Self-interacting Dark Matter

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Cold Collisionless Dark Matter

- Large scales: very well

- Small scales (dwarf galaxies, subhalos, galaxy clusters): ?
Core VS. Cusp Problem

- DM-dominated systems (dwarfs, LSBs)

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

IC 2574 from THINGS Oh et al. (2011)

\[ V \sim \sqrt{GM_\odot/r} \]

Flores, Primack (1994), Moore et al. (1999)…
Too-Big-to-Fail Problem

- Milky Way dwarf galaxies

  Boylan-Kolchin, Bullock, Kaplinghat (2011)

  \[ V \sim \sqrt{\frac{GM}{r}} \]

  - Most massive subhalos in CDM simulations are too dense to host observed galaxies in the Milky Way
  - On the other hand, it is easier for stars to form in massive subhalos

  subhalos in Andromeda and field dwarfs in Local Group
Even Galaxy Clusters!

- Seven galaxy clusters

Newman, Treu, Ellis, Sand (2013)

- CDM halos contain more DM in the central region than needed
- CDM may break down on galactic scales
Self-interacting Dark Matter

- Self-interactions can reduce the central DM density

\[ \frac{\sigma}{m_X} \approx 0.5 - 50 \text{ cm}^2/\text{g} \]
for \( v \approx 10 - 30 \text{ km/s} \)

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

Spergel, Steinhardt (2000)

Elbert et al. (2014)
Challenges

• A really large scattering cross section!

\[ \sigma \sim 1 \text{cm}^2 \left( \frac{m_X}{g} \right) \sim 2 \times 10^{-24} \text{ cm}^2 \left( \frac{m_X}{\text{GeV}} \right) \]

For a WIMP: \( \sigma \sim 10^{-38} \text{ cm}^2 \left( \frac{m_X}{100 \text{ GeV}} \right) \)

SIDM indicates a new mass scale

• How to avoid the constraints on large scales?

\[ \frac{\sigma}{m_X} < 1 \text{ cm}^2/g \text{ for } 3000 \text{ km/s (Bullet cluster)} \]

In particular, if \( \sigma \sim \text{constant} \)  

Spergel, Steinhardt (2000)
Particle Physics of SIDM

- SIDM indicates light mediators
  
  \[
  \sigma \approx 5 \times 10^{-23} \text{ cm}^2 \left( \frac{\alpha_X}{0.01} \right)^2 \left( \frac{m_X}{10 \text{ GeV}} \right)^2 \left( \frac{10 \text{ MeV}}{m_\phi} \right)^4
  \]
  
  in the perturbative and small velocity limit

- With a light mediator, DM self-scattering is velocity-dependent

  \[
  \sigma \sim \frac{\alpha_X^2}{m_X^2 v^4} \quad \text{ and } \quad m_X v >> m_\phi
  \]

  \[
  V(r) = \pm \frac{\alpha_X}{r} e^{-m_\phi r}
  \]

  - DM is self-scattering on small scales (v~10-30 km/s)
  - DM is collisionless on large scales (v~3000 km/s)

The SIDM Paradigm

- The SIDM paradigm is predictive

WIMP paradigm

SIDM paradigm

The mediator may dominate the energy density of the Universe

- The mediator decays before BBN: lifetime of $\phi$ is $\sim$1 second

\[ \epsilon \gtrsim 10^{-10} \sqrt{10 \text{ MeV} / m_\phi} \]

A super model!
Direct Detection of SIDM

- Complementarity

\[
\frac{d\sigma}{dq^2} = \frac{4\pi \alpha_{em} \alpha_X \epsilon^2 Z^2}{(q^2 + m_\phi^2)^2 v^2}
\]

DD cross section:
- suppressed by the tiny coupling
- enhanced by the \( \phi \) mass

Asymmetric SIDM (\( \epsilon_\gamma = 10^{-10} \))

Kaplinghat, Tulin, HBY (2013)
Smoking-Gun Signatures

\[
d\sigma/dq^2 = \frac{4\pi\alpha em \alpha X e^2 Z^2}{(q^2 + m_{\phi}^2 v^2)^2} \quad q^2 = 2m_N E_R
\]

\[q = 2m_N E_R\]

- In the WIMP case, \(m_\phi >> q\)
- For SIDM, \(m_\phi \sim 1-100\ \text{MeV}\), which is comparable to \(q\)
- A new region for the direct detection community

For XENON: \(q \sim 50\ \text{MeV}\)

See Laha’s talk for other interesting signals

Del Nobile, Kaplinghat, HBY (in preparation)
Indirect Detection

- Lighting up the galactic center, but not dwarf galaxies!

\[ \Phi \rightarrow \text{electrons/neutrinos} \]

\[ m_\Phi \sim 10 \text{ MeV} \]

Inverse Compton scattering

\[ \sim (20 \text{ GeV}/m_e)^2 E_{\text{ISRF}} \]

\[ E_{\text{ISRF}} \sim 1 \text{ eV} \]

- No IC signal from dwarfs
- Soft electron spectrum
- The IC signal is spherically symmetric

Kaplinghat, Linden, HBY (2015) (PRL Editors’ suggestion)
What if SIDM is Hidden...

• The mediator decays before BBN: lifetime of $\phi$ is $\sim 1$ second

$$\epsilon \gtrsim 10^{-10}\sqrt{10 \text{ MeV}/m_\phi}$$

Nightmare scenario?
Idea 1: Tying SIDM to Baryons

• SIDM: equilibrium ideal gas with gravity

\[ p = k_B T \rho / m \]

\[ \nabla p = -\rho \nabla \Phi \]

\[ \nabla^2 \Phi = 4\pi G(\rho + \rho_B) \]

• If \( \Phi \sim \Phi_B \), SIDM follows the stellar distribution!

\[ \nabla^2 \Phi = 4\pi G[\rho + \rho_B] \]
Halo Morphology: Milky Way

- SIDM particles follow the stellar distribution

Correlation between the stellar distribution and the SIDM distribution

constant density contours

Kaplinghat, Linden, Keeley, HBY (2013) (PRL Editors’ suggestion)
Idea 2: Dark Matter “Colliders”

Dwarf galaxies

MW-size galaxies

Clusters

“B-factor” (v~30 km/s)

“LEP” (v~200 km/s)

“LHC” (v~1000 km/s)

Self-scattering kinematics

Measure particle physics parameters

Observations on all scales
SIDM From Dwarfs to Clusters

- Consider 7 THINGS dwarfs, 7 LSBs (blue), and 6 galaxy clusters

\[ p = k_B T \rho / m \]
\[ \nabla p = -\rho \nabla \Phi \]
\[ \nabla^2 \Phi = 4\pi G (\rho + \rho_B) \]
\[ \Gamma t_{\text{age}} = \frac{\rho_0}{m_X} \langle \sigma v \rangle = N \rightarrow \frac{\langle \sigma v \rangle}{m_X} = \frac{N}{\rho_0 t_{\text{age}}} \]

Constant \( \sigma \) is disfavored!

**Bullet Cluster**: \( \sigma < 1 \text{ cm}^2/\text{g} \)

Kaplinghat, Tulin, HBY (in preparation)
Measuring Dark Matter Mass

- Self-scattering kinematics determines SIDM mass

\[ \alpha_X \times 0.01 \]

\[ m_X \text{ VS. } m_\phi \]

- If \( m_X \) too large, \( \sigma \sim 1/v^4 \)
  \( \sigma \) too small for clusters

- If \( m_X \) too small, \( \sigma \sim \text{const} \)
  \( \sigma \) too large for clusters

Mild dependence on \( \alpha_X \)

\[ \sigma \sim \alpha_X^2 m_X^2 / m_\phi^4 \]

\[ \alpha_X = 0.01 \]

\[ m_X: \sim 10 - 200 \text{ GeV}, \ m_\phi: \sim 5 - 40 \text{ MeV} \]

Kaplinghat, Tulin, HBY (in preparation)
Idea 3: Rotation Curves

\[ p = k_B T \rho / m \]
\[ \nabla p = -\rho \nabla \Phi \]
\[ \nabla^2 \Phi = 4\pi G (\rho + \rho_B) \]

Kamada, Kaplinghat, HBY (in preparation)

McGaugh et al. (2006)

IC 2574

[Graphs showing rotation curves and equations related to galaxy dynamics]
Summary & Outlook

• CDM has serious issues on galactic scales

• It is time to think about new approaches to the dark matter problem

• SIDM has novel features
  - Solve small-scale issues
  - Smoking-gun signatures in direct and indirect detection experiments
  - Measure dark matter mass via self-scattering kinematics
  - Tie dark matter to baryons
Summary & Outlook

- **Puzzle 1: The diversity of spiral galaxies**

Oman+ (2015)
de Naray, Martinez, Bullock, Kaplinghat (2009)
Summary & Outlook

- **Puzzle 2: Constant DM halo surface density**

\[ \rho(r_0) = \rho_0/2 \]

\[ r_0 \]

\[ \rho_0 \, r_0 (\text{M}_\odot \text{pc}^{-2}) \]

\[ M_B \]

Donato+ (2009)

Kormendy, Freeman (2004)
Summary & Outlook

- Puzzle 3: The baryonic Tully-Fisher relation

\[ M_b = A V_f^4 \text{ with } A = 47 \pm 6 \, M_\odot \, \text{km}^{-4} \, \text{s}^4 \]

Milgrom (1983)

Sanders (2009)

McGaugh (2011)