# Towards Model-Independent Tests of WIMP Dark Matter

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# Outline

**Introduction**

- Standard WIMP searches
- Direct detection
- Indirect detection (at neutrino telescopes)

**Main focus**

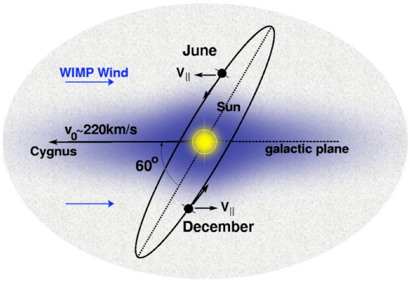
- Non-relativistic effective theory of WIMP-nucleon interactions
- Predictions:

  a) Overview of selected results

  b) DAMA vs null results

  c) WIMP capture and annihilation in the Earth

- **Motivation and strategy**:




- **Physical observable**: rate of dark matter-nucleus scattering events in terrestrial detectors:

$$\frac{\mathrm{d}\mathcal{R}}{\mathrm{d}E_{\rm nr}} = \frac{\rho_{\rm dm}}{m_\chi m_T} \int_{|\mathbf{v}|>v_{\rm min}} \mathrm{d}^3\mathbf{v}\, |\mathbf{v}| f(\mathbf{v}) \frac{\mathrm{d}\sigma_T}{\mathrm{d}E_{\rm nr}}$$

Astrophysics

Particle Physics

- **Modulation**: the Earth's orbit inclination induces an annual modulation in the rate of recoil events

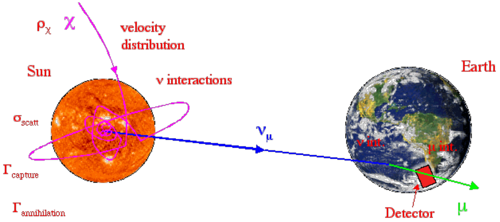
$$\mathcal{A}(E_-, E_+) = \frac{1}{E_+ - E_-} \frac{1}{2} \left[ \mathcal{R}(E_-, E_+) \Big|_{\text{June 1st}} - \mathcal{R}(E_-, E_+) \Big|_{\text{Dec 1st}} \right]$$

- **Kinematics**:

  a) For $m_\chi \sim 100$ GeV, one expects a flux of $\sim 7 \times 10^4$ cm$^{-2}$ s$^{-1}$

  b) Expected recoil energy, $E_R = (2\mu_T^2 v^2 / m_T) \cos^2\theta \sim \mathcal{O}(10)$ keV

- **Motivation and strategy**:




- **Aim**: the search for neutrinos produced by the annihilation of dark matter particles bound to the Sun/Earth

# Indirect detection / Neutrino telescopes

- **Physical observable:** flux of neutrinos produced by dark matter annihilation in the Sun/Earth

$$\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} = \frac{\Gamma_a}{4\pi D^2} \sum_f B_\chi^f \frac{\mathrm{d}N_\nu^f}{\mathrm{d}E_\nu}$$

$$\Gamma_a = \Gamma_a \left[\rho_{\mathrm{dm}}, f(\mathbf{v}), \mathrm{d}\sigma_T/\mathrm{d}E_{\mathrm{nr}}\right]$$

**Theory of WIMP-nucleon interactions**

- More specifically, $\Gamma_a$ depends on

$$\frac{\mathrm{d}\mathcal{C}}{\mathrm{d}V} = \int_0^\infty \mathrm{d}u \, \frac{\rho_{\mathrm{dm}} \langle f(u) \rangle}{u} \sum_T n_T w^2 \, \Theta \int \mathrm{d}E_{\mathrm{nr}} \, \frac{\mathrm{d}\sigma_T}{\mathrm{d}E_{\mathrm{nr}}}$$

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

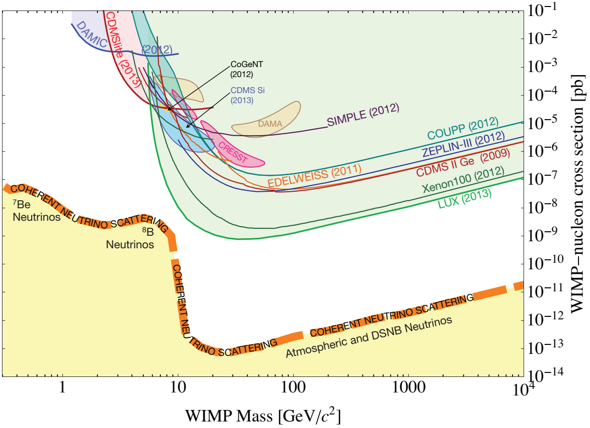
$$\frac{\mathrm{d}\sigma_T}{\mathrm{d}E_{\rm nr}} = \frac{m_T}{2\pi v^2}\frac{1}{(2j_\chi+1)(2J+1)}\sum_{\rm spins}\left|\langle F|\sum_{i=1}^{A} e^{-i\mathbf{q}\cdot\mathbf{r}_i}\left(\mathcal{H}_{\rm SI}+\mathcal{H}_{\rm SD}\right)|I\rangle\right|^2$$

one-body DM-nucleon interaction

nucleus $\otimes$ DM state

# Conflicting experimental results

J. Billard, L. Strigari and E. Figueroa-Feliciano Phys. Rev. **D89** (2014) no. 2, 023524



# Standard paradigm based upon SI and SD interactions

- Is it complete? No
- Is it favored by observations? No

- **Conflicting data** and the **increase in sensitivity** due to already operating ton-scale and km$^3$ detectors motivate the exploration of more general approaches

# Effective Theory (ET) of WIMP-nucleon interactions

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

- **Separation of scales**: $|\mathbf{q}|/m_V \ll 1$, where $m_V$ is the mediator mass
- **Basic symmetries**: Galilean and translational invariance
- **Four "degrees of freedom"**:
  - Consider the scattering $\chi(\mathbf{p}) + N(\mathbf{k}) \to \chi(\mathbf{p}') + N(\mathbf{k}')$
  - Momentum conservation $\to \mathcal{M}(\mathbf{p}, \mathbf{k}, \mathbf{q})$
  - Galilean invariance $\to \mathcal{M}(\mathbf{v} = \mathbf{p}/m_\chi - \mathbf{k}/m_N, \mathbf{q})$
  - In general, $\mathcal{M} = \mathcal{M}(\mathbf{v}, \mathbf{q}, \mathbf{S}_\chi, \mathbf{S}_N)$
  - We therefore identify four basic operators

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

- The most general Hamiltonian density is therefore a power series in $\hat{\mathbf{q}}$. Each term is Galilean invariant and constructed from the four basic operators:

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

a) $t^0 = \mathbb{1}$, $t^1 = \tau_3$

b) $c_k^p = (c_k^0 + c_k^1)/2$ and $c_k^n = (c_k^0 - c_k^1)/2$

# Dark matter-nucleon interaction operators

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

# Connection to Simplified Models for dark matter

J. B. Dent, L. M. Krauss, J. L. Newstead and S. Sabharwal, Phys. Rev. **D92** (2015) no. 6, 063515

| WIMP spin | Mediator spin | $\mathcal{L}$ terms | leading NR operator | Eqv. $M_m$ |
|---|---|---|---|---|
| 0 | 0 | $h_1, g_1$ | $\mathcal{O}_1$ | 13 TeV |
| 0 | 0 | $h_2, g_1$ | $\mathcal{O}_{10}$ | 14 GeV |
| 0 | 1 | $h_4, g_4$ | $\mathcal{O}_{10}$ | 8 GeV |
| 0 | $1/2^{\dagger}$ | $y_1$ | $\mathcal{O}_1$ | 3.2 PeV |
| 0 | $1/2^{\dagger}$ | $y_2$ | $\mathcal{O}_1$ | 3.2 PeV |
| 0 | $1/2^{\dagger}$ | $y_1, y_2$ | $\mathcal{O}_{10}$ | 41 GeV |
| $1/2$ | 0 | $h_1, \lambda_1$ | $\mathcal{O}_1$ | 12.7 TeV |
| $1/2$ | 0 | $h_2, \lambda_1$ | $\mathcal{O}_{10}$ | 293 GeV |
| $1/2$ | 0 | $h_1, \lambda_2$ | $\mathcal{O}_{11}$ | 14 GeV |
| $1/2$ | 0 | $h_2, \lambda_2$ | $\mathcal{O}_6$ | 1.9 GeV |
| $1/2$ | 1 | $h_3, \lambda_3$ | $\mathcal{O}_1$ | 6.3 TeV |
| $1/2$ | 1 | $h_4, \lambda_3$ | $\mathcal{O}_9$ | 6.4 GeV |
| $1/2$ | 1 | $h_3, \lambda_4$ | $\mathcal{O}_8$ | 180 GeV |
| $1/2$ | 1 | $h_4, \lambda_4$ | $\mathcal{O}_4$ | 135 GeV |
| $1/2$ | $0^{\dagger}$ | $l_1$ | $\mathcal{O}_1$ | 7.1 TeV |
| $1/2$ | $0^{\dagger}$ | $l_2$ | $\mathcal{O}_1$ | 5.5 TeV |
| $1/2$ | $1^{\dagger}$ | $d_1$ | $\mathcal{O}_1$ | 5.9 TeV |
| $1/2$ | $1^{\dagger}$ | $d_2$ | $\mathcal{O}_1$ | 6.7 TeV |

- Non standard operators are the leading interaction in 6 additional cases if dark matter has spin 1

- Dark matter-nucleus scattering cross-section:

$$\frac{\mathrm{d}\sigma_T}{\mathrm{d}E_{\mathrm{nr}}} \propto \sum_{\mathrm{spins}} \left| \langle F | \sum_{i=1}^{A} \int \mathrm{d}\mathbf{r}\, e^{-i\mathbf{q}\cdot\mathbf{r}} \hat{\mathcal{H}}_i(\mathbf{r}) | I \rangle \right|^2$$

- In the ET framework, it depends on **28 coupling constants** and **8 nuclear response functions**
- Nuclear response functions for 16 elements in the Sun: R. Catena & B. Schwabe 2015

## Direct detection

- Current experiments place limits on commonly neglected WIMP-nucleon interaction operators that are comparable with those on the strength of the SD interaction

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

- Destructive operator interference effects can weaken standard direct detection exclusion limits by up to one order of magnitude in the coupling constants

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

- Standard analyses can be significantly biased if WIMPs do not interact via SI or SD interactions

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

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

- New ring-like features are expected in the angular distribution of nuclear recoil events

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

- DAMA compatibilty with null results revisited

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

## Indirect detection

- In contrast to standard expectations, Hydrogen is not the most important element in the capture in the Sun for most of the new spin-dependent interactions

  For some of the new operators the rate of dark matter capture in the Sun can be larger than for $\mathcal{O}_4$

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

- Exclusion limits must be reevaluated accordingly

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

- Dark matter self-interactions can be incorporated in the same framework straightforwardly

  R. Catena and A. Widmark, arXiv:1609.04825

- Resonances in the rate of WIMP capture in the Earth strongly depend on the WIMP-nucleon interaction

  R. Catena, arXiv:1609:08967

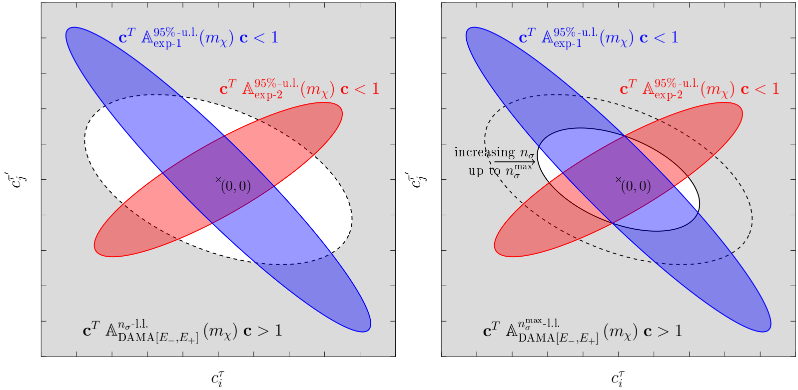
# DAMA confronts null searches I

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

- In the ET framework, this question can be reformulated in terms of intersection of ellipsoids

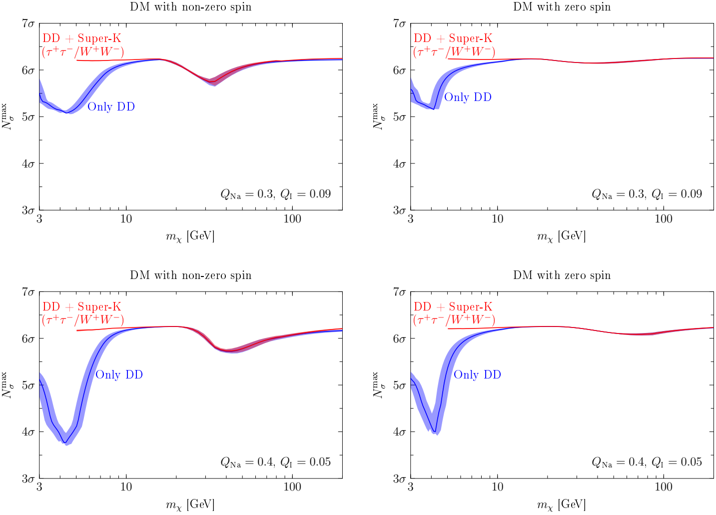
# DAMA confronts null searches II

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



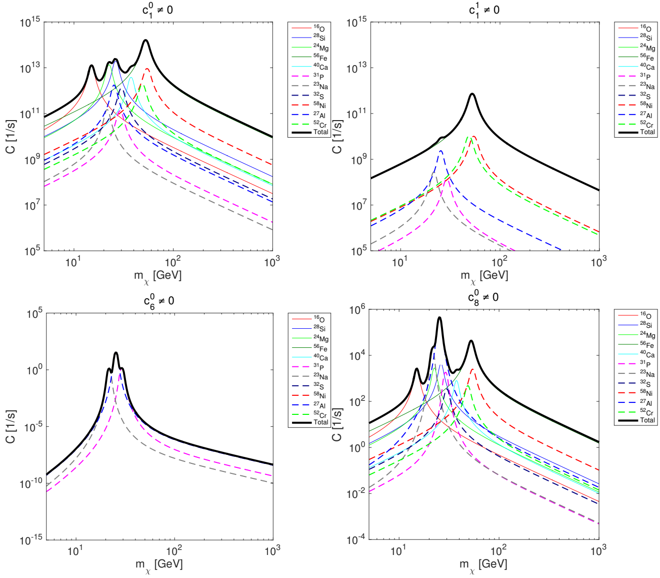
# DAMA confronts null searches III

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



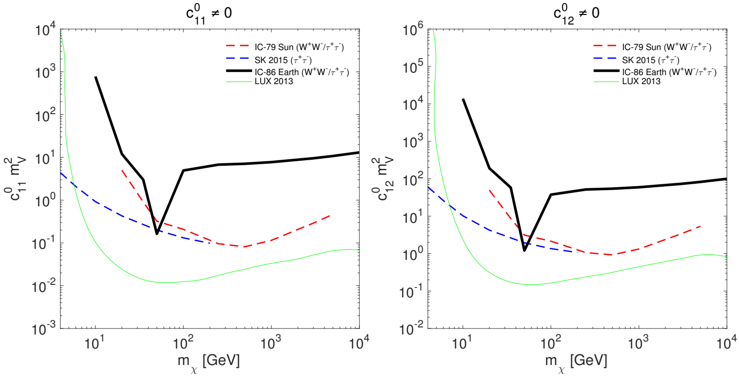
# WIMP capture in the Earth revisited

R. Catena, arXiv:1609:08967



# WIMP annihilation in the Earth revisited

R. Catena, arXiv:1609:08967



# Summary

- WIMP-nucleon interactions have been systematically classified in an effective theory framework
- It is the first step towards model-independent direct (and indirect) tests of WIMP dark matter
- In the talk I have reviewed the phenomenology of this general theoretical framework

- **Highlights**:

  a) Direct detection exclusion limits need to be reconsidered in the ET framework

  b) The same is true for the capture and annihilation of WIMPs in the Sun and Earth

  c) New ring-like features predicted at directional detection experiments

  d) In the (elastic) ET framework, DAMA remains incompatible with the null searches