Self-interacting dark matter science with galaxy-scale strong lenses

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Self-interacting dark matter

Acronym clarity: for cosmology/astrophysics SIDM = “self-interacting dark matter”

Characterized by a small but non-zero cross section for self-interaction $\sigma$ between dark sector particles

Number of interactions in a Hubble time

$$N \sim \langle \sigma v \rangle \times \rho \times t$$

$$N \sim 10^{-4} \left( \frac{\sigma}{1 \text{ cm}^2 \text{g}^{-1}} \right) \left( \frac{\rho}{\rho_{\text{crit}}} \right) \left( \frac{v}{1000 \text{ km s}^{-1}} \right) \left( \frac{t}{13.7 \text{ Gyr}} \right)$$

-> effectively collisionless (cold dark matter) unless density is extremely high
effectively collisionless unless density is extremely high

effectively collisionless outside of dark matter halos
SIDM alters the internal structure of halos

\[ N \sim 10^{-4} \left( \frac{\sigma}{1 \text{ cm}^2 \text{g}^{-1}} \right) \left( \frac{\rho}{150 \, M_\odot \text{kpc}^{-3}} \right) \left( \frac{v}{1000 \text{ km s}^{-1}} \right) \left( \frac{t}{13.7 \text{ Gyr}} \right) \]

For a cluster-mass halo \( M \sim 10^{14} \, M_\odot \):  
velocity dispersion \( \sim v \sim 1000 \text{ km s}^{-1} \)  
\( \rho \sim 10^6 \, M_\odot \, \text{kpc}^{-3} \)  
\( N \sim 1 \)

For a 10^7 solar mass subhalo or field halo:  
\( v \sim 5 \text{ km s}^{-1} \)  
\( \rho \sim 10^8 \, M_\odot \, \text{kpc}^{-3} \)  
\( N \sim 3 \)
SIDM alters the internal structure of halos

SIDM drives core formation in halos

Nishikawa et al. (2020)
SIDM alters the internal structure of halos

SIDM can lead to “gravothermal catastrophe” or core collapse.

Dwarf 1
$M_{200}^{IC} : 2 \times 10^9 M_{\odot}$
$c_{200}^{IC} : 29.5$
$r_{per} : 26 \text{ kpc}$
Small-Scale Challenges to the ΛCDM Paradigm

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Why care?

-> SIDM potentially resolves “challenges” to LCDM on sub-galactic scales
What implications does SIDM have for astrophysics?

Different halo masses ->
  different velocity dispersions ->
constraints on velocity-dependent cross sections
What implications does SIDM have for astrophysics?

Viable SIDM models have velocity-dep. interactions.

Stringent upper limits from galaxy clusters.

Large amplitude cross section in dwarf galaxies and galaxies.

Kaplinghat et al. (2016)
What implications does SIDM have for astrophysics?

viable SIDM models have velocity-dep. interactions

Below $10^8$ solar masses, halos are dark we can’t infer their density profile through stellar dynamics

Solution: strong gravitational lensing
Intro to strong lensing

Movie by Yashar Hezaveh
Gravitational lensing: deflection of light by gravitational fields

- Massive object
- Observed source
- True source
- Light travel path
Strong lensing produces multiple images of a single source.
Galaxy-scale strong lens

Four images of a background quasar

Galaxy doing the lensing

Lensed image of the galaxy that surrounds the quasar

ESA/Hubble
Substructure lensing

CDM and SIDM predict that galactic halos contain an abundance of substructure

-> subhalos around a galaxy
  -> field halos along the line of sight
CDM and SIDM predict that galactic halos contain an abundance of substructure:

- subhalos around a galaxy
- field halos along the line of sight
Image magnifications an extremely sensitive probe of low-mass substructure.
Image flux ratios impacted by structure along the entire line of sight -> potentially probe SIDM structure in the field across Gyr timescales
Can we use flux ratios to detect the structural properties of low-mass SIDM halos?

Strong lensing signatures of self-interacting dark matter in low-mass halos

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Posted to the arXiv in May
The SIDM cross section

Assume a weak, long-range interaction with $v^{-4}$ behavior at high $v$

$$\sigma(v) = \sigma_0 \left( 1 + \frac{v^2}{v_0^2} \right)^{-2}$$

All structure formation properties depend only on the thermal average and the halo velocity dispersion $v(M)$

$$\langle \sigma v \rangle = \frac{1}{2\sqrt{\pi} \ v (M_{\text{halo}})^3} \int_0^\infty \sigma(v') v' \times v'^2 \exp \left( \frac{-v'^2}{4 \ v (M_{\text{halo}})^2} \right) dv'$$
The SIDM cross section

\[ \sigma(v) = \sigma_0 \left( 1 + \frac{v^2}{v_0^2} \right)^{-2} \]

Permits a large cross section on sub-galactic scales, while evading constraints from larger scales.
Lensing requires density profiles
1) core formation

We use the “fitting function” of Kaplinghat et al. (2016) to compute the core size

\[ \rho_{\text{NFW}}(r_1) \langle \sigma v \rangle t(z) = 1 \]

\[ + \]

\[ \nu_{\text{rms}}^2 \nabla^2 \log \rho_{\text{SIDM}} = -4\pi G \rho_{\text{SIDM}} \]

\[ + \]

Boundary conditions at \( r_1 \)

\[ = \]

Central core density \( \rho_0 \)
Lensing requires density profiles
1) core formation

Core size as a function of halo mass
Lensing requires density profiles
2) core collapse

\[ t_{\text{relax}} = \frac{1}{\langle \sigma v \rangle \rho} \]

Model based on results by Nishikawa et al. (2020) and the relation time

Tidally disrupted halos (subhalos around the main deflector)
collapse after \( \sim 10 t_r \).

Field halos collapse after \( \sim 100 t_r \).

\( \pm \) scatter around these times to account for different tidal stripping histories, mergers, etc.
Modeling core collapse

![Graph showing relaxation time as a function of $M_{200}$ and corresponding halo mass scale $M_0$. The graph includes different lines for various initial conditions, such as $\sigma_0 = 35$ cm$^2$ g$^{-1}$, $v_0 = 10$ km s$^{-1}$, etc.]

- Relaxation time [Gyr]
- $M_{200}$ [$M_\odot$]
- $M_0$ scale
Modeling core collapse

- $10^6 < \frac{M_{200}}{M_\odot} < 10^8$
- $10^8 < \frac{M_{200}}{M_\odot} < 10^{10}$
Halo density profiles

\[ \rho \left[ M_\odot \text{kpc}^{-3} \right] \]

- NFW profile
- isothermal solution
- cored NFW profile
- core collapsed profile
- \( r_1 \)

\[ \beta = 0.37 \]

\[ r / r_s \]
Lensing properties of SIDM halos

Magnification cross section for a single halo

$M_{200} = 5 \times 10^7 M_\odot$
source size 35 pc

- NFW
- cored $\beta = 0.36$
- core collapsed
Lensing properties of SIDM halos

Below: a 2D representation of a lensing mass distribution in 3D (including line of sight)

Cold dark matter
Forecasts for lensing constraints on SIDM

-> use simulated datasets to test a particular model for SIDM physics

Constraints on the cross section combining a sample of lenses
DM theory (A specific SIDM model)

Realizations of dark matter structure

A background source model

Gravitational lensing computations

Main deflector lens model

Measurement uncertainties

Model-predicted flux ratios

Observed flux ratios

Posterior probability distributions/inferences obtained through summary statistics

Inference framework -> applied 500,000 times per lens

Things we know or want to infer nuisance parameters
Example inference with CDM “truth”

- **mid-IR flux ratios**
  - uncertainties 2%

- **narrow-line flux ratios**
  - uncertainties 4%

**Input:**
- $\sigma_0 = 0.5 \text{ cm}^2 \text{ g}^{-1}$
- $v_0 = 10 \text{ km s}^{-1}$
Forecasts: ruling out SIDM

Recast constraints in terms of $\sigma_{20} \equiv \sigma (v = 20 \text{ kms}^{-1})$

Mid-IR flux ratios are more constraining because the background source is more compact.

Constraints scale with the amplitude of subhalo mass function because subhalos can core collapse.
Forecasts: ruling out CDM

Recast constraints in terms of $\sigma_{20} \equiv \sigma(v = 20 \text{ km s}^{-1})$

Phrase results in terms of the relative likelihood of SIDM:CDM

Assuming SIDM
$\sigma_0 = 40 \text{ cm}^2 \text{g}^{-1}$
$v_0 = 30 \text{ km s}^{-1}$

mid-IR flux ratios
2% uncertainty
narrow-line flux ratios
4% uncertainty
Take home messages:

1) Strong lensing offers a novel means to detect SIDM structure on sub-galactic scales across cosmological distances. Lensing probes the cross section at velocities below 30 km/sec, independent of systematics associated with stellar dynamics.

2) Constraints scale with the amplitude of subhalo mass function.
   -> more core collapsed subhalos give stronger constraints.

3) Mid-IR datasets that we will obtain through JWST GO-02046 (PI Nierenberg) will give the strongest constraints.
Supplementary material: halo density profiles

\[ \rho(x, \beta, \tau) = \frac{\rho_s}{(x^a + \beta^a)\left(1 + x^2\right)^2} \frac{\tau^2}{\tau^2 + x^2} \]

Cored, truncated NFW profile with beta = rc / rs

\[ \rho(r) = \rho_0 \left(1 + \frac{r}{b}\right)^{-\gamma} \]

A cored power-law profile with gamma around -3 (Turner et al. 2020)

Fix the normalization by conserving mass between NFW profile and core collapsed profile within 2 * r_s
Computing the likelihood $p(\sigma_{20} | \text{data})$

$\rightarrow$ remove the implicit prior on $\sigma_{20}$ that corresponds to the uniform prior on $\sigma_0$ and $\nu_0$
<table>
<thead>
<tr>
<th>parameter</th>
<th>description</th>
<th>prior</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_0$ [cm$^2$ g$^{-1}$]</td>
<td>asymptotic value of the interaction cross section at low velocity (Equation 1)</td>
<td>$U$ (0.5, 50)</td>
</tr>
<tr>
<td>$\sigma_{20}$ [cm$^2$ g$^{-1}$]</td>
<td>cross section amplitude at 20 km s$^{-1}$ (derived quantity)</td>
<td></td>
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<tr>
<td>$v_0$ [km s$^{-1}$]</td>
<td>velocity scale of the SIDM cross section $\sigma(v) \propto v^{-4}$ for $v &gt; v_0$ (Equation 11)</td>
<td>$U$ (10, 50)</td>
</tr>
<tr>
<td>$b$</td>
<td>core size in units of $r_s$ of core collapsed halos (Equation 11)</td>
<td>$U$ (0.01, 0.05)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>logarithmic slope of core collapsed halo density profiles (Equation 11)</td>
<td>$U$ (2.9, 3.1)</td>
</tr>
<tr>
<td>$\Sigma_{sub}$ [kpc$^{-2}$]</td>
<td>subhalo mass function normalization (Equation 14)</td>
<td>$\mathcal{N}$ (0.050, 0.010)</td>
</tr>
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<td></td>
<td>tidal stripping efficiency $0.5 \times$ Milky Way</td>
<td>$\mathcal{N}$ (0.032, 0.007)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>logarithmic slope of subhalo mass function (Equation 14)</td>
<td>$U$ (-1.95, -1.85)</td>
</tr>
<tr>
<td>$\delta_{los}$</td>
<td>rescales the line of sight halo mass function $10^6 &lt; m &lt; 10^{10} M_\odot$ (Equation 16)</td>
<td>$U$ (0.8, 1.2)</td>
</tr>
<tr>
<td>$\sigma_{src}$ [pc]</td>
<td>background source size nuclear narrow-line emission mid-IR emission</td>
<td>$U$ (25, 60) $U$ (0.5, 5)</td>
</tr>
<tr>
<td>$\gamma_{macro}$</td>
<td>logarithmic slope of main deflector mass profile</td>
<td>$U$ (1.9, 2.2)</td>
</tr>
<tr>
<td>$a_4$</td>
<td>controls boxyness/diskyness of main deflector mass profile</td>
<td>$\mathcal{N}$ (0, 0.01)</td>
</tr>
<tr>
<td>$\delta_{xy}$ [m.a.s.]</td>
<td>image position measurement uncertainty</td>
<td>$\mathcal{N}$ (0, 3)</td>
</tr>
<tr>
<td>$\delta f$</td>
<td>image flux measurement uncertainties mid-IR narrow-line</td>
<td>2% 4%</td>
</tr>
</tbody>
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