Effective theory of dark matter direct detection

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Outline

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

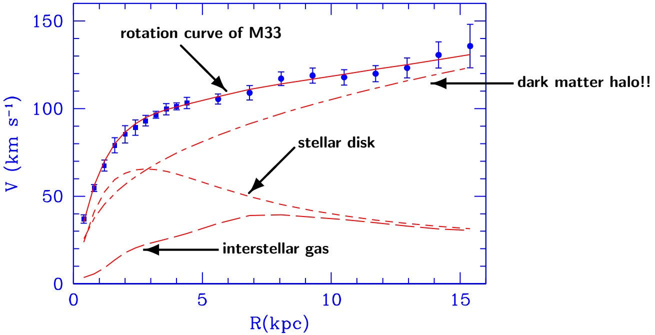
R. Catena, A. Ibarra, S. Wild, arXiv:1602.04074
R. Catena and P. Gondolo, JCAP **1508**, 08, 022 (2015)
R. Catena, JCAP **1409**, 09, 049 (2014)
R. Catena and P. Gondolo, JCAP **1409**, 09, 045 (2014)
R. Catena, JCAP **1407**, 07, 055 (2014)

} Direct Detection

Evidence for dark matter

- Dark matter is a dissipation-less *fluid* that makes up about 5/6 of the total *matter* in the Universe

- The most famous evidence: the rotation curves of spiral galaxies



Evidence for dark matter

- Further evidence: from the motion of stars in the solar neighborhood, to the largest scales we see in the Universe
- The most compelling evidence: the formation of cosmological structures

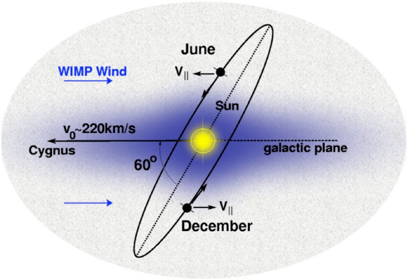
  If only ordinary matter and photons are present in the Universe, galaxies unavoidably form too late

  The dissipative coupling of electron/protons and photons delays the formation of galaxies

  Need for a dissipation-less fluid $\Rightarrow$ dark matter

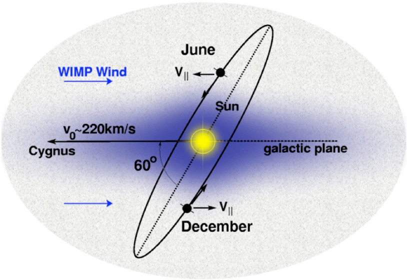
- Yet, the particles forming dark matter have so far escaped detection . . .

- Geometry:



- Basic concept: It searches for nuclear recoil events induced by the non-relativistic scattering of Milky Way dark matter particles in low-background detectors

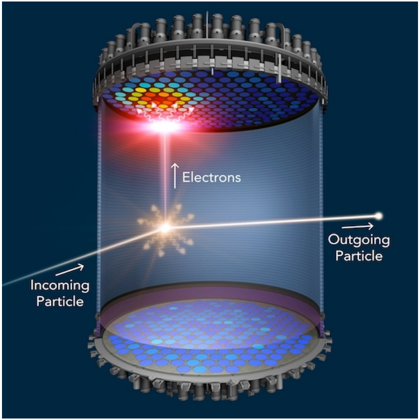
- Geometry:



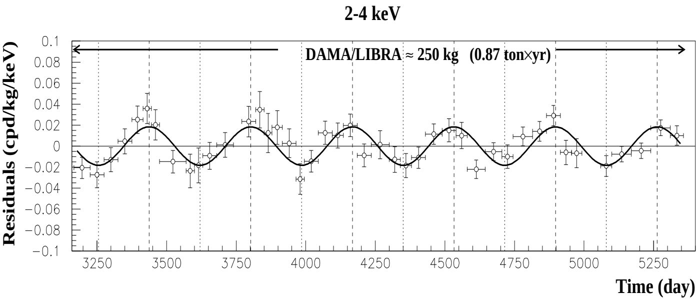
- Kinematics:
  - For $m_\chi \sim 100$ GeV, one expects a flux of $\sim 7 \times 10^4$ cm^{-2} s^{-1}
  - Expected recoil energy, $E_R = (2\mu_T^2 v^2/m_T)\cos^2\theta \sim \mathcal{O}(10)$ keV

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

Example: scintillation plus charge signal (e.g. LUX, XENON, LZ)



DAMA results: data vs cosinusoidal fitting function



- Rate of dark matter-nucleus scattering events:

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

galactic distribution **particle nature**

- Modulation amplitude:

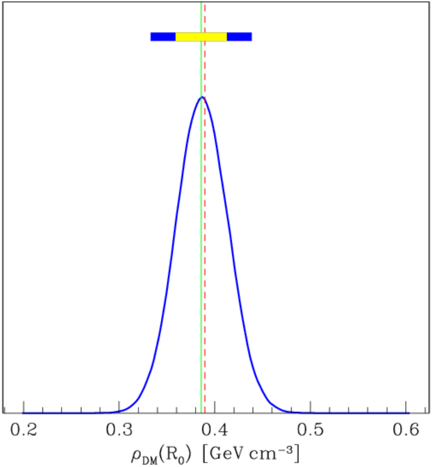
$$A(E_-, E_+) = \frac{1}{E_+ - E_-} \frac{1}{2} \left[R(E_-, E_+)\Big|_{\text{June 1st}} - R(E_-, E_+)\Big|_{\text{Dec 1st}} \right]$$

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

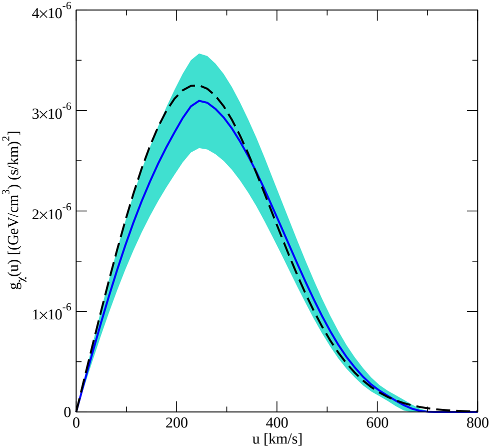


Local dark matter velocity distribution in 5 + 3 steps

- 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

Local dark matter velocity distribution: Bayesian analysis

Bozorgnia, Catena and Schwetz 2014



Dark matter-nucleus scattering cross-section

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

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

one-body DM-nucleon interaction

nucleus $\otimes$ DM state

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

- 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**:

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

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

- Underlying **non-relativistic Hamiltonian**

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

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

- 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**

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

- Rate of dark matter-nucleus scattering events:

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

galactic distribution

particle nature

- Modulation amplitude:

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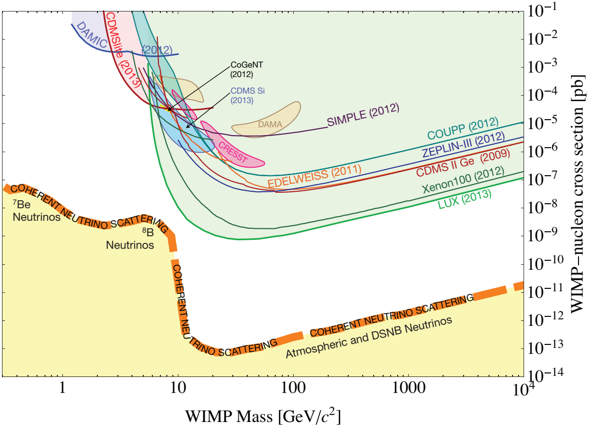
Billard et al. 2014



Effective Theory (ET) of dark matter direct detection

- Assumption: $|\mathbf{q}|/m_V \ll 1$, where m_V is the mediator mass

- ET basic symmetries: Galilean and translation invariance

- ET basic operators:
  - 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 five basic operators

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

- The most general Hamiltonian for χ-N interactions is a power series in $\hat{\mathbf{q}}/m_V$. Each term in the series is a scalar combination of basic operators.

- Only 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

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

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

Dark matter-nucleon interaction operators

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

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

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

- This expression depends on:
  - 28 coupling constants
  - 8 nuclear response functions
- Available nuclear response functions:
  - For Xe, Ge, I, Na, F: Anand et al. 2013
  - For 16 elements in the Sun: R. Catena & B. Schwabe 2015

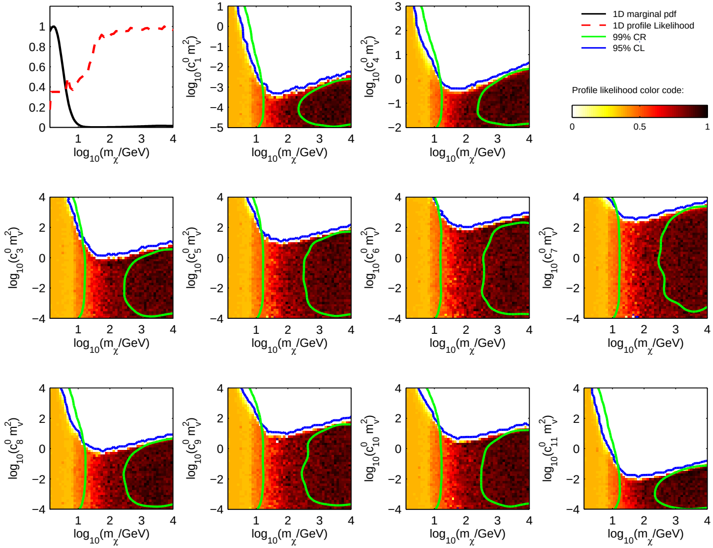
Comparison with null searches

- I compare theory and observations in global multidimensional statistical analyses varying all model parameters *simultaneously*

- Experimental data *simultaneously* included in the fit:
  - LUX
  - XENON100
  - XENON10
  - CDMS-Ge
  - CDMS-LT
  - SuperCDMS
  - CDMSlite
  - PICASSO
  - SIMPLE
  - COUPP

Global limits: mass vs interaction strengths

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

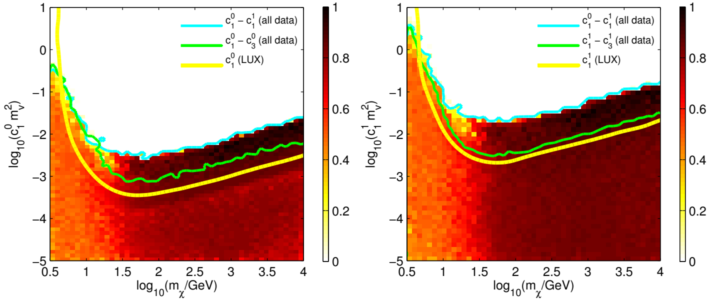


Operator interference

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

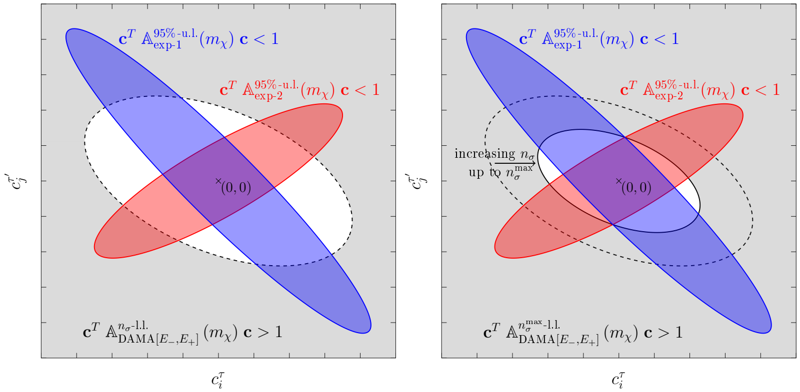
$$\langle|\mathcal{M}_{NR}|^2\rangle_{\rm spins} = \frac{4\pi}{2J+1}\sum_{\tau\tau'}\Bigg[c_1^\tau c_1^{\tau'} W_M^{\tau\tau'}(y) + \frac{1}{8}\frac{q^2}{m_N^2} v_T^{\perp 2} c_3^\tau c_3^{\tau'} W_{\Sigma'}^{\tau\tau'}(y) + \frac{q^2}{m_N^2}\left(\frac{q^2}{4m_N^2} c_3^\tau c_3^{\tau'} W_{\Phi''}^{\tau\tau'}(y) + c_1^\tau c_3^{\tau'} W_{\Phi'' M}^{\tau\tau'}(y)\right)\Bigg]$$

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



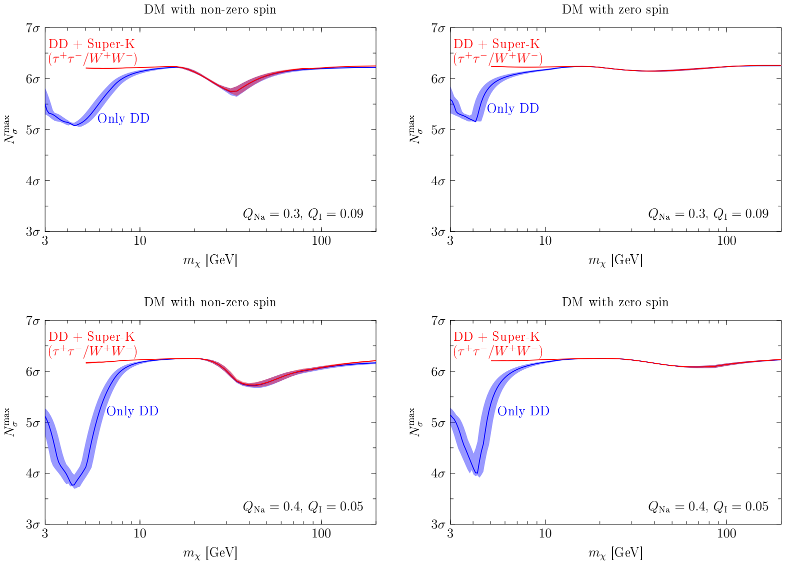
DAMA confronts null searches I

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



R. Catena, A. Ibarra, S. Wild, arXiv:1602.04074

DAMA confronts null searches II



R. Catena, A. Ibarra, S. Wild, arXiv:1602.04074

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 impossible to reconcile DAMA with null searches