MARVEL-ous Dark Matter Constraints using Simulated Dwarf Galaxies

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CDM predictions at large scales ✓

CDM predictions at small scales ✗

(At least without considering baryons)

There is No Small Scale "Crisis" for CDM

CDM= cold dark matter, WDM= warm dark matter, SIDM= self-interacting dark matter

"challenge"	CDM+ baryons	WDM	SIDM	
Bulge-less disk galaxies	✓			Governato+ 2010; Brook+ 2011
The Cusp/Core Problem	✓		✓	Pontzen & Governato+ 2012; Chan+ 2015
Too Big to Fail	✓	✓	✓	Zolotov+ 2012; Garrison-Kimmel+ 2015
Missing Satellites	✓	✓		Brooks+ 2013; Buck+ 2019
Missing Dwarfs	✓	✓	✓	Maccio+ 2016; Brooks+ 2017
Diversity	✓?		✓	Santos-Santos+ 2018; Munshi+ 2021
Planes of Satellites	Still to be explored/contentious			Buck+ 2016; Ahmed+ 2017

**Scorecard adapted from A. Brooks

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Bulge-less disk galaxies	✓	✓	✓
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Missing Satellites	✓	✓	✓
Missing Dwarfs	✓	✓	✓
Diversity	✓?	?	✓?
Planes of Satellites	Still to be explored		

**Scorecard adapted from A. Brooks

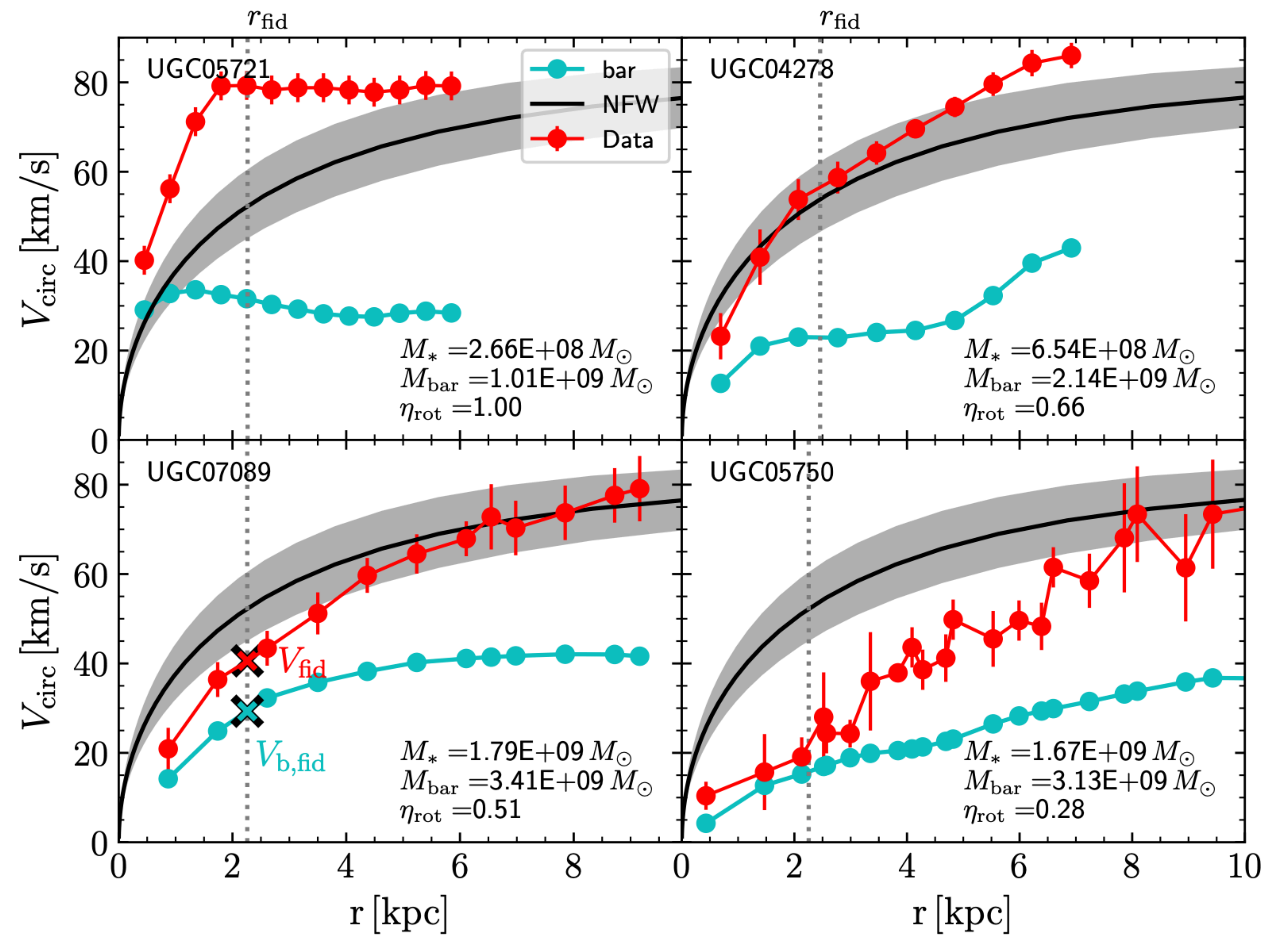
The Diversity of Rotations Curves "Problem"

ΛCDM Prediction:

For systems with the same V_{max} rotation curve shapes in ΛCDM are expected to be nearly identical

Observations:

For halos with a given V_{max} halos can have a wide range of central densities/rotation curve shapes

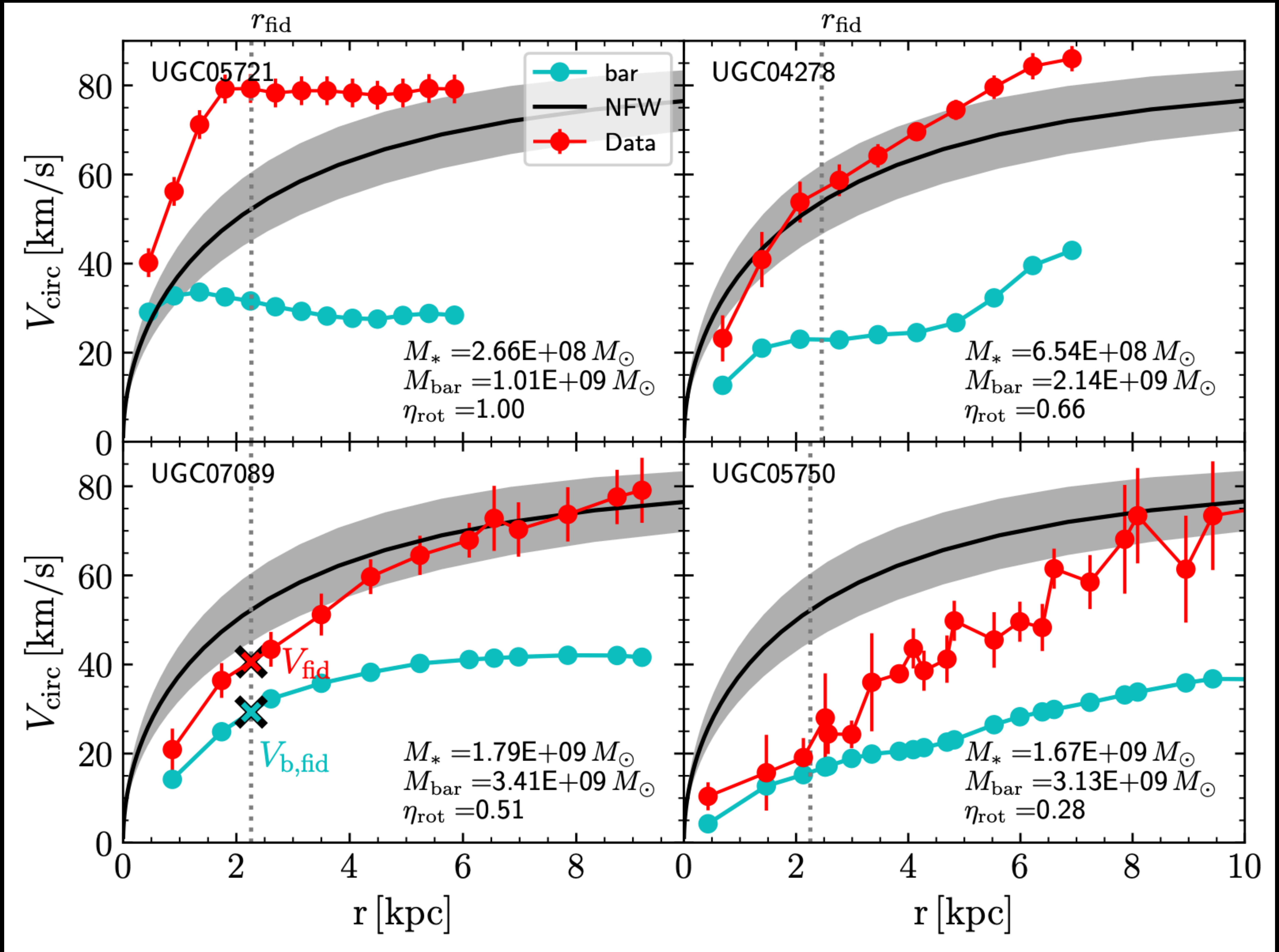


Santos-Santos+ (2020)

Motivation for a Velocity Dependent cross section

Core collapsed SIDM halos could potentially help explain the “diversity problem” of dwarf galaxies

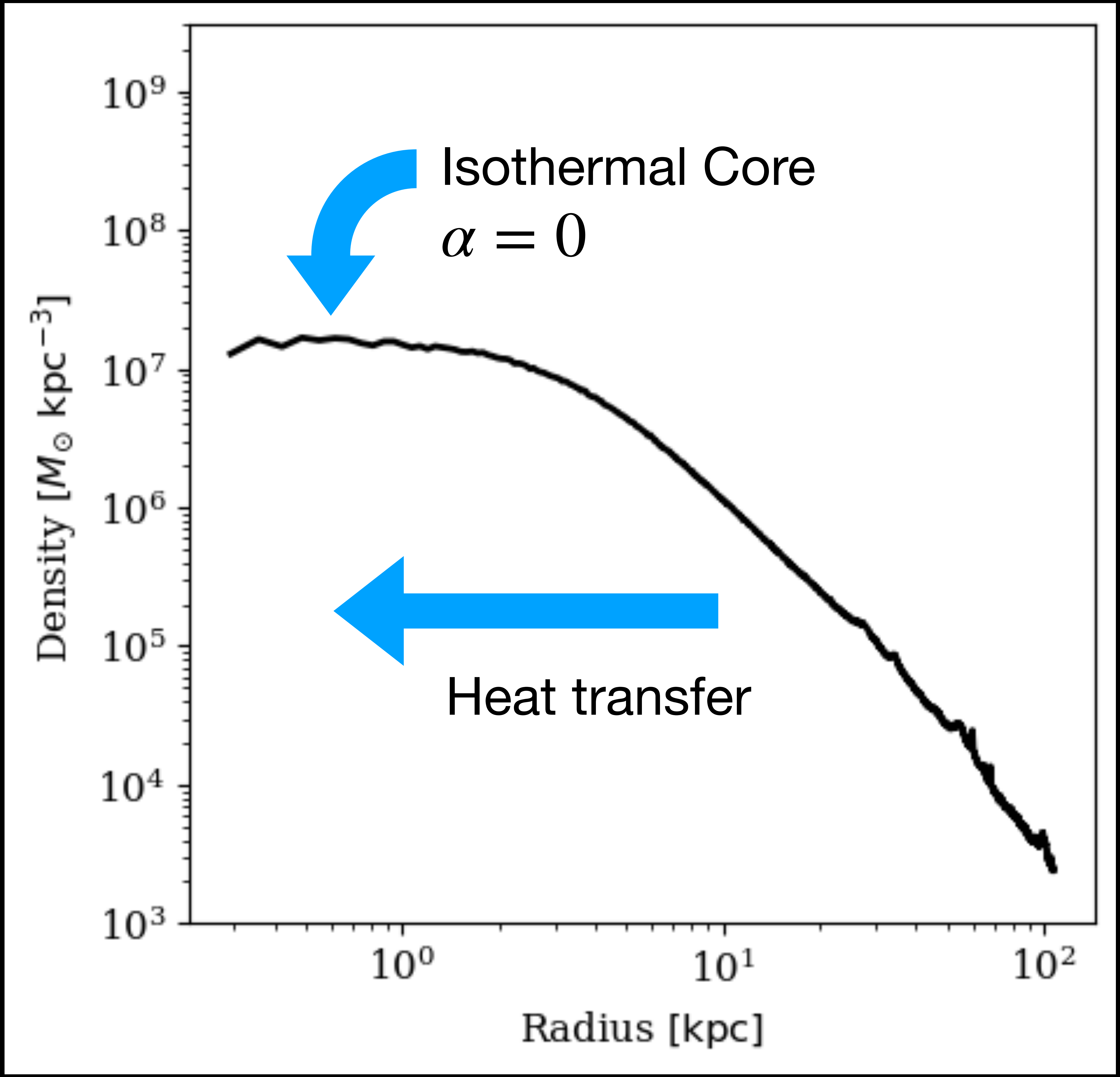
But CDM+ baryons works also (see work by A. Cruz!)



Santos-Santos+ (2020)

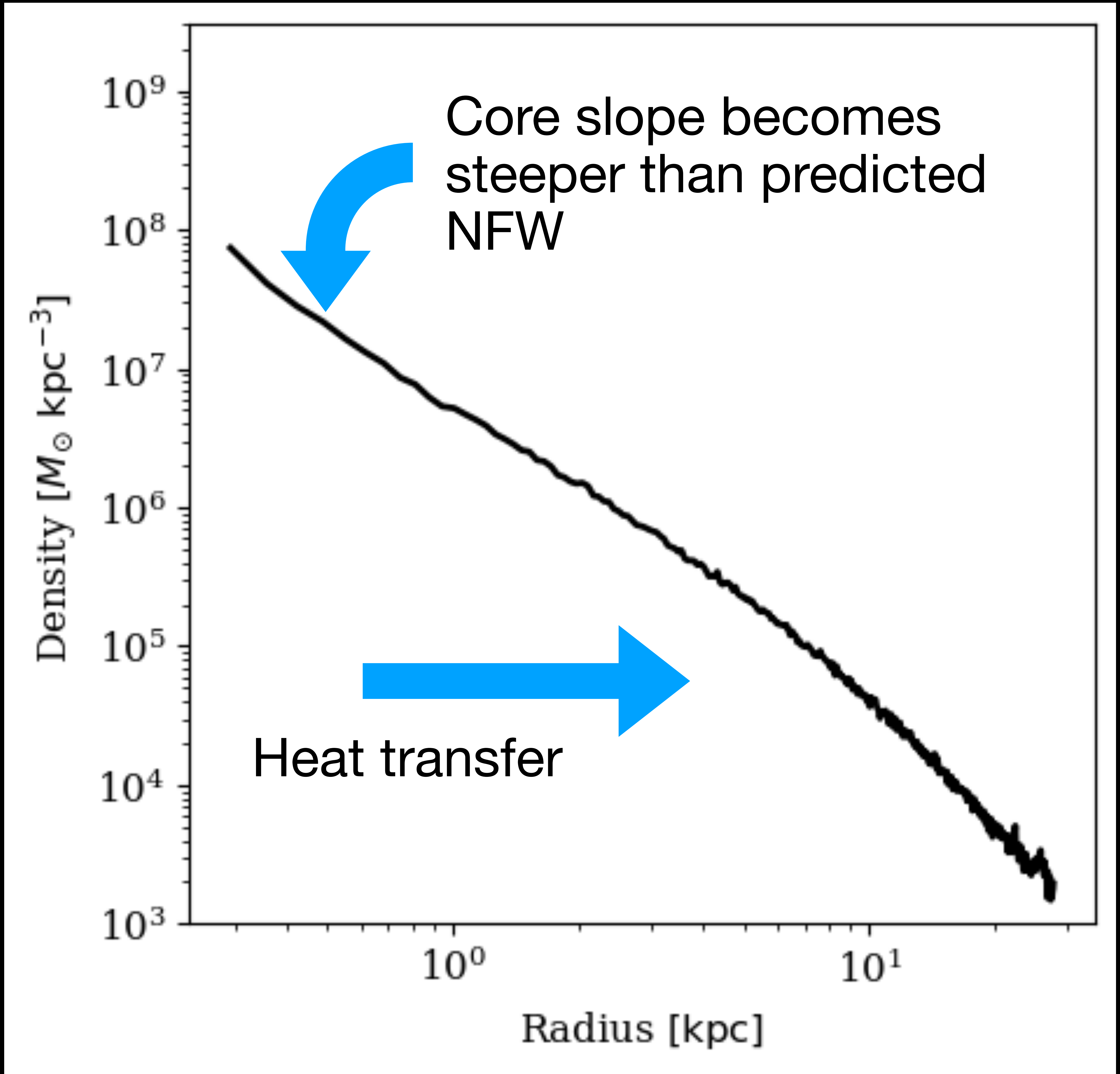
SIDM Core Formation

- Inner region of DM halo is initially colder than its outskirts
- Self interactions allows energy transfers throughout the halo
- Heat gets transferred inwards
- Halo forms an isothermal core
- Increasing central temperature pushes central particles out

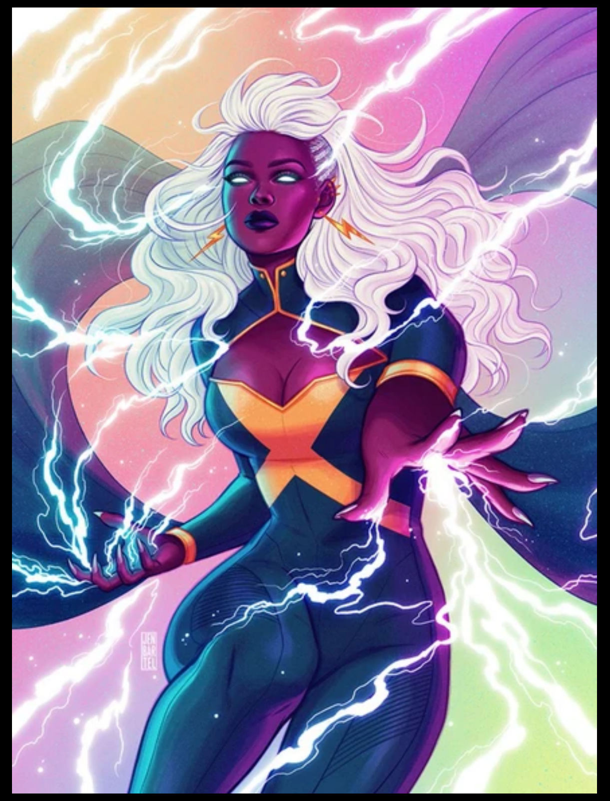


Gravothermal Core Collapse

- Heat gets transferred outwards
- DM halos are gravitationally bound systems that obey $E_{tot} = KE + PE = -KE$ $(PE = -2KE)$
- SIDM core has a negative heat capacity (negative total energy) so as heat flows out, KE increases and PE decreases



Storm (CDM)



One of the 4 MARVEL-ous simulation volumes (Munshi+ 2021)

Dark Matter Only (DMO) run

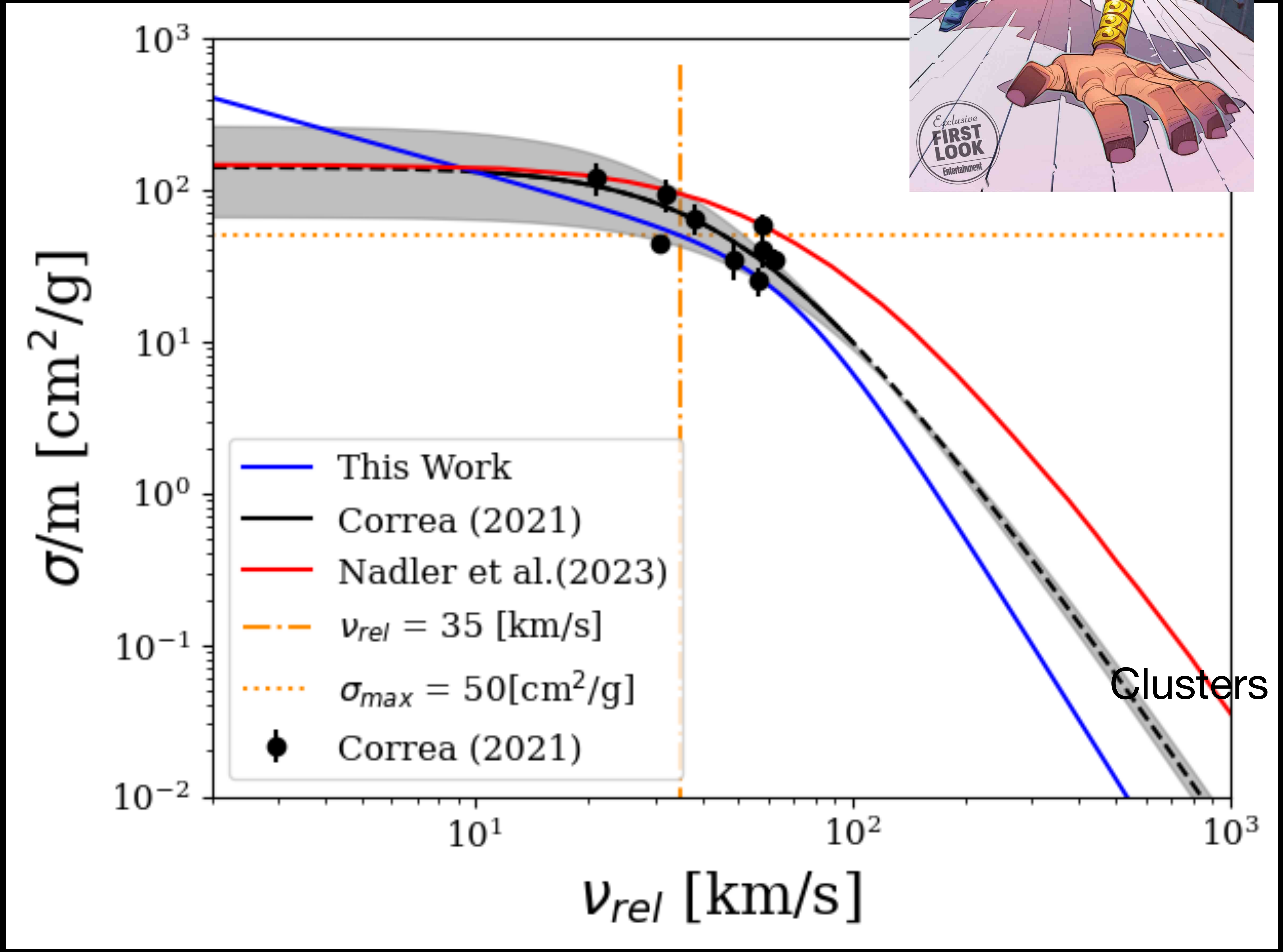
- Gravitational Softening Length = 65 pc
- DM particle mass $= 8070 M_\odot$

Hydrodynamic run

- Gravitational Softening Length = 60 pc
- DM, Initial Star, and Gas particle mass $= 6650 M_\odot, 420 M_\odot, 1410 M_\odot$
- Superbubble feedback (Keller et al.2014)

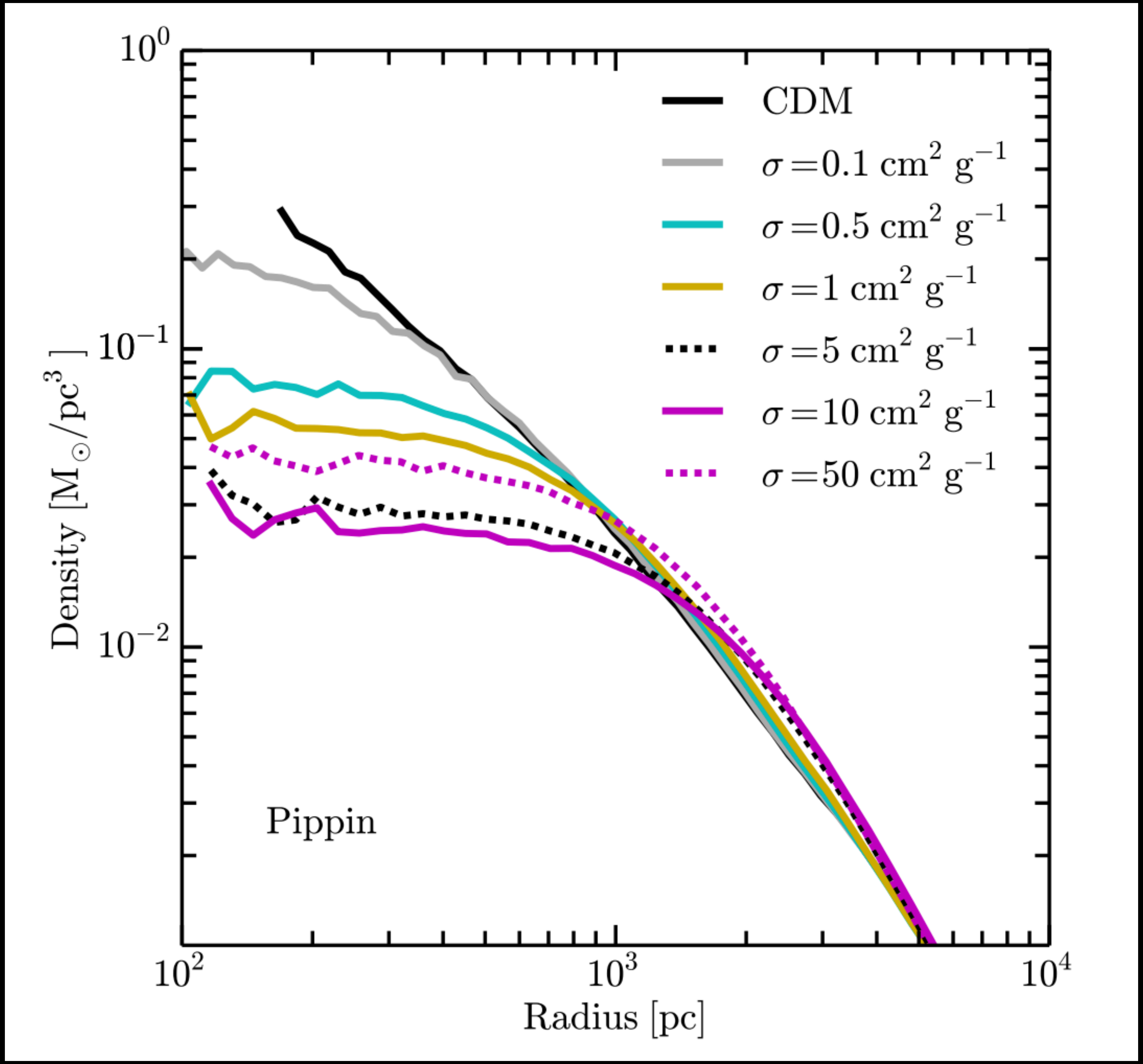
(Magnificent) Ms. Marvel (SIDM)

- Velocity Dependent cross section of interaction
  - $V_{max} = 35km/s$
  - $\sigma/m_{max} = 50cm^2/g$
- Gravitational Softening Length = 65 pc
- DM particle mass $= 8070M_{\odot}$



Cruz+ (in prep)

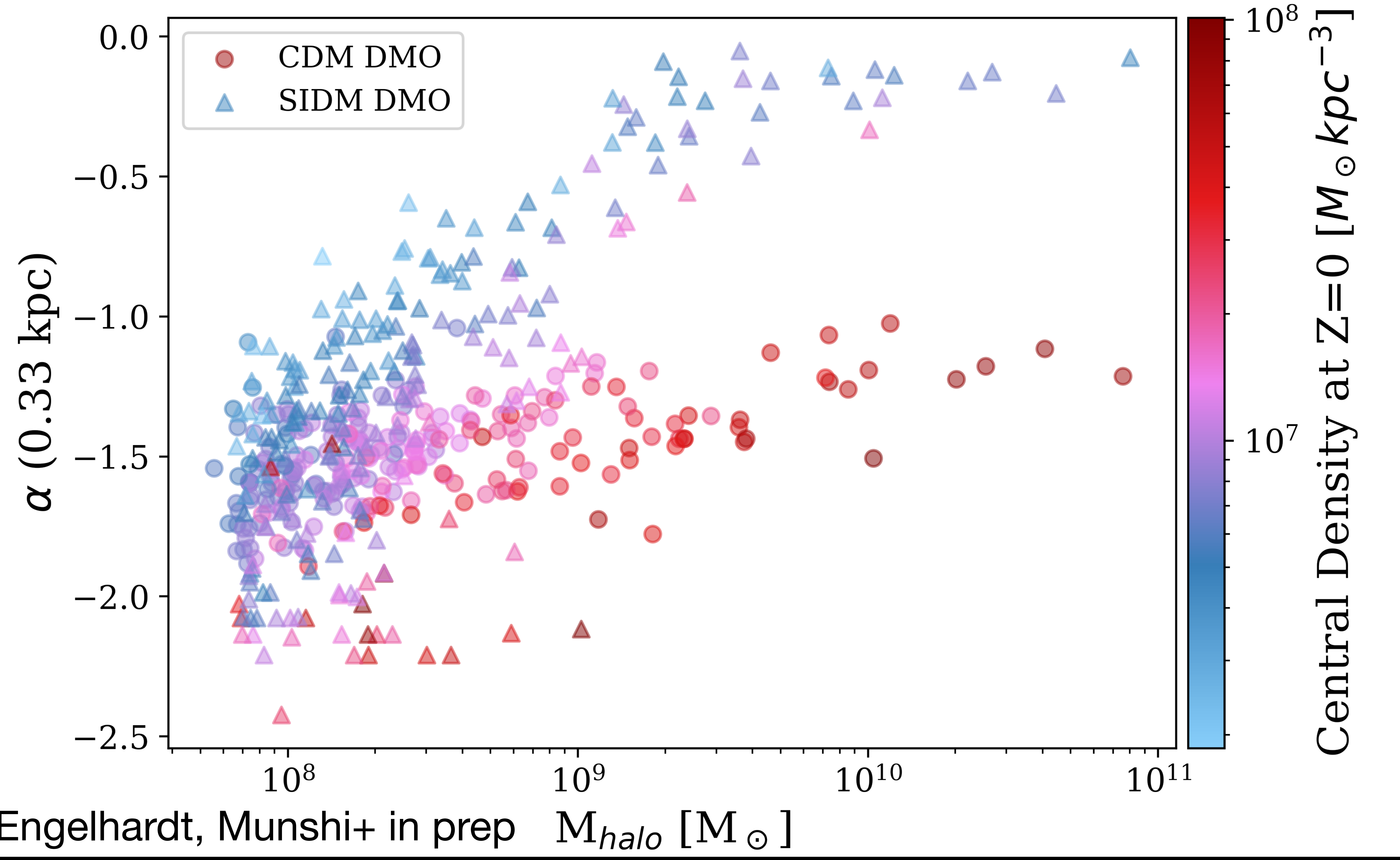
Creating Cores with SIDM



Isolated SIDM dwarfs with a large cross section of interaction ($1 - 50 cm^2 g^{-1}$) can form cores (Elbert+ 2015)

$$M_{vir} = 9 \times 10^9 M_\odot$$

Core slopes of “classical” dwarf galaxy mass halos could be used to discriminate between SIDM and CDM + Baryonic feedback



Engelhardt, Munshi+ in prep

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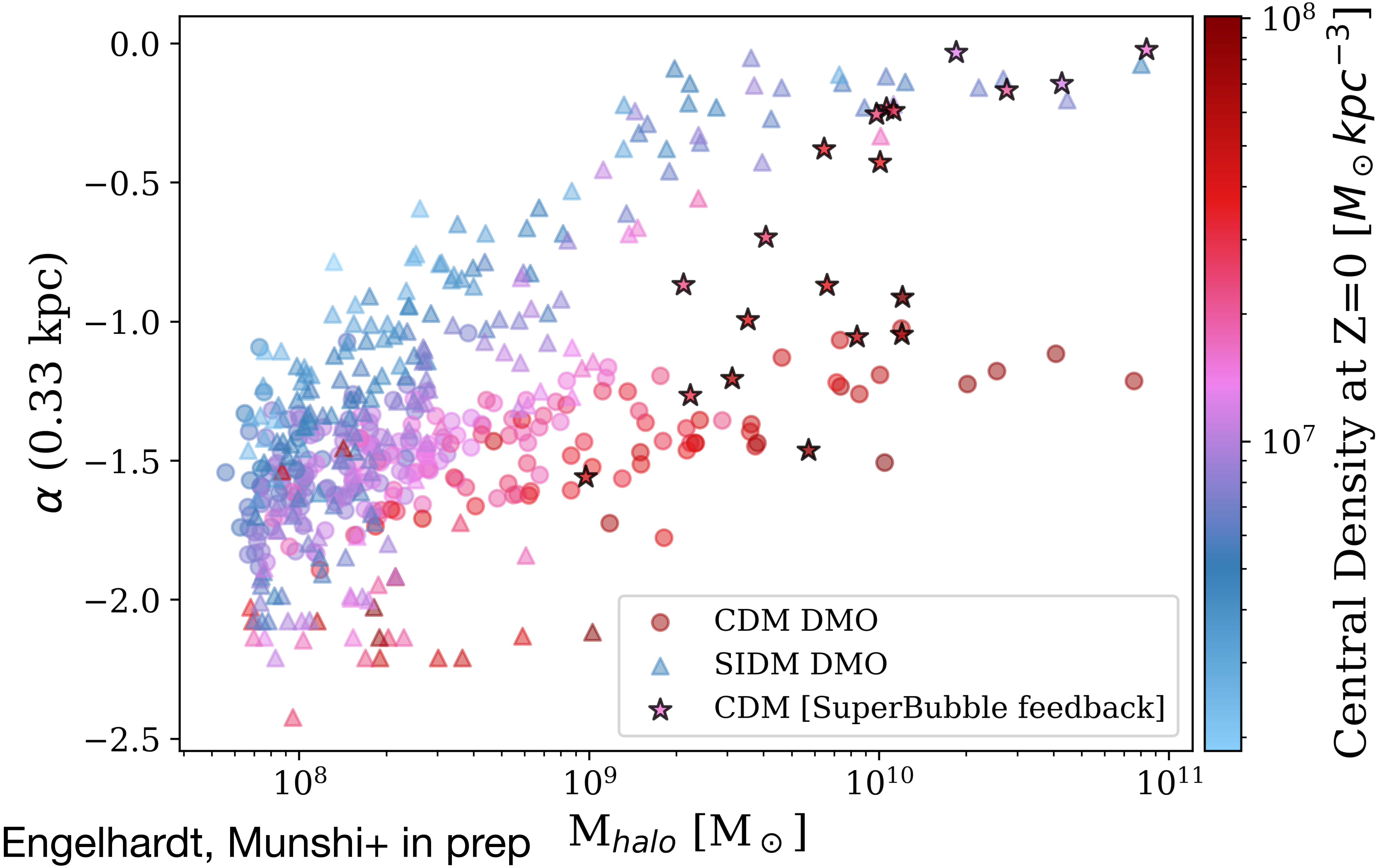
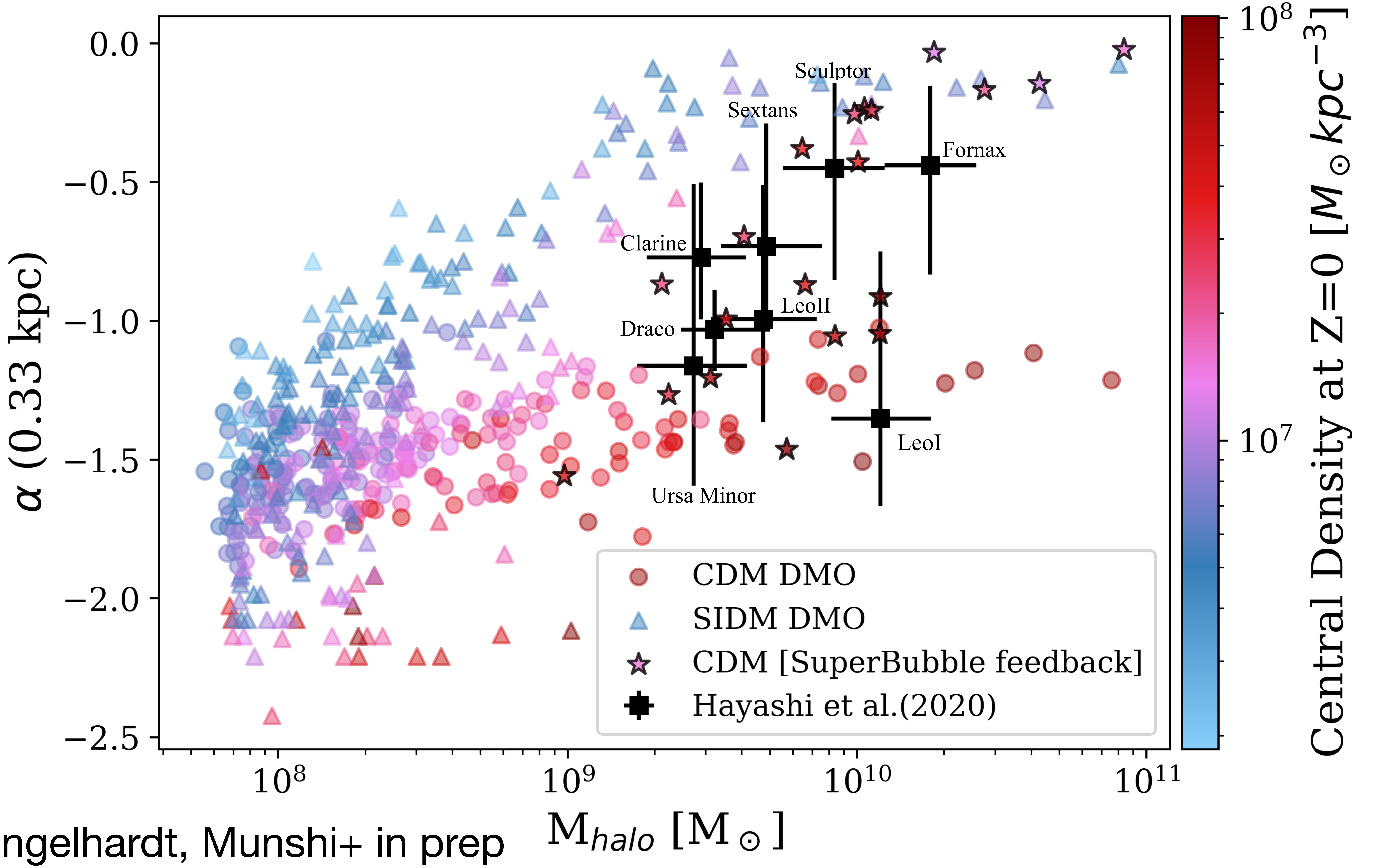


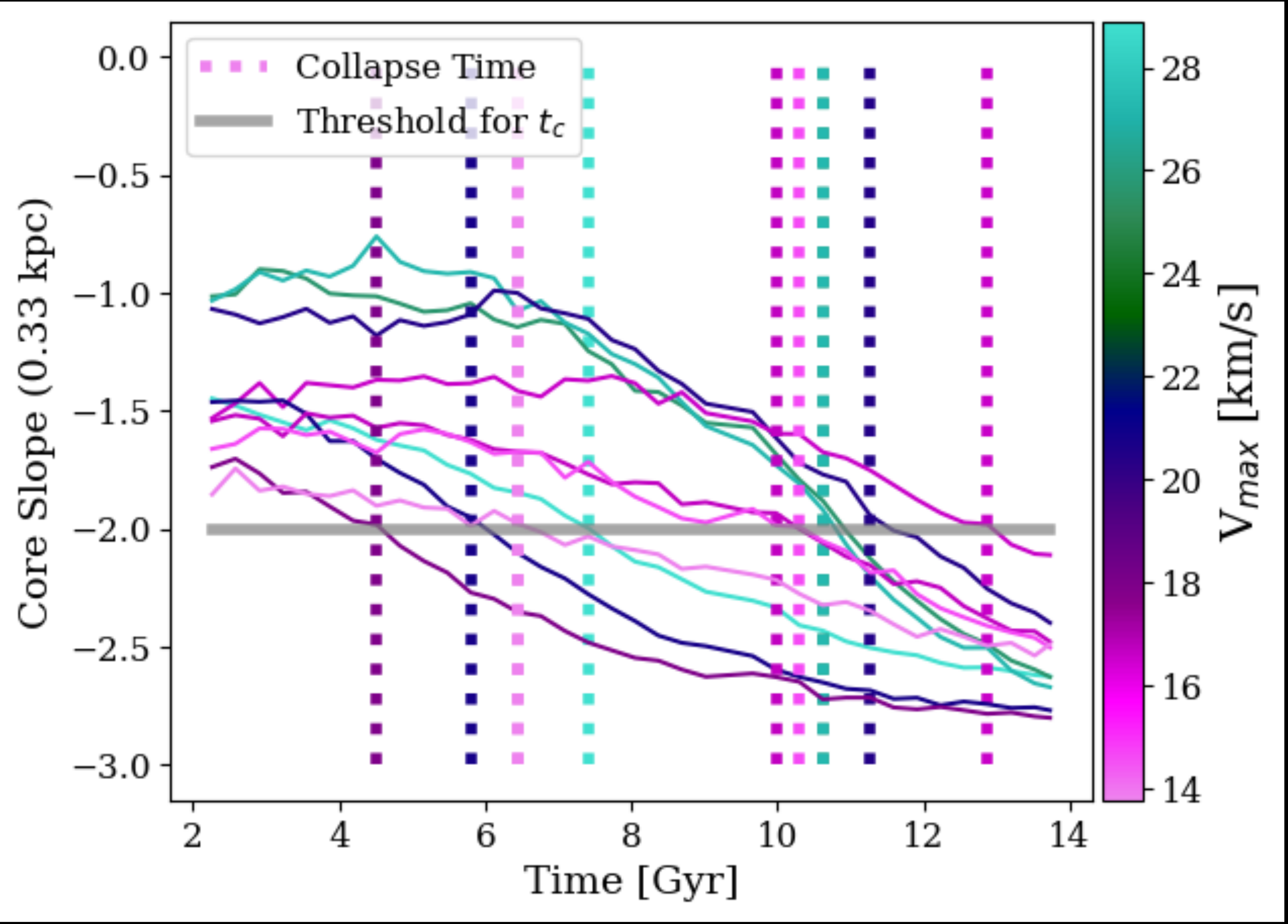
Engelhardt, Munshi+ in prep

Core slopes of “classical” dwarf galaxy mass halos could be used to discriminate between SIDM and CDM + Baryonic feedback



Engelhardt, Munshi+ in prep

We define a collapse time (t_c) as the time when the halo first enters the core collapse phase, characterized by a core slope more negative than -2.0



Analytic Calculation of Collapse Time

$$t_c = \frac{150}{\beta} \frac{1}{(\sigma_{eff}/m) r_{eff} \rho_{eff}} \frac{1}{\sqrt{4\pi G \rho_{eff}}}$$

Constant Scalar tuned to simulations
Yang et al.(2024) set $\beta = 0.75$

Yang+ 2024

Analytic Calculation of Collapse Time

$$t_c = \frac{150}{\beta} \frac{1}{(\sigma_{eff}/m) r_{eff} \rho_{eff}} \frac{1}{\sqrt{4\pi G \rho_{eff}}}$$

Effective Cross Section of Interaction

Yang+ 2024

Analytic Calculation of Collapse Time

$$t_c = \frac{150}{\beta} \frac{1}{(\sigma_{eff}/m) r_{eff} \rho_{eff}} \frac{1}{\sqrt{4\pi G \rho_{eff}}}$$

Effective Radius

$$r_{eff} = \frac{R_{max}}{2.1626} \qquad V_{max} = V_{circ}(R_{max})$$

Yang+ 2024

Analytic Calculation of Collapse Time

$$t_c = \frac{150}{\beta} \frac{1}{(\sigma_{eff}/m) r_{eff} \rho_{eff}} \frac{1}{\sqrt{4\pi G \rho_{eff}}}$$

Effective Density

$$\rho_{eff} = \left(\frac{V_{max}}{1.648 r_{eff}} \right)^2 \times G^{-1}$$

$$r_{eff} = \frac{R_{max}}{2.1626}$$

$$V_{max} = V_{circ}(R_{max})$$

Yang+ 2024

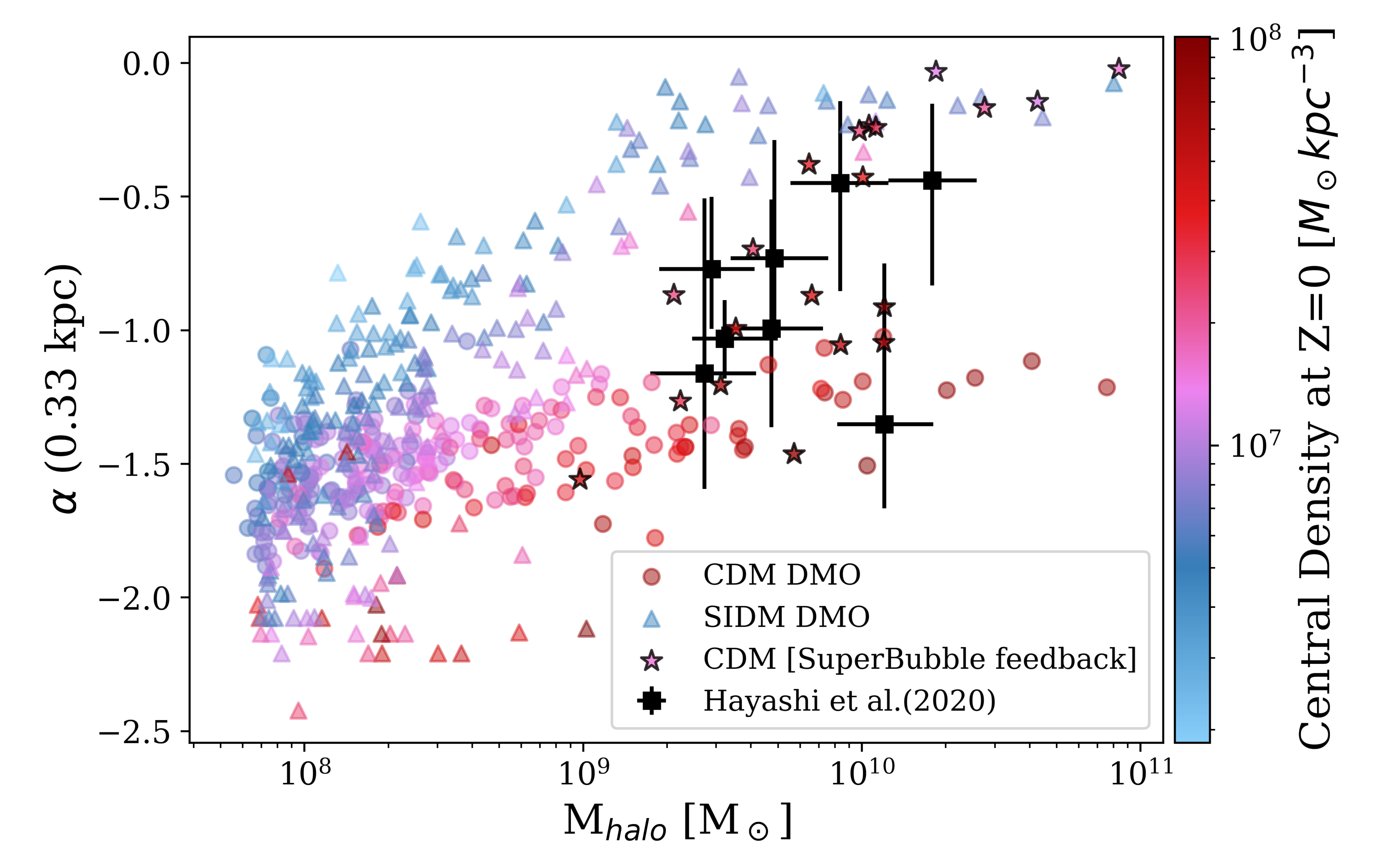
Using core slope to determine when halos enter core-formation & core-collapse agrees with the analytic calculations

Nadler+2024, Yang+2024

Engelhardt, Munshi+ in prep

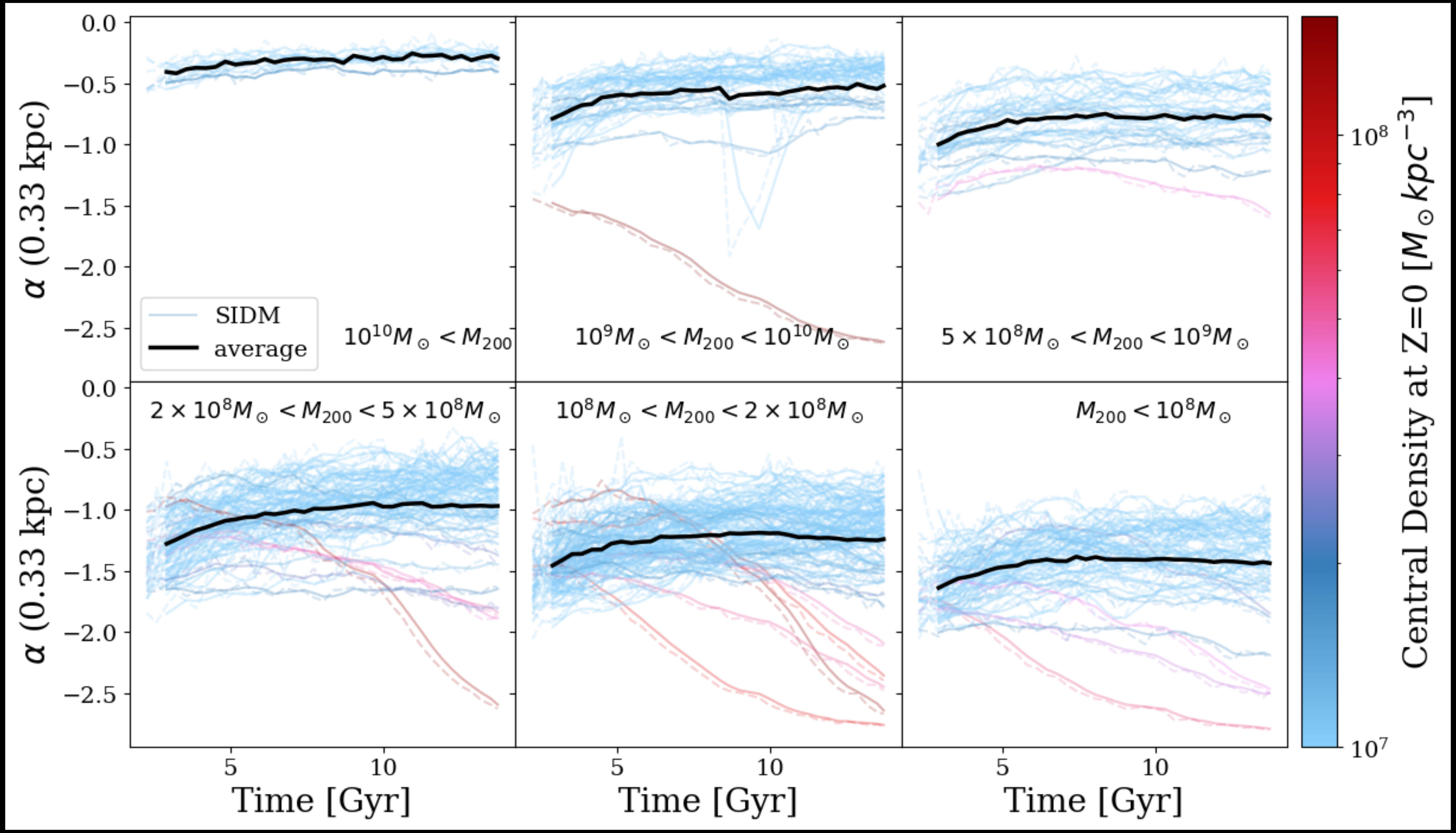
Conclusions

- Predictions for the measured core slopes of DM halos from SIDM (DMO) and CDM +baryons simulations diverge in the “classical dwarf” mass range, indicating that it may be possible to observationally distinguish between DM models at this mass scale



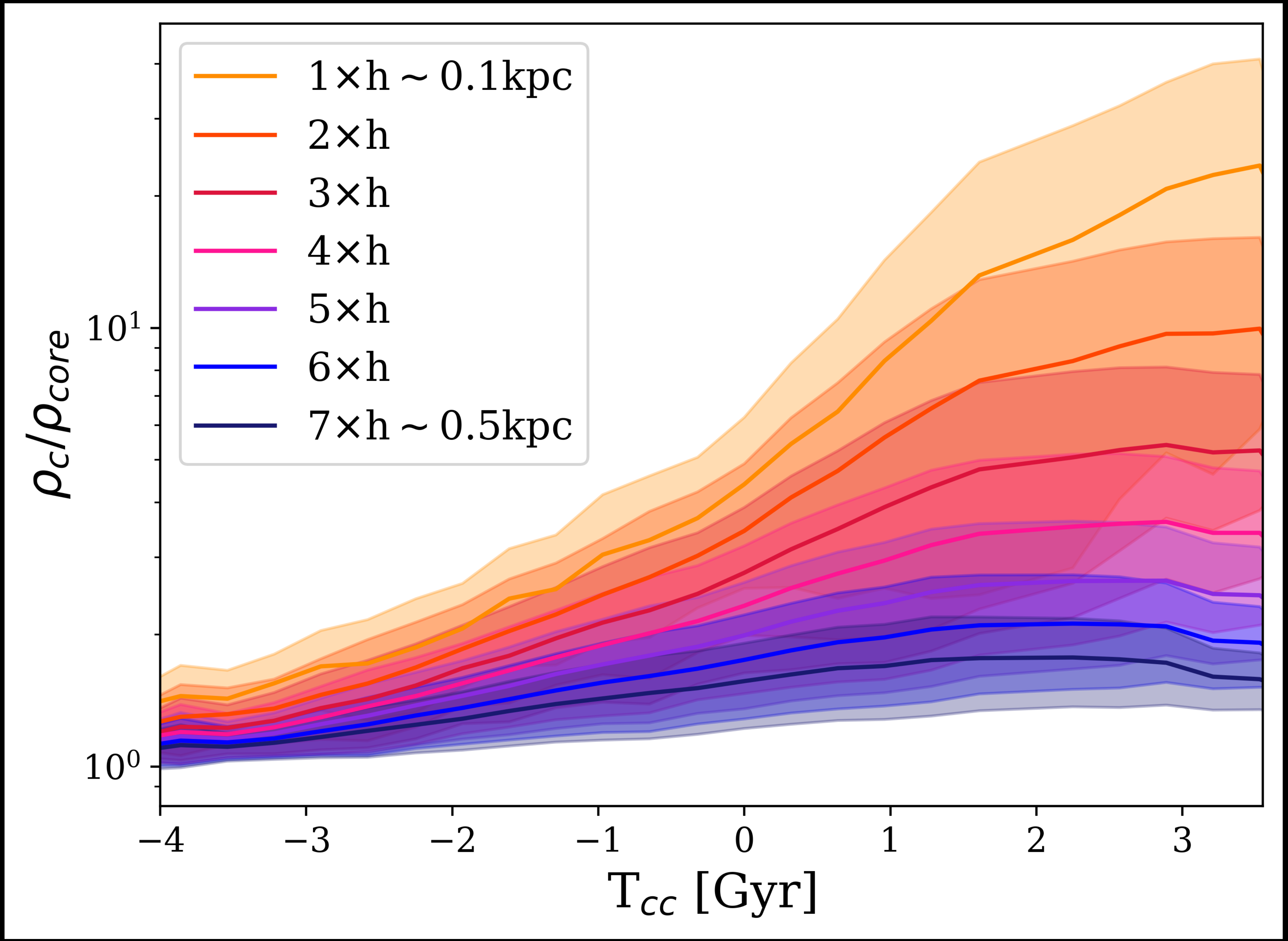
Conclusions

- Core slopes of SIDM halos exhibit strong dependence on mass and the effective cross section of interaction



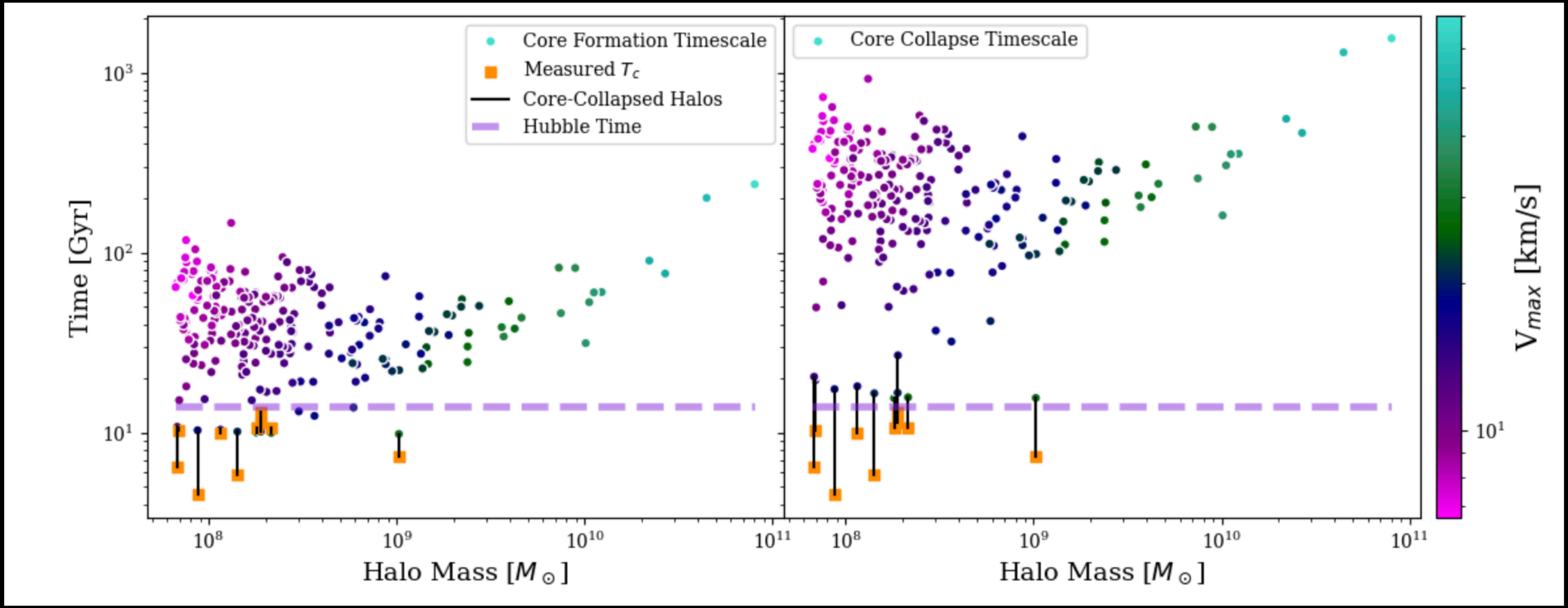
Conclusions

- Central density also traces core-collapse, however this property depends on the aperture of the measurement as well as the halo's merger history



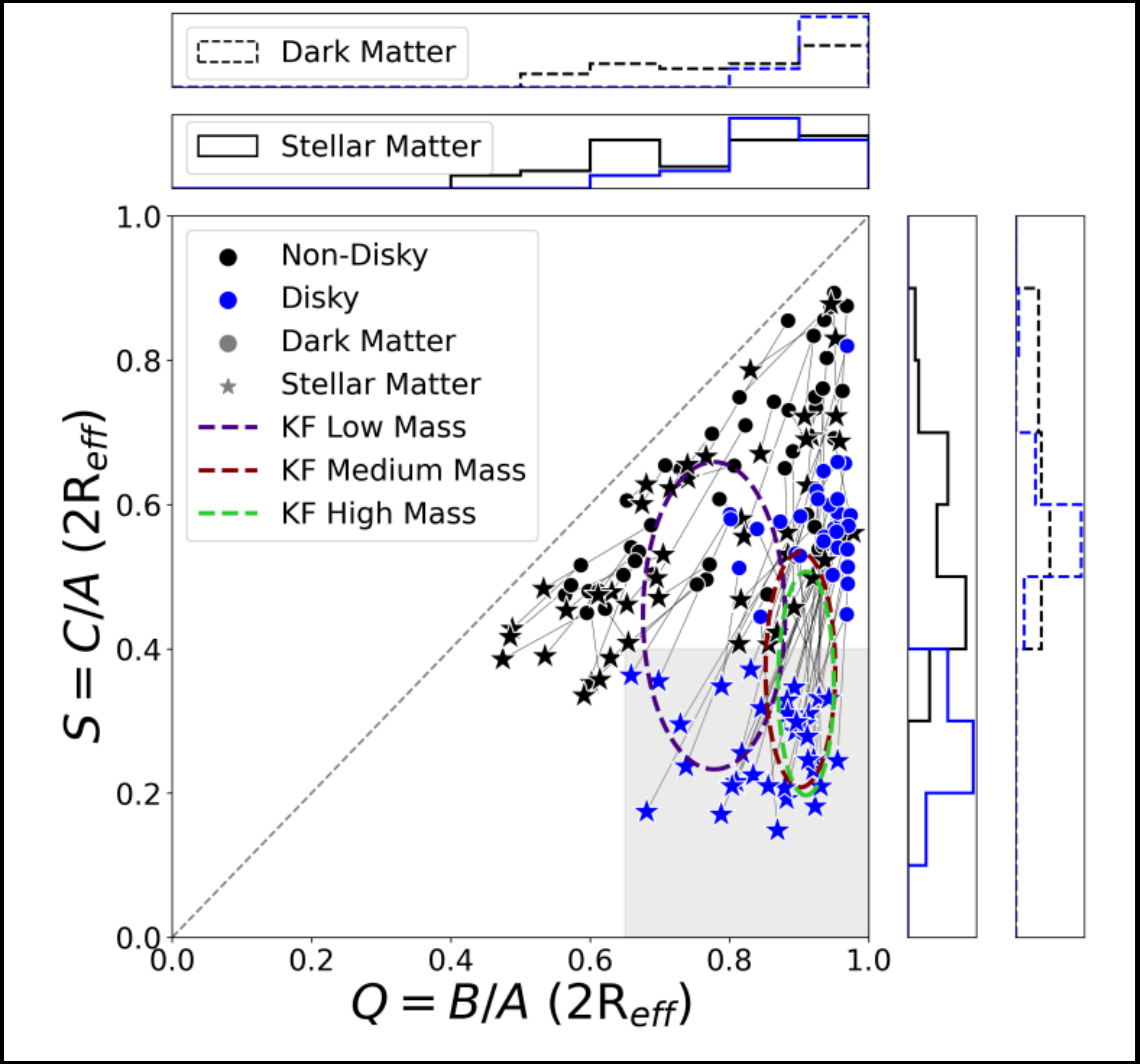
Conclusions

- We find that core slope is the best determinant of when halos first enter the core collapse phase



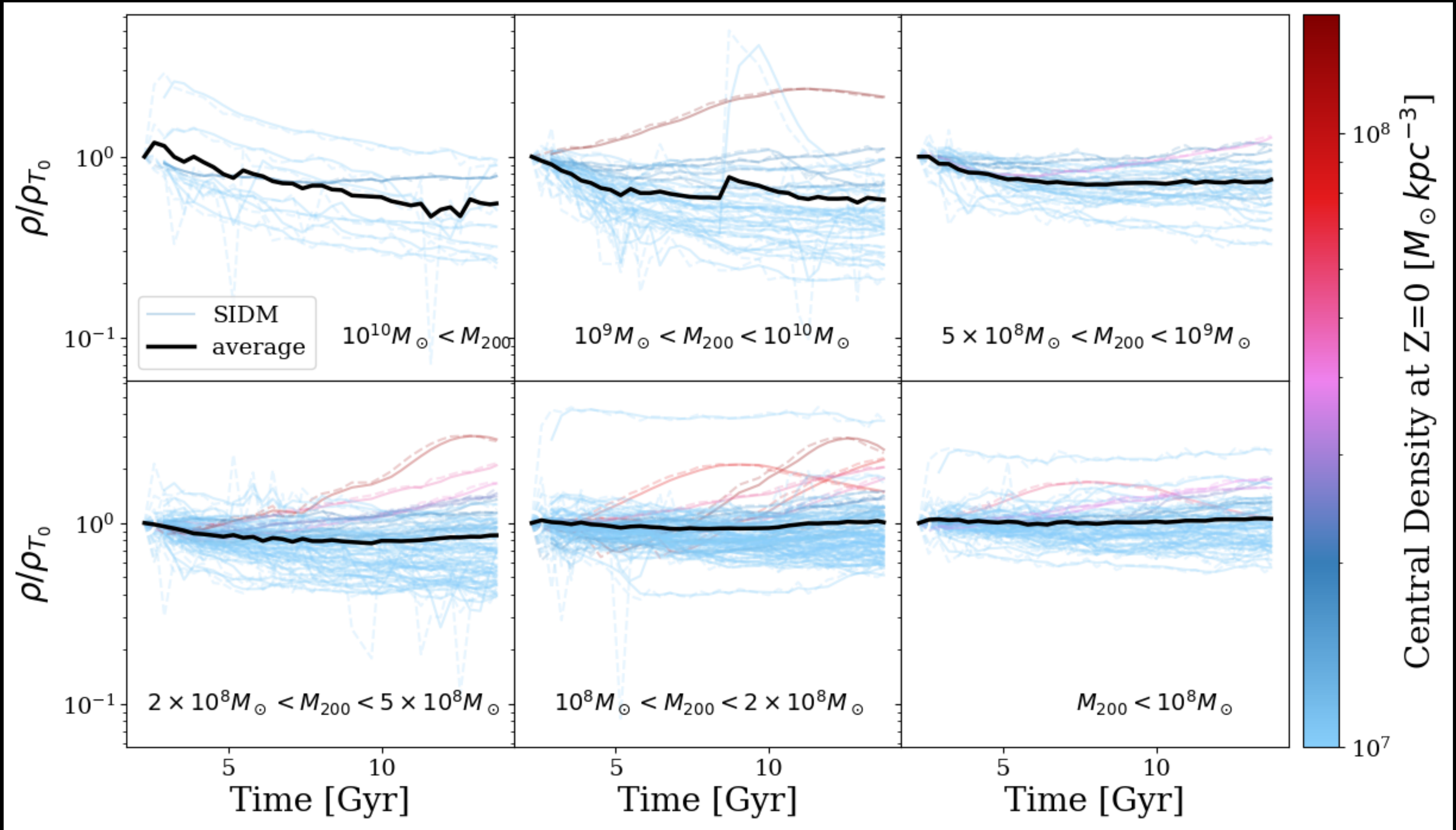
Advertisement: galaxy shapes

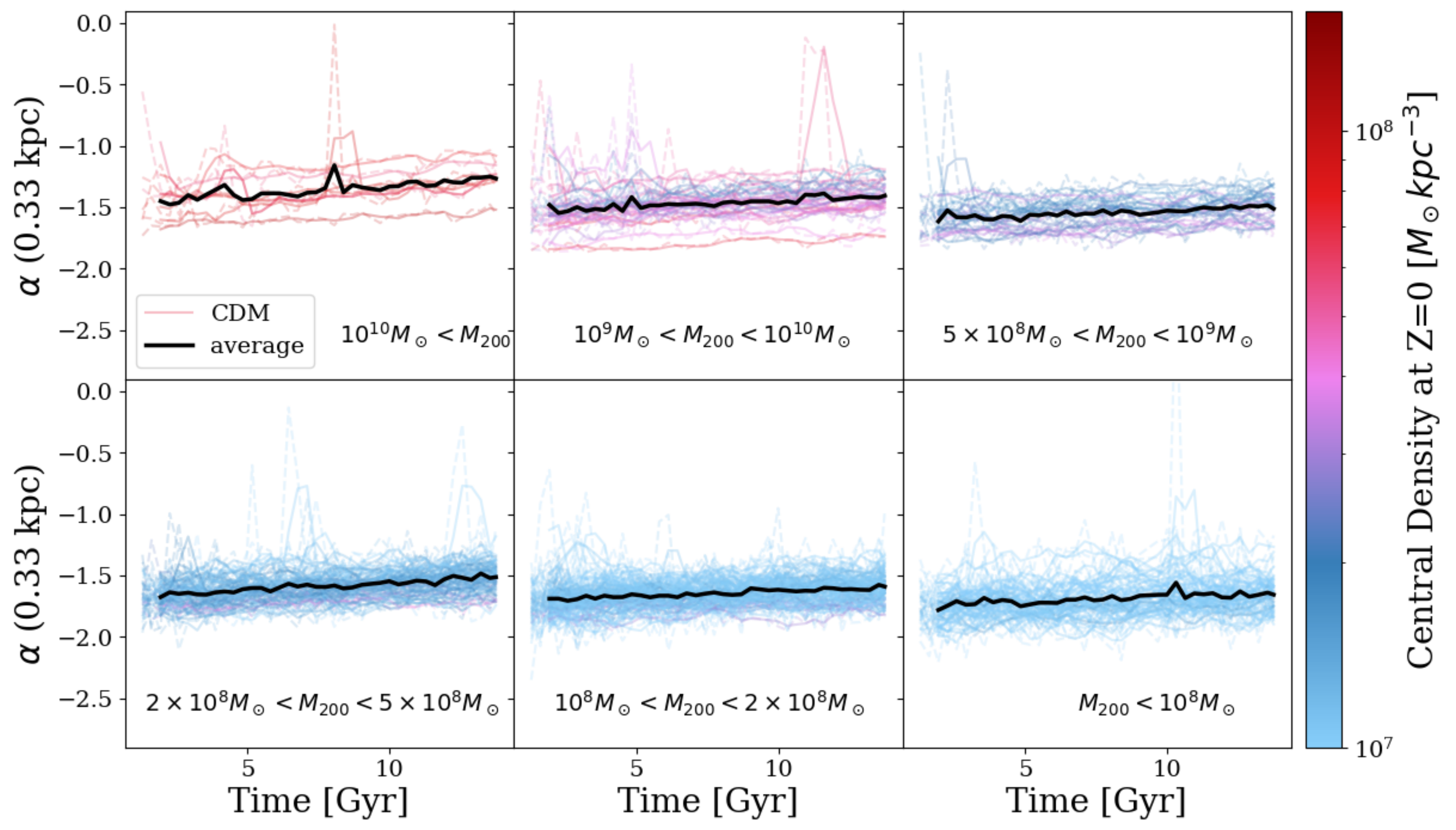
- How well is DM shape represented by stellar shape? (Keith, Munshi+ 2025)
- SIDM version is in prep!



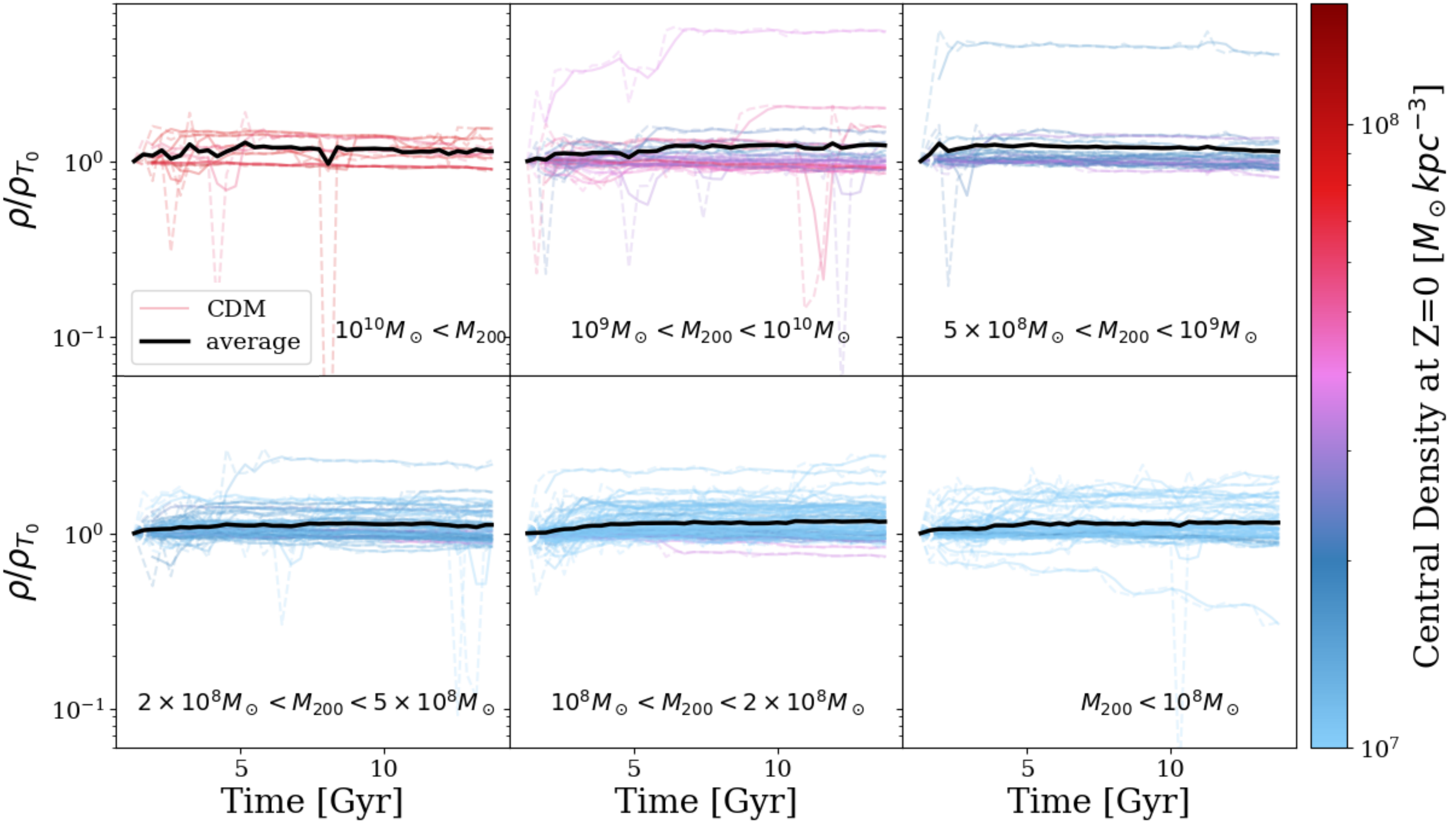
Back-Up slides

Tracing Central density through time reveals same trends as core slope, but is less subject to temporary fluctuations





CDM
average
$10^{10}M_\odot < M_{200}$
$10^9M_\odot < M_{200} < 10^{10}M_\odot$
$5\times10^8M_\odot < M_{200} < 10^9M_\odot$
$2\times10^8M_\odot < M_{200} < 5\times10^8M_\odot$
$10^8M_\odot < M_{200} < 2\times10^8M_\odot$
$M_{200} < 10^8M_\odot$
α (0.33 kpc)
Time [Gyr]
Central Density at Z=0 [$M_\odot kpc^{-3}$]



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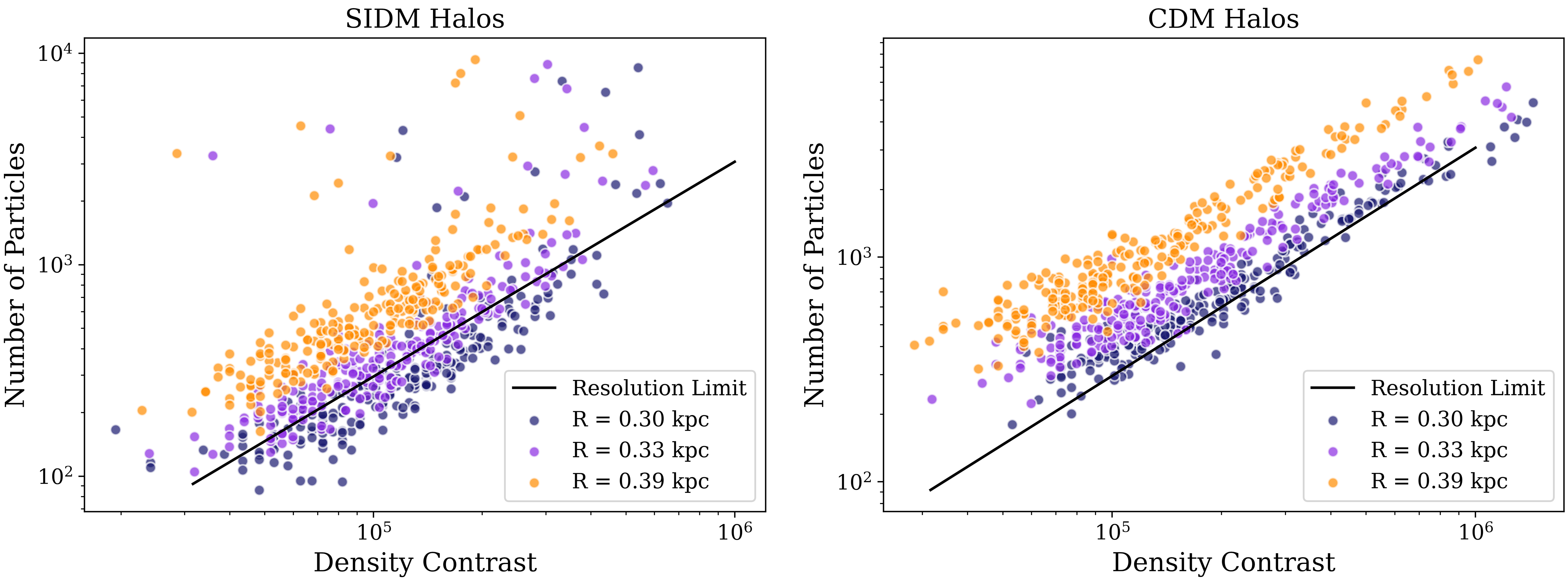
$M_{200} < 10^8 M_\odot$
ρ/ρ_{T_0}
Time [Gyr]
Central Density at Z=0 $[M_\odot kpc^{-3}]$



Resolution limit adopted from Power et al.(2003)

$$\frac{\rho_0}{\rho_{crit}} = \text{central density/critical density of the universe}$$