Maximizing Direct Detection with HYPER Dark Matter

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Direct Detection Refresher

\[ \chi \xrightarrow{\text{DM}} N \xrightarrow{\text{nucleus}} \chi \]

Credit: The XENON Experiment
Direct Detection Refresher

XENON Collaboration [1805.12562]
Direct Detection Future

Go lighter

Go higher?

Go lower
Bounds from Cosmic Ray Scattering

C. Cappiello, K. Ng, J. Beacom [1810.07705]
T. Bringmann, M. Pospelov [1810.10543]
C. Cappiello, J. Beacom [1906.11283]
Is Dark Matter here?
Where is Dark Matter?
Outline

Is Dark Matter here?

What is the max cross section of sub-GeV DM scattering off nucleons?

Where is the Dark Matter?

Is there a sub-GeV DM candidate which
1. may be detected at proposed experiments?
2. may approach such a max cross section?
What is the \textit{max cross section} of sub-GeV DM scattering off nucleons?
The Basics

\[ \mathcal{L} \supset - m_\chi \bar{\chi} \chi - y_n \phi \bar{n} n - y_\chi \phi \bar{\chi} \chi \]

\[
\sigma_{\chi n}^{\text{max}} \equiv \frac{(y_n \max y_\chi \max)^2}{4\pi} \frac{\mu_{\chi n}^2}{\left[ (m_{\phi} \min)^2 + v_{\text{DM}}^2 m_{\chi}^2 \right]^2}
\]
$m_{\phi}^\text{min} = 0.31 \text{ MeV}, \ y_n^{\text{max}} = 1.6 \times 10^{-5}$
DM Self Interactions

\[ \langle \sigma v \rangle / m \text{ (cm}^2/\text{g} \times \text{km/s)} \]

\[ \sigma / m = 0.01 \text{ cm}^2/\text{g} \]

Dwarf, LSB, SIDM N-body, cluster data

\[ \sigma_{xx} / m_\chi \lesssim 1 \text{ cm}^2/\text{g} \]

at \( v \sim 10^{-3} \)
Is Dark Matter here?

also see G. Krnjaic, S. McDermott [1908.00007] for BBN bounds on Cosmic Ray Upscattered Dark Matter
So what?
Challenges for Achieving $\sigma_{\chi n}^{\text{max}}$

A light $\phi$ with sizable couplings to DM and nuclei

Large $\bar{\chi}\chi \rightarrow \phi\phi$

fast annihilations deplete relic abundance

constrained by indirect detection

Thermalization of $\phi$ increases $N_{\text{eff}}$
Is there a sub-GeV DM candidate which
1. may be detected at proposed experiments?
2. may approach such a max cross section?
Highly interactive Particle Relics (HYPERS)
HYPER History

UV freeze-in \( \Omega_X h^2 = 0.12 \) relic abundance set early and depends on \( T_R \) and \( m_\phi \)
UV Freeze-In

\[ \mathcal{L} \ni \lambda \phi \bar{\psi} \psi \longrightarrow \frac{\alpha_s}{4 \Lambda} \phi G_{\mu \nu}^a G^{a \mu \nu} \]

heavy $\phi$

\[ \frac{\alpha_s y_X y_n}{2.6 m_n (m^i_\phi)^2} \bar{\chi} X G_{\mu \nu}^a G^{a \mu \nu} \]

10 GeV $\lesssim T_R \lesssim 300$ GeV

F. Elahi, C. Kolda, J. Unwin [1410.6157]
HYPER History

- **UV freeze-in**
  \[ \Omega_{\chi} h^2 = 0.12 \]

- **Dark-sector phase transition**
  \[ m^i_{\phi} \rightarrow m_{\phi} \ll m^i_{\phi} \]

- Other instances of dark PT changing masses & pheno
  - T. Cohen, D. Morrissey, A. Pierce [0808.3994]
  - M. Baker, J. Kopp [1608.07578]
  - D. Croon et al. [2012.15284]
HYPER History

- UV freeze-in
  \[ \Omega_\chi h^2 = 0.12 \]

- Dark-sector phase transition
  \[ m^i_\phi \rightarrow m_\phi \ll m^i_\phi \]

- Direct detection cross section grows!
  \[ \left( \frac{m^i_\phi}{m_\phi} \right)^4 \]

Interactions much stronger today than when relic abundance was set.

K. Boddy, S. Carroll, M. Trodden
[1208.4376]
HYPER History

$T_R$

UV freeze-in

$\Omega_\chi h^2 = 0.12$

$T_{PT}$

Dark-sector phase transition

$m^i_\phi \to m_\phi \ll m^i_\phi$

Today

Direct detection cross section grows!

$(m^i_\phi/m_\phi)^4$

Changes

- abundance?
- BBN?
- CMB?
Changes relic abundance? ✓

\[ m_{\chi} < m_{\pi^0} \rightarrow \chi\chi \rightarrow \text{hadrons} \]

\[ T_{PT} \ll m_{\pi^0} \rightarrow \text{hadrons} \rightarrow \chi\chi \]

\[ \gamma\gamma \rightarrow \phi(\phi) \]
What about $\bar{\chi} \chi \rightarrow \phi \phi$?

Have to suppress $\rightarrow$ HYPERs can’t always have max direct detection
Results
Boundary found by maximizing $\sigma_{\chi n}$ via judicious choice of $(m_\phi, y_\chi)$.
Where is Dark Matter?
Future Directions

Repeat for electron scattering; lower PT = interesting

Fully explore hadrophilic HYPER space
(e.g. vector mediator models)

Flesh out the dark sector PT

Many more!
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Is Dark Matter here?

What is the max cross section of sub-GeV DM scattering off nucleons? A: Not that big. Good to know.

Where is the Dark Matter?

Is there a sub-GeV DM candidate which
1. may be detected at proposed experiments?
2. may approach such a max cross section?
A: HYPERs