Chiral Effective Theory of DM Direct Detection

Or, What is the size of the DM nucleus cross section?

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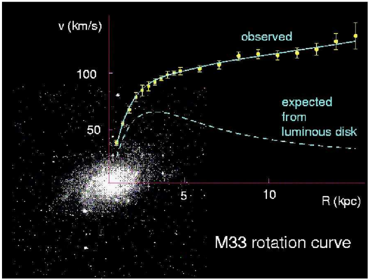
JCAP02(2017)009 [arxiv:1611.00368] & work in progress

Dark Matter Facts

- DM exists
  - All evidence via its gravitation
- Particle nature?
- What we know about DM
  - DM is non-baryonic, cold, and neutral
  - Relic abundance $\Omega_{\mathrm{DM}} h^2 = 0.1198(26)$
    [PLANCK / PDG 2014]



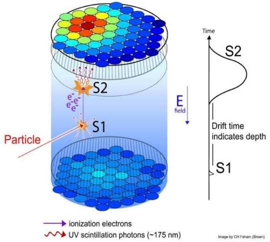
- Thermal history motivates interaction with SM

Direct Detection Basics

- Direct detection – scattering on nuclei
  - Complementary information, proves cosmological lifetime
  - Assume velocity distribution (Maxwell); $v \sim 10^{-3}$
  - Maximal momentum transfer is $q \lesssim 200\,\text{MeV}$

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_A m_\chi} \int_{v_{min}} dv\, v\, f_1(v) \frac{d\sigma}{dE_R}(v, E_R)\,.$$

[Lewin & Smith, Astropart.Phys.6 (1996)]



LUX

Calculating the cross section

- Calculate cross section from nonrelativistic, Galilean-invariant interactions [Fitzpatrick et al., 1203.3542]
- Constructed from
  - momentum transfer $i\vec{q}$
  - relative transverse incoming DM velocity $v_T^\perp$
  - nucleon spin $\vec{S}_N$ (DM spin $\vec{S}_\chi$)
- Lead to six nuclear responses, e.g.
  - Spin-independent (“M”): e.g. $\mathcal{O}_1^p = 1_\chi \, 1_N$
  - Spin-dependent (“Σ', Σ”): e.g. $\mathcal{O}_4^p = \vec{S}_\chi \cdot \vec{S}_N$
  - Nuclear angular momentum (“Δ”): e.g. $\mathcal{O}_9^p = \vec{S}_\chi \cdot \left(\vec{S}_p \times \frac{i\vec{q}}{m_N}\right)$

Nuclear matrix elements

$$\mathcal{O}_1^N = 1_\chi 1_N \,, \qquad \mathcal{O}_2^N = (v_\perp)^2\, 1_\chi 1_N \,, \qquad \mathcal{O}_3^N = 1_\chi\, \vec{S}_N \cdot \Big(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\Big) \,,$$

$$\mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N \,, \qquad \mathcal{O}_5^N = \vec{S}_\chi \cdot \Big(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\Big)\, 1_N \,, \qquad \mathcal{O}_6^N = \Big(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\Big)\Big(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\Big),$$

$$\mathcal{O}_7^N = 1_\chi\, (\vec{S}_N \cdot \vec{v}_\perp) \,, \qquad \mathcal{O}_8^N = (\vec{S}_\chi \cdot \vec{v}_\perp)\, 1_N \,, \qquad \mathcal{O}_9^N = \vec{S}_\chi \cdot \Big(\frac{i\vec{q}}{m_N} \times \vec{S}_N\Big) \,,$$

$$\mathcal{O}_{10}^N = -1_\chi \Big(\vec{S}_N \cdot \frac{i\vec{q}}{m_N}\Big) \,, \qquad \mathcal{O}_{11}^N = -\Big(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N}\Big)\, 1_N \,, \qquad \mathcal{O}_{12}^N = \vec{S}_\chi \cdot \Big(\vec{S}_N \times \vec{v}_\perp\Big) \,,$$

$$\mathcal{O}_{13}^N = -\Big(\vec{S}_\chi \cdot \vec{v}_\perp\Big)\Big(\vec{S}_N \cdot \frac{i\vec{q}}{m_N}\Big) \,, \qquad \mathcal{O}_{14}^N = -\Big(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N}\Big)\Big(\vec{S}_N \cdot \vec{v}_\perp\Big) \,,$$

- Calculation of nuclear response functions for all NR operators (available for F, Na, Ge, I, Xe)
  [Fitzpatrick et al. 1203.3542]
- Rough scaling:
  - $W_M \sim \mathcal{O}(A^2)$
  - $W_{\Sigma'}\,, W_{\Sigma''}\,, W_\Delta\,, W_{\Delta\Sigma'} \sim \mathcal{O}(1)$

What is the input?

- Automatic calculation of pheno observables, given the coefficients of $\mathcal{O}_i^N$
  [`Mathematica` package DMFormFactor, Anand et al. 1308.6288]

- Problems
  - Coefficients are not independent
  - Coefficients can be momentum dependent
  - Coefficients are specified at low energies
    - Explicit connection to UV models?
    - Combination with collider / indirect bounds?

Effective UV Lagrangian

$$\mathcal{L}^{\text{eff}} = \mathcal{L}^{(4)}\big|_{n_f} + \mathcal{L}^{\text{DM}}\big|_{n_f} + \sum \hat{\mathcal{C}}_j^{(5)}\big|_{n_f} Q_j^{(5)} + \sum \hat{\mathcal{C}}_j^{(6)}\big|_{n_f} Q_j^{(6)} + \sum \hat{\mathcal{C}}_j^{(7)}\big|_{n_f} Q_j^{(7)} + \dots$$

- Dim.5: $\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu}\,, \dots$
- Dim.6: $\mathcal{Q}_{1,f}^{(6)} = (\bar{\chi}\gamma_\mu\chi)(\bar{f}\gamma^\mu f)\,,$ $\mathcal{Q}_{4,f}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{f}\gamma^\mu\gamma_5 f)\,,$ $\dots$
- Dim.7: $\mathcal{Q}_{5,f}^{(7)} = m_f(\bar{\chi}\chi)(\bar{f}f)\,, \dots$

Low-energy limit

- Need "HQET" version of dark matter [Hill, Solon 1111.0016; 1409.8290]
  - $\bar\chi\gamma^\mu\chi \to v^\mu \bar\chi_v \chi_v + \frac{1}{2m_\chi}\bar\chi_v i \overleftrightarrow{\partial}_\perp^\mu \chi_v + \frac{1}{2m_\chi}\partial_\nu\left(\bar\chi_v \sigma_\perp^{\mu\nu}\chi_v\right) + \cdots$
  - $\bar\chi\gamma^\mu\gamma_5\chi \to 2\bar\chi_v S_\chi^\mu \chi_v - \frac{i}{m_\chi} v^\mu \bar\chi_v S_\chi \cdot \overleftrightarrow{\partial}\chi_v + \cdots$
  - $\bar\chi i\gamma_5\chi \to \frac{1}{m_\chi}\partial_\mu \bar\chi_v S_\chi^\mu \chi_v + \ldots$
  - ...
- For hadronic current, can in principle use nuclear form factors
  - For instance, $\langle A'|\bar q\gamma^\mu q|A\rangle = \bar u_A'\Big[F_1(q^2)\gamma^\mu + \frac{i}{2m_A}F_2(q^2)\sigma^{\mu\nu}q_\nu\Big]u_A$
- However, these are not known for general hadronic currents
- Need low-energy "effective theory"

Chiral Effective Theory

- Recall maximum momentum transfer in DM scattering is $q_{\max} \approx 200\,\mathrm{MeV}$
- Expansion in $q/(4\pi f_\pi)$ is good to $\mathcal{O}(20\%)$
- Can use (Heavy Baryon) Chiral Perturbation Theory (HBChPT)
  [Jenkins et al. Phys.Lett. B255 (1991) 558, see also Hoferichter et al. 1503.04811]
  - Hadronic degrees of freedom are pions, nucleons,. . .
- Treat DM currents as $SU(3)_L \times SU(3)_R$ spurions
- Can write hadronization of quark currents explicitly, e.g.:
  - Pseudo-scalar meson current: $\bar{q} i \gamma_5 q \to -B_0 f_\pi m_u \big(\pi^0 + \eta/\sqrt{3}\big) + \ldots$
  - Nuclear vector current: $\bar{u}\gamma^\mu u \to v^\mu (2\bar{p}_v p_v + \bar{n}_v n_v) + \ldots$
- Describe hadronic physics in terms of few parameters $(f_\pi, g_A, \mu_N, \sigma_{\pi N} \ldots)$

Low-energy limit – Interactions

- Momentum / velocity independent:
  - $Q_{1,p}^{(0)} = \big(\bar{\chi}_v \chi_v\big)\big(\bar{p}_v p_v\big)$
  - $Q_{2,p}^{(0)} = \big(\bar{\chi}_v S_\chi^\mu \chi_v\big)\big(\bar{p}_v S_{N,\mu} p_v\big)$
- Linear in momentum / velocity:
  - $Q_{1,p}^{(1)} = \big(\bar{\chi}_v \chi_v\big)\big(\bar{p}_v iq\cdot S_N p_v\big)$
  - $Q_{2,p}^{(1)} = \big(\bar{\chi}_v iq\cdot S_\chi \chi_v\big)\big(\bar{p}_v p_v\big)$
  - $Q_{3,p}^{(1)} = m_N \big(\bar{\chi}_v \chi_v\big)\big(\bar{p}_v\, v_\perp\cdot S_N\, p_v\big)$
  - ...
- Quadratic in momentum / velocity:
  - $Q_{1,p}^{(2)} = \big(\bar{\chi}_v iq\cdot S_\chi \chi_v\big)\big(\bar{p}_v\, iq\cdot S_N\, p_v\big)$
  - $Q_{2,p}^{(2)} = im_N\, \epsilon^{\alpha\beta\mu\nu} v_\alpha q_\beta v_{\perp,\mu} \big(\bar{\chi}_v S_{\chi,\nu} \chi_v\big)\big(\bar{p}_v p_v\big)$
  - ...

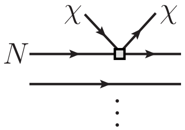
Chiral power counting

- Power counting scheme: $M_{A,\chi} \sim p^{\nu}$

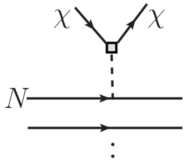
  [Weinberg NP **B363** (1991) 3; Kaplan, Savage, Wise, nucl-th/9605002; Cirigliano, Graesser, Ovanesyan 1205.2695]

  - $\nu = 4 - A - 2C + 2L + \sum_i V_i(d_i - n_i/2 - 2) + \epsilon_W$
  - Resonances, shallow bound states etc. can upset power counting

    [Bedaque et al. nucl-th/0203055, Epelbaum et al. 0811.1338, Epelbaum 1001.3229, Valderrama et al. 1407.0437; see also de Vries et al., 1704.01150]



- Only leading diagram for most DM-SM interactions
- Leading diagram for $A \cdot A$ interaction



- Gives q-dependent "form factor" $1/(m_\pi^2 + \vec{q}^{\,2})$
- Only leading diagram for $S \cdot P$ and $P \cdot P$
- Leading diagram for $A \cdot A$ interaction

Effect of NLO operators – meson exchange

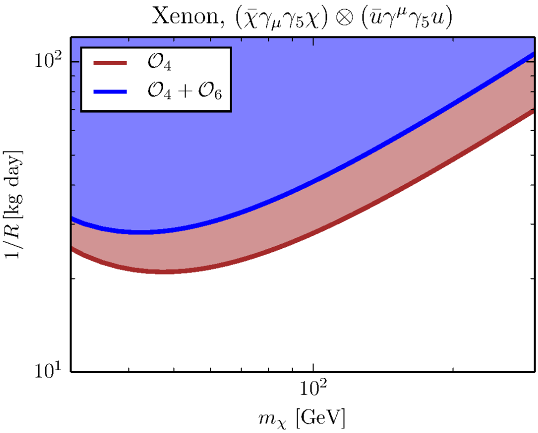
- $\mathcal{Q}_{4,q}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)$
  - Contact term: $\mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N$
  - Previously neglected meson exchange contribution:

    $\mathcal{O}_6^N = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$

- The coefficients are
  - $c_{\mathrm{NR},4}^p \supset -4\left(\Delta u_p\,\hat{\mathcal{C}}_{4,u}^{(6)} + \Delta d_p\,\hat{\mathcal{C}}_{4,d}^{(6)} + \Delta s\,\hat{\mathcal{C}}_{4,s}^{(6)}\right)$
  - $c_{\mathrm{NR},6}^p \supset m_N^2\left\{\frac{2}{3}\frac{(\Delta u_p + \Delta d_p - 2\Delta s)}{m_\eta^2 + \vec{q}^{\,2}}\left(\hat{\mathcal{C}}_{4,u}^{(6)} + \hat{\mathcal{C}}_{4,d}^{(6)} - 2\hat{\mathcal{C}}_{4,s}^{(6)}\right) + \frac{2g_A}{m_\pi^2 + \vec{q}^{\,2}}\left(\hat{\mathcal{C}}_{4,u}^{(6)} - \hat{\mathcal{C}}_{4,d}^{(6)}\right)\right\}$

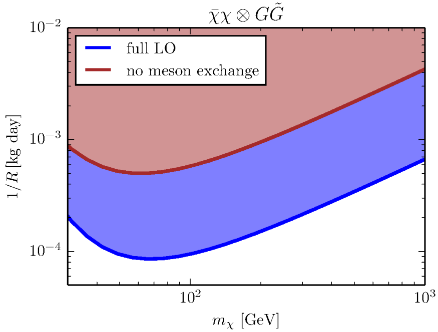
Effect of NLO operators – meson exchange

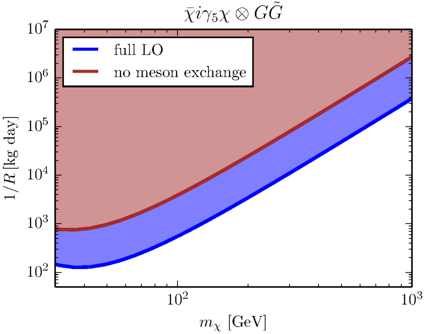
- Pion pole compensates for $\vec{q}^{\,2}$ suppression



Effect of NLO operators – meson exchange

- $\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi}\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}, \qquad \mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi}i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$
  - Previously neglected meson exchange is leading contribution!
  - Order-of-magnitude improvement in bound

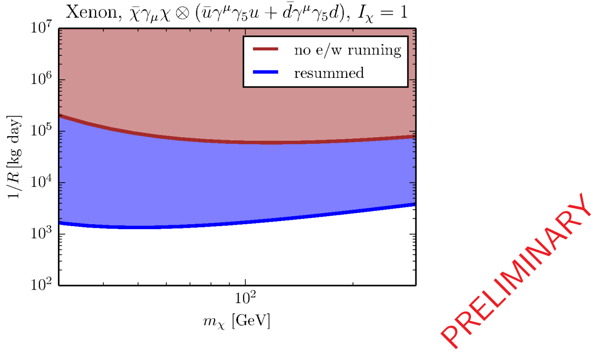




Effect of NLO operators – fine tuning

- Chirally leading terms cancel in $(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu\gamma_5 q)$
  - Only velocity / momentum suppressed interactions
- Electroweak corrections can regenerate LO terms

  [Bishara, Brod, Grinstein, Zupan, work in progress]



Summary

- Established explicit connection between UV and nuclear physics
  - Meson exchange contributions can have significant impact
  - Electroweak mixing can have significant impact

- Provide public code for automatic running from UV to nuclear scale
  [Bishara, Brod, Grinstein, Zupan, work in progress]
  - Calculate NR coefficients $c^N_{\mathrm{NR},i}$ (NR operators)...
  - ...in terms of UV Wilson coefficients $\mathcal{C}^{(d)}_{i,f}$ (UV operators)