

Effective theories for dark matter-nucleon interactions

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- ▶ 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

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 $\chi(\mathbf{p}) + N(\mathbf{k}) \rightarrow \chi(\mathbf{p}') + N(\mathbf{k}')$
- ▶ Its amplitude \mathcal{M} is restricted by
 - Momentum conservation $\rightarrow \mathbf{p}, \mathbf{k}, \mathbf{q}$
 - Galilean invariance $\rightarrow \mathbf{v} = \mathbf{p}/m_\chi - \mathbf{k}/m_N$
- ▶ 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

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

Dark matter-nucleon interaction operators

$$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$$

$$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp \right)$$

$$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$$

$$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp \right)$$

$$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N} \right) \left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N} \right)$$

$$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$$

$$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp$$

$$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N} \right)$$

$$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}$$

$$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}$$

$$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp \right)$$

$$\hat{\mathcal{O}}_{13} = i \left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp \right) \left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N} \right)$$

$$\hat{\mathcal{O}}_{14} = i \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N} \right) \left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp \right)$$

$$\hat{\mathcal{O}}_{15} = - \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N} \right) \left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp \right) \cdot \frac{\hat{\mathbf{q}}}{m_N} \right]$$

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

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

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

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

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

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

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

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

- ▶ 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

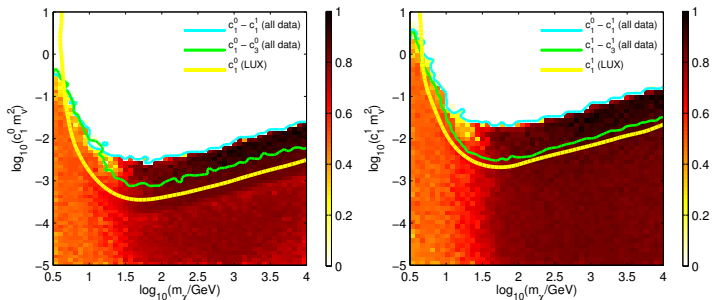
- ▶ I compare theory and observations in a profile likelihood analysis varying all model parameters *simultaneously*
- ▶ From the profile Likelihood, I derive 2D 95% confidence intervals in planes dark matter mass vs coupling constant
- ▶ Experimental data *simultaneously* included in the fit:
 - LUX
 - XENON100
 - XENON10
 - CDMS-Ge
 - CDMS-LT
 - SuperCDMS
 - CDMSlite
 - PICASSO
 - SIMPLE
 - COUPP

Operator interference

- ▶ 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

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

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



Directional Detection

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

- ▶ Double differential energy spectrum at directional detection experiments:

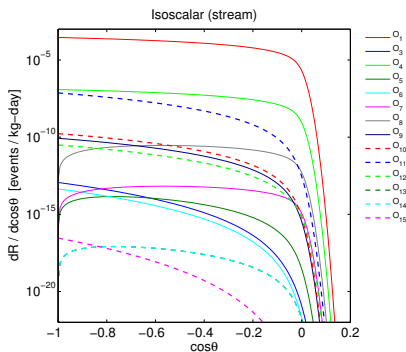
$$\frac{d^2\mathcal{R}}{dE_R d\Omega} = \sum_T \frac{\xi_T}{(2\pi)} \frac{\rho_X}{m_X m_T} \int \delta(\mathbf{v} \cdot \mathbf{w} - w_T) F(\mathbf{v} + \mathbf{v}_e(t)) v^2 \frac{d\sigma_T}{dE_R}(v^2, q^2) d^3\mathbf{v}$$

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

Neutrino telescopes

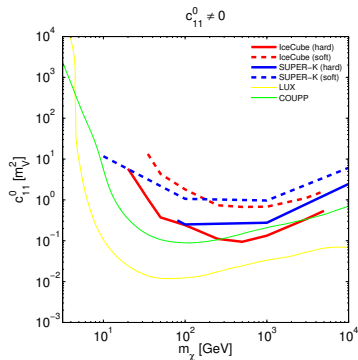
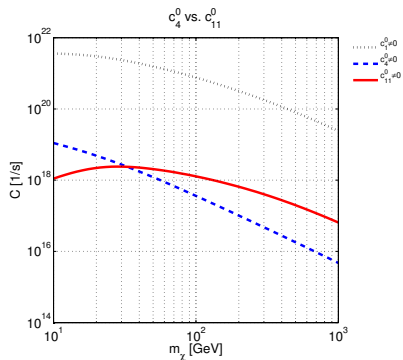
R. C. and B. Schwabe JCAP **1504** 04, 042 (2015) ← computation of relevant nuclear response functions

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

Direct detection vs neutrino telescopes: highlights

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

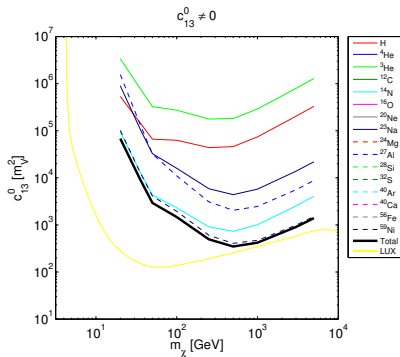
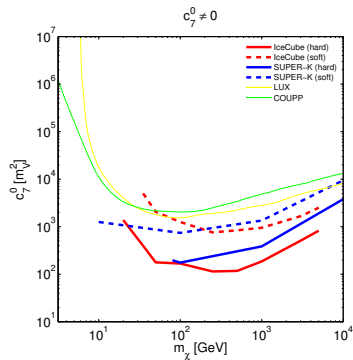
R. C. and B. Schwabe JCAP **1504** 04, 042 (2015)



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

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 $dR/d\cos\theta$ 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.