CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Velocity dependent self-interacting dark matter in galaxy cluster mergers

[2310.07769]

Sabarish V. M.

University of Hamburg

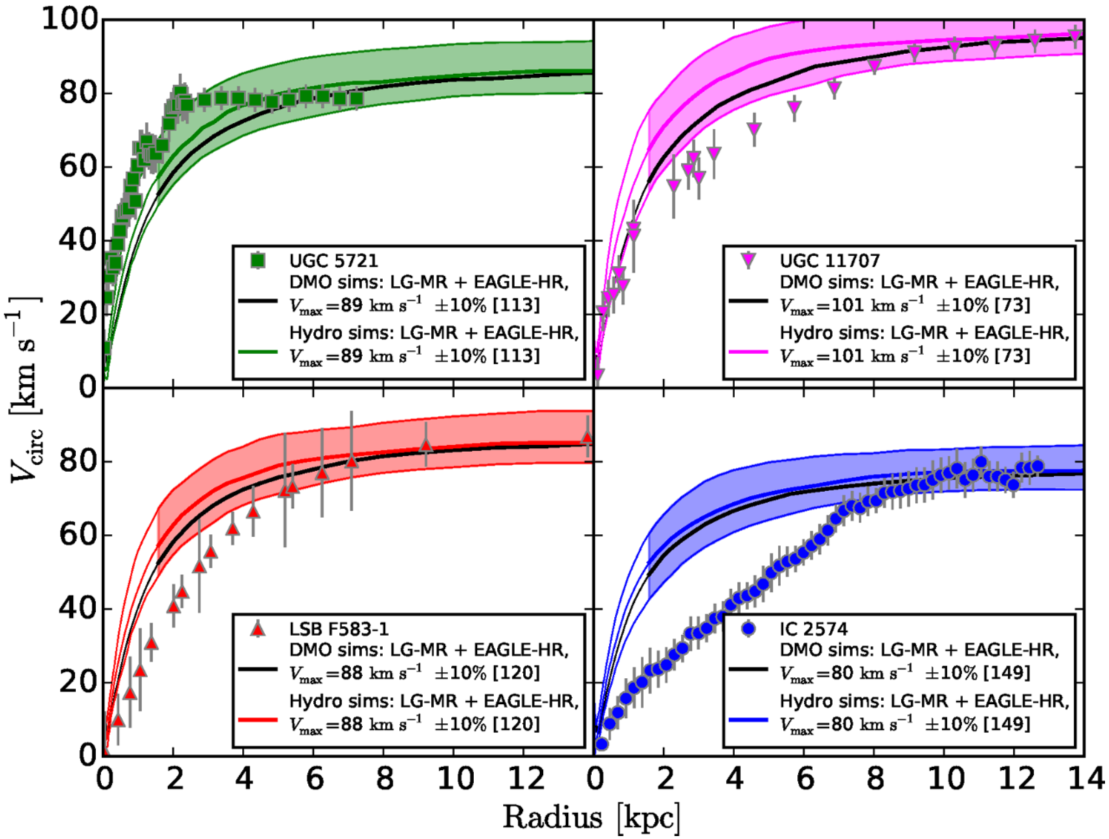
sabarish.venkataramani@uni-hamburg.de

Collaborators : Marcus Brüggen, Kai-Schmidt Hoberg, Moritz Fischer, Felix Kahlhoefer

Outline

- Motivation for velocity-dependent SIDM.
- N-Body simulations of angular and velocity dependant self-interactions.
- Galaxy cluster merger simulations.
- Results.

Diversity problem

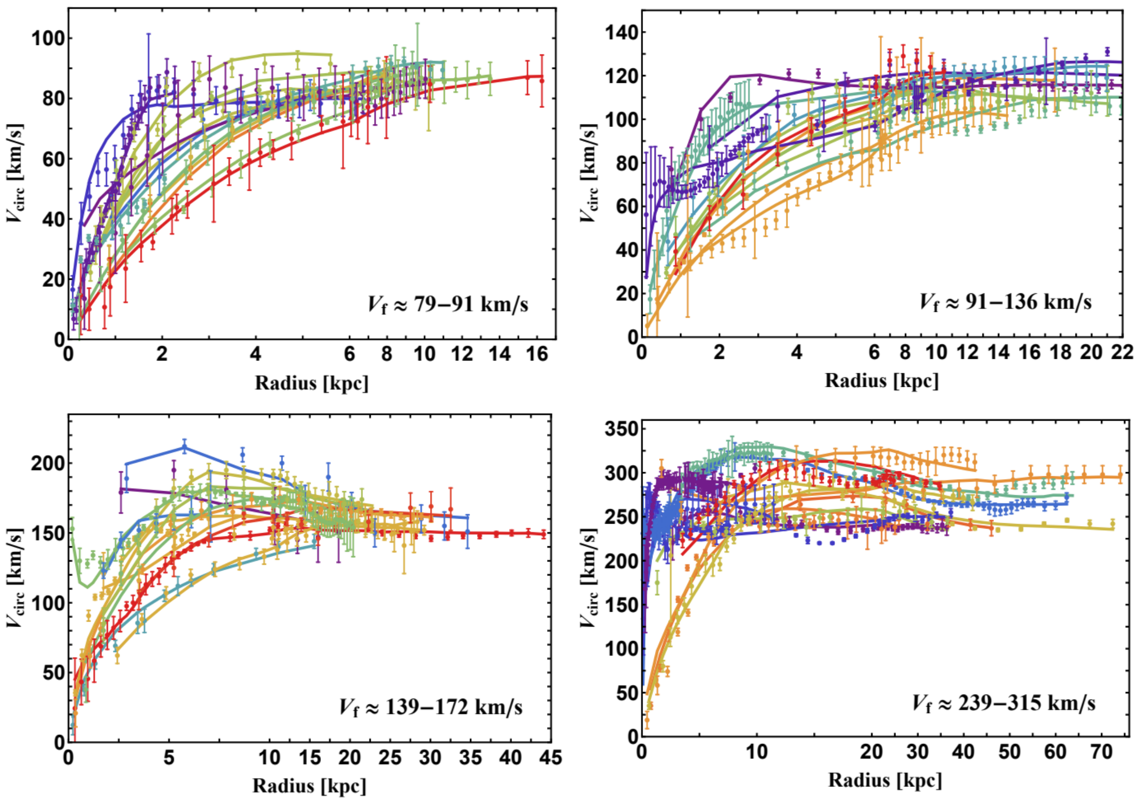


[Oman et. al 1504.01437]

- Approximately the same $V_{\max}$
- Rotation curves are diverse
- $\Rightarrow$ Diverse density profiles

$$V(r) \propto \sqrt{GM(r)/r}$$

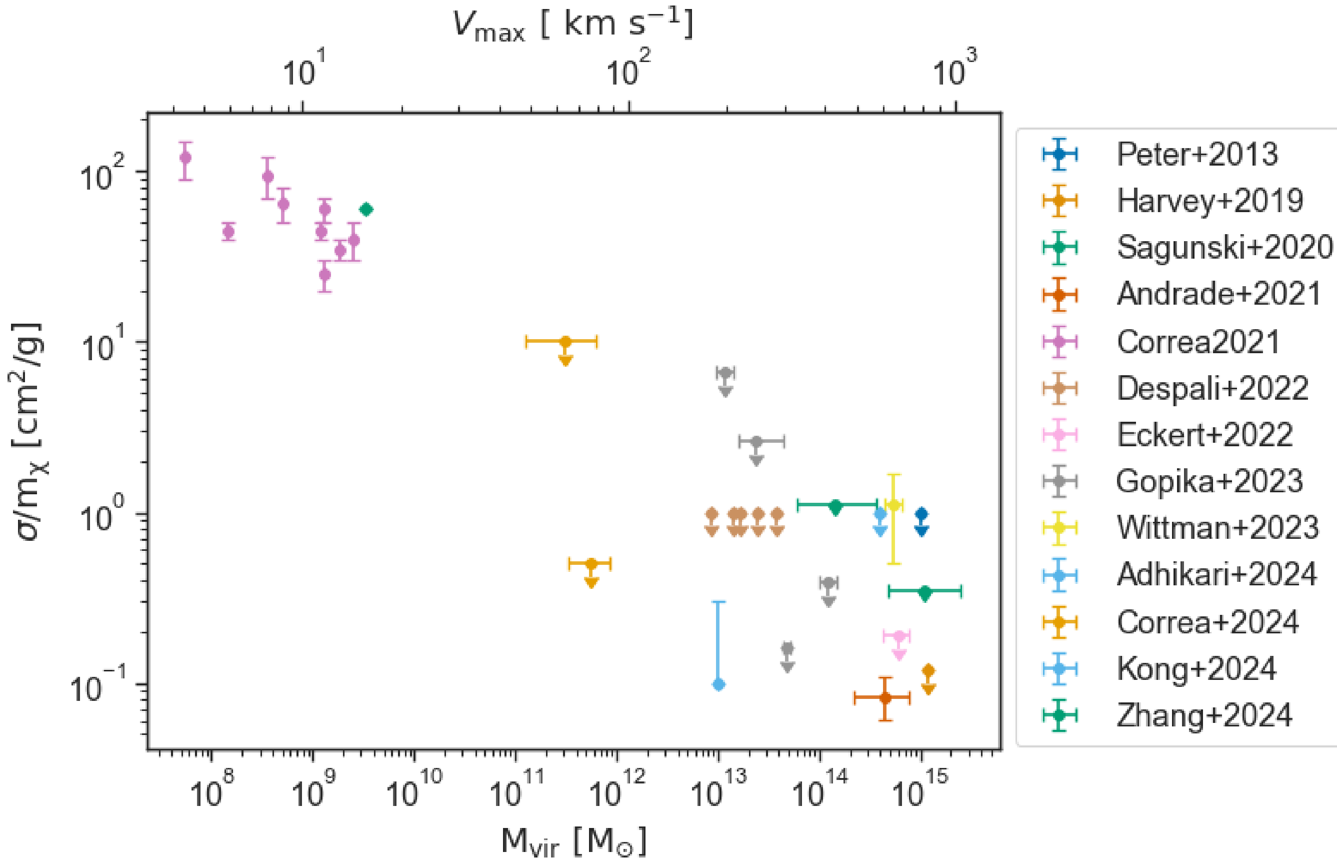
Diversity problem with SIDM



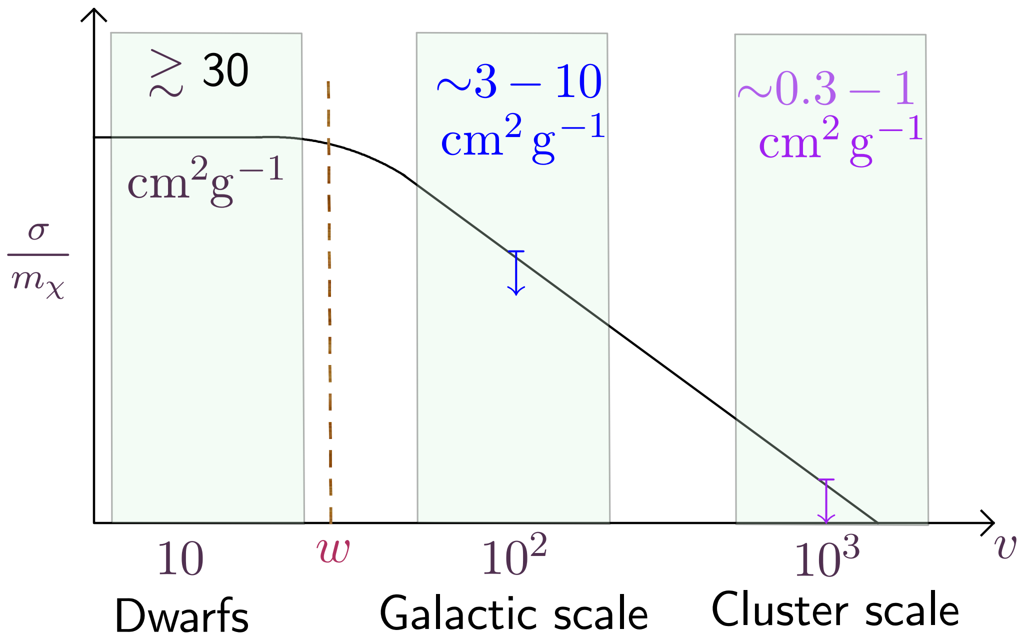
[Ren et. al 1808.05695]

- 125 Galaxies from SPARC
- $\sigma/m = 3 - 10\,\mathrm{cm}^2\mathrm{g}^{-1}$
- Fitting SIDM density profile parameters

Existing constraints



Connecting the dots - Velocity dependance



- Solid line - Generic form

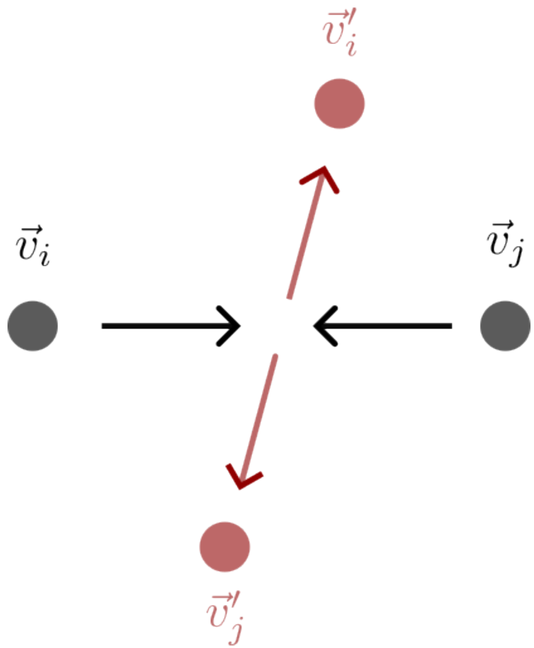
$$\sigma_{0m}\left(1+\frac{v^2}{w^2}\right)^{-2}$$

[Gilman et al. 2207.13111] , [Yang et al. 2205.02957]

Angular Dependence

Angular dependance - Isotropic case (rare.)

- Standard implementation for SIDM [Adhikari et. al 2207.10638]



- Scattering probability,

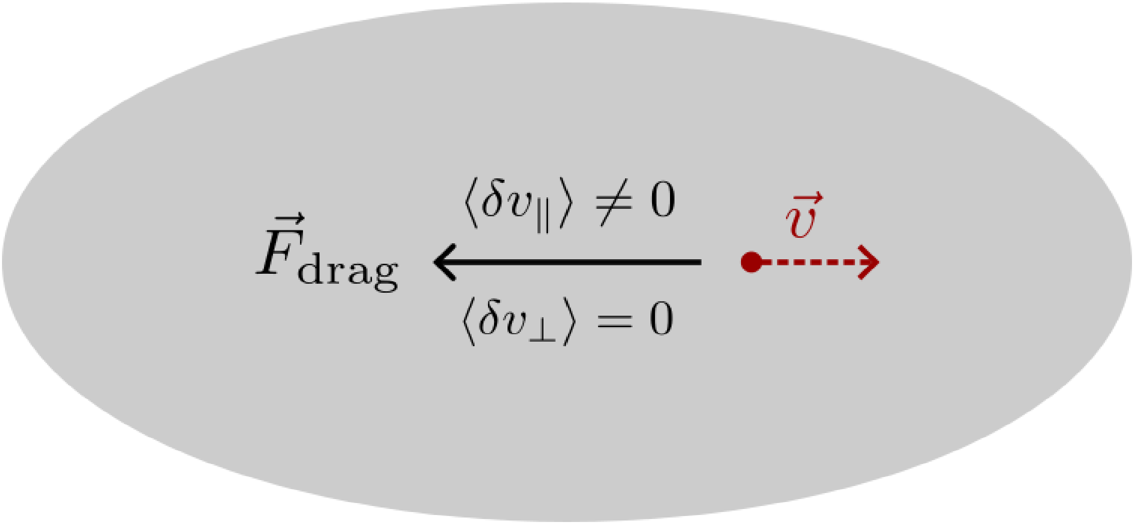
$$P_{ij} \propto \frac{\sigma_{\text{Tot}}}{m_{\text{DM}}} \Delta t$$

- Computationally expensive for SIDM models with,

$$\sigma_{\text{Tot}} \to \infty, \text{ leads to } \Delta t \to 0$$

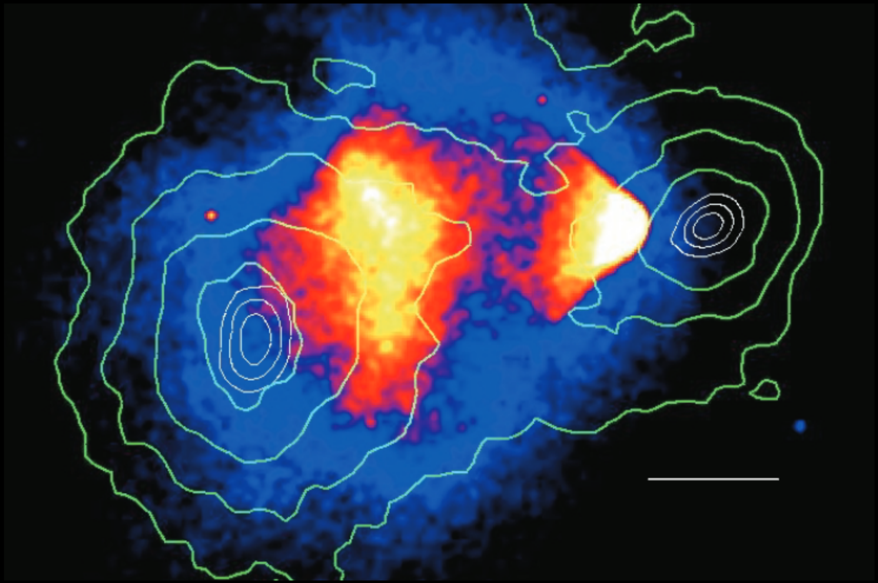
Angular Dependence - Strongly ansiotropic (frequent.)

Effective description of self-interactions as given in [Kahlhoefer et al. 1308.3419]

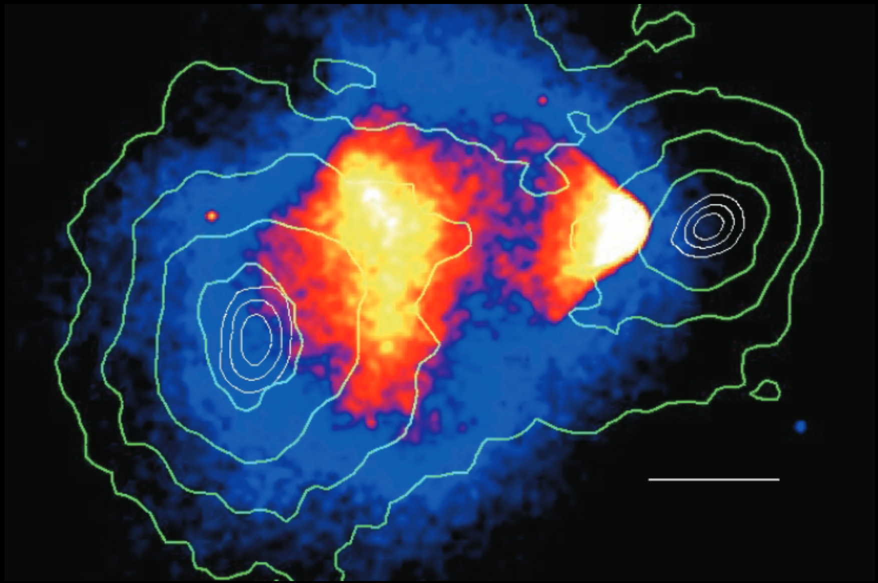


- Strongly anisotropic cross-sections
- Drag force leads to deceleration of the DM particle
- $R_{\rm dec} = \frac{\rho v \sigma_T}{2 m_{\rm DM}}$
- Implemented in OPEN-GADGET3 [Fischer et. al 2012.10277]

Galaxy Cluster Mergers



Galaxy cluster Mergers



- Qualitative features in velDep mergers !
- Is it possible to have observable offsets given the current bounds ?

Setup :

- Simulations with 10^6 particles
- DM, Gal, BCG

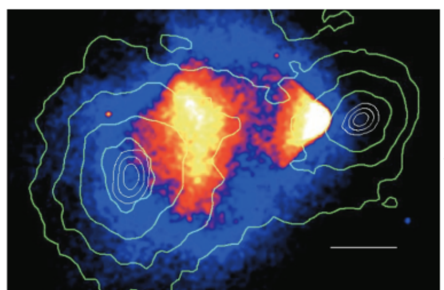
Methodology

$\sigma_{\mathrm{Tot}} = 0.35\ \mathrm{cm^2 g^{-1}}$

(Velocity-independence & isotropy)

Anisotropic-SIDM + $(\sigma_{0\mathrm{m}}, w)$

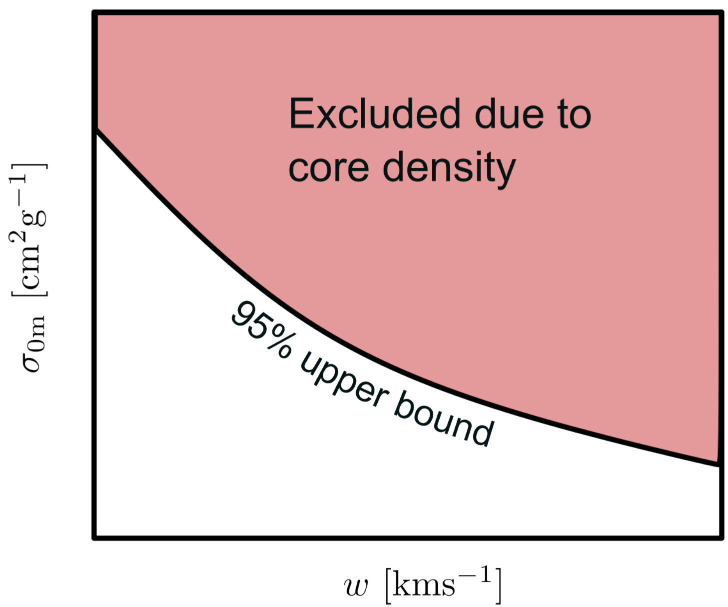
Isotropic-SIDM + $(\sigma_{0\mathrm{m}}, w)$



How large of an offset ?

Mapping the constraint-I

- Stringent bounds from core densities [Sagunski et al. 2006.12515, Andrade et al. 2012.06611]
- Simulate isolated haloes with velocity dependence that has similar central density.



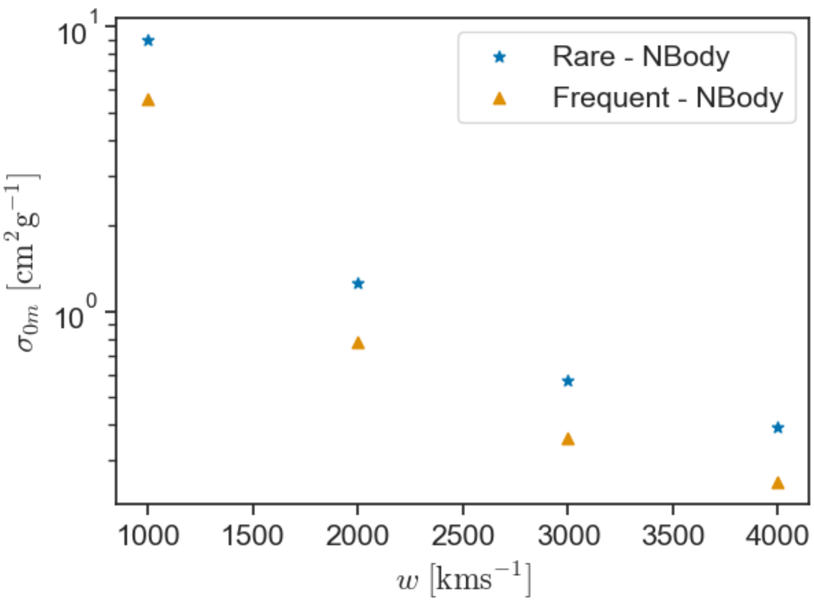
At a given w,

$\sigma_{0m} \uparrow \implies \rho_{\mathrm{core}} \downarrow$

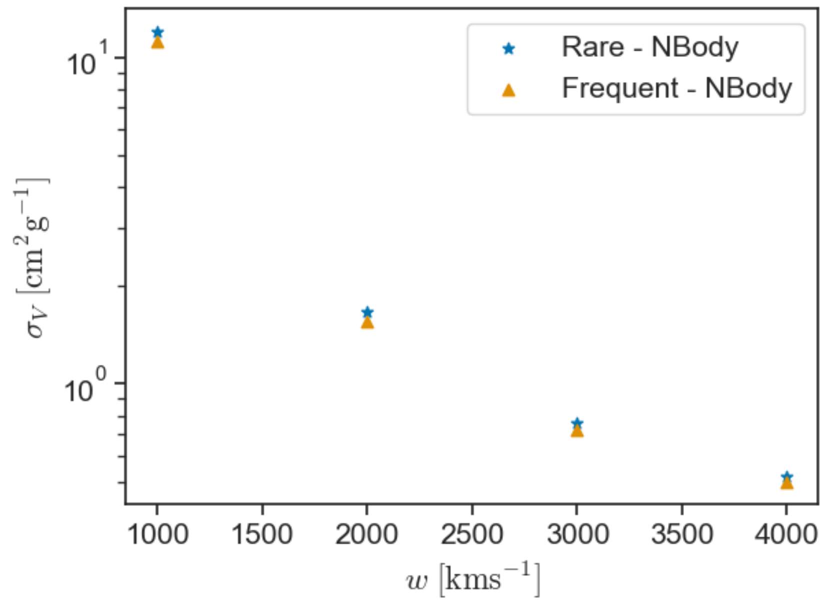
$\sigma_{0m} \uparrow \implies d_{\mathrm{DM-BCG}} \uparrow$

Mapping the constraint-II

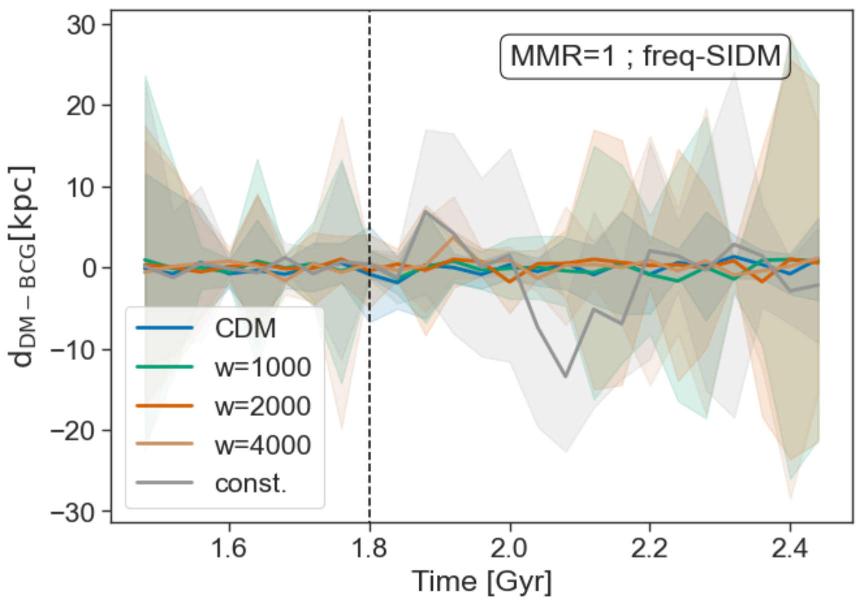
σ_{0m} vs. w

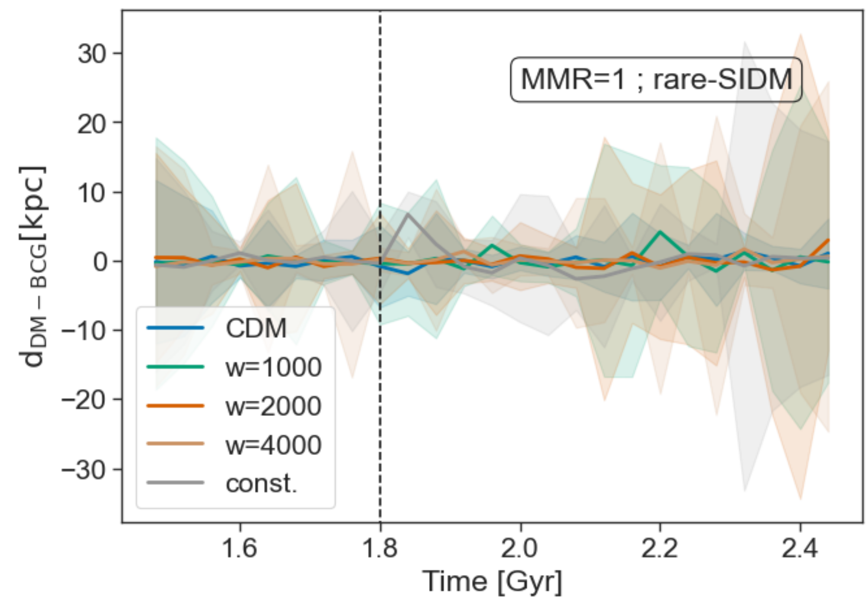


Viscosity cross-section σ_V vs. w

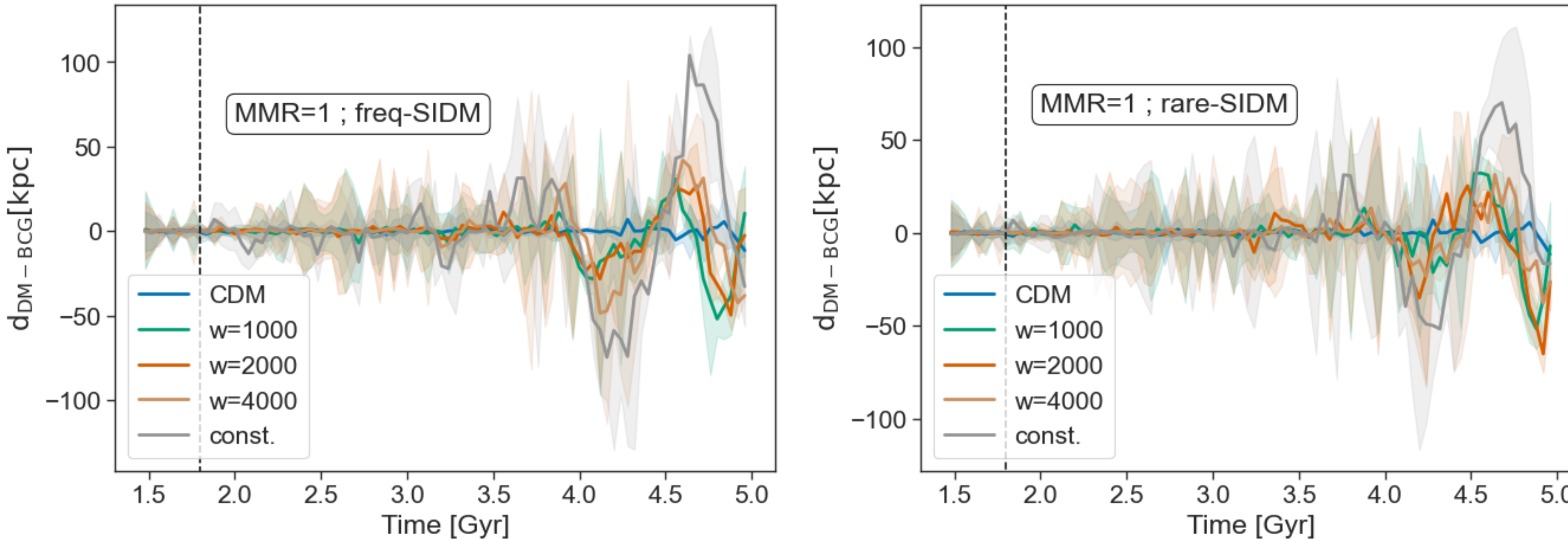


DM-BCG offset at first pericentre passage





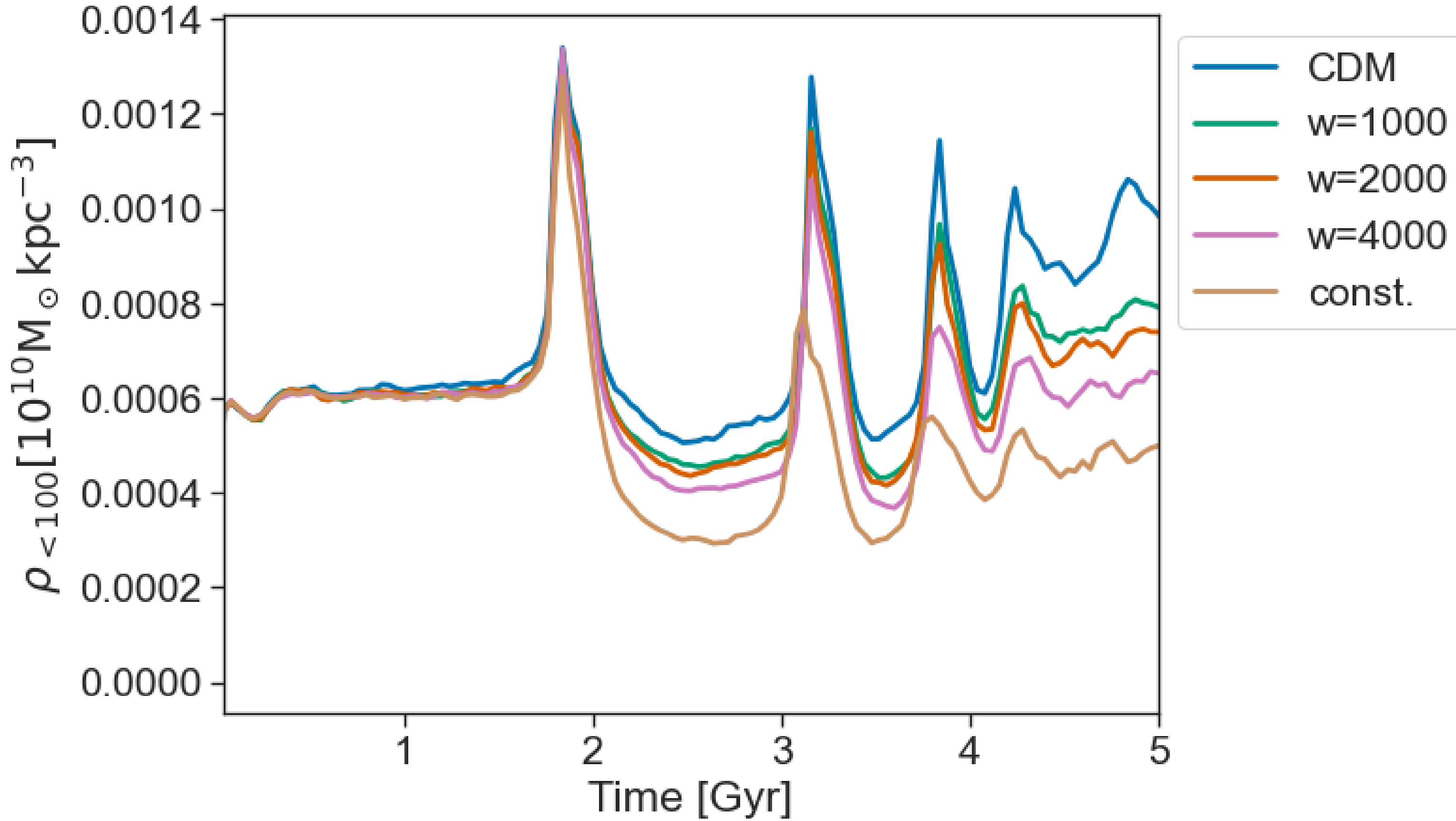
Offsets between DM and BCG at later stages



BCG oscillations have different behaviour due to evolving central densities at late stages.

[Sabarish et. al 2310.07769]

Central density evolution - freq. SIDM

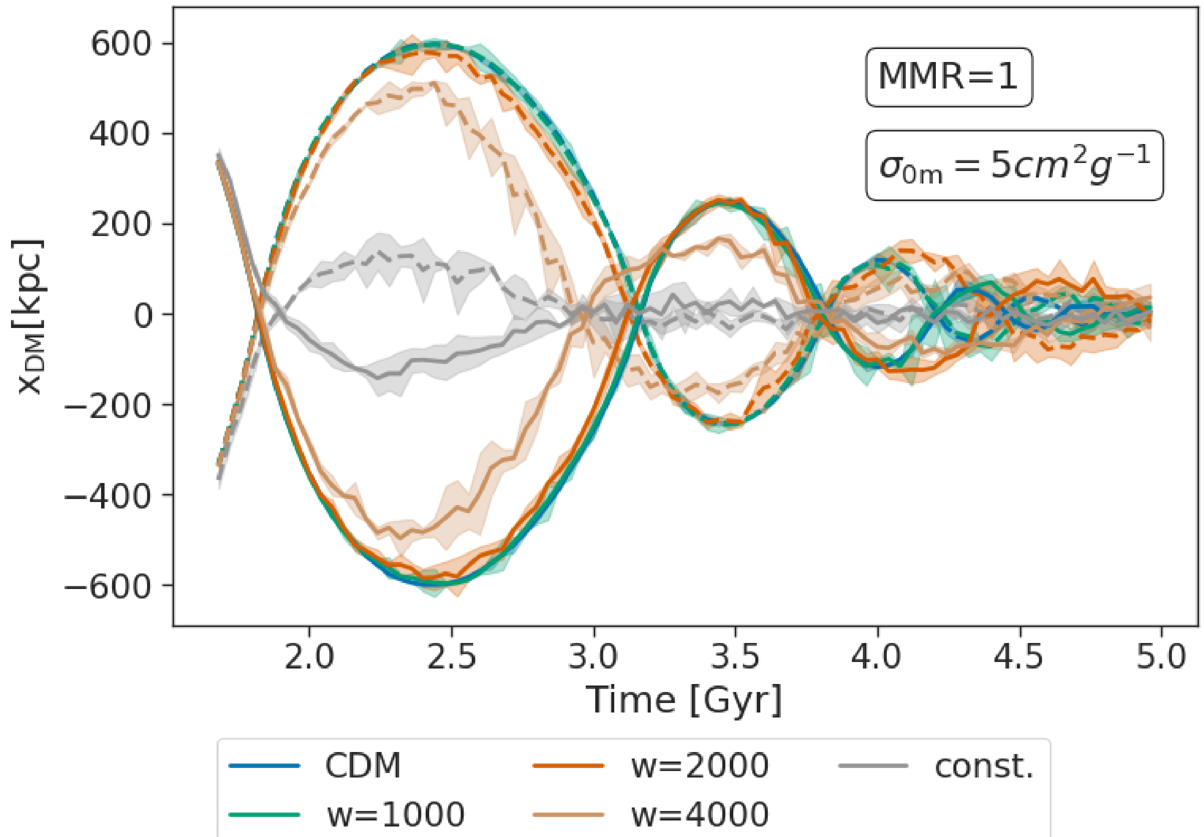


Summary

- Constraints at different velocity scales $\longrightarrow$ Velocity dependent SIDM
- Simulations with isotropic and strongly anisotropic cross-sections have been performed.
- Qualitative differences between CDM, cSIDM and vSIDM seen in BCG oscillations.
- Offsets in simulations after first pericentre are not large enough to be measured given typical astronomical uncertainties.

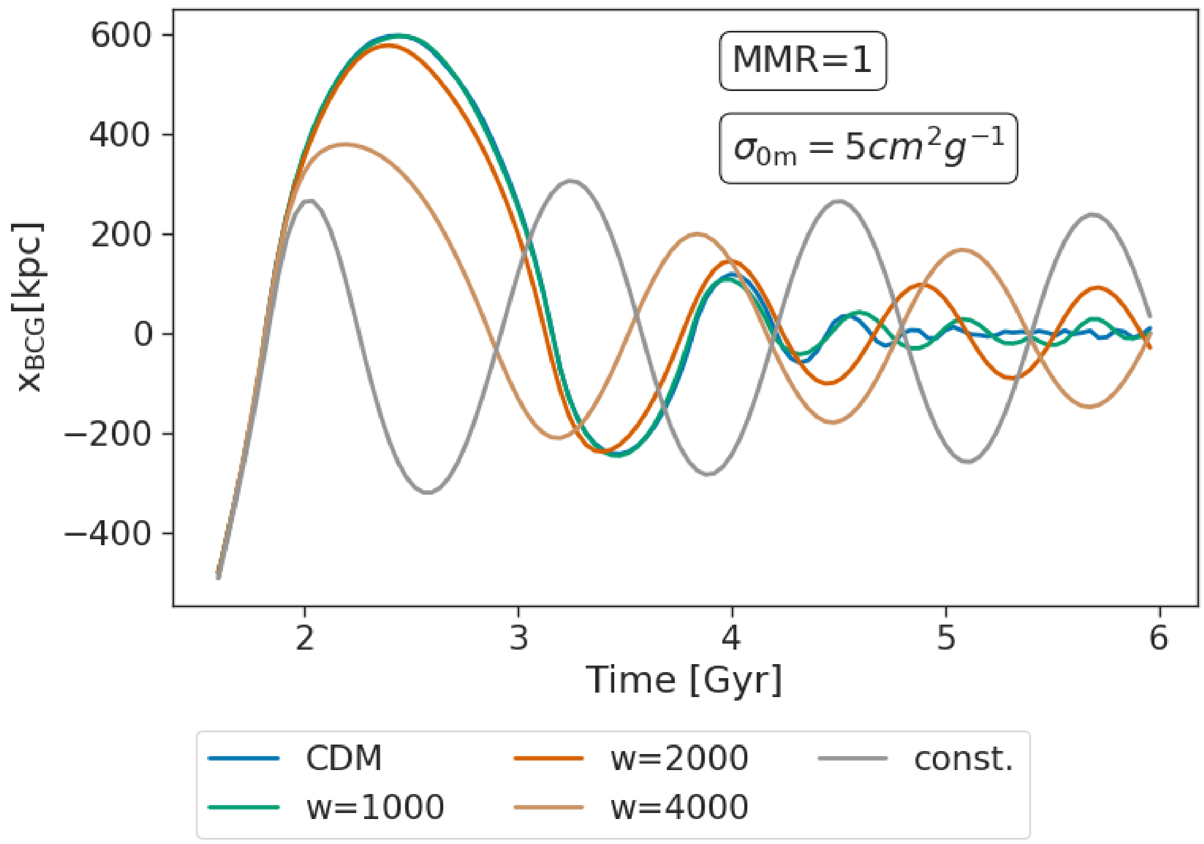
Backup slides

Varying w : DM peaks



- Anisotropic cross-section

Varying w : BCG Oscillations

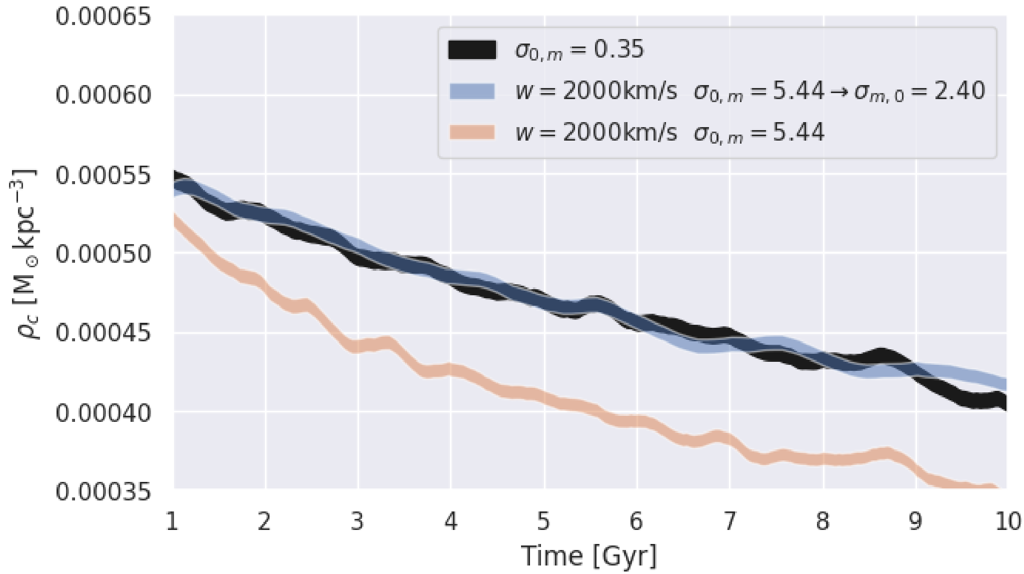


- BCG oscillations have different behaviour due to evolving central densities

Different cross-sections

Total	Momentum-transsfer	Viscosity
$\sigma_{\rm Tot} = \int \frac{{\rm d}\sigma}{{\rm d}\Omega}\,{\rm d}\Omega$	$\sigma_T \propto \int \frac{{\rm d}\sigma}{{\rm dcos}\theta}(1 - \lvert{\rm cos}\theta\rvert)\,{\rm dcos}\theta$	$\sigma_V \propto \int {\rm dcos}\theta\,\sin^2\theta \frac{{\rm d}\sigma}{{\rm dcos}\theta}$

For cross-section with $\theta \to 0, \frac{{\rm d}\sigma}{{\rm d}\cos\theta} \to \infty$, $\sigma_T \to {\rm finite}, \sigma_V \to {\rm finite}$



- Central density matching [Balberg et. al 0110561] [Yang et. al 2205.03392]
- $t_{\rm fac} = \dfrac{\sigma_{0,m}\,(\text{guess})}{\sigma_{0,m}\,(\text{new})}$
- Initial guess should not be way too off

- Ballpark estimate for $\sigma_{0,m}$: solve for $\sigma_{0,m}$ in the equation $\sigma_{\rm eff} = 0.35$

$$\sigma_{\rm eff} \propto \int v^2 {\rm d}v\, {\rm dcos}\theta\, v^5 \sin^2\theta\, \frac{{\rm d}\sigma}{{\rm dcos}\theta}(\sigma_{0,m}) \exp\left(-\frac{v^2}{4\sigma_{1D}^2}\right) \text{[Yang et. al 2205.03392]}$$

Mapping between frequent and rare

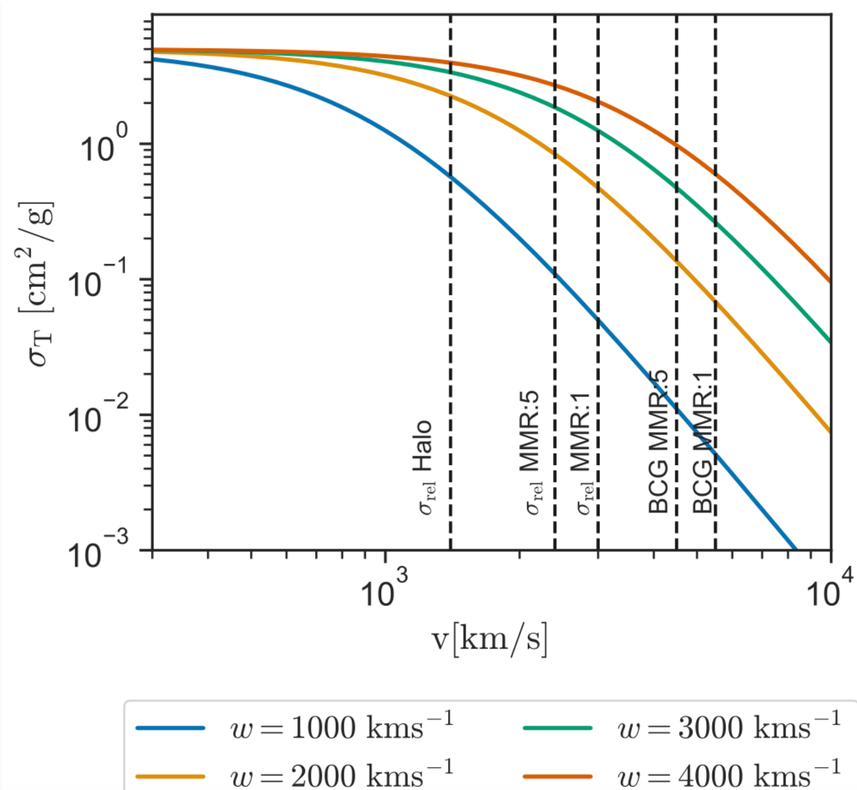
- Effective cross-section

$$\sigma_{\text{eff}}^{(n)} \propto \int v^2 \mathrm{d}v \, \mathrm{d}\cos\theta \, v^n \sin^2\theta \, \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta}(\sigma_{0,m}) \exp\left(-\frac{v^2}{4\sigma_{1D}^2}\right)$$ [Yang et. al 2205.03392]

- [Sabarish et. al 2310.07769]

$$\sigma_{\text{eff}}^{(n)}(\text{freq.}) = \sigma_{\text{eff}}^{(n)}(\text{rare.}) \Rightarrow \sigma_{0m}(\text{freq.}) = \frac{2}{3}\sigma_{0m}(\text{rare.})$$

Relevant velocity scales in the system



- Different velocity scales
- Internal velocity dispersion
- Merger collision velocity