Chiral Effective Theory of DM Direct Detection

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

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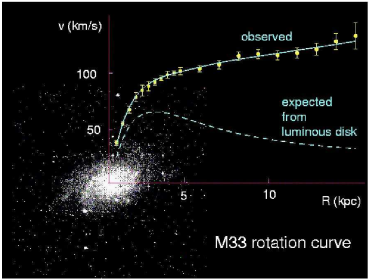
JCAP02(2017)009 [arxiv:1611.00368] & work in progress

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 $\Omega_{\text{DM}} h^2 = 0.1198(26)$ [PLANCK / PDG 2014]



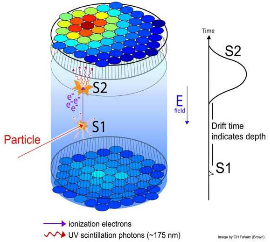
- Thermal history motivates interaction with SM

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]

- Coefficients specified at low energy scale
- Explicit connection to UV models?
- Combination with collider / indirect bounds?

Nonrelativistic limit – cartoon

- *DM currents:*
  - Vector: $\bar{\chi}\gamma^\mu\chi \quad \rightsquigarrow \quad \Psi_\chi^\dagger\Big(1, \quad \vec{v}^\perp + \frac{\vec{q}}{2m_\chi} + i\frac{\vec{q}\times\vec{S}_\chi}{m_\chi}\Big)\Psi_\chi$
  - Axial vector: $\bar{\chi}\gamma^\mu\gamma_5\chi \quad \rightsquigarrow \quad \Psi_\chi^\dagger\Big(\vec{v}^\perp\cdot\vec{S}_\chi + \frac{\vec{q}\cdot\vec{S}_\chi}{2m_\chi}, \ \vec{S}_\chi\Big)\Psi_\chi$
- *SM currents:*
  - Vector: $\bar{N}\gamma^\mu N \quad \rightsquigarrow \quad \Psi_N^\dagger\Big(1, \ \frac{\vec{q}}{2m_N} - i\frac{\vec{q}\times\vec{S}_N}{m_N}\Big)\Psi_N$
  - Axial vector: $\bar{N}\gamma^\mu\gamma_5 N \quad \rightsquigarrow \quad \Psi_N^\dagger\Big(\frac{\vec{q}\cdot\vec{S}_N}{m_N}, 2\vec{S}_N\Big)\Psi_N$
- "Spin independent" vs. "spin dependent" scattering
- Momentum / velocity - suppressed interactions
- Need systematic understand of NR limit
  - (Comprises "$Q_L, q_R, L_L, \ell_R, g, \ldots$ vs. $p, n, \pi, Xe, \ldots$")

Effective UV Lagrangian

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

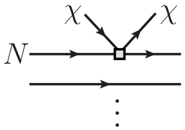
- Dim.5: $\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\bar\chi\sigma^{\mu\nu}\chi)F_{\mu\nu}\,, \dots$
- Dim.6: $\mathcal{Q}_{1,f}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar f\gamma^\mu f)\,, \dots$
- Dim.7: $\mathcal{Q}_{5,f}^{(7)} = m_f(\bar\chi\chi)(\bar f f)\,, \dots$

- NR limit – need "HQET" version of dark matter [Hill, Solon 1111.0016; 1409.8290]
  - $\bar\chi\gamma^\mu\chi \to v^\mu\bar\chi_v\chi_v + \frac{1}{2m_\chi}\bar\chi_v i\overset{\leftrightarrow}{\partial}{}_\perp^\mu\chi_v + \frac{1}{2m_\chi}\partial_\nu\left(\bar\chi_v\sigma_\perp^{\mu\nu}\chi_v\right) + \cdots$
  - $\bar\chi\gamma^\mu\gamma_5\chi \to 2\bar\chi_v S_\chi^\mu\chi_v - \frac{i}{m_\chi}v^\mu\bar\chi_v S_\chi\cdot\overset{\leftrightarrow}{\partial}\chi_v + \cdots$
  - $\bar\chi i\gamma_5\chi \to \frac{1}{m_\chi}\partial_\mu\bar\chi_v S_\chi^\mu\chi_v + \dots$

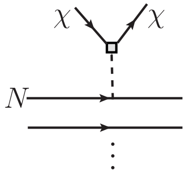
NR limit – transition to the nucleon picture

- Recall maximum momentum transfer in DM scattering is $q_{\rm max} \approx 200\,{\rm MeV}$
- 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 $SU(3)_L \times SU(3)_R$ flavor-symmetric spurions
- Can write hadronization of quark currents explicitly, e.g.:
  - Pseudo-scalar meson current: $\bar{q} i\gamma_5 q \to -B_0 f_\pi m_u (\pi^0 + \eta/\sqrt{3}) + \ldots$
  - 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 $(f_\pi, g_A, \mu_N, \sigma_{\pi N} \ldots)$

Chiral power counting



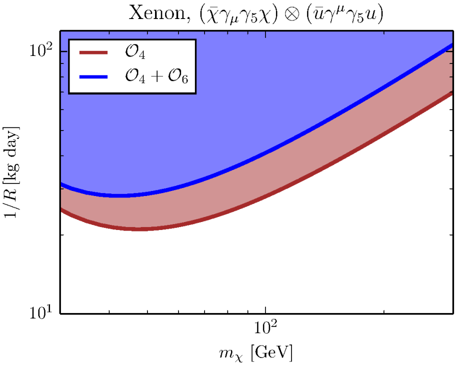
- Only leading diagram for most DM-SM interactions
- Leading diagram for $A \cdot A$ interaction



- Gives q-dependent "form factor" $1/(m_\pi^2 + \vec{q}^{\,2})$
  - Not previously fully known!
- Only leading diagram for $S \cdot P$ and $P \cdot P$
- Leading diagram for $A \cdot A$ interaction

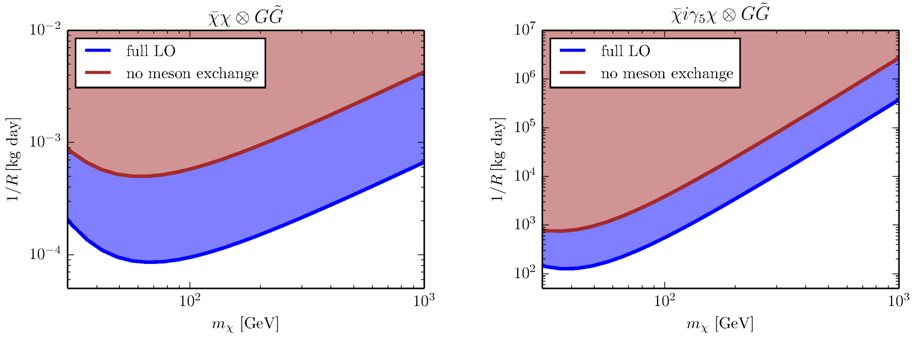
Effect of NLO operators – meson exchange

- $\mathcal{Q}_{4,q}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)$
  - Contact term: $\mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N$
  - Previously neglected meson exchange contribution: $\mathcal{O}_6^N = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$
  - Pion pole compensates for $\vec{q}^{\,2}$ suppression



Effect of NLO operators – meson exchange

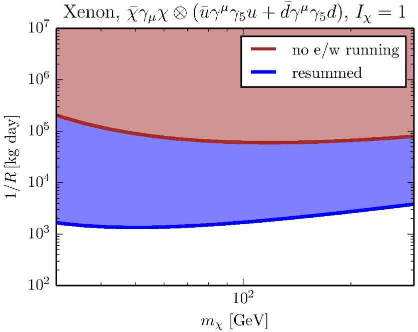
- $\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi}\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}, \qquad \mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi}i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$
  - Previously neglected meson exchange is leading contribution!
  - Order-of-magnitude improvement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



PRELIMINARY

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)