Two-body currents in WIMP–nucleus scattering

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Nuclear ab initio Theories and Neutrino Physics

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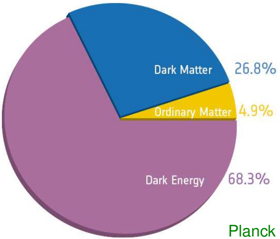
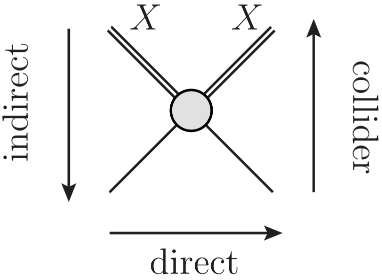
PLB 746 (2015) 410, PRD 94 (2016) 063505, PRL 119 (2017) 181803, with P. Klos, J. Menéndez, A. Schwenk
1802.04294, with A. Fieguth, P. Klos, J. Menéndez, A. Schwenk, C. Weinheimer
work in progress

How to search for dark matter?

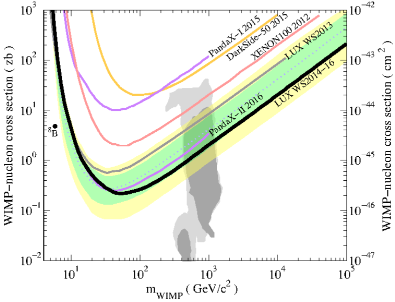
- Search strategies: direct, indirect, collider
- Assume DM particle is WIMP
- **Direct detection**: search for **WIMPs** scattering off nuclei in the large-scale detectors
- Ingredients for interpretation:
  - **DM halo**: velocity distribution
  - **Nucleon matrix elements**: WIMP–nucleon couplings
  - **Nuclear structure factors**: embedding into target nucleus

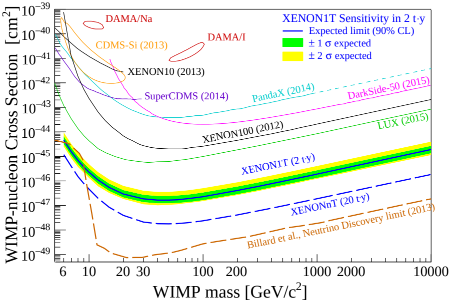


Planck 2013



Direct detection of dark matter: schematics

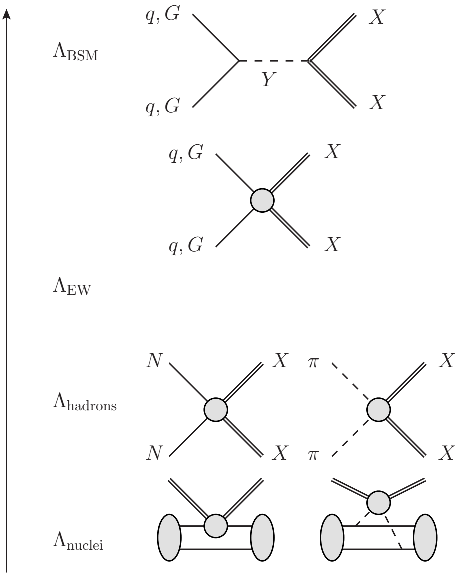




- **Nuclear recoil** in WIMP–nucleus scattering
  - **Flux factor** Φ: DM halo and velocity distribution
  - **WIMP–nucleus cross section**
- **Spin-independent**: coherent $\propto A^2$
- **Spin-dependent**: $\propto \langle \mathbf{S}_p \rangle$ or $\langle \mathbf{S}_n \rangle$
- Information on BSM physics encoded in normalization at $q = 0$

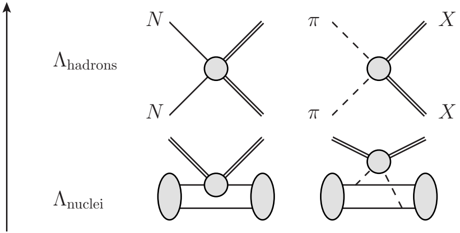
$\hookrightarrow$ for SI case: $\sigma_{\chi N}^{\mathrm{SI}}$

Direct detection of dark matter: scales



1. **BSM scale** Λ_{BSM}: $\mathcal{L}_{\text{BSM}}$
2. **Effective Operators**: $\mathcal{L}_{\text{SM}} + \sum_{i,k} \frac{1}{\Lambda^i_{\text{BSM}}} \mathcal{O}_{i,k}$
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: scales



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

- Typical WIMP–nucleon **momentum transfer**

$$|\mathbf{q}_{\text{max}}| = 2\mu_{\mathcal{N}\chi}|\mathbf{v}_{\text{rel}}| \sim 200\,\text{MeV} \qquad |\mathbf{v}_{\text{rel}}| \sim 10^{-3} \qquad \mu_{\mathcal{N}\chi} \sim 100\,\text{GeV}$$

- QCD constraints: spontaneous breaking of chiral symmetry

  $\Rightarrow$ **Chiral effective field theory for WIMP–nucleon scattering**

  Prézeau et al. 2003, Cirigliano et al. 2012, 2013, Menéndez et al. 2012, Klos et al. 2013, MH et al. 2015, Bishara et al. 2017

- In NREFT Fan et al. 2010, Fitzpatrick et al. 2012, Anand et al. 2013 need to **match to QCD** to extract information on BSM physics $\Rightarrow$ “the” EFT approach not unique!

Outline

Chiral EFT: a modern approach to nuclear forces

- Traditionally: meson-exchange potentials
- Chiral effective field theory
  - Based on **chiral symmetry** of QCD
  - **Power counting**
  - **Low-energy constants**
  - Hierarchy of multi-nucleon forces
  - Consistency of *NN* and 3*N*

$\hookrightarrow$ modern theory of nuclear forces

- Long-range part related to **pion–nucleon scattering**

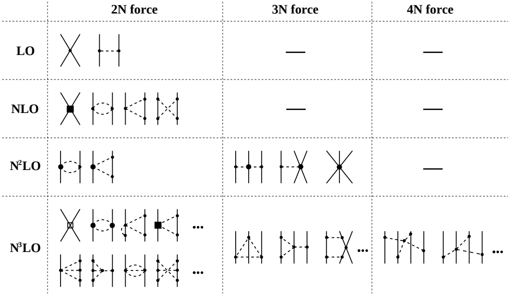
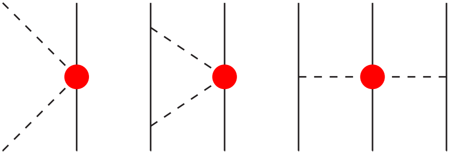


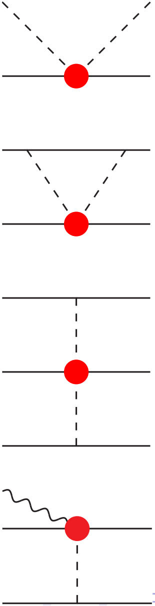
Figure taken from 1011.1343

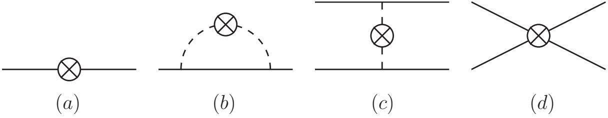


Chiral EFT: currents

- Coupling to **external sources** $\mathcal{L}(v_\mu, a_\mu, s, p)$
- Same LECs appear in **axial current**

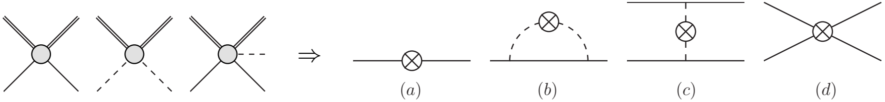
  $\hookrightarrow$ β decay, neutrino interactions, dark matter
- Vast literature for v_μ and a_μ, up to one-loop level
  - With unitary transformations: Kölling et al. 2009, 2011, Krebs et al. 2016
  - Without unitary transformations: Pastore et al. 2008, Park et al. 2003, Baroni et al. 2015
- For **dark matter** further currents: s, p, tensor, spin-2, θ^μ_μ





$\hookrightarrow$ in this talk: concentrate on **2b effects** (c)+(d)

Direct detection and chiral EFT



- Expansion around **chiral limit** of QCD

  ↪ simultaneous expansion in momenta and quark masses
- Three classes of corrections:
  - **Subleading 1b responses** (a)
  - **Radius corrections** (b)
  - **Two-body currents** (c), (d)
- NREFT covers (a), but misses (b)–(d)
  - (b): modifies coefficient of $\mathcal{O}_i$ by momentum-dependent factor
  - (c), (d): do not match directly onto NREFT, need **normal ordering**

$$\langle N^\dagger N\rangle N^\dagger N \to \mathcal{O}_i^{\text{eff}}$$

- (a)+(b) just **ChPT for nucleon form factors**, but (c)+(d) genuinely new effects

Chiral counting

- Starting point: **effective WIMP Lagrangian** Goodman et al. 2010

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

- **Chiral power counting**

$$\partial = \mathcal{O}(p), \qquad m_q = \mathcal{O}(p^2) = \mathcal{O}(M_\pi^2), \qquad a_\mu, v_\mu = \mathcal{O}(p), \qquad \frac{\partial}{m_N} = \mathcal{O}(p^2)$$

$\hookrightarrow$ construction of effective Lagrangian for nucleon and pion fields

$\hookrightarrow$ organize in terms of **chiral order ν**, $\mathcal{M} = \mathcal{O}(p^\nu)$

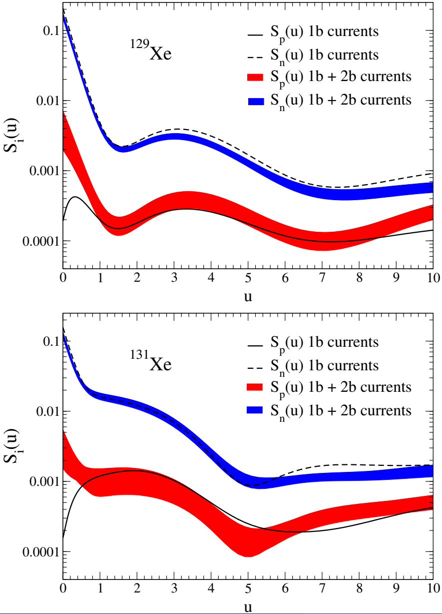
Chiral counting: summary

WIMP	Nucleon	V t	V $\mathbf{x}$	A t	A $\mathbf{x}$
V	1b	0	$1+2$	2	$0+2$
	2b	4	$2+2$	2	$4+2$
	2b NLO	—	—	5	$3+2$
A	1b	$0+2$	1	$2+2$	0
	2b	$4+2$	2	$2+2$	4
	2b NLO	—	—	$5+2$	3

WIMP	Nucleon	S	P
S	1b	2	1
	2b	3	5
	2b NLO	—	4
P	1b	$2+2$	$1+2$
	2b	$3+2$	$5+2$
	2b NLO	—	$4+2$

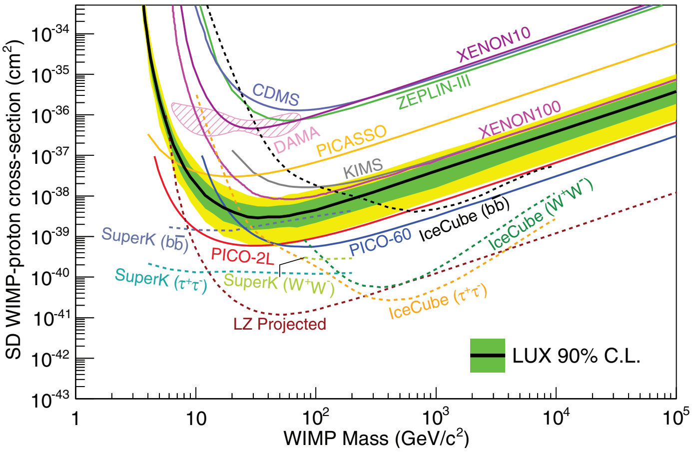
- $+2$ from NR expansion of WIMP spinors, terms can be dropped if $m_\chi \gg m_N$
- Red: all terms up to $\nu = 3$
- Two-body currents: *AA* Menéndez et al. 2012, Klos et al. 2013, *SS* Prézeau et al. 2003, Cirigliano et al. 2012, but **new currents in *AV* and *VA* channel** 1503.04811
- Worked out the matching to NREFT and BSM Wilson coefficients for spin-$1/2$
  $\hookrightarrow$ **hierarchy** predicted from chiral expansion

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, normal ordering over Fermi gas
  - $u = q^2 b^2/2$ related to momentum transfer
- 2b currents probe the same combination of BSM Wilson coefficients and hadronic couplings
  $\hookrightarrow$ absorb into 1b current

Two-body currents: SD case

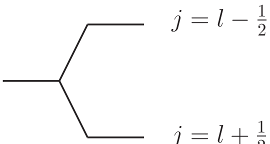


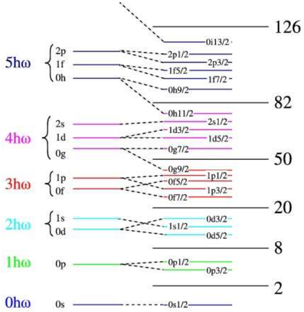
Xenon becomes competitive for σ_p thanks to 2b currents!

Coherence effects

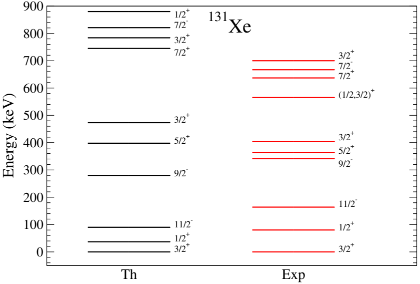
- Six distinct nuclear responses
  Fitzpatrick et al. 2012, Anand et al. 2013
  - $M \leftrightarrow \mathcal{O}_1 \leftrightarrow$ SI
  - $\Sigma', \Sigma'' \leftrightarrow \mathcal{O}_4, \mathcal{O}_6 \leftrightarrow$ SD
  - $\Phi'' \leftrightarrow \mathcal{O}_3 \leftrightarrow$ quasi-coherent, spin-orbit operator
  - $\Delta, \tilde{\Phi}'$: not coherent
- **Quasi-coherence** of Φ''
  - Spin-orbit splitting
  - Coherence until mid-shell
  - About 20 coherent nucleons in Xe
  - Interference M–$\Phi'' \leftrightarrow \mathcal{O}_1$–$\mathcal{O}_3$
- Coherent 2b currents:
  - Scalar $\propto N + Z$
  - Vector $\propto N - Z$

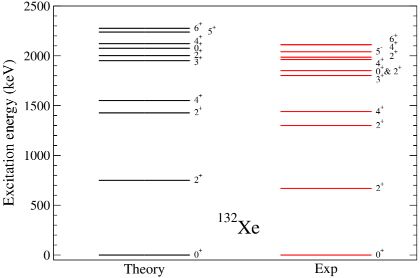
$\hookrightarrow$ concentrate on scalar case





Spectra and shell-model calculation





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

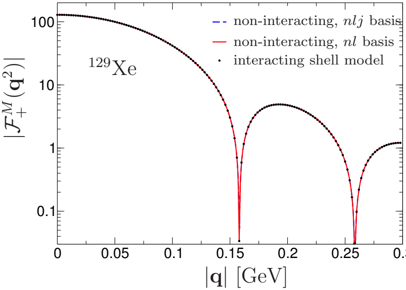
  $\hookrightarrow$ chiral-EFT-based interactions in the future?

  $\hookrightarrow$ **ab-initio calculations for light nuclei?**

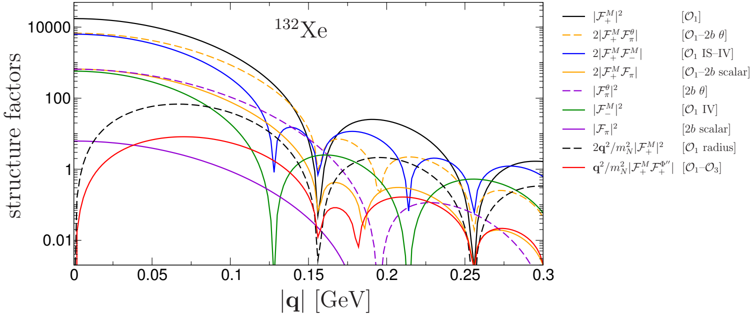
Scalar two-body currents

$$\mathcal{F}_\pi(\mathbf{q}^2) = \frac{M_\pi}{2}\left(\frac{g_A}{2F_\pi}\right)^2 \sum_{n_1 l_1 n_2 l_2} \sum_{\tau_1 \tau_2} \int \frac{d^3p_1 d^3p_2 d^3p_1' d^3p_2'}{(2\pi)^6} R_{n_1 l_1}(|\mathbf{p}_1'|) R_{n_2 l_2}(|\mathbf{p}_2'|) R_{n_1 l_1}(|\mathbf{p}_1|) R_{n_2 l_2}(|\mathbf{p}_2|)$$
$$\times \frac{(2l_1+1)(2l_2+1)}{16\pi^2} P_{l_1}(\hat{\mathbf{p}}_1'\cdot\hat{\mathbf{p}}_1) P_{l_2}(\hat{\mathbf{p}}_2'\cdot\hat{\mathbf{p}}_2)(2\pi)^3 \delta^{(3)}(\mathbf{p}_1+\mathbf{p}_2-\mathbf{p}_1'-\mathbf{p}_2'-\mathbf{q})$$
$$\times (3-\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2) \frac{\mathbf{q}_1^{\text{ex}}\cdot\mathbf{q}_2^{\text{ex}}}{((\mathbf{q}_1^{\text{ex}})^2+M_\pi^2)((\mathbf{q}_2^{\text{ex}})^2+M_\pi^2)}$$

- Two-body current defines genuinely **new structure factor**
- Checked the oscillator model for 1b case
  $\hookrightarrow$ reproduces perfectly the $L=0$ multipole
- Another structure factor related to **trace anomaly θ^μ_μ**



Full set of coherent contributions

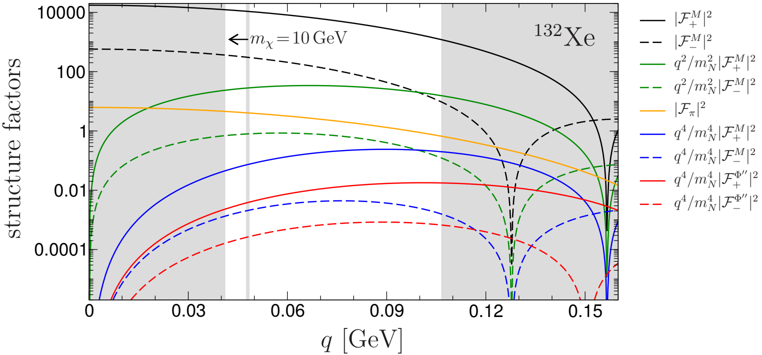


- Parameterize cross section as

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

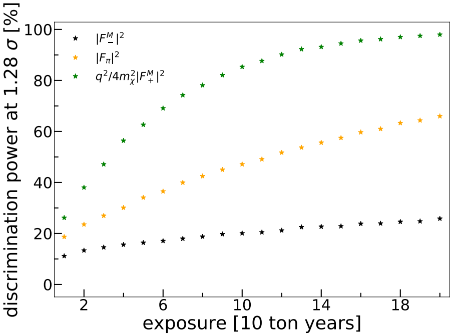
- Single-nucleon cross section: $\sigma_{\chi N}^{SI} = \mu_N^2|c_+^M|^2/\pi$
- c related to Wilson coefficients and nucleon form factors

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

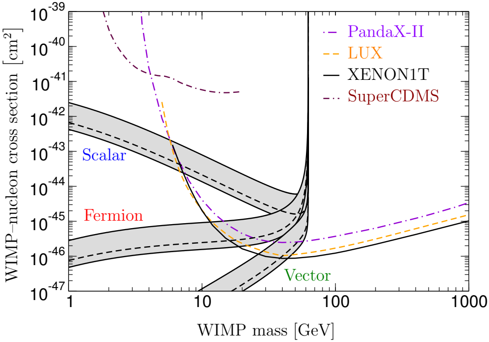


- DARWIN-like setting, $m_\chi = 100\,\text{GeV}$
- q-dependent responses more easily distinguishable
- If interaction not much weaker than current limits, DARWIN could discriminate most responses from standard SI structure factor

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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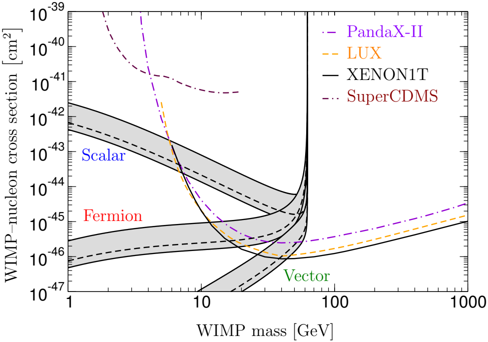
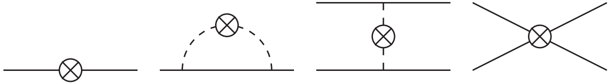


- Translation requires input for **Higgs–nucleon coupling**

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

- Issues: input for $f_N = 0.260\ldots0.629$ outdated, 2b currents missing



- **One-body contribution**

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

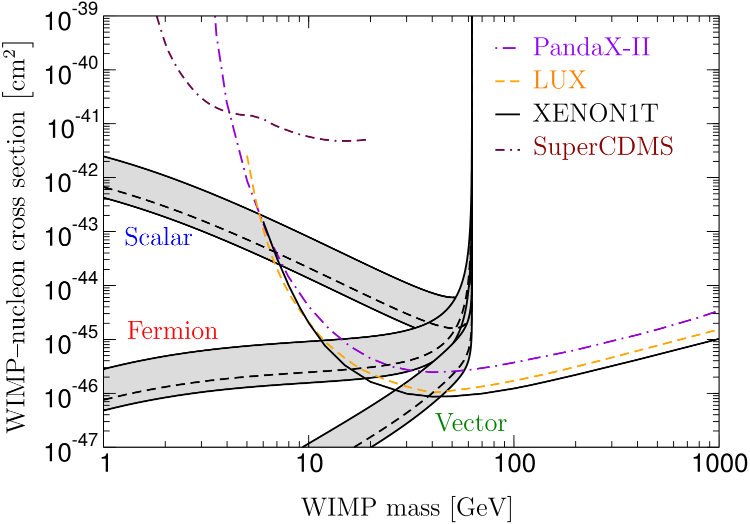
- Limits on WIMP–nucleon cross section subsume **2b effects**

  $\hookrightarrow$ 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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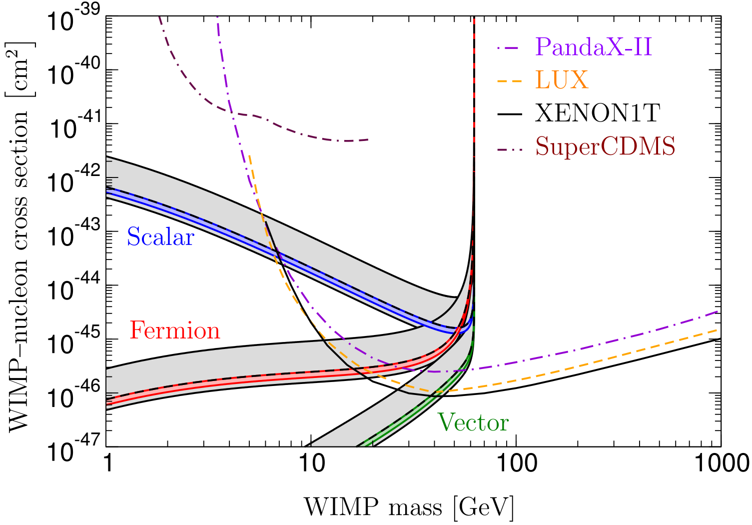


Chiral counting for neutrino–nucleus scattering

WIMP	Nucleon	V t	V **x**	A t	A **x**
V	1b	0	$1+2$	2	$0+2$
	2b	4	$2+2$	2	$4+2$
	2b NLO	—	—	5	$3+2$
A	1b	$0+2$	1	$2+2$	0
	2b	$4+2$	2	$2+2$	4
	2b NLO	—	—	$5+2$	3

WIMP	Nucleon	S	P
S	1b	2	1
	2b	3	5
	2b NLO	—	4
P	1b	$2+2$	$1+2$
	2b	$3+2$	$5+2$
	2b NLO	—	$4+2$

Chiral counting for neutrino–nucleus scattering

	Nucleon	*V*		*A*	
WIMP		*t*	**x**	*t*	**x**
V	1b	0	1	2	0
	2b	4	2	2	4
	2b NLO	—	—	5	3
A	1b	0	1	2	0
	2b	4	2	2	4
	2b NLO	—	—	5	3

	Nucleon	*S*	*P*
WIMP			
S	1b	2	1
	2b	3	5
	2b NLO	—	4
P	1b	2	1
	2b	3	5
	2b NLO	—	4

Chiral counting for neutrino–nucleus scattering

WIMP	Nucleon	V: t	V: $\mathbf{x}$	A: t	A: $\mathbf{x}$
	1b	0	1	2	0
V	2b	4	2	2	4
	2b NLO	—	—	5	3
	1b	0	1	2	0
A	2b	4	2	2	4
	2b NLO	—	—	5	3

WIMP	Nucleon	S	P
	1b	2	1
S	2b	3	5
	2b NLO	—	4
	1b	2	1
P	2b	3	5
	2b NLO	—	4

- **Standard interactions**: coherent 2b currents scale with $N - Z$, but

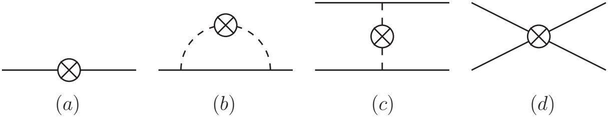
$$C_u^{VV} = \frac{G_F}{2\sqrt{2}\cos^2\theta_W}\Big(1 - \frac{8}{3}\sin^2\theta_W\Big) \qquad C_d^{VV} = \frac{G_F}{2\sqrt{2}\cos^2\theta_W}\Big(-1 + \frac{4}{3}\sin^2\theta_W\Big)$$

$\hookrightarrow$ proton coupling $2C_u^{VV} + C_d^{VV} \propto 1 - 4\sin^2\theta_W$ suppressed

$\hookrightarrow$ 1b only scales with N^2, not $(N+Z)^2$

- **Non-standard interactions**: potentially large corrections from scalar 2b currents

Conclusions



- **Chiral EFT** for WIMP–nucleon scattering
- Predicts **hierarchy** for corrections to leading coupling
- Connects nuclear and hadronic scales
- Ingredients: **nuclear matrix elements** and **structure factors**
- Applications:
  - σ_p^{SD} limits from xenon via two-body currents
  - Discriminating nuclear responses
  - Improved limits on Higgs Portal dark matter from LHC searches
- Outlook: same formalism applies to low-energy neutrino scattering