Self-interacting dark matter on small and large scales

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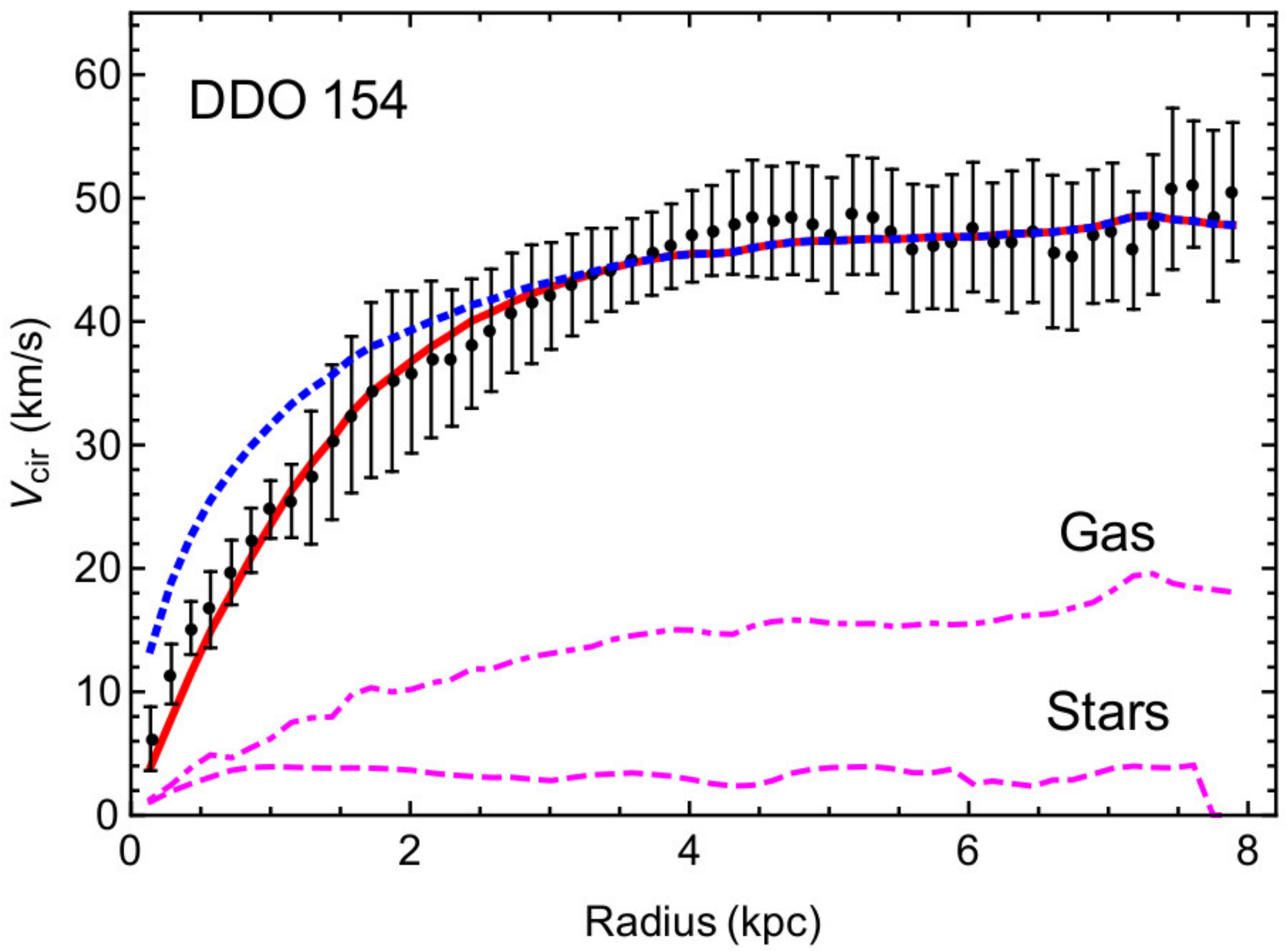
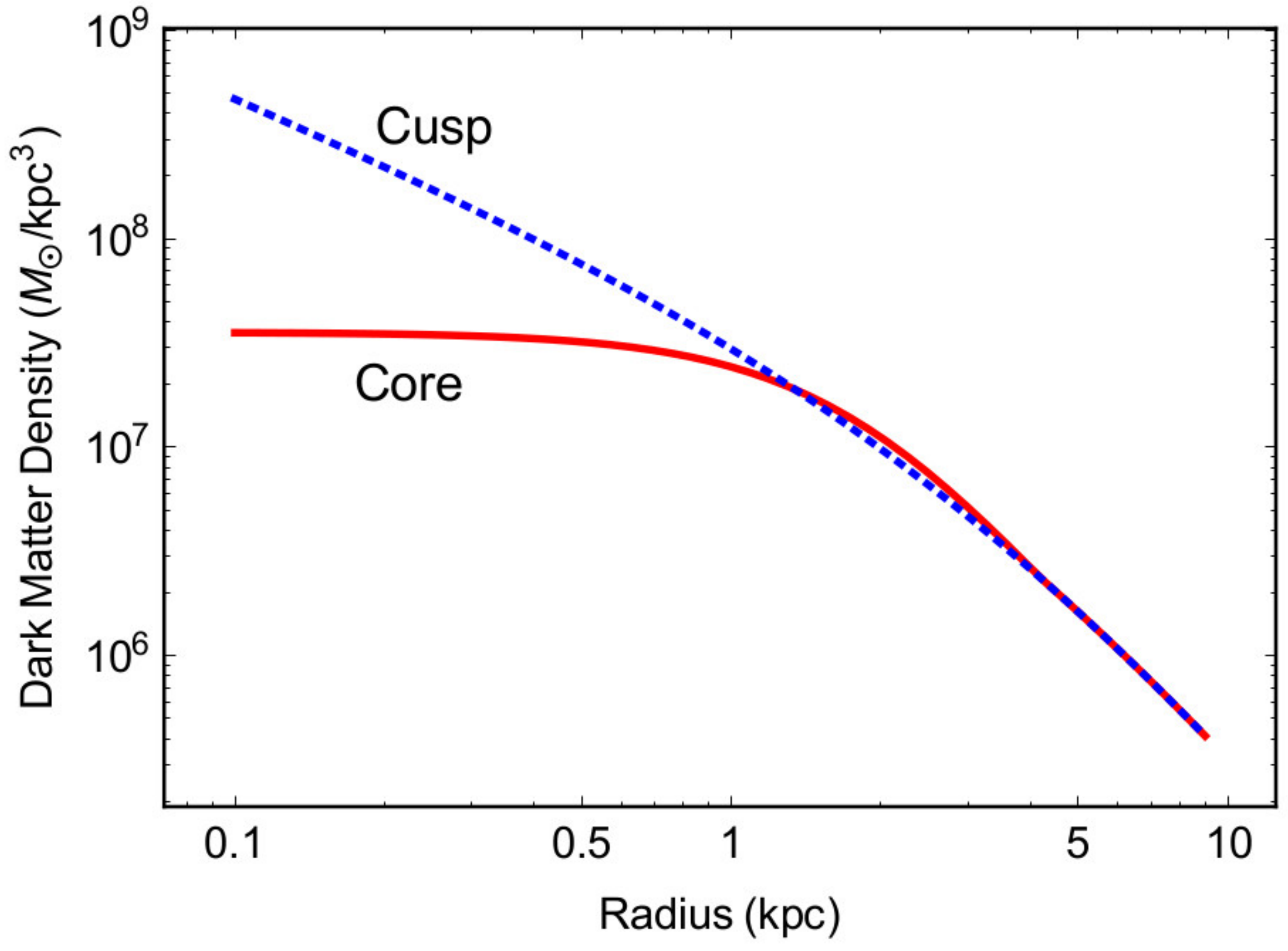
UNIVERSITY OF AMSTERDAM

Why Self-Interacting Dark Matter?

- To solve cusp-core problem





DM particles collisions create constant density cores

(e.g. Davé et al. 2001; Colín et al. 2002; Vogelsberger et al. 2012; Rocha et al. 2013; Dooley et al. 2016; Vogelsberger et al. 2019; Robles et al. 2019)

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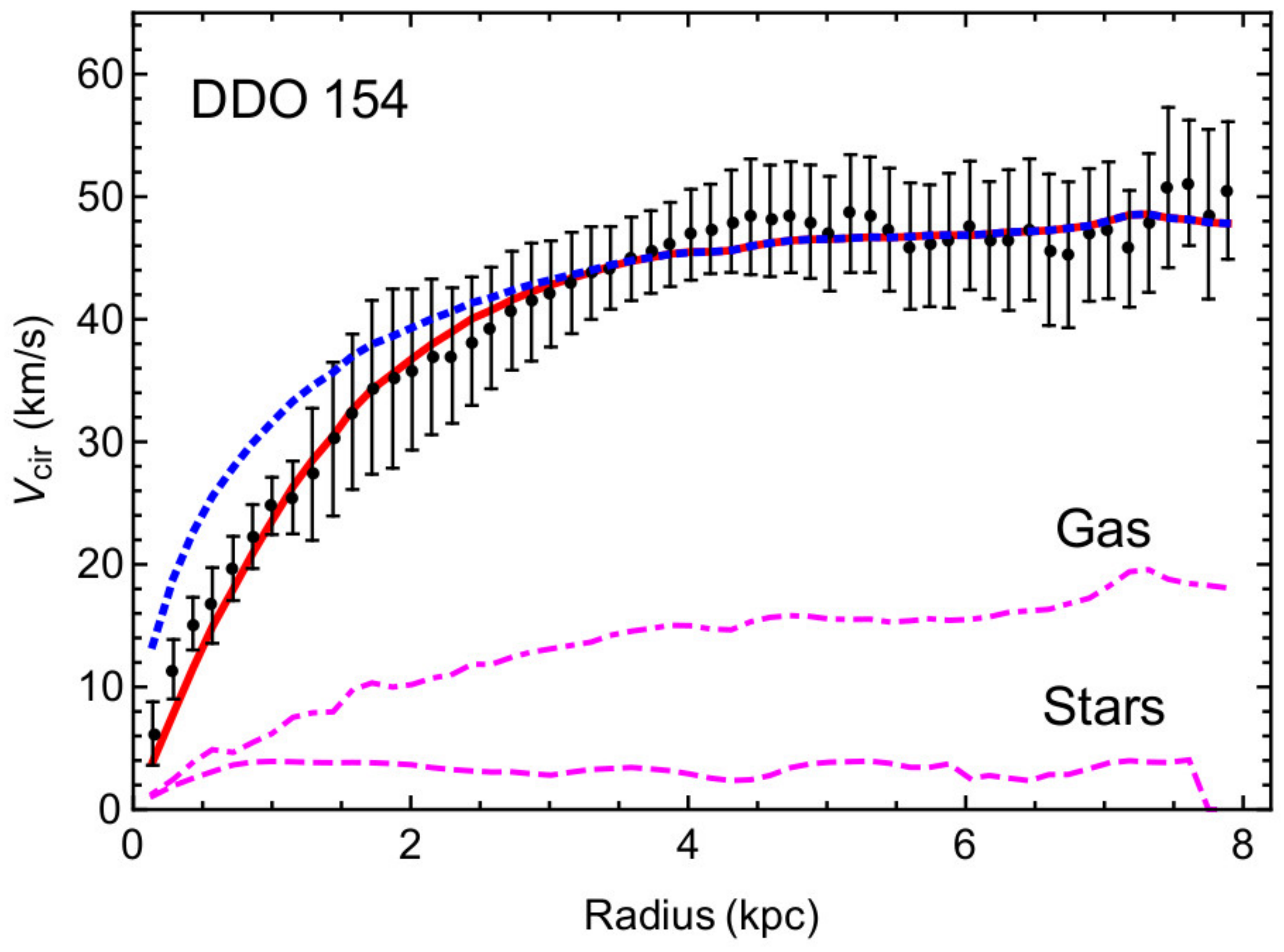

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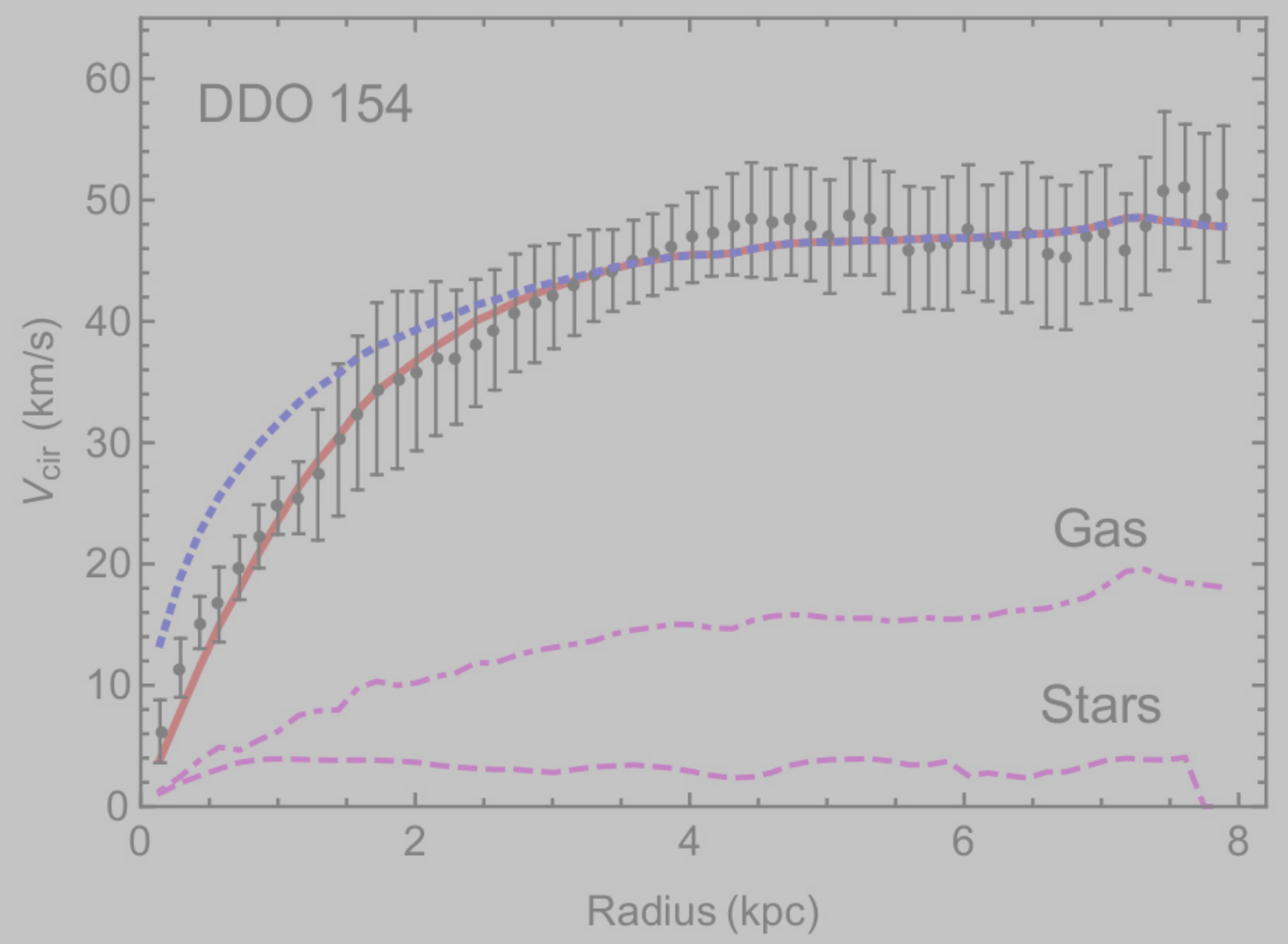

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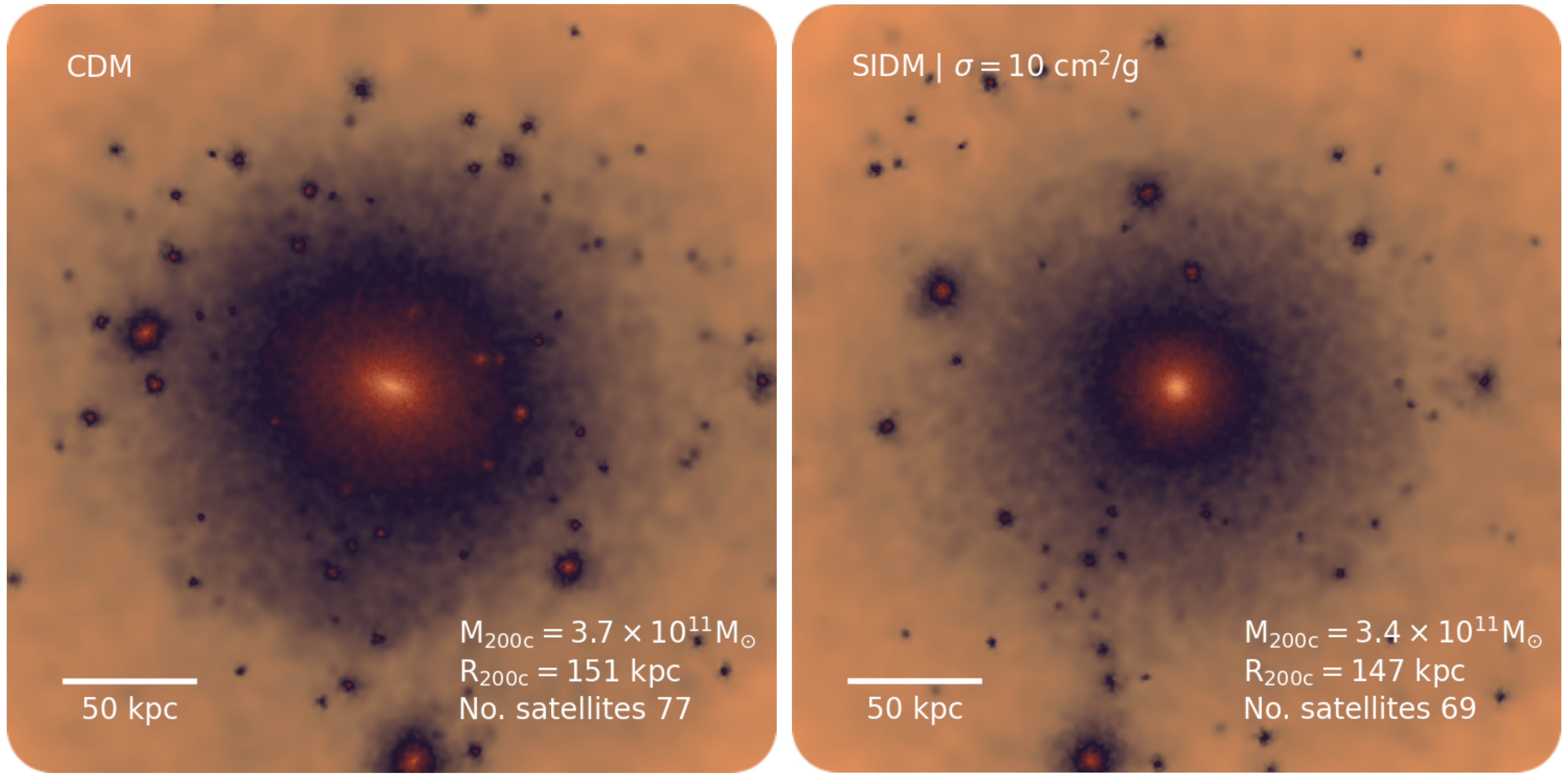
- To solve missing-satellites problem

CDM → SIDM



DM interactions between the host and the satellites enhance the destruction of satellites from tidal stripping
(Vogelsberger et al. 2012; Nadler et al. 2020)

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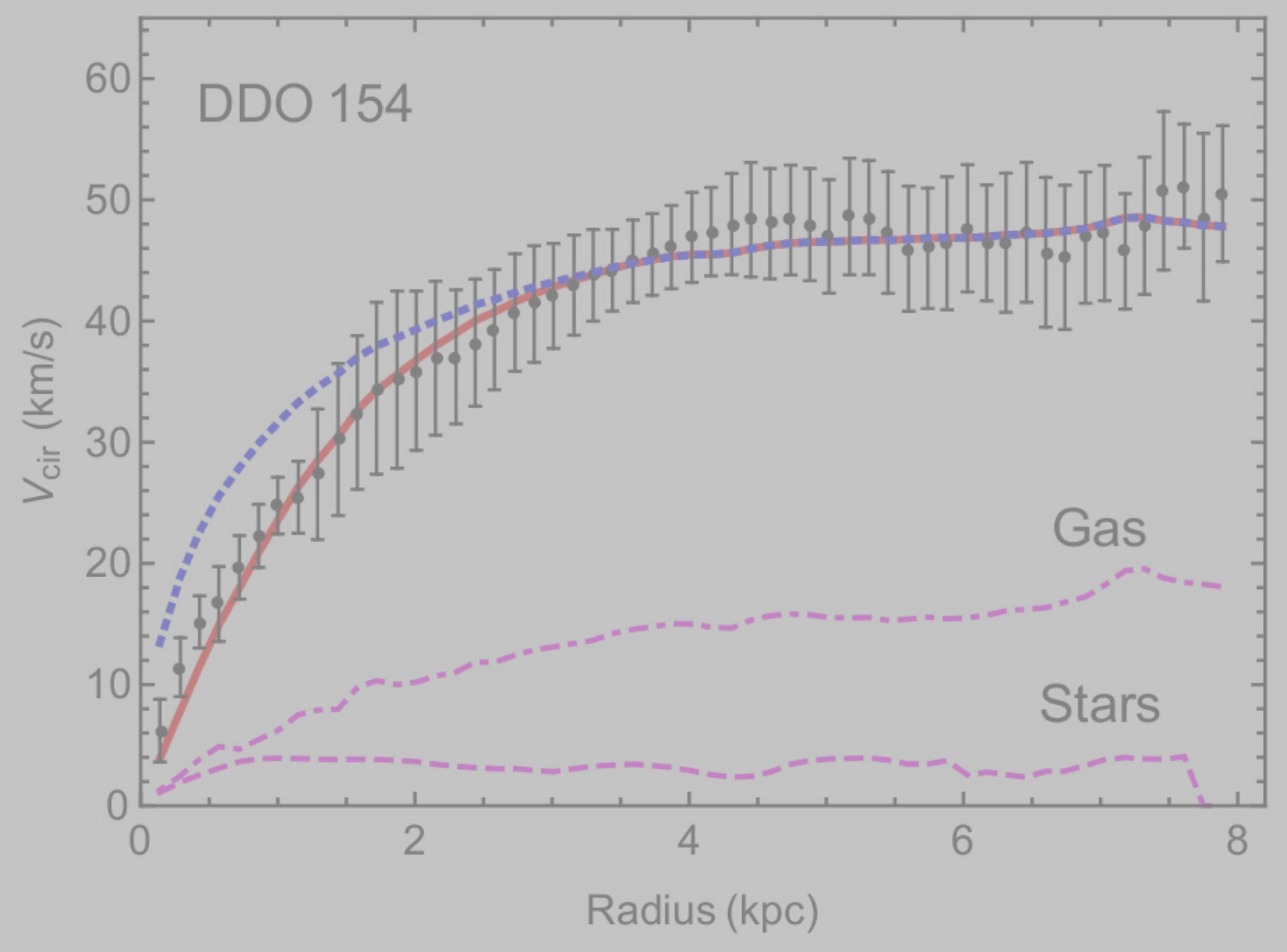

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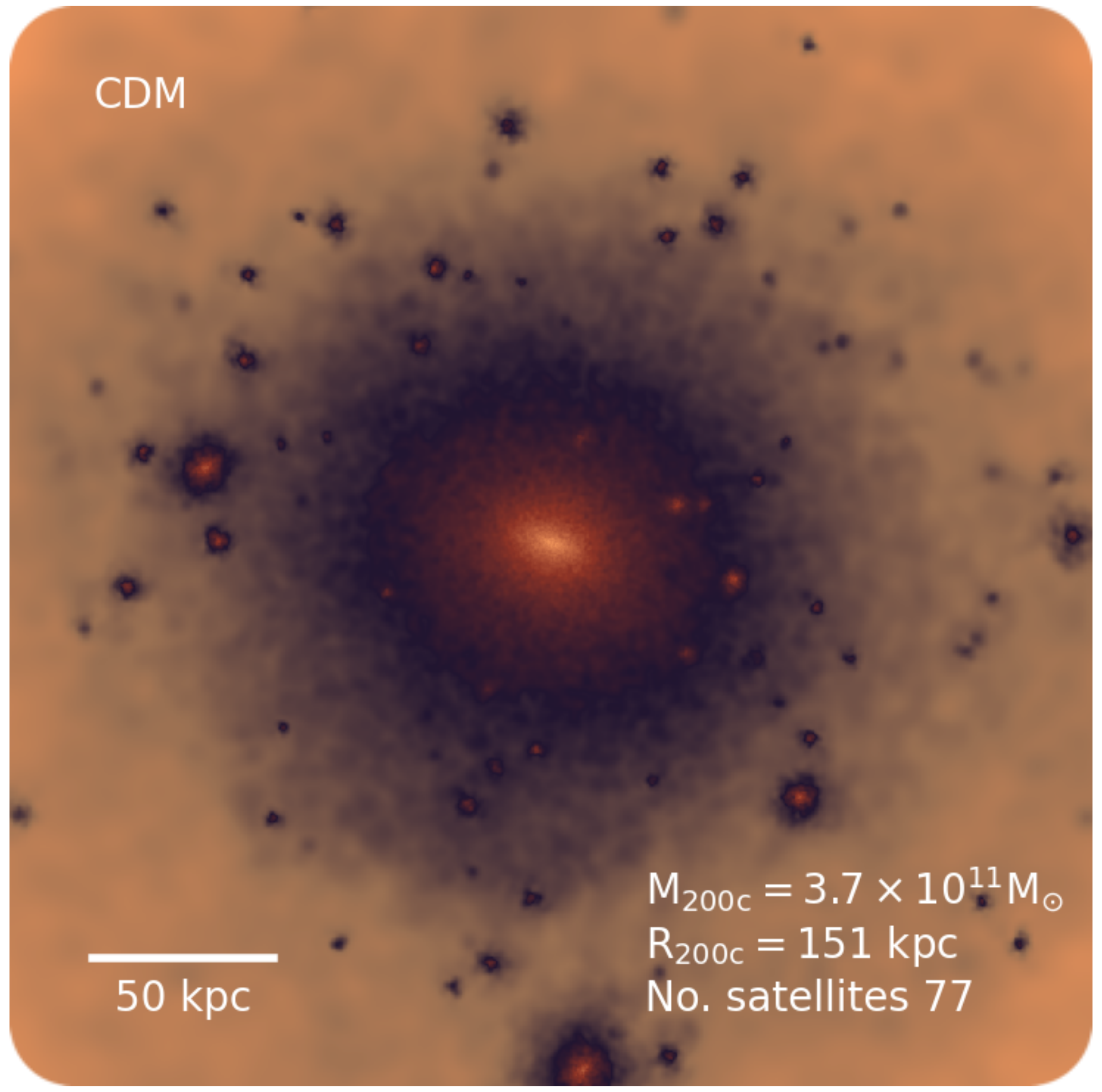

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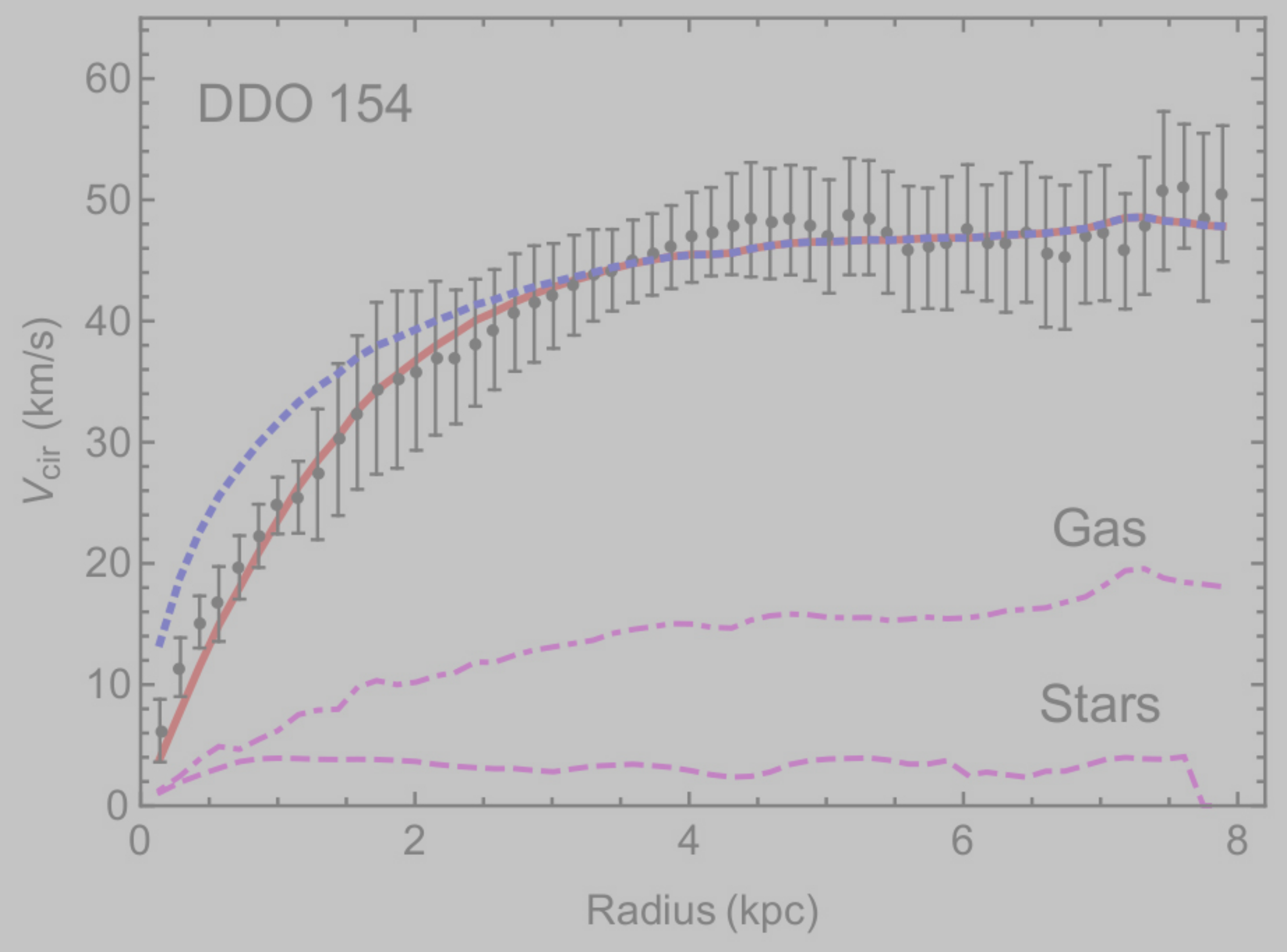

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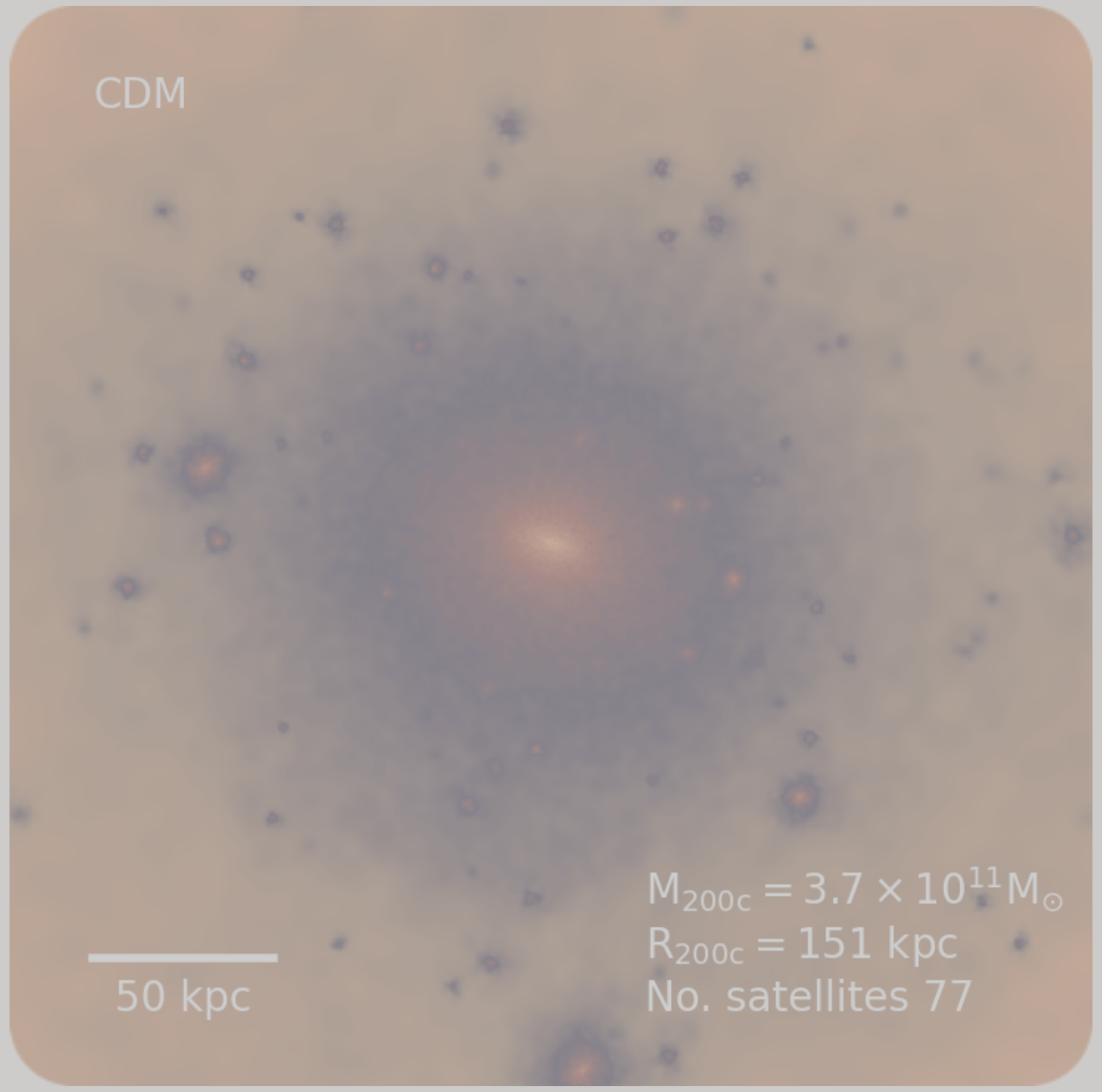

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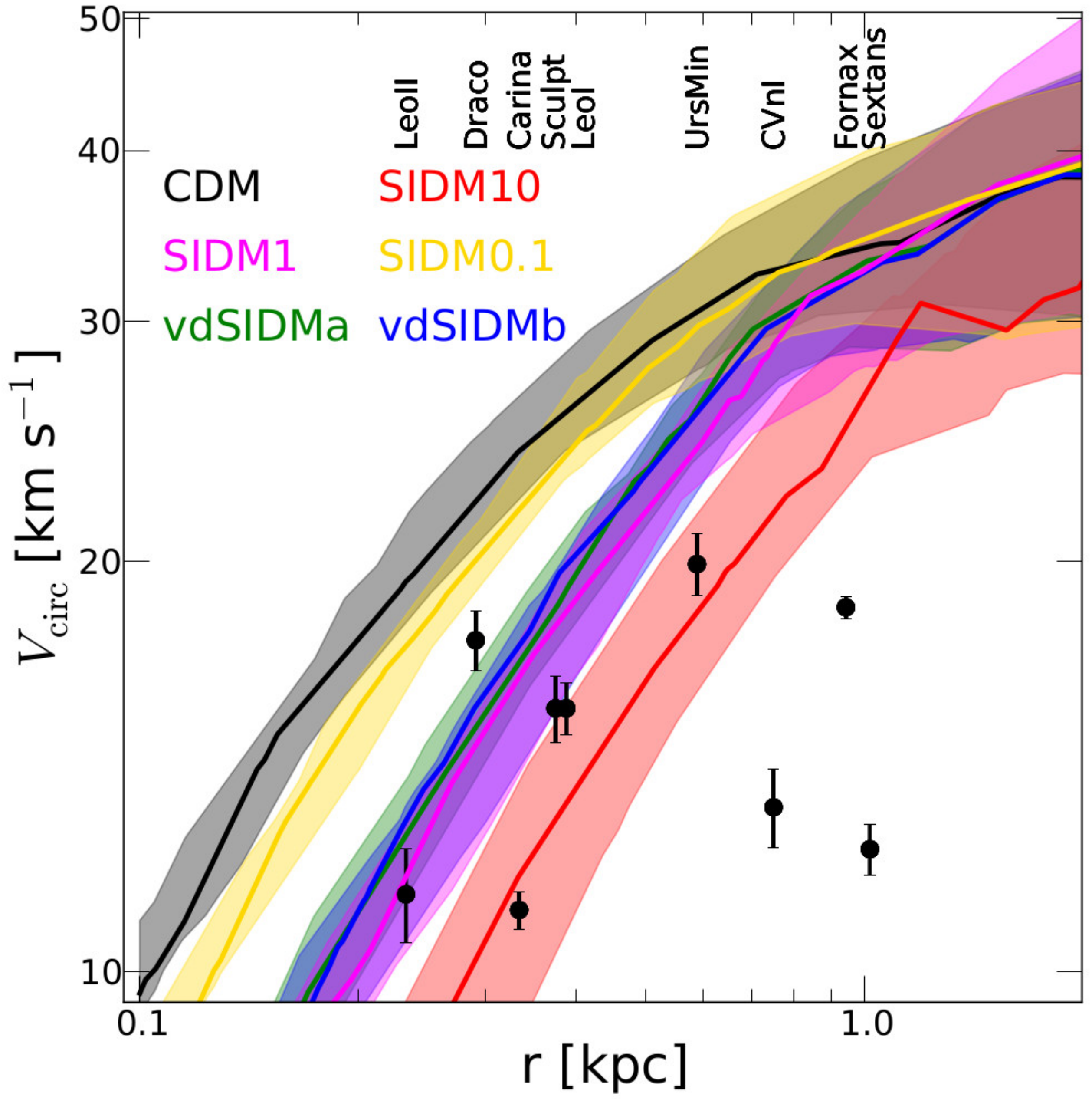
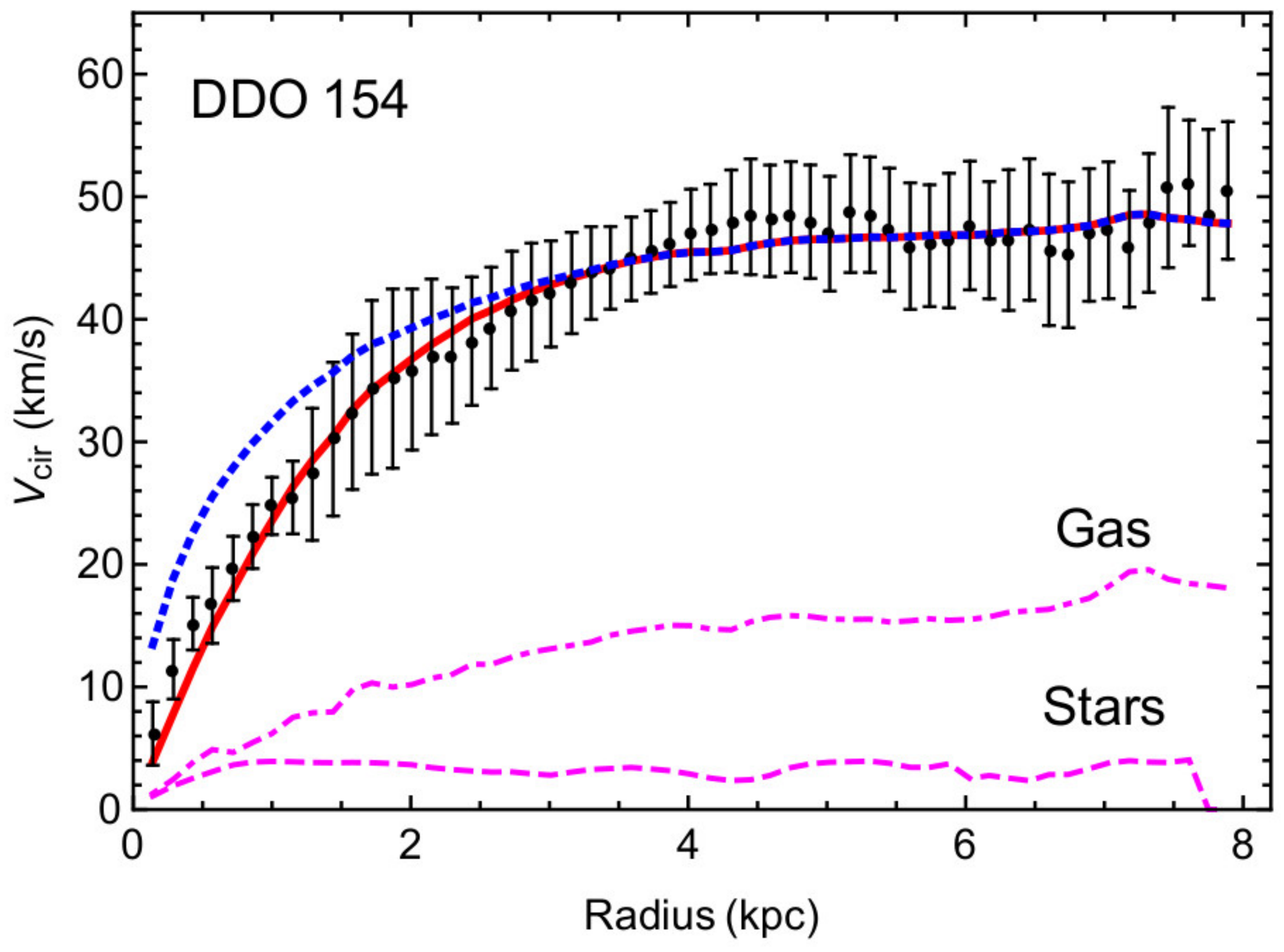
To solve too-big-to-fail problem



SIDM lowers the central density of the most massive satellites, agreeing with kinematic measurements from local dwarf spheroidals (Zavala 2013)

Why Self-Interacting Dark Matter?

To solve cusp-core problem



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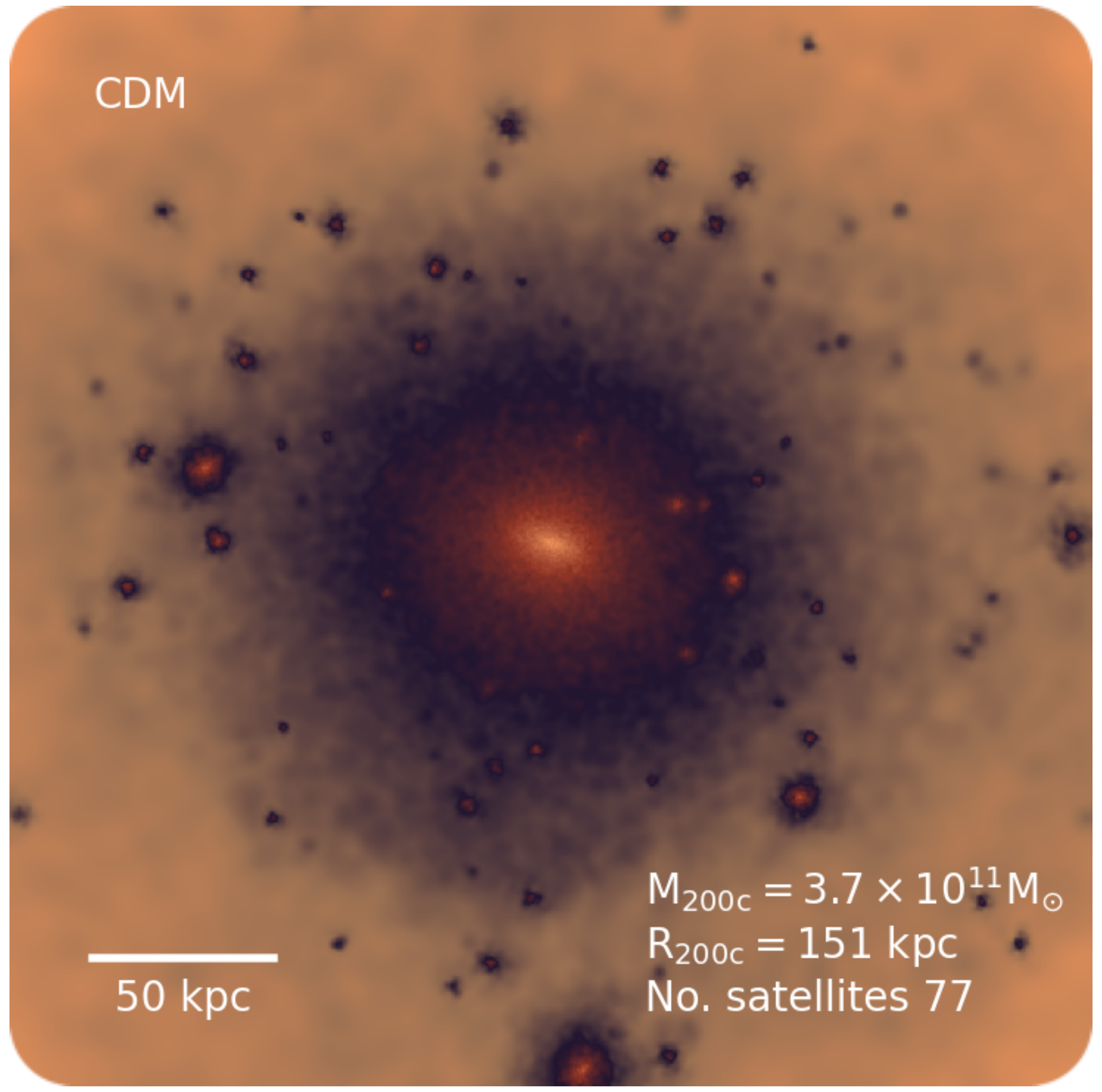

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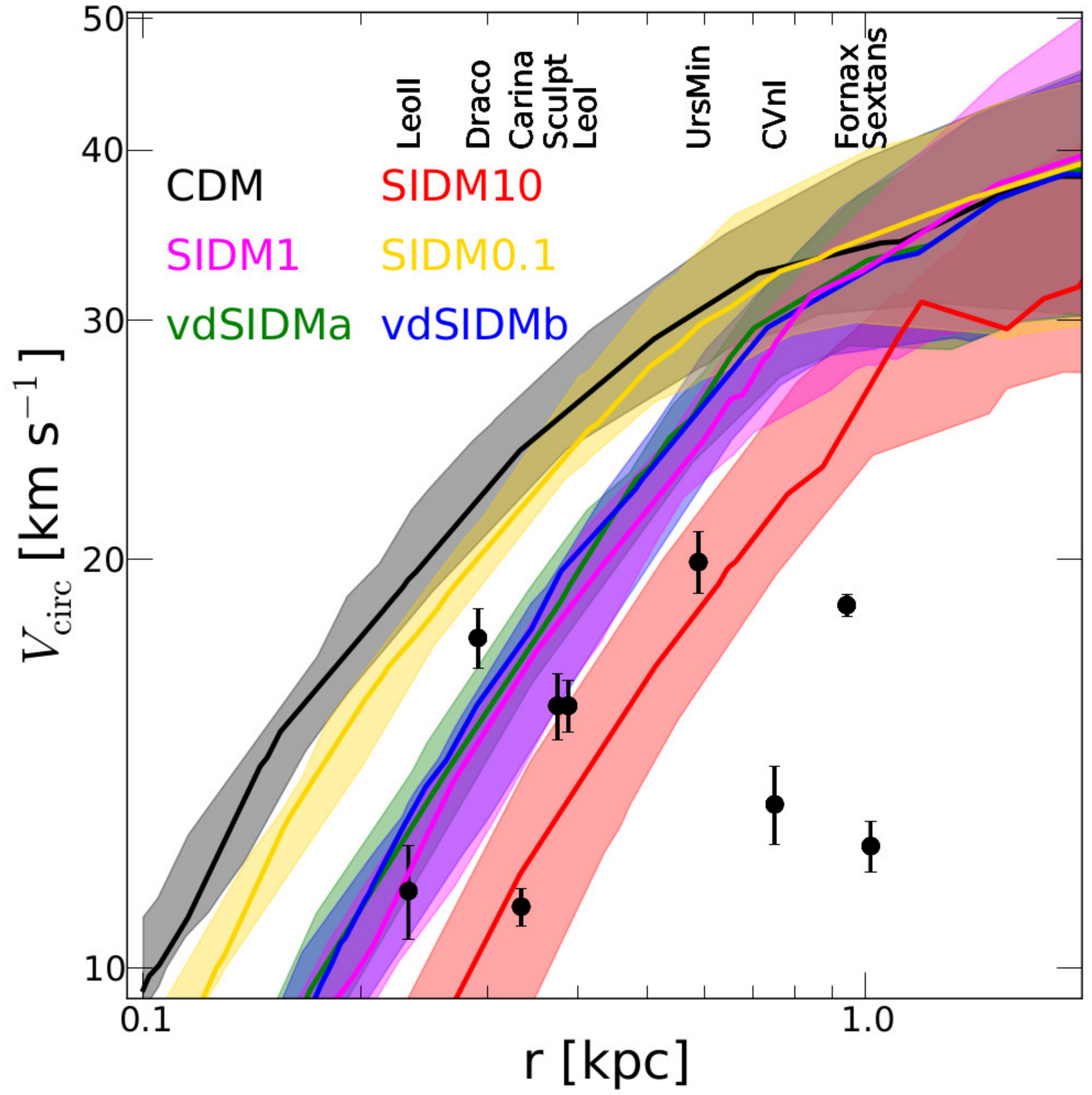

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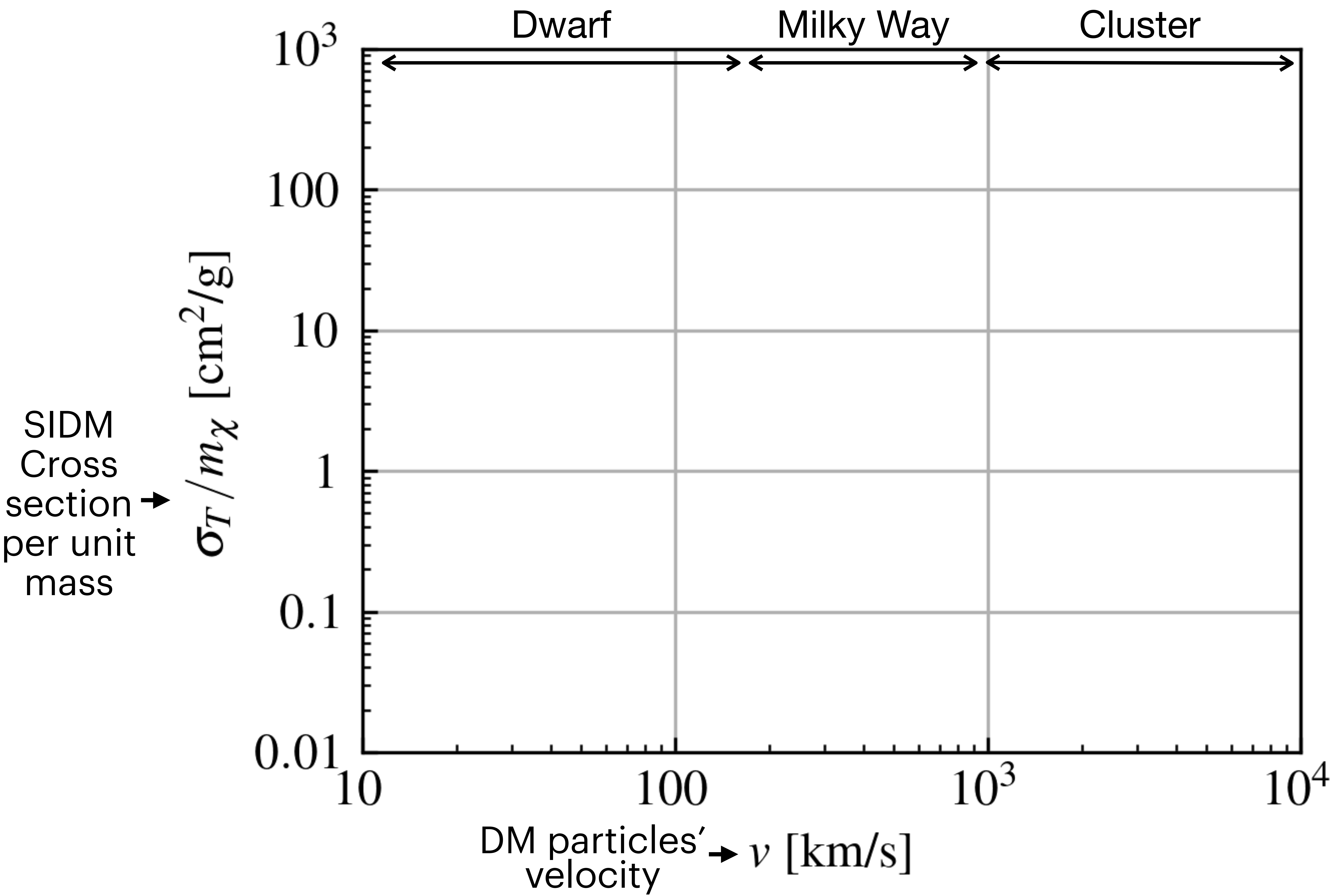
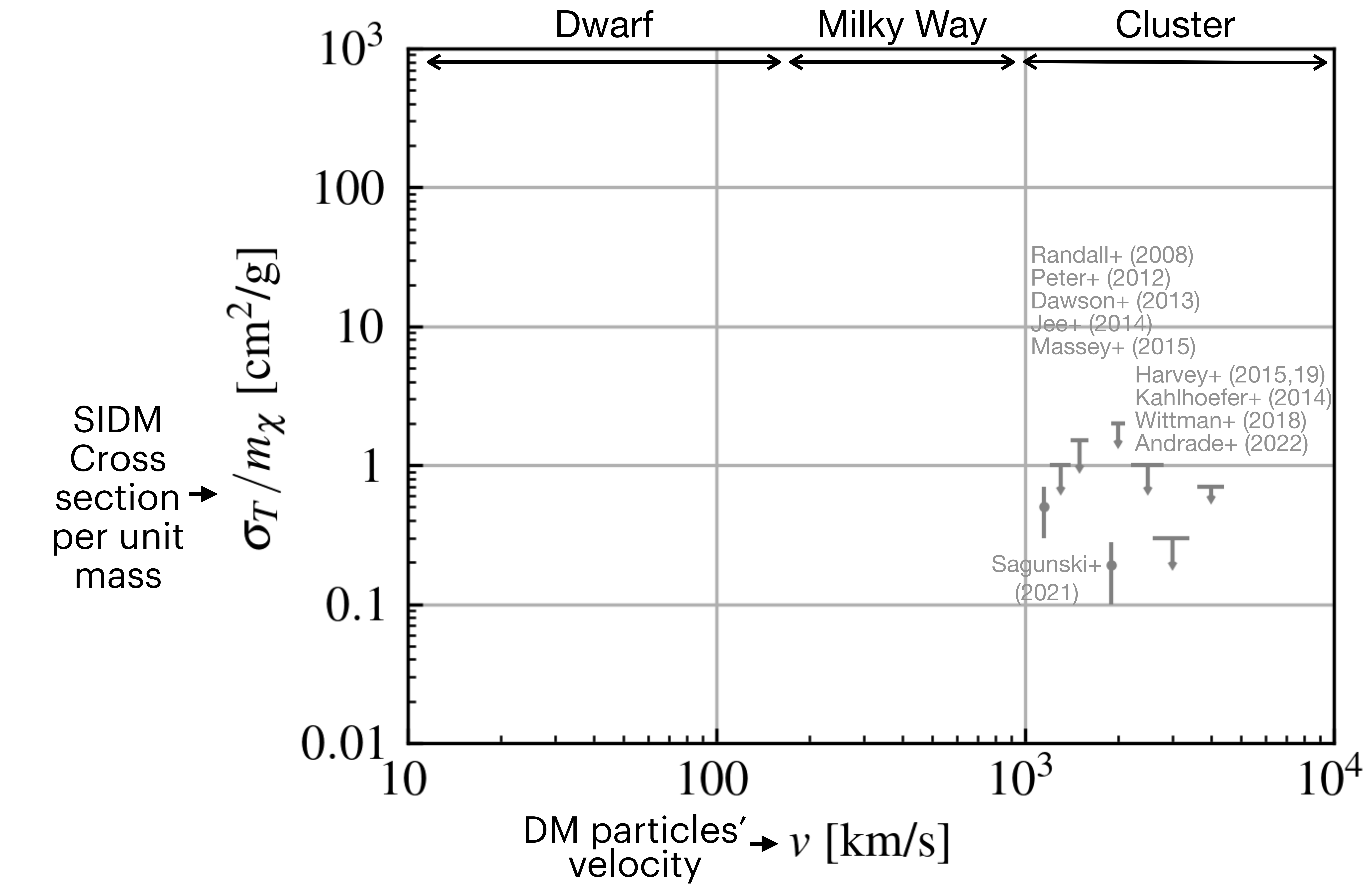


Dwarf
Milky Way
Cluster
10^3
100
10
1
0.1
0.01
10
100
10^3
10^4
SIDM Cross section per unit mass
σ_T/m_χ [cm^2/g]
DM particles' velocity
v [km/s]



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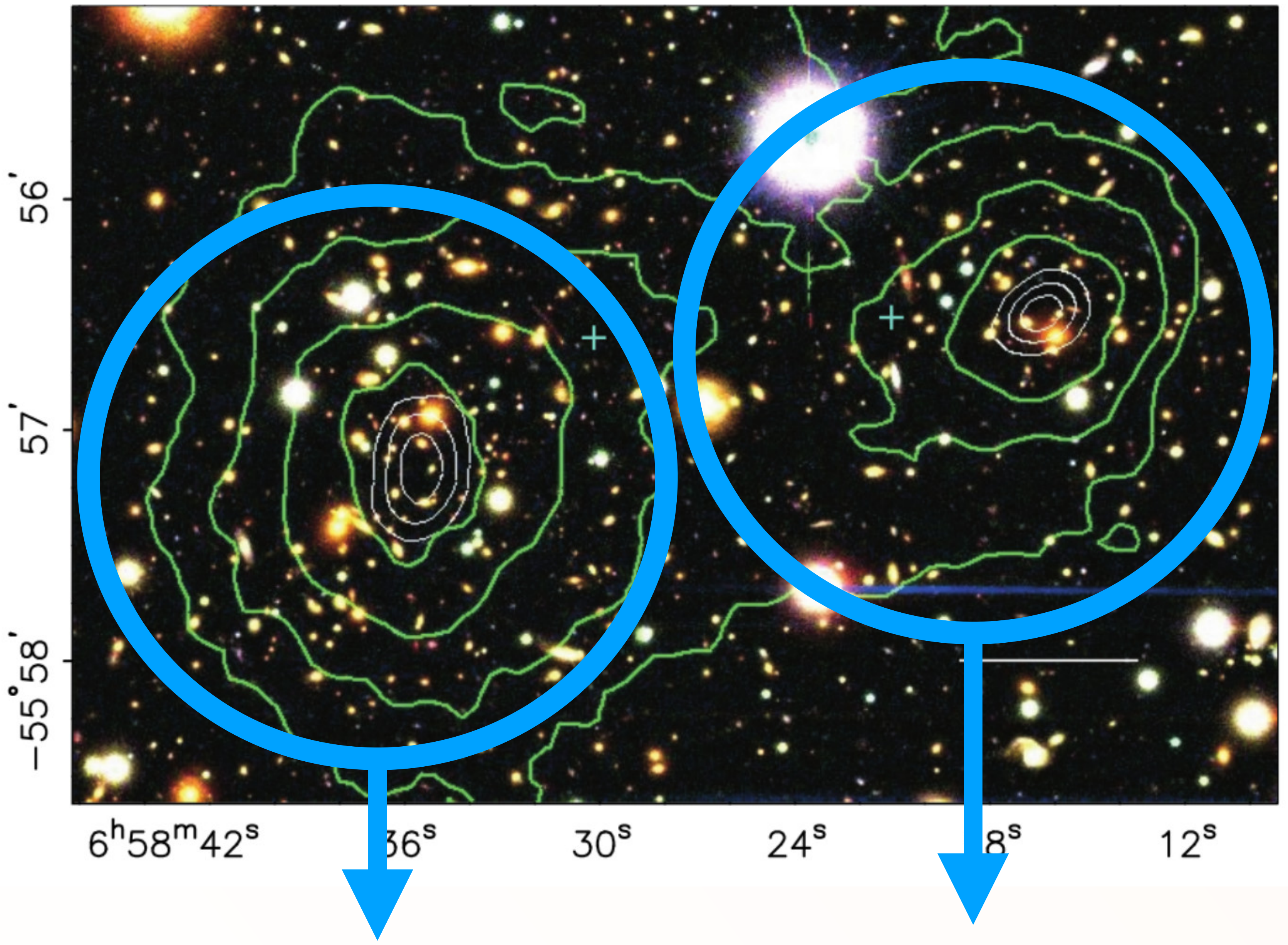
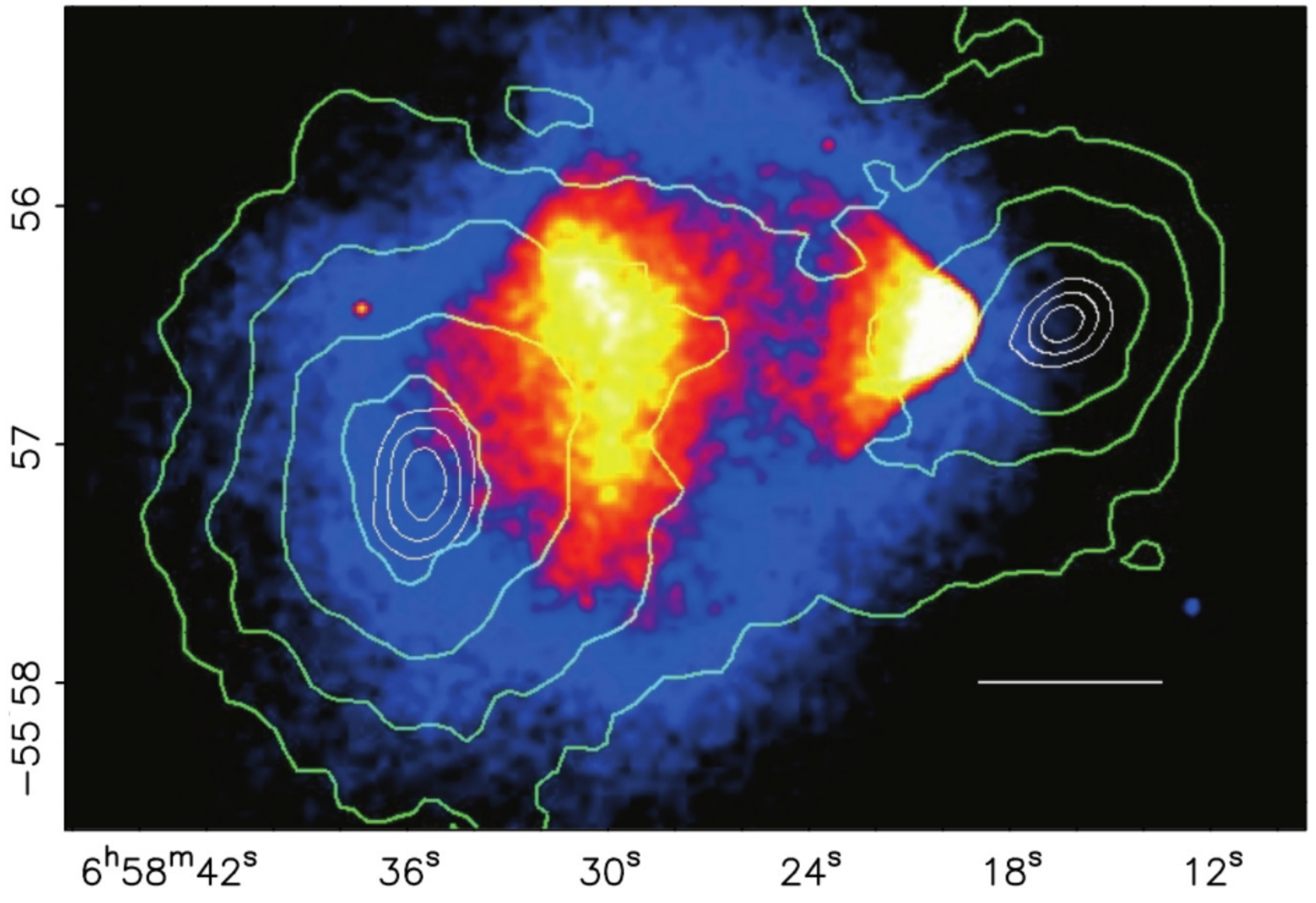
Sagunski+
(2021)
SIDM
Cross
section
per unit
mass
DM particles'
velocity

SIDM constraints: cluster-size haloes

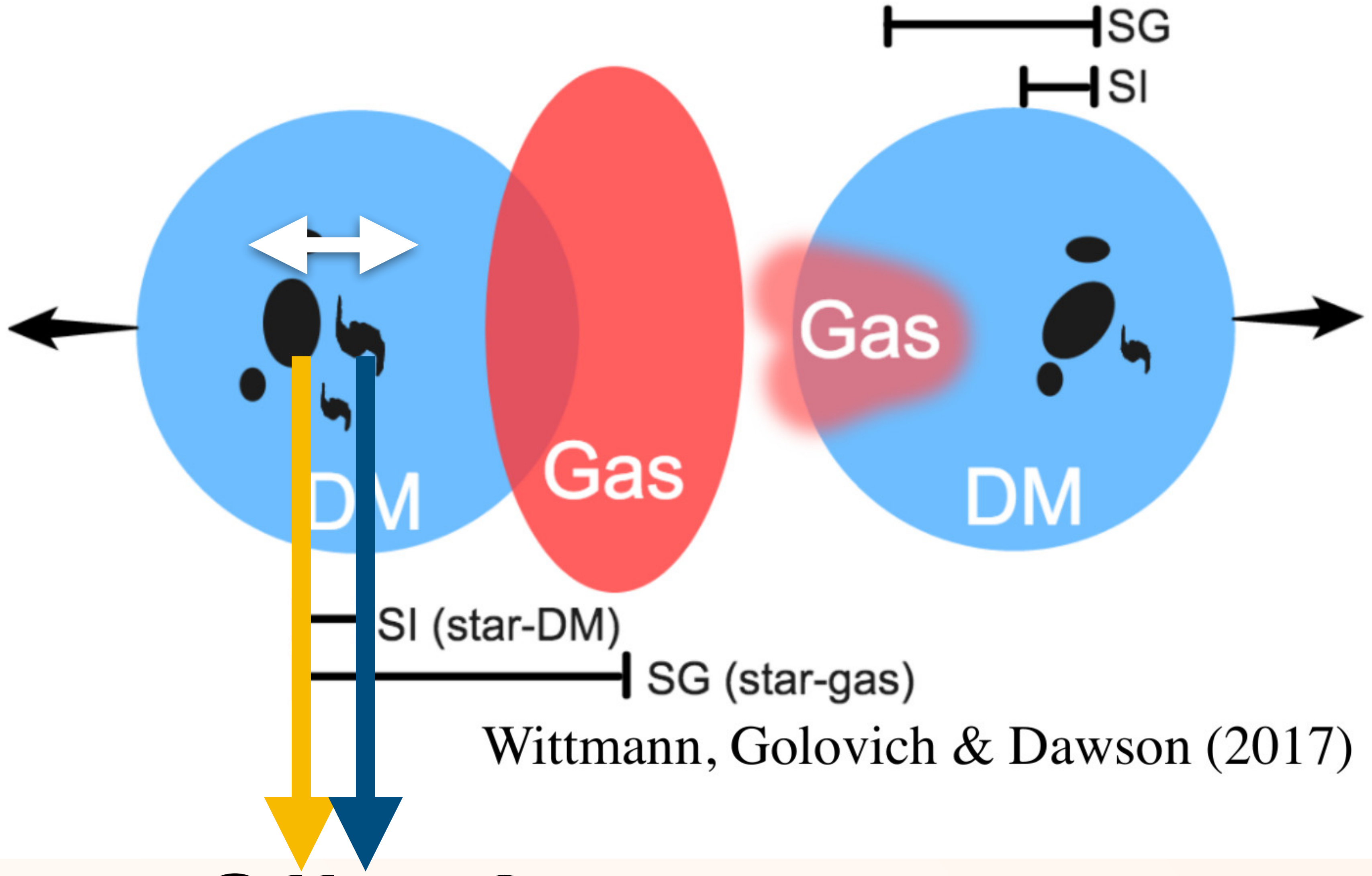
Dark matter distribution (green contours, gravitational lensing maps)



Ordinary matter in color (NASA's Chandra X Observatory)



Theoretical scenario of the clusters of galaxies colliding

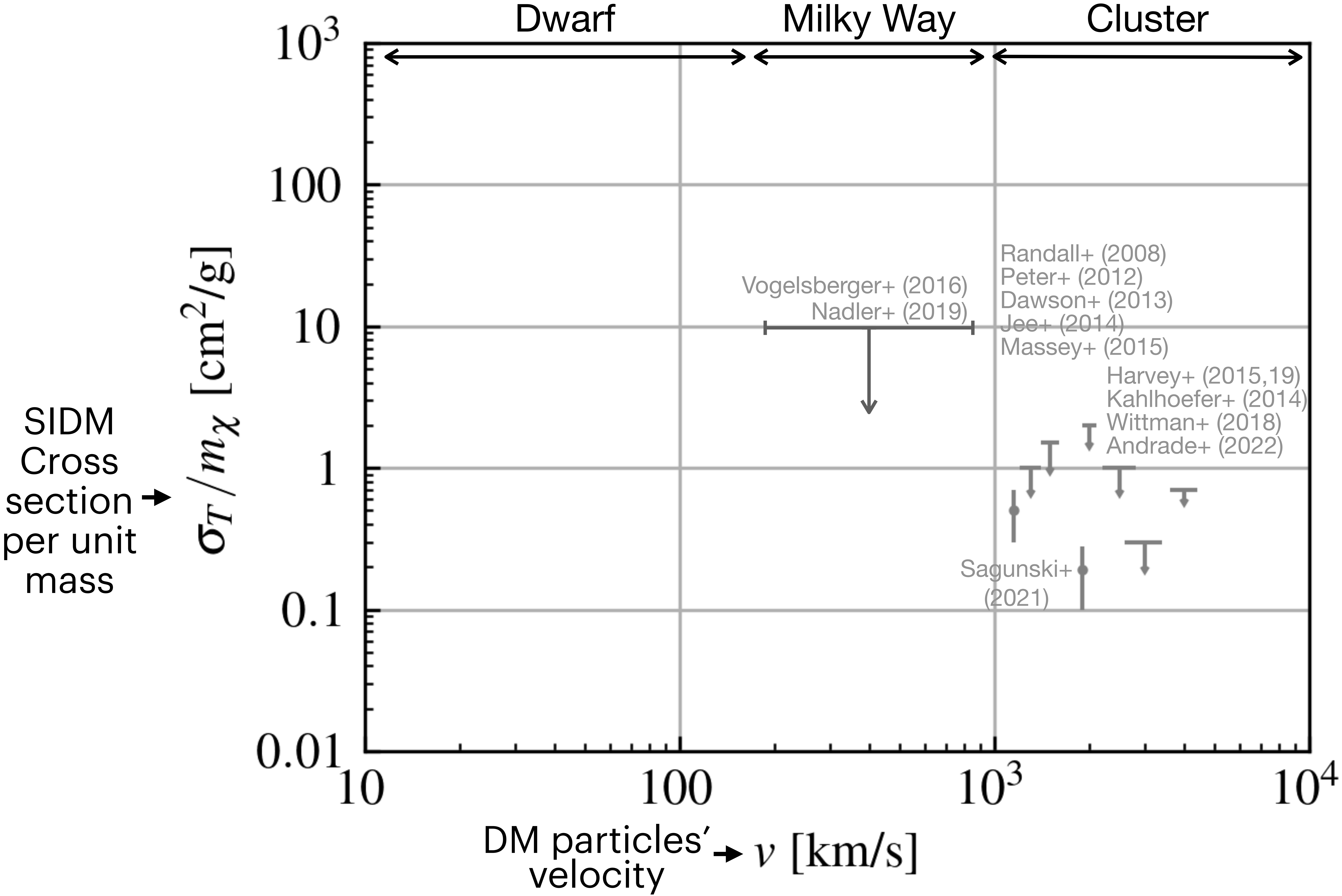


Cluster A collides with Cluster B

Offset?

Dark matter is not self-interacting → No Offset

Dark Matter is self-interacting! → Offset >0



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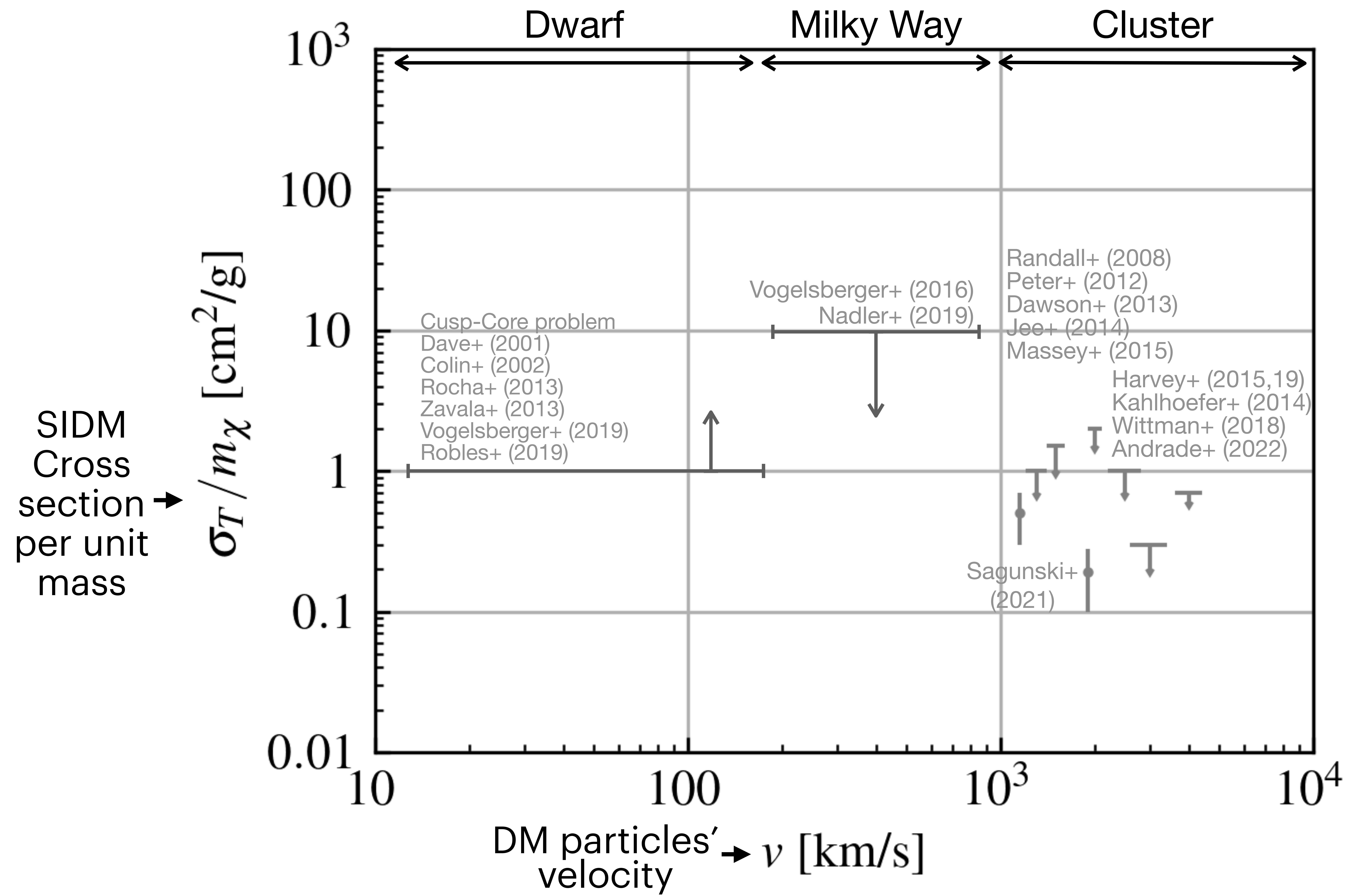

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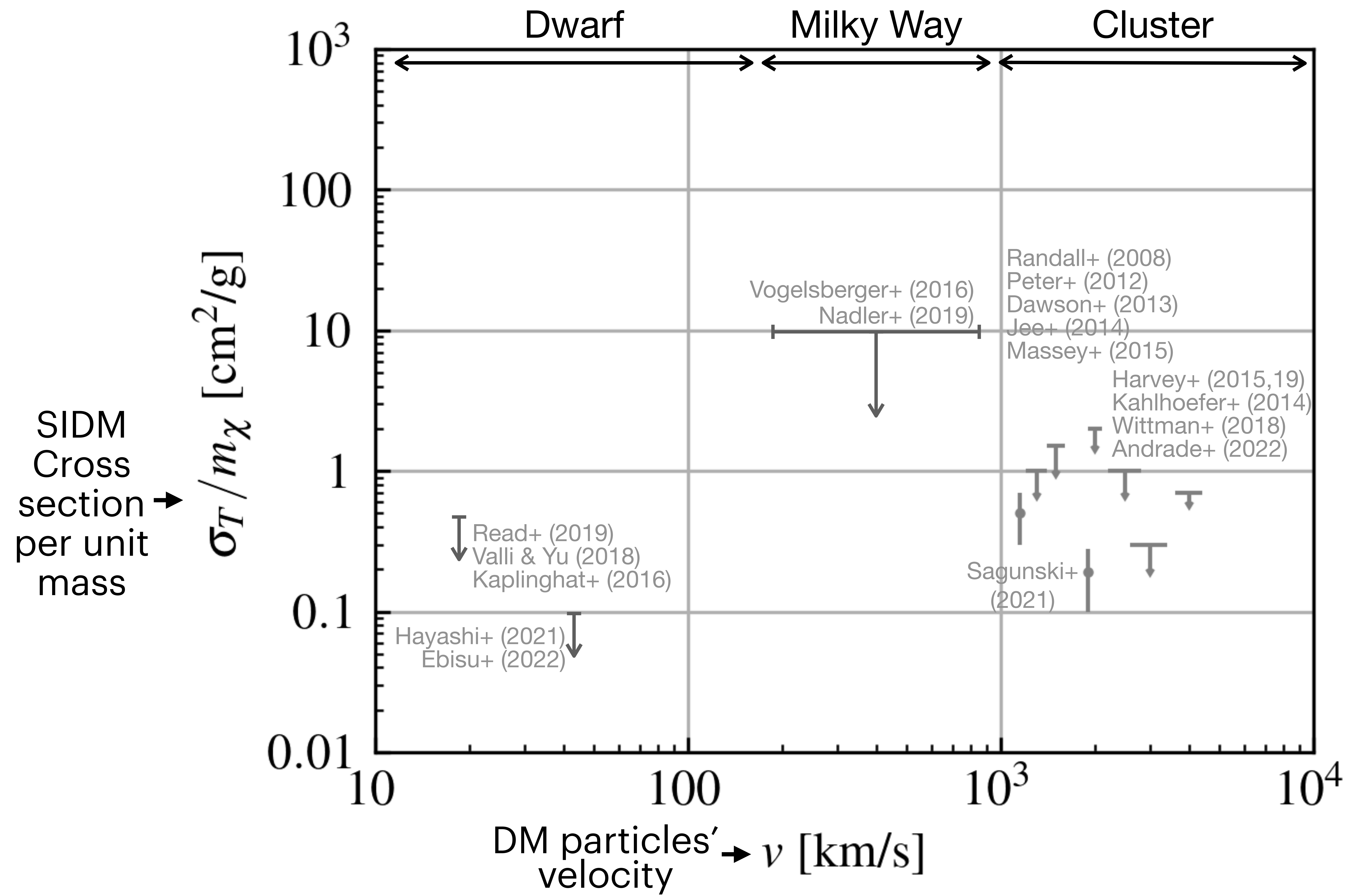

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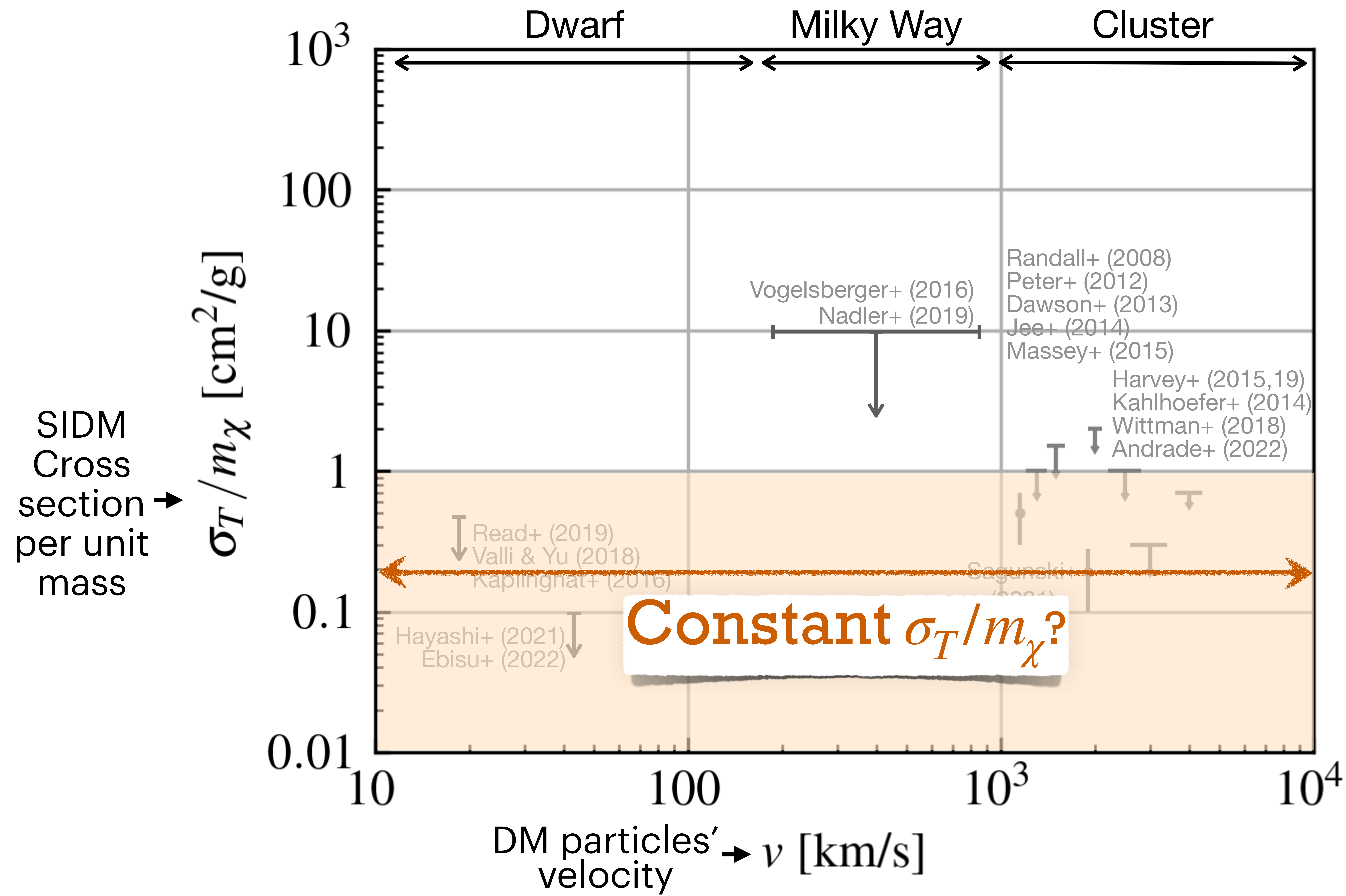

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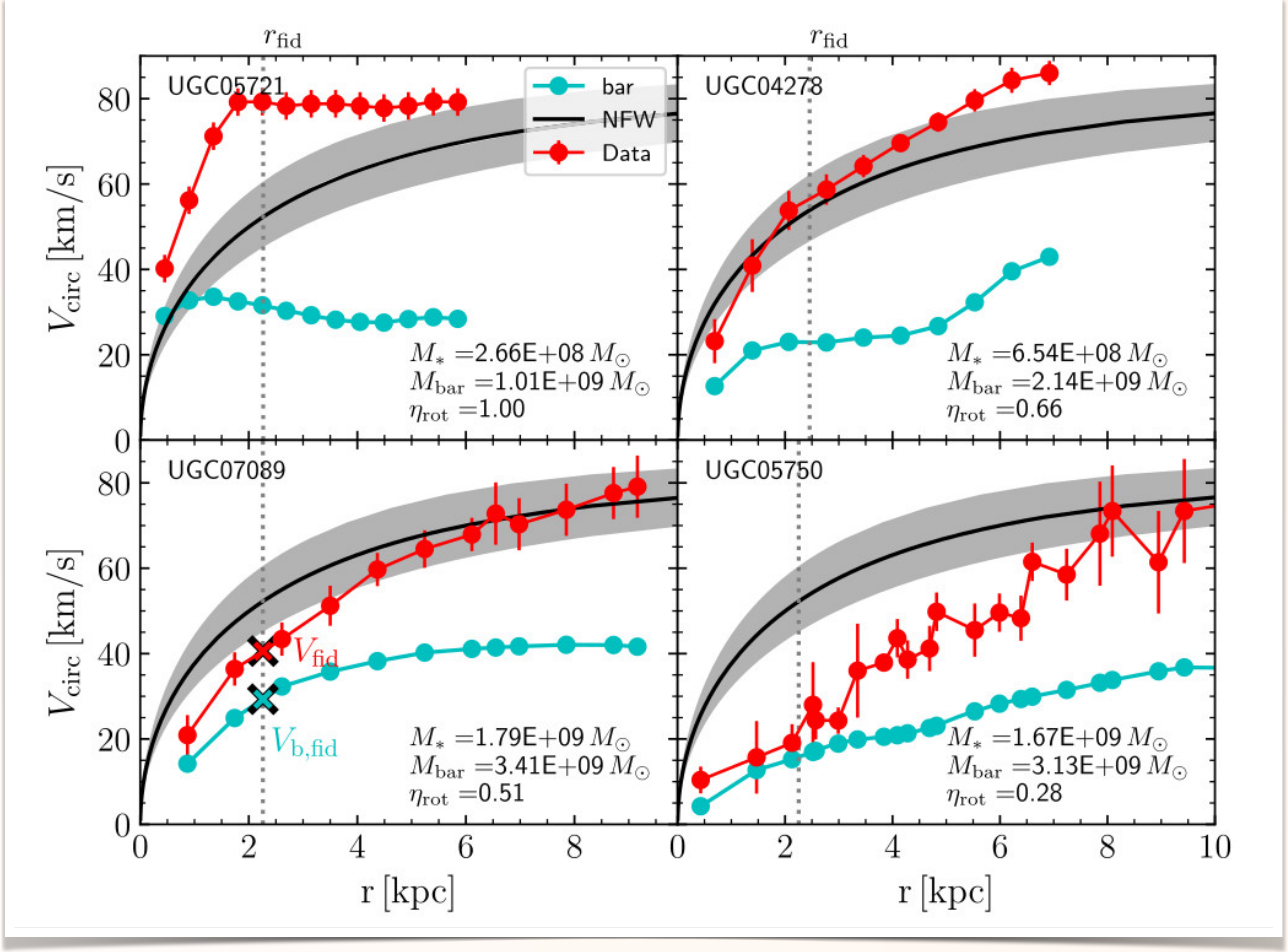
Constant σ_T/m_χ?

SIDM constraints: Dwarf Galaxies

Gas-rich dwarf galaxies show a wide range of shapes in the inner regions
(e.g. Gilmore et al. 2007; Normandy et al. 2009; Oh et al. 2011, 2015; Oman et al. 2015; Lelli et al. 2016)



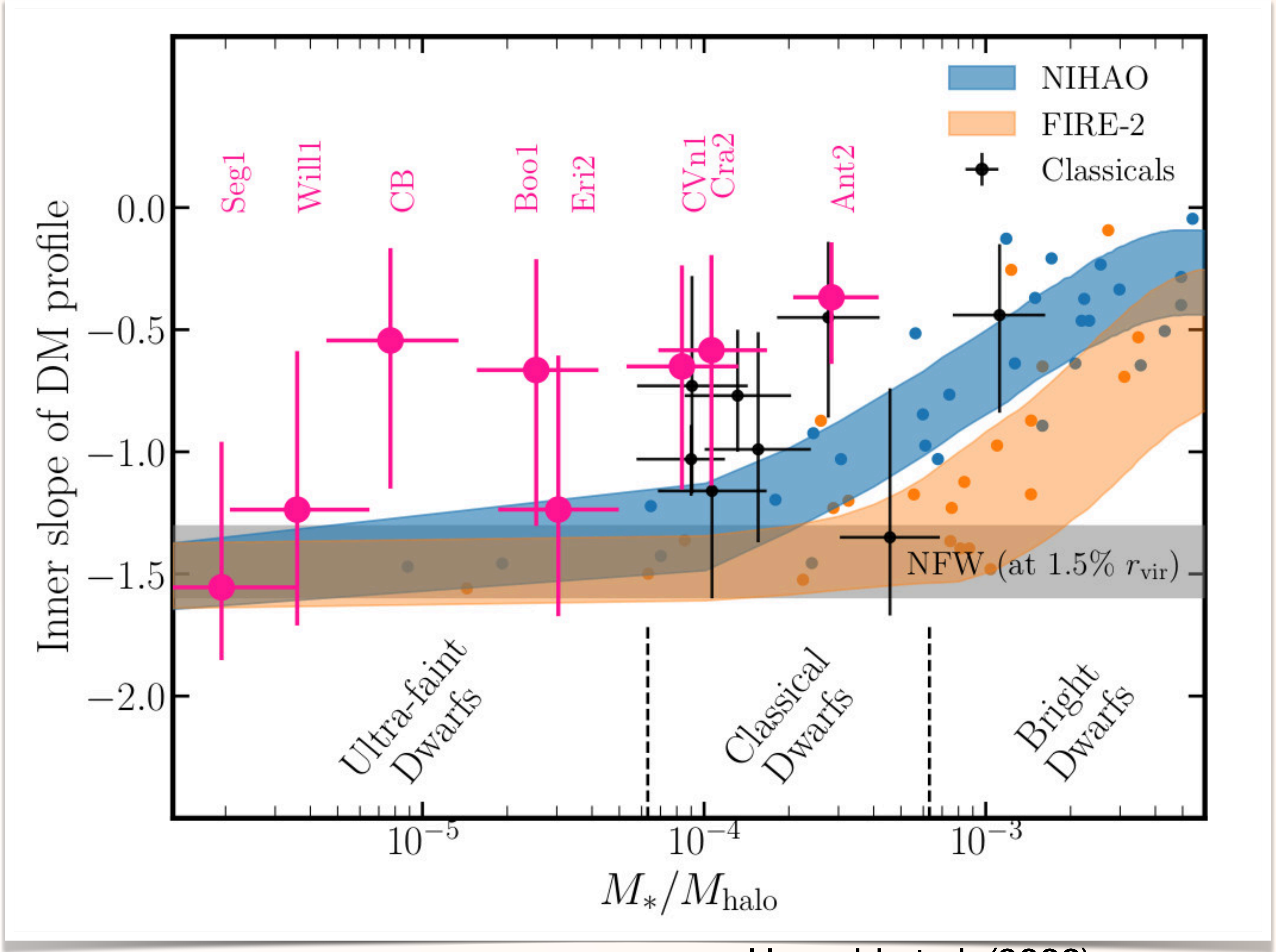
Diversity of rotation curves at fixed Vmax

Santos-Santos et al. (2020)

SIDM constraints: Dwarf Galaxies

Classical dwarfs and ultra-faint galaxies indicate there is a diversity in the inner DM distribution

No correlation of inner DM slope with M_*/M_{halo} or star formation history
Hayashi, Chiba & Ishiyama (2020)



Hayashi et al. (2022)
(See also Hayashi et al. 2020; Read et al. 2019; 2018)

SIDM constraints: Dwarf Galaxies

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(and ultra-faint galaxies)
indicate there is a diversity

Can SIDM explain the *diversity* problem in dwarf galaxies?

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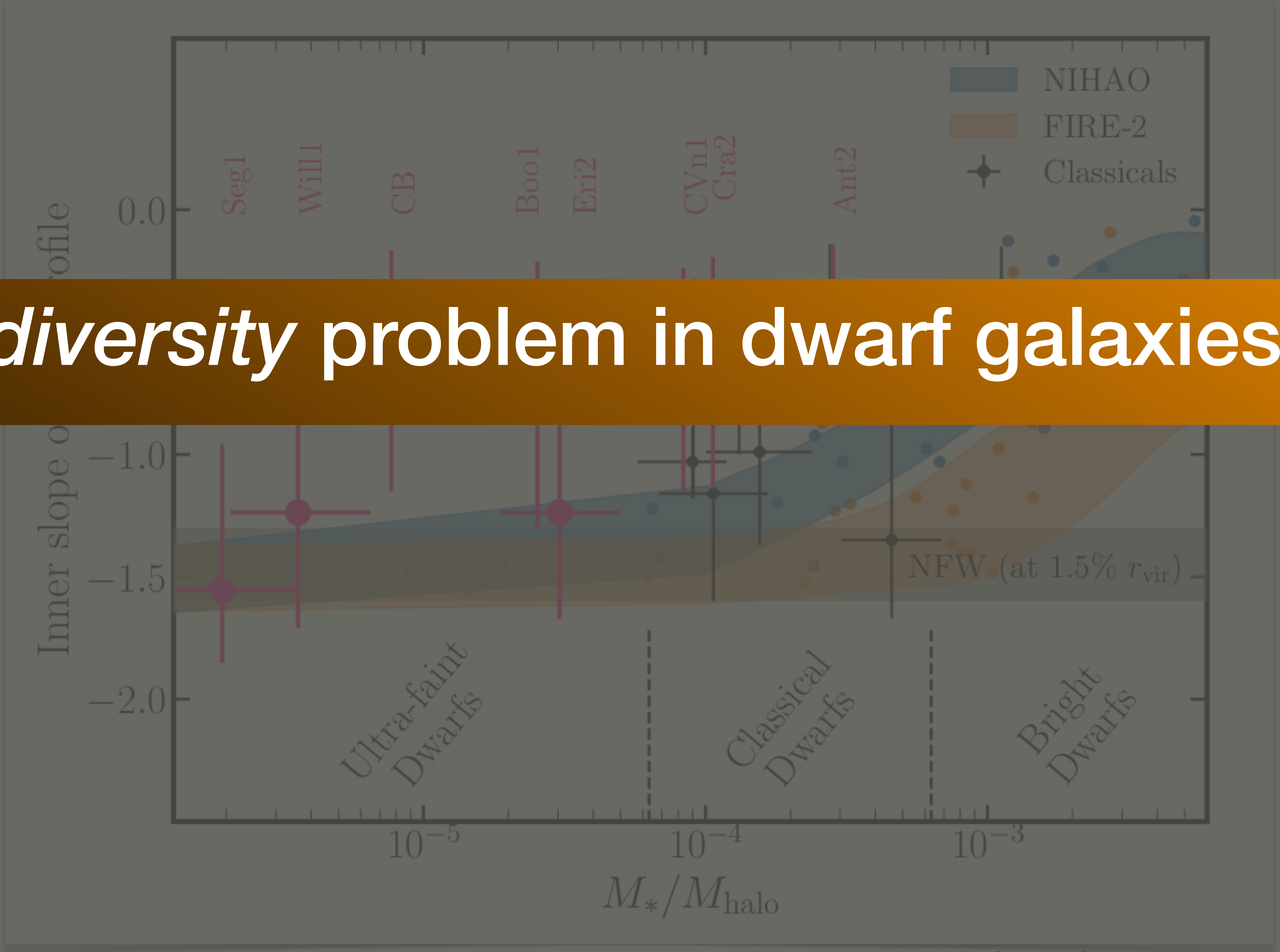

Hayashi et al. (2022)
(See also Hayashi et al. 2020;
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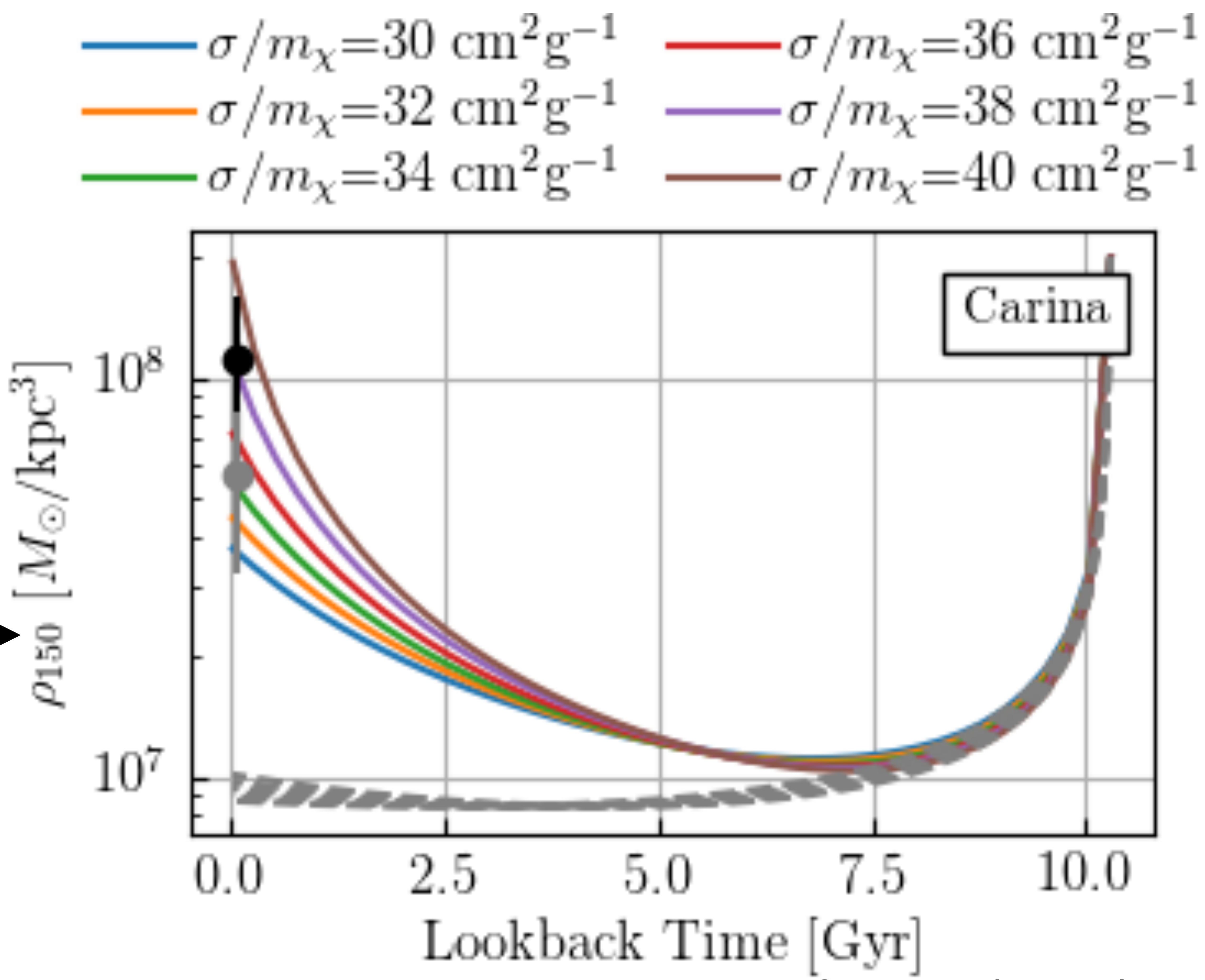
SIDM and Gravothermal Core-Collapse (Correa 2021)

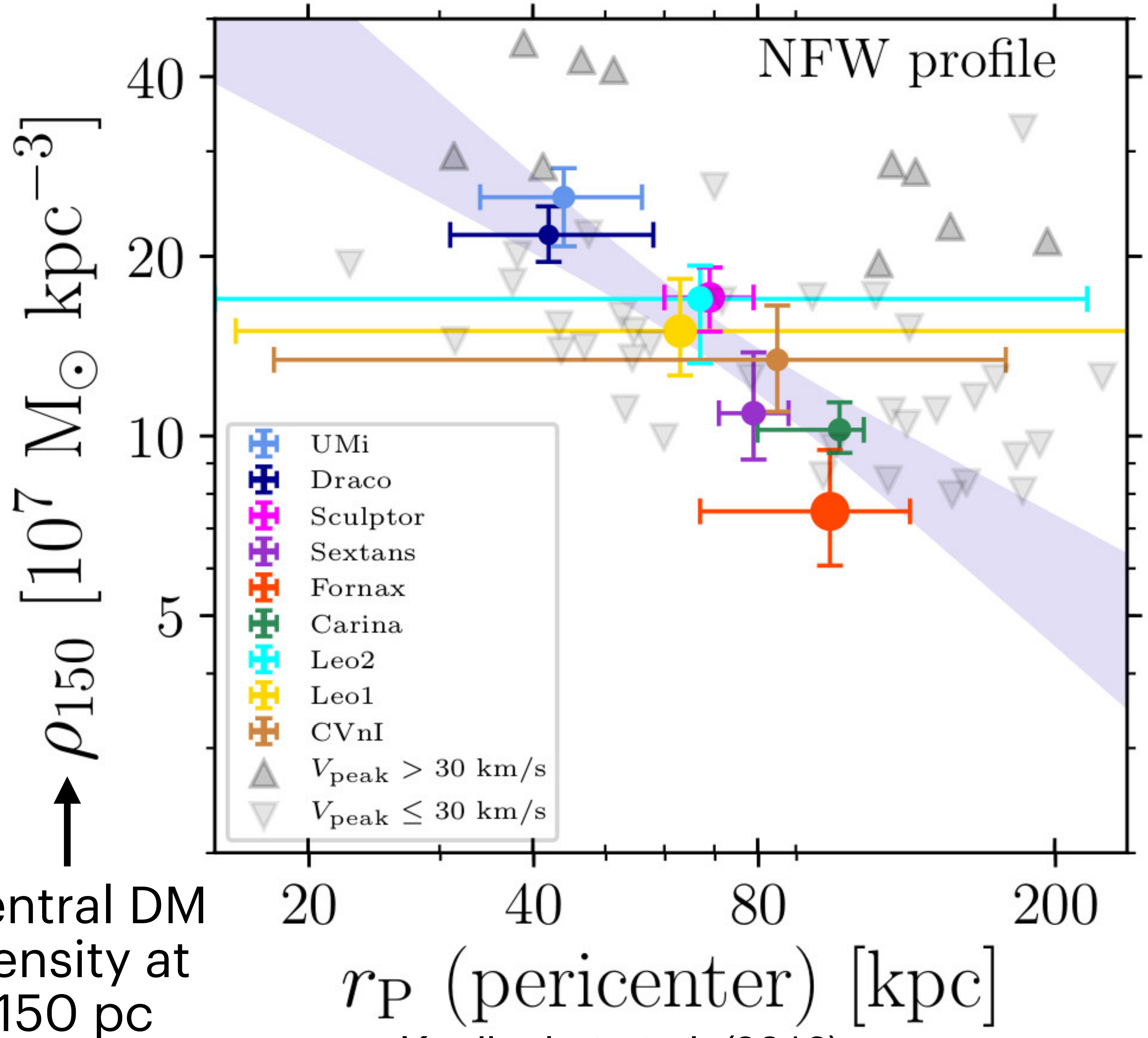
Central density, example: satellite galaxy Carina



Correa (2021)

- Very frequent DM particle interactions rapidly heat the central DM halo core, causing it to contract and raise in density! -> This regime is known as gravothermal core collapse (e.g. Balberg et al. 2002; Koda & Shapiro 2011; Elbert et al. 2015; Sameie et al. 2020; Nishikawa et al. 2020; Turner et al. 2021; Carton Zeng et al. 2021)

Anti-correlation between $\rho_{\mathrm{DM,150pc}}$ and pericenter

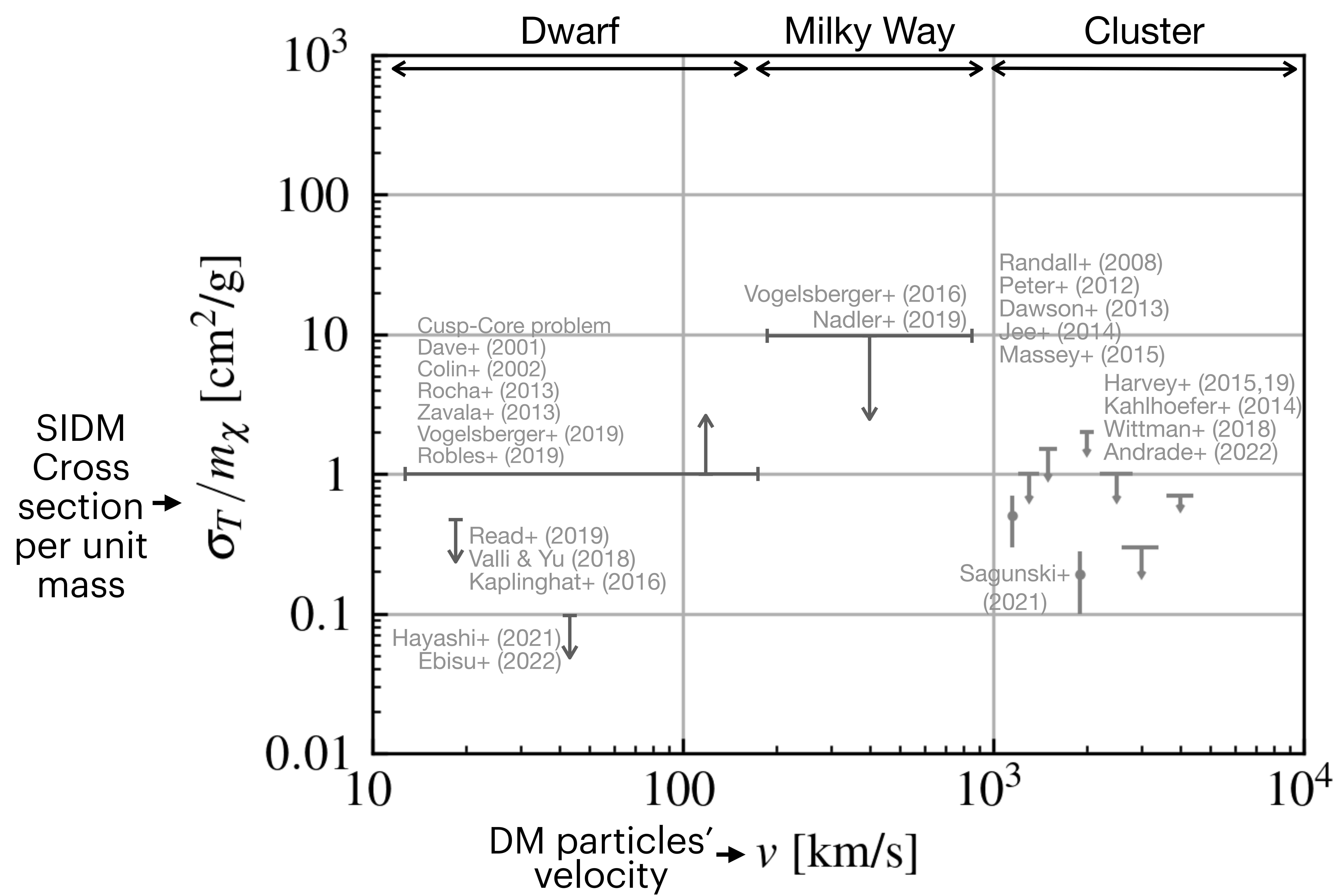


Central DM density at 150 pc

Kaplinghat et al. (2019)

Milky Way (MW) dwarf spheroidal galaxies that have come closer to the MW centre are more dense in DM than those that have not come so close.

Which range of σ_T/m_χ explains this anti-correlation?



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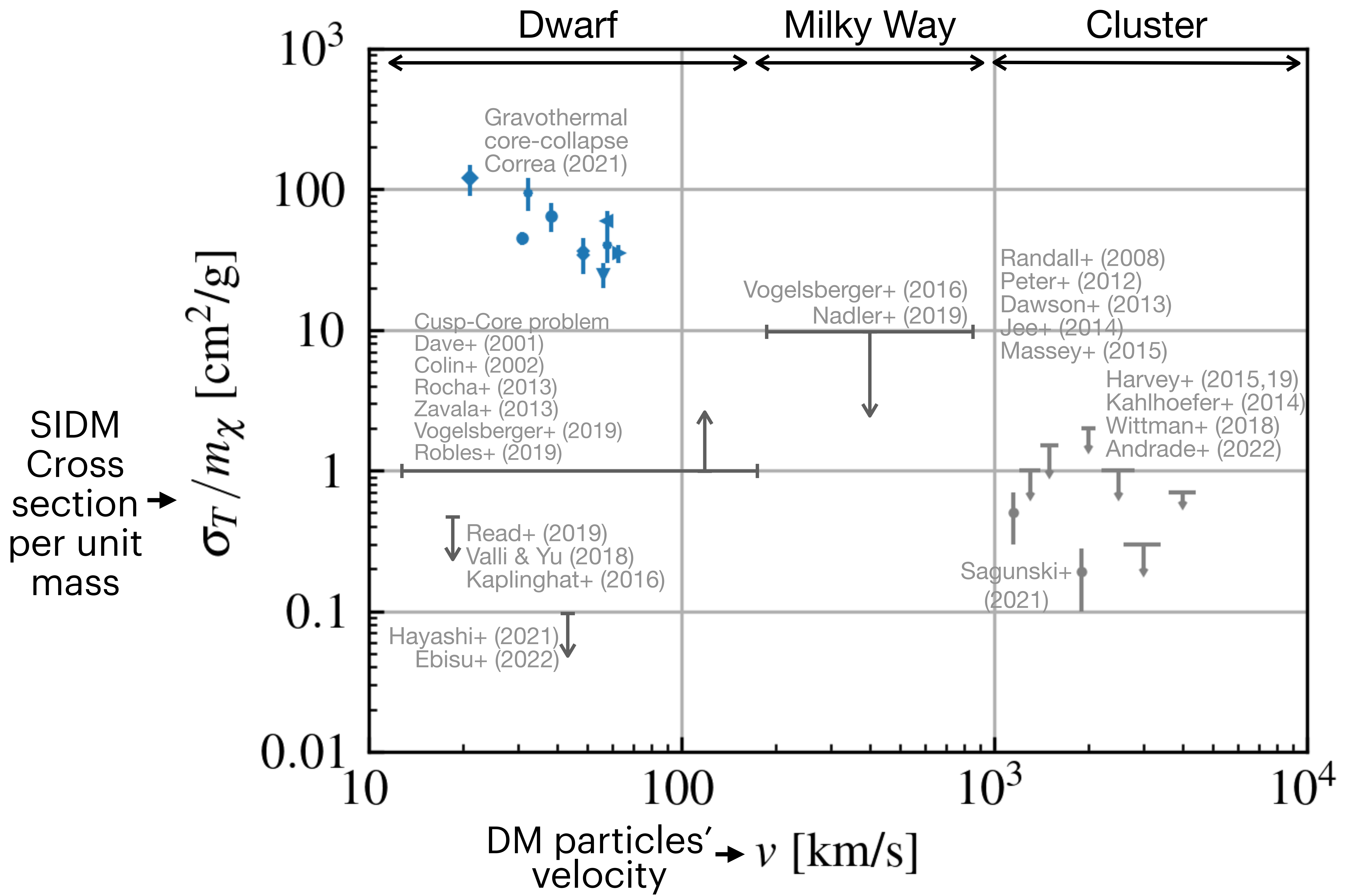

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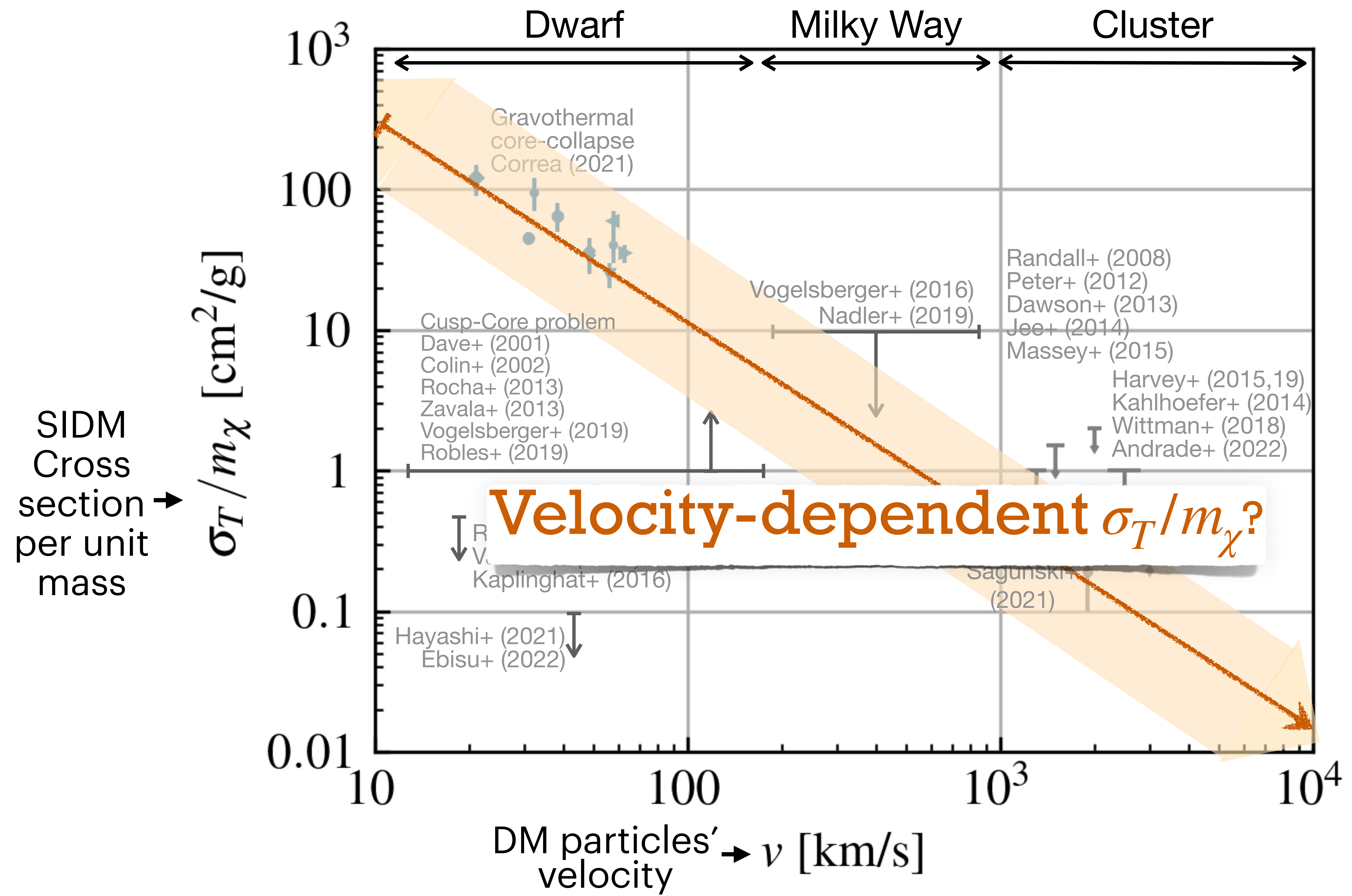

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Velocity-dependent σ_T/m_χ?
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σ_T/m_χ [cm^2/g]
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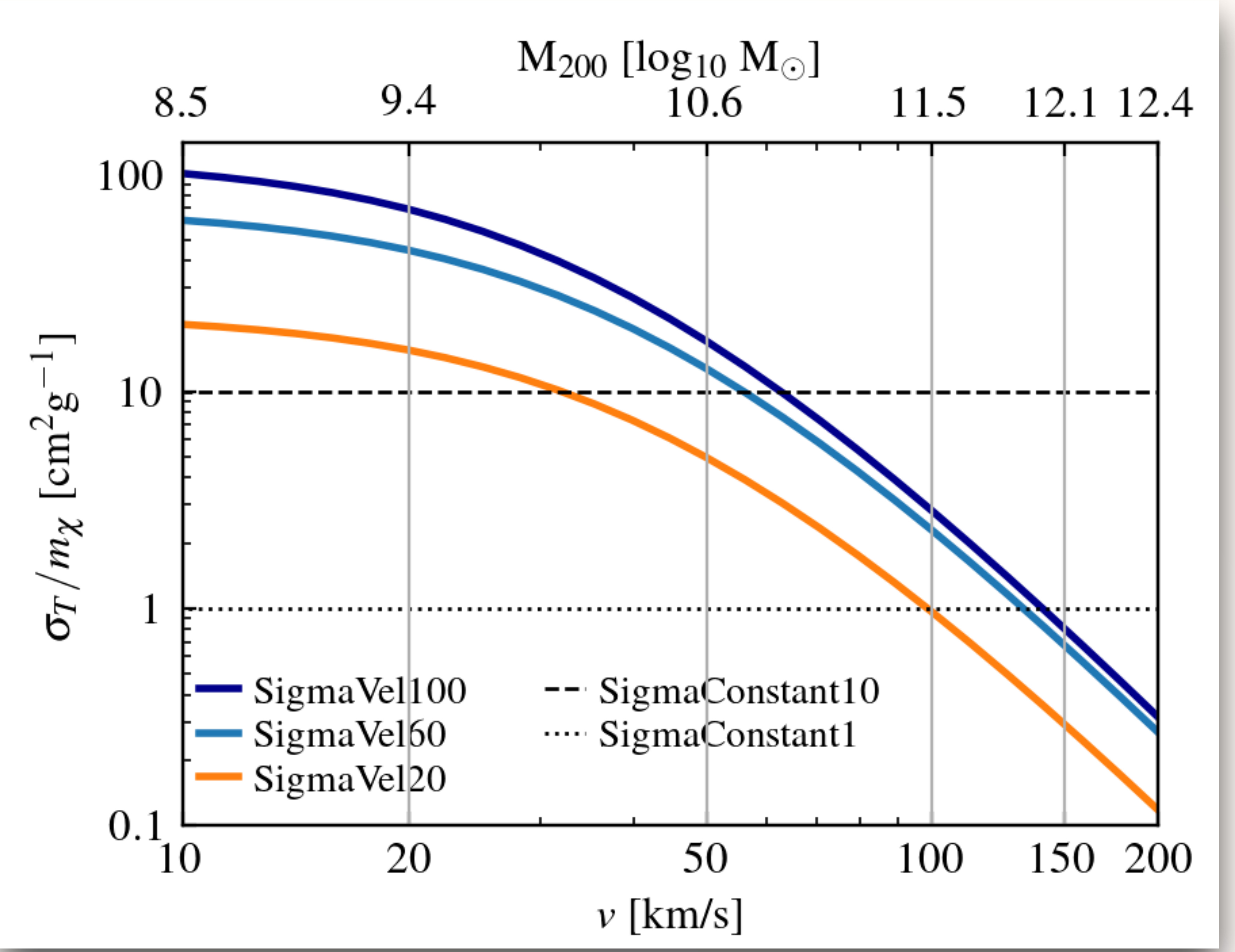
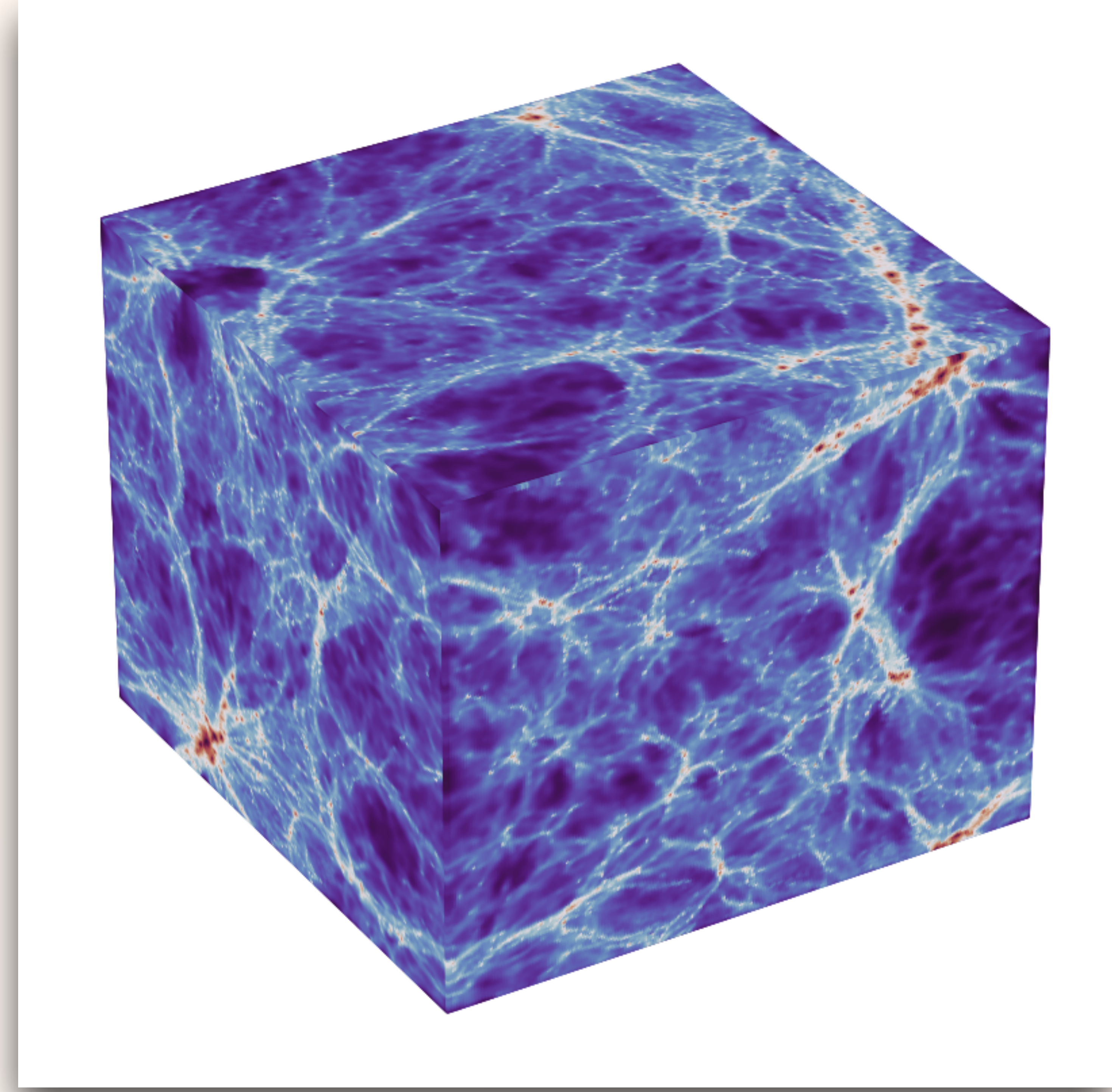
TangoSIDM project: Tantalising models of SIDM



We implemented SIDM on the gravity and hydrodynamics solver code: **SWIFT**

TangoSIDM consists on a set of DM-only and hydrodynamical cosmological simulations of (25 Mpc)^3



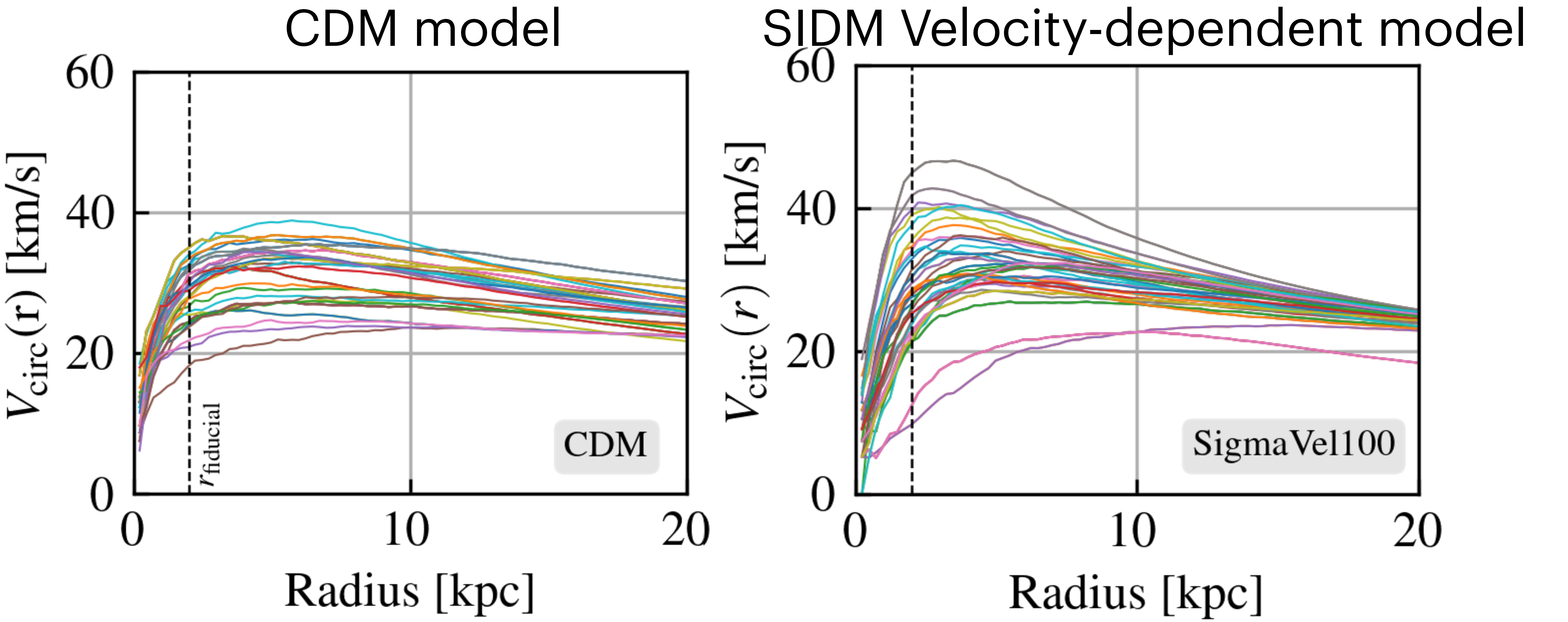
Project collaborators:

Matthieu Schaller, Sylvia Ploeckinger, Noemi Anau Montel, Shinichiro Ando & Christoph Weniger

This work on arxiv !
https://arxiv.org/abs/2206.11298

TangoSIDM project. Results

Example of circular velocities from $10^{9.5}M_{\odot}$ satellite haloes →



- Velocity-dependent SIDM models in Cosmological Dark Matter-Only simulations are able to produce a "diversity" in the rotation curves of low-mass haloes

Correa et al., arxiv: 2206.11298

Conclusions

- Velocity-dependent SIDM is a promising model to solve diversity problem on dwarf-galaxy scales
- SIDM (Velocity-dependent!) dark matter-only simulations easily produce a diversity in rotation curves of low-mass haloes
- Gravothermal core-collapse has important implications for galaxy formation studies!

Thank you!

- Contact:
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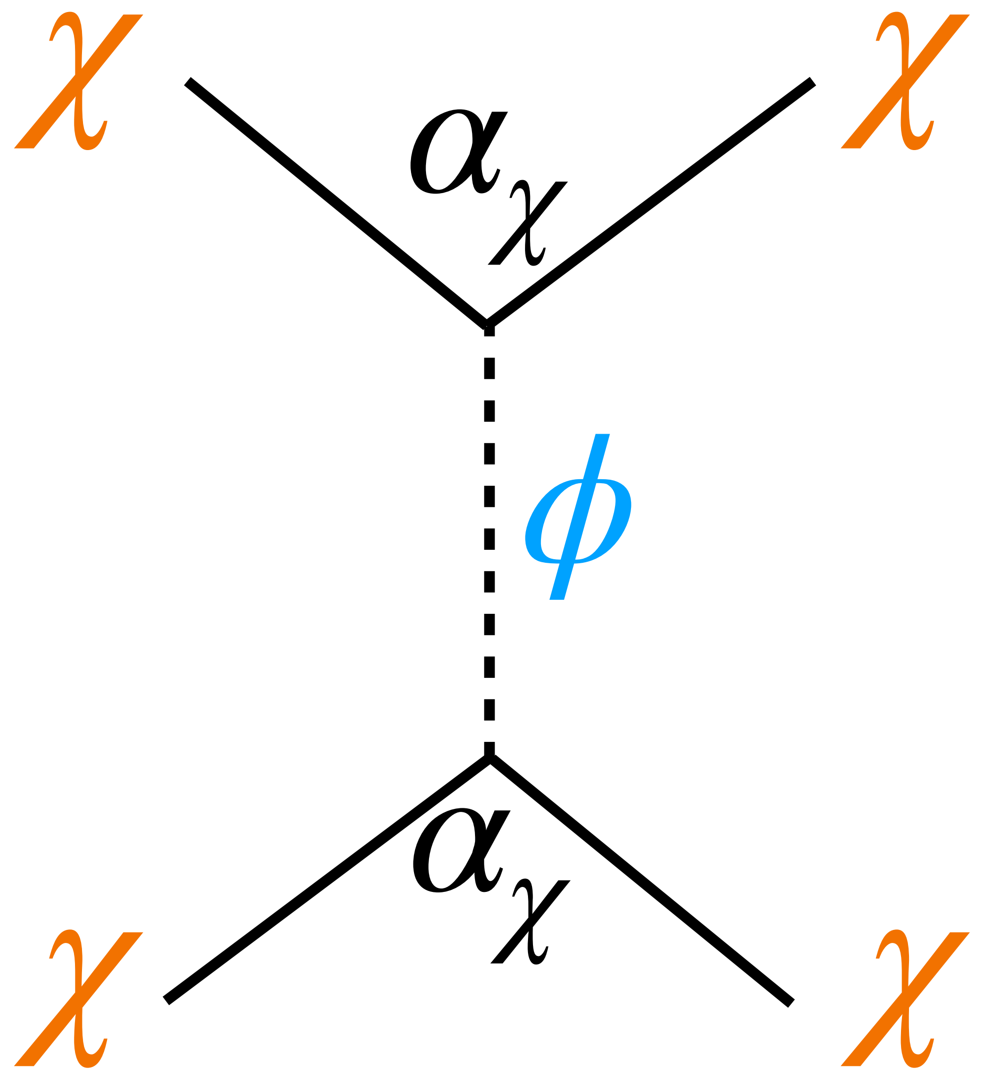
https://camilacorrea.com
twitter: @_astrocamila

Back-up slides

TangoSIDM project. Particle-physics connection



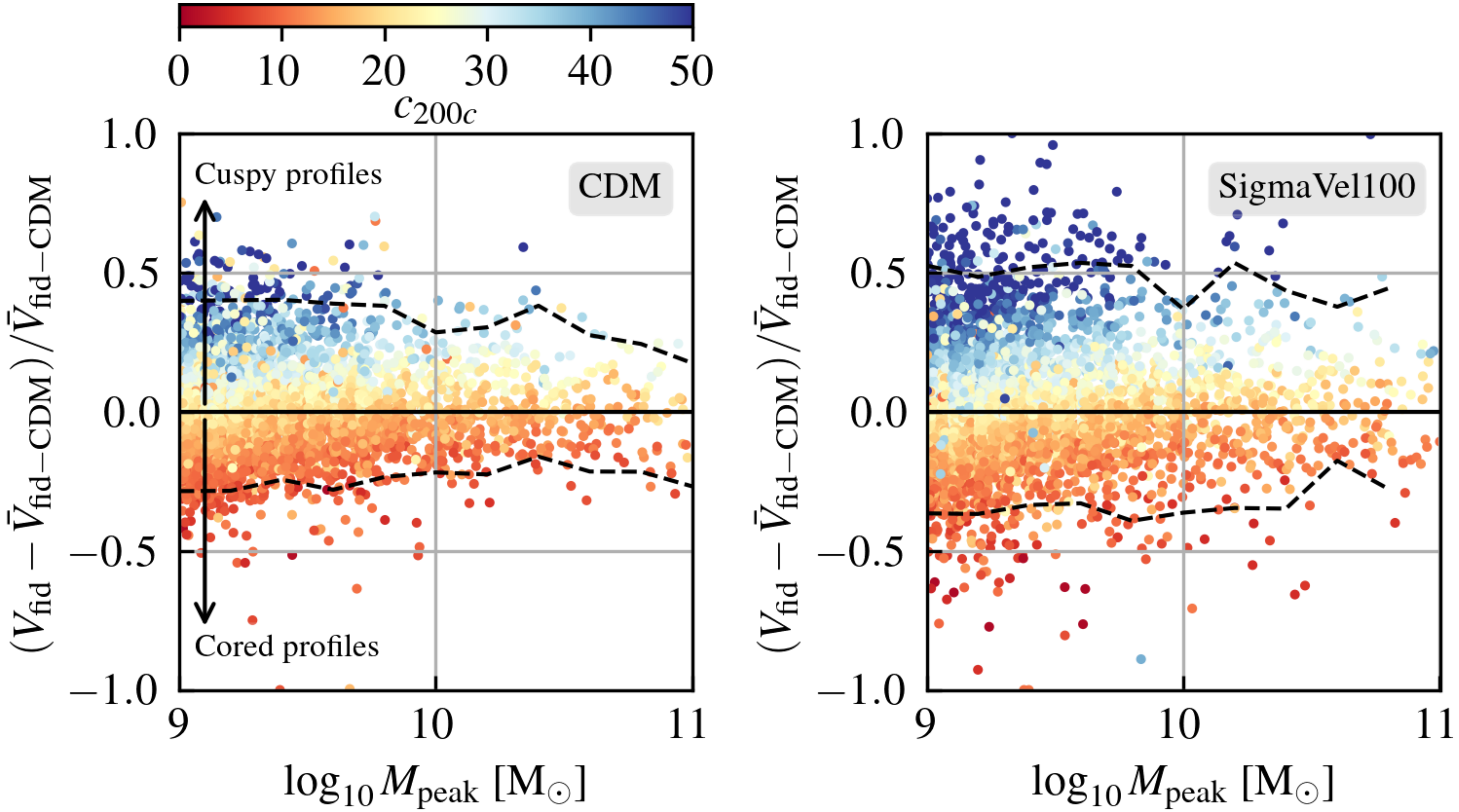
2. Calculated the probability of collision

$$P_{ij} = m_j(\sigma/m)|\mathbf{v}_i - \mathbf{v}_j| g_{ij}(\delta \mathbf{r}_{ij}) \Delta t,$$

- DM particles, χ, interact via a light mediator, ϕ ($m_\phi \ll m_\chi$)
- In the non-relativistic limit, self-interactions can be described by a Yukawa potential: $V(r) = \pm \frac{\alpha_\chi}{r} e^{-m_\phi r}$
- In the perturbative limit ($\alpha_\chi m_\chi / m_\phi \ll 1$), the Born differential cross section is $\frac{d\sigma}{d\Omega} = \frac{\alpha_\chi^2 m_\chi^2}{\left[m_\chi^2 v_{\rm rel}^2 (1-\cos\theta)/2 + m_\phi^2\right]^2}.$

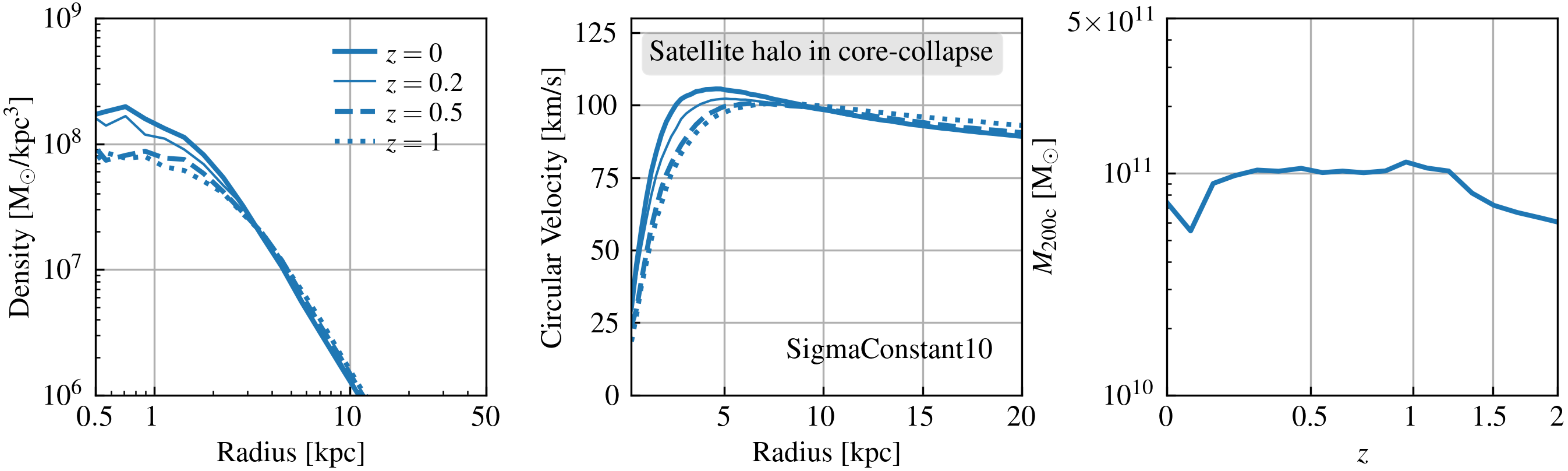
TangoSIDM project. Results

Scatter of circular velocities at fiducial radius from satellite haloes →



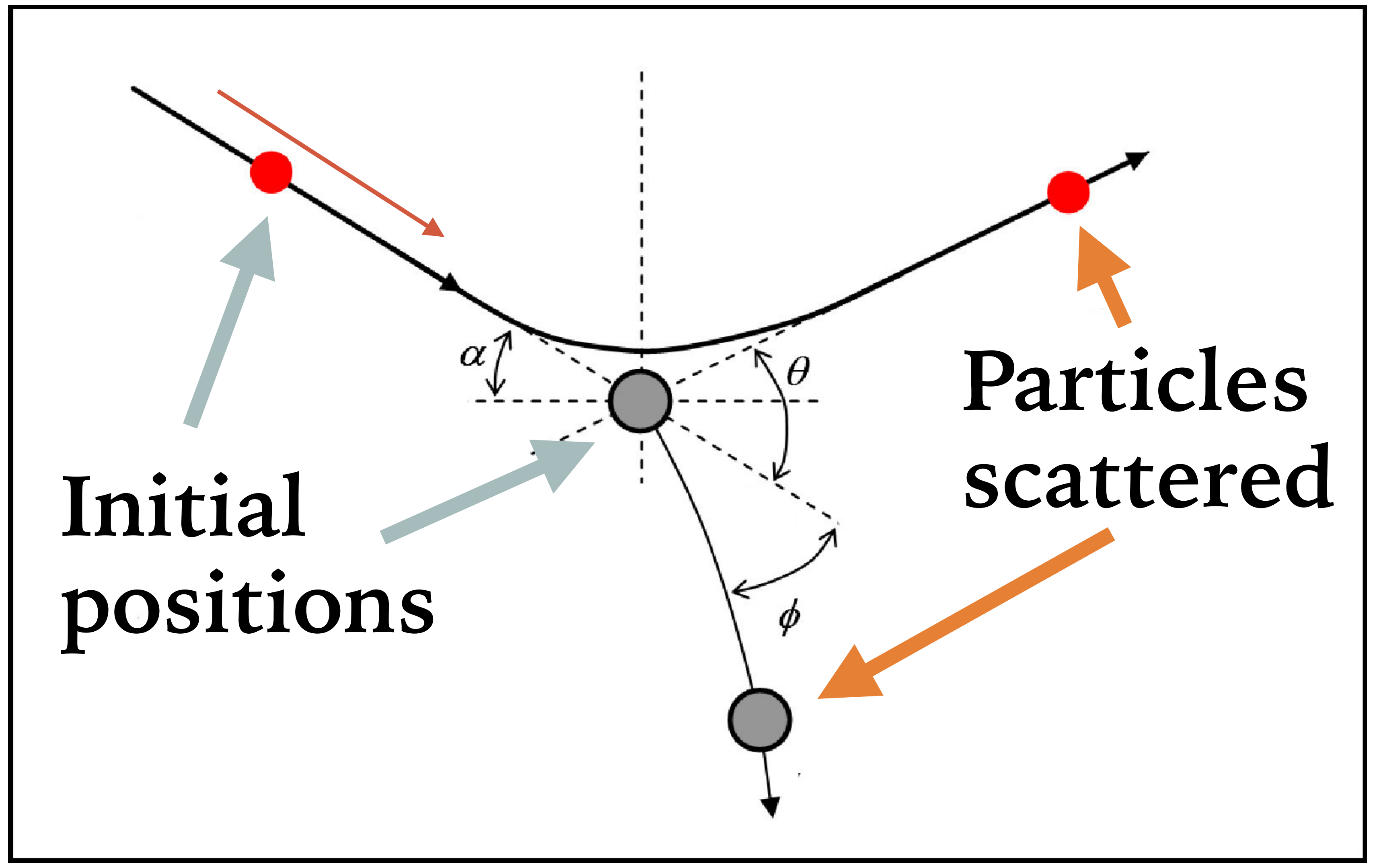
- Velocity-dependent SIDM models in Cosmological DMONLY simulations are able to produce an increased scatter in the rotation curves of haloes relative to CDM Correa et al., arxiv: 2206.11298

TangoSIDM project, gravothermal core-collapse



- Example of satellite halo in gravothermal core collapse

TangoSIDM project. Code development



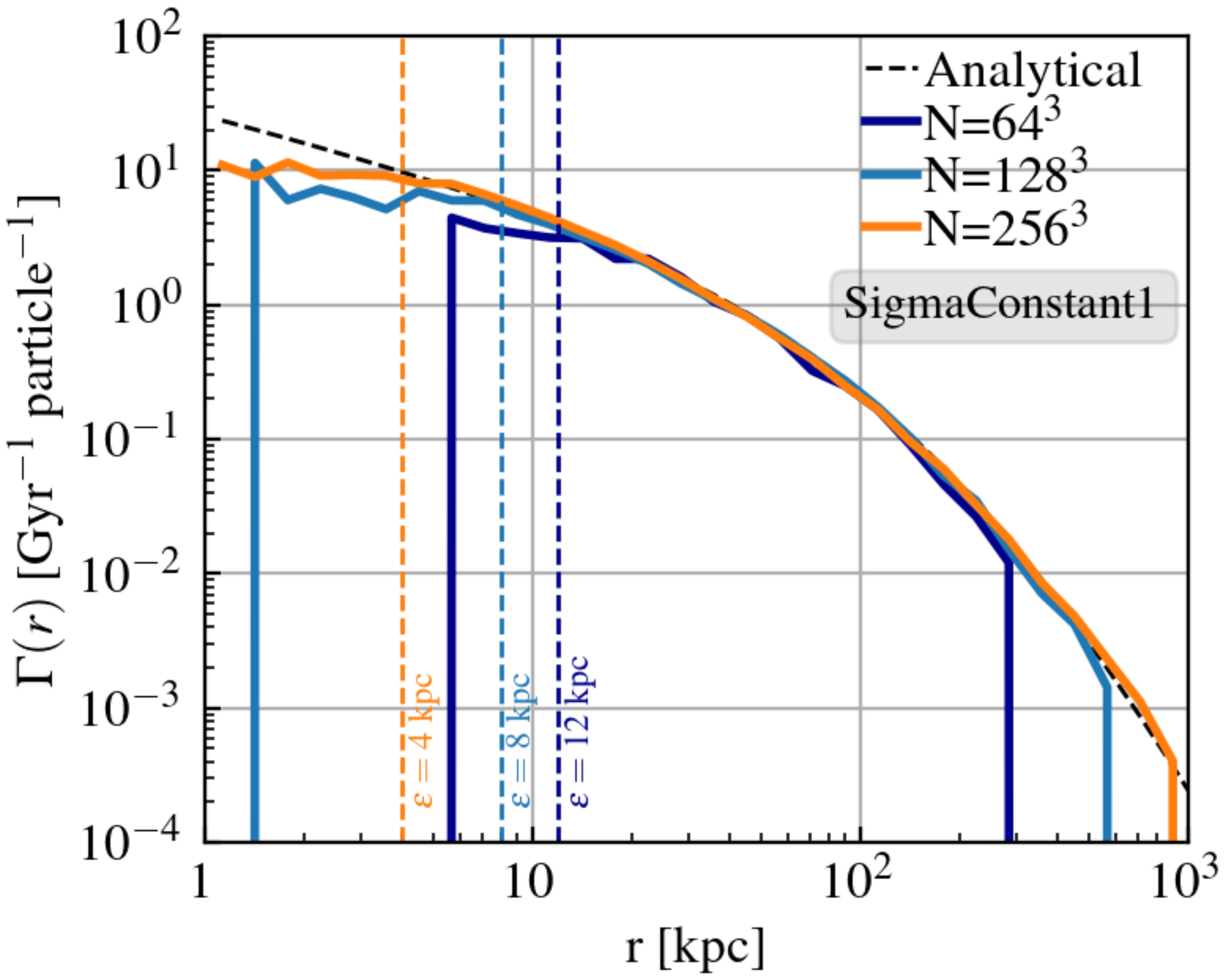
1. We applied a SPH-inspired methodology to search for neighbour particles

2. Calculated the probability of collision

$$P_{ij} = m_j(\sigma/m)|\mathbf{v}_i - \mathbf{v}_j| g_{ij}(\delta\mathbf{r}_{ij})\Delta t,$$

$$g_{ij}(\delta\mathbf{r}_{ij}) = N \int_0^{\max(h_i,h_j)} d^3\mathbf{r}' W(|\mathbf{r}'|, h_i) W(|\delta\mathbf{r}_{ij} + \mathbf{r}'|, h_j),$$

TangoSIDM project. Code development



1. We applied an SPH-inspired methodology to search for neighbour particles

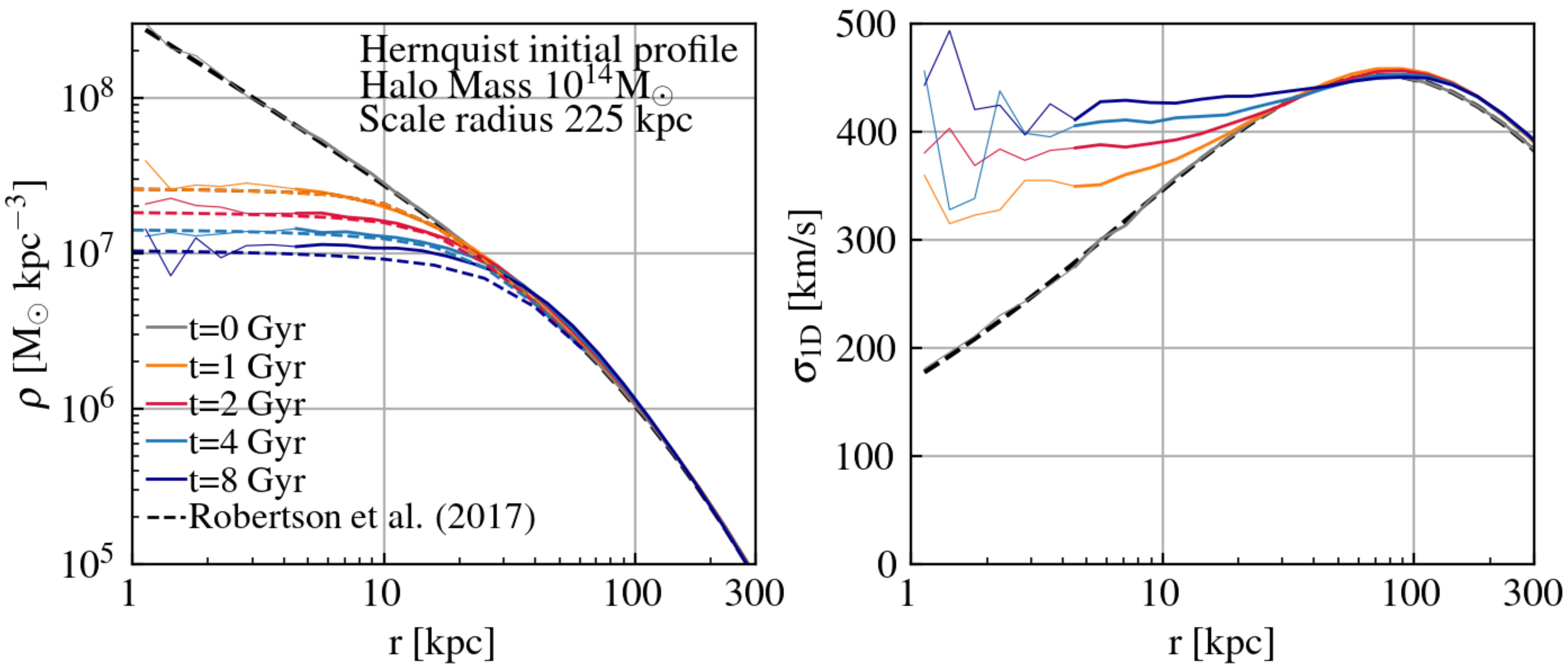
2. Calculated the probability of collision

$$P_{ij} = m_j(\sigma/m)|\mathbf{v}_i - \mathbf{v}_j| g_{ij}(\delta\mathbf{r}_{ij})\Delta t,$$

$$g_{ij}(\delta\mathbf{r}_{ij}) = N \int_0^{\max(h_i,h_j)} d^3\mathbf{r}' W(|\mathbf{r}'|, h_i) W(|\delta\mathbf{r}_{ij} + \mathbf{r}'|, h_j),$$

3. Tested it for an isolated halo with particle-collisions disabled.

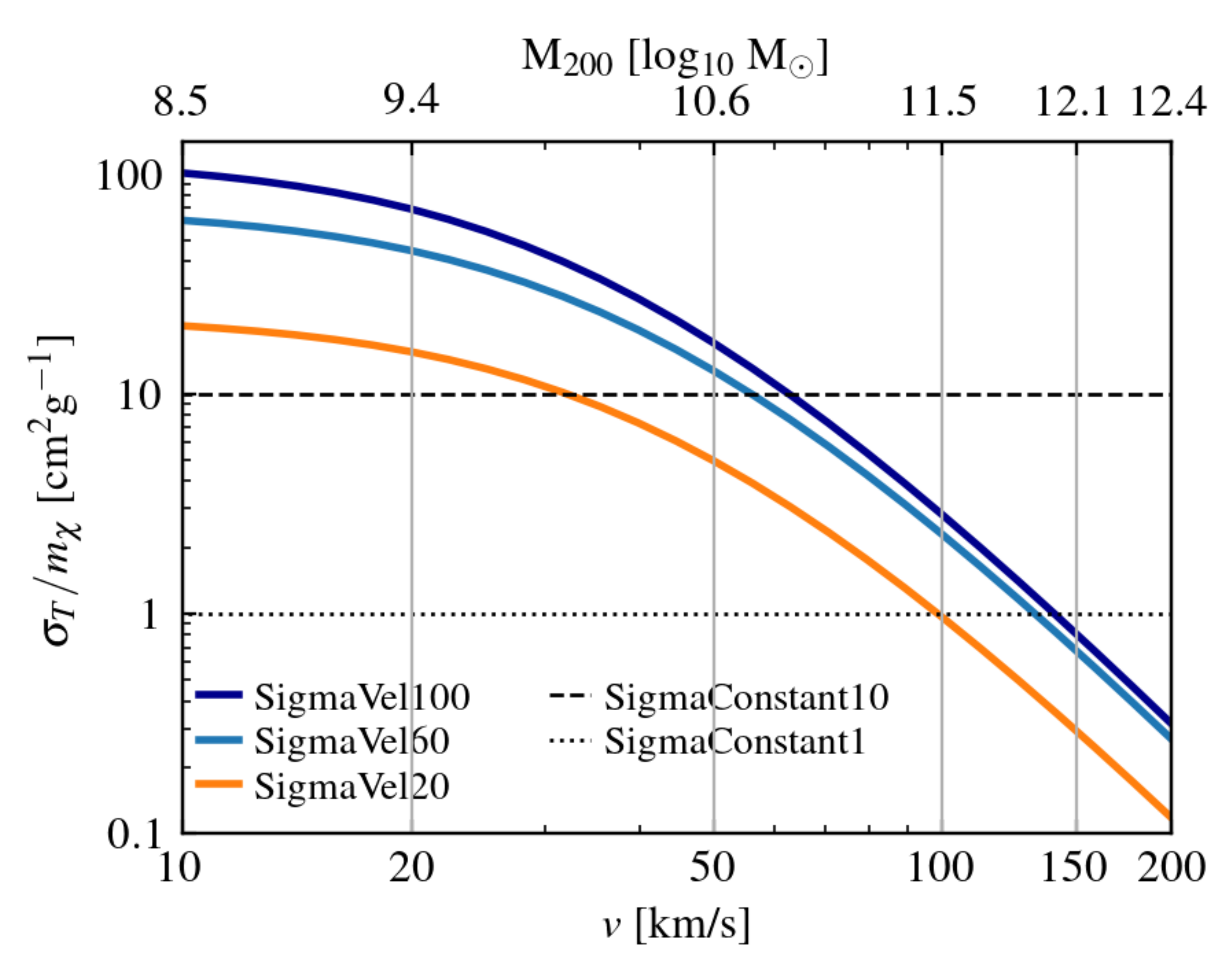
TangoSIDM project. Code development



Example of $10^{14} M_\odot$ Hernquist halo after 1, 2, 4 and 8 Gyrs, comparing with the evolution reported by Robertson et al. (2017) for a similar setup.

TangoSIDM project. Code development

TangoSIDM project: Tantalising models of SIDM



Volumes of $(25\ \text{Mpc})^3$ with 752^3 particles, and resolution:

$$m_{\rm DM} = 1.44 \times 10^6 M_\odot,\ \epsilon = 650\ \text{pc}$$

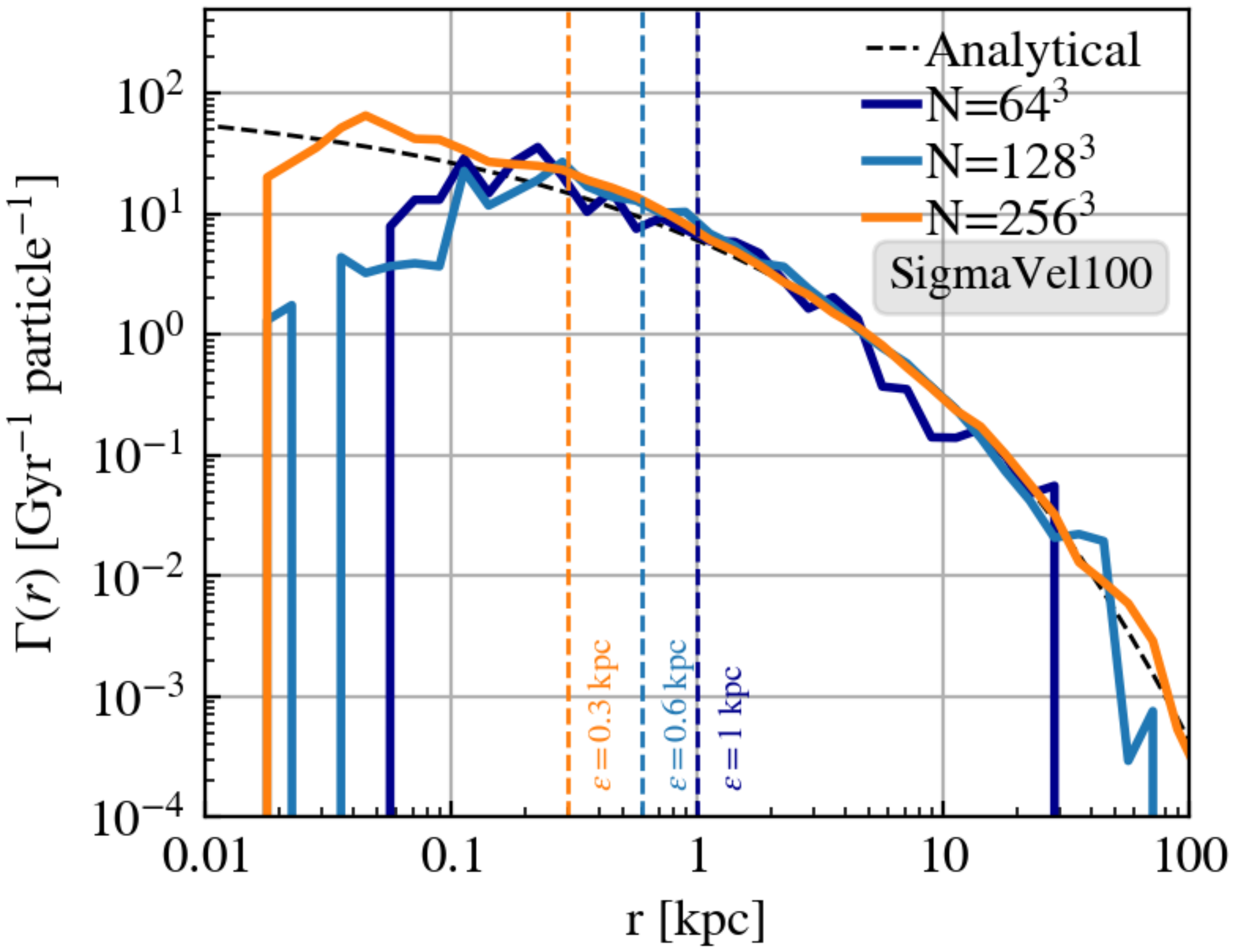
Simulation Name	SIDM parameters m_χ [GeV]	m_ϕ [MeV]	α	DM interaction
CDM	/	/	/	No interaction
SigmaConstant1	/	/	/	Isotropic
SigmaConstant10	/	/	/	Isotropic
SigmaVel20	3.056	0.309	1.23×10^{-5}	Anisotropic
SigmaVel60	3.855	0.356	1.02×10^{-5}	Anisotropic
SigmaVel100	4.236	0.350	4.96×10^{-6}	Anisotropic

Project collaborators:

Matthieu Schaller, Sylvia Ploeckinger, Noemi Anau Montel, Shinichiro Ando & Christoph Weniger

This work on arxiv !
https://arxiv.org/abs/2206.11298

TangoSIDM project. Code development



1. We applied an SPH-inspired methodology to search for neighbour particles

2. Calculated the probability of collision

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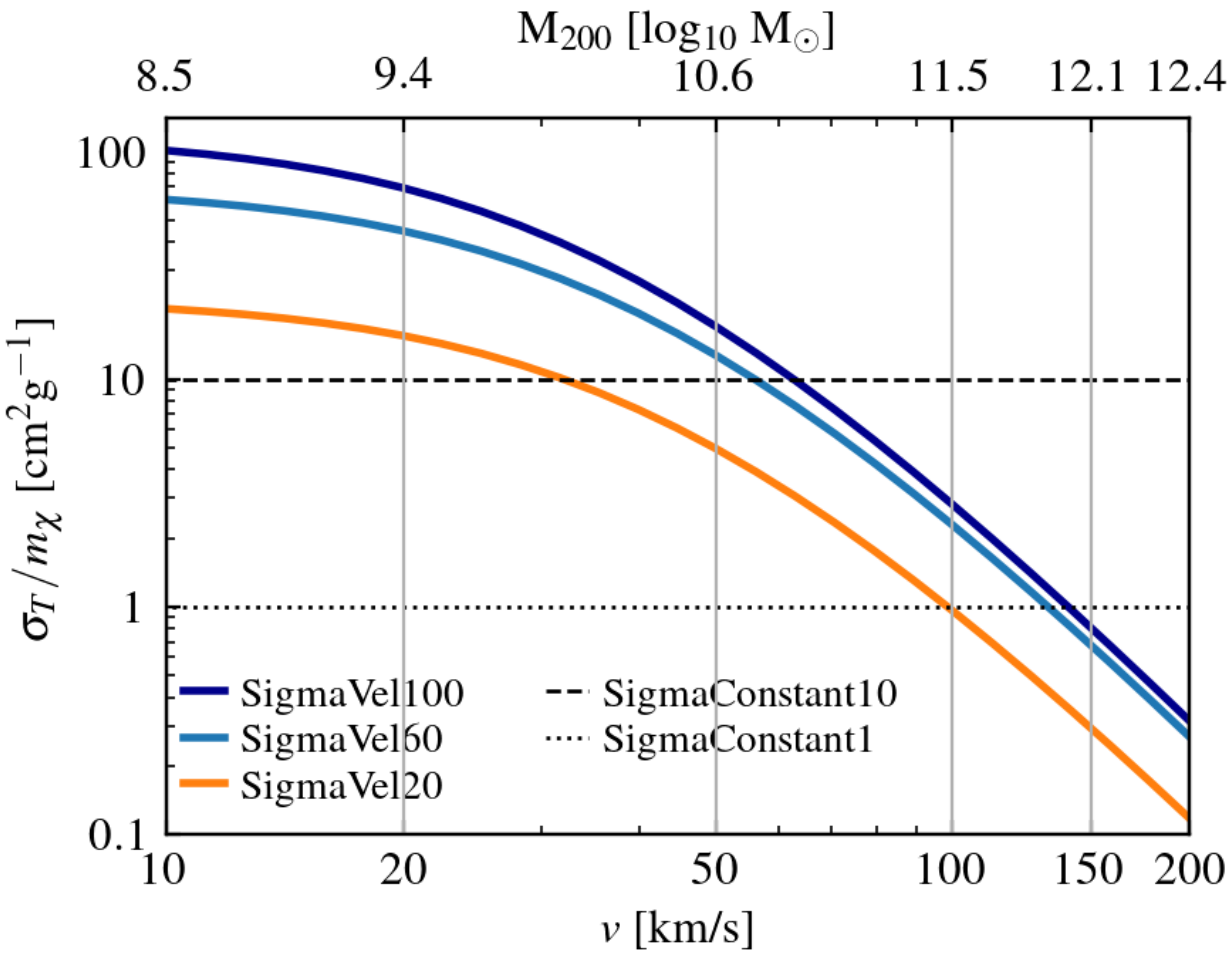
3. Tested it for an isolated halo with particle-collisions disabled. See example of velocity-dependent cross-section

TangoSIDM project. Particle-physics connection



2. Calculated the probability of collision

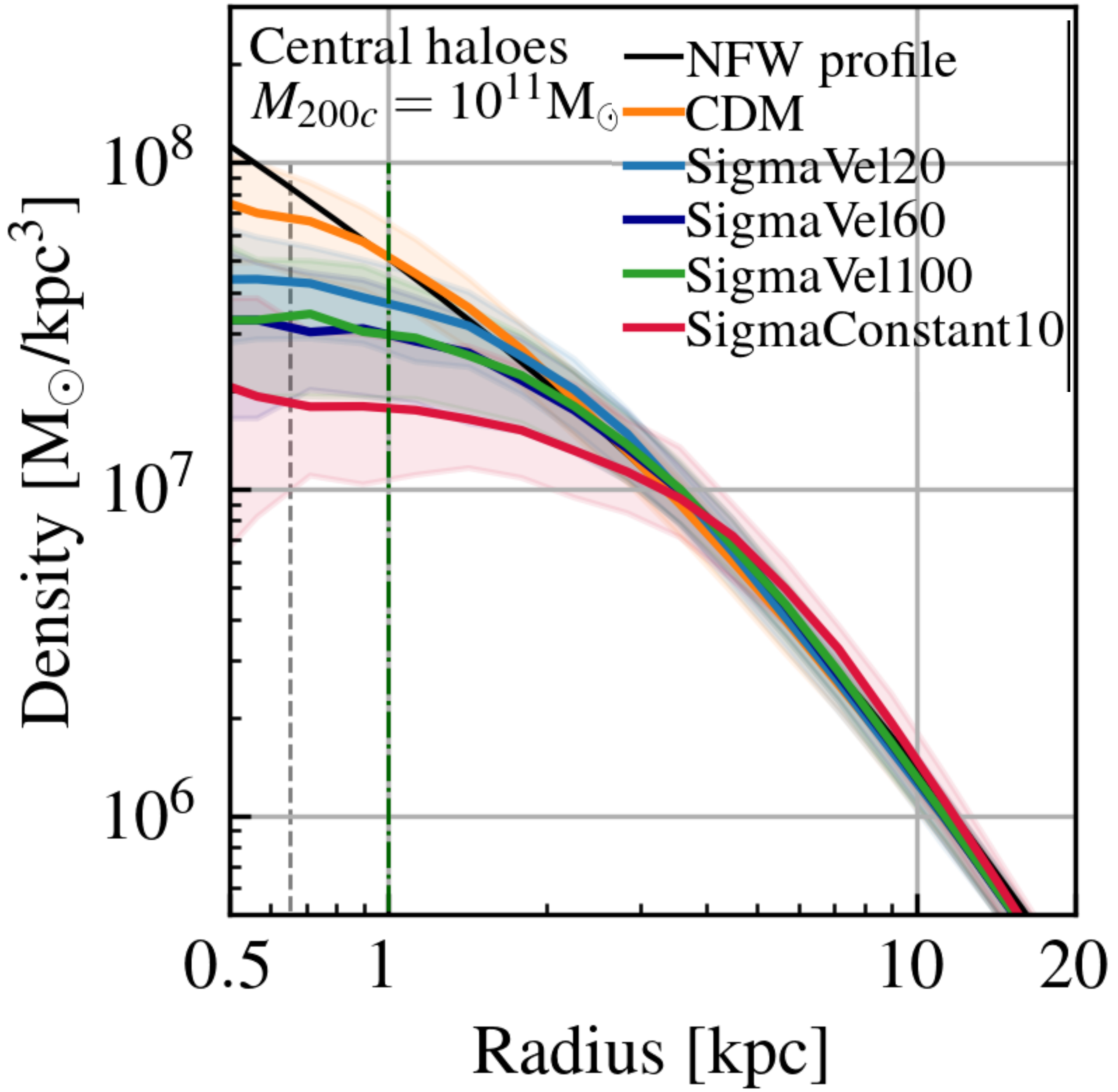
$$P_{ij} = m_j(\sigma/m)|\mathbf{v}_i - \mathbf{v}_j|g_{ij}(\delta\mathbf{r}_{ij})\Delta t,$$

$$V(r) \pm \frac{\alpha_{\rm DM}}{r}e^{-m_\theta r}$$

$$\sigma \rightarrow \frac{\alpha_{\rm DM}^2 m_{\rm DM}^2}{[m_{\rm DM}^2 v^2(1-\cos\theta)/2 + m_\theta^2]^2}$$

TangoSIDM project. Results

- Dark matter haloes form cores

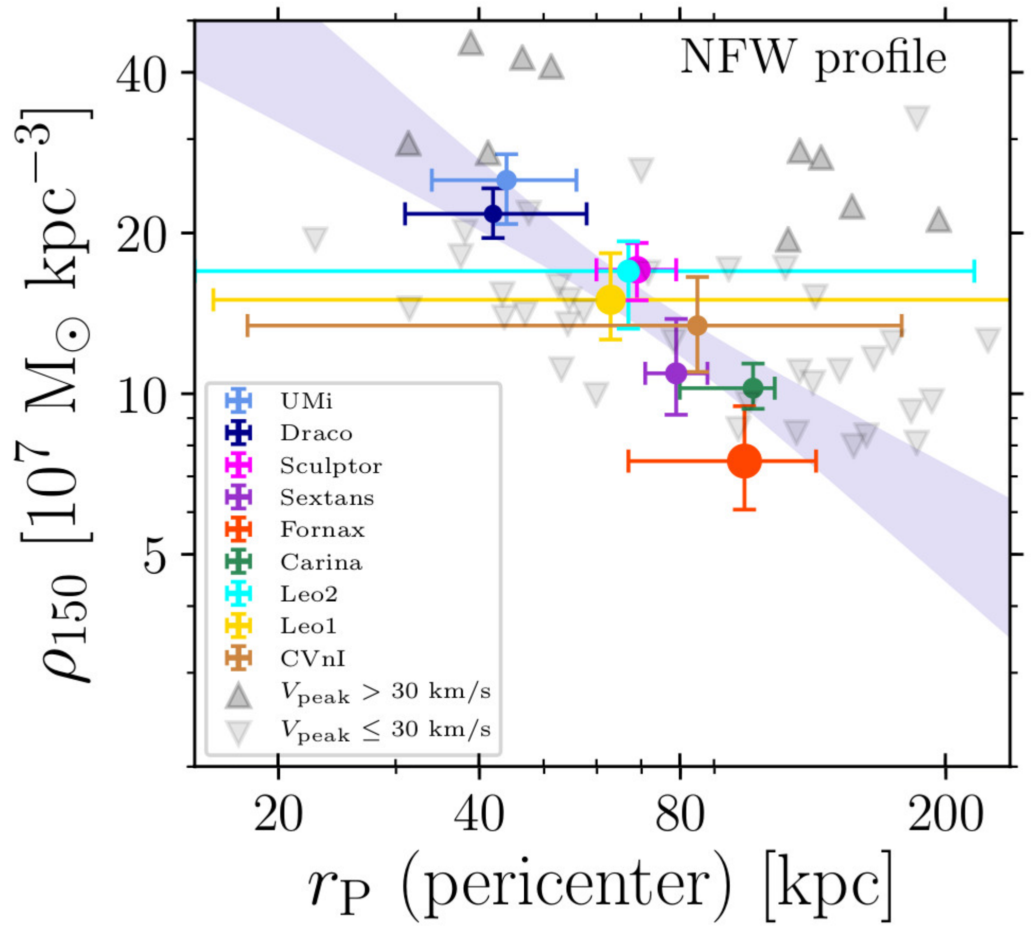


TangoSIDM project. Results

- Dark matter haloes change shape under various SIDM models

SIDM Halo Model - Correa (2021)

Road map



← $\rho_{DM}(r, t)$ ← **Gravitational tidal stripping** ← **Galactic orbit integration**

↑ **Gravothermal Fluid approximation**

↑

$$\rho_{DM,ini}(r) \; + \; \sigma/m_\chi$$

t_{ini} = 3.5 Gyr (redshift = 1.87)

↑ Orbital parameters from Gaia mission (Helmi et al. 2018, Fritz et al. 2018)

$$d_{GC}, \; v_R, \; v_T$$

SIDM Halo Model - Correa (2021)

Fluid approximation

$$\frac{\partial m}{\partial r} = 4\pi r^2 \rho,$$

$$\frac{\partial(\rho v^2)}{\partial r} = -\frac{Gm\rho}{r},$$

$$\frac{L}{4\pi r^2} = -\kappa\frac{\partial T}{\partial r},$$

$$\frac{\partial L}{\partial r} = -4\pi r^2 \rho v^2 \left(\frac{\partial}{\partial t}\right)_m \log\left(\frac{v^3}{\rho}\right),$$

$$\rightarrow \frac{L}{4\pi r^2} \propto t_{smfp} + t_{lmfp} \rightarrow \frac{L}{4\pi r^2} = -\frac{3}{2}b\rho v\left[\left(\frac{1}{\lambda}\right) + \left(\frac{v t_r}{CH^2}\right)\right]^{-1}\frac{\partial v^2}{\partial r},$$

Relaxation time:

$$t_r = \lambda/(av)$$

Collisional scale for mean free path:

$$\lambda = 1/(\rho[\sigma/m_\chi])$$

Balberg, Shapiro & Inagaki (2001), Balberg & Shapiro (2002), Koda & Shapiro (2011), Shapiro (2018)

SIDM Halo Model - Correa (2021)

Gravitational tidal stripping

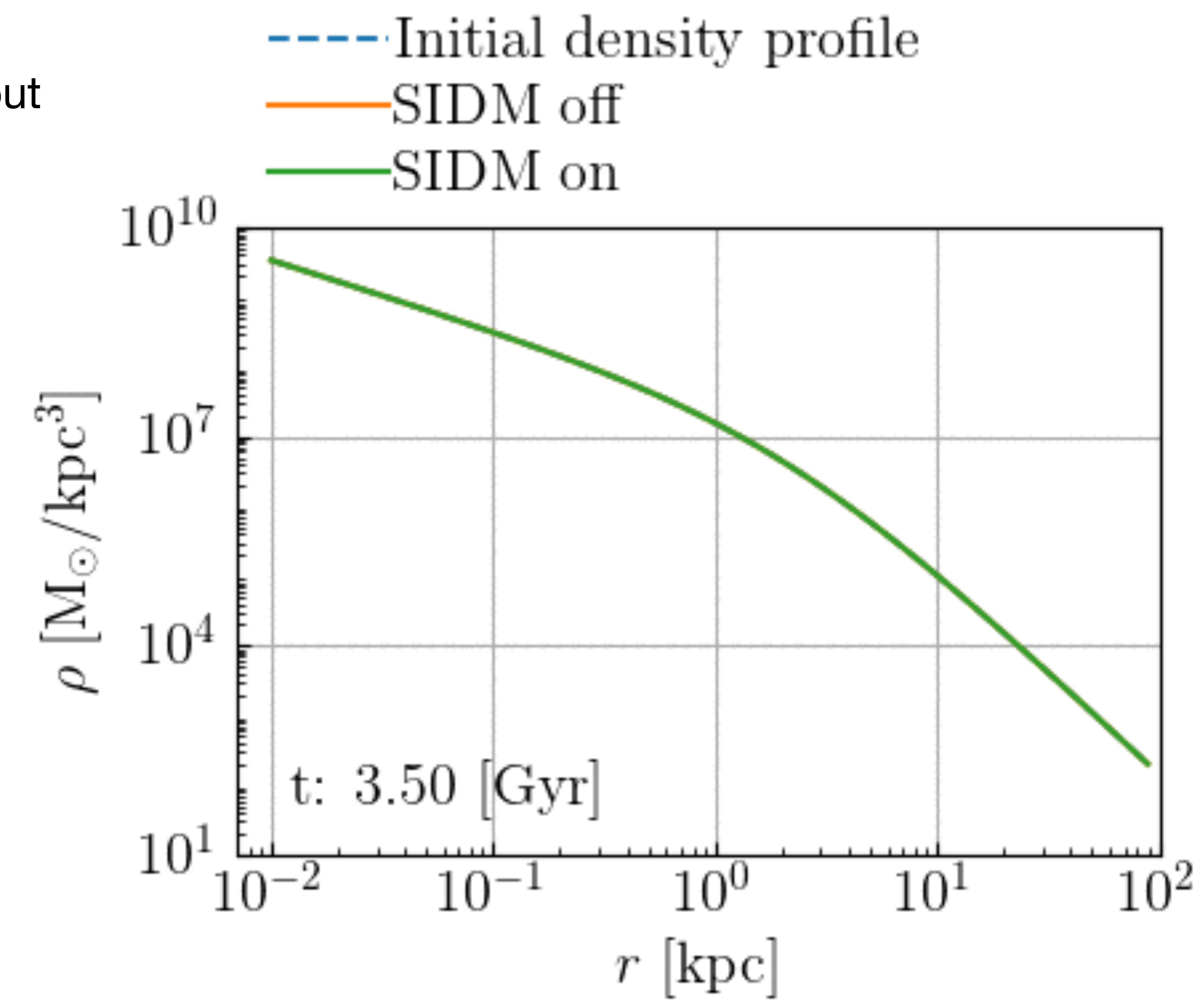
I adopt the following tidal stripping rate:

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \frac{m(>r_t)}{\tau_{\mathrm{orb}}/\alpha}$$

e.g. King 1962; Tollet et al. (2017); but see van den Bosch et al. (2018)

+ transfer function from Green & van den Bosch (2019):

$$\rho(r, t_n) = \rho(r, t_{n-1}) \times H(r, t_n, f_b, c_{200}(t_{n-1}))$$



SIDM Halo Model - Correa (2021)
Initial conditions

Name	Orbital parameters d_{GC} [kpc]	v_R [km/s]	v_T [km/s]	$M_{200,\mathrm{init}}$ [10^9 M$_\odot$]	Initial Conditions $c_{200,\mathrm{init}}$	$\rho_{s,\mathrm{init}}$ [10^7 M$_\odot$/kpc^3]	$r_{s,\mathrm{init}}$ [kpc]	σ/m_χ
UM	78	−71	136	0.60	6.87	1.84	1.30	?
Draco	79	−89	134	3.46	6.36	1.54	2.52	
Carina	105	2	163	2.13	6.53	1.62	2.09	
Sextans	89	79	229	0.67	6.99	1.83	1.34	
CvnI	211	82	94	1.09	6.68	1.73	1.63s	
Sculptor	85	75	184	4.74	6.28	1.49	2.82	
Fornax	141	−41	132	3.54	6.38	1.53	2.54	
LeoII	227	20	74	0.14	7.30	2.13	0.76	
LeoI	273	167	72	3.23	6.40	1.55	2.44	

taken from Fritz et al. (2018)

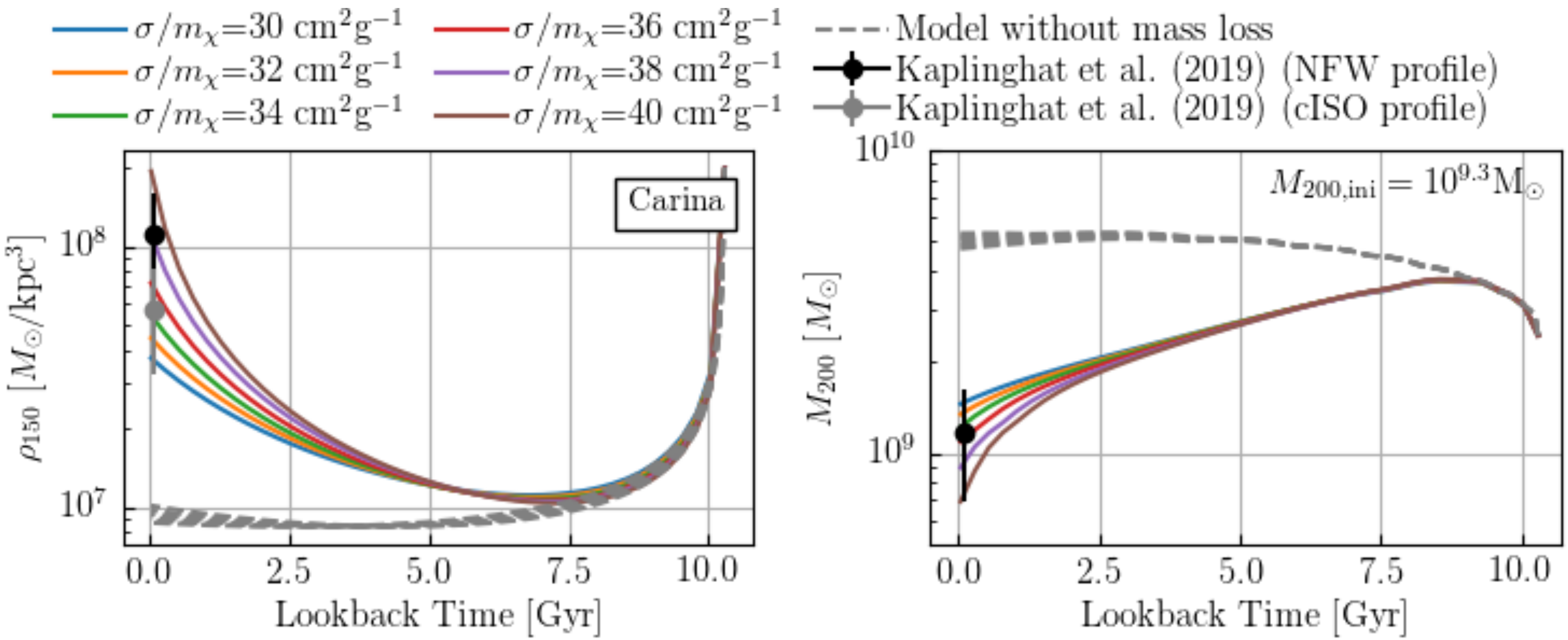
$z = 1.87, t = 3.5$ Gyr

$$\log_{10} c_{200}(M_{200}, z) = \alpha(z) + \beta(z)\log_{10}(M_{200}/\mathrm{M}_\odot) \times [1 + \gamma(z)(\log_{10} M_{200}/\mathrm{M}_\odot)^2], \quad (12)$$

Correa et al. (2015a,b,c)

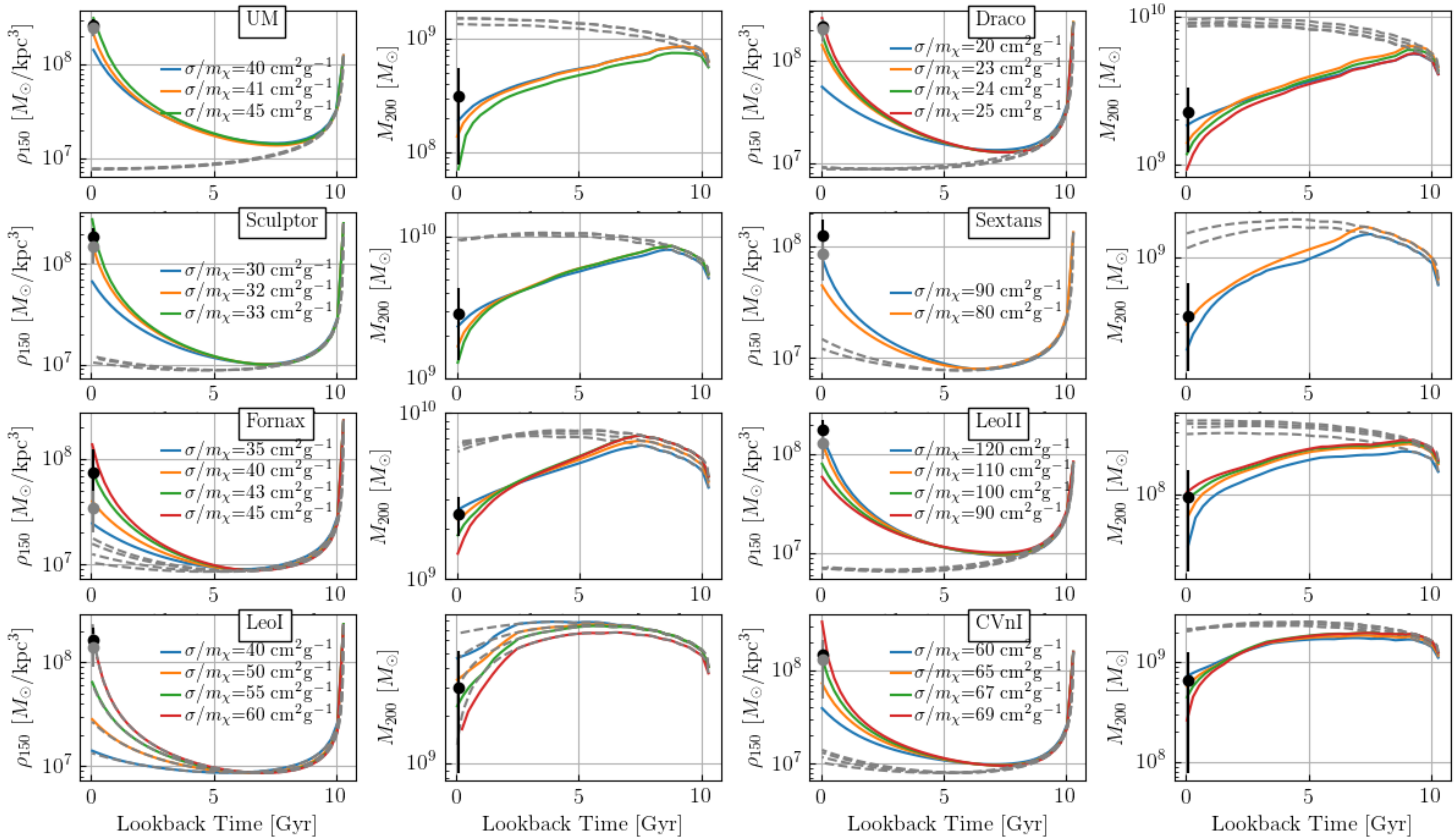
Results - Correa (2021)

Central density evolution - Carina



Results - Correa (2021)

Central density evolution - all



Results - Correa (2021)

Velocity-dependent cross section