Self-Interacting Dark Matter and Diverse Galactic Rotation Curves

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Review for Physics Reports: Tulin & HBY (2017)
Beyond the WIMP Paradigm

Some guidance

• Theory-driven: different production mechanisms
• Technology-driven: what can we do with current technologies?
• Observation-driven: how can we determine the particle nature of DM from astrophysical observations?

• Note the WIMP is a typical collisionless cold dark matter (CDM) candidate
• CDM works very well on large scales, >\(O(100)\) kpc
Core vs Cusp Problem

- DM-dominated systems (dwarfs, LSBs)

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

Flores, Primack (1994), Moore (1994)…

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

The Diversity Problem

Oman et al. (2015)

Colored bands: hydrodynamical simulations of $\Lambda$CDM, "smooth/weak" baryonic feedback

Oman et al. (2015)
The Diversity Problem

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

Colored bands: hydrodynamical simulations of $\Lambda$CDM

Oman et al. (2015)
A Big Challenge to $\Lambda$CDM

$max_{\circ} \approx 10^9 - 10^{12} M_\odot$

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

Oman et al. (2015)
The diversity is expected if dark matter has strong self-interactions
Self-Interacting Dark Matter

- Self-interactions thermalize the inner halo, not the outer halo

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

\[ \rho_{\text{IM}} = (\rho/m_X) \sim H_0 \]

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

Spergel & Steinhardt (PRL 1999)

\[ \sigma/m_X \sim 1 \text{ cm}^2/\text{g} \text{ (nuclear scale)} \]

\[ \text{CDM} \]

\[ \text{SIDM} \]

From Ran Huo

see Tulin & HBY (2017) for a review
Modelling SIDM Halos

Matching conditions:

\[
\begin{align*}
\rho_{\text{iso}}(r) &= \rho_{\text{NFW}}(r), \quad r < r_1 \\
\rho_{\text{NFW}}(r) &= \rho_{\text{NFW}}(r_1)
\end{align*}
\]

\[
M_{\text{iso}}(r_1) = M_{\text{NFW}}(r_1)
\]

\[
\begin{pmatrix} \rho_0, \sigma_0 \end{pmatrix} \leftrightarrow \begin{pmatrix} \rho_S, r_S \end{pmatrix}
\]

with Kaplinghat, Tulin (PRL 2015)

Ideal gas: PV = nRT

\[
\text{rate} \times \text{time} \approx \frac{\langle \sigma v \rangle}{m} \rho(r_1) t_{\text{age}} \approx 1
\]

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

MW-sized halo

\[
\rho(r) = \begin{cases} 
\rho_{\text{iso}}(r), & r < r_1 \\
\rho_{\text{NFW}}(r), & r > r_1
\end{cases}
\]

\[
\Phi_{\text{tot}} = \Phi_{\text{dm}} + \Phi_b
\]

\[
\nabla^2 \Phi_{\text{tot}} = 4\pi G (\rho_{\text{dm}} + \rho_b)
\]

Ideal gas: PV = nRT

\[
\text{rate} \times \text{time} \approx \frac{\langle \sigma v \rangle}{m} \rho(r_1) t_{\text{age}} \approx 1
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with Kaplinghat, Keeley, Linden (PRL 2013)

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)
Addressing the Diversity Problem

- DM self-interactions tie DM together with baryons

Thermalization leads to higher DM density due to the baryonic influence

\[ \rho_X \sim e^{-\Phi_{\text{tot}}/\sigma^2_0} \sim e^{-\Phi_B/\sigma^2_0} \]

with Kamada, Kaplinghat, Pace (PRL 2016)
- Scatter in the halo concentration-mass relation ($\sim2\sigma$)
- Scatter in the baryon distribution
- SIDM thermalization ties DM and baryon distributions

Isolated N-body simulations: with Creasey, Sameie, Sales et al. (MNRAS 2016)

$\sigma/m = 3 \text{ cm}^2/\text{g}$

30 galaxies

$V_{\text{max}} \sim 25-300 \text{ km/s}$
Hydro SIDM Simulations

- The SIDM distribution is sensitive to the final baryon distribution
- But, it is **not** sensitive to the formation history

Predicted in Kaplinghat, Keeley, Linden, HBY (PRL 2013)
**Strong Feedback vs SIDM**

Gray: NIHAO CDM simulations

“strong/violent” feedback

Observed scatter: ~4  (3σ away)

Simulations: ~2

Solid lines: SIDM fits

(~2σ in the $c_{200}$-$M_{200}$ relation)

Santos-Santos et al. (2017)

with Kamada, Kaplinghat, Pace (PRL 2016)
We have fitted to 135 galaxies with Kaplinghat, Kwa, Ren (in prep)
Radial Acceleration Relation

Observations
3012 points

McGaugh, Lelli, Schombert (PRL 2016)

$g_{\text{tot}} = \frac{g_{\text{bar}}}{1 - e^{-\sqrt{g_{\text{bar}}/g_{\ddag}}}}$

SIDM
3012 points

$g_{\ddag}: 1.19 \times 10^{-10} \text{ m/s}^2$
SD: 0.119 dex

$g_{\ddag}: 1.37 \times 10^{-10} \text{ m/s}^2$
SD: 0.100 dex

With Kaplinghat, Kwa, Ren (in prep)

135 galaxies
SIDM from Dwarfs to Clusters

Galaxies: $M_{\text{halo}} \sim 10^9 - 10^{12} \, M_\odot$
Clusters: $M_{\text{halo}} \sim 10^{14} - 10^{15} \, M_\odot$

DM halos as particle colliders

Using the data from Newman et al. (2013)

Clusters: $\sim 0.1 \, \text{cm}^2/\text{g}$
Galaxies: $\sim 2 \, \text{cm}^2/\text{g}$
Bullet Cluster: $< \sim 2 \, \text{cm}^2/\text{g}$

With Kaplinghat, Tulin (PRL, 2015)
Measuring Dark Matter Mass

- Self-scattering kinematics determines SIDM mass

\[ \alpha_X = \frac{1}{137} \]

\[ m_X : \sim 15 \text{ GeV}, \ m_\phi : \sim 17 \text{ MeV} \]

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

- Familiar examples in the visible sector

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

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

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

\[ \sigma/m (\text{cm}^2/\text{g}) \]

Tulin & HBY (2017)
Terrestrial Experiments

With Ren et al., the PandaX-II collaboration (2018)

\[ \text{WIMP: } m_{\phi} \sim 1 \text{ TeV} \gg q \]

\[ \text{SIDM: } m_{\phi} \sim 10 \text{ MeV} \sim q \]

PandaX-II

\[ \text{SIDM at the LHC} \]

WIMP: Mono-X+Missing Energy

With Ren, Tsai, Xu (in prep)

Shepherd, Tait, Zaharijas (PRD 2009)

An, Echenard, Pospelov, Zhang (PRL 2015)

Tsai, Wang, Zhao (PRD 2015)

With Del Nobile, Kaplinghat (2015)

With Ren et al., the PandaX-II collaboration (2018)
Summary

• SIDM provides a unified explanation to the stellar kinematics from dwarf galaxies to galaxy clusters.
• It simultaneously explains the diversity and the uniformity of the galactic rotation curves.
• There is a strong hint that the inner halo is thermalized.
Thank You!