Effective theories for dark matter-nucleon interactions

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Overview

How to theoretically model the dark matter-nucleon interaction?

The currently favored approach relies on drastic simplifying assumptions, e.g.:

- dark matter only couples to the nuclear vector charge (SI)
- dark matter only couples to the nuclear spin current (SD)

The progress recently made in the field, and the efforts planned for the next decade, motivate more advanced strategies.
Effective theory of dark matter-nucleon interactions


Comparison with observations:

R. C. and P. Gondolo, JCAP 1508, 08, 022 (2015)
R. C., JCAP 1409, 09, 049 (2014)
R. C. and P. Gondolo, JCAP 1409, 09, 045 (2014)
R. C., JCAP 1407, 07, 055 (2014)

Direct Detection

R. C. JCAP 1507 07, 026 (2015)

Directional Detection

Direct Detection

R. C., JCAP 1504, 04, 052 (2015)
R. C. and B. Schwabe JCAP 1504, 04, 042 (2015)

Neutrino-Telescopes
EFT of dark matter-nucleon interactions
Consider the scattering $\chi(p) + N(k) \rightarrow \chi(p') + N(k')$

Its amplitude $\mathcal{M}$ is restricted by
- Momentum conservation $\rightarrow p, k, q$
- Galilean invariance $\rightarrow v = p/m_\chi - k/m_N$

In general, $\mathcal{M} = \mathcal{M}(v, q, S_\chi, S_N)$

Any non-relativistic Hamiltonian leading to such a scattering amplitude can be expressed as a combination of 5 Hermitian operators

$$\mathbb{1}_{\chi N} \quad i\hat{q} \quad \hat{v}^\perp = \hat{v} + \frac{\hat{q}}{2\mu_N} \quad \hat{S}_\chi \quad \hat{S}_N$$
### Dark matter-nucleon interaction operators

<table>
<thead>
<tr>
<th>Operator</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\hat{O}_1$</td>
<td>$\mathbb{1}_{\chi N}$</td>
</tr>
<tr>
<td>$\hat{O}_2$</td>
<td>$i\hat{S}_\chi \cdot \hat{S}_N$</td>
</tr>
<tr>
<td>$\hat{O}_3$</td>
<td>$i\hat{S}<em>N \cdot \left( \frac{\hat{q}}{m_N} \times \hat{v}</em>\perp \right)$</td>
</tr>
<tr>
<td>$\hat{O}_4$</td>
<td>$\hat{S}<em>\chi \cdot \left( \frac{\hat{q}}{m_N} \times \hat{v}</em>\perp \right)$</td>
</tr>
<tr>
<td>$\hat{O}_5$</td>
<td>$\left( \hat{S}_\chi \cdot \frac{\hat{q}}{m_N} \right) \left( \hat{S}_N \cdot \frac{\hat{q}}{m_N} \right)$</td>
</tr>
<tr>
<td>$\hat{O}_6$</td>
<td>$\hat{S}<em>N \cdot \hat{v}</em>\perp$</td>
</tr>
<tr>
<td>$\hat{O}_7$</td>
<td>$\hat{S}<em>\chi \cdot \hat{v}</em>\perp$</td>
</tr>
<tr>
<td>$\hat{O}_8$</td>
<td>$i\hat{S}_\chi \cdot \left( \hat{S}_N \times \frac{\hat{q}}{m_N} \right)$</td>
</tr>
<tr>
<td>$\hat{O}_9$</td>
<td>$i\hat{S}_\chi \cdot \left( \hat{S}_N \times \frac{\hat{q}}{m_N} \right)$</td>
</tr>
<tr>
<td>$\hat{O}_{10}$</td>
<td>$i\hat{S}_N \cdot \frac{\hat{q}}{m_N}$</td>
</tr>
<tr>
<td>$\hat{O}_{11}$</td>
<td>$i\hat{S}_\chi \cdot \frac{\hat{q}}{m_N}$</td>
</tr>
<tr>
<td>$\hat{O}_{12}$</td>
<td>$\hat{S}_\chi \cdot \left( \hat{S}<em>N \times \hat{v}</em>\perp \right)$</td>
</tr>
<tr>
<td>$\hat{O}_{13}$</td>
<td>$i\left( \hat{S}<em>\chi \cdot \hat{v}</em>\perp \right) \left( \hat{S}_N \cdot \frac{\hat{q}}{m_N} \right)$</td>
</tr>
<tr>
<td>$\hat{O}_{14}$</td>
<td>$i\left( \hat{S}_\chi \cdot \frac{\hat{q}}{m_N} \right) \left( \hat{S}<em>N \cdot \hat{v}</em>\perp \right)$</td>
</tr>
<tr>
<td>$\hat{O}_{15}$</td>
<td>$-\left( \hat{S}_\chi \cdot \frac{\hat{q}}{m_N} \right) \left[ \left( \hat{S}<em>N \times \hat{v}</em>\perp \right) \cdot \frac{\hat{q}}{m_N} \right]$</td>
</tr>
</tbody>
</table>
Only 14 linearly independent operators can be constructed, if we demand that they are at most linear in $\hat{S}_N$, $\hat{S}_\chi$ and $\hat{v}^\perp$.

The most general Hamiltonian density is therefore

$$\hat{H}(r) = \sum_k c_k \hat{O}_k(r)$$
Hamiltonian for dark matter-nucleon scattering

- Only 14 linearly independent operators can be constructed, if we demand that they are at most linear in $\hat{S}_N$, $\hat{S}_\chi$ and $\hat{v}^\perp$

- The most general Hamiltonian density is therefore

$$\hat{\mathcal{H}}(r) = \sum_{\tau=0,1} \sum_k c^\tau_k \hat{O}_k(r) t^\tau$$

- $t^0 = \mathbb{1}$, $t^1 = \tau_3$

- $c^\rho_k = (c^0_k + c^1_k)/2$ and $c^n_k = (c^0_k - c^1_k)/2$
The dark matter-nucleus scattering cross-section is

$$\frac{d\sigma_T(v^2, E_R)}{dE_R} = \frac{m_T}{2\pi v^2} \langle |\mathcal{M}_{NR}|^2 \rangle_{\text{spins}}$$

The transition probability $\langle |\mathcal{M}_{NR}|^2 \rangle_{\text{spins}}$ factorizes as follows

$$\langle |\mathcal{M}_{NR}|^2 \rangle_{\text{spins}} = \frac{4\pi}{2J+1} \sum_{\tau, \tau'} \left[ \sum_{k=M, \Sigma', \Sigma''} R_{k}^{\tau \tau'}(v^2, q^2) W_{k}^{\tau \tau'}(q^2) \right]$$

$$+ \frac{q^2}{m_N^2} \sum_{k=\Phi'', \Phi'M, \Phi', \Delta, \Delta \Sigma'} R_{k}^{\tau \tau'}(v^2, q^2) W_{k}^{\tau \tau'}(q^2)$$

Available nuclear response functions $W_{k}^{\tau \tau'}(q^2)$:

- For Xe, Ge, I, Na, F: Anand et al. 2013
- For 16 elements in the Sun: R. C. & B. Schwabe 2015
Comparison with observations
Direct Detection

R. C. and P. Gondolo, JCAP 1508, 08, 022 (2015) ← analysis of current data (this talk)
R. C., JCAP 1409, 09, 049 (2014) ← forecasts for DD with ton-scale detectors
R. C. and P. Gondolo, JCAP 1409, 09, 045 (2014) ← analysis of current data (isoscalar case only)
R. C., JCAP 1407, 07, 055 (2014) ← forecasts for DD with ton-scale detectors
Global multidimensional statistical analysis

- I compare theory and observations in a profile likelihood analysis varying all model parameters *simultaneously*.
- From the profile Likelihood, I derive 2D 95% confidence intervals in planes dark matter mass vs coupling constant.
- Experimental data *simultaneously* included in the fit:
  - LUX
  - XENON100
  - XENON10
  - CDMS-Ge
  - CDMS-LT
  - SuperCDMS
  - CDMSlite
  - PICASSO
  - SIMPLE
  - COUPP
Pairs of operators, or isoscalar and isovector components of the same operator can interfere. For instance, the operators $\hat{O}_1$ and $\hat{O}_3$ generate a transition probability proportional to

$$
\langle |\mathcal{M}_{NR}|^2 \rangle_{\text{spins}} = \frac{4\pi}{2J+1} \sum_{\tau\tau'} \left[ c_1^\tau c_1^{\tau'} W^\tau_{M} (y) + \frac{1}{8} \frac{q^2}{m_N^2} v_{T}^{-2} c_3^{\tau} c_3^{\tau'} W^\tau_{\Sigma} (y) \right. \\
\left. + \frac{q^2}{m_N^2} \left( \frac{q^2}{4m_N^2} c_3^{\tau} c_3^{\tau'} W_{\phi'} (y) + c_1^{\tau} c_3^{\tau'} W_{\phi'}^M (y) \right) \right]
$$

R. C. and P. Gondolo, JCAP 1508, 08, 022 (2015)
Directional Detection

Formalism

- Double differential energy spectrum at directional detection experiments:

\[
\frac{d^2 R}{dE_R d\Omega} = \sum_T \frac{\xi_T}{(2\pi)} \frac{\rho_\chi}{m_\chi m_T} \int \delta(v \cdot w - w_T) F(v + v_e(t)) v^2 \frac{d\sigma_T}{dE_R}(v^2, q^2) d^3v
\]

- It requires:
  - The Radon transform of higher moments of \( F \)
  - Nuclear response functions for, e.g., CF\(_4\), CS\(_2\), \(^3\)He, etc.

New ring-like features


We find new ring-like features in $dR/d\cos \theta$

This result was confirmed in


Different ring-like features in $d^2R/d\cos \theta dE_R$ were previously found in

Neutrino telescopes

R. C. and B. Schwabe JCAP 1504 04, 042 (2015) ← computation of relevant nuclear response functions
R. C., JCAP 1504 04, 052 (2015) ← application to neutrino telescopes
Direct detection vs neutrino telescopes: highlights

R. C., JCAP 1504 04, 052 (2015)
R. C. and B. Schwabe JCAP 1504 04, 042 (2015)

\[ \hat{O}_4 = \hat{S}_\chi \cdot \hat{S}_N, \quad \hat{O}_{11} = i\hat{S}_\chi \cdot \hat{q}/m_N \]
R. C., JCAP 1504 04, 052 (2015)

$$c_7^0 \neq 0$$

$$c_{13}^0 \neq 0$$

![Graphs showing the sensitivity of direct detection and neutrino telescopes for different mass eigenvalues.](image-url)
Conclusions

- Current direct detection data place interesting constraints on dark matter-nucleon interaction operators commonly neglected.
- Destructive interference effects can weaken standard direct detection exclusion limits by up to 1 order of magnitude in the coupling constants.
- We find new ring-like features in $\frac{dR}{d\cos \theta}$ at directional detection experiments.
- For certain velocity-dependent interaction operators neutrino telescopes are superior to direct detection experiments.
- Hydrogen is not the most important element in the dark matter capture by the Sun for the majority of the spin-dependent operators.