SELF-INTERACTING DARK MATTER

Manoj Kaplinghat, University of California, Irvine, USA
Plan

* Motivations for SIDM from astrophysics
* SIDM predictions for the density profile of dark matter
* Direct searches for SIDM (illustrated through a simple example)
* Indirect searches for SIDM (illustrated through a simple example)
What is SIDM?

For this talk, we will define Self-Interacting Dark Matter (SIDM) as a form of Cold Dark Matter that has a significant elastic scattering cross section. In particular, the dark matter perturbation power spectrum is unchanged from the model without self-interaction.
Why bother with SIDM?
(After all, cold dark matter does so well.)

* Cold non-interacting dark matter (CDM) is a useful approximation. Whether it breaks down on sub-parsec scales or kilo-parsec scales depends on the particle physics model.

* Visible sector is complicated. Perhaps the “dark sector” (five times as abundant) is also complicated and we have much to explore.

* Galaxy formation in LCDM/LSIDM/LWDM models should serve as a final check that we fully understand the dark sector.

* SIDM seems to be a better match to observations.
Bullet cluster constrains $\sigma/m$ to be less than about 0.7 cm$^2$/g. At around this value, observable effects can be seen in dwarf galaxies to clusters (so as to solve some of the small-scale puzzles).

Just as importantly, SIDM cross sections decrease with increasing relative velocity, making the constraints highly model-dependent.

Markevitch et al, Clowe et al
Aren’t these cross sections crazy big?

- A simple model is one where the dark matter interacts through gravity and a new force. *(More on this later.)* If this new force carrier has $O(\text{MeV})$ mass, then you get self-interaction cross sections large enough to produce observable effects in the centers of galaxies.

- Another way to think about this is to imagine a hidden sector not unlike our own (closer in spirit to the SIDM model proposed by Spergel and Steinhardt). See next slide.
Example: neutron-proton scattering cross section

Realistically, SIDM model cross sections will vary significantly over the range of velocities probed by dwarf galaxies to clusters. Clusters and dwarfs are important anchors.

$0.05 \text{ MeV} = \frac{1}{2} \text{ 1 GeV } v^2$
$v = 0.01 \text{ c } = 3000 \text{ km/s}$

**Bullet cluster relative velocity**

$0.005 \text{ MeV} = \frac{1}{2} \text{ 1 GeV } v^2$
$v = 0.003 \text{ c } \sim 1000 \text{ km/s}$

**Musket Ball relative velocity**
If SIDM is the dominant form of dark matter, does this mean that the SUSY framework is wrong?

* No. SUSY (or some other BSM physics) framework could be the same as many particle theorists expect and LHC may discover this new physics eventually.

* $\Omega_{\text{LSP}} \ll \Omega_{\text{DM}}$, which is entirely natural.

* No reasonable argument why $\Omega_{\text{LSP}} = \Omega_{\text{DM}}$.

* SIDM can be part of the SUSY framework in the context of hidden sectors.
Dark matter densities in the inner regions of galaxies

<table>
<thead>
<tr>
<th>Clusters of galaxies (10^{14}-10^{15} , M_{\odot})</th>
<th>Scales of interest (distance from center of galaxy)</th>
<th>Cores (region of roughly constant density)</th>
<th>Lower densities than predicted by CMD-only simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-50 kpc</td>
<td>?</td>
<td>Sand et al; Newman et al</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dwarf galaxies; More massive low surface brightness galaxies (10^{10}-10^{11} , M_{\odot})</th>
<th>Scales of interest (distance from center of galaxy)</th>
<th>Cores (region of roughly constant density)</th>
<th>Lower densities than predicted by CMD-only simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5-5 kpc</td>
<td>Oh et al (THINGS); Simon et al; Kuzio de Naray et al</td>
<td>Same as box on left.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dwarf galaxies within the Milky Way (satellites) (10^{9}-10^{10} , M_{\odot})</th>
<th>Scales of interest (distance from center of galaxy)</th>
<th>Cores (region of roughly constant density)</th>
<th>Lower densities than predicted by CMD-only simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3-1 kpc</td>
<td>Walker and Penarrubia</td>
<td>Too big to fail?</td>
<td></td>
</tr>
</tbody>
</table>
Disentangling dark and luminous matter in clusters of galaxies

- Massive clusters, with total mass in the vicinity of $10^{15}$ Msun.
- Weak lensing, strong lensing, kinematics of stars in the central galaxy.

Newman et al. 2012
Clusters of galaxies

Massive clusters, with total mass in the vicinity of $10^{15} \, M_{\odot}$.

Weak lensing, strong lensing, kinematics of stars in the central galaxy.

``gNFW'' density $\propto 1/r^\beta(r_s+r)^{3-\beta}$

``cNFW'' density $\propto 1/(r+\text{core})(r_s+r)^2$
Nearby dwarf galaxies

Abundance matching predicts that all these galaxies should be in halos with masses \(~10^{10}\) M\(_{\odot}\) or larger
The THINGS dwarfs in some more detail

Close-by (< 5 Mpc), DM dominated, low mass (V ~ 30-100 km/s)

$$\alpha = \frac{\partial \ln(\text{Density})}{\partial \ln(r)}$$

Oh et al 2011 (THINGS)
Nearby low surface brightness (spiral) galaxies

Note the linear rise in rotation velocity at small radii for all galaxies => constant density cores

Kuzio de Naray, McGaugh, de Blok, Bosma 2005, 2006
Kuzio de Naray, Martinez, Bullock, Kaplinghat, ApJL 2010
Scatter in core sizes and densities of spiral galaxies

How do you explain the scatter and correlations?

Adding feedback interesting for SIDM since you already start with a core.
Milky Way satellites

Discovered in SDSS
Pre-SDSS
MW 1: Too big to fail? The most massive apparently don’t light up...

- Subhalos from Aquarius simulation [Springel et al 2009] shown
- Bright satellites shown with estimated masses within half-light radii
- Too many dense (massive) subhalos


Radius enclosing half the luminosity, $r_h$ (parsec)

- Size of points scales as Luminosity$^{1/4}$
- Lines are LCDM (Aquarius) profiles
MW 1: Too big to fail? The most massive apparently don’t light up...

Magellanic clouds

Star formation not UV-suppressed at all redshifts

Boylan-Kolchin, Bullock, Kaplinghat 2012
Perhaps this isn’t really a problem because MW is an outlier

The comparison to LCDM expectations is not valid because the Milky Way is not as massive as the range (9e11 to 2e12 Msun) in Aquarius [Wang, Frenk, Navarro and Gao 2012]

- Dynamics of Large Magellanic Cloud (rare if not bound)
- Kinematics of Leo I (not bound if MW virial mass less than ~1e12 Msun). See recent measurements by Boylan-Kolchin et al 2012.
- See comment about Andromeda.

Milky Way just doesn’t have these subhalos. Live with it! [Purcell and Zentner 2012]

- Must explain Magellanic Clouds, which are more massive than the dwarf satellites
- Analogs of satellites in the outskirts of MW and Andromeda (Kirby et al, in prep)

Boylan-Kolchin, Bullock, Kaplinghat 2012
Two stellar pops with different spatial distributions =>
Two mass measurements at different (half-light) radii

Amorisco and Evans MNRAS 411, 2118 (2011)
Feedback from energy input due to supernovae can create cores. Feedback designed to explain the lack of bulge. [Governato et al 2012]

How realistic is this feedback and how do we test it?

Can this explain the larger LSBs?
Use feedback to reduce the central densities of the most massive subhalos that host the visible bright Milky Way satellites


The meagre stellar content of the satellites is a stringent limitation.
The nature of the star formation in the subhalos varies with mass. All of the more massive, luminous satellites (classical dSphs, but some are too faint.) The nature of the star formation in the subhalos varies with mass. All of the more massive, luminous satellites (classical dSphs, but some are too faint.)

The nature of the star formation in the subhalos varies with mass. All of the more massive, luminous satellites (classical dSphs, but some are too faint.)

Satellite dynamics have extended SFHs (in line with observational data, e.g., Kravtsov 2010; Rashkov et al. 2012; Hearin et al. 2011). In halos with 20 km/s typically lose their gas prior to accretion onto the parent halo. Heating from the uniform UV background, combined with early star formation and SN feedback, removes a substantial amount of gas from these satellites (too big to fail?)

Many subhalos lose most of their gas after infall and surround gas, shutting off star formation for a period of time until the gas can again cool and condense. The subsequent SN feedback following a burst of star formation heats the gas cools in the central galaxy. The subsequent SN feedback following a burst of star formation heats the gas cools in the central galaxy.

While some subhalos lose their gas nearly instantly at infall, some are capable of retaining more of their gas for longer, allowing them to lose a substantial amount of gas from these satellites (too big to fail?)

Feedback following a burst of star formation heats the gas cools in the central galaxy. The subsequent SN feedback following a burst of star formation heats the gas cools in the central galaxy.
Inside or outside; they seem to look the same

* Comparison of satellites of Andromeda and Milky Way to similar galaxies in the outskirt may be an excellent way forward to disentangle the issues of the effect of environment.

Kirby et al, in prep
## Solutions and questions

<table>
<thead>
<tr>
<th>Model</th>
<th>Satellites</th>
<th>Spirals</th>
<th>Clusters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LCDM + Feedback</strong></td>
<td>• MW and And mass &lt; 1E12 Msun?</td>
<td>• Feedback reasonable?</td>
<td>• AGN feedback?</td>
</tr>
<tr>
<td></td>
<td>• MW and And outliers?</td>
<td>• Explain large LSBs?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Environment?</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Cores?</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LWDM (no feedback)</strong></td>
<td>• No large cores.</td>
<td>• Likely same as LCDM for the more massive ones.</td>
<td>• Same as LCDM.</td>
</tr>
<tr>
<td></td>
<td>• Number of satellites consistent with MW/And?</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LSIDM (no feedback)</strong></td>
<td>• Particle physics model?</td>
<td>• Reproduce scatter?</td>
<td>• SIDM in stellar-dominated limit?</td>
</tr>
</tbody>
</table>
Self-interacting dark matter solution


* **Relic density: thermal or asymmetric**
Self-interacting dark matter solution

* Milky Way bright satellite problem can be solved with the production of large CORES. [Vogelsberger, Zavala and Loeb 2012, Vogelsberger, Zavala and Walker 2012]
SIDM is the same as CDM on large scales

Constant cross-section over mass of 1 cm$^2$/g

Rocha, Peter, Bullock, Kaplinghat, Garrison-Kimmel, Onorbe, Moustakas 2012
SIDM is the same as CDM on large scales

Constant cross-section over mass of 1 cm$^2$/g

Rocha, Peter, Bullock, Kaplinghat, Garrison-Kimmel, Onorbe, Moustakas 2012
Sizes of cores in constant cross section SIDM

Outside this core radius, things look like CDM. Large scale structure success carries over.

For a cross section that does not vary much with velocity, the core size is roughly a fixed fraction of RMAX. For $\sigma/m = 1\text{cm}^2/\text{g}$ core is about 0.3 RMAX (with scatter).

$r_s \sim \text{RMAX}/2.2$

Rocha, Peter, Bullock, Kaplinghat, Garrison-Kimmel, Onorbe, Moustakas 2012
The core size-halo mass relation

Vogelsberger, Zavala and Walker 2012: Cross section $\geq 0.5 \text{ cm}^2/\text{g}$ is needed to explain the densities of MW satellites
SIDM predictions for the inner density profile

Isothermal core

\[ V_{\text{max}} = 159 \text{ km/s} \]
\[ r_s = 20 \text{ kpc} \]

\[ M_{\text{vir}} = 1 \times 10^{12} M_\odot \]
\[ r_s = 20 \text{ kpc} \]

One interaction on average

Rocha, Peter, Bullock, Kaplinghat, Garrison-Kimmel, Onorbe, Moustakas 2012
Simple analytic model explains core sizes

* Compute radius ($r_1$) at which you have one interaction on average over the age of the galaxy

$$\Gamma(r_1) = \rho(\sigma/m) v_{\text{rel}} = 1/\text{age}.$$  

* Total mass and kinetic energy within $r_1$ is unchanged due to self-interactions (matching condition)

* Assume equilibrium and solve Jeans equation with matching conditions.
Constraints from shapes of halos

Peter et al.

Figure 2. Surface density profiles for the same halo shown in Fig. 1, now projected along the intermediate axis. Deviations from axisymmetry are highest along this projection.

Figure 3. Host halo shapes in shells of radius scaled by the virial radius in three virial-mass bins as indicated. The black solid lines denote the 20th percentile (lowest), median (middle), and 80th percentile (highest) value of $c/a$ at fixed $r/r_{\text{vir}}$ for CDM. The blue dashed lines show the median and 20th/80th percentile ranges for $\sigma/m = 1$ cm$^2$/g, and the green dotted lines show the same for $\sigma/m = 0.1$ cm$^2$/g. There are 440, 65, and 50 halos in each mass bin (lowest mass bin to highest).

3 SIMULATED HALO SHAPES

3.1 Preliminary Illustration

Before presenting a statistical comparison of CDM and SIDM halo populations, we provide a pictorial illustration of how an individual halo changes shape as we vary the cross section. The columns of Figs. 1 and 2 show surface density maps for the same halo simulated in CDM, SIDM$_{0.1}$, and SIDM$_{1}$ from left to right. In Fig. 1, we project the halo along the major axis, which is the orientation that maximizes the strong-lensing cross section (van de Ven, Mandelbaum & Keeton 2009; Mandelbaum, van de Ven & Keeton 2009). In Fig. 2, we project the halo along the intermediate axis, which is the orientation that deviates the most from axisymmetry.

Constraints not better than about 1 cm$^2$/g.
Constraints from shapes of halos

Shapes of LoCuSS clusters (Richards et al. 2010) disfavors $\sigma/m = 1$ cm$^2$/g (assuming constant cross section).

Peter, Rocha, Bullock, Kaplinghat 2012
What happens in the presence of baryons?

\[ \nabla_x^2 \left( h(\vec{x}) + \frac{\Phi_B(\vec{x})}{\sigma_0^2} \right) + a_0 \exp \left( h(\vec{x}) \right) = 0 \]

\[ \vec{x} = \frac{\vec{r}}{r_0} \]

\[ a_1 = -\frac{\Phi_B(0)}{\sigma_0^2} \]

\[ a_0 = \frac{4\pi G N \rho_{\text{core}} r_0^2}{\sigma_0^2} \]

Core radial velocity dispersion (km/s)

Milky Way

Contour of core radius = 0.34 kpc

Kaplinghat, Linden, Yu, in prep
Why is the core radius small when baryons dominate?

Solution to isotropic Jeans equation
SIDM cores

- SIDM halo core sizes are small in galaxies that are dominated by stars in the center. Core size is correlated with the scale length of the potential well (set by the stars). A disk-halo conspiracy of sorts!

- Central densities much higher than predicted by dark matter only SIDM simulations in galaxies where stars dominate the potential well in the center. How much higher depends on other factors such as feedback. (See next slide.)

- In less luminous galaxies, core sizes are closer to the dark matter only SIDM predictions we have seen before.

- Halo shape should follow the potential of the stars in the regions where stars dominate!
Central SIDM density in baryon dominated regions

Adiabatic compression

No adiabatic compression

Kaplinghat, Linden, Yu, in prep
Core sizes in clusters

* Even for $\sigma/m = O(0.01 \text{ cm}^2/\text{g})$ the isothermal solution we just discussed should be applicable to clusters of galaxies.

* Predicted core sizes for Newman et al clusters is around a few kiloparsecs -- consistent with the observations.
A simple SIDM model

\[ \mathcal{L} = g_\chi \bar{\chi} \gamma^\mu \chi \phi_\mu + m_\chi \bar{\chi} \chi + m_\phi^2 \phi^\mu \phi_\mu \]

Relic density depends on \( \chi \bar{\chi} \rightarrow \phi \phi \)

Lot of work on hidden sector dark matter models like this. This model was popularized by Arkani-Hamed et al 2009 in the context of explaining PAMELA.

\[ V = \pm \frac{\alpha_x}{r} \exp \left( -m_\phi r \right) \]

Similar SIDM phenomenology in SU(N) hidden sectors

[Boddy, Feng, Kaplinghat and Tait, in prep]
A simple SIDM model

- Born: $\alpha_X m_X / m_\phi << 1$
- Classical: $m_X v / m_\phi >> 1$

![Graph showing velocity-dependence of cross section](image-url)

Tulin, Yu, Zurek 2012
A simple SIDM model

The mediator should decay before BBN. Unless there are light dof in the hidden sector, this should happen through the coupling to SM fields. **Direct and indirect searches.**

If there are light dof in the hidden sector, then **Neff > 3.045.**

We also consider Higgs portal and Z-mixing. Picture qualitatively similar.

Kaplinghat, Tulin, Yu, in preparation
A simple SIDM model

The mediator should decay before BBN. Unless there are light dof in the hidden sector, this should happen through the coupling to SM fields. **Direct and indirect searches.**

If there are light dof in the hidden sector, then **Neff > 3.045.**

We also consider Higgs portal and Z-mixing. Picture qualitatively similar.
A simple SIDM model

For light mediators (less than 100 MeV), decays only possible to electrons, positrons, neutrinos and photons.

For the previous kinetic mixing case, decays to electrons and positrons only.

**Strong constraints from positron fraction measurements in AMS-02.**
A simple SIDM model

Inverse Compton due to electrons and positrons leads to gamma rays from Galactic Center

Kaplinghat, Linden, Yu, in preparation

Leftovers. Researchers began with a map of the gamma-ray emissions from near the galactic center (left) and subtracted the contributions from known sources (white circles) and other backgrounds to produce a map of emissions that could come from dark matter.

Credit: Kevork Abazajian/University of California, Irvine

The coming decade will be the decade of dark matter, some scientists say, as efforts to detect the mysterious stuff will either pay off or rule out the most promising hypothesis about what it is. But astronomers may have already detected signs of dark matter in the heart of our own Milky Way galaxy, a pair of astrophysicists now says.

Data from NASA's space-borne Fermi Gamma-ray Space Telescope reveal an excess of gamma-rays coming from the galactic center that could be produced as particles of dark matter annihilate one another, Kevork Abazajian and Manoj Kaplinghat of the University of California, Irvine, report in a paper posted to the arXiv preprint server. “There's definitely some source there, and it fits with the dark matter interpretation,” Abazajian says. But other researchers say the excess could be an artifact of the way Abazajian and Kaplinghat model the gamma-ray flux, or it could originate from more-mundane sources.

Astronomers have ample evidence that dark matter provides most of the gravity that keeps stars from flying out of the galaxies. And cosmologists have shown that it makes up 85% of all matter in the universe. But physicists don't know what dark matter is.

The leading hypothesis is that dark matter could be made up of weakly interacting massive particles, or WIMPs, which are predicted by some theories. WIMPs would be massive enough to produce lots of gravity but would otherwise interact with ordinary matter only very weakly. Each galaxy would form within a vast cloud of WIMPs.

Abazajian and Kaplinghat say that the more than 400 researchers working with the Fermi satellite may have already found that evidence. The two theorists analyzed data collected between August 2008 to June 2012, focusing on a 7-degree-by-7-degree patch of sky around the galactic center. For each of four energy ranges, they mapped the emission across the sky. They fit each map with a “baseline model” that included 17 point-like sources of gamma rays that Fermi had already found in that area, a “diffuse” background that accounts for the general emission from the galactic center, and a spatially uniform background.

They then fit the data with another model that included a contribution from dark matter annihilations, including theoretical estimates of the dark matter's distribution and how the particle annihilations produce gamma rays. Adding
Summary

- Last 5 years have seen a revival of small-scale issues
- New observations (Satellites, Spirals, Clusters)
- Progress in simulations with baryons
- Observations capable of resolving the innermost regions suggest that densities of dark matter are lower than dark-matter-only LCDM predictions.

- LSIDM provides an explanation while maintaining the success of LCDM on larger scales. Makes this an interesting model to study.
- In the baryon-dominated limit, core sizes set by the scale of the potential well.
- Many interesting particle models and a lot of physics still to be explored (including early universe).
- There are concrete predictions for direct and indirect searches of SIDM in the simplest models.