What can we learn from self-interacting dark matter?

Kai Schmidt-Hoberg
How to constrain the properties of dark matter?

- Our 'usual way' to search for dark matter
How to constrain the properties of dark matter?

- Our 'usual way' to search for dark matter
- A fourth way...

![Diagram showing different ways to search for dark matter: Indirect detection, Direct detection, Collider searches, and Self-interactions.](image)
Motivation: Cosmology

- The collisionless cold dark matter paradigm fits perfectly at large scales.
- There are however various discrepancies between N-body simulations of collisionless cold DM and astrophysical observations on galactic scales:
  - Cusp-vs-core problem
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![Image of Missing Satellites](image-url)
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Spergel & Steinhard: astro-ph/9909386
Aarsen, Bringmann, Pfommer, 1205.5809
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But it's clearly all **baryons**, as shown in 1702.xxxxx!

But **baryons** clearly cannot do it, see 1702.yyyyy!

Spergel & Steinhard: astro-ph/9909386
Aarsen, Bringmann, Pfrommer, 1205.5809
Motivation: Particle physics

- Dark sector often assumed to be simple, mainly because we don’t know much…
- Large self-interactions are natural in models with a more complex dark sector (e.g. with a new gauge group)
  - Strongly interacting DM
  - New light mediator in the dark sector

- Bonus: We can potentially study the dark sector even if DM has highly suppressed couplings to Standard Model particles.

Kusenko, Steinhardt: astro-ph/0106008
Feng, Kaplinghat, Yu: arXiv:0905.3039
Buckley & Fox: arXiv:0911.3898
Loeb & Weiner: arXiv:1011.6374
To be observable on astrophysical scales, self-interaction cross sections have to be large, typically

\[ \sigma/m_\chi \sim 1 \text{ cm}^2/\text{g} \sim 2 \text{ barns/GeV} \]

The nucleon nucleon scattering cross section \(~20\text{b}\) at low energies

The typical cross section of a WIMP is 20 orders of magnitude smaller!

Potential impact:
Evidence for DM self-interactions on astrophysical scales would rule out most popular models for DM, such as supersymmetric WIMPs, gravitinos, axions...
• Various astrophysical observations give constraints on SIDM:
  
  – Bullet cluster
    Randall et al 0704.0261
  
  – Subhalo evaporation rate
    Gnedin, Ostriker: astro-ph/0010436
  
  – Halo ellipticity
    Miralda-Escude (2002)
  
  – Core density in clusters and dwarfs
    Yoshida et al.: astro-ph/0006134
    Dave et al.: astro-ph/0006218

• SIDM probed at different velocities in different systems
  → a handle on the velocity dependence of the self scattering cross section!
Smoking gun signal? Separation between dark matter halo and stars of a galaxy falling into a galaxy cluster.
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Observed offset: 1.62 +/- 0.48 kpc

• Recently been observed in A3827

Massey et al., arXiv:1504.03388
Smoking gun?

- Smoking gun signal? Separation between dark matter halo and stars of a galaxy falling into a galaxy cluster

  Observed offset: 1.62 +/- 0.48 kpc

  How large a cross section would be needed to achieve such a separation?

- Recently been observed in A3827
  Massey et al., arXiv:1504.03388
Frequent vs. rare scatters

The momentum transfer in a collision of two DM particles is completely fixed by the scattering angle. The effective momentum transfer is given by

$$\sigma_T = 2\pi \int_{-1}^{1} \frac{d\sigma}{d\Omega} (1 - |\cos \theta|) \, d\cos \theta$$

This is the quantity typically studied.

However, this is not all that matters...

Can be obtained with **rare scatters and large momentum transfer** (e.g. isotropic scattering) or **frequent scatters with small momentum transfer** (e.g. long range interactions)

Kahlhoefer et al, 1308.3419
Distinguishing different types of SIDM

- **Effective drag force:** the DM subhalo retains its shape, while the distribution of stars are both shifted and deformed.
- **Contact interactions:** the DM subhalo is deformed due to the scattered DM particles leaving the subhalo in the backward direction.
- Potentially distinguishable!
Distinguishing different types of SIDM

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Velocity dependent self-interactions

> Idea: Relate core size of different systems to SIDM cross section

> DM self-interactions seem to depend on the typical relative velocity of DM particles.

> Seems to point to light mediator!

Loeb & Weiner: arXiv:1011.6374

> Consider a mediator with mass $m_{\text{med}} \sim m_{\text{DM}} v_{\text{DM}}$:

- Scattering for small momentum transfer ($q < m_{\text{med}}$) proportional to $1/m_{\text{med}}^4$

- Scattering for large momentum transfer ($q > m_{\text{med}}$) proportional to $1/q^4$

Kaplinghat et al., arXiv:1508.03339
Interesting feature: The relic abundance is typically set by annihilations into pairs of mediators (so-called dark sector freeze-out):

![Diagram of dark matter annihilation into mediators](image)
A new light mediator

- Interesting feature: The relic abundance is typically set by annihilations into pairs of mediators (so-called dark sector freeze-out):

- To avoid overclosing the Universe, the mediator should ultimately decay, so its couplings to SM states cannot be arbitrarily small.
Enhancement of DM self-interactions

- DM self-interactions are enhanced also by non-perturbative effects due to multiple mediator exchange.
- Scalar and vector mediators particularly interesting

Tulin et al., arXiv:1302.3898
Enhancement of DM self-interactions

- DM self-interactions are enhanced also by non-perturbative effects due to multiple mediator exchange.

- Scalar and vector mediators particularly interesting
- In this case also Sommerfeld enhancement of annihilations
  → very strong reionisation bounds from the CMB for s-wave annihilation

- Also the DM-nucleon scattering cross section is strongly enhanced for light mediators
Vector mediators

- Example: A new gauge boson from a spontaneously broken U(1)′ gauge group that mixes with the neutral gauge bosons of the Standard Model.

\[ \mathcal{L} \supset -g^V_\chi \phi^\mu \bar{\chi} \gamma^\mu \chi - \frac{1}{2} \sin \epsilon B_{\mu\nu} \phi^{\mu\nu} - \delta m^2 \phi^\mu Z_\mu \]

- Kinetic mixing: Mediator obtains photon-like couplings
- Mass mixing: Mediator obtains Z-like couplings

- Main difference:
  - A gauge boson with kinetic mixing is effectively stable below the electron threshold.
  - Mass mixing induces sizeable decay rates into neutrinos
For vector mediators, DM annihilation proceeds via s-wave:

- Large Sommerfeld enhancement for small velocities
- Strong constraints from indirect detection and CMB measurements

Bringmann et al., arXiv:1612.00845
Indirect constraints on vector mediators are very strong!

Allowed parameter space if the mediator decays only into neutrinos.

Constraints are essentially independent of the mixing between the mediator and the SM.

Only assumption: The two sectors are in thermal equilibrium in the early Universe.

But even for different temperatures in the two sectors, we find strong constraints.

Bringmann et al., arXiv:1612.00845
Constraints on scalar mediators

- For fermionic DM and scalar mediators annihilation proceeds via p-wave.
- No constraints from indirect detection or the CMB.
- Direct detection constraints are very strong for scalar mediators.
Direct detection constraints can be suppressed if the mediator couples very weakly to the SM.

If the couplings become very small, two new problems arise:

- The mediator can no longer bring the dark sector in thermal contact with the visible sector.
- The mediator obtains a lifetime $\tau > 1$ s, so that it typically decays during or after BBN.

Impossible to satisfy all requirements and have large self-interaction cross sections.
A mixed mediator (CP violation)

\[ \mathcal{L}_{\text{DM}} \supset y_\psi \cos \delta_\psi \; \bar{\psi} \psi \phi + y_\psi \sin \delta_\psi \; i \bar{\psi} \gamma^5 \psi \phi \]

- For \( \delta_\psi \sim 0 \) (like a scalar) DM self-interactions can be large.

- For \( \delta_{\text{SM}} \sim \pi/2 \) (like a pseudoscalar) direct detection constraints are strongly suppressed.

- Large allowed parameter space!

- Constraints on the CP-violating phase \( \delta_{\text{SM}} \) (e.g. from electron EDMs) can be satisfied even for very light mediators as long as \( y_{\text{SM}} \) is sufficiently small \( (y_{\text{SM}} \ll 10^{-2}) \).
The return of CMB constraints

- Central problem: The fact that annihilation can only proceed via p-wave was a consequence of CP conservation.

- As soon as $\delta_\psi$ is not exactly zero, s-wave annihilation is again possible and will receive huge Sommerfeld enhancement.
Future directions for light mediators

- There are a number of ways to evade the various constraints
  - Inert decays of the mediator, for example into (sterile) neutrinos
  - Thermalization via a different mechanism (possibly leading to different temperatures during freeze-out)
  - No thermalization (DM production via the freeze-in mechanism)
  - Suppressed couplings to quarks (to evade direct detection constraints)

- Nevertheless, constraints from BBN and from the CMB are very generic and will generally be relevant to any model of DM interacting via a new light mediator.

- Exciting phenomenology and interesting model-building challenges!
Self interacting dark matter could solve some problems of the collisionless cold dark matter paradigm and can arise naturally in more complex dark sectors.

Orthogonal handle on properties of DM: We can potentially study the dark sector even if DM has highly suppressed couplings to Standard Model particles.

Can potentially distinguish effective drag forces (from frequent self-interactions) and rare self-interactions.

Also could infer the velocity dependence of the cross section.

The simplest possibilities (scalar or vector mediator coupling to fermionic dark matter with no additional new states) are in strong tension with direct and indirect detection experiments.

One simple way out is spontaneous CP violation in the dark sector.

Huge possible impact, ruling out WIMPs, axions, gravitinos,...
Thank you!