Nuclear physics aspects of dark matter direct detection

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Outline

structure factors for **spin-dependent** WIMP scattering
with P. Klos, J. Menéndez, D. Gazit, PRD (2012, 2013)

based on **large-scale nuclear structure calculations** and
systematic expansion of **WIMP-nucleon currents in chiral EFT**

signatures of WIMP **inelastic scattering**
see **talk by Philipp Klos** this afternoon, Baudis et al., PRD (2013)

spin-independent WIMP scattering off xenon
with L. Vietze, P. Klos, J. Menéndez, W.C. Haxton, arXiv to appear.

Dark matter direct detection

WIMP scattering off nuclei needs **nuclear structure factors** as input

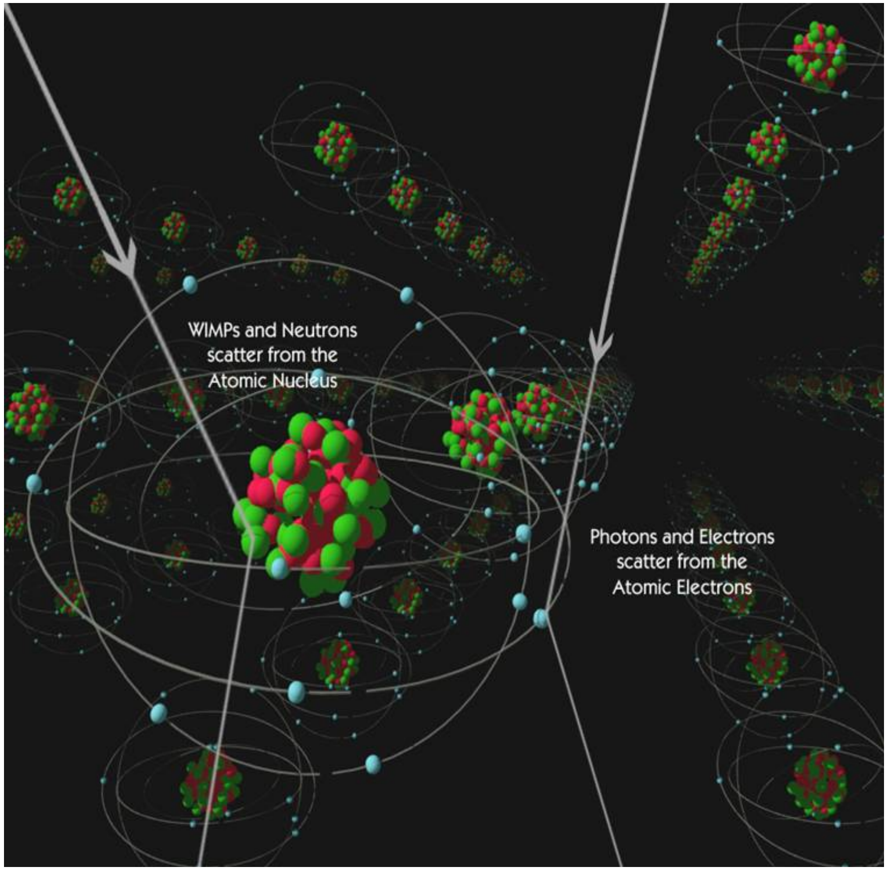
particularly sensitive to nuclear physics for **spin-dependent** couplings

relevant momentum transfers ~ m_π

calculate systematically
with chiral effective field theory

Menéndez, Gazit, AS, PRD (2012),
Klos, Menéndez, Gazit, AS, PRD (2013),
Baudis et al., PRD (2013)

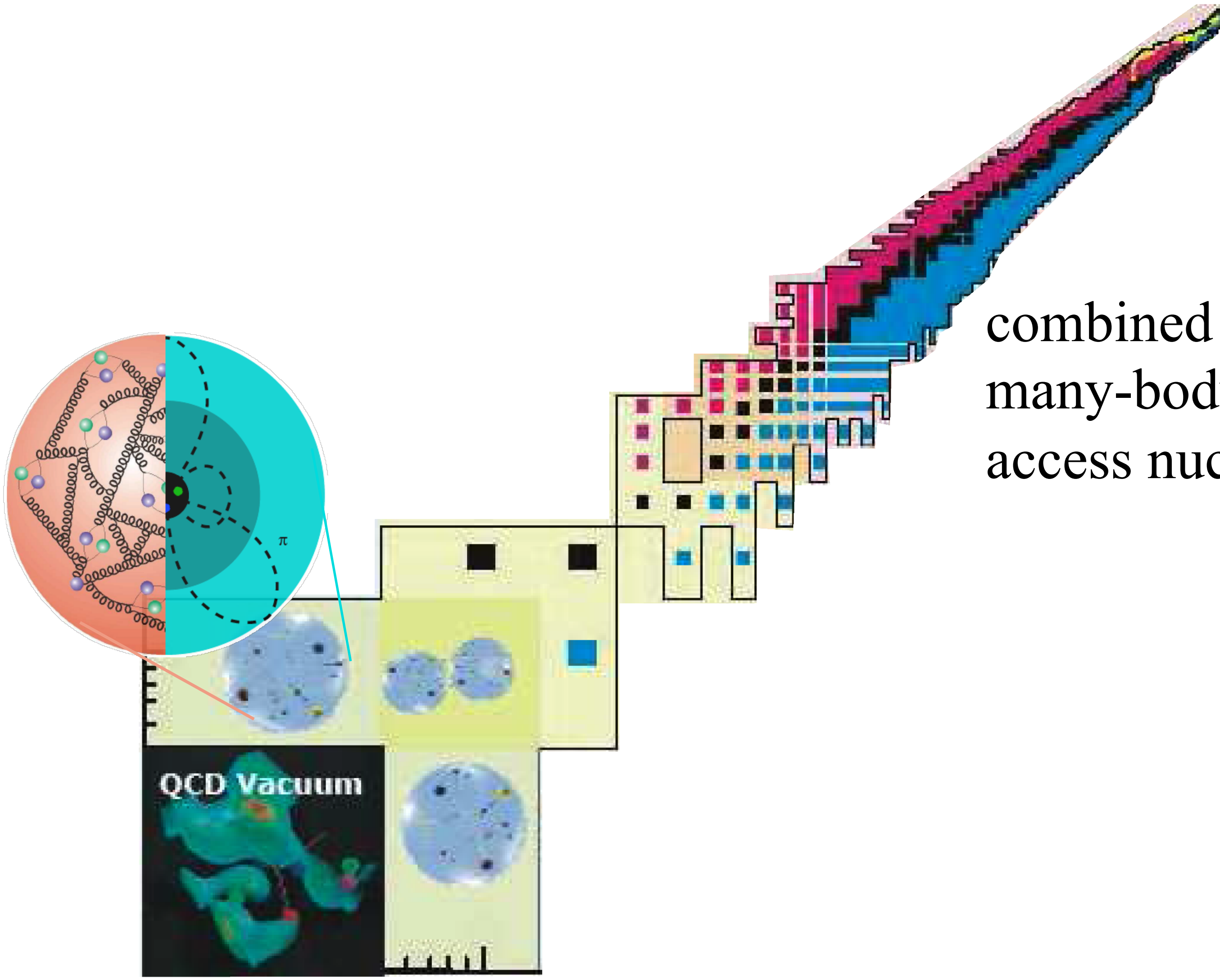
incorporate what we know
about QCD/nuclear physics



from CDMS collaboration

From QCD to nuclei

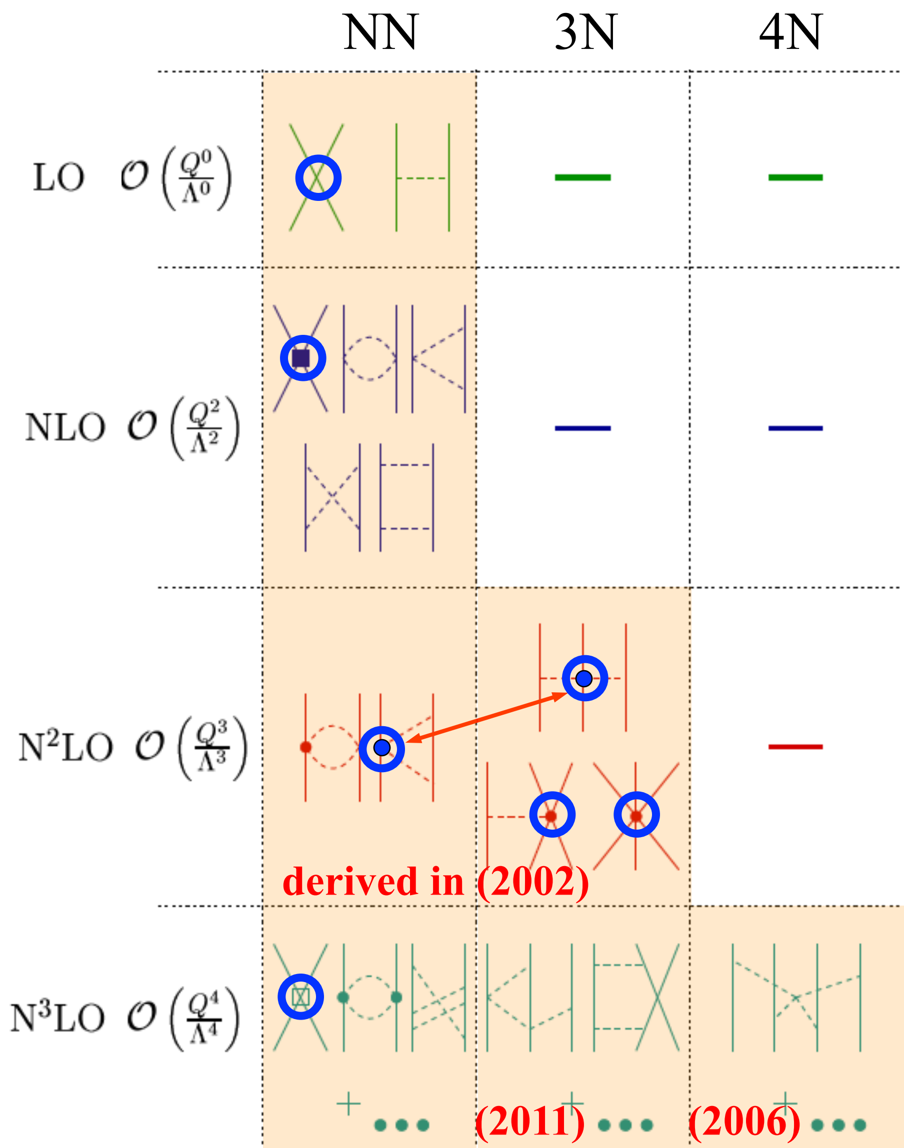
Chiral EFT provides a systematic basis for nuclear forces and the coupling to external probes based on the Standard Model



combined with powerful many-body methods can access nuclei

Chiral effective field theory for nuclear forces

Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale ~500 MeV



limited resolution at low energies, can expand in powers $(Q/\Lambda_b)^n$

expansion parameter ~ 1/3 for nuclei

include long-range pion physics

few short-range couplings, fit to experiment once

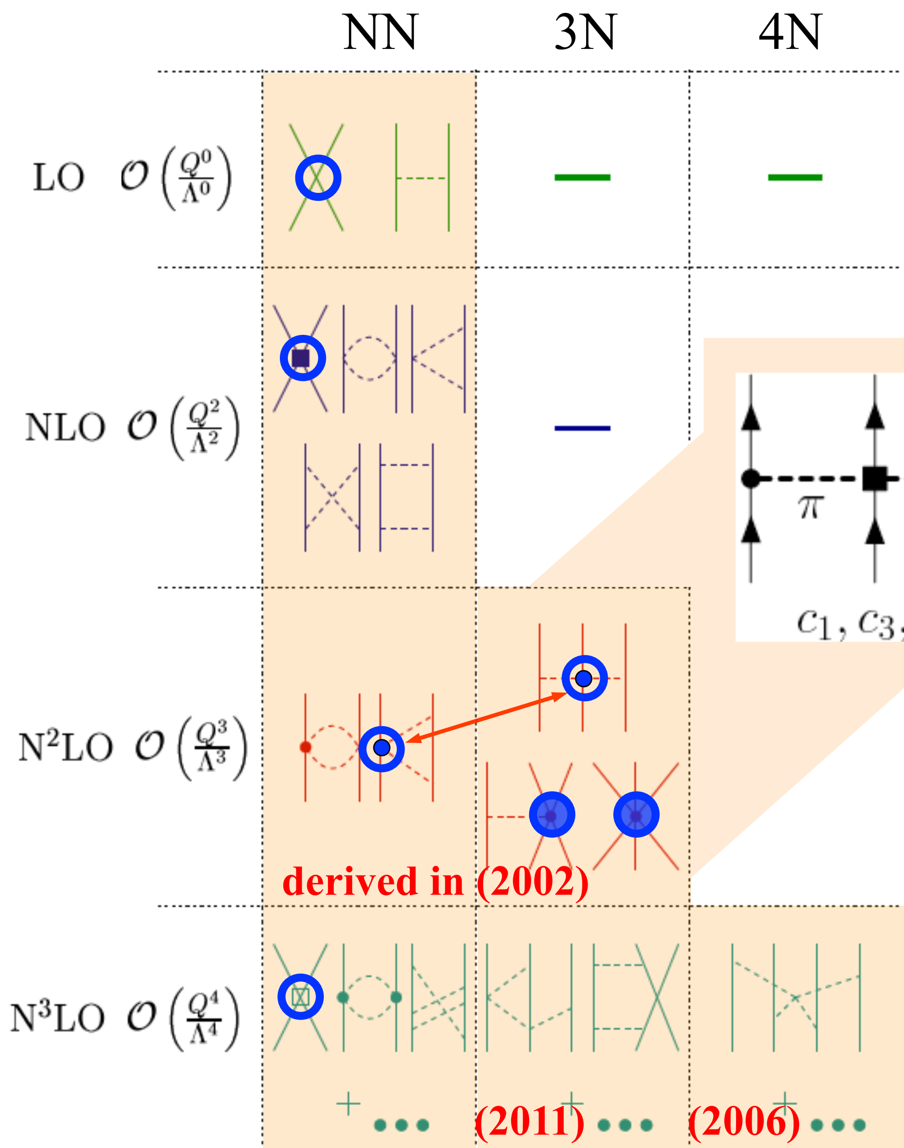
systematic: can work to desired accuracy and obtain **error estimates**

consistent **electroweak interactions** and **matching to lattice QCD**

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

Chiral effective field theory and **many-body forces**

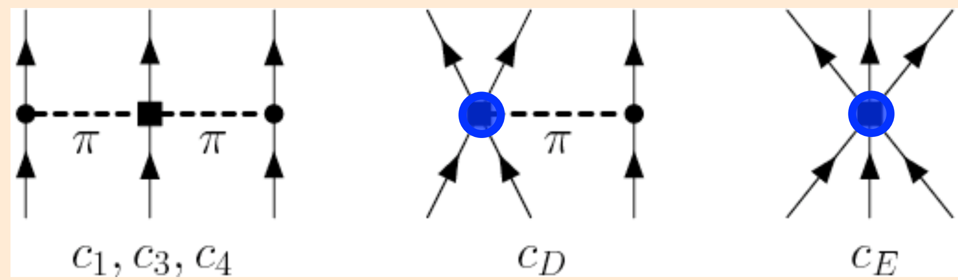
Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale ~500 MeV



consistent NN-3N-4N interactions

3N,4N: **2 new couplings to N³LO**

+ no new couplings for neutrons



c_i from πN and NN Meissner, LAT 2005

$$c_1 = -0.9^{+0.2}_{-0.5}\,, \quad c_3 = -4.7^{+1.2}_{-1.0}\,, \quad c_4 = 3.5^{+0.5}_{-0.2}$$

c_D, c_E fit to light nuclei only

Weinberg, van Kolck, Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Machleidt, Meissner,…

Frontier of ab initio calculations at A~50

doi:10.1038/nature12226

Masses of exotic calcium isotopes pin down nuclear forces

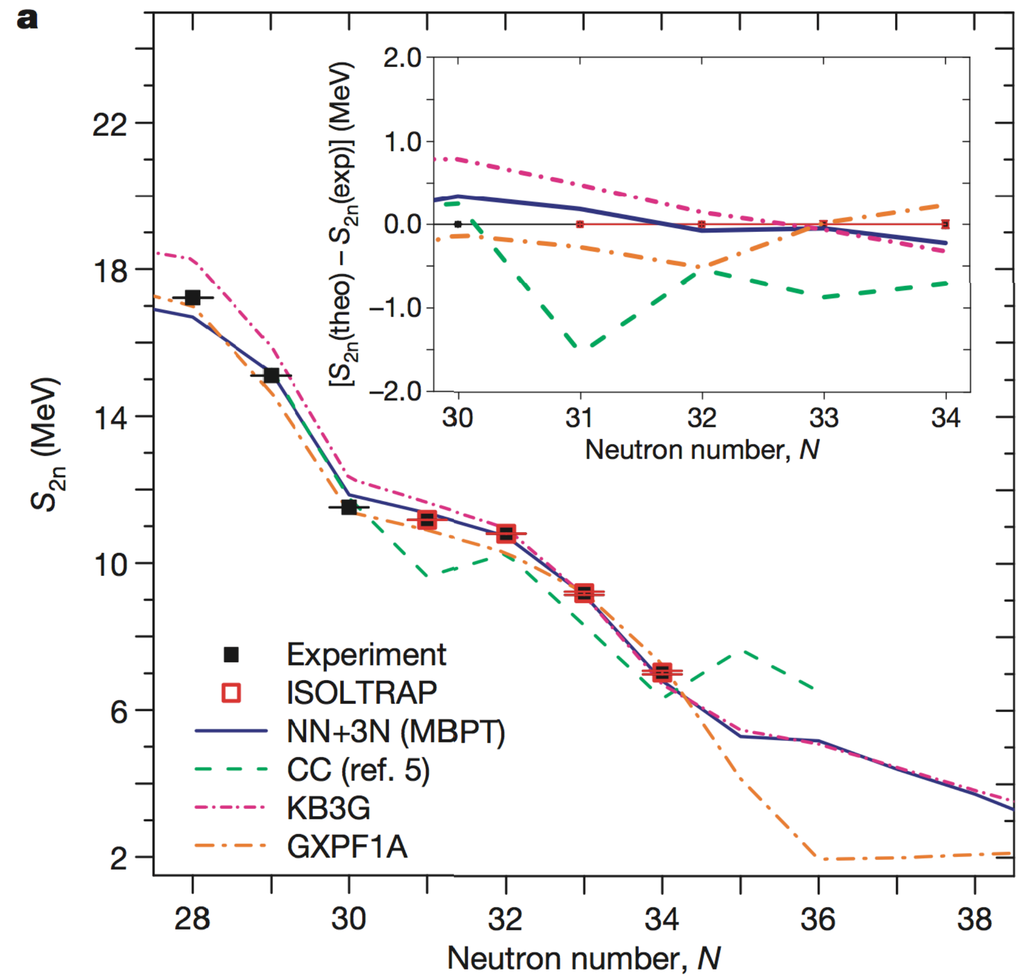
F. Wienholtz[1], D. Beck[2], K. Blaum[3], Ch. Borgmann[3], M. Breitenfeldt[4], R. B. Cakirli[3,5], S. George[1], F. Herfurth[2], J. D. Holt[6,7], M. Kowalska[8], S. Kreim[3,8], D. Lunney[9], V. Manea[9], J. Menéndez[6,7], D. Neidherr[2], M. Rosenbusch[1], L. Schweikhard[1], A. Schwenk[7,6], J. Simonis[6,7], J. Stanja[10], R. N. Wolf[1] & K. Zuber[10]

^{51,52}Ca masses at TITAN
Gallant et al., PRL (2012)

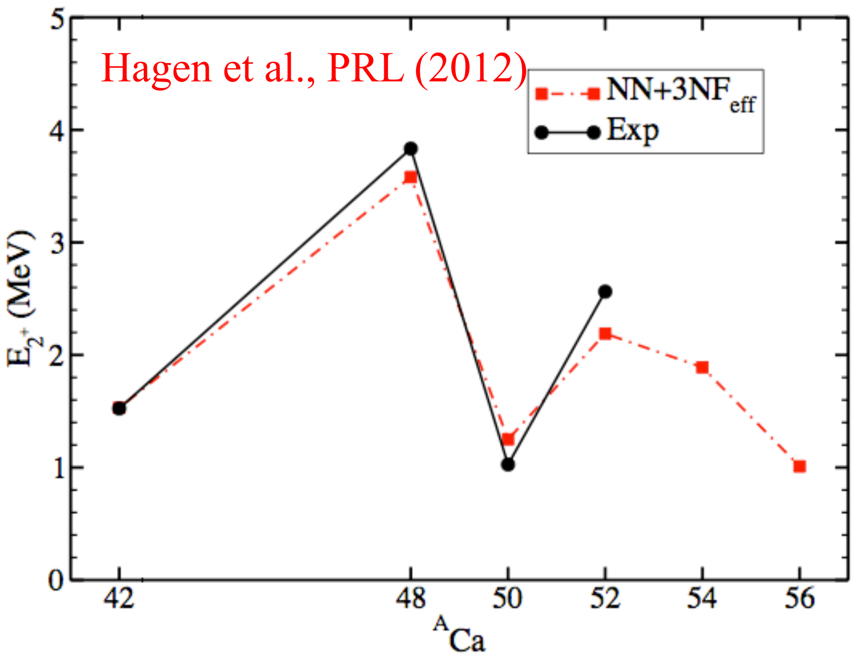
^{53,54}Ca masses measured at ISOLTRAP using new MR-TOF mass spectrometer

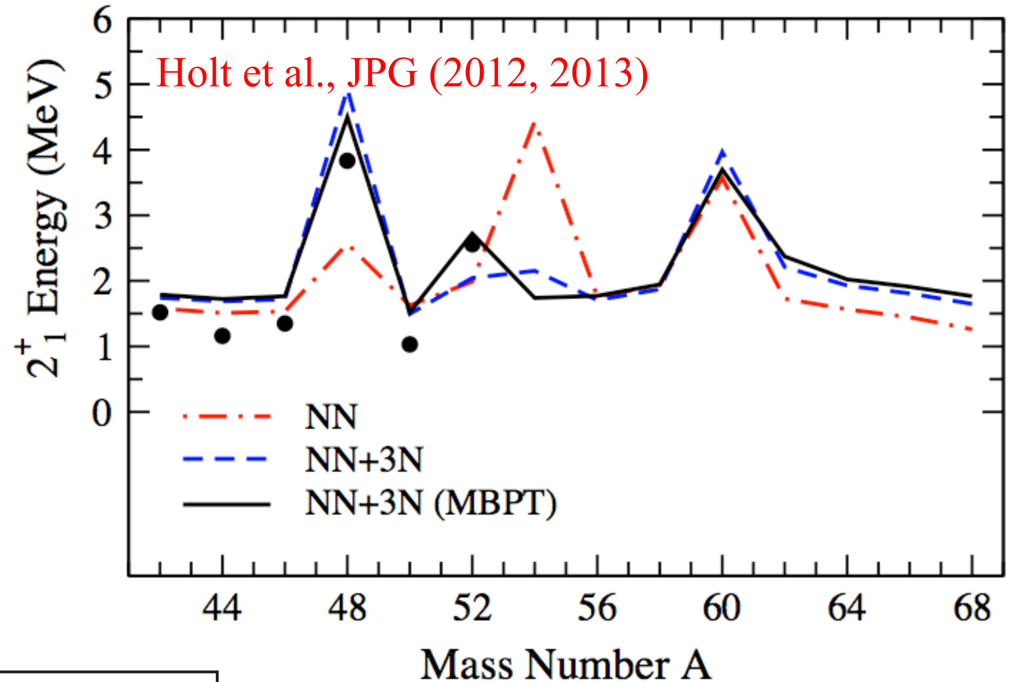
establish prominent N=32 shell closure in calcium

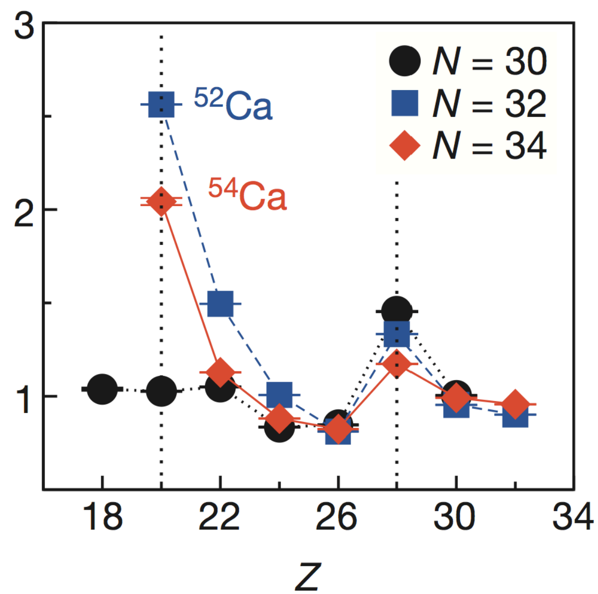
excellent agreement with theoretical NN+3N prediction



3N forces and magic numbers







2^+ energy measured at RIBF suggests magic number N=34

Steppenbeck et al., Nature (2013)

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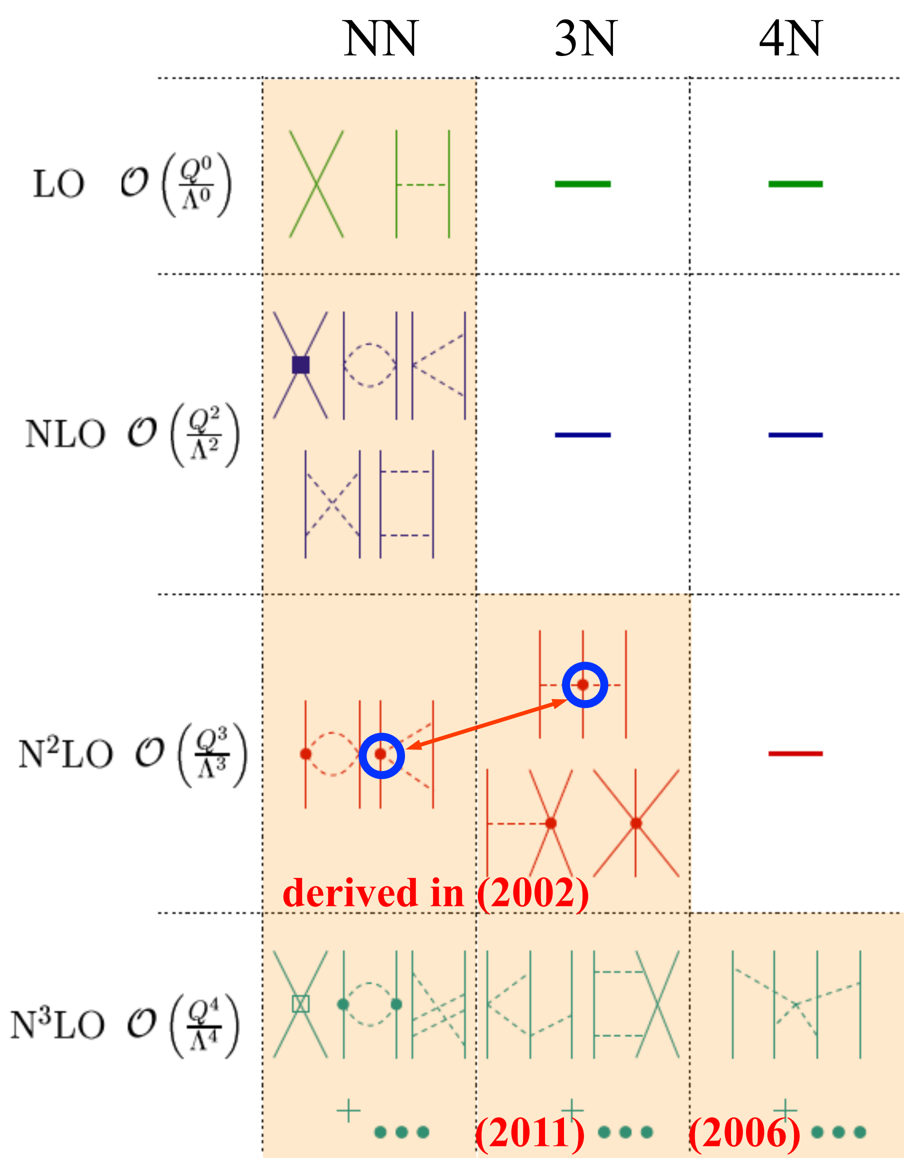
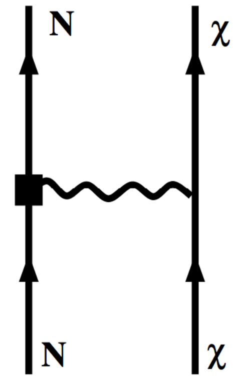
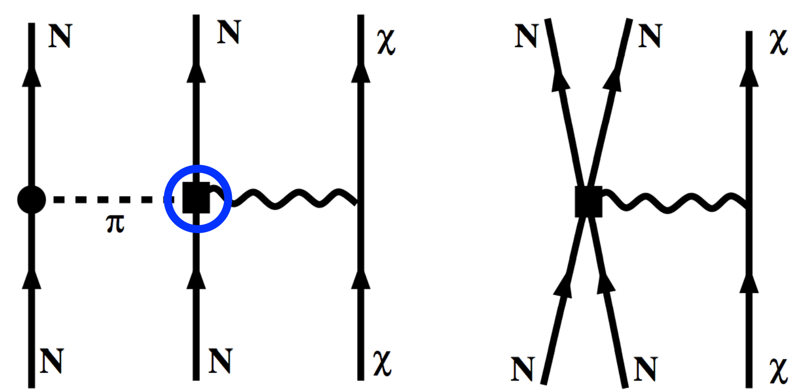
Chiral EFT for spin-dependent WIMP currents in nuclei



one-body currents at Q^0 and Q^2



+ two-body currents at Q^3

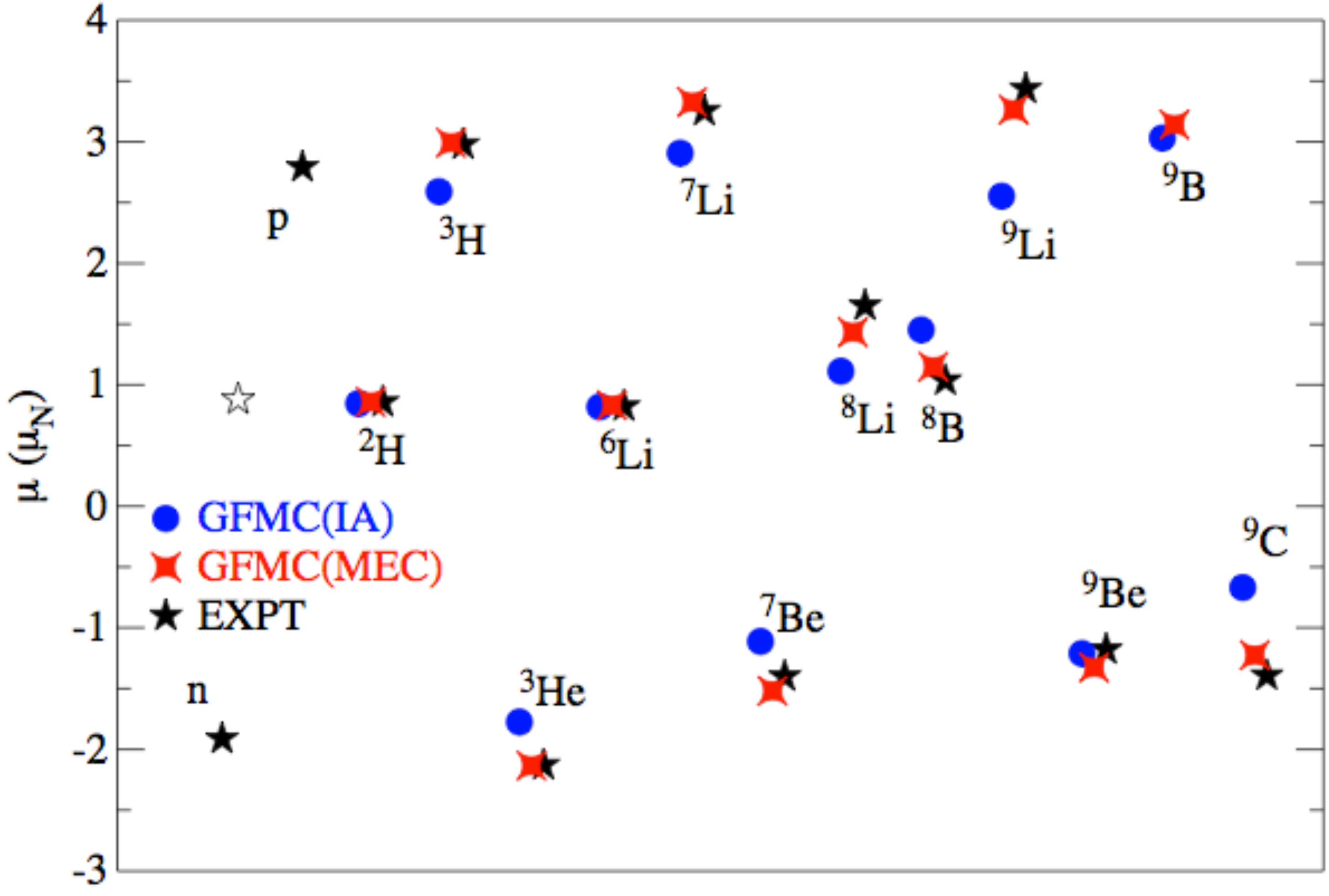


same couplings in forces and currents!

Chiral EFT currents and electromagnetic interactions

predicts consistent electromagnetic 1+2-body currents

GFMC calculations of magnetic moments in light nuclei Pastore et al. (2012)
2-body currents (meson-exchange currents=MEC) are key!

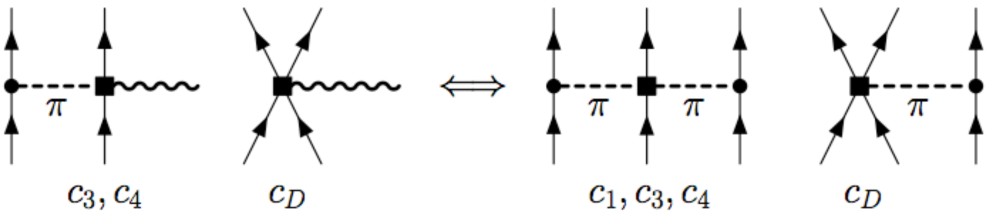


Two-body currents and 3N forces

weak axial currents and spin-dependent WIMP currents couple to spin, similar to pions

two-body currents predicted by πN, NN, 3N couplings to N^3LO

Park et al., Phillips,…



two-body analogue of Goldberger-Treiman relation $g_{\pi NN} F_\pi = g_A m_N$

explored in light nuclei, but not for larger systems

dominant contribution to Gamow-Teller transitions,
important in nuclei (Q~100 MeV)

3N couplings predict quenching of g_A (dominated by long-range part) and predict momentum dependence (weaker quenching for larger p)

Menendez, Gazit, AS, PRL (2011)

Spin-dependent WIMP currents in nuclei and uncertainties

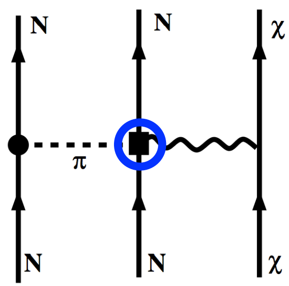
one-body currents with isoscalar/isovector couplings $a_{0/1}$ Engel et al. (1992)

$$Q^0: \quad \sum_{i=1}^{A} \mathbf{J}_{i,1\mathrm{b}} = \sum_{i=1}^{A} \frac{1}{2}\left[a_0\sigma_i + a_1\tau_i^3\sigma_i\right]$$

$$Q^2: \quad \sum_{i=1}^{A} \mathbf{J}_{i,1\mathrm{b}} = \sum_{i=1}^{A} \frac{1}{2}\left[a_0\sigma_i + a_1\tau_i^3\left(\frac{g_A(p^2)}{g_A}\sigma_i - \frac{g_P(p^2)}{2mg_A}(\mathbf{p}\cdot\sigma_i)\mathbf{p}\right)\right]$$

Q^2 similar to phenomenological currents, but slightly different p-dep.

two-body currents at Q^3 predicted by c_3, c_4 couplings from πN/NN/3N



$$\mathbf{J}_{12}^3 = -\frac{g_A}{4F_\pi^2}\frac{1}{m_\pi^2+k^2}\Big[2\left(c_4+\frac{1}{4m}\right)\mathbf{k}\times(\sigma_\times\times\mathbf{k})\tau_\times^3 + 4c_3\mathbf{k}\cdot(\sigma_1\tau_1^3+\sigma_2\tau_2^3)\mathbf{k} - \frac{i}{m}\mathbf{k}\cdot(\sigma_1-\sigma_2)\mathbf{q}\tau_\times^3\Big]$$

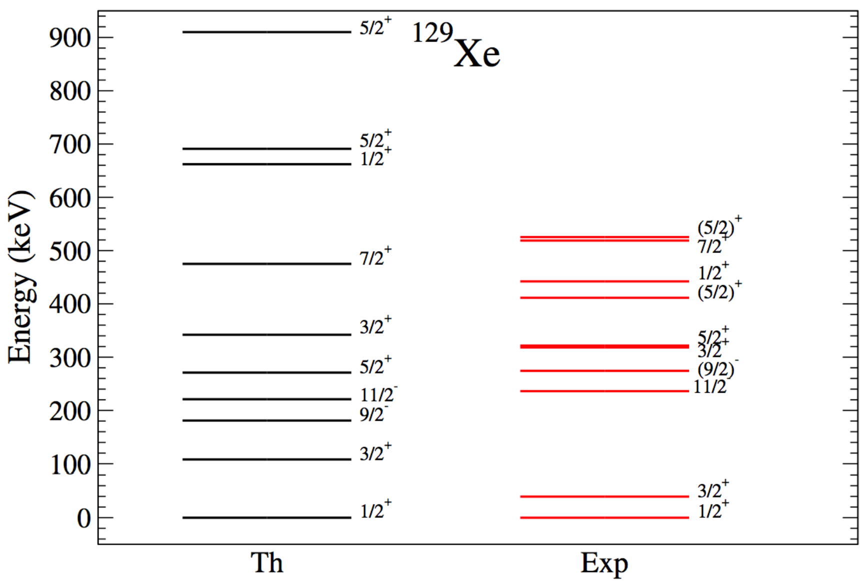
+ additional corrections at finite p Klos, Menéndez, Gazit, AS, PRD (2013)

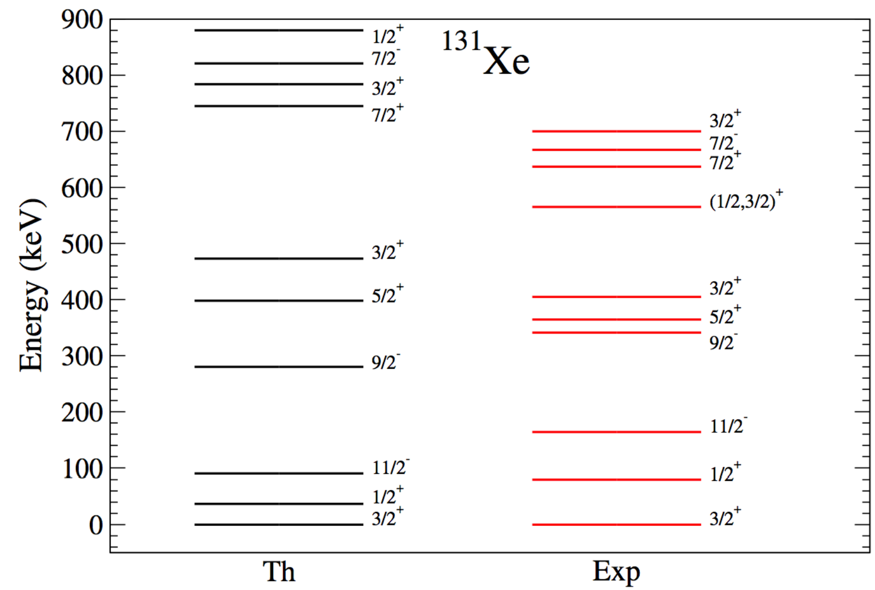
include as density-dependent one-body currents (normal ordering),
uncertainties due to leading-order two-body currents reflected in c_3, c_4

Nuclear structure for direct detection

valence-shell Hamiltonian calculated from NN interactions + corrections to compensate for not including 3N forces (will improve in the future)

valence spaces and interactions have been tested successfully in nuclear structure calculations, largest spaces used





very good agreement for spectra; ordering and grouping well reproduced

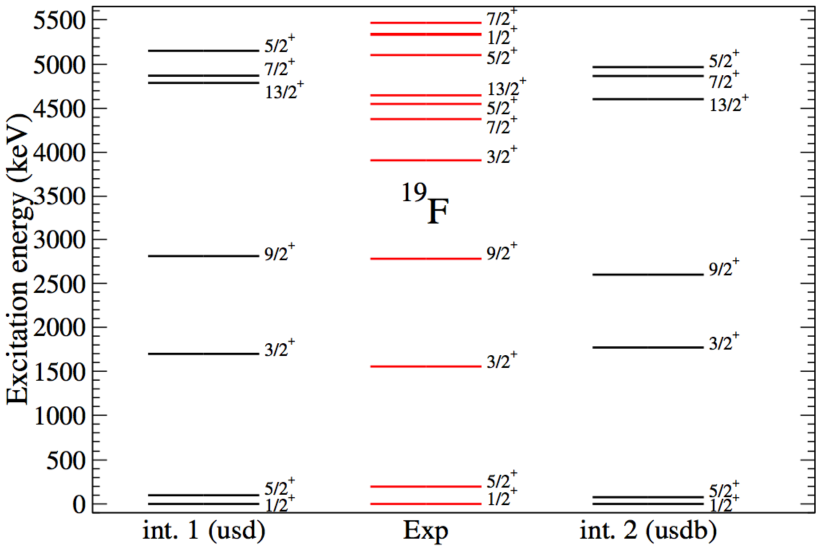
Menendez, Gazit, AS, PRD (2012)

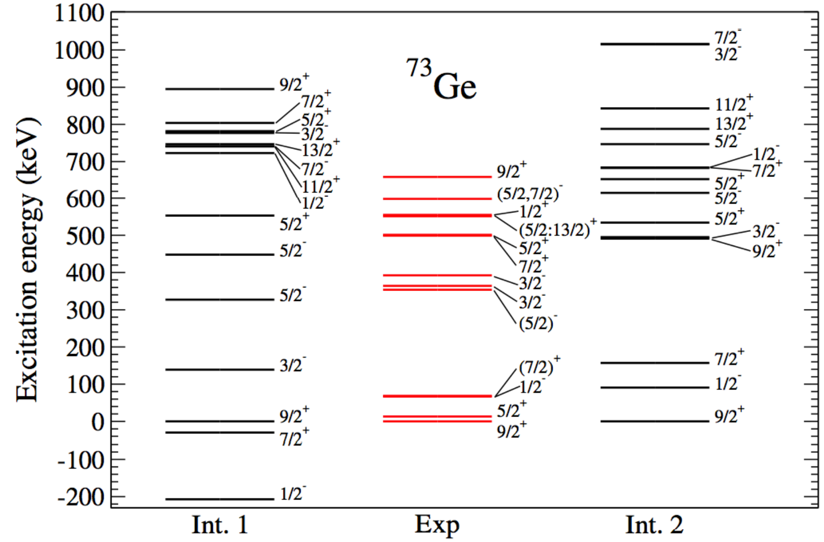
connects WIMP direct detection with double-beta decay

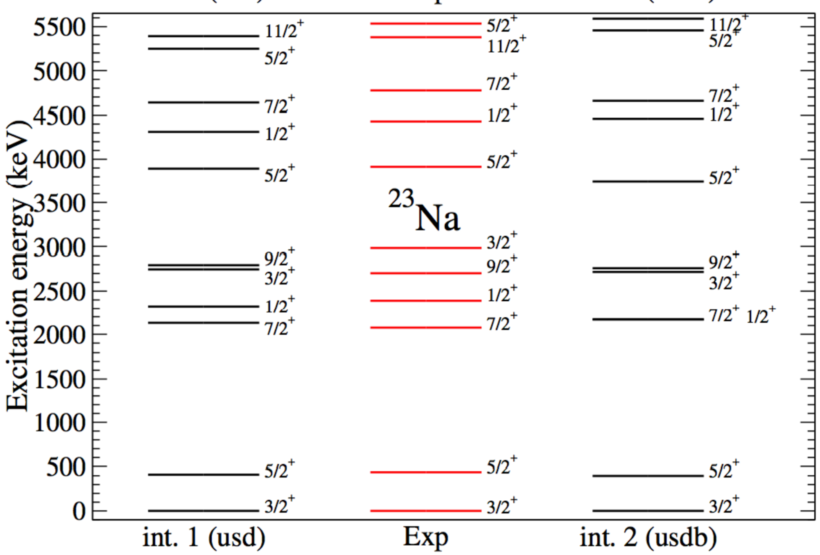
Nuclear structure II

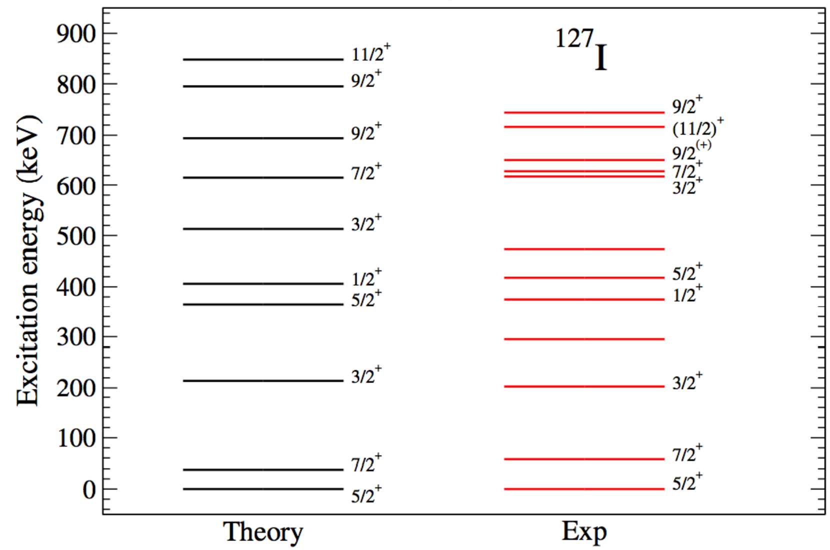
similar agreement for other nuclei relevant to direct detection

Klos, Menéndez, Gazit, AS, PRD (2013)









Nuclear structure factors

differential cross section for spin-dependent WIMP scattering
~ axial-vector structure factor $S_A(p)$ Engel et al. (1992)

$$\frac{d\sigma}{dp^2} = \frac{1}{(2J_i+1)\pi v^2} \sum_{s_f,s_i} \sum_{M_f,M_i} \left| \langle f | \, \mathcal{L}_\chi^{\rm SD} \, | i \rangle \right|^2$$
$$= \frac{8G_F^2}{(2J_i+1)v^2} \, S_A(p) \,,$$

decompose into longitudinal, transverse electric and transverse magnetic

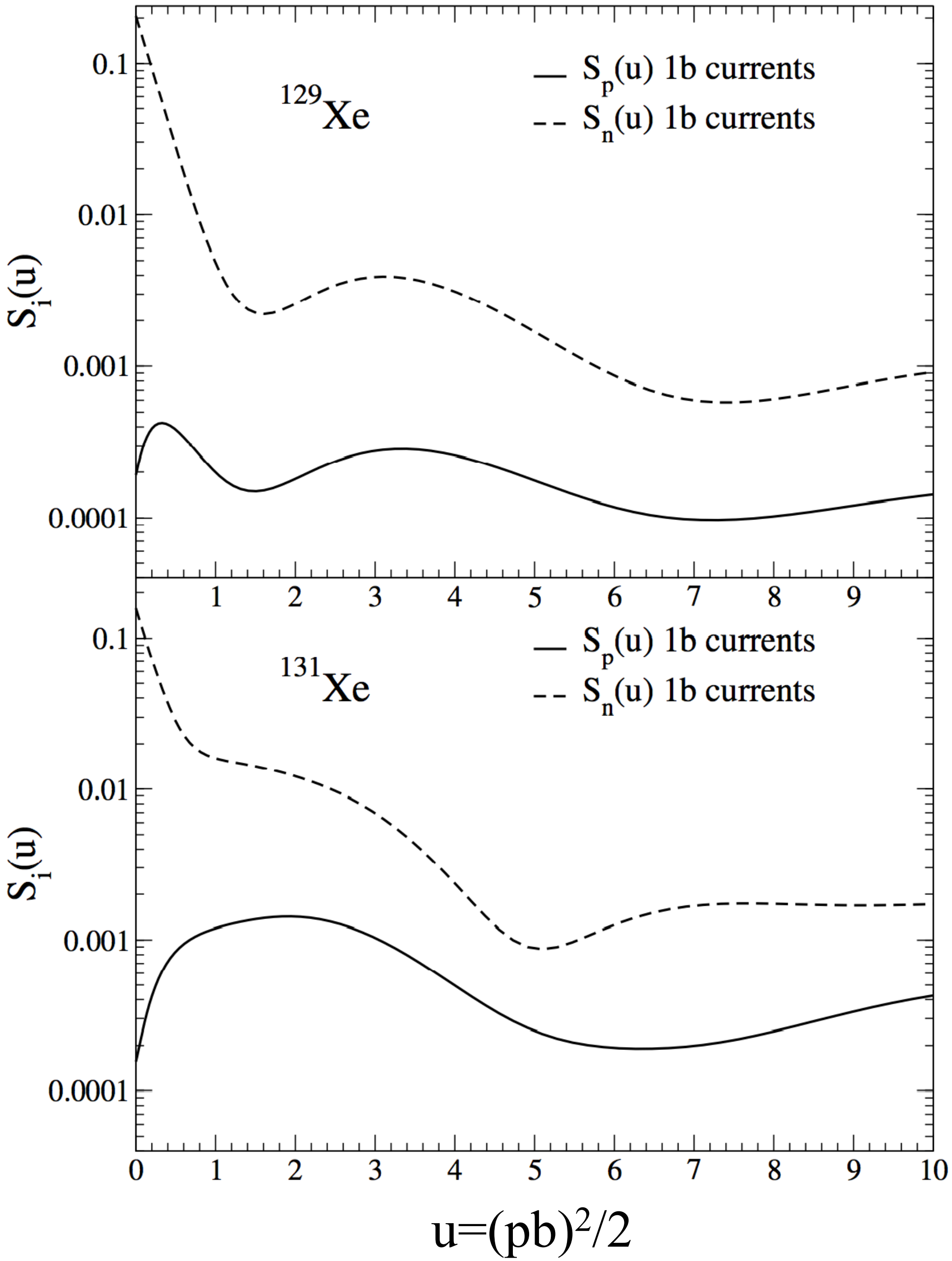
$$S_A(p) = \sum_{L \geqslant 0} \left| \langle J_f || \mathcal{L}_L^5 || J_i \rangle \right|^2 + \sum_{L \geqslant 1} \left(\left| \langle J_f || \mathcal{T}_L^{\rm el5} || J_i \rangle \right|^2 + \left| \langle J_f || \mathcal{T}_L^{\rm mag5} || J_i \rangle \right|^2 \right)$$

transverse magnetic multipoles vanish for elastic scattering

can also decompose into isoscalar/isovector structure factors $S_{ij}(p)$

$$S_A(p) = a_0^2 \, S_{00}(p) + a_0 a_1 S_{01}(p) + a_1^2 \, S_{11}(p)$$

Xenon response with one-body currents



^{129,131}Xe are even Z, odd N, spin is carried mainly by neutrons

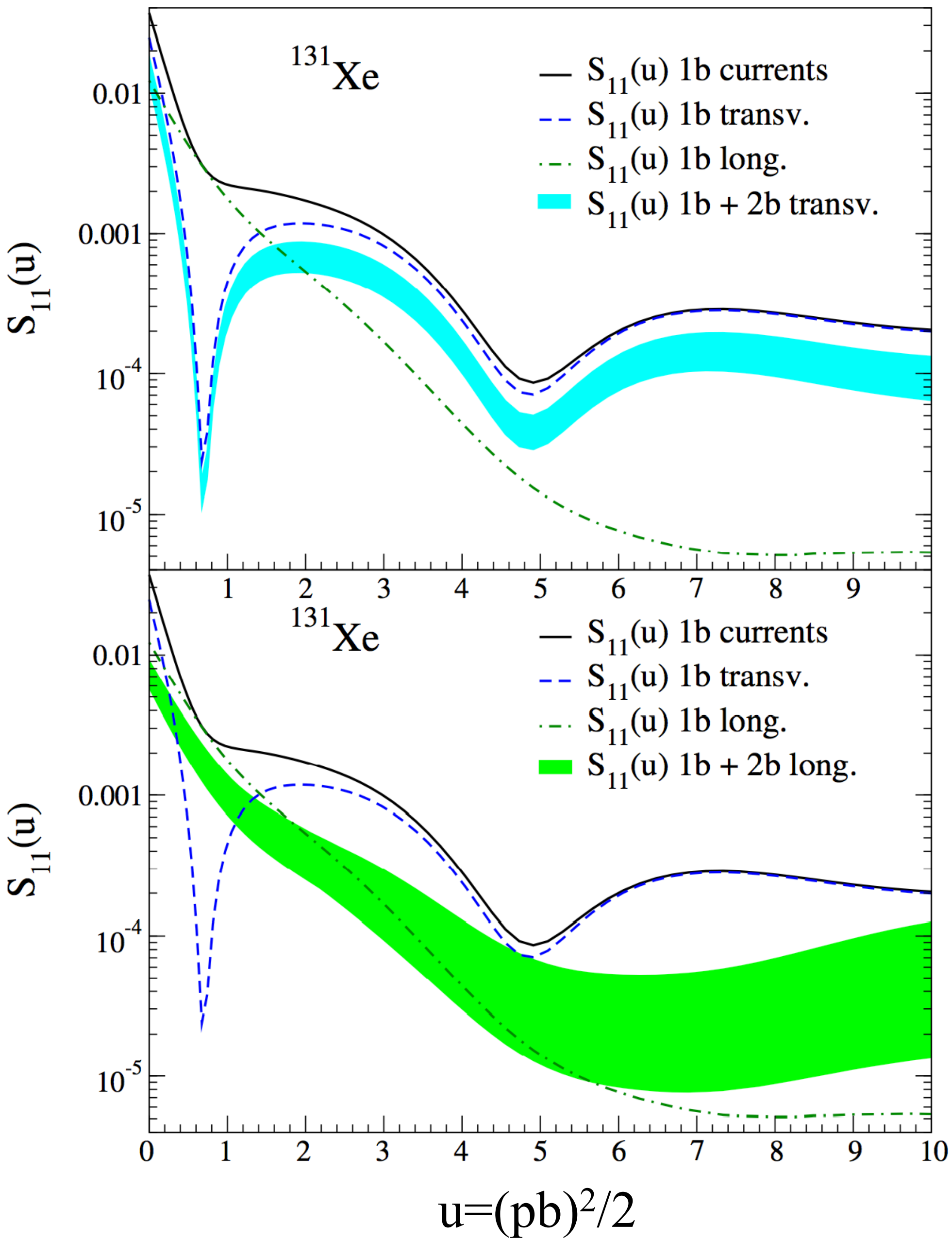
at p=0 structure factors at the level of one-body currents dominated by "neutron"-only

$$S_A = \frac{(2J+1)(J+1)}{\pi J} \left| a_p \langle S_p \rangle + a_n \langle S_n \rangle \right|^2,$$

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

$$S_n(0) \propto \left| \langle S_n \rangle \right|^2 \; S_p(0) \propto \left| \langle S_p \rangle \right|^2.$$

Xenon response with 1+2-body currents



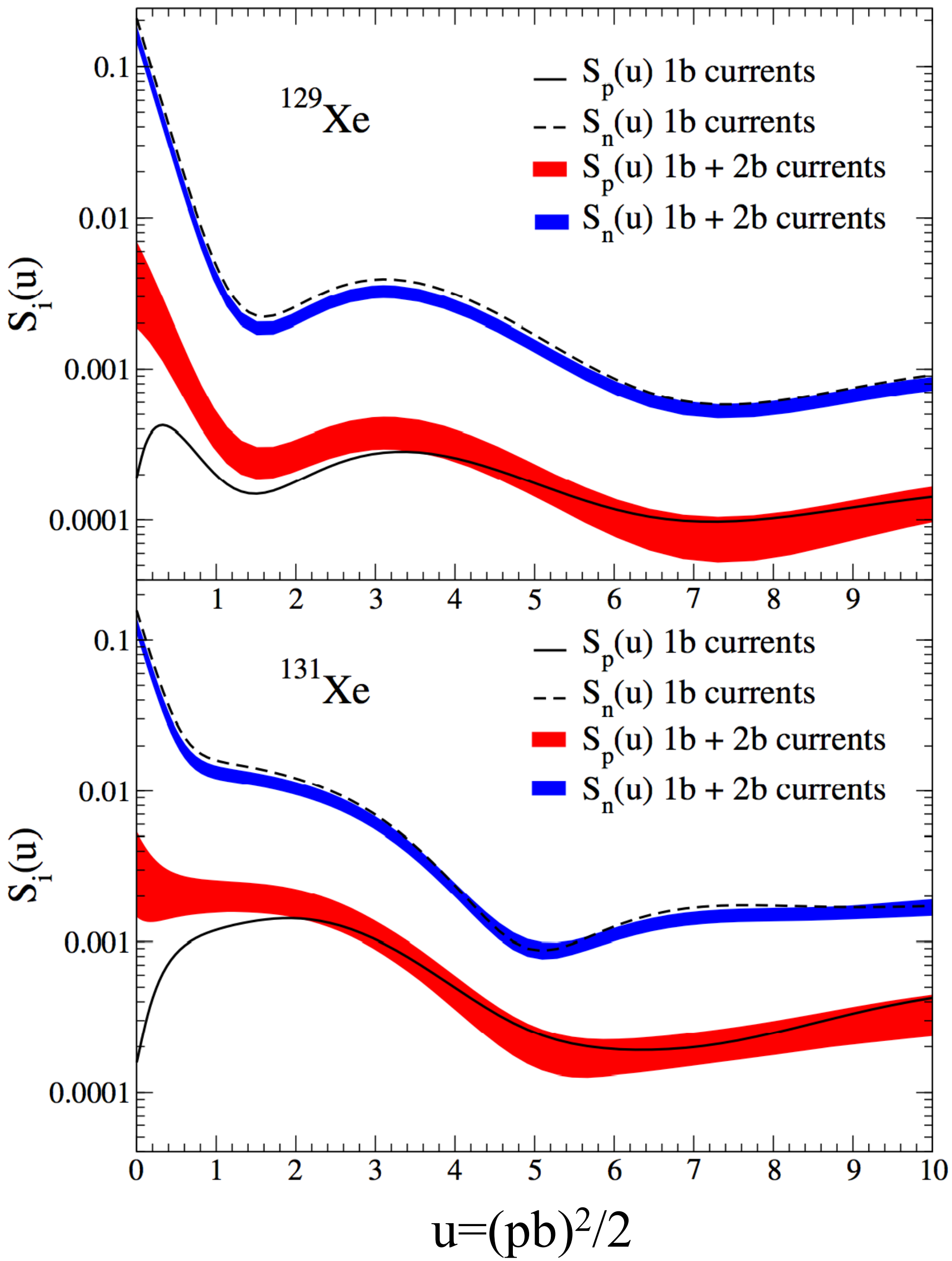
leading two-body currents renormalize isovector coupling: not “neutron”/“proton” only

lead to reduction of axial current enhancement of pseudoscalar curr.

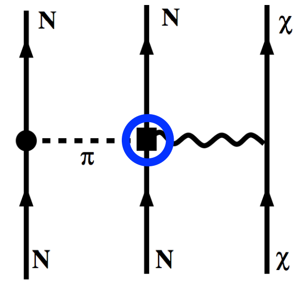
transverse multipoles reduced; longitudinal reduced at low p, but enhanced at high p

uncertainty band due to c_3, c_4 and normal-ordering

Xenon response with 1+2-body currents



two-body currents due to strong interactions among nucleons

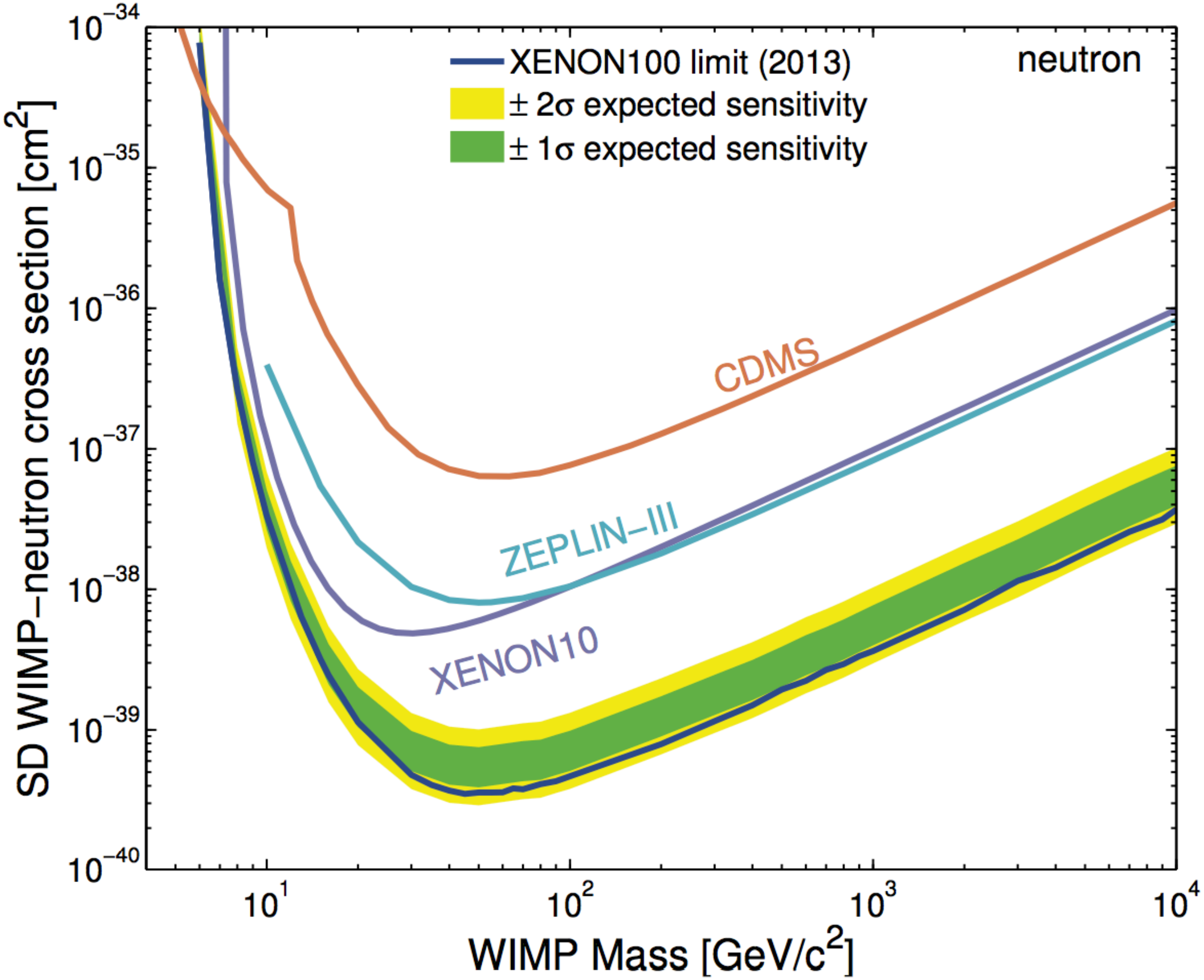


WIMPs couple to neutrons and protons at the same time

enhances coupling to even species in all cases (protons for Xe)

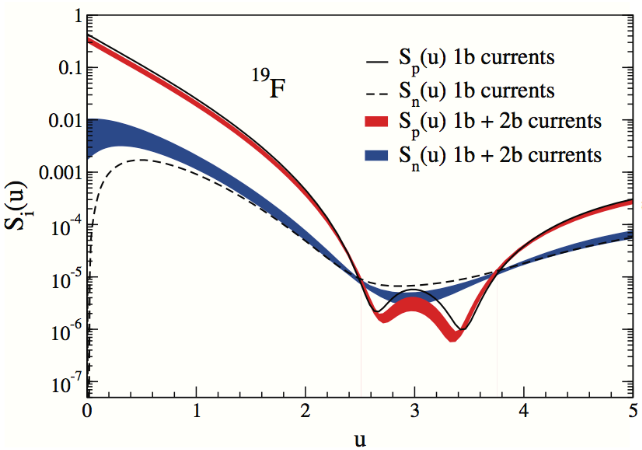
Limits on SD WIMP-neutron interactions

best limits from XENON100 Aprile et al., PRL (2013)
used our calculations with uncertainty bands for WIMP currents in nuclei

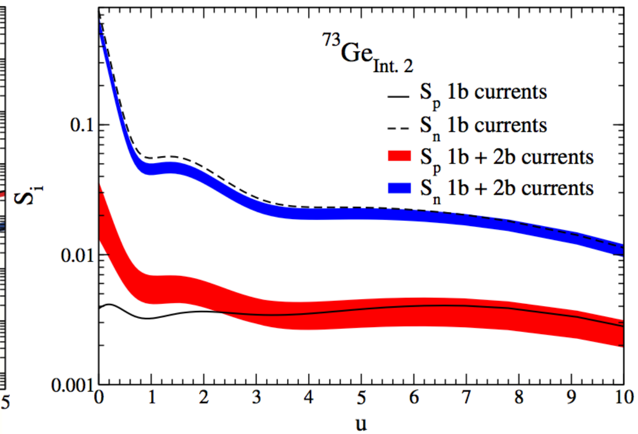


Spin-dependent WIMP-nucleus response for ^{19}F, ^{23}Na, ^{27}Al, ^{29}Si, ^{73}Ge, ^{127}I

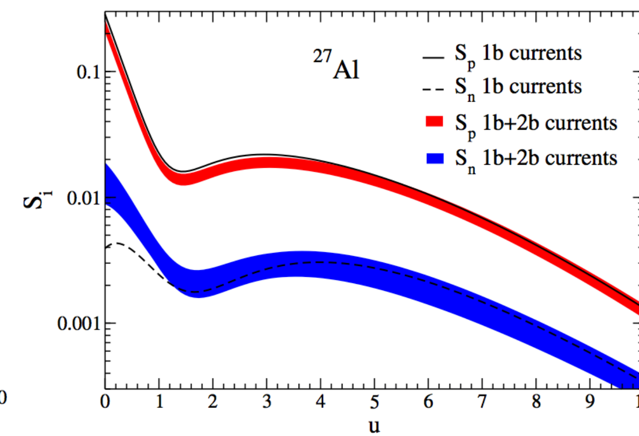
Klos, Menéndez, Gazit, AS, PRD (2013)



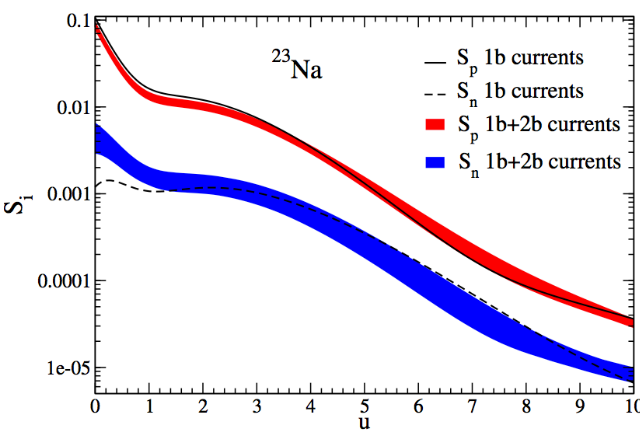
PICASSO, COUPP, SIMPLE



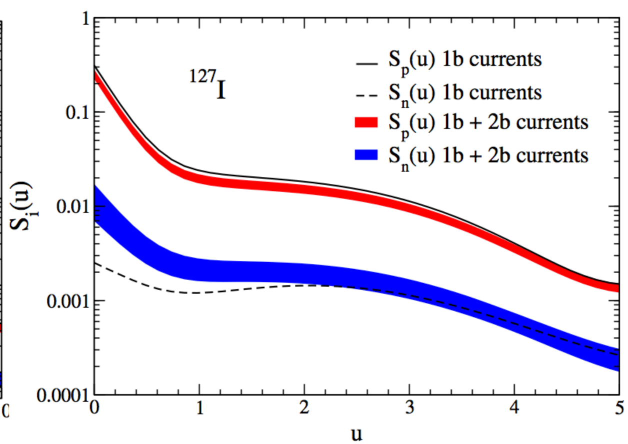
CDMS, EDELWEISS, EURECA



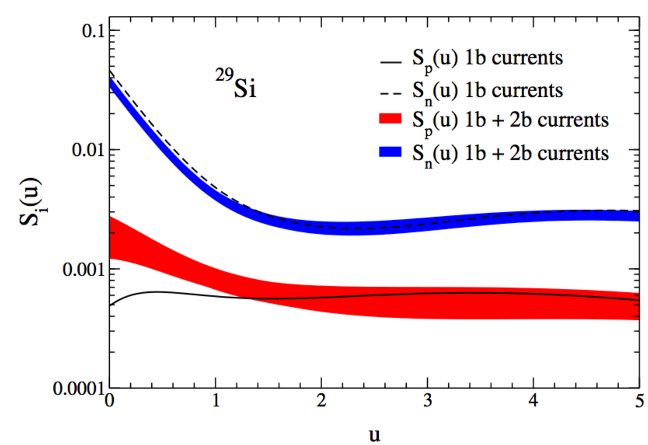
CRESST



DAMA, ANAIS, DM-Ice



DAMA, ANAIS, DM-Ice, KIMS



CDMS-II

Comparison of spin expectation values

TABLE III. Calculated spin expectation values for protons $\langle \mathbf{S}_p \rangle$ and neutrons $\langle \mathbf{S}_n \rangle$ of ^{129,131}Xe, ^{127}I, ^{73}Ge, ^{29}Si, ^{27}Al, ^{23}Na, and ^{19}F, compared to the previous calculations of Refs. [13,17–23].

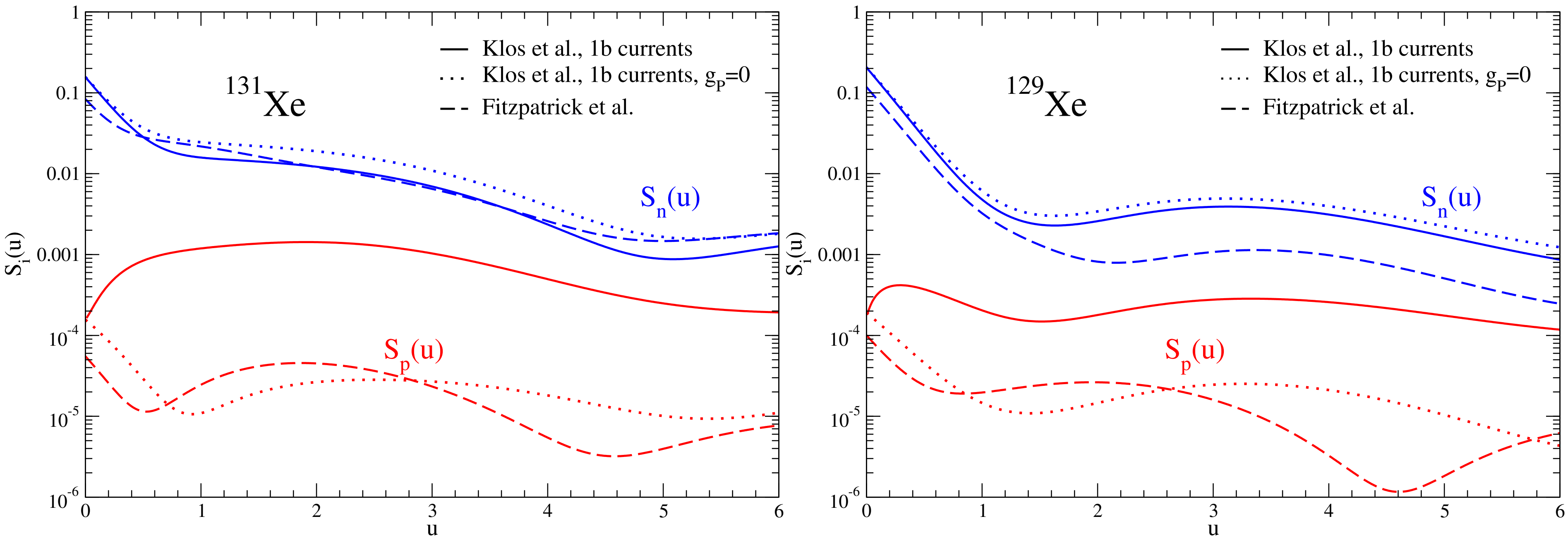
	^{129}Xe		^{131}Xe		^{127}I		^{73}Ge		^{29}Si		^{27}Al		^{23}Na		^{19}F	
	$\langle \mathbf{S}_n \rangle$	$\langle \mathbf{S}_p \rangle$	$\langle \mathbf{S}_n \rangle$	$\langle \mathbf{S}_p \rangle$	$\langle \mathbf{S}_n \rangle$	$\langle \mathbf{S}_p \rangle$	$\langle \mathbf{S}_n \rangle$	$\langle \mathbf{S}_p \rangle$	$\langle \mathbf{S}_n \rangle$	$\langle \mathbf{S}_p \rangle$	$\langle \mathbf{S}_n \rangle$	$\langle \mathbf{S}_p \rangle$	$\langle \mathbf{S}_n \rangle$	$\langle \mathbf{S}_p \rangle$	$\langle \mathbf{S}_n \rangle$	$\langle \mathbf{S}_p \rangle$
This work	0.329	0.010	−0.272	−0.009	0.031	0.342	0.439	0.031	0.156	0.016	0.038	0.326	0.024	0.224	−0.002	0.478
(Int. 1)							0.450	0.006								
[20] (Bonn A)	0.359	0.028	−0.227	−0.009	0.075	0.309							0.020	0.248		
[20] (Nijm. II)	0.300	0.013	−0.217	−0.012	0.064	0.354										
[18]											0.030	0.343				
[17]							0.468	0.011	0.13	−0.002						
[19]							0.378	0.030								
[23]	0.273	−0.002	−0.125	-7×10^{-4}	0.030	0.418										
[22]					0.038	0.330	0.407	0.005					0.020	0.248		
[21]									0.133	−0.002			0.020	0.248	−0.009	0.475
[13]	0.248	0.007	−0.199	−0.005	0.066	0.264	0.475	0.008					0.020	0.248	−0.009	0.475

typically within ±25% of our calculations for odd species
(except for outlier in ^{131}Xe)
+ corrections from two-body currents

Comparison to Fitzpatrick et al.

based on **one-body currents only**
probes sensitivity to nucl. interactions

	^{129}Xe		^{131}Xe	
	$\langle \mathbf{S}_p \rangle$	$\langle \mathbf{S}_n \rangle$	$\langle \mathbf{S}_p \rangle$	$\langle \mathbf{S}_n \rangle$
Klos *et al.* [12]	0.010	0.329	−0.009	−0.272
Fitzpatrick *et al.* [15]	0.007	0.248	−0.005	−0.199



very similar for n-only, with largest differences due to spin exp. values and at higher momentum transfers

p-only differences from pseudoscalar contributions (couples to neutrons)

Vietze, Klos, Menéndez, Haxton, AS, arXiv to appear.

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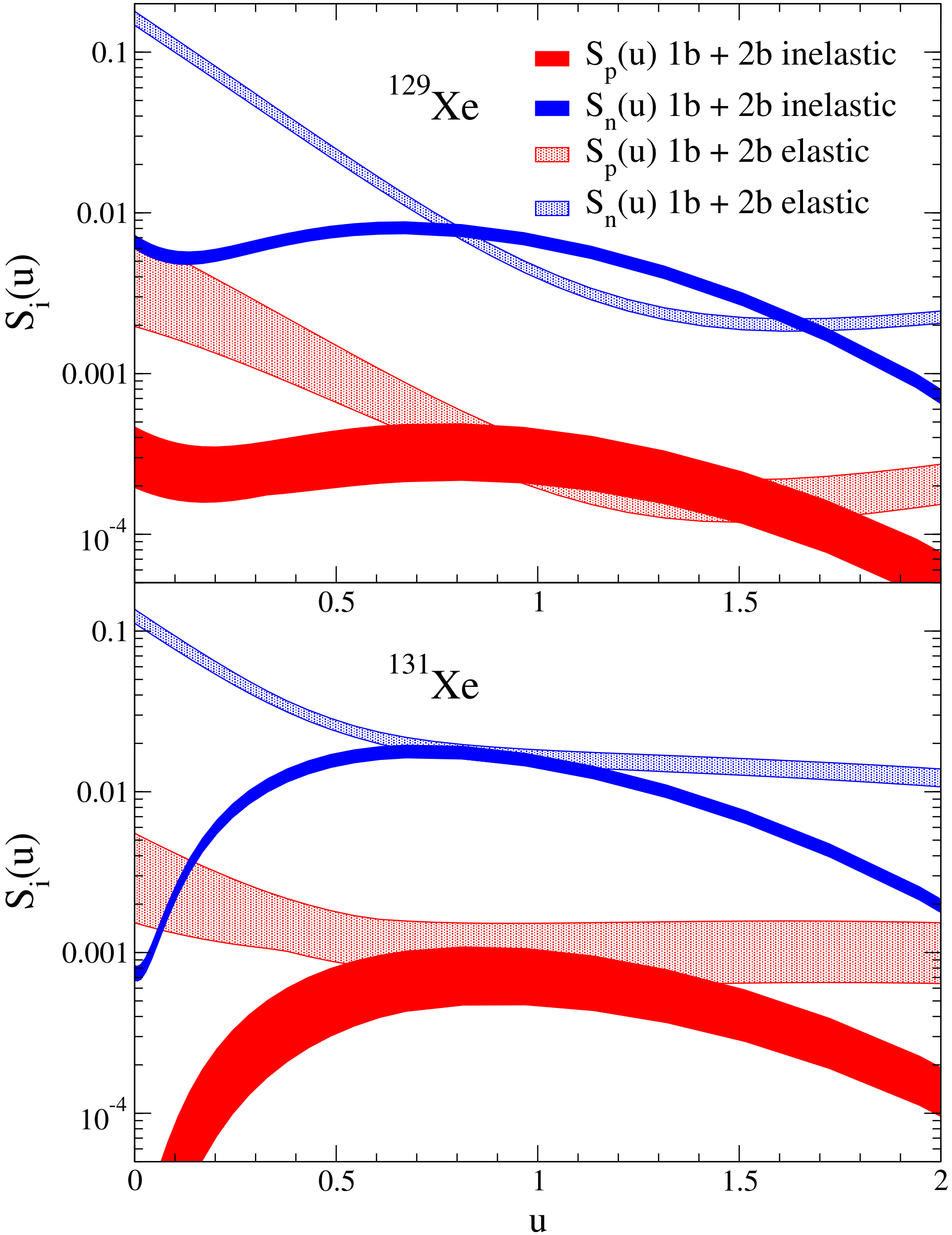
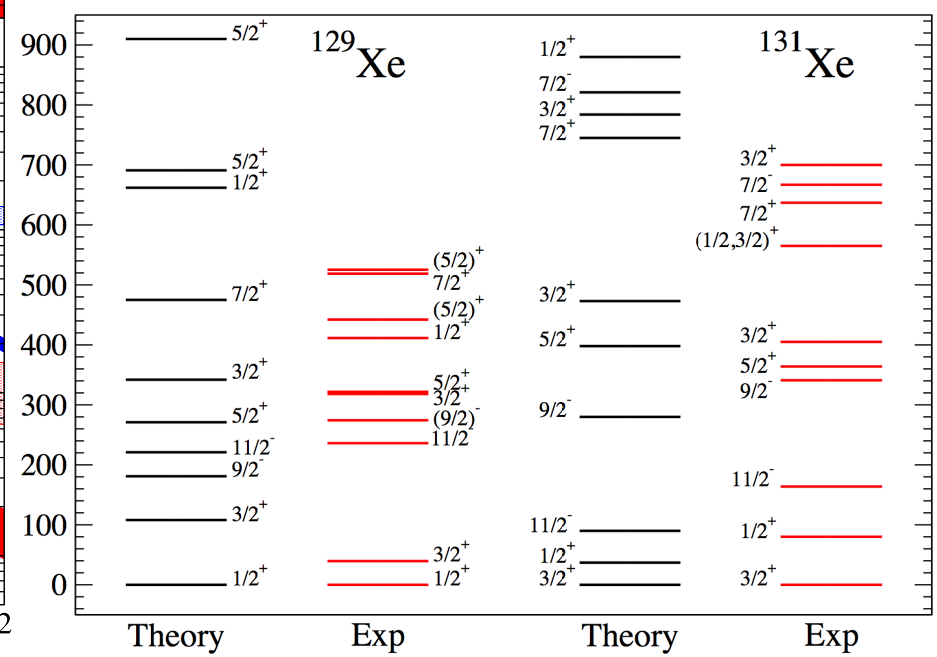
Inelastic WIMP scattering to 40 and 80 keV excited states

Baudis, Kessler, Klos, Lang, Menéndez, Reichard, AS, PRD (2013)



inelastic channel comparable/ dominates elastic channel for p ~ 150 MeV

inelastic may be at same level as momentum suppressed responses?



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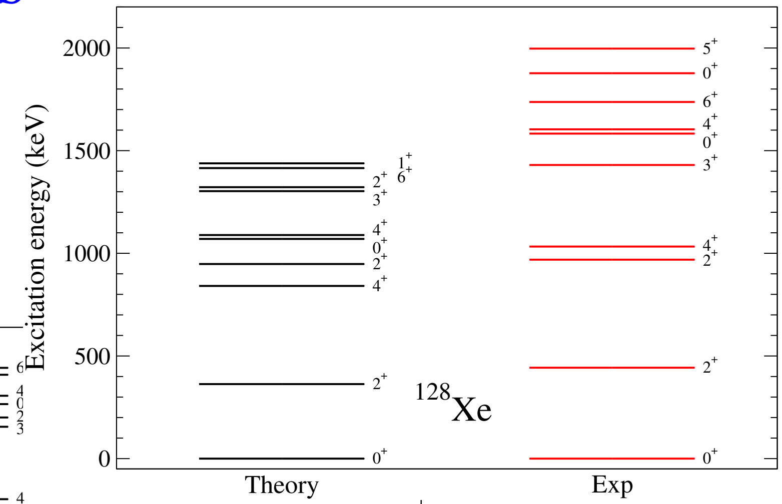
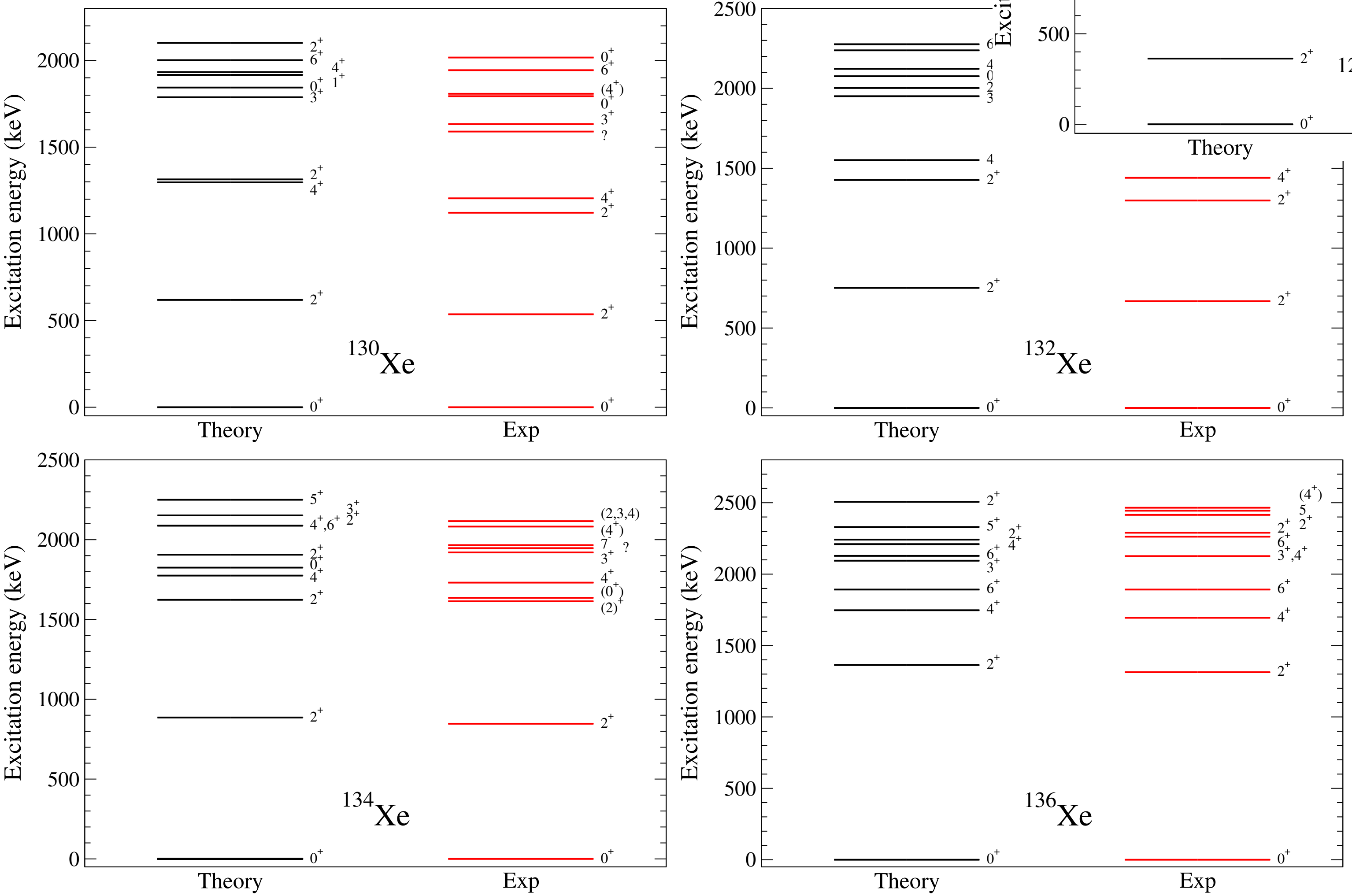
Spectra of even-mass xenon isotopes

based on same nuclear interactions

very good agreement with exp. spectra



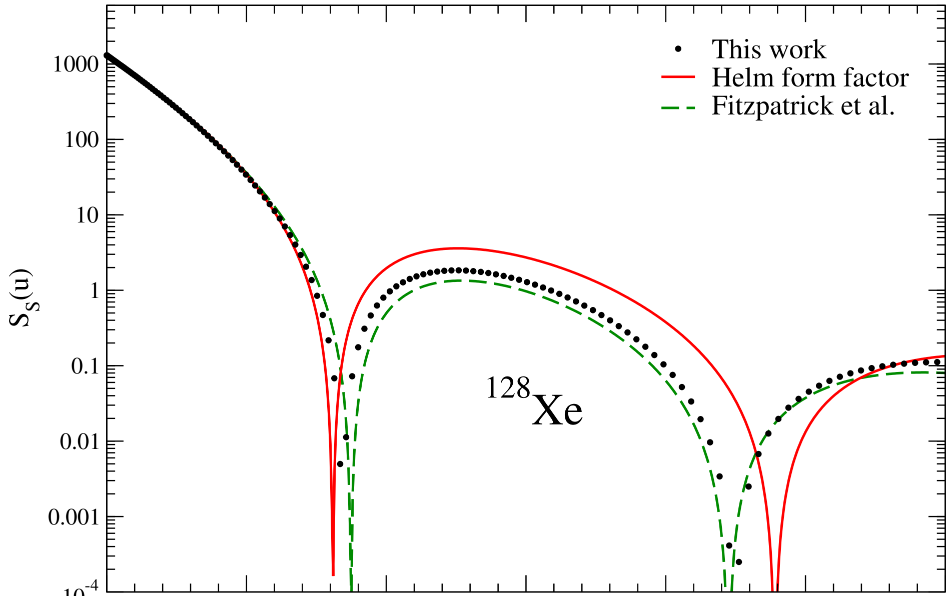


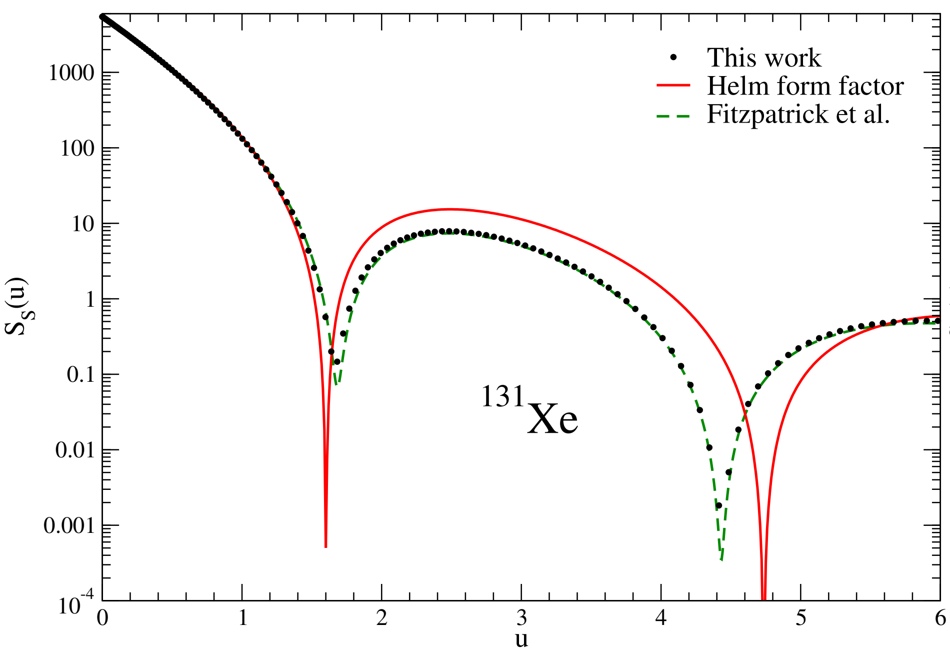
Spin-independent WIMP scattering

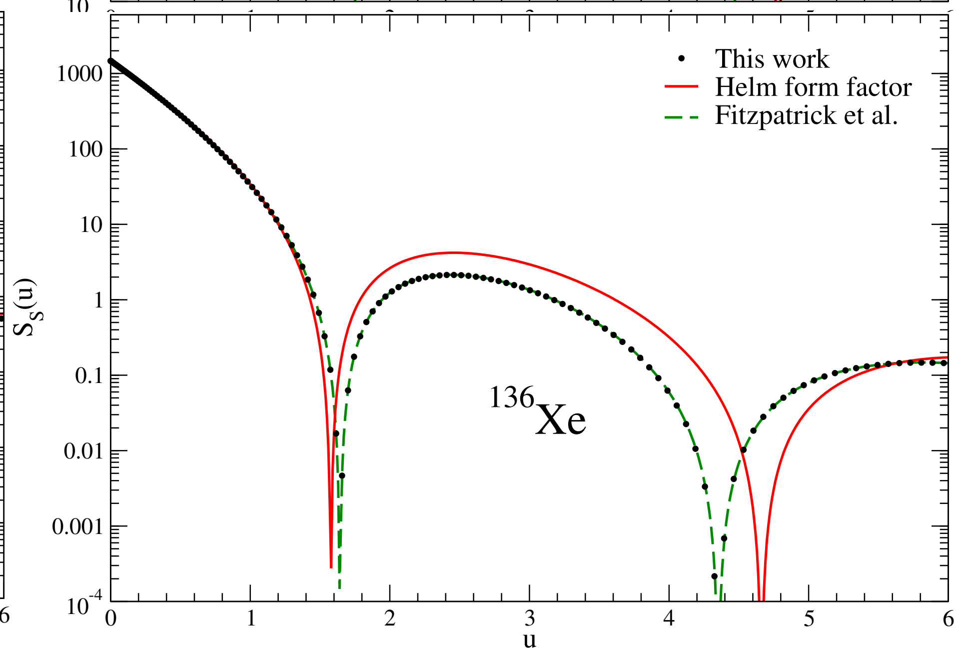
based on **one-body currents only**

for relevant momentum transfers very good agreement with pheno. Helm form factors and Fitzpatrick et al.

less sensitive to nucl. struct. details, need to include two-body currents







Summary

Thanks to **P. Klos, J. Menéndez**, D. Gazit, L. Baudis, G. Kessler, W.C. Haxton, R. Lang, S. Reichardt, L. Vietze

chiral effective field theory
nuclear forces and electroweak/WIMP/… interactions,
systematic for energies below ~300 MeV, so for direct detection

structure factors for elastic/inelastic WIMP scattering
based on **large-scale nuclear structure calculations** and
systematic expansion of **WIMP-nucleon currents in chiral EFT**

included **predicted chiral two-body currents** for the first time
renormalizes isovector coupling and p-dependence

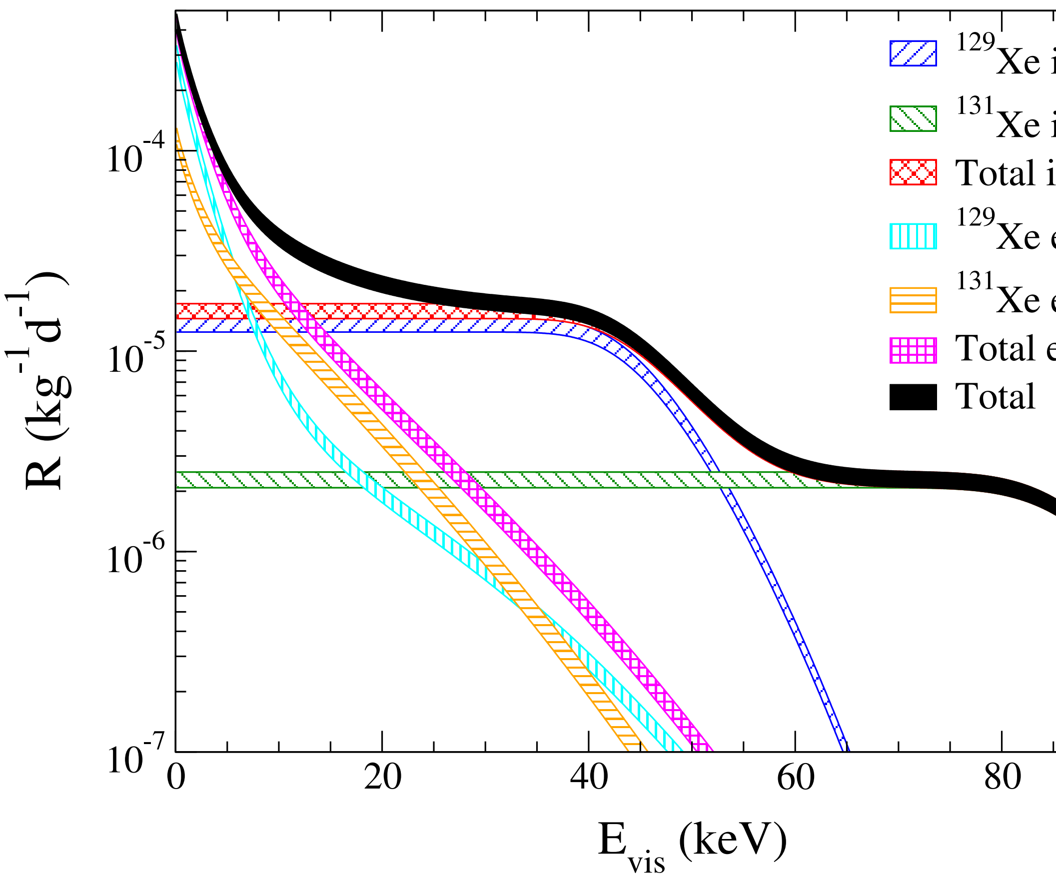
spin-independent results similar to Helm form factors
but need to include two-body currents see Cirigliano et al. (2012)

Signatures for **inelastic** WIMP scattering

elastic recoil **+ prompt γ from de-excitation**

combined information from elastic and inelastic channel will allow to **determine dominant interaction channel** in one experiment

inelastic excitation sensitive to WIMP mass



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.