

Non-relativistic effective theory approach to dark matter direct detection

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- ▶ Introduction
- ▶ Effective theory of dark matter-nucleon interactions (Fitzpatrick et. al, 2013)
- ▶ Comparison with observations:

R. Catena, A. Ibarra, S. Wild, JCAP **1605**, 05, 039 (2016)

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

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

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

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

R. Catena, JCAP **1407**, 07, 055 (2014)

} Direct Detection

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

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

} Indirect Detection

- ▶ Rate of dark matter-nucleus scattering events:

$$\frac{dR}{dE_R} = \sum_T \xi_T \frac{\rho_\chi}{m_T m_\chi} \int_{v > v_{\min}(q)} f(\mathbf{v} + \mathbf{v}_e(t)) v \frac{d\sigma_T}{dE_R}(v^2, q^2) d^3v$$

galactic distribution

particle nature

- ▶ Modulation amplitude:

$$A(E_-, E_+) = \frac{1}{E_+ - E_-} \frac{1}{2} \left[R(E_-, E_+) \Big|_{\text{June 1st}} - R(E_-, E_+) \Big|_{\text{Dec 1st}} \right]$$

Dark matter-nucleus scattering cross-section

- ▶ Standard paradigm: spin-independent and spin-dependent dark matter-nucleon interactions

$$\frac{d\sigma_T}{dE_R} = \frac{m_T}{2\pi v^2 [j_\chi][J_T]} \sum_{\text{spins}} \left| \langle F | \sum_{i=1}^A e^{-i\mathbf{q}\cdot\mathbf{r}_i} (\mathcal{H}_{\text{SI}} + \mathcal{H}_{\text{SD}}) | I \rangle \right|^2$$

The diagram shows the equation above with several annotations. A blue arrow points from the text 'nucleus ⊗ DM state' at the bottom left to the bra-ket expression $\langle F | \dots | I \rangle$. A red arrow points from the text 'one-body DM-nucleon interaction' to the interaction terms $(\mathcal{H}_{\text{SI}} + \mathcal{H}_{\text{SD}})$ inside the sum. A blue arrow also points from the text 'one-body DM-nucleon interaction' to the exponential phase factor $e^{-i\mathbf{q}\cdot\mathbf{r}_i}$.

Spin-independent interaction \mathcal{H}_{SI}

- ▶ Scalar/Scalar coupling: $\mathcal{L}_{SS} = \frac{1}{\Lambda^3} \sum_q C_q^{SS} \bar{\chi} \chi m_q \bar{q} q$

- ▶ **S-matrix element:**

$$\begin{aligned} \langle f | iS | i \rangle &= -i \bar{u}_\chi(p') u_\chi(p) \int d^4x e^{i q x} \langle N' | \sum_q c_q \bar{q}(x) q(x) | N \rangle \\ &\simeq -i (2\pi)^4 \delta^4(q - k' + k) \xi_\chi^\dagger \xi_\chi \xi_N^\dagger (b_0 + b_1 \tau_3) \xi_N \end{aligned}$$

- ▶ Underlying **non-relativistic Hamiltonian**

$$\mathcal{H}_{SI} = \sum_{\tau=0,1} b_\tau \mathbb{1}_\chi \mathbb{1}_N t^\tau \equiv \sum_{\tau=0,1} c_1^\tau \mathbb{1}_\chi N t^\tau$$

Spin-dependent interaction \mathcal{H}_{SD}

▶ Axial-Vector/Axial-Vector: $\mathcal{L}_{AA} = \frac{1}{\lambda^2} \sum_q C_q^{AA} \bar{\chi} \gamma^\mu \gamma_5 \chi \bar{q} \gamma_\mu \gamma_5 q$

▶ **S-matrix element:**

$$\begin{aligned} \langle f | iS | i \rangle &= -i \bar{u}_\chi(p') \gamma_\mu \gamma_5 u_\chi(p) \int d^4x e^{iqx} \langle N' | \sum_q c_q \bar{q}(x) \gamma^\mu \gamma_5 q(x) | N \rangle \\ &\simeq -i (2\pi)^4 \delta^4(q - k' + k) \xi_\chi'^\dagger \sigma_\chi \xi_\chi \cdot \xi_N'^\dagger (a_0 + a_1 \tau_3) \sigma_N \xi_N \end{aligned}$$

▶ Underlying **non-relativistic Hamiltonian**

$$\mathcal{H}_{SD} = \sum_{\tau=0,1} a_\tau \sigma_\chi \cdot \sigma_N t^\tau \equiv \sum_{\tau=0,1} c_4^\tau \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N t^\tau$$

Effective Theory (ET) of dark matter-nucleon interactions

- ▶ It relies on a separation of scales: $|\mathbf{q}|/m_V \ll 1$, where m_V is the mediator mass
- ▶ The most general Hamiltonian for χ - N interactions is a power series in $\hat{\mathbf{q}}/m_V$. Each term in the series preserves 3 **fundamental symmetries**, and is a combination of **basic operators**.
- ▶ **Fundamental symmetries**: Galilean, rotational and translational invariance
- ▶ **Basic operators**:
 - ▶ Consider the scattering $\chi(\mathbf{p}) + N(\mathbf{k}) \rightarrow \chi(\mathbf{p}') + N(\mathbf{k}')$
 - ▶ Momentum conservation $\rightarrow \mathcal{M}(\mathbf{p}, \mathbf{k}, \mathbf{q})$
 - ▶ Galilean invariance $\rightarrow \mathcal{M}(\mathbf{v} = \mathbf{p}/m_\chi - \mathbf{k}/m_N, \mathbf{q})$
 - ▶ In general, $\mathcal{M} = \mathcal{M}(\mathbf{v}, \mathbf{q}, \mathbf{S}_\chi, \mathbf{S}_N)$
 - ▶ We therefore identify five basic operators

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

Effective Hamiltonian for dark matter-nucleon interactions

- ▶ 14 linearly independent operators can be constructed from the basic operators, if we demand that they are at most quadratic in $\hat{\mathbf{q}}$ (and arise from the exchange of a mediator of spin ≤ 1)
- ▶ The most general Hamiltonian density is therefore

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

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

Dark matter-nucleon interaction operators

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Dark matter-nucleus scattering cross-section

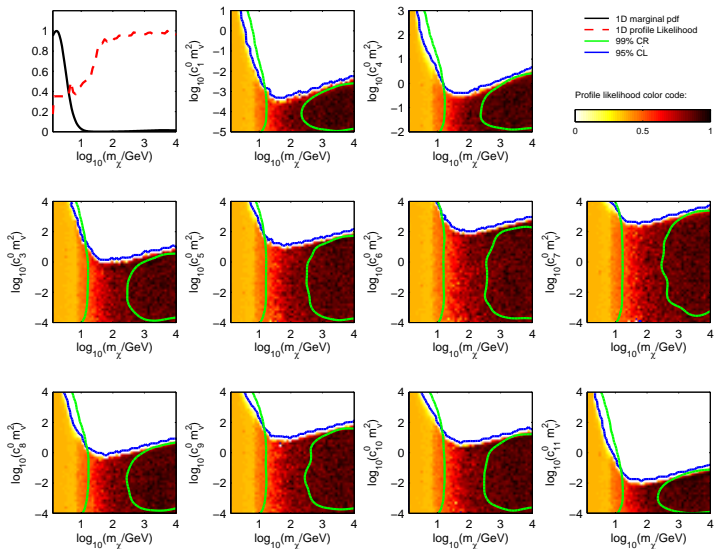
- ▶ In the ET framework, the dark matter-nucleus scattering cross-section is

$$\frac{d\sigma_T}{dE_R} = \frac{m_T}{2\pi v^2 [j_\chi][J_T]} \sum_{\text{spins}} \left| \langle F | \sum_{i=1}^A \int d\mathbf{r} e^{-i\mathbf{q}\cdot\mathbf{r}} \hat{\mathcal{H}}_i(\mathbf{r}) | I \rangle \right|^2$$

- ▶ This expression depends on:
 - 28 coupling constants
 - 8 nuclear response functions
- ▶ Response functions for 16 elements in the Sun:
 - R. Catena and B. Schwabe JCAP **1504** 04, 042 (2015)

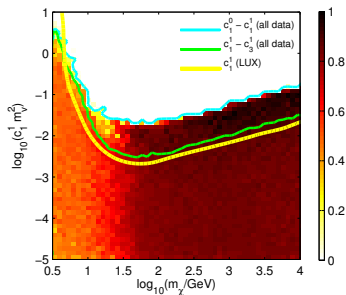
Global limits: mass vs coupling constants

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



Operator interference

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

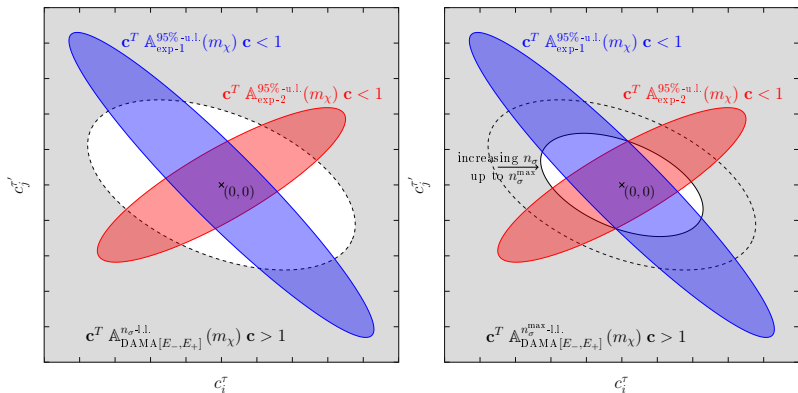


- ▶ Pairs of operators, or isoscalar and isovector components of the same operator can interfere
- ▶ For instance, the operators \hat{O}_1 and \hat{O}_3 generate a transition probability proportional to

$$\begin{aligned}
 \mathcal{P}^{c_1 c_3} \propto \sum_{\tau\tau'} & \left[c_1^\tau c_1^{\tau'} W_M^{\tau\tau'}(q) + \frac{1}{8} \frac{q^2}{m_N^2} v_T^{\perp 2} c_3^\tau c_3^{\tau'} W_{\Sigma'}^{\tau\tau'}(q) \right. \\
 & \left. + \frac{q^2}{m_N^2} \left(\frac{q^2}{4m_N^2} c_3^\tau c_3^{\tau'} W_{\Phi'''}^{\tau\tau'}(q) + c_1^\tau c_3^{\tau'} W_{\Phi'''}^{\tau\tau'}(q) \right) \right]
 \end{aligned}$$

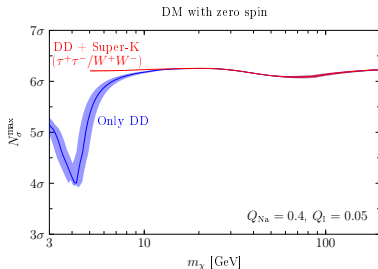
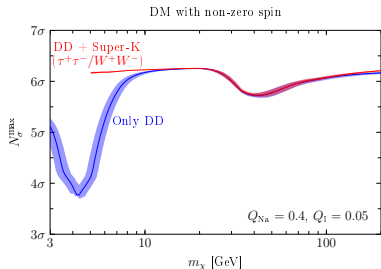
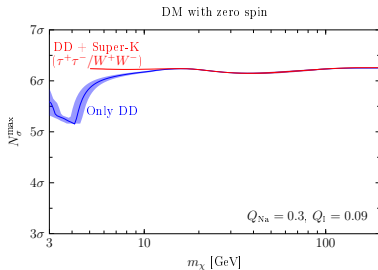
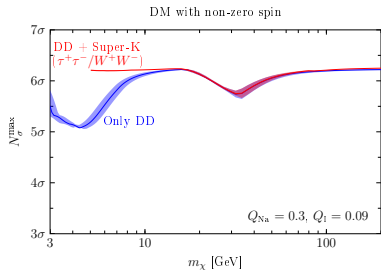
DAMA confronts null searches I

Is there a linear combination of \hat{O}_k such that DAMA can be reconciled with null searches?



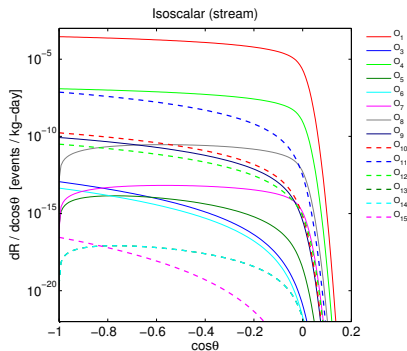
R. Catena, A. Ibarra, S. Wild, JCAP **1605**, 05, 039 (2016)

DAMA confronts null searches II



New ring-like features at directional detectors

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



- ▶ New ring-like features in $dR/d\cos\theta$

see also B. J. Kavanagh, Phys.Rev. **D92** (2015) no.2, 023513

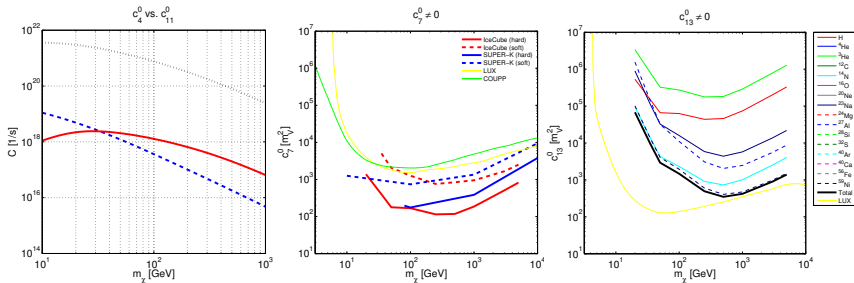
- ▶ Different ring-like features in $d^2R/d\cos\theta dE_R$ were previously found in

N. Bozorgnia, G. B. Gelmini and P. Gondolo, JCAP **1206** (2012) 037.

Neutrino telescopes: highlights

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

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



- $\hat{O}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$, $\hat{O}_{11} = i\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{q}}/m_N$
- $\hat{O}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$
- $\hat{O}_{13} = i \left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp \right) \left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N} \right)$

Conclusions

- ▶ A complete classification of all one-body dark matter-nucleon interaction operators has recently been performed
- ▶ 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
- ▶ Even within this general theoretical framework, it seems to be difficult to reconcile DAMA with null searches