Beyond Collisionless DM

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Based on:  
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Exploring the dark sector

Direct detection

Indirect detection

Colliders

Can we learn about the dark sector if DM has highly suppressed couplings to SM?
Exploring the dark sector

Direct detection

Indirect detection

Colliders

Self-interactions
Outline

• Cold collisionless DM paradigm in trouble (??)
  – Discrepancy between N-body simulations and astrophysical observations on smallest scales
  – Dwarf galaxies: laboratories for studying DM

• DM may have self-interactions
  – Particle physics implications of self-interacting DM
CDM in trouble

   - Central densities of dwarf halos exhibit cores
     \[\rho \sim r^{\alpha}\quad \alpha \sim -1 \text{ (cusp, NFW)} \text{ or } \alpha \sim 0 \text{ (core)}\]

   - Simulations predict O(10) massive MW satellites more massive than observed MW dSphs

   - Fewer small MW dSphs than predicted by simulation
   - Small enough to fail
1. Core-vs-cusp problem

Cores in dwarf galaxies outside the MW halo

Moore (1994), Flores & Primack (1994), ...

THINGS (dwarf galaxy survey) - Oh et al. (2011)

Baryonic feedback from supernovae may flatten central cusps (Governato et al 2012)
1. Core-vs-cusp problem

Cores in MW dwarf spheroidals (dSphs)

Stellar subpopulations (metal-rich & metal-poor) as “test masses” in gravitational potential

Walker & Penarrubia (2011)

Enclosed mass $M(<r) = \int d^3 r \rho$

Not enough baryonic feedback from supernovae (Garrison-Kimmel et al 2013)

Estimate enclosed mass from line-of-sight dispersion: $M(<r) = \mu r <\sigma_{\text{los}}^2>/G \quad \mu=2.5$
1. Core-vs-cusp problem

Cores in MW dwarf spheroidals (dSphs)

Frenk, Strigari, White (2013) [C. Frenk’s Aspen talk]

MW dSphs can be consistent with NFW profiles due to uncertainty in $\mu$

Cores in MW dSphs favored from longevity of $\sim 10$ Gyr old globular clusters

Cusps lead to inspiral of GCs on $\sim$ few Gyr timescale by dynamical friction, cores do not

1. Core-vs-cusp problem

Cores in low surface brightness galaxies (LSBs)

Metal-poor galaxies with limited star formation history (more pristine)

Not enough baryonic feedback to affect DM cusps

Kuzio de Naray & Spekkens (2011)

de Blok & Bosma (2002)
2. Too-big-to-fail problem

MW galaxy should have $O(10)$ satellite galaxies which are more massive than the most massive (classical) dwarf spheroidals

From Weinberg, Bullock, Governato, Kuzio de Naray, Peter (2013)
2. Too-big-to-fail problem

Boylan-Kolchin, Bullock, Kaplinghat (2011 + 2012)

MW galaxy should have $O(10)$ satellite galaxies which are more massive than the most massive (classical) dwarf spheroidals

- Variation in number of satellites ($\sim 10\%$ “tuning”)  
  Purcell & Zentner (2012)

- Uncertainty in MW halo mass
Self-interactions

- Self-interactions can solve small scale structure problems

*Vogelsberger, Zavala, Loeb (2012); see also Rocha et al, Peter et al (2012)*

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**Core vs cusp problem**

- Black = CDM
- Red/green/blue = SIDM

**Too big to fail problem**

- DM self-scattering moves predicted circular velocities into (closer) alignment with MW dSph
Self-interacting dark matter

• What does this tell us about the underlying particle physics theory of the dark sector?
Self-interacting dark matter

• What does this tell us about the underlying particle physics theory of the dark sector?

• History of particle physics models for SIDM

  1. $\sigma=\text{const}$  

  2. $\sigma\sim 1/\nu$  

  3. $\sigma\sim 1/\nu^4$ (massless mediator)  
     * Ackerman et al (2008)

  4. Scattering with a finite mass mediator  
Five particle physics lessons for SIDM
Five particle physics lessons for SIDM

1. Large self-interaction cross section required

Figure-of-merit: \[ \frac{\sigma}{m_\chi} \sim 1 \text{ cm}^2/\text{g} \approx 2 \text{ barns}/\text{GeV} \]

- Typical WIMP: \( \sigma \sim 1 \text{ pb}, m_\chi \sim 100 \text{ GeV} \)

\[ \frac{\sigma}{m_\chi} \sim 10^{-14} \text{ barns}/\text{GeV} \]

- New mediator \( \phi \) much lighter than weak scale

[Diagram]

\[ m_\phi \sim 1 - 100 \text{ MeV} \]

self-interaction
Five particle physics lessons for SIDM

2. Light mediator implies velocity-dependent self-interaction cross section

\[ \frac{\sigma}{m_X} \text{ enhanced at low velocity, suppressed at high velocity (like Rutherford scattering)} \]
Five particle physics lessons for SIDM

3. Different size DM halos have different velocities

DM appears collisionless on larger scales
Five particle physics lessons for SIDM

3. Different size DM halos have different velocities

- Dwarfs $v \sim 30 \text{ km/s}$ SIDM
- LSBs $v \sim 100 \text{ km/s}$ SIDM
- MW-sized halos $v \sim 200 \text{ km/s}$ Collisionless DM
- Clusters $v \sim 1000 \text{ km/s}$ Collisionless DM

Natural for self-interactions to manifest in smaller halos
Five particle physics lessons for SIDM

4. Annihilation channel for the DM relic density

\[ \chi \quad \text{---} \cdot \Phi \]

\[ \chi^* \quad \text{---} \cdot \Phi \]

- Preserves WIMP miracle

\[ \Omega_{\text{dm}} \sim 0.2 \times \left( \frac{6 \times 10^{-26} \text{ cm}^3/\text{s}}{\langle \sigma v \rangle_{\text{ann}}} \right) \sim 0.2 \times \left( \frac{\alpha_X}{10^{-2}} \right)^{-2} \times \left\{ \begin{array}{ll} (m_X/300 \text{ GeV})^2 & \text{vector} \\ (m_X/100 \text{ GeV})^2 & \text{scalar} \end{array} \right\} \]
Five particle physics lessons for SIDM

5. Mediator particles should decay before BBN

\[
\begin{tikzpicture}
\node (SM) at (0,0) {SM};
\node (phi) at (-1,0) {$\phi$};
\draw [dashed] (phi) -- (SM);
\node (sm) at (1,0) {SM};
\end{tikzpicture}
\]

Minimal setup with no new particles: $\phi$ decays to SM fermions before BBN

- Upper bound on $\phi$ lifetime implies lower bound on direct detection cross section

\[
\begin{tikzpicture}
\node (X) at (0,0) {X};
\node (phi) at (0,-1) {$\phi$};
\node (f) at (-1,-2) {f};
\node (X_prime) at (0,-2) {X};
\node (f_prime) at (1,-2) {f};
\draw (X) -- (phi) -- (SM);\draw (SM) -- (SM);
\draw (f) -- (phi) -- (X);
\draw (X_prime) -- (phi) -- (X);
\draw (f_prime) -- (phi) -- (X_prime);
\end{tikzpicture}
\]

Direct detection constraints rule out large parameter region for SIDM
Simplified models for SIDM

- DM particle $X +$ light mediator $\phi$

\[ \mathcal{L}_{\text{int}} = \begin{cases} g_X \bar{X} \gamma^\mu X \phi_\mu & \text{vector mediator} \\ g_X \bar{X} X \phi & \text{scalar mediator} \end{cases} \]

\[ \alpha_X = \frac{g_X^2}{4\pi} \]

DM self-interactions

DM annihilation

Direct detection
Simplified models for SIDM

- DM particle $X$ + light mediator $\phi$

$$\mathcal{L}_{\text{int}} = \begin{cases} 
  g_X \bar{X} \gamma^\mu \chi \phi_\mu & \text{vector mediator} \\
  g_X \bar{X} \chi \phi & \text{scalar mediator}
\end{cases}$$

$$\alpha_X = g_X^2/(4\pi)$$

![Diagram](image)

Portals for direct detection: kinetic mixing

$$\mathcal{L}_{\text{mix}} = -\frac{\xi_\gamma}{2} \phi_{\mu \nu} F^{\mu \nu}$$

Holdom (1984); Pospelov et al (2007); Arkani-Hamed et al (2009); Lin et al (2011) ...

$\phi$ lifetime:

$$\frac{1}{\Gamma_\phi} \approx 2.7 \text{ second} \times \left(\frac{\xi_\gamma}{10^{-10}}\right)^{-2} \left(\frac{m_\phi}{10 \text{ MeV}}\right)^{-1}$$
Constraints on kinetic mixing

Dent, Ferrer, Krauss (2012)

Kinetic mixing case very constrained for SIDM: $\varepsilon_\gamma \sim 10^{-10}$ (!)
DM self-interaction cross section

• Nonperturbative calculation
  
  – Similar to Sommerfeld enhancement for annihilation

  \[ X - \phi - X + X - \phi - X + X - \phi - X + \ldots \]

  – Equivalent to solving the Schrödinger equation

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

• Compute phase shifts
  
  \[ \frac{d\sigma}{d\Omega} = \frac{1}{k^2} \left| \sum_{\ell=0}^{\infty} (2\ell + 1) e^{i\delta_\ell} P_\ell(\cos \theta) \sin \delta_\ell \right|^2 \]

• Transfer cross section
  
  \[ \sigma_T \equiv \int d\Omega \ (1 - \cos \theta) \frac{d\sigma}{d\Omega} \]
Parameter space for symmetric SIDM

SIDM region for solving dwarf anomalies

Wide range of DM mass Mediator ~ 1 – 100 MeV

Assume dwarf halos with characteristic velocity 30 km/s

Peaks are where DM self-scattering has quantum mechanical resonances (bound states)
Parameter space for symmetric SIDM

Shaded region: solve dwarf anomalies

Halo shape bound
Parameter space for symmetric SIDM

- Shaded region: solve dwarf anomalies
- Halo shape bound

- Velocity-independent cross section
- Velocity-dependent cross section
Parameter space for symmetric SIDM

- Shaded region: solve dwarf anomalies
- Halo shape bound
- Direct detection via kinetic mixing

\[ \sigma_{Xp}^{SI} \approx 1.5 \times 10^{-24} \text{ cm}^2 \times \varepsilon_\gamma^2 \times \left( \frac{\alpha_X}{10^{-2}} \right) \left( \frac{m_\phi}{30 \text{ MeV}} \right)^{-4} \]
Parameter space for symmetric SIDM

Shaded region: solve dwarf anomalies

Halo shape bound

Direct detection via kinetic mixing

XENON bounds with mixing parameter $\varepsilon_\gamma = 10^{-10}$
Parameter space for symmetric SIDM

Shaded region: solve dwarf anomalies

Halo shape bound

Direct detection via kinetic mixing

XENON bounds with mixing parameter $\varepsilon_\gamma = 10^{-10}$

CMB bound

Parameter space for asymmetric SIDM

Shaded region: solve dwarf anomalies
Parameter space for asymmetric SIDM

- **Shaded region**: solve dwarf anomalies
- **Halo shape bound**
Parameter space for asymmetric SIDM

Shaded region: solve dwarf anomalies

Halo shape bound

Bullet cluster
Parameter space for asymmetric SIDM

- Shaded region: solve dwarf anomalies
- Halo shape bound
- Bullet cluster
- Future merging clusters bound (??)

Graph showing the parameter space for asymmetric SIDM with markers for various constraints and regions.
Parameter space for asymmetric SIDM

Shaded region: solve dwarf anomalies

Halo shape bound

Bullet cluster

Direct detection with $\varepsilon_\gamma = 10^{-10}$
Parameter space for asymmetric SIDM

- Shaded region: solve dwarf anomalies
- Halo shape bound
- Bullet cluster
- Direct detection with $\varepsilon_\gamma = 10^{-10}$
Parameter space for asymmetric SIDM

Shaded region: solve dwarf anomalies

Halo shape bound

Bullet cluster

Direct detection from scattering on electrons with $\varepsilon_\gamma = 10^{-4}$

Essig et al (2011+2012)
Direct detection

Benchmarks from SUSY
SIDM benchmarks for direct detection

Asymmetric SIDM with $\varepsilon_p = \varepsilon_n = 10^{-10}$

Symmetric SIDM with $\varepsilon_p = \varepsilon_n = 10^{-10}$
SIDM benchmarks for direct detection
Conclusions (part 1)

- Simplified model: DM $\chi +$ mediator $\phi$
- Anomalies on dwarf scales: $m_\phi \sim 1 - 100$ MeV
- Although SIDM may be decoupled from direct detection, expect DM-SM coupling at some level
- Light mediator means direct detection sensitive to very small DM-SM couplings
- Current & future direct detection exploring “BBN parameter region” ($\phi \rightarrow$ SM before BBN)
Conclusions (part 2)

• Direct detection complementary to astrophysics
  – Constraints on large scales (e.g. Bullet Cluster) constrain SIDM at low DM mass (constant $\sigma$)
  – Direct detection constrain SIDM at WIMP-scale masses (corresponding to $v$-dependent $\sigma$)
Backup
Comparison to previous work

1. More efficient method for matching onto asymptotic solution of Bessel functions, not sines (B&F had $\ell_{\text{max}} = 5$)

2. More efficient formula for summing partial waves

\[ \sigma_T = \frac{4\pi}{k^2} \sum_{\ell=0}^{\ell_{\text{max}}} \left[ (2\ell + 1) \sin^2 \delta_\ell - 2(\ell + 1) \sin \delta_\ell \sin \delta_{\ell+1} \cos(\delta_{\ell+1} - \delta_\ell) \right] \]

ST, H.-B. Yu, K. Zurek (2013)

\[ \sigma_T = \frac{4\pi}{k^2} \sum_{\ell=0}^{\ell_{\text{max}}} (\ell + 1) \sin^2(\delta_{\ell+1} - \delta_\ell) \]

Buckley & Fox 2009

\[
\begin{align*}
\sigma_T^{\text{clas}}/m_X
\end{align*}
\]

$m_X = 200 \text{ GeV}$
$m_\phi = 1 \text{ MeV}$
$\alpha_X = 10^{-2}$
$v = 1000 \text{ km/s}$
SIDM and direct detection

Self-interactions change phase space distribution of DM halo

Vogelsberger and Zavala (2012)

O(10%) effect on DM recoil rate in direct detection experiments
Also effect annual modulation amplitude and phase
Portals to the dark sector

1. Vector mediator ($\phi$ mixes with Z or $\gamma$)
   - Kinetic mixing with photon
     $$\mathcal{L}_{\text{mix}} = -\frac{\varepsilon_{\gamma}}{2} \phi_{\mu\nu} F^{\mu\nu}$$
     Holdom (1984); Pospelov et al (2007); Arkani-Hamed et al (2009); Lin et al (2011) ...
   - Z mass mixing ($\varepsilon_Z$ is Z-$\phi$ mixing angle):
     $$\mathcal{L}_{\text{mix}} = \varepsilon_Z m_Z^2 \phi_{\mu} Z^{\mu}$$
     Babu et al (1997); Davoudiasl et al (2012) ...

2. Scalar mediator
   - Higgs mixing ($\varepsilon_h$ is h-$\phi$ mixing angle)
     $$\mathcal{L}_{\text{mix}} = -\varepsilon_h m_h^2 \phi h$$
     (Assume $\varepsilon << 1$, $m_\phi \sim 1 - 100$ MeV $<< m_Z$)