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

Outline

- Effective theory of dark matter-nucleon interactions

  A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers and Y. Xu JCAP **1302**, 004 (2013)

- 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

  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

EFT building blocks

- Consider the scattering $\chi(\mathbf{p}) + N(\mathbf{k}) \to \chi(\mathbf{p}') + N(\mathbf{k}')$
- Its amplitude $\mathcal{M}$ is restricted by
  - Momentum conservation $\to$ $\mathbf{p}$, $\mathbf{k}$, $\mathbf{q}$
  - Galilean invariance $\to$ $\mathbf{v} = \mathbf{p}/m_\chi - \mathbf{k}/m_N$
- In general, $\mathcal{M} = \mathcal{M}(\mathbf{v}, \mathbf{q}, \mathbf{S}_\chi, \mathbf{S}_N)$
- Any non-relativistic Hamiltonian leading to such a scattering amplitude can be expressed as a combination of 5 Hermitian operators

$$\mathbb{1}_{\chi N} \qquad i\hat{\mathbf{q}} \qquad \hat{\mathbf{v}}^{\perp} = \hat{\mathbf{v}} + \frac{\hat{\mathbf{q}}}{2\mu_N} \qquad \hat{\mathbf{S}}_\chi \qquad \hat{\mathbf{S}}_N$$

Dark matter-nucleon interaction operators

$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$	$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$
$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$	$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}$
$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$	$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}$
$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$	$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$
$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$	$\hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$
$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$	$\hat{\mathcal{O}}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$
$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp$	$\hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$

Hamiltonian for dark matter-nucleon scattering

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

- The most general Hamiltonian density is therefore

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

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

  - $t^0 = \mathbb{1}$, $t^1 = \tau_3$
  - $c_k^p = (c_k^0 + c_k^1)/2$ and $c_k^n = (c_k^0 - c_k^1)/2$

Dark matter-nucleus scattering cross-section

- The dark matter-nucleus scattering cross-section is

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

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

$$\langle |\mathcal{M}_{NR}|^2 \rangle_{\rm spins} = \frac{4\pi}{2J+1} \sum_{\tau,\tau'} \Bigg[\sum_{k=M,\Sigma',\Sigma''} R_k^{\tau\tau'}(v^2, q^2) W_k^{\tau\tau'}(q^2) + \frac{q^2}{m_N^2} \sum_{k=\Phi'',\Phi''M,\tilde{\Phi}',\Delta,\Delta\Sigma'} R_k^{\tau\tau'}(v^2, q^2) W_k^{\tau\tau'}(q^2) \Bigg]$$

- 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)	$\longleftarrow$	analysis of current data (this talk)
R. C., JCAP **1409**, 09, 049 (2014)	$\longleftarrow$	forecasts for DD with ton-scale detectors
R. C. and P. Gondolo, JCAP **1409**, 09, 045 (2014)	$\longleftarrow$	analysis of current data (isoscalar case only)
R. C., JCAP **1407**, 07, 055 (2014)	$\longleftarrow$	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

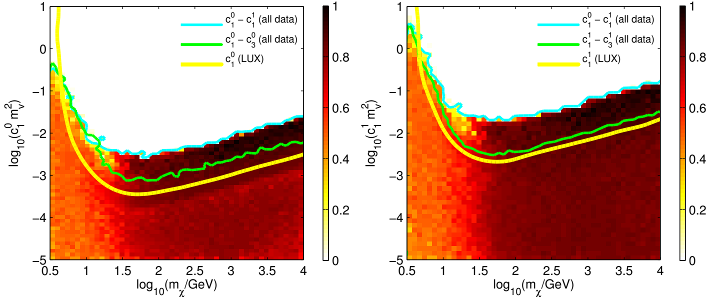
- Experimental data *simultaneously* included in the fit:
  - LUX
  - XENON100
  - XENON10
  - CDMS-Ge
  - CDMS-LT
  - SuperCDMS
  - CDMSlite
  - PICASSO
  - SIMPLE
  - COUPP

Operator interference

- Pairs of operators, or isoscalar and isovector components of the same operator can interfere
- For instance, the operators $\hat{\mathcal{O}}_1$ and $\hat{\mathcal{O}}_3$ generate a transition probability proportional to

$$\langle|\mathcal{M}_{NR}|^2\rangle_{\rm spins} = \frac{4\pi}{2J+1}\sum_{\tau\tau'}\Big[c_1^\tau c_1^{\tau'} W_M^{\tau\tau'}(y) + \frac{1}{8}\frac{q^2}{m_N^2} v_T^{\perp 2} c_3^\tau c_3^{\tau'} W_{\Sigma'}^{\tau\tau'}(y) + \frac{q^2}{m_N^2}\left(\frac{q^2}{4m_N^2} c_3^\tau c_3^{\tau'} W_{\Phi''}^{\tau\tau'}(y) + c_1^\tau c_3^{\tau'} W_{\Phi'' M}^{\tau\tau'}(y)\right)\Big]$$

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



Directional Detection

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

Formalism

- Double differential energy spectrum at directional detection experiments:

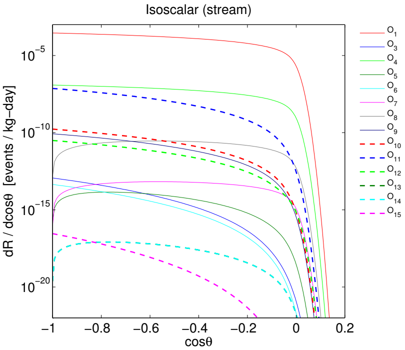
$$\frac{\mathrm{d}^2\mathcal{R}}{\mathrm{d}E_R\,\mathrm{d}\Omega} = \sum_T \frac{\xi_T}{(2\pi)}\frac{\rho_\chi}{m_\chi m_T}\int \delta(\mathbf{v}\cdot\mathbf{w} - w_T)\, F(\mathbf{v}+\mathbf{v_e}(t))\, v^2\, \frac{\mathrm{d}\sigma_T}{\mathrm{d}E_R}(v^2, q^2)\, \mathrm{d}^3\mathbf{v}$$

- It requires:
  - The Radon transform of higher moments of F
  - Nuclear response functions for, e.g., CF_4, CS_2, ^3He, etc...

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

New ring-like features

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



- We find new ring-like features in $\mathrm{d}R/\mathrm{d}\cos\theta$
- This result was confirmed in

  B. J. Kavanagh arXiv:1505.07406 [hep-ph].
- Different ring-like features in $\mathrm{d}^2R/\mathrm{d}\cos\theta\mathrm{d}E_R$ were previously found in
  N. Bozorgnia, G. B. Gelmini and P. Gondolo, JCAP **1206** (2012) 037.

Neutrino telescopes

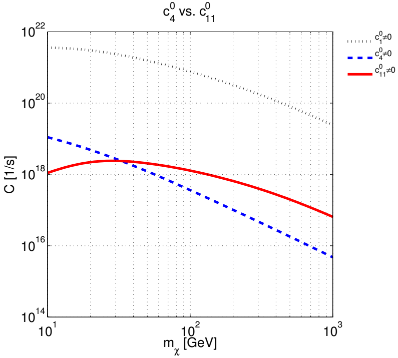
R. C. and B. Schwabe JCAP **1504** 04, 042 (2015) $\longleftarrow$ computation of relevant nuclear response functions

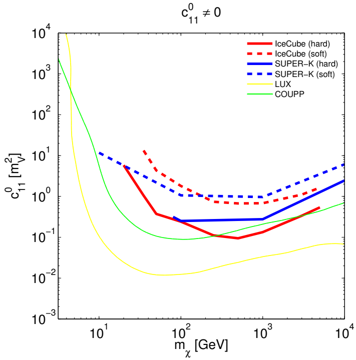
R. C., JCAP **1504** 04, 052 (2015) $\longleftarrow$ application to neutrino telescopes

Direct detection vs neutrino telescopes: highlights

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

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

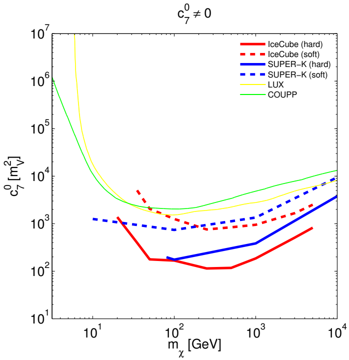


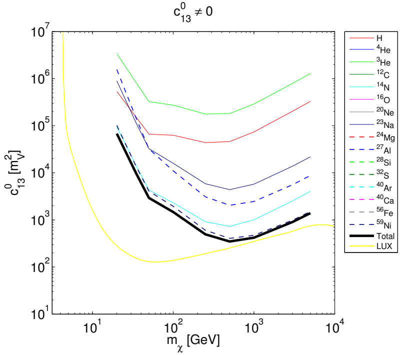


- $\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$, $\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{q}}/m_N$

Direct detection vs neutrino telescopes: highlights

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





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 $\mathrm{d}R/\mathrm{d}\cos\theta$ 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.