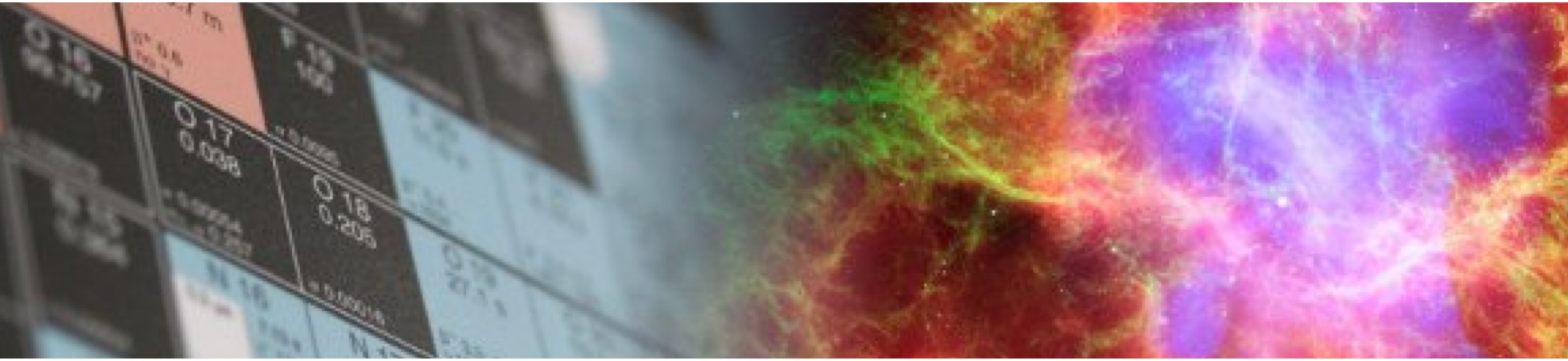
Chiral effective field theory for nuclei and dark matter direct detection

Achim Schwenk

TECHNISCHE UNIVERSITÄT DARMSTADT



ECT* Workshop "Precise beta decay calculations …", April 10, 2019

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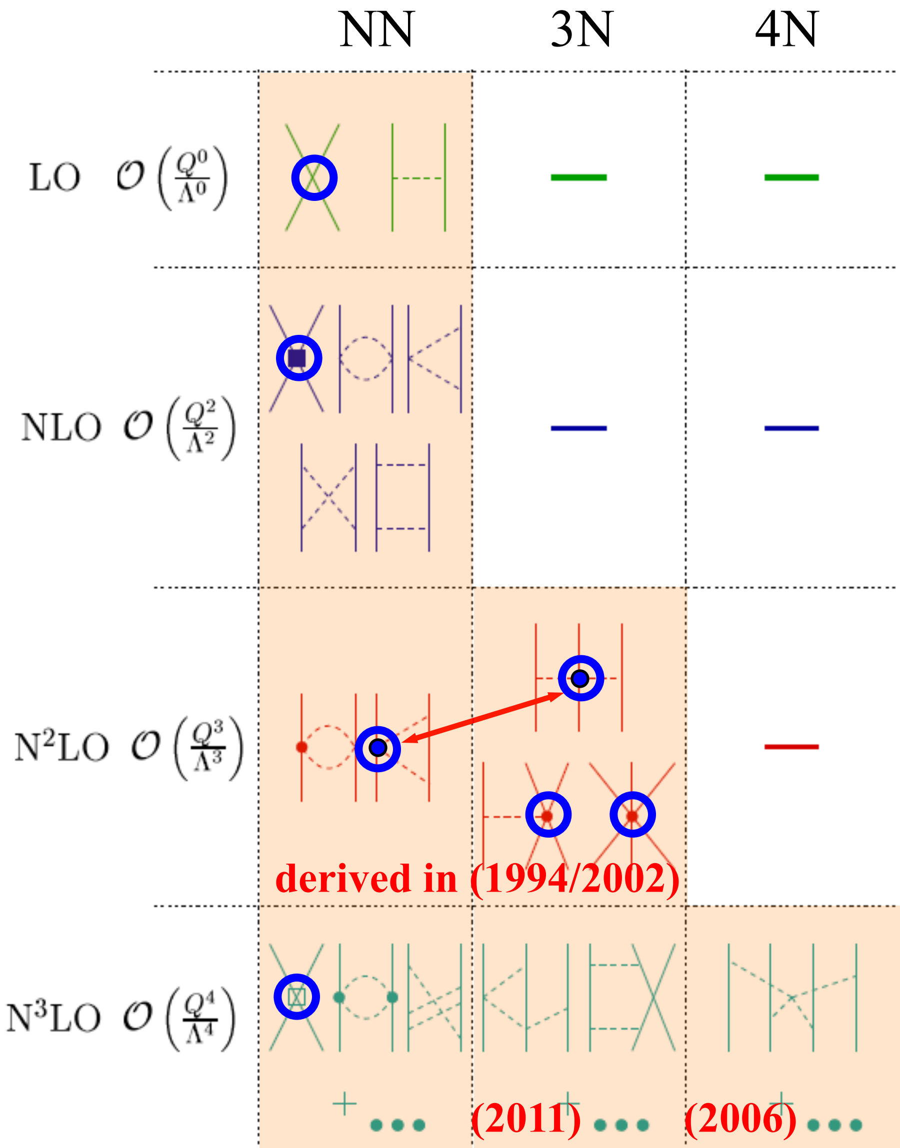
Chiral EFT for nuclear forces

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**

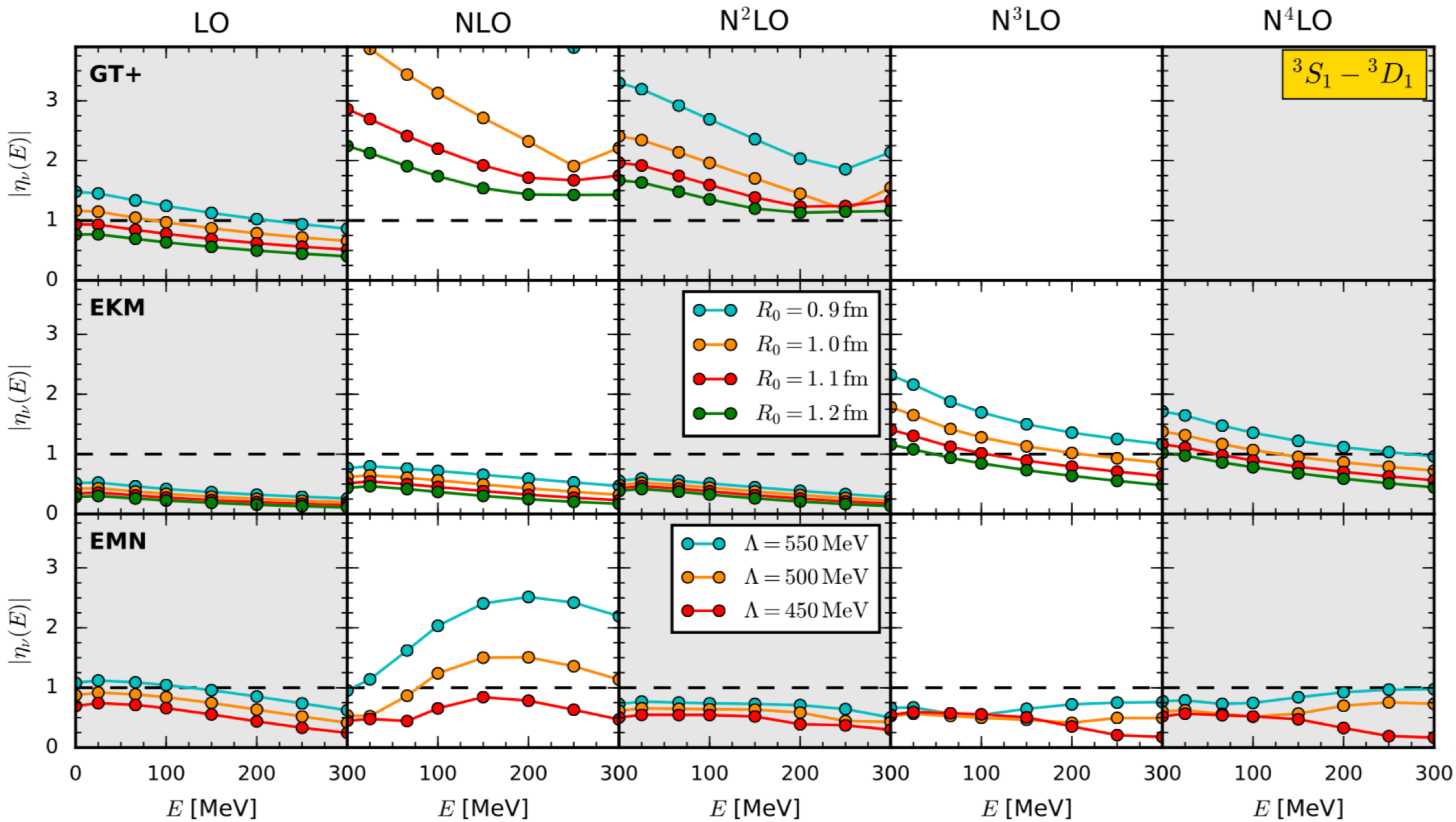
from quarks to nucleons/pions for
coupling to beyond SM particles

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

Need to explore broader range of chiral EFT interactions

Weinberg eigenvalues of local GT+, semi-local EKM, nonlocal EMN

Hoppe, Drischler et al., PRC (2017)

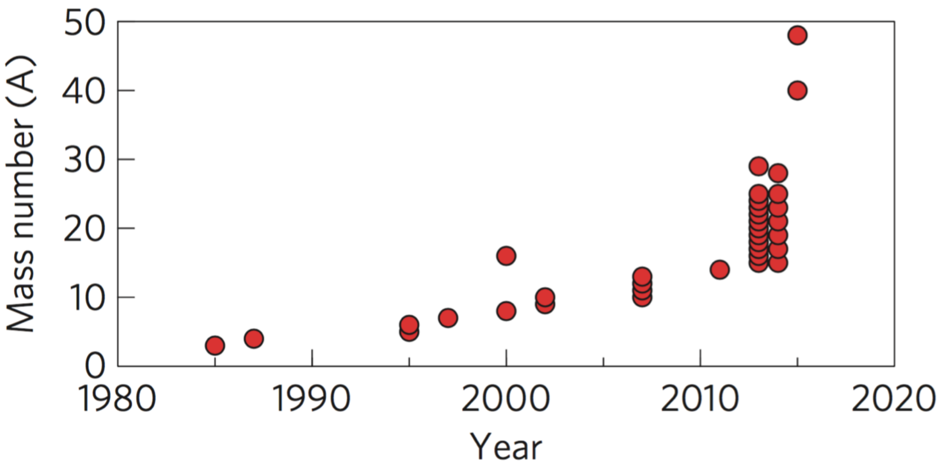


+ soft local Durant, Huth et al., PLB (2018) and soft semi-local Reinert et al., EPJA (2018)

+ Delta-full potentials Piarulli et al., PRC (2015), Ekström et al., PRC (2018)

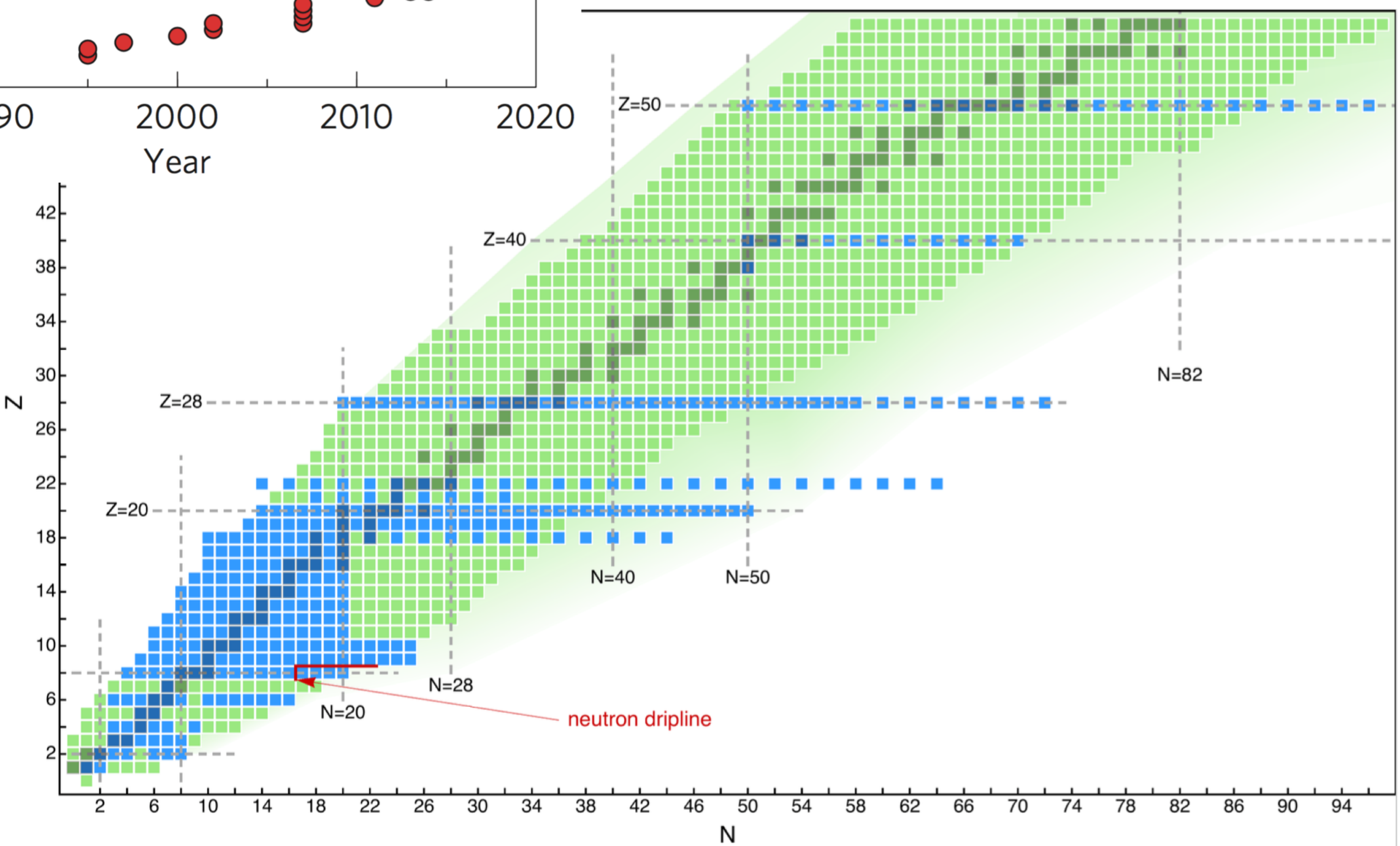
Progress in ab initio calculations of nuclei

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)



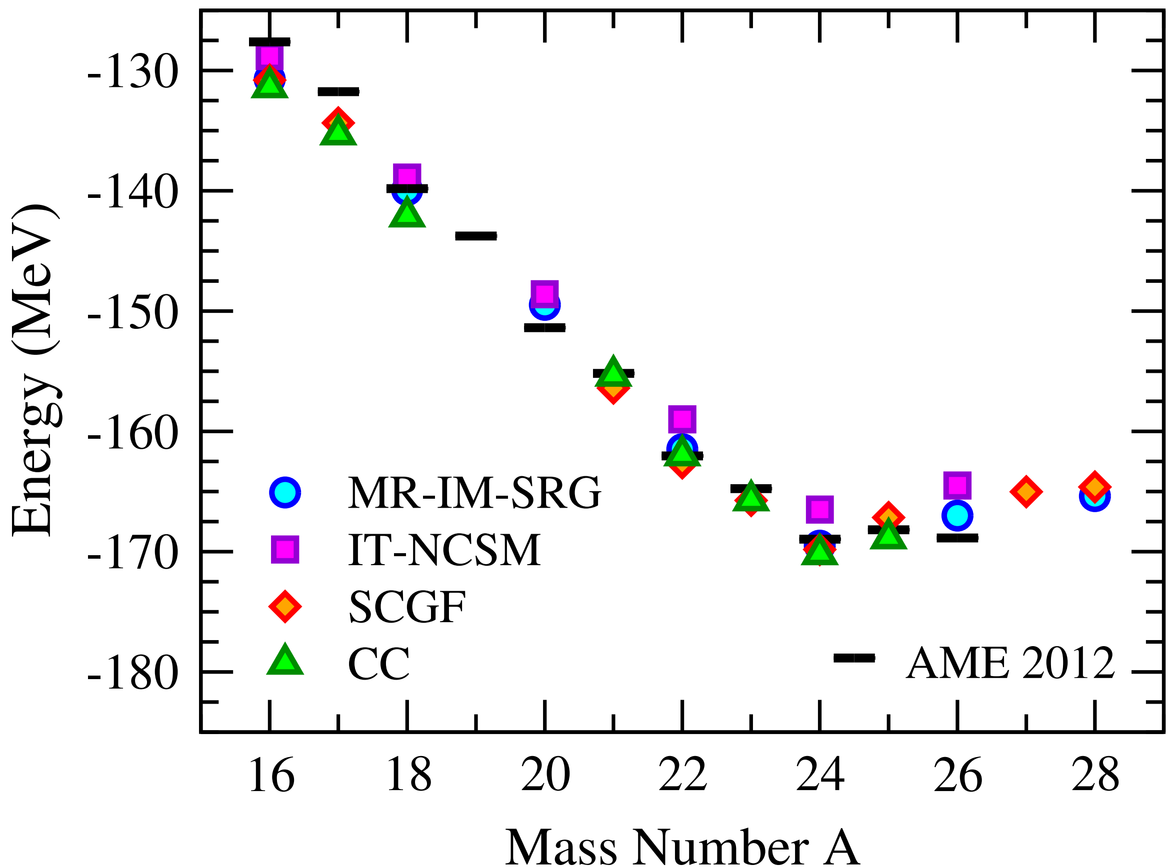
Ab initio calculations of neutron-rich oxygen isotopes

based on same NN+3N interactions with different many-body methods

CC theory/CCEI
Hagen et al., PRL (2012),
Jansen et al., PRL (2014)

Multi-Reference In-Medium SRG and IT-NCSM
Hergert et al., PRL (2013)

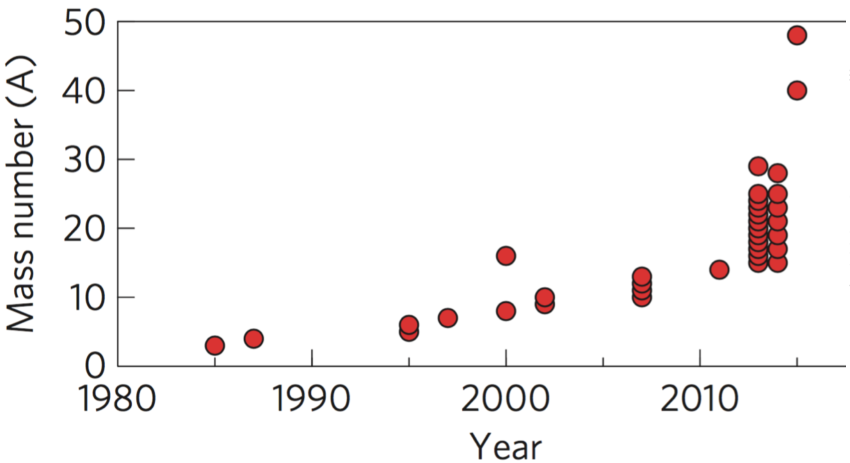
Self-Consistent Green's Functions
Cipollone et al., PRL (2013)

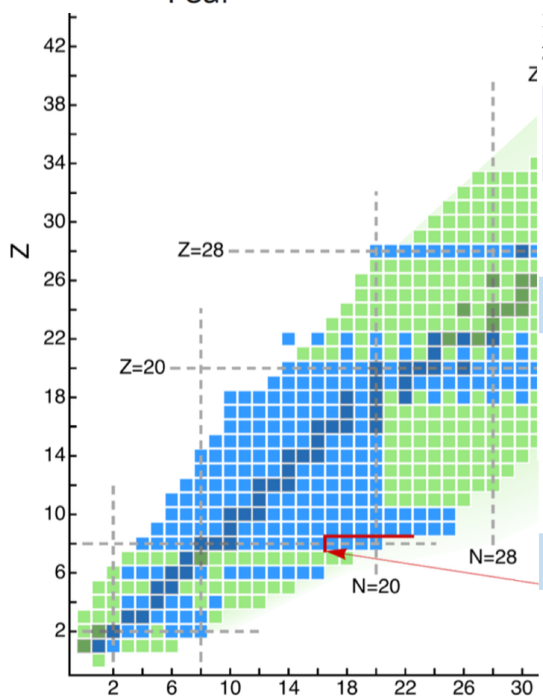


Many-body calculations of medium-mass nuclei have smaller uncertainty compared to uncertainties in nuclear forces

Progress in ab initio calculations of nuclei

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





LETTER

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]

doi:10.1038/nature12522

Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

ARTICLES

nature physics

PUBLISHED ONLINE: 2 NOVEMBER 2015 | DOI: 10.1038/NPHYS3529

Neutron and weak-charge distributions of the ^{48}Ca nucleus

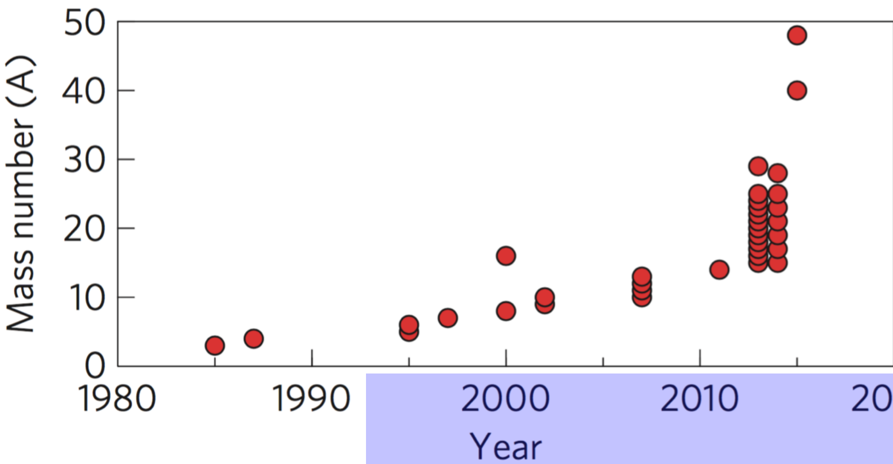
G. Hagen[1,2]★, A. Ekström[1,2], C. Forssén[1,2,3], G. R. Jansen[1,2], W. Nazarewicz[1,4,5], T. Papenbrock[1,2], K. A. Wendt[1,2], S. Bacca[6,7], N. Barnea[8], B. Carlsson[3], C. Drischler[9,10], K. Hebeler[9,10], M. Hjorth-Jensen[4,11], M. Miorelli[6,12], G. Orlandini[13,14], A. Schwenk[9,10] and J. Simonis[9,10]

Unexpectedly large charge radii of neutron-rich calcium isotopes

R. F. Garcia Ruiz[1]★, M. L. Bissell[1,2], K. Blaum[3], A. Ekström[4,5], N. Frömmgen[6], G. Hagen[4], M. Hammen[6], K. Hebeler[7,8], J. D. Holt[9], G. R. Jansen[4,5], M. Kowalska[10], K. Kreim[3], W. Nazarewicz[4,11,12], R. Neugart[3,6], G. Neyens[1], W. Nörtershäuser[6,7], T. Papenbrock[4,5], J. Papuga[1], A. Schwenk[3,7,8], J. Simonis[7,8], K. A. Wendt[4,5] and D. T. Yordanov[3,13]

Progress in ab initio calculations of nuclei

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



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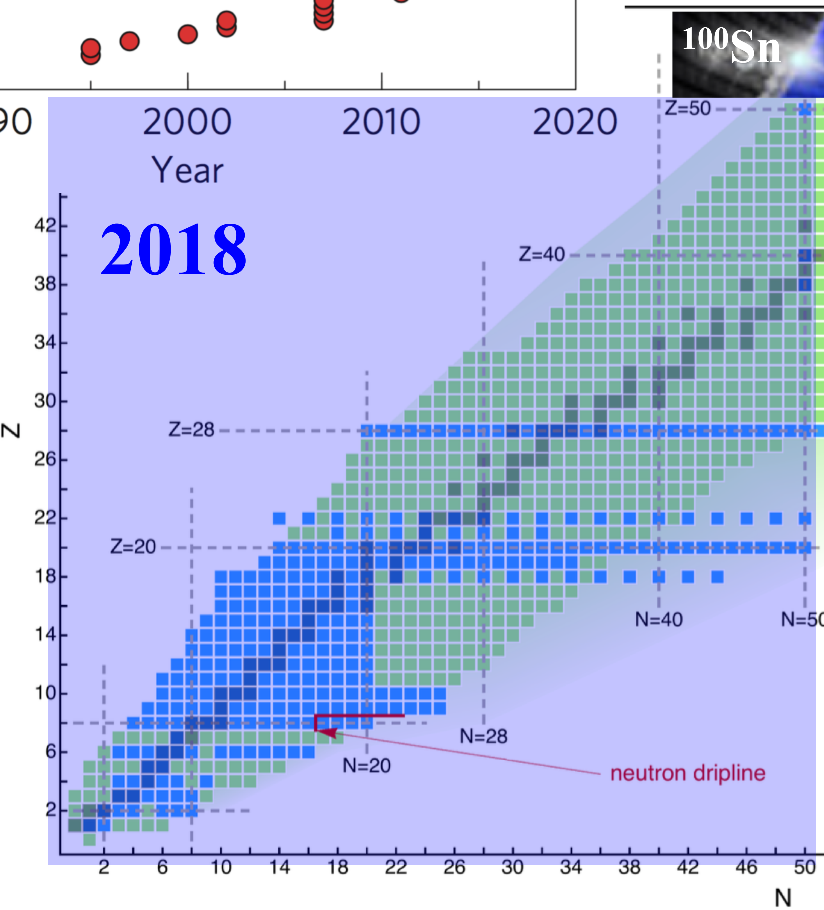
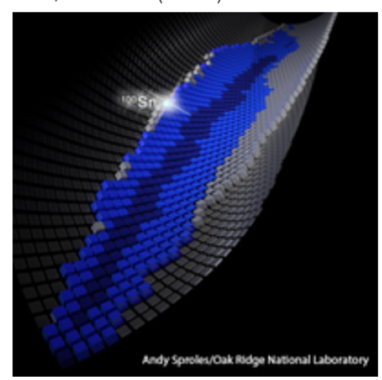


Editors' Suggestion

Structure of the Lightest Tin Isotopes

T. D. Morris, J. Simonis, S. R. Stroberg, C. Stumpf, G. Hagen, J. D. Holt, G. R. Jansen, T. Papenbrock, R. Roth, and A. Schwenk

Phys. Rev. Lett. **120**, 152503 (2018) – Published 12 April 2018

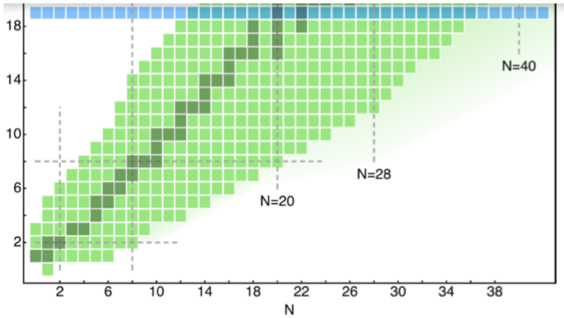


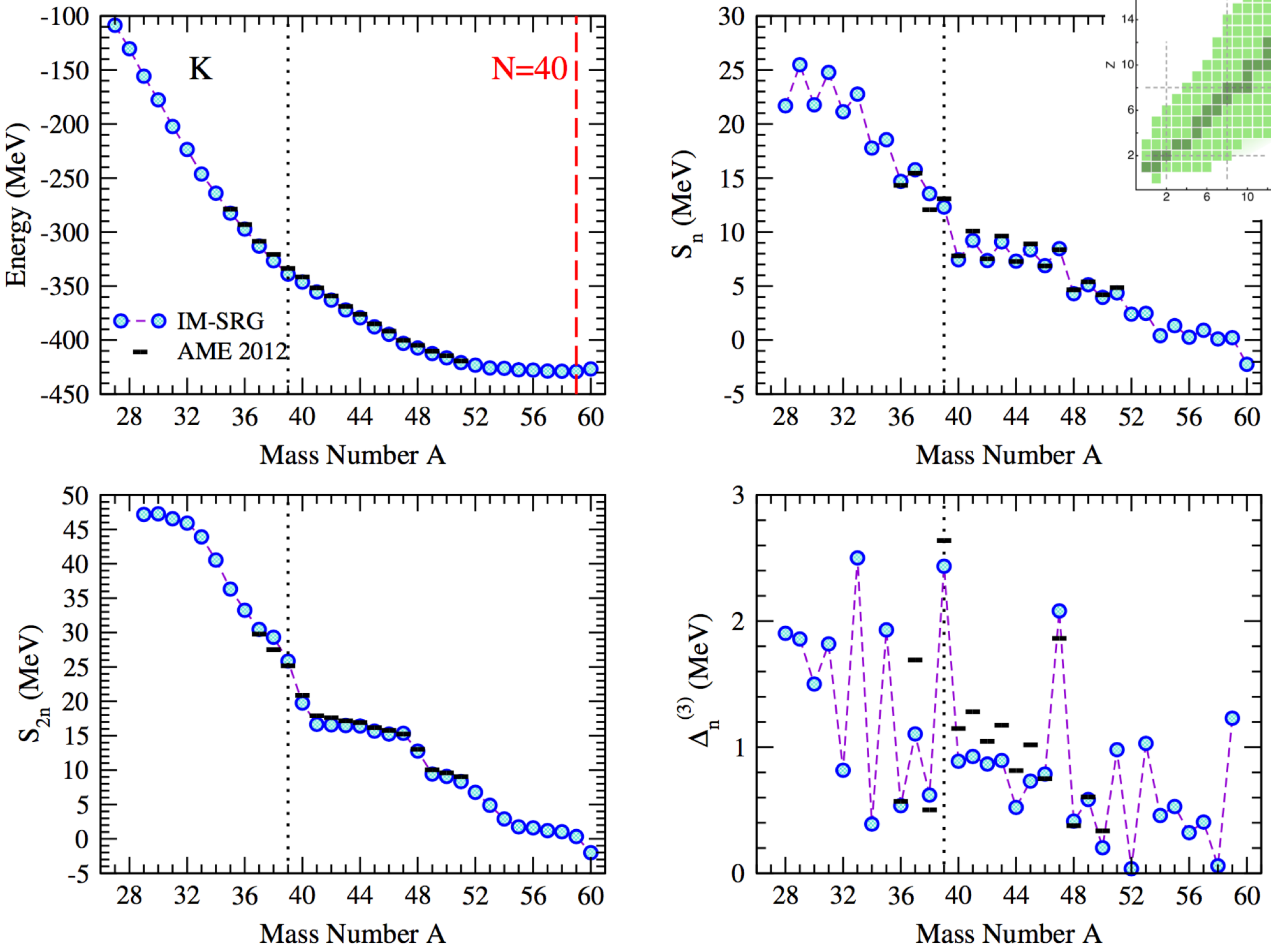
Ab-inito calculations of ^{100}Sn with $N = Z = 50$ predict it to be doubly magic.

Great progress from medium to heavy nuclei

VS-IMSRG with ensemble normal ordering from NN+3N 1.8/2.0 (EM)

Tsukiyama, Bogner, AS, Hergert, Holt, Stroberg, Simonis,…





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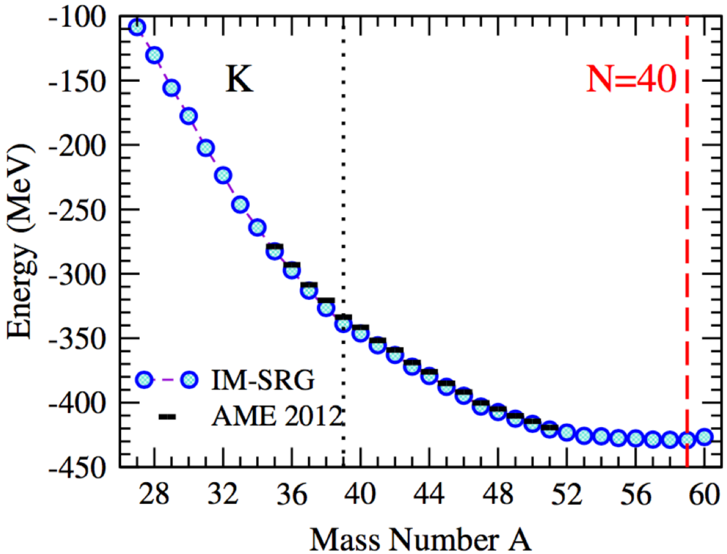
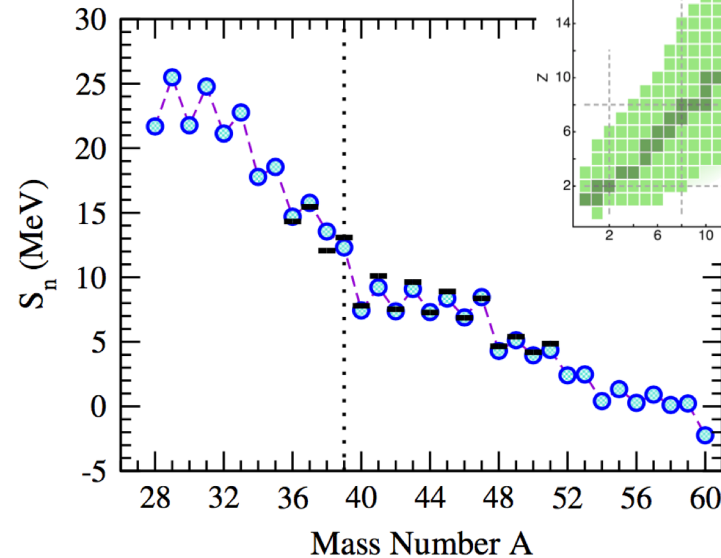
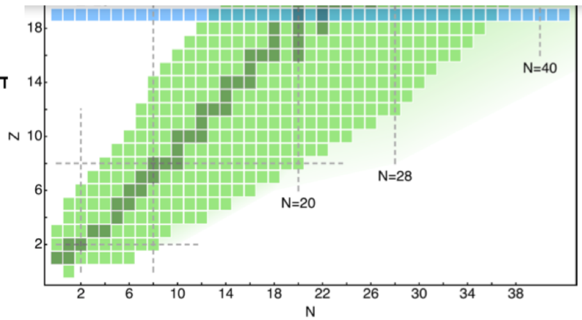






Important for medium-mass nuclei:

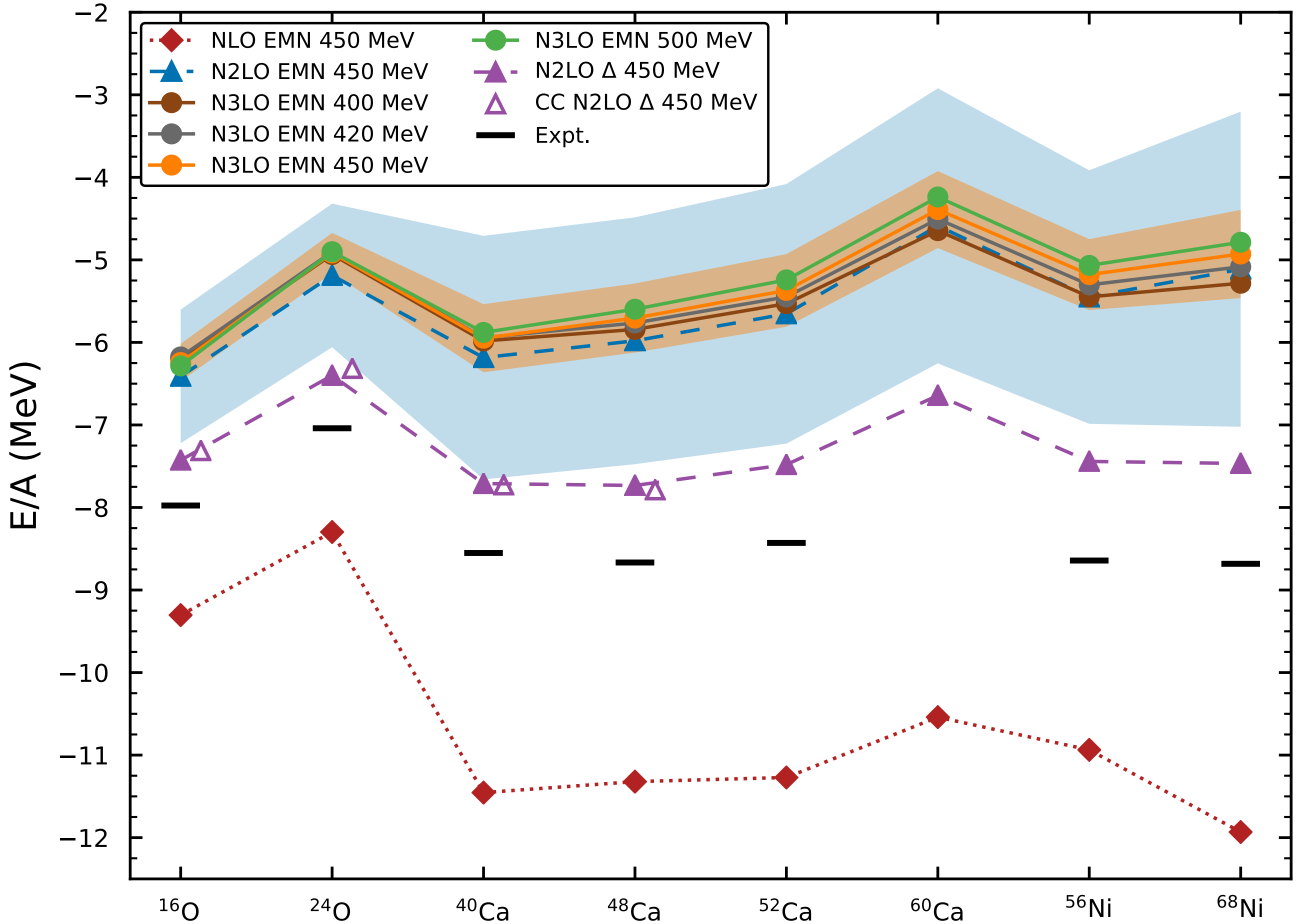
Consider nuclear forces with good (nuclear matter) saturation properties

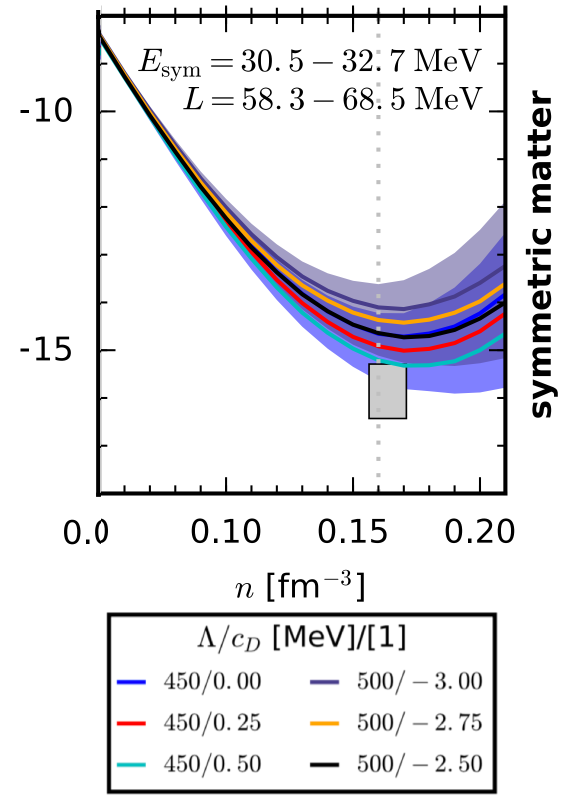
N^2LO_{sat} fit to selected nuclei up to A=24 Ekström et al. (2015)

NN evolved + 3N fit to ^{3}H, ^{4}He Hebeler et al. (2011)

First N^3LO results for medium-mass nuclei Hoppe et al., in prep.

NLO, N^2LO, N^3LO (EMN 450) with EFT uncertainty bands





bands overlap and at N^3LO cutoff variation is within band

underbinding expected from saturation point

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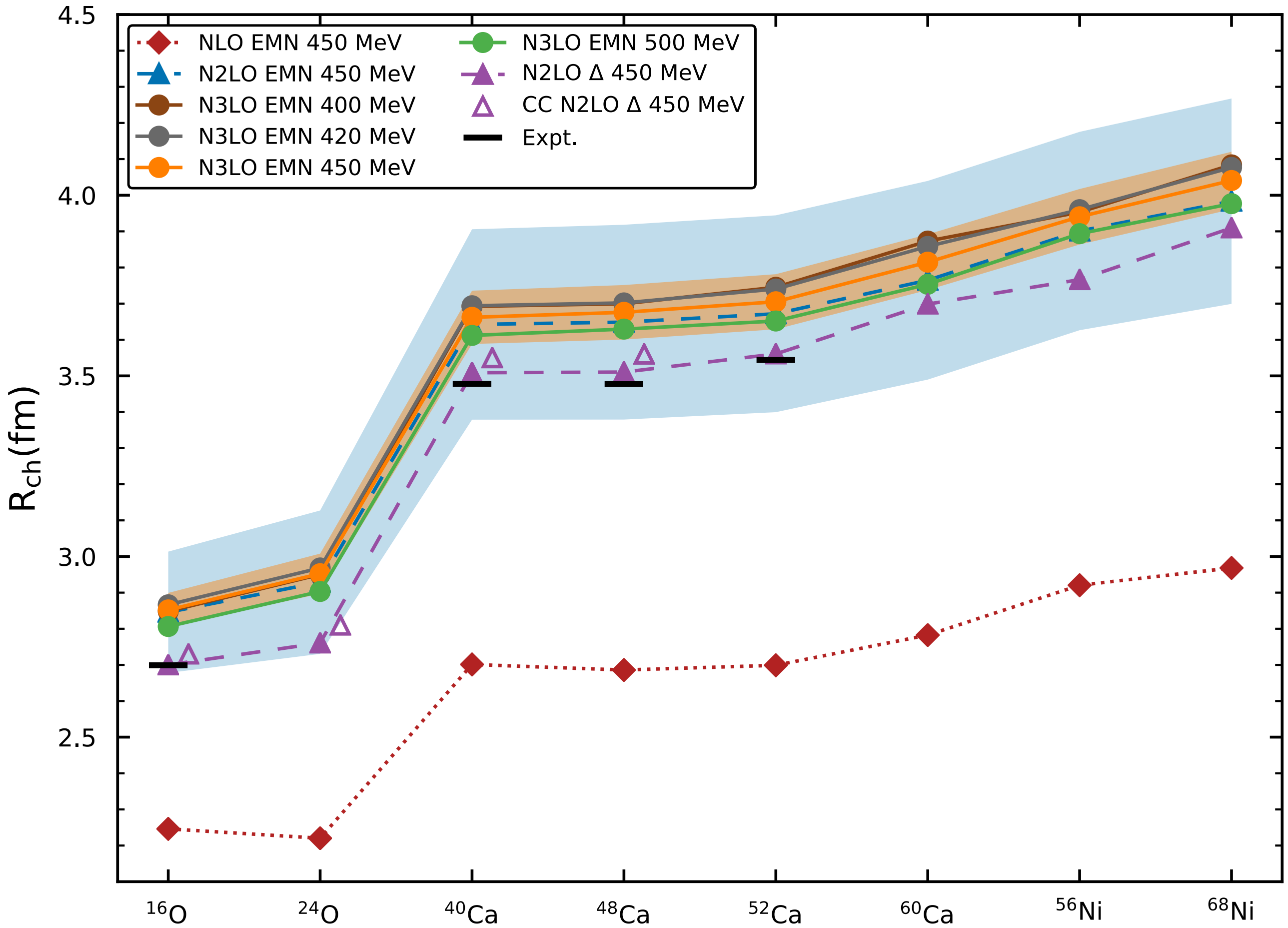
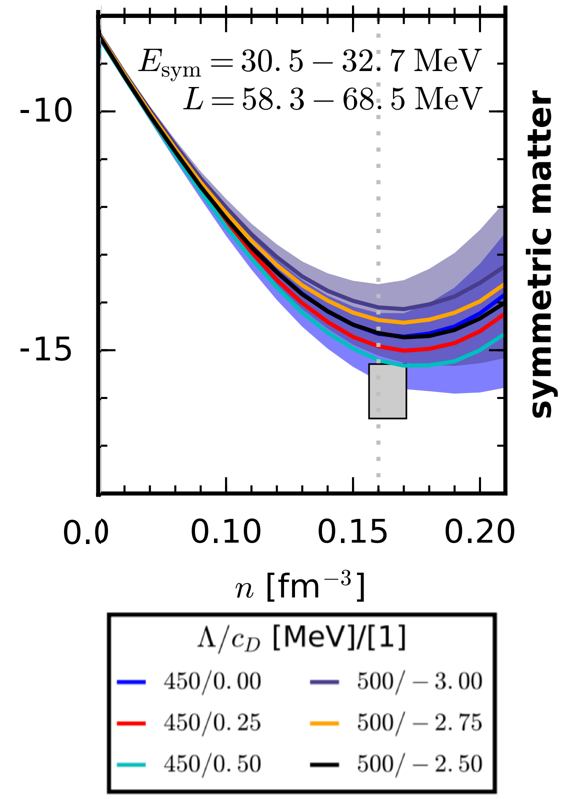
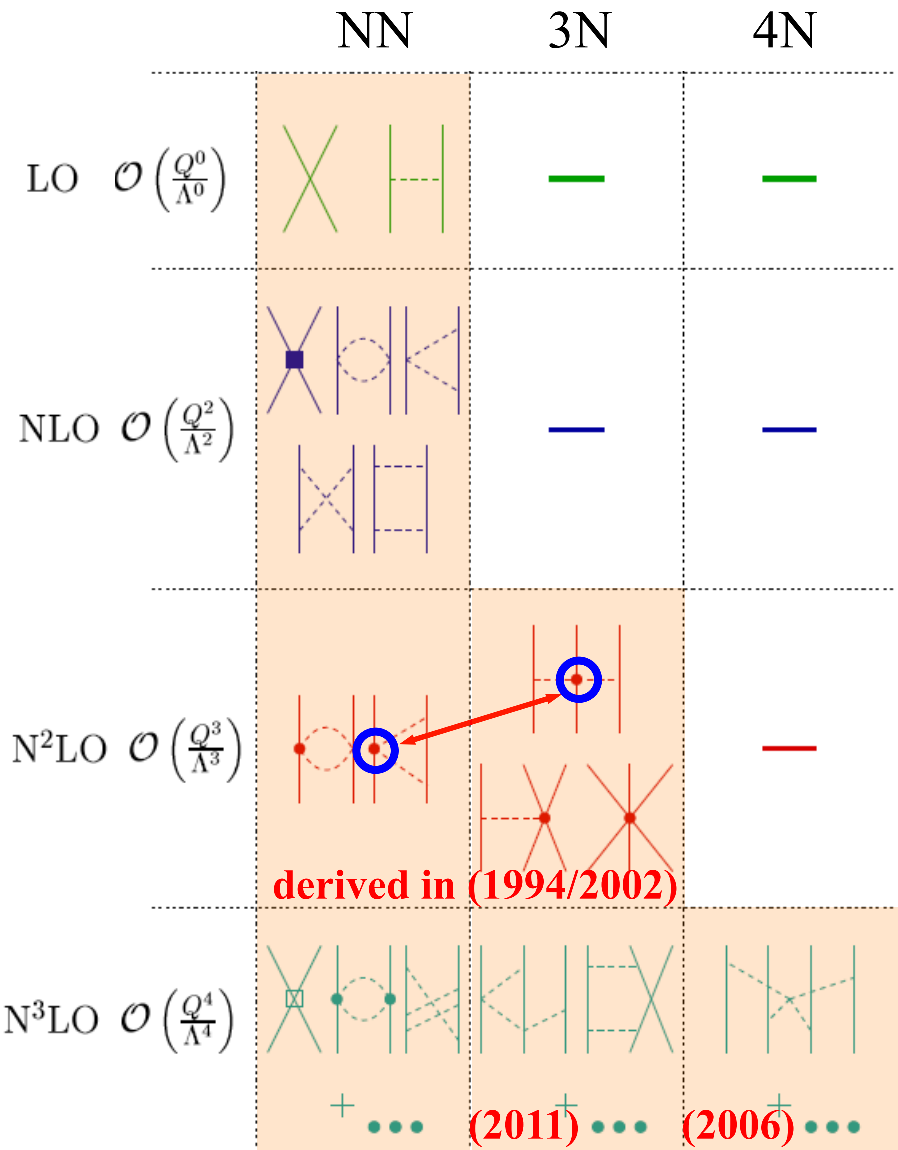




bands overlap and at N^3LO cutoff variation is within band

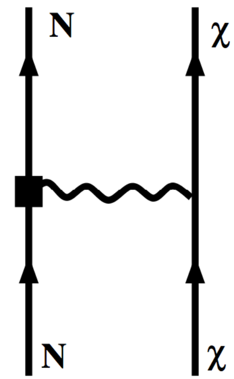
radii in better agreement, larger than expected from saturation point

Chiral EFT for coupling to external sources

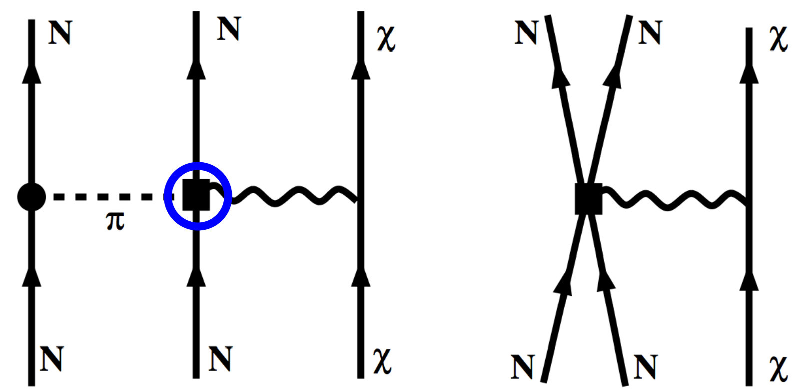


example: axial-vector currents

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



+ two-body currents at Q^3



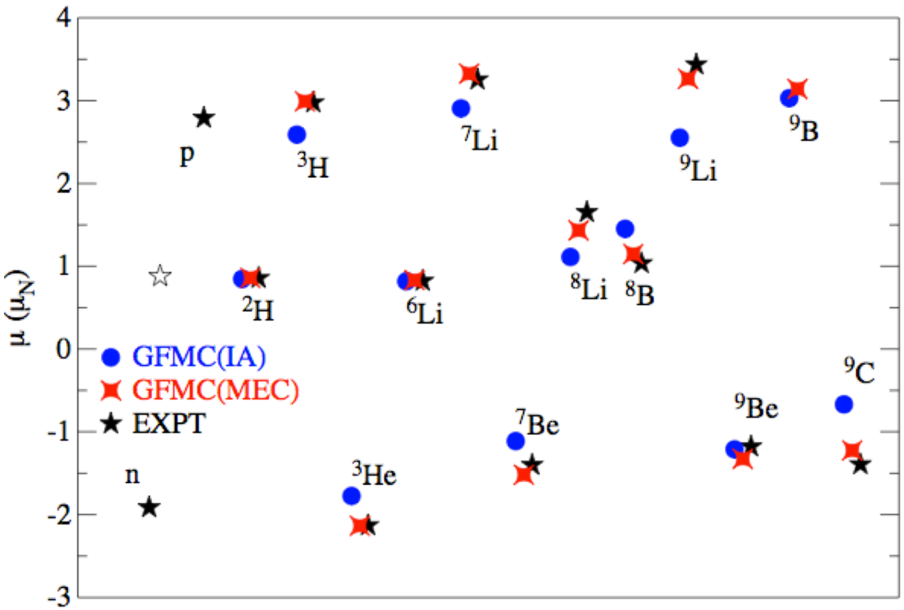
same couplings in forces and currents!

Chiral EFT for electroweak currents

consistent electroweak one- and two-body (meson-exchange) currents

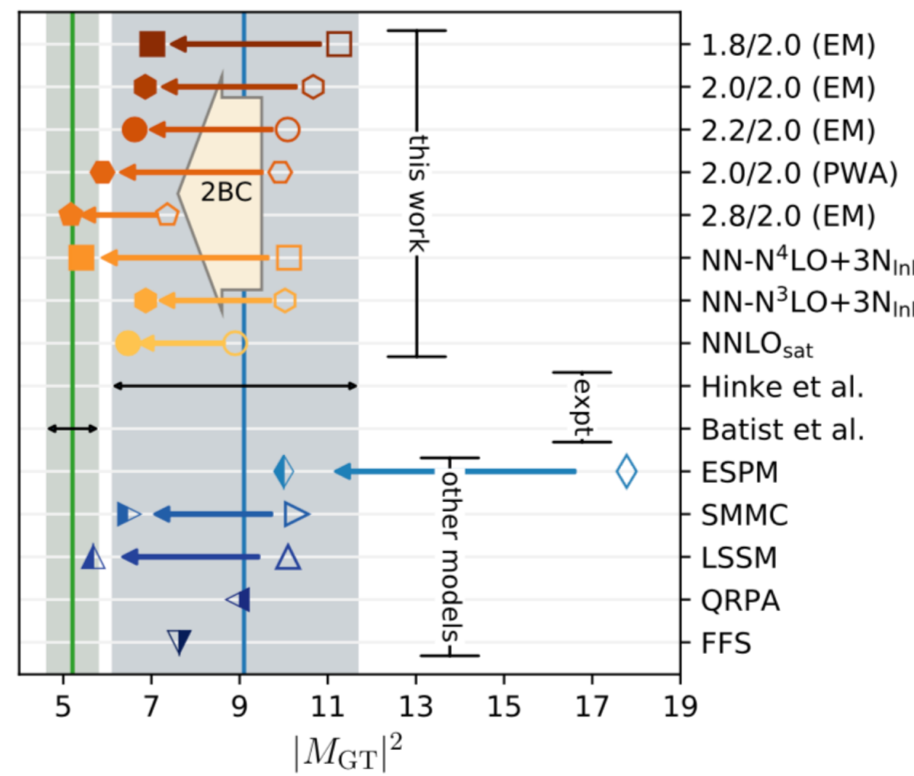
magnetic moments in light nuclei

Pastore et al. (2012-)



Gamow-Teller beta decay of ^{100}Sn

Gysbers, Hagen et al., Nature Phys. (2019)



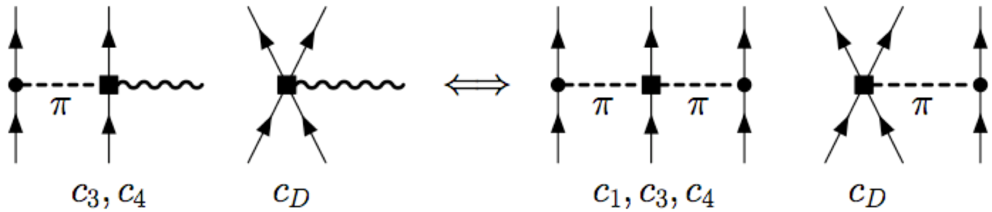
two-body currents are key for quenching puzzle of beta decays

Axial-vector currents and 3N forces

weak axial-vector currents couple to spin, similar to pions

two-body currents predicted by NN, 3N couplings to N^2LO

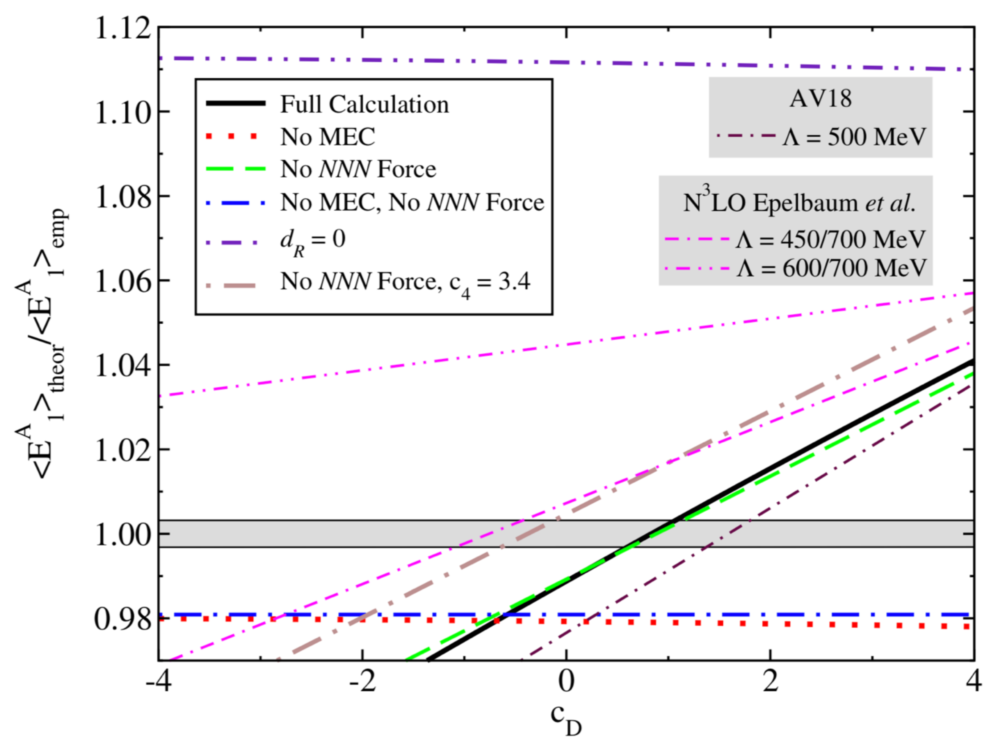
Park et al., Gardestig and Phillips,…



two-body analogue of Goldberger-Treiman relation

used in a pionneering study to determine c_D

Gazit, Quaglioni, Navratil, PRL (2009)
+ 2018 Schiavilla correction



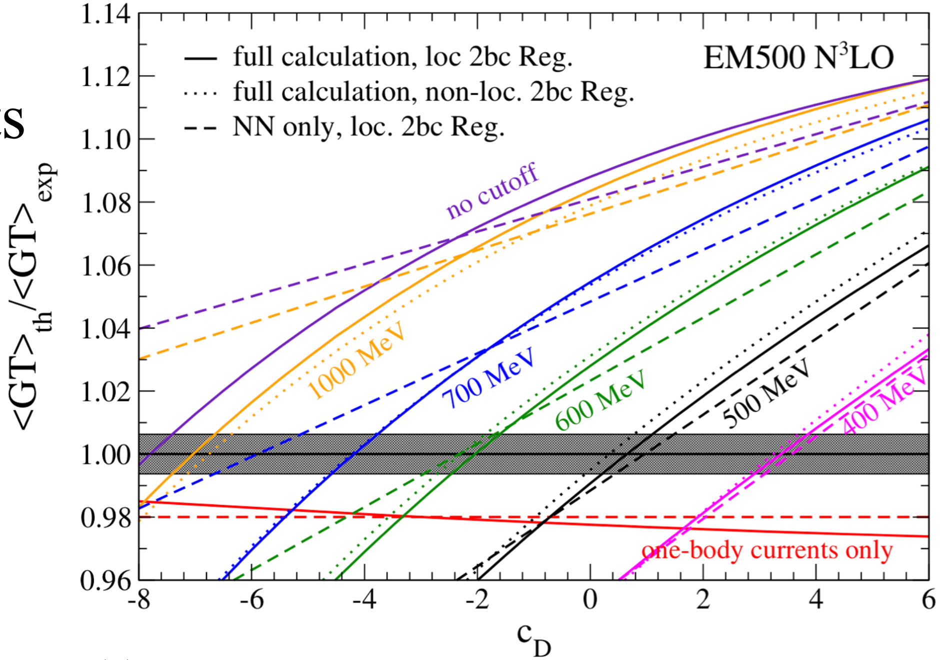
very attractive because:
^3H half-life precisely known,
uncorrelated with ^3H energy
c_D, c_E fully determined from A=3

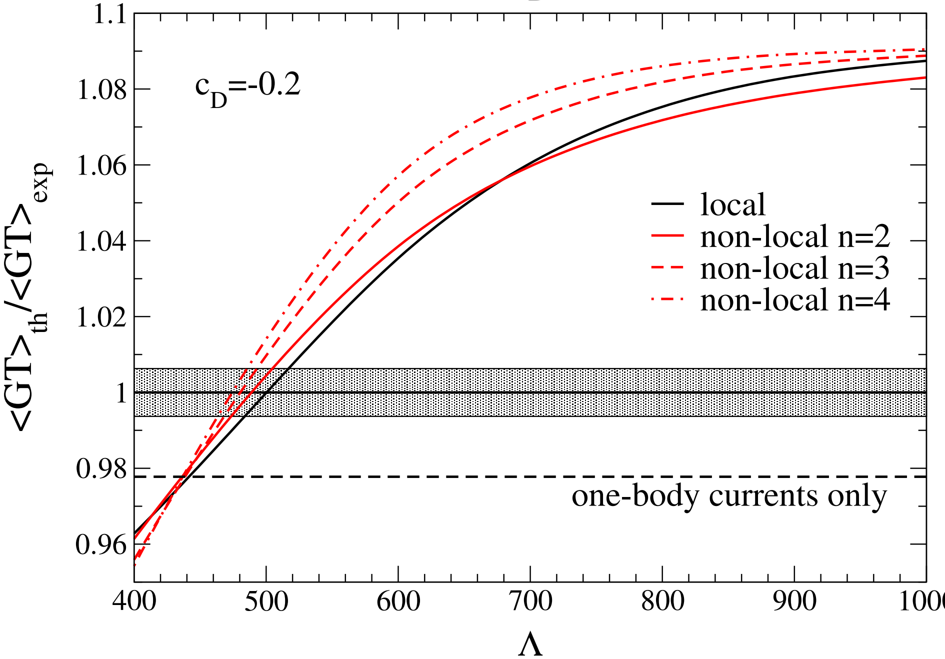
Axial-vector currents and 3N forces Klos, Carbone et al., EPJA (2017)

However: ^3H beta decay fit only performed for fixed cutoff in currents

cutoff dependence significant

cutoff dependence in two-body currents can be significant/ larger than 2BC contribution





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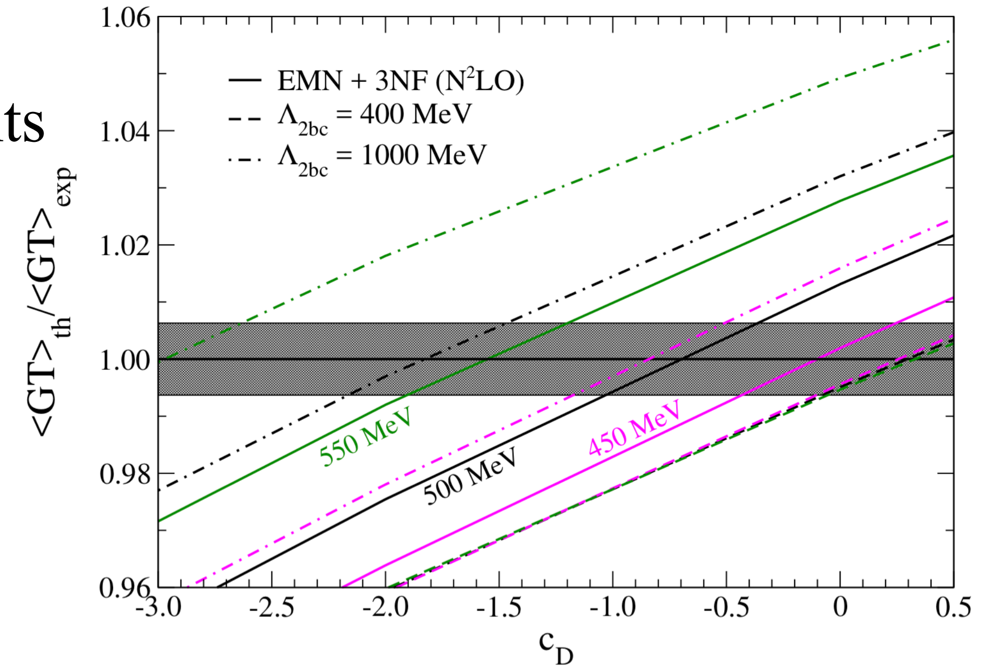
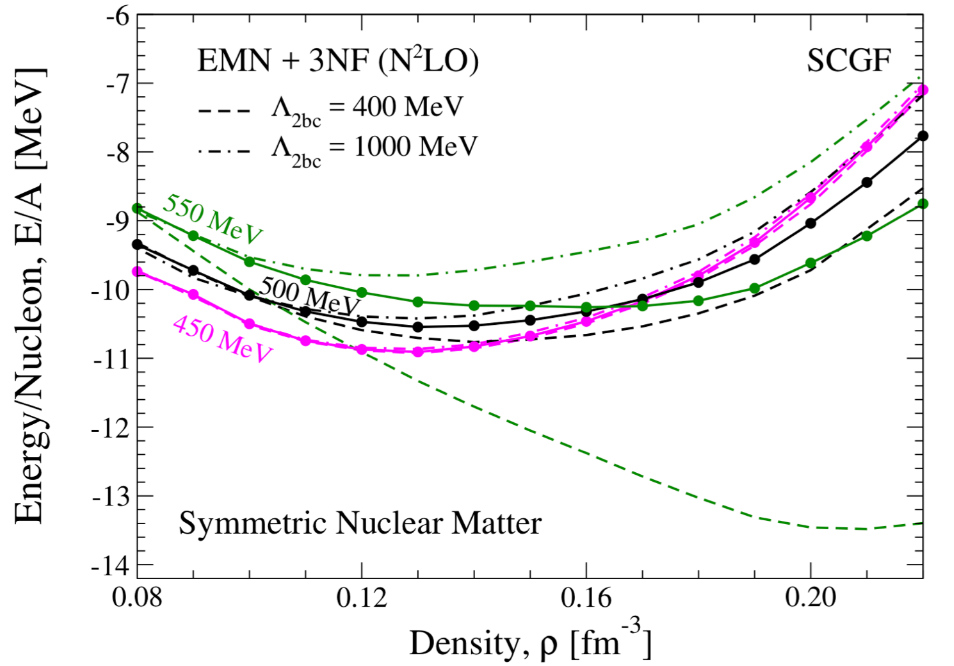
obtained c_D value depends on cutoff in currents

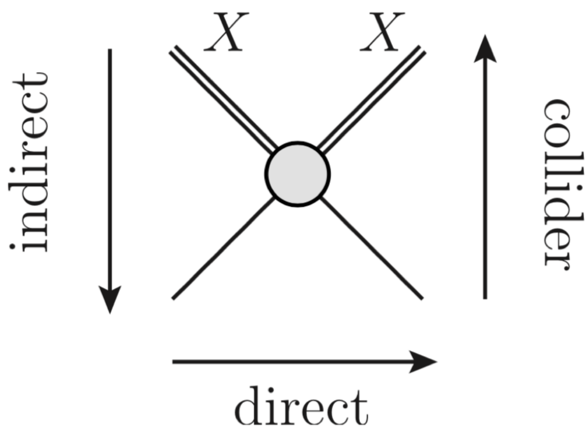
cutoff in currents effects 3N forces!? Example: impact on nuclear matter





Dark matter direct detection

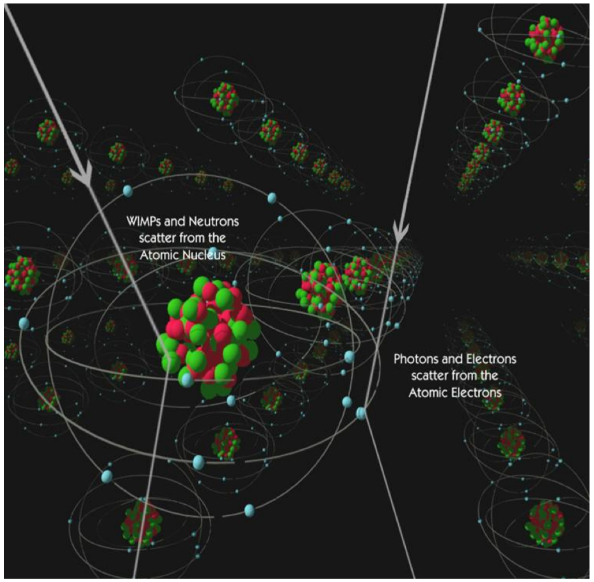
Assume DM particle is WIMP, search strategies:



Direct detection:
WIMP scattering off nuclei, needs as input

Nucleon matrix elements
WIMP-quark/gluon 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), PRD (2016), PRL (2017), PRD (2019),
Fieguth et al., PRD (2018), XENON1T + Hoferichter et al., PRL (2019)

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), Andreoli et al., PRC (2019)

Scales in DM direct detection

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

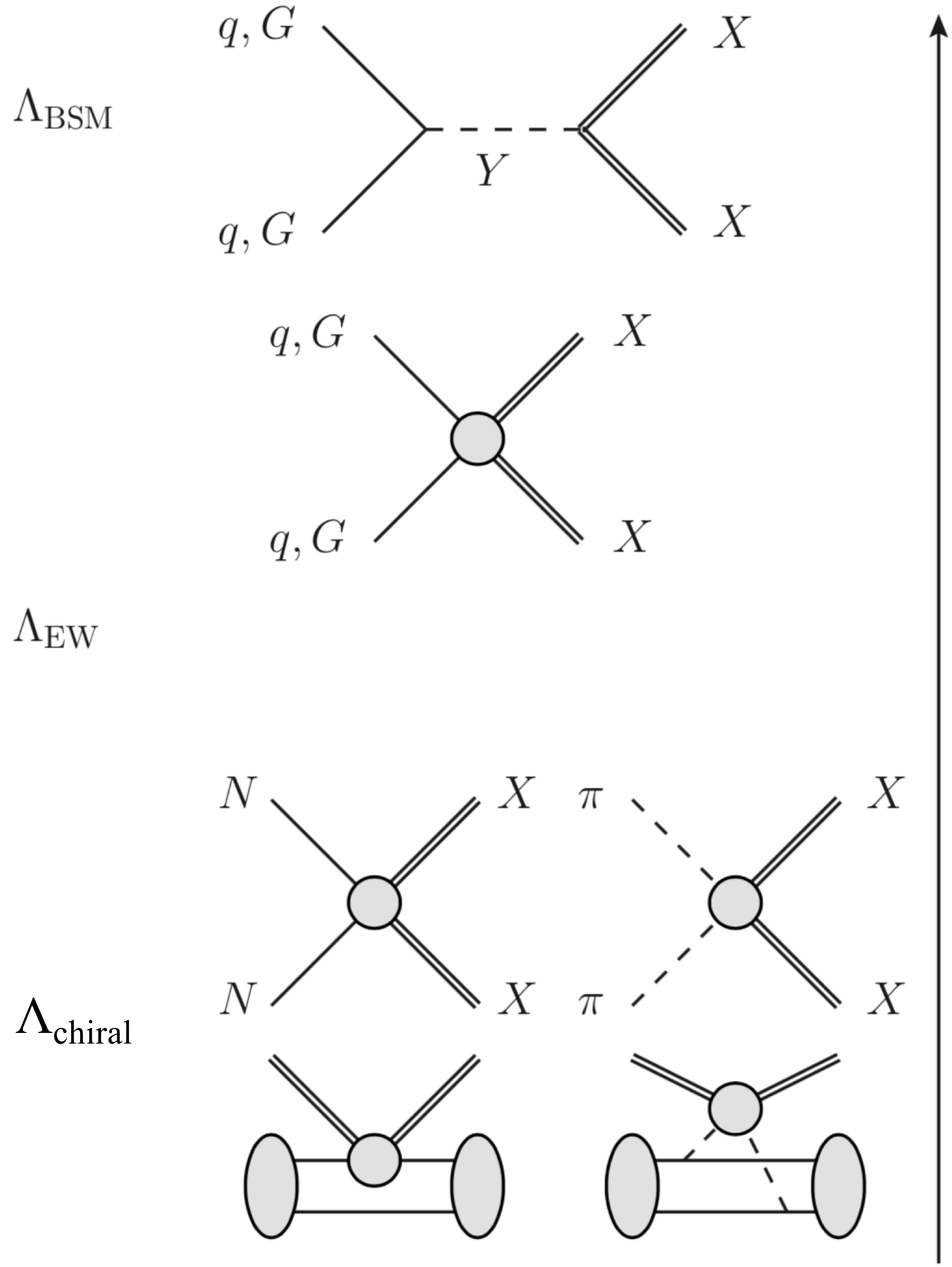
SM + **effective operators**

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

Integrate out **EW physics**

Chiral EFT scale: WIMP coupling to nucleons and pions

Nuclear structure: embedding chiral EFT operators in nucleus



Main messages

structure factors for **spin-dependent** WIMP scattering (axial-vector)
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)

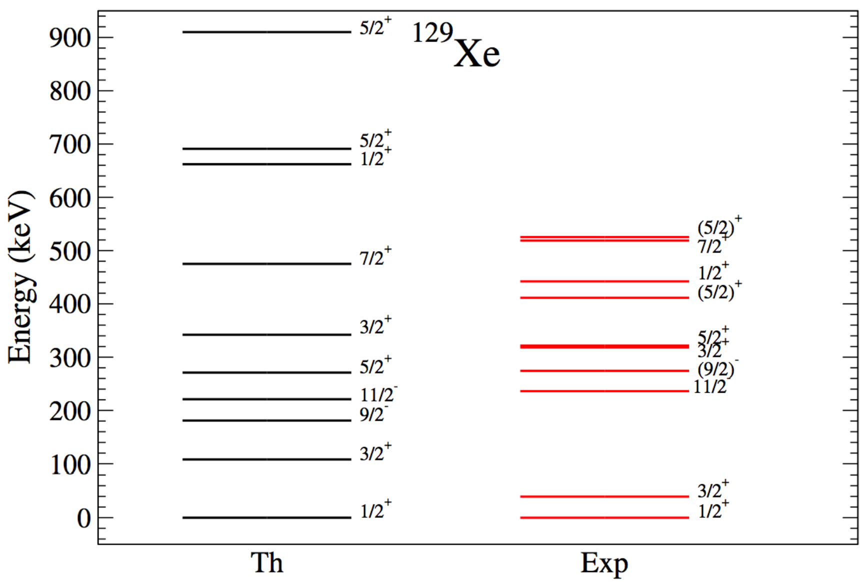
general coherent (SI+) WIMP-nucleus scattering
with Hoferichter, Klos, Menéndez, PRD (2016), PRD (2019)

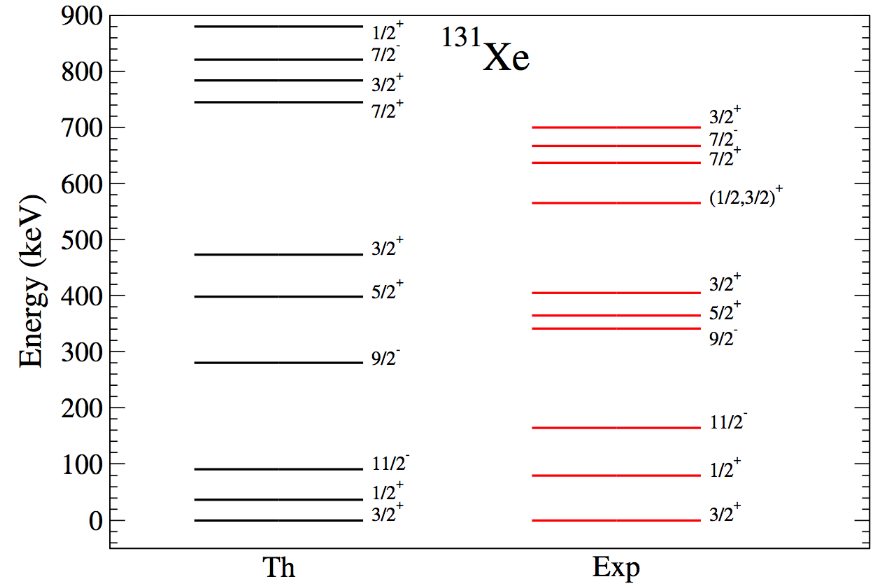
First limits for **WIMP-pion interactions**
XENON1T + Hoferichter, Klos, Menéndez, AS, PRL (2019)

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

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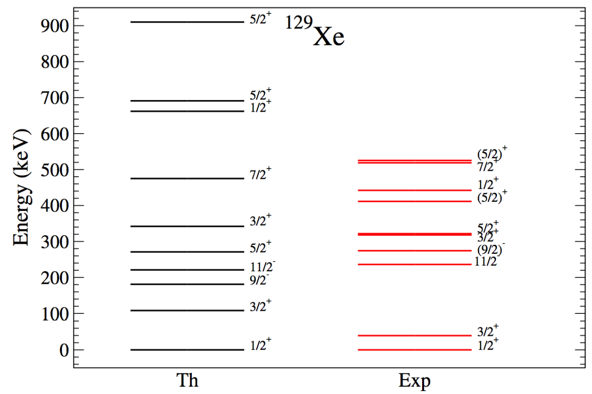
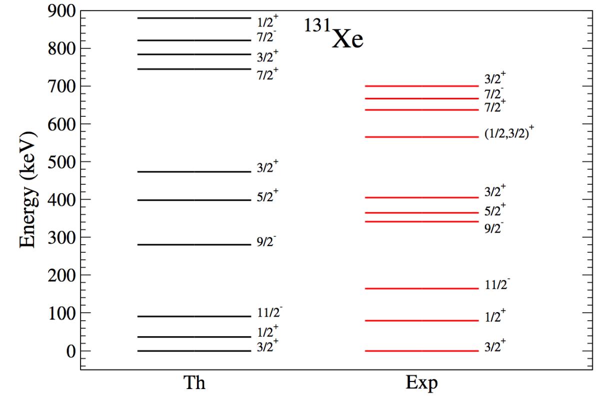
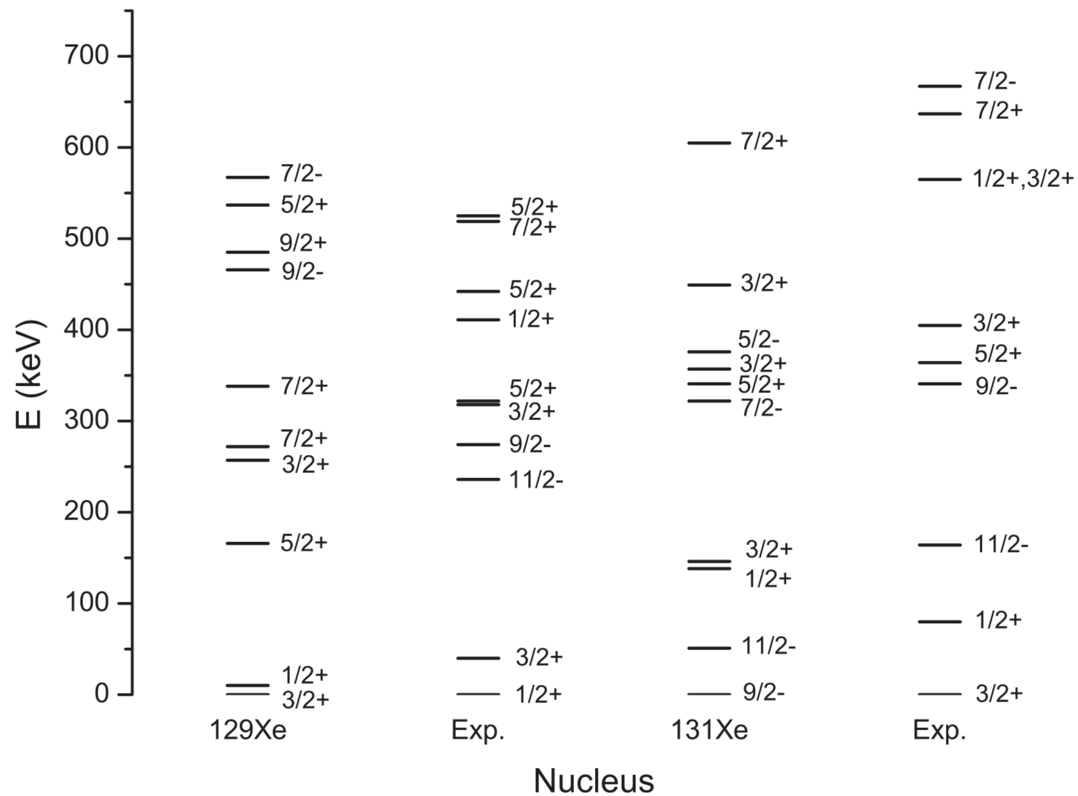




compare to other calculations for WIMP scattering



Nuclear structure factors

differential cross section for spin-dependent WIMP scattering

~ axial-vector structure factor $S_A(p)$ Engel et al. (1992)

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

$$= \frac{8G_F^2}{(2J_i+1)v^2} S_A(p) \,,$$

decompose into longitudinal, transverse electric and transverse magnetic

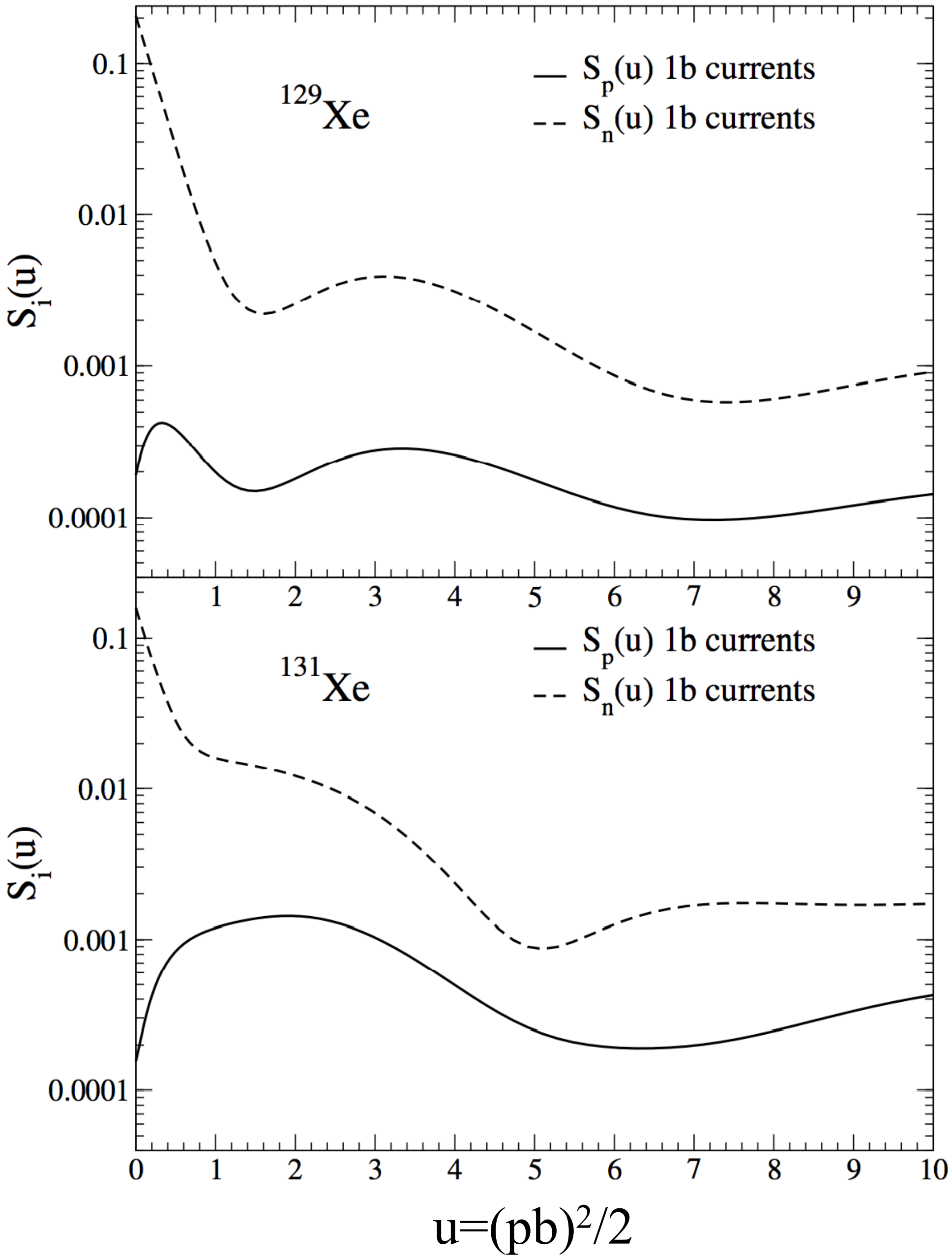
$$S_A(p) = \sum_{L \geqslant 0} \left| \langle J_f || \mathcal{L}_L^5 || J_i \rangle \right|^2 + \sum_{L \geqslant 1} \left(\left| \langle J_f || \mathcal{T}_L^{\mathrm{el}5} || J_i \rangle \right|^2 + \left| \langle J_f || \mathcal{T}_L^{\mathrm{mag}5} || J_i \rangle \right|^2 \right)$$

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

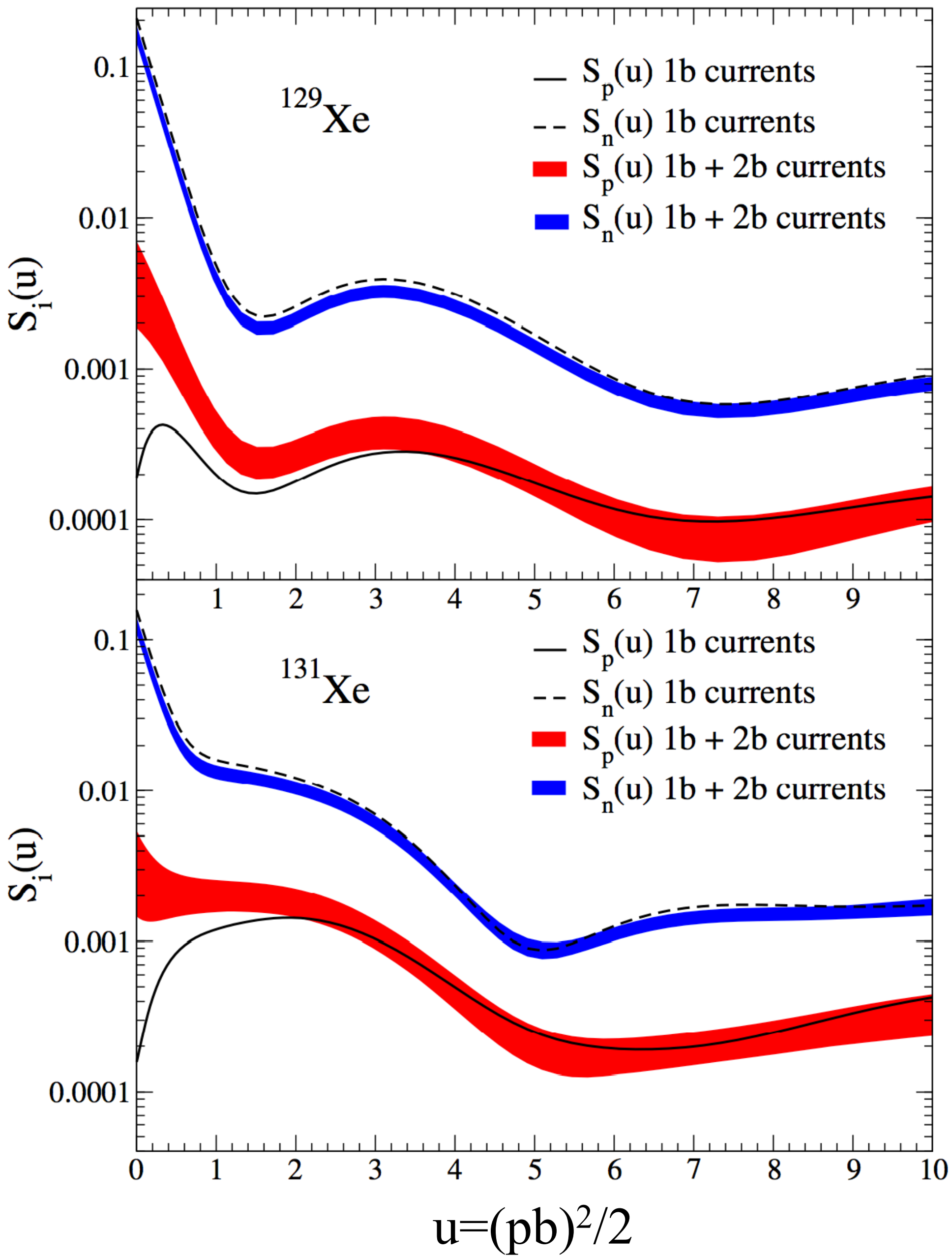


^{129,131}Xe are even Z, odd N, spin is carried mainly by neutrons

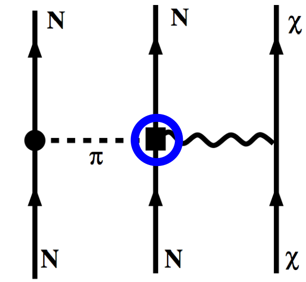
at p=0 structure factors at the level of one-body currents dominated by "neutron"-only

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

Xenon response with 1+2-body currents



two-body currents due to strong interactions among nucleons

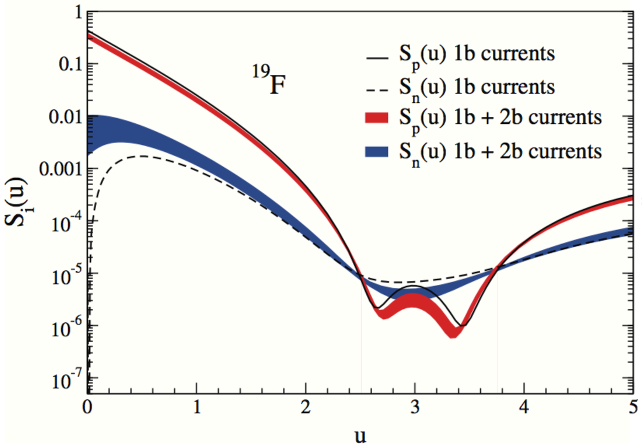


WIMPs couple to neutrons and protons at the same time

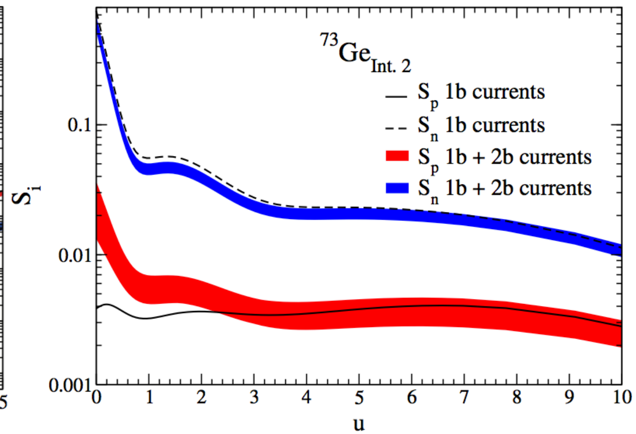
enhances coupling to even species in all cases (protons for Xe)

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

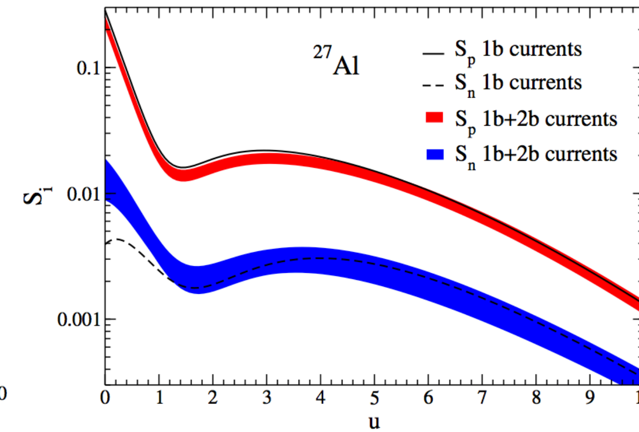
Klos, Menéndez, Gazit, AS, PRD (2013) includes structure factor fits for all isotopes



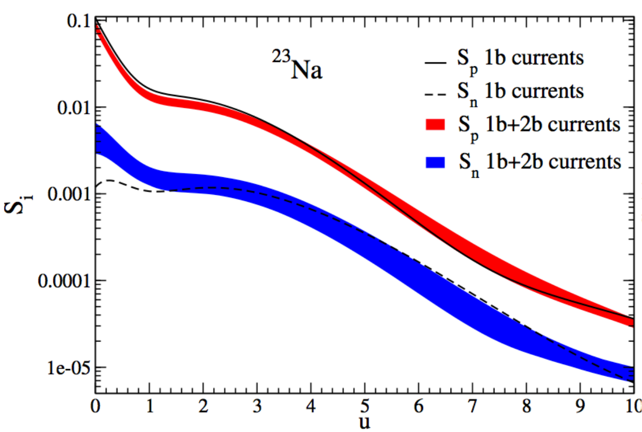
PICASSO, COUPP, SIMPLE



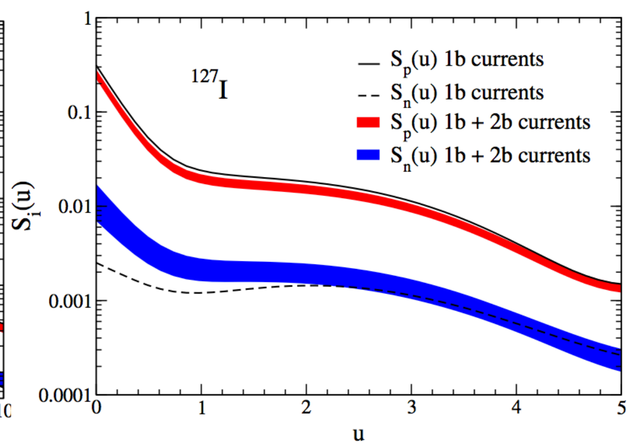
CDMS, EDELWEISS, EURECA



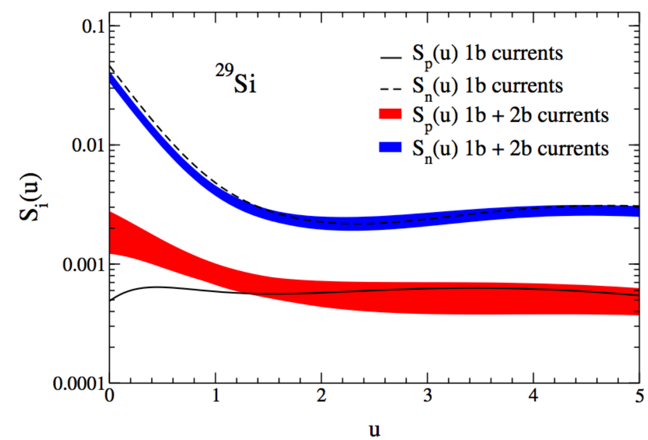
CRESST



DAMA, ANAIS, DM-Ice



DAMA, ANAIS, DM-Ice, KIMS

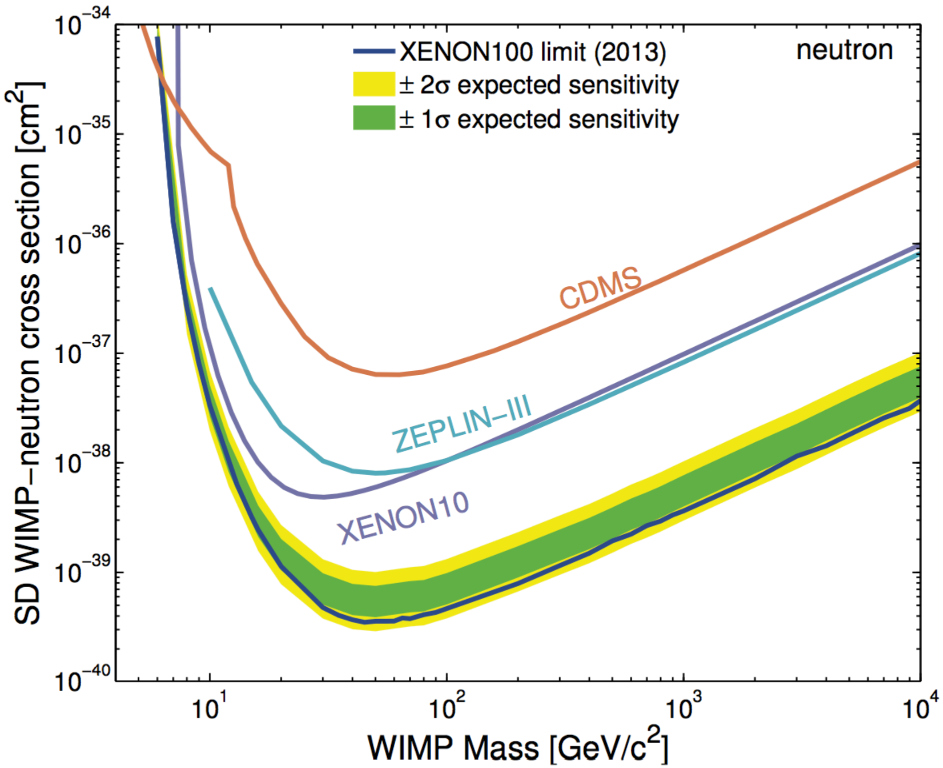


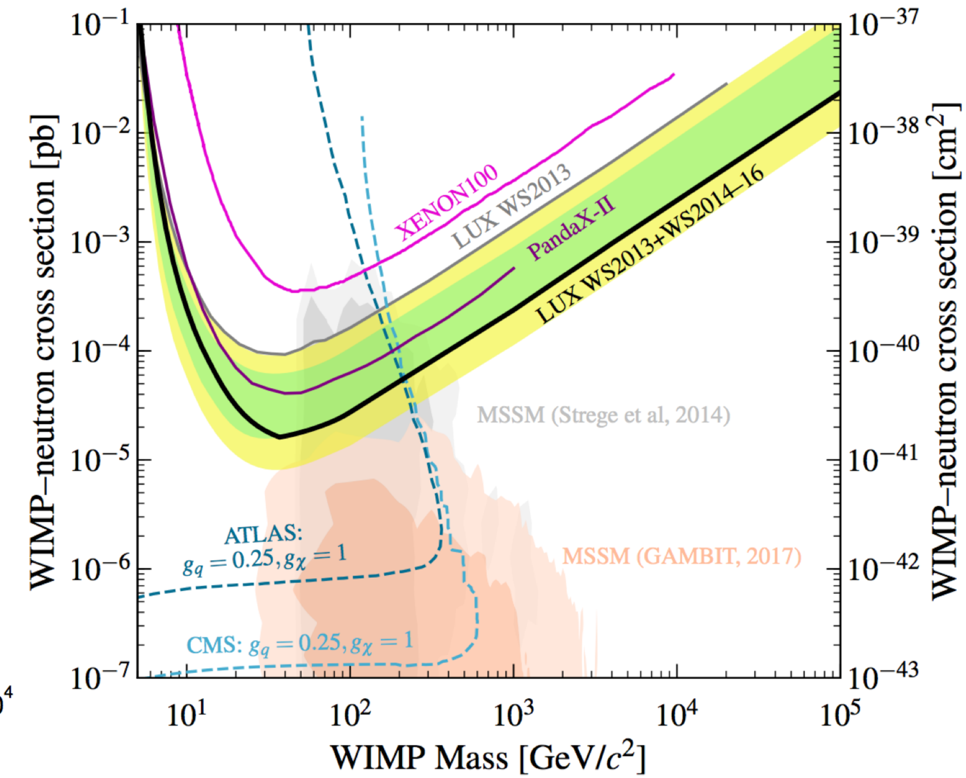
CDMS-II

Limits on SD WIMP-neutron interactions

limits from XENON100 Aprile et al., PRL (2013) XENON1T Aprile et al., PRL (2019) 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

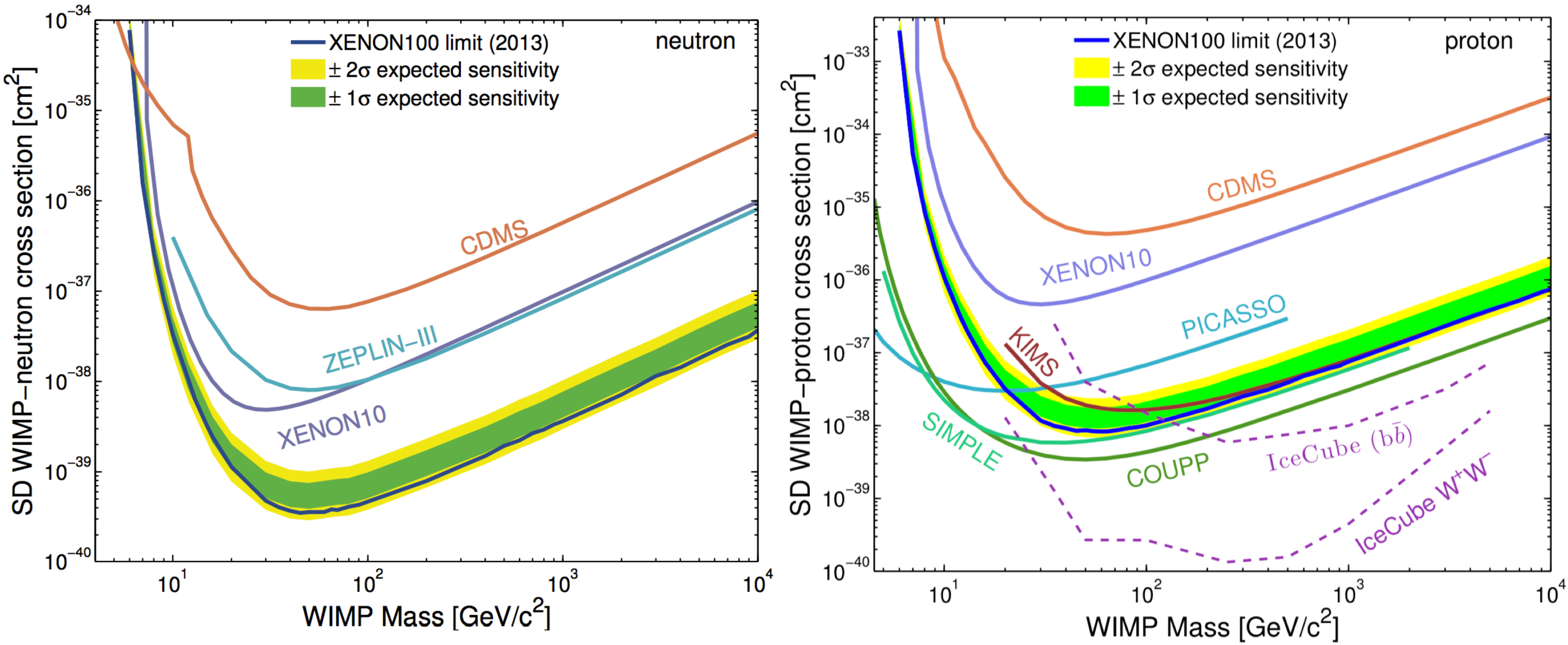




Limits on SD **WIMP-proton interactions**

limits from XENON100 Aprile et al., PRL (2013) XENON1T Aprile et al., PRL (2019) PandaX-II Fu et al., PRL (2017) and LUX Akerib et al., PRL (2017)

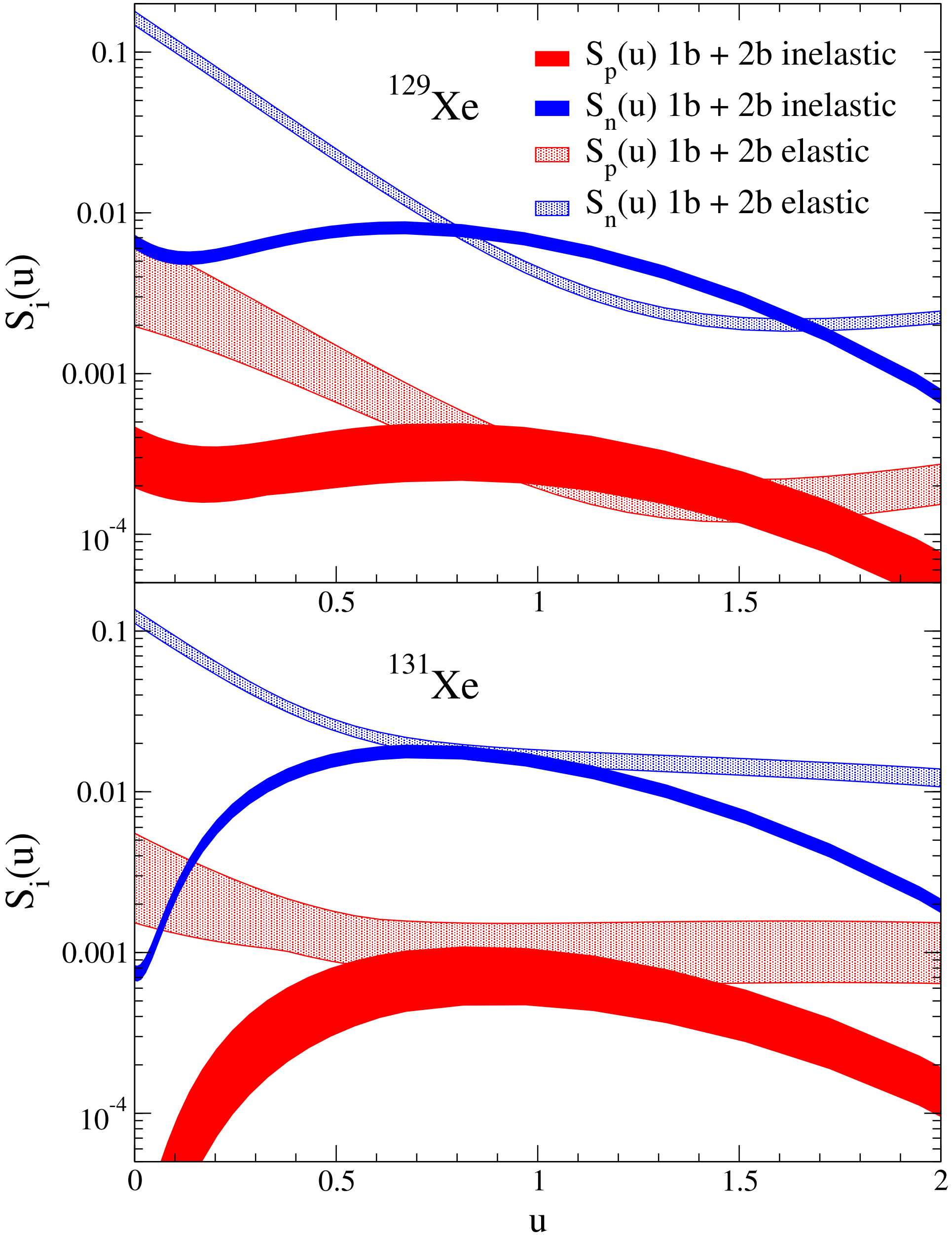
used our calculations with uncertainty bands for WIMP currents in nuclei



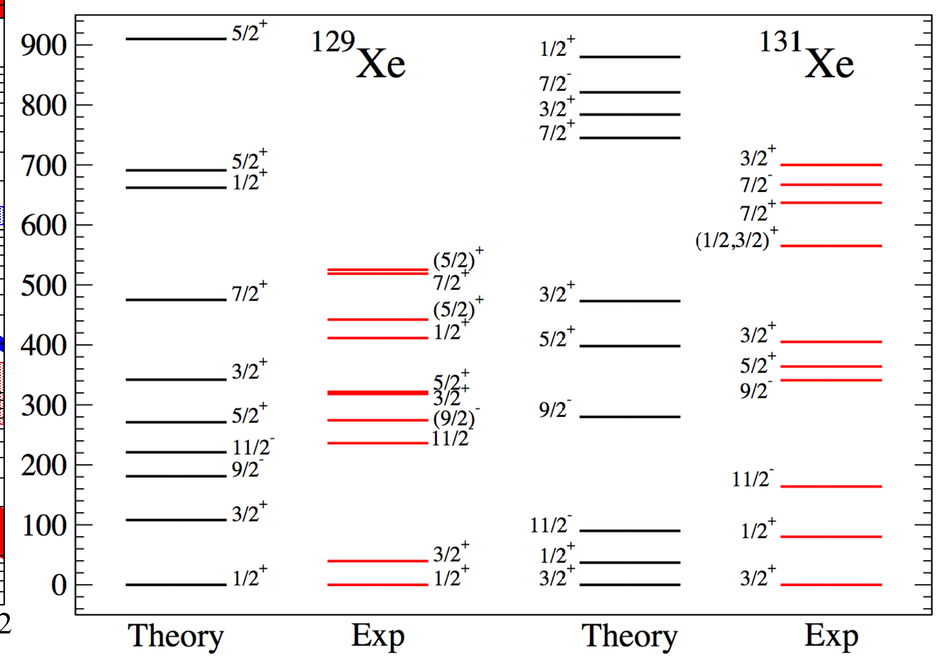
XENON competitive for WIMP-proton coupling due to 2-body currents

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

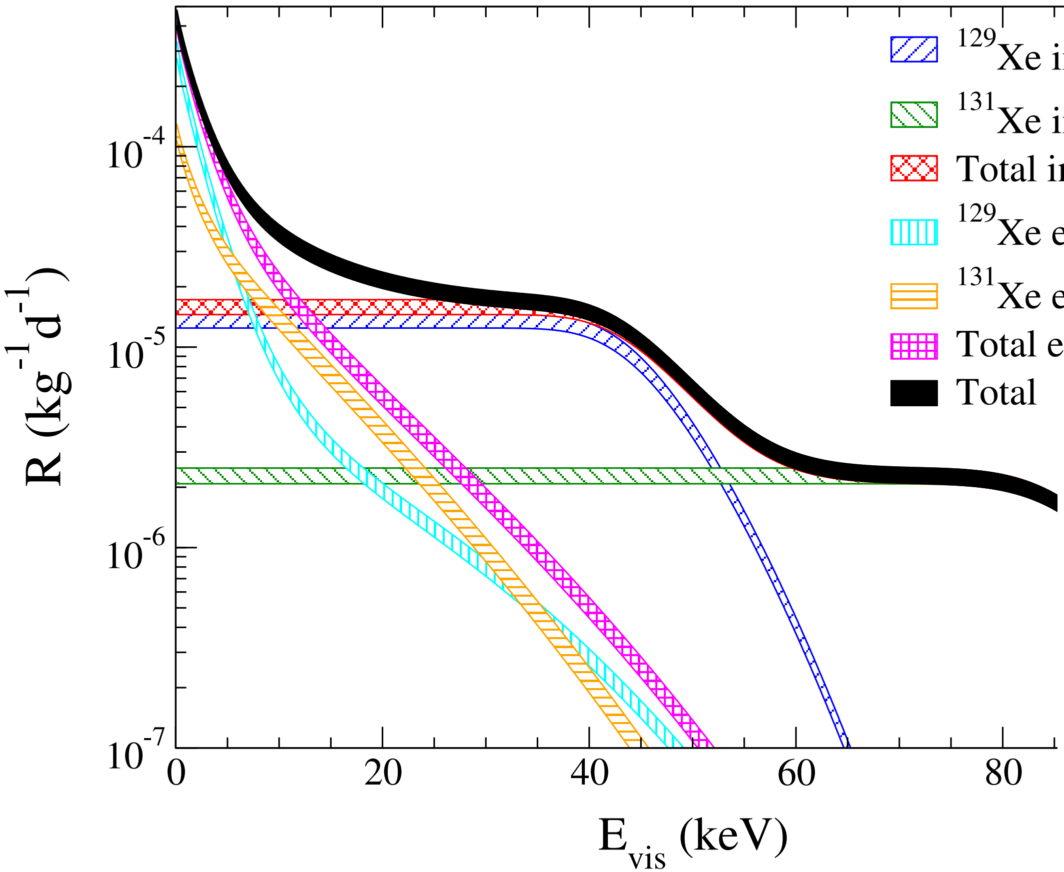


Signatures for **inelastic** WIMP scattering

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 $E_{\rm vis}$ 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

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

matching to non-relativistic EFT

Fitzpatrick et al., JCAP (2013)

without chiral physics

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

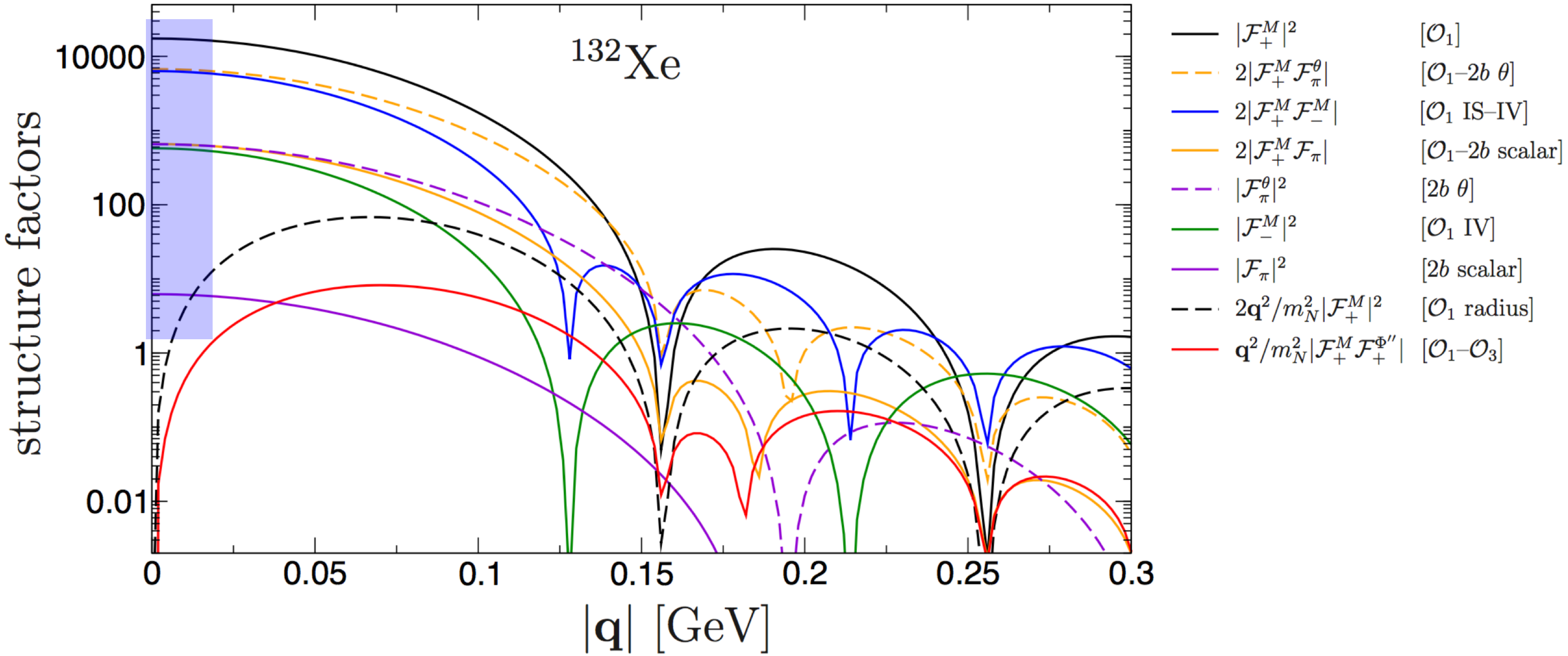
shows that NREFT operators are not linearly indep. (e.g., 4+6 are SD)

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), PRD (2019)

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



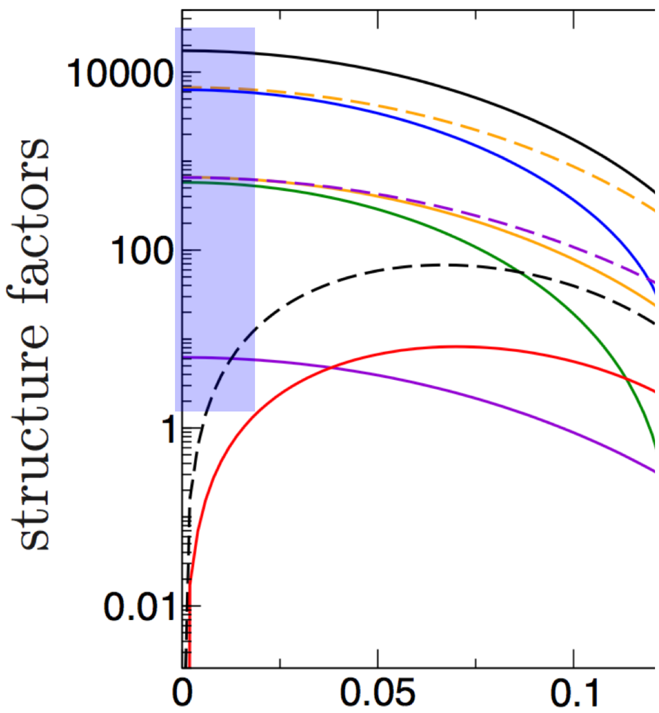
dominant corrections are QCD effects: scalar current coupling to pion, isovector correction, radius correction to formfactor

first new operator O_3 contribution is 4 orders smaller

General coherent (SI+) WIMP nucleus scattering

for scalar currents: Hoferichter, Klos, Menéndez, AS, PRD (2016), PRD (2019)

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

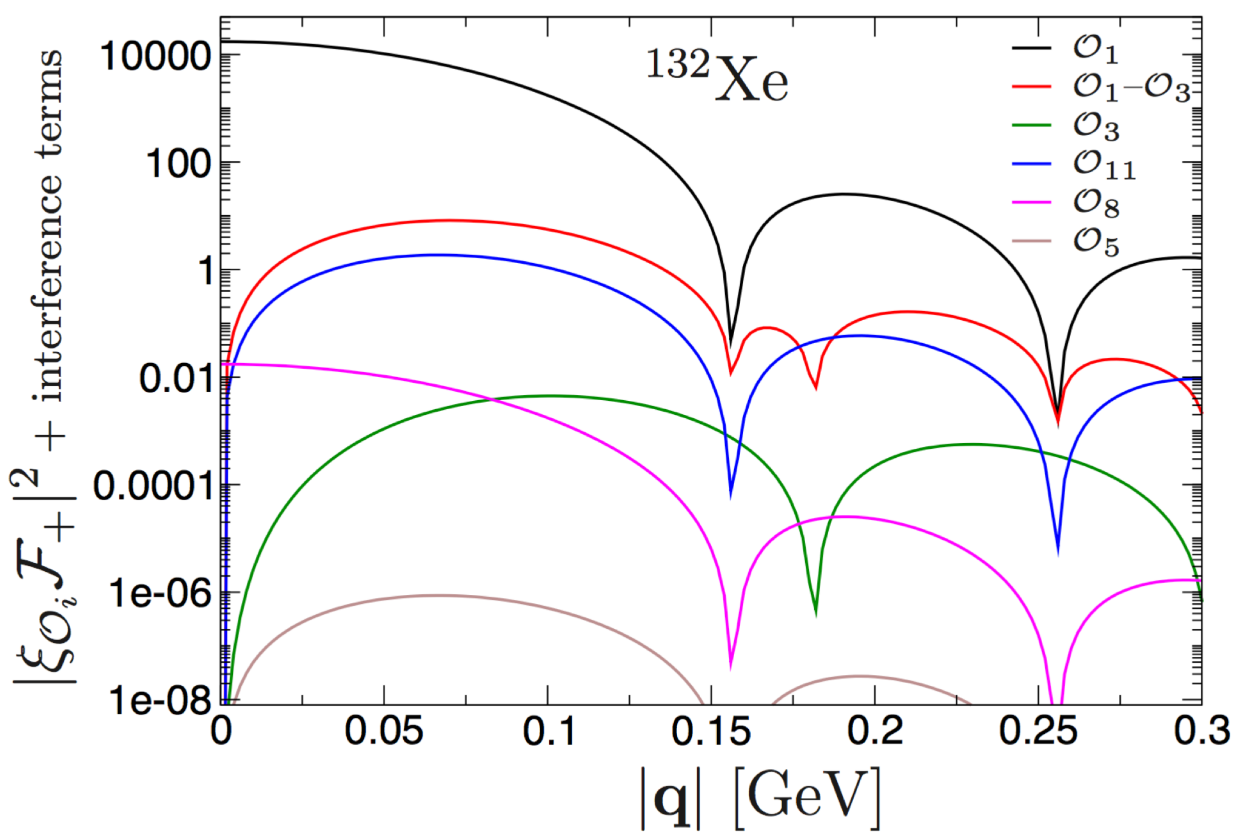


$$\mathcal{O}_1 = \mathbb{1}, \quad \mathcal{O}_2 = (\mathbf{v}^\perp)^2, \quad \mathcal{O}_3 = i\mathbf{S}_N \cdot (\mathbf{q} \times \mathbf{v}^\perp),$$

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

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

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



dominant corrections are

isovector correction, radi

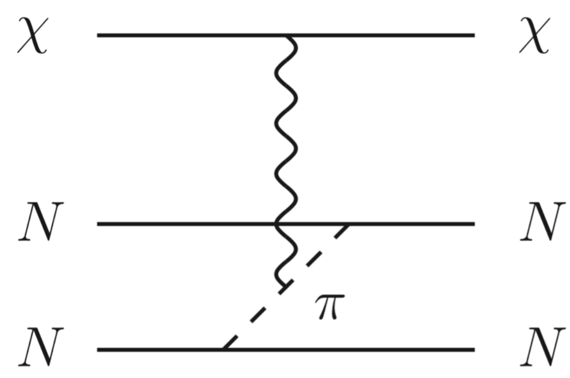
first new operator O_3 cor

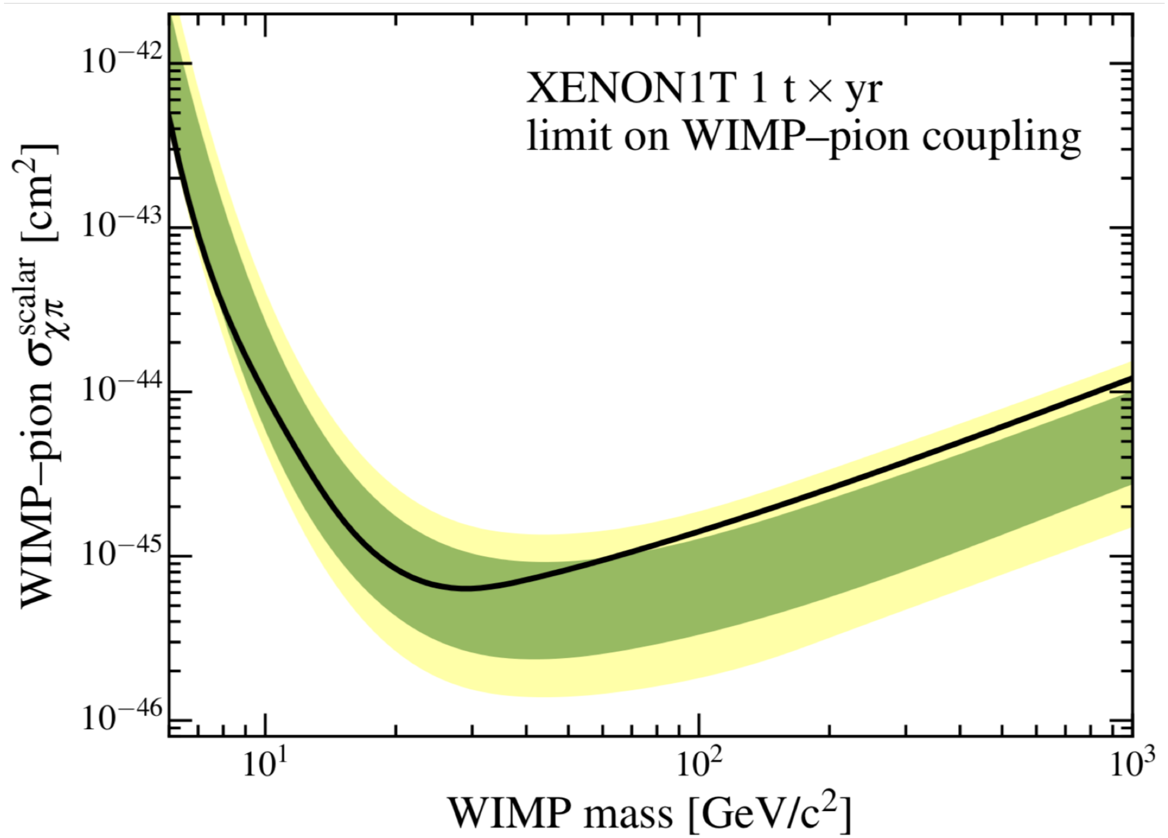
First limits for WIMP-pion interactions Aprile et al., PRL (2019)

based on chiral EFT for WIMP-pion interactions are partially coherent (between SI and SD)

$$A^2 \gg 4\left(\frac{M_\pi}{\Lambda_\chi}\right)^6\left(\frac{m_N}{M_\pi}\right)^2 A^2 \gg \frac{4}{3}\frac{J+1}{J}\langle \mathbf{S}_{n/p}\rangle^2$$

$$1.7\times 10^4 \gg 1.1\times 10^3 \gg 0.34, 0.13 \text{ for } {}^{129,131}\text{Xe}$$





Summary

Thanks to: Scott Bogner, **Arianna Carbone, Christian Drischler,** Gaute Hagen, Heiko Hergert, Jason Holt, **Jan Hoppe,** Kai Hebeler, **Martin Hoferichter, Philipp Klos, Javier Menéndez,** Thomas Papenbrock, **Johannes Simonis, Ragnar Stroberg, Kyle Wendt**

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, frontier 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-q/g interactions