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

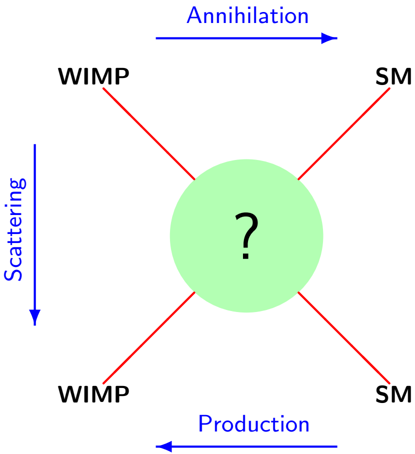
  c) WIMP capture and annihilation in the Earth

Weakly Interacting Massive Particles (WIMPs)

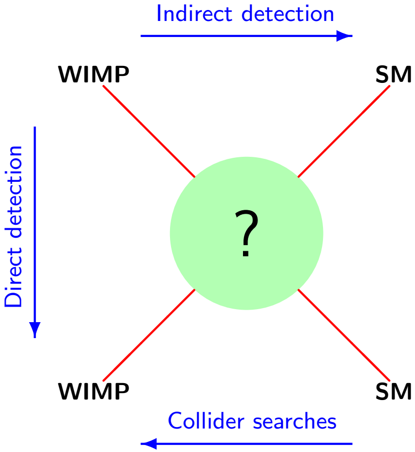
- Most studied candidate for dark matter, and **a testable scenario!**

  Expected mass: $m_{\mathrm{WIMP}} \sim 1\ \mathrm{GeV} - 100\ \mathrm{TeV}$

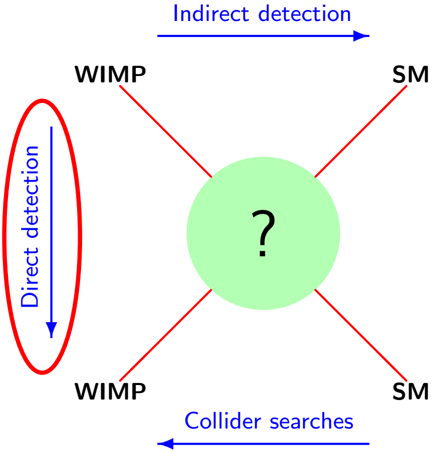
  WIMP interactions:



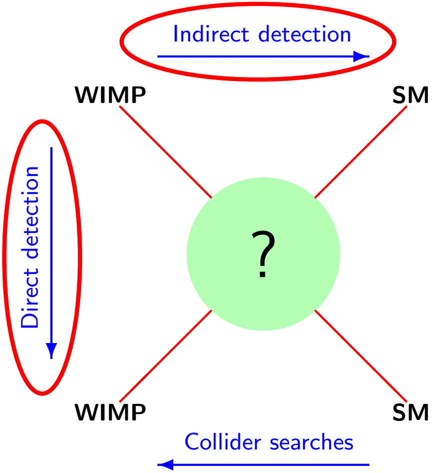
WIMP detection strategies



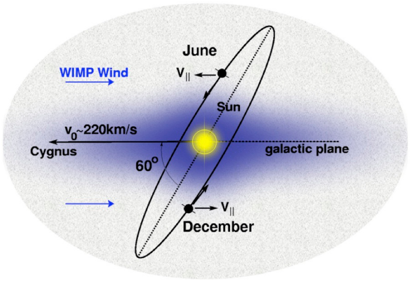
WIMP detection strategies



WIMP detection strategies



- **Motivation and strategy**:



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

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

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}

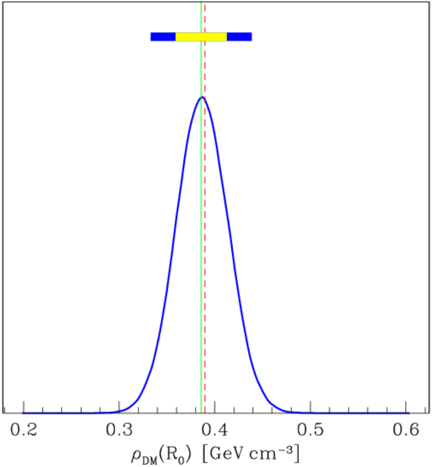
  b) Expected recoil energy, $E_R = (2\mu_T^2 v^2/m_T)\cos^2\theta \sim \mathcal{O}(10)$ keV

Local dark matter density in 5 steps

- Assume a mass model for the Milky Way: halo, stellar disk, bulge
- Calculate the observables: rotation curves, surface density, velocity dispersion of stars, weak lensing optical depth, etc ...
- Compare predictions with astronomical observations: the Bayesian approach has proven to be a powerful tool for this
- Extract preferred regions in parameter space, e.g. credible regions
- Translate them into an estimate for the local dark matter density, e.g. posterior PDF

Local dark matter density: Bayesian analysis

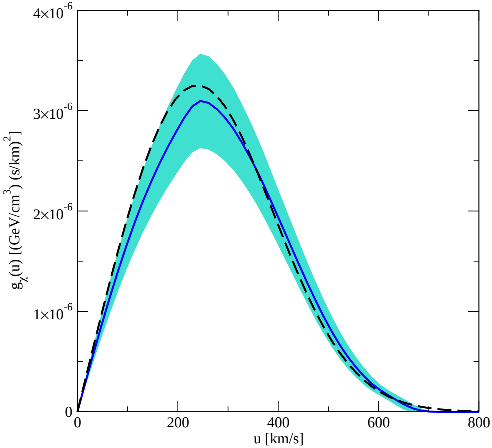
Catena & Ullio 2010



Local dark matter velocity distribution in 5 + 3 steps

- Simplifying assumption: spherically symmetric galactic gravitational potential
- Use Eddington's inversion formula to relate the local dark matter velocity distribution to the parameters of the assumed mass model
- From the posterior PDF of the model parameters, obtain the posterior PDF of local dark matter velocity distribution at sampled velocities

Bozorgnia, Catena and Schwetz 2014



WIMP-nucleus scattering cross-section

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

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

one-body DM-nucleon interaction

nucleus $\otimes$ DM state

- 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**:

$$\langle f|iS|i\rangle = -i\bar{u}_\chi(p')u_\chi(p) \int d^4x\, e^{i\,qx} \langle N'| \sum_q c_q \bar{q}(x) q(x) |N\rangle$$

$$\simeq -i(2\pi)^4 \delta^4(q - k' + k)\, \xi_\chi'^\dagger \xi_\chi\ \xi_N'^\dagger (b_0 + b_1 \tau_3) \xi_N$$

- Underlying **non-relativistic Hamiltonian**

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

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

- 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**:

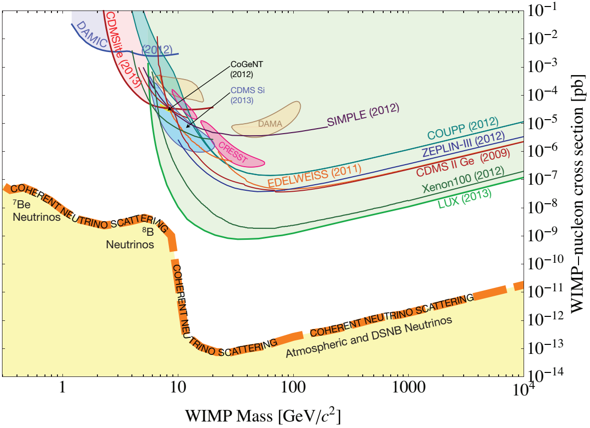
$$\langle f|iS|i\rangle = -i\bar{u}_\chi(p')\gamma_\mu\gamma_5 u_\chi(p)\int d^4x\, e^{i\,qx}\langle N'|\sum_q c_q\bar{q}(x)\gamma^\mu\gamma_5 q(x)|N\rangle$$
$$\simeq -i(2\pi)^4\delta^4(q-k'+k)\,\xi_\chi'^\dagger\boldsymbol{\sigma}_\chi\xi_\chi\,\cdot\,\xi_N'^\dagger(a_0+a_1\tau_3)\boldsymbol{\sigma}_N\xi_N$$

- Underlying **non-relativistic Hamiltonian**

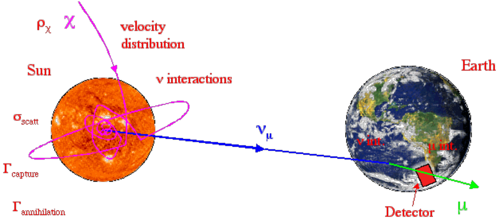
$$\mathcal{H}_{\mathrm{SD}} = \sum_{\tau=0,1} a_\tau\boldsymbol{\sigma}_\chi\cdot\boldsymbol{\sigma}_N t^\tau \equiv \sum_{\tau=0,1} c_4^\tau\hat{\mathbf{S}}_\chi\cdot\hat{\mathbf{S}}_N t^\tau$$

Conflicting experimental results

Billard et al. 2014



- **WIMP searches at neutrino telescopes**



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

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

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

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

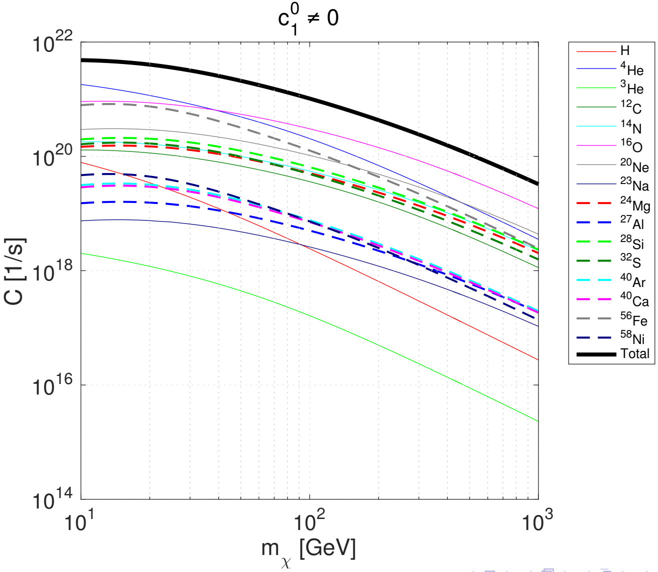
Theory of WIMP-nucleon interactions

- More specifically, Γ_a depends on

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

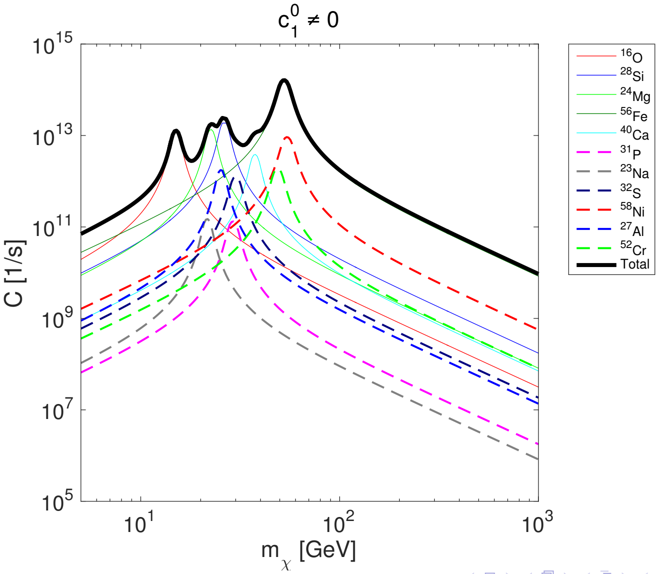
WIMP capture in the Sun

Catena and Schwabe 2015



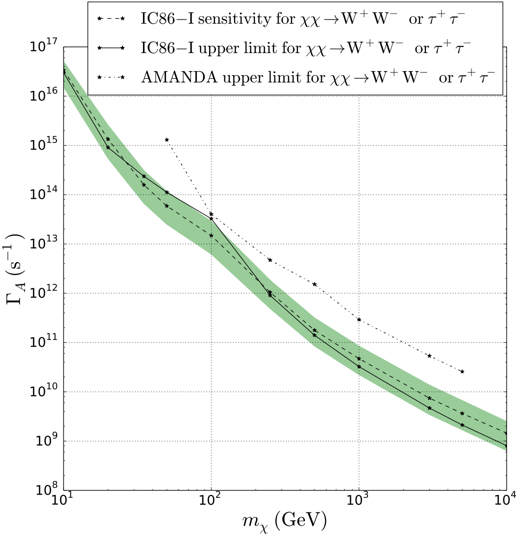
WIMP capture in the Earth

Catena 2016



IceCube search for WIMP annihilations in the Earth

IceCube collaboration 2016



Standard paradigm based upon SI and SD interactions

- Is it complete? No
- Is it favoured 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

Fitzpatrick et al. 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

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

Dark matter-nucleus scattering cross-section

- 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
- Destructive operator interference effects can weaken standard direct detection exclusion limits by up to one order of magnitude in the coupling constants
- The interpretation of direct detection experiments can be significantly biased if WIMPs interact via neglected interactions
- New ring-like features are expected in the angular distribution of nuclear recoil events

Indirect detection

- WIMP capture and annihilation in the Sun and Earth need to be revisited

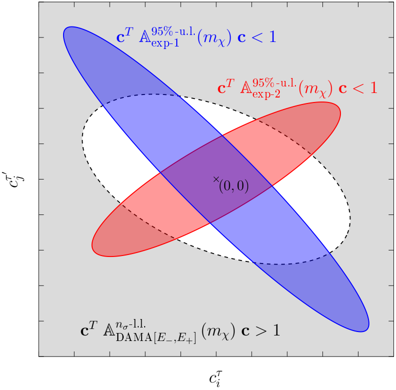
DAMA confronts null searches I

- 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

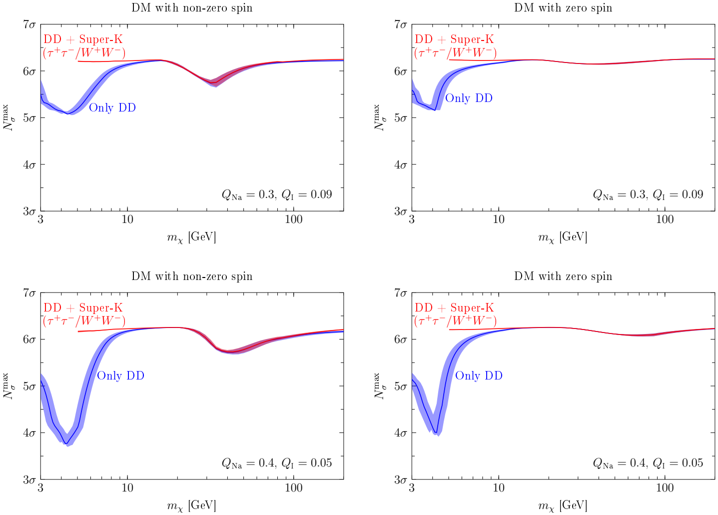
DAMA confronts null searches II

Catena, Ibarra and Wild 2016



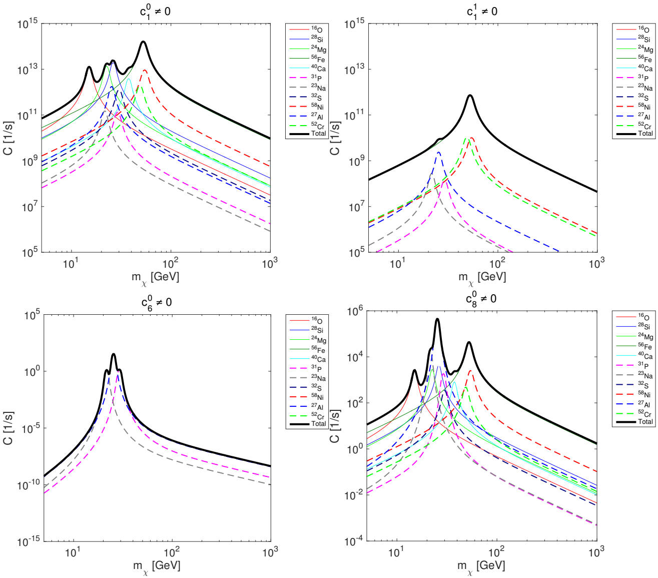
DAMA confronts null searches III

Catena, Ibarra and S. Wild 2016



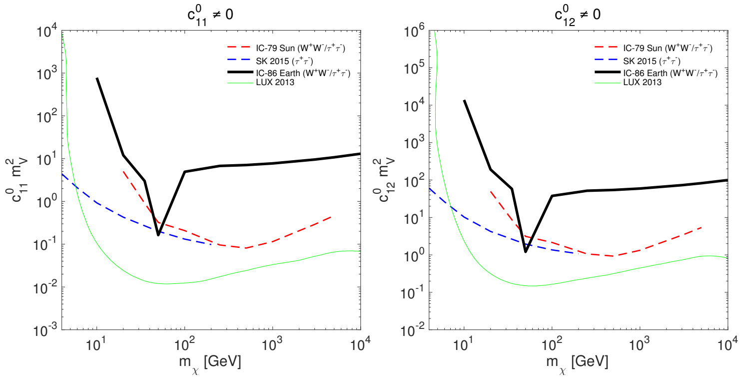
WIMP capture in the Earth revisited

Catena 2016



WIMP annihilation in the Earth revisited

Catena 2016



Connection to Simplified Models for dark matter

Dent et al. 2015

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, λ_1	$\mathcal{O}_1$	12.7 TeV
$1/2$	0	h_2, λ_1	$\mathcal{O}_{10}$	293 GeV
$1/2$	0	h_1, λ_2	$\mathcal{O}_{11}$	14 GeV
$1/2$	0	h_2, λ_2	$\mathcal{O}_6$	1.9 GeV
$1/2$	1	h_3, λ_3	$\mathcal{O}_1$	6.3 TeV
$1/2$	1	h_4, λ_3	$\mathcal{O}_9$	6.4 GeV
$1/2$	1	h_3, λ_4	$\mathcal{O}_8$	180 GeV
$1/2$	1	h_4, λ_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

Summary

- WIMP-nucleon interactions have been systematically classified in terms of Galilean invariant operators
- 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

- **Selected results**:

  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) DAMA remains incompatible with the null searches