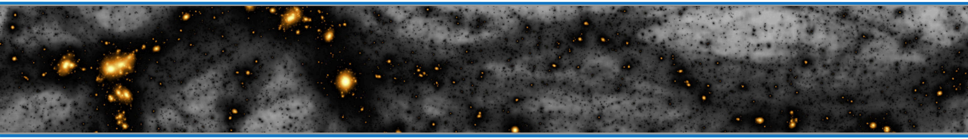

# How could we probe the angular dependence of dark matter self-interactions?

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Collaborators:
Klaus Dolag, Marcus Brüggen, Felix Kahlhoefer, Antonio Ragagnin, Andrew Robertson, Kai Schmidt-Hoberg

# Modelling Dark Matter Self-Interactions

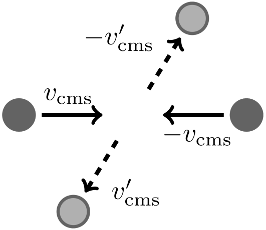
- SIDM is neither collisonless (like CDM) nor fully collisonal (like a fluid)
- Requires 6D phase-space information
- We have to solve the collisional Vlasov-Poisson / Boltzmann equation:

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

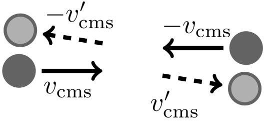
- Self-interactions are described by a collison term

# 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:

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

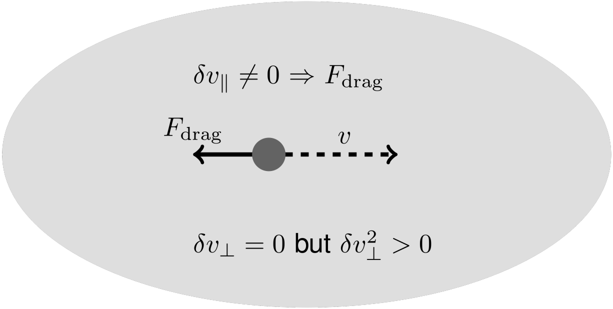
$\rightarrow$ Impracticable for frequent scattering, because $\Delta t \rightarrow 0$

# 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 $\delta v_{\parallel} \neq 0$:

$$\vec{p}_i^{\,*} = \vec{p}_i - \Delta\vec{p}_{\mathrm{drag}}\,, \qquad \vec{p}_j^{\,*} = \vec{p}_j + \Delta\vec{p}_{\mathrm{drag}}$$

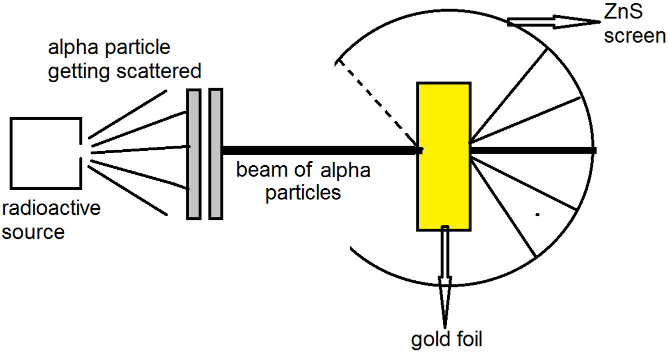
2. model $\delta v_{\perp}^2 > 0$:

$$\vec{p}_i^{\,\prime} = \vec{p}_i^{\,*} + \Delta\vec{p}_{\mathrm{rand}}\,, \qquad \vec{p}_j^{\,\prime} = \vec{p}_j^{\,*} - \Delta\vec{p}_{\mathrm{rand}}$$

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

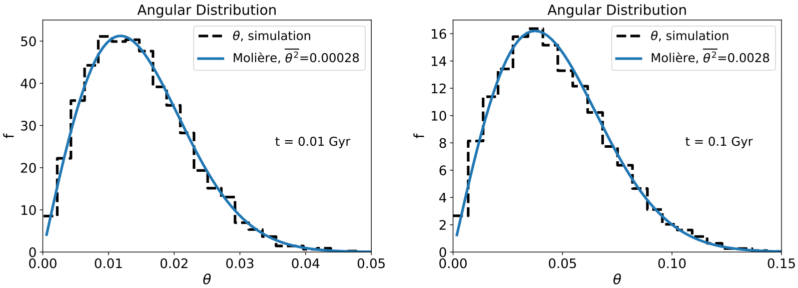
We implemented our novel scheme in GADGET-3.

# Rutherford’s Experiment




Credits: sciencecurio.blogspot.com

# Angular Deflection Problem

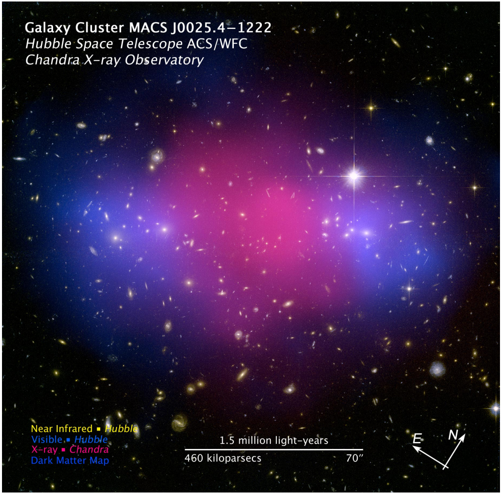



Fischer et al. 2021a

- Molière tells us:

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

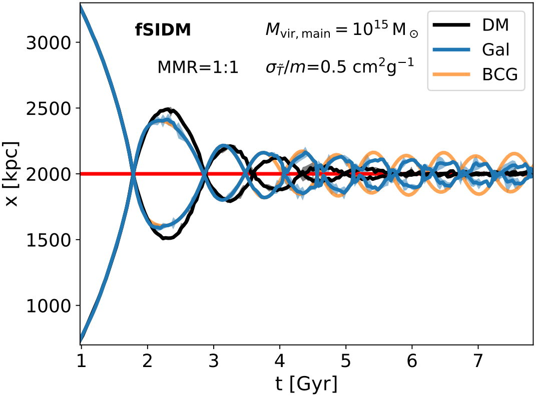
# Galaxy Cluster Merger




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

# Equal-Mass Merger

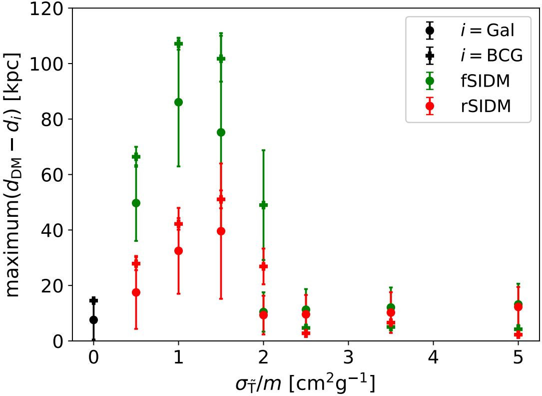
**Offsets at later merger stages are much larger**




Fischer et al. 2021b

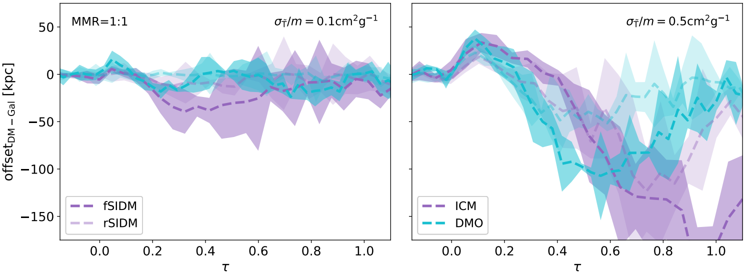
# Maximum Offset

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




Fischer et al. 2021a

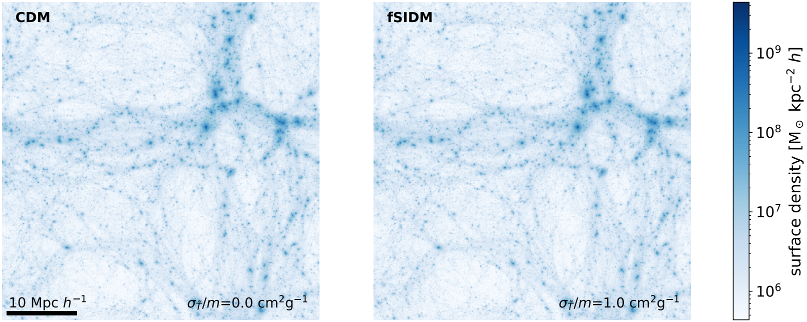
# Equal-Mass Merger: Offsets comparison




Fischer et al. 2023

**Offsets at later times are much larger when including ICM**

# Cosmological Study

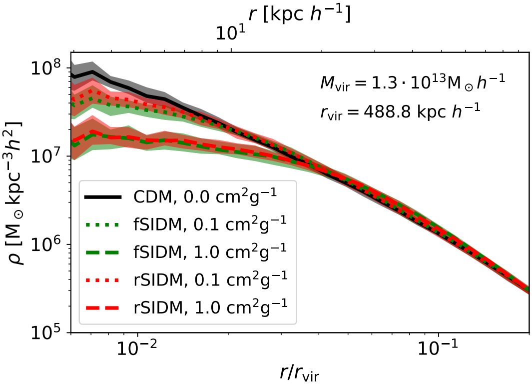



Fischer et al. 2022

**No differences on large scales**

# Cosmological Study: Density Profile

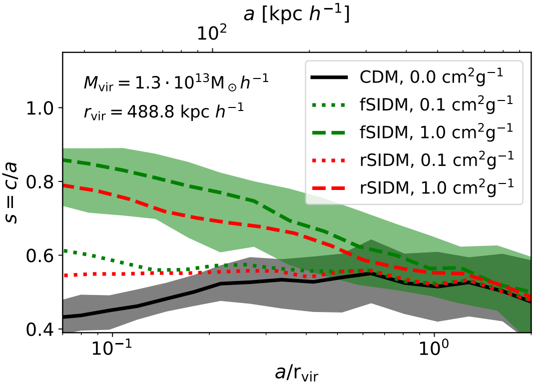
**Self-interactions produce density cores**




Fischer et al. 2022

# Cosmological Study: Halo Shape

**Self-interactions make haloes rounder**

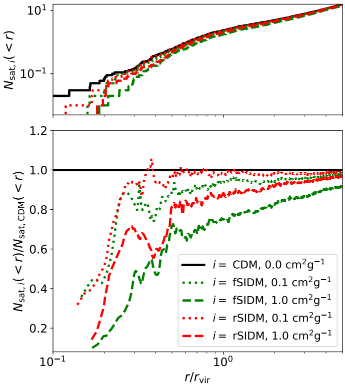



Fischer et al. 2022

# 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

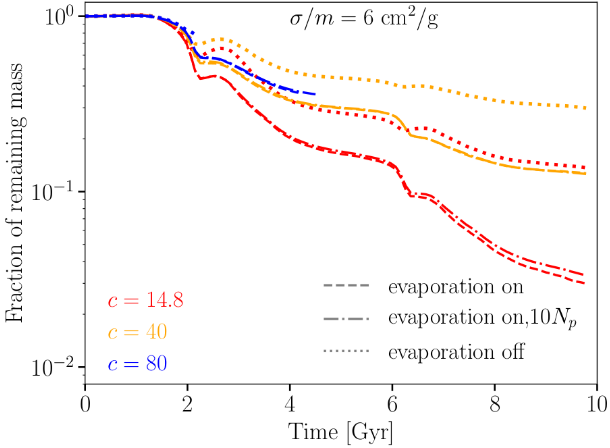



Fischer et al. 2022

**Interestingly large suppression of satellites for fSIDM**

# Subhalo Evaporation

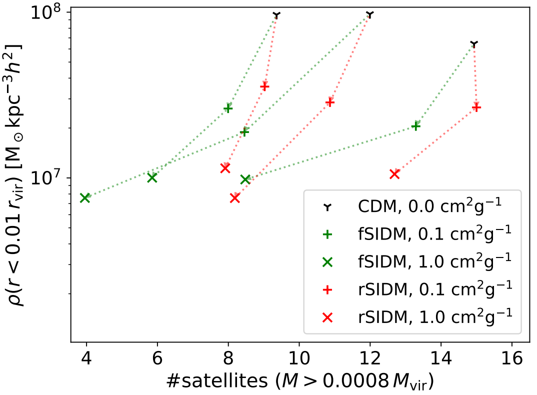
**Host-Satellite interactions are important**




Credits: Zeng et al. 2021

# Central Density vs. Number of Satellites

**Qualitative difference between rare and frequent scattering**




Fischer et al. 2022

# 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 ($\lesssim 0.1\,\mathrm{cm}^2/\mathrm{g}$).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