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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY.

Simulations of dark matter with frequent and rare self-interactions

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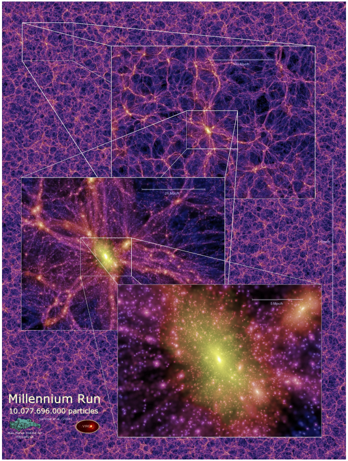
Evidence for Dark Matter

All evidence comes from astronomy:

- Galactic rotation curves
- Velocity dispersion
- Galaxy cluster masses
- Gravitational lensing
- Cosmic microwave background
- Large-scale structure
- ...

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

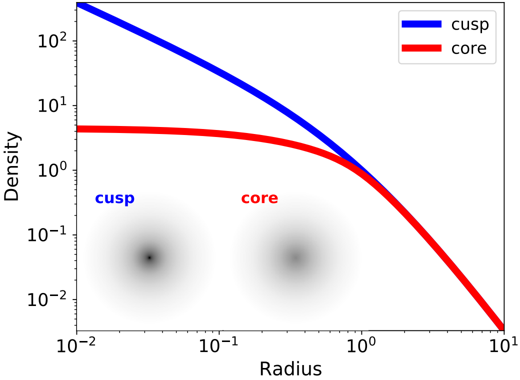
There are several “problems” on small scales:

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

$\rightarrow$ **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?

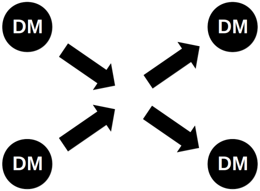
Solve or mitigate small scale problems:

- 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

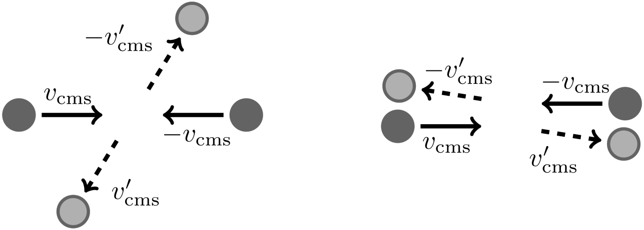
- SIDM is neither collisonless (like CDM) nor fully collisonal (like a fluid)
- Requires 6D phase-space information
- We have to solve the collisional Vlasov-Poisson / Boltzmann equation:

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

- 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:

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

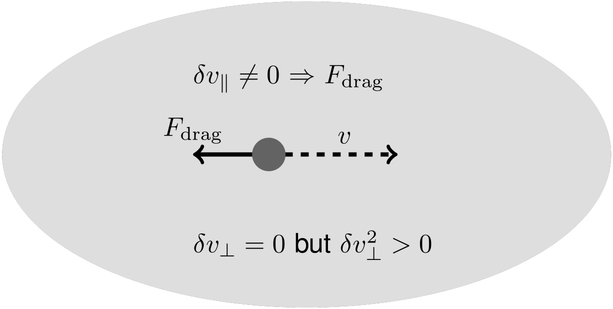
$\rightarrow$ Impracticable for frequent scattering, because $\Delta t \rightarrow 0$

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

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

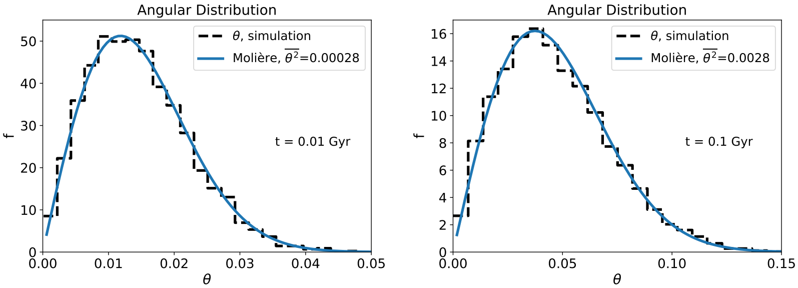
2. model $\delta v_{\perp}^2 > 0$:

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

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

We implemented our novel scheme in GADGET-3.

Angular Deflection Problem

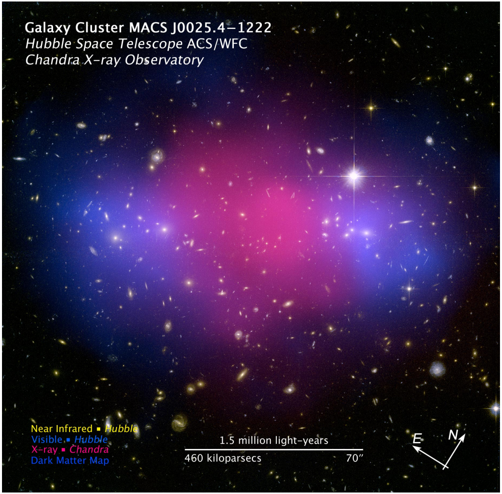


Fischer et al. 2021a

- Molière tells us:

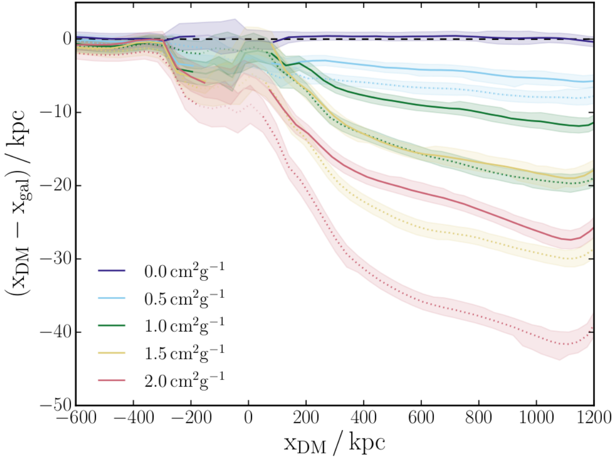
$$f(\theta) = \frac{2\,\theta}{\overline{\theta^2}} \exp\left(-\frac{\theta^2}{\overline{\theta^2}}\right) \qquad \text{with} \quad \overline{\theta^2} = 2\,\rho\,l\,\frac{\sigma_{\tilde{\mathrm{T}}}}{m_\chi}$$

Galaxy Cluster Merger



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

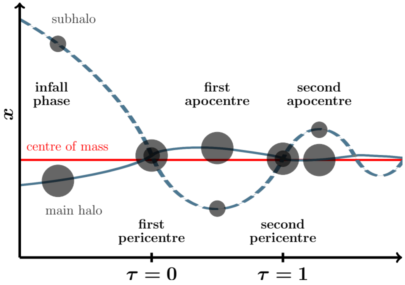
Anisotropic Cross-Section



Credits: Robertson et al. 2017

Simulation Setup

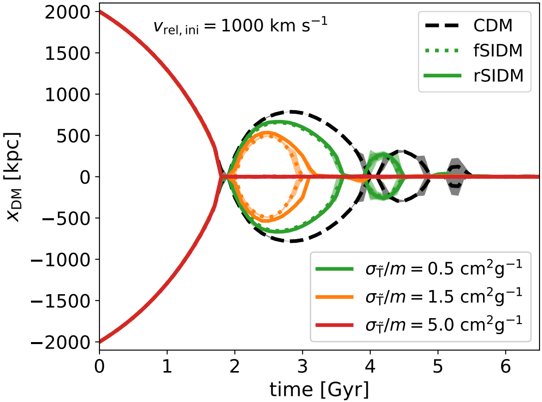
- Head-on mergers of galaxy clusters
- NFW halo, $M_{\mathrm{vir}} = 10^{15}\,\mathrm{M}_\odot$
- equal and unequal-mass mergers
- GADGET-3 with own fSIDM and rSIDM implementation



Fischer et al. 2021b

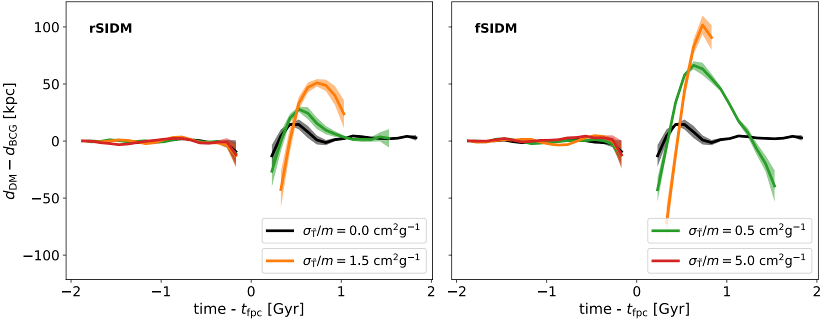
Equal Mass Merger

Small difference between dark matter peaks of fSIDM and rSIDM



Fischer et al. 2021a

BCG – Dark Matter Offsets

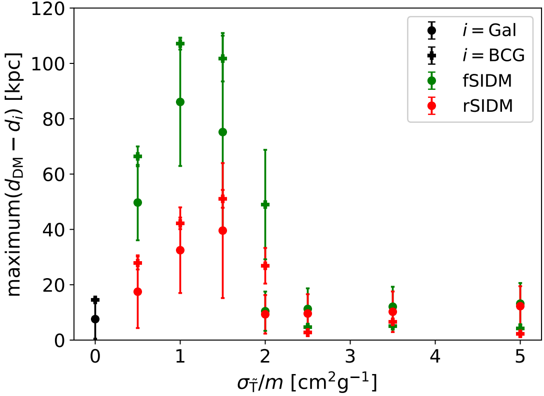


Fischer et al. 2021a

offsets are much larger for fSIDM than for rSIDM

Maximum Offset

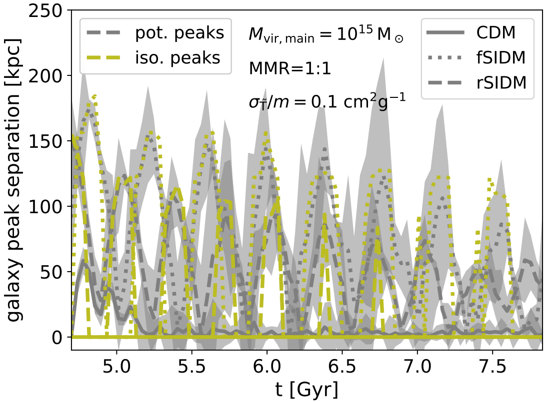
The maximum achievable offset is much larger for fSIDM than for rSIDM



Fischer et al. 2021a

Core Sloshing

There can exist separate galactic components at late times



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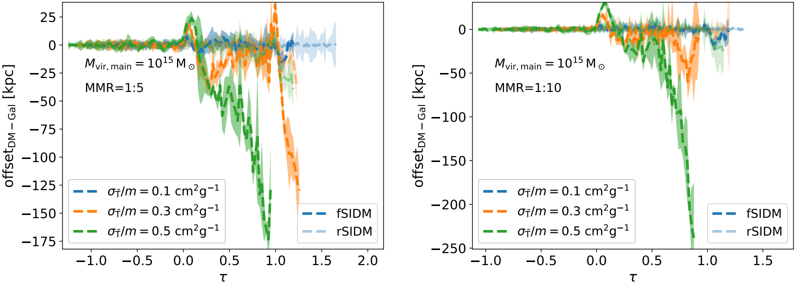
Unequal-Mass Merger: Offsets

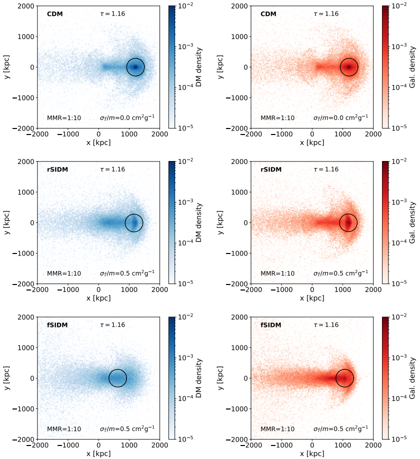


Fischer et al. 2021b

offsets are much larger for fSIDM than for rSIDM

Unequal-Mass Merger: Morphology

- physical density of subhalo in merger plane
- head on collision after second pericenter
- **DM and Galaxy distribution differ significantly between the DM models**



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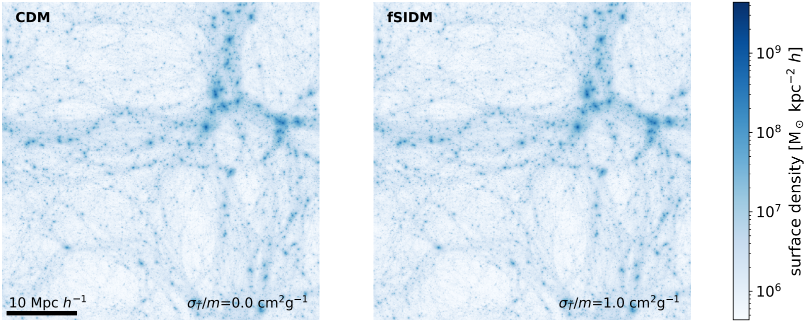
Cosmological Study

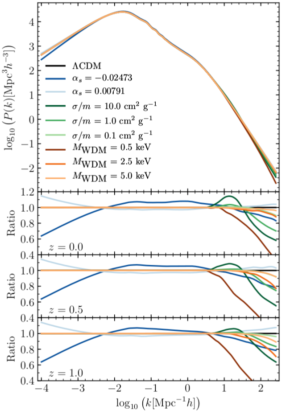


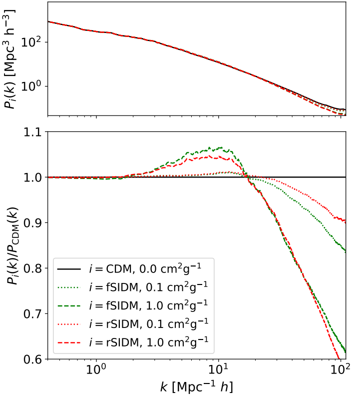
Fischer et al. 2022

No differences on large scales

Cosmological Study: Power Spectrum

Credits: Stafford et al. 2020



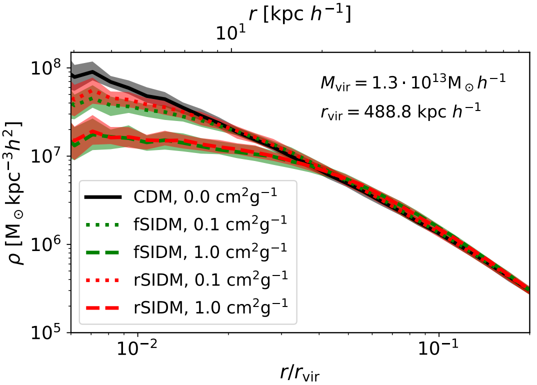


Fischer et al. 2022

Difference only on small scales

Cosmological Study: Density Profile

Self-interactions produce density cores

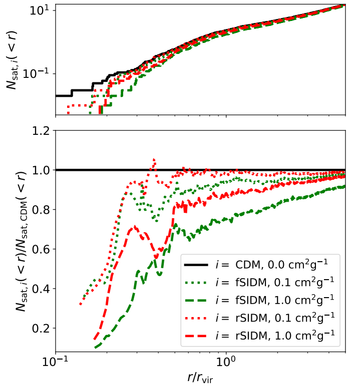


Fischer et al. 2022

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

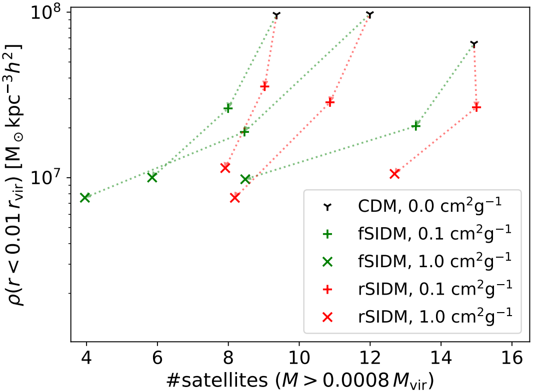


Fischer et al. 2022

Interestingly large suppression of satellites for fSIDM

Central Density vs. Number of Satellites

Qualitative difference between rare and frequent scattering



Fischer et al. 2022

Outlook

In future simulation we may 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 ($\lesssim 1\,\mathrm{cm}^2/\mathrm{g}$).