Advances in dark matter direct detection

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Outline

- Theory of dark matter direct detection
  - Astrophysics
  - Nuclear physics
- Effective theory approach
- Complementarity with indirect searches
- Conclusions

Dark matter direct detection

- Basic considerations behind the direct detection technique
  - Dark matter halos host the visible galaxies, including our galaxy
  - The Earth's motion in the galactic halo induces a flux of dark matter particles through the Earth
  - Particles from the Milky Way dark matter halo can scatter off nuclei of a terrestrial detector
  - Small nuclear recoil energies might be measurable in low background environments

- More specifically
  - The Local Standard of Rest velocity is of about 220 km s^{-1}
  - For $m_\chi \sim 100$ GeV, one expects a flux of $\sim 7 \times 10^4$ cm^{-2} s^{-1}
  - From the conservation equations,

$$E_R = (2\mu_T^2 v^2 / m_T) \cos^2\theta \sim \mathcal{O}(10)\ \mathrm{keV}$$

  - One needs low-threshold detectors, e.g. $E_{\rm th} \sim 1$ keV

Differential recoil spetrum

- In a direct detection experiment, the differential recoil spectrum is

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

- Astrophysics
- Nuclear physics

Astrophysics

Astrophysical uncertainties in dark matter direct detection

- Sources of astrophysical uncertainties in dark matter direct detection are the local dark matter density and velocity distribution

- Methods to account for/eliminate these uncertainties

  - Fits of mass models for the Galaxy to astronomical observations ($\star$)
    Bertone, Bovy, Catena, De Boer, Fairbairn, Fornasa, Green, Pato, Peter, Read, Tremaine, ...

  - Halo independent data analysis
    Fox et al. 2010, Frandsen et al. 2012, ...

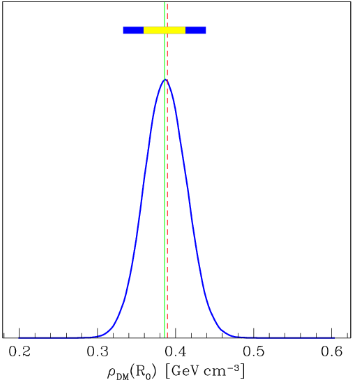
  - Use of direct detection data to measure astrophysical parameters (in the future) Bertone, Green, Peter, Strigari, Trotta, ...

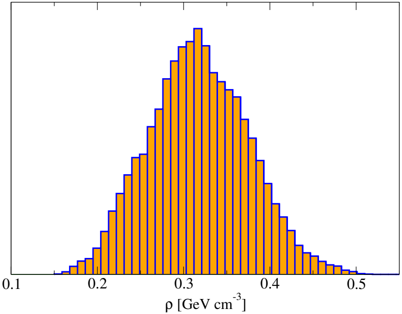
The local dark matter density in 5 steps

- 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

The local dark matter density: Bayesian analysis

Left panel: Catena & Ullio 210; Right panel: Fairbairn et al. 2012.

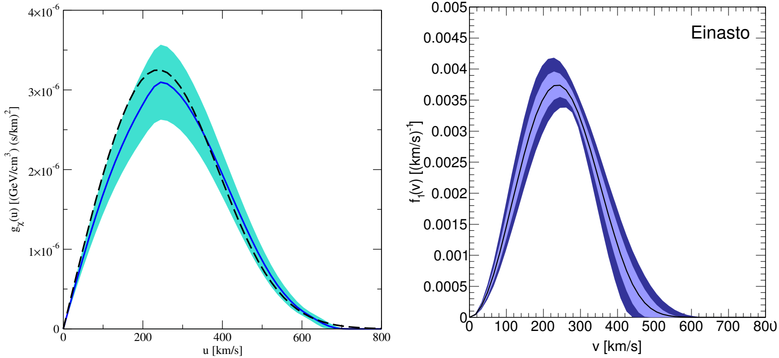




Local dark matter velocity distribution in 5 + 3 steps

- 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

Left panel: Bozorgnia, Catena and Schwetz 2014; Right panel: Fornasa et al. 2014.



Nuclear physics

Dark matter-nucleus interaction

- Standard assumption
  - One-body dark matter-nucleon interactions

- Recently, progress has been made in the description of the dark matter-nucleon interactions using an affective theory approach

  Fan *et al*. 2010, Fitzpatrick *et al*. 2013

Effective theory of dark matter nucleon interactions

- General considerations
  - It includes all dark matter-nucleon interactions compatible with momentum conservation and Galilean invariance
  - It is therefore an ideal framework for model independent analyses
  - This generality comes at the price of many model parameters

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

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

- 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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- The most general Hamiltonian density is therefore

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

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

Dark matter-nucleon interaction operators

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

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

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

- $\hat{l}^{\tau}_{\rm SI} = c^{\tau}_1 + i(\hat{\mathbf{q}}/m_N) \cdot \hat{\mathbf{S}}_\chi\ c^{\tau}_{11} + \ldots$
- $\hat{\mathbf{l}}^{\tau}_{\rm SD} = \hat{\mathbf{S}}_\chi\ c^{\tau}_4/2 + i(\hat{\mathbf{q}}/m_N) \times \hat{\mathbf{v}}^{\perp}_{T}\ c^{\tau}_3/2 + \ldots$

Transition amplitude

- The transition amplitude for dark matter-nucleus scattering is

$$i\mathcal{M}_{NR} = \langle J, M_J, T, M_T| \sum_{\tau=0,1} t^{\tau}_{(i)} \Bigg[\langle \hat{l}^{\tau}_{\mathrm{SI}} \rangle \sum_{i=1}^{A} e^{-i\mathbf{q}\cdot\mathbf{r}_i} + \langle \hat{\mathbf{l}}^{\tau}_{\mathrm{SD}} \rangle \cdot \sum_{i=1}^{A} \vec{\sigma}_i \; e^{-i\mathbf{q}\cdot\mathbf{r}_i}$$

$$+ \text{ convection } + \text{ spin/velocity} \Bigg] |J, M_J, T, M_T\rangle$$

- $\langle \mathbf{p}', \mathbf{k}' |\, i\hat{\mathbf{q}} \,| \mathbf{p}, \mathbf{k} \rangle = i\mathbf{q}\, e^{-i\mathbf{q}\cdot\mathbf{r}} \, (2\pi)^3 \delta(\mathbf{k}' + \mathbf{p}' - \mathbf{k} - \mathbf{p})$
- $\langle \hat{l}^{\tau}_{\mathrm{SI}} \rangle = c^{\tau}_1 + i(\mathbf{q}/m_N) \cdot \langle j_\chi, M_\chi | \hat{\mathbf{S}}_\chi \; c^{\tau}_{11} | j_\chi, M_\chi \rangle + \ldots$

- Example: multipole expansion of the nuclear spin current

$$\langle \hat{\mathbf{l}}_5^\tau \rangle \cdot \sum_{i=1}^{A} \vec{\sigma}_i \; e^{-i\mathbf{q}\cdot\mathbf{r}_i} = \sum_{L=0}^{\infty} \sqrt{4\pi(2L+1)}(-i)^L \; i\Sigma''_{L0;\tau}(q)(\langle \hat{\mathbf{l}}_5^\tau \rangle \cdot \mathbf{e}_0)$$

$$- \sum_{L=1}^{\infty} \sqrt{2\pi(2L+1)}(-i)^L \sum_{\lambda=\pm 1} i\Sigma'_{L-\lambda;\tau}(q)(\langle \hat{\mathbf{l}}_5^\tau \rangle \cdot \mathbf{e}_\lambda)$$

  - $\Sigma''_{LM;\tau}(q) = \sum_{i=1}^{A} \left[\frac{1}{q} \overrightarrow{\nabla}_{\mathbf{r}_i} M_{LM}(q\mathbf{r}_i) \right] \cdot \vec{\sigma}_i t^\tau_{(i)}$
  - $M_{LM}(q\mathbf{r}_i) = j_L(qr_i) Y_{LM}(\Omega_{\mathbf{r}_i})$

- Overall, there are 6 nuclear response operators: M, Σ', Σ'', Φ'', $\tilde{\Phi}'$, Δ

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

- Assumptions:
  - Assume that nuclear ground states are eigenstates of P and CP
  - Sum (average) $|\mathcal{M}_{NR}|^2$ over final (intial) spin configurations

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

$$\text{dark matter response} \quad R_k^{\tau\tau} \sim |\langle \hat{l}_{\rm SI}^{\tau} \rangle|^2 \, ; \, \ldots$$

$$\text{nuclear response} \quad W_k^{\tau\tau} \sim \sum_L |\langle J, T, M_T || \, \Sigma''_{L;\tau}(q) \, || J, T, M_T \rangle|^2 \, ; \, \ldots$$

Nuclear response functions

- The result factorizes: "dark matter response" $\times$ "nuclear response"

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

- Available nuclear response functions
  - For Xe, Ge, I, Na, F: Anand et al. 2013
  - For 16 elements in the Sun: Catena & Schwabe 2015

- The dark matter-nucleus scattering cross-section is

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

- Remember that $\mathrm{d}\sigma_T/\mathrm{d}E_R$ determines
  - The rate of scattering events in a direct detection experiment
  - The rate of dark matter capture by the Sun

Data analysis in EFT

Statistical framework

- Bayesian approach → marginal posterior probability density functions

$$\mathcal{P}_{\rm marg}(\theta_1, \theta_2|\mathbf{d}) \propto \int d\theta_3 \dots d\theta_m \, \mathcal{P}(\boldsymbol{\Theta}|\mathbf{d}) \,.$$

  - Relatively small number of Likelihood evaluations
  - Subject to prior and volume effects

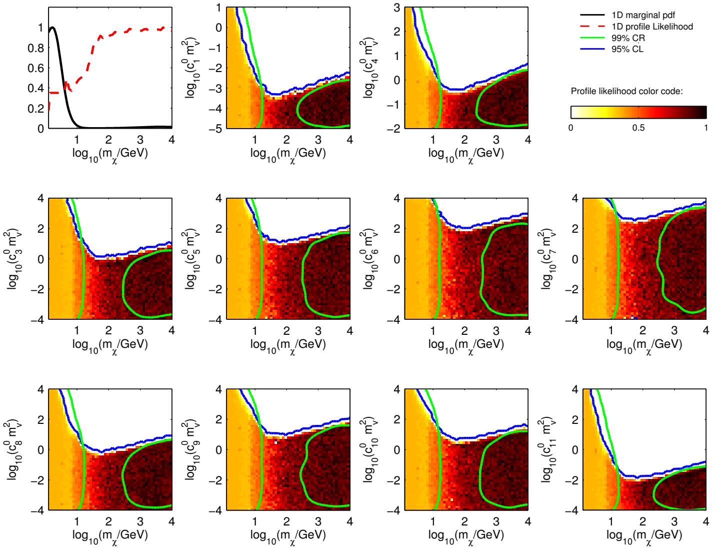
- Frequentist approach → profile Likelihoods

$$\mathcal{L}_{\rm prof}(\mathbf{d}|\theta_1, \theta_2) \propto \max_{\theta_3,\dots,\theta_m} \mathcal{L}(\mathbf{d}|\boldsymbol{\Theta}) \,.$$

  - Computationally expensive (exact coverage?)
  - Insensitive to prior and volume effects

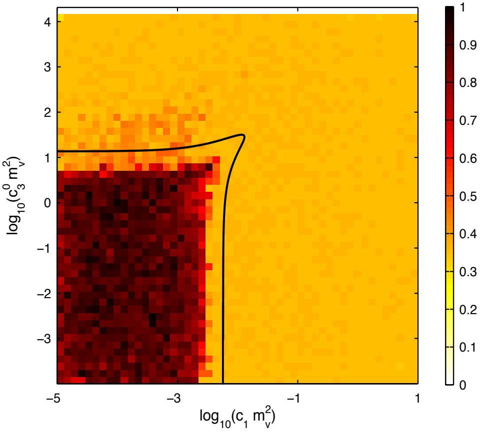
Global limits: mass vs interaction strengths

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



c_1^0 vs c_3^0 correlation (2D profile likelihood)

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



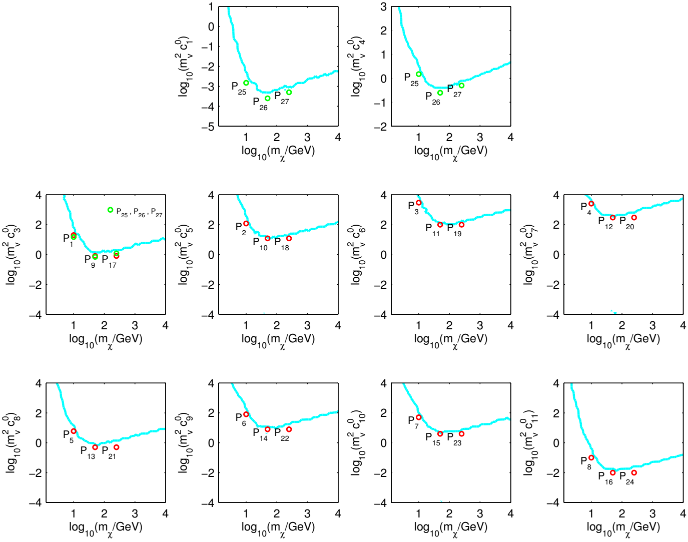
$$R_M^{\tau\tau'} = c_1^\tau c_1^{\tau'} + \dots$$

$$R_{\Phi''}^{\tau\tau'} = \frac{q^2}{4m_N^2} c_3^\tau c_3^{\tau'}$$

$$R_{\Phi'' M}^{\tau\tau'} = c_3^\tau c_1^{\tau'}$$

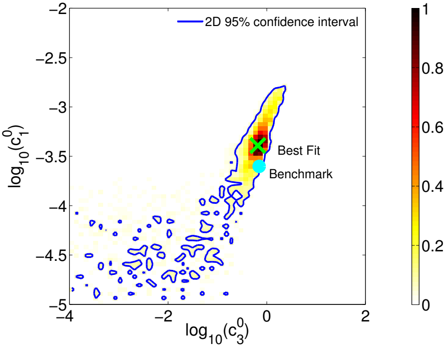
Prospects (benchmark points)

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



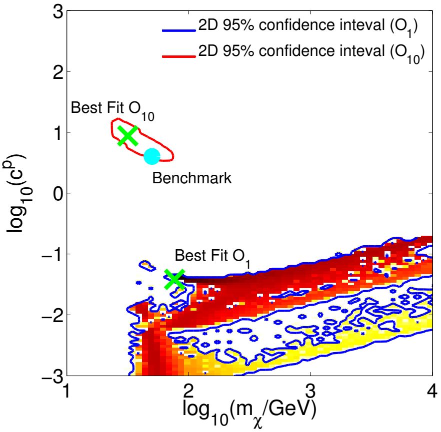
Prospects ($m_\chi = 50$ GeV; c_1^0, c_3^0, c_4^0)

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



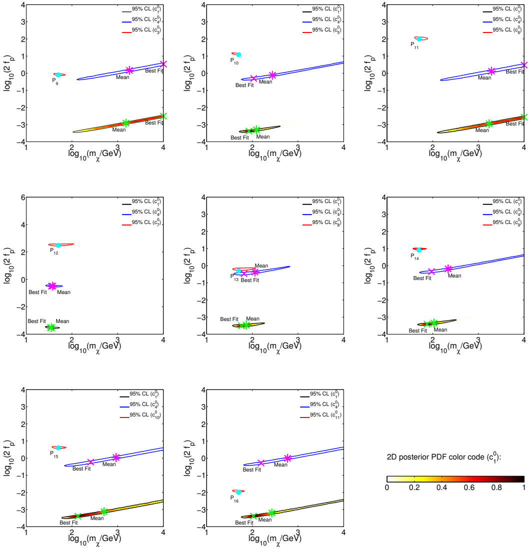
Theoretical bias (I)

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



Theoretical bias (II)

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



Complementarity with indirect searches

Neutrino signals from dark matter annihilation in the Sun

- Dark matter can be captured, and annihilate in the Sun, producing a flux of energetic neutrinos observable at neutrino telescopes

- Differential rate of dark matter capture by Sun:

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

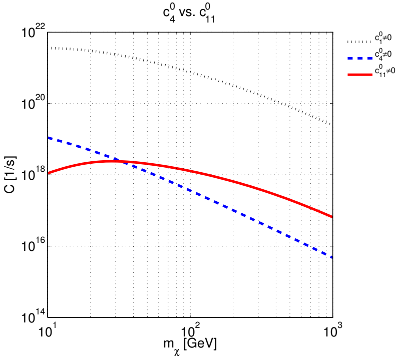
- Same cross-section as in direct detection, but different target materials

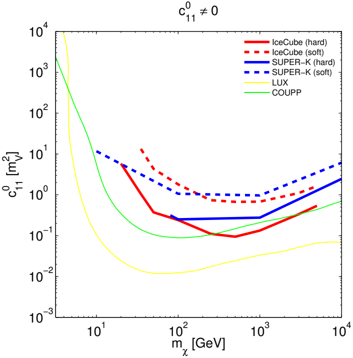
- Different nuclear response functions $W_k^{\tau\tau'}$!

- Nuclear response functions for the 16 most abundant elements in Sun have been calculated in R. Catena and B. Schwabe arXiv:1501.03729

Direct detection vs neutrino telescopes: highlights

R. Catena arXiv:1503.04109





Direct detection vs neutrino telescopes: highlights

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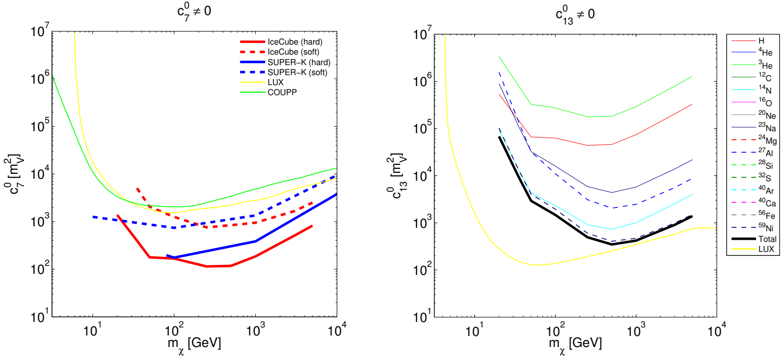

Conclusions

- Prospects for direct detection of dark matter depend on astrophysics and nuclear physics inputs.
- Recently, progress has been made in this field exploring all possible dark matter-nucleon interactions within an effective theory approach
- Current direct detection data contain sufficient information to constrain several dark matter-nucleon interaction operators
- For certain velocity-dependent interaction operators neutrino telescopes are superior