Leading corrections to SI scattering and strategies for general SI analysis

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"Dark Matter Interpretations for Direct Detection"

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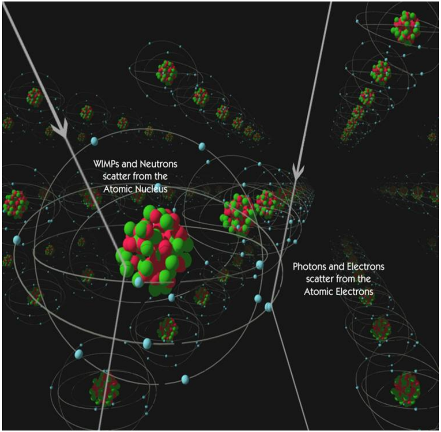
KAKENHI

Direct dark matter detection

Overwhelming evidence dark matter exists,
the challenge is direct dark matter detection to understand its nature

Assume dark matter (eg WIMPs) interact with quarks, gluons
$\Rightarrow$ direct detection possible via scattering off nuclear targets

Direct detection experiments:
XENON, LUX, CDMS...
nuclear recoil from WIMP scattering
sensitive to dark matter masses $\gtrsim$ 1 GeV



CDMS Collaboration

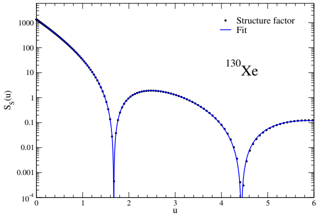
WIMP scattering off nuclei: standard analysis

Standard direct detection analyses consider two very different cases

Spin-Independent (SI) interaction:
WIMPs couple to the nuclear density ($\mathbb{1}_\chi \mathbb{1}_N$)

For elastic scattering, coherent sum
over nucleons and protons in the nucleus

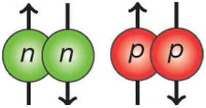
Cross section enhancement by factor A^2



Spin-Dependent (SD) interaction:
WIMP spins couple to the nuclear spin ($S_\chi \cdot S_N$)

Pairing interaction: Two spins couple to $S = 0$
Only relevant in stable odd-mass nuclei

Cross section scale set by proton/neutron
spin expectation value $\langle S_n \rangle^2$, $\langle S_p \rangle^2 \sim 0.1$



How can direct detection analyses be generalized?

Non-relativistic effective field theory

SI and SD interactions only consider the leading-order operators ($\mathcal{O}_1$, $\mathcal{O}_4$) in the non-relativistic basis spanned by $\mathbb{1}_\chi$, $\mathbb{1}_N$, S_N, S_χ, $\mathbf{q}$, $v^\perp$

$$\mathcal{O}_1 = 1_\chi 1_N,$$
$$\mathcal{O}_2 = (v^\perp)^2,$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N,$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$$
$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right),$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp,$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp,$$
$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right),$$
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N},$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}.$$
$$\ldots$$

Fitzpatrick et al. JCAP02 004(2013), Anand et al. PRC89 065501 (2014)

Interferences occur between some of the terms,
which map into 6 different nuclear responses

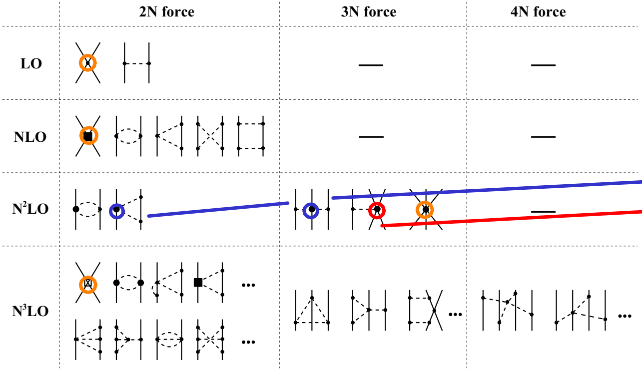
All terms taken to be independent

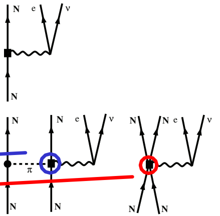
Chiral effective field theory

Chiral EFT: low energy approach to QCD, nuclear structure energies

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and currents





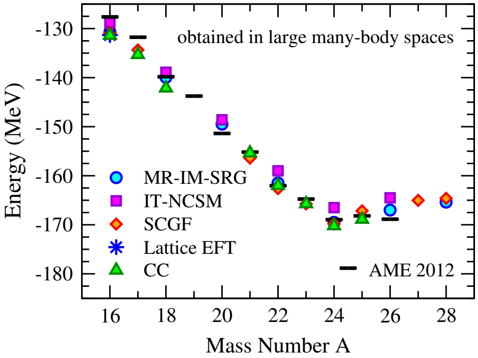
Weinberg, van Kolck, Kaplan, Savage, Weise, Epelbaum, Meißner...

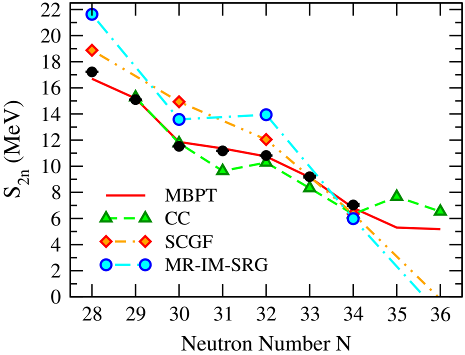
Park et al.
PRC67 055206(2003)

Short-range couplings fitted to experiment once

Nuclear structure wich chiral EFT forces

Great sucess prediction of oxygen dripline and calcium separation energies





Hergert et al. PRL110 242501 (2013)

Cipollone et al. PRL111 062501 (2013)

Jansen et al. PRL113 142502 (2014)

Gallant et al. PRL 109 032506 (2012)

Wienholtz et al. Nature 498 346 (2013)

Hagen et al. PRL 109 032502 (2012)

Somà et al. PRC 89 061301 (2014)

Hergert et al. PRC 90 041302 (2014)

Chiral EFT WIMP-nucleus interactions

Consider scalar, pseudoscalar, vector and axial WIMP and nucleon currents, derive all one-body (1b) and two-body (2b) hadronic terms up to third order in the chiral expansion (Weinberg counting)

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

Hoferichter, Klos, Schwenk PLB 746 410 (2015)

Terms with "+2" suppressed by $1/m_\chi$, not relevant for heavy WIMPs

Matching to NREFT operators

Chiral EFT WIMP-nucleus interactions to third order mapped into NREFT

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

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

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

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

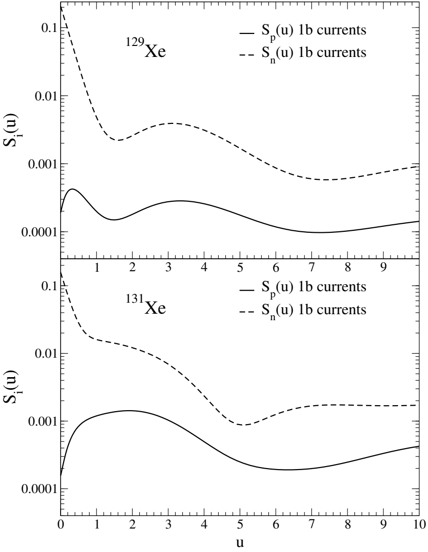
Hoferichter, Klos, Schwenk PLB 746 410 (2015)

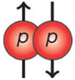
Chiral EFT introduces hierarchy into NREFT

Chiral EFT hierarchy complemented with coherent (i.e. nuclear) effects

Additionally, 2b currents (up to third order)
axial-axial (SD), scalar-scalar, axial-vector, vector-axial and scalar-scalar

SD structure factors with 1b currents





In $^{129,131}_{54}$Xe $\langle \mathbf{S}_n \rangle \gg \langle \mathbf{S}_p \rangle$,
Neutrons carry most nuclear spin

$$\mathbf{S}_n = \sum_{i=1}^{N} \boldsymbol{\sigma}_i/2, \; \mathbf{S}_p = \sum_{i=1}^{Z} \boldsymbol{\sigma}_i/2$$

$$\frac{S_A(0)}{2J+1} = \frac{(J+1)}{\pi J} \left| a_p \langle \mathbf{S}_p \rangle + a_n \langle \mathbf{S}_n \rangle \right|^2$$

$$a_{n/p} = (a_0 \mp a_1)/2,$$

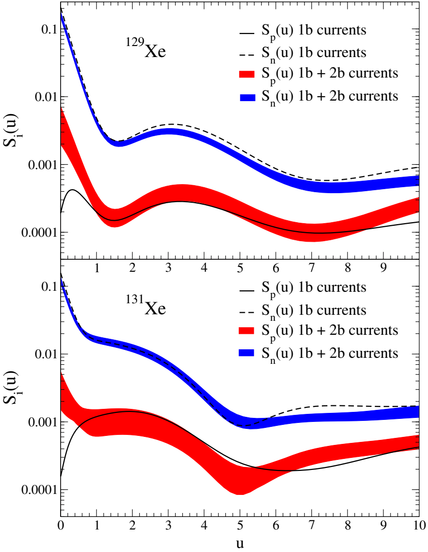
$$S_n(0) \propto \left| \langle \mathbf{S}_n \rangle \right|^2 \; S_p(0) \propto \left| \langle \mathbf{S}_p \rangle \right|^2.$$

Couplings more sensitive to protons ($a_0 = a_1$) or neutrons ($a_0 = -a_1$)

JM, Gazit, Schwenk, PRD86 103511(2012)

Klos, JM, Gazit, Schwenk, PRD88 083516(2013)

SD structure factors with 1b+2b currents



JM, Gazit, Schwenk, PRD86 103511(2012)

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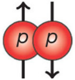
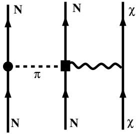


Neutrons carry most nuclear spin

Couplings more sensitive to protons ($a_0 = a_1$) or neutrons ($a_0 = -a_1$)

2b currents naturally involve both neutrons and protons:

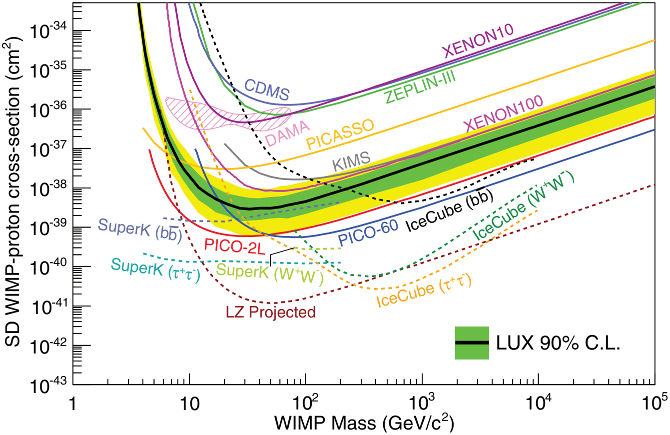


Neutrons always contribute with 2b currents, dramatic increase in $S_p(u)$

Impact on dominant species $\sim 20\%$

Application to experiment: LUX

2b contributions make LUX SD results (more sensitive to neutrons) competitive also for the SD WIMP-proton cross-section

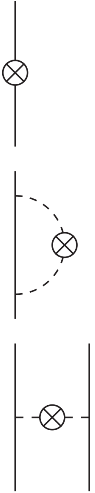


Akerib et al. PRL116 161302 (2016)

Generalized SI scattering

Generalized SI scattering: all coherent contributions
Separation in terms of kind of interaction less useful than SI/SD case
WIMP-spin or nucleon-spin interactions can be coherent

All 1b operators, radius corrections to 1b terms, 2b currents
scalar, pseudoscalar, vector and axial interactions



General WIMP-nucleus scattering cross-section:

$$\frac{d\sigma^{SI}_{\chi\mathcal{N}}}{d\mathbf{q}^2} \propto \left| \sum_i c_i \, \zeta_i \, \mathcal{F}_i \right|^2,$$

c coefficients: convolution of hadronic matrix elements
and WIMP couplings to quark, gluons (Wilson coefficients),
c's probe different new physics: hadronic, particle physics

ζ: kinematics $(\mathbf{q}^2, \cdots)$

$\mathcal{F}$ functions: nuclear response functions,
$\mathcal{F}^2 \sim$ structure factor: nuclear physics

One-body corrections: isovector SI scattering

Study structure factors $\sim \zeta^2 \mathcal{F}^2$
responsible for coherence, assume similar c's

$$\frac{\mathrm{d}\sigma^{\mathrm{SI}}_{\chi\mathcal{N}}}{\mathrm{d}\mathbf{q}^2} \propto \left| \sum_i c_i \, \zeta_i \, \mathcal{F}_i \right|^2 ,$$

In standard SI analyses only isovector $\mathcal{O}_1$ response

Isoscalar structure factor: $A^2 \sim 130^2$

Isovector structure factor: $(N-Z)^2 \sim 30^2$

Isoscalar-Isovector interference: $A(N-Z) \sim 130 * 30$

Isovector counterpart of $\mathcal{O}_1 \sim 20\%$ correction
especially important in heavier nuclei (neutron-rich)

May be suppressed in models with small isospin-breaking

Isoscalar and isovector contributions
constrain different new physics parameters
from scalar and vector couplings

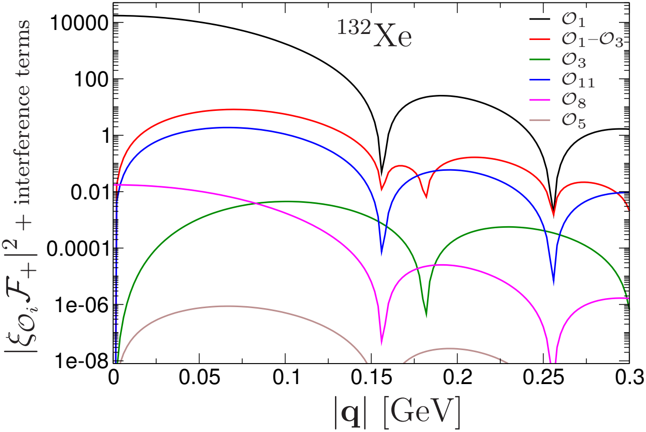
$$c_{\pm} \propto \left(f_p \pm f_n + f_1^{V,p} \pm f_1^{V,n} \right)$$

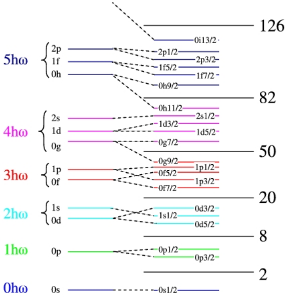
c_0 related to the single-nucleon cross-section

$$\sigma^{\mathrm{SI}}_{\chi N} = \frac{\mu_N^2}{\pi} \left| f_N + f_1^{V,N} \right|^2$$

One-body corrections: $\mathcal{O}_3$ operator

In addition to standard SI operator $\mathcal{O}_1$,
contribution from coherent $\mathcal{O}_{11,8,5}$, quasi-coherent $\mathcal{O}_3$ operator (Φ'' response)



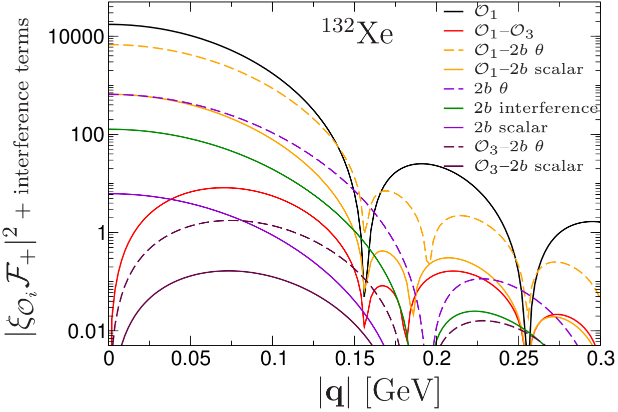


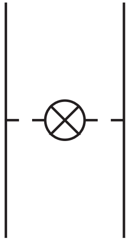
O_3 quasi-coherence:
spin $\parallel$ ang. momentum
lower energy orbitals

$\mathcal{O}_3 \rightarrow \Phi''$ response $\sim$ nucleon spin orbit operator, interferes with $\mathcal{O}_1$
$\mathcal{O}_{11,8,5}$ suppressed by $1/m_\chi$ or $v \sim 10^{-3}$, no $\mathcal{O}_1$ interference (S_χ depend.)

Two-body currents

Two coherent contributions from 2b currents:
π coupling via scalar current, trace anomaly of energy momentum tensor (θ^{μ}_{μ})





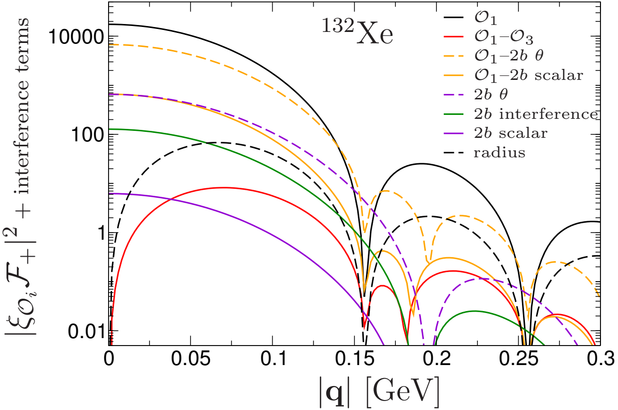
2b scalar currents also explored by

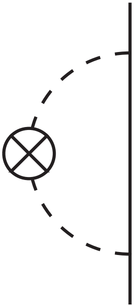
Cirigliano et al.
JHEP10 25(2012)
PLB739 293(2014)

2b structure factors numerically large, especially 2b θ (gluonic coupling)
However, estimated correction to leading 1b terms $\lesssim$ 10% in simple models:
scalar interactions (no s quark) / purely gluonic couplings

Radius corrections

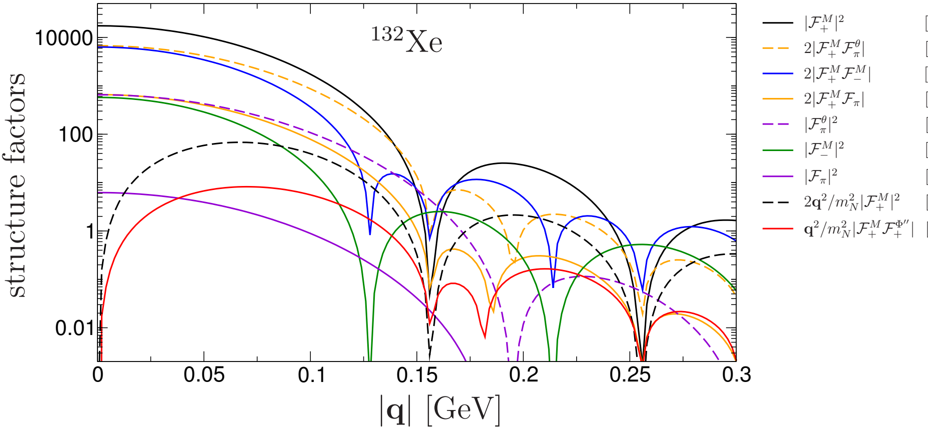
Hadronic radius corrections (q^2 corrections) to the $\mathcal{O}_1$ operator also coherent





Vanishing at $q = 0$, for finite q values comparable to 2b terms, in agreement with chiral EFT (both third-order corrections)

Finally, the leading coherent WIMP-nucleus structure factors are



including besides the standard isoscalar SI operator $\mathcal{O}_1$:

the isovector counterpart of $\mathcal{O}_1$, the scalar and θ-term 2b currents

radius corrections to $\mathcal{O}_1$, and the nucleon spin-orbit $\mathcal{O}_3$ operator

Generalized SI cross-section

The corresponding expression for the WIMP-nucleus scattering cross-section includes 8 (non-independent) contributions

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

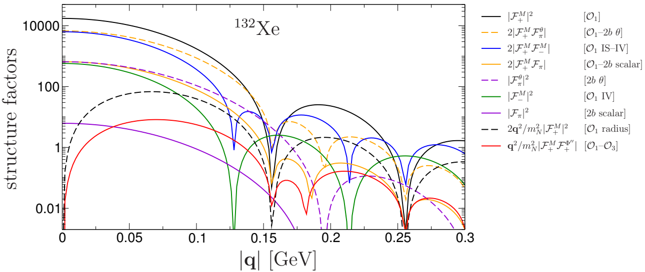
Ideally, correlated analysis considering several nuclear targets

Parameters c not all independent:
Only 7/4 independent Wilson coefficients for Dirac/Majorana spin-$1/2$ WIMPs
C_q^{SS}, $C_g^{\prime S}$, C_q^{VV} ($q = u, d, s$), no C_q^{VV}'s in Majorana case

Minimal extension of SI analyses

The hierarchy in structure factors allows to propose a minimal extension:

$$\frac{d\sigma^{\mathrm{SI}}_{\chi\mathcal{N}}}{d\mathbf{q}^2} = \frac{1}{4\pi\mathbf{v}^2}\left| c_+^M \mathcal{F}_+^M(\mathbf{q}^2) + c_-^M \mathcal{F}_-^M(\mathbf{q}^2) + c_\pi \mathcal{F}_\pi(\mathbf{q}^2) + c_\pi^\theta \mathcal{F}_\pi^\theta(\mathbf{q}^2) \right|^2,$$



Strategy for analyzing single experiment: one-operator-at-a-time

set limits on each c-coefficient (setting other $c_i = 0$),

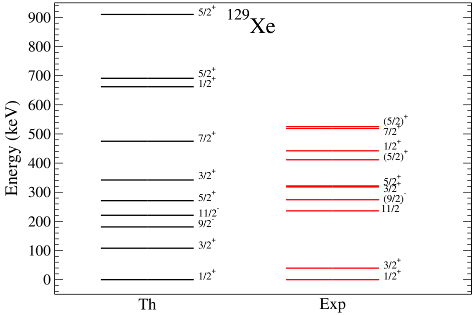
particular slice in parameter space

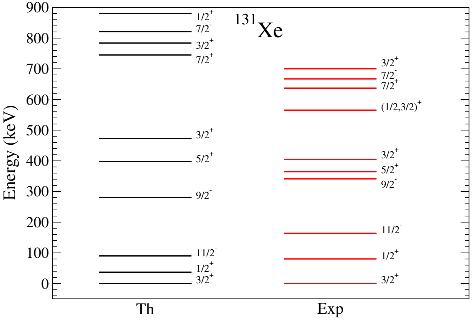
Constrain 4 different combinations of new-physics parameters (not only c_+)

Similar strategy used in EDM and $\beta\beta$ decay searches

Xenon spectra

For all xenon isotopes also very good agreement with experiment





JM, Gazit, Schwenk PRD86 103511(2012)

Vietze, Klos, JM, Haxton, Schwenk PRD91 043520 (2015)

Parametrizations of all structure factors provided for stable xenon isotopes in
Hoferichter, Klos, JM, Schwenk arXiv:1605.08043

In progress: parametrizations for all other nuclear targets: Ge, Ar, F...

Summary

Comprehensive study of coherent WIMP scattering off nuclei keeping all scalar, pseudoscalar, vector and axial contributions up to third order in chiral EFT

Main corrections to standard SI contribution
Isovector counterpart of usual SI term
2b currents (scalar and θ coupling)

More detailed cross-section:
radius corrections
Φ'' response ($\mathcal{O}_3$ operator)

One-operator-at-a-time strategy proposed for analyzing a single experiment

Ideally, correlated analysis with several nuclear targets