Interpreting limits from direct detection experiments

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KITP Program on

The Small-Scale Structure of Cold(?) Dark Matter

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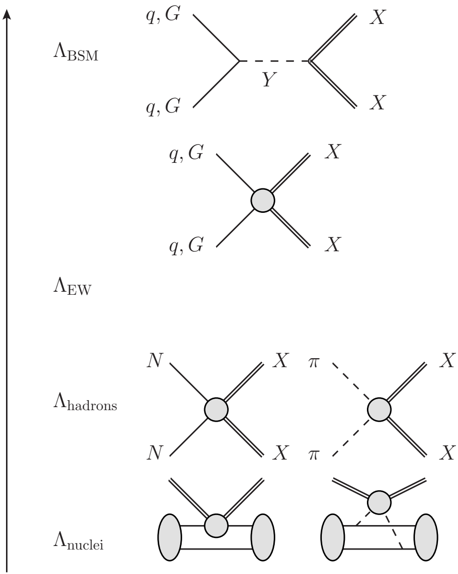
PLB 746 (2015) 410, PRD 94 (2016) 063505, PRL 119 (2017) 181803 with P. Klos, J. Menéndez, A. Schwenk

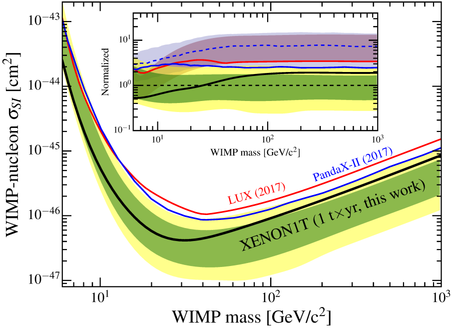
PRD 97 (2018) 103532 with A. Fieguth, P. Klos, J. Menéndez, A. Schwenk, C. Weinheimer

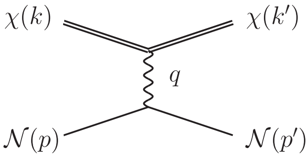
Direct detection of dark matter: scales



1. **BSM scale** Λ_{BSM}: $\mathcal{L}_{\mathrm{BSM}}$
2. **Effective Operators**: $\mathcal{L}_{\mathrm{SM}} + \sum_{i,k} \frac{1}{\Lambda^i_{\mathrm{BSM}}} \mathcal{O}_{i,k}$
3. Integrate out **EW physics**
4. **Hadronic scale**: nucleons and pions
   $\hookrightarrow$ effective interaction Hamiltonian H_I
5. **Nuclear scale**: $\langle \mathcal{N} | H_I | \mathcal{N} \rangle$
   $\hookrightarrow$ nuclear wave function

Direct detection of dark matter: schematics





- Schematically:

$$\frac{d\sigma_{\chi\mathcal{N}}}{dq^2} = \frac{\sigma^{SI}_{\chi N}}{4\mu_N^2 v^2}|\mathcal{F}(q^2)|^2 \qquad \mu_N = \frac{m_N m_\chi}{m_N + m_\chi}$$

- Rate after convolution with halo velocity distribution (not covered here)
- Information about BSM physics encoded in $\sigma^{SI}_{\chi N}$

Direct detection of dark matter: SI and SD limits

- Traditionally, consider **spin-independent (SI)** and **spin-dependent (SD)** limits
- **SI scattering**:
  - Coherence: $\mathcal{F}(0) = A$
  - Underlying operator: $\bar{\chi}\chi\bar{q}q$, $\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q, \ldots$
- **SD scattering**:
  - Response dominated by unpaired nucleons: $\mathcal{F}(0) \propto \langle \mathbf{S}_{p/n} \rangle$
  - Underlying operator: $\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu\gamma_5 q, \ldots$
- This talk: take a look at the assumptions that go into these scenarios

Outline

1. From quarks and gluons to nucleons
2. From nucleons to nuclei
3. Applications: q-dependence, σ_p^{SD} from Xe, Higgs Portal dark matter

Effective WIMP Lagrangian

- Starting point: take a spin-$1/2$ WIMP
  $\hookrightarrow$ **effective WIMP Lagrangian** Goodman et al. 2010

$$\mathcal{L}_\chi = \frac{1}{\Lambda^3}\sum_q \Big[C_q^{SS}\bar\chi\chi\, m_q\bar q q + C_q^{PS}\bar\chi i\gamma_5\chi\, m_q\bar q q + C_q^{SP}\bar\chi\chi\, m_q\bar q i\gamma_5 q + C_q^{PP}\bar\chi i\gamma_5\chi\, m_q\bar q i\gamma_5 q\Big]$$
$$+\frac{1}{\Lambda^2}\sum_q \Big[C_q^{VV}\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu q + C_q^{AV}\bar\chi\gamma^\mu\gamma_5\chi\,\bar q\gamma_\mu q + C_q^{VA}\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu\gamma_5 q + C_q^{AA}\bar\chi\gamma^\mu\gamma_5\chi\,\bar q\gamma_\mu\gamma_5 q\Big]$$
$$+\frac{1}{\Lambda^3}\Big[C_g^S\bar\chi\chi\,\alpha_s G^a_{\mu\nu}G_a^{\mu\nu}\Big]$$

- **Nucleon matrix elements**

$$\langle N(p)|m_q\bar q q|N(p)\rangle = m_N f_q^N \qquad \langle N(p)|\bar q\gamma^\mu\gamma_5 q|N(p)\rangle = \Delta q^N\langle N(p)|\gamma^\mu\gamma_5|N(p)\rangle \qquad \ldots$$

- **WIMP–nucleon cross section** $\sigma_{\chi N}$ depends on BSM Wilson coefficients and nucleon matrix elements

Matching to nonrelativistic EFT

- Operator basis for **WIMP and nucleon fields** Fan et al. 2010, Fitzpatrick et al. 2012

$$\mathcal{O}_1 = \mathbb{1} \qquad \mathcal{O}_2 = (\mathbf{v}^\perp)^2 \qquad \mathcal{O}_3 = i\mathbf{S}_N \cdot (\mathbf{q} \times \mathbf{v}^\perp) \qquad \mathcal{O}_4 = \mathbf{S}_\chi \cdot \mathbf{S}_N$$

$$\mathcal{O}_5 = i\mathbf{S}_\chi \cdot (\mathbf{q} \times \mathbf{v}^\perp) \qquad \mathcal{O}_6 = \mathbf{S}_\chi \cdot \mathbf{q}\,\mathbf{S}_N \cdot \mathbf{q} \qquad \mathcal{O}_7 = \mathbf{S}_N \cdot \mathbf{v}^\perp \qquad \mathcal{O}_8 = \mathbf{S}_\chi \cdot \mathbf{v}^\perp$$

$$\mathcal{O}_9 = i\mathbf{S}_\chi \cdot (\mathbf{S}_N \times \mathbf{q}) \qquad \mathcal{O}_{10} = i\mathbf{S}_N \cdot \mathbf{q} \qquad \mathcal{O}_{11} = i\mathbf{S}_\chi \cdot \mathbf{q} \qquad \ldots$$

- Matching to relativistic amplitudes

$$\mathcal{M}^{SS}_{1,\mathrm{NR}} = \mathcal{O}_1 f_N(t) \qquad \mathcal{M}^{SP}_{1,\mathrm{NR}} = \mathcal{O}_{10} g_5^N(t) \qquad \mathcal{M}^{PP}_{1,\mathrm{NR}} = \frac{1}{m_\chi}\mathcal{O}_6 h_5^N(t)$$

$$\mathcal{M}^{VV}_{1,\mathrm{NR}} = \mathcal{O}_1 \Big(f_1^{V,N}(t) + \frac{t}{4m_N^2} f_2^{V,N}(t)\Big) + \frac{1}{m_N}\mathcal{O}_3 f_2^{V,N}(t) + \frac{1}{m_N m_\chi}\Big(t\mathcal{O}_4 + \mathcal{O}_6\Big) f_2^{V,N}(t)$$

$$\mathcal{M}^{AV}_{1,\mathrm{NR}} = 2\mathcal{O}_8 f_1^{V,N}(t) + \frac{2}{m_N}\mathcal{O}_9 \Big(f_1^{V,N}(t) + f_2^{V,N}(t)\Big)$$

$$\mathcal{M}^{AA}_{1,\mathrm{NR}} = -4\mathcal{O}_4 g_A^N(t) + \frac{1}{m_N^2}\mathcal{O}_6 g_P^N(t) \qquad \mathcal{M}^{VA}_{1,\mathrm{NR}} = \Big\{-2\mathcal{O}_7 + \frac{2}{m_\chi}\mathcal{O}_9\Big\} h_A^N(t)$$

- Observations
  - SI: $\mathcal{O}_1$, SD: combination of $\mathcal{O}_4$ and $\mathcal{O}_6$
  - Not all the $\mathcal{O}_i$ equally important, QCD implies relations among them

$\hookrightarrow$ can one analyze QCD constraints more systematically?

Chiral symmetry and WIMPs

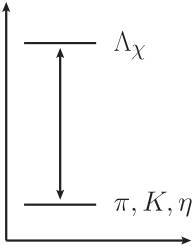
- **Chiral symmetry** of QCD

$$\mathcal{L}_{\text{QCD}} = \bar{q}_L i\not{D} q_L + \bar{q}_R i\not{D} q_R - \bar{q}_L \mathcal{M} q_R - \bar{q}_R \mathcal{M} q_L - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$

$\hookrightarrow$ invariant under L, R rotations for $\mathcal{M} \to 0$

- Pions are (pseudo) Goldstone Bosons of the spontaneous breaking of chiral symmetry
- Expansion in momenta p/Λ_χ and quark masses $m_q \sim p^2$

$\hookrightarrow$ **scale separation**



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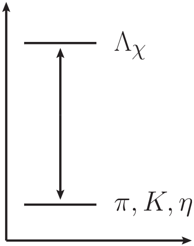
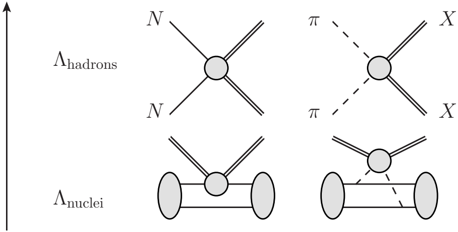
- For WIMPs:
  - Typical momentum transfer $q \lesssim 200\,\text{MeV} = \mathcal{O}(M_\pi)$
  - WIMPs can couple to pions (**pion-exchange currents**)
  - EFT power counting predicts hierarchy



From nucleons to nuclei



4. **Hadronic scale**: nucleons and pions

   ↪ effective interaction Hamiltonian H_I

5. **Nuclear scale**: $\langle \mathcal{N} | H_I | \mathcal{N} \rangle$

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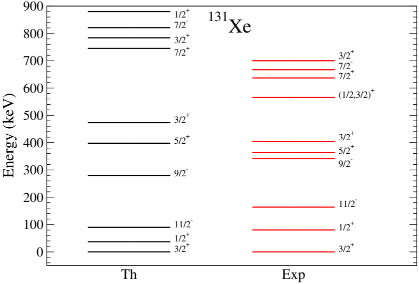
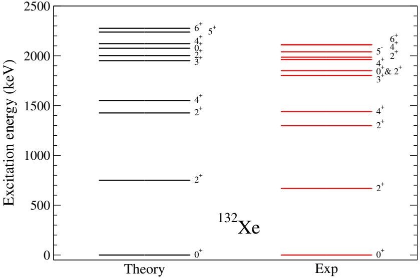
Spectra and shell-model calculation



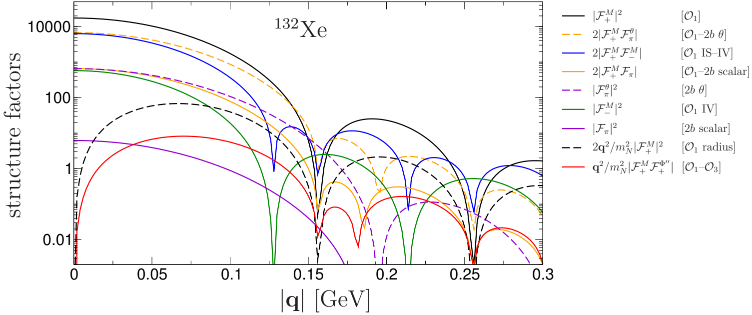


- **Shell-model diagonalization** for Xe isotopes with ^{100}Sn core
- **Uncertainty estimates**: currently phenomenological shell-model interaction

  ↪ chiral-EFT-based interactions in the future?

  ↪ **ab-initio calculations for light nuclei?**

Full set of coherent contributions



- Parameterize cross section as

$$\frac{d\sigma_{\chi\mathcal{N}}^{\text{SI}}}{d\mathbf{q}^2}=\frac{1}{4\pi\mathbf{v}^2}\bigg|\Big(c_+^M-\frac{\mathbf{q}^2}{m_N^2}\dot{c}_+^M\Big)\mathcal{F}_+^M(\mathbf{q}^2)+\Big(c_-^M-\frac{\mathbf{q}^2}{m_N^2}\dot{c}_-^M\Big)\mathcal{F}_-^M(\mathbf{q}^2)$$
$$+c_\pi\mathcal{F}_\pi(\mathbf{q}^2)+c_\pi^\theta\mathcal{F}_\pi^\theta(\mathbf{q}^2)+\frac{\mathbf{q}^2}{2m_N^2}\Big[c_+^{\Phi''}\mathcal{F}_+^{\Phi''}(\mathbf{q}^2)+c_-^{\Phi''}\mathcal{F}_-^{\Phi''}(\mathbf{q}^2)\Big]\bigg|^2$$

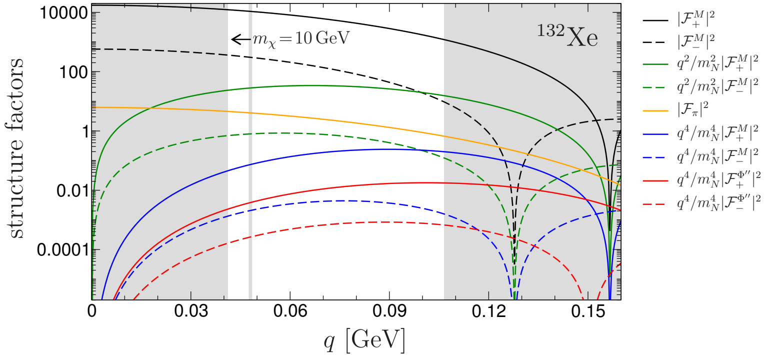
- Single-nucleon cross section: $\sigma_{\chi N}^{\text{SI}}=\mu_N^2|c_+^M|^2/\pi$

  $\hookrightarrow$ reproduces SI search

Conclusions

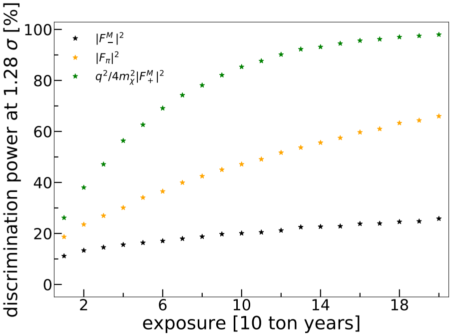
- SI and SD single-nucleon cross sections
  - correspond to particular **slices through the WIMP parameter space**
  - are not truly "single-nucleon" quantities (but see SD two-body currents below)
  - provide constraints on a combination of BSM Wilson coefficients and nucleon matrix elements
- Chiral EFT predicts
  - a hierarchy of the subleading corrections
  - new class thereof (**pion-exchange currents**) that emerge as the most relevant coherent ones
- Of course, all of this becomes much more relevant once there is a signal!

Discriminating different response functions



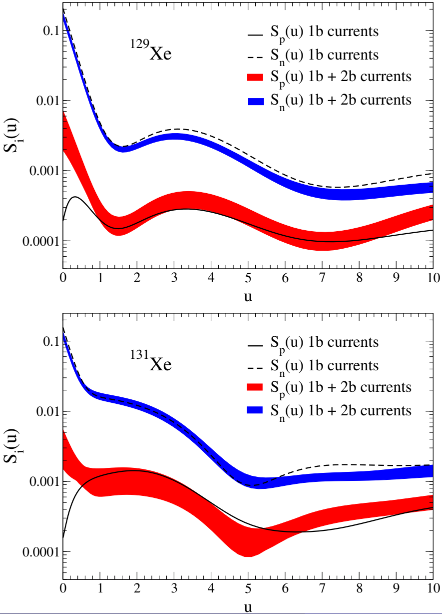
- White region accessible to XENON-type experiment
- Can one tell these curves apart in a realistic experimental setting?
- Consider XENON1T-like, XENONnT-like, DARWIN-like settings

Discriminating different response functions



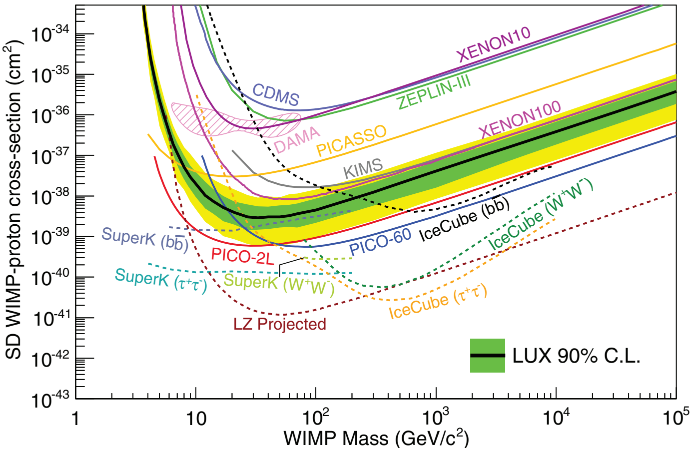
- DARWIN-like setting, $m_\chi = 100\,\text{GeV}$
- q-dependent responses more easily distinguishable
- If interaction not much weaker than current limits, DARWIN could discriminate most responses from standard SI structure factor

Two-body currents: SD case



- Nuclear structure factors for **spin-dependent interactions**
  Klos et al. 2013
  - Based on chiral EFT currents (1b+2b)
  - Shell model
  - $u = q^2 b^2/2$ related to momentum transfer
- 2b currents absorbed into redefinition of 1b current

Two-body currents: SD case

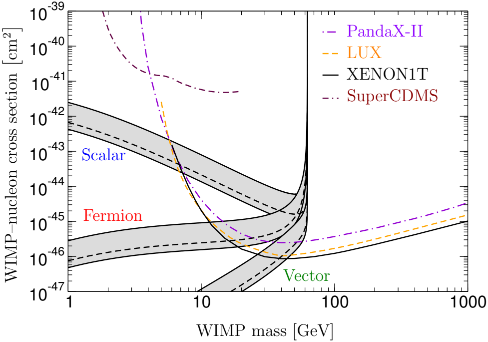


Xenon becomes competitive for σ_p thanks to two-body currents!

Higgs Portal dark matter

- **Higgs Portal**: WIMP interacts with SM via the Higgs
  - **Scalar**: $H^\dagger H S^2$
  - **Vector**: $H^\dagger H V_\mu V^\mu$
  - **Fermion**: $H^\dagger H \bar{f} f$
- If $m_h > 2m_\chi$, should happen at the LHC

  $\hookrightarrow$ limits on **invisible Higgs decays**



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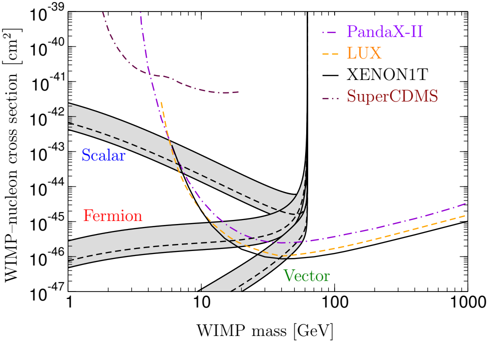
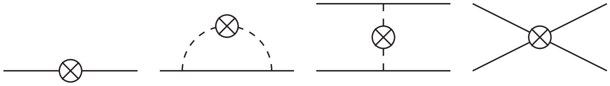


- Translation requires input for **Higgs–nucleon coupling**

$$f_N = \sum_{q=u,d,s,c,b,t} f_q^N = \frac{2}{9} + \frac{7}{9} \sum_{q=u,d,s} f_q^N + \mathcal{O}(\alpha_s) \qquad m_N f_q^N = \langle N | m_q \bar{q} q | N \rangle$$

- Issues: input for $f_N = 0.260 \ldots 0.629$ outdated, two-body currents missing

Higgs–nucleon coupling



(a) (b) (c) (d)

- **One-body contribution**

$$f_N^{1b} = 0.307(9)_{ud}(15)_s(5)_{\text{pert}} = 0.307(18)$$

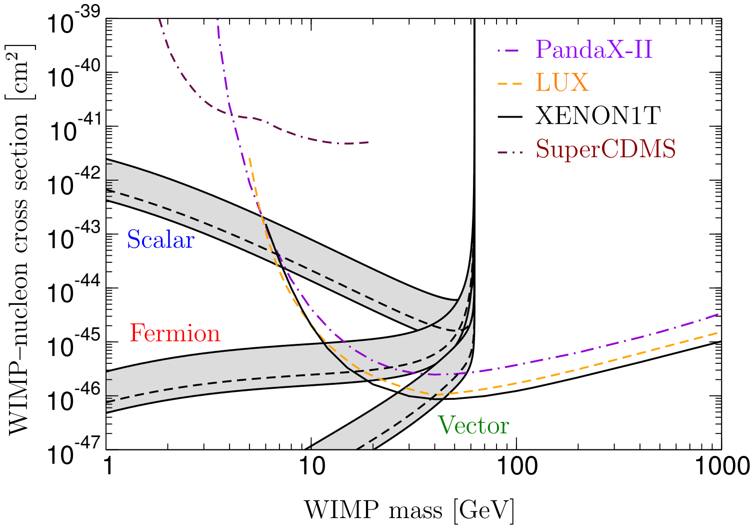
- Limits on WIMP–nucleon cross section subsume **two-body effects**

  $\hookrightarrow$ have to be included for meaningful comparison

- **Two-body contribution**
  - Need s and θ^μ_μ currents
  - Treatment of θ^μ_μ tricky: several ill-defined terms combine to $\langle\Psi|T + V_{NN}|\Psi\rangle = E_b$
  - A cancellation makes the final result anomalously small

$$f_N^{2b} = \big[-3.2(0.2)_A(2.1)_{\text{ChEFT}} + 5.0(0.4)_A\big] \times 10^{-3} = 1.8(2.1) \times 10^{-3}$$

Improved limits for Higgs Portal dark matter



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