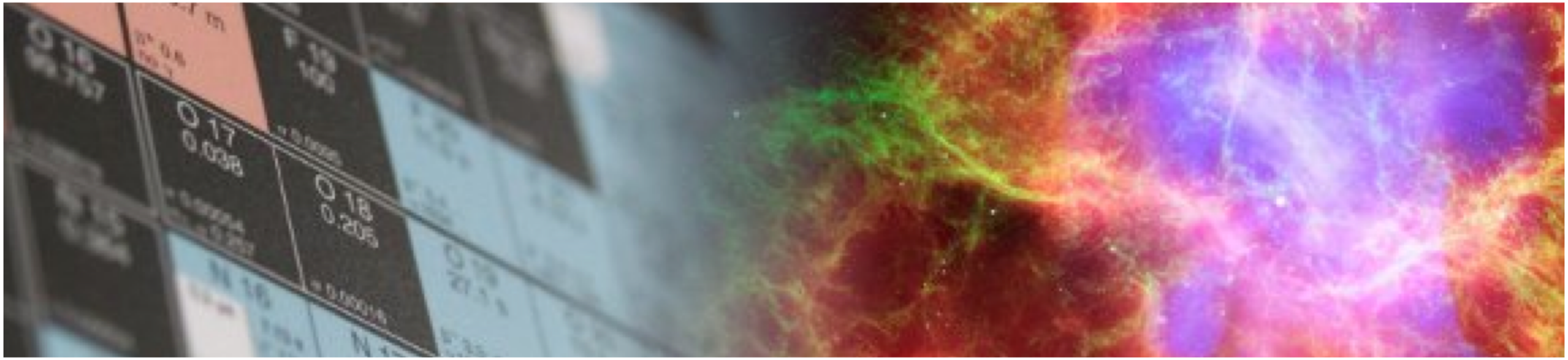
Effects of many-body currents in dark matter detection and WIMP-nucleus scattering

Achim Schwenk

TECHNISCHE UNIVERSITÄT DARMSTADT



ECT*, Trento, April 24, 2018

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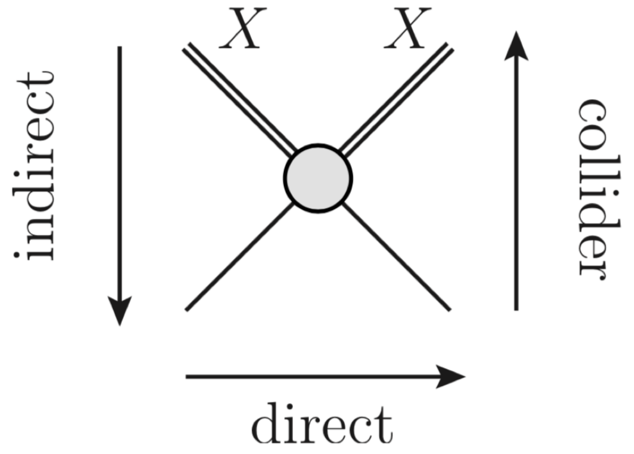
DM in direct detection

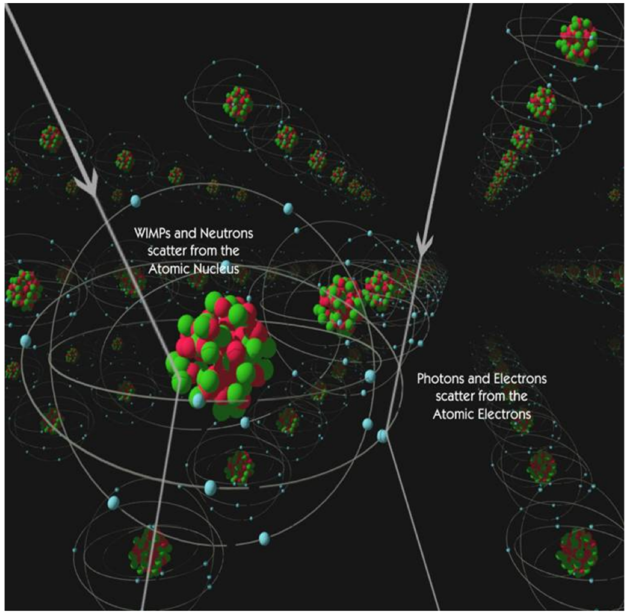
Assume DM particle is WIMP, search strategies:



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 ~ m_π
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)
Hoferichter et al., PRL (2017), Fieguth et al., PRD in press

incorporate what we know about **QCD/nuclear physics**
see also Prézeau et al., PRL (2003), Cirigliano et al., JHEP (2012), PLB (2014), Hill and Solon, PRD (2015),
Körber et al., PRC (2017), Bishara et al., JCAP (2017), Gadza et al., PRC (2017)

Scales in DM direct detection

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

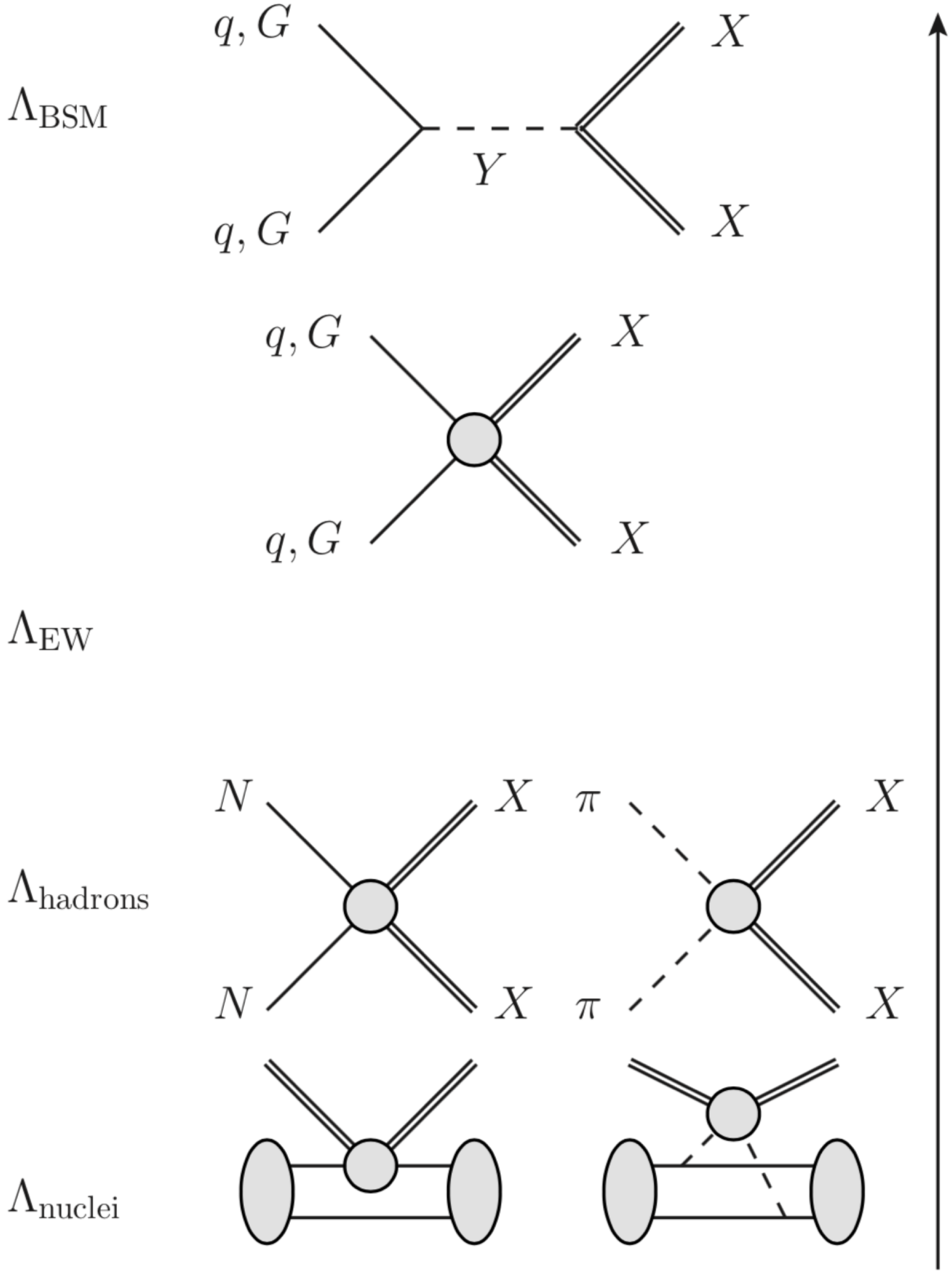
SM + **effective operators**

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

Integrate out **EW physics**

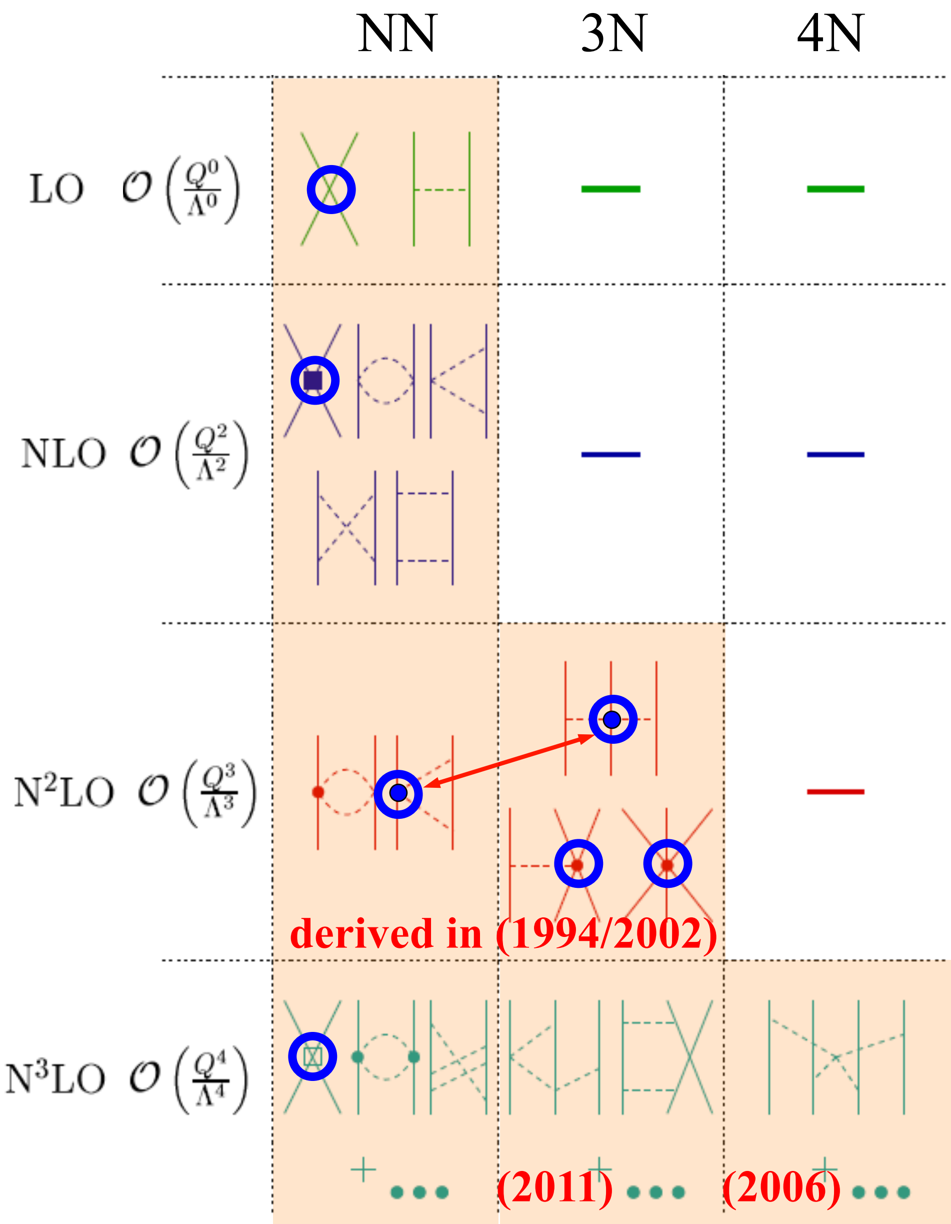
Chiral EFT scale: WIMP coupling to nucleons and pions

Nuclear structure: 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**

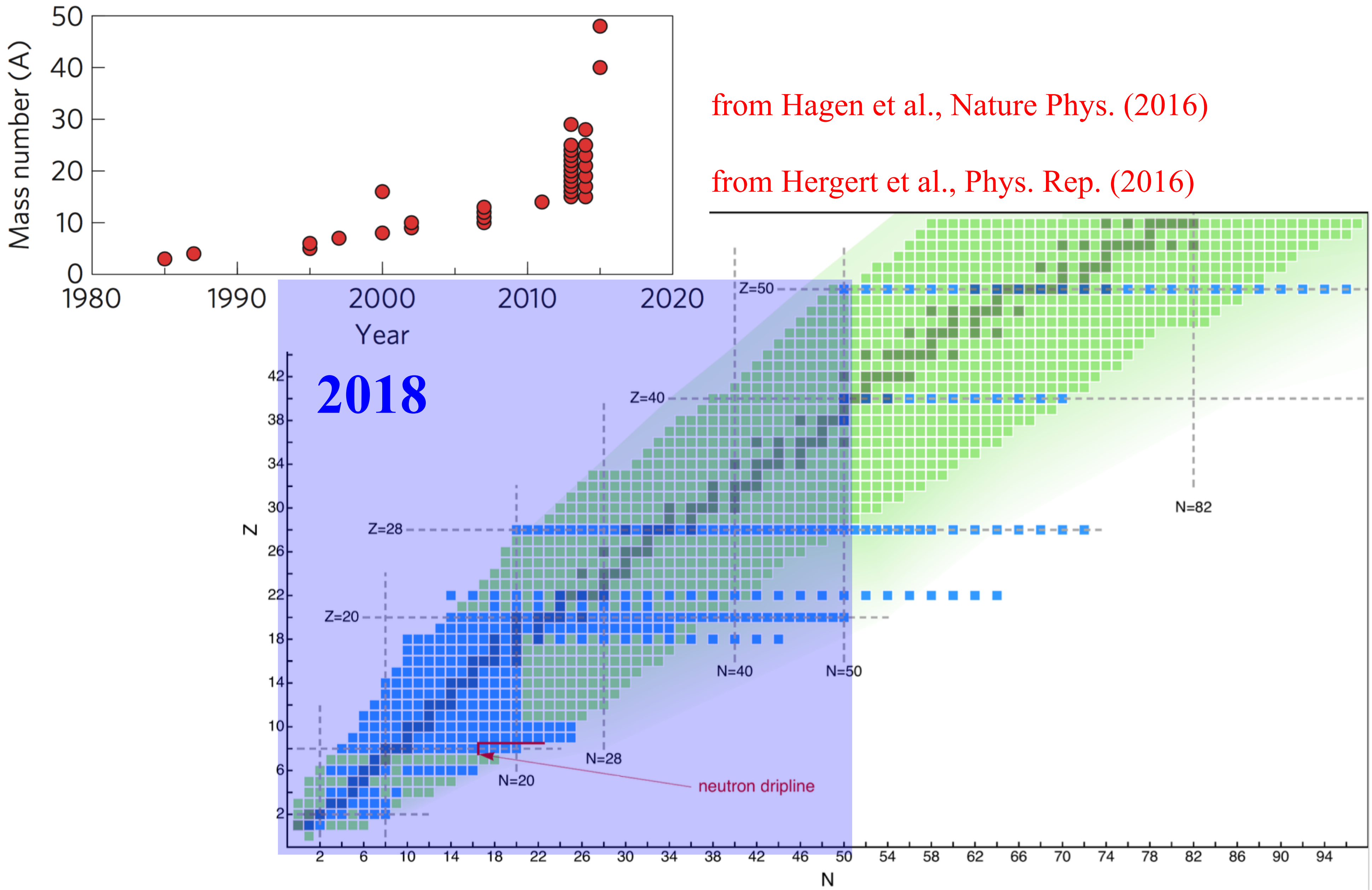
Weinberg, van Kolck, Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Machleidt, Meissner,…

Progress in ab initio calculations of nuclei

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

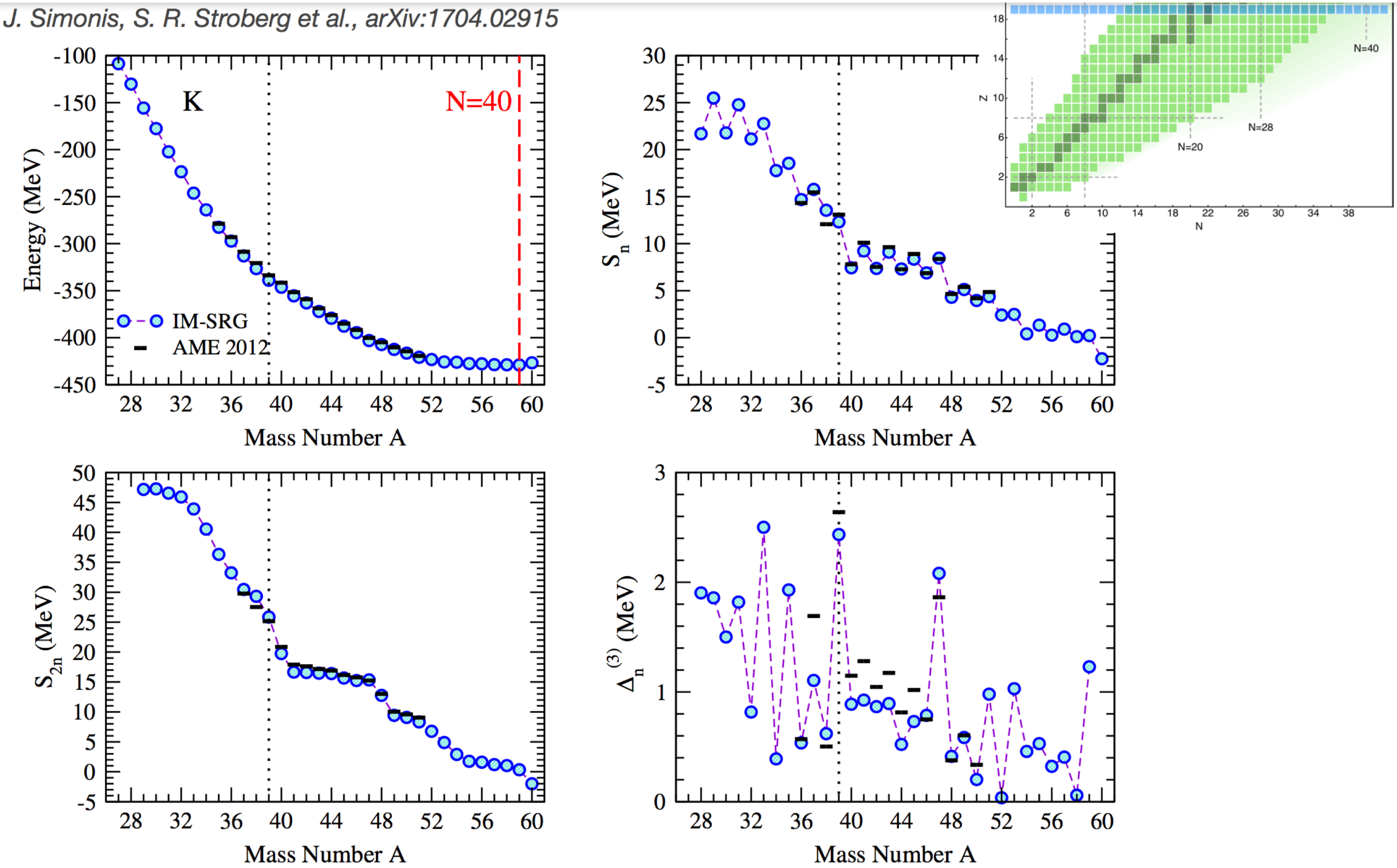
from Hagen et al., Nature Phys. (2016)

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



Preview

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

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

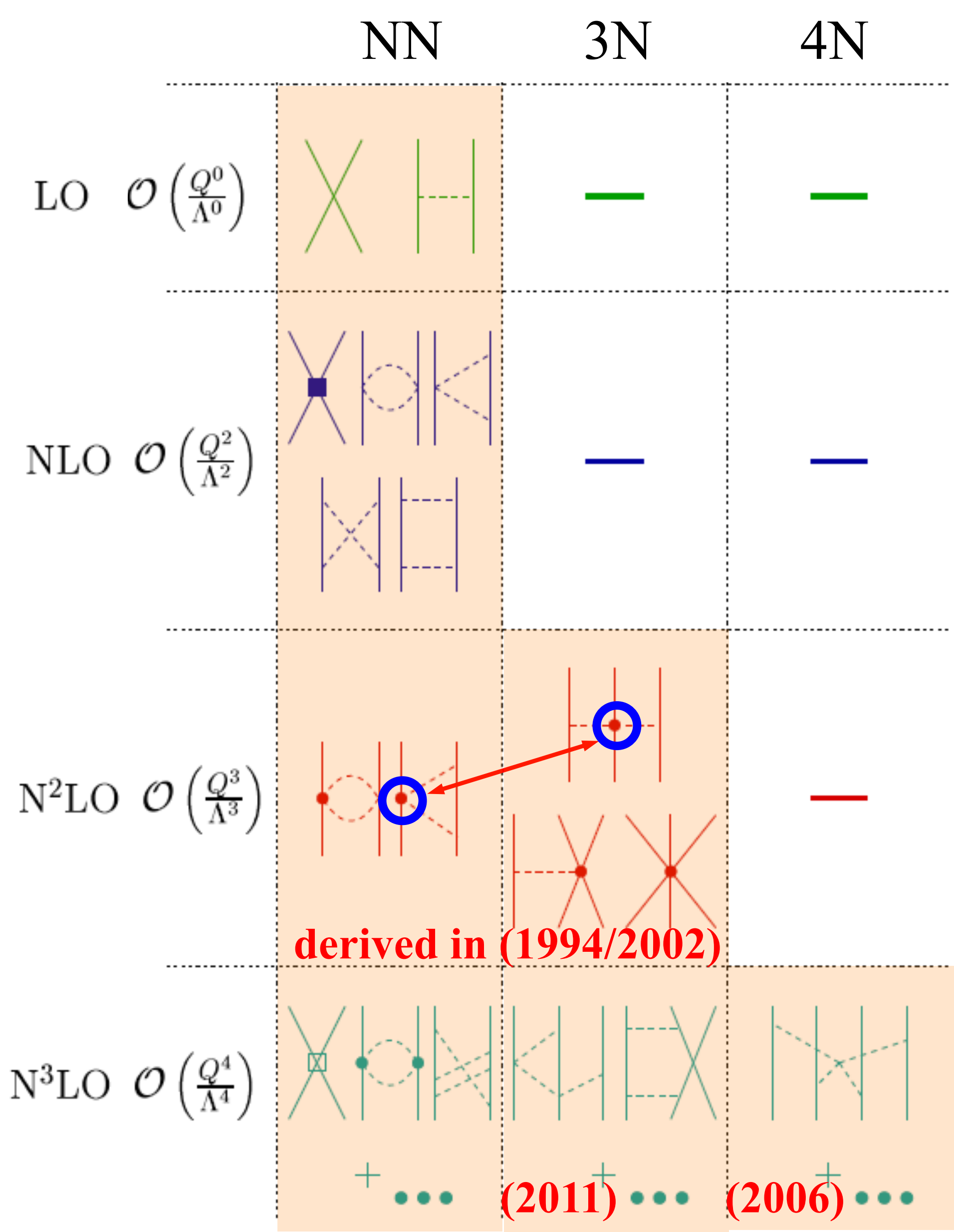
signatures of WIMP **inelastic scattering**
with Baudis et al., PRD (2013)

WIMP-nucleon interactions in chiral EFT to N^2LO
with Hoferichter, Klos, PLB (2015)

general coherent (SI+) WIMP-nucleus scattering
with Hoferichter, Klos, Menéndez, PRD (2016)

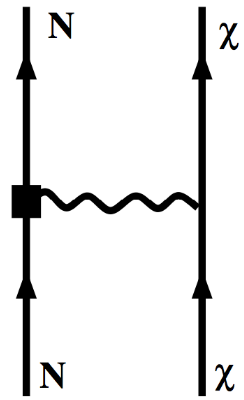
Linking **LHC and direct detection** results in **Higgs Portals**
with Hoferichter, Klos, Menéndez, PRL (2017)

Chiral EFT for coupling to external sources

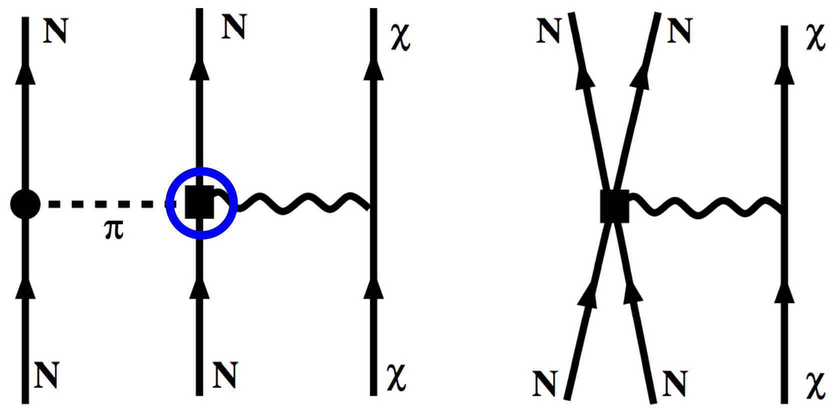


example: axial-vector currents

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



+ two-body currents at Q^3



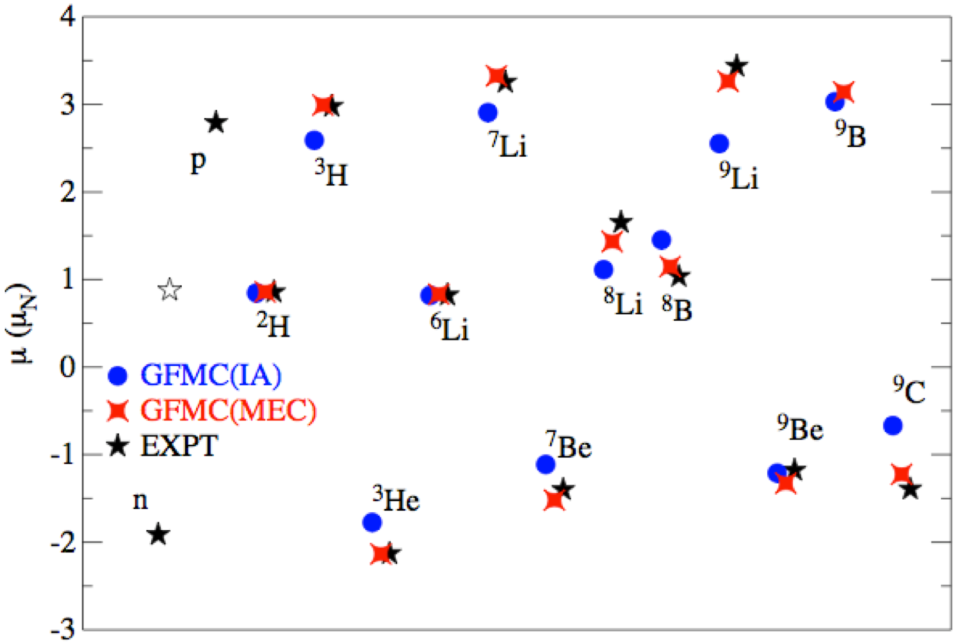
same couplings in forces and currents!

Chiral EFT currents

predicts consistent electroweak 1+2-body currents

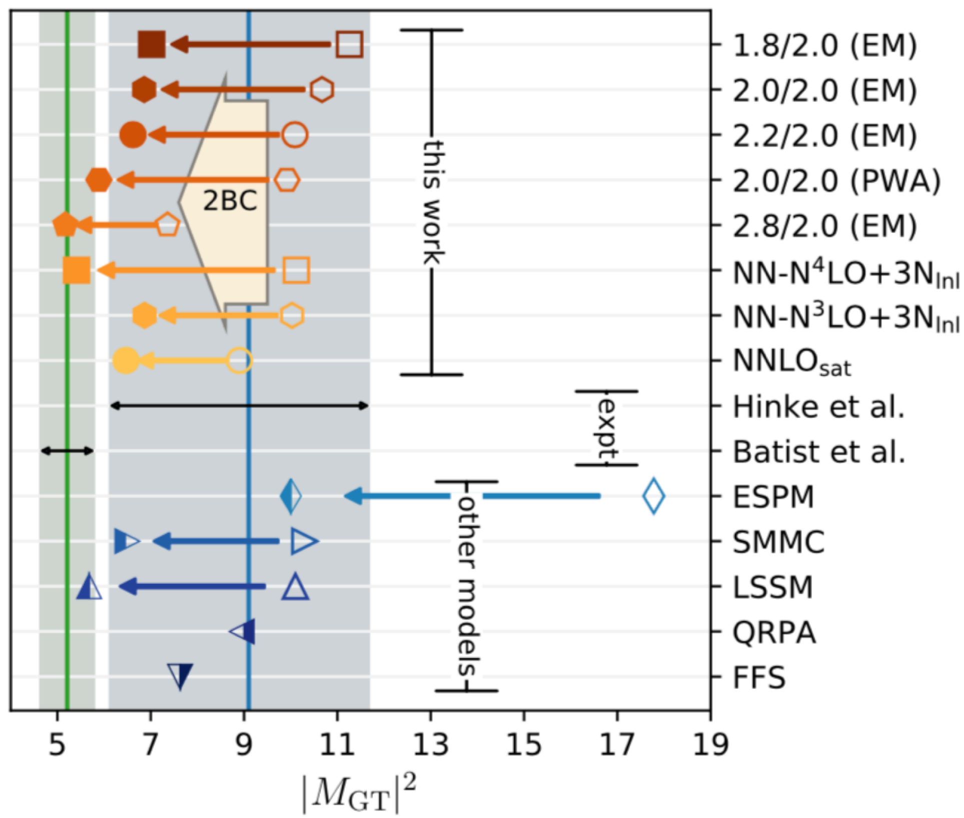
magnetic moments in light nuclei

Pastore et al. (2012-)



GT beta decay of ^{100}Sn

Gysbers et al., see talks by Gaute, Jason, and Petr

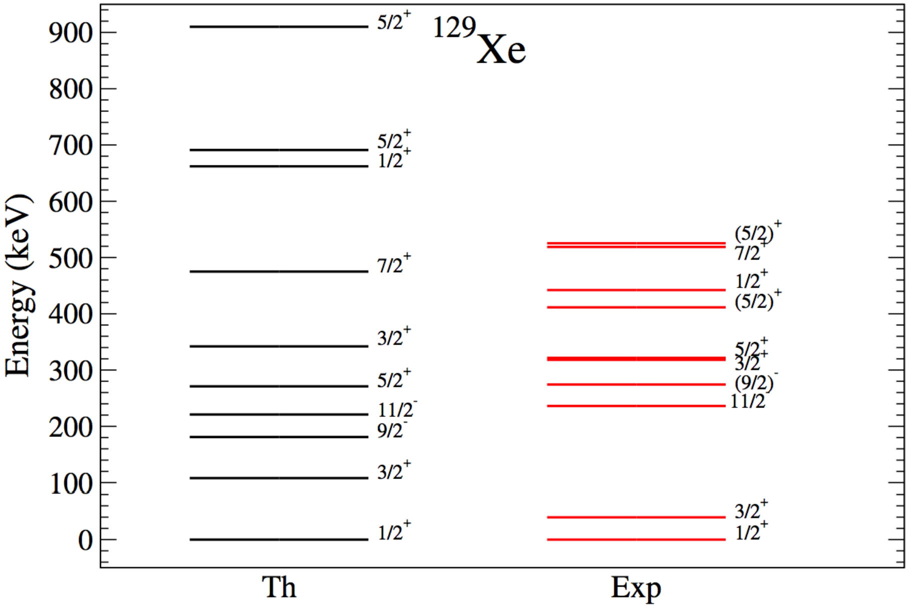


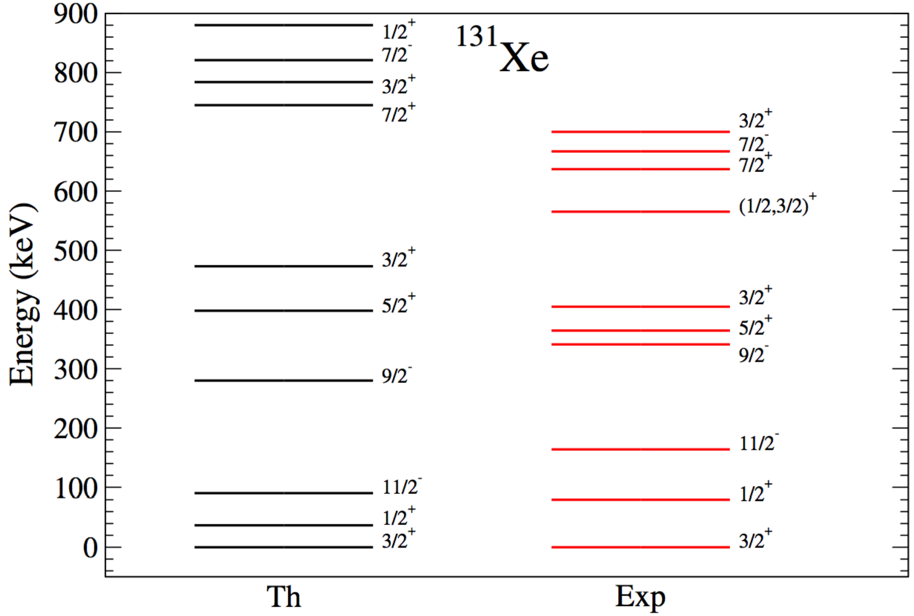
contributions from 2-body currents are key!

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

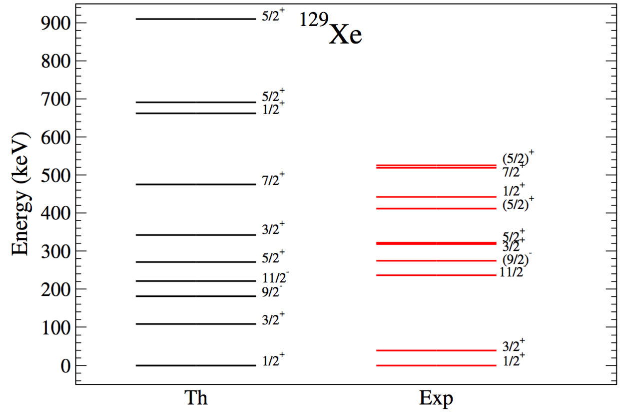
Menendez, Gazit, AS, PRD (2012)

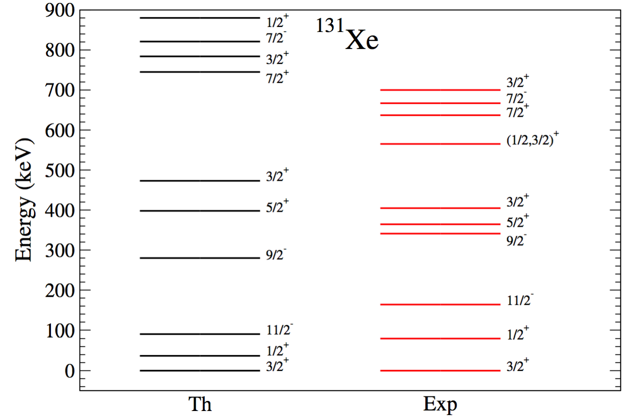
connects WIMP direct detection with double-beta decay

Nuclear structure for direct detection

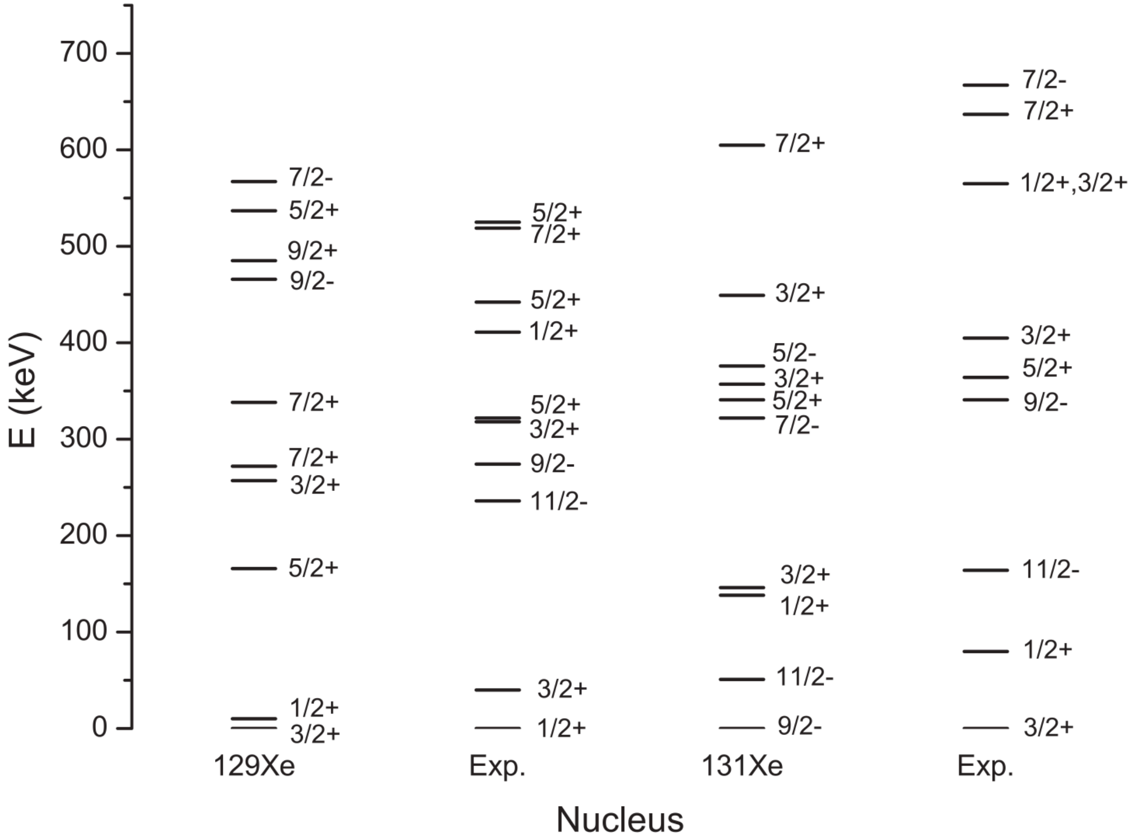
very good agreement for spectra; ordering and grouping well reproduced

Menendez, Gazit, AS, PRD (2012)





compare to other calculations for WIMP scattering



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

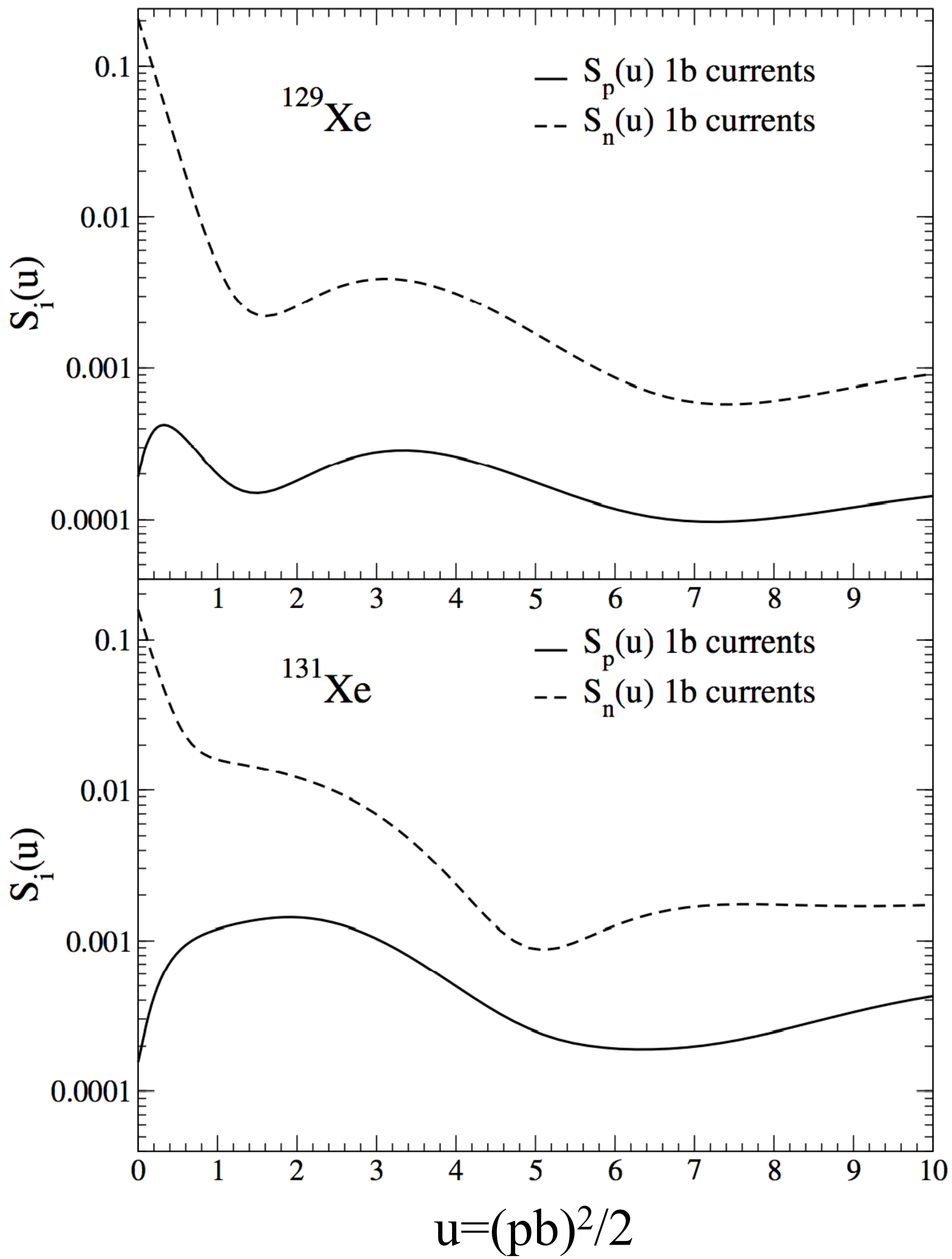
$$S_A(p) = \sum_{L \geqslant 0} \left| \langle J_f || \mathcal{L}_L^5 || J_i \rangle \right|^2 + \sum_{L \geqslant 1} \left(\left| \langle J_f || \mathcal{T}_L^{\rm el5} || J_i \rangle \right|^2 + \left| \langle J_f || \mathcal{T}_L^{\rm mag5} || J_i \rangle \right|^2 \right)$$

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

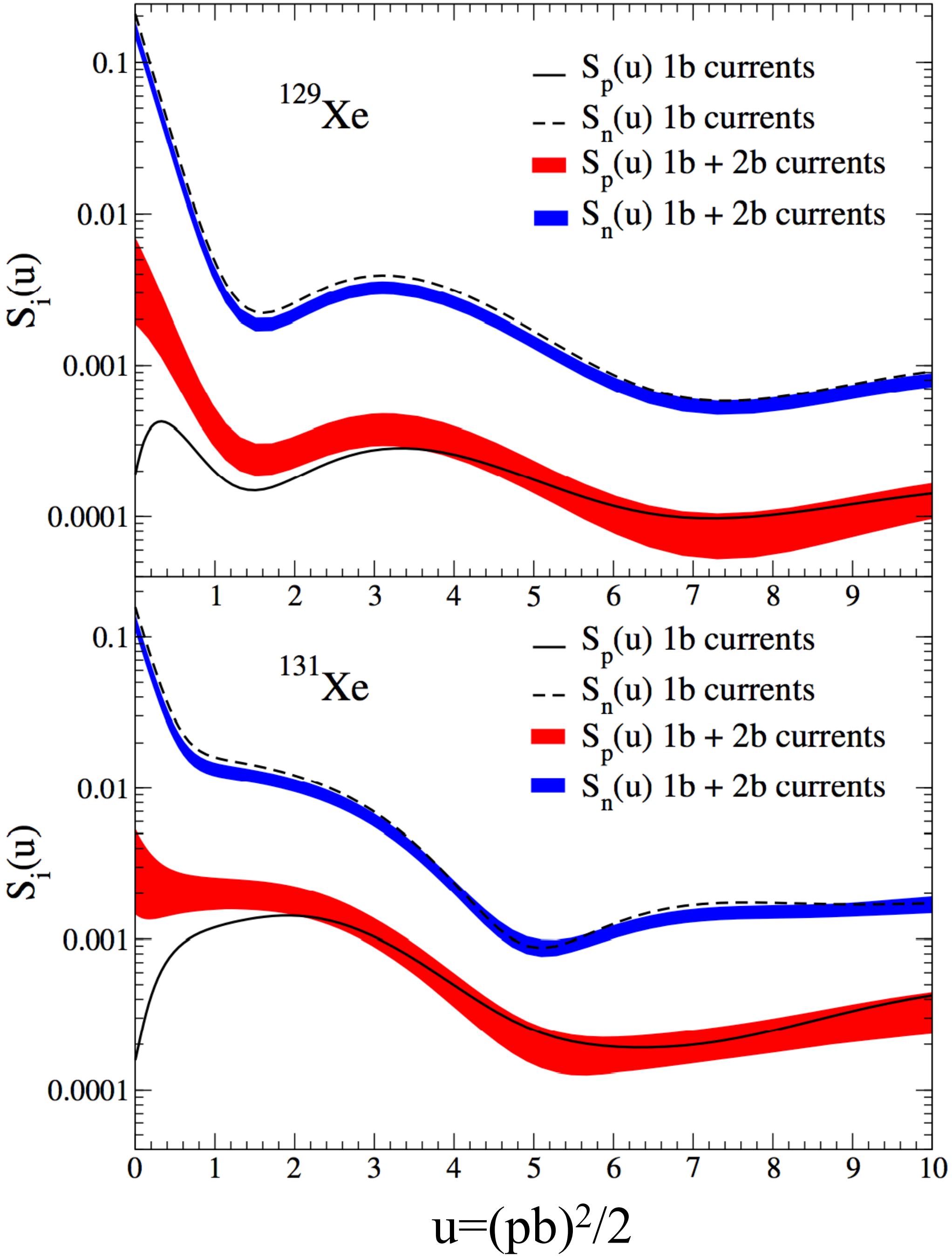


^{129,131}Xe are even Z, odd N, spin is carried mainly by neutrons

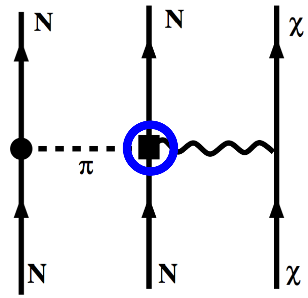
at p=0 structure factors at the level of one-body currents dominated by "neutron"-only

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

Xenon response with 1+2-body currents



two-body currents due to strong interactions among nucleons

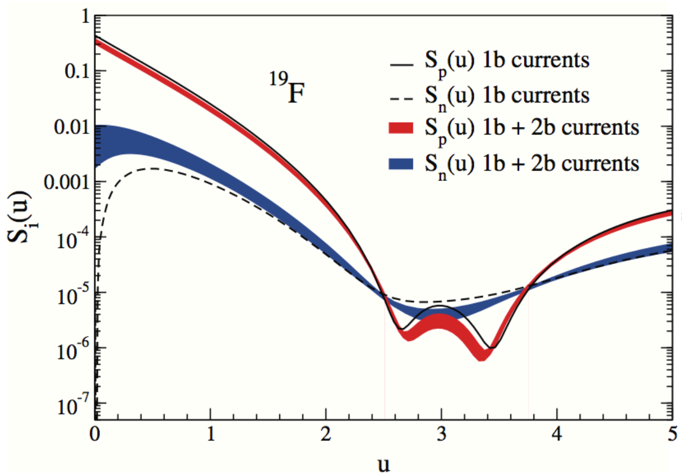


WIMPs couple to neutrons and protons at the same time

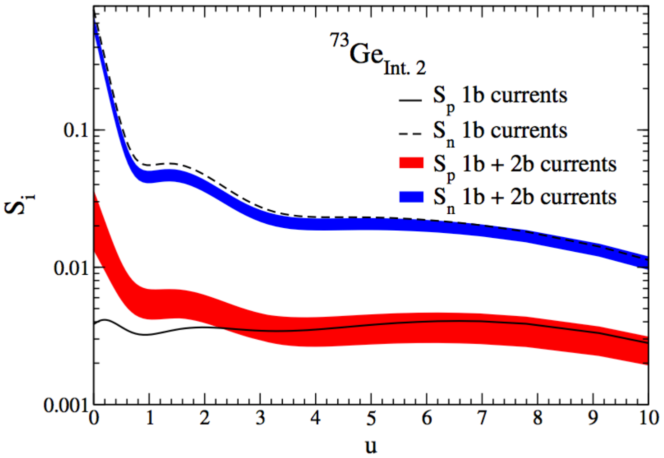
enhances coupling to even species in all cases (protons for Xe)

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

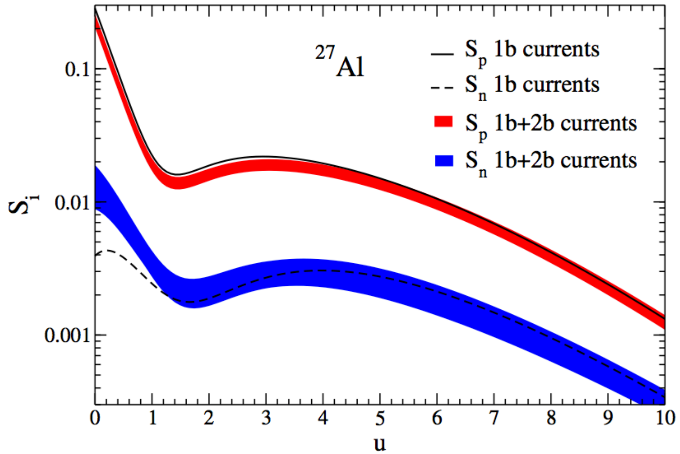
Klos, Menéndez, Gazit, AS, PRD (2013) includes structure factor fits for all isotopes



PICASSO, COUPP, SIMPLE



CDMS, EDELWEISS, EURECA



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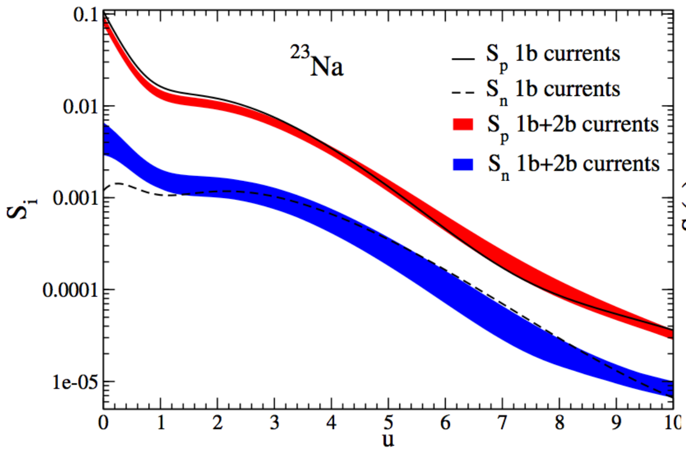
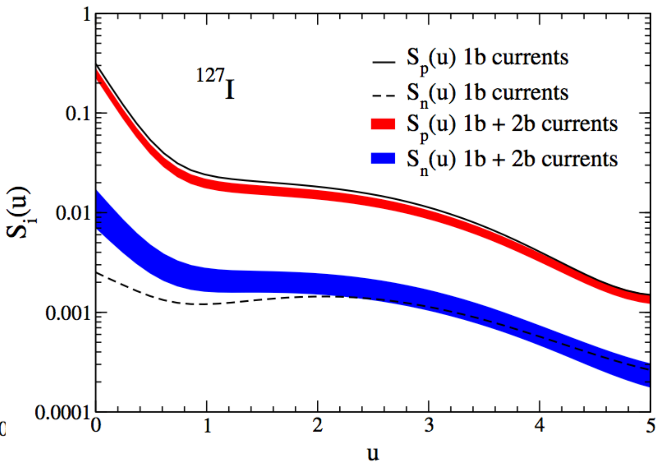
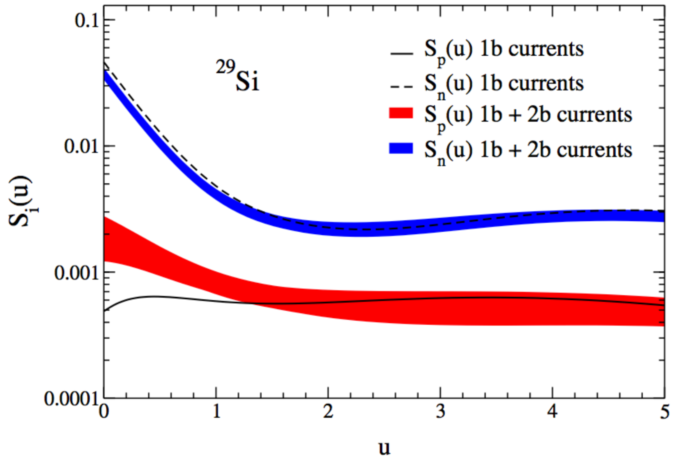


DAMA, ANAIS, DM-Ice



DAMA, ANAIS, DM-Ice, KIMS



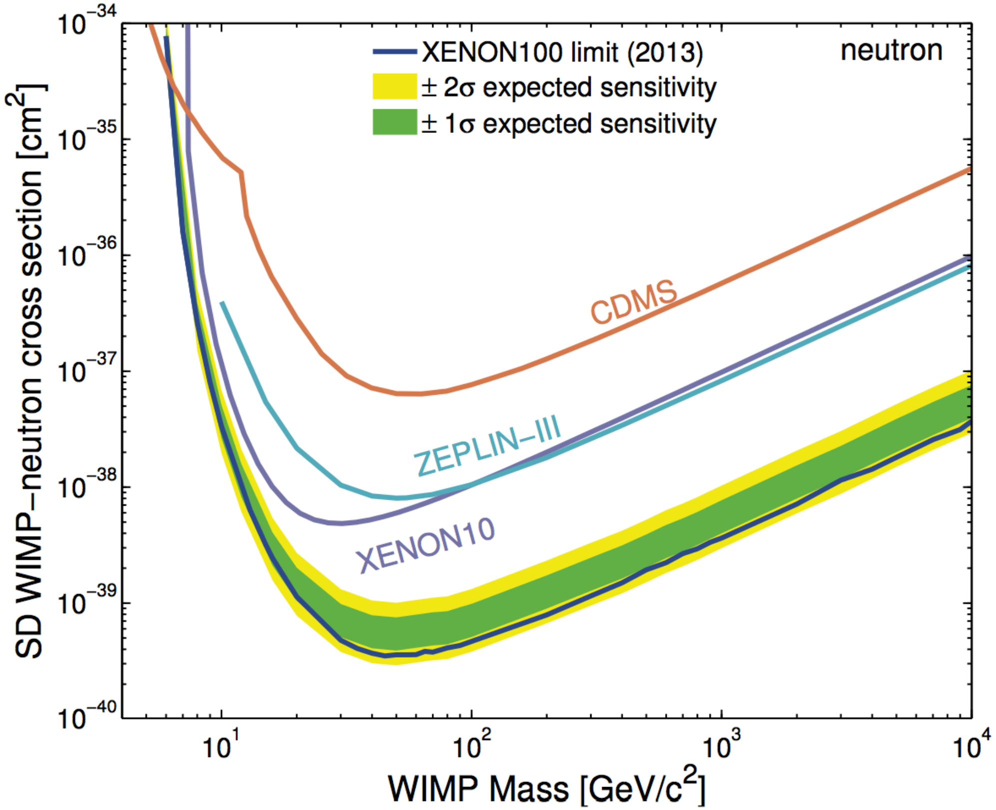
CDMS-II

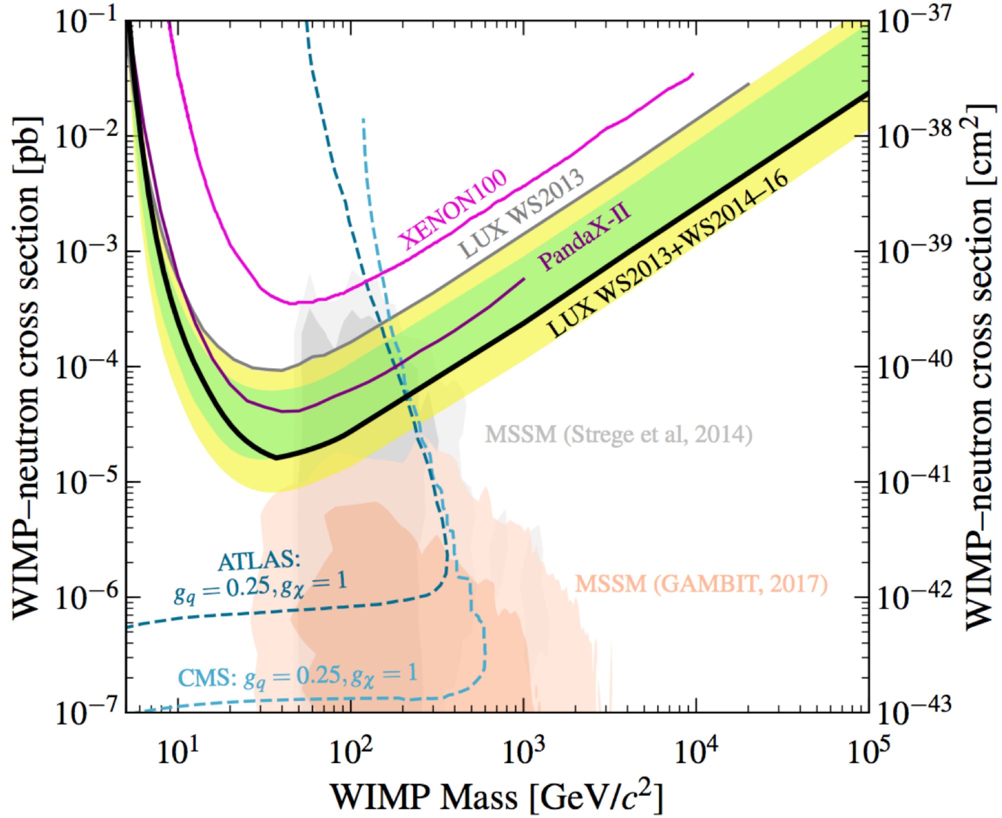
Limits on SD WIMP-neutron interactions

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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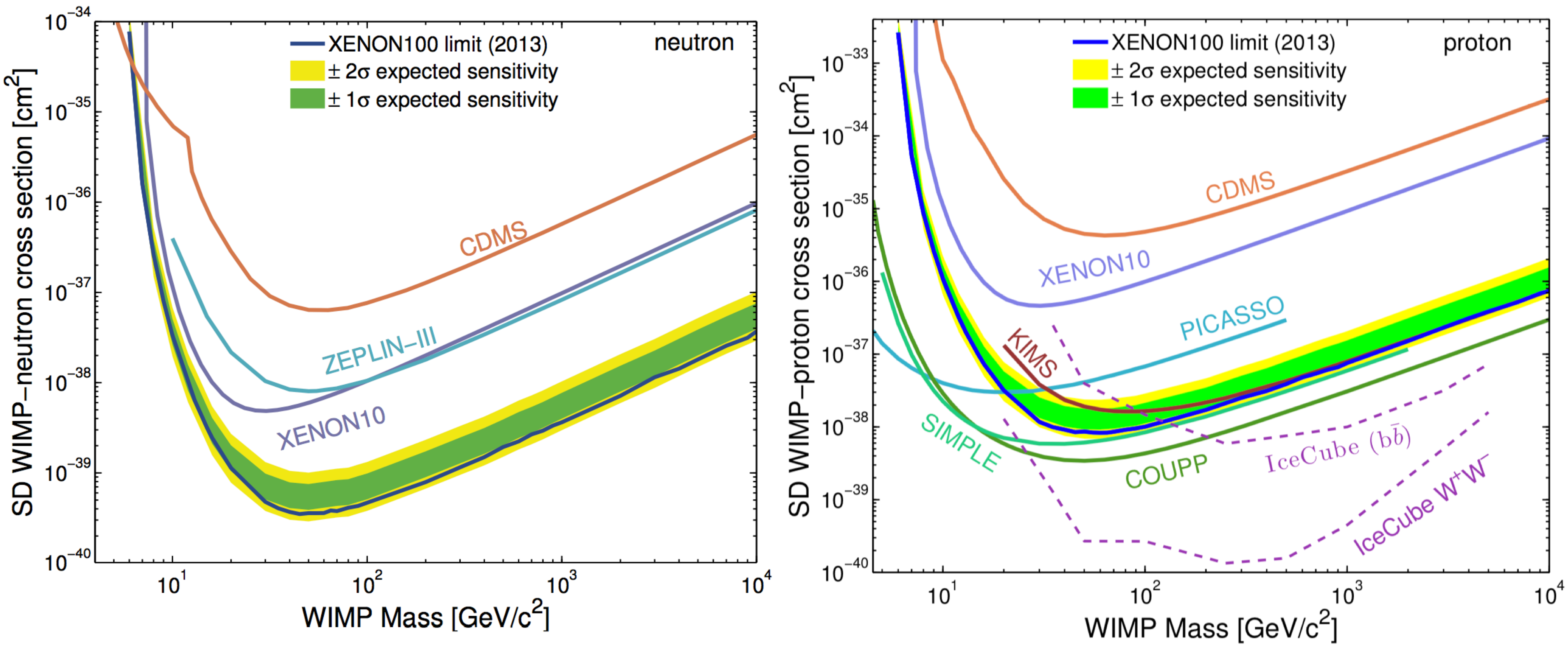
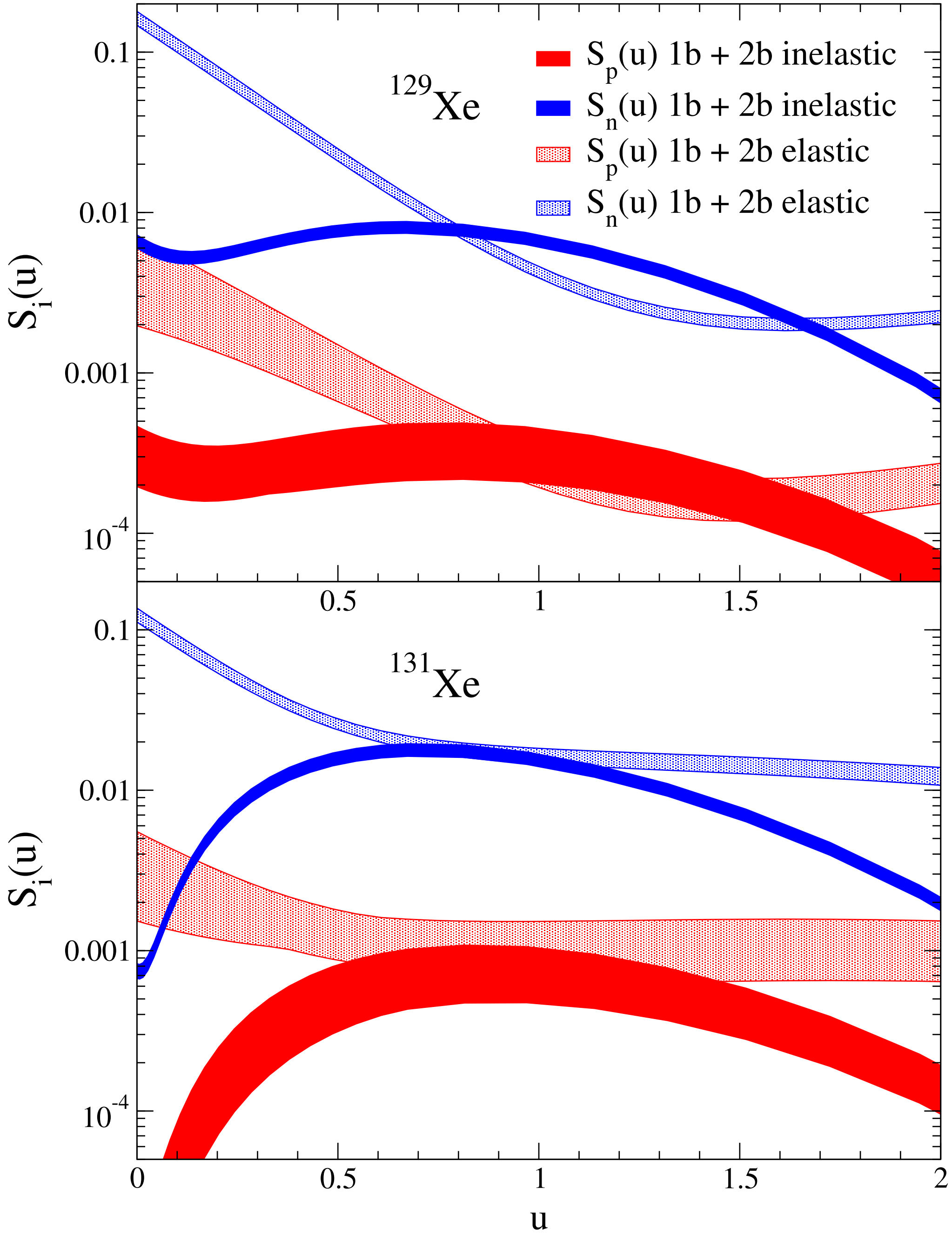
used our calculations with uncertainty bands for WIMP currents in nuclei



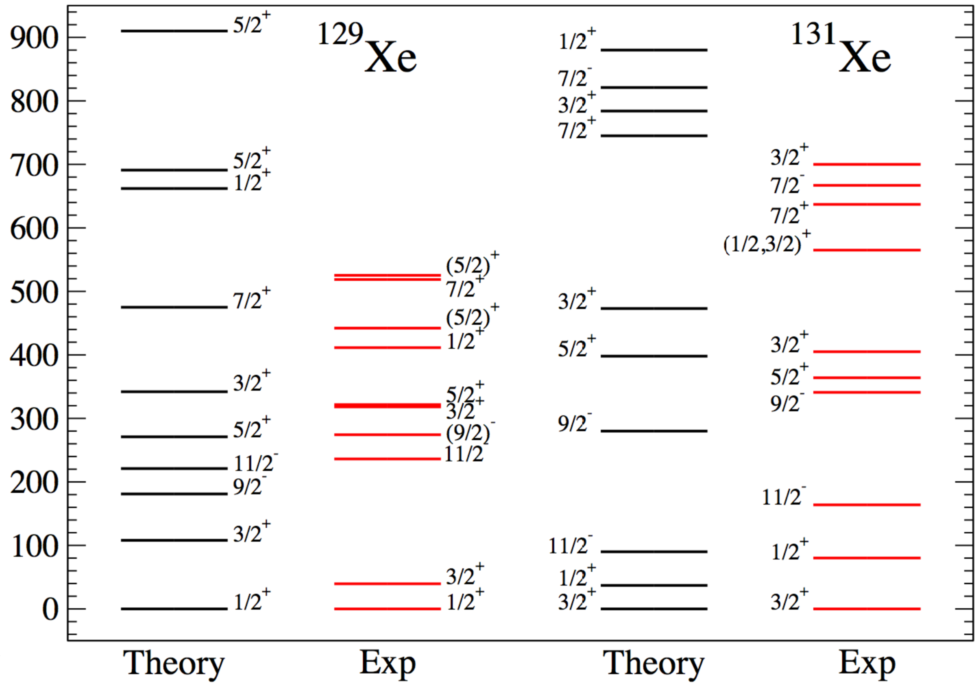
XENON competitive for WIMP-proton coupling due to 2-body currents

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

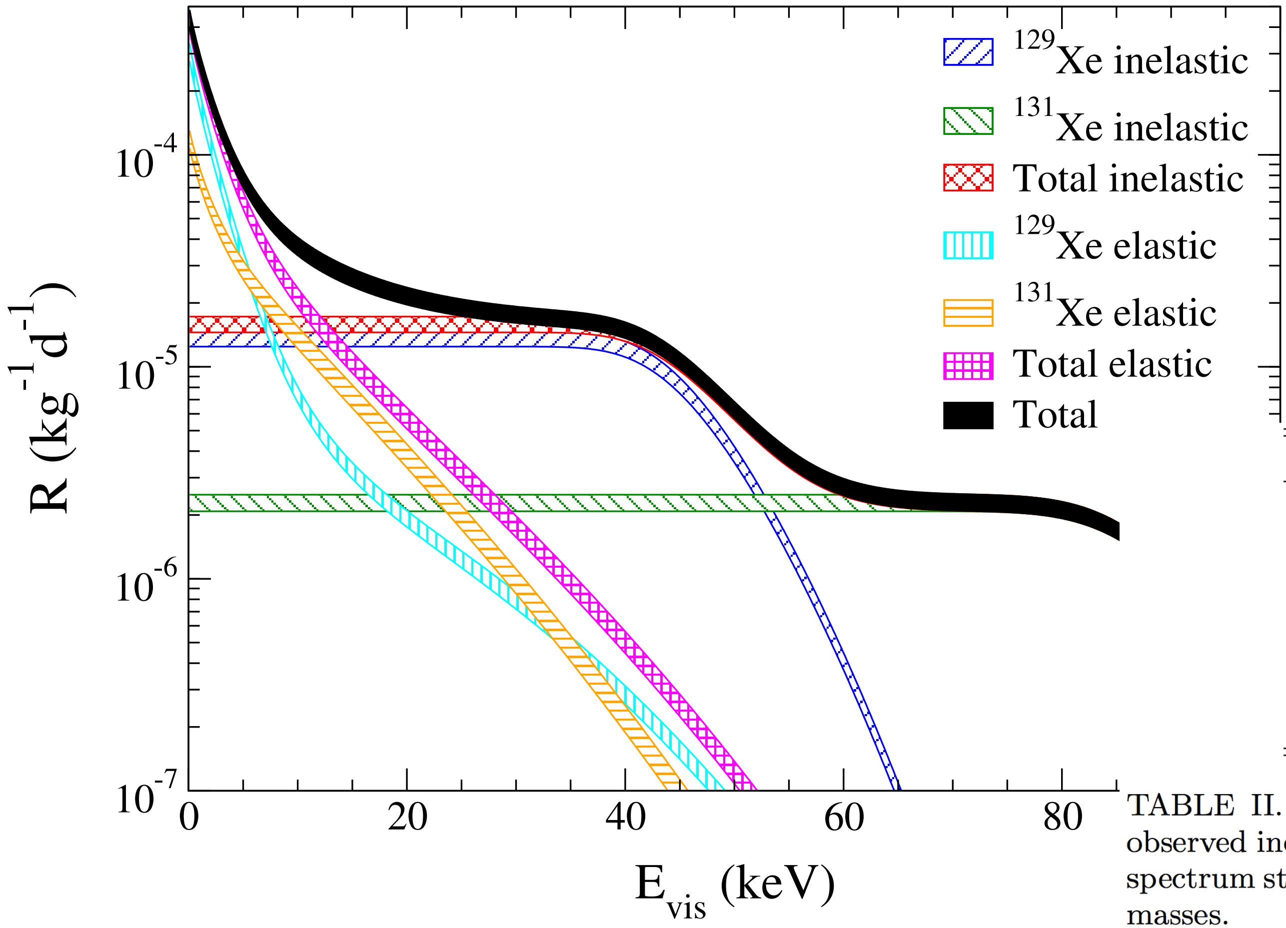


Signatures for **inelastic** WIMP scattering

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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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

$$\mathcal{O}_1 = \mathbb{1}, \quad \mathcal{O}_2 = (\mathbf{v}^\perp)^2, \quad \mathcal{O}_3 = i\mathbf{S}_N \cdot (\mathbf{q} \times \mathbf{v}^\perp),$$

$$\mathcal{O}_4 = \mathbf{S}_\chi \cdot \mathbf{S}_N, \quad \mathcal{O}_5 = i\mathbf{S}_\chi \cdot (\mathbf{q} \times \mathbf{v}^\perp), \quad \mathcal{O}_6 = \mathbf{S}_\chi \cdot \mathbf{q}\, \mathbf{S}_N \cdot \mathbf{q},$$

$$\mathcal{O}_7 = \mathbf{S}_N \cdot \mathbf{v}^\perp, \quad \mathcal{O}_8 = \mathbf{S}_\chi \cdot \mathbf{v}^\perp, \quad \mathcal{O}_9 = i\mathbf{S}_\chi \cdot (\mathbf{S}_N \times \mathbf{q}),$$

$$\mathcal{O}_{10} = i\mathbf{S}_N \cdot \mathbf{q}, \quad \mathcal{O}_{11} = i\mathbf{S}_\chi \cdot \mathbf{q},$$

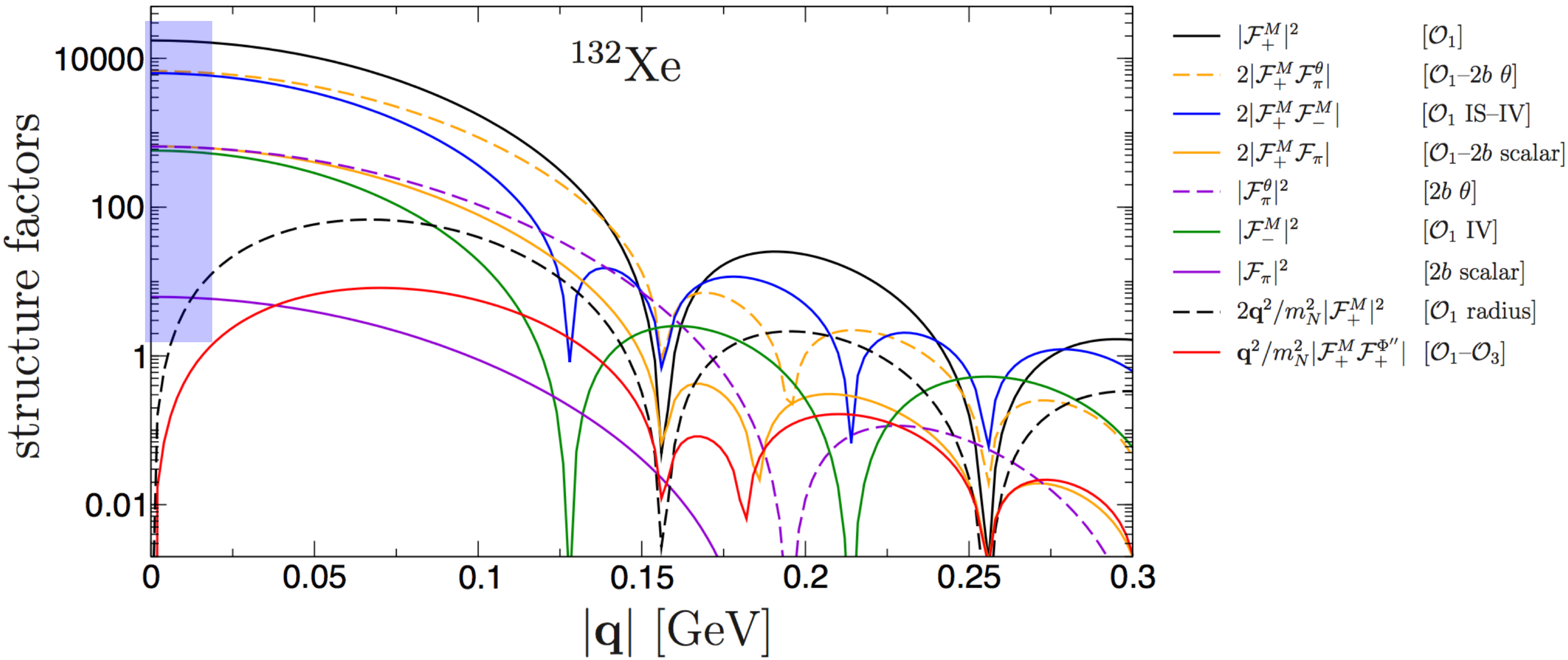
shows that NREFT operators are not linearly indep. (e.g., 4+6 are SD)

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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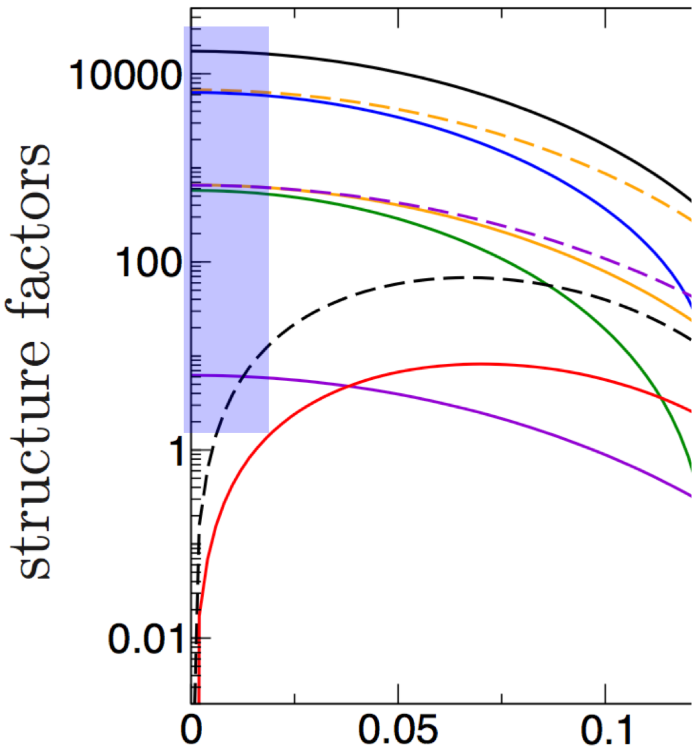
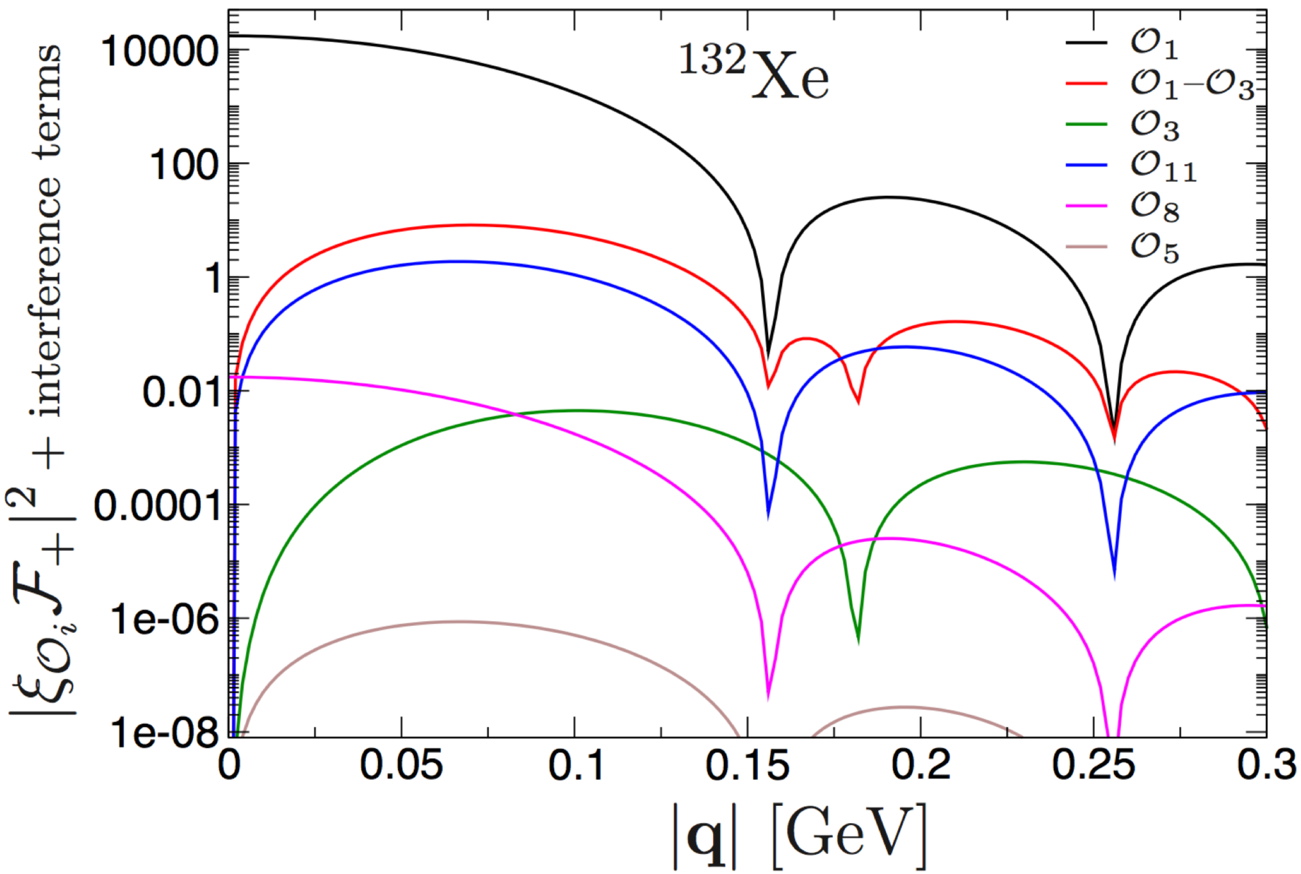
$$\mathcal{O}_{10} = i\mathbf{S}_N \cdot \mathbf{q}, \quad \mathcal{O}_{11} = i\mathbf{S}_\chi \cdot \mathbf{q},$$





dominant corrections are

isovector correction, radi

first new operator O_3 cor

General coherent (SI+) WIMP nucleus scattering

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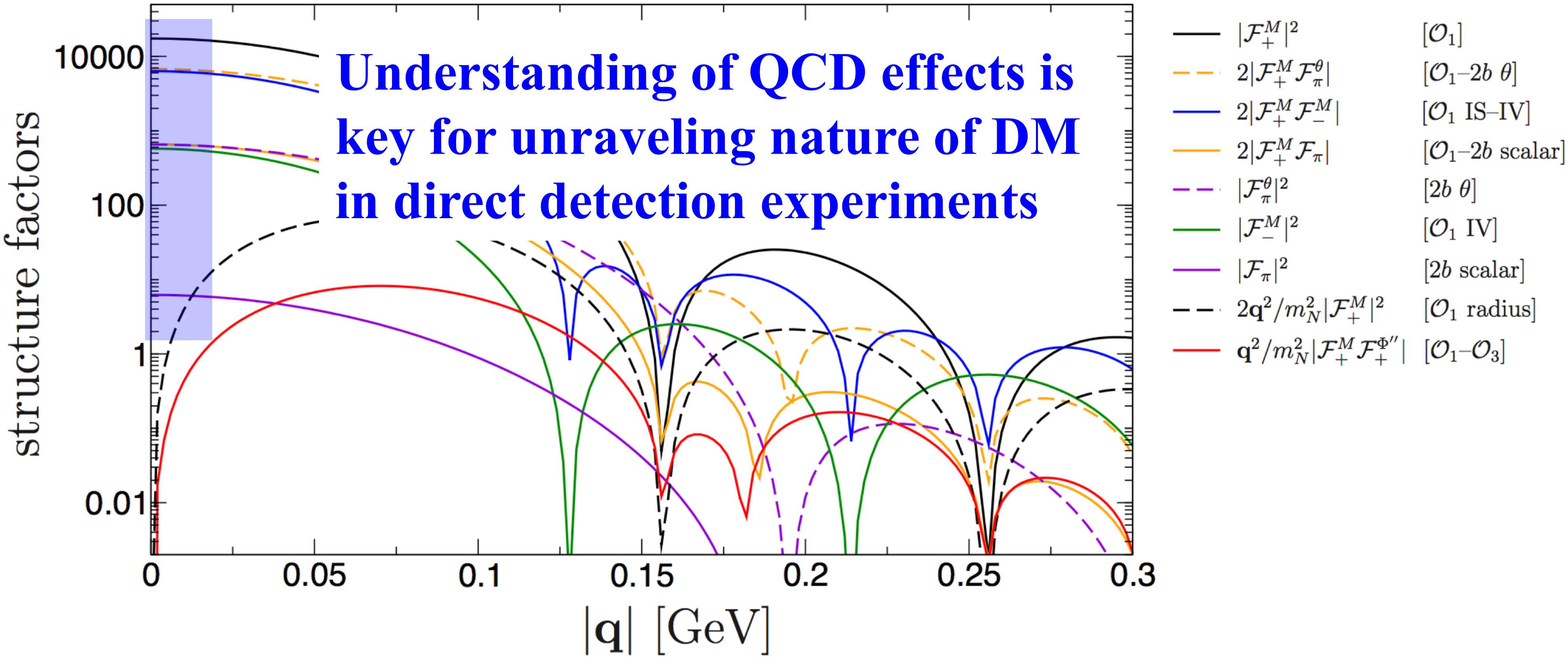


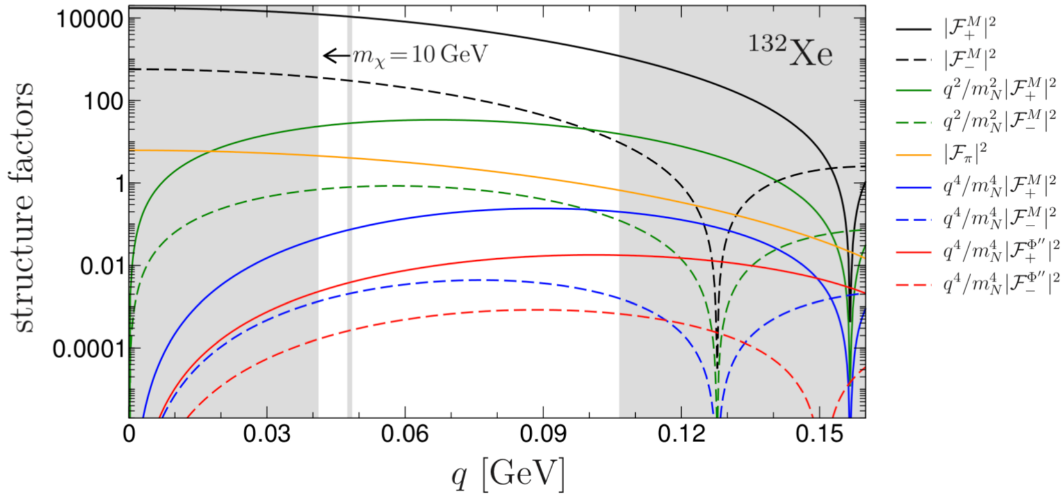
Understanding of QCD effects is key for unraveling nature of DM in direct detection experiments

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

Disriminating different WIMP-nucleus response functions

Fieguth et al., PRD in press white region accessible to XENON-type experiment

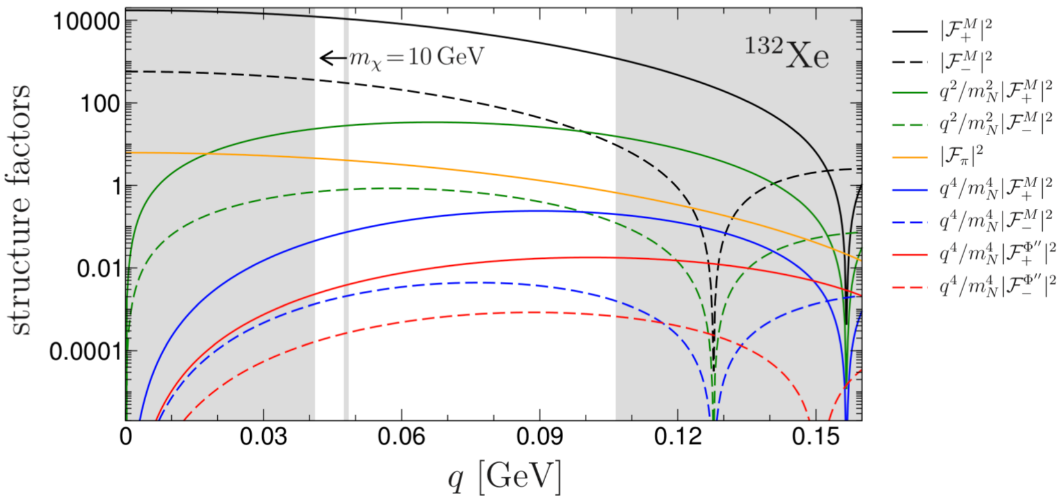


$$\frac{\mathrm{d}\sigma}{\mathrm{d}q^2} = \frac{1}{4\pi v^2}\bigg| \sum_{I=\pm} \left(c_I^M - \frac{q^2}{m_N^2}\,\dot{c}_I^M\right)\mathcal{F}_I^M(q^2) + c_\pi \mathcal{F}_\pi(q^2) + \frac{q^2}{2m_N^2}\sum_{I=\pm} c_I^{\Phi''}\mathcal{F}_I^{\Phi''}(q^2)\bigg|^2 + \frac{1}{4\pi v^2}\bigg|\sum_{I=\pm}\frac{q}{2m_\chi}\tilde{c}_I^M\mathcal{F}_I^M(q^2)\bigg|^2.$$

Can one discriminate responses in XENON1T, nT or DARWIN?

Disriminating different WIMP-nucleus response functions

Fieguth et al., PRD in press white region accessible to XENON-type experiment



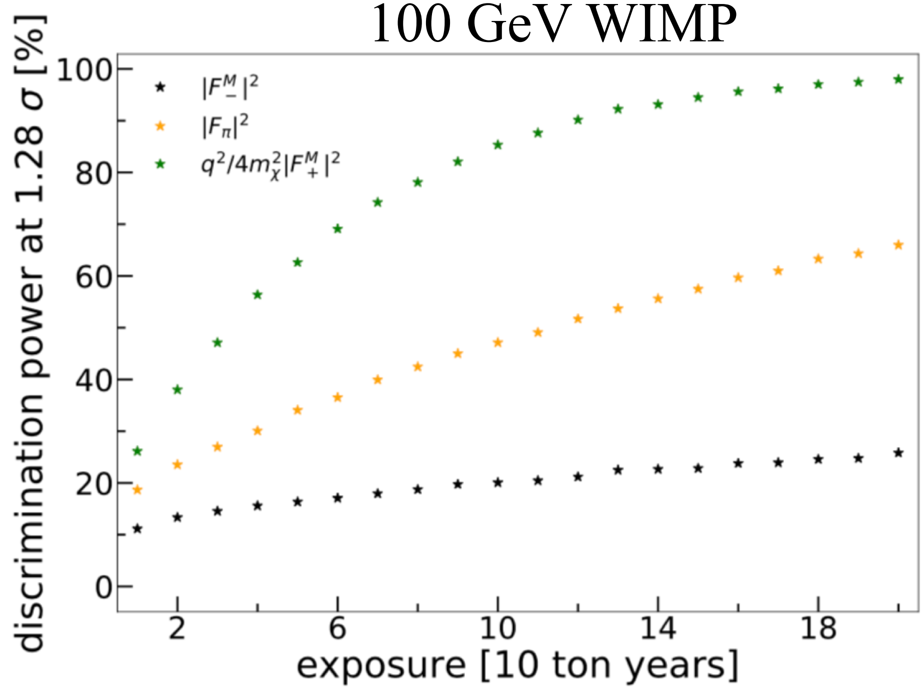
$$\frac{d\sigma}{dq^2} = \frac{1}{4\pi v^2}\left|\sum_{I=\pm}\left(c_I^M - \frac{q^2}{m_N^2}\dot{c}_I^M\right)\mathcal{F}_I^M(q^2) + c_\pi\mathcal{F}_\pi(q^2) + \frac{q^2}{2m_N^2}\sum_{I=\pm}c_I^{\Phi''}\mathcal{F}_I^{\Phi''}(q^2)\right|^2 + \frac{1}{4\pi v^2}\left|\sum_{I=\pm}\frac{q}{2m_\chi}\tilde{c}_I^M\mathcal{F}_I^M(q^2)\right|^2.$$

Can one discriminate responses in XENON1T, nT or **DARWIN**?

compared to standard SI response (Helm form factor)

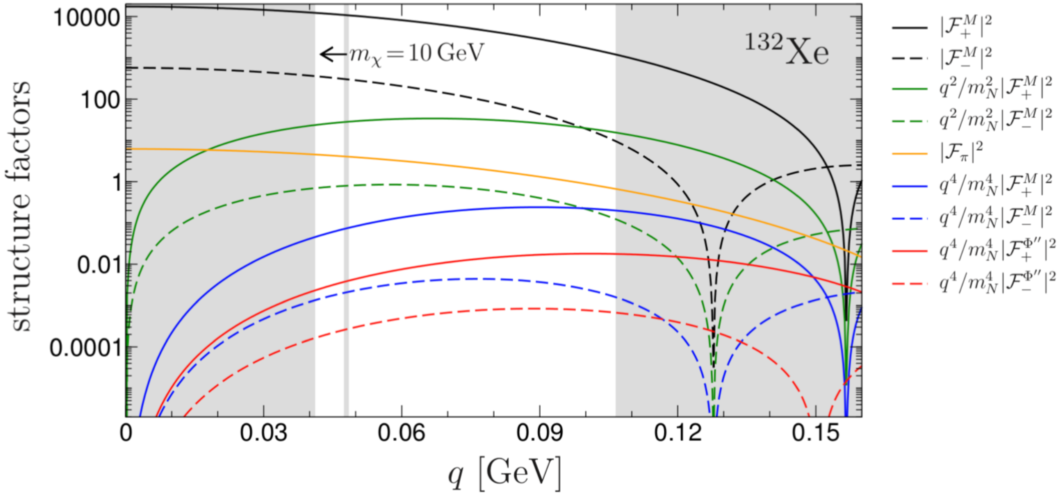
q-dependent responses more easily distinguishable

100 GeV WIMP



Disriminating different WIMP-nucleus response functions

Fieguth et al., PRD in press white region accessible to XENON-type experiment



$$\frac{\mathrm{d}\sigma}{\mathrm{d}q^2} = \frac{1}{4\pi v^2}\bigg| \sum_{I=\pm} \Big(c_I^M - \frac{q^2}{m_N^2}\,\dot{c}_I^M\Big)\mathcal{F}_I^M(q^2) + c_\pi \mathcal{F}_\pi(q^2) + \frac{q^2}{2m_N^2}\sum_{I=\pm} c_I^{\Phi''}\mathcal{F}_I^{\Phi''}(q^2)\bigg|^2 + \frac{1}{4\pi v^2}\bigg|\sum_{I=\pm}\frac{q}{2m_\chi}\tilde{c}_I^M \mathcal{F}_I^M(q^2)\bigg|^2.$$

Can one discriminate responses in XENON1T, nT or **DARWIN**?

compared to standard SI response (Helm form factor)

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

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

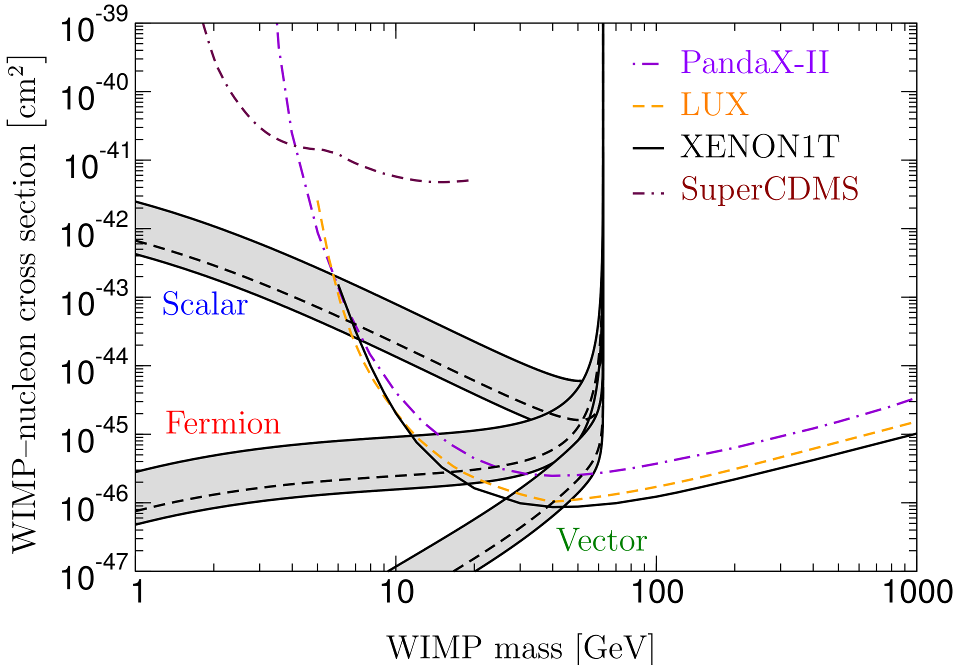
m_χ	100 GeV			1 TeV		
σ_0 [cm^2]	10^{-46}	10^{-47}	10^{-48}	10^{-45}	10^{-46}	10^{-47}
$\lvert\mathcal{F}_-^M\rvert^2$	94	26	12	100	35	13
$q^2/4m_\chi^2\lvert\mathcal{F}_+^M\rvert^2$	100	100	34	100	100	41
$q^2/4m_\chi^2\lvert\mathcal{F}_-^M\rvert^2$	100	98	25	100	100	32
$q^4/m_N^4\lvert\mathcal{F}_+^M\rvert^2$	100	100	55	100	100	63
$q^4/m_N^4\lvert\mathcal{F}_-^M\rvert^2$	100	100	47	100	100	53
$\lvert\mathcal{F}_\pi\rvert^2$	100	66	17	100	81	20
$q^4/4m_N^4\lvert\mathcal{F}_+^{\Phi''}\rvert^2$	100	100	58	100	100	69
$q^4/4m_N^4\lvert\mathcal{F}_-^{\Phi''}\rvert^2$	100	100	55	100	100	64

Higgs Portal dark matter

WIMP interacts with q,G via Higgs

fermion, scalar and vector WIMPS

for $m_h > 2m_\chi$ should be seen at LHC



linking LHC and direct detection requires Higgs-nucleon coupling

$$f_N = \sum_{q=u,d,s,c,b,t} f_q^N = \frac{2}{9} + \frac{7}{9} \sum_{q=u,d,s} f_q^N + \mathcal{O}(\alpha_s)$$ use outdated input $f_N = 0.260 \ldots 0.629$

Higgs Portal dark matter

WIMP interacts with q,G via Higgs
fermion, scalar and vector WIMPS

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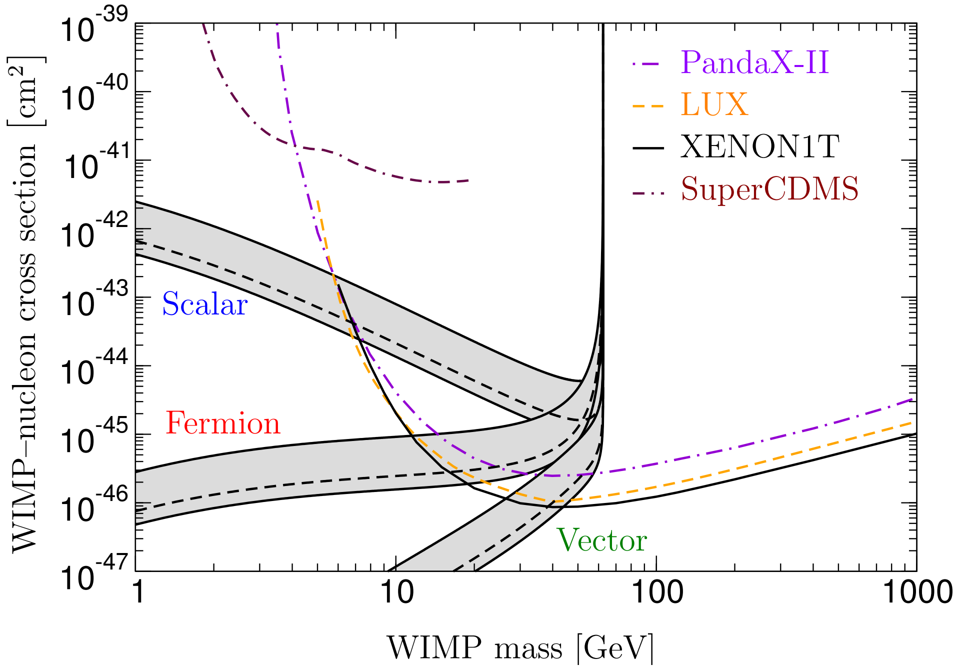


linking LHC and direct detection
requires Higgs-nucleon coupling

$f_N = \sum_{q=u,d,s,c,b,t} f_q^N = \frac{2}{9} + \frac{7}{9} \sum_{q=u,d,s} f_q^N + \mathcal{O}(\alpha_s)$ use outdated input $f_N = 0.260 \ldots 0.629$

with new lattice results and χPT: $f_N^{1b} = 0.307(9)_{ud}(15)_s(5)_{\text{pert}} = 0.307(18)$

two-body current contributions from scalar and trace anomaly coupling:
combine to coupling to pion and binding energy correction

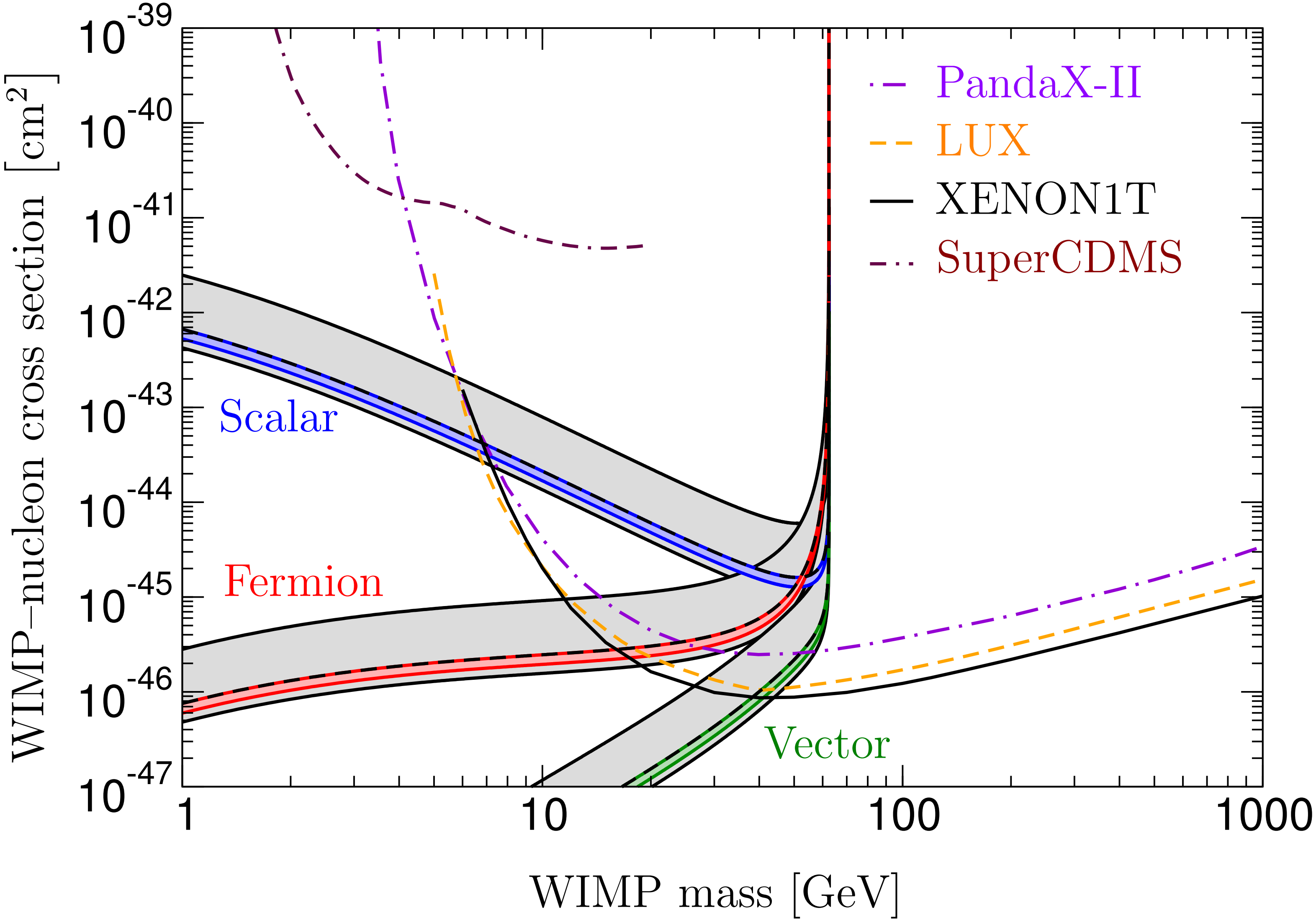
$f_N^{2b} = \left[-3.2(0.2)_A(2.1)_{\text{ChEFT}} + 5.0(0.4)_A\right] \times 10^{-3} = 1.8(2.1) \times 10^{-3}$

cancellation gives very small 2-body current contribution

Linking LHC and direct detection results in Higgs Portals

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