Diverse Galactic Rotation Curves & Self-Interacting Dark Matter

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See Anna Kwa’s talk

Review for Physics Reports: Sean Tulin, HBY arXiv: 1705.02358
ACDM Cosmology

- Success on large scales: larger than $\sim 10-100$ kpc

- Crisis on small scales: galactic scales, $< 10-100$ kpc

Core vs. Cusp
Diversity
Missing Satellites
Too-Big-To-Fail
Core vs. Cusp Problem

- DM-dominated systems (dwarfs, LSBs)

\[
\frac{\rho_s}{r/r_s(1 + r/r_s)^2}
\]

universal density profile, NFW profile

\(\rho_s\) and \(r_s\) are strongly correlated

Navarro, Frenk, White (1996)

Many dwarf galaxies prefer a shallow density core, instead of a steep cusp
The Diversity Problem

All galaxies have the **same** $V_{\text{max}}$!

Colored bands: hydrodynamic simulations of $\Lambda$CDM

Oman et al. (2015)

See also Kuzio de Naray, Martinez, Bullock, Kaplinghat (2009)
A Big Challenge for $\Lambda$CDM

$V_{\text{circ}}(2\,\text{kpc})$ has a factor of 3-4 scatter for fixed $V_{\text{max}}$

$M_{\text{halo}} \sim 10^9 - 10^{12} M_\odot$
The diversity is expected if dark matter has strong self-interactions
Self-Interacting Dark Matter

- Self-interactions thermalize the inner halo

\[ \frac{\sigma}{m_X} = 2 \text{ cm}^2/\text{g} \]

MW-sized halo

\[ \frac{\sigma}{m_X} / m_X \approx 1 \text{ cm}^2/\text{g} \]

\[ \Gamma \approx n\sigma v = (\rho/m_X)\sigma v \approx H_0 \]

From Huo & Sameie (UCR SIDM code)

Spergel, Steinhardt (2000)  Tulin, HBY (2017) for a review

Ideal gas: \( PV = nRT \)
Modelling SIDM Halos

- The model works well remarkably

DM velocity dispersion
Simulations: 119 km/s
Model: 122 km/s

also tested with MIT/UCI simulation results

MIT: Vogelsberger et al. (2012)
UCI: Rocha et al., Peter et al. (2012)

• Ideal gas: $PV = nRT$

\[ \rho_s \frac{r}{r_s (1 + r/r_s)^2} \]

with Kaplinghat, Tulin (PRL 2015)
with Kamada, Kaplinghat, Pace (PRL 2016)
Addressing the Diversity Problem

- DM self-interactions thermalize the inner halo

DM-dominated galaxies: Lower the central density and the circular velocity

Isothermal distribution

$$\rho_X \sim e^{-\Phi_{\text{tot}}/\sigma_0^2} \sim e^{-\Phi_X/\sigma_0^2}$$

with Kamada, Kaplinghat, Pace (PRL 2016)
High Luminous Galaxies

- DM self-interactions tie DM together with baryons

Thermalization leads to higher DM density due to the baryonic influence

\[ \rho_X \sim e^{-\Phi_{\text{tot}}/\sigma_0^2} \sim e^{-\Phi_B/\sigma_0^2} \]

with Kamada, Kaplinghat, Pace (PRL 2016)
with Kaplinghat, Keeley, Linden (PRL 2013)
with Kaplinghat, Linden (PRL 2013)
Solving the Diversity Problem

- Scatter in the halo concentration
- Spread in the baryon distribution
- Self-interactions tie the DM and baryon distributions together

with Kamada, Kaplinghat, Pace (PRL 2016) (30 galaxies, Vmax=25-300 km/s)

See Anna’s talk: ~120 galaxies
Simulations

Controlled N-body simulations: with Creasey, Sameie, Sales, Vogelsberger, Zavala (MNRAS 2016)
Density Cores in Galaxy Clusters

With Kaplinghat, Tulin (PRL 2015)

Newman et al. (2013)

Clusters: $M_{\text{halo}} \sim 10^{14}-10^{15} \ M_\odot$

Galaxies: $M_{\text{halo}} \sim 10^9-10^{12} \ M_\odot$
SIDM from Dwarfs to Clusters

- Consider 5 THINGS dwarfs (red), 7 LSBs (blue), 6 galaxy clusters (green)
- 8 simulated halos with $\sigma/m=1$ cm$^2$/g (gray) for calibration

Galaxies: $\sim$2-3 cm$^2$/g
Clusters: $\sim$0.1 cm$^2$/g
Core size in clusters: $\sim$10 kpc
If it were $\sim$1 cm$^2$/g in clusters, the core size would be $\sim$100 kpc

The strongest limit!

DM halos as “particle colliders” with Kaplinghat, Tulin (PRL 2015)
Measuring Dark Matter Mass

- Self-scattering kinematics determines SIDM mass

\[ \alpha_X = 1/137 \]
\[ m_X: \sim 15 \text{ GeV}, m_\phi: \sim 17 \text{ MeV} \]

with Kaplinghat, Tulin (PRL 2015)
Particle Physics of SIDM

- Familiar examples in the visible sector

\[ V(r) = \frac{\alpha_{EM}}{r} \]

\[ V(r) = \frac{1}{r} e^{-m_{\pi} r} \]

\[ V(r) = \frac{\alpha_{EM}}{r} e^{-m_D r} \]

Other examples: atomic DM, SU(N) composite DM...

Need two scales to generate the \( v \)-dependence

Tulin, HBY (2017)  
Data: Obloinsk et al. (2011)
SIDM at Colliders

- Striking collider signals

\[ pp \rightarrow \text{Monojet+Missing Energy} \]

An, Echenard, Pospelov, Zhang (PRL 2015)
Tsai, Wang, Zhao (PRD 2015)
Shepherd, Tait, Zaharijas (PRD 2009)
SIDM Direct Detection

\[ d\sigma dq^2 = \frac{4\pi \alpha_m \alpha_X e^2 Z^2}{(q^2 + m^2_\phi)^2 v^2} \]

\[ q^2 = 2m_N E_R \]

WIMPs: \( m_w \gg q \)
SIDM: \( m_\phi \sim q \)

- Experiments with different targets
- Annual modulation

with Del Nobile, Kaplinghat (JCAP 2015)
with Kaplinghat, Tulin (PRD 2013)
# Particle Properties

<table>
<thead>
<tr>
<th>Positive observations</th>
<th>$\sigma/m$</th>
<th>$v_{\text{rel}}$</th>
<th>Observation</th>
<th>Refs.</th>
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<tbody>
<tr>
<td>Cores in spiral galaxies (dwarf/LSB galaxies)</td>
<td>$\gtrsim$ 1 cm$^2$/g</td>
<td>30 – 200 km/s</td>
<td>Rotation curves</td>
<td>[77, 93]</td>
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<td><strong>Too-big-to-fail problem</strong></td>
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<td>Milky Way</td>
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<td>50 km/s</td>
<td>Stellar dispersion</td>
<td>[87]</td>
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<td>Local Group</td>
<td>$\gtrsim$ 0.5 cm$^2$/g</td>
<td>50 km/s</td>
<td>Stellar dispersion</td>
<td>[88]</td>
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<tr>
<td>Cores in clusters</td>
<td>$\sim$ 0.1 cm$^2$/g</td>
<td>1500 km/s</td>
<td>Stellar dispersion, lensing</td>
<td>[93, 103]</td>
</tr>
<tr>
<td><strong>Abell 3827 subhalo merger</strong></td>
<td>$\sim$ 1.5 cm$^2$/g</td>
<td>1500 km/s</td>
<td>DM-galaxy offset</td>
<td>[104]</td>
</tr>
<tr>
<td><strong>Abell 520 cluster merger</strong></td>
<td>$\sim$ 1 cm$^2$/g</td>
<td>2000 – 3000 km/s</td>
<td>DM-galaxy offset</td>
<td>[105, 106, 107]</td>
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<tr>
<td><strong>Constraints</strong></td>
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<tr>
<td>Halo shapes/ellipticity</td>
<td>$\lesssim$ 1 cm$^2$/g</td>
<td>1300 km/s</td>
<td>Cluster lensing surveys</td>
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<td>Substructure mergers</td>
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<td>$\sim$ 500 – 4000 km/s</td>
<td>DM-galaxy offset</td>
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<td>Merging clusters</td>
<td>$\lesssim$ few cm$^2$/g</td>
<td>2000 – 4000 km/s</td>
<td>Post-merger halo survival</td>
<td>Table II</td>
</tr>
<tr>
<td><strong>Bullet Cluster</strong></td>
<td>$\lesssim$ 0.7 cm$^2$/g</td>
<td>4000 km/s</td>
<td>Mass-to-light ratio</td>
<td>[81]</td>
</tr>
</tbody>
</table>

Tulin, HBY (2017)