Chiral effective field theory for dark matter direct detection

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Hadronic Contributions to New Physics Searches

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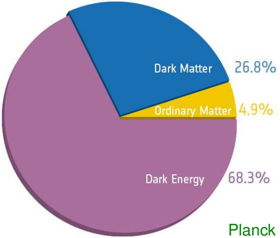
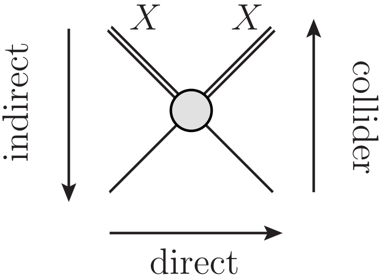
Outline

1. Direct detection of dark matter
2. Chiral effective field theory
3. Corrections beyond standard nuclear response
   - Subleading one-body responses
   - Two-body currents
   - Radius corrections
4. Conclusions

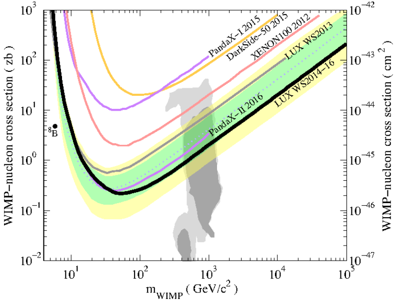
- Search strategies: direct, indirect, collider
- Assume DM particle is WIMP
- **Direct detection**: search for **WIMPs** scattering off nuclei in the large-scale detectors
- Ingredients for interpretation:
    - **DM halo**: velocity distribution
    - **Nucleon matrix elements**: WIMP–nucleon couplings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

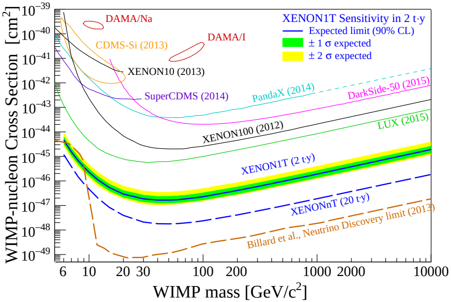


Planck 2013



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: $\sigma^{\text{SI}}_{\chi N}$

Rate and structure factors

- **Rate**

$$\frac{dR}{d\mathbf{q}^2} = \frac{\rho M}{m_A m_\chi} \int_{v_{\min}}^{v_{\text{esc}}} d^3v\, |\mathbf{v}| f(|\mathbf{v}|) \frac{d\sigma_{\chi\mathcal{N}}}{d\mathbf{q}^2}$$

- **Halo-independent methods** Drees, Shan 2008, Fox, Liu, Weiner 2010, …
- **Nuclear structure factors** Engel, Pittel, Vogel 1992

$$\frac{d\sigma_{\chi\mathcal{N}}}{d\mathbf{q}^2} = \frac{8G_F^2}{(2J+1)v^2}\Big[S_A(q) + S_S(q)\Big]$$

- Normalization at $|\mathbf{q}| = 0$:

$$S_S(0) = \frac{2J+1}{4\pi}\Big|c_0 A + c_1(Z-N)\Big|^2$$

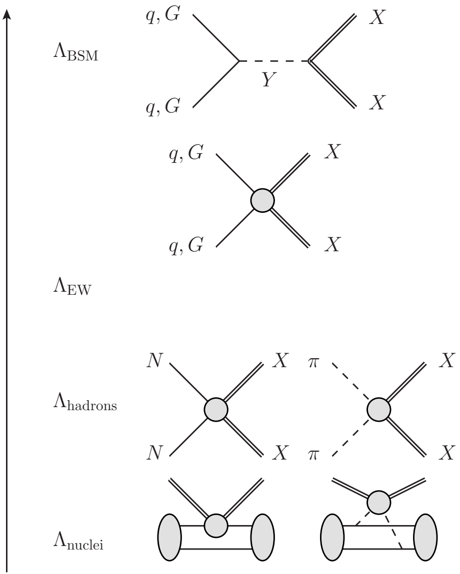
$$S_A(0) = \frac{(2J+1)(J+1)}{4\pi J}\Big|(a_0+a_1)\langle\mathbf{S}_p\rangle + (a_0-a_1)\langle\mathbf{S}_n\rangle\Big|^2$$

- Assume $c_1 = 0$ and SI scattering

$$\frac{d\sigma_{\chi\mathcal{N}}^{\text{SI}}}{d\mathbf{q}^2} = \frac{\sigma_{\chi N}^{\text{SI}}}{4\mathbf{v}^2\mu_N^2}\mathcal{F}_{\text{SI}}^2(\mathbf{q}^2)$$

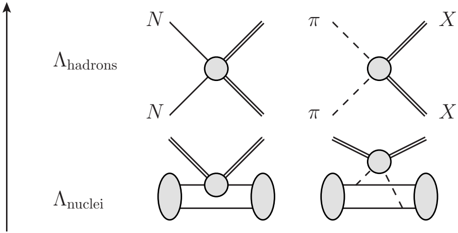
$\hookrightarrow$ phenomenological **Helm form factor** $\mathcal{F}_{\text{SI}}^2(\mathbf{q}^2)$

Effective field theories for the direct detection of dark matter



1. **BSM scale** $\Lambda_{\rm BSM}$: $\mathcal{L}_{\rm BSM}$
2. **Effective Operators**: $\mathcal{L}_{\rm SM} + \sum_{i,k} \frac{1}{\Lambda^i_{\rm BSM}} \mathcal{O}_{i,k}$
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
   ↪ effective interaction Hamiltonian H_I

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

⇒ **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

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**

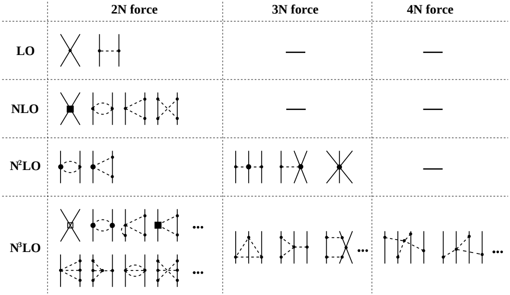
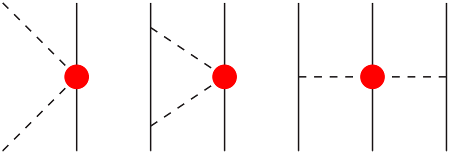


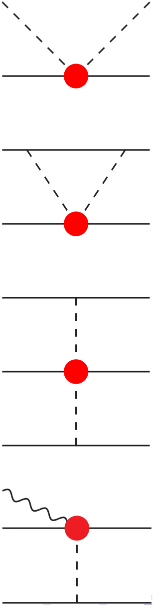
Figure taken from 1011.1343

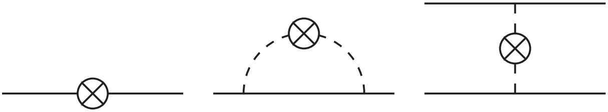


Chiral EFT: currents

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

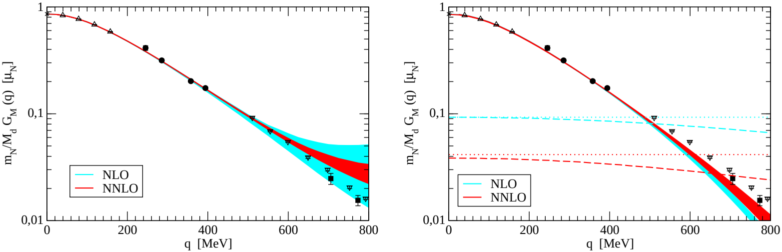
  $\hookrightarrow$ β decay, neutrino interactions, dark matter
- Vast literature for v_μ and a_μ, up to one-loop level
  - With unitary transformations: Kölling et al. 2009, 2011, Krebs et al. to appear
  - Without unitary transformations: Pastore et al. 2008, Park et al. 2003, Baroni et al. 2015
- For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



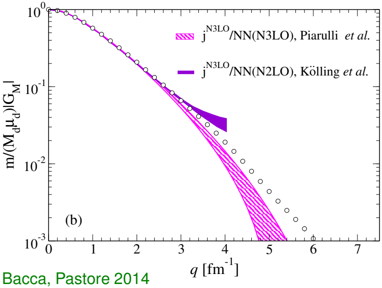


(a) (b) (c)

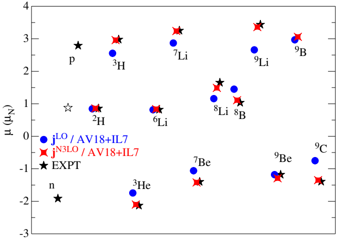
Vector current in chiral EFT: deuteron form factors, magnetic moments



Kölling, Epelbaum, Phillips 2012

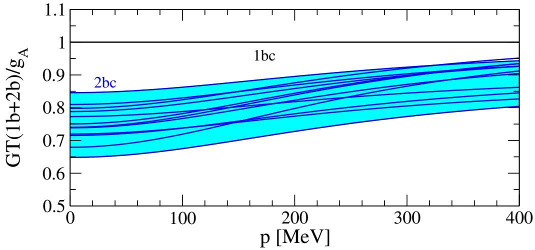


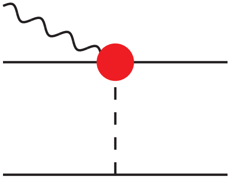
Bacca, Pastore 2014



Pastore et al. 2013

Axial-vector current in chiral EFT: ν-less double β decay

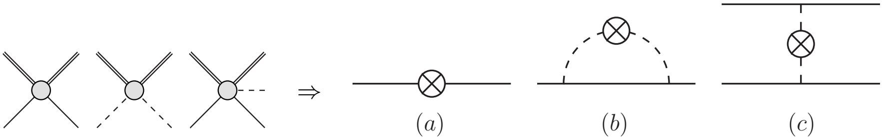




Menéndez, Gazit, Schwenk 2011

- Normal ordering over Fermi sea $\Rightarrow$ effective one-body currents
- **Two-body currents** contribute to **quenching of g_A** in Gamov–Teller operator $g_A\boldsymbol{\sigma}\tau^-$

Direct detection and chiral EFT



- Expansion around **chiral limit** of QCD

  ↪ simultaneous expansion in momenta and quark masses
- Three classes of corrections:
  - **Subleading one-body responses** (*a*) Fan et al. 2010, Fitzpatrick et al. 2012, Anand et al. 2013
  - **Radius corrections** (*b*)
  - **Two-body currents** (*c*), (*d*)

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: 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

- $+2$ 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

Example: chiral counting in scalar channel

- Leading pion–nucleon Lagrangian

$$\mathcal{L}_{\pi N}^{(1)} = \bar{\Psi}\left[i\gamma_\mu\left(\partial^\mu - i v^\mu\right) - m_N + \frac{g_A}{2}\gamma_\mu\gamma_5\left(2a^\mu - \frac{\partial^\mu \boldsymbol{\pi}}{F_\pi}\right) + \cdots\right]\Psi$$

$\hookrightarrow$ **no scalar source**!

WIMP	Nucleon	S
	1b	2
S	2b	3

Example: chiral counting in scalar channel

- Leading pion–nucleon Lagrangian

$$\mathcal{L}_{\pi N}^{(1)} = \bar{\Psi}\Big[i\gamma_\mu\left(\partial^\mu - i{\color{red}v^\mu}\right) - m_N + \frac{g_A}{2}\gamma_\mu\gamma_5\Big(2{\color{red}a^\mu} - \frac{\partial^\mu \boldsymbol{\pi}}{F_\pi}\Big) + \cdots\Big]\Psi$$

$\hookrightarrow$ **no scalar source**!

- Scalar coupling

$$f_N = \frac{m_N}{\Lambda^3}\sum_{q=u,d,s} C_q^{SS} f_q^N + \cdots \qquad \langle N|m_q\bar{q}q|N\rangle = f_q^N m_N$$

$\hookrightarrow$ for $q = u, d$ related to **pion–nucleon σ-term** $\sigma_{\pi N}$

- Chiral expansion

$$\sigma_{\pi N} = -4c_1 M_\pi^2 - \frac{9g_A^2 M_\pi^3}{64\pi F_\pi^2} + \mathcal{O}(M_\pi^4) \qquad \dot{\sigma} = \frac{5g_A^2 M_\pi}{256\pi F_\pi^2} + \mathcal{O}(M_\pi^2)$$

$\hookrightarrow$ slow convergence

	Nucleon	S
WIMP		
	1b	2
S	2b	3

Matching to nonrelativistic EFT

- Operator basis in NREFT Fan et al. 2010, Fitzpatrick et al. 2012, Anand et al. 2013

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

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

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

- Matching to chiral EFT ($f_N,\ldots$: Wilson coefficients + nucleon form factors)

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

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

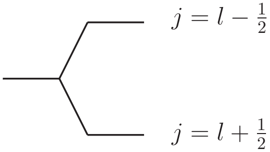
$$\mathcal{M}^{AV}_{1,\mathrm{NR}} = 2\mathcal{O}_8 f_1^{V,N}(t) + \frac{2}{m_N}\mathcal{O}_9\Big(f_1^{V,N}(t) + f_2^{V,N}(t)\Big)$$

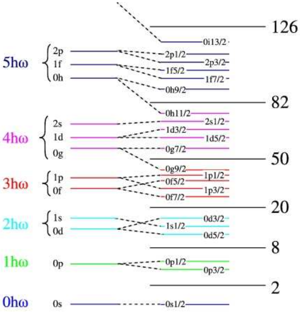
$$\mathcal{M}^{AA}_{1,\mathrm{NR}} = -4\mathcal{O}_4 g_A^N(t) + \frac{1}{m_N^2}\mathcal{O}_6 g_P^N(t) \qquad \mathcal{M}^{VA}_{1,\mathrm{NR}} = \Big\{-2\mathcal{O}_7 + \frac{2}{m_\chi}\mathcal{O}_9\Big\}h_A^N(t)$$

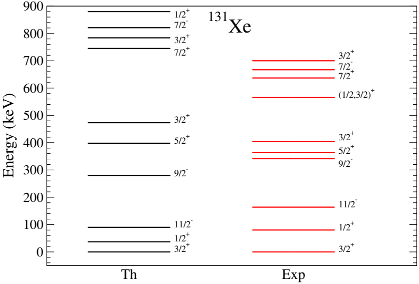
- Conclusions
  - $\mathcal{O}_2$, $\mathcal{O}_5$, and $\mathcal{O}_{11}$ do not appear at $\nu = 3$, not all $\mathcal{O}_i$ independent
  - 2b operators of similar or even greater importance than some of the 1b operators
  - Next: **phenomenological implications**

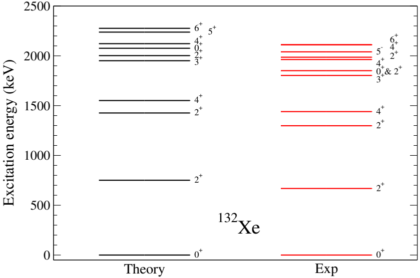
Coherence effects

- 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–$\Phi'' \leftrightarrow \mathcal{O}_1$–$\mathcal{O}_3$
- Further coherent M-responses from $\mathcal{O}_5$, $\mathcal{O}_8$, $\mathcal{O}_{11}$, but no interference with $\mathcal{O}_1$ due to sum over $\mathbf{S}_\chi$





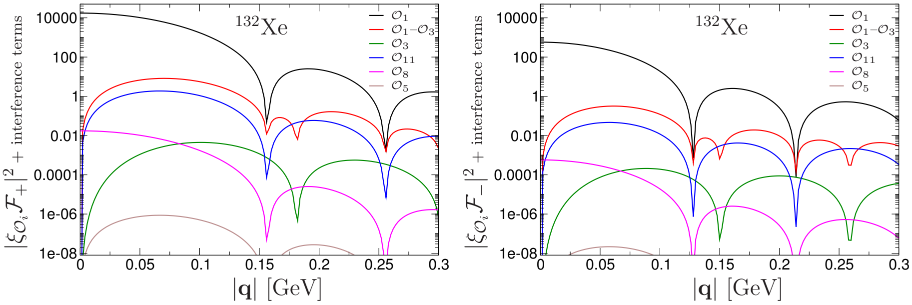




- **Shell-model diagonalization** for Xe isotopes with ^{100}Sn core
- **Uncertainty estimates**: currently phenomenological shell-model interaction

  ↪ chiral-EFT-based interactions in the future

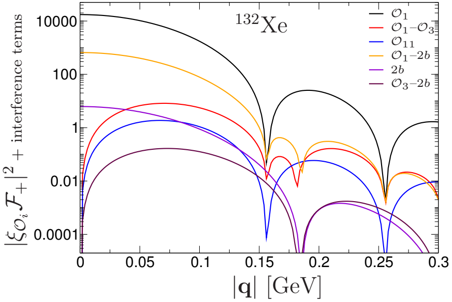
Consequences for the structure factors

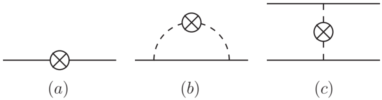


- $\xi_{\mathcal{O}_i}$ kinematic factors for $\mathcal{O}_i$, e.g. $\xi_{\mathcal{O}_1} = 1$, $\xi_{\mathcal{O}_3} = \frac{\mathbf{q}^2}{2m_N^2}$
- $\mathcal{O}_{11}$ assumes $m_\chi = 2\,\text{GeV}$

  $\hookrightarrow$ much stronger suppressed for heavy WIMPs
- Structure factors imply **hierarchy** as long as coefficients do not differ strongly

Two-body currents: SI case



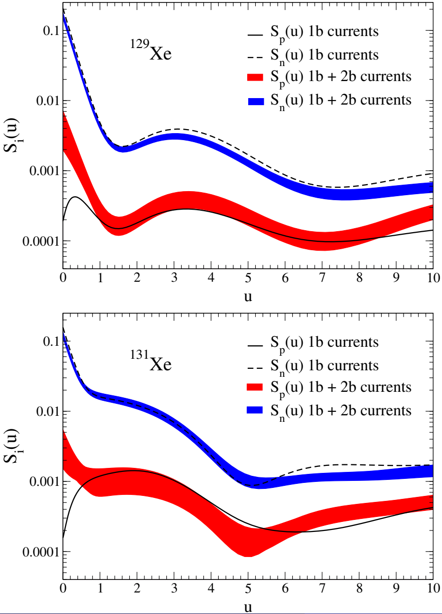


- Finite at $|\mathbf{q}| = 0$
- Most important next to IS and IV $\mathcal{O}_1$
- Sensitive to **new combination of Wilson coefficients**, e.g. for scalar channel

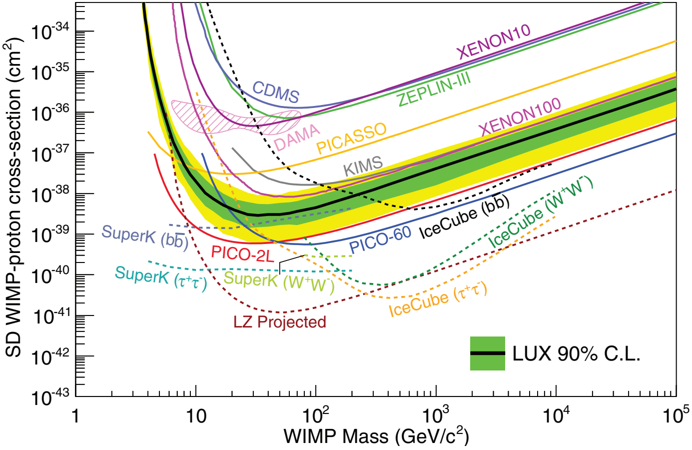
$$f_N = \frac{m_N}{\Lambda^3}\bigg(\sum_{q=u,d,s} C_q^{SS} f_q^N - 12\pi f_Q^N C_g'^S\bigg) \qquad f_\pi = \frac{M_\pi}{\Lambda^3}\sum_{q=u,d}\bigg(C_q^{SS} + \frac{8\pi}{9}C_g'^S\bigg) f_q^\pi \qquad \ldots$$

- Typically (5–10)% effect, enhanced whenever cancellations occur: **blind spots**, **heavy WIMP limit**

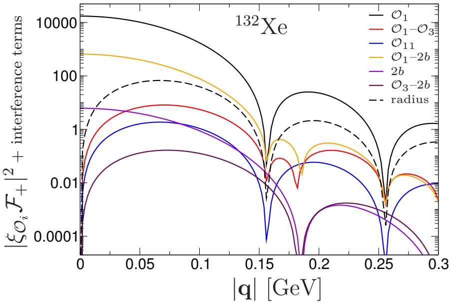
Two-body currents: SD case

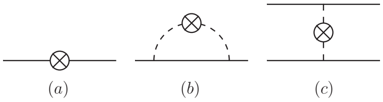


- Nuclear structure factors for **spin-dependent interactions**
  Klos et al. 2013
  - Based on chiral EFT currents (1b+2b)
  - Shell model
  - $u = q^2 b^2 / 2$ related to momentum transfer
- 2b currents absorbed into redefinition of 1b current


SD WIMP-proton cross-section (cm^2)
WIMP Mass (GeV/c^2)
XENON10
ZEPLIN-III
CDMS
DAMA
PICASSO
XENON100
KIMS
SuperK ($b\bar{b}$)
PICO-2L
PICO-60
IceCube ($b\bar{b}$)
IceCube (W^+W^-)
SuperK ($\tau^+\tau^-$)
SuperK (W^+W^-)
IceCube ($\tau^+\tau^-$)
LZ Projected
LUX 90% C.L.

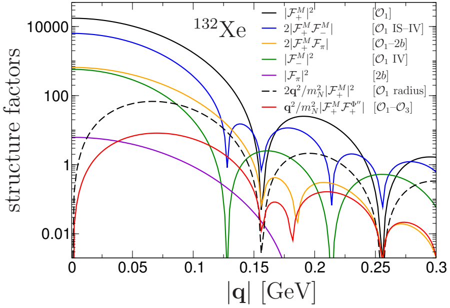
Radius corrections





- Set scale as $\mathbf{q}^2/m_N^2$
- Strong suppression at small $|\mathbf{q}|$, but potentially relevant later
- Yet another new combination

$$\dot{f}_N = \frac{m_N}{\Lambda^3}\left(\sum_{q=u,d,s} C_q^{SS}\dot{f}_q^N - 12\pi \dot{f}_Q^N C_g'^S\right)$$



- Parameterize cross section as

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

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

- c related to Wilson coefficients and nucleon form factors

Analysis strategies

- Parameters ($\zeta = 1(2)$ for Dirac (Majorana)):

$$c_\pm^M = \frac{\zeta}{2}\Big[f_p \pm f_n + f_1^{V,p} \pm f_1^{V,n}\Big] \qquad c_\pi = \zeta f_\pi \qquad c_\pm^{\Phi''} = \frac{\zeta}{2}\Big(f_2^{V,p} \pm f_2^{V,n}\Big)$$

$$\dot{c}_\pm^M = \frac{\zeta m_N^2}{2}\bigg[\dot{f}_p \pm \dot{f}_n + \dot{f}_1^{V,p} \pm \dot{f}_1^{V,n} + \frac{1}{4m_N^2}\Big(f_2^{V,p} \pm f_2^{V,n}\Big)\bigg]$$

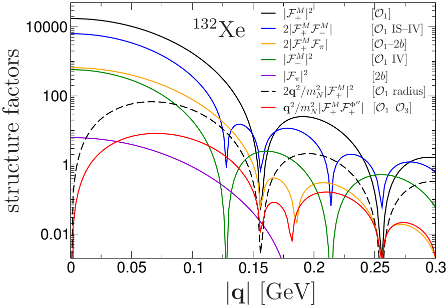
- Couplings

$$f_N = \frac{m_N}{\Lambda^3}\bigg(\sum_{q=u,d,s} C_q^{SS} f_q^N - 12\pi f_Q^N C_g^{\prime S}\bigg) \qquad f_\pi = \frac{M_\pi}{\Lambda^3}\sum_{q=u,d}\bigg(C_q^{SS} + \frac{8\pi}{9}C_g^{\prime S}\bigg) f_q^\pi \qquad \ldots$$

- Conclusions
  - Different c probe **different linear combinations** of Wilson coefficients
  - Ideally: global analysis of different experiments
  - **One-operator-at-a-time strategy**: producing limits e.g. on c_-^M and c_π in addition to c_+^M would provide additional information on BSM parameter space

Conclusions

- **Analysis of direct detection searches** including
  1. standard SI isoscalar WIMP–nucleon interaction
  2. its isovector counterpart
  3. two-body currents
  4. radius corrections
  5. quasi-coherent response associated with the Φ'' operator



$\hookrightarrow$ canonical generalization of SI searches

$\hookrightarrow$ captures all coherent contributions up to third chiral order

Contact terms

- Scalar source also suppressed for $(N^\dagger N)^2$

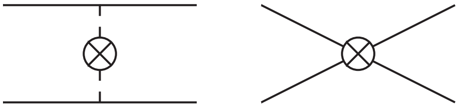
  $\hookrightarrow$ **long-range contribution dominant** (in Weinberg counting)

- Typical size **(5–10)%**

  $\hookrightarrow$ reflected by results for structure factors

  $\hookrightarrow$ more important in case of cancellations

- Contact terms $\leftrightarrow$ nuclear σ-terms Beane et al. 2014



Spin-2 and coupling to the energy-momentum tensor

- Effective Lagrangian truncated at dim-7, but if WIMP heavy $m_\chi/\Lambda = \mathcal{O}(1)$

  $\hookrightarrow$ heavy-WIMP EFT Hill, Solon 2012, 2014

$$\mathcal{L} = \frac{1}{\Lambda^4}\bigg\{\sum_q C_q^{(2)}\bar\chi\gamma_\mu i\partial_\nu\chi\frac{1}{2}\bar q\Big(\gamma^{\{\mu}iD_-^{\nu\}} - \frac{m_q}{2}g^{\mu\nu}\Big)q + C_g^{(2)}\bar\chi\gamma_\mu i\partial_\nu\chi\Big(\frac{g_{\mu\nu}}{4}G^a_{\lambda\sigma}G_a^{\lambda\sigma} - G_a^{\mu\lambda}G^\nu_{a\lambda}\Big)\bigg\}$$

  $\hookrightarrow$ leading order: **nucleon pdfs**

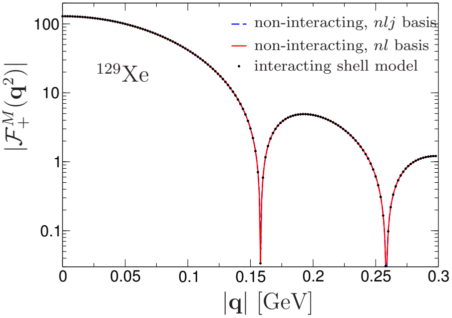
  $\hookrightarrow$ similar two-body current as in scalar case, pion pdfs, EMC effect

- Coupling of trace anomaly θ^μ_μ to $\pi\pi$

$$\theta^\mu_\mu = \sum_q m_q\bar q q + \frac{\beta_{\text{QCD}}}{2g_s}G^a_{\mu\nu}G_a^{\mu\nu} \quad\Leftrightarrow\quad \langle\pi(p')|\theta_{\mu\nu}|\pi(p)\rangle = p_\mu p'_\nu + p'_\mu p_\nu + g_{\mu\nu}(M_\pi^2 - p\cdot p')$$

  $\hookrightarrow$ probes gluon Wilson coefficient C_g^S

Some details on the implementation



- **Shell-model diagonalization** for Xe isotopes with ^{100}Sn core
- Correlations among valence nucleons, *j*-coupling small

  $\hookrightarrow$ treat two-body currents in the same way
- **Uncertainty estimates**: currently phenomenological shell-model interaction

  $\hookrightarrow$ ChEFT based interactions in the future