Dark Matter searches at neutrino telescopes in effective theories

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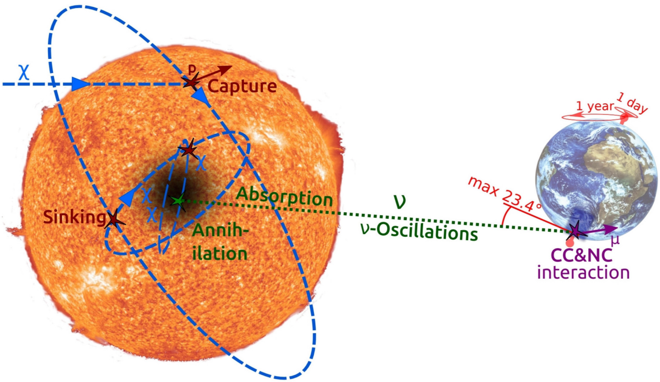
Overview



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Outline

- Dark Matter (DM) capture in the Sun/Earth and DM-nucleon interactions
- Effective theory of Dark Matter-nucleon interactions
- Application to DM capture in the Sun/Earth
- Revisiting the exclusion limits from the null result of operating neutrino telescopes
- Revisiting the prospects for DM discovery at next generation neutrino telescopes
- Summary

DM capture in the Sun/Earth

- The rate at which DM particles from the galactic halo are "captured" by the Sun/Earth is

$$\frac{\mathrm{d}C}{\mathrm{d}V} = n_{\mathrm{DM}} \int_0^{u_{\mathrm{max}}} \mathrm{d}u \, \frac{f(u)}{u} \sum_T n_T v^2 \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} \mathrm{d}E_R \, \frac{\mathrm{d}\sigma_T}{\mathrm{d}E_{\mathrm{nr}}} \left(v^2, q^2\right)$$

- The time evolution of the number of DM particles in the Sun/Earth is governed by the equation

$$\dot{N} = C - 2\Gamma_a \,,$$

where $2\Gamma_a = C_a N^2$.

- At equilibrium, $\Gamma_a = C/2$

Induced neutrino and muon fluxes

- The differential neutrino flux from DM annihilation in the Sun/Earth depends linearly on Γ_a

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

- The neutrino yield at detector, $\mathrm{d}N_\nu^f/\mathrm{d}E_\nu$, must take into account neutrino interactions and oscillations on their way from the production point to the detector location

- Current null results of neutrino telescopes are presented in terms of 90% C.L. upper bounds on ϕ_ν, or ϕ_μ (the flux of neutrino-induced muons at detector)

Effective theory of DM-nucleon interactions I

- I will model $\mathrm{d}\sigma_T/\mathrm{d}E_{\rm nr}$ within the effective theory of DM-nucleon interactions

  Fan et al., 1008.1591; Fitzpatrick et al., 1203.3542

- The theory assumes:
  - DM and nucleons are the only relevant degrees of freedom
  - There is a separation of scales: $|\mathbf{q}|/m_N \ll 1$, where m_N is the nucleon mass; and $v/c \ll 1$
  - Energy and momentum conservation
  - Galilean invariance
  - Invariance under three-dimensional rotations

- Under the above assumptions, consider the elastic DM-nucleon scattering process

$$\chi(\mathbf{p}) + N(\mathbf{k}) \to \chi(\mathbf{p}') + N(\mathbf{k}')$$

- What is the most general scattering amplitude $\mathscr{M}$ compatible with these assumptions?

- Momentum conservation and Galilean invariance imply that only two momenta out of $(\mathbf{k}, \mathbf{p}, \mathbf{k}', \mathbf{p}')$ are independent. A convenient choice is $\mathbf{q}$ and $\mathbf{v}^{\perp}$ ($\mathbf{v}^{\perp} \cdot \mathbf{q} = 0$)

- Furthermore, the amplitude $\mathscr{M}$ can be expanded at the desired order in $\mathbf{q}/m_N$ and $\mathbf{v}^{\perp}$

Effective theory of DM-nucleon interactions

- It follows that the most general amplitude for DM-nucleon scattering can be written as

$$\mathscr{M} = \sum_{\tau=0,1} \sum_i c_i^\tau \mathcal{O}_i \, t^\tau$$

- For spin 1/2 DM, $\mathcal{O}_i$ are Galilean and rotational invariant quantities depending on $\mathbf{q}$, $\mathbf{v}^\perp$, $\mathbf{S}_\chi$ and $\mathbf{S}_N$

- The matrices $t^0 = \mathbb{1}_{\mathrm{iso}}$, $t^1 = \tau_3$ allow for different couplings to protons and neutrons

Effective theory of DM-nucleon interactions

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

Effective theory of DM-nucleon interactions

- The DM-nucleon interaction Hamiltonian $\mathscr{H}_{(n)}$ is the inverse Fourier transform of $\mathscr{M}$

- DM-nucleus interaction Hamiltonian: $\mathscr{H} = \sum_{n=1}^{A} \mathscr{H}_{(n)}$

- DM-nucleus scattering cross section: $\mathrm{d}\sigma_T/\mathrm{d}E_{\mathrm{nr}} \propto |\langle F|\mathscr{H}|I\rangle|^2$, where $|\cdot\rangle$ is a DM-nucleus state

- Inspection of the $\mathscr{O}_i$'s generating $\mathscr{H}$ shows that at linear order in the transverse relative velocity $\mathbf{v}^\perp$, they only depend on 5 nucleon charges and currents:

$$\mathbb{1}_N \qquad \mathbf{S}_N \qquad \mathbf{v}^\perp \qquad \mathbf{v}^\perp \cdot \mathbf{S}_N \qquad \mathbf{v}^\perp \times \mathbf{S}_N$$

- These nuclear currents admit longitudinal (i.e. parallel to $\mathbf{q}$) and transverse components

Effective theory of DM-nucleon interactions

- This leads to 8 nuclear response functions F_k, if nuclear ground states are P and CP eigenstates

- In terms of F_k, the DM-nucleus scattering cross section reads

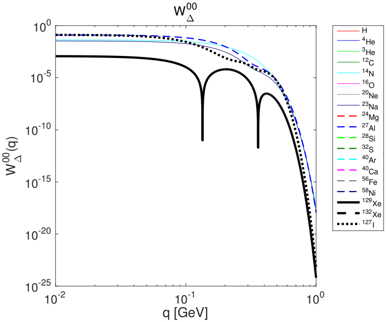
$$\frac{\mathrm{d}\sigma_T}{\mathrm{d}E_{\mathrm{nr}}} = \frac{2m_T}{v^2} \sum_{\tau,\tau',k} R_k^{\tau\tau'}\left(v^2, \frac{q^2}{m_N^2}\right) F_k^{\tau\tau'}(q^2)$$

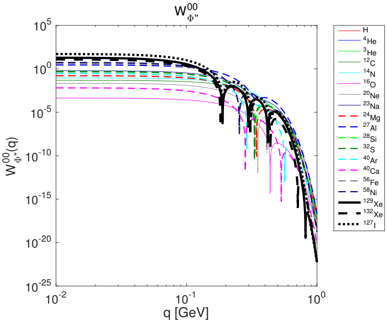
- The $R_k^{\tau\tau'}$'s factors are known functions of the DM-nucleus relative velocity, v, and of the momentum transfer $\mathbf{q}$. They are quadratic in the coupling constants c_i^τ

- In order to interpret neutrino telescopes' results in this framework, we computed the nuclear response functions W's for the most abundant elements in the Sun/Earth

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

$$\mathbf{v}^{\perp} \longrightarrow W_{\Delta}(q)$$
$$\mathbf{v}^{\perp} \times \mathbf{S}_N \longrightarrow W_{\Phi''}(q)$$

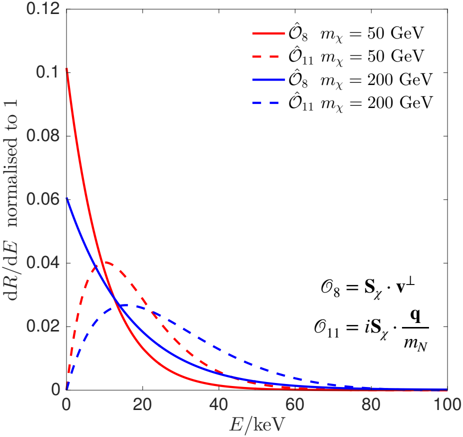




Effective theory of DM-nucleon interactions

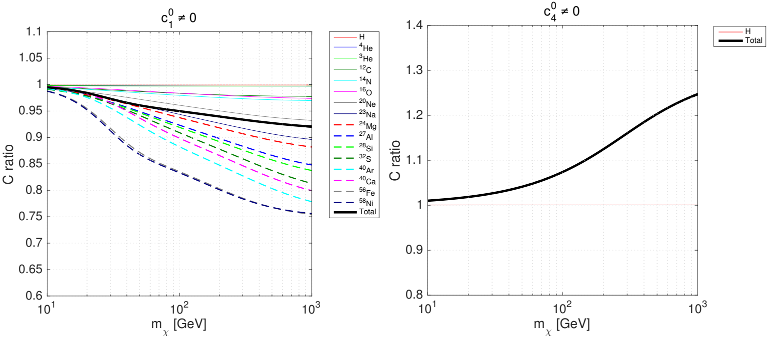
- Nuclear recoil energy spectra divide into two different families: "featureless" and "bumpy"

  S. Baum, R. Catena, J. Conrad, K. Freese and M. B. Krauss, Phys. Rev. D **97** (2018) no.8, 083002



- Comparison with darksusy in the case of spin-independent and spin-dependent interactions

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

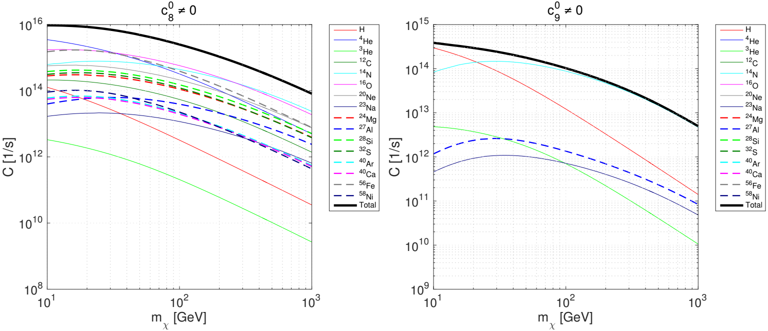


- Capture rate for selected velocity- and momentum-dependent interactions:

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

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

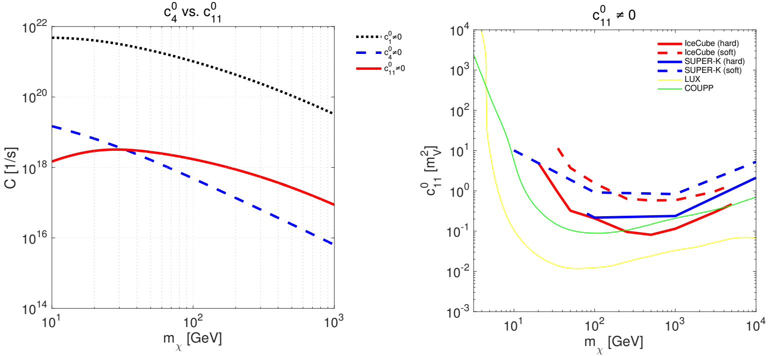
R. Catena and B. Schwabe, JCAP **1504** (2015) 042



- Comparing the spin-dependent interaction $\mathcal{O}_4$ with the momentum-dependent interaction $\mathcal{O}_{11}$:

$$\mathcal{O}_4 = \mathbf{S}_\chi \cdot \mathbf{S}_N;$$
$$\mathcal{O}_{11} = i\mathbf{S}_\chi \cdot \frac{\mathbf{q}}{m_N}$$

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



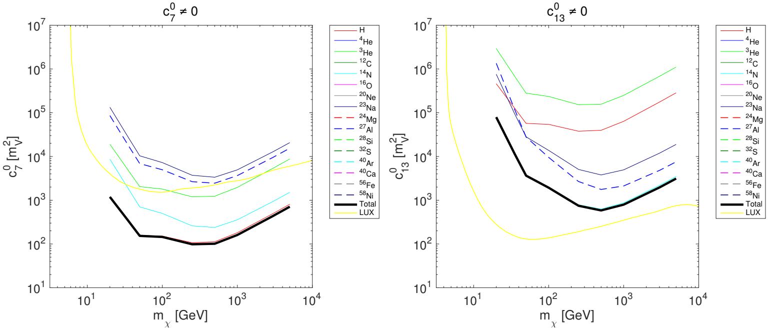
DM capture in the Sun / Selected exclusion limits

- Exclusion limits on selected coupling constants from IceCube 2013 data (hard spectrum)

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

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

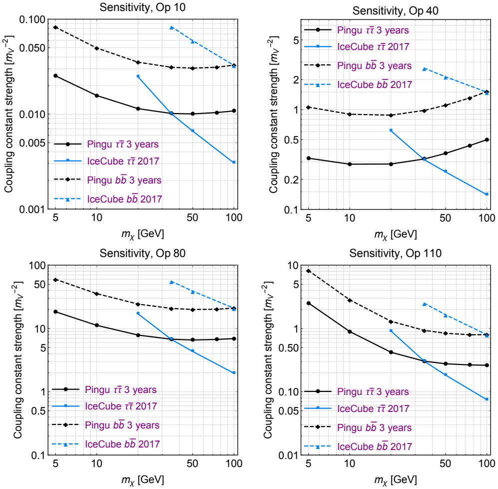
R. Catena, JCAP **1504** (2015) 052



DM capture in the Sun / Discovery potential

- PINGU's 5σ sensitivity contours in the DM particle mass – coupling constant plane

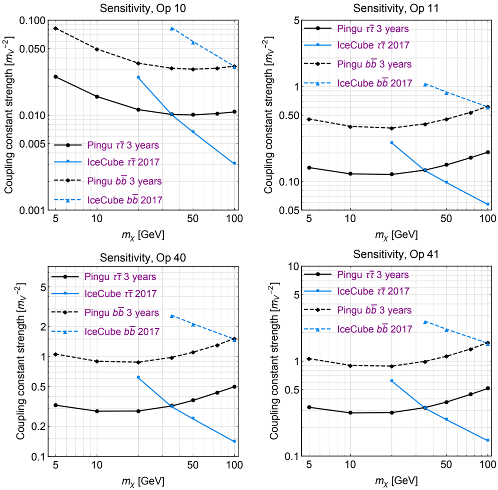
  A. Bäckström, R. Catena and C. Pérez de los Heros, JCAP **1905** (2019) 023



DM capture in the Sun / Discovery potential

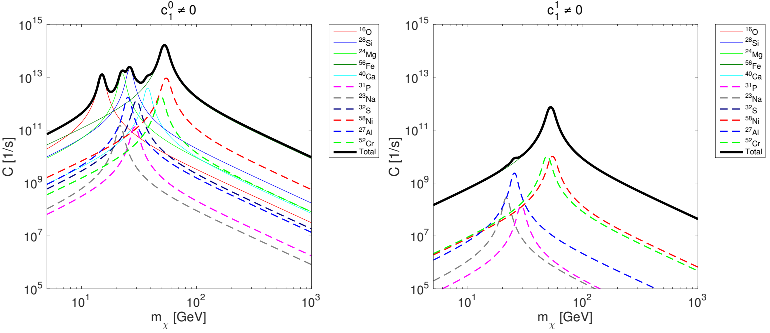
- Comparing isoscalar interactions ($\mathscr{M} \propto t^0 = \mathbb{1}_{\rm iso}$) with isovector interactions ($\mathscr{M} \propto t^1 = \tau_3$)

  A. Bäckström, R. Catena and C. Pérez de los Heros, JCAP **1905** (2019) 023



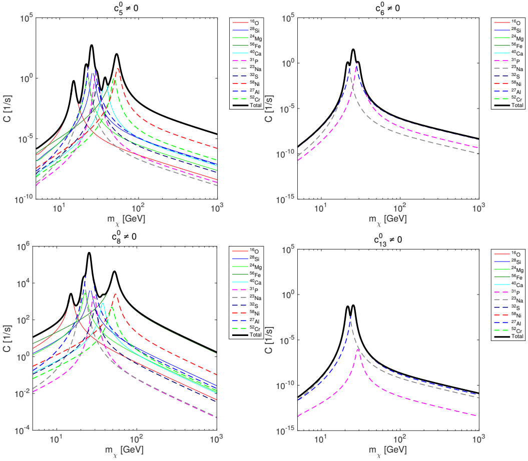
- Comparing isoscalar interactions ($\mathscr{M} \propto t^0 = \mathbb{1}_{\rm iso}$) with isovector interactions ($\mathscr{M} \propto t^1 = \tau_3$)

  R. Catena, JCAP **1701** (2017) 059



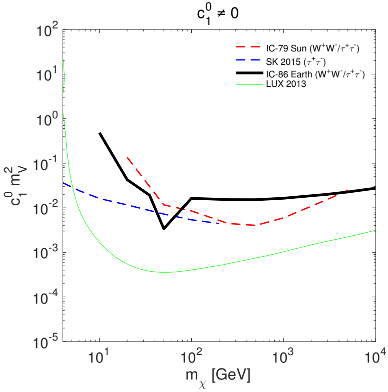
- Peak location in the capture rate vs DM particle mass plot for selected interactions

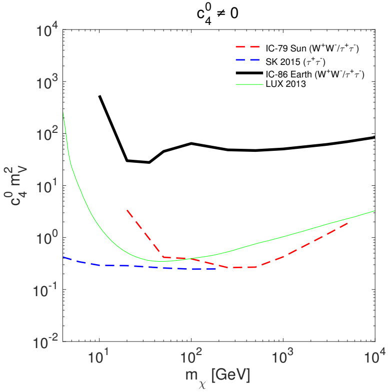
  R. Catena, JCAP **1701** (2017) 059



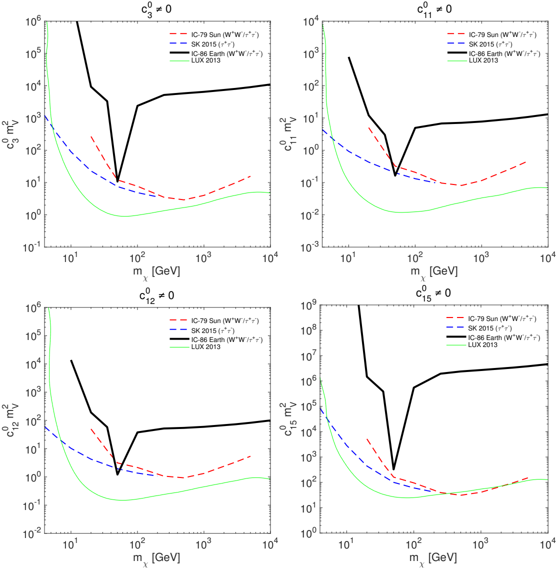
DM capture in the Earth / Selected exclusion limits

R. Catena, JCAP **1701** (2017) 059





R. Catena, JCAP **1701** (2017) 059



Summary

- I have revised the capture and annihilation of DM in the effective theory of DM-nucleon interactions
- This required the calculation of nuclear response functions previously not available
- Searching for solar DM, velocity-dependent interactions can effectively be proved by neutrino telescopes
- Furthermore, elements up to iron can be important in the DM capture process
- PINGU's 5σ sensitivity contours are significantly below current IceCube 90% C.L. exclusion limits when $b\bar{b}$ is the leading DM annihilation channel
- If $\tau\bar{\tau}$ is the leading channel, PINGU will improve upon current exclusion limits for DM masses below 35 GeV, independently of the assumed DM-nucleon interaction
- In the case of DM capture in the Earth, resonant capture by DM scattering off iron is important for several interactions (not only for the standard spin-independent one)
- For $m_{\rm DM} \sim 50$ GeV, exclusion limits from the search for DM in the Earth can be stronger than the ones from solar DM searches