Anisotropic velocity dependent self-interactions in galaxy cluster mergers

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Outline

- Anisotropic / Frequent self-interactions without velocity dependence
- Velocity dependent frequent self-interactions
- Results

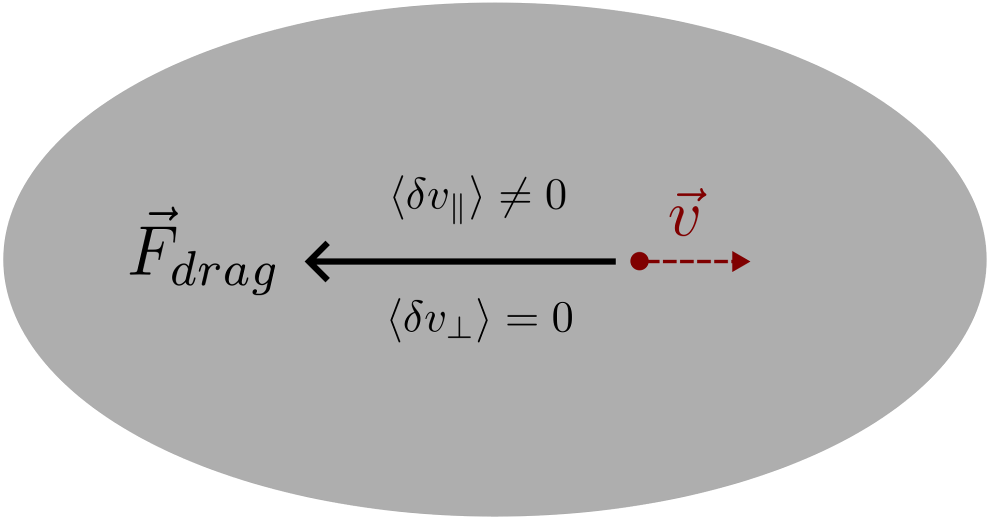
Strongly anisotropic cross-section

- Introduced by Kahlhoefer et al. [1308.3419], to study evaporation rate, and deceleration of subhalo falling into host.
- Features :
  - Divergent $\mathrm{d}\sigma / d\theta$ for $\theta \to 0$
  - Divergent total cross-section, $\sigma_{\mathrm{Tot}} \to \infty$
  - But $\sigma_T \propto \int \mathrm{d}\sigma / d\theta \,(1 - \cos(\theta))\, \mathrm{d}\theta$ is finite
- Self-interactions in frequent self-interacting dark matter (fSIDM), can be seen as drag force

$$R_{\mathrm{dec}} = \frac{\rho_2 \, v_0 \sigma_T}{2 m_{\mathrm{DM}}}$$

R_{dec} is the deceleration rate

Forward small angle scatterings $\Rightarrow$ Drag force



fSIDM in N-Body simulations

- Typical N-Body code for SIDM,

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

- For fSIDM, $\sigma_{\text{Tot}} \rightarrow \infty$, leads to $\Delta t \rightarrow 0$
- Drag force to the rescue.
- Implementation in GADGET-3 by Fischer et. al [2012.10277]
- How does it stand against isotropic SIDM ?

Comparing $\{\sigma\}_{\rm Rare} \leftrightarrow \{\sigma\}_{\rm Fre}$

Simple case : Velocity independent $\Rightarrow \{\sigma_0/m_\chi\}$ [Fischer et. al 2109.10035]

- Frequent (Anisotropic) : σ_T
- Rare (Isotropic) : $\sigma_{\rm Tot}$; $\sigma_T = 2\sigma_{\rm Tot}$
- Matching is done by $\sigma_T({\rm Freq}) \leftrightarrow \sigma_T({\rm Rare})$

What is observed ?

- Offsets grows with cross-sections
- For same σ_T, fSIDM produces larger offset

Velocity dependence

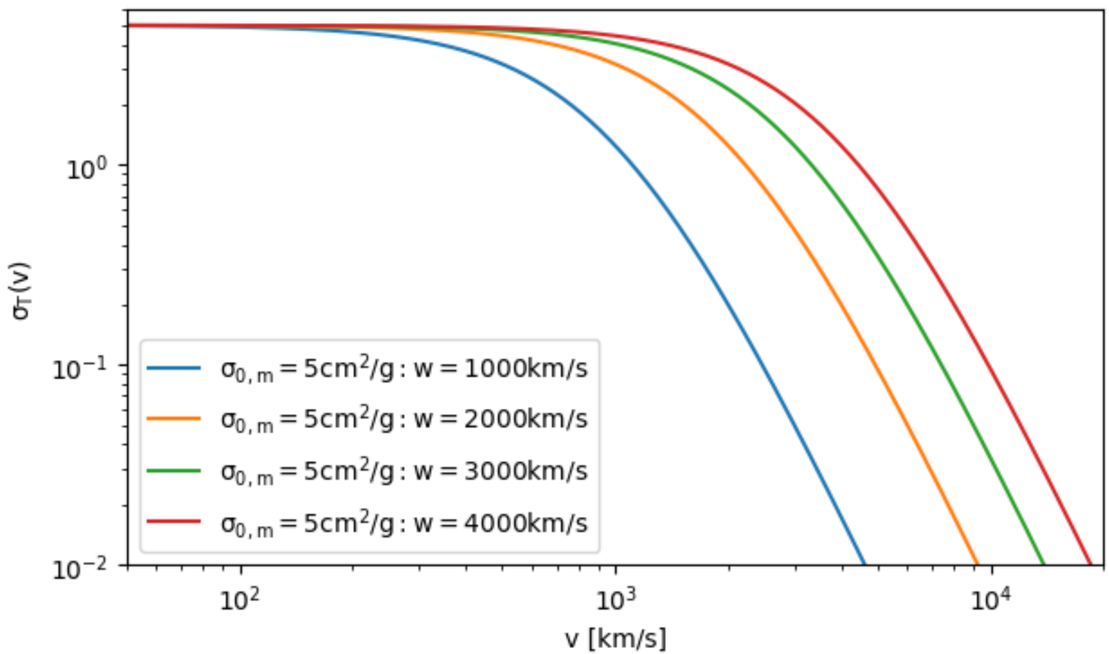
- Qualitative features in velDep mergers !
- Is it possible to have observable offsets given the current bounds ?
- Firstly, Cross-section parameterization [Gilman et al. 2207.13111] , [Yang et al. 2205.02957]

$$\sigma_{T,m} = \sigma_{0,m}\left(1 + \frac{v^2}{w^2}\right)^{-2} \quad ; \qquad w = m_\phi / m_\chi$$

- For $v \gg w$: Interaction is suppressed
- For $w \gg v$: Interaction is velocity independent

Choosing w

Typical velocities at first pericenter $\langle v_{12} \rangle \approx \{2000, 3000, 4000\}$ for Mergers



Choice for $\sigma_{0,m}$

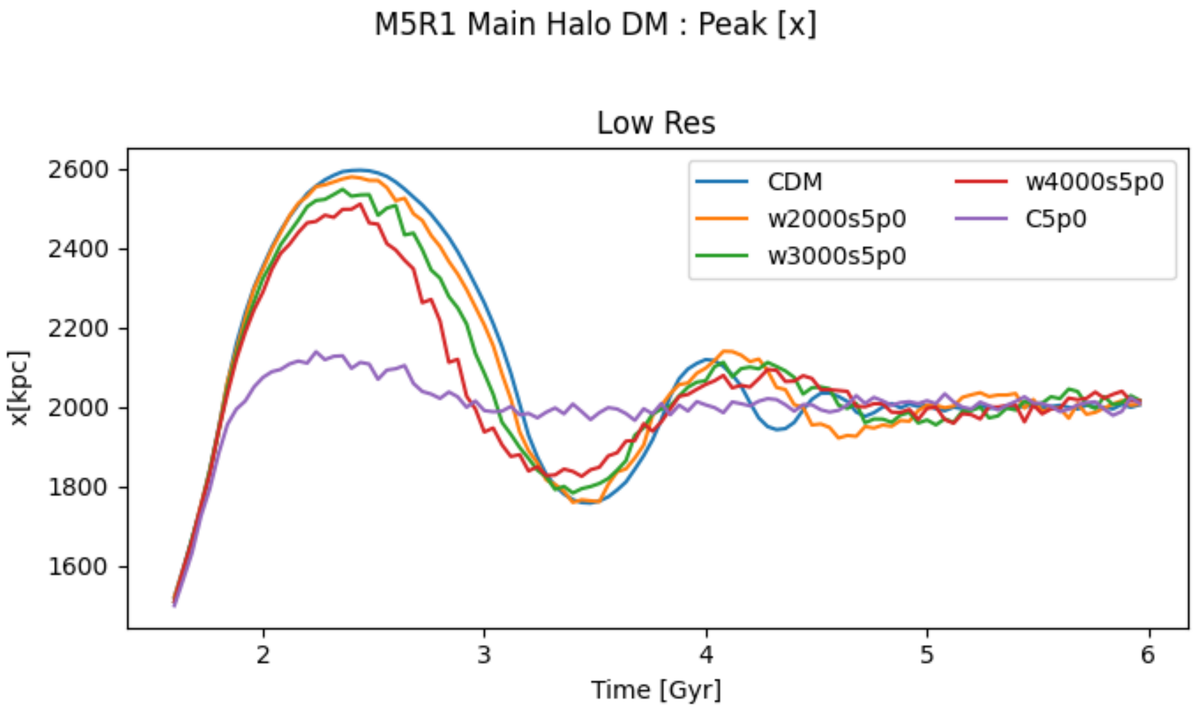
Method 1 :

- Same $\sigma_{0,m}$ with different w's
- Compare expectations with results
- The effects of velocity dependence is easier to understand

Simulation setup :

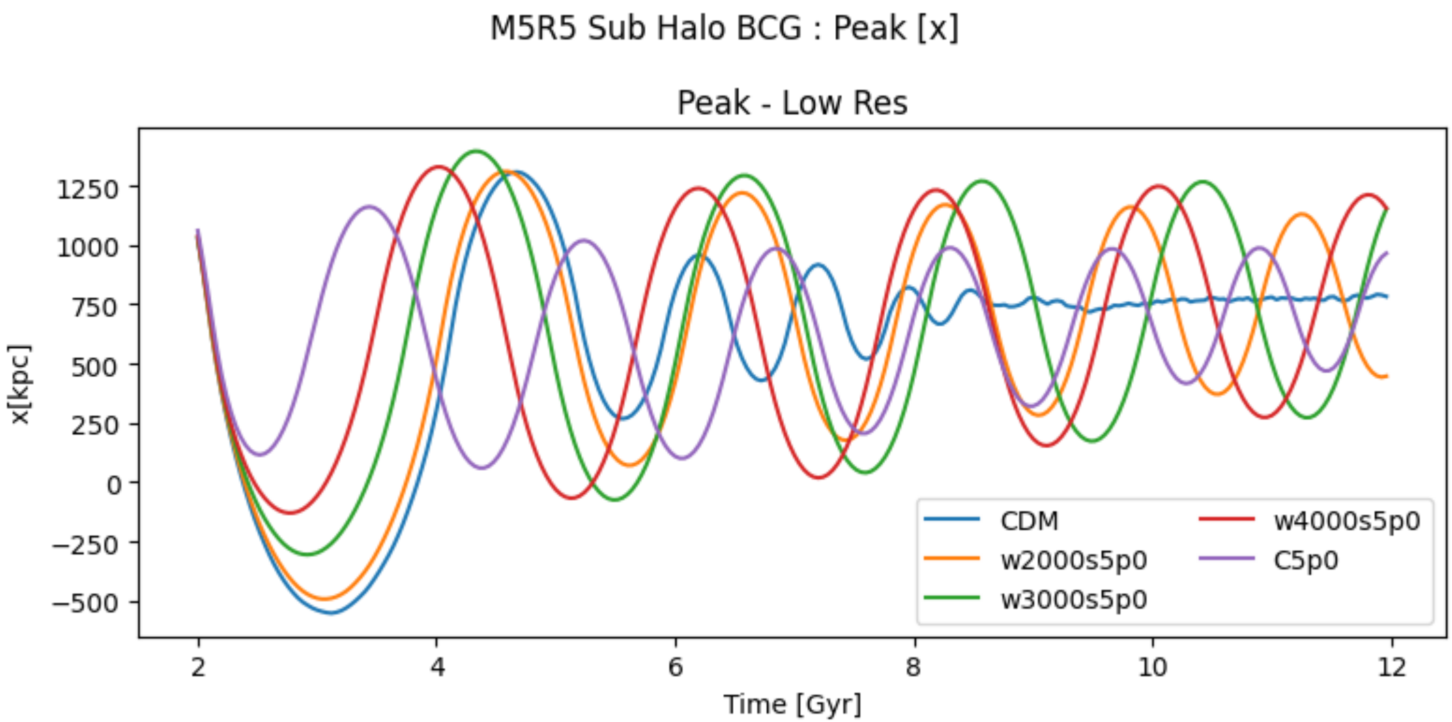
- Mass of first halo = $10^{15}\,\mathrm{M}_{\odot}$ = Mass of second halo
- Cross-section parameters : $\sigma_{0,m} = 5.0\,\mathrm{cm}^2\,\mathrm{g}^{-1}$, with $w \in \{2000, 3000, 4000\}\,\mathrm{km\ s}^{-1}$
- Halos are shot at each other $1000\,\mathrm{kms}^{-1}$
- Three components : SIDM, Galaxy, BCG

Same $\sigma_{0,m}$: DM peaks



- Large cross-sections $\Rightarrow$ DM halos coalesce

Same $\sigma_{0,m}$: BCG Oscillations

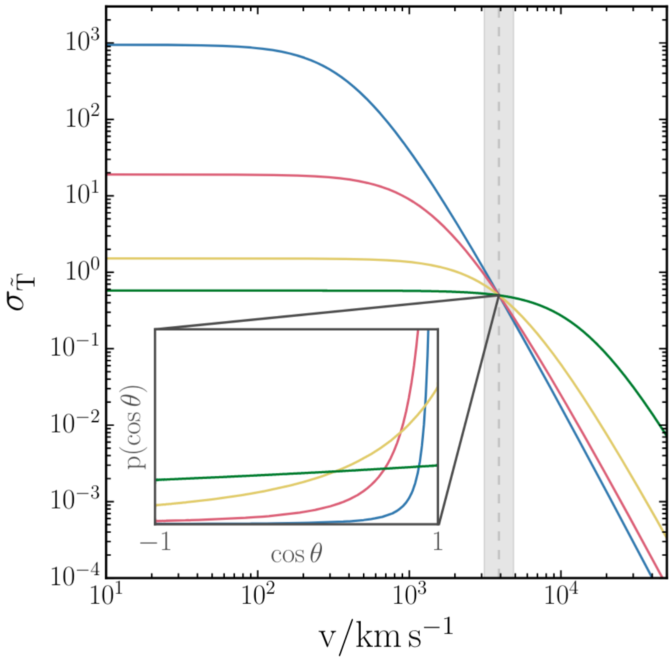


- BCG oscillations have qualitative difference because, coring starts at late times for strong velocity dependent interactions

Matching at First pericenter

Method 2:

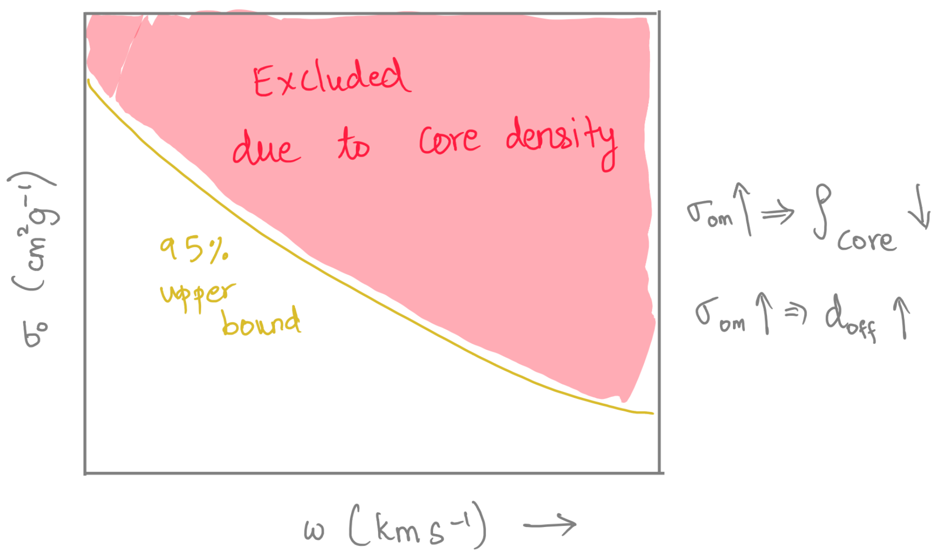
$\sigma_{0,m}$ by matching the overall cross-section at some characteristic velocity [Robertson et. al 1612.03906]



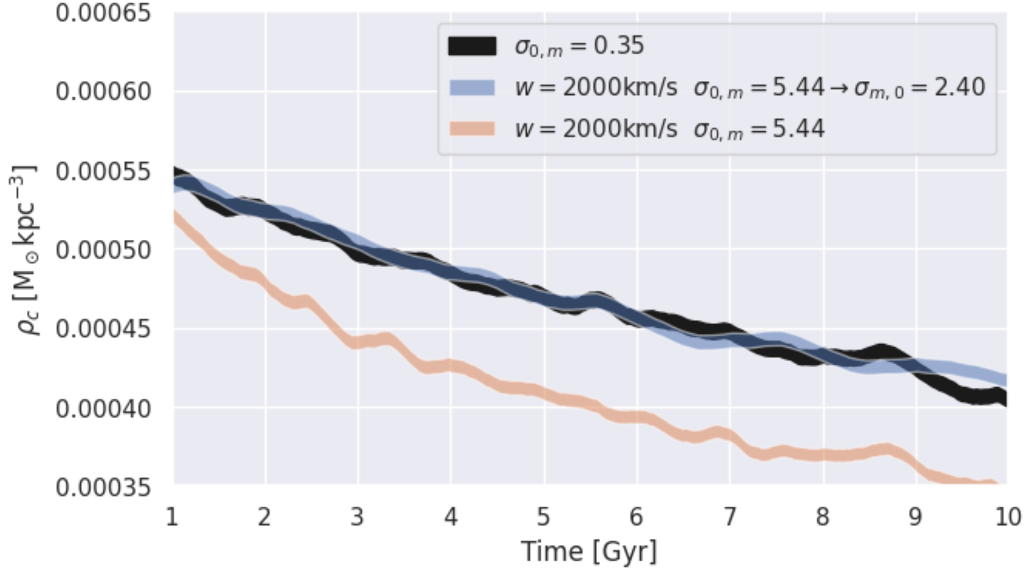
Central Density matching

Method 3 :

- 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.



Central Density matching



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

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

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

Central Density matching

Observed offsets for fSIDM in Simulations

$w\,[\mathrm{km/s}]$	$\sigma_{0,m}\,[\mathrm{cm}^2/\mathrm{g}]$	$d_{\mathrm{DM-BCG}}\,[\mathrm{kpc}]$
1000	5.6	2.5 ± 2
2000	0.78	1.4 ± 1.2
3000	0.38	1.2 ± 1
4000	0.25	5 ± 2.5
∞	0.11	6.4 ± 5

Summary

Key result :

- Offsets in idealised cluster mergers are not large enough to distinguish vel.dep. SIDM from const. SIDM (at low resolution)
- Early time vs. late time BCG oscillations at least at the level of simulations is qualitatively different.

Future directions :

- Simulate different merger mass ratios
- Zoom in simulations of lower mass systems
- Are BCG oscillations in vel.dep regime a viable observable ? [Harvey et. al 1812.06981]