Dark Matter Self-Interactions and Small-Scale Structure

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He exhausted all avenues in heaven and the nether world, … he could not bring her existence to light.

A Song of Immortal Regret, Bai Juyi (772-846)
A Critical Rethinking: Cold Dark Matter (CDM)

- Large scales: very well

- Small scales (dwarf galaxies, sub-halos, galaxy clusters)
  - Core vs Cusp
  - Diversity
  - Too Big To Fail
  - Cores in clusters
  - Ultra diffuse galaxies
The Diversity Problem

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

$V \sim \sqrt{GM/r}$

Colored bands: hydrodynamical simulations of CDM  Oman+ (2015)

Dark matter distributions are diverse in spiral galaxies
A Big Challenge

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

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

Reproduced from the data compiled in Oman+ (2015)
The diversity can be explained if dark matter has strong self-interactions.
Self-Interacting Dark Matter

- Self-interactions thermalize the inner halo

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

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

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

From Ran Huo

Review: w/ Tulin (Physics Reports 2017)
Low Surface Brightness Galaxies

- DM self-interactions thermalize the inner halo

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

Isothermal distribution

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

w/ Kamada, Kaplinghat, Pace (PRL 2017)
High Surface Brightness Galaxies

- DM self-interactions tie DM together with baryons

Thermalization leads to higher DM density due to the baryonic influence

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

w/ Kaplinghat, Keeley, Linden (PRL 2014)
w/ Kamada, Kaplinghat, Pace (PRL 2017)
We fitted 135 galaxies (3.6 μm band)!
SPARC dataset, Lelli, McGaugh, Schombert (2016)

w/ Ren, Kwa, Kaplinghat (PRX 2018)
w/ Kamada, Kaplinghat, Pace (PRL 2017)
w/ Creasey, Sameie, Sales+ (MNRAS 2017)
Add one more parameter $\sigma/m$

Explain the diverse rotation curves of spiral galaxies (puzzled us for ~25 years)
Beyond Field Galaxies

Image: Bullock+
Dark matter distributions are also diverse in satellite galaxies.

Naively, we would get $\sigma/m_\chi \sim 10$ cm$^2$/g for Fornax, but $\sigma/m_\chi \sim 0.3$ cm$^2$/g for Draco.

w/ Valli (Nature Astronomy 2018)  
 w/ Kaplinghat, Valli (MNRAS, 2019)
Reconciling Draco & Fornax in SIDM

SIDM predictions with tidal effects

Core-expansion phase

Core-collapse phase

SIDM can explain diverse DM distributions in both satellite and field galaxies

$\sigma/m = 3 \text{ cm}^2/\text{g}$
Ultra-Diffuse Galaxies

They contain very little dark matter!

Milky Way

\[ \frac{M_{DM}}{M_{\text{star}}} \approx 30 \]

DF2 and DF4

\[ M_{\text{star}} \approx 10^8 M_\odot \]

Expected

\[ \frac{M_{DM}}{M_{\text{star}}} \sim 200 \]

Observed

\[ \frac{M_{DM}}{M_{\text{star}}} \lesssim 1 \]

Dragonfly team, van Dokkum+ (Nature 2018, AJPL 2019)
Initial, $t=0 \text{ Gyr}$

$M_{200} = 6 \times 10^{10} \, M_\odot$

$M_* = 3.2 \times 10^8 \, M_\odot$

$M_{200}/M_* \approx 188$

Final, $t=11 \text{ Gyr}$

$M_{DM} = 1.5 \times 10^8 \, M_\odot$

$M_{star} = 1.3 \times 10^8 \, M_\odot$

$M_{DM}/M_{star} \approx 1$

SIDM leads to core formation, boosting tidal mass loss

Halo concentration $c_{200}$

CDM: 4 (-4$\sigma$)

SIDM3: 7 (-1.8$\sigma$)

SIDM5: 10 (-0.4$\sigma$)

w/ Yang, An (PRL 2020)
Galaxies with Little Dark Matter

DF2 and DF4 are most likely to be satellite galaxies of NGC 1052 (recently confirmed by observations)

They are much more naturally realized in SIDM than in CDM through tidal stripping

with/ Yang, An (PRL 2020)

Dragonfly team, van Dokkum+ (Nature 2018, AJPL 2019)
Galaxy Clusters

A2537

Six well-relaxed galaxy clusters data from Newman+(2013)

\[ M_{\text{halo}} \sim 10^{15} \, M_\odot \]

Shallow inner DM density profiles
Core sizes \( \sim 10 \, \text{kpc} \) and smaller

Clusters: \( \sigma/m \sim 0.1 \, \text{cm}^2/\text{g} \)
SIDM from Dwarfs to Clusters

Ultra-diffuse galaxies (dark-matter-deficient)  Milky Way satellites  Spiral galaxies  Galaxy clusters

\[ M_{\text{halo}} \sim 10^8 \, \text{M}_\odot \]  \[ M_{\text{halo}} \sim 10^9 - 10^{13} \, \text{M}_\odot \]  \[ M_{\text{halo}} \sim 10^{15} \, \text{M}_\odot \]

SIDM can explain diverse dark matter distributions over a wide range of galactic systems (halo masses \( \sim 10^8 - 10^{15} \, \text{M}_\odot \)).
Particle Physics Models

Galaxies: $M_{\text{halo}} \sim 10^8-10^{13} \, M_\odot$

Galaxy clusters: $M_{\text{halo}} \sim 10^{14}-10^{15} \, M_\odot$

$\sigma/\langle m \rangle$ (cm$^2$/g)

Dark matter relative velocity (km/s)

Mediator mass (MeV)

Combined fit

- 95% CL
- 99% CL

Galaxies

Clusters

$X$ $\phi$ $X$

$X$ $X$

Dark halos as particle colliders

$\alpha_X = 1/137$

Predict: $m_X \sim 15 \, \text{GeV}$, $m_\phi \sim 17 \, \text{MeV}$

The nightmare scenario is not hopeless!

w/ Kaplinghat, Tulin (PRL 2015)

See also Lee’s and Chu’s talks
Gravothermal Catastrophe

The first stage: heat comes in, DM goes out, core expansion

The second stage: heat goes out, DM comes in, core collapse

From Yi-Ming Zhong

Balberg, Shapiro, Inagaki (APJ 2002), Balberg, Shapiro (PRL 2002), w/ Essig, McDermott, Zhong (PRL 2019)
Seeding Supermassive Black Holes

The most challenging one, J1205-0000

Mass $2.2 \times 10^9 \, M_\odot$

$z=6.7$

$f_{\text{Edd}}=0.16$

Onoue et al. (2019)

$\sim 800 \, \text{Myr after the Big Bang}$

w/ Feng, Zhong (2020)

The predicted self-scattering cross section is broadly consistent with the one used to explain diverse dark matter distributions in galaxies.
Conclusions & Outlook

- SIDM predicts rich phenomenology

Vera C. Rubin Observatory

Thirty Meter Telescope

Strong hints/evidence

- SIDM predicts rich phenomenology

light dark sectors (MeV-GeV) resonant regimes
Thank You!

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