Can we identify the theory of dark matter with direct detection?

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Broad scope:

What can we really learn about dark matter parameters and interactions from direct detection?
DM-nucleus scattering

\[
\frac{dR}{dE_R}(E_R) = \frac{\rho \chi}{m_T m_\chi} \int_{v_{\min}}^{v_{\text{esc,lab}}} v f(v) \frac{d\sigma_T}{dE_R}(E_R, v) d^3v.
\]
DM-nucleus scattering

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\]

“Observable”  DM particle + nuclear physics

Astrophysics
After introducing each of these prerequisites, we present the results of our analysis. The main results we report are the following: xenon and germanium targets (with several ton-year, and several hundred kilogram-year exposures, respectively) are sufficient to correctly identify momentum dependence of the scattering cross-section for a wide range of WIMP masses. Thus, they will be able to successfully reject widely different phenomenologies (such as for example, those arising from the standard SI coupling of DM, from those arising from dipole coupling). However, on their own, they cannot distinguish models with the same momentum and velocity dependence, even if novel nuclear responses contribute to scattering rate; for this purpose, new targets with different spin and mass structure, such as iodine and fluorine, will be necessary. For example, a modest 100 kilogram-years of exposure on iodine target helps break degeneracies between a wide variety of theories that would otherwise be indistinguishable with xenon and germanium. We also find that the accuracy of mass reconstruction is not necessarily a monotonic function of the number of observed events, and might sensitively depend on the underlying scattering model. We quantify these statements in detail in §6.

The rest of this paper is organized as follows. In §3 we assemble a representative list of WIMP-nucleon scattering operators compatible with the symmetries of the non-relativistic scattering (as advocated in Refs. [13, 15]). In §4 we describe our simulations of the recoil energy spectra (including Poisson noise) of G2 direct-detection experiments, under each of these scenarios. In §5 we describe the analysis of simulated data. In §6 we present and discuss our results. We conclude in §7.
DM-nucleus scattering

The nuclear recoil energy spectrum is the number count of nuclear recoil events observed per recoil energy $E_R$, per unit time, per unit target mass:

$$ \frac{dR}{dE_R}(E_R) = \rho \frac{\chi}{m_T m_\chi} \int_{v_{\text{min}}}^{v_{\text{esc,lab}}} v f(v) \frac{d\sigma_T}{dE_R}(E_R, v) d^3v. $$

Traditionally assumed momentum and velocity independent SI or SD scattering

**“Observable”**

**DM particle + nuclear physics**

Astrophysics

- $\rho$ - DM density
- $\chi$ - DM mass
- $m_T$ - Total target mass
- $m_\chi$ - DM mass
- $v_{\text{esc,lab}}$ - Escape velocity in the lab frame
- $f(v)$ - Velocity distribution
- $\frac{d\sigma_T}{dE_R}(E_R, v)$ - Scattering cross-section

**Number of events**

**Nuclear recoil energy (keV) **
Context: noisy recoil-energy spectra
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Context: noisy recoil-energy spectra
Main question:

How likely is direct detection to successfully identify the correct theory, and which experimental strategies maximize chances for success?
Theory ingredients:

Fan et al, 2010; Fitzpatrick et al, 2012; Anand et al, 2013; Gresham & Zurek, 2014; etc.

• Spin $\frac{1}{2}$ DM, elastic scattering through scalar or vector mediators

• Broad range of (UV complete) theories

• Nuclear responses triggered by non-standard interactions $(M, \Sigma', \Sigma'', \Delta, \Phi'')$

• Variety of target elements with natural abundances of isotopes
### 14 models (hypotheses)

<table>
<thead>
<tr>
<th>Model name</th>
<th>Lagrangian</th>
<th>(\vec{q}, v) Dependence</th>
<th>Response</th>
<th>(f_n/f_p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI</td>
<td>(\bar{\chi}\chi\bar{N}N)</td>
<td>1</td>
<td>(M)</td>
<td>+1</td>
</tr>
<tr>
<td>SD</td>
<td>(\bar{\chi}\gamma^\mu\gamma_5\chi\bar{N}\gamma_\mu\gamma_5N)</td>
<td>1</td>
<td>(\Sigma' + \Sigma'')</td>
<td>-1.1</td>
</tr>
<tr>
<td>Anapole</td>
<td>(\bar{\chi}\gamma^\mu\gamma_5\chi\partial^\nu F_{\mu\nu})</td>
<td>(v^{1/2}) (\vec{q}^2/m_N^2)</td>
<td>(M)</td>
<td>(\Delta + \Sigma')</td>
</tr>
<tr>
<td>Millicharge</td>
<td>(\bar{\chi}\gamma^\mu A_\mu)</td>
<td>(m_N^2m_N^2/q^4)</td>
<td>(M)</td>
<td>photon–like</td>
</tr>
<tr>
<td>MD (light med.)</td>
<td>(\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu})</td>
<td>1 + (v^{1/2}m_N^2/q^2)</td>
<td>(M)</td>
<td>(\Delta + \Sigma')</td>
</tr>
<tr>
<td>ED (light med.)</td>
<td>(\bar{\chi}\sigma^{\mu\nu}\gamma_5 F_{\mu\nu})</td>
<td>(m_N^2/q^2)</td>
<td>(M)</td>
<td>photon–like</td>
</tr>
<tr>
<td>MD (heavy med.)</td>
<td>(\bar{\chi}\sigma^{\mu\nu}\partial_\mu\chi\partial_\alpha F_{\alpha\nu})</td>
<td>(\vec{q}^4) + (v^{1/2}m_N^2\vec{q}^2) (\vec{q}^4/\Lambda^4)</td>
<td>(M)</td>
<td>(\Delta + \Sigma')</td>
</tr>
<tr>
<td>ED (heavy med.)</td>
<td>(\bar{\chi}\sigma^{\mu\nu}\gamma_5\partial_\mu\chi\partial_\alpha F_{\alpha\nu})</td>
<td>(\vec{q}^2m_N^2/\Lambda^4)</td>
<td>(M)</td>
<td>photon–like</td>
</tr>
<tr>
<td>SI_{q^2}</td>
<td>(i\bar{\chi}\gamma_5\chi\bar{N}N)</td>
<td>(\vec{q}^2/m_N^2)</td>
<td>(M)</td>
<td>+1</td>
</tr>
<tr>
<td>SD_{q^2} (Higgs-like/flavor–univ.)</td>
<td>(i\bar{\chi}\chi\bar{N}\gamma_5N)</td>
<td>(\vec{q}^2/m_N^2)</td>
<td>(\Sigma'')</td>
<td>+1/ - 0.05</td>
</tr>
<tr>
<td>SD_{q^4} (Higgs-like/flavor–univ.)</td>
<td>(\bar{\chi}\gamma_5\chi\bar{N}\gamma_5N)</td>
<td>(\vec{q}^4/m_N^2)</td>
<td>(\Sigma'')</td>
<td>+1/ - 0.05</td>
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<tr>
<td>(\vec{L}\cdot\vec{S})-like</td>
<td>(\bar{\chi}\gamma_\mu\chi\partial^2\bar{N}\gamma_\mu N/m_N^2 + \bar{\chi}\gamma_\mu\chi\partial^2\bar{N}\gamma_\mu N/m_N^2)</td>
<td>(\vec{q}^4/m_N^4)</td>
<td>(M)</td>
<td>(\Phi'')</td>
</tr>
<tr>
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<td>(\bar{\chi}\gamma_\mu\chi\partial^2\bar{N}\gamma_\mu N/m_N^2 + \bar{\chi}\gamma_\mu\chi\partial^2\bar{N}\gamma_\mu N/m_N^2)</td>
<td>(\vec{q}^4/m_N^4)</td>
<td>(M)</td>
<td>(\Phi'')</td>
</tr>
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See also: Gresham & Zurek, 2014
14 models (hypotheses)
## Experiments: G2+

<table>
<thead>
<tr>
<th>Label</th>
<th>A (Z)</th>
<th>Energy window [keVnr]</th>
<th>Exposure [kg-yr]</th>
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<tbody>
<tr>
<td>Xe(1)</td>
<td>131 (54)</td>
<td>5-40</td>
<td>2000</td>
</tr>
<tr>
<td>Ge</td>
<td>73 (32)</td>
<td>0.3-100</td>
<td>100</td>
</tr>
<tr>
<td>I</td>
<td>127 (53)</td>
<td>22.2-600</td>
<td>212</td>
</tr>
<tr>
<td>F</td>
<td>19 (9)</td>
<td>3-100</td>
<td>606</td>
</tr>
<tr>
<td>Na</td>
<td>23 (11)</td>
<td>6.7-200</td>
<td>38</td>
</tr>
<tr>
<td>Ar</td>
<td>40 (18)</td>
<td>25-200</td>
<td>3000</td>
</tr>
<tr>
<td>He</td>
<td>4 (2)</td>
<td>3-100</td>
<td>300</td>
</tr>
<tr>
<td>Xe(1)</td>
<td>131 (54)</td>
<td>1-40</td>
<td>2000</td>
</tr>
<tr>
<td>Xe(2)</td>
<td>131 (54)</td>
<td>5-100</td>
<td>2000</td>
</tr>
<tr>
<td>Xe(3)</td>
<td>131 (54)</td>
<td>1-100</td>
<td>2000</td>
</tr>
<tr>
<td>I(1)</td>
<td>127 (53)</td>
<td>1-600</td>
<td>212</td>
</tr>
<tr>
<td>XeG3</td>
<td>131 (54)</td>
<td>5-40</td>
<td>40 000</td>
</tr>
<tr>
<td>I+</td>
<td>127 (53)</td>
<td>1-600</td>
<td>424</td>
</tr>
<tr>
<td>F+</td>
<td>19 (9)</td>
<td>3-100</td>
<td>1200</td>
</tr>
</tbody>
</table>

Baseline analysis

Table 3. Mock experiments considered in this work. The efficiency and the fiducialization of the target mass are included in the exposure. The first group of experiments is used for most of the simulations in this work and is chosen such to be representative of the reach of G2 experiments for Xe, Ge, I, and F. The exposure for Xe and Ge is chosen to agree with the projected exclusion curves for LZ and SuperCDMS presented in Ref. [1]. The second group of experiments is used to test impact of the energy window on prospects for model selection; note that only the energy window differs from the corresponding experiments of the first group. The last group represents futuristic experiments, where XeG3 reaches the level of atmospheric neutrino backgrounds.
Analysis

1. Simulate events under different hypotheses, for a signal just below the current detection threshold.

2. Reconstruct posteriors for one or more mock experiments jointly (fit for: mass and cross-section)

3. Compare models *a posteriori* (Bayesian model selection)
Results
Simulations preferring true model (with >0.9 probability):

True model: SI (mass: 50 GeV)
Complementarity of targets is essential
Momentum dependence is robust

True model: SI (mass: 50 GeV)

Simulations preferring true class (with >0.9 probability):
- Ge: 54%
- Xe: 74%
- Ge+Xe: 98%

Probability of true class

Simulations preferring true class (with >0.9 probability):
- Ge: 100%
- Xe: 94%
- Ge+Xe: 100%

True model: Millicharge (mass: 50 GeV)

Simulations preferring true class (with >0.9 probability):
- Ge: 100%
- Xe: 70%
- Ge+Xe: 100%

Probability of true class

Simulations preferring true class (with >0.9 probability):
- Ge: 6%
- Xe: 84%
- Ge+Xe: 98%

True model: ED (light med.) (mass: 50 GeV)

Simulations preferring true class (with >0.9 probability):
- Ge: 100%
- Xe: 70%
- Ge+Xe: 100%

Probability of true class

Simulations preferring true class (with >0.9 probability):
- Ge: 6%
- Xe: 84%
- Ge+Xe: 98%

True model: ED (heavy med.) (mass: 50 GeV)
Wrong model fits lead to biased mass estimation biases when a wrong model is fit to data; the input DM mass is 50 GeV, shown with a vertical red line. Bottom row: an example of simulated recoil-energy spectrum, shown together with the true underlying model (blue solid), and the fitting model (red dashed) for maximum-likelihood values of the fitting parameters. These simulations correspond to the posteriors shown in the middle row of this Figure. By eye, SI does not look like a bad fit to these data, for either xenon (LHS) or germanium (RHS).
fn/fp uncertainty is **not** a show stopper

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**Parameter estimation:**

- Left panel: $m_X$ vs. $f_n/f_p$
- Right panel: $m_X$ vs. $f_n/f_p$

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**Model selection:**

- **Ge+Xe+F**:
  - True model: SI (mass: 50 GeV)
  - Simulations preferring true model (with >0.9 probability): 23%
  - Probability of true model: 100%

- **Ge+Xe+F**:
  - True model: Anapole (mass: 50 GeV)
  - Simulations preferring true model (with >0.9 probability): 100%
  - Probability of true model: 100%
Conclusions

✓ Low thresholds, complementary targets, and a joint analysis of all available data are key to identifying DM theory in an agnostic approach.

✓ **dmdd** python code @ GitHub:  

>> `pip install dmdd`

![Graph showing probability of true model simulations]