Effective theory of dark matter direct detection

Riccardo Catena
University of Göttingen

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Effective theory of dark matter-nucleon interactions

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Outline

- Effective theory of dark matter-nucleon interactions

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

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

- Phenomenology:

  R. C. and P. Gondolo, arXiv:1504.06554 [hep-ph]
  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

  R. C. arXiv:1505.06441 [hep-ph] } 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

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

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-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-nucleus scattering

- Assuming one-body dark matter-nucleon interactions, the Hamiltonian density for **dark matter-nucleus** interactions is

$$\hat{\mathcal{H}}_{\mathrm{T}}(\mathbf{r}) = \sum_{\tau=0,1} \left\{ \sum_{i=1}^{A} \hat{l}_{\mathrm{SI}}^{\tau}\ \delta(\mathbf{r}-\mathbf{r}_i) + \sum_{i=1}^{A} \hat{\mathbf{l}}_{\mathrm{SD}}^{\tau} \cdot \vec{\sigma}_i\, \delta(\mathbf{r}-\mathbf{r}_i) \right. \\ + \hat{\mathbf{l}}_{M}^{\tau} \cdot\ \text{convection current} \\ \left. + \hat{\mathbf{l}}_{E}^{\tau} \cdot\ \text{spin/velocity current} \right\} t^{\tau}$$

- $\hat{l}_{\mathrm{SI}}^{\tau} = c_1^{\tau} + i(\hat{\mathbf{q}}/m_N) \cdot \hat{\mathbf{S}}_{\chi}\ c_{11}^{\tau} + \ldots$
- $\hat{\mathbf{l}}_{\mathrm{SD}}^{\tau} = \hat{\mathbf{S}}_{\chi}\ c_4^{\tau}/2 + i(\hat{\mathbf{q}}/m_N) \times \hat{\mathbf{v}}_T^{\perp}\ c_3^{\tau}/2 + \ldots$

Transition probability $\langle|\mathcal{M}_{NR}|^2\rangle_{\rm spins}$

- $\langle|\mathcal{M}_{NR}|^2\rangle_{\rm spins}$ factorizes: "dark matter response" $\times$ "nuclear response"

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

- 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

Dark matter-nucleus scattering cross-section

- The dark matter-nucleus scattering cross-section is

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

- Importantly, $\mathrm{d}\sigma_T/\mathrm{d}E_R$ 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

Dark matter-nucleus scattering cross-section

- Rate of scattering events at direct detection experiments:

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \sum_T \xi_T \frac{\rho_\chi}{M_T m_\chi} \int_{v > v_{\min}(q)} F(\vec{v} + \vec{v}_e(t))\, v \frac{\mathrm{d}\sigma_T}{\mathrm{d}E_R}(v^2, q^2)\, d^3 v$$

- Rate of dark matter capture by the Sun:

$$\frac{\mathrm{d}C}{\mathrm{d}V} = \int_0^\infty \mathrm{d}u \frac{f(u)}{u} \sum_T n_T w^2\, \Theta\left(\frac{\mu_T}{\mu_{+,T}^2} - \frac{u^2}{w^2}\right) \int_{E_{\min}}^{E_{\max}} \mathrm{d}E_R \frac{\mathrm{d}\sigma_T}{\mathrm{d}E_R}\left(w^2, q^2\right)$$

Phenomenology

Direct Detection

R. C. and P. Gondolo, arXiv:1504.06554 [hep-ph].

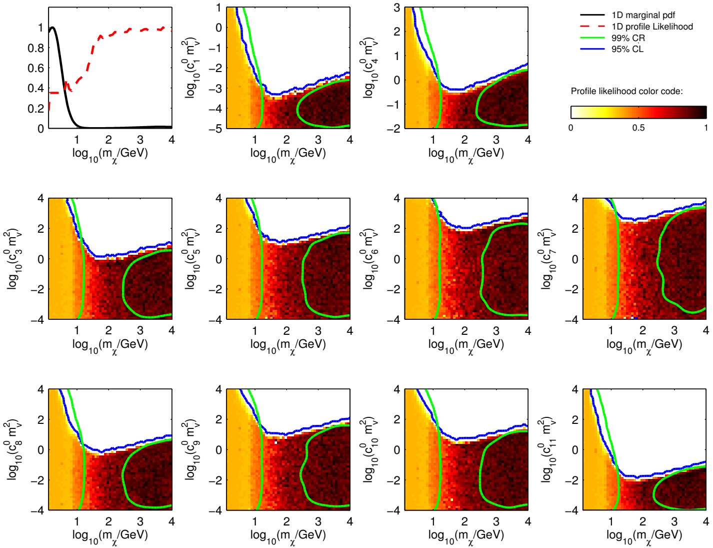
R. C., JCAP **1409**, 09, 049 (2014)

R. C. and P. Gondolo, JCAP **1409**, 09, 045 (2014)

R. C., JCAP **1407**, 055 (2014)

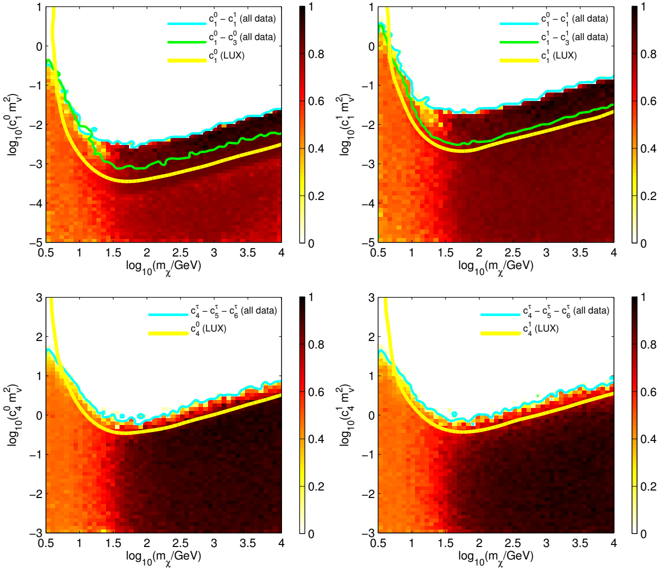
Global limits: mass vs interaction strengths

R. C. and P. Gondolo, JCAP **1409** 045 (2014)



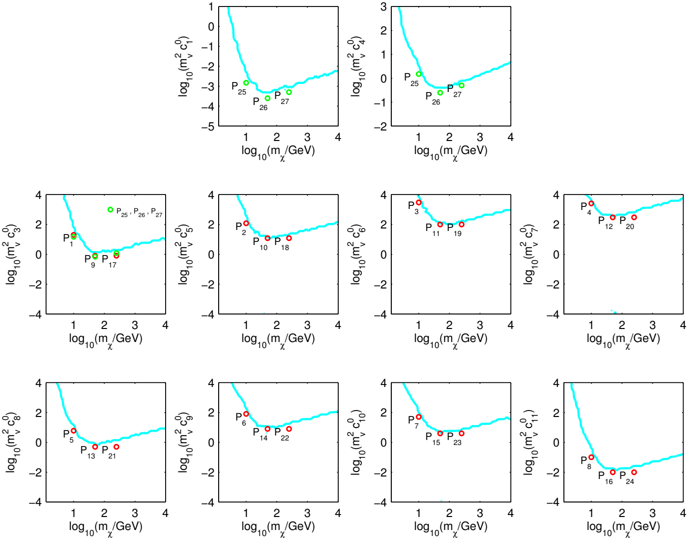
Operator interference

R. C. and P. Gondolo, ariXiv:1504.06554



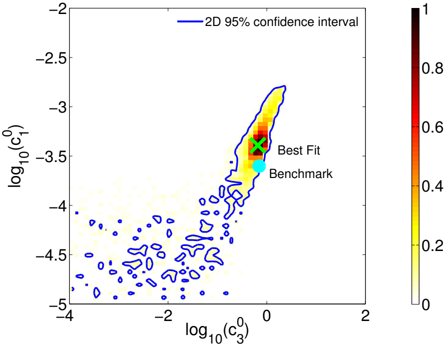
Prospects (all benchmark points)

R. C., JCAP **1407** 055 (2014)



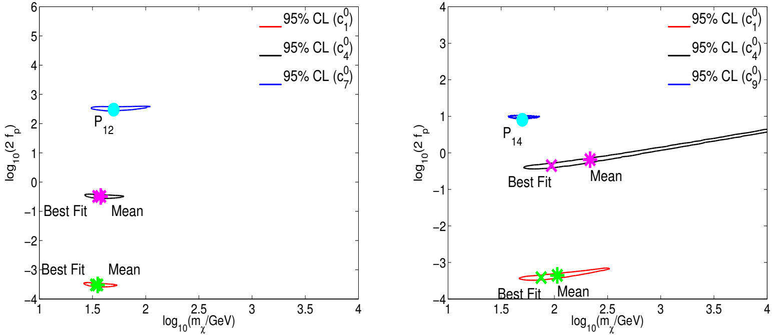
Prospects ($m_\chi = 50$ GeV; c_1^0, c_3^0, c_4^0)

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

R. C. arXiv:1505.06441 [hep-ph].

Formalism

- Double differential energy spectrum at directional detection experiments:

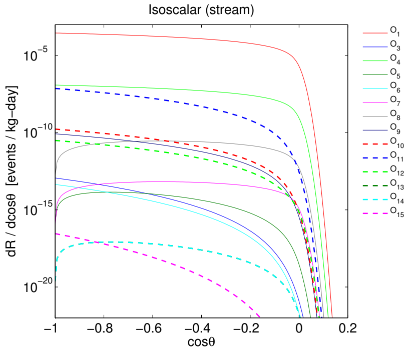
$$\frac{\mathrm{d}^2\mathcal{R}}{\mathrm{d}E_R\,\mathrm{d}\Omega} = \sum_T \frac{\xi_T}{(2\pi)} \frac{\rho_\chi}{m_\chi m_T} \int \delta(\mathbf{v}\cdot\mathbf{w} - w_T)\, F(\mathbf{v} + \mathbf{v}_\mathbf{e}(t))\, v^2\, \frac{\mathrm{d}\sigma_T}{\mathrm{d}E_R}(v^2, q^2)\,\mathrm{d}^3\mathbf{v}$$

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

R. C. arXiv:1505.06441 [hep-ph].

New ring-like features

R. C. arXiv:1505.06441 [hep-ph].



- 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., JCAP **1504** 04, 052 (2015)

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

Direct detection vs neutrino telescopes: highlights

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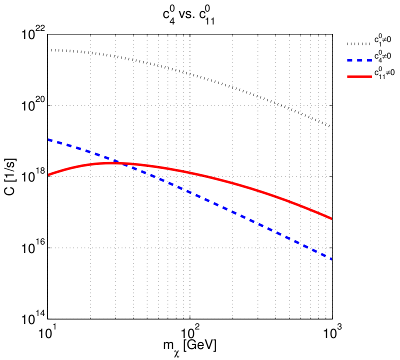
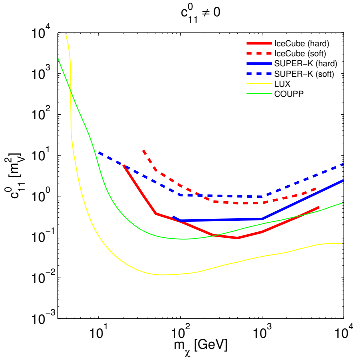
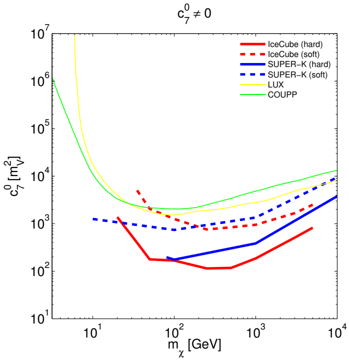


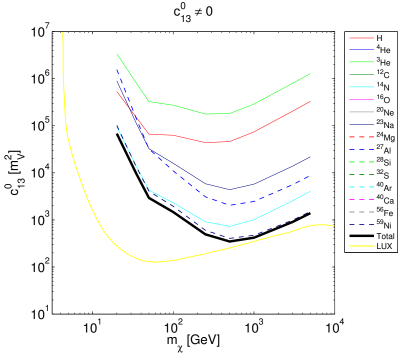


- $\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$, $\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{q}}/m_N$

Direct detection vs neutrino telescopes: highlights

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





Conclusions

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