Constraining Dark Matter Self-Interactions from Weak Lensing

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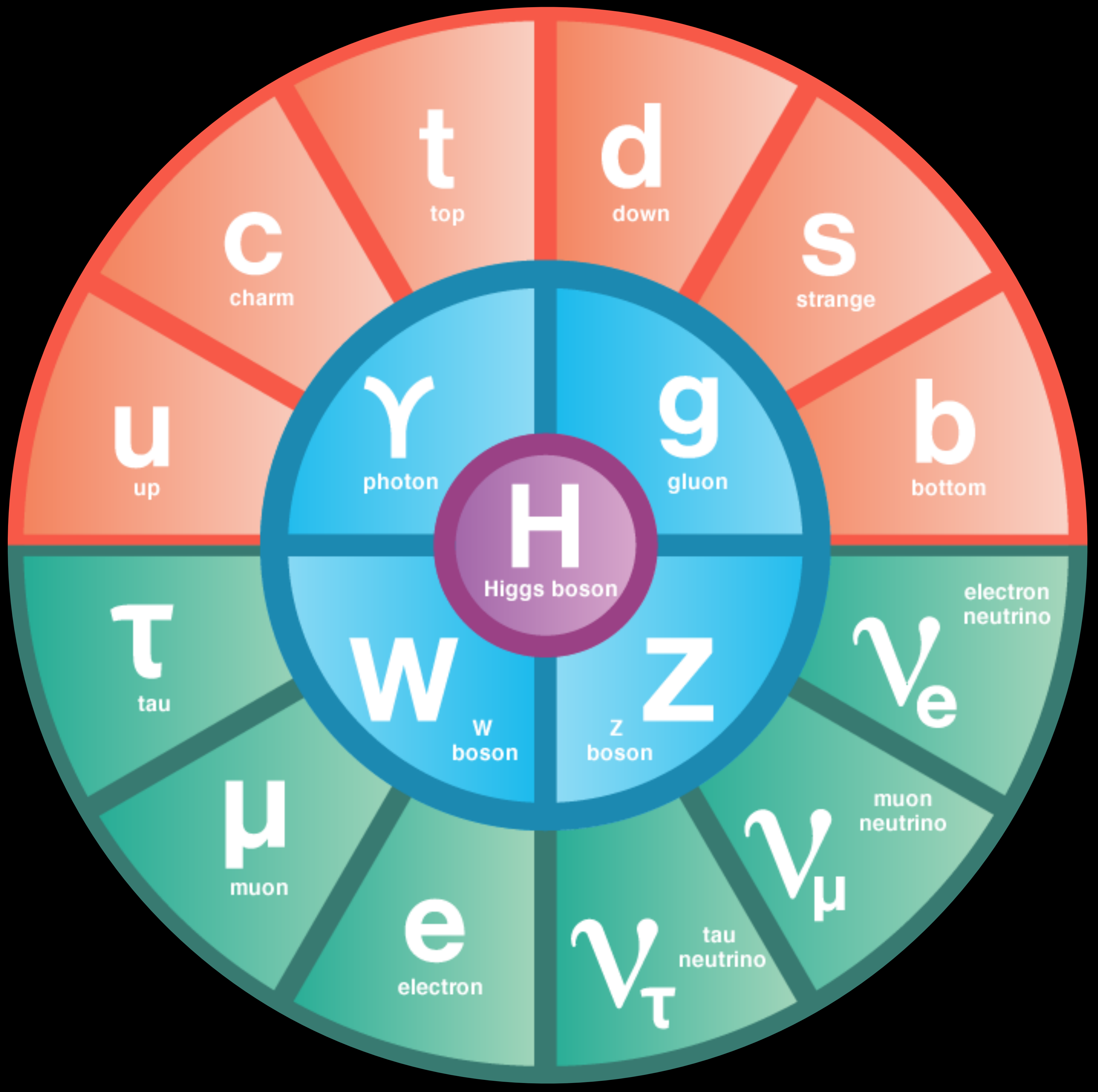
w/ S. Adhikari, A. Banerjee, B. Jain & T.-H. Shin [arXiv: 2401.05788], submitted to ApJ

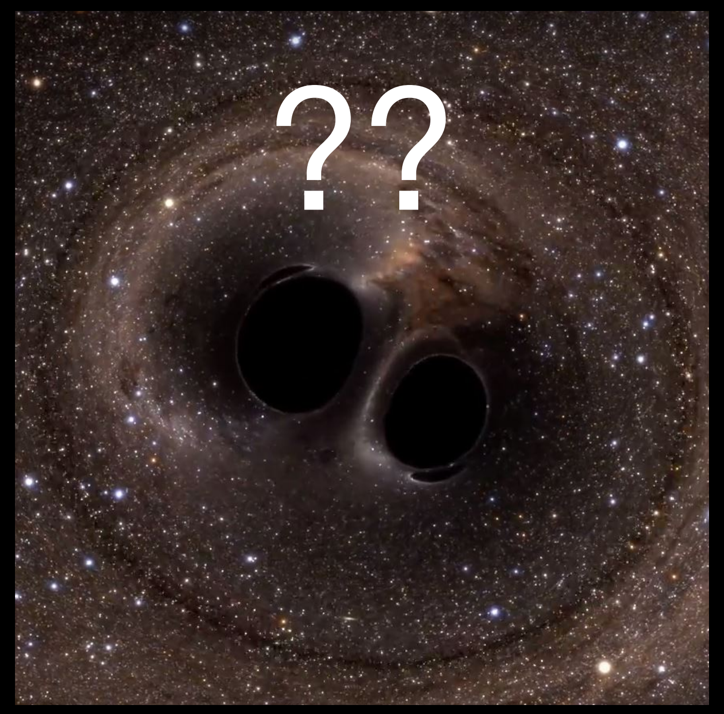
Particle Physics Phenomenology Workshop, 24/10/2024

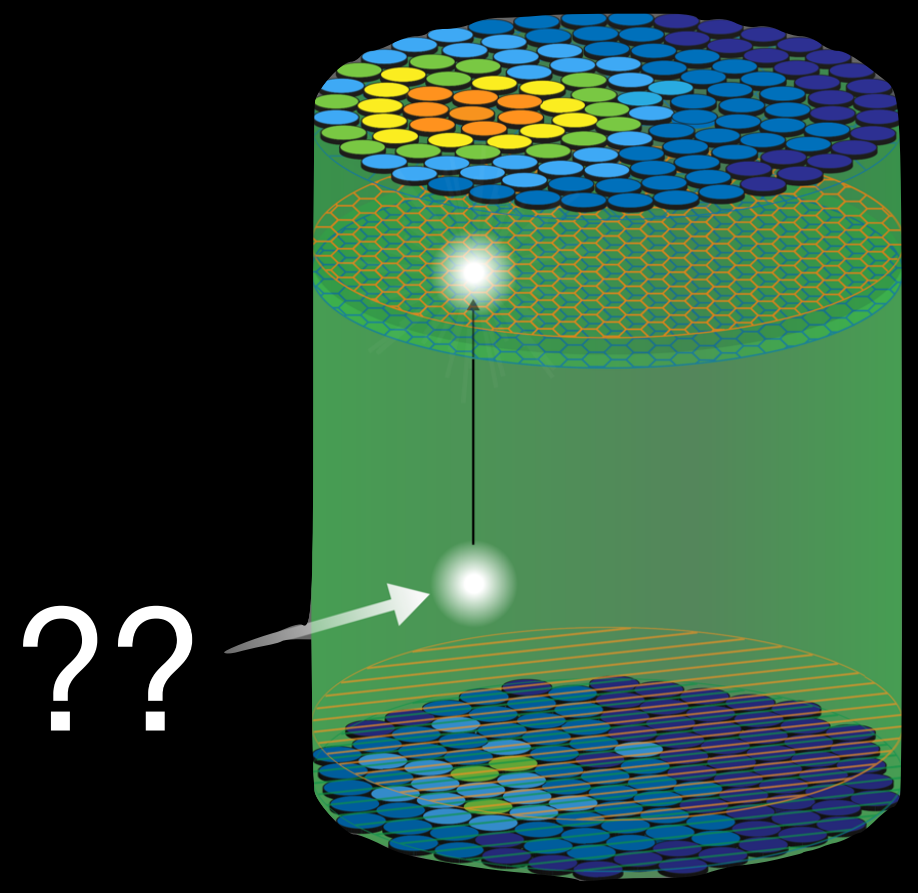
Outline

- Introduction
  - Dark matter self-interactions
  - Effects on halos
- Using ACT x DES weak lensing measurement to constrain SIDM
- Summary



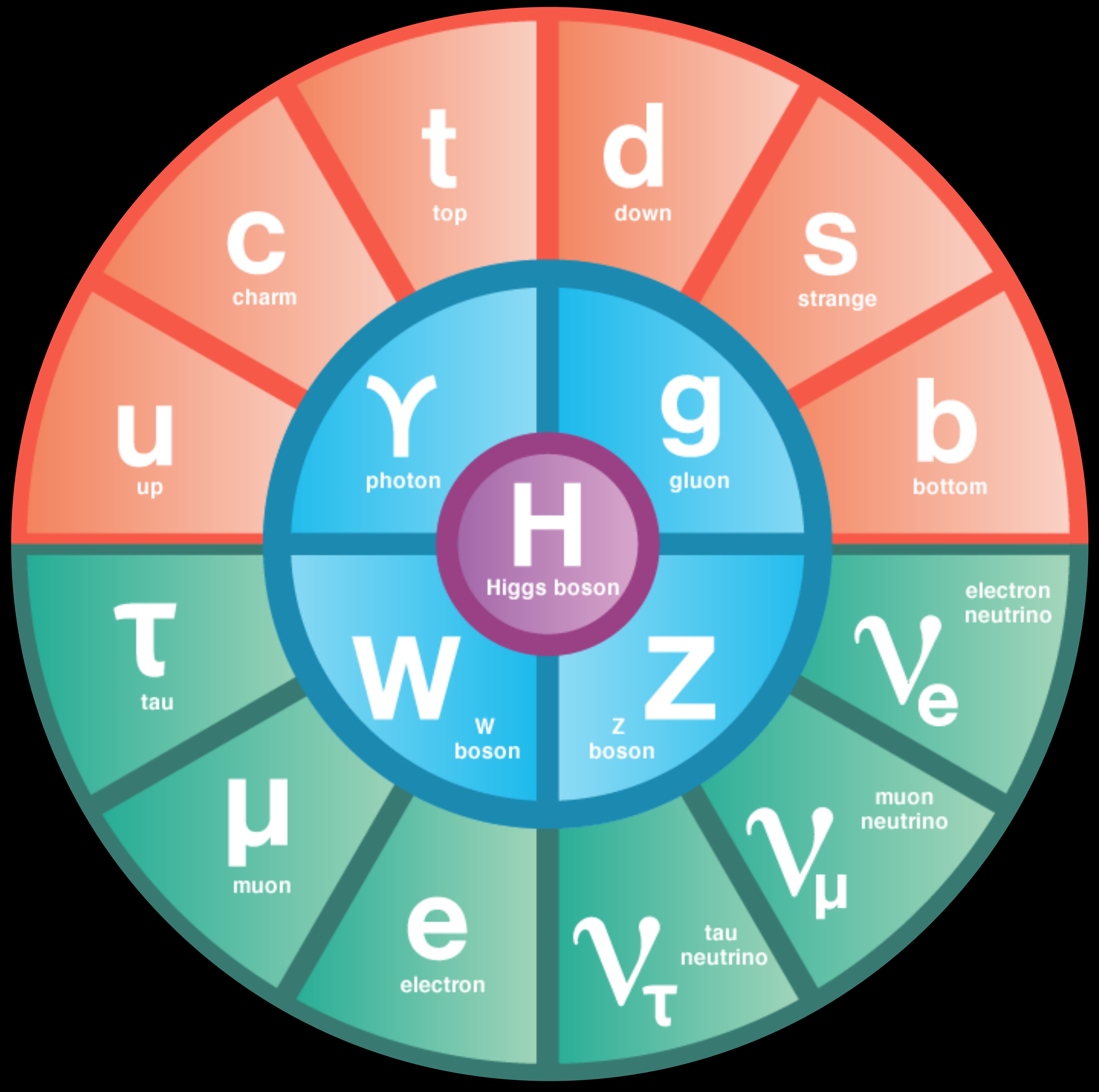
Ordinary matter



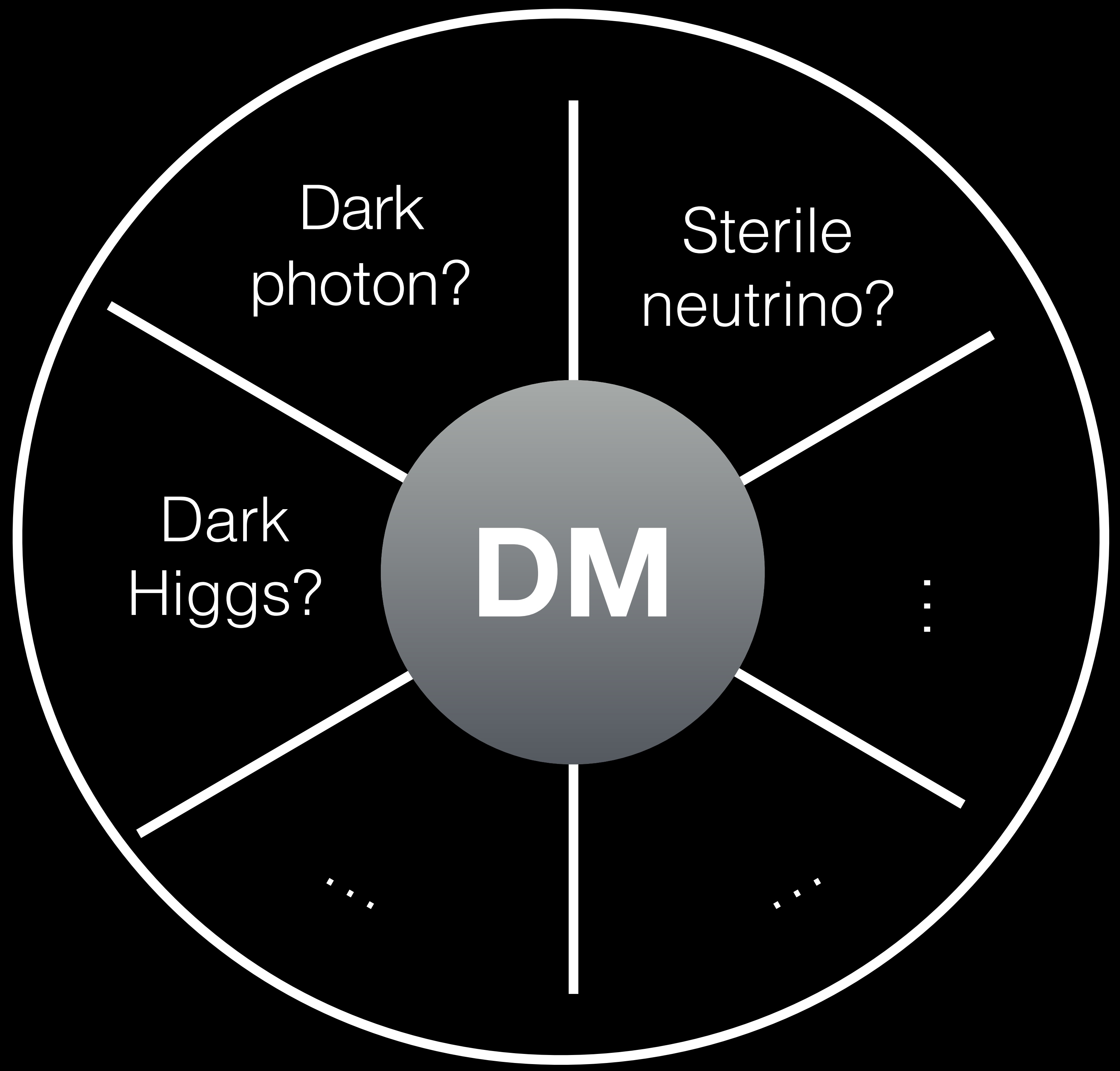


What is dark matter?

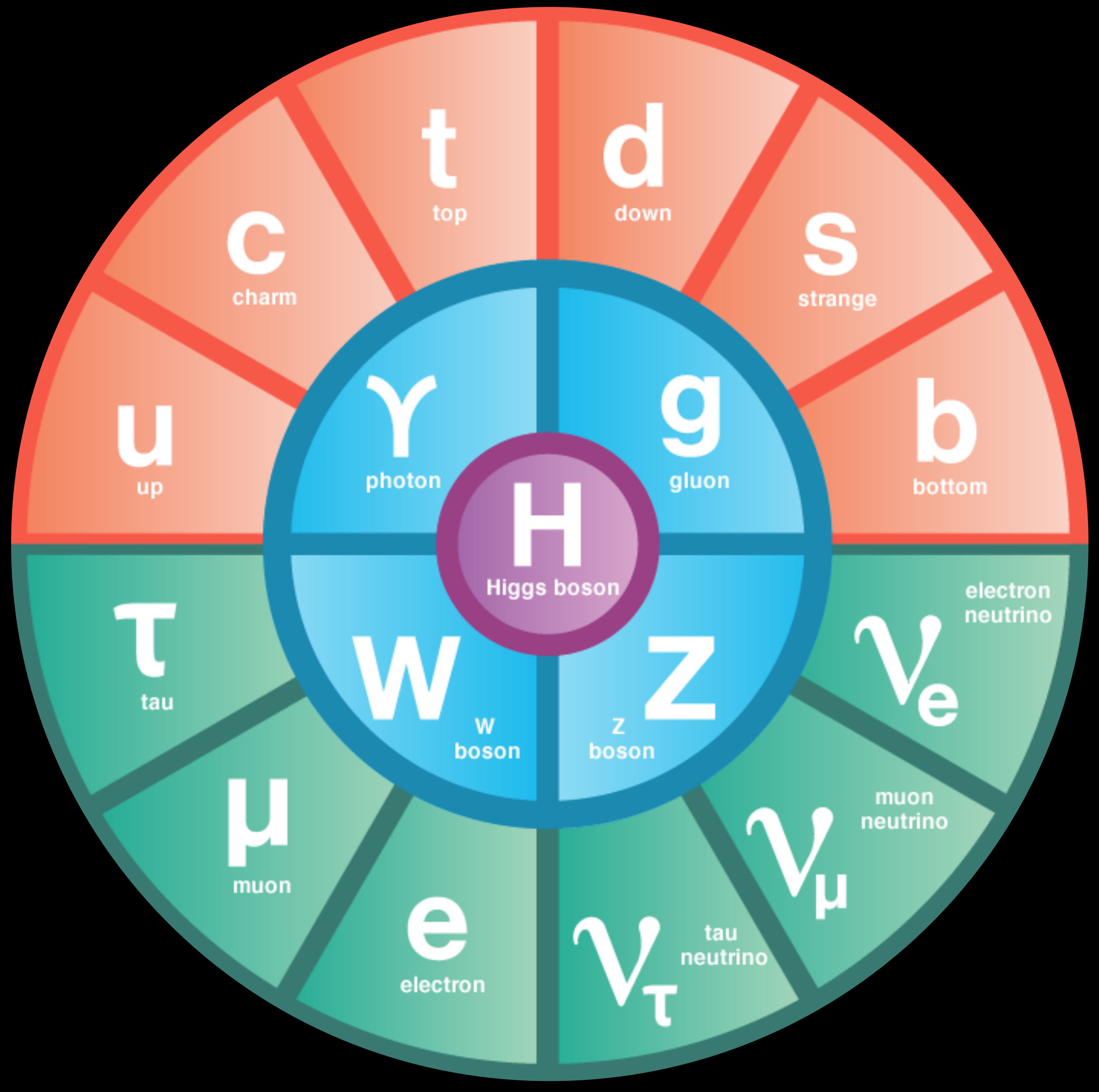
Maybe dark matter is not alone…



Ordinary matter

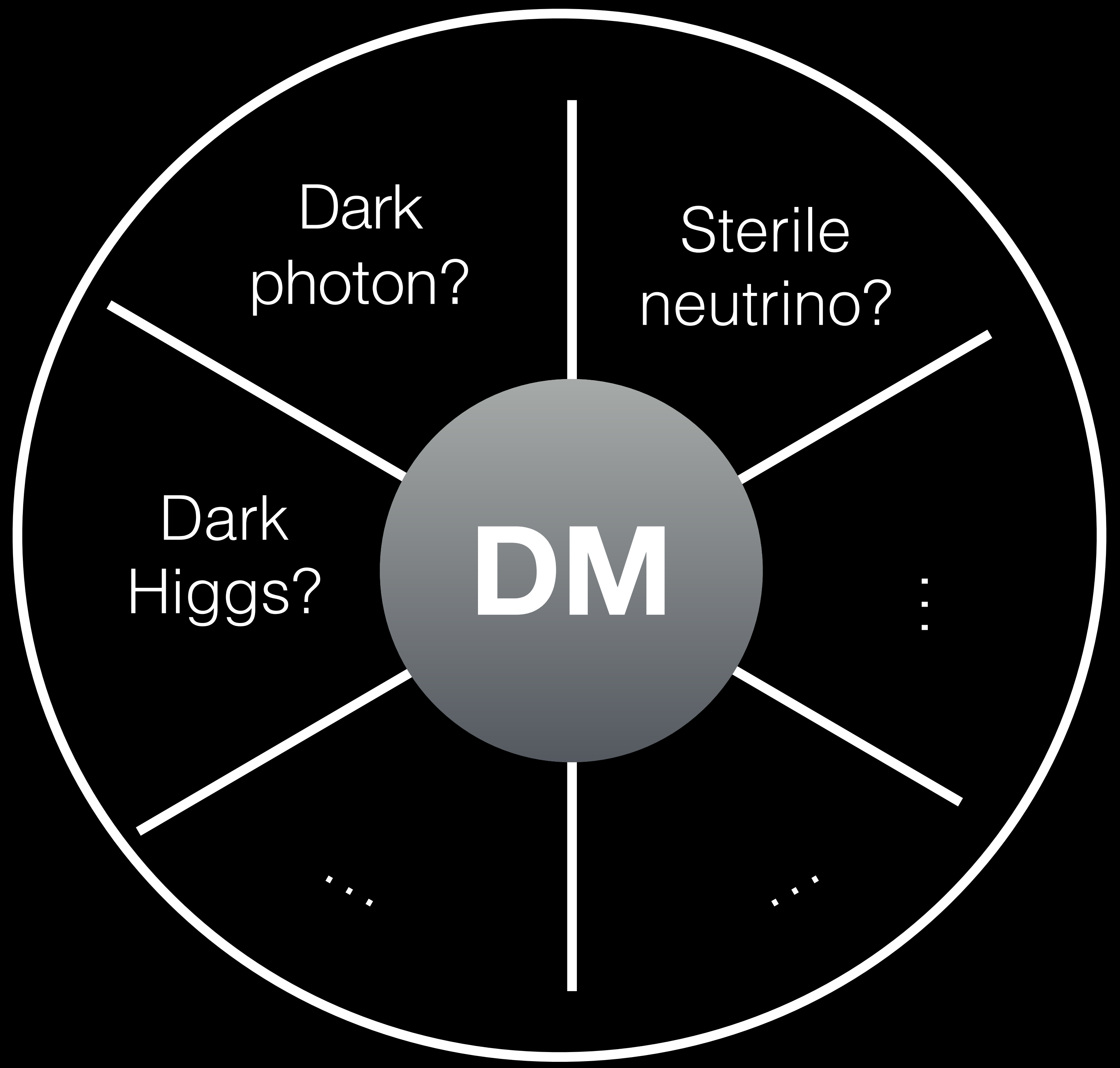


Dark sector



Portal?

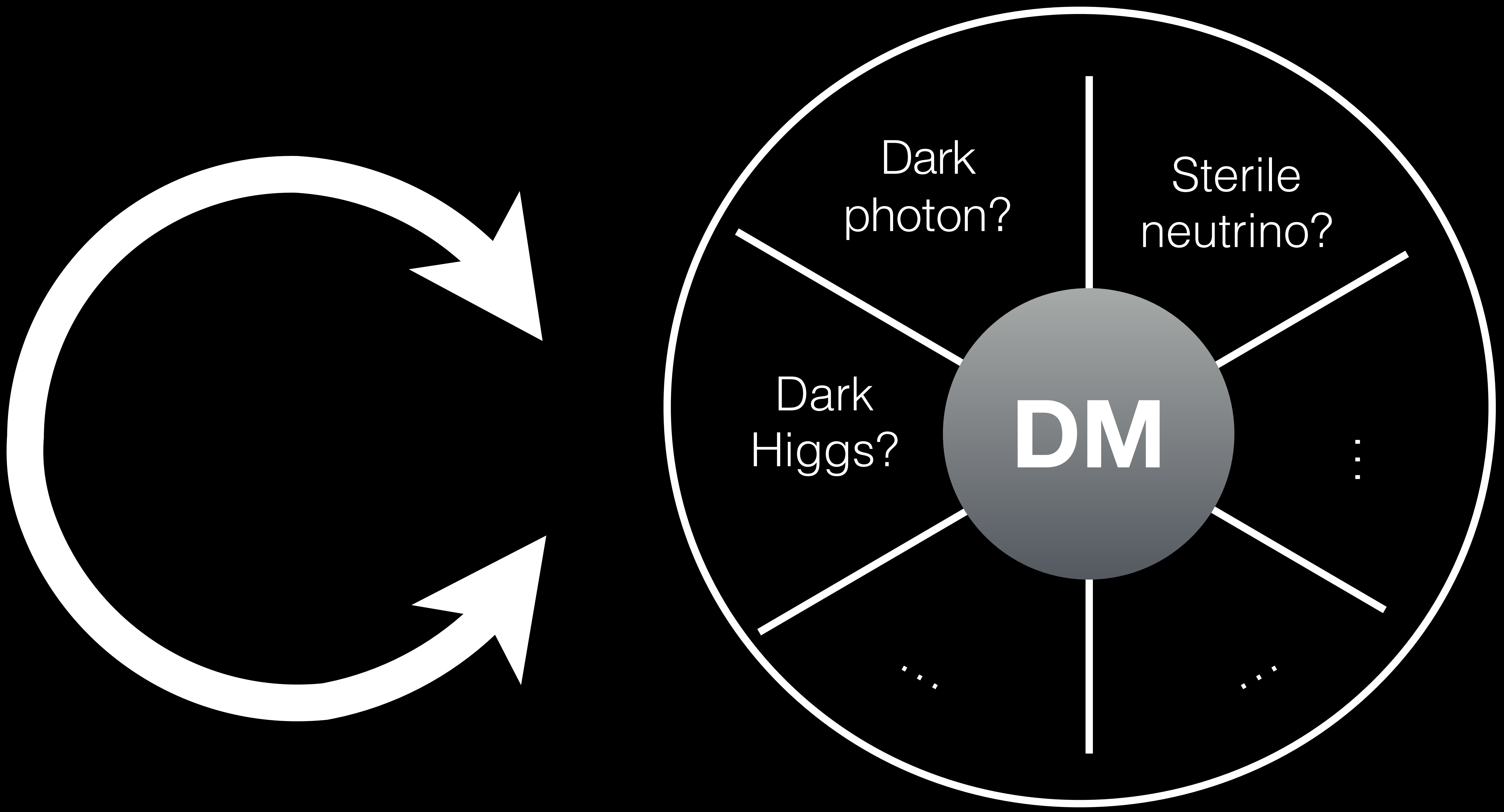
⟷



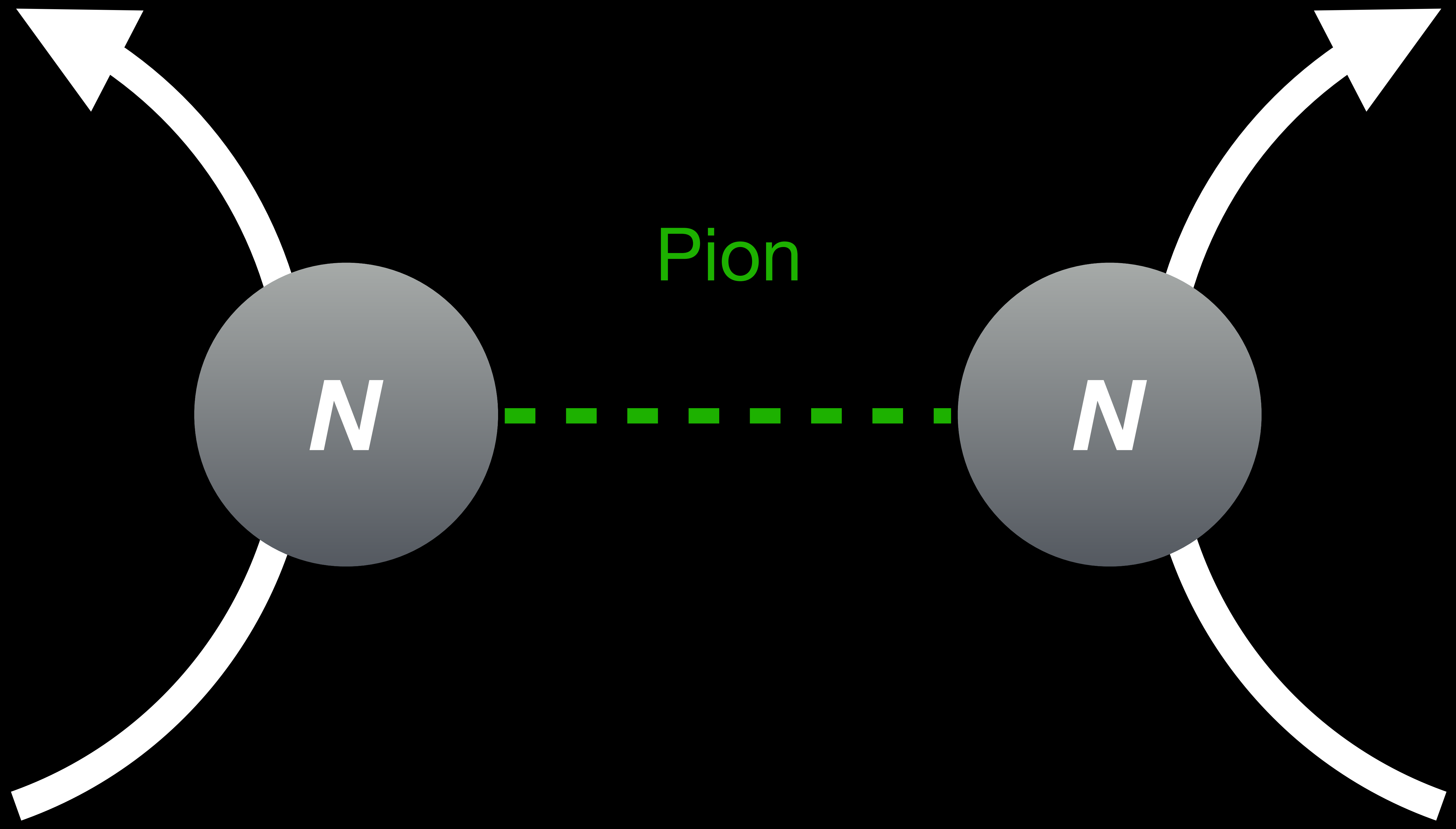
Ordinary matter

Dark sector

Self-interactions?



Dark sector

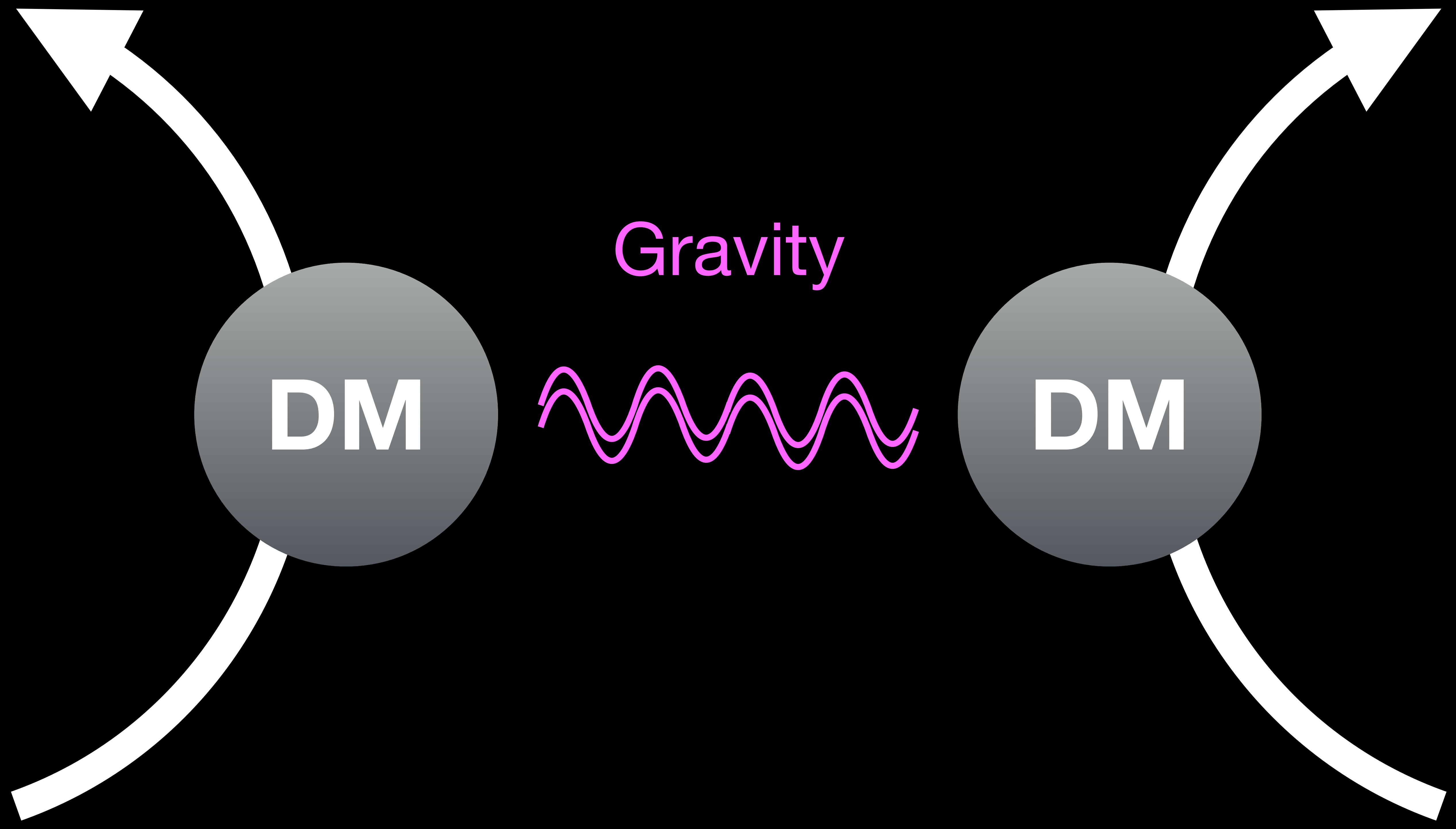


Nucleon-nucleon self-interaction

Cross section strength: $\sigma_{\mathrm{T}}/m_{\mathrm{N}} \sim 10\,\mathrm{cm}^2/\mathrm{g}$

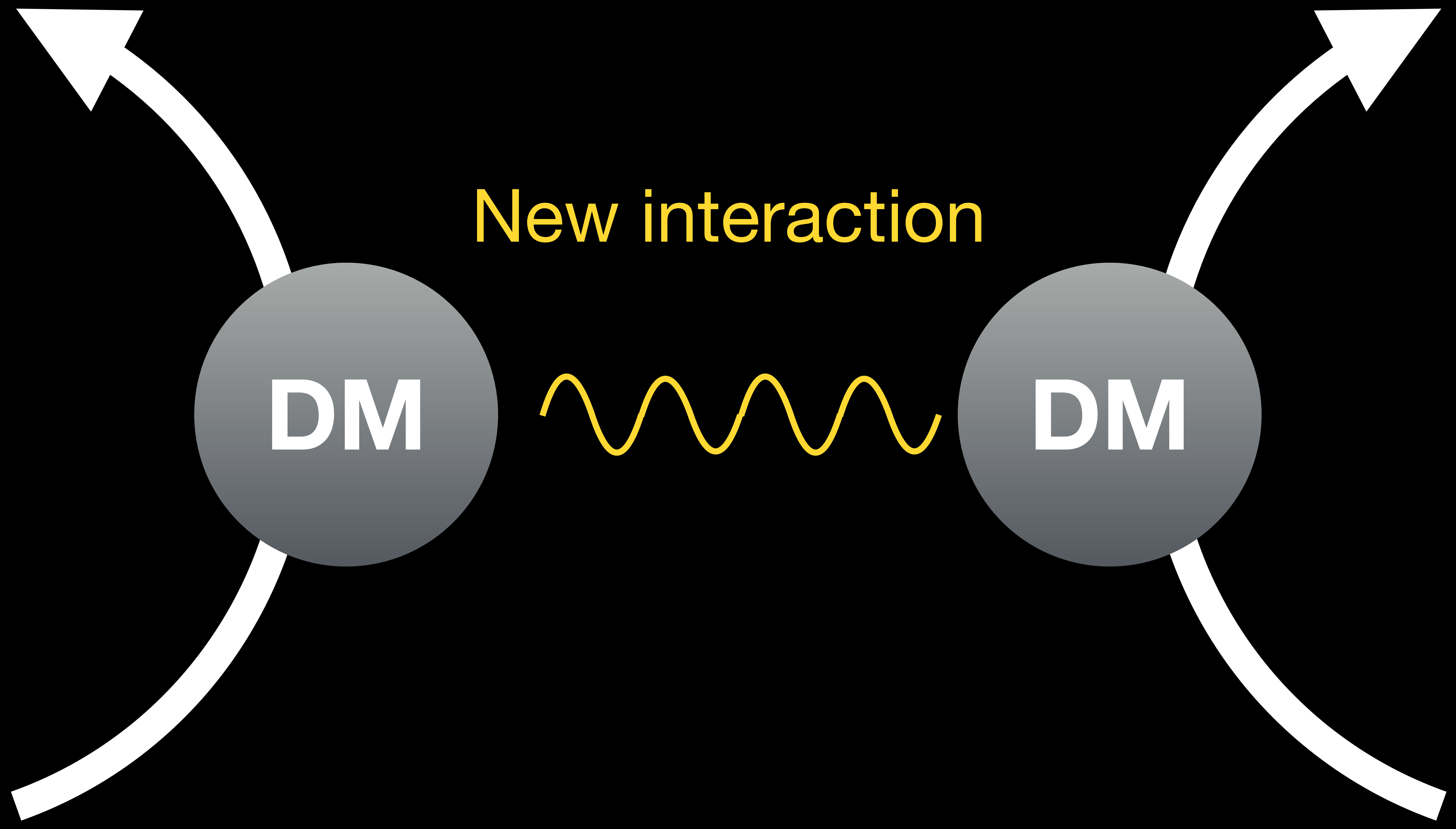
Nuclear Data Sheets '11

$1\,\mathrm{cm}^2/\mathrm{g}$
$\approx 2\,\mathrm{barn}/\mathrm{GeV}$



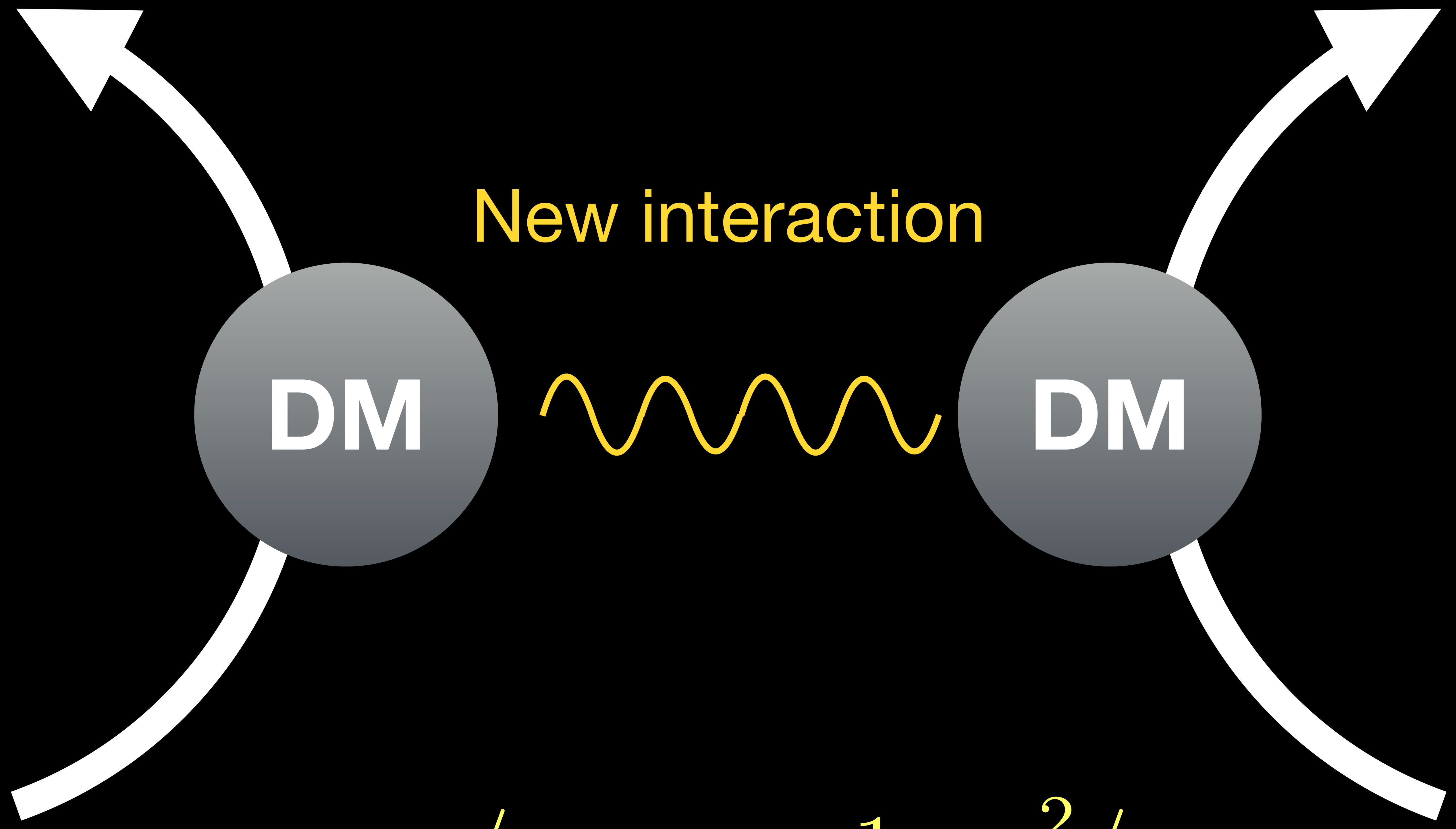
Cold Collisionless Dark Matter (CDM)

Cross section strength: $\sigma_{\mathrm{T}}/m_{\mathrm{DM}} \sim 10^{-70}\,\mathrm{cm}^2/\mathrm{g}$ (DM mass~ GeV)



Self-Interacting Dark Matter (SIDM)

Cross section strength: $\sigma_{\rm T}/m_{\rm DM} \sim 1\,{\rm cm^2/g}$



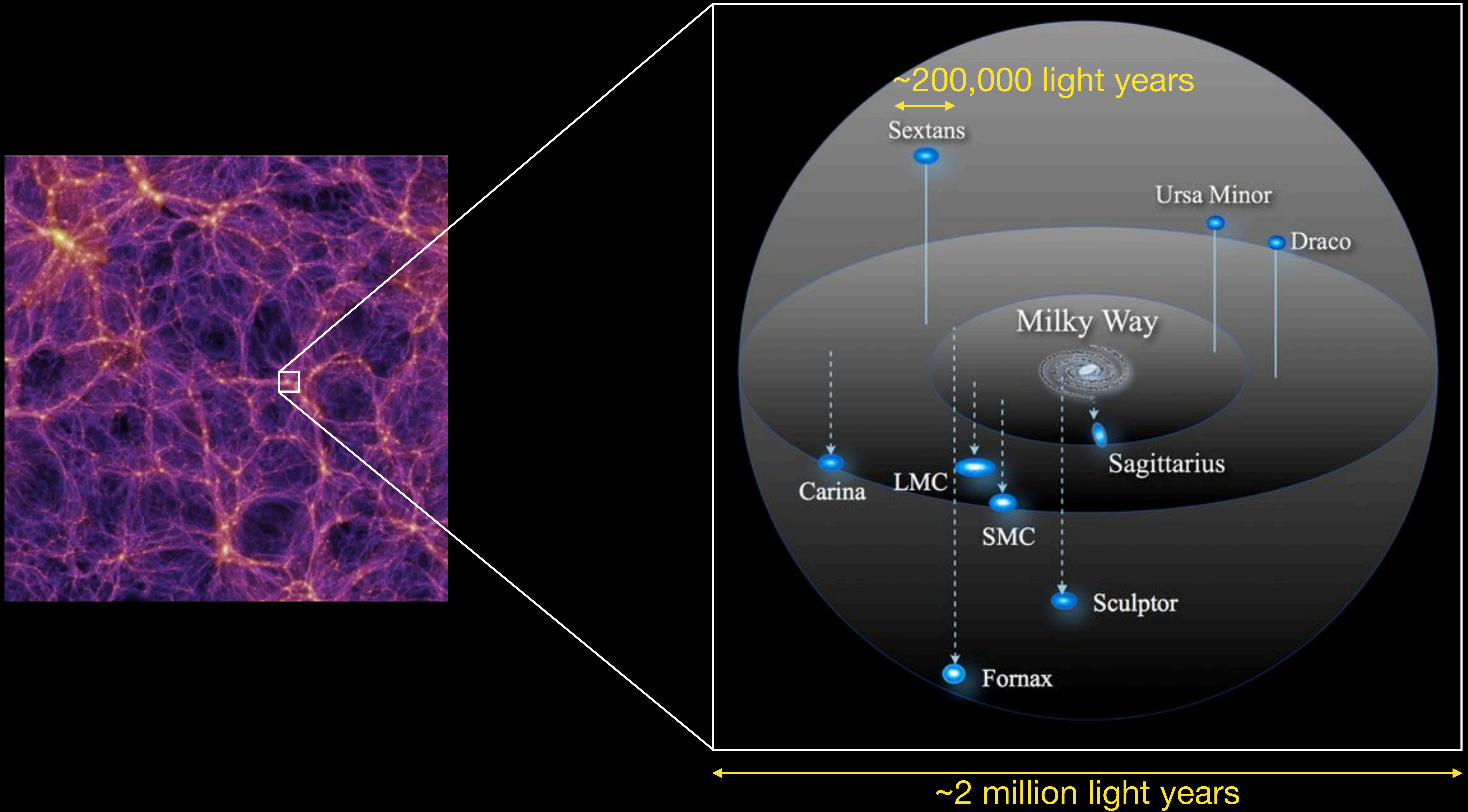
$$\sigma_{\mathrm{T}}/m_{\mathrm{DM}} \sim 1\,\mathrm{cm}^2/\mathrm{g}$$

$$t_{\mathrm{rlx}} = \frac{1}{\rho(\sigma/m)v} \sim 10\,\mathrm{Gyr}\left(\frac{0.4\,\mathrm{GeV/cm^3}}{\rho}\right)\left(\frac{1\,\mathrm{cm^2/g}}{\sigma/m}\right)\left(\frac{200\,\mathrm{km/s}}{v}\right)$$

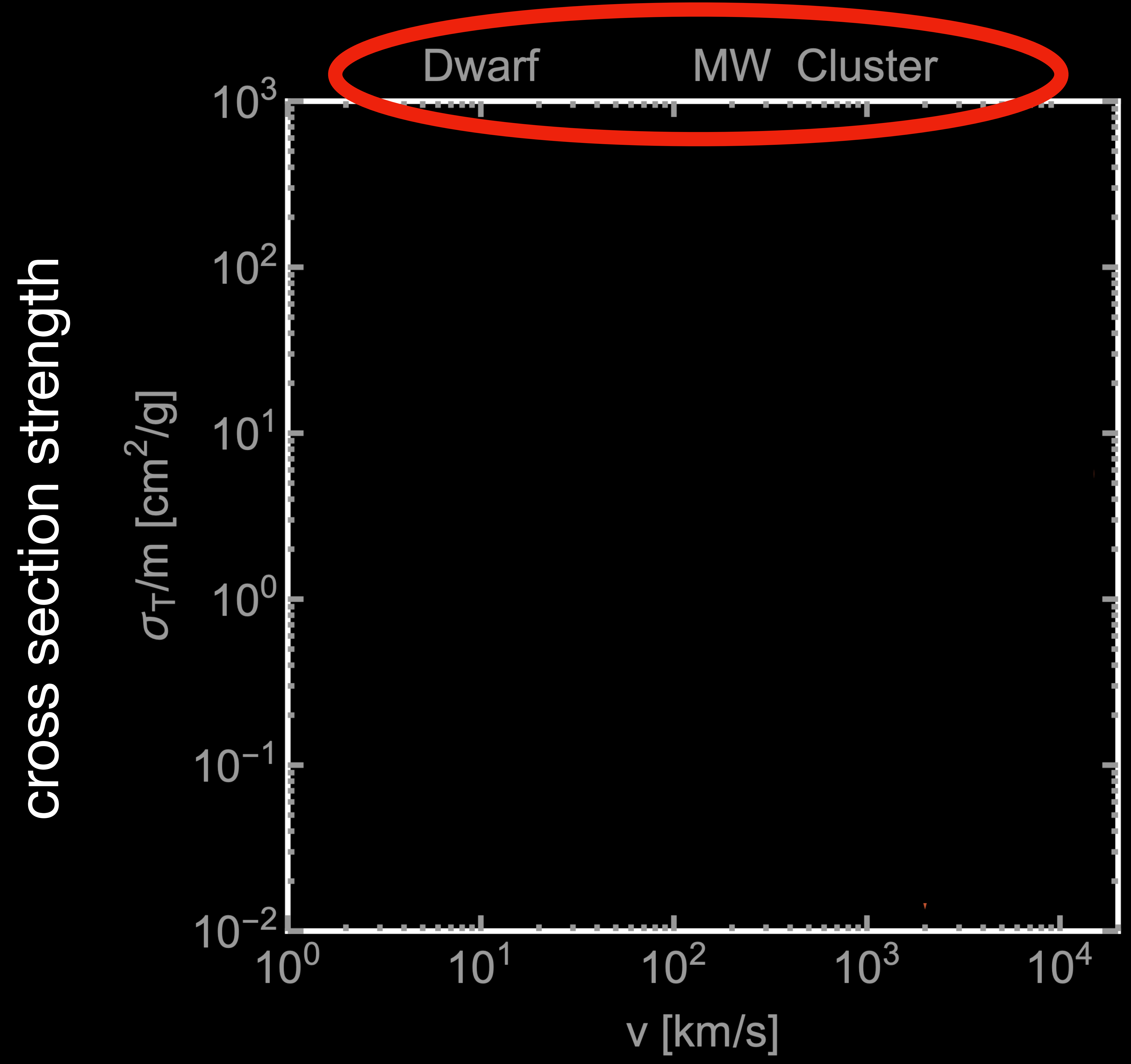
Spergel & Steinhardt ‘00

Where to look at?

Dark matter halos

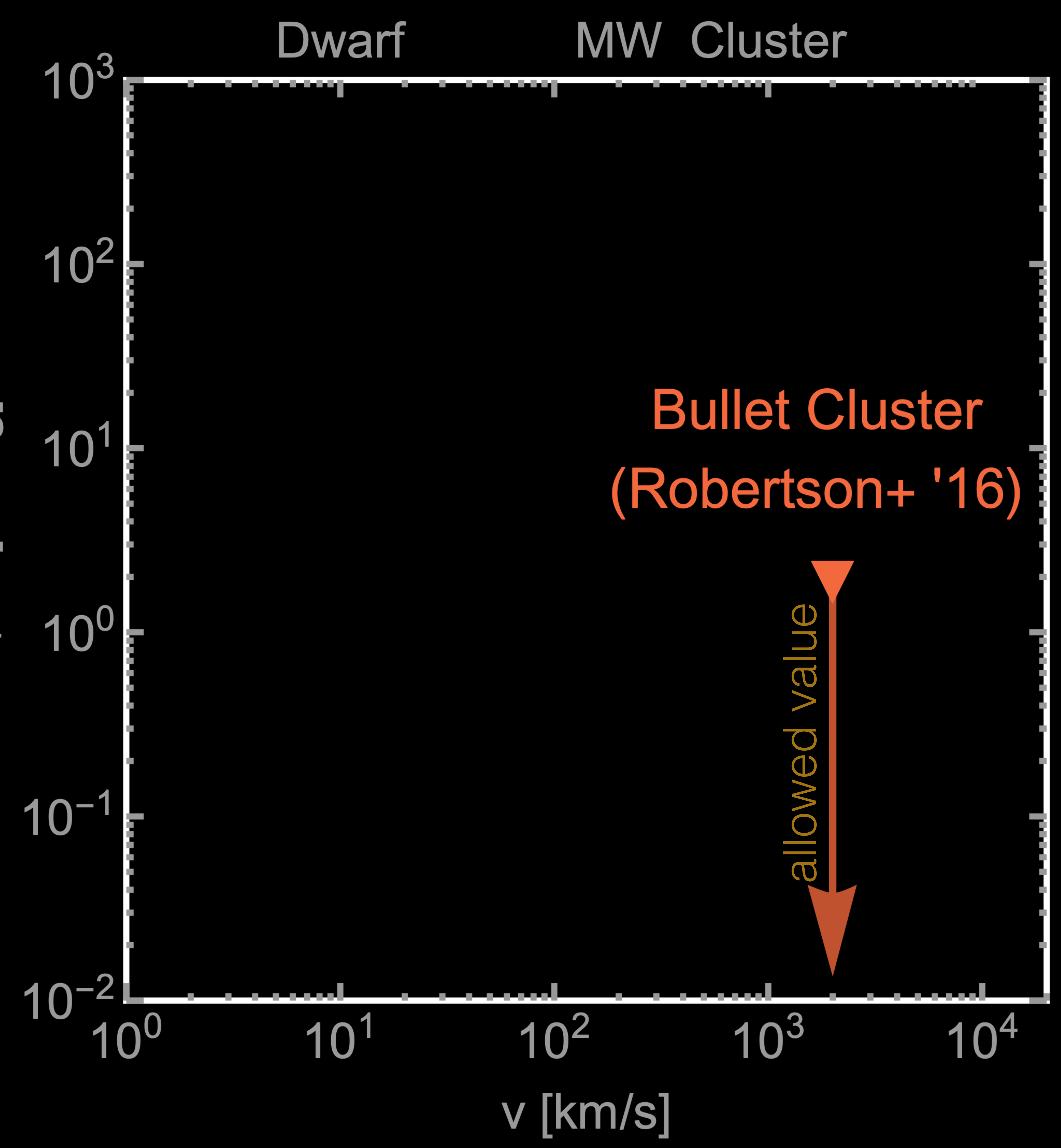


Constraints on dark matter self-interaction

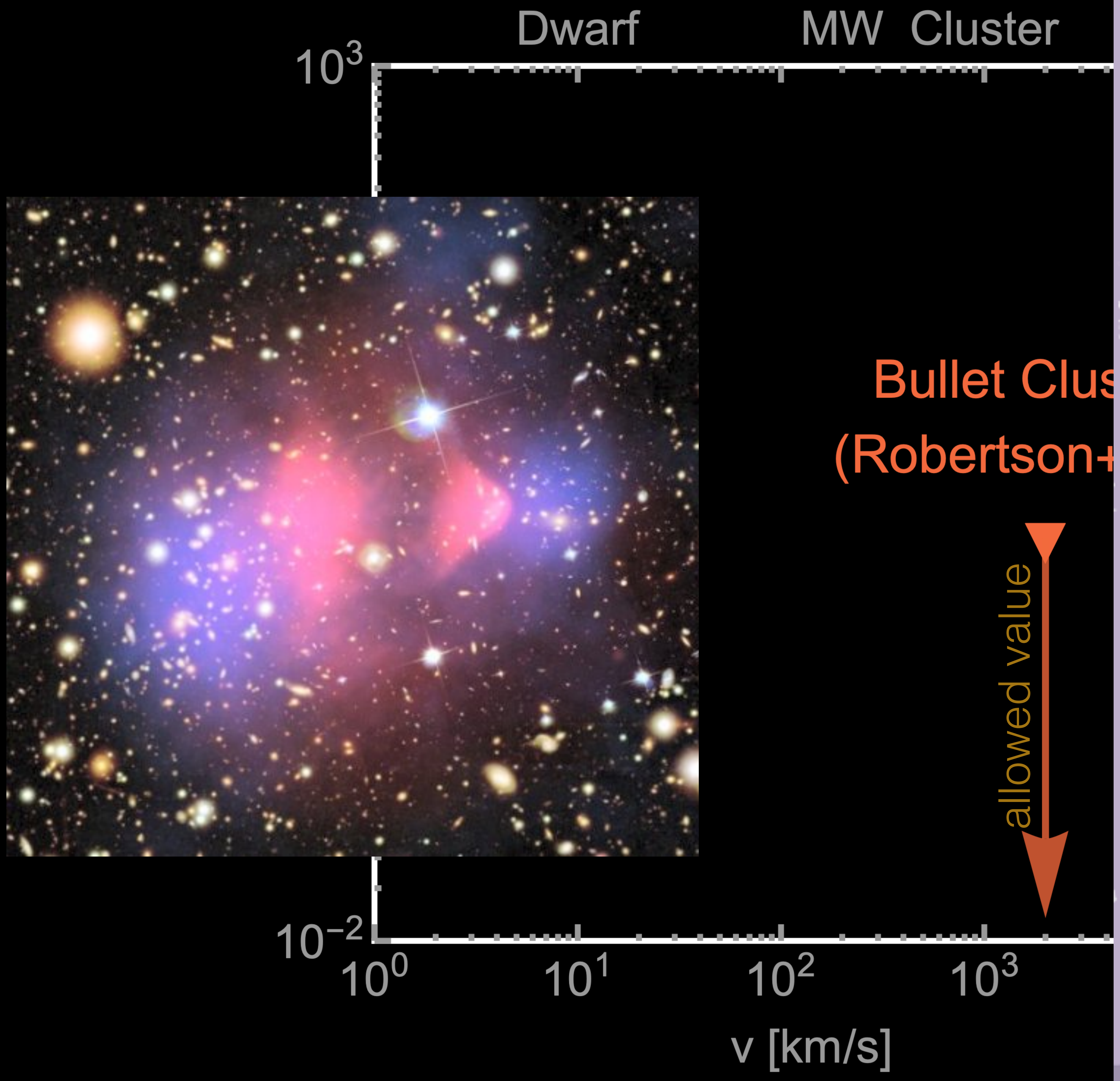


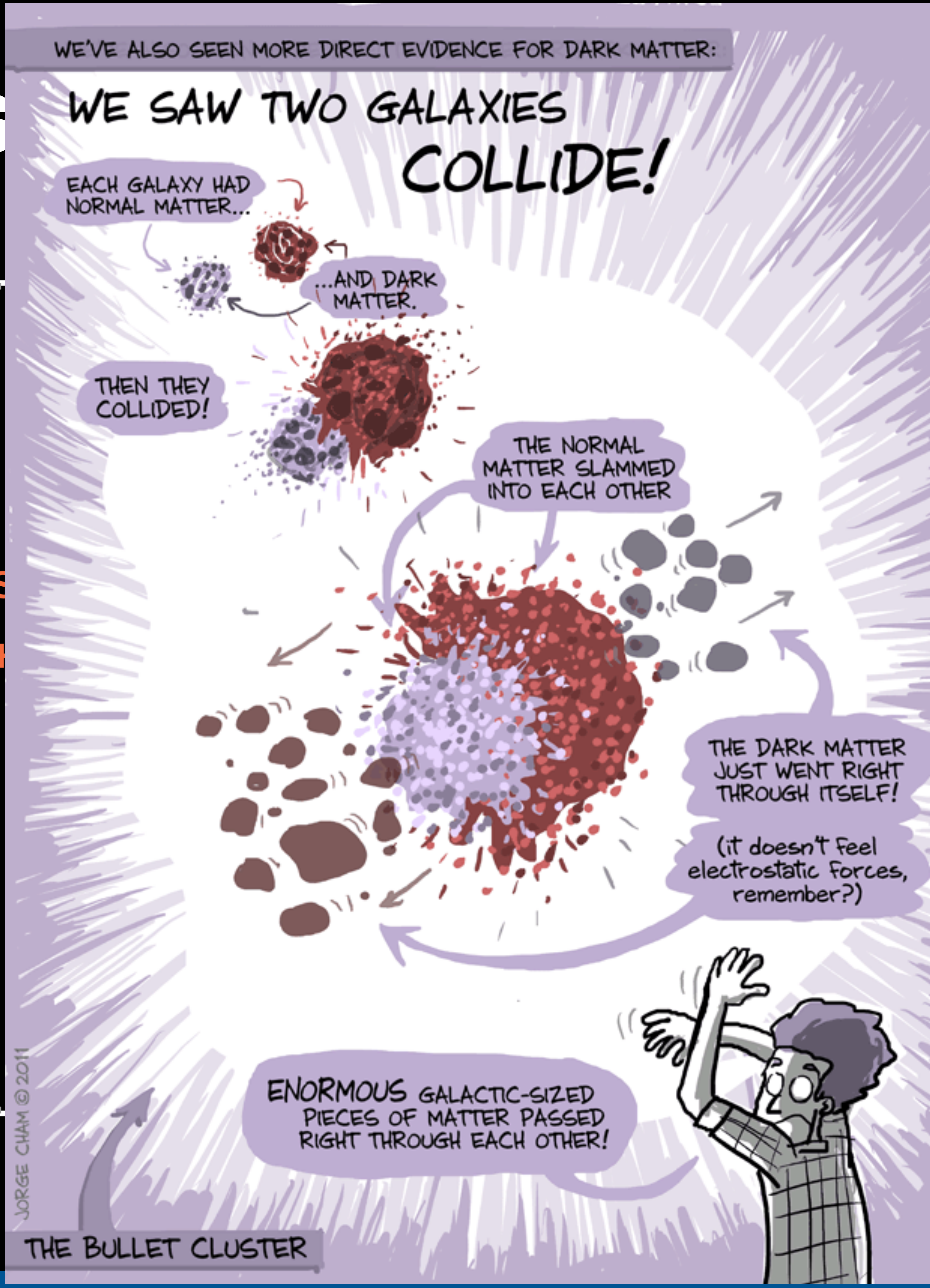
Constraints on dark matter self-interaction

cross section strength



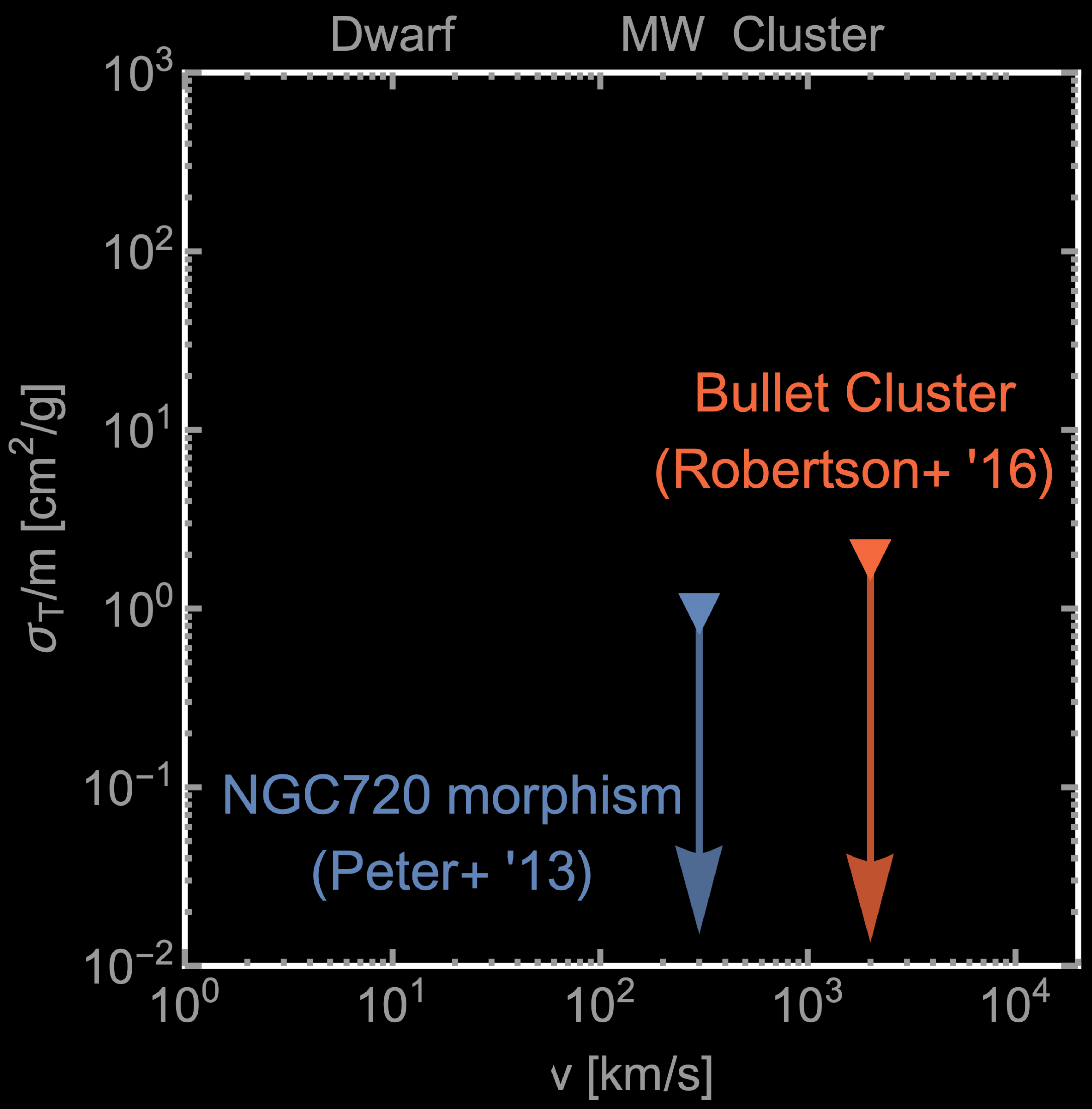
Constraints on dark matter s

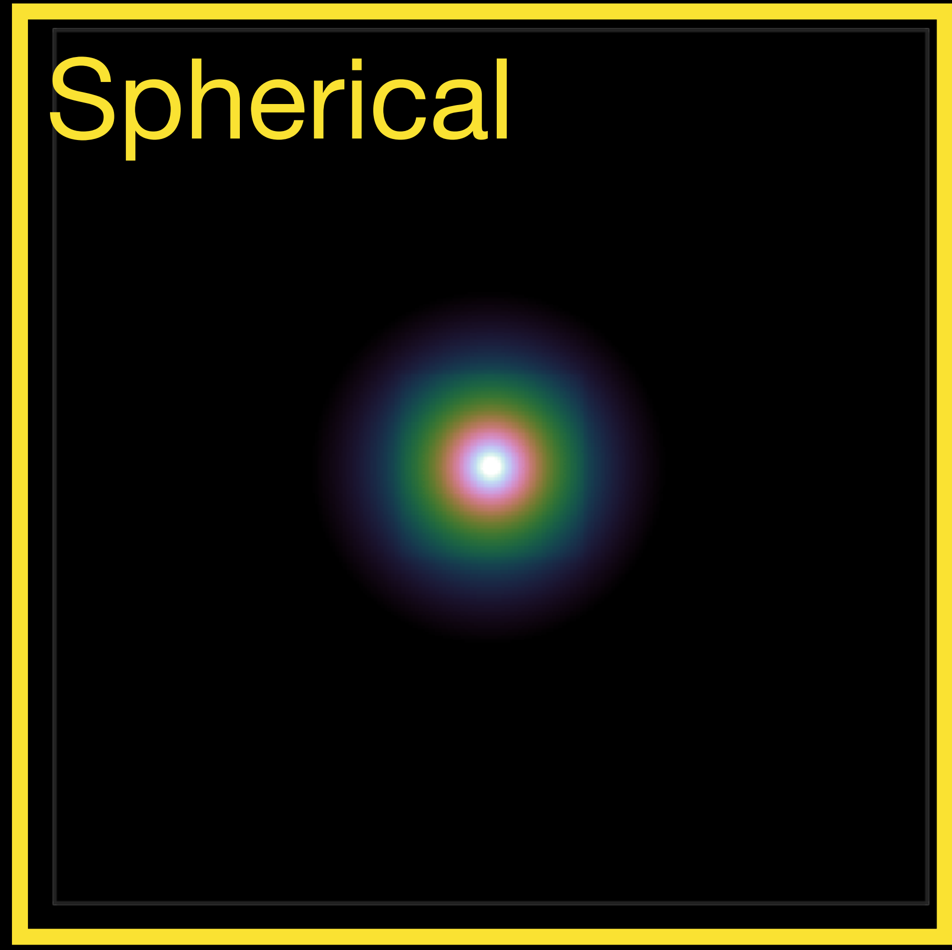


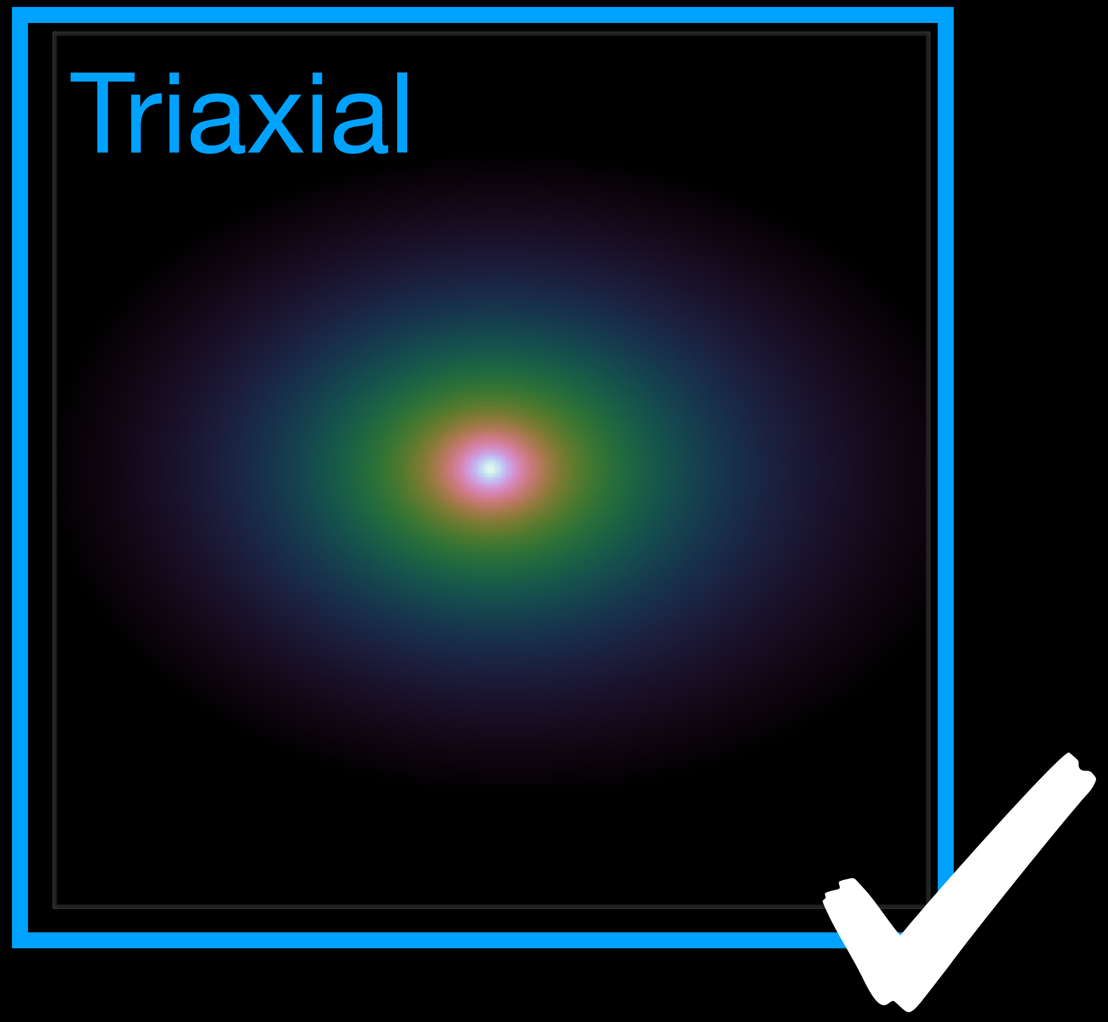


Constraints on dark matter self-interaction

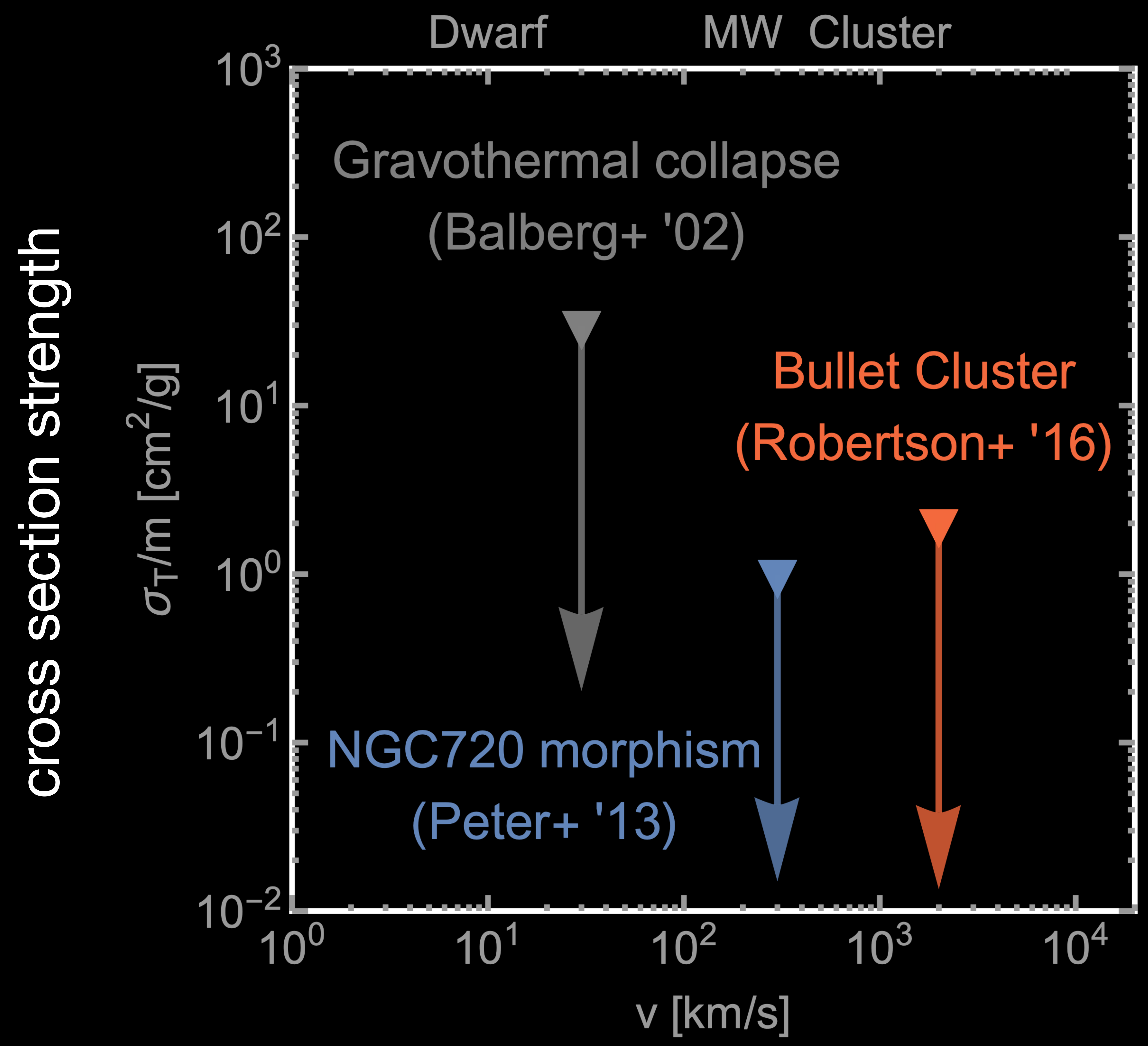
cross section strength







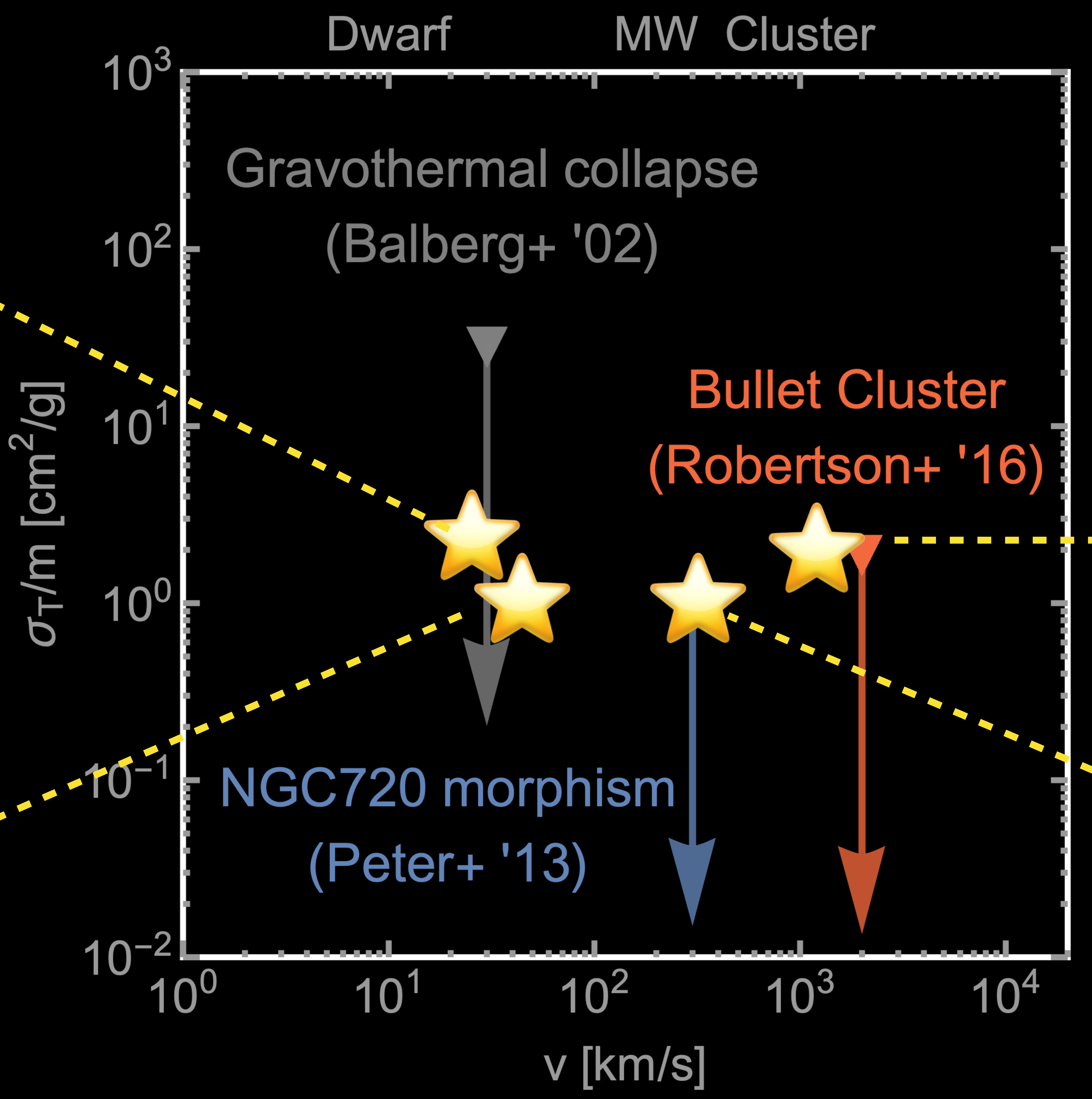
Constraints on dark matter self-interaction



Constrains & sol to the "small-scale problems"

Diversity
(Kamada+ '16)

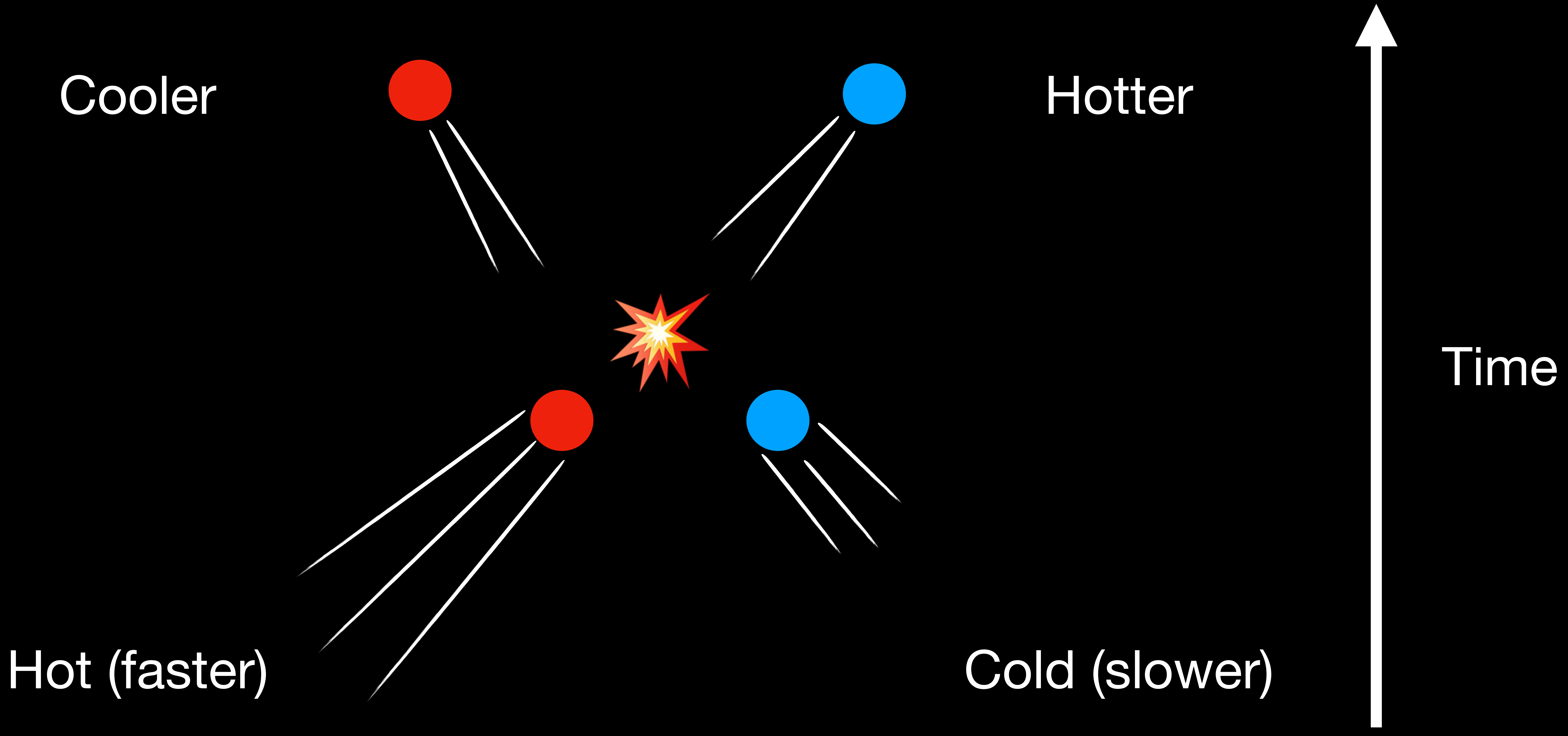
Too big to fail
(Zavala+'12
Elbert+ '14)



Splashback
radius deficit
(More+ '16)

Cusp vs core
(Wandelt+ '00)

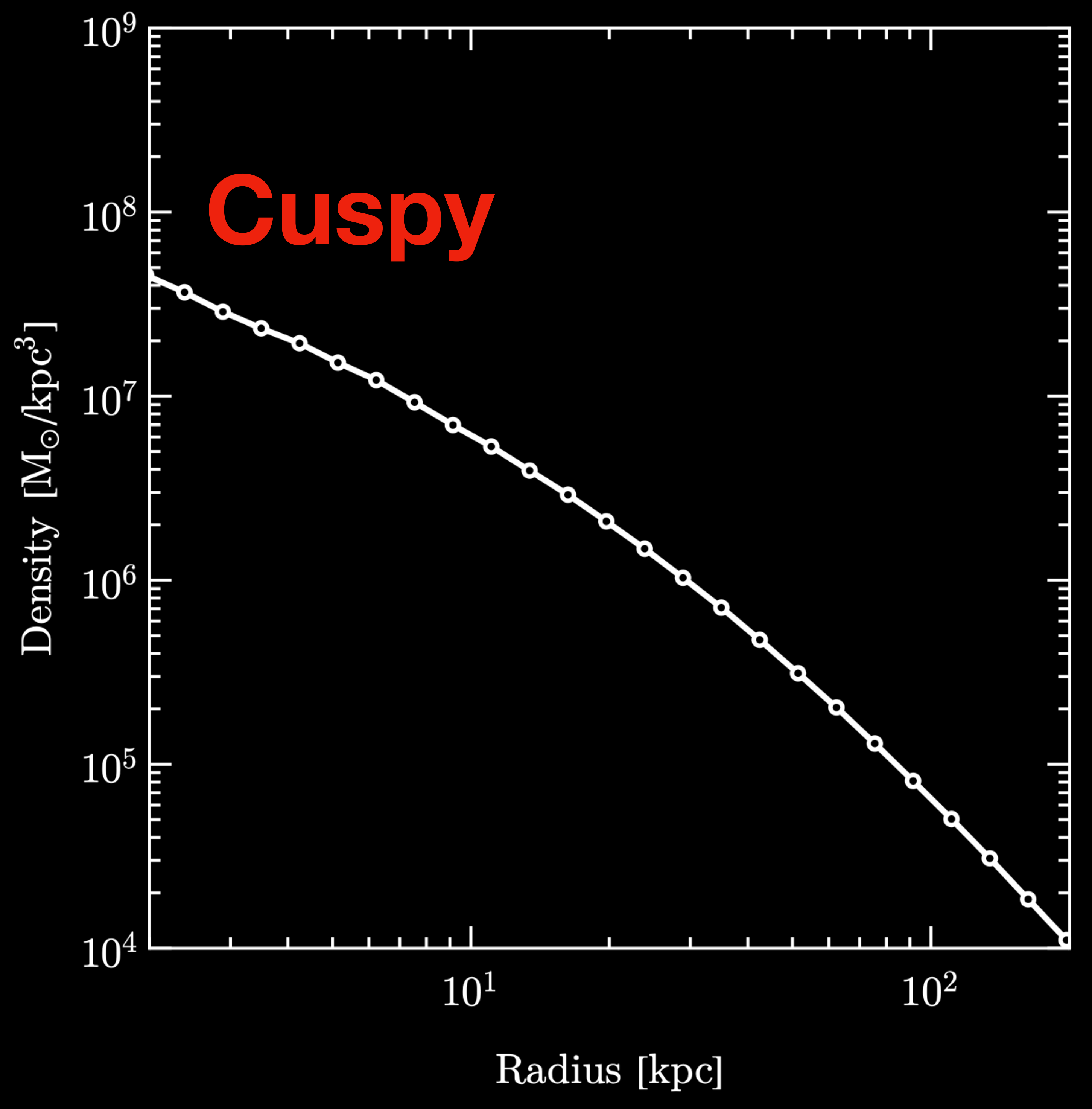
Effects of self-interaction

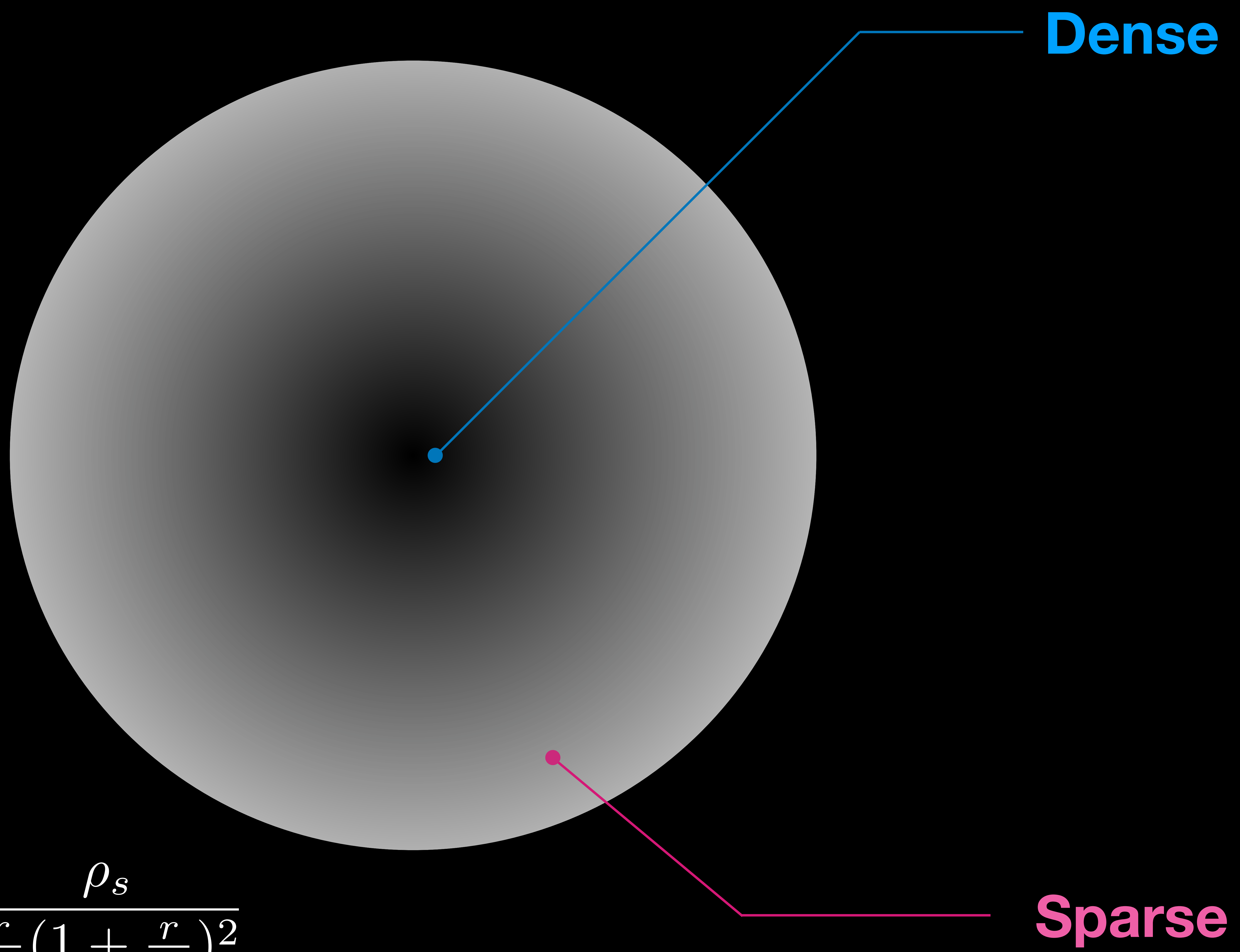


Equipartition

0. Halo formation

Density profile
(density at given radii)

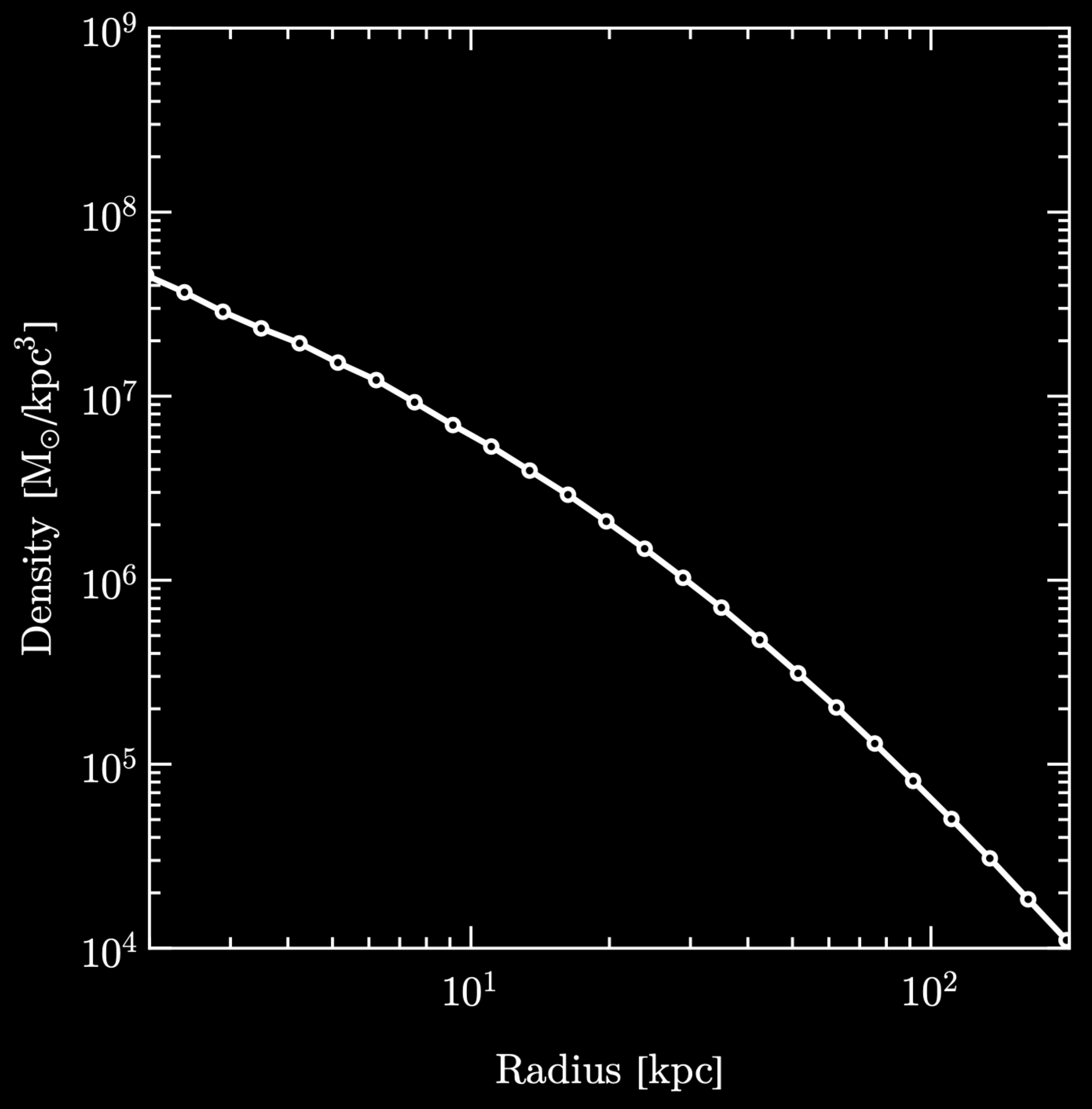




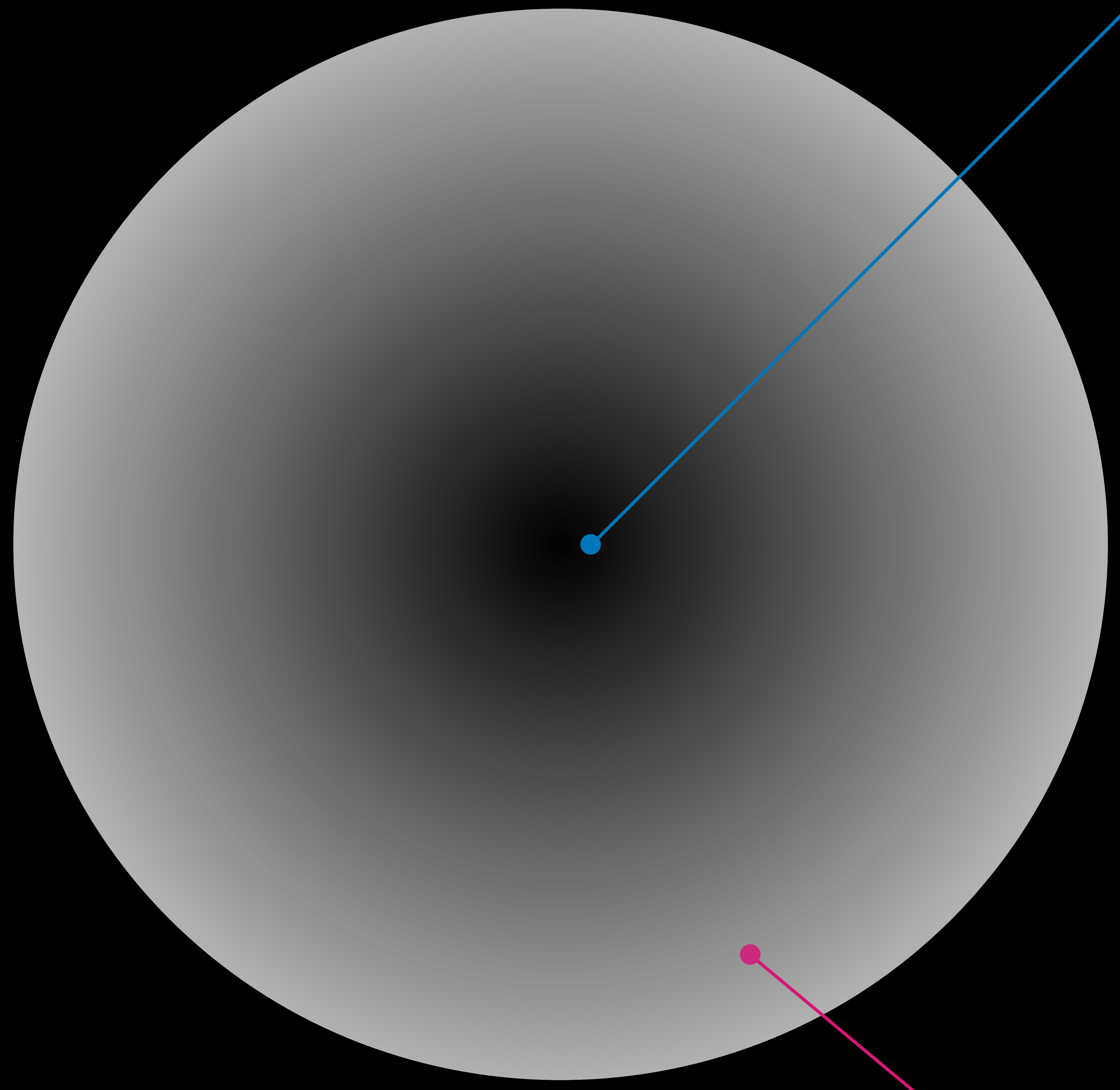
Navarro-Frenk-White (NFW) profile $\rho = \dfrac{\rho_s}{\frac{r}{r_s}(1+\frac{r}{r_s})^2}$

0. Halo formation

Density profile
(density at given radii)

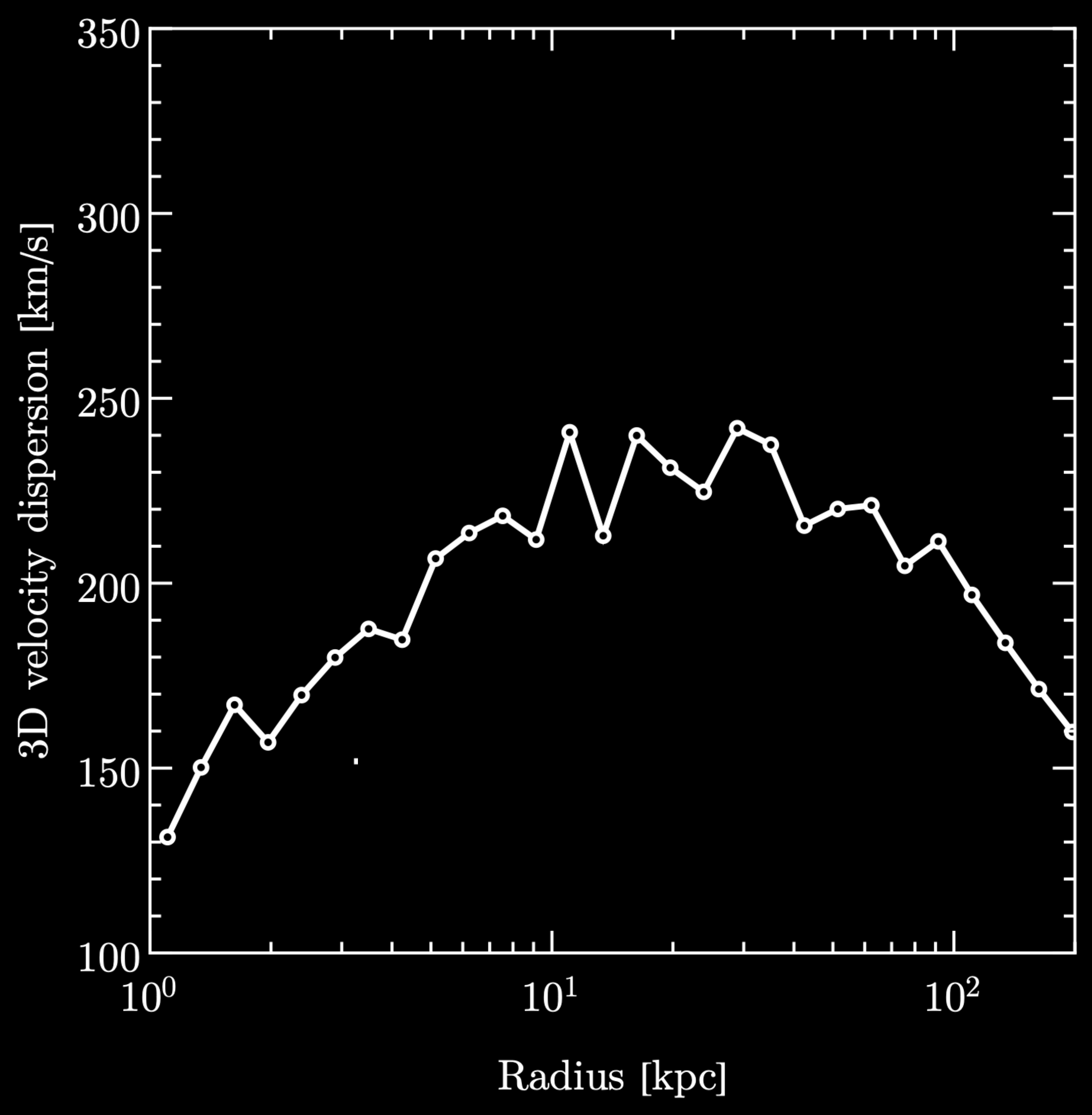


Dense, Cold

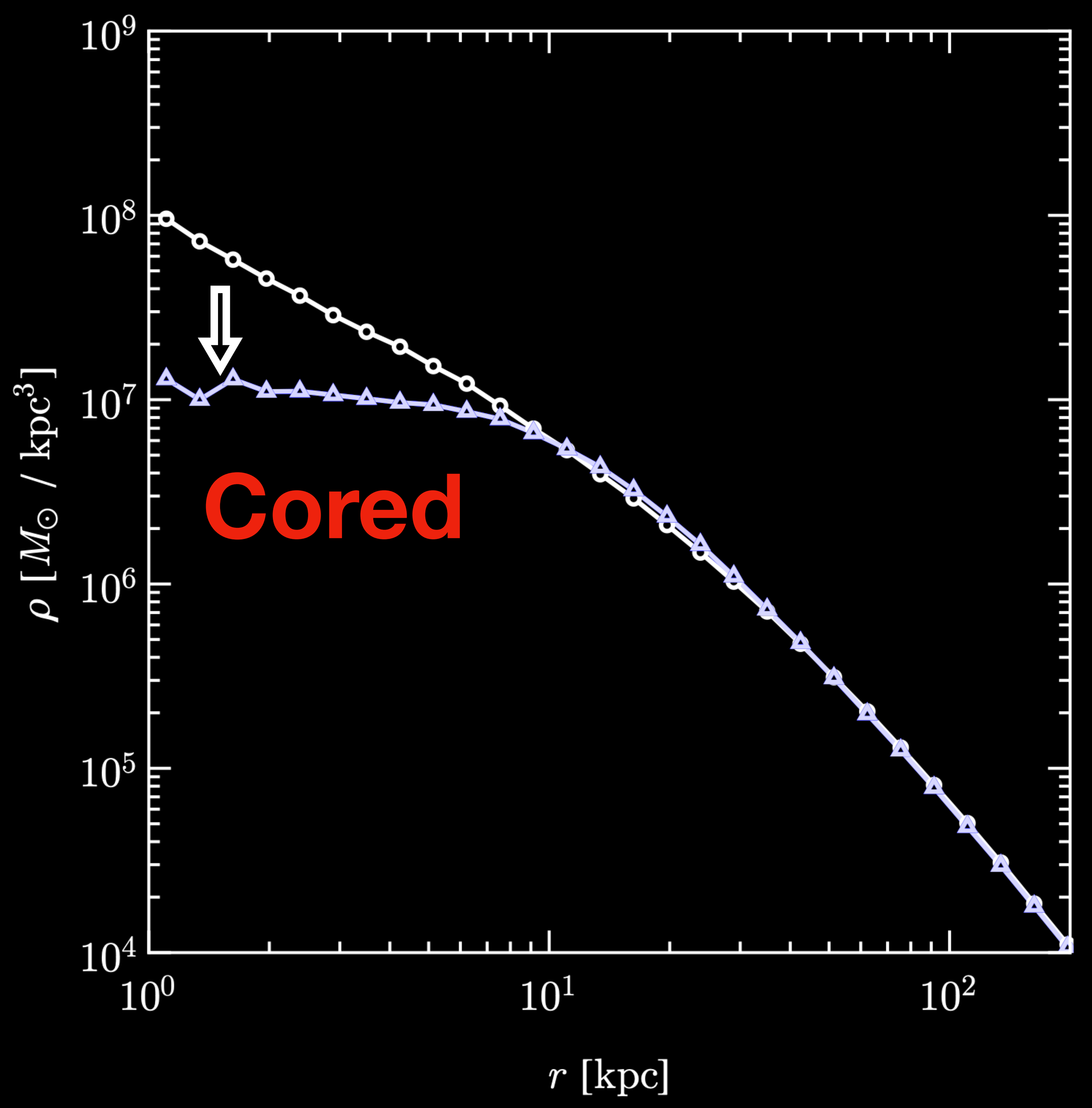


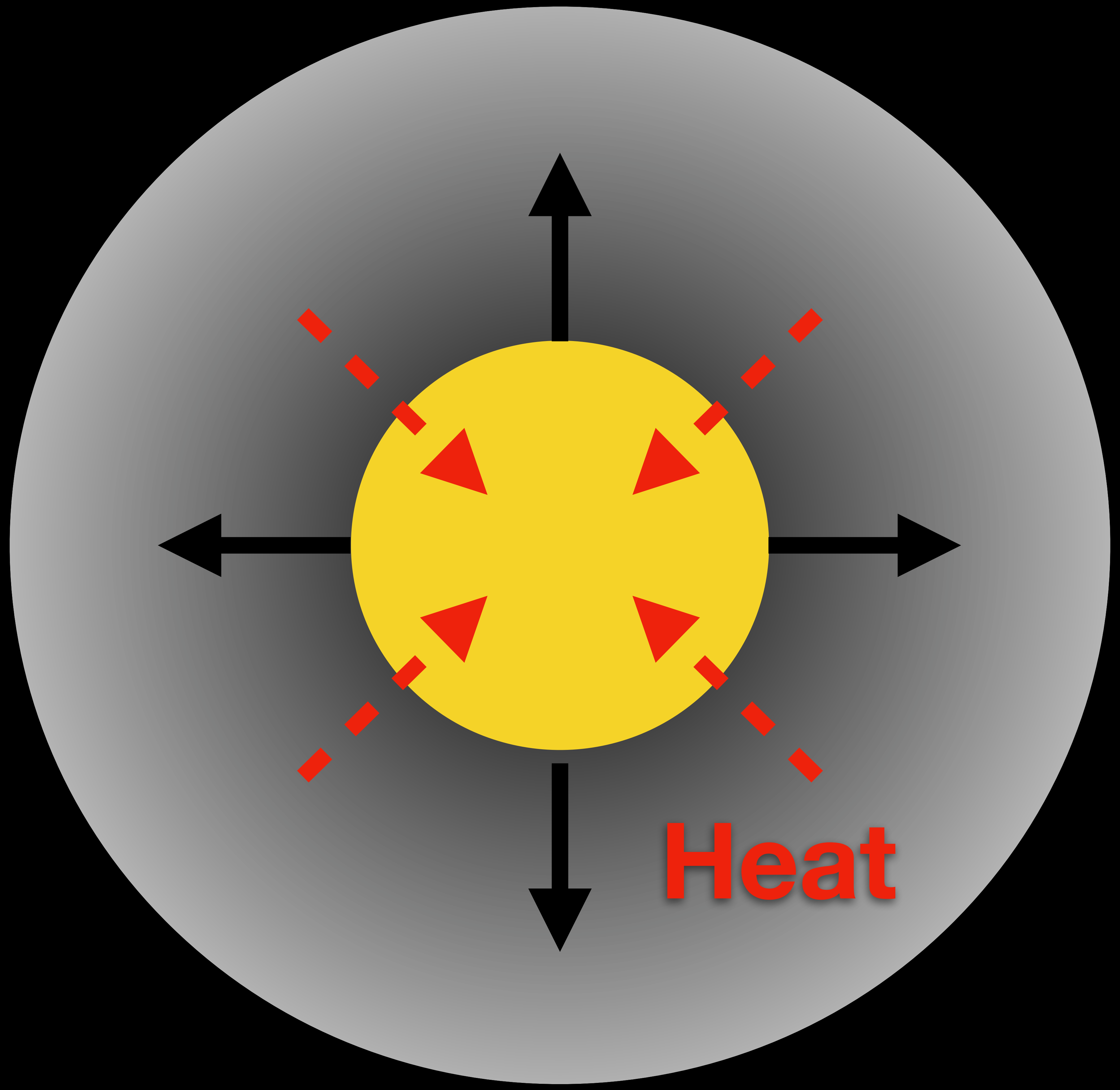
Sparse, Hot

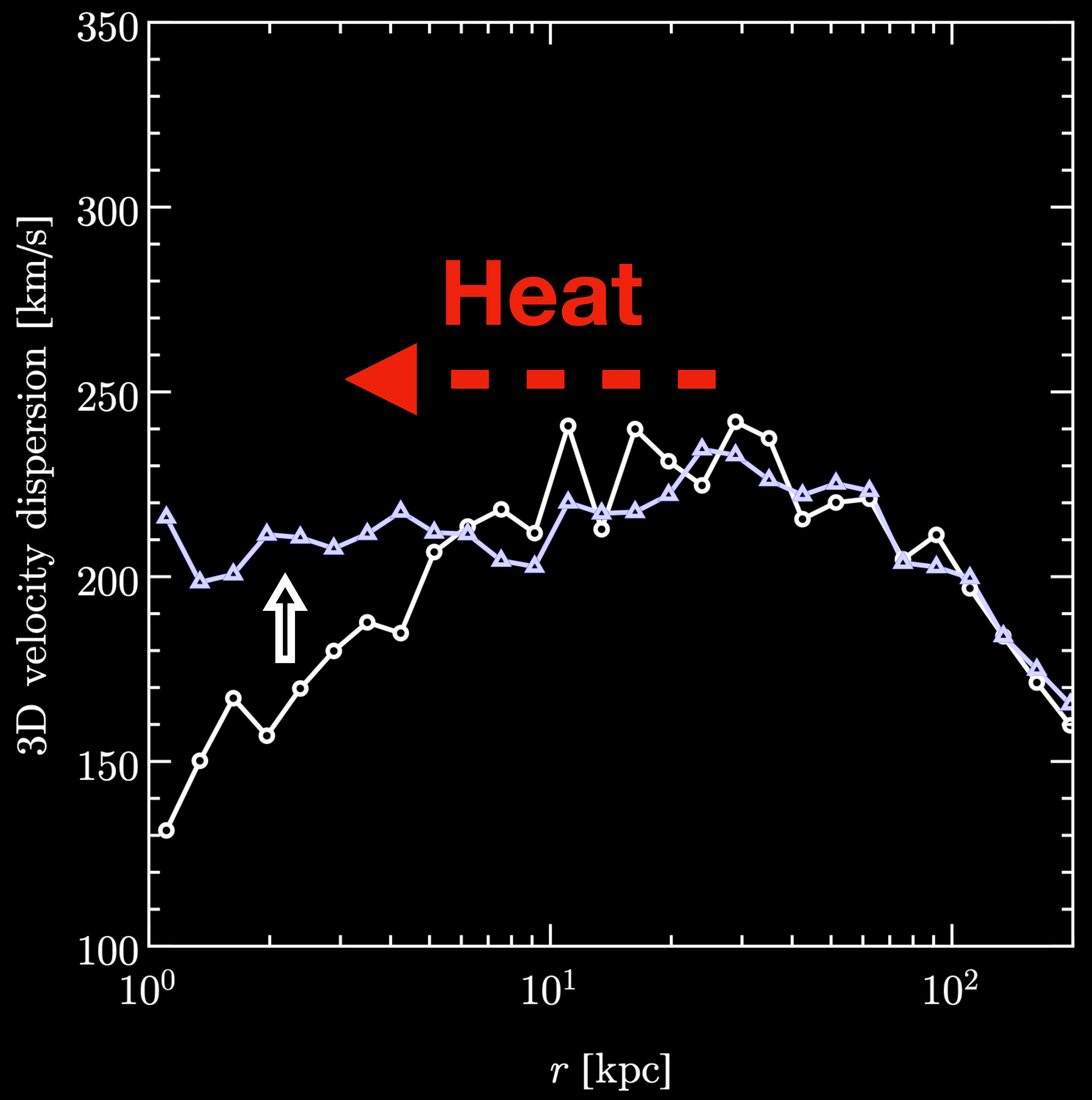
Velocity dispersion profile



1. Core expansion

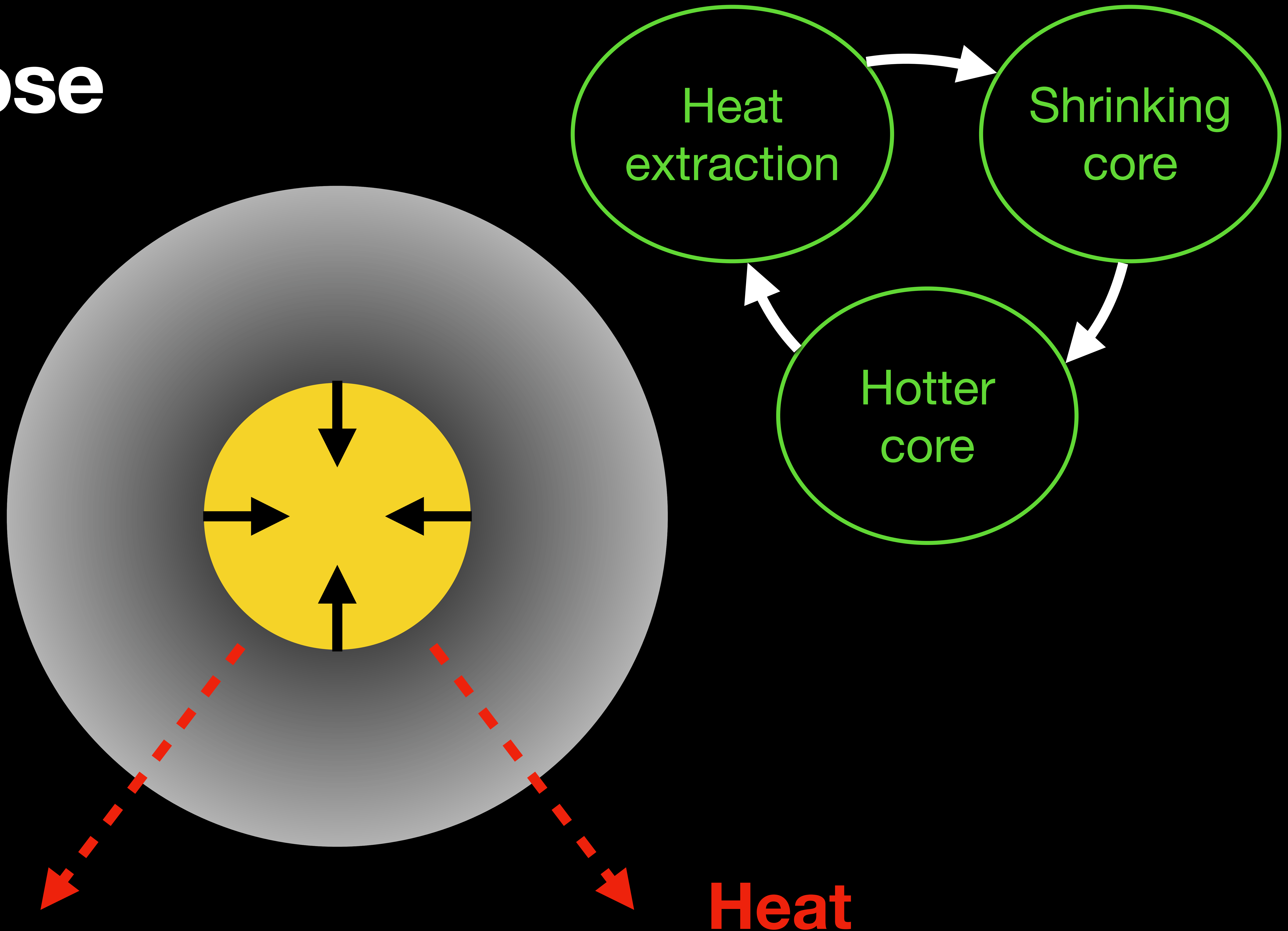




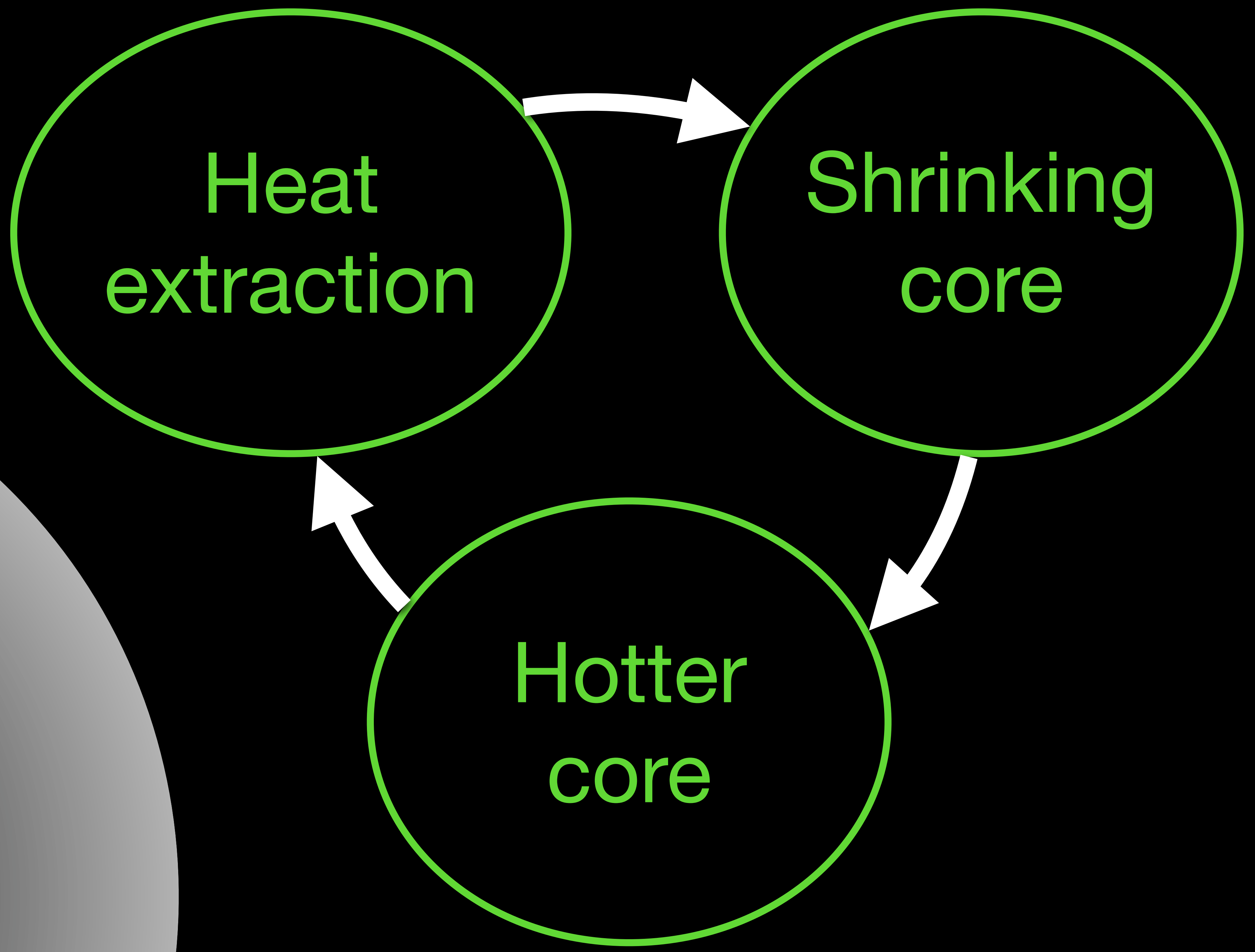


Huo, Yu & **YZ** ‘20

2. Core collapse



2. Core collapse



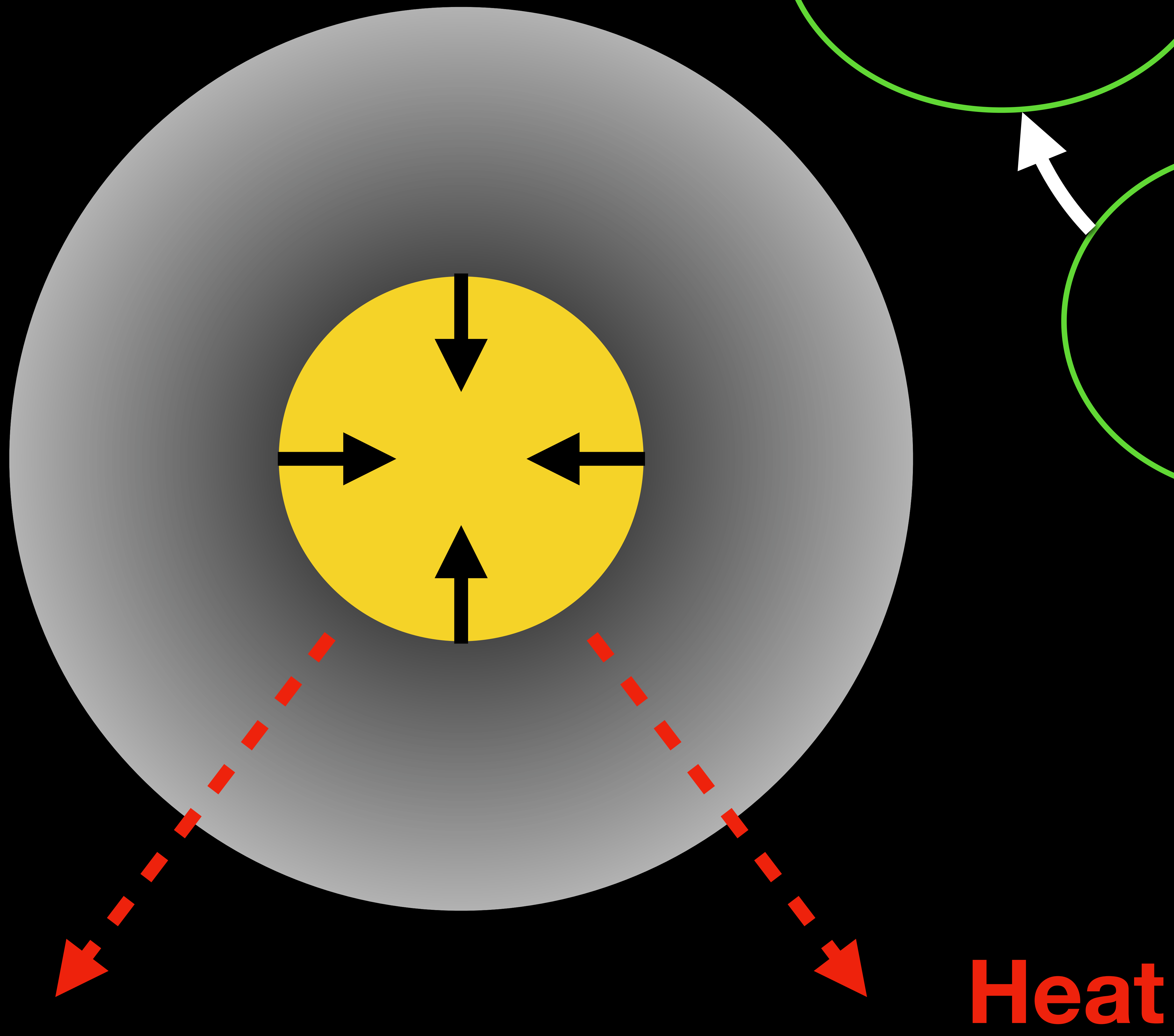
$$2E_{\text{kin}} + E_{\text{pot}} = 0$$

$$\Downarrow$$

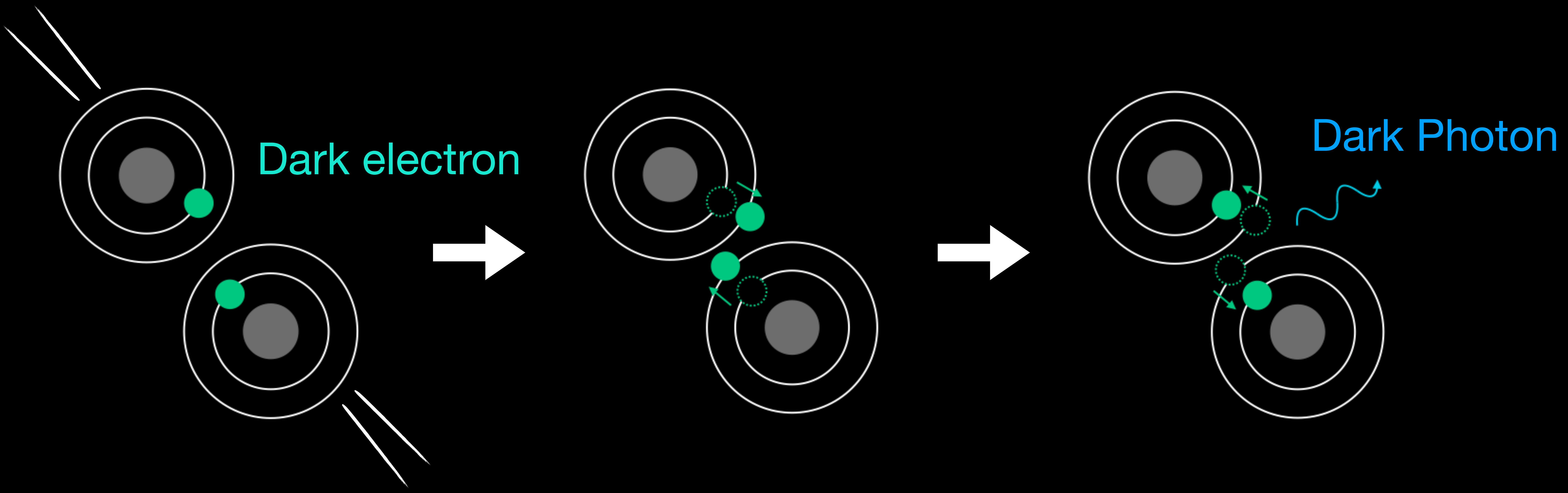
$$E_{\text{total}} = -E_{\text{kin}}$$

$$\Downarrow \quad E_{\text{kin}} \propto T$$

$$C \equiv \frac{E_{\text{total}}}{T} < 0$$



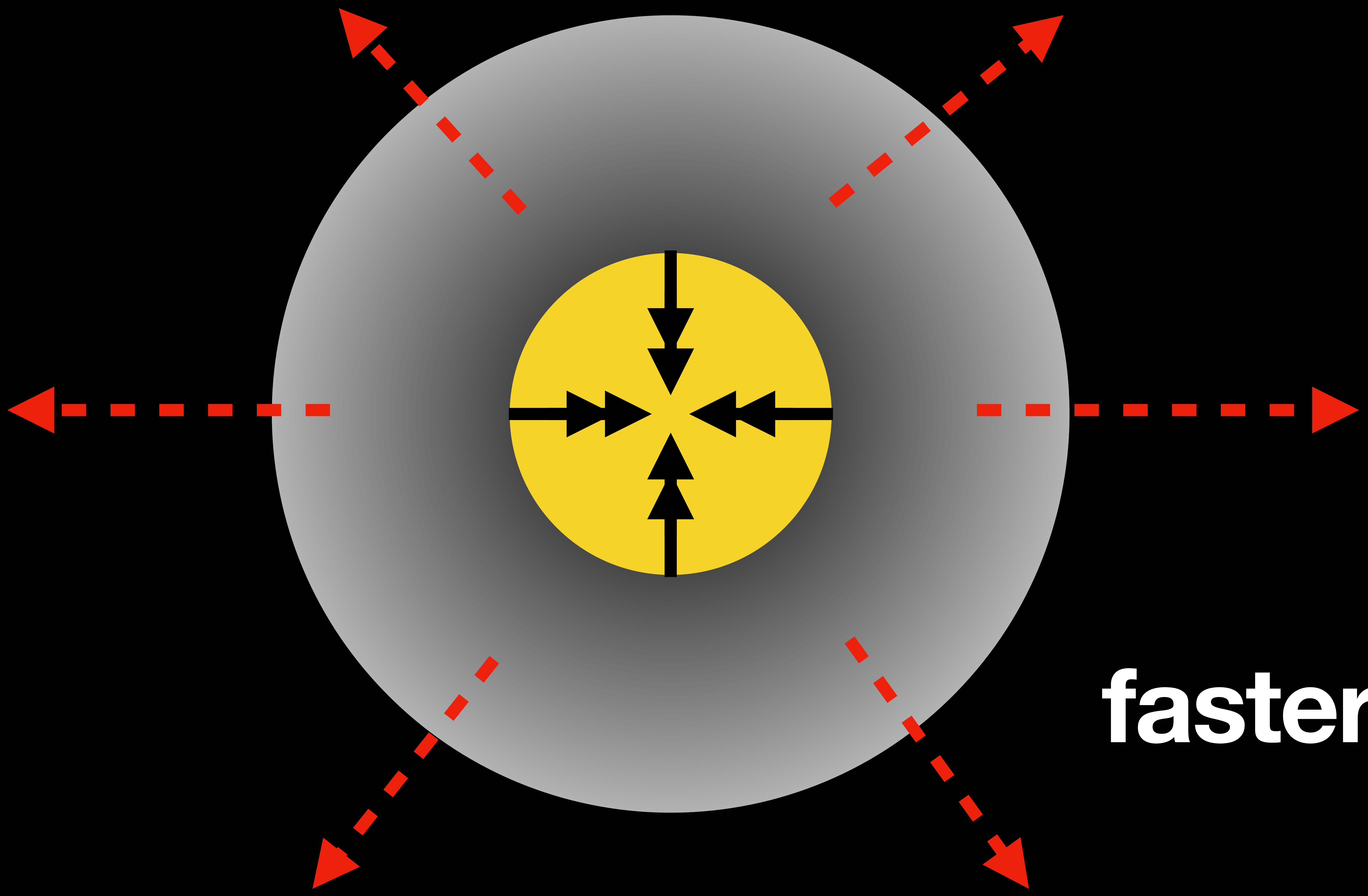
Dissipative SIDM



e.g., Atomic Dark Matter

Essig, Mcdermott, Yu & **YZ** (2019)

More heat out



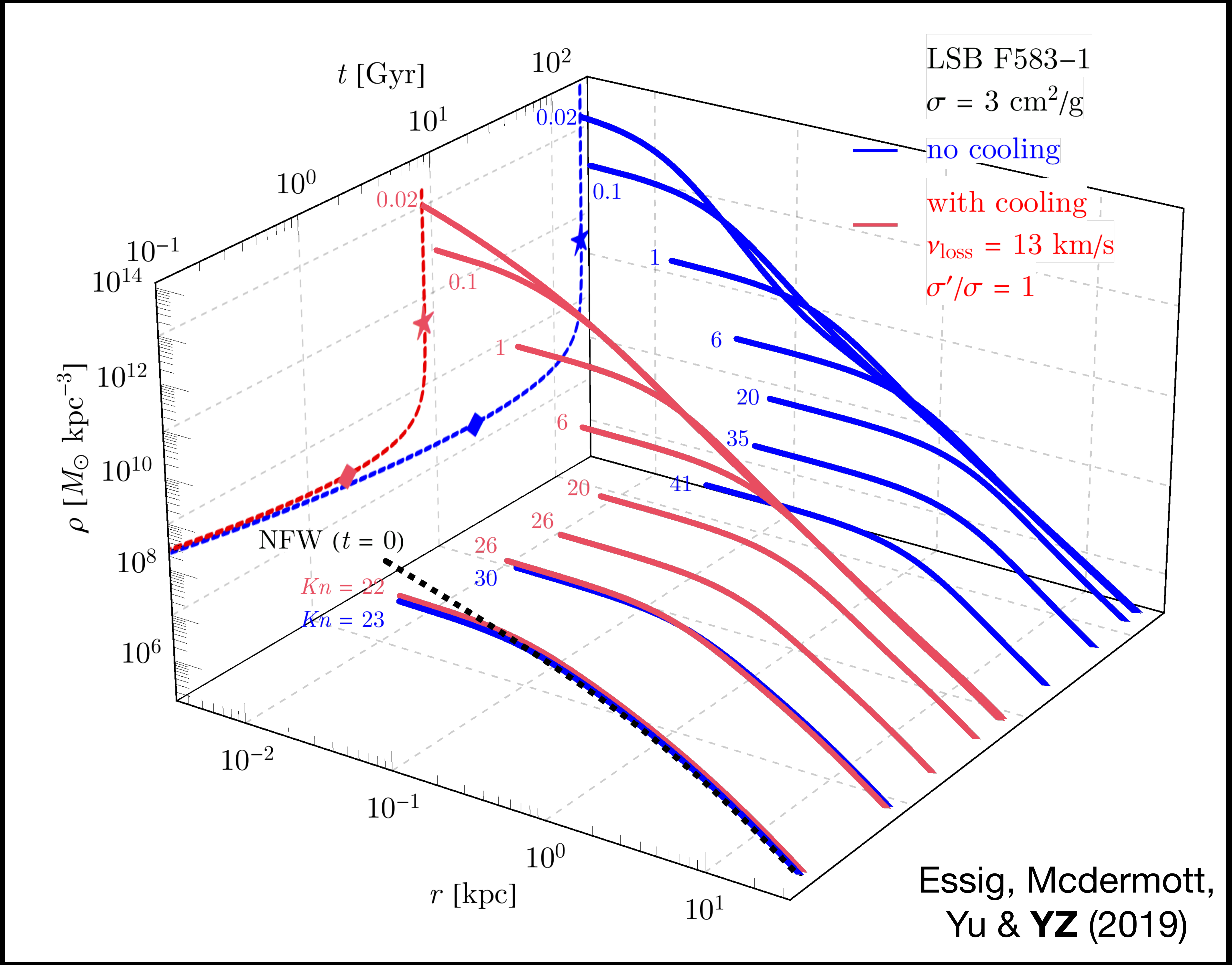
faster collapse

Density profile evolution

Evolution stages:

0. Halo formation
1. Core expansion
2. Core collapse

Dissipative SIDM Elastic SIDM



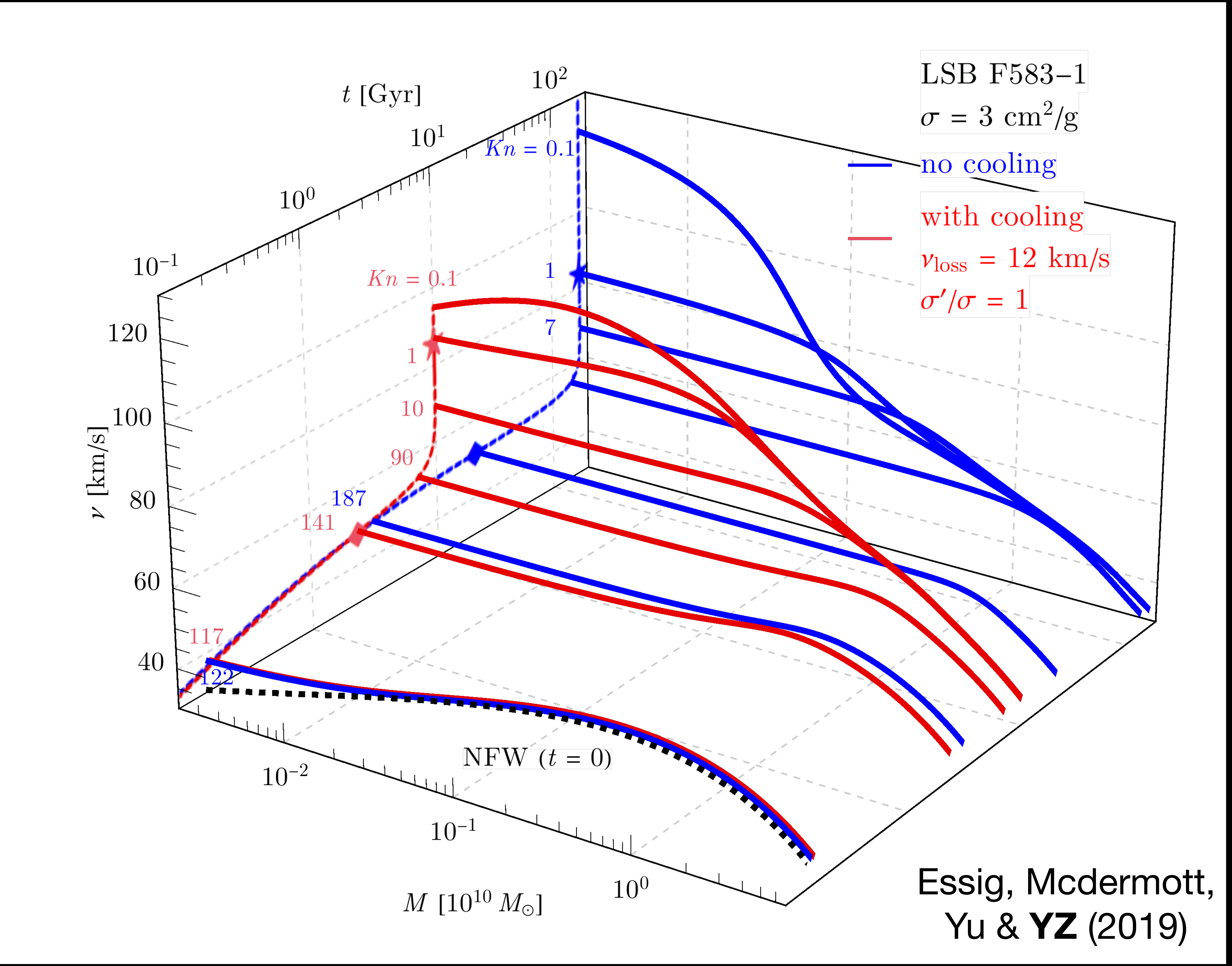
Essig, Mcdermott, Yu & **YZ** (2019)

Velocity dispersion profile evolution

Evolution stages:

0. Halo formation
1. Core expansion
2. Core collapse

Dissipative SIDM Elastic SIDM



Essig, Mcdermott, Yu & **YZ** (2019)

Density profile evolution

Cut at t = 10 Gyrs:

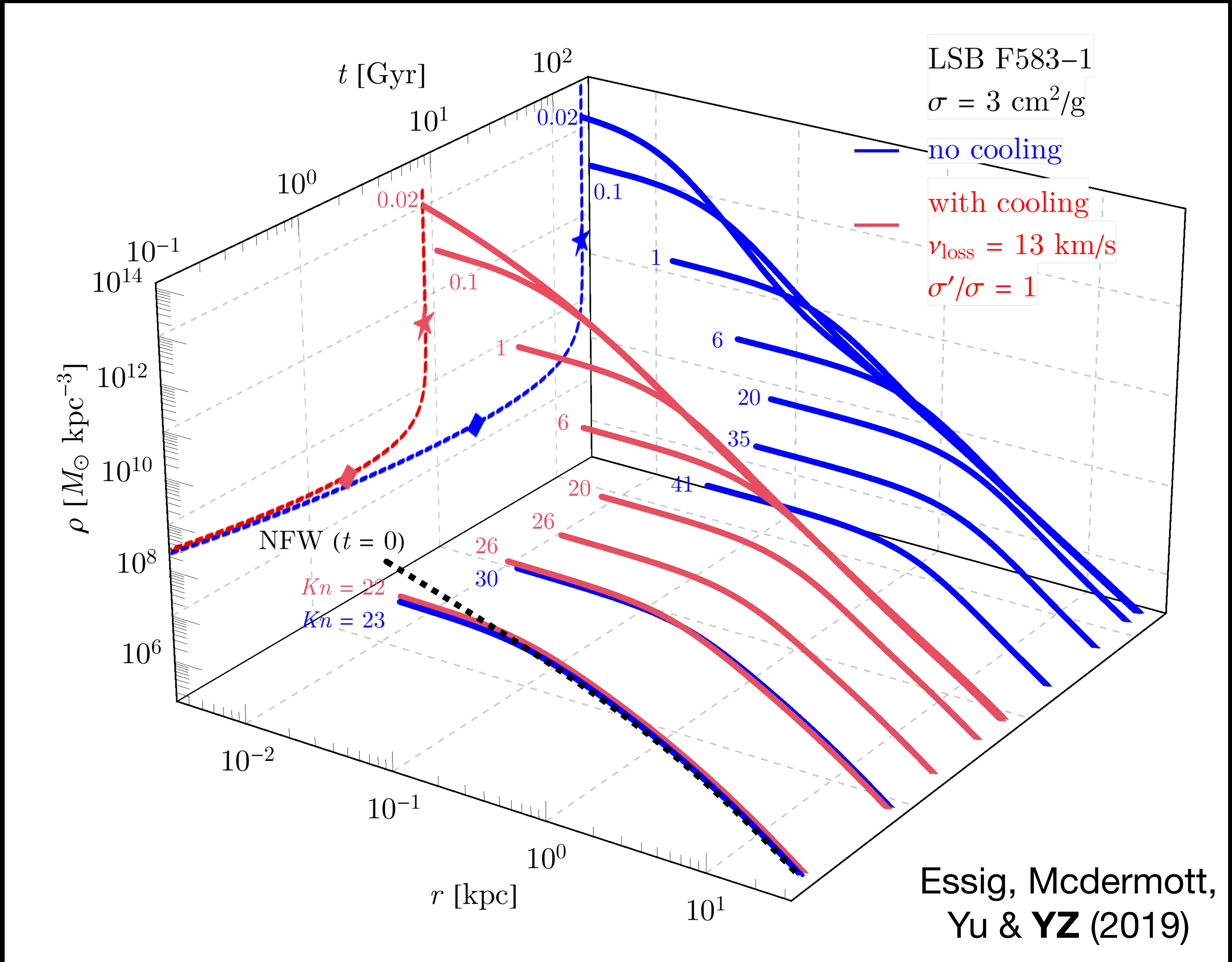
Elastic SIDM:

Cored profile

Dissipative SIDM:

Quasi-isothermal profile (cuspier than NFW)

Dissipative SIDM Elastic SIDM



Essig, Mcdermott, Yu & **YZ** (2019)

Density profile evolution

Evolution time is set by:

Elastic SIDM

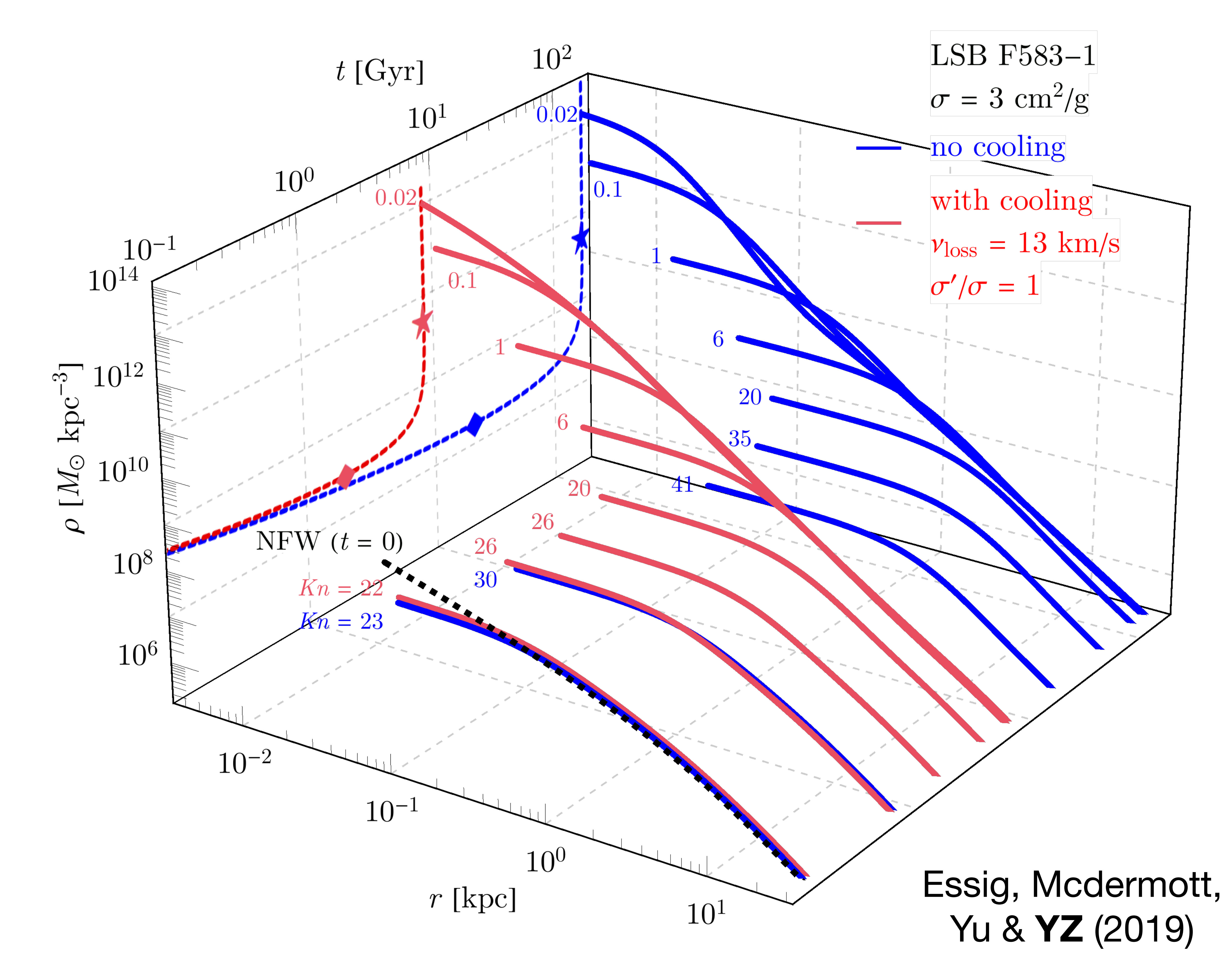
- Cross section strength

Dissipative SIDM

- Cross section strengths

- Energy loss per collision

Dissipative SIDM Elastic SIDM

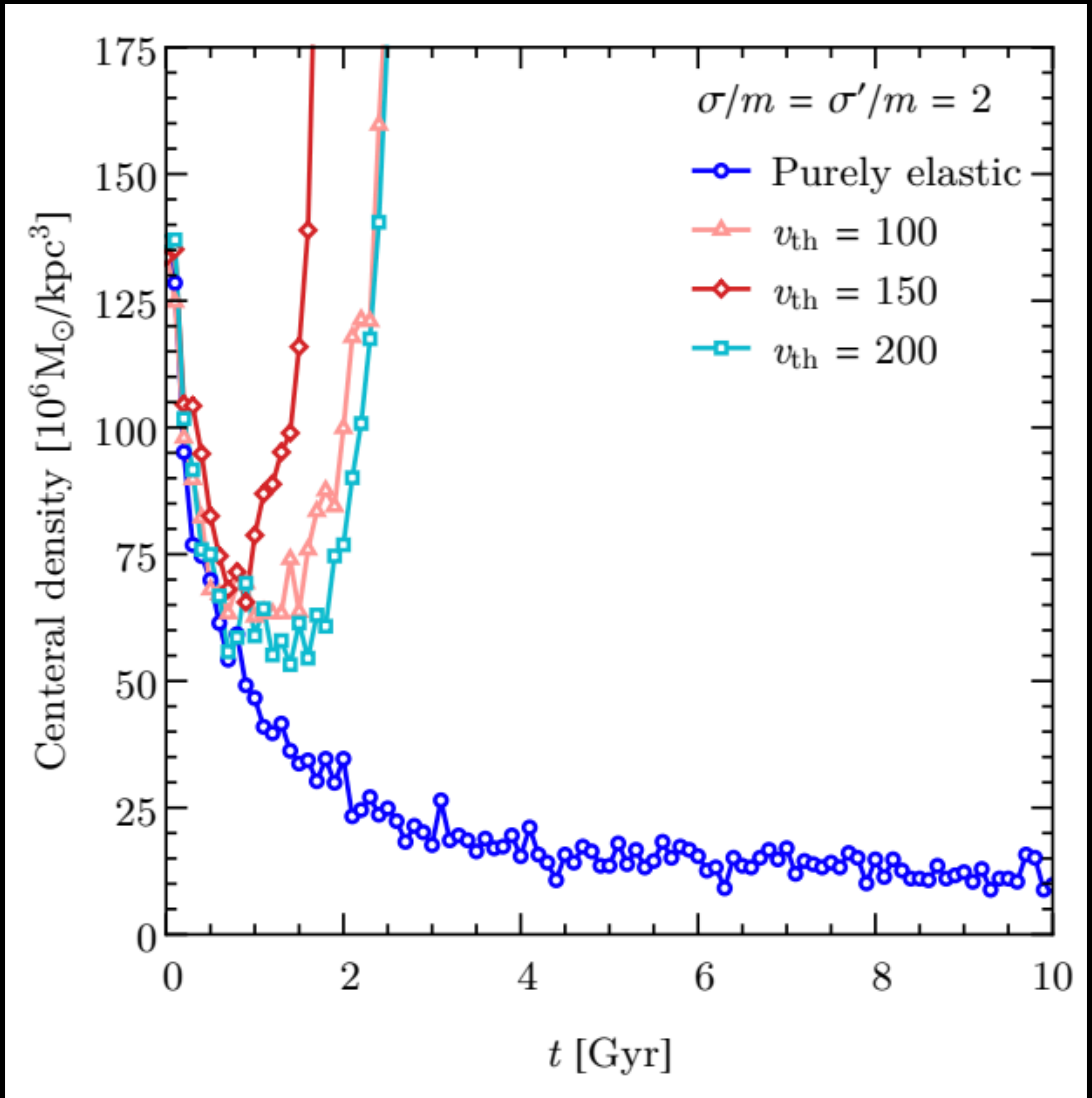


Essig, Mcdermott, Yu & **YZ** (2019)

N-body simulation results

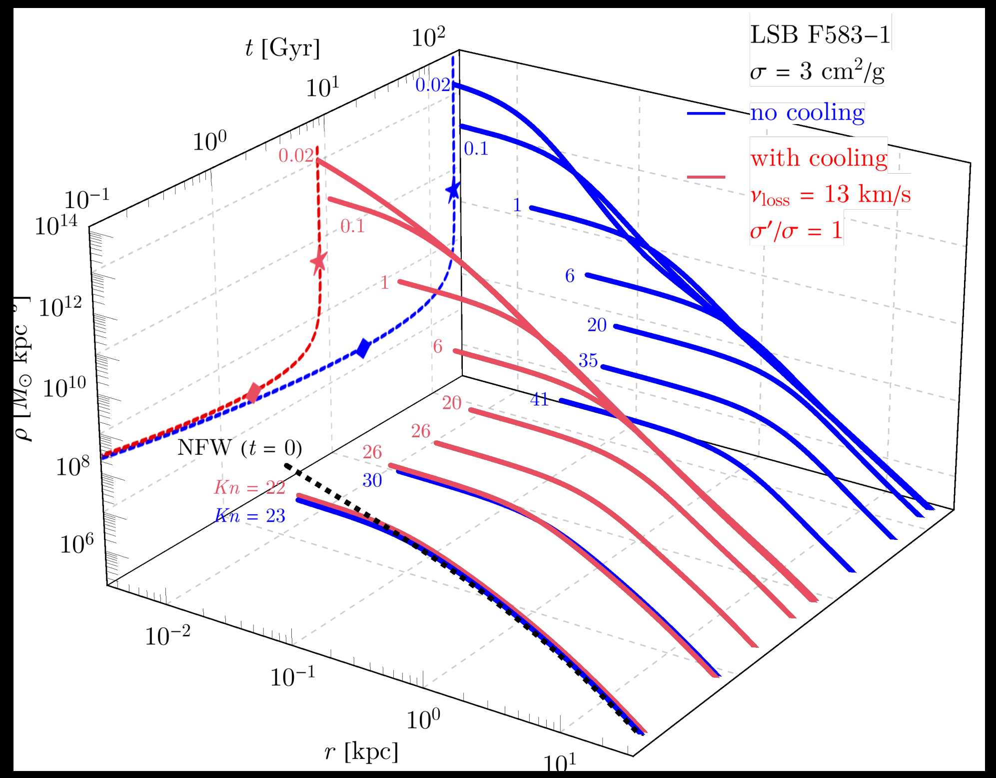
- Consider Inelastic dark matter with state χ and χ' $(m_\chi > m_{\chi'})$
- Loss energy for $\chi\chi \to \chi'\chi'$
- Define

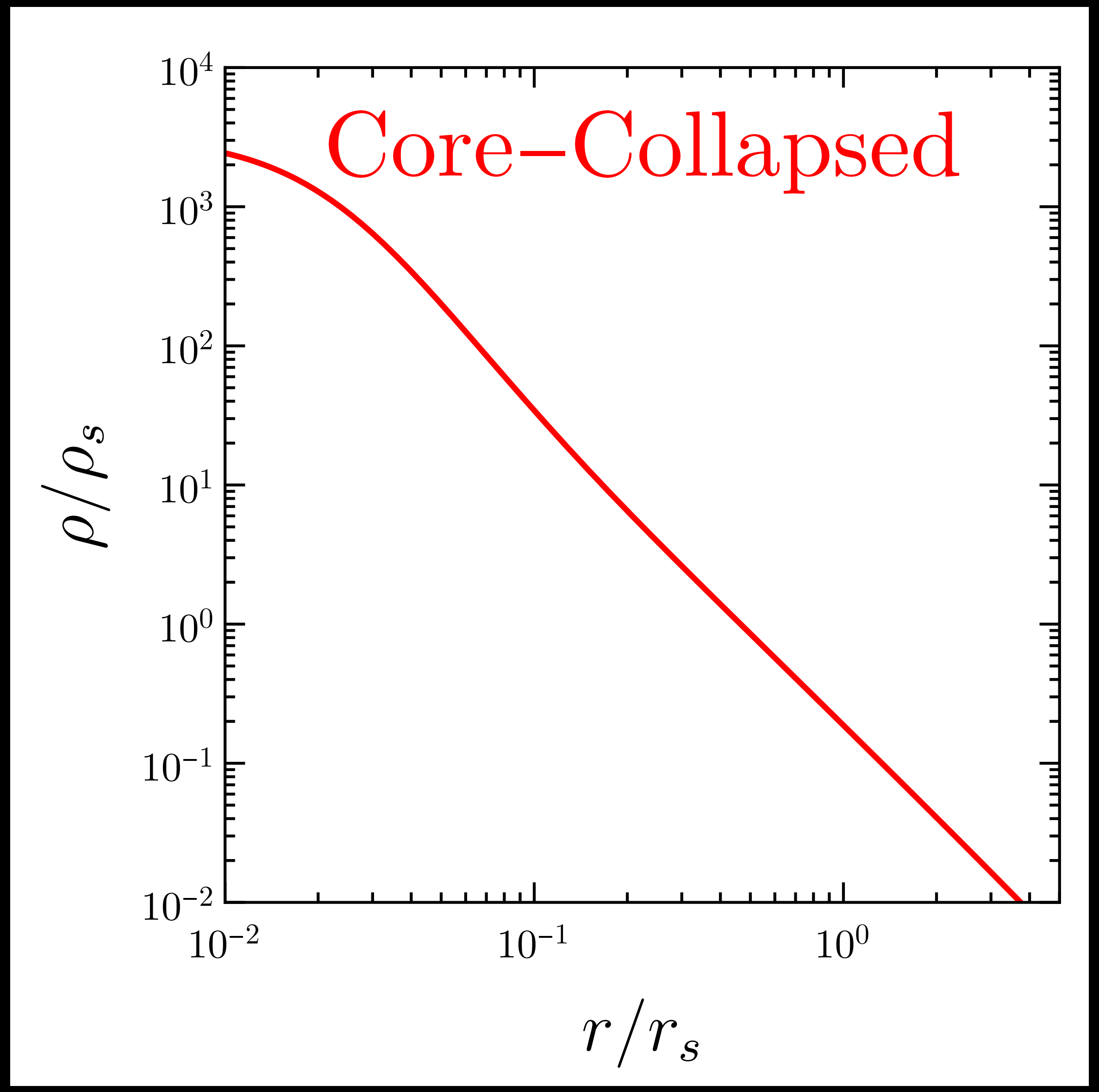
$$v_{\text{th}} = c\sqrt{2(m_\chi - m'_\chi)/m_\chi}$$

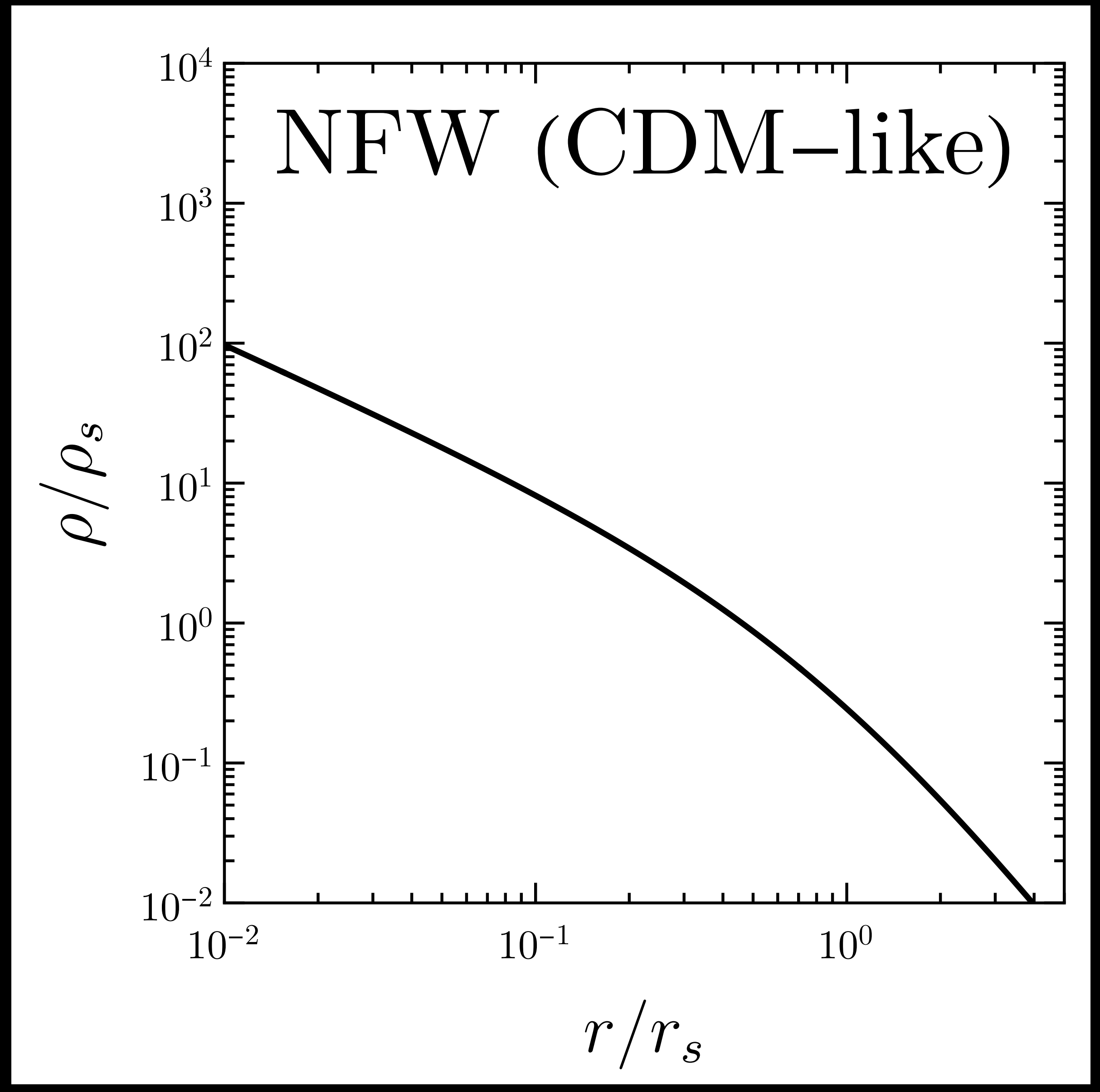


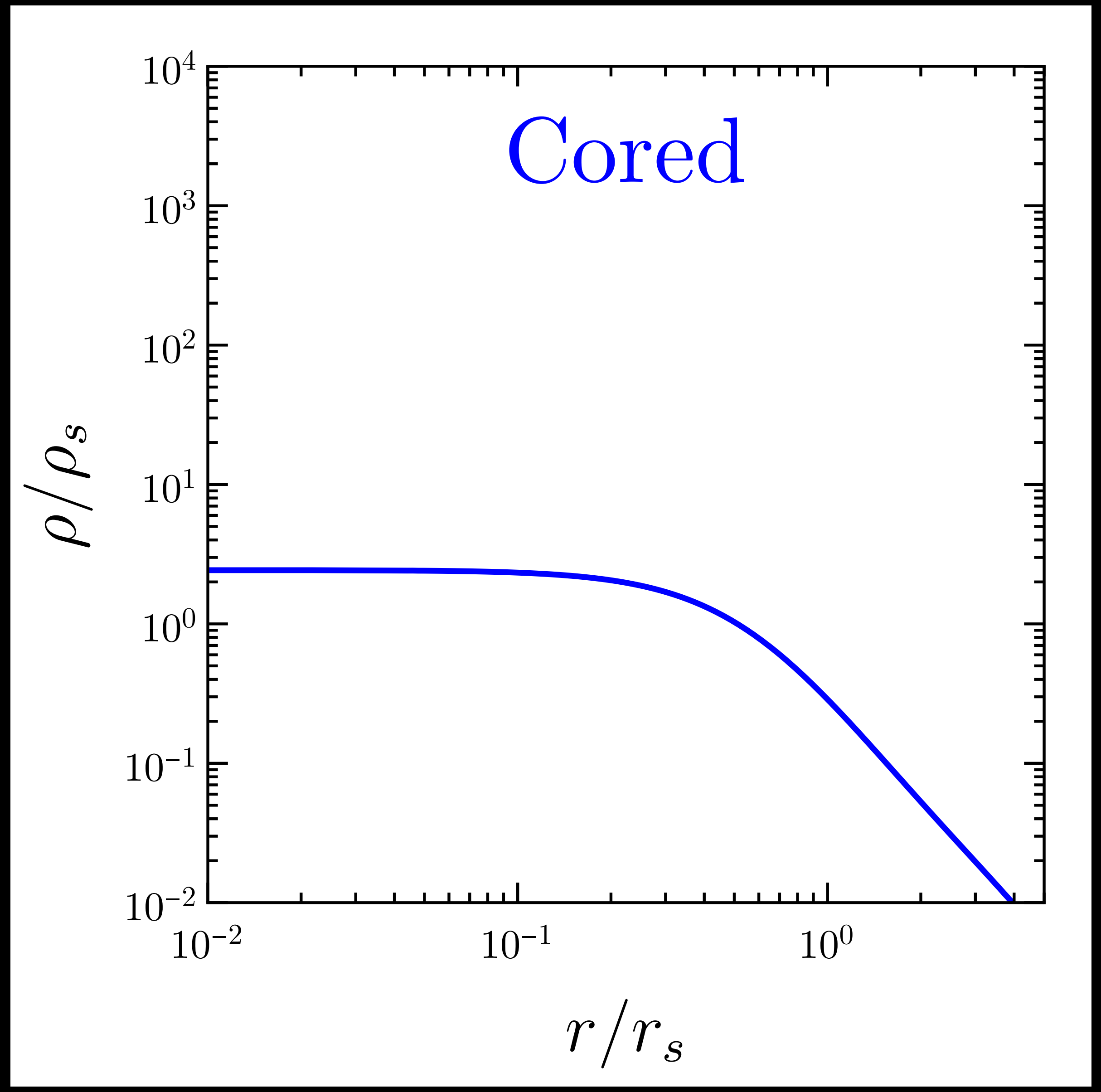
Huo, Yu & **YZ** (2020)

Self-interactions increase halo's **diversity**



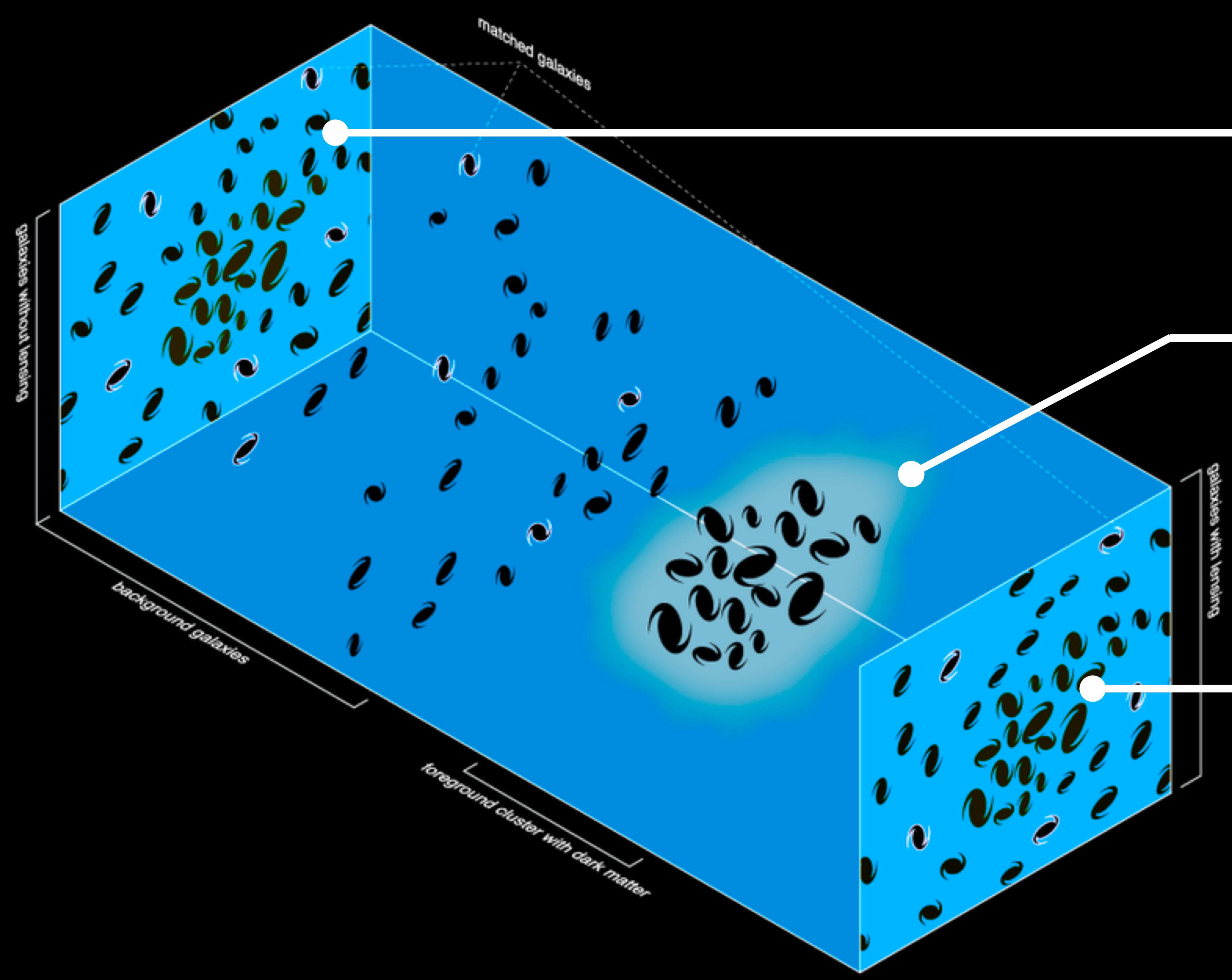






Constraining SIDM from ACT x DES weak lensing measurement

Weak lensing

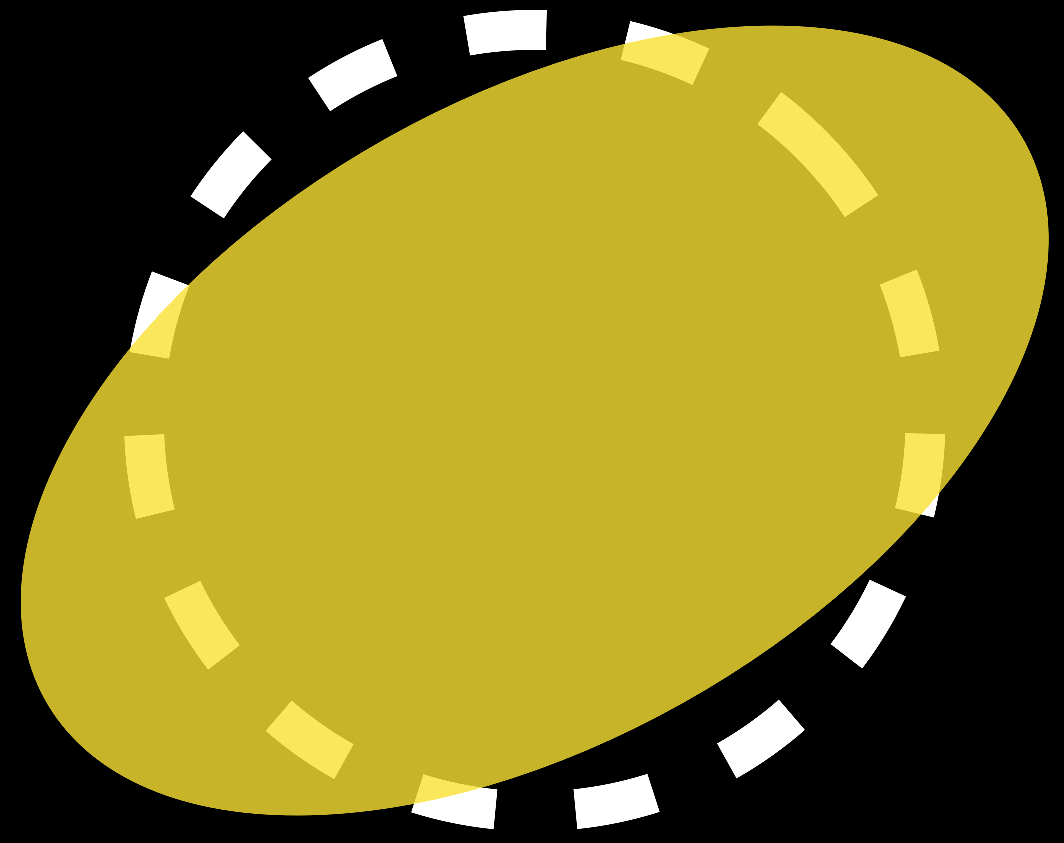


Credit: Sachs

Source
(galaxies)

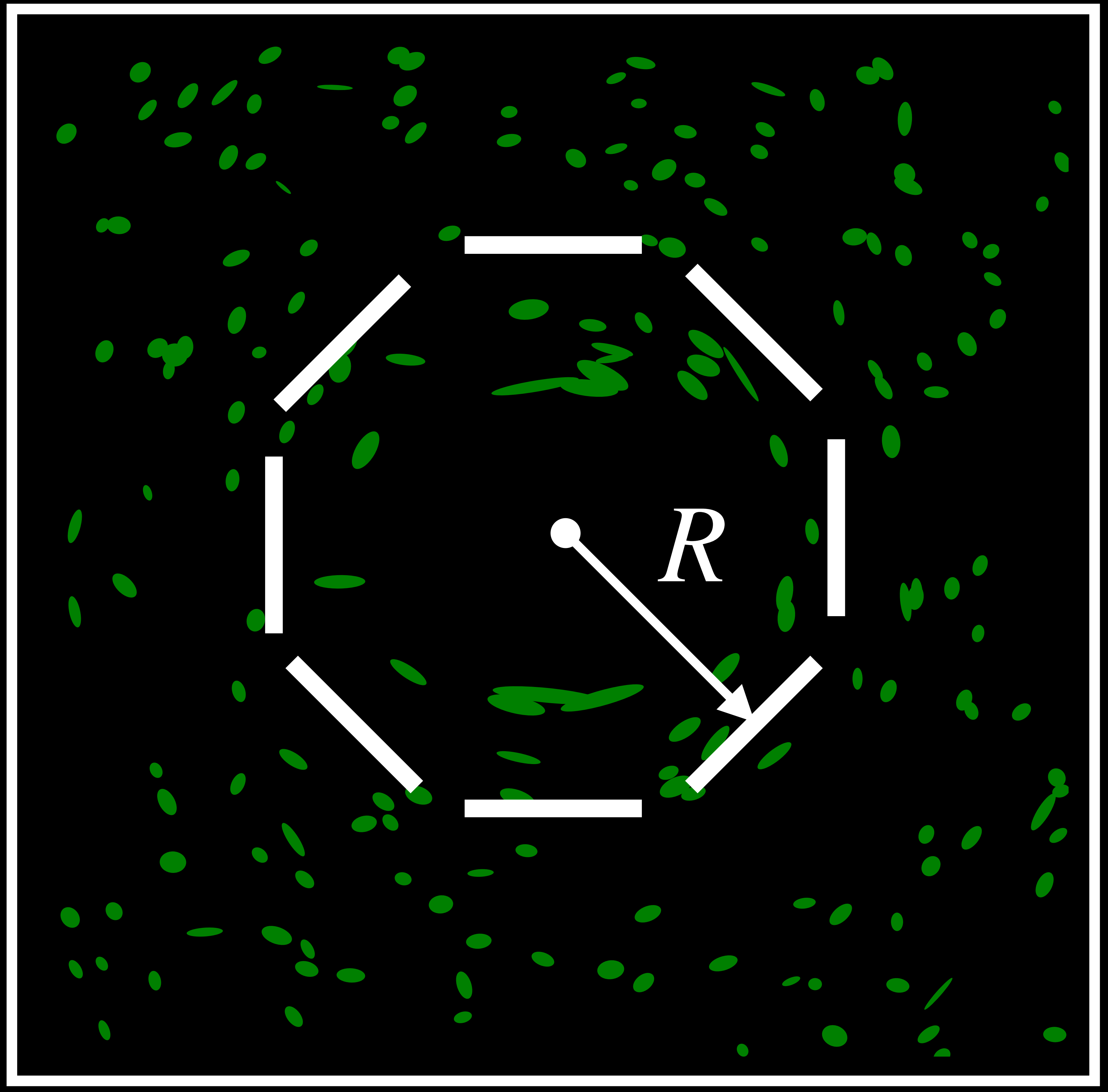
Lens
(cluster)

Image
(galaxies)



Shear

Tangential Shear & halo's density



See Dodelson '22

The tangential shear, γ_t, is sensitive to the excess of the projected lens mass

$$\gamma_t(R) \propto \Delta\Sigma(R)$$
$$= \langle \Sigma(< R) \rangle - \Sigma(R)$$

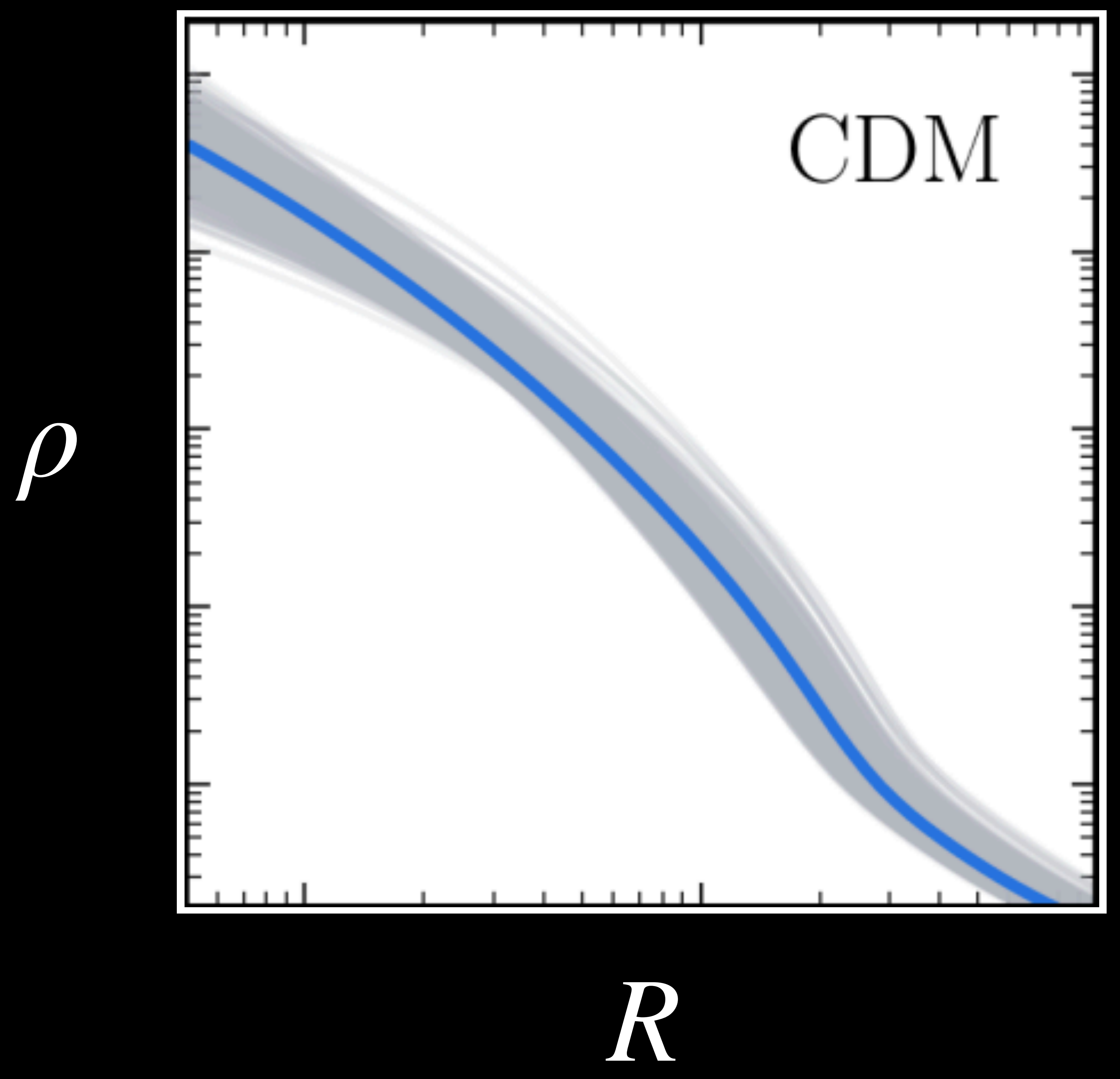
$$\frac{1}{\pi R^2} \int_{R'<R} \mathrm{d}^2 R' \, \Sigma(R')$$

Data

- Used the weak lensing measurement from Shin et al. (2021).
- Lens: clusters sampled from Atacama Cosmology Telescope (ACT) DR5.
- Source/Image: galaxies from the Dark Energy Survey (DES) Y3 near the sampled clusters.

Selection of the lens

- Stacked ~1000 galaxy clusters
- Redshift: 0.15—0.7
- Mass: ~10^{14} $\mathrm{M}_{\odot}/h$
- Radius range: 0.2—20 Mpc/h

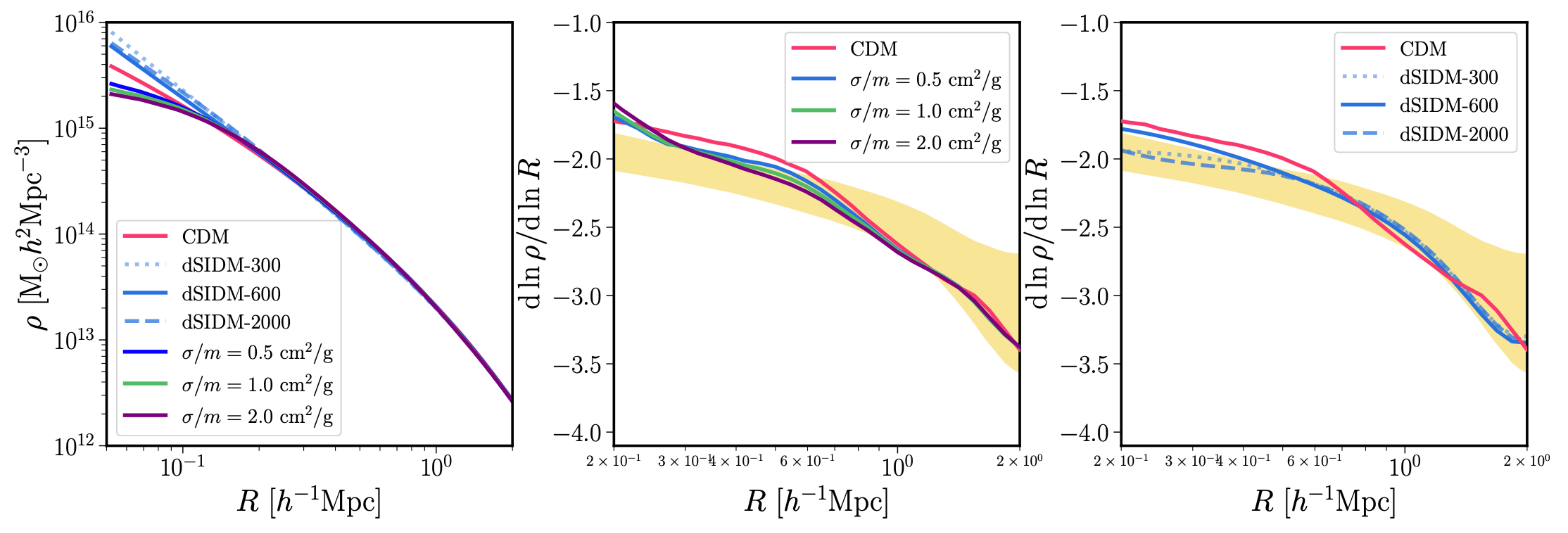


Modeling of the lens

- Modeled the lens for CDM, elastic SIDM (eSIDM), and dissipative SIDM (dSIDM).
- Simulated 1000+ halos for each benchmark.

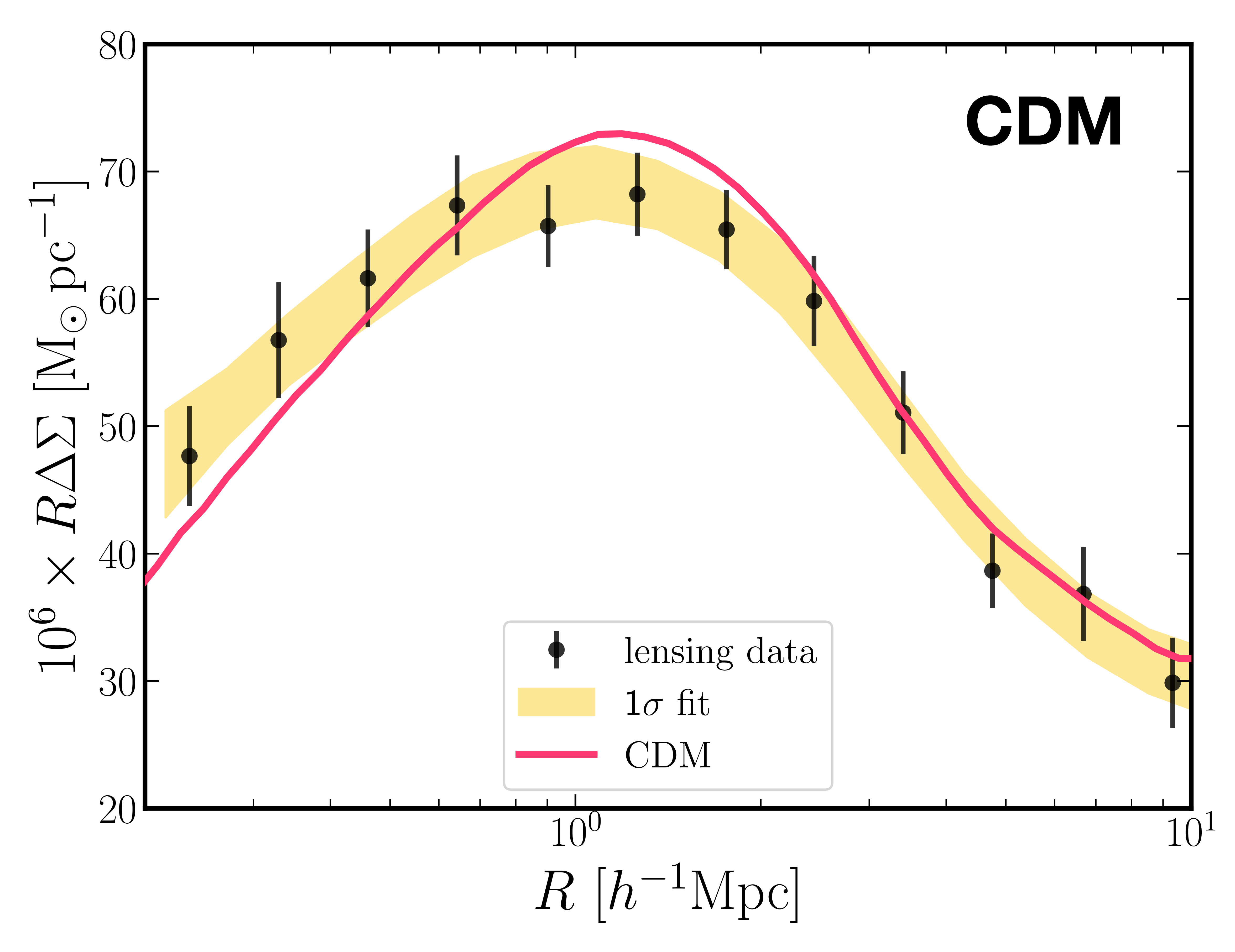
Name	σ/m [cm^2/g]	σ'/m [cm^2/g]	$\nu_{\rm loss}$ [km/s]
CDM	–	–	–
eSIDM	0.2	–	–
	0.5	–	–
	1.0	–	–
	2.0	–	–
dSIDM-300	1.0	1.0	300
dSIDM-600	1.0	1.0	600
dSIDM-2000	1.0	1.0	2000

Stacked 3D density for the benchmarks

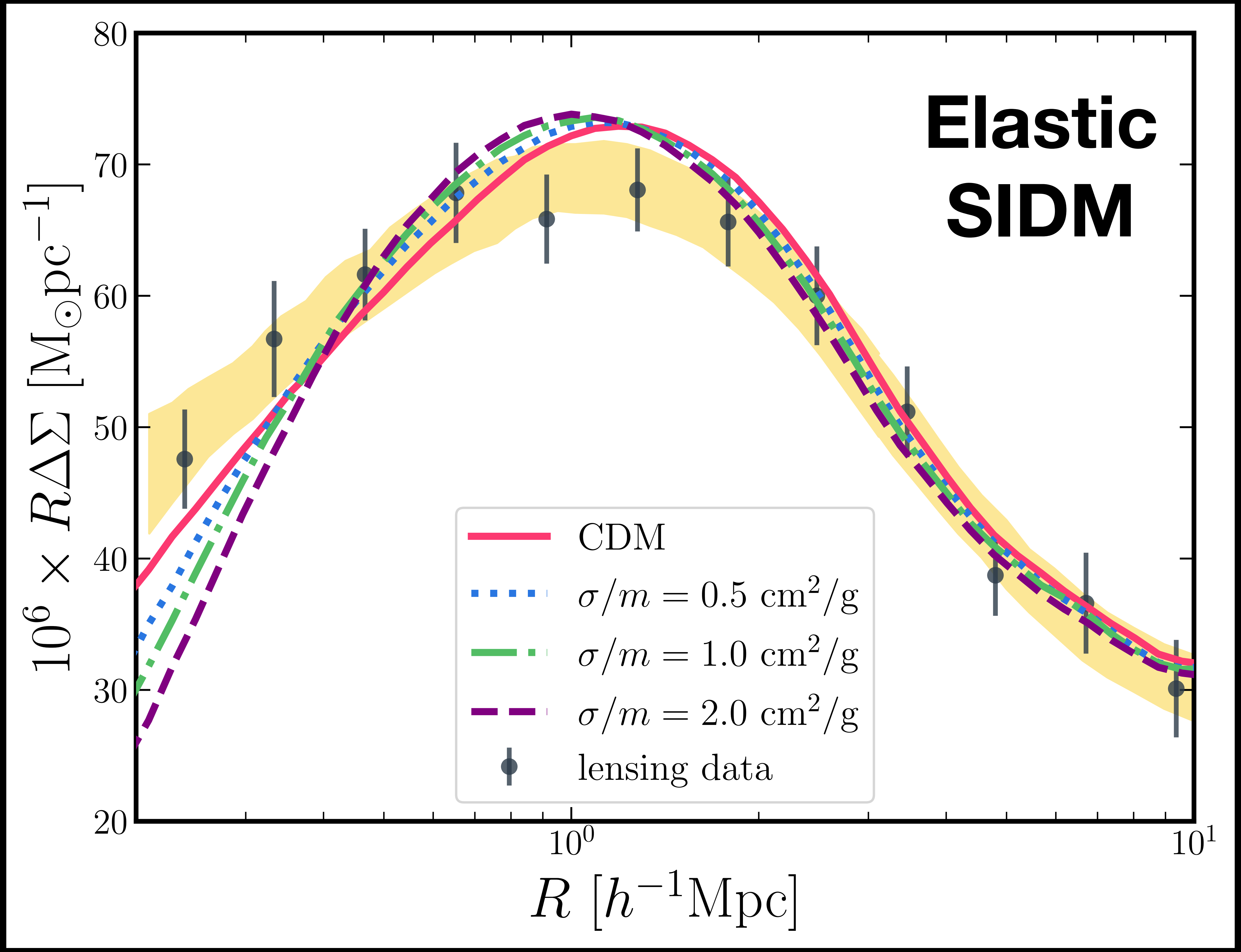


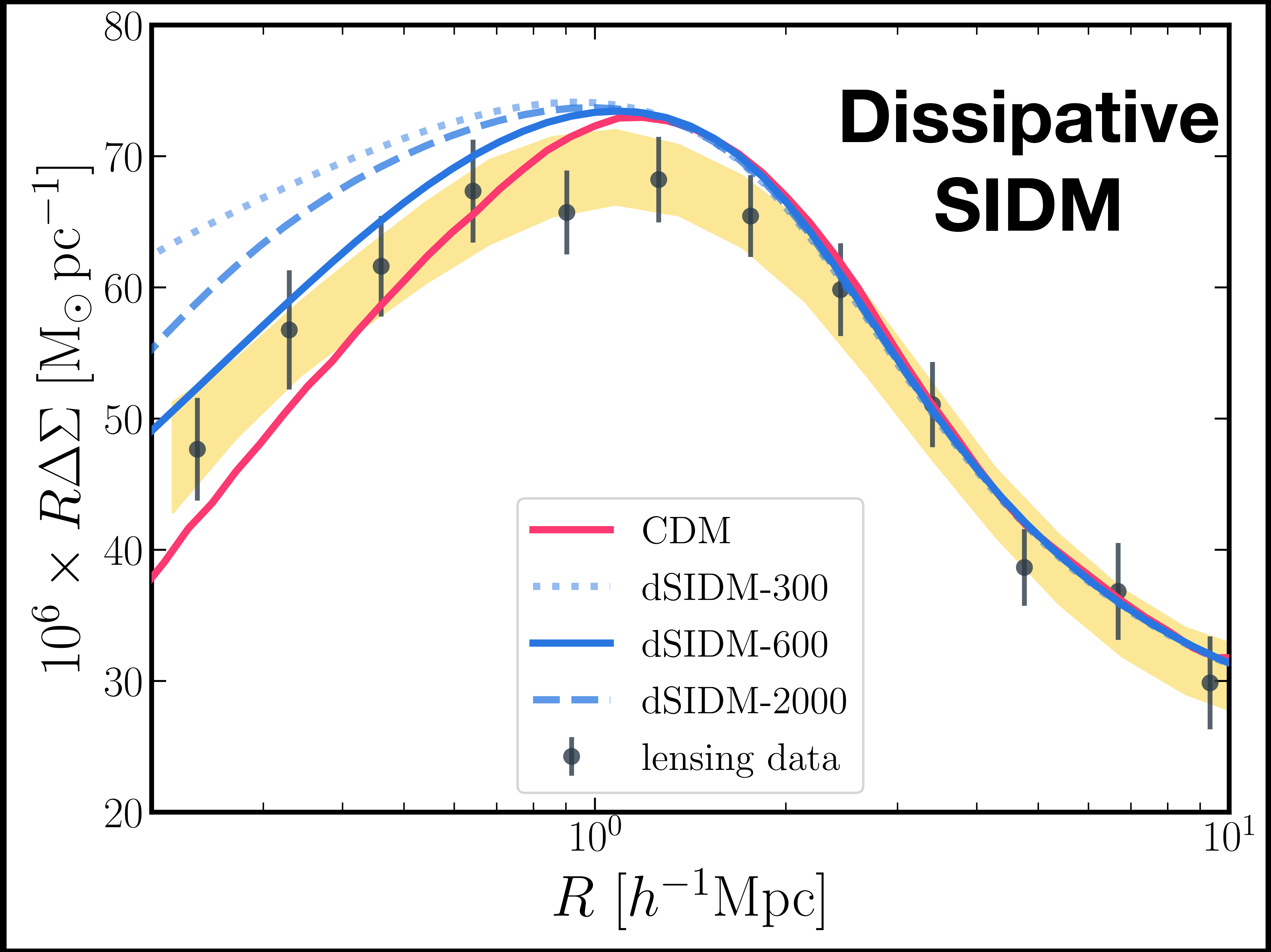
Excess of stacked surface density

CDM under predicts $\Delta\Sigma$ at small radii.



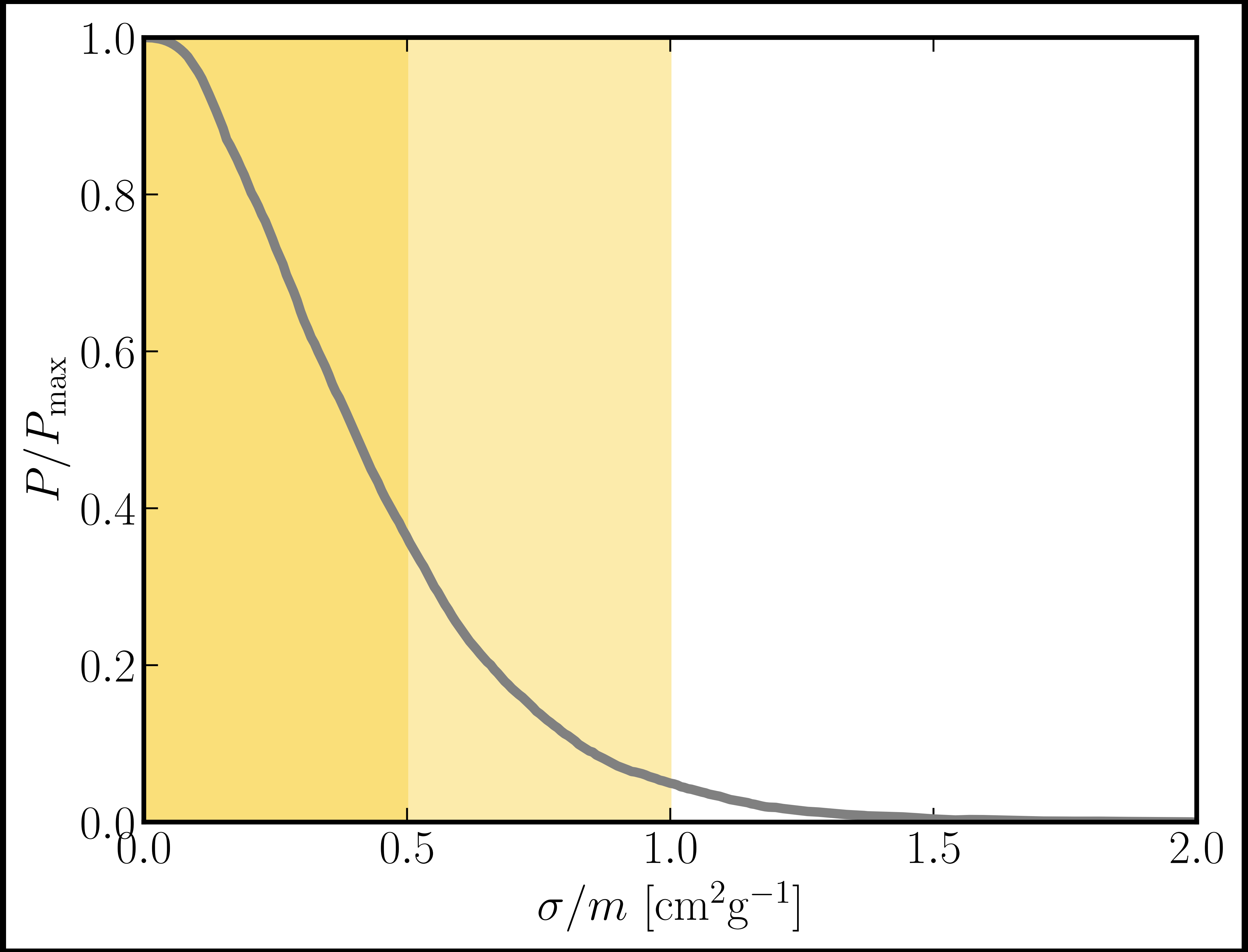
Excess of stacked surface density





Better fit by dSIDM-600

Allowed parameters of *elastic* SIDM

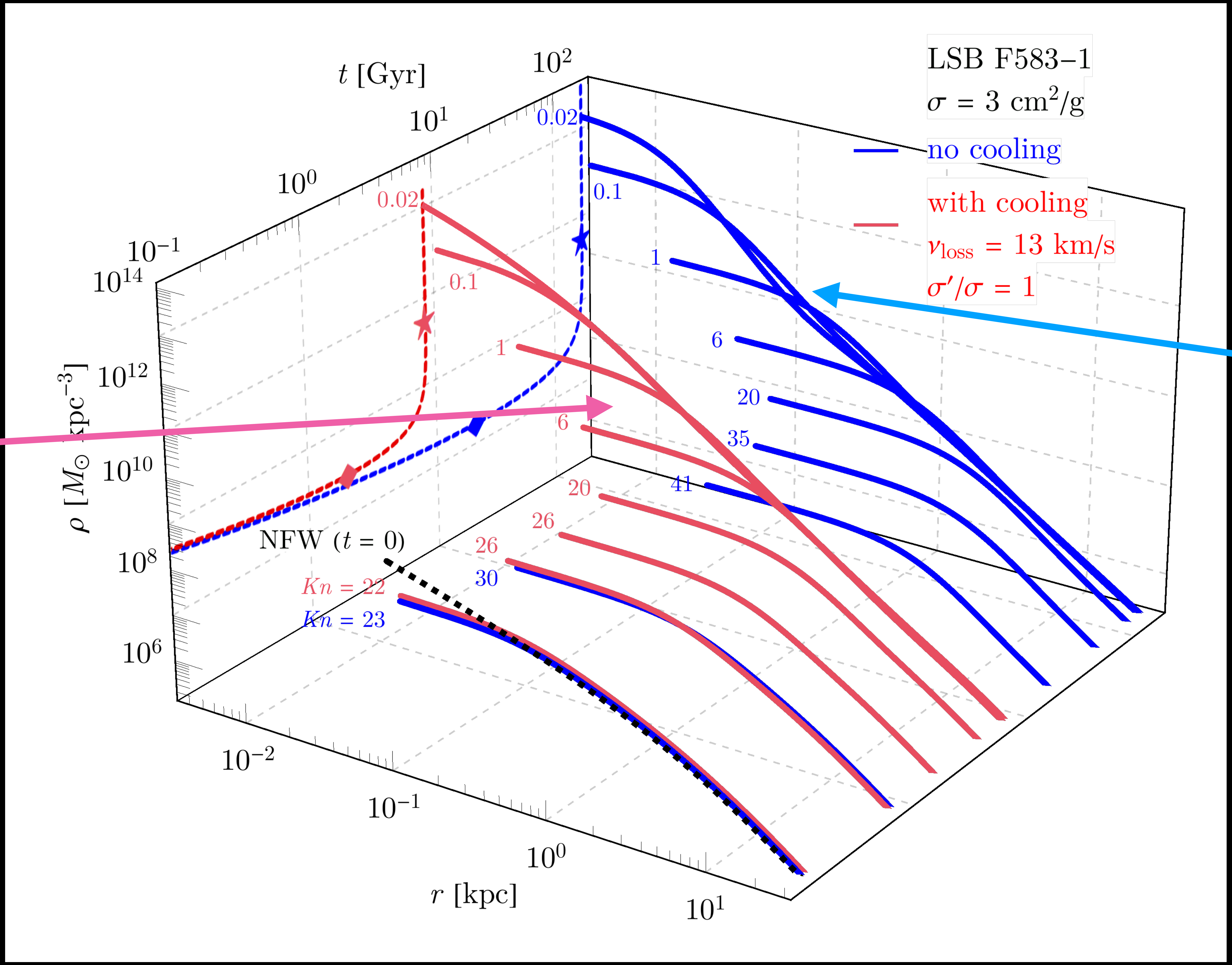


$$\sigma/m < 1\,\mathrm{cm}^2/\mathrm{g}$$

(95% CL)

Cuspiness

Dissipative SIDM Elastic SIDM



Log-slope ~ -1.8

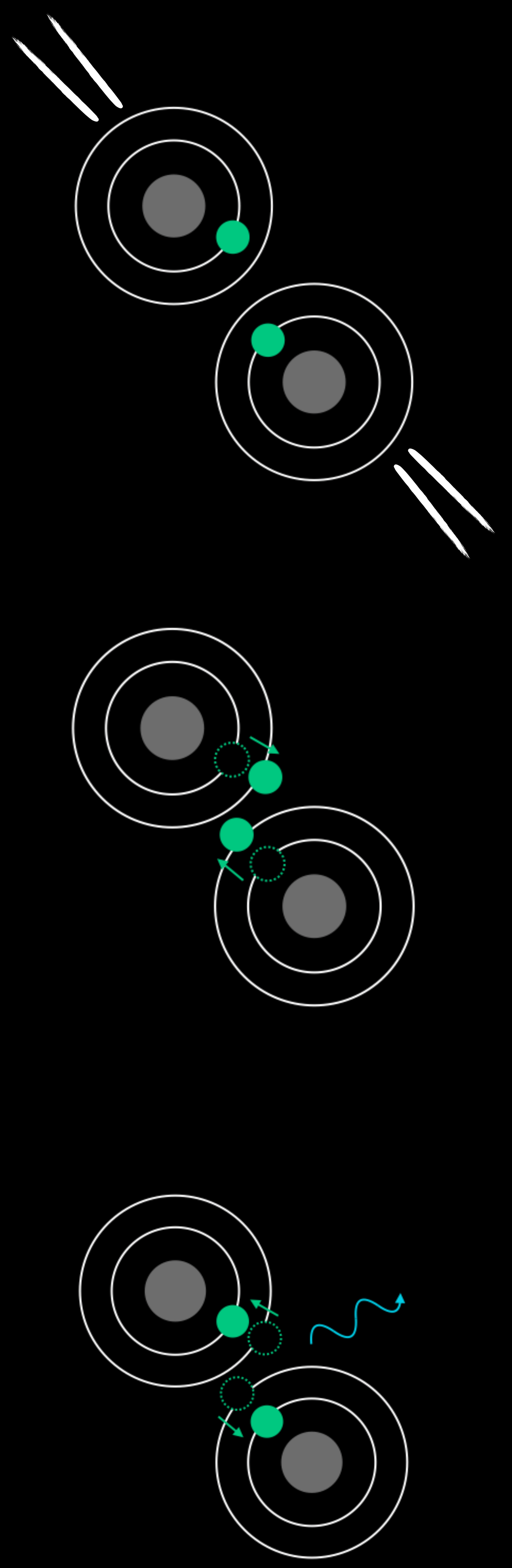
Less cuspy

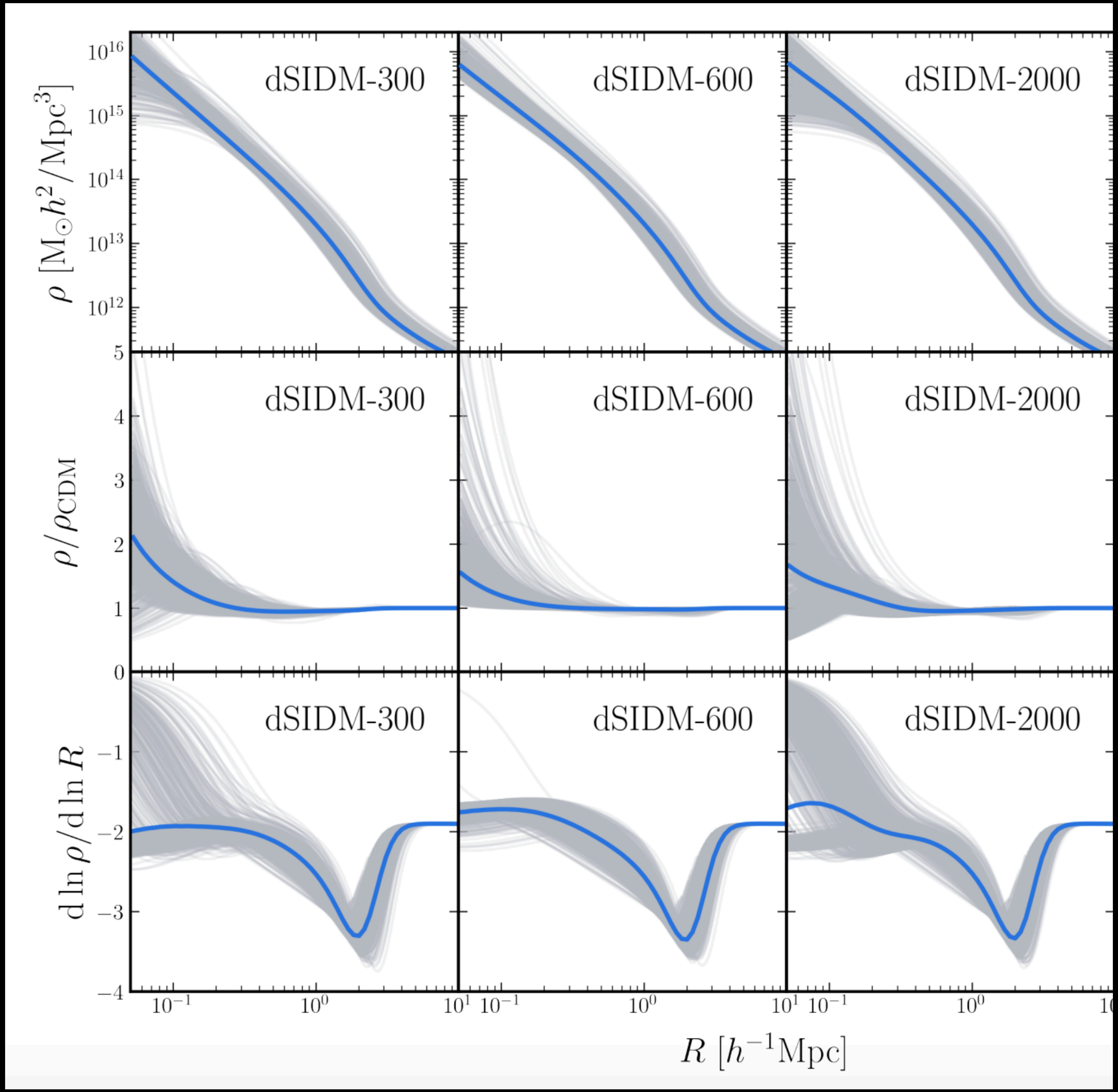
Log-slope ~ -2.2

More cuspy

Constraining on $v_{\rm loss}$ for dSIDM

$$v_{\rm loss} \equiv \sqrt{E_{\rm loss}/m}$$

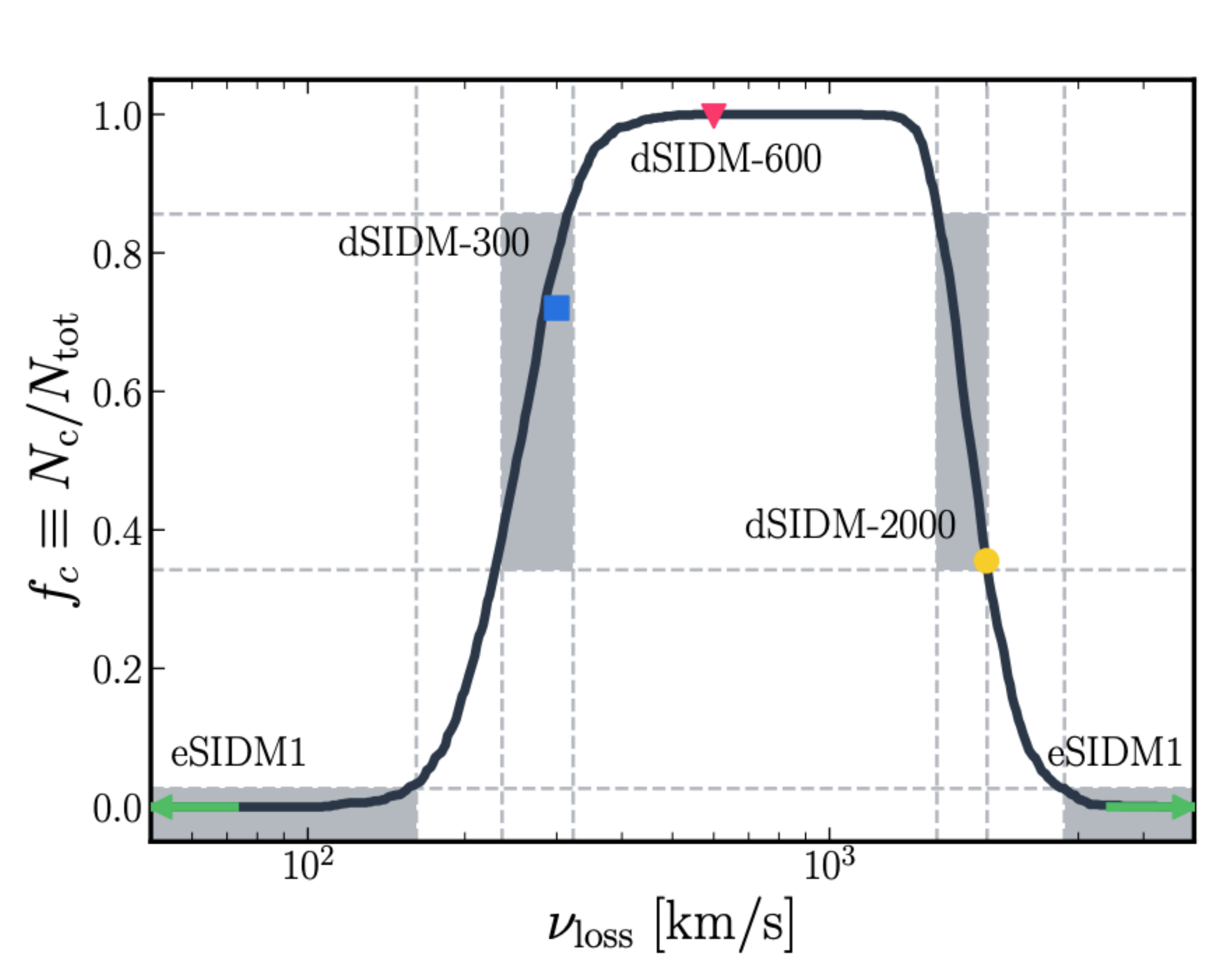




Constraining on $v_{\rm loss}$ for dSIDM

Assume

$$\sigma/m = \sigma'/m = 1\,\mathrm{cm}^2/\mathrm{g}$$



Allowed parameters of *dissipative* SIDM

Assume $\sigma/m = \sigma'/m = 1\,\mathrm{cm}^2/\mathrm{g}$

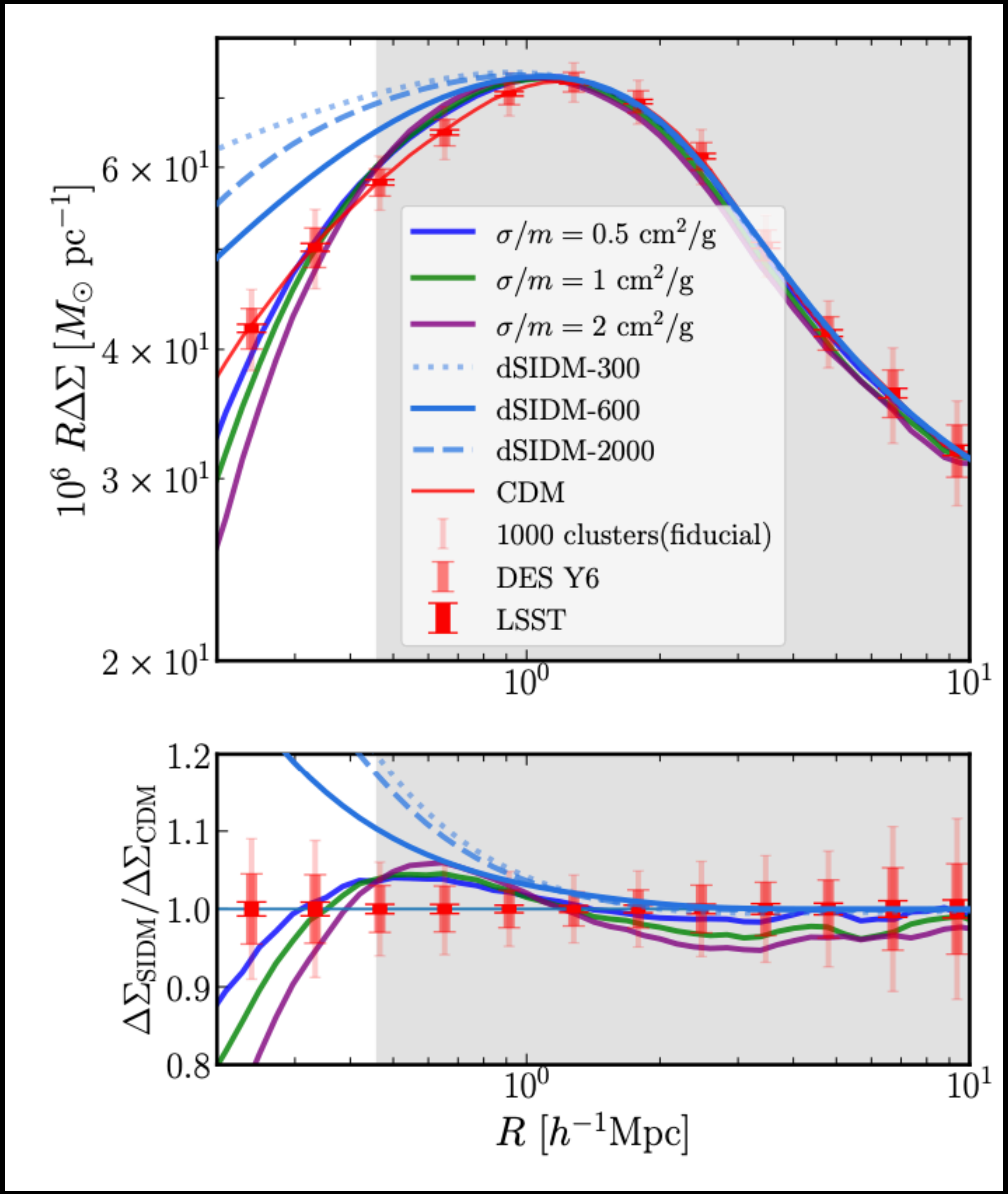
$$\nu_{\rm loss} \equiv \sqrt{E_{\rm loss}/m}$$

$$1.6 \times 10^2 \leq \nu_{\rm loss} \leq 2.4 \times 10^2\,\mathrm{km/s}$$
$$3.2 \times 10^2 \leq \nu_{\rm loss} \leq 1.6 \times 10^3\,\mathrm{km/s}$$
$$2 \times 10^3 \leq \nu_{\rm loss} \leq 2.8 \times 10^3\,\mathrm{km/s}$$

(95% CL)

Outlook

- Future surveys, like Rubin Observatory, will increase the cluster sample size by ~10^5.
- Can significantly reduce the statistical & systematical errors.



Summary

- Halos are interesting probes of dark matter properties.
- Gravothermal evolution increases the diversity of SIDM halos.
- Weak lensing measurements from current and future galaxy surveys can effectively probe various types of dark matter self-interactions.