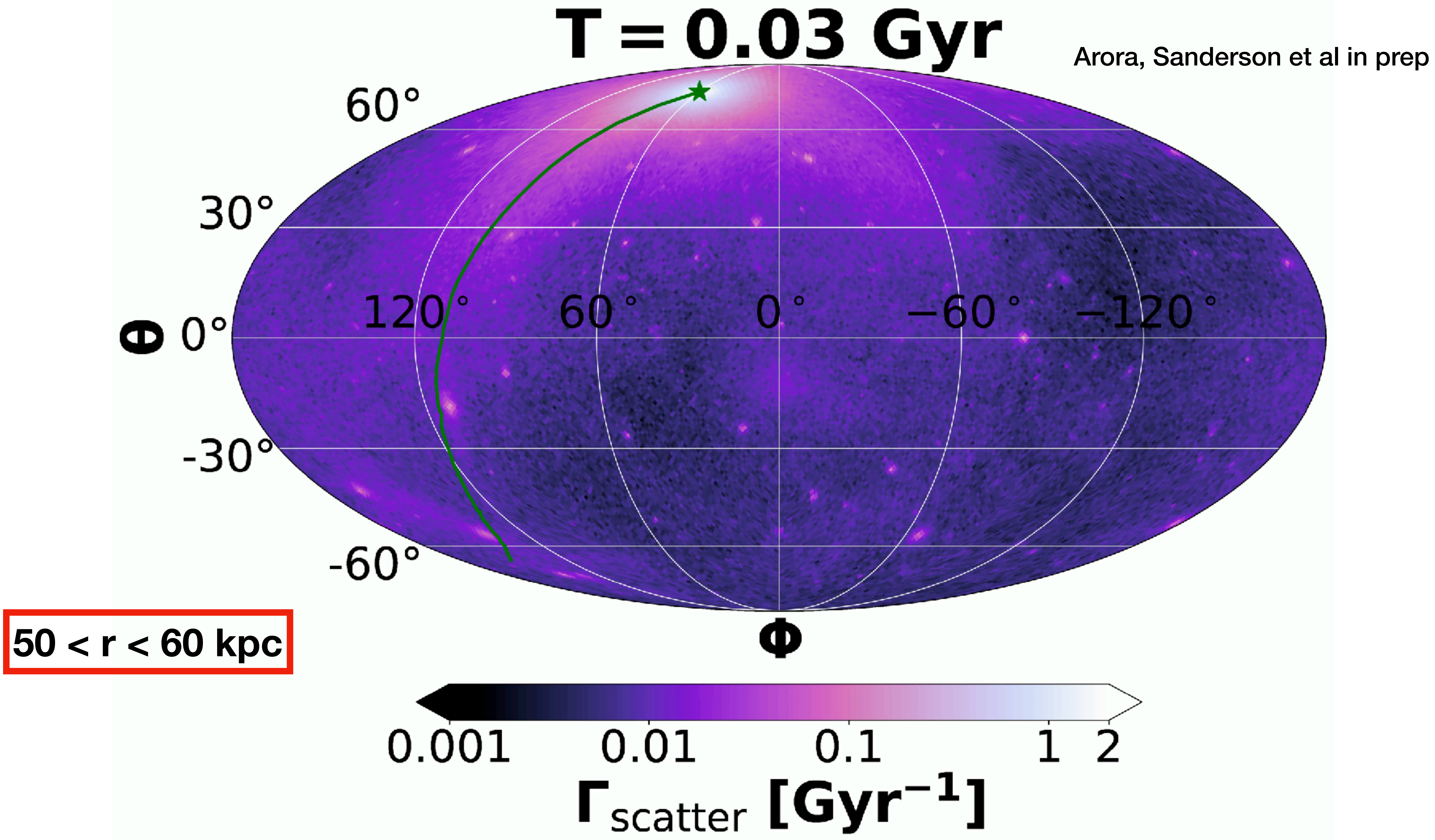


Arora, Sanderson et al in prep

SIDM scattering rate in the main halo

Arora, Sanderson et al in prep




T = 0.03 Gyr
Arora, Sanderson et al in prep
60°
30°
0°
-30°
-60°
Θ
120°
60°
0°
−60°
−120°
Φ
50 < r < 60 kpc
0.001
0.01
0.1
1
2
$\Gamma_{\rm scatter}$ [Gyr^{-1}]

The LMC analog at pericenter

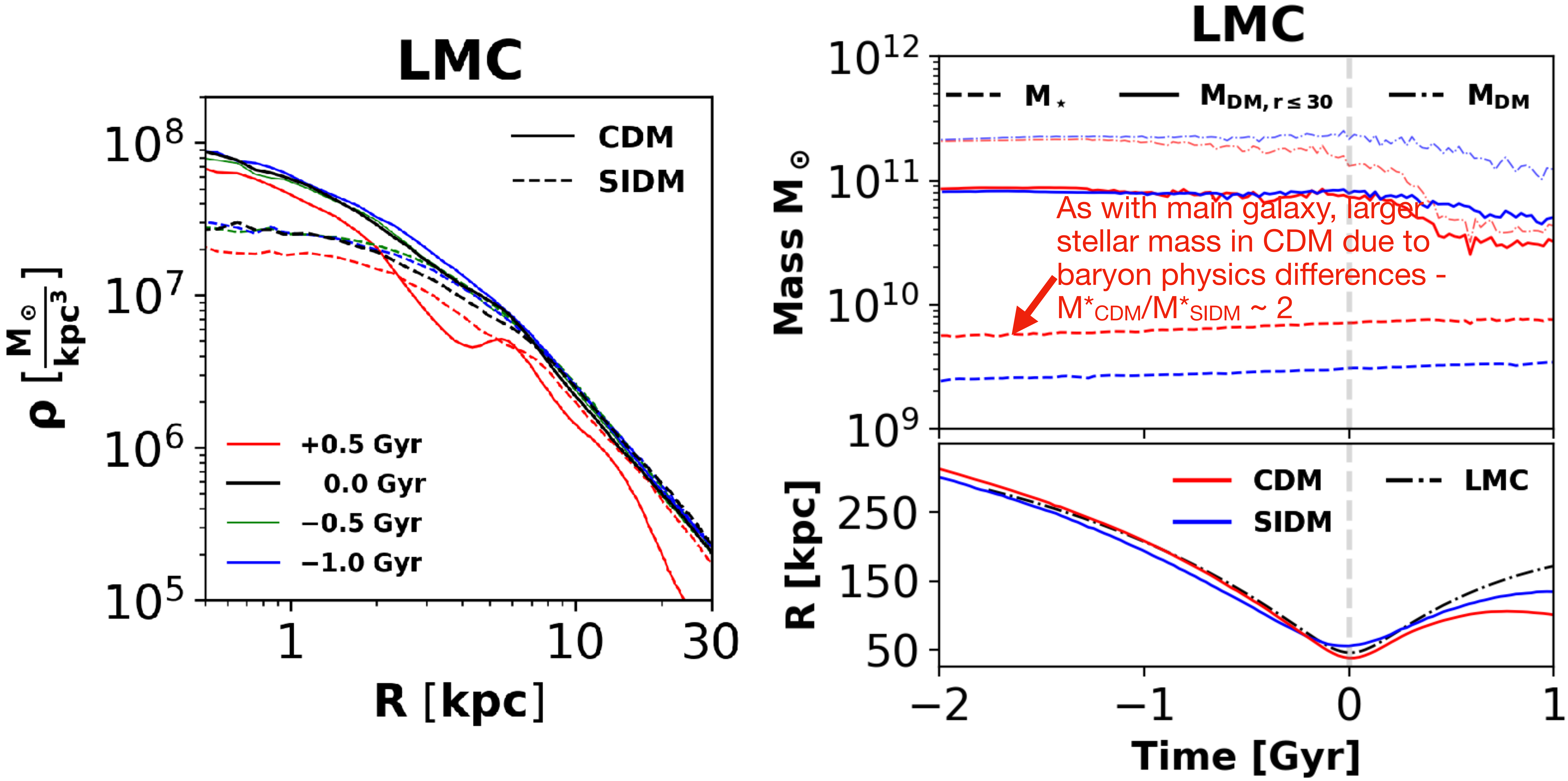
Arora, Sanderson et al in prep

CDM
M_{LMC}/M_{MW} = 7.8
d_{peri} = 38 kpc

SIDM
M_{LMC}/M_{MW} = 4.8
d_{peri} = 51 kpc

Properties of the LMC analog

Arora, Sanderson et al in prep



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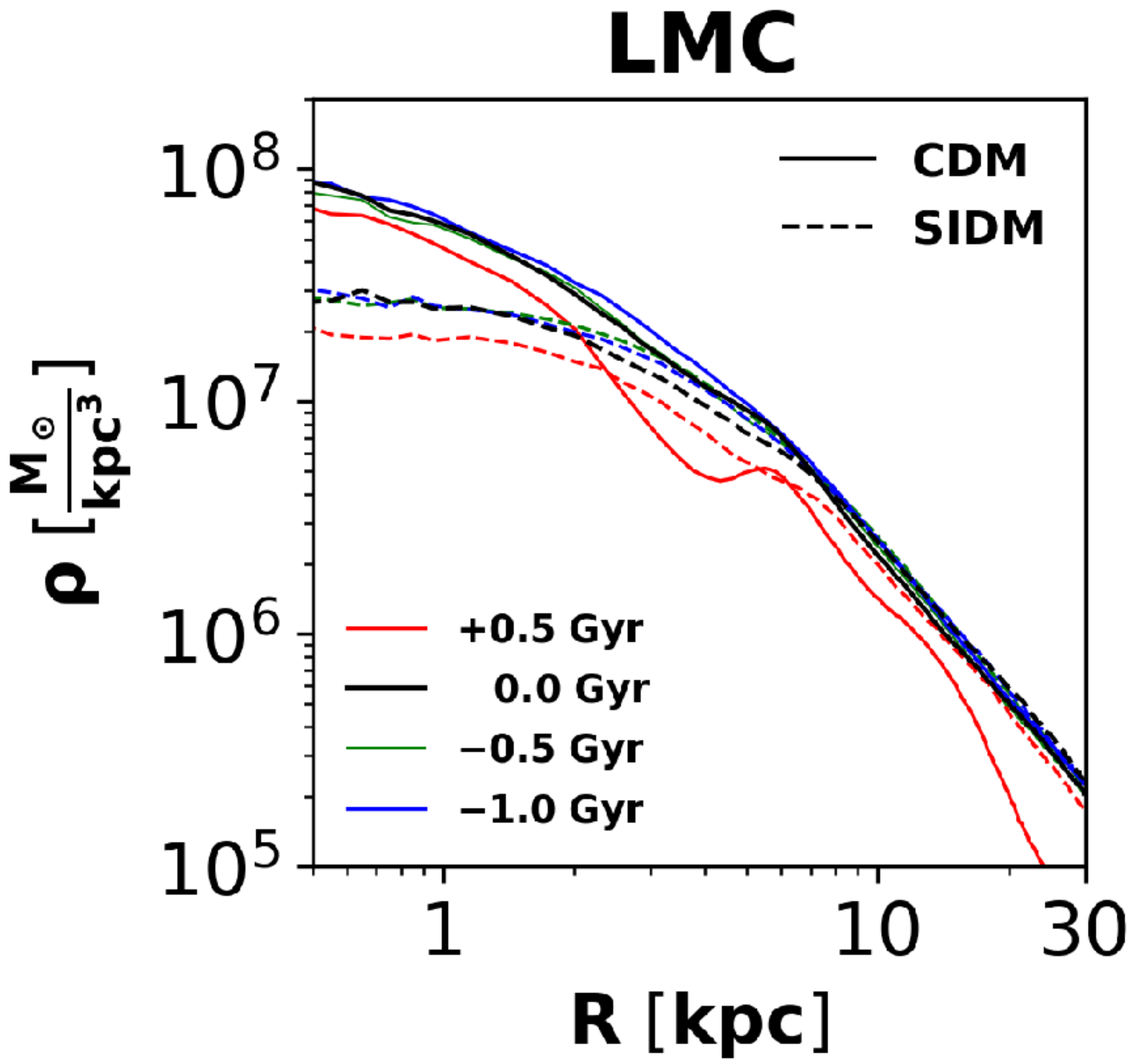

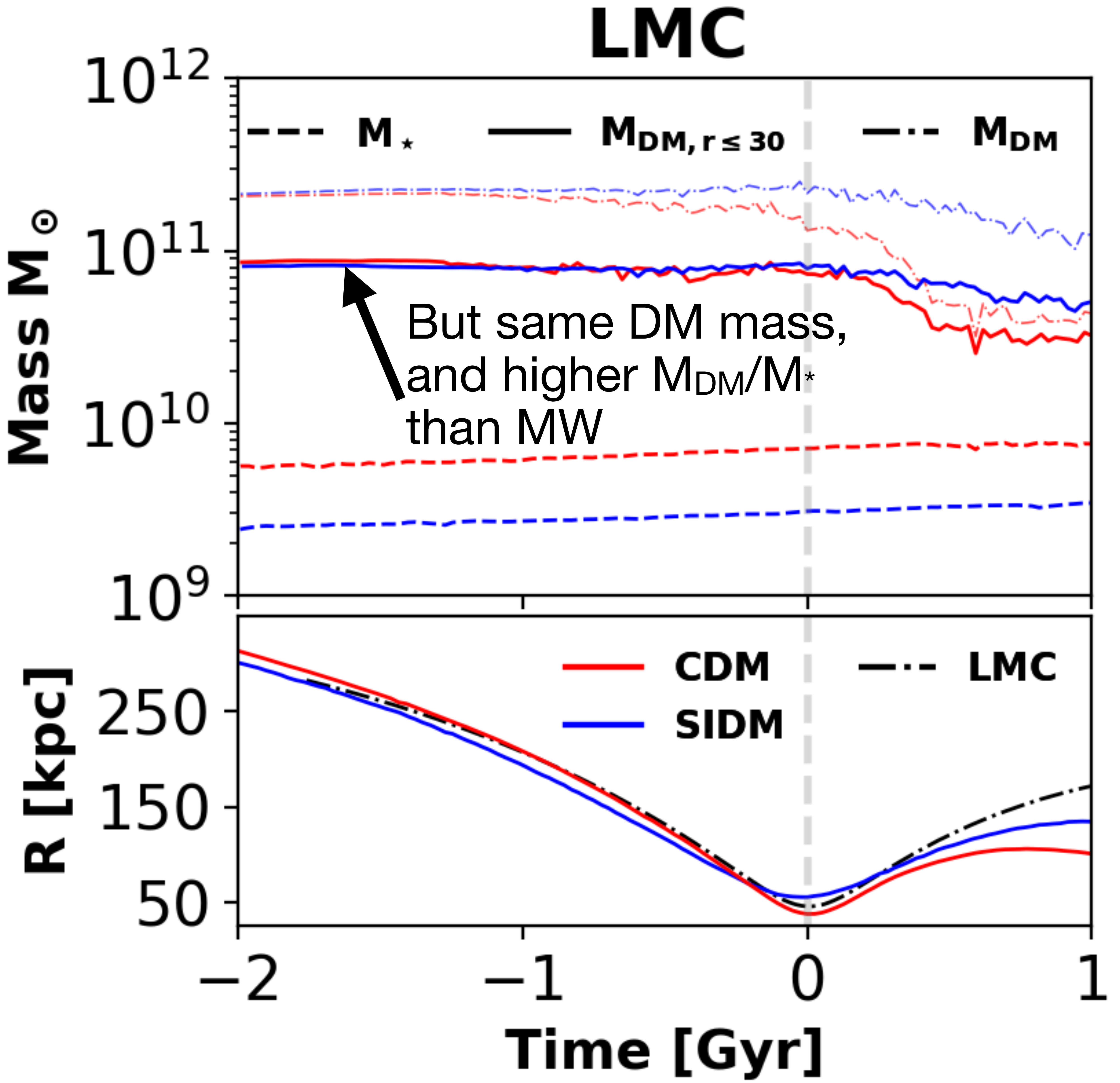

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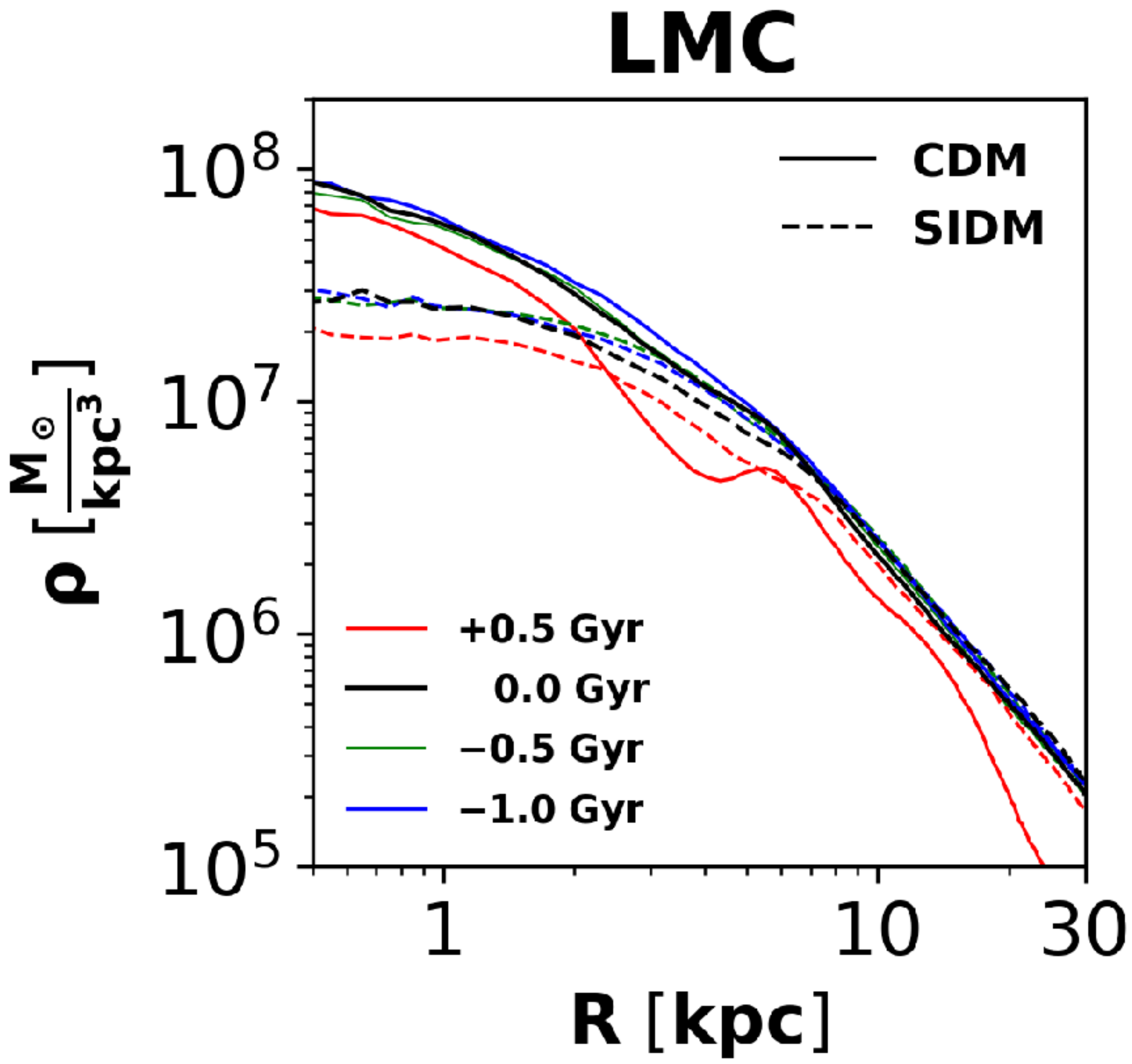
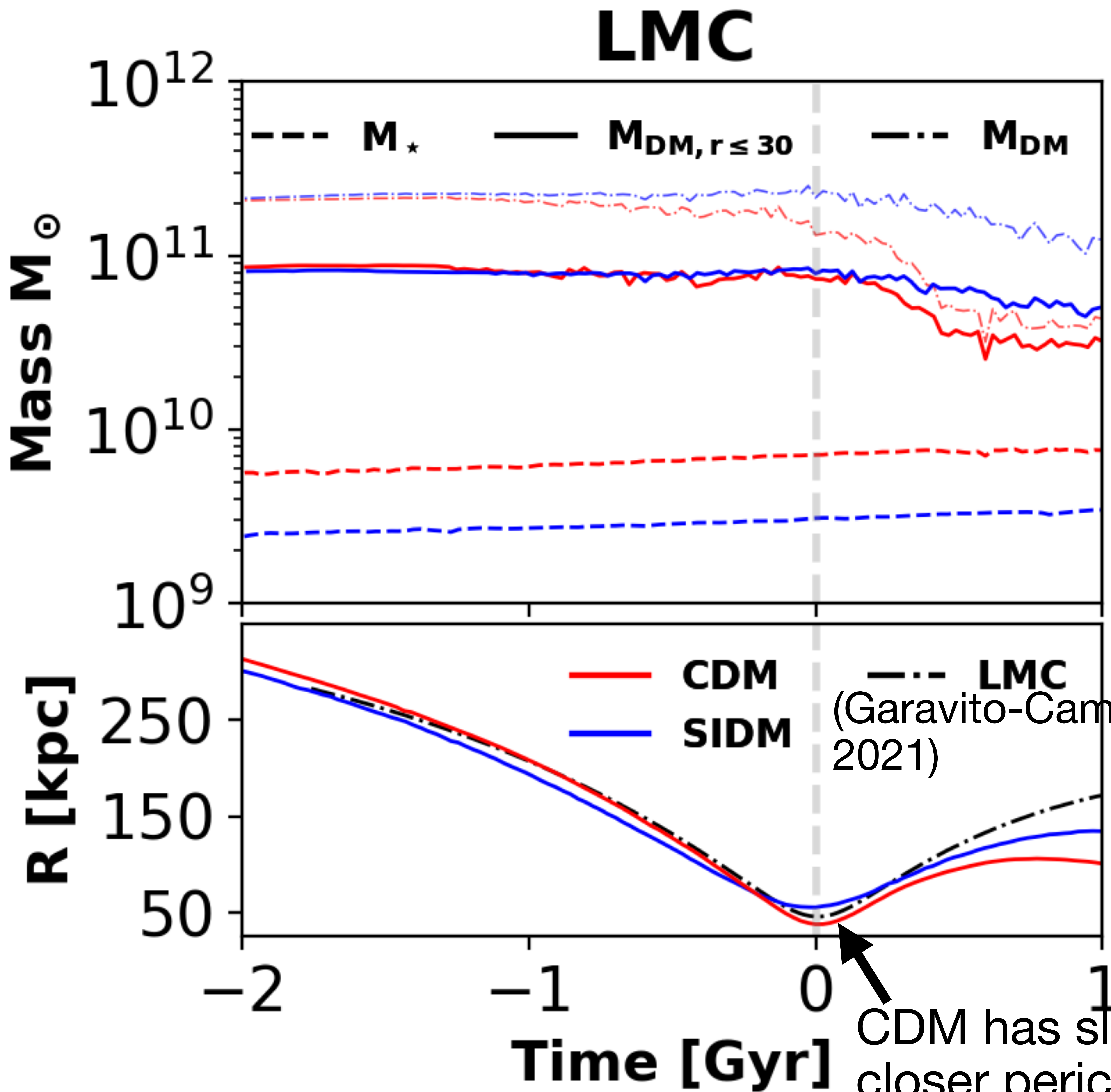


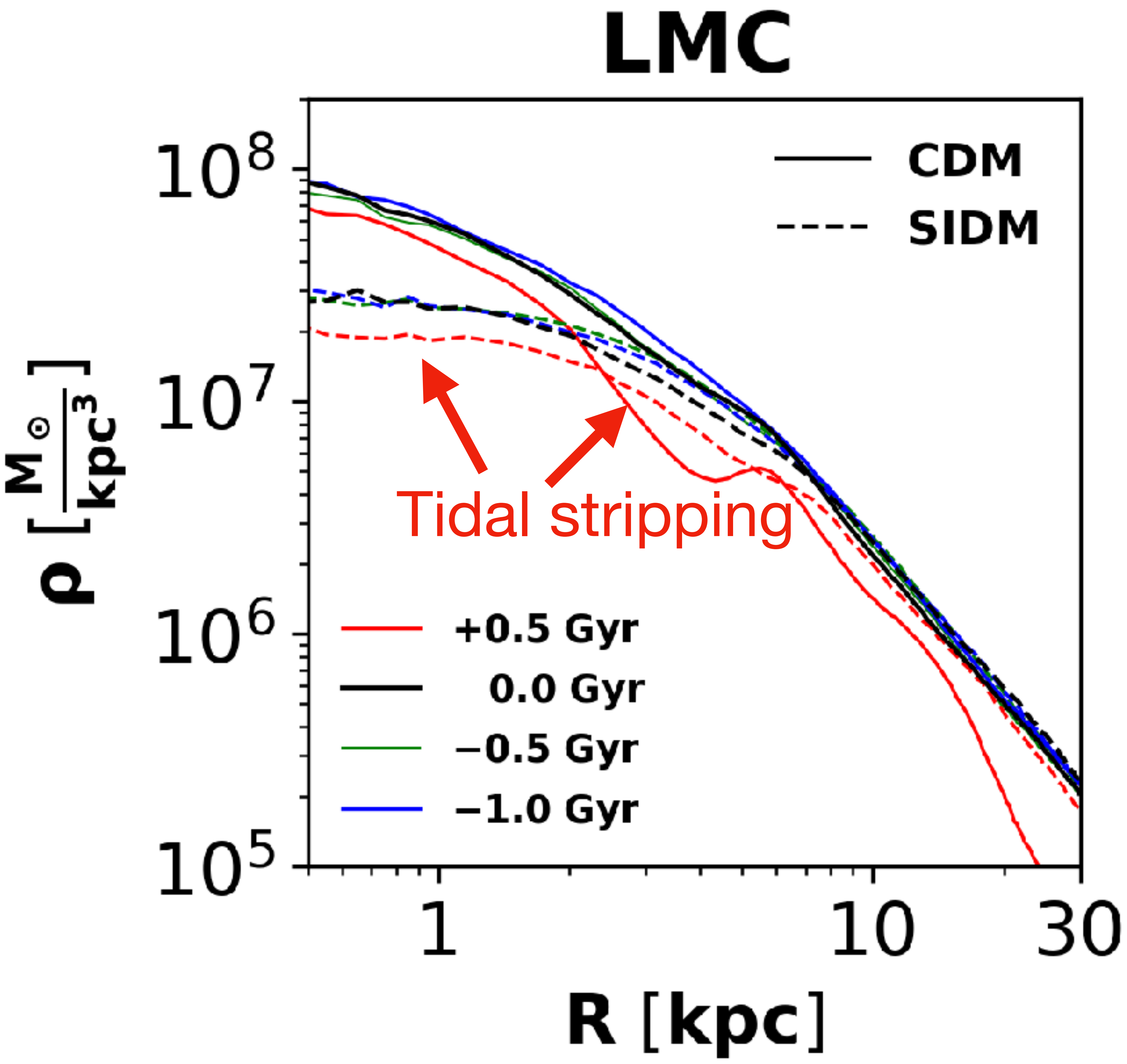


(Garavito-Camargo+, 2021)

CDM has slightly closer pericenter*

Properties of the LMC analog

Arora, Sanderson et al in prep

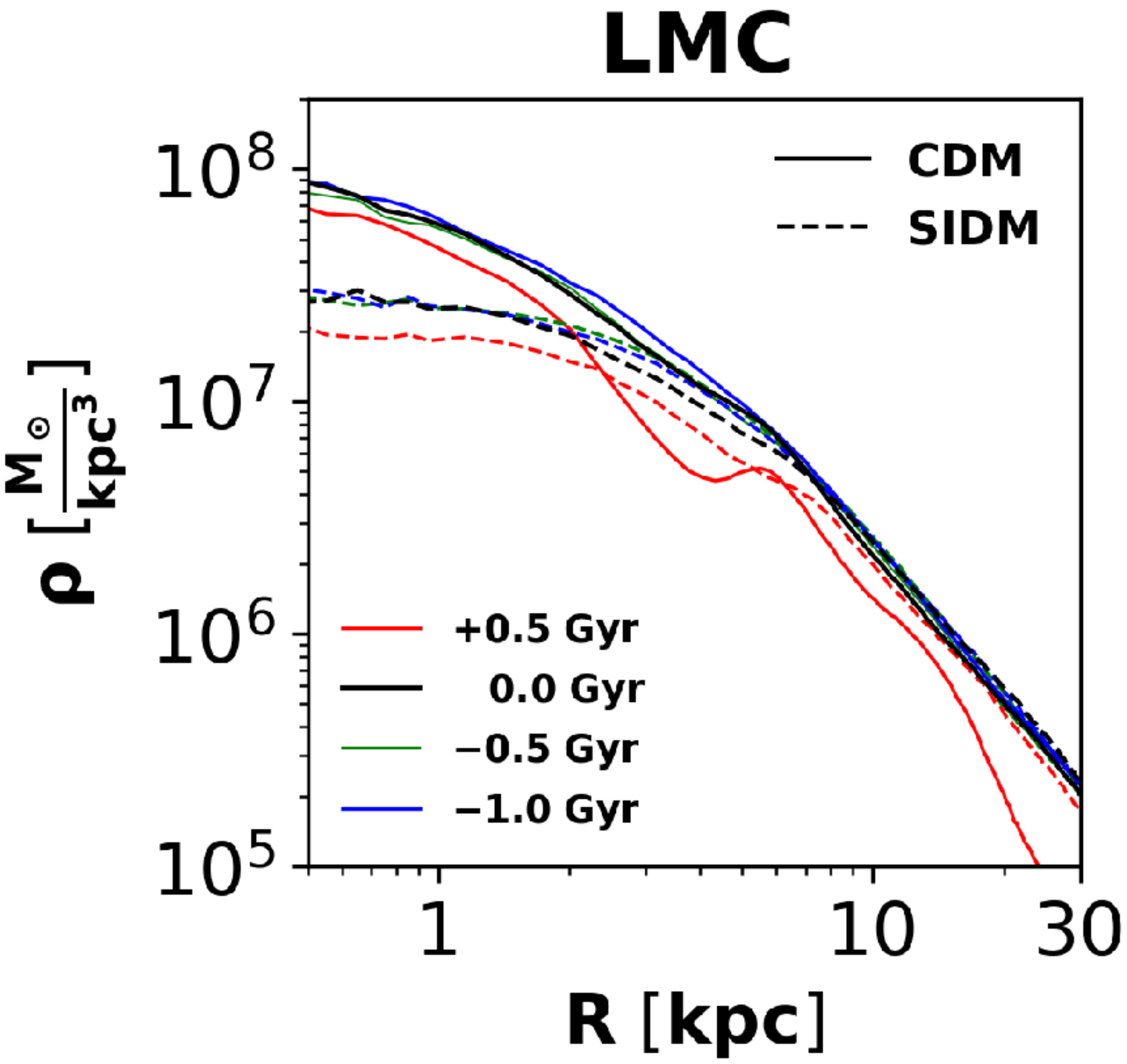


Quantity	LMC	CDM simulation	SIDM simulation
M_{MW}/M_{LMC}	5—10	7.9	4.8
d_{peri} [kpc]	50	38	56
v_{tot} [km/s]	380	350	292
Tidal tensor [λ_{max}, 1/Gyr^2]	~23	31	11

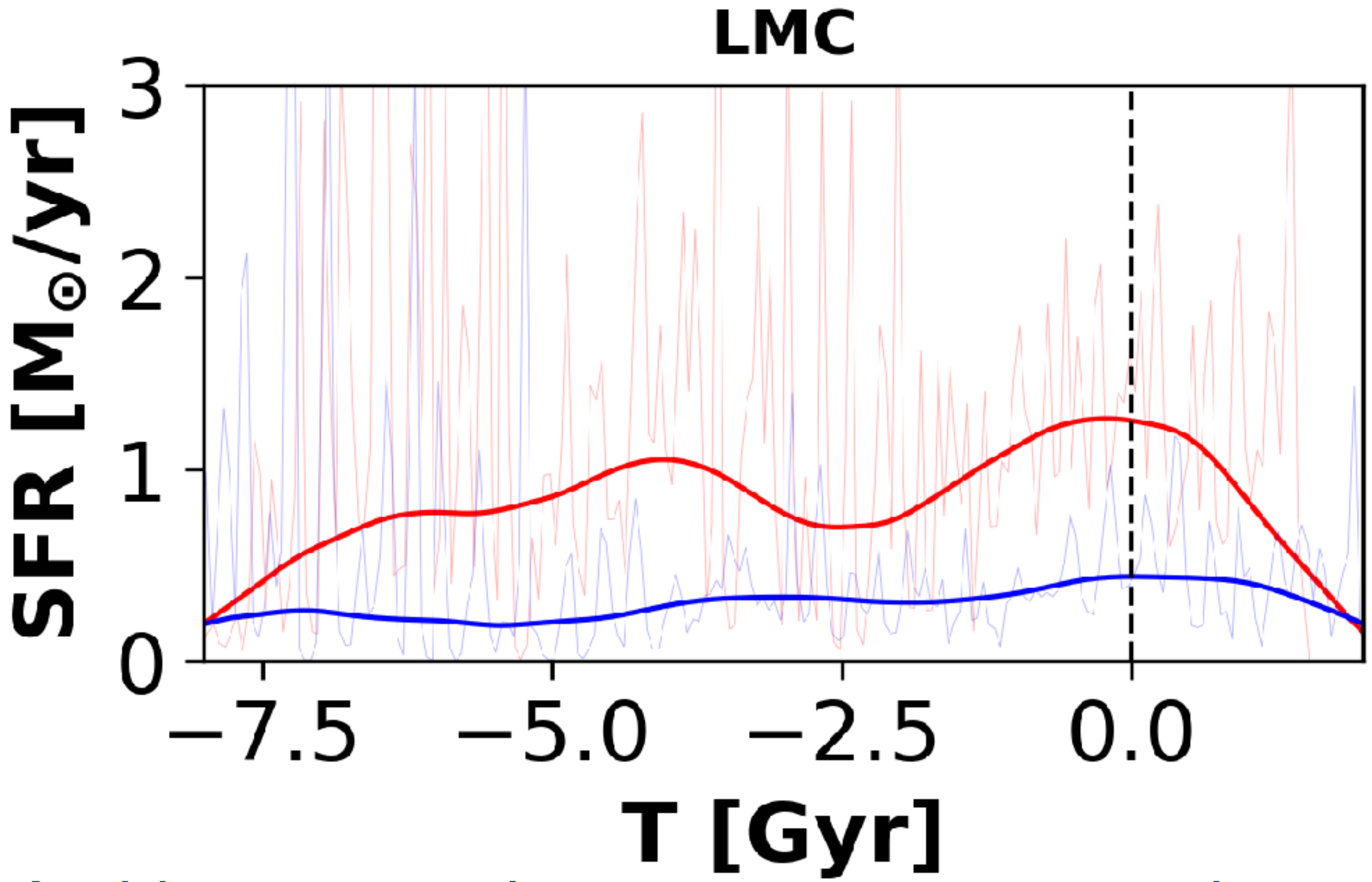
Tidal stripping is 3x stronger in ***CDM*** due to difference in central galaxy concentration — baryons, not DM.

Properties of the LMC analog

Arora, Sanderson et al in prep

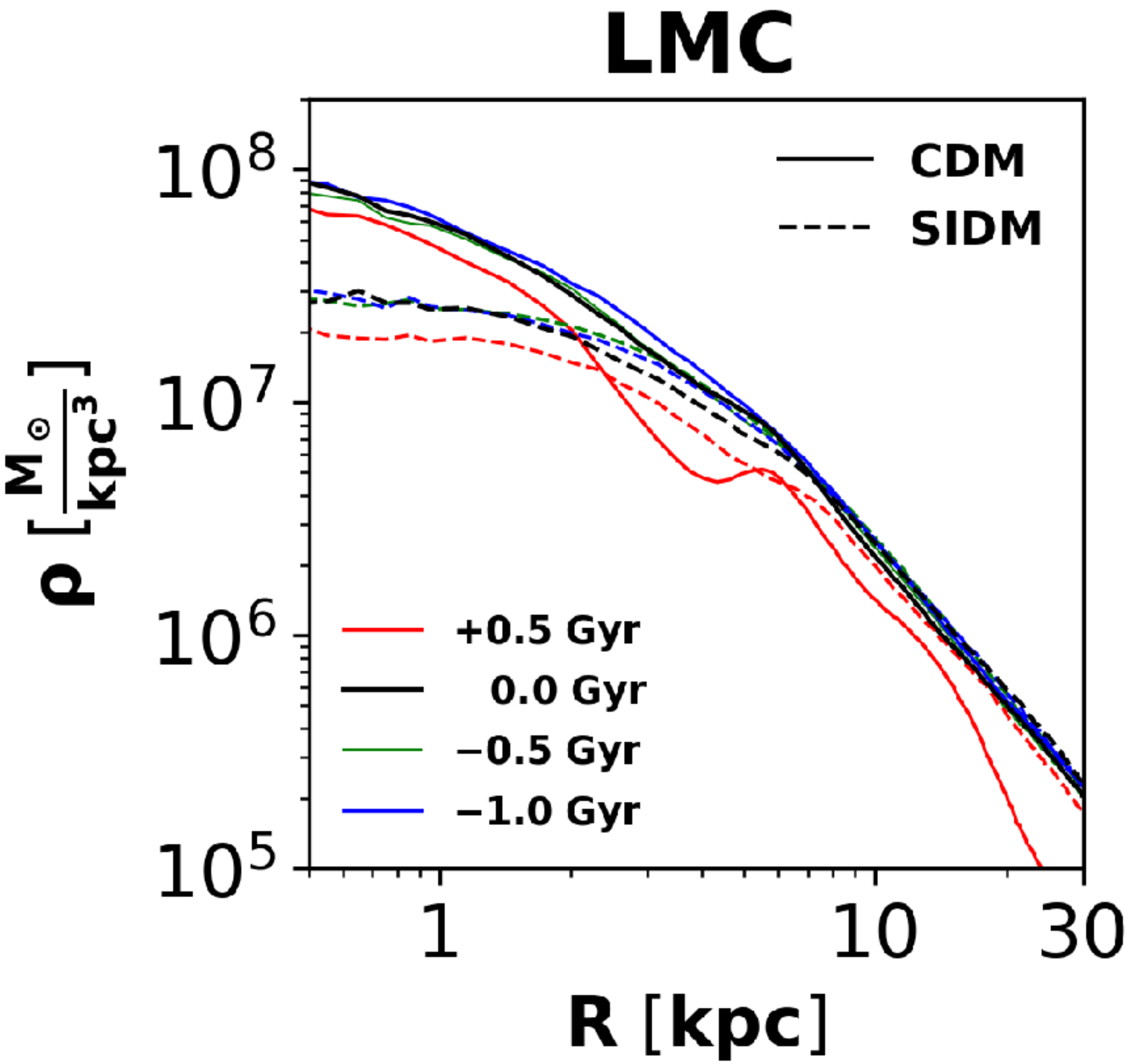


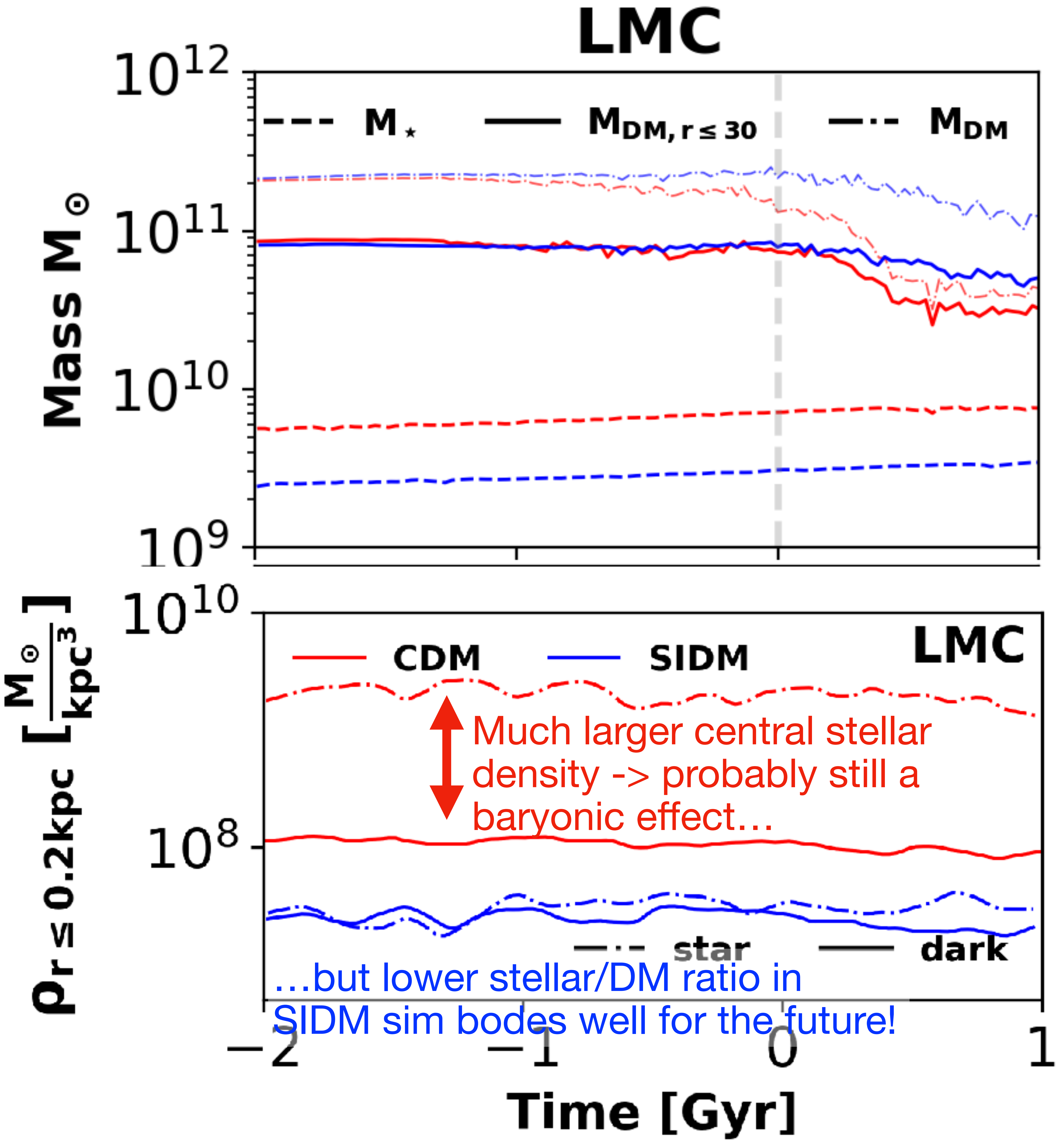
As for main galaxy, CDM forms more stars over time due to baryonic physics differences



At this mass scale one expects repeated starbursts to create a core…yet SIDM is still more cored than CDM —> ***DM, not baryons?***

Properties of the LMC analog

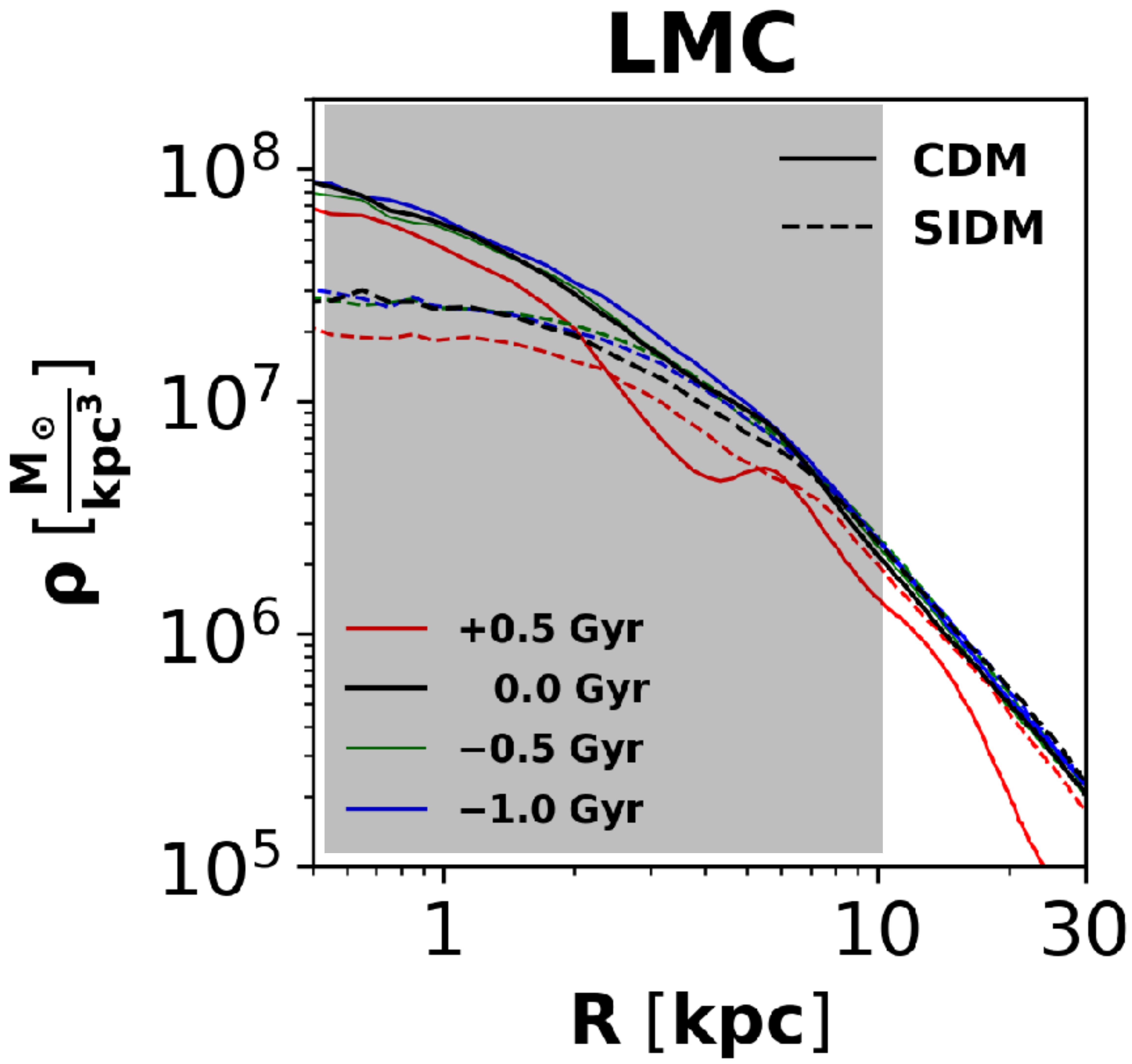


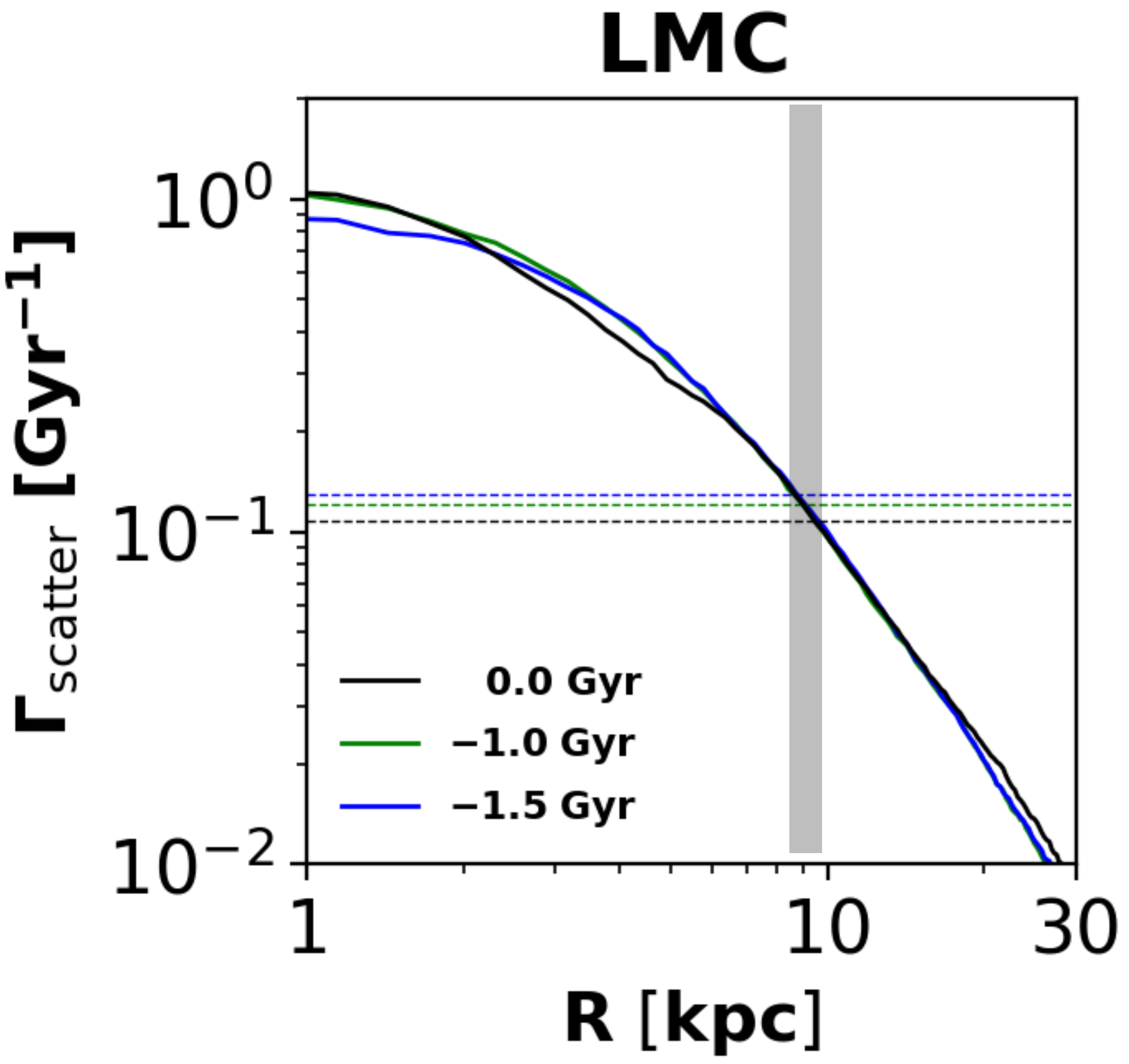


Arora, Sanderson et al in prep

Properties of the LMC analog

Arora, Sanderson et al in prep

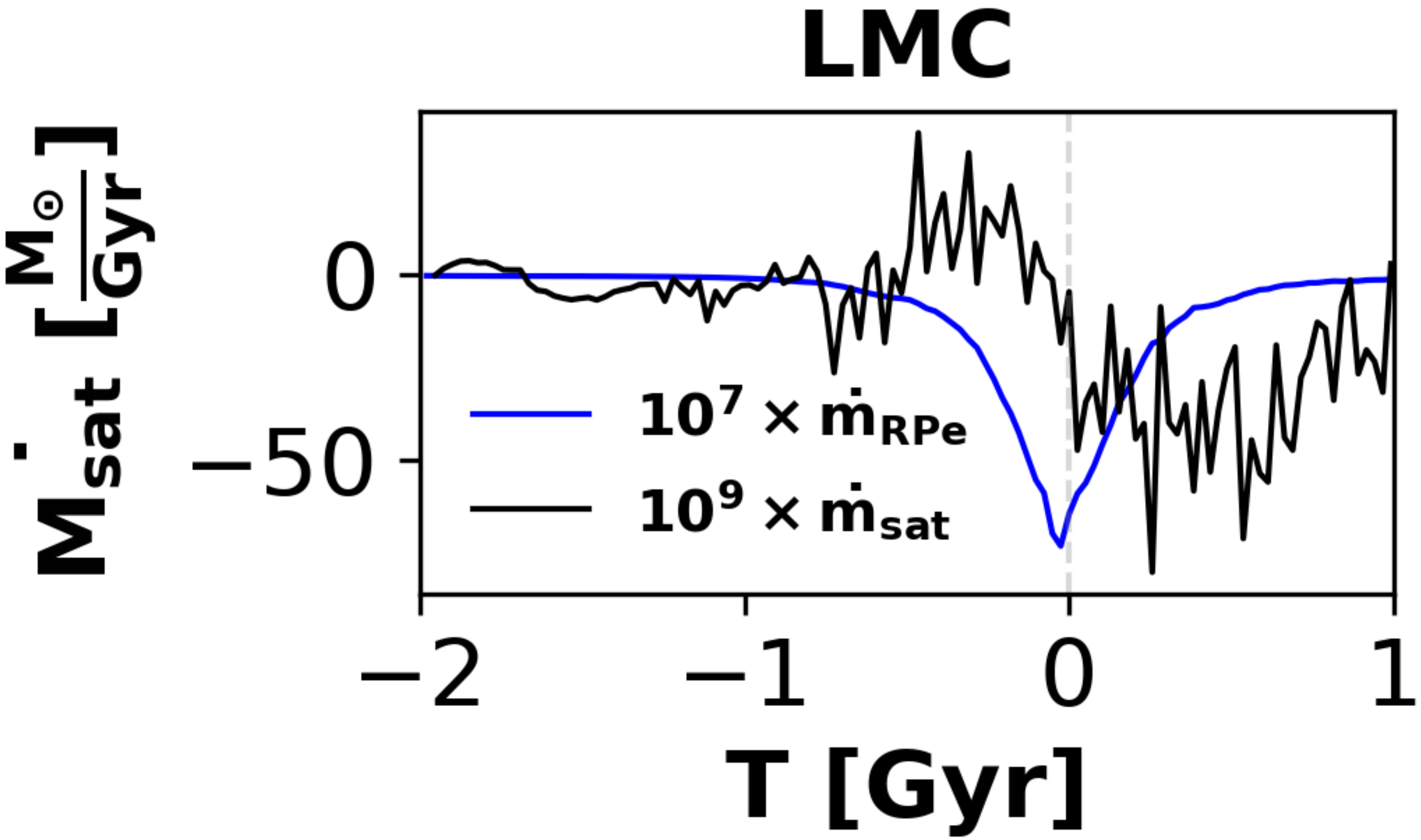




Arora, Sanderson et al in prep

compare to expectations from analytics

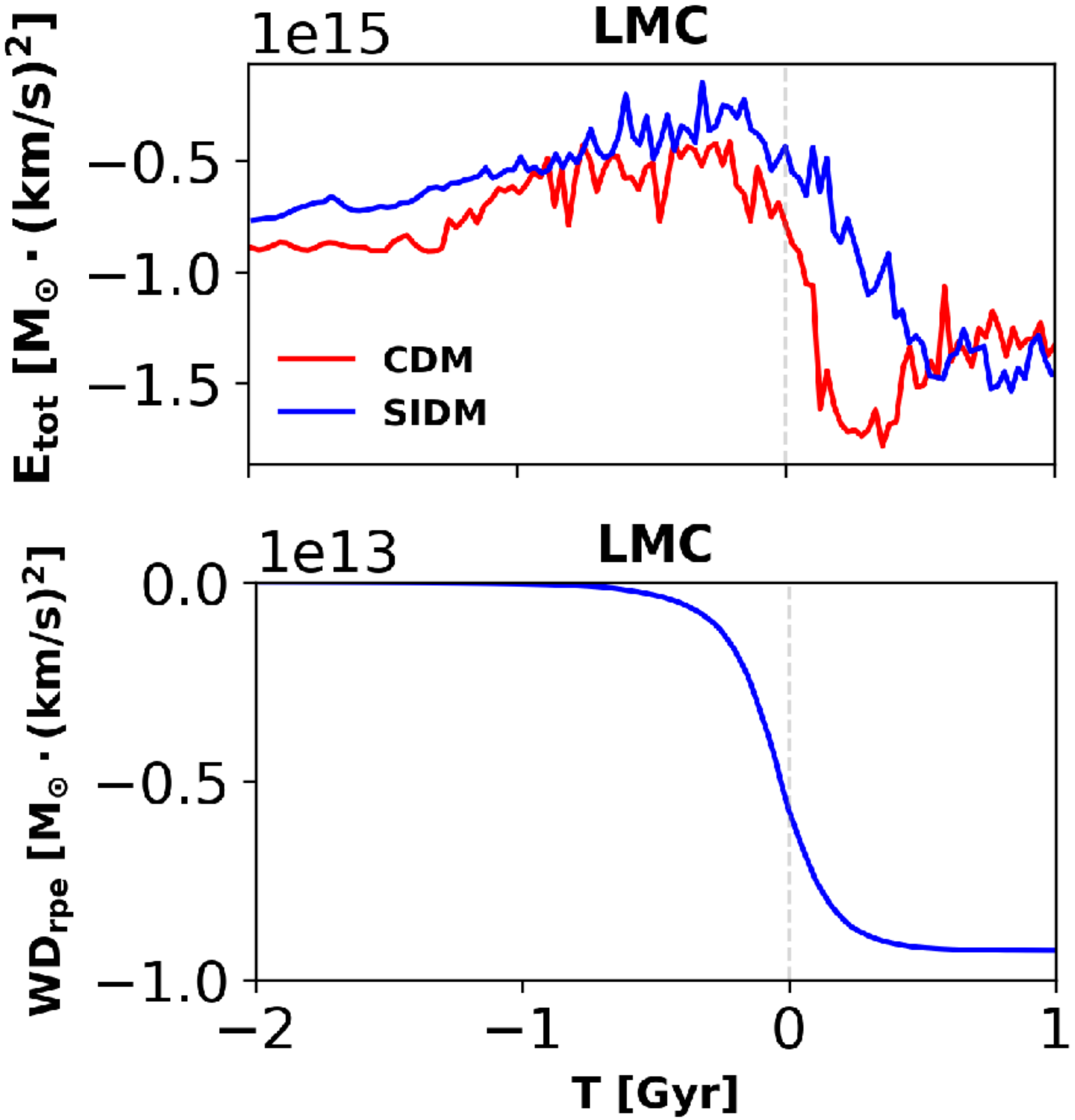
- Ram pressure stripping contributes about 2-3% of total mass loss
- *Timing* is different - RP stripping symmetric around pericenter, but tidal stripping mostly post-peri



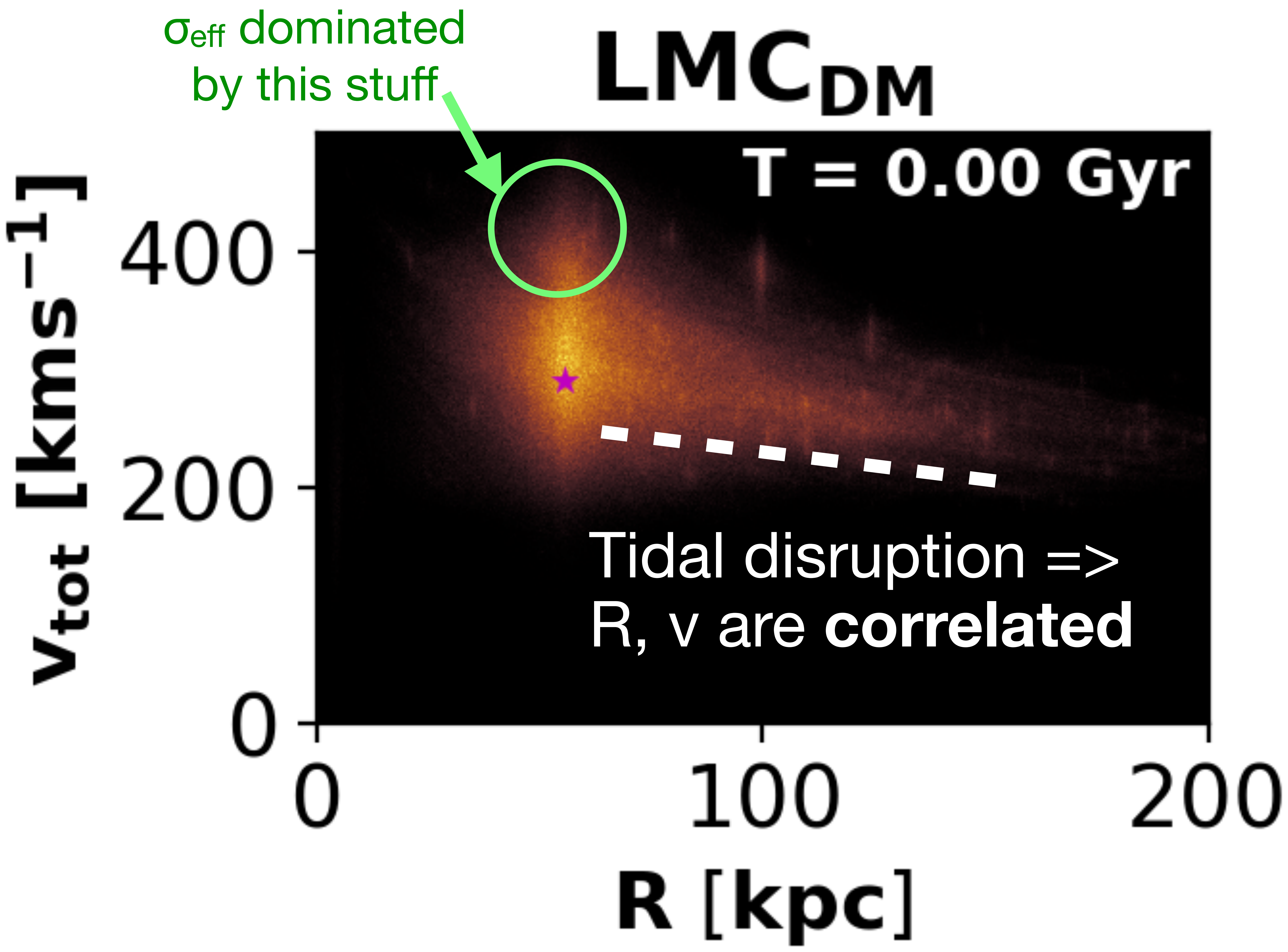
compare to expectations from analytics

- Ram pressure stripping contributes about 2-3% of total mass loss
- *Timing* is different - RP stripping symmetric around pericenter, but tidal stripping mostly post-peri
- Deceleration from ram pressure drag does work on earlier timescale relative to dynamical friction

Arora, Sanderson et al in prep

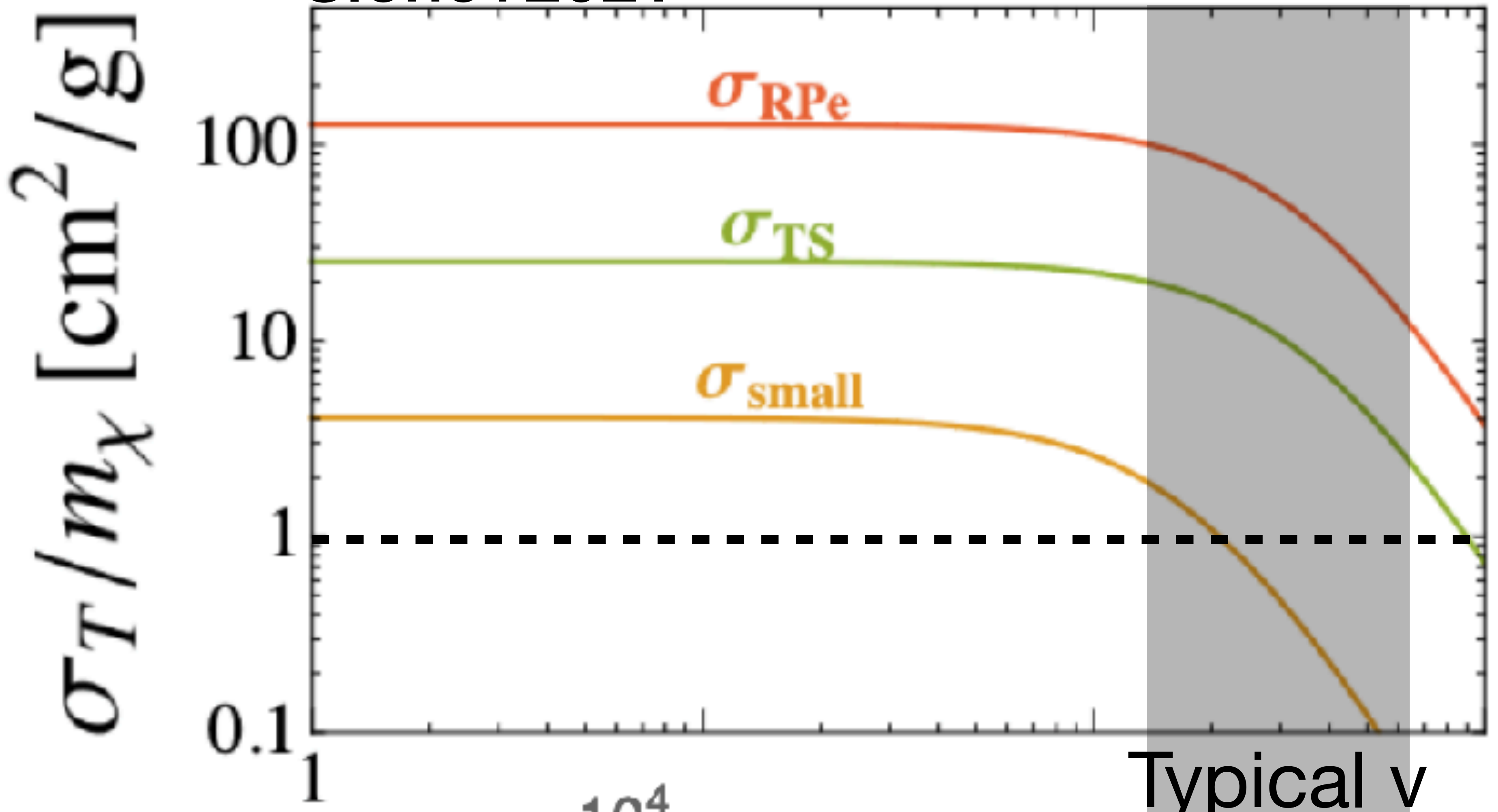


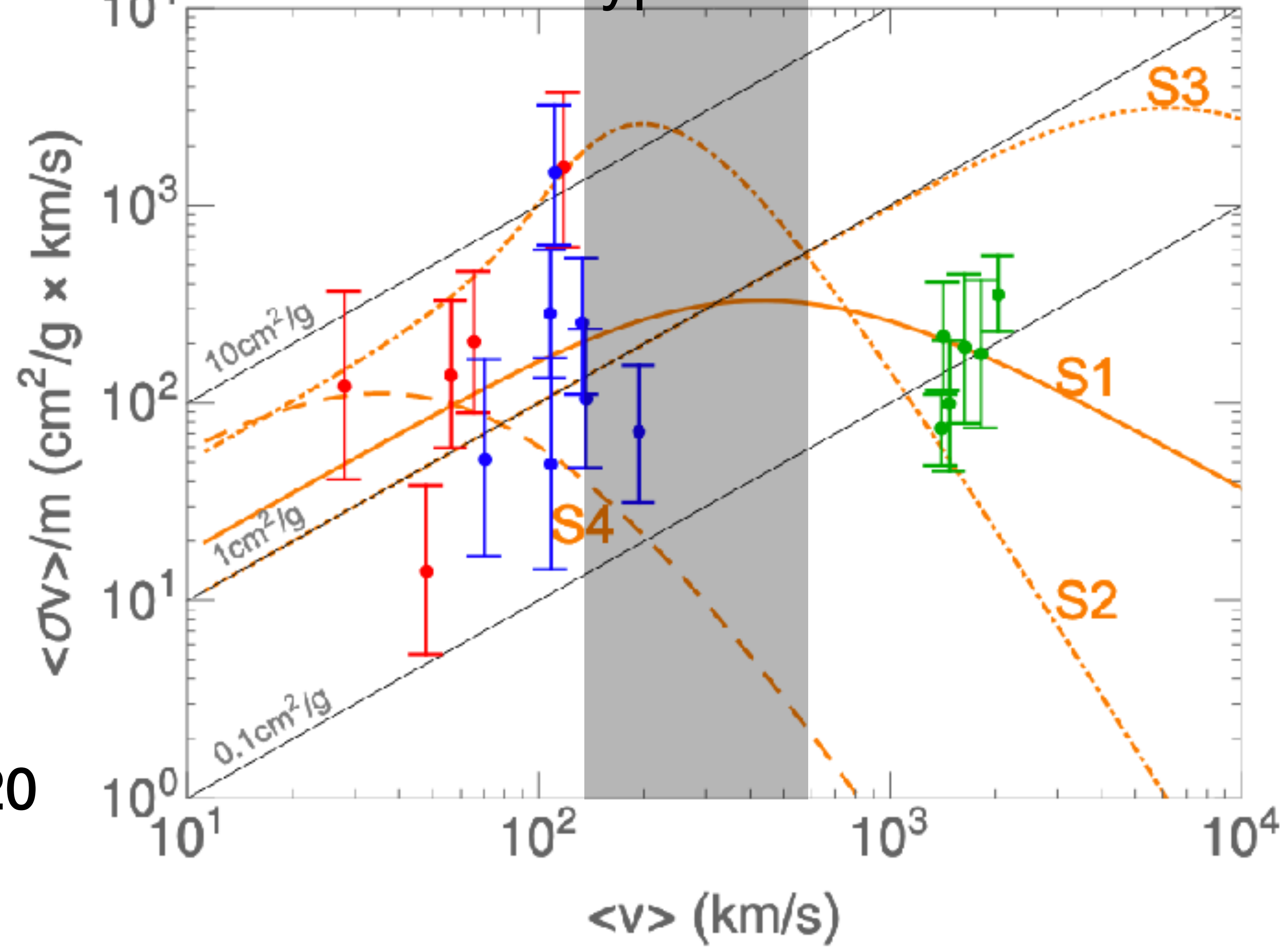
Mergers are a potentially powerful probe of velocity-dependence in the cross section



Arora, Sanderson et al in prep

Slone+2021





Chu+2020

summary

- Satellites amplify interaction rate *significantly, locally*
- Orbital evolution consistent with analytic expectations
- Timing offset of RP and DF effects poses interesting possibilities
- Tidal interactions probe the range where $d\sigma/dv$ large, and produce correlated $v(r)$ - incorporating velocity dependence in future sims is crucial to properly exploiting this
- Untangling baryonic / DM effects is complex, but possible with controlled numerical experiments and good choice of tests
- Real galaxy properties do vary by this much, so this is a useful real-world exercise
- Do we really know the LMC/MW's properties well enough yet to match sims to the level needed to test DM?