Dark Matter at “Colliders”

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The WIMP Paradigm

Weakly-Interacting Massive Particle (WIMP)

mass $\sim 100$ GeV, it carries the weak (scale) interaction
WIMP at the LHC

Visible

Invisible

pp → Monojet + Missing Energy

Birkedal, Matchev, Perelstein (2004)
Feng, Su, Takayama (2006)
Goodman, Ibe, Rajaraman, Shepherd, Tait, HBY (2010)
LHC Constraints

ATLAS Collaboration (EPJC, 2017)
Small-Scale Issues of ΛCDM

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

• Solutions

Observational uncertainties (?)
Baryon physics (?)
New physics (?)

The WIMP is a typical CDM candidate
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)…
The Diversity Problem

Colored bands: hydrodynamic simulations of $\Lambda$CDM, “weak/adiabatic feedback”

Oman et al. (2015)
The Diversity Problem

All galaxies have the same Vmax!

Maximal (Measured) Velocity

Colored bands: hydrodynamic simulations of ΛCDM

Oman et al. (2015)

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

$M_{\text{halo}} \sim 10^9 - 10^{12} M_\odot$

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

Oman et al. (2015)
The unexpected diversity of dwarf galaxy rotation curves

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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

From Huo and Sameie

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

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

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

Matching conditions:

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

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

\[
\left(\rho_0, \sigma_0\right) \leftrightarrow \left(\rho_s, r_s\right)
\]

Ideal gas: \(PV = nRT\)

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

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

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

\(\sigma/m_\chi = 2 \text{ cm}^2/\text{g}\)

MW-sized halo

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

Red: NFW; Blue: SIDM simulations; Black: Analytical Model

With Kaplinghat, Tulin (2015)

With Kamada, Kaplinghat, Pace (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 (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 (2016)
with Kaplinghat, Keeley, Linden (2013)
Scatter in the halo concentration-mass relation
Baryon distribution
DM self-interactions correlate DM and baryon distributions

with Kamada, Kaplinghat, Pace (2016)  with Kaplinghat, Kwa, Ren (in prep)
Strong Feedback vs. SIDM

NIHAI0 simulations of $\Lambda$CDM

“strong/violent” feedback

Observed scatter: $\sim 4$
Simulations: $\sim 2$

Santos-Santos et al. (2017)

with Kaplinghat, Kwa, Ren (in prep)

with Kamada, Kaplinghat, Pace (2016)

SIDM
More Galaxies…

Two independent approaches:
UCR: thin desk model, Poisson’s equation on a grid
UCI: spherical stellar model, MCMC

120 spiral galaxies with high-quality data from the SPARC dataset

Agreement is within $<\sim 10\%$

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

with Kaplinghat, Kwa, Ren (in prep)
More Galaxies…

With Kaplinghat, Kwa, Ren (in prep)

• $\sim 114/120$ galaxies can be fitted within $2\sigma$ range of the halo concentration-mass relation predicted in $\Lambda$CDM cosmology (from Dutton, Maccio, 2014)

• The SIDM fits reproduce the Tully-Fisher relation
Radial Acceleration Relation

2693 points

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

McGaugh, Lelli, Schombert (2016)

The same SPARC dataset

With Kaplinghat, Kwa, Ren (in prep)

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

Controlled N-body simulations: with Creasey, Sales, Sameie+ (2016)
SIDM with Strong Feedback

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

The SIDM halo is FIRE-proof, see Robles et al. (2017)
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: ~0.1 cm$^2$/g
Galaxies: ~2 cm$^2$/g

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

Core size in clusters: ~10 kpc

With Kaplinghat, Tulin (2015)
Elbert et al. (2016)
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 (2015)

with Feng, Kaplinghat (2009)
Particle Physics of SIDM

- Familiar examples in the visible sector

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

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

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

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

Need two scales to generate v-dependence

with Tulin (2017)
Dark Matter “Colliders”

Dwarf galaxies

MW-size galaxies

Clusters

Observations on all scales

Self-scattering kinematics

Measure particle physics parameters \( \sigma_X, m_X, g_X \)

“B-factory” (\( v \sim 30 \text{ km/s} \))

“LEP” (\( v \sim 200 \text{ km/s} \))

“LHC” (\( v \sim 1000 \text{ km/s} \))
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*with Tulin (2017)*