Cosmological Simulations With Self-Interacting DM

Miguel Rocha (UCI)
Santa Cruz 2012

Annika Peter  Manoj Kaplinghat  James Bullock  Shea Garrison-Kimmel’s  Jose Onorbe
Cosmological Simulations With Self-Interacting CDM

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Cosmological Simulations With Self-Interacting CDM

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With all the good things that "Coldness" brings

- Right Structure
- Right Clustering
- Right Abundances

All large scale properties
> ~1 Mpc
With all the good things that “Coldness” brings

- Right Structure
- Right Clustering
- Right Abundances

All large scale properties
> \( \sim 1 \) Mpc

We owe all this to just it being “Cold”!
Cold + ?
Cold + ?

What else can we add?
CDM + Self-Interactions?

Particle Physics Motivations:

Loeb & Weiner 2011, Stieie et al. 2011, Peter 2012
CDM + Self-Interactions?

Particle Physics Motivations:

- DM Self-Interactions as strong as the standard model
  strong interactions are allowed by primordial nucleosynthesis

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CDM + Self-Interactions?

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CDM + Self-Interactions?

Particle Physics Motivations:

- DM Self-Interactions as strong as the standard model strong interactions are allowed by primordial nucleosynthesis. Wimpless Miracle!
- They are a generic consequences of hidden-sector extensions to the Standard Model
- Even if dark sector particles have no couplings to the Standard Model particles they might experience strong interactions with themselves

CDM + Self-Interactions?

Astrophysical Motivations:

Spergerl & Steinhardt 2000

\[(\sigma/m = 0.1-100 \text{ cm}^2 / \text{g})\]
CDM + Self-Interactions?

Astrophysical Motivations:

- Lower central densities and form constant density cores in DM halos

Spergerl & Steinhardt 2000

\( \sigma/m = 0.1-100 \text{ cm}^2/\text{g} \)
CDM + Self-Interactions?

Astrophysical Motivations:

• Lower central densities and form constant density cores in DM halos

• Reduce the number if subhalos through subhalo evaporation

Spergerl & Steinhardt 2000

\(\sigma/m = 0.1-100 \text{ cm}^2 /\text{g}\)
### Previous Constraints

<table>
<thead>
<tr>
<th>Reference</th>
<th>Constraint [cm²/g]</th>
<th>From</th>
<th>Problem</th>
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<tbody>
<tr>
<td>Yoshidal et. al 2000</td>
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<td>Cluster density core</td>
<td>One cluster</td>
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<td>Dave et. al 2001</td>
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<td>Dwarfs density Cores</td>
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<td>Overestimated subhalo evaporation</td>
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<tr>
<td>Miralda-Escude 2002</td>
<td>$\sigma/m &lt; 0.02$</td>
<td>Halo shapes</td>
<td>Overestimated halo sphericity</td>
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<td>Randall et al. 2008</td>
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<td>Peter et al. arXiv:1208.3026</td>
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Modeling DM Self-Interactions

Revisiting the Simplest Model:

- Elastic
- Velocity Independent
- Isotropic

\[ \Gamma \simeq \rho \left( \frac{\sigma}{m} \right) v_{rms} \]
Modeling DM Self-Interactions

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Modeling DM Self-Interactions

Revisiting the Simplest Model:

• Elastic
• Velocity Independent
• Isotropic

\[ \Gamma \approx \rho \left( \frac{\sigma}{m} \right) v_{rms} \]

\[ \sigma/m \sim 0.1, 1 \text{ cm}^2 /\text{g} \]
Pair-wise Scattering

New algorithm derived self-consistently from the Boltzmann equation.

N-body particles are given a self-interacting smoothing length “hsi” to represent phase-space blobs.
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New algorithm derived self-consistently from the Boltzmann equation

N-body particles are given a self-interacting smoothing length “hsi” to represent phase-space blobs

We test it!

Rocha et al. 2012
arXiv:1208.3025
Simulation Set

50 Mpc/h Box: Np = 512^3, mp ~ 7e7 Msun

25 Mpc/h Box: Np = 512^3, mp ~ 9e6 Msun

Zoom halo Mvir = 5e11 Msun, mp ~ 1.5e6 Msun

Zoom halo Mvir = 1e12 Msun, mp ~ 2e5 Msun

All of them run with σ/m = 0, 1, 0.1 cm^2 /g
Identical Large-Scale Structure

$\Lambda + CDM$

$\sigma/m = 1 \text{ cm}^2 / \text{g}$

50 Mpc/h

Rocha et al. 2012
arXiv:1208.3025
Identical abundance of halos at all redshifts

![Graph showing the cumulative number of halos as a function of maximum circular velocity](Image)

Identical abundance of halos at all redshifts.
\( \Lambda + \text{CDM} \)

\( \Lambda + \text{SIDM} \)

\( \sigma/m = 1 \text{ cm}^2 / \text{g} \)

Rocha et al. 2012
arXiv:1208.3025

200 Kpc/h
Modest suppression of subhalo numbers

![Modest suppression of subhalo numbers](image_url)
“Cold” Dark Matter + Self-Interactions

Astrophysical Motivations:

• Lower central densities and constant density cores in DM halos

• Subhalo Evaporation

This is good!!
Given the beginnings of very small cores we are seeing with a correspondingly smaller core. A multiple parameter fit may reasonably well be characterized by a single scale radius Burkert profile. These Burkert fits are shown as blue dashed lines. They are good to Burkert profiles and can fully quantify the expected differences between CDM and SIDM. Profiling are not a good fit to our SIDM. Figure 4.

With self-interactions turned on, halo central densities decrease, forming cored density profiles. Solid lines are for the best NFW and Burkert fits. This brings to mind the rotation curves of the CDM and SIDM. The circular velocity curves for the same set of halos discussed above are shown in Figure 5. The SIDM rotation curves rise more steeply and have a lower normalization than for CDM within the radius of the corresponding CDM halo density profile (black solid line). Burkert profiles provide a reasonable fit to our SIDM halos. The circular velocity curves for the same set of halos discussed in the last paragraph. At radii well outside the core radius, it actually is slightly higher for the SIDM than for the CDM. This is due to the peak circular velocity, which is the NFW scale radius. Another qualitative fact worth noting is that the density profile, which is isothermal core, can be gained from studying their velocity dispersion. This observation invites us to consider a toy model for SIDM halos where the effect of SIDM particles redistribute energy and move towards a constant density. We will develop this model further to explain the difference in the data points is noticeable. This is due to the difference in the data points is noticeable. Another qualitative fact worth noting is that the density profile, which is isothermal core, can be gained from studying their velocity dispersion. This observation invites us to consider a toy model for SIDM halos where the effect of SIDM particles redistribute energy and move towards a constant density. We will develop this model further to explain the differences in the data points is noticeable. This is due to the difference in the data points is noticeable. Another qualitative fact worth noting is that the density profile, which is isothermal core, can be gained from studying their velocity dispersion. This observation invites us to consider a toy model for SIDM halos where the effect of SIDM particles redistribute energy and move towards a constant density. We will develop this model further to explain the differences in the data points is noticeable. This is due to the difference in the data points is noticeable.
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In the increase in the difference as one looks at the generally the reduction in substructure counts at a fixed evaporation arguments xGnedin x Ostriker, 00 fi.

Figure 6. We can understand both trends, the increase in the difference.

In CDM halos, the reduction in substructure counts at a fixed evaporation arguments xGnedin x Ostriker, 00 fi.

Figure 6. We can understand both trends, the increase in the difference.

The host (r)(b)

The central regions of the halo, using the results from the previous section.

Figure 6. We can understand both trends, the increase in the difference.

The associated virial masses for each host halo are shown in the diagrams.

In SIDM, the effects of self-interactions between dark matter particles in cosmological halos found in CDM halos, most of which are in the outer parts.

The maximum orbital speed of the subhalo at position.

Vmax = 159 km/s

Vmax = 846 km/s

rs = 20 kpc

rs = 249 kpc

σ/m = 1

σ/m = 0.1

Rocha et al. 2012

arXiv:1208.3025

Note: The diagrams show velocity dispersion profiles for six example halos from our SIDM case because of the mass differences.

The effect of SIDM self-interactions between dark matter particles in cosmological halos found in CDM halos, most of which are in the outer parts.

The rotation curves of the CDM and SIDM halos steeply and have a lower normalization than for CDM within the central regions of the halo.

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We can understand both trends, the increase in the difference.
The difference between the CDM and SIDM is more pronounced at large radii. Similarly, there appears to be slightly more reduction of the subhalos within the virial radius of each host. Here we show the cumulative number of subhalos larger than a given value. The associated virial masses for each host halo are shown in the figure.

The increase in destruction of subhalos with host halo mass is not strong, but it is clear from the above arguments that subhalos become cored can be gained from studying their velocity dispersion profiles compared to their CDM counterparts, as illustrated in simulations.

While the increase in destruction of subhalos with host halo mass is not strong, it is clear from the above arguments that subhalos converge more quickly in the SIDM compared to CDM. This effect is strongly dependent on the self-interaction cross section.

The rotation curves of the CDM and SIDM halos converge at large radii, but revealing different phenomenology near the halo centers. The rotation curves of the CDM and SIDM halos are shown in the figure.

The velocity dispersion of the halos shown in the figure is constrained by a single scale, and SIDM halos overshoot the CDM density profiles near the halo centers. The self-interaction cross section comes from analytic subhalo residents.

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The typical speed of the subhalo is similar to the rms speed of than large. Similarly, there appears to be slightly more reduction of but non-zero and that the effects appear to be stronger at small radii. We see that generating subhalos within half of the virial radius. We find that generating within the virial radius of each host and the right panel restricts the analysis to subhalos within one interaction on average over the lifetime of the halo. See Figure 7.

A distinct core is with a correspondingly smaller core. A multiple parameter fit may actually be slightly higher for the SIDM. It just so happens that for this cross section the radius where dark sonably well characterized by a single scale radius. Burkert profile.

Another qualitative fact worth noting is that the density profile for all subhalos is the mass density of the host halo and

$$\rho \propto \frac{1}{r^2}$$

functions as

$$\rho \propto \frac{1}{r^2}$$

steeply and have a lower normalization than for CDM within the central regions of the halo, and thus.

We can understand both trends. The increase in the difference of self-interactions between dark matter particles in cosmological systems.

Note that the density profiles are reasonably well characterized by a single scale radius. Burkert profile.

For the SIDM, we expect that as particles scatter in the center, those that gain energy will redistribute energy and move towards a constant density.

While the increase in destruction of subhalos with host halo mass is confined to a region smaller than a radius of about.

For a smaller cross section, the values are remarkably stable in proportion to the CDM. We will develop this model further to explain the increase in the difference of subhalos in the innermost region of the halo were accreted much worse at large radii. The blue arrows in each panel show the value of

$$\sigma/m = 1$$

$$\sigma/m = 0.1$$

Note that the peak circular velocity is confined to a region smaller than a radius of about.

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Figure 6.

\[ \Gamma \sim \rho \left( \frac{\sigma}{m} \right) v_{rms} \sim H_0 \]

\[ V_{\text{max}} = \begin{cases} 159 \text{ km/s} & r_s = 20 \text{ kpc} \\ 846 \text{ km/s} & r_s = 249 \text{ kpc} \end{cases} \]

\[ \sigma/m = \begin{cases} 1 \\ 0.1 \end{cases} \]

\[ r/s \]

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<thead>
<tr>
<th>Density</th>
<th>Velocity Dispersion</th>
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<td>CDM</td>
<td>SIDM _0.1</td>
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Rocha et al. 2012

arXiv:1208.3025
We will consider what happens when well resolved halos from our SIDM power-law in radius (Taylor & Navarro 2001). By noting that we use the observed fact that the phase space density is a realistic velocity distributions in because the dependence $V_{max}$. These perturbed halos were not included in the fit for the scal results with more appropriate profiles later. Our two constr for ease of comparison to the fits presented here and then chec this by either assuming an isothermal profile or something liker the radial velocity dispersion and mass) fully specify the d part of the scaling relations are well-cap interations. In reality, this divide will not be sharp but w which demarcates the inner region where self-interactions effeeffective from the outer region that is mostly undisturbed by t with their formation times, and in partic- for our combined sample of $\eta = 1$ cm$^2$/g. The final resultst the outer region. The main features of the scaling relations are well-cap.
Figure 11.

There is a one-to-one correlation indicating that the core sizes and central densities can be predicted from the velocity profile (Figure 10). The predictions are accurate within a factor of 3, which is indicated by the scatter in the data. The figure shows data from different SIDM models (SIDM\textsubscript{1}-50, SIDM\textsubscript{1}-25, SIDM\textsubscript{1}-Z12, SIDM\textsubscript{1}-Z11) and demonstrates that the predictions are consistent with observations.

**Up to a factor of 3 scatter**
### Comparison to observed core sizes

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<tr>
<th>Size Range (kpc)</th>
<th>10-75</th>
<th>95-155</th>
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<tr>
<td><strong>MW dSphs</strong></td>
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<td>700-1000 km/s</td>
<td>$6-2.5$ $10^{-2} \ M_\odot/\text{pc}^3$</td>
<td>$0.5-0.4$ $10^{-2} \ M_\odot/\text{pc}^3$</td>
<td>$4 \times 10^{-2} \ M_\odot/\text{pc}^3$</td>
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<td><strong>Low-Mass Spirals</strong></td>
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<td>50-130 km/s</td>
<td>$50-1$ $10^{-2} \ M_\odot/\text{pc}^3$</td>
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<td><strong>MW dSphs</strong></td>
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<td>20-50 km/s</td>
<td>$\sim 10$ $10^{-2} \ M_\odot/\text{pc}^3$</td>
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## Comparison to observed core densities

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<td><strong>σ/m=1 cm^2/g</strong></td>
<td>0.5-0.4 10^{-2} M_{sun}/pc^3</td>
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<td><strong>σ/m=0.1 cm^2/g</strong></td>
<td>4 10^{-2} M_{sun}/pc^3</td>
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**Observed**


**Comparison to observed core densities**


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**Thursday, August 16, 2012**
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This Solves TBTF


Wolf & Bullock 2012
Conclusions

• It is interesting to look at the astrophysical effects of DM properties other than it being cold, if nothing else to provide constraints to particle physicist.

• Past constraints on SIDM are weaker than previously thought. Our simulations suggest that $\sigma/m = 1 \text{ cm}^2/\text{g}$ is ruled out by the high DM central densities observed.

• With $\sigma/m \sim 0.1 \text{ cm}^2/\text{g}$ we find that SIDM predicts central densities and core sizes consistent with observations at all scales, from MW dSphs to large galaxy clusters. And is an alternative possible solution to the cusp/core problem and TBTF.

• Higher resolution simulations are necessary to determine the scatter in our scaling relations and verify what our analytical model predicts for $\sigma/m \sim 0.1 \text{ cm}^2/\text{g}$