Linking LHC and direct detection results in Higgs Portals

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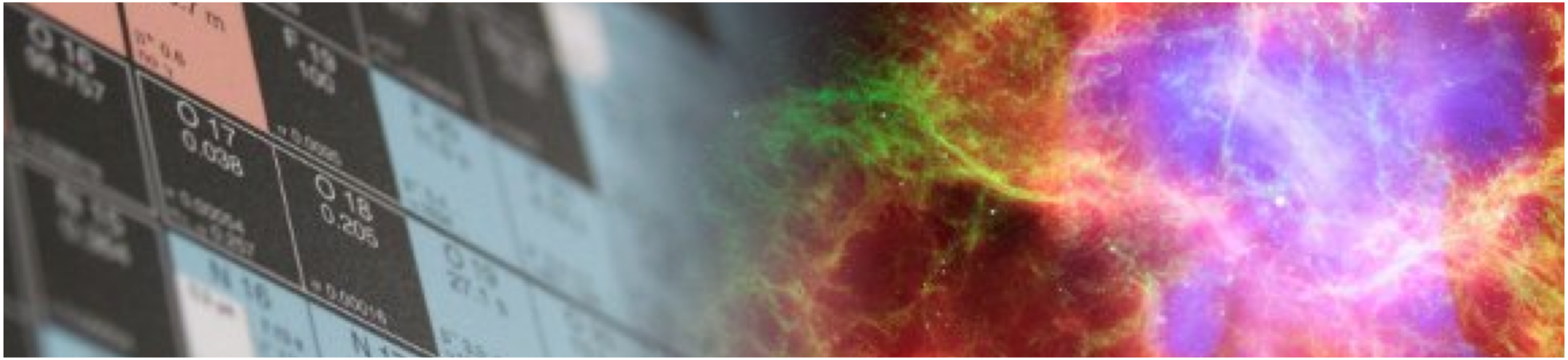

DM@LHC, Heidelberg, April 5, 2018

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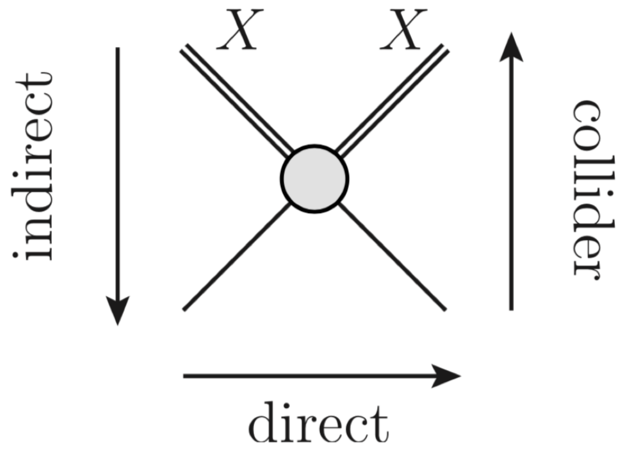
DM in direct detection and at LHC

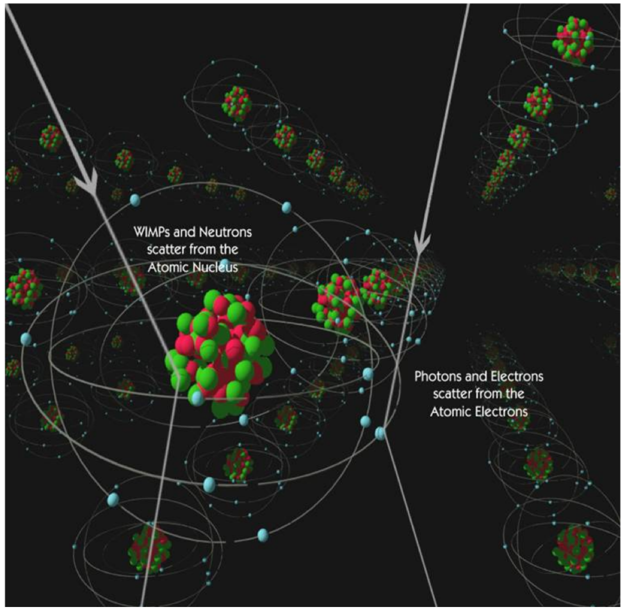
Assume DM particle is WIMP, search strategies:



Direct detection:
WIMP scattering off nuclei, needs as input

Nucleon matrix elements
WIMP-q,G couplings in nucleons

Nuclear structure factors
sensitive to nuclear physics



relevant momentum transfers $\sim m_\pi$
calculate systematically with chiral EFT
Menéndez et al., PRD (2012), Klos et al., PRD (2013),
Baudis et al., PRD (2013), Vietze et al., PRD (2015),
Hoferichter et al., PLB (2015), Hoferichter et al., PRD (2016)

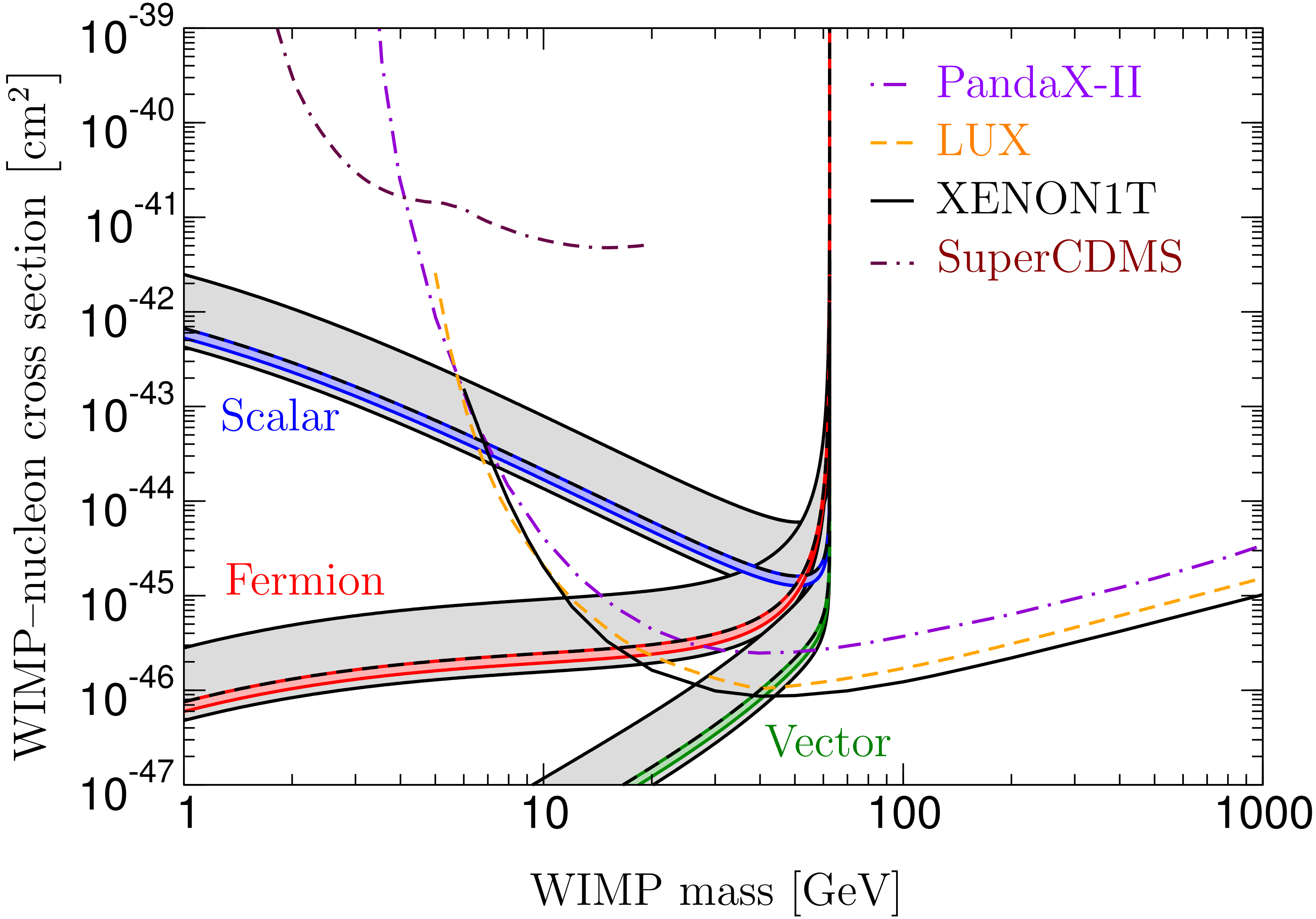
incorporate what we know about **QCD/nuclear physics**

same nucleon matrix elements enter **Higgs Portals** Hoferichter et al., PRL (2017)

Linking LHC and direct detection results in Higgs Portals

Main result: **improved and consistent limits for Higgs Portals**

Hoferichter, Klos, Menéndez, AS, PRL (2017)



Scales in DM direct detection

BSM scale: WIMPs coupling to q,G via exchange particles

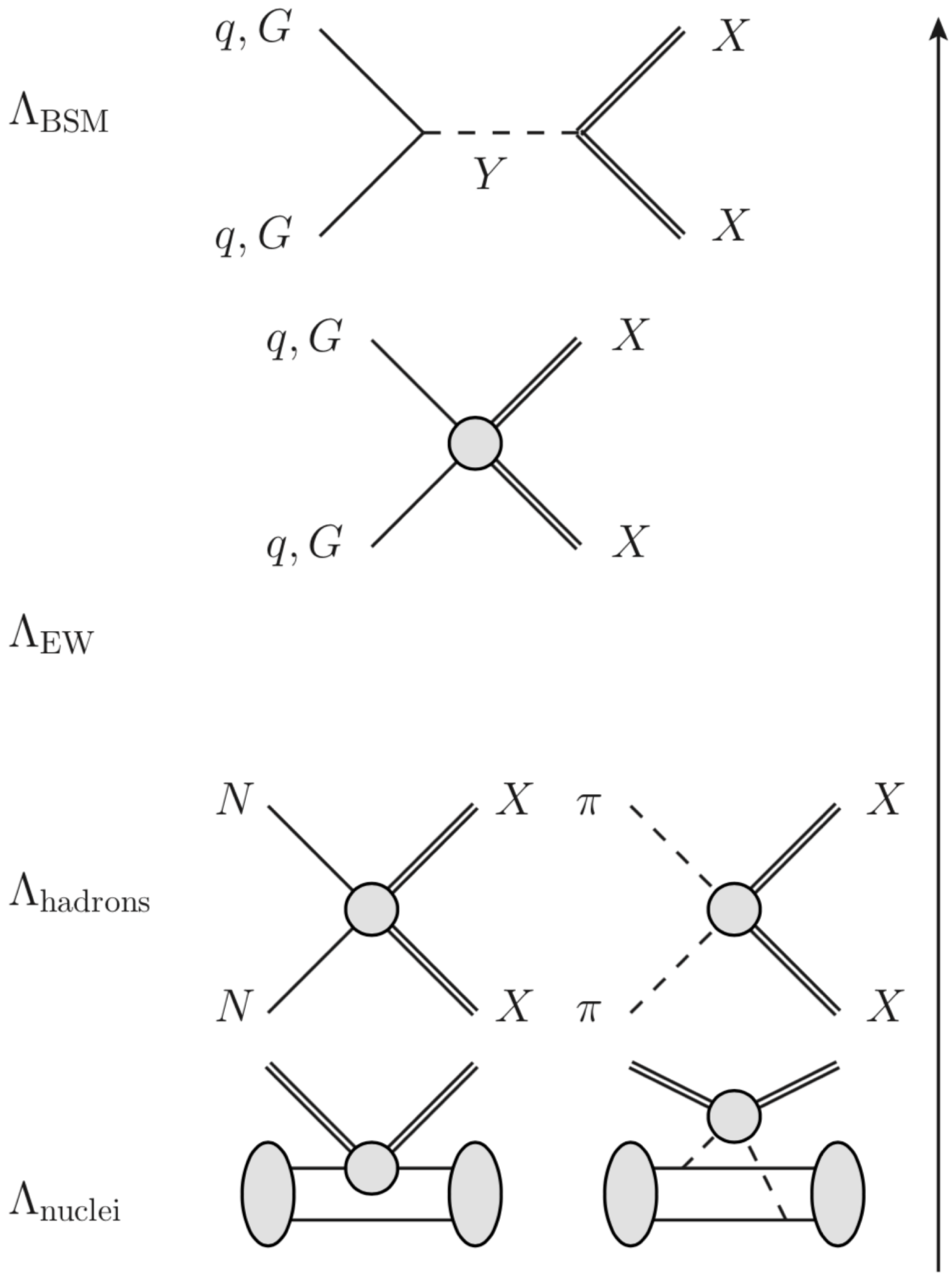
SM + **effective operators**

$$\mathcal{L}_{\rm SM} + \sum_{i,k} \frac{1}{\Lambda^i_{\rm BSM}} \mathcal{O}_{i,k}$$

Integrate out **EW physics**

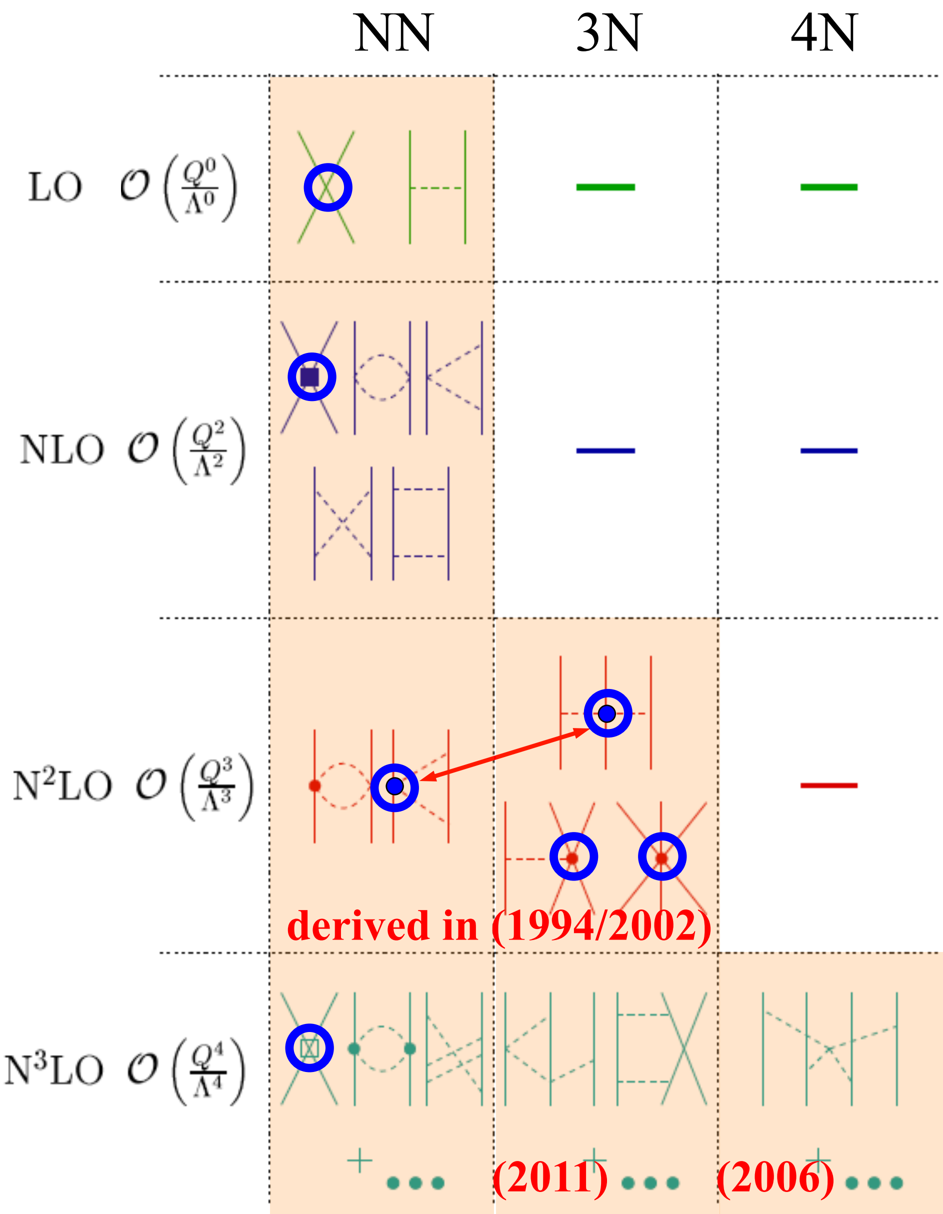
Chiral EFT scale: WIMP coupling to nucleons and pions

Nuclear scale: embedding chiral EFT operators in nucleus



Chiral EFT for nuclear forces

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



include long-range pion physics

few short-range couplings,
fit to experiment once

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

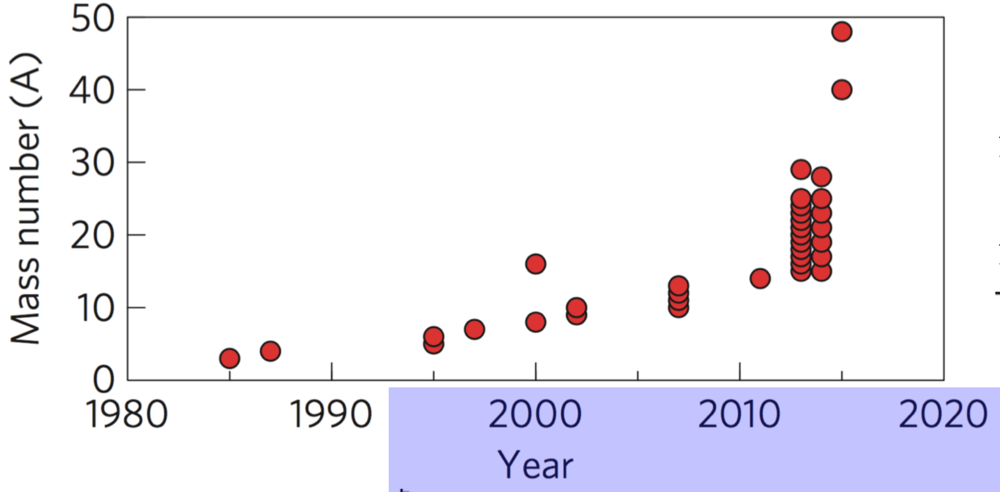
consistent **electroweak interactions** and **matching to lattice QCD**

from quarks to nucleons/pions for **coupling to beyond SM particles**

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

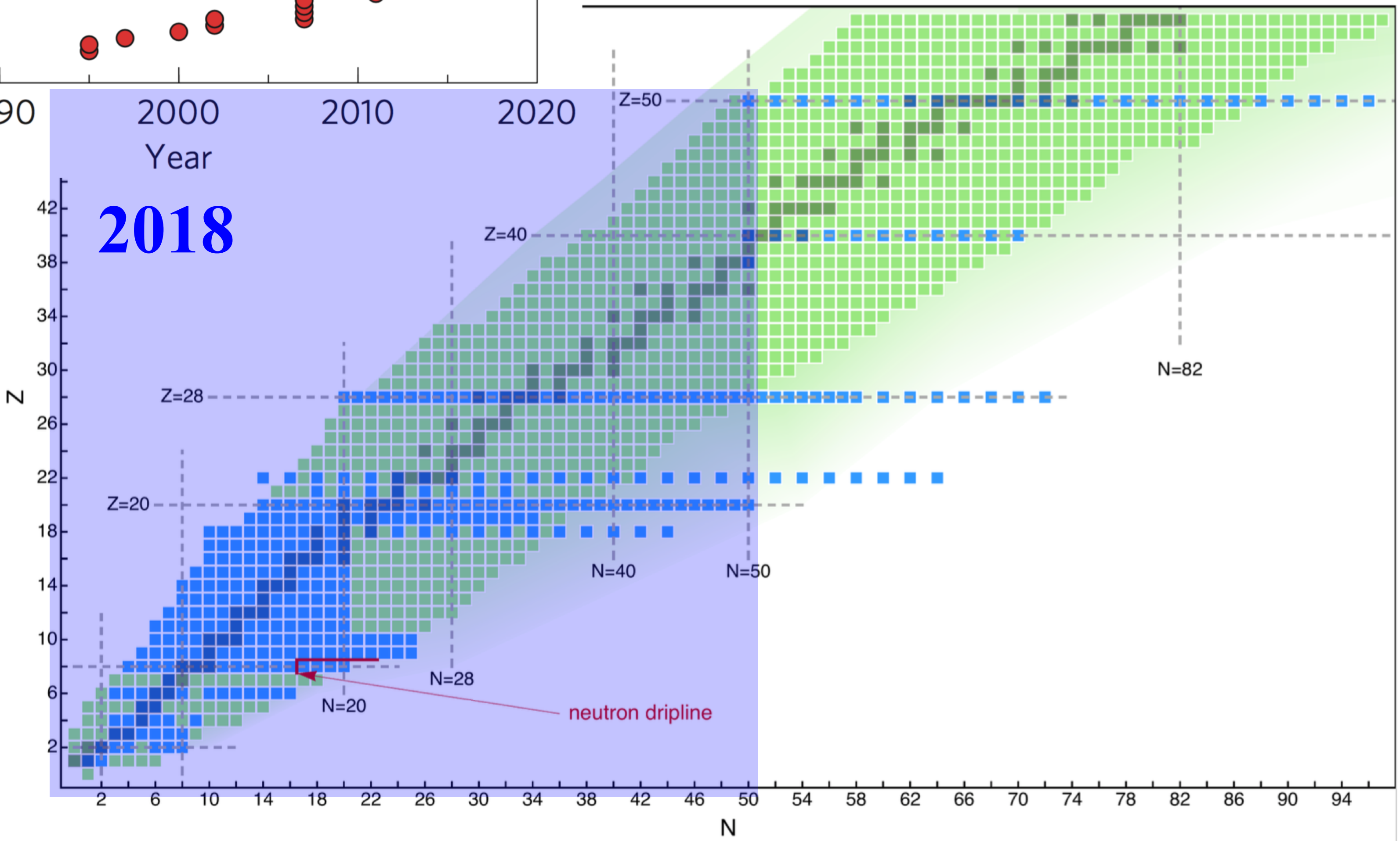
Progress in ab initio calculations of nuclei

dramatic progress in last 5 years to access nuclei up to A ~ 50



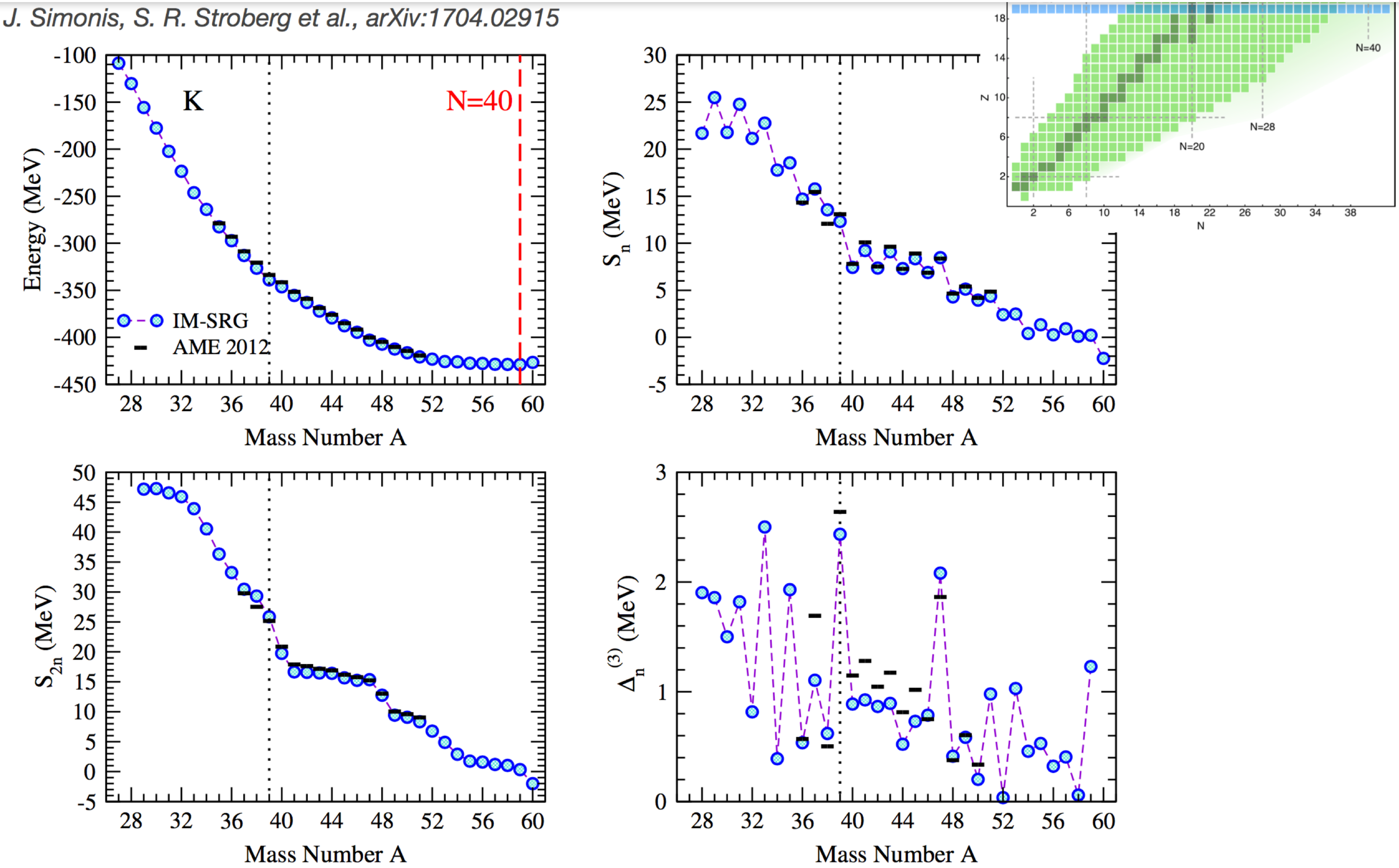
from Hagen et al., Nature Phys. (2016)

from Hergert et al., Phys. Rep. (2016)

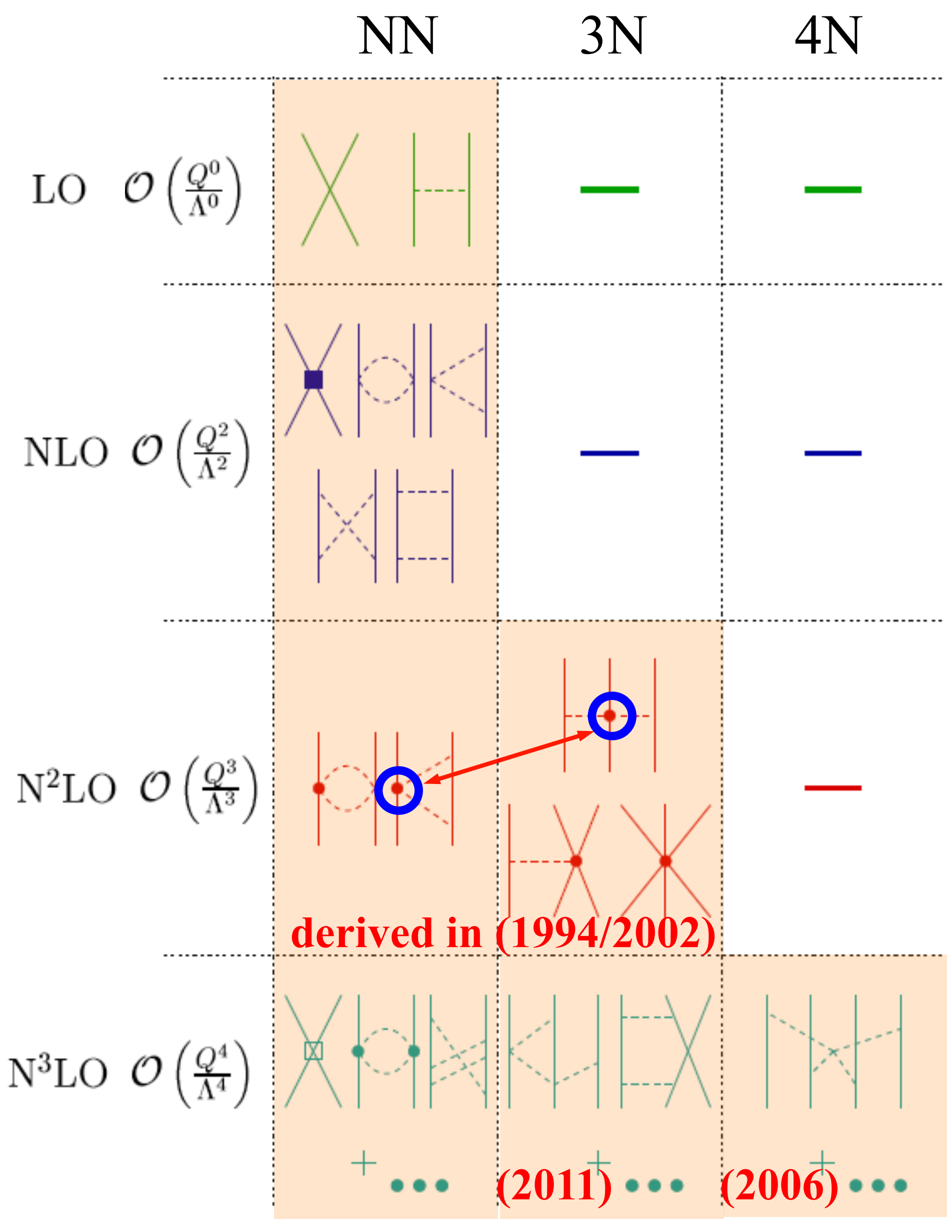


Ab initio prediction of medium-mass nuclei possible

J. Simonis, S. R. Stroberg et al., arXiv:1704.02915

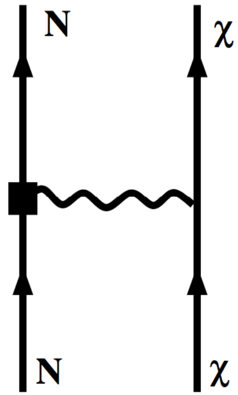


Chiral EFT for coupling to external sources

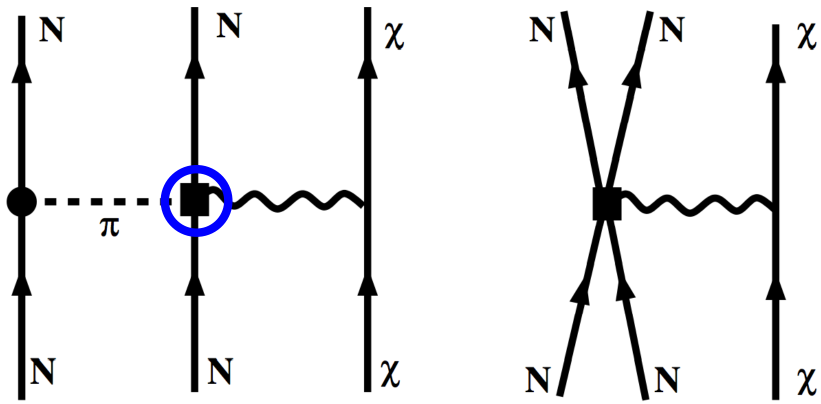


example: axial-vector currents

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



+ two-body currents at Q^3

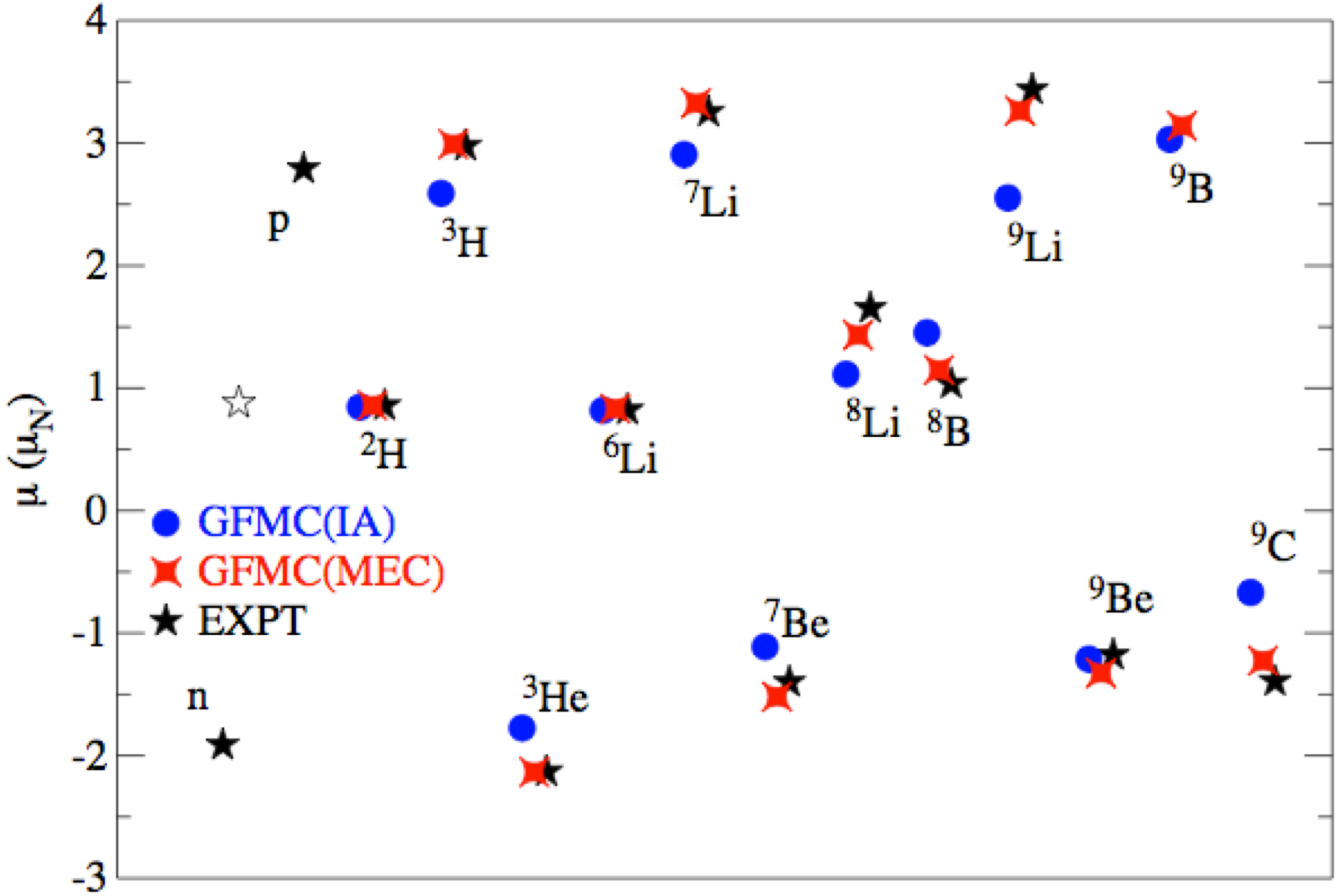


same couplings in forces and currents!

Chiral EFT currents and electromagnetic interactions

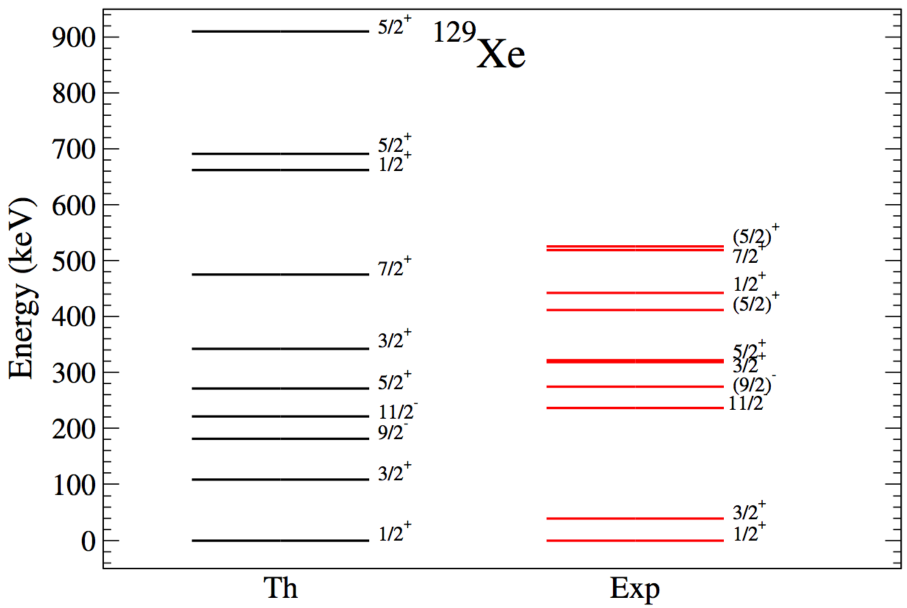
predicts consistent electromagnetic 1+2-body currents

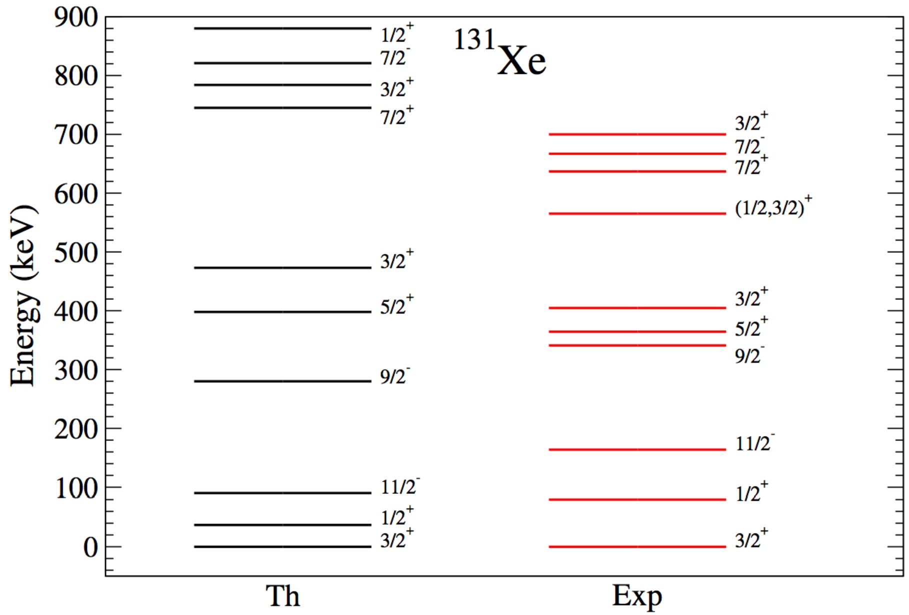
GFMC calculations of magnetic moments in light nuclei Pastore et al. (2012-)
2-body currents (meson-exchange currents=MEC) are key!



Nuclear structure for direct detection

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





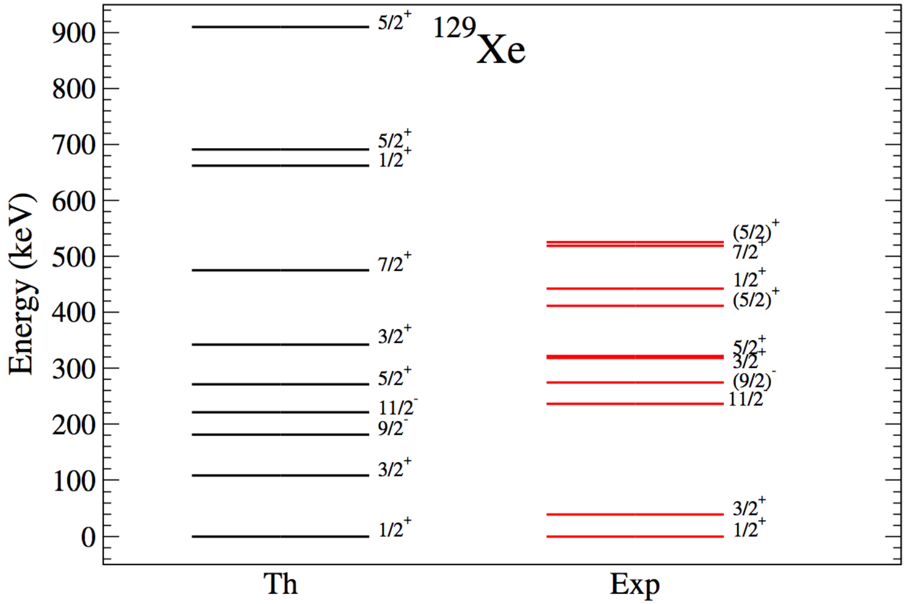
very good agreement for spectra; ordering and grouping well reproduced

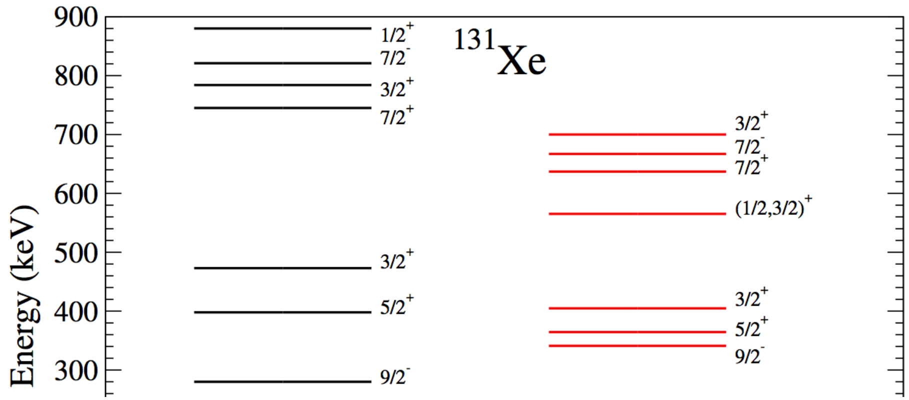
Menendez, Gazit, AS, PRD (2012)

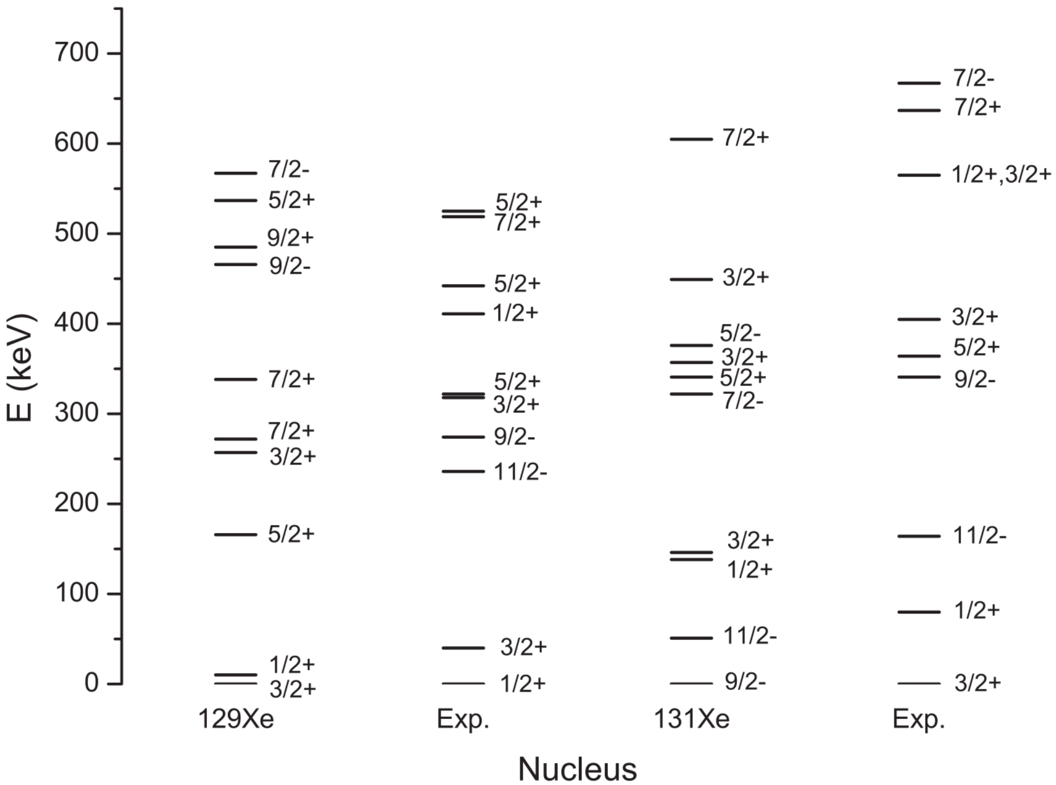
connects WIMP direct detection with double-beta decay

Nuclear structure for direct detection

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





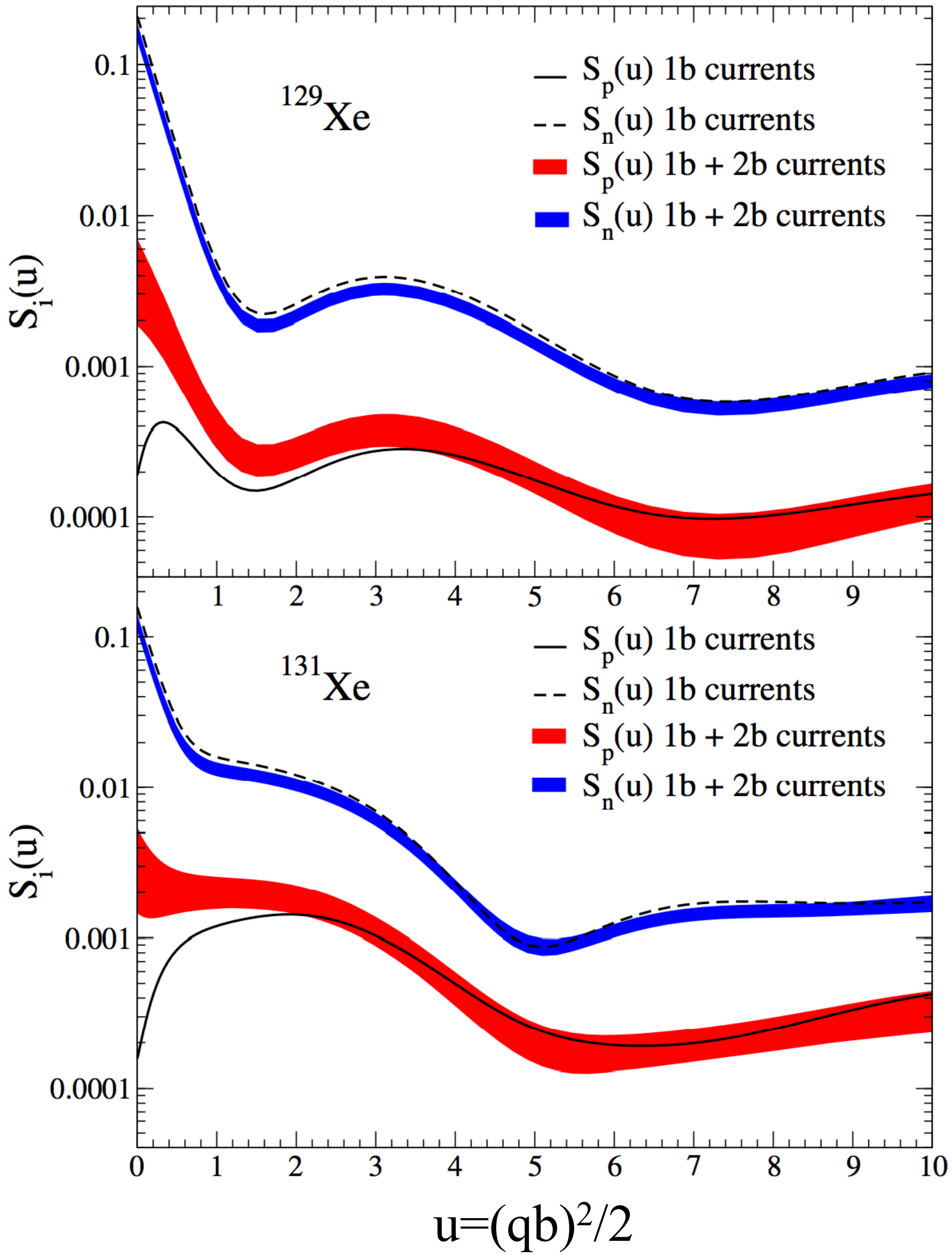


very good agreement for spectra;

Menendez, Gazit, AS, PRD (2012)

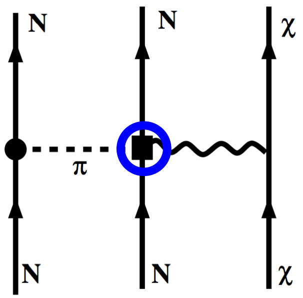
compare to other calculations for WIMP scattering

Spin-dependent Xenon reponse with 1+2-body currents



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

two-body currents due to strong interactions among nucleons



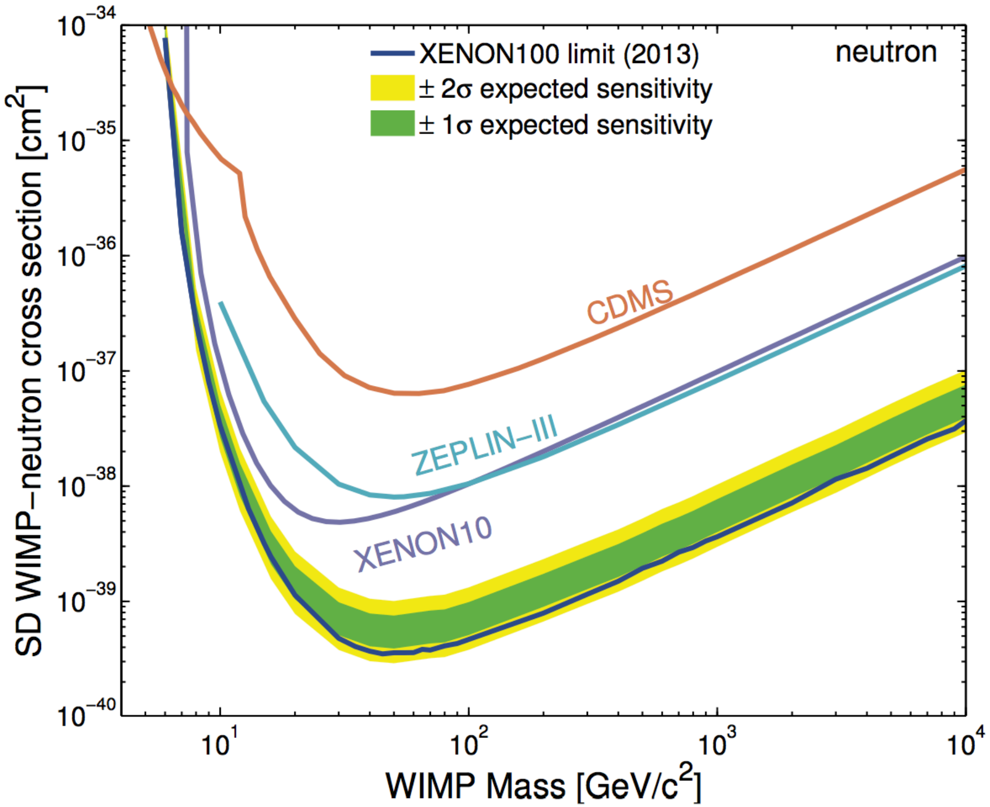
WIMPs couple to neutrons and protons at the same time

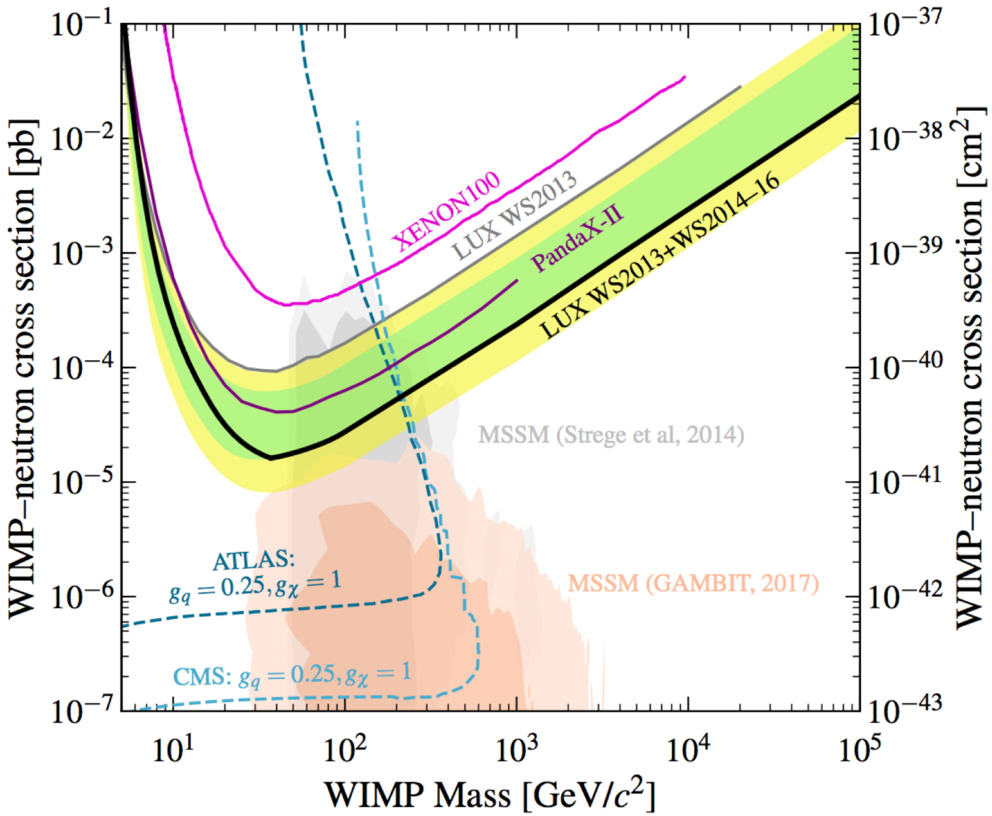
enhances coupling to even species in all cases (protons for Xe)

Limits on SD WIMP-neutron interactions

limits from XENON100 Aprile et al., PRL (2013)
PandaX-II Fu et al., PRL (2017) and LUX Akerib et al., PRL (2017)

used our calculations with uncertainty bands for WIMP currents in nuclei





Limits on SD **WIMP-proton interactions**

limits from XENON100 Aprile et al., PRL (2013)

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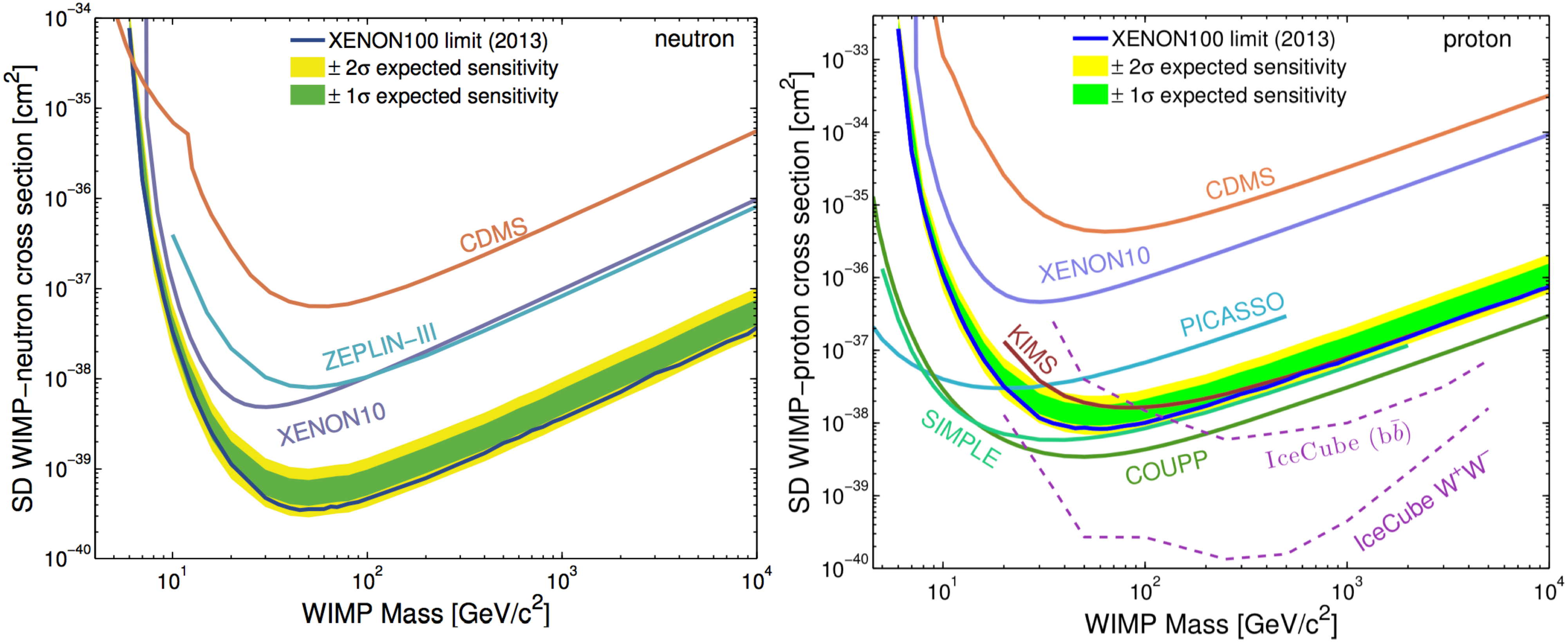
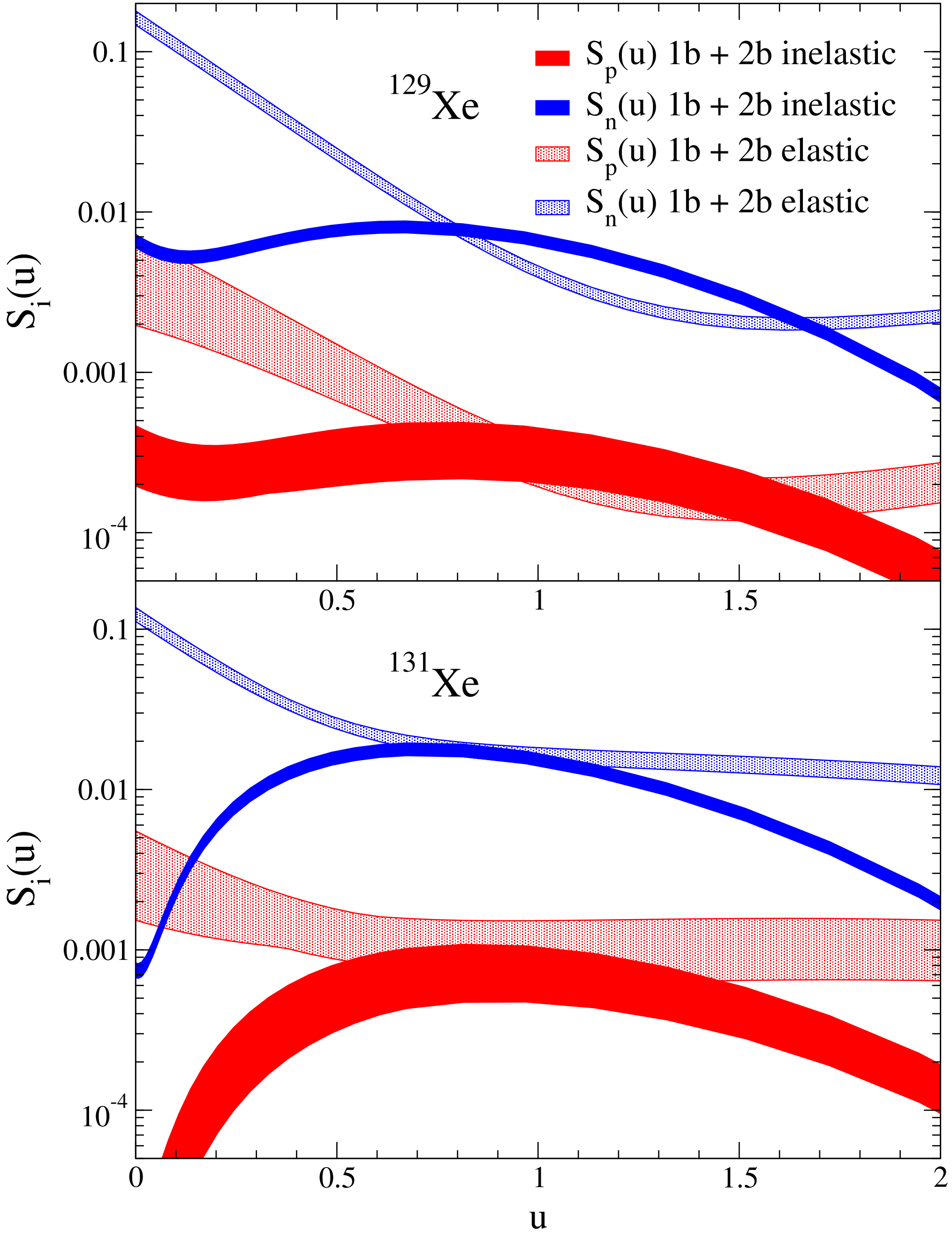


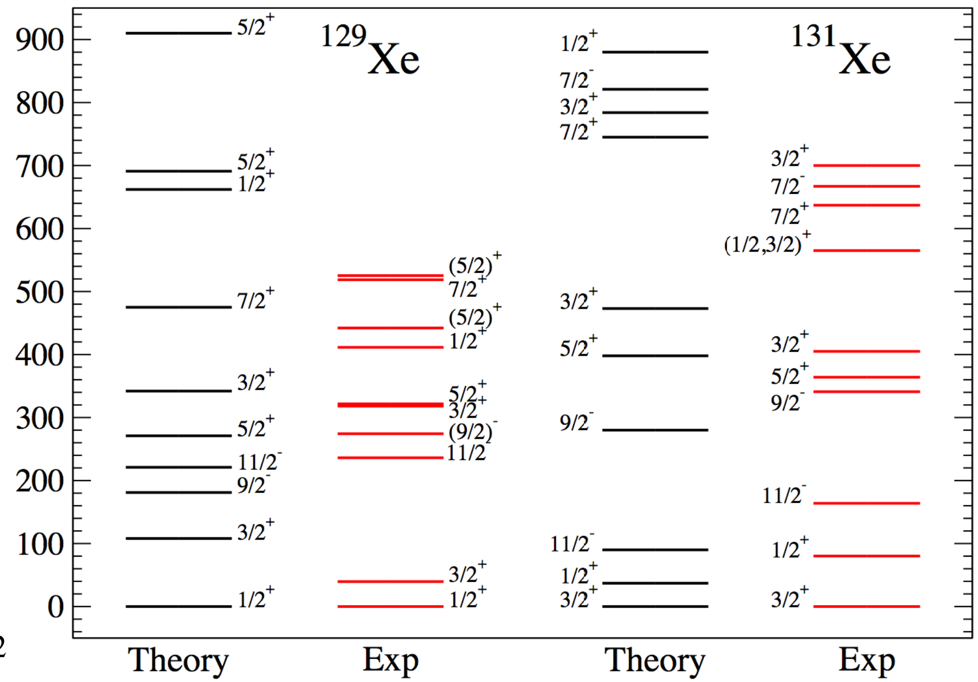
XENON competitive for WIMP-proton coupling due to 2-body currents

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

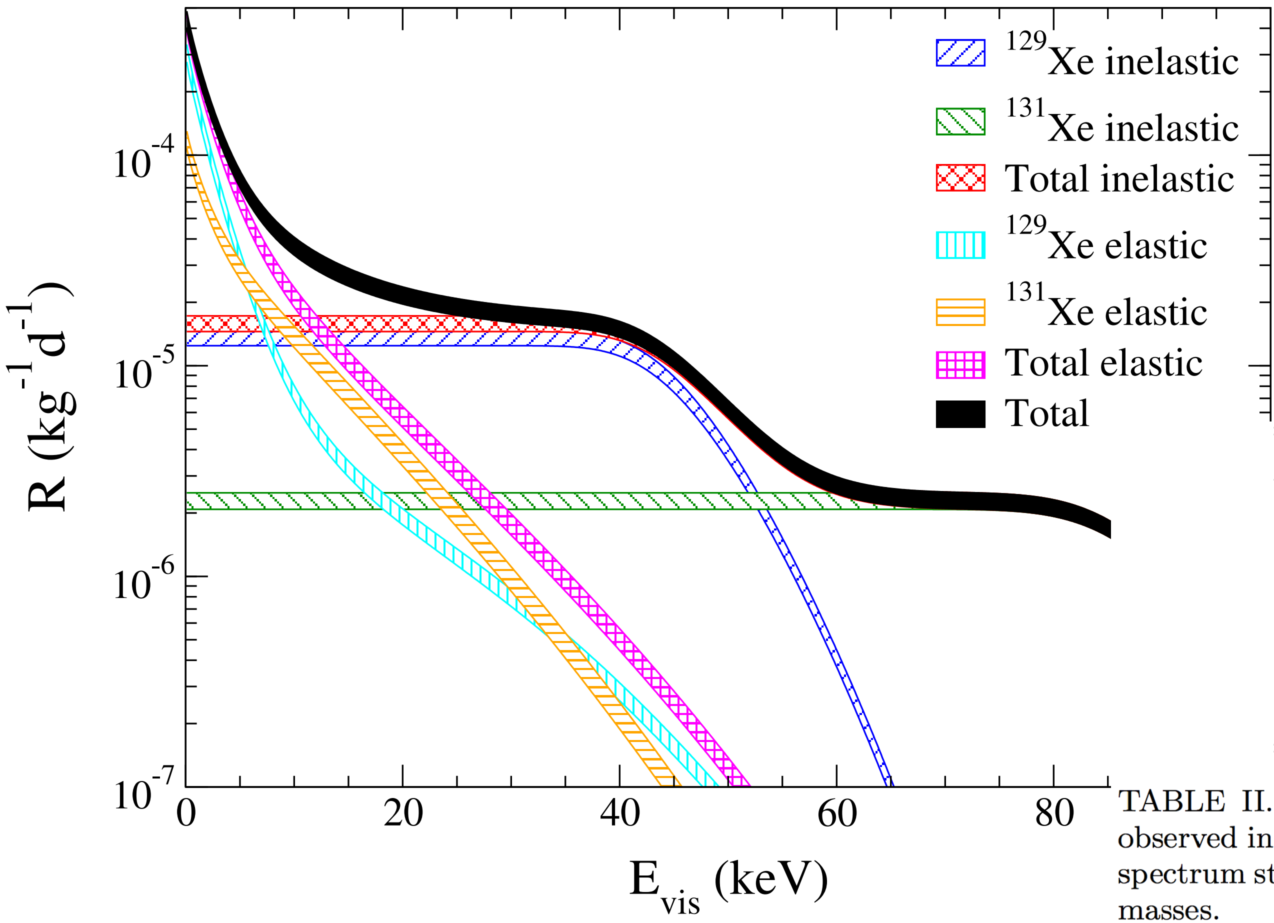


Signatures for **inelastic** WIMP scattering

elastic recoil **+ promt 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.

Chiral EFT for general WIMP-nucleon interactions

chiral symmetry implies a hierarchy for general responses with Q^ν

Hoferichter, Klos, AS, PLB (2015)

WIMP	Nucleon	V t	V $\mathbf{x}$	A t	A $\mathbf{x}$
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	–	$4+2$

SD interactions are axial-vextor (A) – A interactions, SI is scalar (S) – S

2-body currents as large as 1-body currents in V-A channel

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chiral symmetry implies a hierarchy for general responses with Q^ν

Hoferichter, Klos, AS, PLB (2015)

WIMP	Nucleon	V t	V $\mathbf{x}$	A t	A $\mathbf{x}$
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

matching to non-relativistic EFT

Fitzpatrick et al., JCAP (2013)

without chiral physics

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

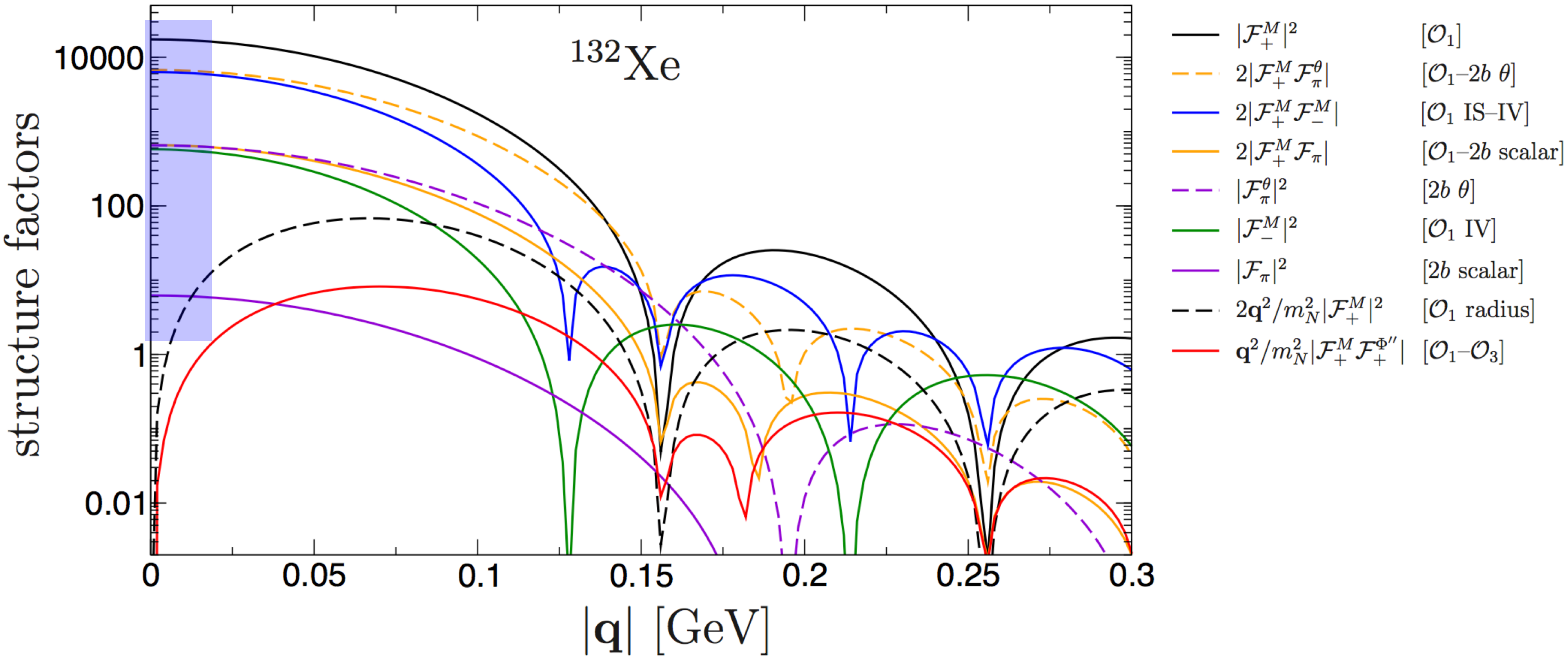
shows that NREFT operators are not linearly indep. (e.g., 4+6 are SD)

and not all are present up to ν=3 (only 8 of 11 operators)

General coherent (SI+) WIMP nucleus scattering

for scalar currents: Hoferichter, Klos, Menéndez, AS, PRD (2016)

include all QCD effects + new operators that are coherent (~A)



dominant corrections are QCD effects: scalar current coupling to pion, isovector correction, radius correction to formfactor

first new operator O_3 contribution is 4 orders smaller

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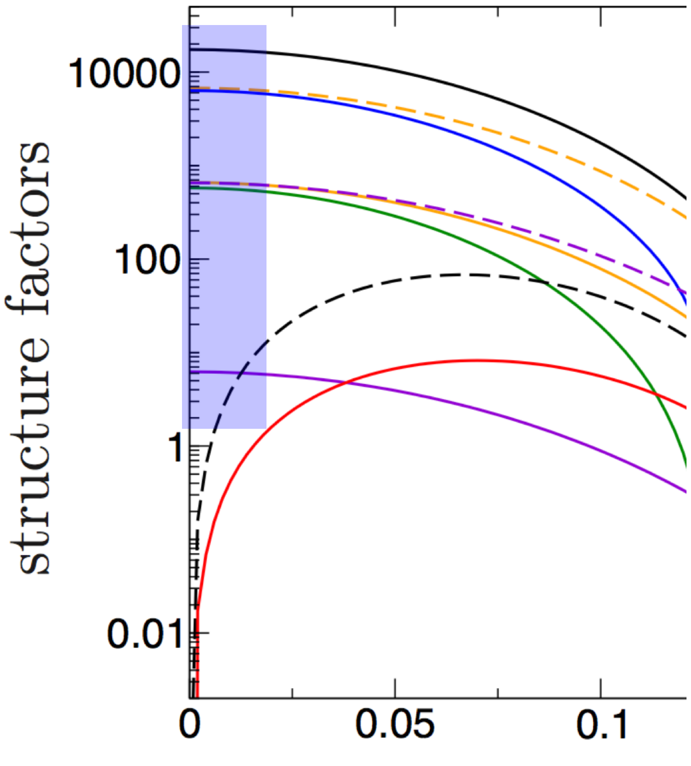
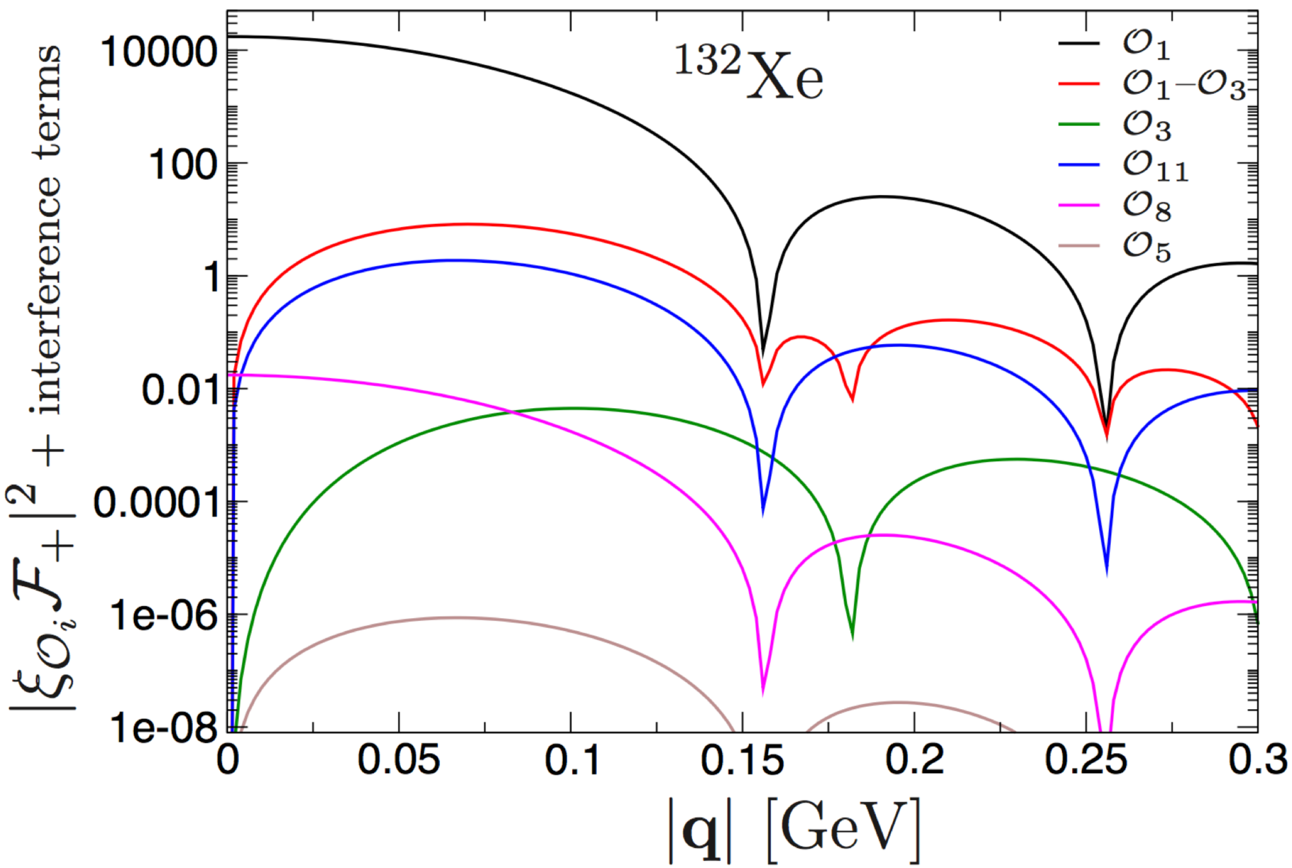


$$\mathcal{O}_1 = \mathbb{1}, \quad \mathcal{O}_2 = (\mathbf{v}^\perp)^2, \quad \mathcal{O}_3 = i\mathbf{S}_N \cdot (\mathbf{q} \times \mathbf{v}^\perp),$$
$$\mathcal{O}_4 = \mathbf{S}_\chi \cdot \mathbf{S}_N, \quad \mathcal{O}_5 = i\mathbf{S}_\chi \cdot (\mathbf{q} \times \mathbf{v}^\perp), \quad \mathcal{O}_6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



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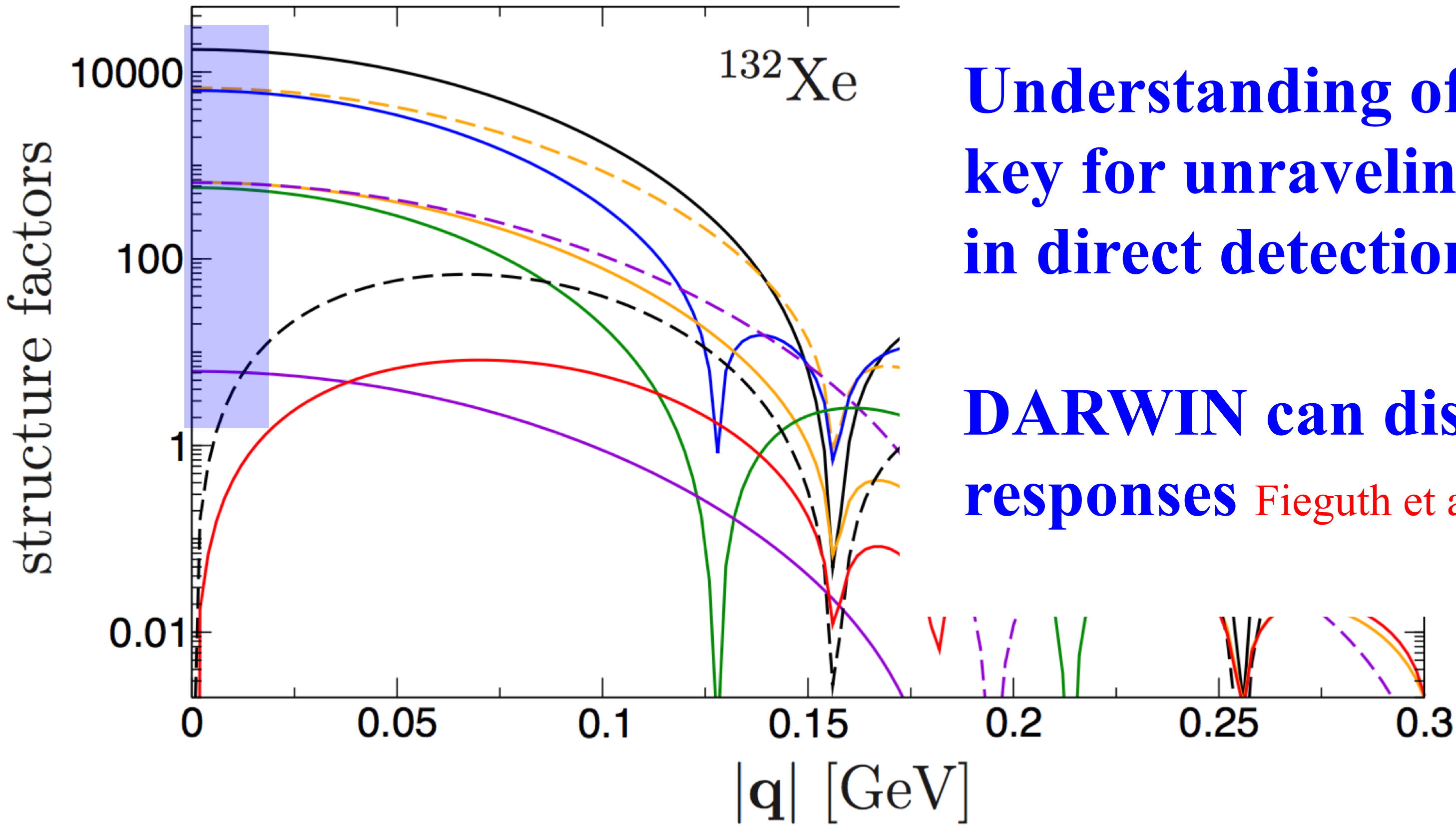


Understanding of QCD effects is key for unraveling nature of DM in direct detection experiments

DARWIN can discriminate most responses Fieguth et al., arXiv:1802.04294

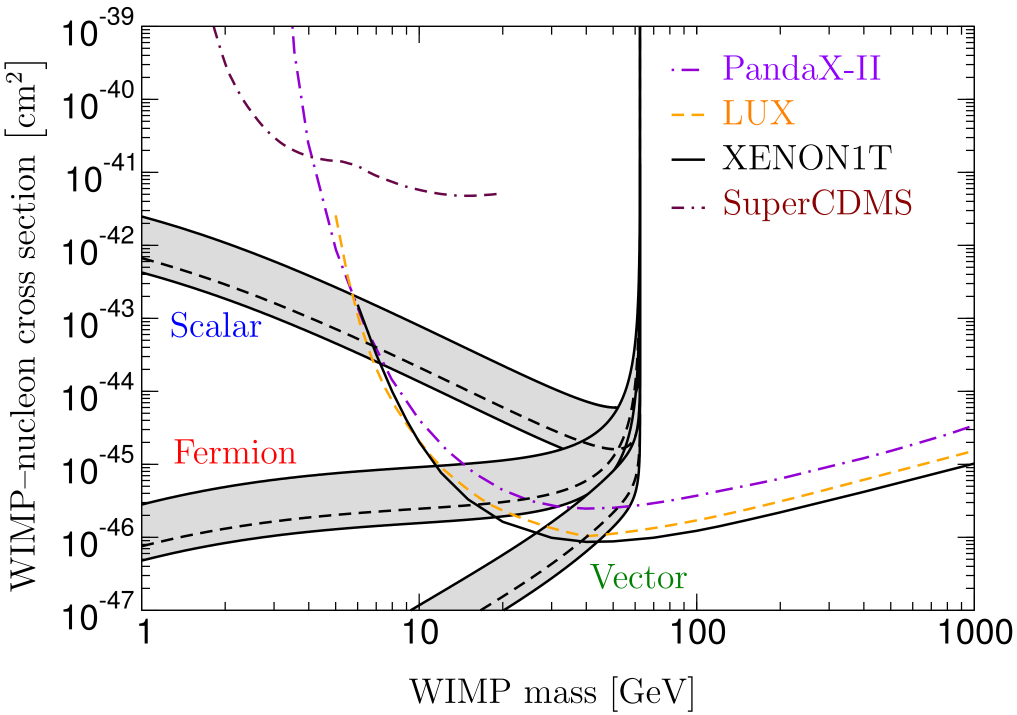
dominant corrections are QCD effects: scalar current coupling to pion, isovector correction, radius correction to formfactor

first new operator O_3 contribution is 4 orders smaller

Higgs Portal dark matter

slides from Martin Hoferichter

- **Higgs Portal**: WIMP interacts with SM via the Higgs
  - **Scalar**: $H^\dagger H S^2$
  - **Vector**: $H^\dagger H V_\mu V^\mu$
  - **Fermion**: $H^\dagger H \bar{f} f$
- If $m_h > 2m_\chi$, should happen at the LHC
  $\hookrightarrow$ limits on **invisible Higgs decays**

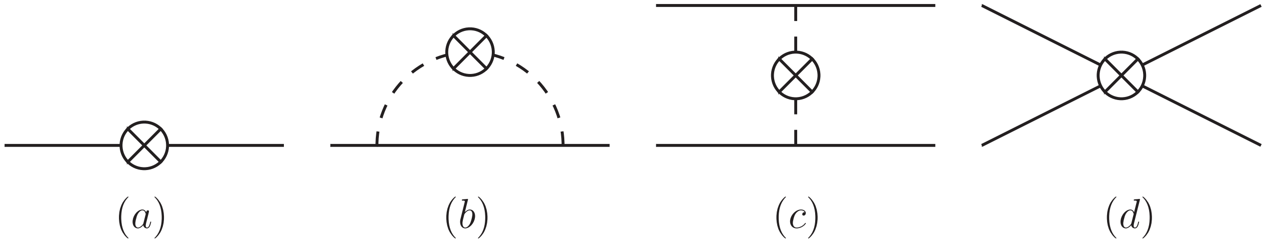


- Translation requires input for **Higgs–nucleon coupling**

$$f_N = \sum_{q=u,d,s,c,b,t} f_q^N = \frac{2}{9} + \frac{7}{9} \sum_{q=u,d,s} f_q^N + \mathcal{O}(\alpha_s) \qquad\qquad m_N f_q^N = \langle N | m_q \bar{q} q | N \rangle$$

- Issues: input for $f_N = 0.260 \ldots 0.629$ outdated, 2b currents missing

Higgs–nucleon coupling



Hoferichter et al., PRL (2017)

- **One-body contribution**

$$f_N^{1\text{b}} = 0.307(9)_{ud}(15)_s(5)_{\text{pert}} = 0.307(18)$$

- Limits on WIMP–nucleon cross section subsume **2b effects**

  $\hookrightarrow$ have to be included for meaningful comparison

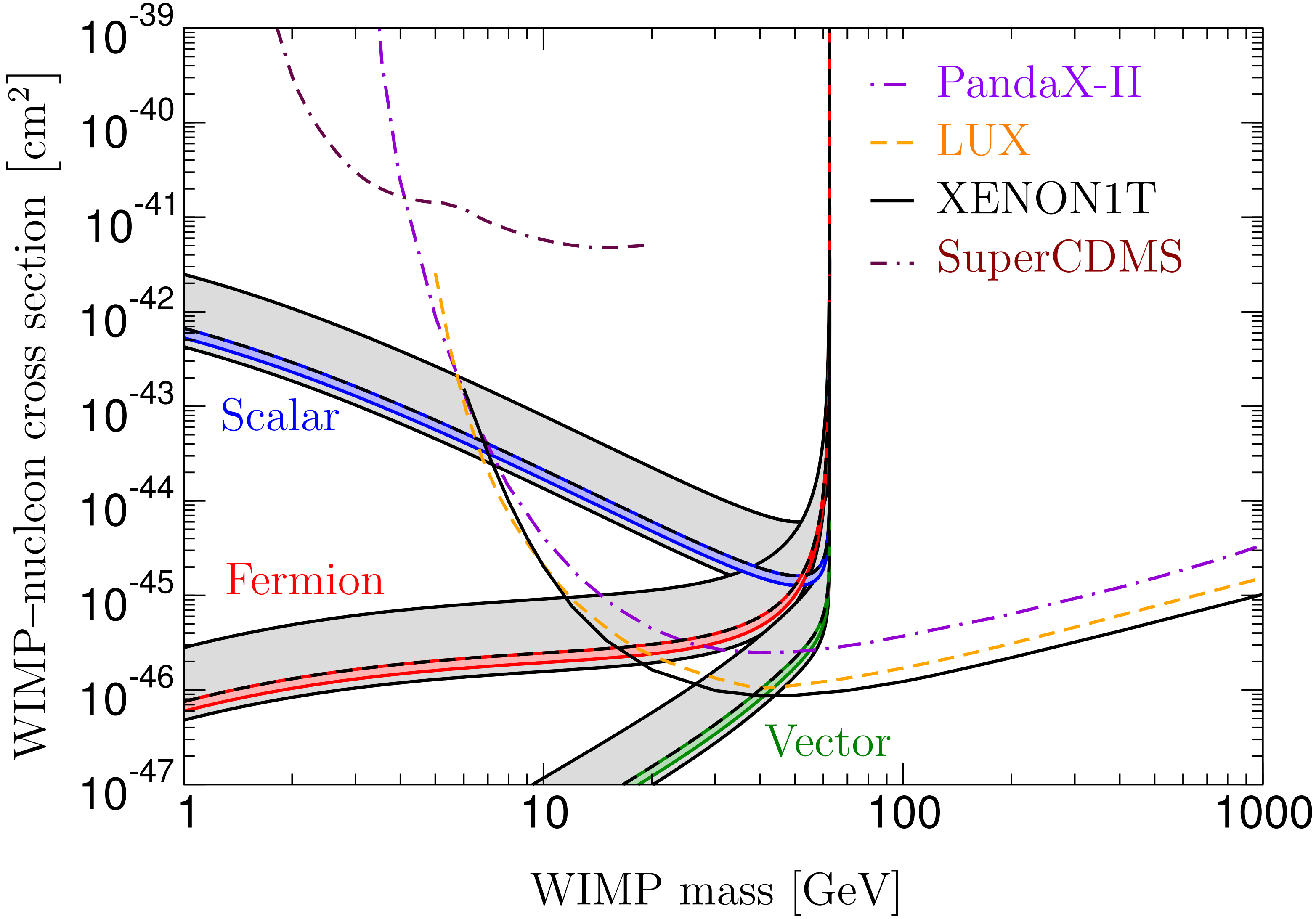
- **Two-body contribution**
  - Need s and θ^μ_μ currents
  - Treatment of θ^μ_μ tricky: several ill-defined terms combine to $\langle\Psi|T + V_{NN}|\Psi\rangle = E_\text{b}$
  - A cancellation makes the final result anomalously small

$$f_N^{2\text{b}} = \big[-3.2(0.2)_A(2.1)_{\text{ChEFT}} + 5.0(0.4)_A\big] \times 10^{-3} = 1.8(2.1) \times 10^{-3}$$

Linking LHC and direct detection results in Higgs Portals

Main result: **improved and consistent limits for Higgs Portals**

Hoferichter, Klos, Menéndez, AS, PRL (2017)



Summary

Thanks to: **M. Hoferichter, P. Klos, J. Menéndez**

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

exciting era in nuclear physics of neutron-rich nuclei
with chiral EFT and powerful many-body calculations

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

incorporate what we know about QCD/nuclear physics
to go from future DM signal to nature of WIMP-quark interactions

improved and consistent limits for Higgs Portal dark matter