Effective theory of dark matter direct detection

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Effective theory of dark matter-nucleon interactions

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Outline

- Effective theory of dark matter-nucleon interactions

  see also, e.g., M. Cirelli, E. Del Nobile, and P. Panci JCAP 1310, 019 (2013)

- Phenomenology:

  R. C., JCAP 1409, 09, 049 (2014)
  R. C. and P. Gondolo, JCAP 1409, 09, 045 (2014)
  R. C., JCAP 1407, 055 (2014)

  \{ Direct Detection \\
  \{ Directional Detection \\
  \{ Neutrino-Telescopes \\

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

\[
\mathbb{1}_\chi, i\hat{q}, \hat{v}^\perp = \hat{v} + \frac{\hat{q}}{2\mu_N}, \hat{S}_\chi, \hat{S}_N
\]
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

$$\hat{\mathcal{H}}(r) = \sum_k c_k \hat{O}_k(r)$$
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

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

- $t^0 = 1$, $t^1 = \tau_3$
- $c_k^p = (c_k^0 + c_k^1)/2$ and $c_k^n = (c_k^0 - c_k^1)/2$
Dark matter-nucleon interaction operators

\[\hat{O}_1 = \mathbb{1}_{\chi N}\]
\[\hat{O}_3 = i\hat{S}_N \cdot \left(\frac{\hat{q}}{m_N} \times \hat{v}^\perp\right)\]
\[\hat{O}_4 = \hat{S}_\chi \cdot \hat{S}_N\]
\[\hat{O}_5 = i\hat{S}_\chi \cdot \left(\frac{\hat{q}}{m_N} \times \hat{v}^\perp\right)\]
\[\hat{O}_6 = \left(\hat{S}_\chi \cdot \frac{\hat{q}}{m_N}\right)\left(\hat{S}_N \cdot \frac{\hat{q}}{m_N}\right)\]
\[\hat{O}_7 = \hat{S}_N \cdot \hat{v}^\perp\]
\[\hat{O}_8 = \hat{S}_\chi \cdot \hat{v}^\perp\]
\[\hat{O}_9 = i\hat{S}_\chi \cdot \left(\hat{S}_N \times \frac{\hat{q}}{m_N}\right)\]
\[\hat{O}_{10} = i\hat{S}_N \cdot \frac{\hat{q}}{m_N}\]
\[\hat{O}_{11} = i\hat{S}_\chi \cdot \frac{\hat{q}}{m_N}\]
\[\hat{O}_{12} = \hat{S}_\chi \cdot \left(\hat{S}_N \times \hat{v}^\perp\right)\]
\[\hat{O}_{13} = i\left(\hat{S}_\chi \cdot \hat{v}^\perp\right)\left(\hat{S}_N \cdot \frac{\hat{q}}{m_N}\right)\]
\[\hat{O}_{14} = i\left(\hat{S}_\chi \cdot \frac{\hat{q}}{m_N}\right)\left(\hat{S}_N \cdot \hat{v}^\perp\right)\]
\[\hat{O}_{15} = -\left(\hat{S}_\chi \cdot \frac{\hat{q}}{m_N}\right)\left[\left(\hat{S}_N \times \hat{v}^\perp\right) \cdot \frac{\hat{q}}{m_N}\right]\]
Assuming one-body dark matter-nucleon interactions, the Hamiltonian density for **dark matter-nucleus** interactions is

\[
\hat{H}_T(r) = \sum_{\tau=0,1} \left\{ \sum_{i=1}^A \hat{\mathcal{I}}_{\text{SI}}^\tau \delta(r - r_i) + \sum_{i=1}^A \hat{\mathcal{I}}_{\text{SD}}^\tau \cdot \vec{\sigma}_i \delta(r - r_i) + \hat{\mathcal{I}}_M^\tau \cdot \text{convection current} + \hat{\mathcal{I}}_E^\tau \cdot \text{spin/velocity current} \right\} t^\tau
\]

- \( \hat{\mathcal{I}}_{\text{SI}}^\tau = c_1^\tau + i(\hat{q}/m_N) \cdot \hat{S}_\chi \ c_{11}^\tau + \ldots \)

- \( \hat{\mathcal{I}}_{\text{SD}}^\tau = \hat{S}_\chi \ c_4^\tau/2 + i(\hat{q}/m_N) \times \hat{\nu}^\tau \ c_3^\tau/2 + \ldots \)
Transition probability $\langle |M_{NR}|^2 \rangle_{\text{spins}}$

- $\langle |M_{NR}|^2 \rangle_{\text{spins}}$ factorizes: “dark matter response” $\times$ “nuclear response”

$$\langle |M_{NR}|^2 \rangle_{\text{spins}} = \frac{4\pi}{2J+1} \sum_{\tau,\tau'} \left[ \sum_{k=M,\Sigma',\Sigma''} R^{\tau\tau'}_k (v^2, q^2) W^{\tau\tau'}_k (q^2) \right. \\
+ \frac{q^2}{m_N^2} \sum_{k=\Phi'',\Phi',M,\Phi,\Delta,\Delta\Sigma'} R^{\tau\tau'}_k (v^2, q^2) W^{\tau\tau'}_k (q^2) \right]$$

- Available nuclear response functions $W^{\tau\tau'}_k (q^2)$
  - For Xe, Ge, I, Na, F: Anand et al. 2013
  - For 16 elements in the Sun: R. C. & B. Schwabe 2015
The dark matter-nucleus scattering cross-section is

\[
\frac{d\sigma_T(v^2, E_R)}{dE_R} = \frac{m_T}{2\pi v^2} \langle |M_{NR}|^2 \rangle_{\text{spins}}
\]

Importantly, \(d\sigma_T/dE_R\) determines:

- The rate of scattering events at direct detection experiments
- The rate of dark matter capture by the Sun, and hence the flux of dark matter-induced neutrinos from the Sun
Rate of scattering events at direct detection experiments:

\[ \frac{dR}{dE_R} = \sum_T \xi_T \frac{\rho_X}{M_T m_\chi} \int_{v > v_{\text{min}}(q)} F(\vec{v} + \vec{v}_e(t)) v \frac{d\sigma_T}{dE_R}(v^2, q^2) d^3v \]

Rate of dark matter capture by the Sun:

\[ \frac{dC}{dV} = \int_0^\infty du \frac{f(u)}{u} \sum_T n_T w^2 \Theta \left( \frac{\mu_T}{\mu_{+T}} - \frac{u^2}{w^2} \right) \int_{E_{\text{min}}}^{E_{\text{max}}} dE_R \frac{d\sigma_T}{dE_R}(w^2, q^2) \]
Phenomenology
Direct Detection

R. C., JCAP 1409, 09, 049 (2014)
R. C. and P. Gondolo, JCAP 1409, 09, 045 (2014)
R. C., JCAP 1407, 055 (2014)
Operator interference

Prospects (all benchmark points)

R. C., JCAP 1407 055 (2014)
Prospects ($m_\chi = 50$ GeV; $c_1^0, c_3^0, c_4^0$)

R. C., JCAP 1407 055 (2014)
Theoretical bias in the dark matter mass and coupling constant reconstruction

R. C., JCAP 1409 049 (2014)
Directional Detection

Formalism

- Double differential energy spectrum at directional detection experiments:

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

- 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., JCAP **1504** 04, 052 (2015)
R. C. and B. Schwabe JCAP **1504** 04, 042 (2015)
Direct detection vs neutrino telescopes: highlights

R. C., JCAP 1504 04, 052 (2015)
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\[ \mathcal{O}_4 = \hat{\mathcal{S}}_{\chi} \cdot \hat{\mathcal{S}}_N, \quad \mathcal{O}_{11} = i \hat{\mathcal{S}}_{\chi} \cdot \hat{q}/m_N \]
Direct detection vs neutrino telescopes: highlights

R. C., JCAP 1504 04, 052 (2015)
Conclusions

- Current direct detection data place interesting constrain 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 $dR/d\cos \theta$ 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 capture by the Sun for the majority of the spin-dependent operators.