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Generalized spin-independent WIMP-nucleus scattering from chiral effective field theory

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XIIIth Quark Confinement and the Hadron Spectrum

Maynooth University, August 2, 2018



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Nuclear physics for DM direct detection

Dark matter direct detection analyses are based on input from nuclear physics

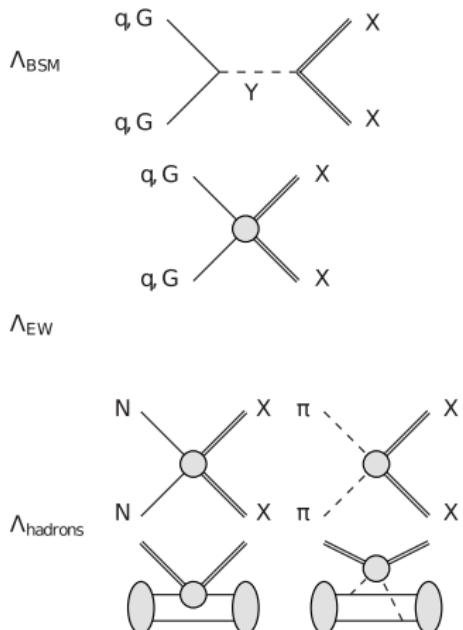
$$\frac{d\sigma}{dq^2} \propto | \langle \text{final} | H_{\chi-\text{nucleus}} | \text{initial} \rangle |^2$$

Two tasks:

Description of initial and final nuclear states

Description of WIMP-nucleus interaction

Scales of WIMP-nucleus interaction



1. BSM scale: WIMPs couple to quarks and gluons via exchange particles
2. Effective Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i,k} \frac{1}{\Lambda_{BSM}^i} \mathcal{O}_{i,k}$$
3. Integrate out EW physics
4. Chiral EFT:
WIMP couples to nucleons and pions
Embedding chiral EFT operators in nucleus

WIMP-nucleus interaction

Interplay of particle, hadronic and nuclear physics scales

General WIMP-nucleus scattering cross-section:

$$\frac{d\sigma}{dq^2} \propto \left| \sum_i c_i \mathcal{F}_i \right|^2,$$

c_i embedding of WIMP couplings to quarks, gluons in hadrons

$\mathcal{F}_i^2 \propto |\langle \text{final} | H_{\chi-\text{nucleus}} | \text{initial} \rangle|^2$ structure factor

Describing nuclei

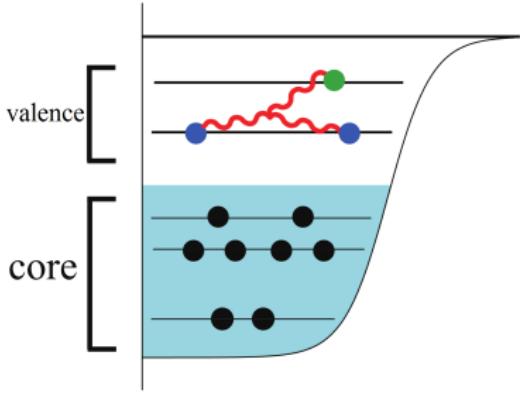
Interacting Shell Model



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Separate space in

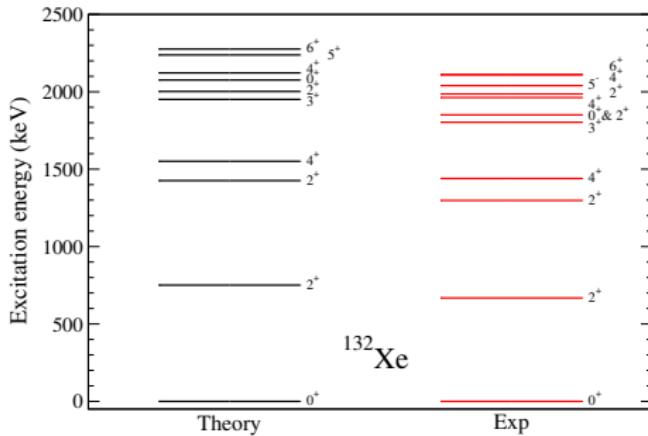
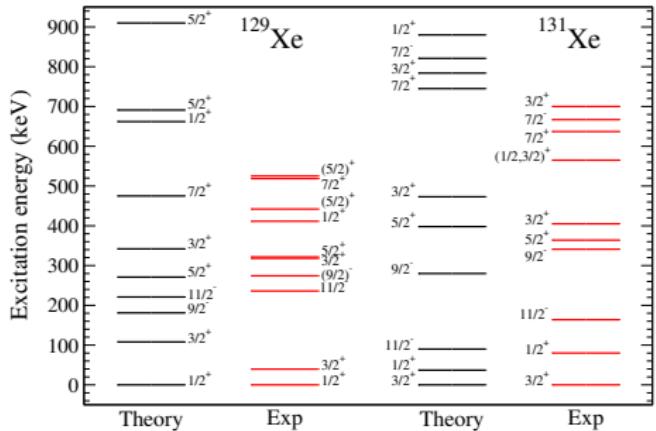
- ▶ **Outer space:** orbits that are always empty
- ▶ **Valence space:** orbits with some nucleons but not completely filled
- ▶ **Inner core:** orbits that are always filled
- ▶ Create effective Hamiltonian in valence space H_{eff} with effects of core and outer space perturbatively included



$$H |\Phi\rangle = E |\Phi\rangle \quad \rightarrow \quad H_{\text{eff}} |\Psi\rangle = E |\Psi\rangle$$

- ▶ → Diagonalize H_{eff} in valence space
- ▶ → ISM code ANTOINE Caurier et al., RMP (2005)

Xenon spectra



- ▶ Phenomenological interactions adjusted to nuclei in the same mass region
- ▶ Good agreement between experimental data and theory

Nuclear physics for DM direct detection

Dark matter direct detection analyses are based on input from nuclear physics

$$\frac{d\sigma}{dq^2} \propto | \langle \text{final} | H_{\chi-\text{nucleus}} | \text{initial} \rangle |^2$$

Two tasks:

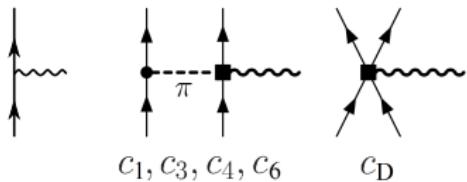
Description of initial and final nuclear states

Description of WIMP-nucleus interaction

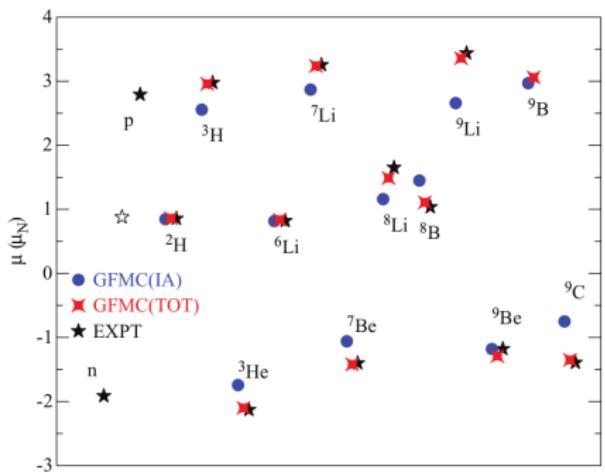
Chiral effective field theory

- ▶ Based on chiral symmetry of QCD
- ▶ Expansion in powers of Q/Λ_b (power counting)
- ▶ Chiral EFT describes consistently both nuclear forces and currents
Epelbaum, Hammer, and Meißner, RMP 81, 1773 (2009)
- ▶ Same low-energy constants appear in nuclear forces and currents

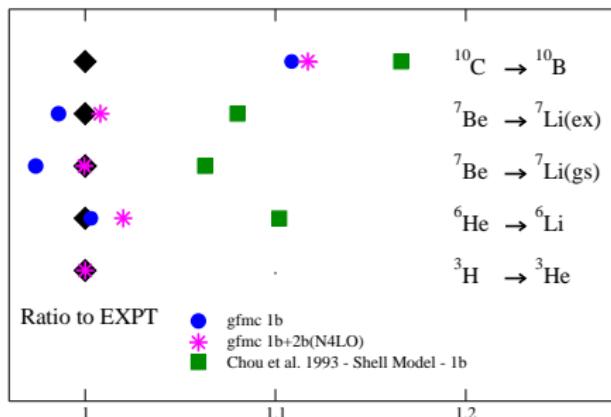
	2N force	3N force	4N force
LO	X H	—	—
NLO	X H H H H H	—	—
N ³ LO	H H H	H H H X	—
N ⁴ LO	X H H H H H —	H H H X —	H H H H H H —



Chiral currents for magnetic moments and weak transitions



Pastore *et al.*, PRC 87, 035503 (2013)



Pastore *et al.*, PRC 97, 022501(R) (2018)

- ▶ Chiral two-body currents necessary to reach experimental data

Traditional WIMP responses

Spin-independent interaction: Scalar-scalar coupling: $\mathcal{L}_{\chi N} = S_\chi S_N$

WIMPs couple to nuclear density ($\mathbb{1}_\chi \mathbb{1}_N$)

$$\left| \sum^A \langle \mathcal{N} | \mathbb{1}_N | \mathcal{N} \rangle \right|^2 = A^2$$

Coherent sum over nucleons in the nucleus

Spin-dependent interaction: Axial-vector–axial-vector: $\mathcal{L}_{\chi N} = (A_\chi)_\mu (A_N)^\mu$

Nuclear pairing: Two spins couple to S=0

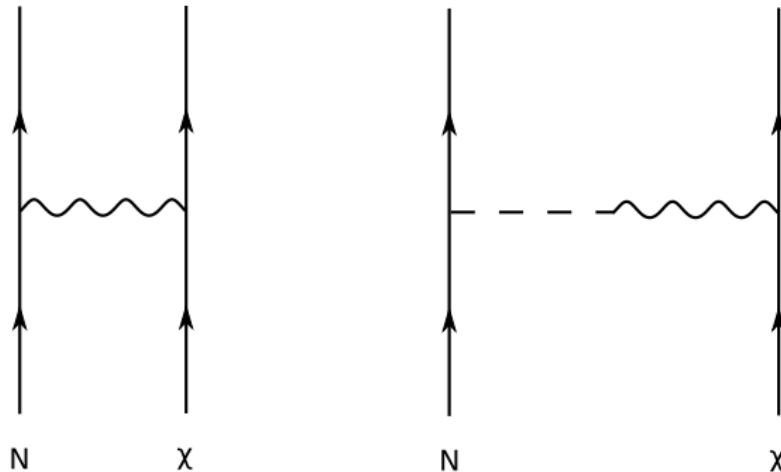
$$\left| \sum^A \langle \mathcal{N} | \mathbf{S}_N | \mathcal{N} \rangle \right|^2 = \langle \mathbf{S}_n \rangle^2, \langle \mathbf{S}_p \rangle^2$$

Cross section scale set by **spin expectation value** of odd numbered species of nucleons

Nuclear currents from chiral EFT

One-body current

Spin-dependent interaction: WIMP spins couple to the nuclear spin

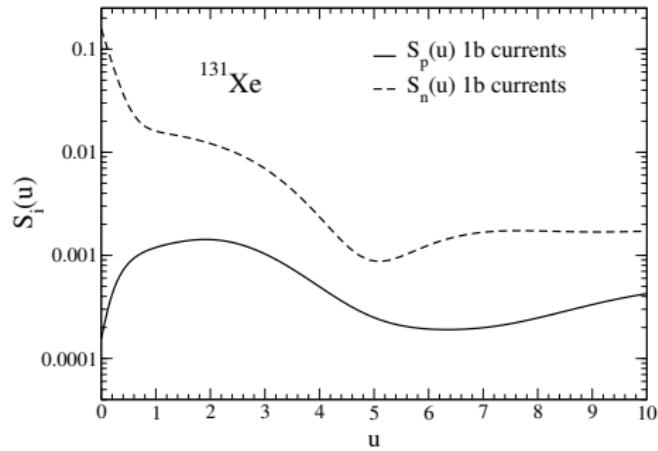
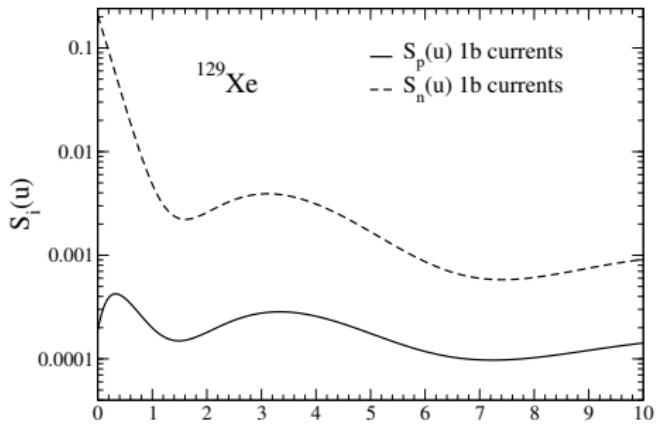


One-body current: WIMP couples to a single nucleon.

Structure factors: Spin-dependent scattering



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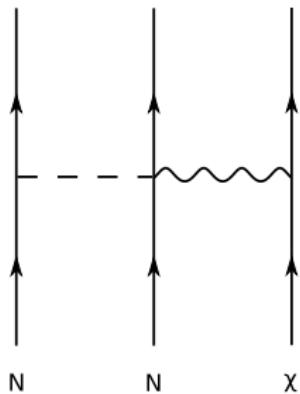
$$u = q^2 b^2 / 2 \text{ with harmonic oscillator length } b$$

129Xe		131Xe	
$\langle \mathbf{S}_p \rangle$	$\langle \mathbf{S}_n \rangle$	$\langle \mathbf{S}_p \rangle$	$\langle \mathbf{S}_n \rangle$
0.010	0.329	-0.009	-0.272

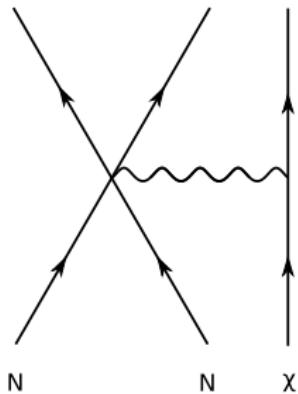
Nuclear currents from chiral EFT

Two-body currents

At order Q^3 , 2b currents enter:



spin dependent

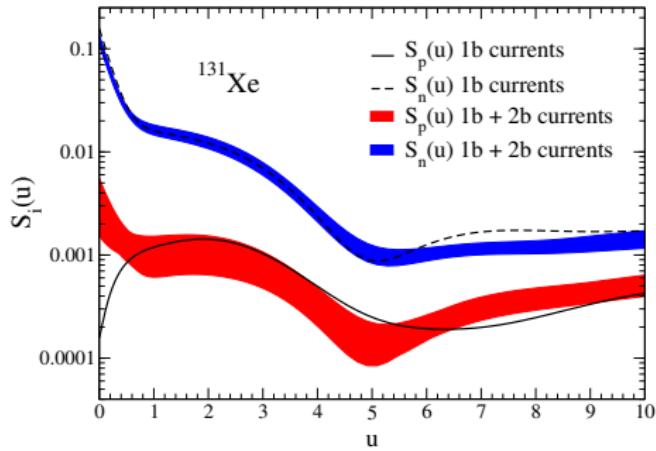
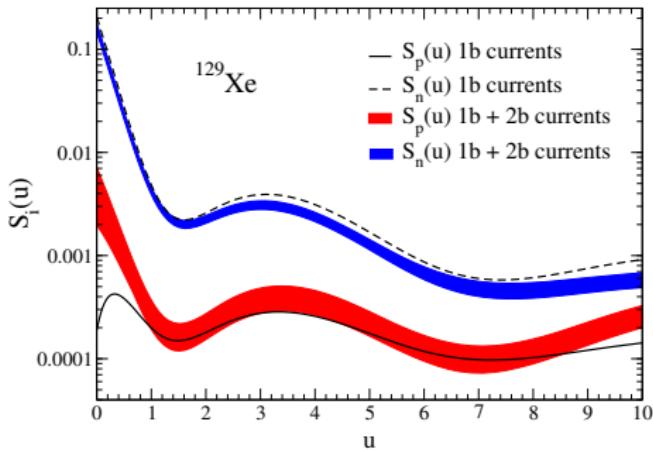


spin independent

Structure factors: Spin-dependent scattering



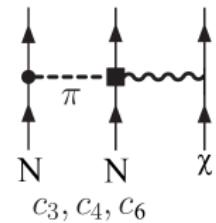
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$$u = q^2 b^2 / 2 \text{ with harmonic oscillator length } b$$

- ▶ 2b currents → at low momentum transfer neutrons contribute to proton structure factor $S_p(u)$
- ▶ $S_n(u)$ reduced by 20% for low momentum transfers

PK, Menéndez, Gazit, Schwenk, PRD 88, 083516 (2013)



Spin-dependent limits: WIMP-neutron

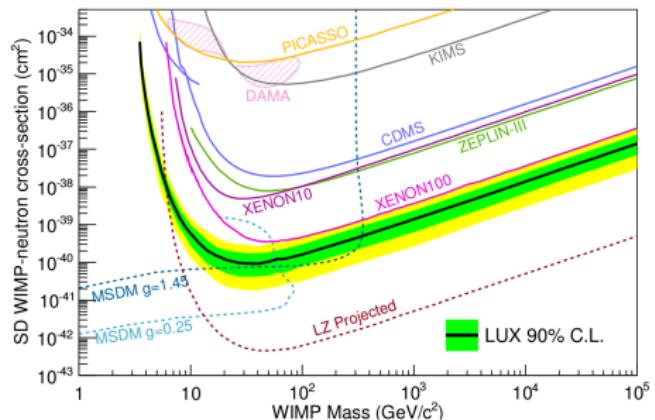


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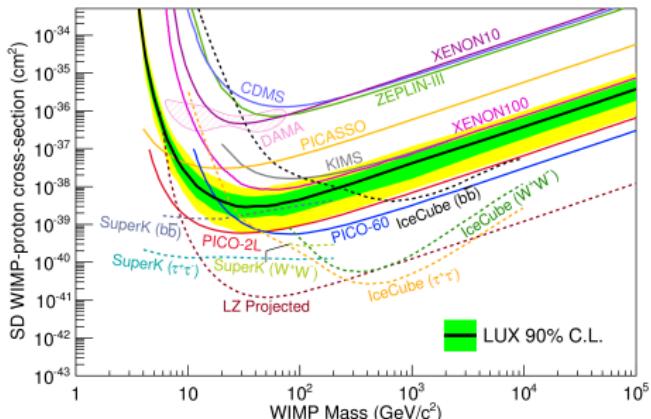
Structure factors and uncertainties in currents used in spin-dependent analysis:

LUX, PRL 116 161302 (2016)

WIMP-neutron



WIMP-proton

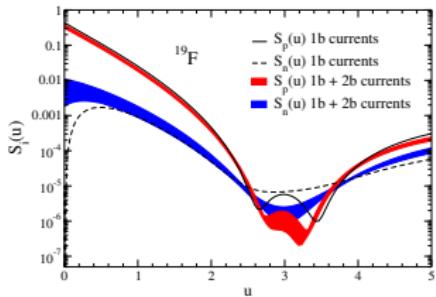


2b currents make LUX competitive for SD WIMP-proton cross-section.

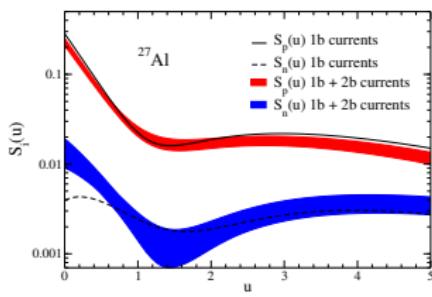
SD Structure factors for different isotopes



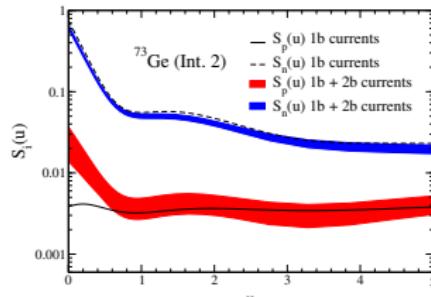
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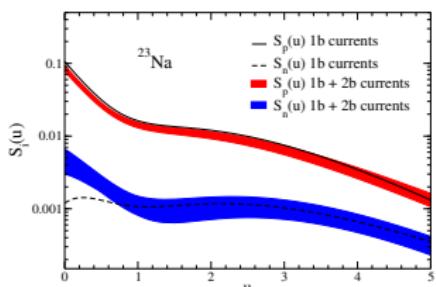
PICASSO, COUPP, SIMPLE



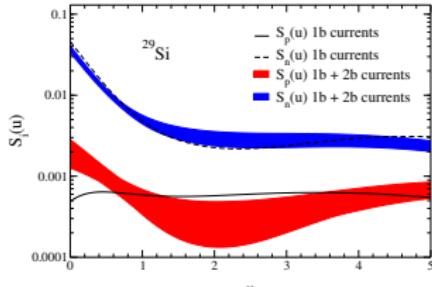
CRESST



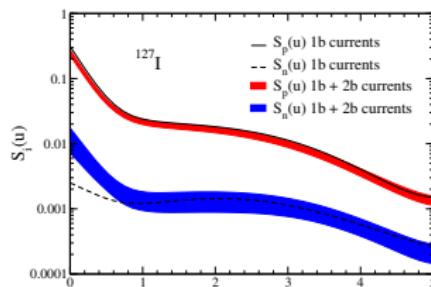
CDMS, EDELWEISS, EURECA



DAMA, ANAIS, DM-Ice



CDMS-II

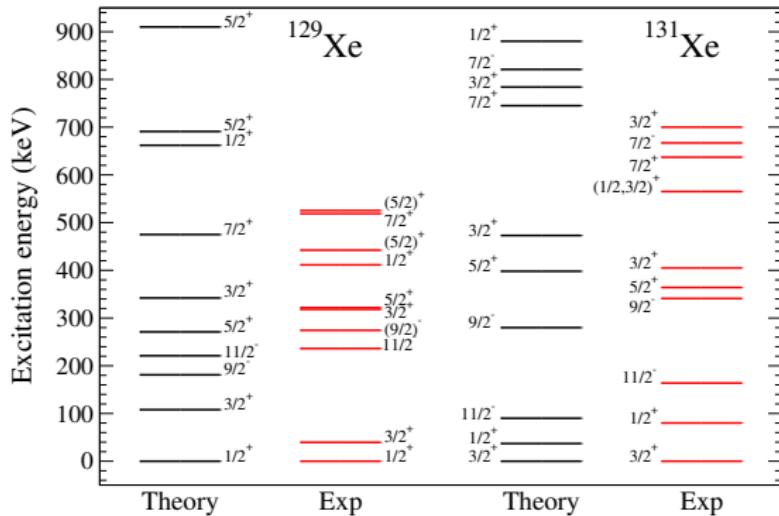


DAMA, ANAIS, DM-Ice

Inelastic scattering Xenon spectra



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- ▶ Excitation to low-lying first excited state (40 keV / 80 keV) possible
- ▶ Nuclear recoil + prompt deexcitation gamma can be observed

Distinguish SI and SD scattering: Inelastic scattering

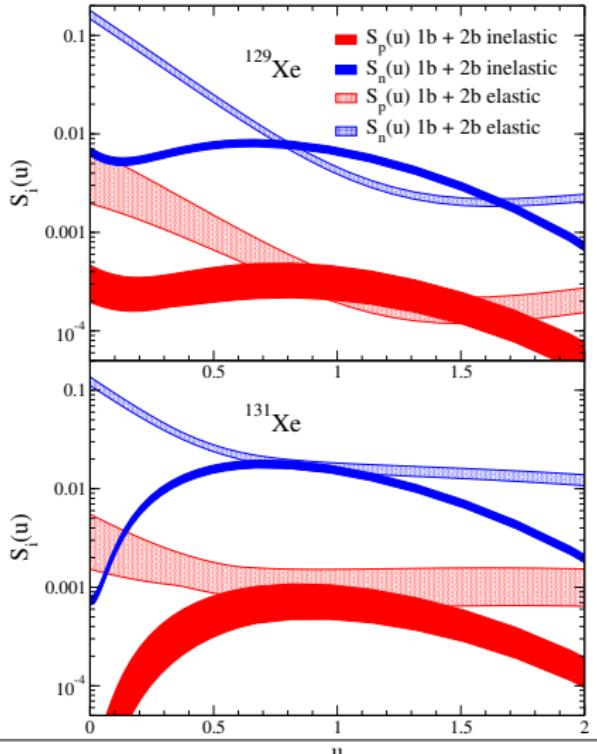
Spin-independent

Elastic: $\langle \text{initial} | \sum_i^A \mathcal{L}_{\chi N}^{\text{SI}} | \text{initial} \rangle \propto A$
Inelastic: $\langle \text{final} | \sum_i^A \mathcal{L}_{\chi N}^{\text{SI}} | \text{initial} \rangle \propto 1$

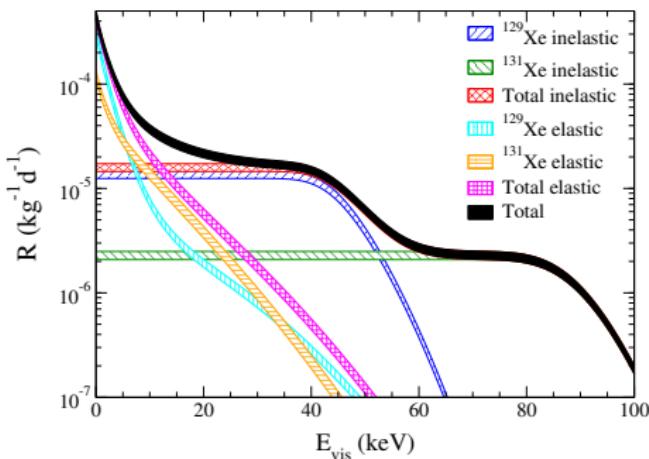
Spin-dependent

Elastic: $\langle \text{initial} | \sum_i^A \mathcal{L}_{\chi N}^{\text{SD}} | \text{initial} \rangle \propto 1$
Inelastic: $\langle \text{final} | \sum_i^A \mathcal{L}_{\chi N}^{\text{SD}} | \text{initial} \rangle \propto 1$

SD channel sensitive to both elastic and inelastic scattering



Inelastic scattering Integrated recoil spectra



Mass [GeV]	^{129}Xe	^{131}Xe	Total
10	—	—	—
25	5	—	5
50	7	17	9
100	7	24	12
250	9	32	19
500	11	35	24

TABLE II. Minimum energy E_{vis} in keV above which the observed inelastic spectrum for ^{129}Xe , ^{131}Xe and for the total spectrum starts to dominate the elastic one for various WIMP masses.

- ▶ Combined information from elastic and inelastic channel will allow to **determine dominant interaction channel in one experiment**
- ▶ **Inelastic excitation sensitive to WIMP mass**

Baudis, Kessler, PK, Lang, Menéndez, Reichard, Schwenk, PRD **88**, 115014 (2013)

General WIMP responses

Spin-independent interaction:

$$\text{Scalar-scalar coupling: } \mathcal{L}_{\chi N} = S_\chi S_N$$

Spin-dependent interaction:

$$\text{Axial-vector–axial-vector coupling: } \mathcal{L}_{\chi N} = (A_\chi)_\mu (A_N)^\mu$$

General WIMP-nucleon interaction Hamiltonian:

$$\mathcal{L}_{\chi N} = (V_\chi + A_\chi)_\mu (V_N + A_N)^\mu + (S_\chi + P_\chi)(S_N + P_N) + \dots$$

V vector

S scalar

A axial-vector

P pseudoscalar

... tensor, spin-2, ...

General WIMP responses

Chiral power counting

Combined counting of WIMP-Nucleon scattering amplitude

	Nucleon	<i>V</i>	<i>A</i>		
WIMP		<i>t</i>	<i>x</i>	<i>t</i>	<i>x</i>
<i>V</i>	1b	0	1 + 2	2	0 + 2
	2b	4	2 + 2	2	4 + 2
	2b NLO	—	—	5	3 + 2
<i>A</i>	1b	0 + 2	1	2 + 2	0
	2b	4 + 2	2	2 + 2	4
	2b NLO	—	—	5 + 2	3

	Nucleon	<i>S</i>	<i>P</i>
WIMP			
<i>S</i>	1b	2	1
	2b	3	5
	2b NLO	—	4
<i>P</i>	1b	2 + 2	1 + 2
	2b	3 + 2	5 + 2
	2b NLO	—	4 + 2

Hoferichter, PK, Schwenk, PLB 746, 410 (2015).

- ▶ WIMP mass counted like nucleon mass
→ "+2" due to non-rel. expansion of WIMP fields
- ▶ More than only scalar-scalar and axial-vector–axial-vector up to Q^3
- ▶ **Coherence effects not included:** $\langle \text{initial} | \sum_i^A H_{\chi N}^{\text{SI}} | \text{initial} \rangle \propto A$
→ **Can easily overcome suppression in Q**

Matching to NREFT

One-body operator basis in NREFT Fitzpatrick, et al., JCAP (2013), Anand et al., PRC (2014)

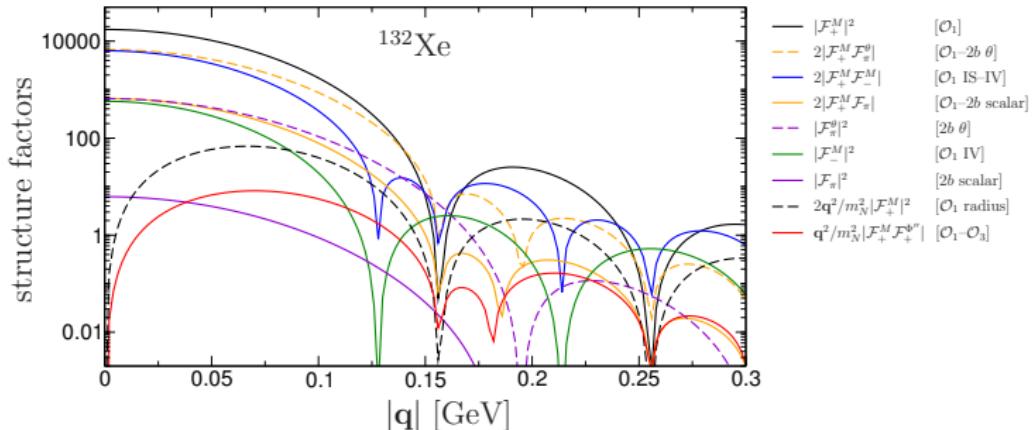
$$\begin{aligned}\mathcal{O}_1 &= \mathbb{1}, & \mathcal{O}_2 &= (\mathbf{v}^\perp)^2, & \mathcal{O}_3 &= i\mathbf{S}_N \cdot (\mathbf{q} \times \mathbf{v}^\perp), & \mathcal{O}_4 &= \mathbf{S}_X \cdot \mathbf{S}_N, \\ \mathcal{O}_5 &= i\mathbf{S}_X \cdot (\mathbf{q} \times \mathbf{v}^\perp), & \mathcal{O}_6 &= \mathbf{S}_X \cdot \mathbf{q} \mathbf{S}_N \cdot \mathbf{q}, & \mathcal{O}_7 &= \mathbf{S}_N \cdot \mathbf{v}^\perp, & \mathcal{O}_8 &= \mathbf{S}_X \cdot \mathbf{v}^\perp, \\ \mathcal{O}_9 &= i\mathbf{S}_X \cdot (\mathbf{S}_N \times \mathbf{q}), & \mathcal{O}_{10} &= i\mathbf{S}_N \cdot \mathbf{q} & \mathcal{O}_{11} &= i\mathbf{S}_X \cdot \mathbf{q}\end{aligned}$$

Matching of NREFT operators \mathcal{O}_i to chiral currents:

$$\begin{aligned}\mathcal{M}_{1,\text{NR}}^{\text{SS}} &= \mathcal{O}_1 f_N(t) \quad (\text{SI}), & \mathcal{M}_{1,\text{NR}}^{\text{SP}} &= \mathcal{O}_{10} g_5^N(t), & \mathcal{M}_{1,\text{NR}}^{\text{PP}} &= \frac{1}{m_\chi} \mathcal{O}_6 h_5^N(t) \\ \mathcal{M}_{1,\text{NR}}^{\text{VV}} &= \mathcal{O}_1 \left(f_1^{V,N}(t) + \frac{t}{4m_N^2} f_2^{V,N}(t) \right) + \frac{1}{m_N} \mathcal{O}_3 f_2^{V,N}(t) + \frac{1}{m_N m_\chi} \left(t\mathcal{O}_4 + \mathcal{O}_6 \right) f_2^{V,N}(t) \\ \mathcal{M}_{1,\text{NR}}^{\text{AV}} &= 2\mathcal{O}_8 f_1^{V,N}(t) + \frac{2}{m_N} \mathcal{O}_9 \left(f_1^{V,N}(t) + f_2^{V,N}(t) \right) \\ \mathcal{M}_{1,\text{NR}}^{\text{AA}} &= -4\mathcal{O}_4 g_A^N(t) + \frac{1}{m_N^2} \mathcal{O}_6 g_P^N(t) \quad (\text{SD}), & \mathcal{M}_{1,\text{NR}}^{\text{VA}} &= \left[-2\mathcal{O}_7 + \frac{2}{m_\chi} \mathcal{O}_9 \right] h_A^N(t).\end{aligned}$$

Chiral EFT: Not all \mathcal{O}_i independent & Two-body currents missing!

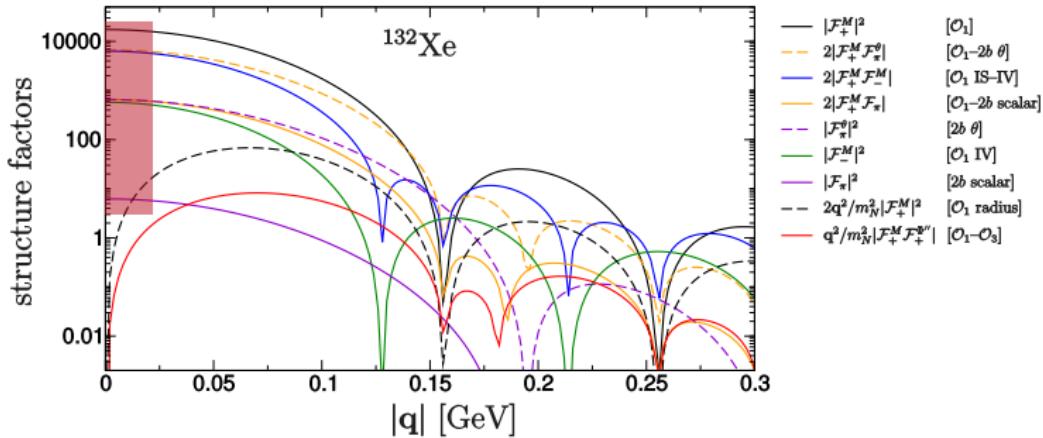
Extension of SI analyses



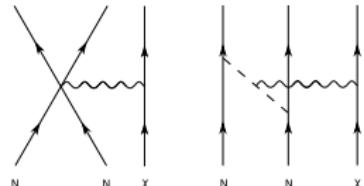
Minimal extension based QCD and **coherence** effects:

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

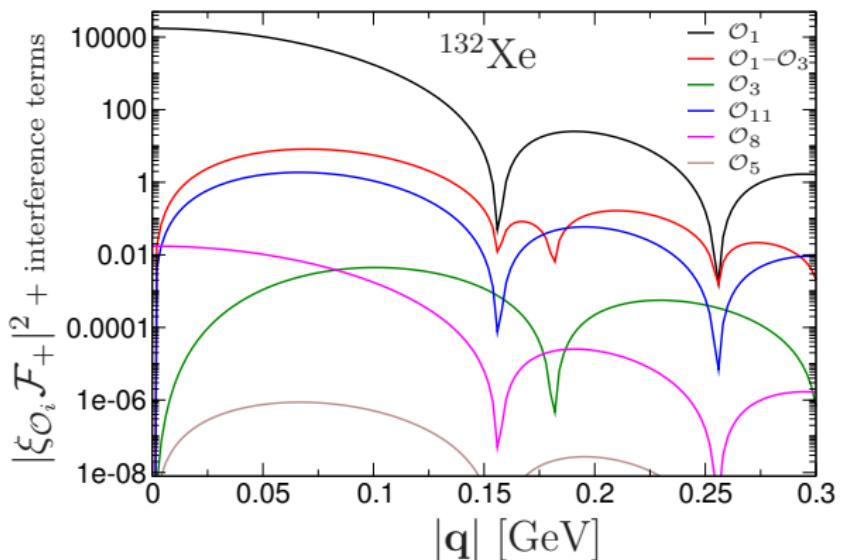
Extension of SI analyses



- ▶ Dominant corrections are QCD effects:
scalar two-body currents $\mathcal{F}_\pi, \mathcal{F}_\pi^\theta$,
isovector correction \mathcal{F}_+^M , radius correction
- ▶ First new operator \mathcal{O}_3 contribution is 4 orders smaller



Extension of SI analyses



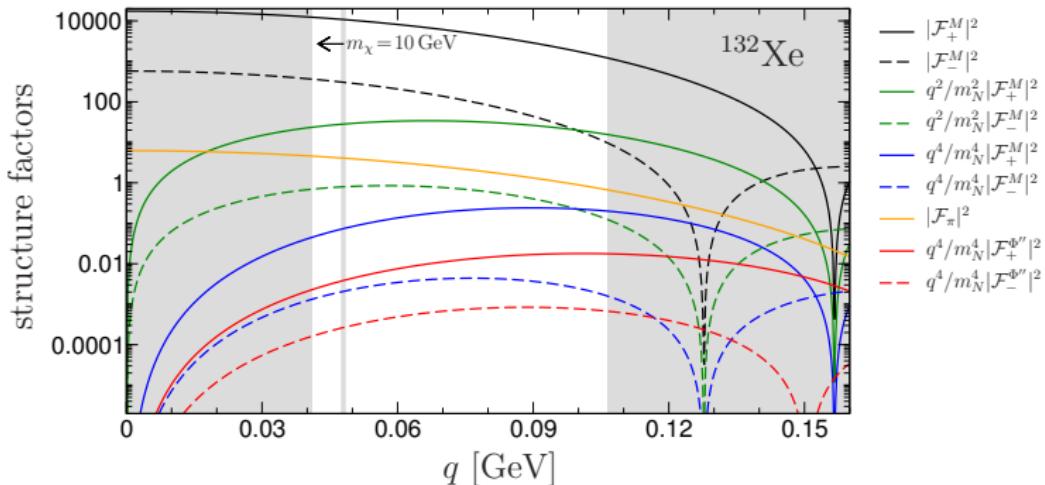
- ▶ Coherence effects determine hierarchy among the different operators
- ▶ Operators that vanish at $q = 0$ are less important for direct detection

Discriminating WIMP-nucleus interactions



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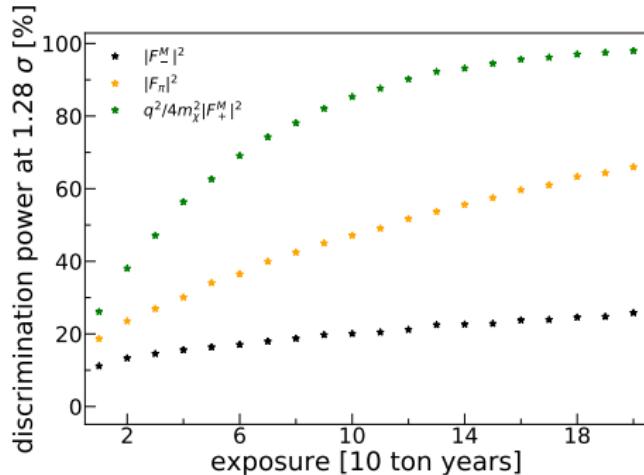
Is it possible to discriminate the different dominant response functions from the standard SI channel in XENON1T, XENONnT, or DARWIN?



Fieguth, Hoferichter, PK, Menéndez, Schwenk, Weinheimer PRD **97**, 103532 (2018)

Discriminating WIMP-nucleus interactions

q -dependence determines which responses are more easily distinguishable



Fiegerth, Hoferichter, PK, Menéndez, Schwenk, Weinheimer PRD **97**, 103532 (2018)

Discriminating WIMP-nucleus interactions

TABLE III: Discrimination power (in %) of a DARWIN-like experiment after 200 ton years of exposure.

m_χ $\sigma_0 [\text{cm}^2]$	100 GeV			1 TeV		
	10^{-46}	10^{-47}	10^{-48}	10^{-45}	10^{-46}	10^{-47}
$ \mathcal{F}_-^M ^2$	94	26	12	100	35	13
$q^2/4m_\chi^2 \mathcal{F}_+^M ^2$	100	100	34	100	100	41
$q^2/4m_\chi^2 \mathcal{F}_-^M ^2$	100	98	25	100	100	32
$q^4/m_N^4 \mathcal{F}_+^M ^2$	100	100	55	100	100	63
$q^4/m_N^4 \mathcal{F}_-^M ^2$	100	100	47	100	100	53
$ \mathcal{F}_\pi ^2$	100	66	17	100	81	20
$q^4/4m_N^4 \mathcal{F}_+^{\Phi''} ^2$	100	100	58	100	100	69
$q^4/4m_N^4 \mathcal{F}_-^{\Phi''} ^2$	100	100	55	100	100	64

DARWIN could discriminate most responses unless
WIMP-nucleon cross section very small

Conclusion

- ▶ State-of-the-art large-scale shell-model calculations used to predict SI / SD and extended SI WIMP responses
- ▶ Extension of standard WIMP responses beyond standard SI/SD requires QCD constraints (via chiral EFT)
- ▶ Nuclear structure predicts hierarchy amongst different responses
[Hoferichter, PK, Menéndez, Schwenk, PRD 94, 063505 \(2016\)](#)
- ▶ Future detectors will be able to discriminate subleading responses from SI response
[Fieguth, Hoferichter, PK, Menéndez, Schwenk, Weinheimer, PRD 97, 103532 \(2018\)](#)
- ▶ Improved limits from Higgs-portal searches
[Hoferichter, PK, Menéndez, Schwenk, PRL 119, 181803 \(2017\)](#)

