Nuclear physics uncertainties in direct detection

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Direct dark matter detection

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

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

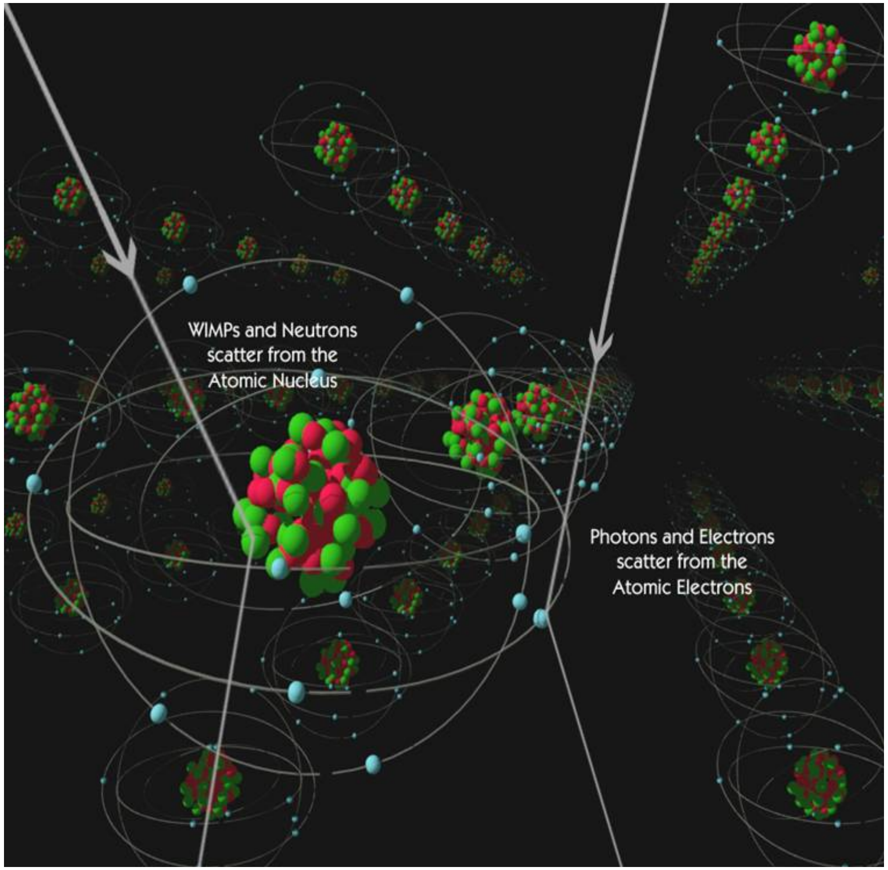
relevant momentum transfers ~ m_π

calculate systematically
with chiral effective field theory

Menendez, Gazit, AS, PRD **86**, 103511 (2012),
Klos, Menendez, Gazit, AS, 1304.7684.

dark matter response may have
more complex couplings in nuclei

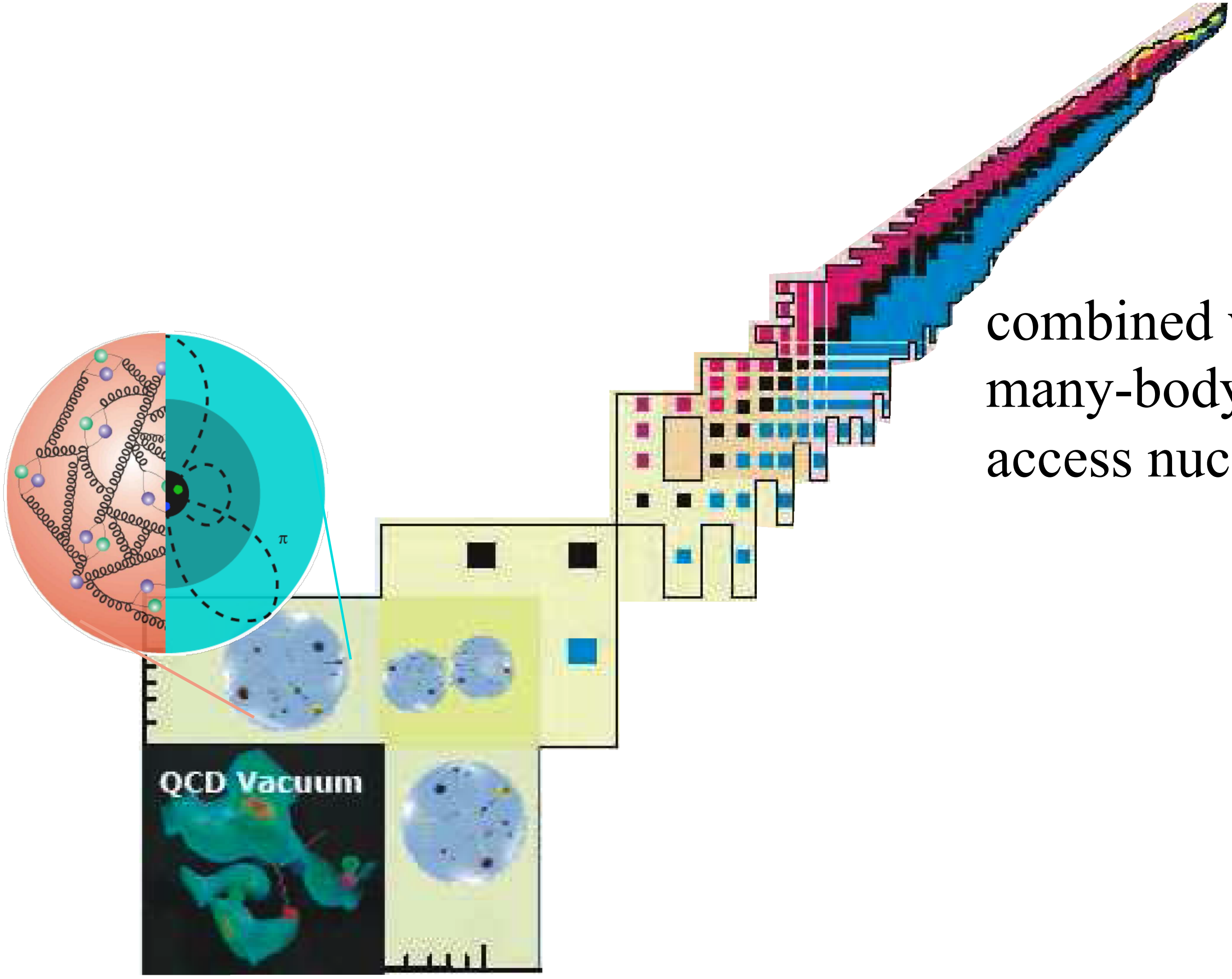
Liam Fitzpatrick, Haxton et al. (2012)



from CDMS collaboration

From QCD to nuclei

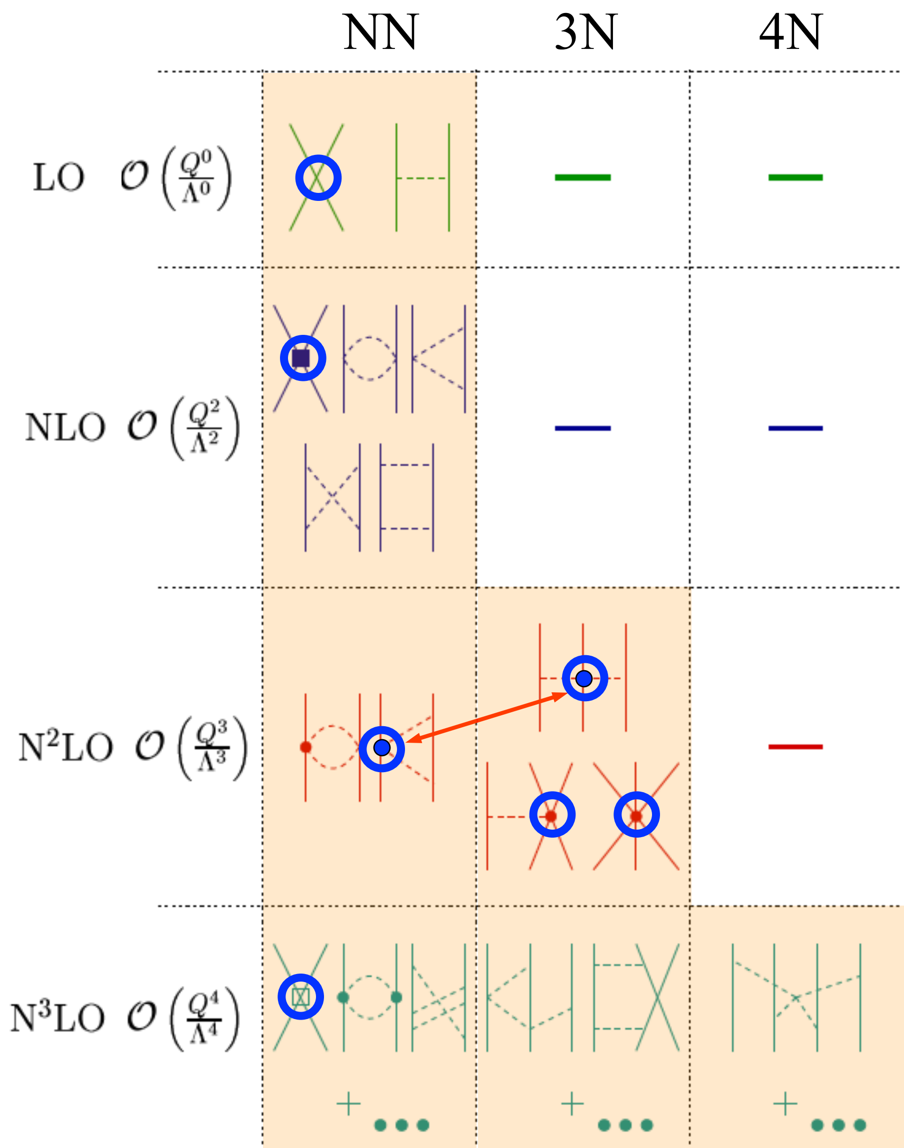
Chiral effective field theory provides a systematic basis for nuclear forces and the coupling to external probes based on the Standard Model



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,…

Frontier of ab-initio calculations at A~50

doi:10.1038/nature12226

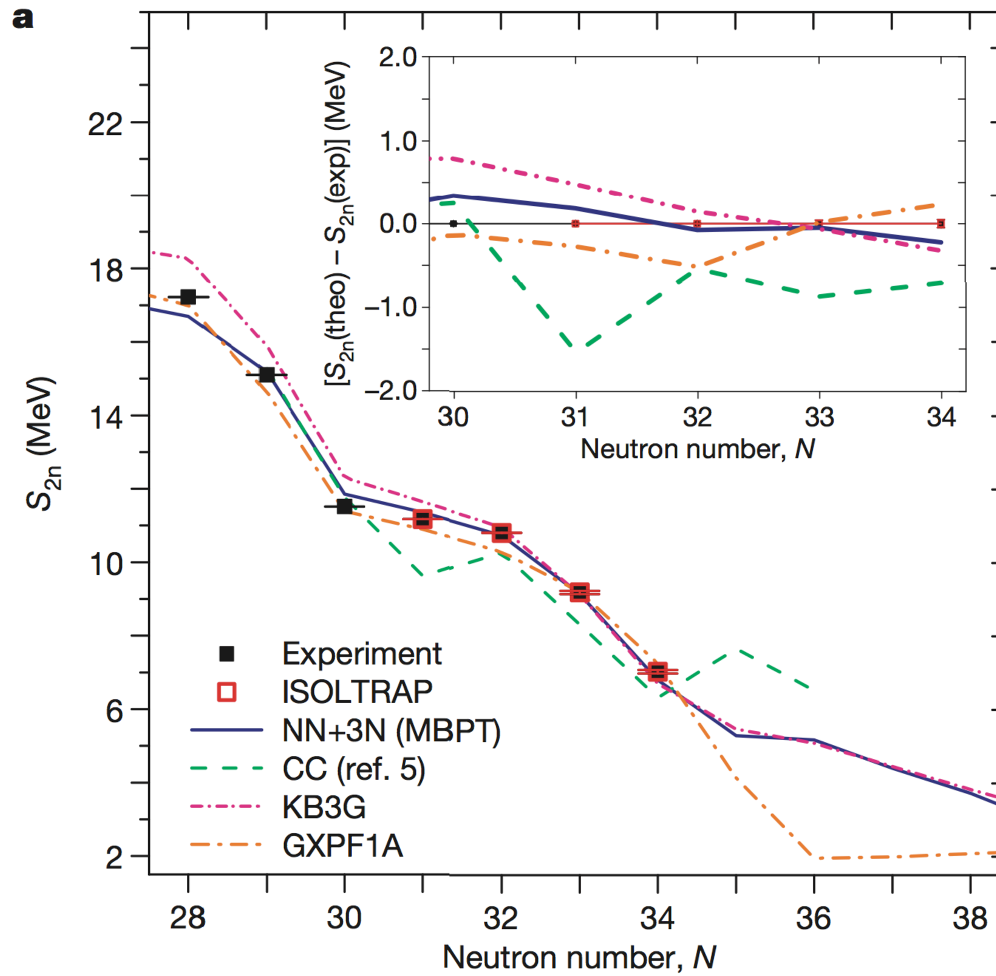
Masses of exotic calcium isotopes pin down nuclear forces

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]

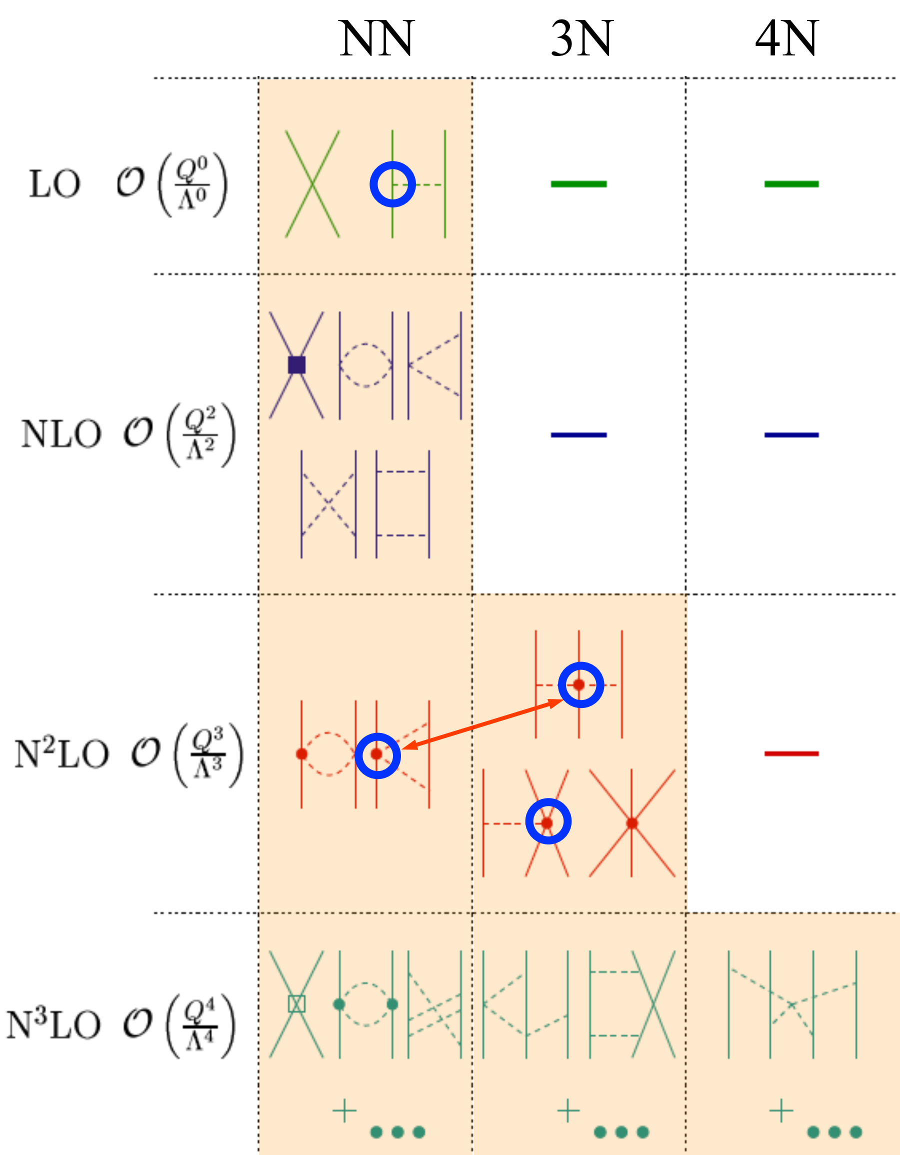
^{53,54}Ca masses measured at ISOLTRAP/CERN using new MR-TOF mass spectrometer

excellent agreement with theoretical predictions from NN+3N forces: NN+3N (MBPT)

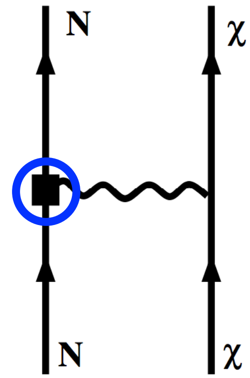
establish prominent N=32 shell closure in calcium



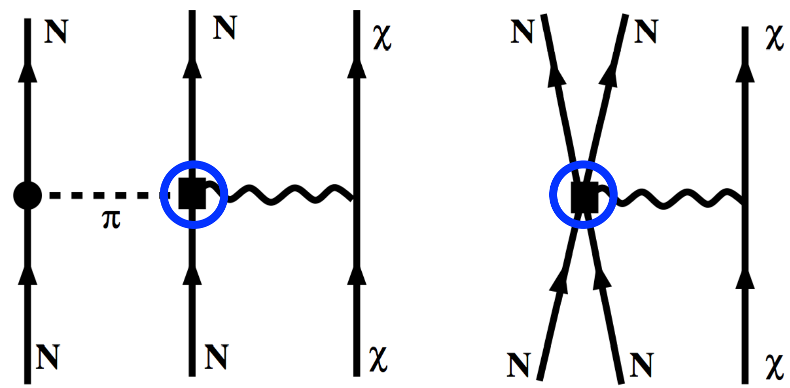
Chiral EFT for WIMP currents in nuclei



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



+ two-body currents at Q^3

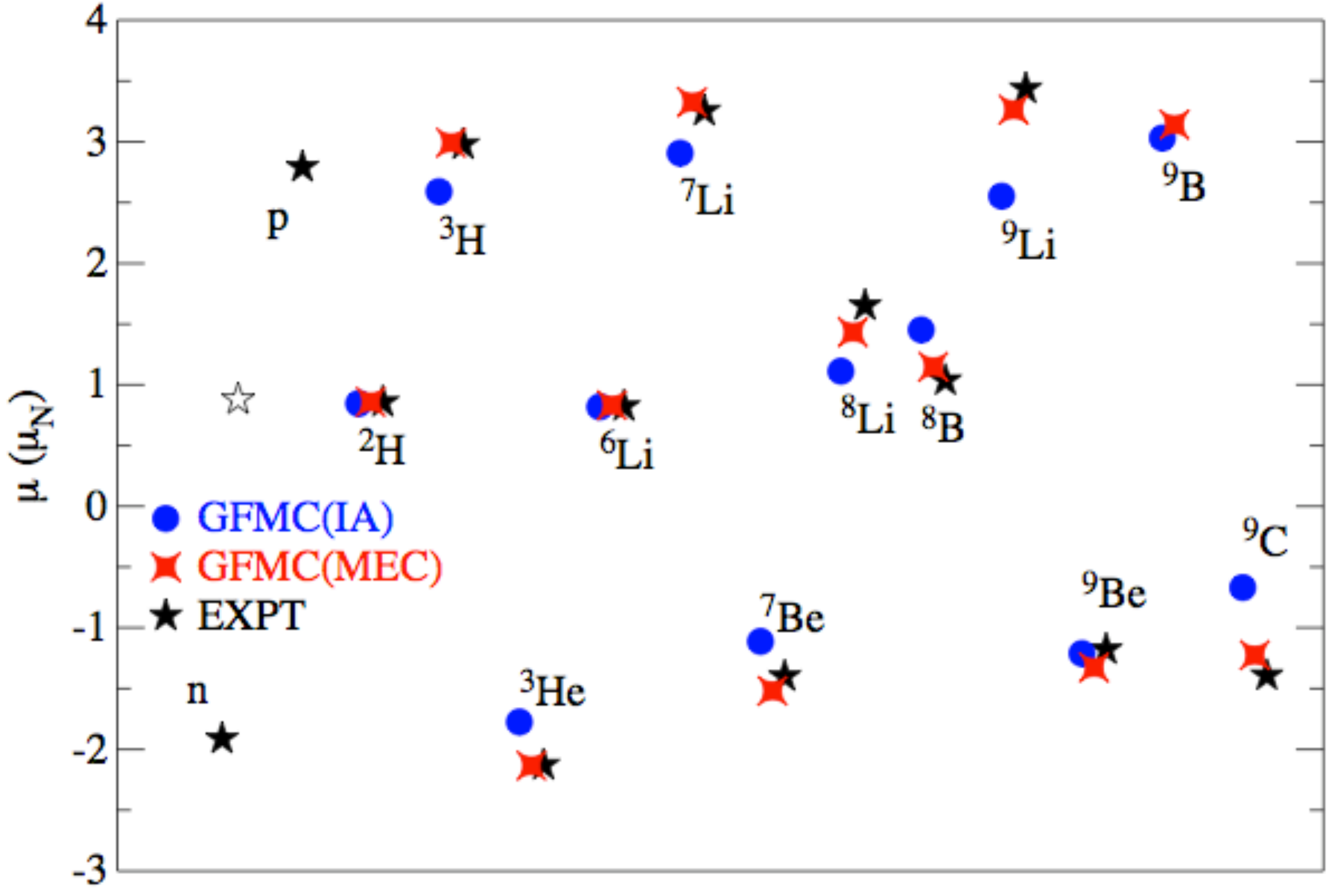


same couplings in forces and currents!

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!

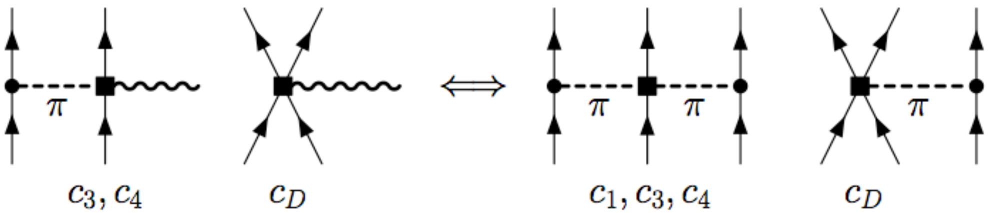


Two-body currents and 3N forces

weak axial currents and WIMP currents couple to spin, similar to pions
spin-dep. WIMP-nucleon int. = isospin rotation of weak axial current

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

Park et al., Phillips,…



two-body analogue of Goldberger-Treiman relation

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 (2011)

WIMP currents in nuclei and uncertainties

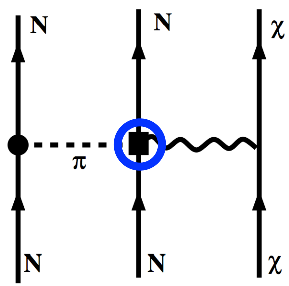
one-body currents with isoscalar/isovector couplings $a_{0/1}$

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

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

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



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

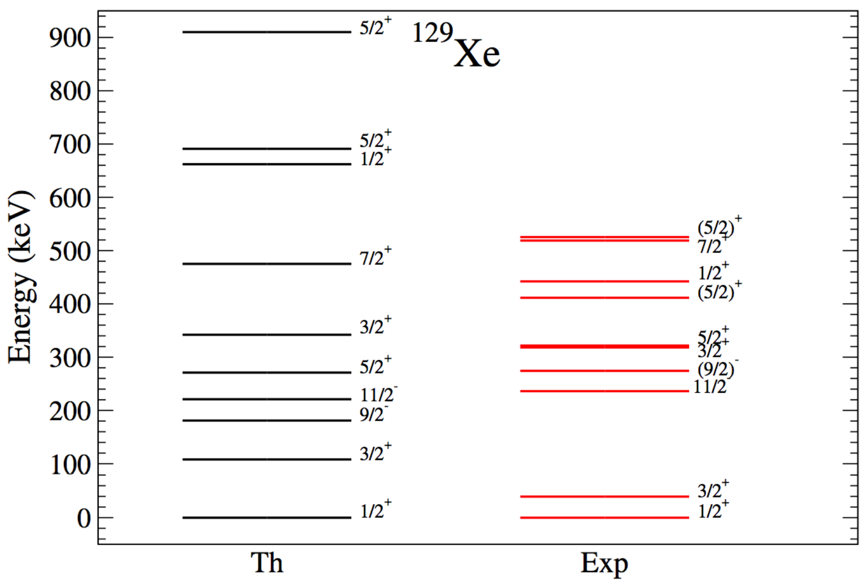
due to interactions among nucleons, dominated by long-range part

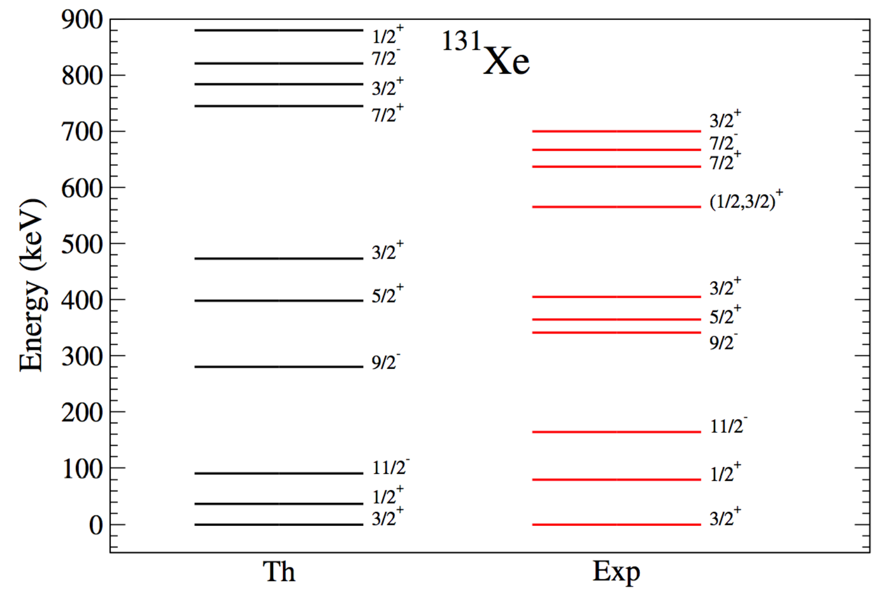
include as density-dependent one-body currents (normal ordering),
uncertainties due to leading-order two-body currents reflected in c_3, c_4

Nuclear structure for direct detection

valence-shell Hamiltonian calculated from NN interactions + corrections to compensate for not including 3N forces (will improved 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

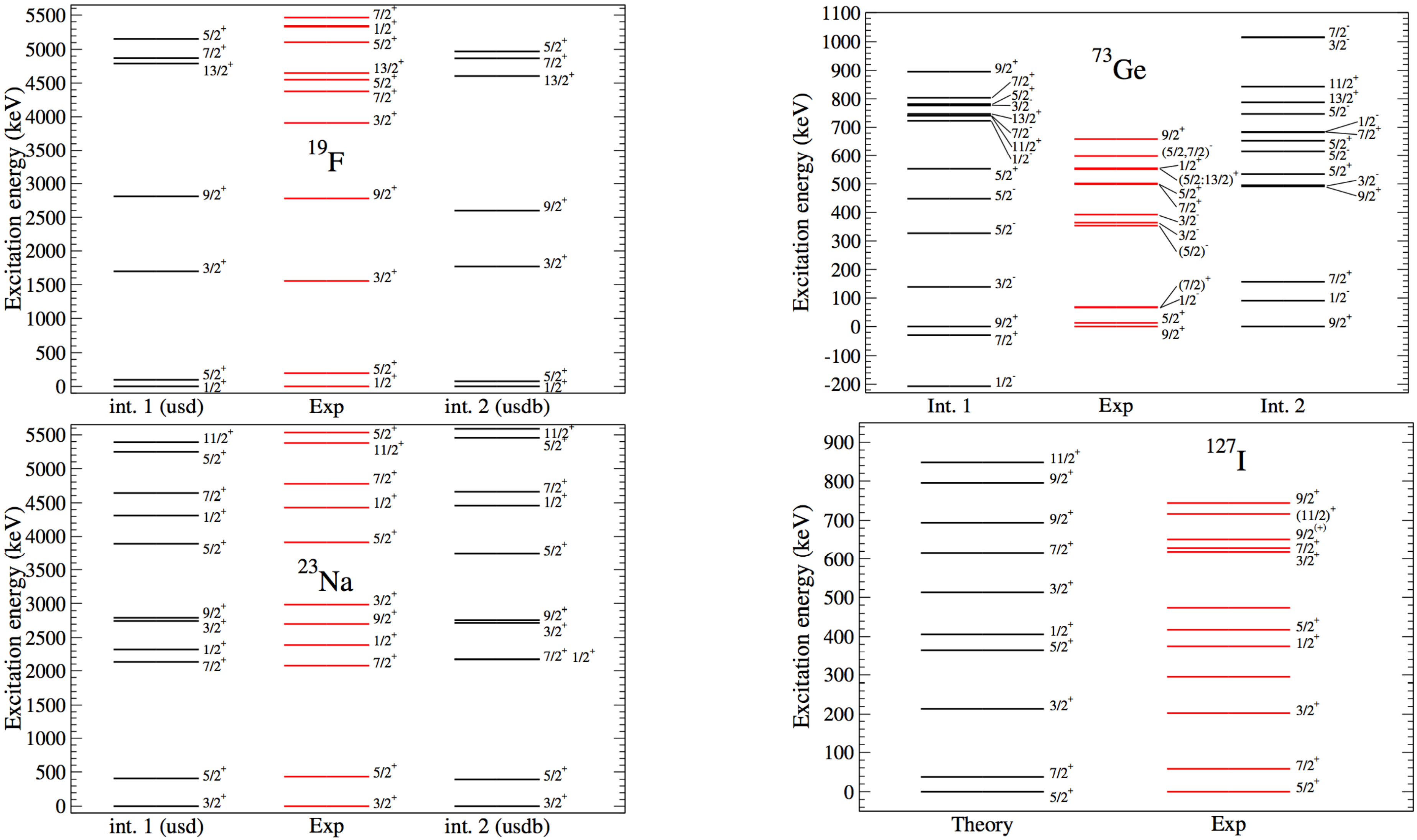
Menendez, Gazit, AS (201)

connects WIMP direct detection with double-beta decay

Nuclear structure II

similar agreement for other nuclei relevant to direct detection

Menendez, Klos, Gazit, AS (2013)



Nuclear structure factors

differential cross section for spin-dependent WIMP scattering

$\sim$ axial-vector structure factor $S_A(p)$

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

decompose into longitudinal, transverse electric and transverse magnetic

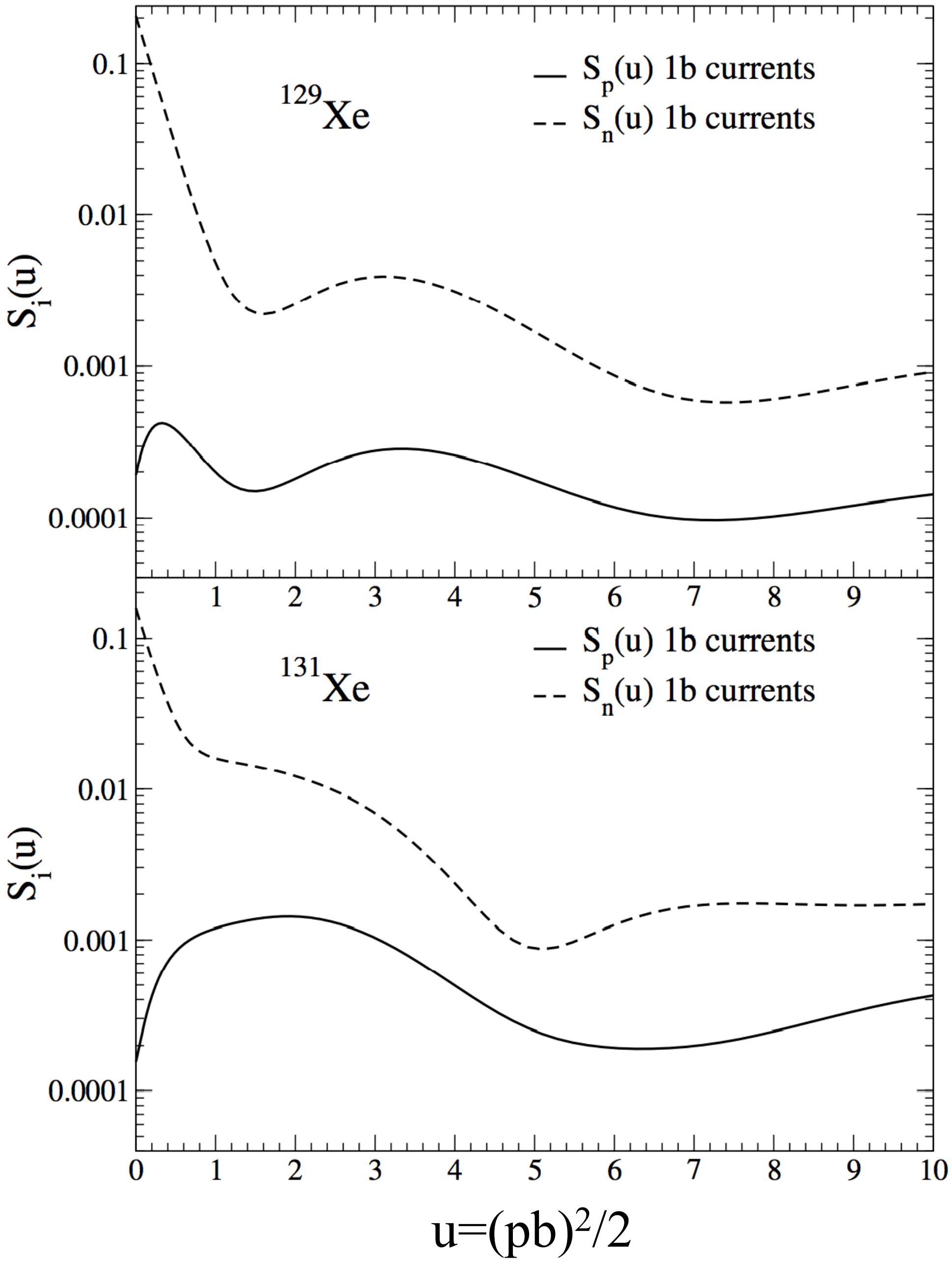
$$S_A(p) = \sum_{L \geqslant 0} \left| \langle J_f || \mathcal{L}_L^5 || J_i \rangle \right|^2 + \sum_{L \geqslant 1} \left(\left| \langle J_f || \mathcal{T}_L^{\rm el5} || J_i \rangle \right|^2 + \left| \langle J_f || \mathcal{T}_L^{\rm mag5} || J_i \rangle \right|^2 \right)$$

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

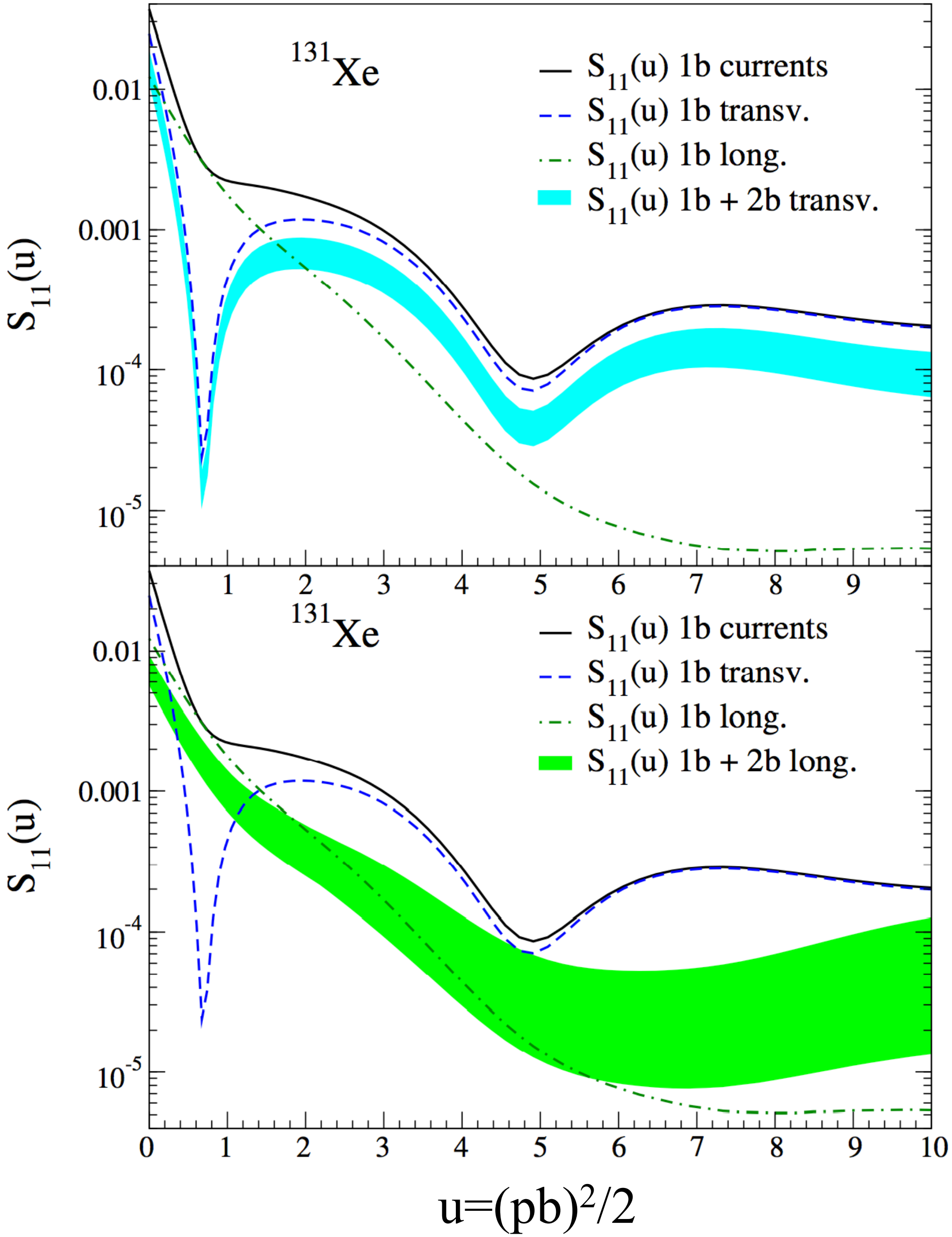
at p=0 structure factors
at the level of one-body currents
dominated by "neutron"-only

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

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

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

Xenon response with 1+2-body currents



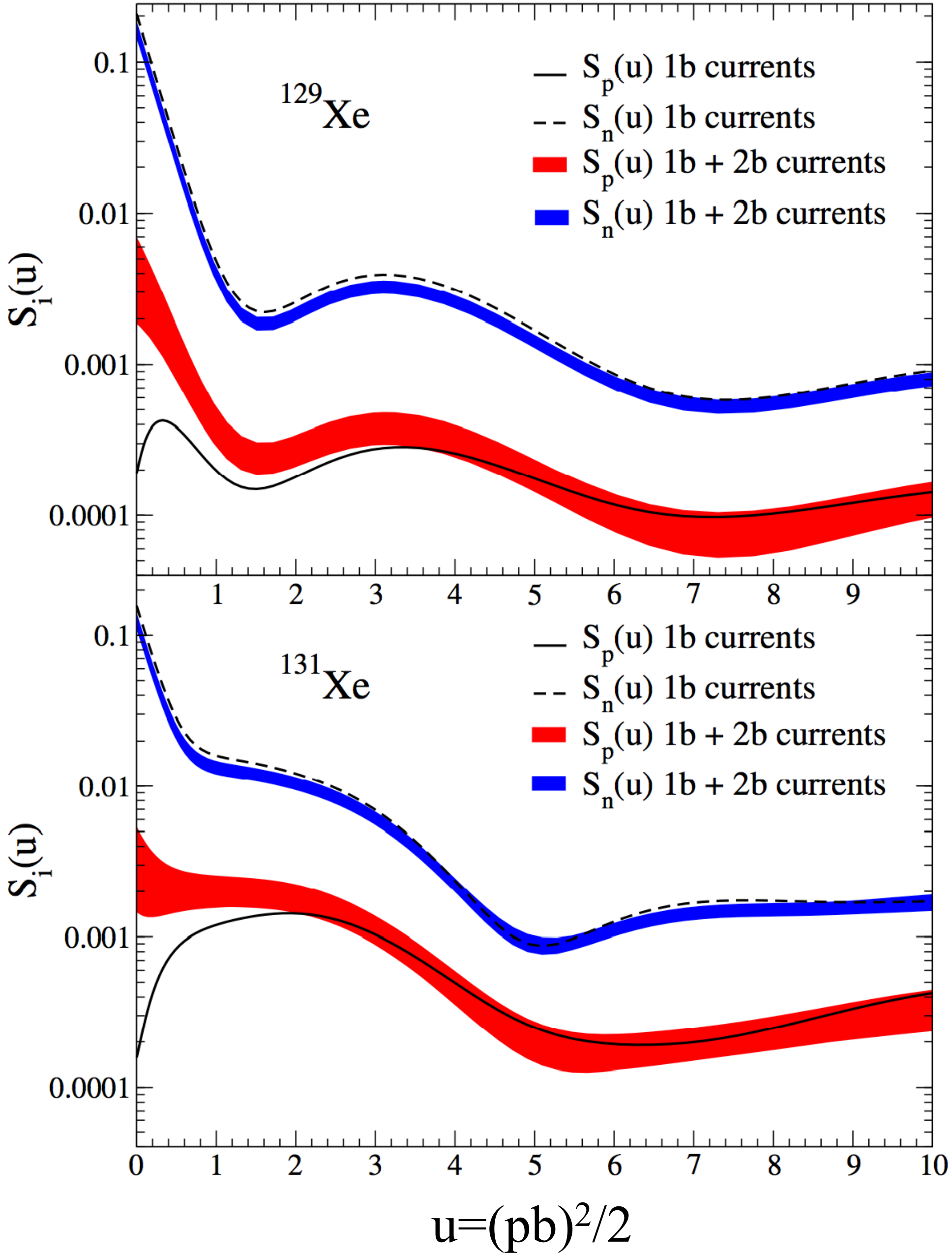
leading two-body currents renormalize isovector coupling: not “neutron”/“proton” only

lead to reduction of axial current enhancement of pseudoscalar curr.

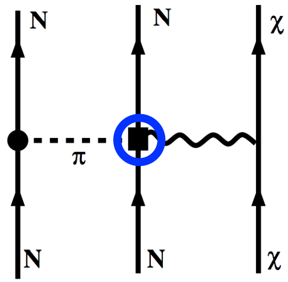
transverse multipoles reduced; longitudinal reduced at low p, but enhanced at high p

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

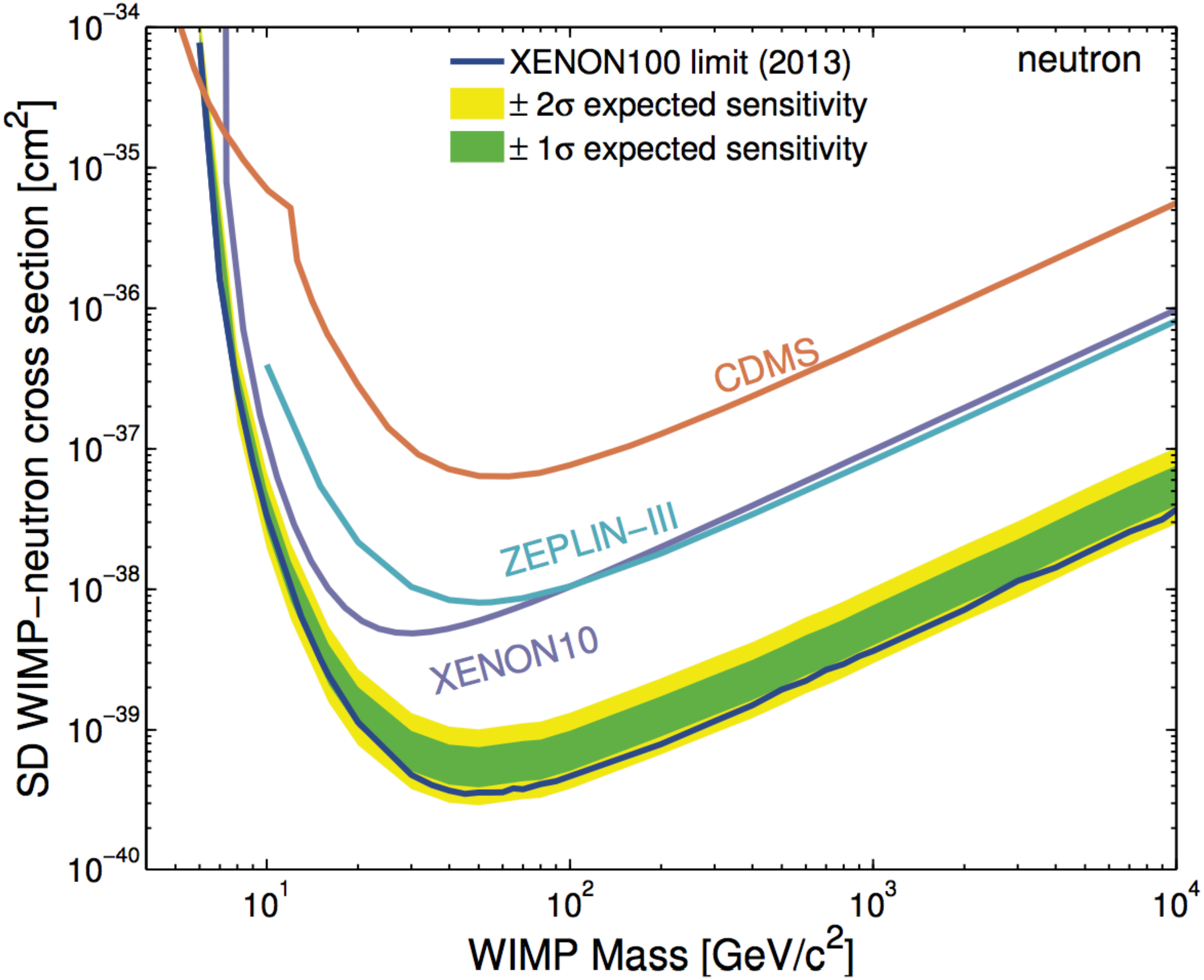
enhances coupling to even species in all cases

first calculations with chiral EFT currents and state-of-the-art nuclear interactions

Limits on SD WIMP-neutron interactions

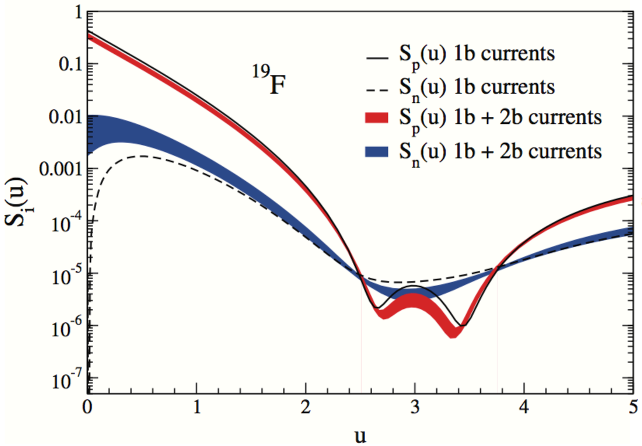
best limits from XENON100 Aprile et al., 1301.6620, see talk by T. Marrodan Undagoitia

used our calculations with uncertainty bands for WIMP currents in nuclei

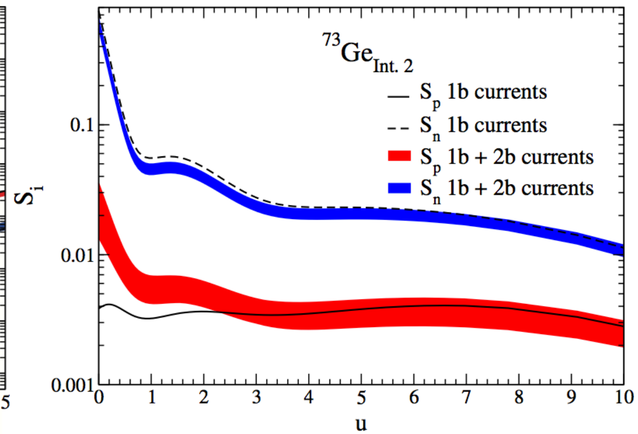


Spin-dependent WIMP-nucleus response for ^{19}F, ^{23}Na, ^{27}Al, ^{29}Si, ^{73}Ge, ^{127}I

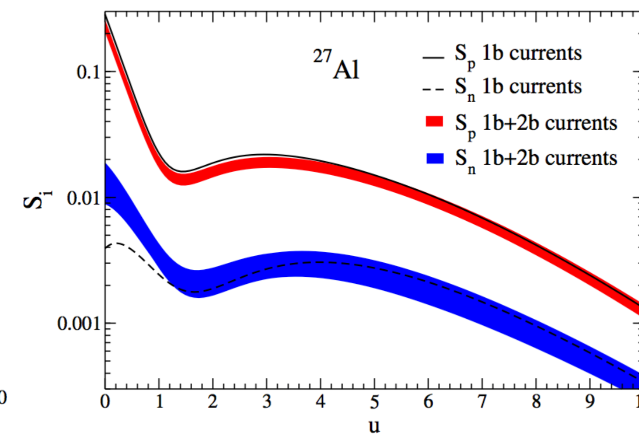
Klos, Menendez, Gazit, AS (2013)



PICASSO, COUPP, SIMPLE



CDMS, EDELWEISS, EURECA



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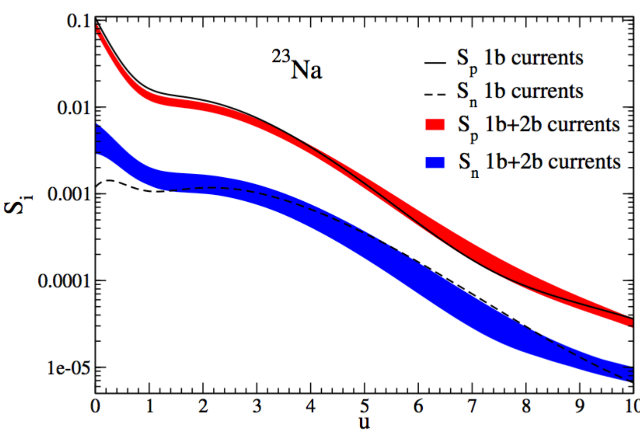
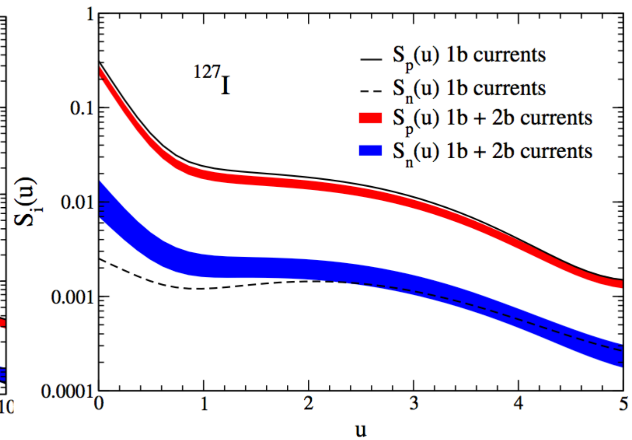
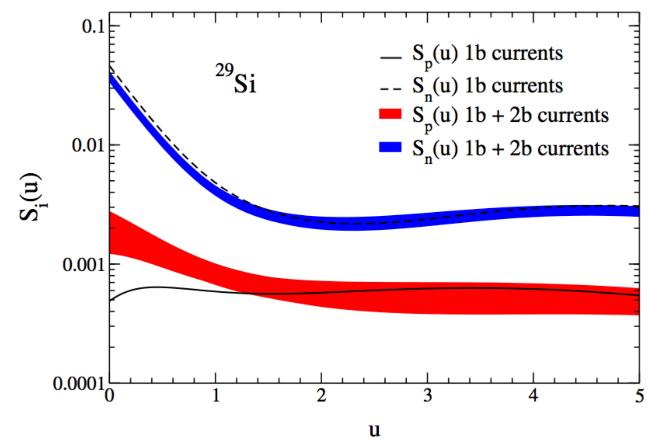


DAMA, ANAIS, DM-Ice



DAMA, ANAIS, DM-Ice, KIMS



CDMS-II

Summary

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

structure factors for spin-dependent elastic 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

similar two-body current contributions to double-beta decay
Menendez, Gazit, AS, PRL **107**, 062501 (2011).

future: advance nuclear structure calcs. based on NN+3N forces