How could we probe the angular dependence of dark matter self-interactions?

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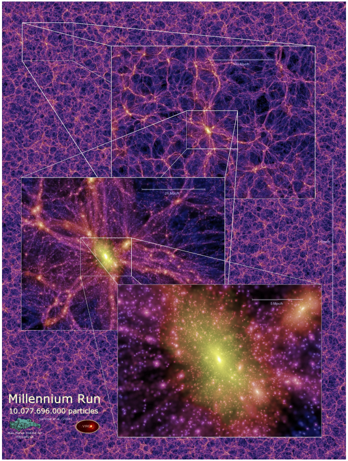
Large-Scale Structure

- Structure formation starts shortly after big bang from Gaussian random field
- Structure formation is strongly non-linear
  $\rightarrow$ simulations required
- ΛCDM simulations agree well with the observed large-scale structure



Credits: Springel et al. (2005)

Small-Scale Crisis of ΛCDM

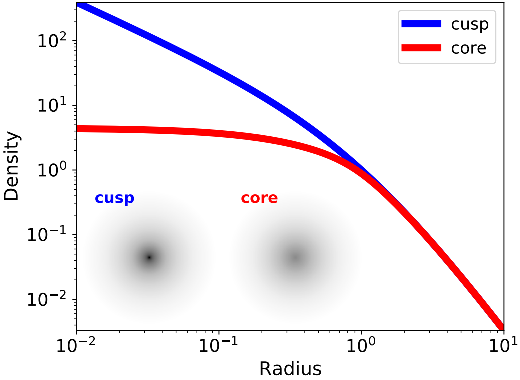
There are several "problems" on small scales:

- Core-cusp problem
- Diversity problem
- Too many satellites problem
- Too-big-to-fail problem
- Plane-of-satellites problem

→ **This is the small-scale crisis of ΛCDM**

Core-Cusp Problem

- CDM predicts cuspy halos,
- but cored halos are observed.



cuspy vs. cored dark matter halo

How to Fix These Problems?

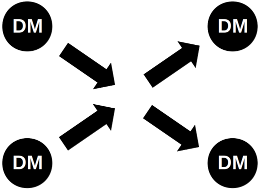
Solve or mitigate small scale problems:

- Alternative dark matter models (WDM, FDM, SIDM, ...)
- Alternative theory of gravity
- Baryons (Feedback from Stars, Supernovae, AGN)
- Improved modelling of the internal dynamics of observed galaxies

$\rightarrow$ **Solution is probably a combination**

SIDM as a Potential Solution

- Self-Interacting Dark Matter (SIDM): Class of particle physics models that assume dark matter to be self-interacting.



- Self-interactions appear to be natural from particle physics.
- SIDM is promising, can solve or at least mitigate small-scale problems.

How Can We Model SIDM?

- Gravothermal fluid model
- Jeans approach

} assumes relaxed halo

- N-body simulations

} computational expensive

Modelling Dark Matter Self-Interactions

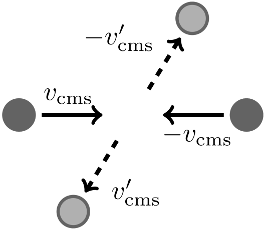
- SIDM is neither collisonless (like CDM) nor fully collisonal (like a fluid)
- Requires 6D phase-space information
- We have to solve the collisional Vlasov-Poisson / Boltzmann equation:

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \nabla_x f - \nabla_x \Phi \cdot \nabla_v f = \left(\frac{\partial f}{\partial t} \right)_{\mathrm{coll}}$$

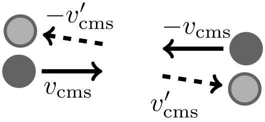
- Self-interactions are described by a collison term

The Collision Term

We distinguish two regimes:



large-angle scattering
– rare –



small-angle scattering
– frequent –

Rare Self-Interacting Dark Matter (rSIDM)

- Interactions of numerical particles are treated as collisions of physical particles
- Probability that two particles interact:

$$P_{ij} = \frac{\sigma}{m_\chi} \, m \, |\Delta \vec{v}_{ij}| \, \Delta t \, \Lambda_{ij}$$

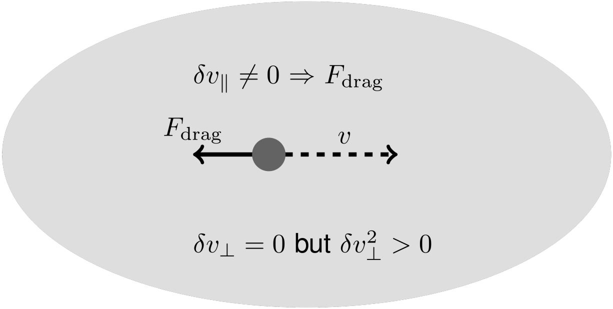
$\rightarrow$ Impracticable for frequent scattering, because $\Delta t \rightarrow 0$

Frequent Self-Interacting Dark Matter (fSIDM)

We need to reformulate the collision term:

- Interactions of numerical particles are **NOT** treated as collisions of physical particles
- Effective description (drag force) is used for the collision term
- If numerical particles are close, they interact (no probability)

Effective Description: Drag Force



Description of drag force from Kahlhoefer et al. 2014

Modelling fSIDM

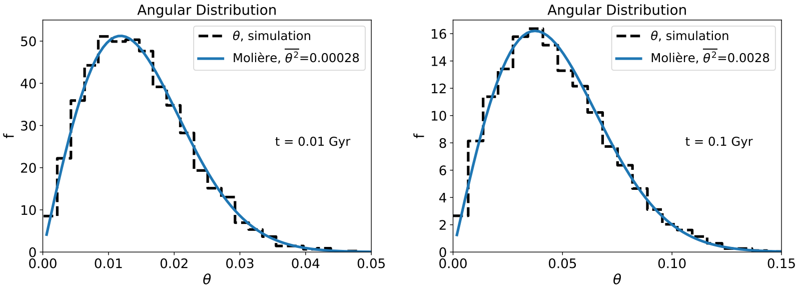
Each particle pair is treated in two steps:

1. model $\delta v_{\parallel} \neq 0$:
$$\vec{p}_i^{\,*} = \vec{p}_i - \Delta\vec{p}_{\mathrm{drag}}\,, \qquad \vec{p}_j^{\,*} = \vec{p}_j + \Delta\vec{p}_{\mathrm{drag}}$$
2. model $\delta v_{\perp}^2 > 0$:
$$\vec{p}_i^{\,\prime} = \vec{p}_i^{\,*} + \Delta\vec{p}_{\mathrm{rand}}\,, \qquad \vec{p}_j^{\,\prime} = \vec{p}_j^{\,*} - \Delta\vec{p}_{\mathrm{rand}}$$

To conserve energy and momentum, the particle pairs need to be executed in serial.
$\rightarrow$ parallelisation is more complicated than for SPH

We implemented our novel scheme in GADGET-3.

Angular Deflection Problem

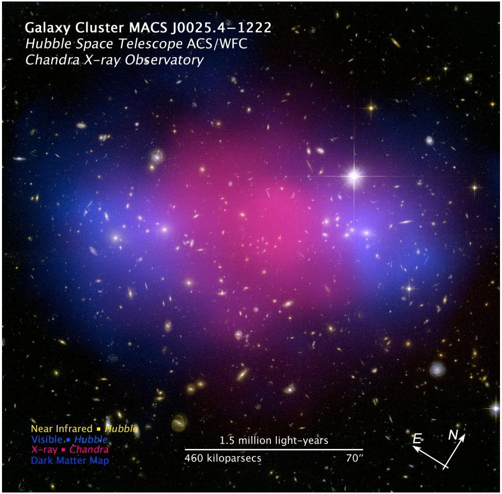


Fischer et al. 2021a

- Molière tells us:

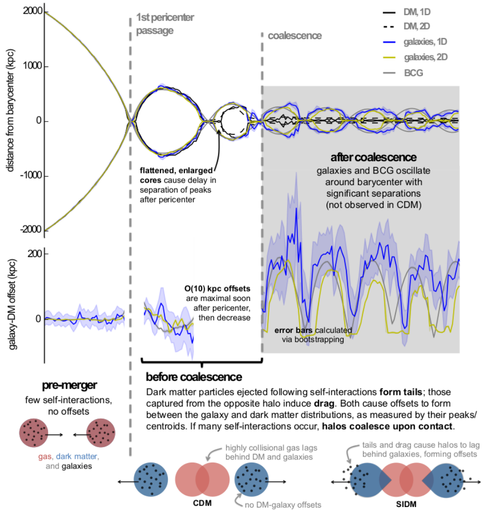
$$f(\theta) = \frac{2\,\theta}{\overline{\theta^2}}\,\exp\left(-\frac{\theta^2}{\overline{\theta^2}}\right) \qquad \text{with} \quad \overline{\theta^2} = 2\,\rho\,l\,\frac{\sigma_{\tilde{\mathrm{T}}}}{m_\chi}$$

Galaxy Cluster Merger



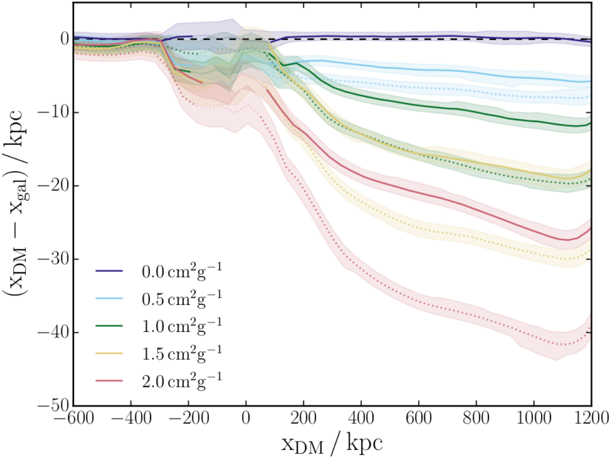
Credits: NASA, ESA, CXC, M. Bradac (University of California, Santa Barbara), and S. Allen (Stanford University)

Equal-Mass Merger



Credits: Kim et al. 2017

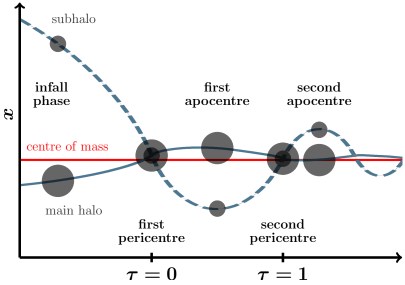
Anisotropic Cross-Section



Credits: Robertson et al. 2017

Simulation Setup

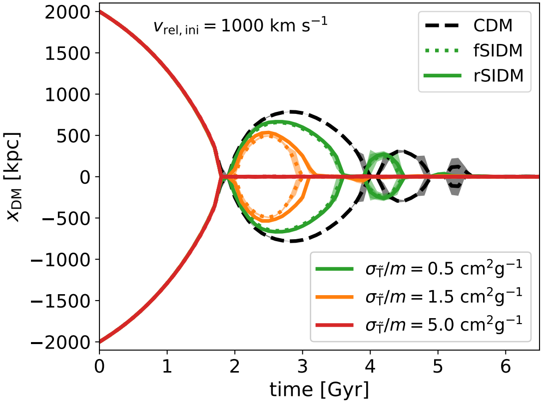
- Head-on mergers of galaxy clusters
- NFW halo, $M_{\mathrm{vir}} = 10^{15}\,\mathrm{M}_\odot$
- equal and unequal-mass mergers
- GADGET-3 with own fSIDM and rSIDM implementation



Fischer et al. 2021b

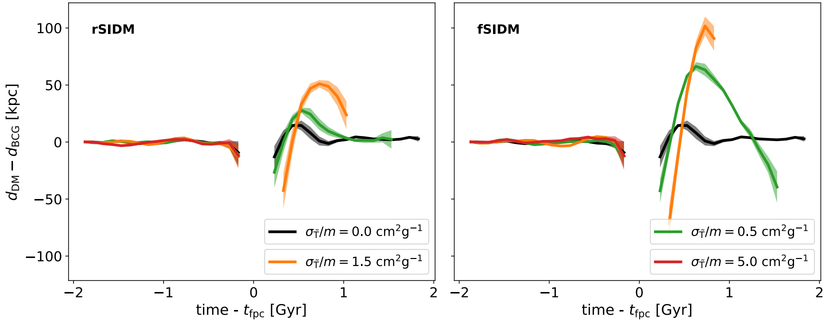
Equal-Mass Merger

Small difference between dark matter peaks of fSIDM and rSIDM



Fischer et al. 2021a

BCG – Dark Matter Offsets

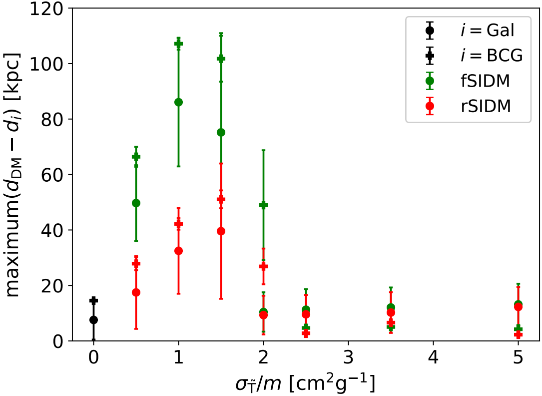


Fischer et al. 2021a

offsets are much larger for fSIDM than for rSIDM

Maximum Offset

The maximum achievable offset is much larger for fSIDM than for rSIDM



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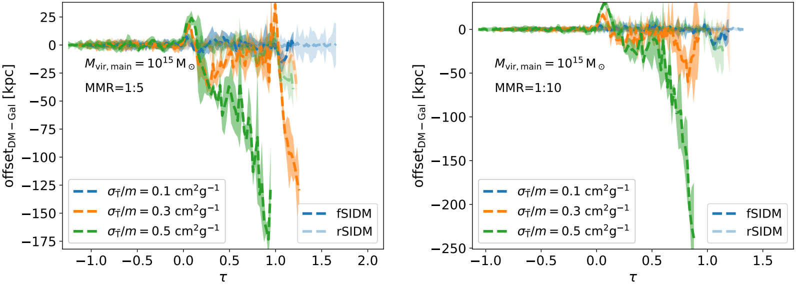
Unequal-Mass Merger: Offsets

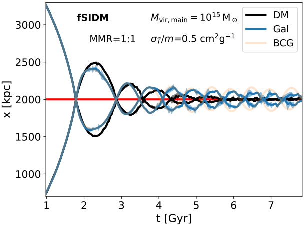


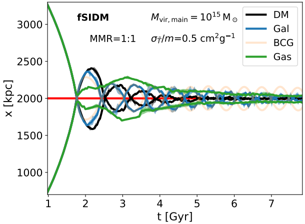
Fischer et al. 2021b

offsets are much larger for fSIDM than for rSIDM

Equal-Mass Merger: The role of the ICM

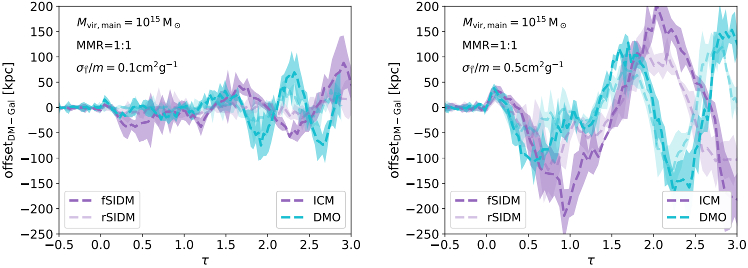
- An offset between the DM and galaxies occurs in both cases.
- In the ICM simulation the later offsets are bigger than in the DMO simulations.
- The ampliutudes of DM and galaxies are larger for DMO simulations.





Credits: Katharina Hollingshausen

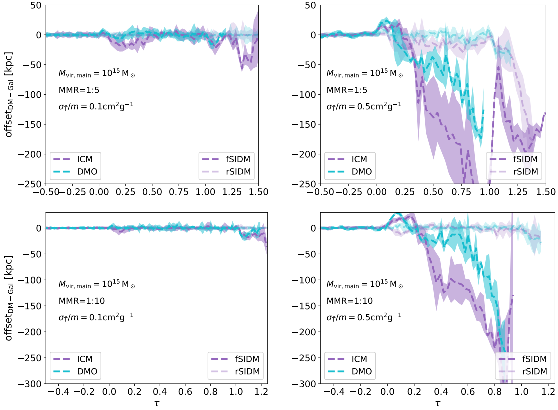
Equal-Mass Merger: Offsets comparison



Credits: Katharina Hollingshausen

Offsets at later times are much larger when including ICM

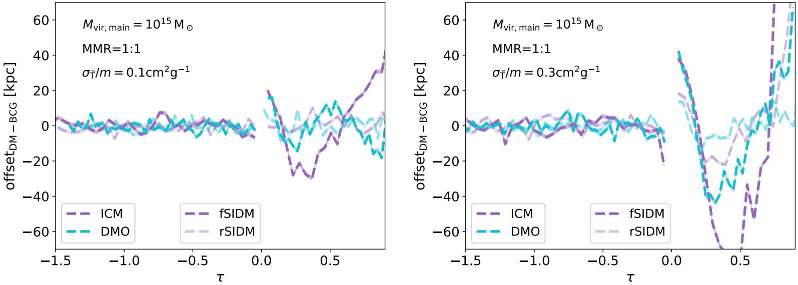
Unequal-Mass Merger: Offsets comparison



Credits: Katharina Hollingshausen

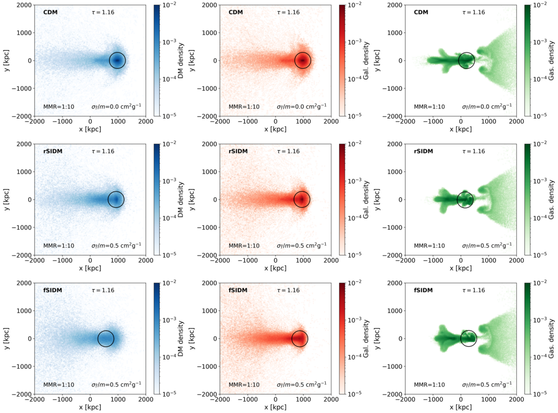
Offsets at later times are much larger when including ICM

BCG – Dark Matter Offsets



- Isodensity peaks, closer to observations
- **Interesting large offsets with ICM**

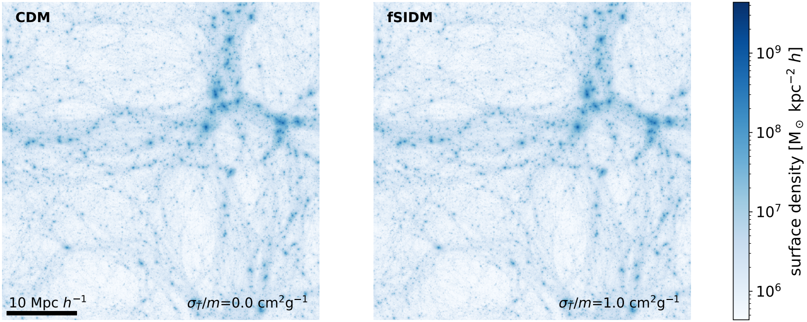
Unequal-Mass Merger: Morphology



Credits: Katharina Hollingshausen

DM, galaxy and gas distribution differ between DM models

Cosmological Study

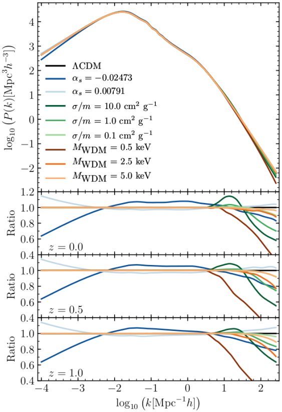


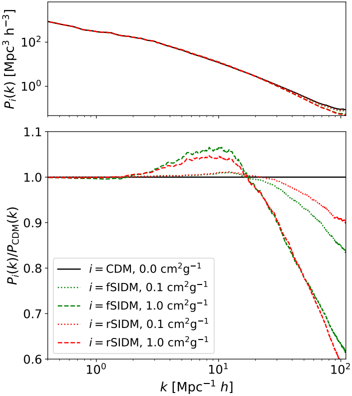
Fischer et al. 2022

No differences on large scales

Cosmological Study: Power Spectrum

Credits: Stafford et al. 2020





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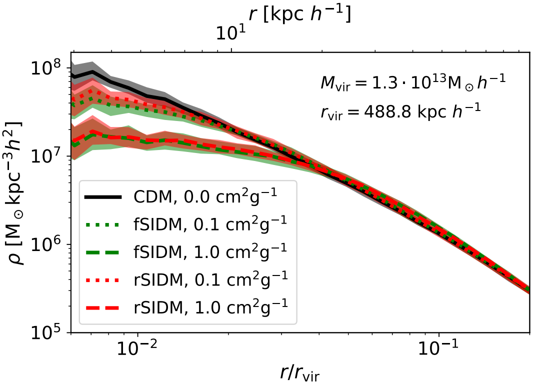
Difference only on small scales

Cosmological Study: Density Profile

Self-interactions produce density cores



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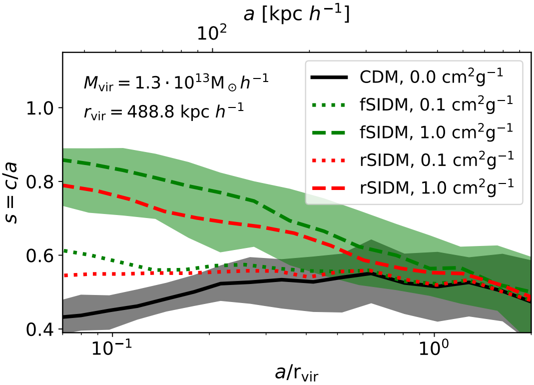
Cosmological Study: Halo Shape

Self-interactions make haloes rounder

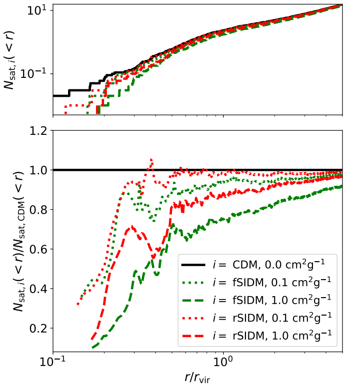


Fischer et al. 2022

Constraints on Frequent Scattering

- The momentum transfer cross-section $\sigma_{\tilde{T}}$ can very roughly match rSIDM and fSIDM (density and shape profiles).
- Typically effects of fSIDM are stronger than for rSIDM (same $\sigma_{\tilde{T}}/m$).
- Thus rSIDM constraints can often be seen as a conservative limit for fSIDM.
- Sagunski et al. 2021: $\sigma_{\tilde{T}}/m \leq 0.55\,\mathrm{cm}^2\mathrm{g}^{-1}$ (groups, CL 95%), $\sigma_{\tilde{T}}/m \leq 0.175\,\mathrm{cm}^2\mathrm{g}^{-1}$ (clusters, CL 95%).

Cosmological Study: Satellite Abundance

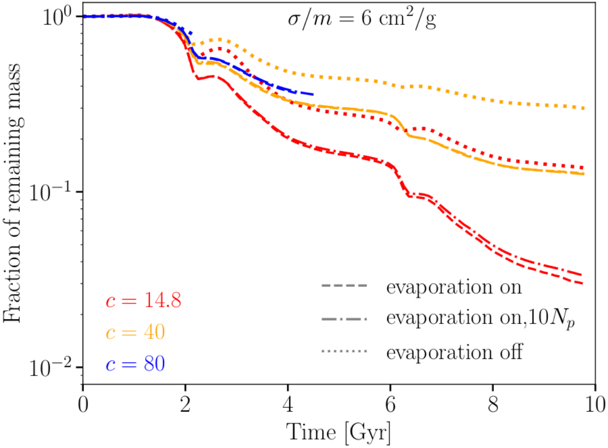


Fischer et al. 2022

Interestingly large suppression of satellites for fSIDM

Subhalo Evaporation

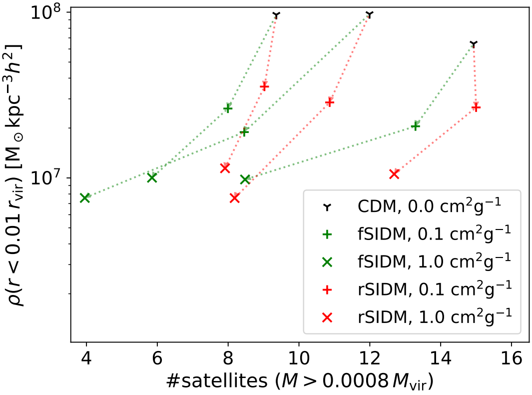
Host-Satellite interactions are important



Credits: Zeng et al. 2021

Central Density vs. Number of Satellites

Qualitative difference between rare and frequent scattering



Fischer et al. 2022

Outlook

In future and current simulations we include:

- Baryons
  - ICM, ISM, star formation, supernovae, AGN, ...
- Velocity-dependent cross-section
  - motivated by observations and particle physics

Take Home Messages

N-body simulations of fSIDM are ...

1. **possible**
   - We developed a new numerical scheme,
   - based on an effective description (drag force).

2. **important**
   - fSIDM and rSIDM have different phenomenology (offsets, satellite abundance),
   - significant difference also at small cross-sections ($\lesssim 0.1\,\mathrm{cm}^2/\mathrm{g}$).