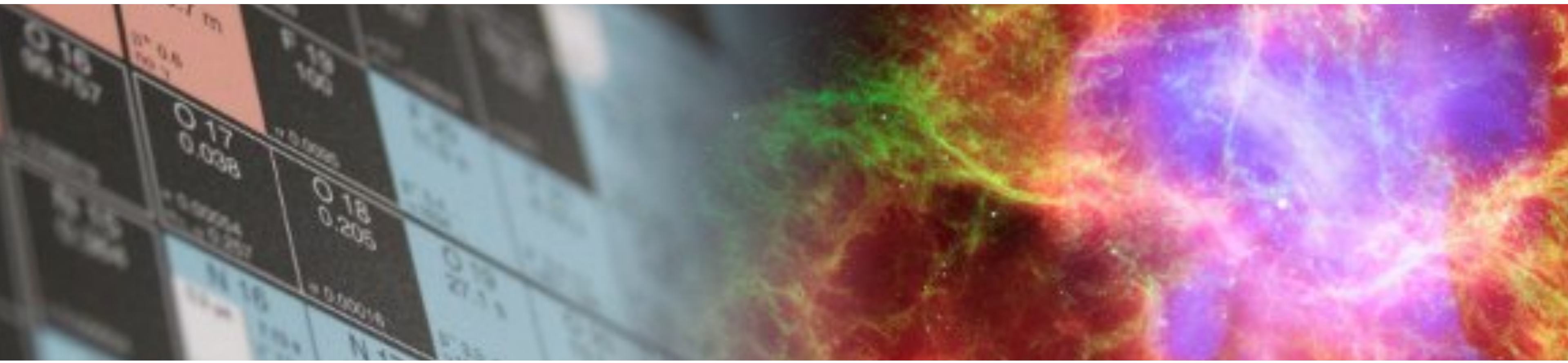
Chiral effective field theory for dark matter direct detection

Achim Schwenk

TECHNISCHE UNIVERSITÄT DARMSTADT

Max Planck Institute for Nuclear Physics



Gentner colloquium, MPIK, July 12, 2017

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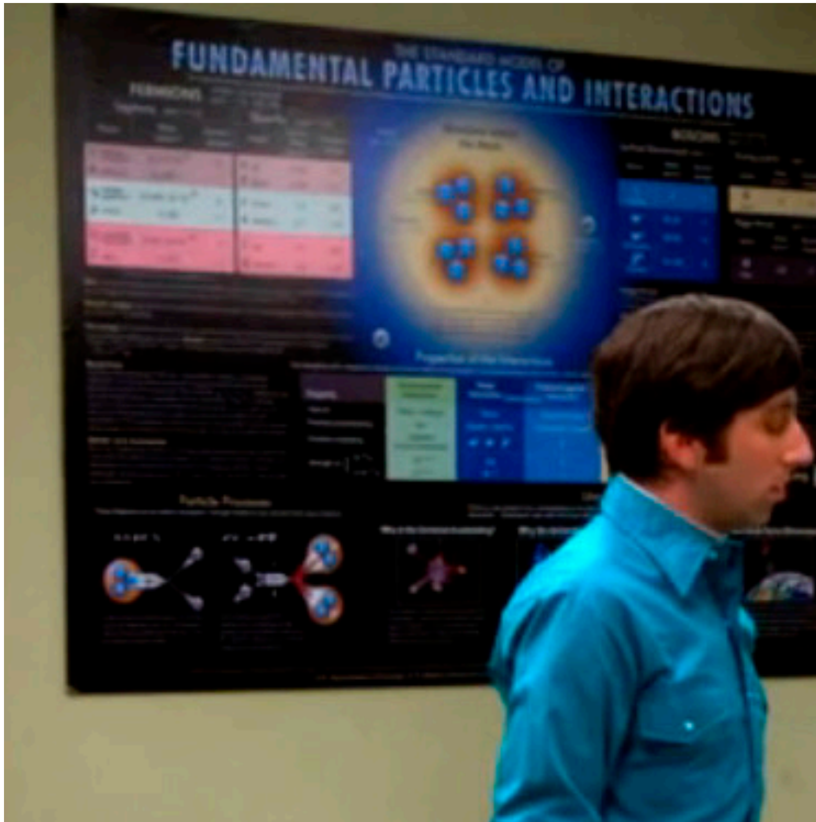
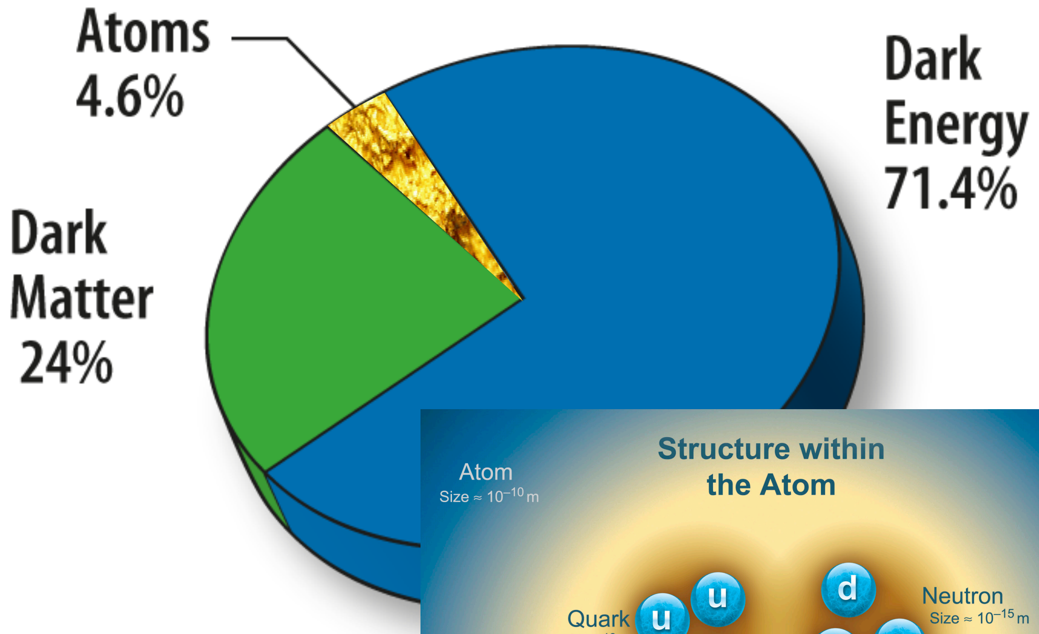
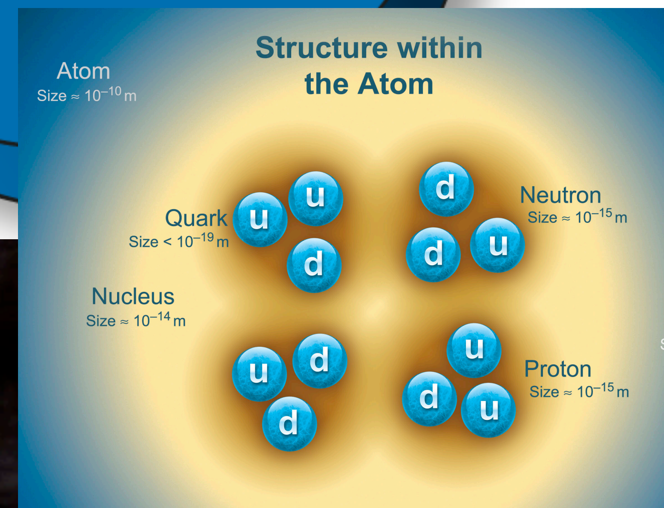
HELMHOLTZ ASSOCIATION

Strong interactions

Strong interactions







Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Nuclei bound by strong interactions

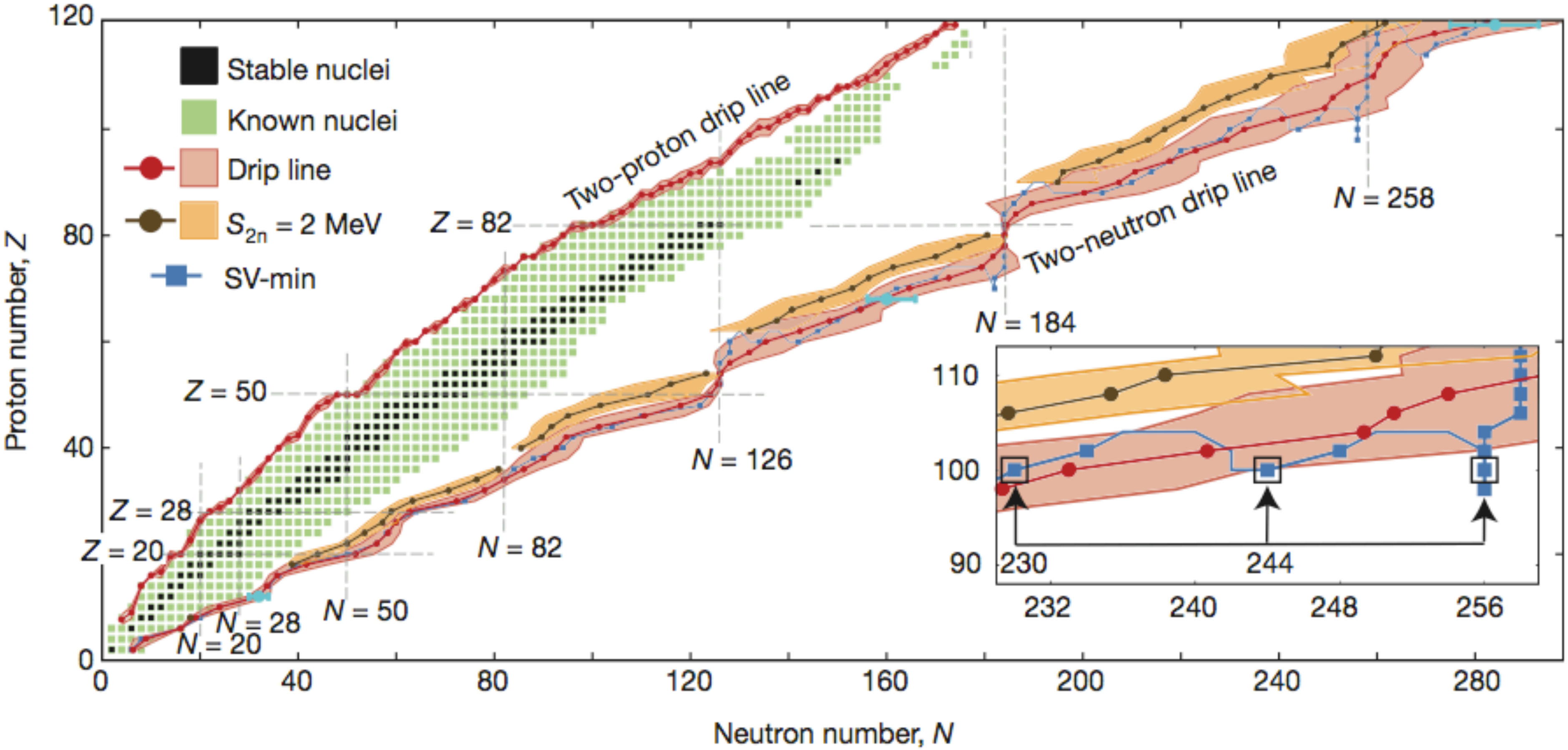
doi:10.1038/nature11188

The limits of the nuclear landscape

Jochen Erler[1,2], Noah Birge[1], Markus Kortelainen[1,2,3], Witold Nazarewicz[1,2,4], Erik Olsen[1,2], Alexander M. Perhac[1] & Mario Stoitsov[1,2]‡

~ 3000 nuclei discovered (288 stable), 118 elements

~ 4000 nuclei unknown, extreme neutron-rich



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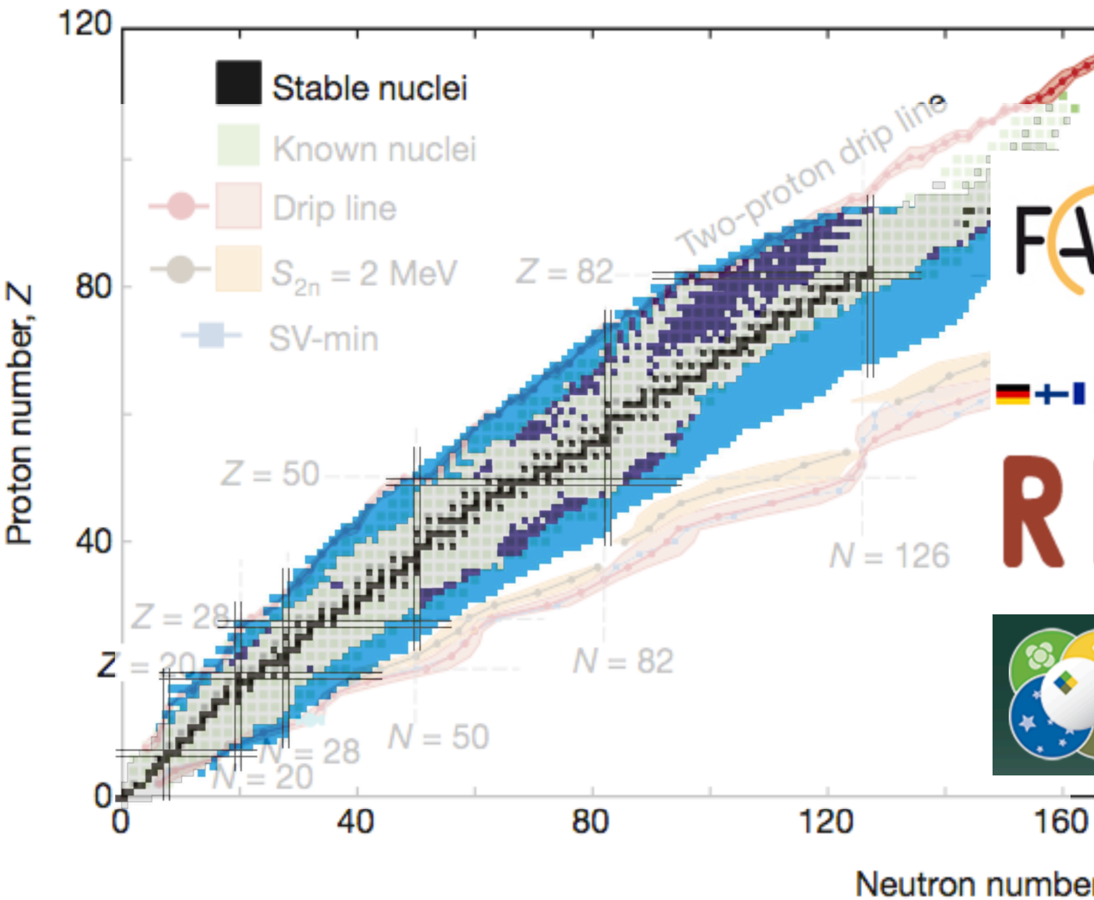

FAIR
Facility for Antiproton
and Ion Research
in Europe GmbH

RIBF | RIKEN NiSHiNA CENTER
RIKEN Nishina Center for Accelerator-Based Science

Facility for Rare Isotope Beams
at Michigan State University

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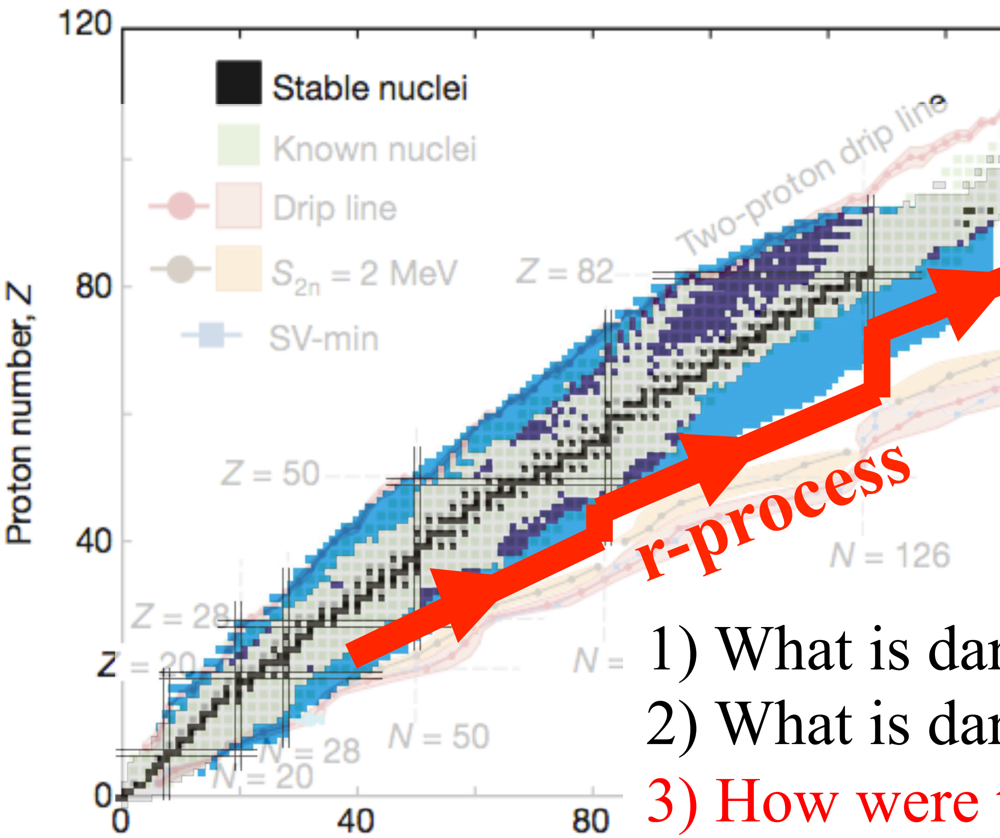

1) What is dark matter?

2) What is dark energy?

3) How were the elements from iron to uranium made?

Nuclei bound by strong interactions

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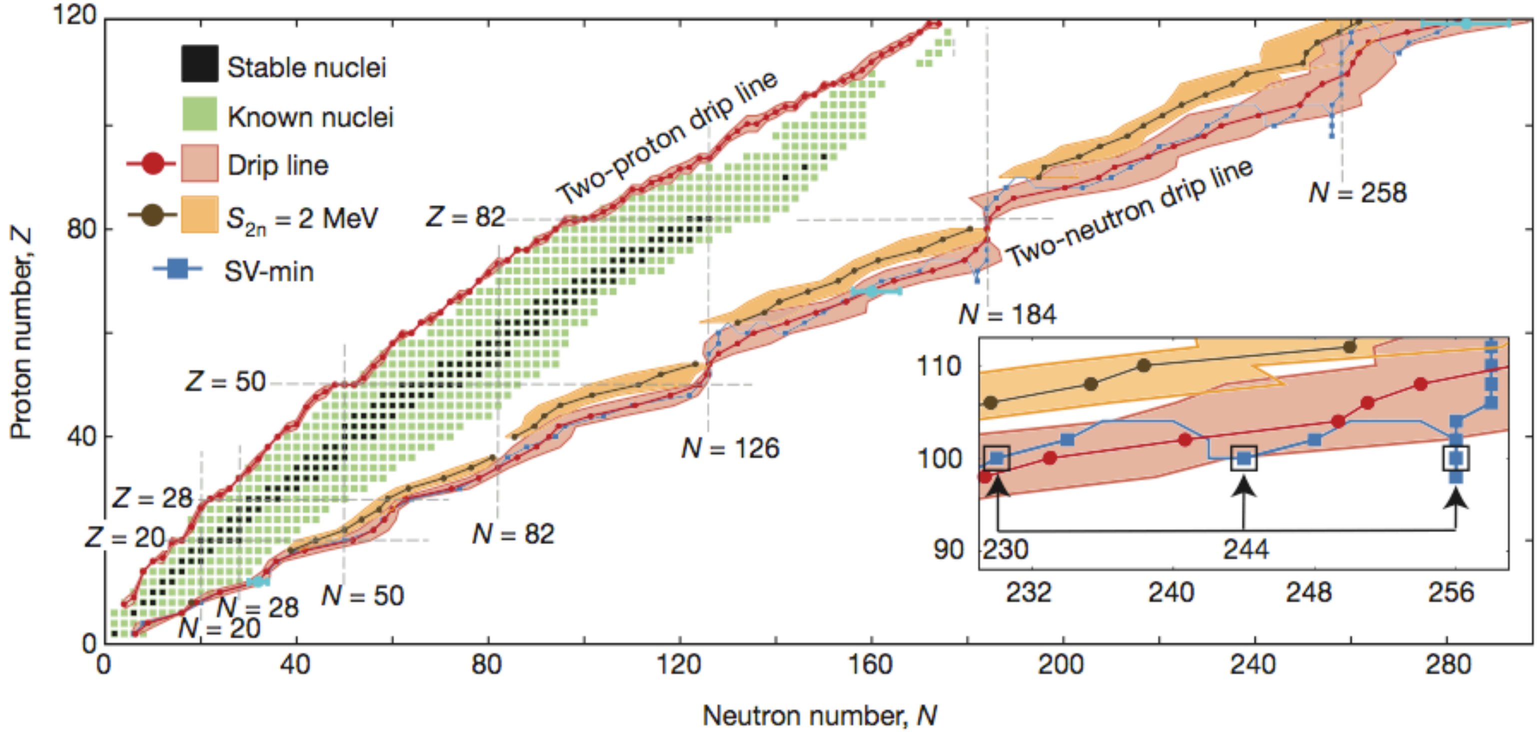
Jochen Erler[1,2], Noah Birge[1], Markus Kortelainen[1,2,3], Witold Nazarewicz[1,2,4], Erik Olsen[1,2], Alexander M. Perhac[1] & Mario Stoitsov[1,2]‡



How does the nuclear chart emerge from quantum chromodynamics?

Lattice QCD and **effective field theories of the strong interaction**

for few nucleons for all nuclei

Effective field theories of the strong interaction

reduce complexity of underlying theory to **relevant degrees of freedom**

applicable at **low energy/low momentum** scales

expansion scheme (e.g., in powers of momenta/derivatives)
power counting with **controlled uncertainties** from truncation

consequence: **need theoretical uncertainties** in **many-body methods**

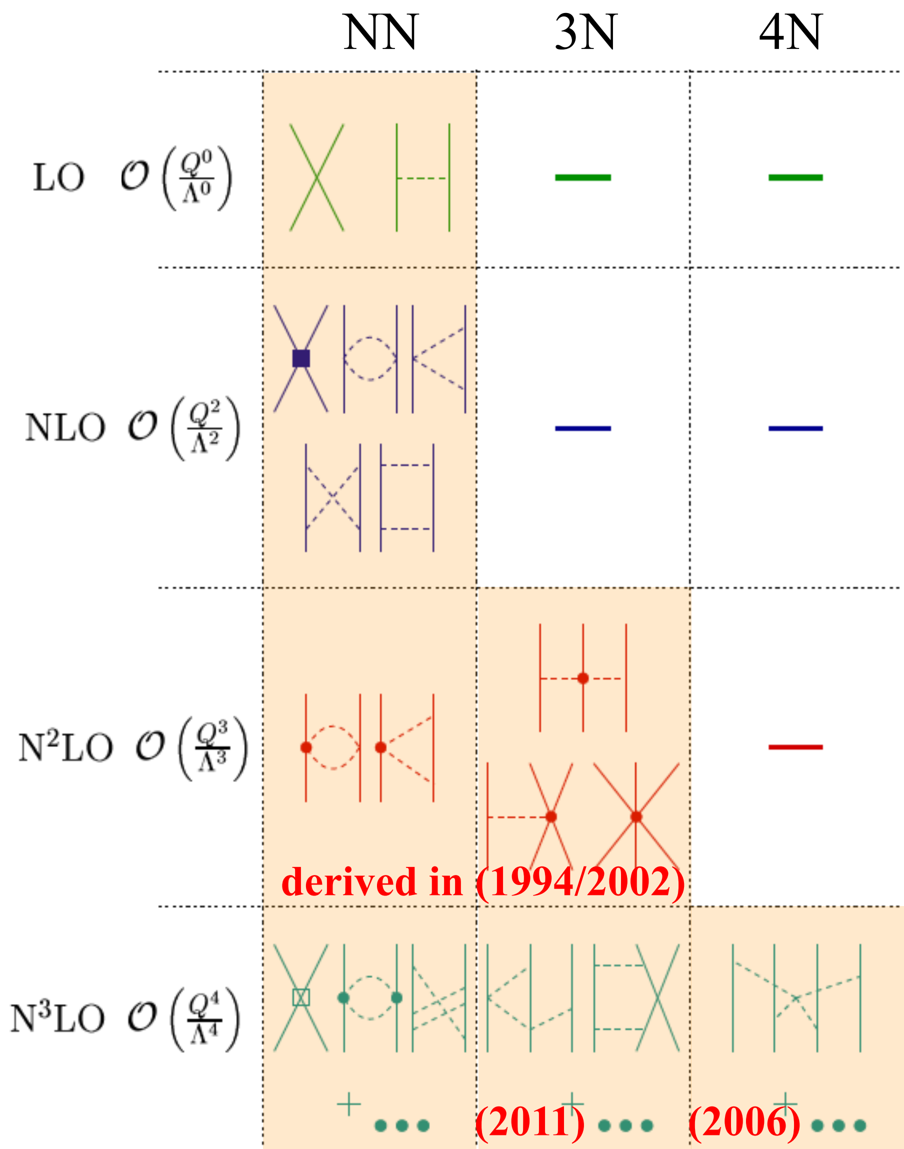
theory enables **systematic coupling to photons and weak interactions**

effective field theories **play guiding role** to improve other approaches

Chiral effective field theory for nuclear forces

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

$\sim m_\Delta - m_N \ldots m_\rho$



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

LO, n=0 - leading order,
NLO, n=2 - next-to-leading order,…

expansion parameter ~ 1/3

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

Chiral effective field theory for nuclear forces

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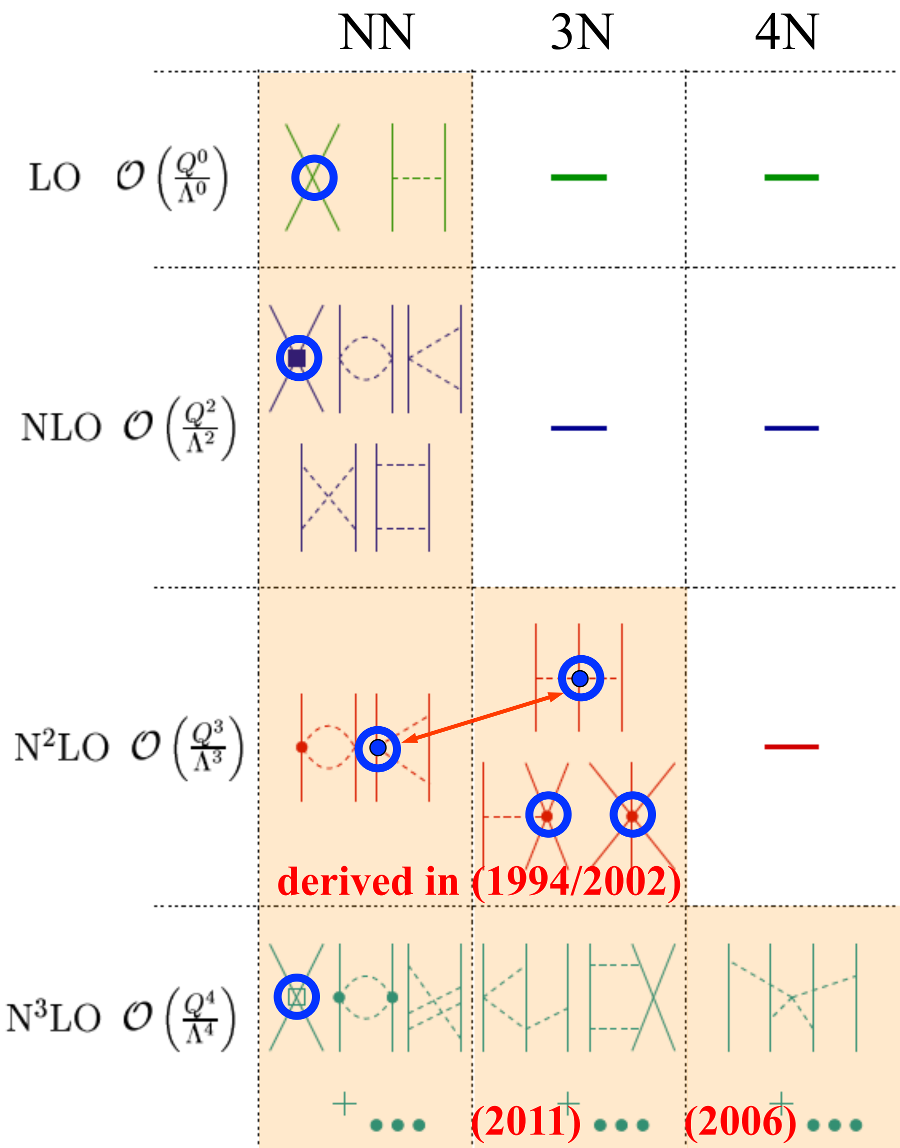


include long-range pion physics

few short-range couplings,
fit to experiment once

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

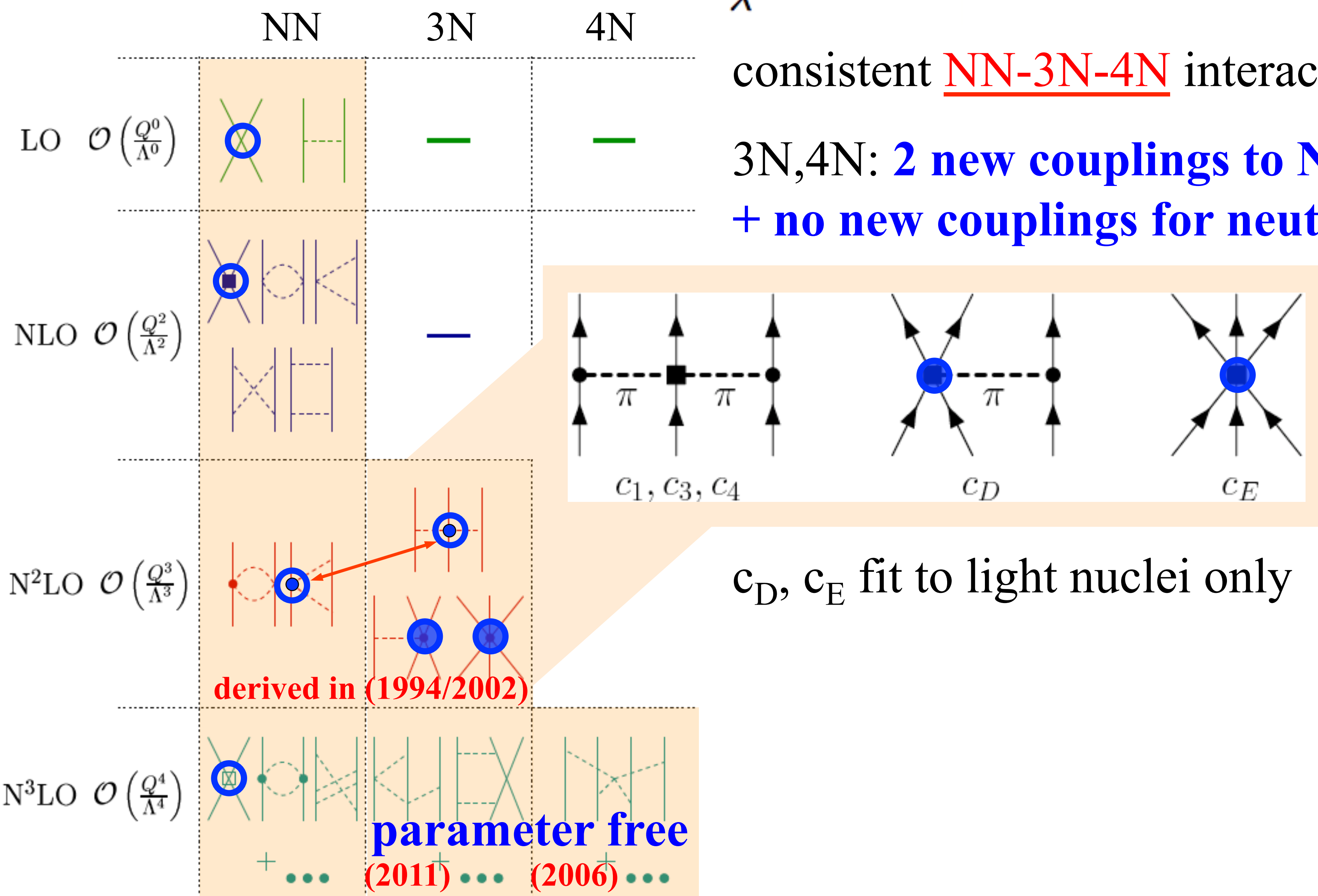
consistent **electroweak interactions** and **matching to lattice QCD**

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

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

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

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



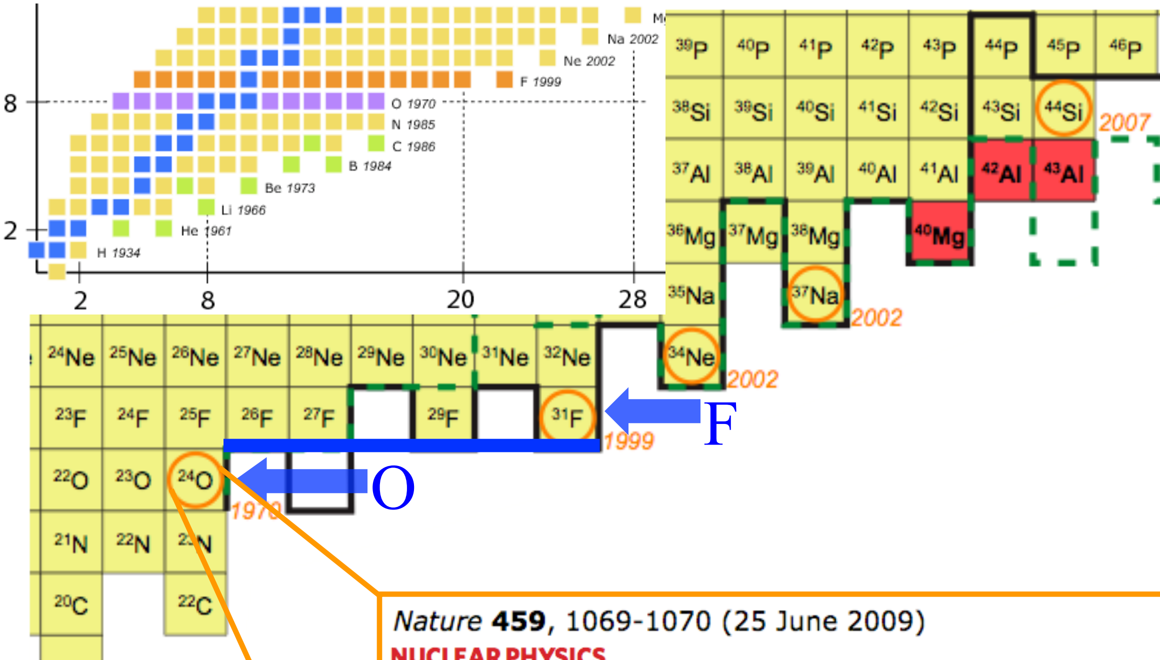
consistent NN-3N-4N interactions

3N,4N: **2 new couplings to N³LO**
+ no new couplings for neutrons

c_D, c_E fit to light nuclei only

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

The oxygen anomaly



Nature **459**, 1069-1070 (25 June 2009)

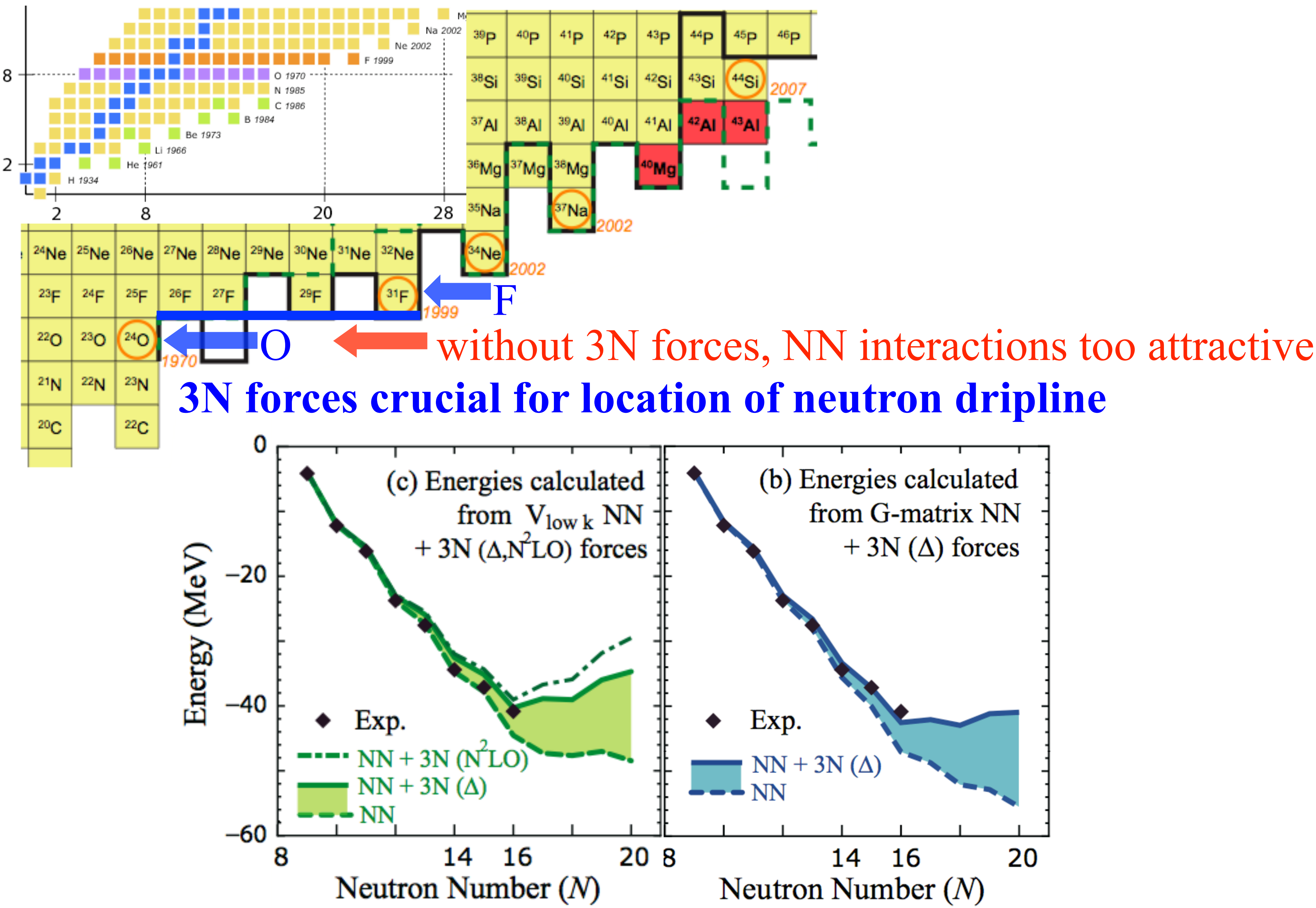
NUCLEAR PHYSICS

Unexpected doubly magic nucleus

Robert V. F. Janssens

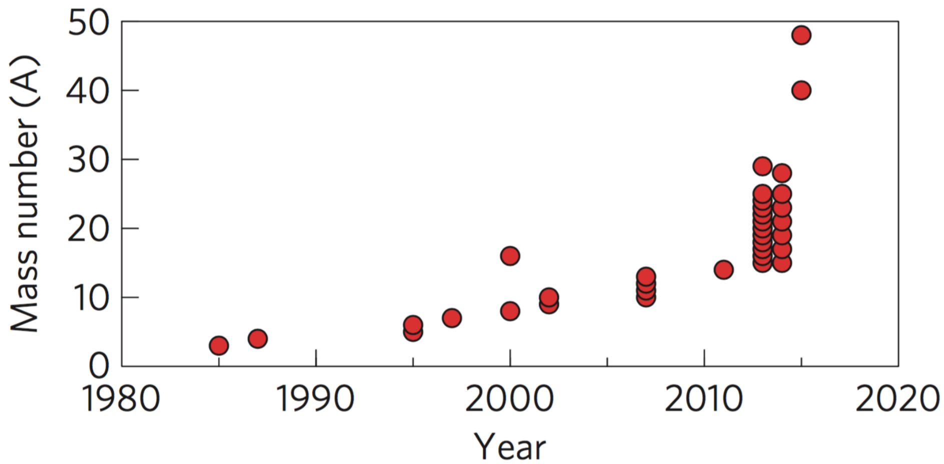
Nuclei with a 'magic' number of both protons and neutrons, dubbed doubly magic, are particularly stable. The oxygen isotope ^{24}O has been found to be one such nucleus — yet it lies just at the limit of stability.

The oxygen anomaly Otsuka, Suzuki, Holt, AS, Akaishi, PRL (2010)



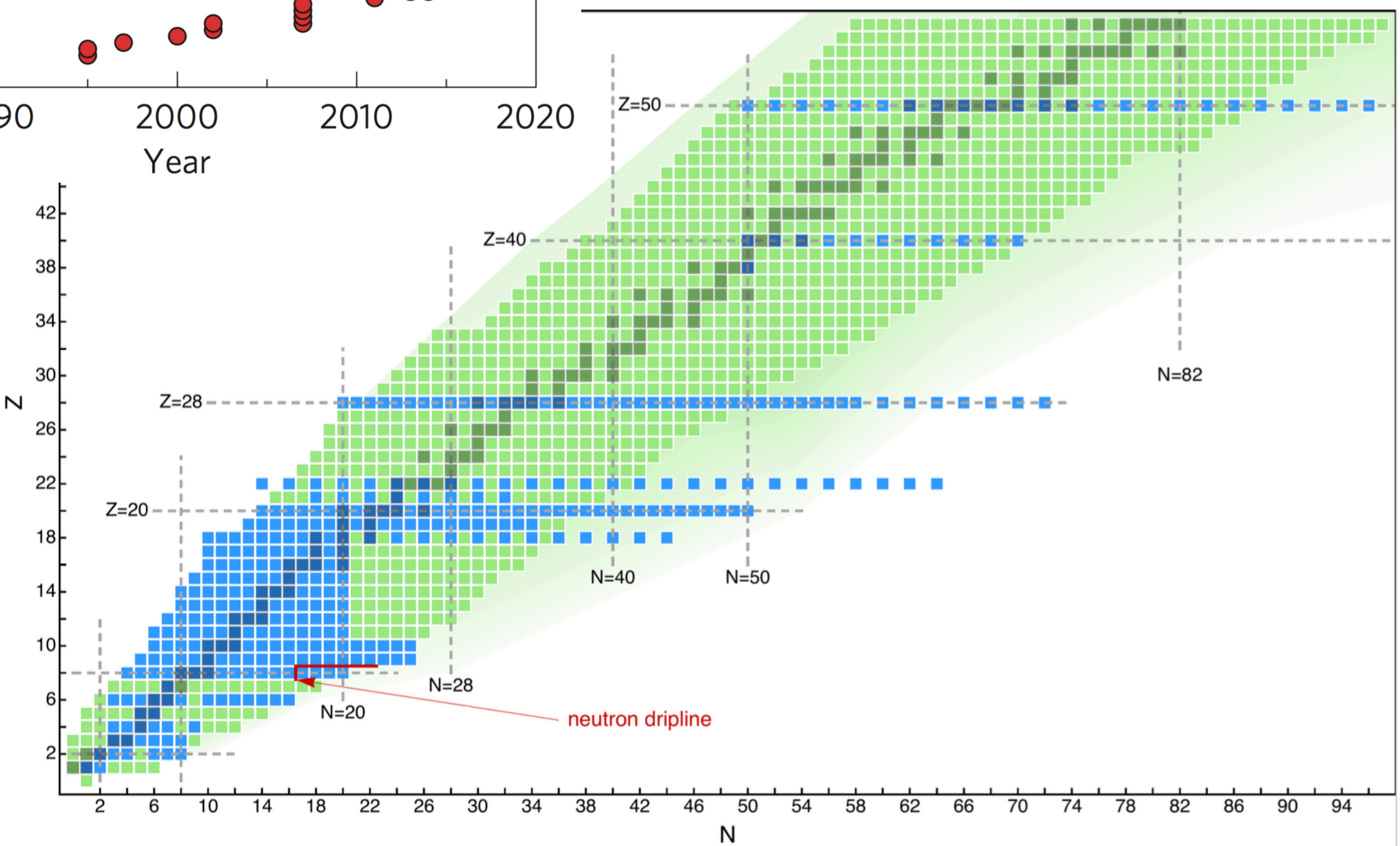
Progress in ab initio calculations of nuclei

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



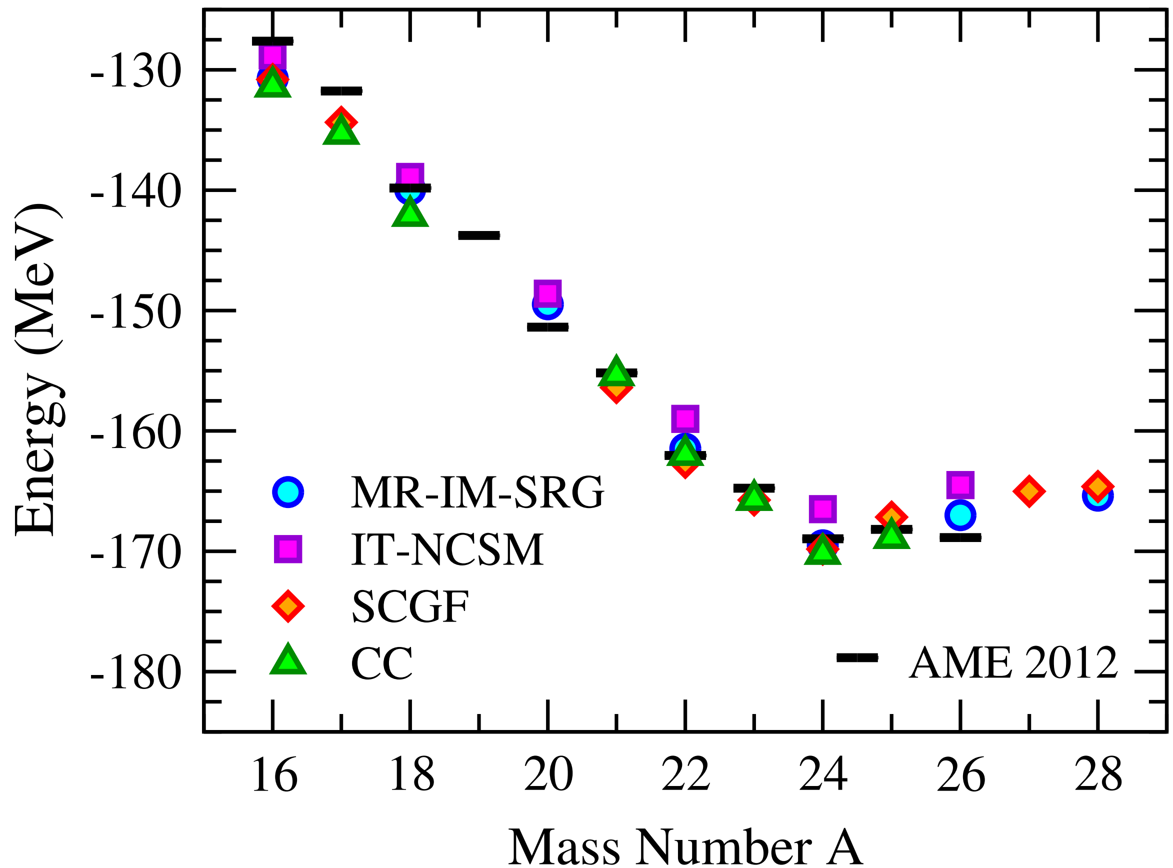
from Hagen et al., Nature Phys. (2016)

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



Ab initio calculations of neutron-rich oxygen isotopes

based on same NN+3N interactions



ab initio methods agree at few % level

Coupled Cluster 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 Function methods Cipollone et al., PRL (2013)

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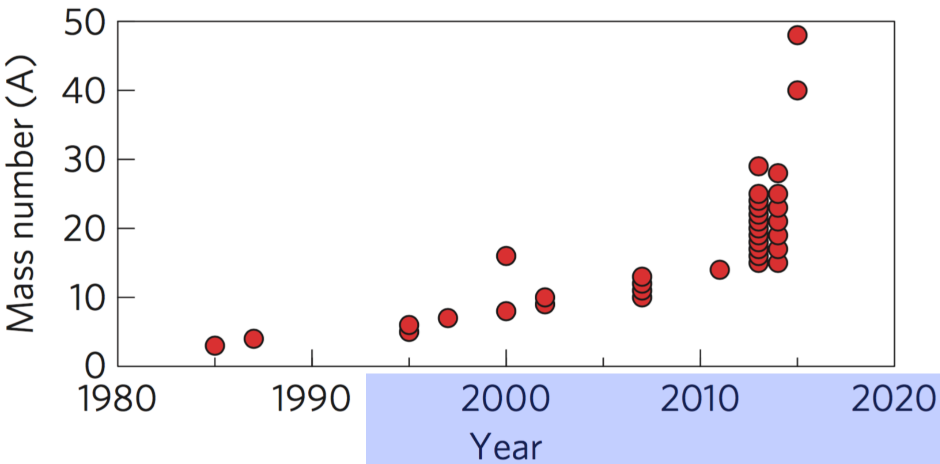

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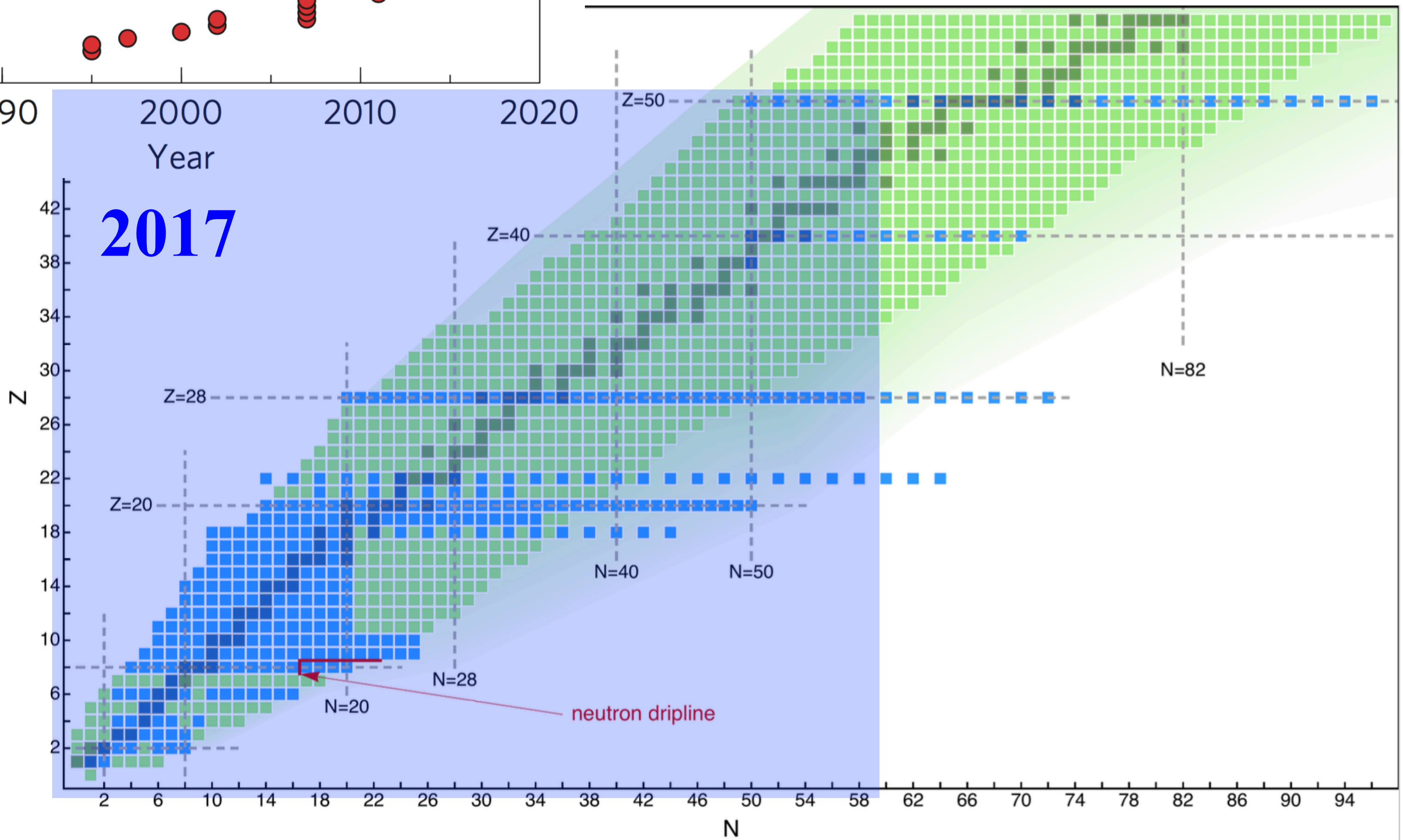
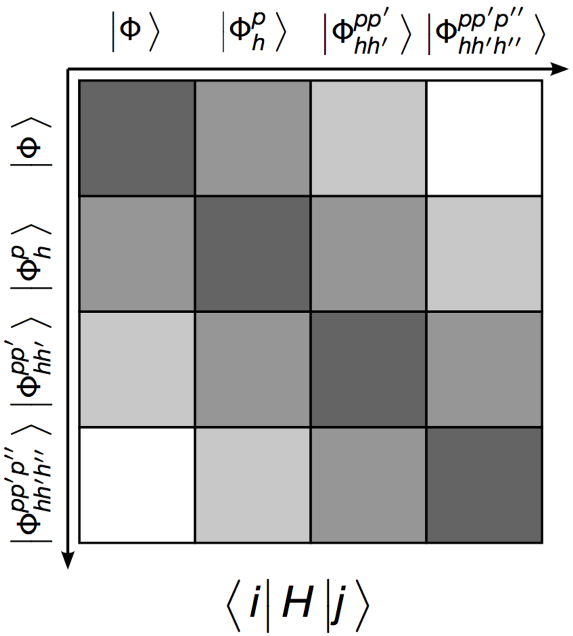
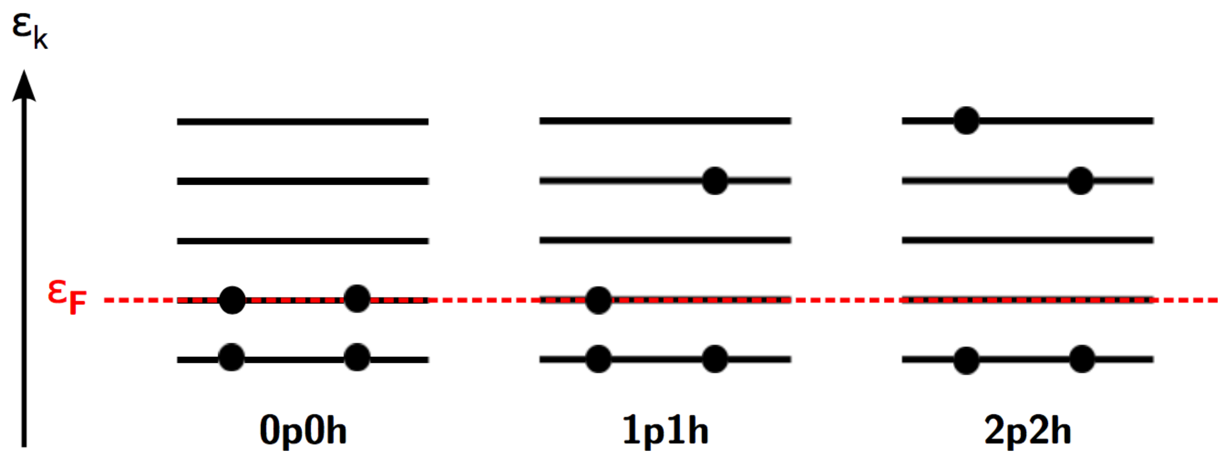


In-medium similarity renormalization group

flow equations to decouple higher-lying particle-hole states

Tsukiyama, Bogner, AS, PRL (2011), Hergert et al., Phys. Rep. (2016)





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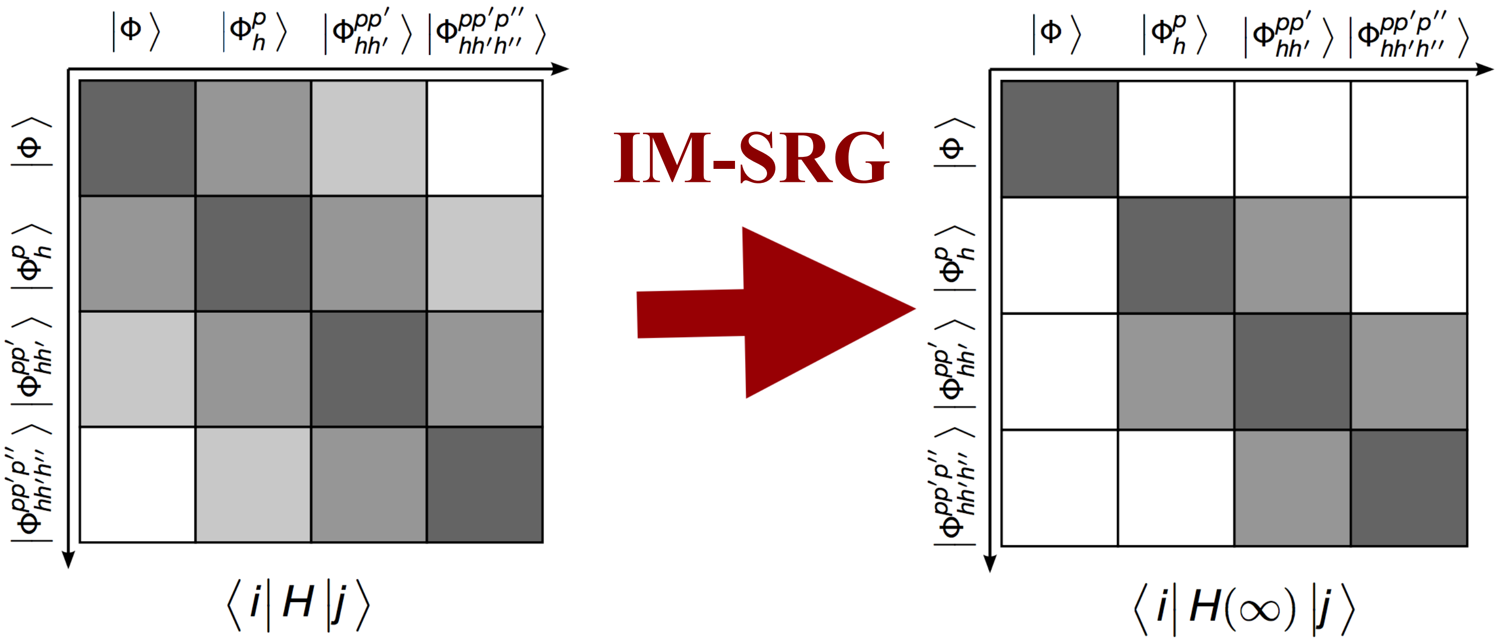

s = 0

$$H(s) = U(s)H(0)U^{\dagger}(s)$$

s = ∞

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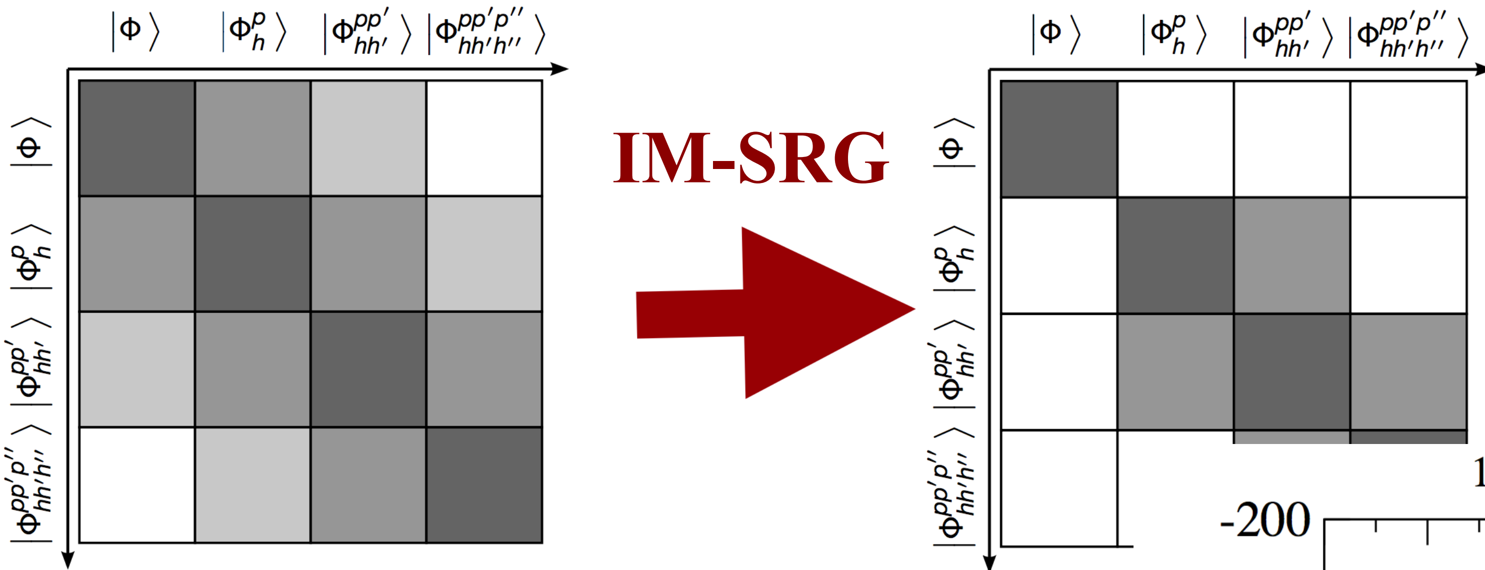


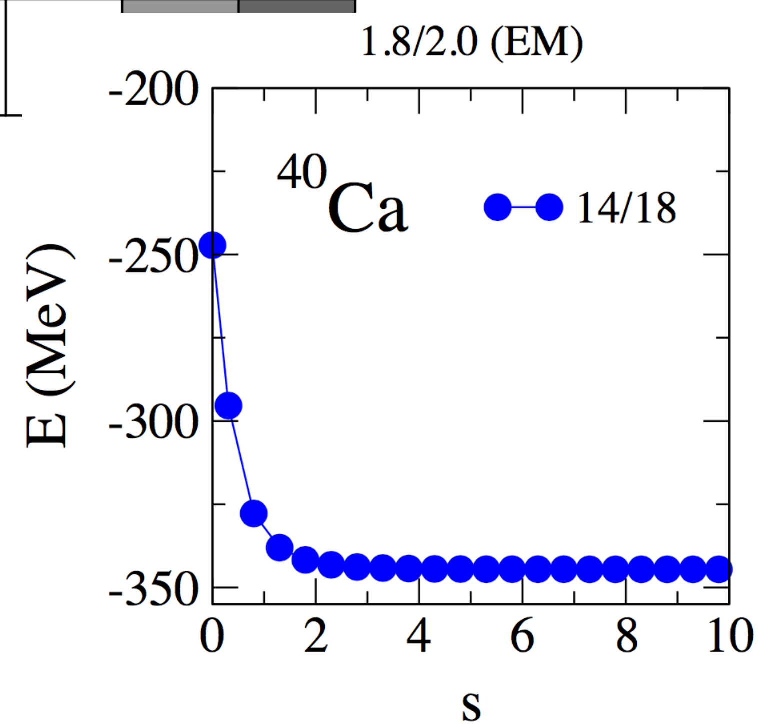
$\langle i | H | j \rangle$

s = 0

$$H(s) = U(s)H(0)U^\dagger(s)$$

$$\frac{d}{ds}H(s) = [\eta(s), H(s)]$$

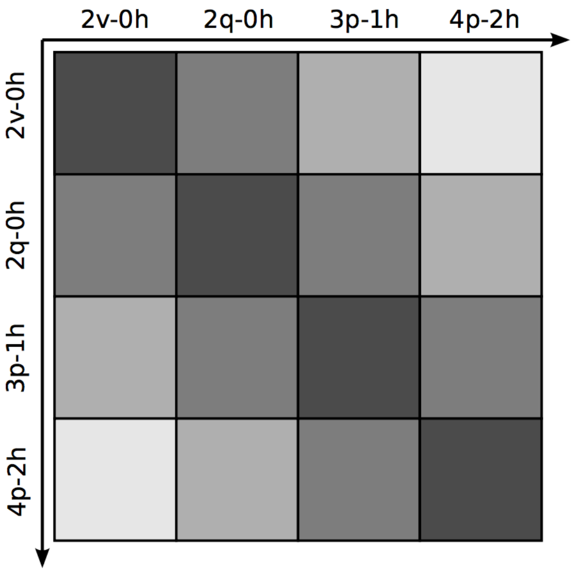
with generator $\eta = [H^d(s), H^{od}(s)]$



Ab initio calculations going open shell

In-Medium SRG to derive nonperturbative shell-model interactions

Tsukiyama, Bogner, AS, PRC (2012); Bogner et al., PRL (2014); Stroberg et al., PRL (2016)



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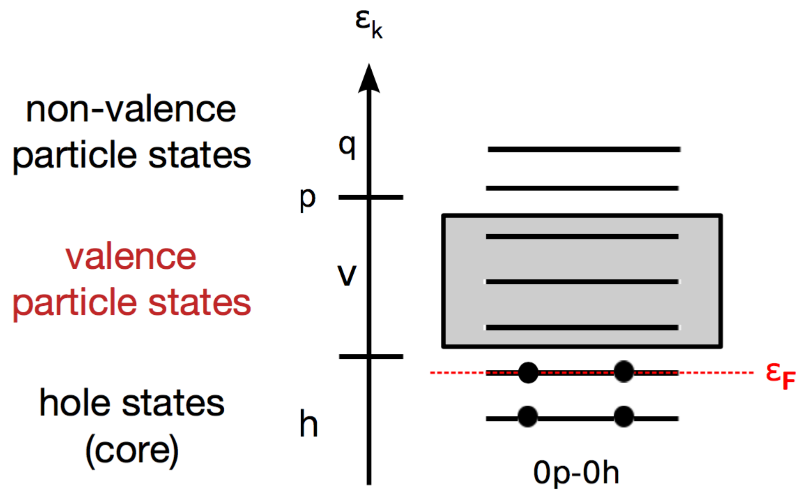

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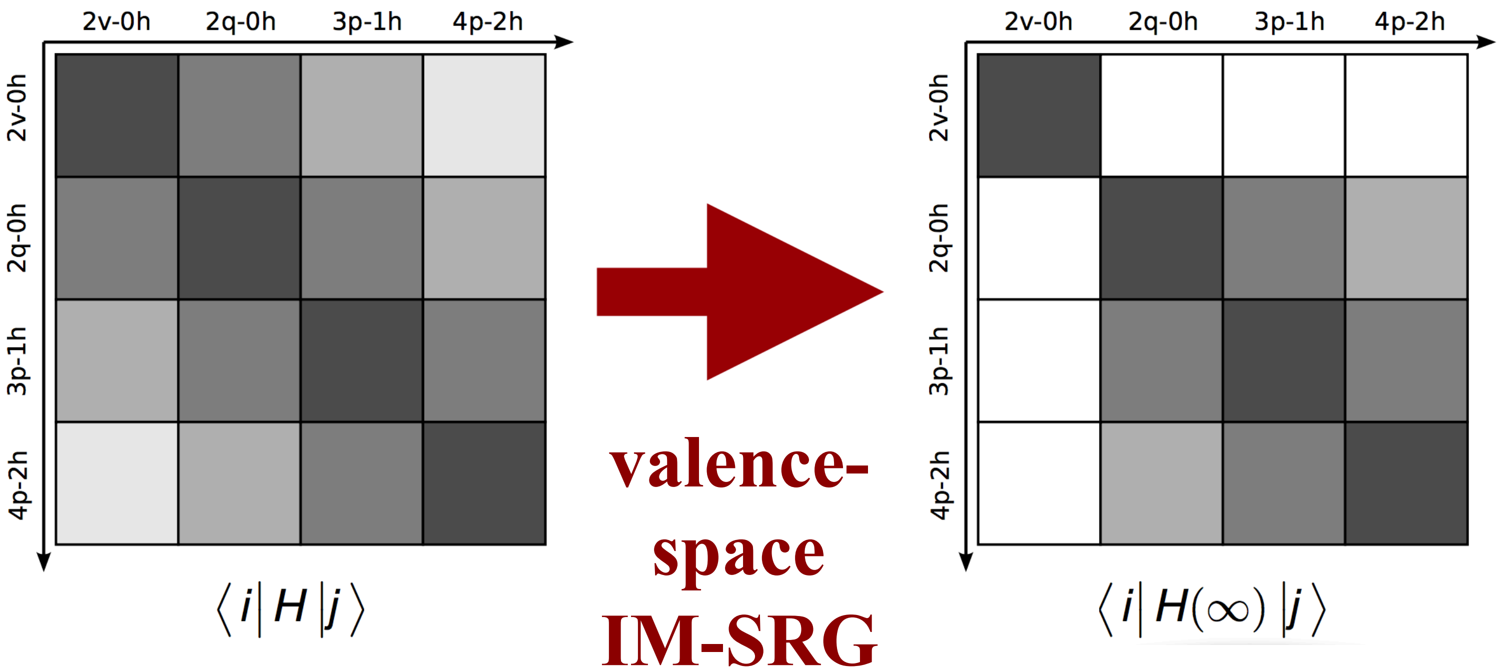

+ diagonalization in valence space (2v-0h block)

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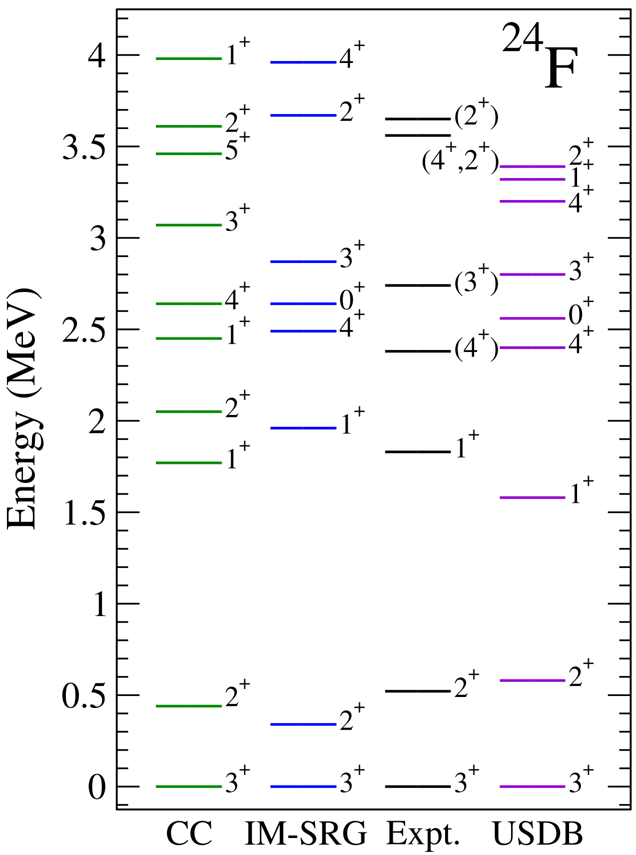
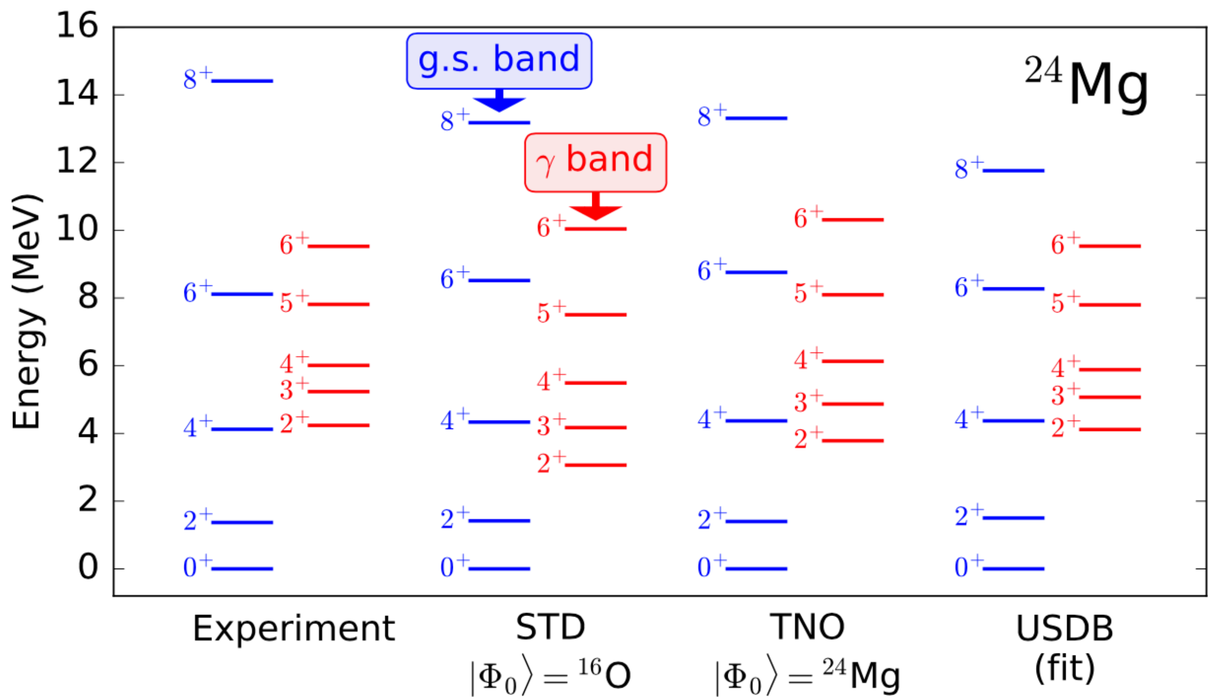


Cáceres et al., PRC (2015)



from R. Stroberg

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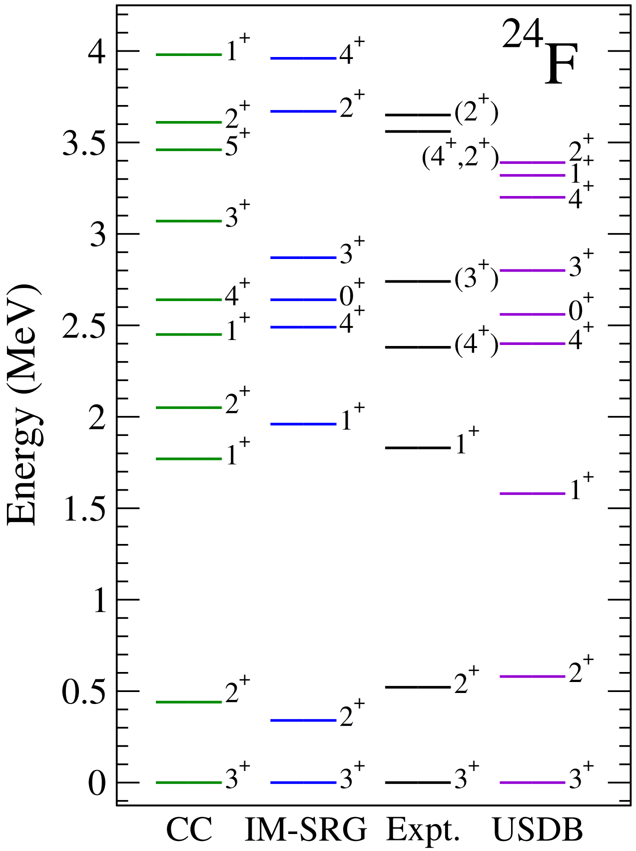
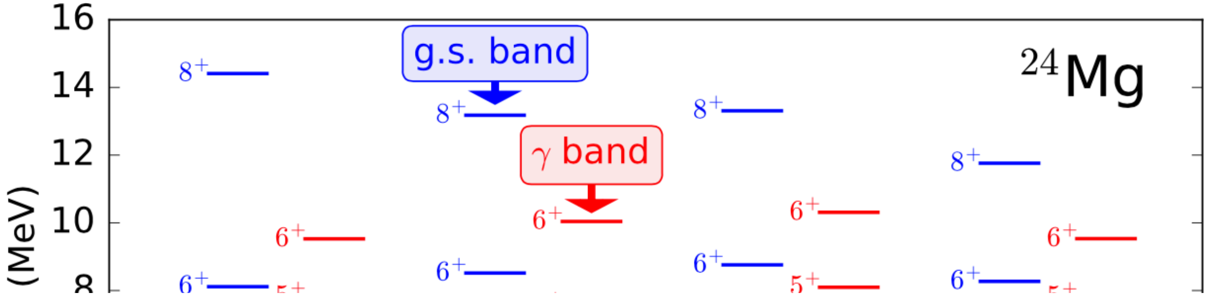
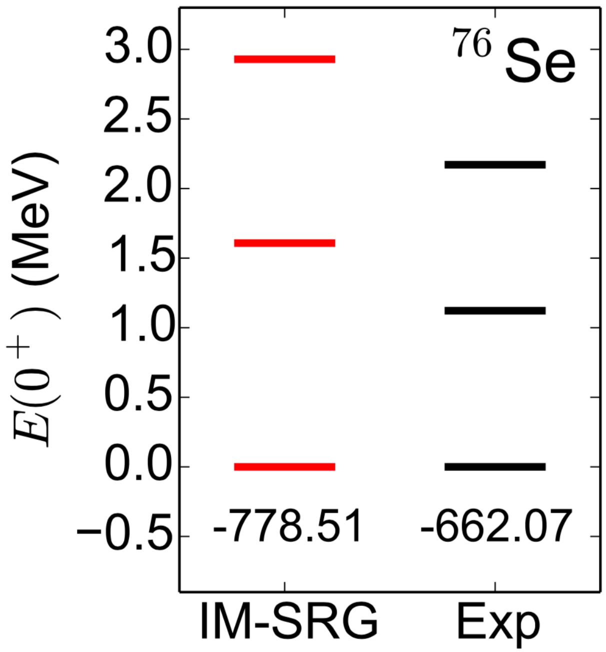
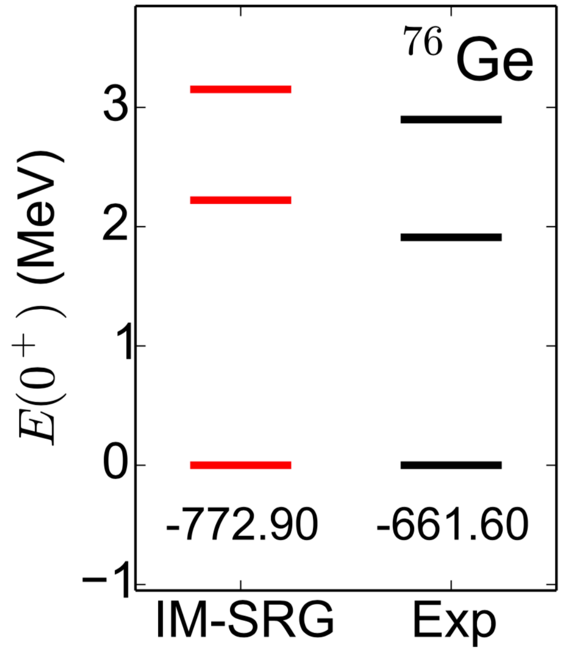


Cáceres et al., PRC (2015)



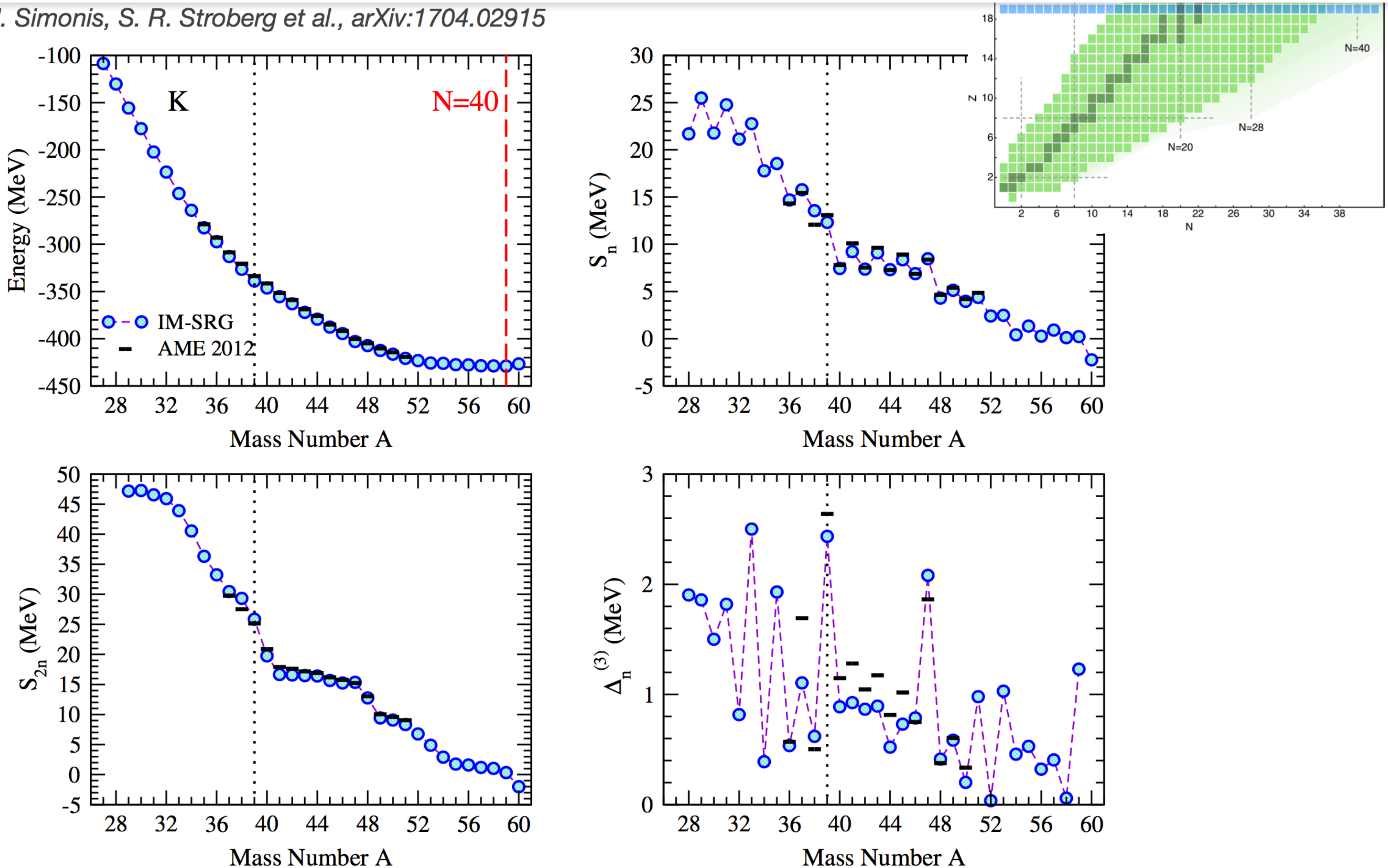




Future: IM-SRG for neutrinoless double-beta decay with J.D. Holt et al.

Great progress from medium to heavy nuclei

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



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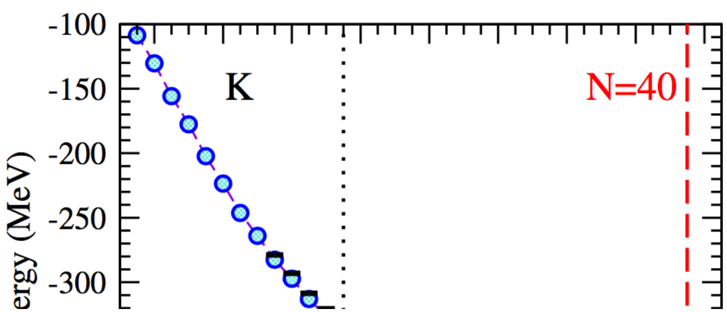
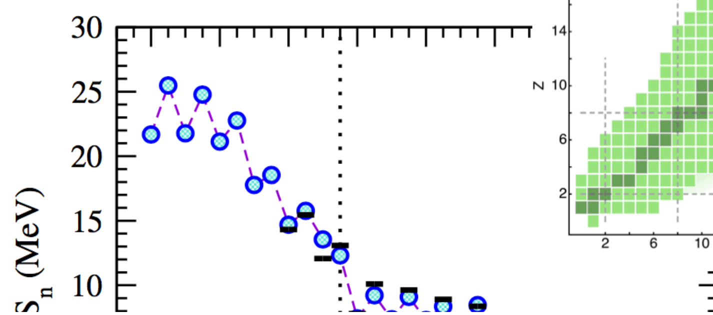
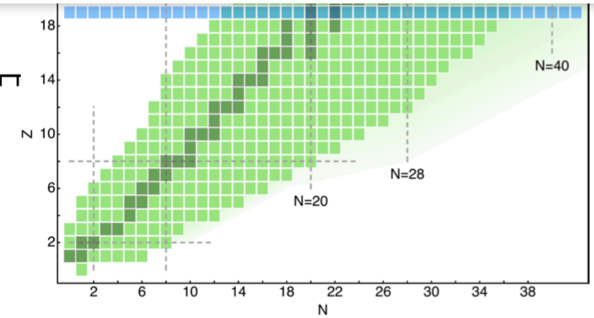
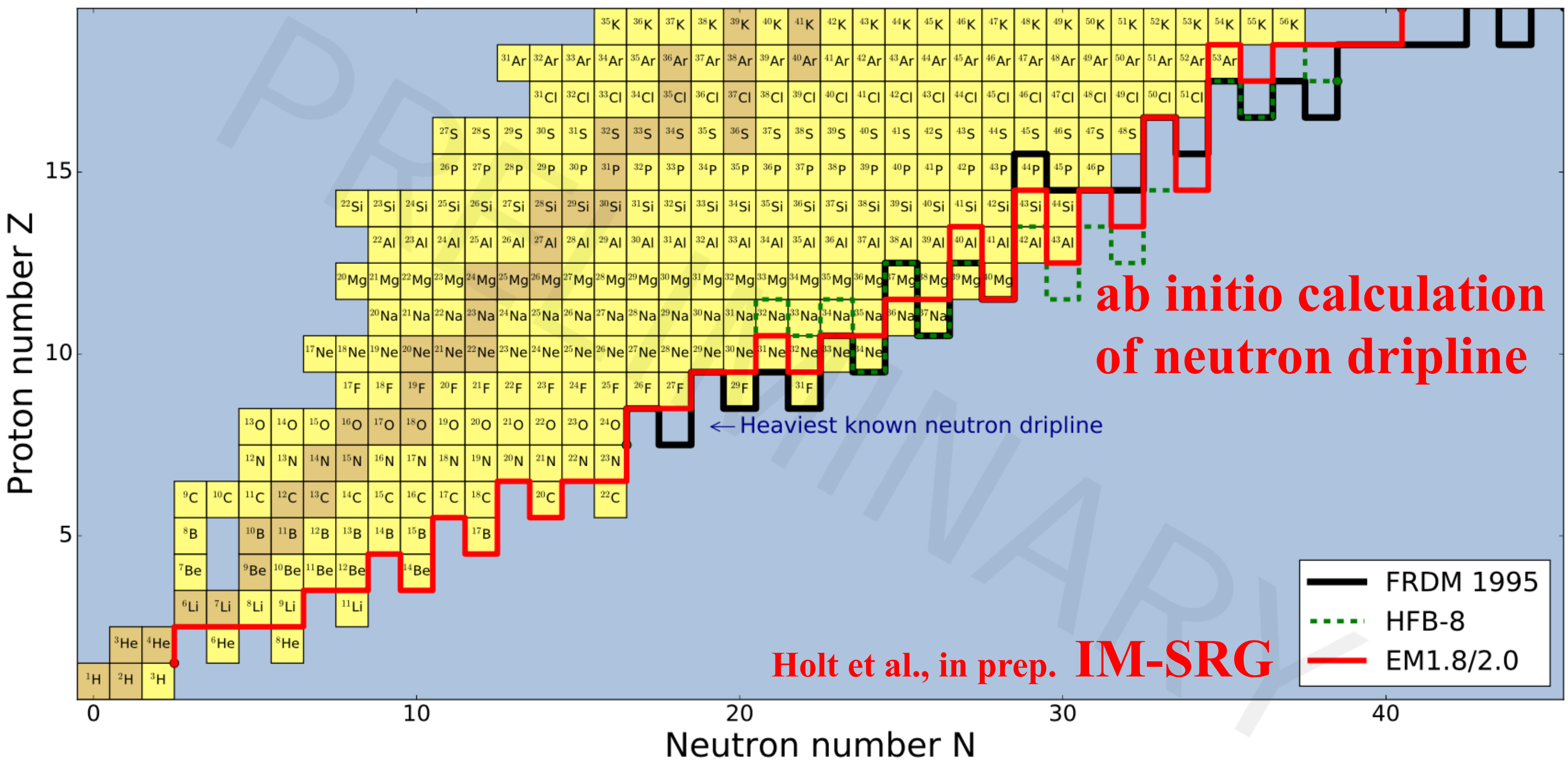








Neutron skin of ^{48}Ca

nature physics

ARTICLES

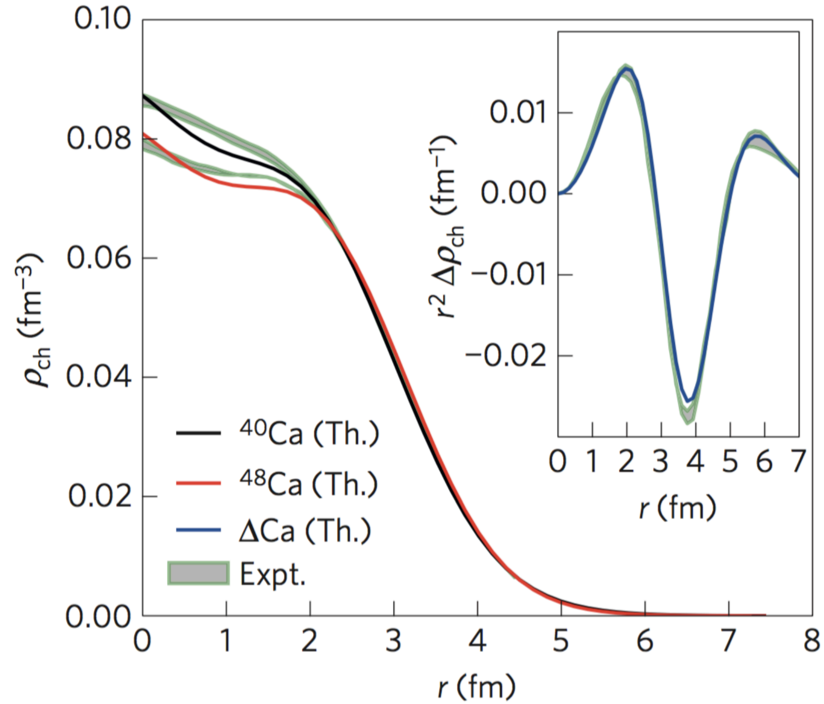
PUBLISHED ONLINE: 2 NOVEMBER 2015 | DOI: 10.1038/NPHYS3529

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]

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

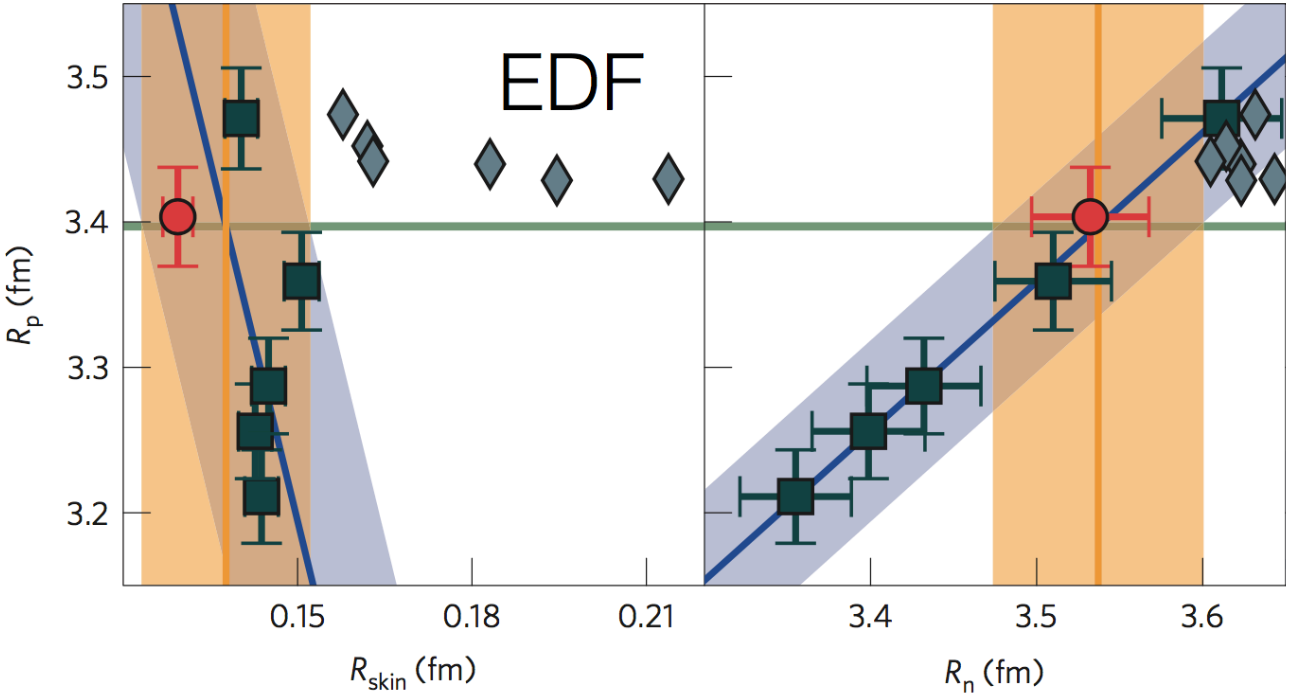
ab initio calculations lead to charge distributions consistent with experiment



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

ab initio calculations lead to charge distributions consistent with experiment

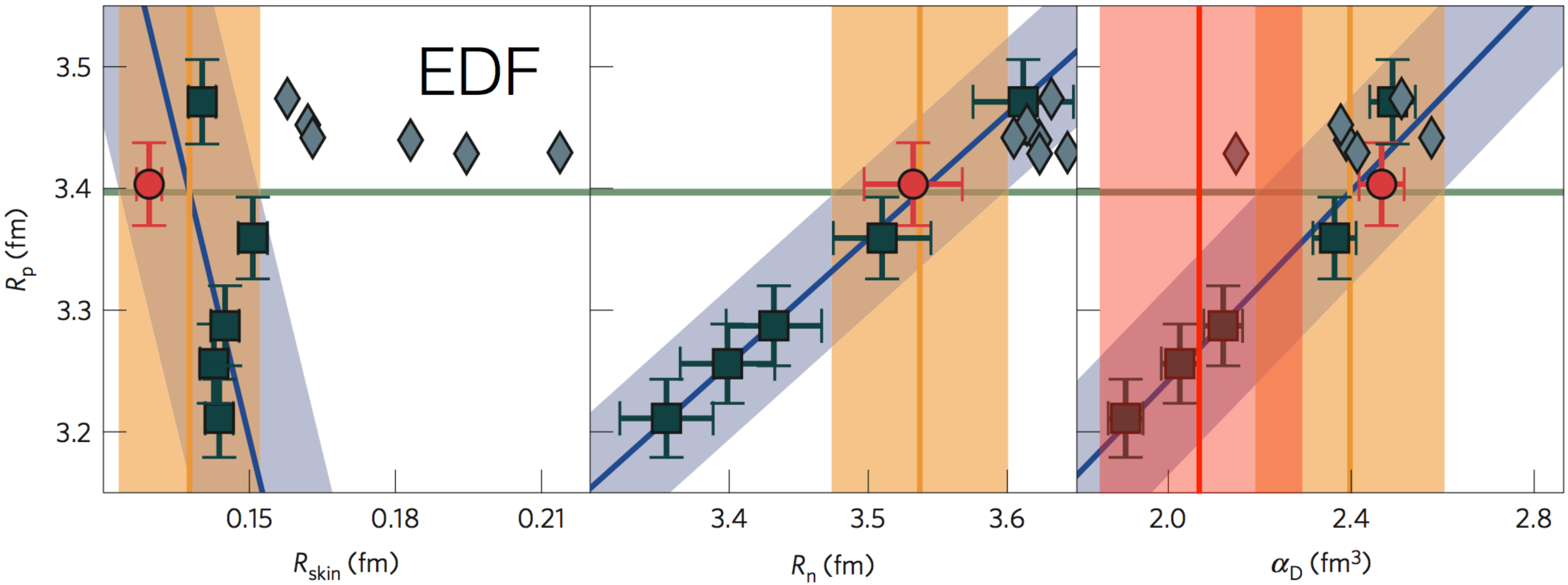
predict **small neutron skin**



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

ab initio calculations lead to charge distributions consistent with experiment

predict **small neutron skin**, dipole polarizability, and weak formfactor



dipole polarizability in good agreement with recent DA-Osaka expt.

Birkhan, Miorelli, et al., PRL (2017)

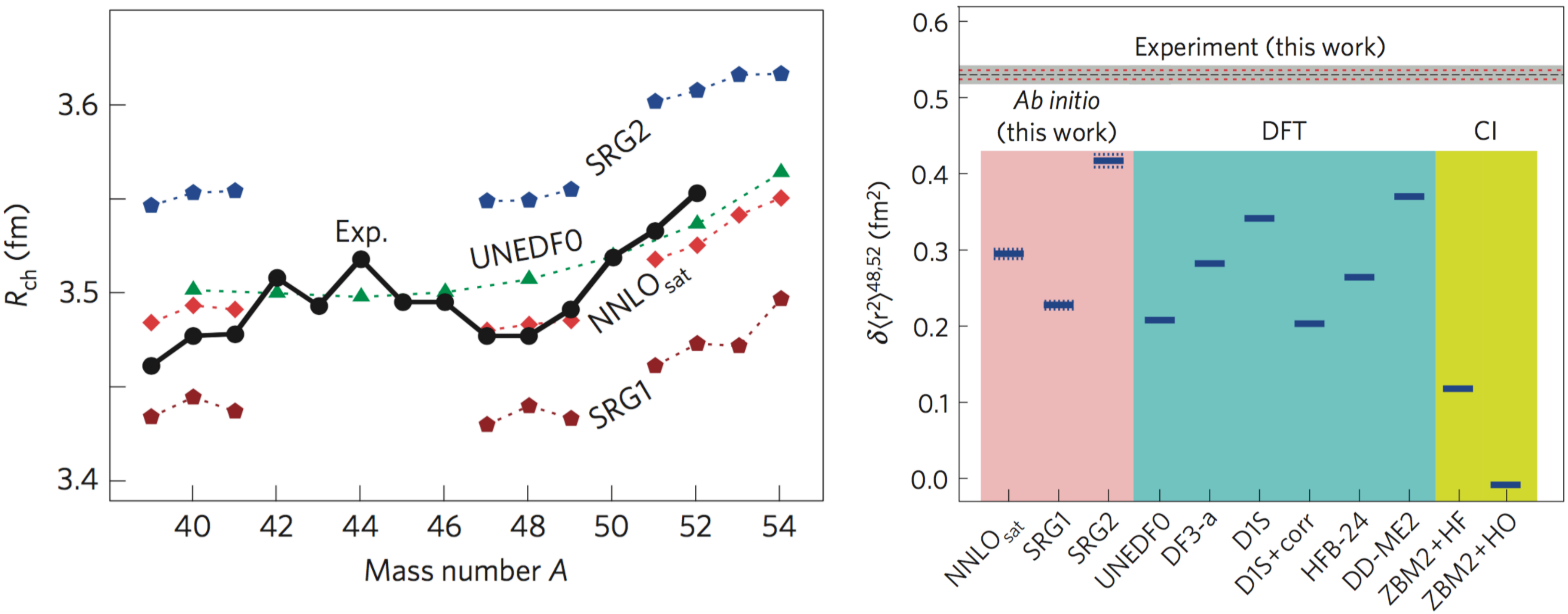
nature physics

ARTICLES

PUBLISHED ONLINE: 8 FEBRUARY 2016 | DOI: 10.1038/NPHYS3645

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]



Nuclear physics of dark matter direct detection

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

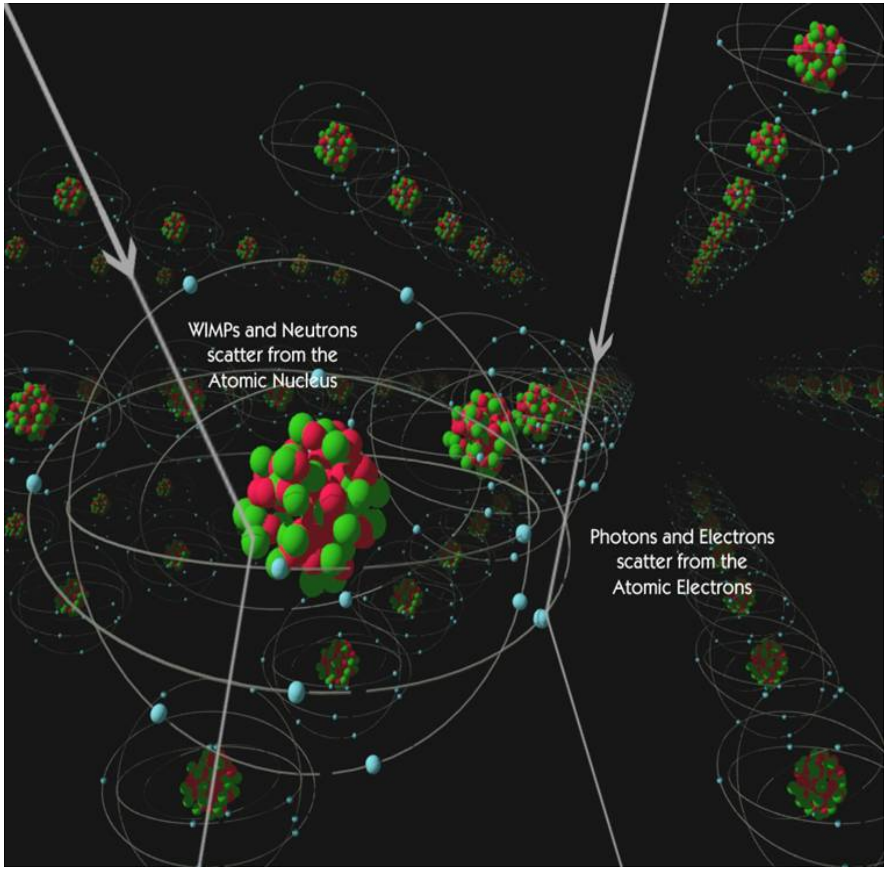
particularly sensitive to nuclear physics for **spin-dep.** or **beyond spin-indep.** WIMP-nucleon interactions

relevant momentum transfers $\sim m_\pi$

calculate systematically with chiral EFT

Menéndez, Gazit, AS, PRD (2012),
Klos, Menéndez, Gazit, AS, PRD (2013),
Baudis et al., PRD (2013),
Vietze et al., PRD (2015),
Hoferichter, Klos, AS, PLB (2015),
Hoferichter et al., PRD (2016)

incorporate what we know about QCD/nuclear physics



from CDMS collaboration

Preview

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

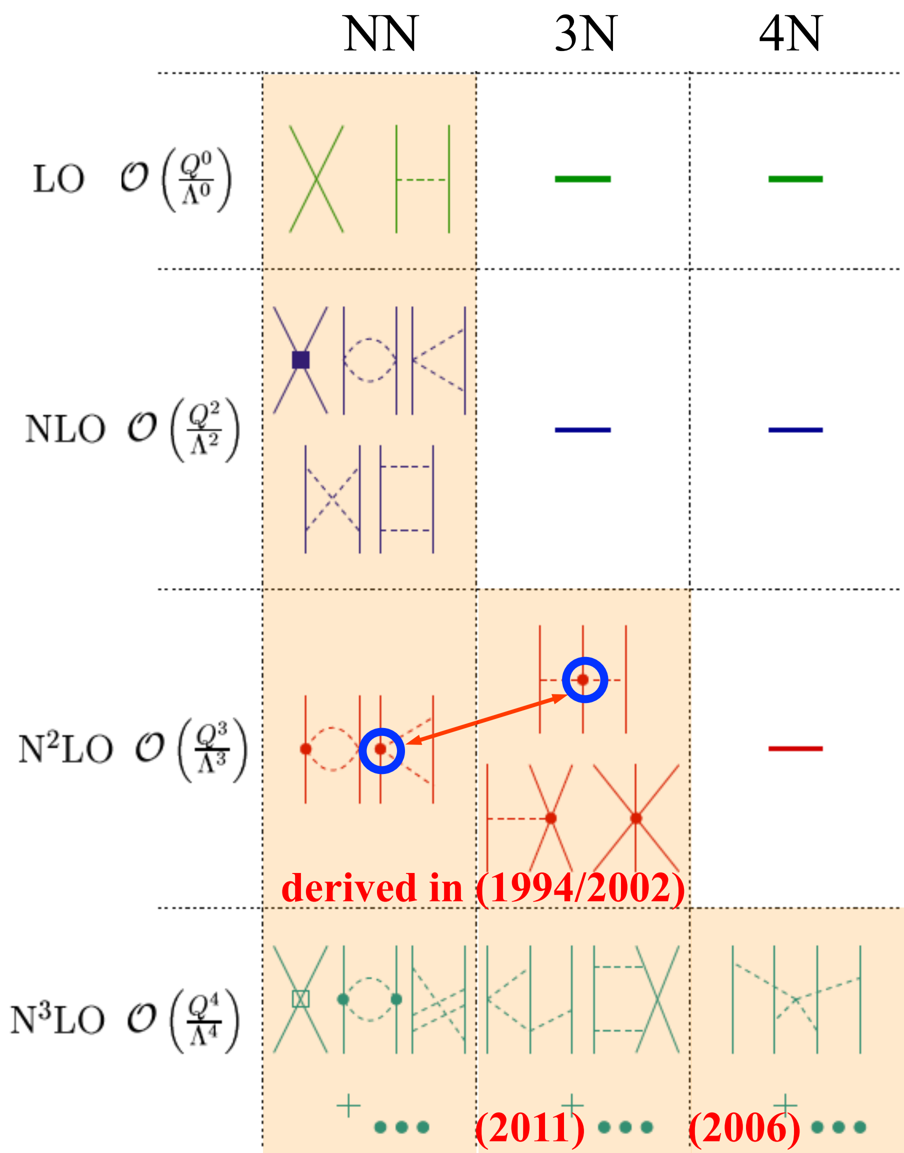
based on **large-scale nuclear structure calculations** and
systematic expansion of **WIMP-nucleon currents in chiral EFT**

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)

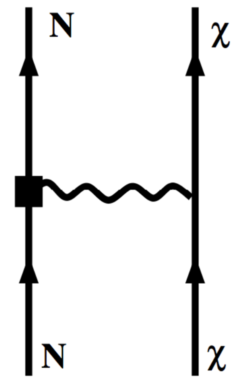
general coherent (SI+) WIMP-nucleus scattering
with Hoferichter, Klos, Menéndez, PRD (2016)

Chiral EFT for (electro)weak interactions in nuclei

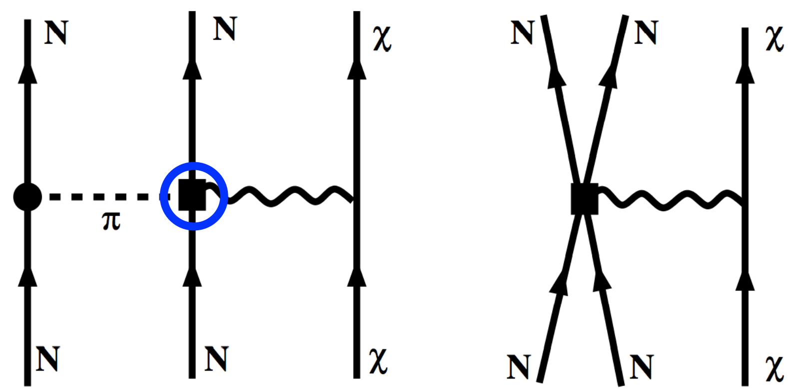


example: axial-vector currents

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



+ two-body currents at Q^3

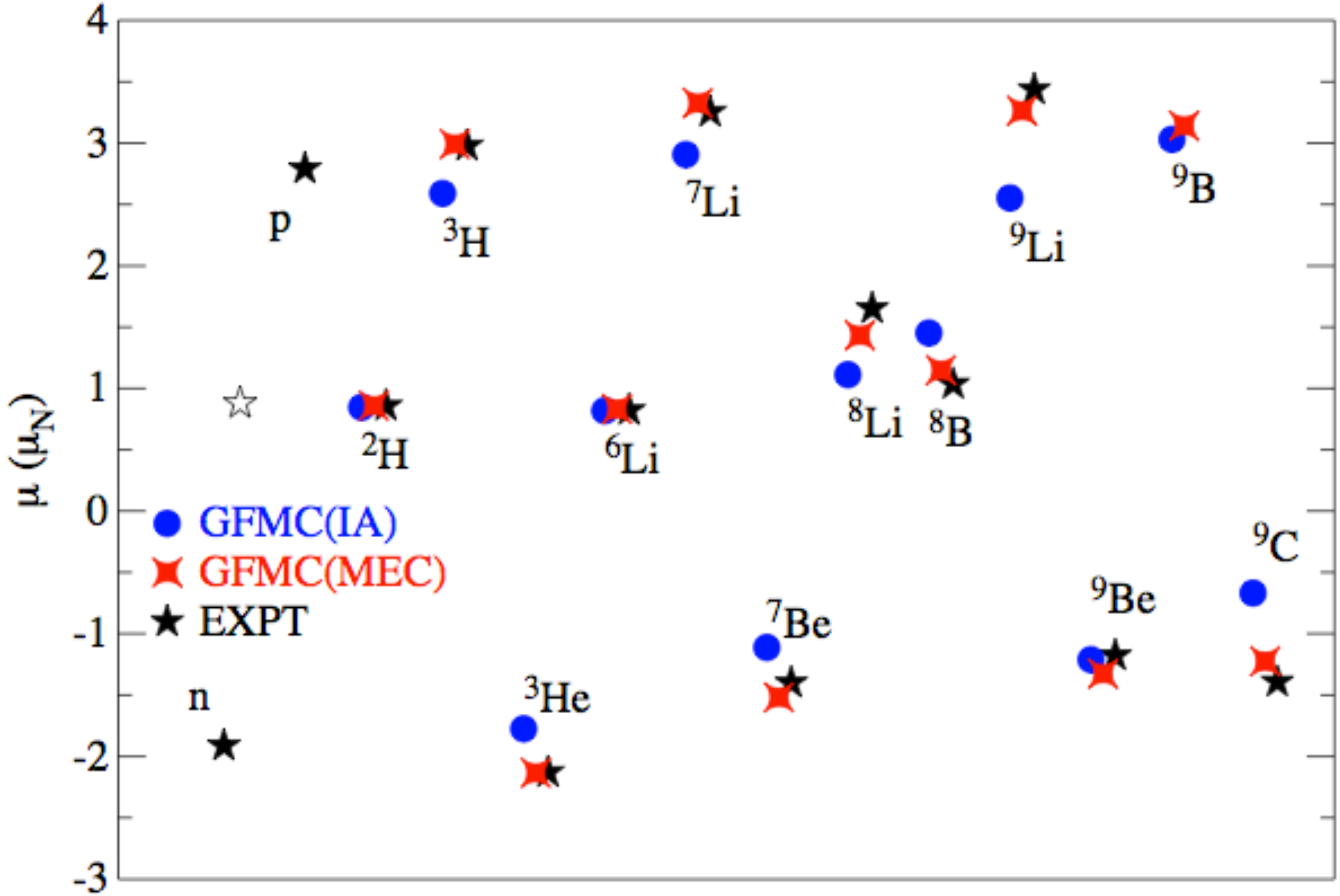


same couplings in forces and currents!

Chiral EFT currents and electromagnetic interactions

predicts consistent electromagnetic 1+2-body currents

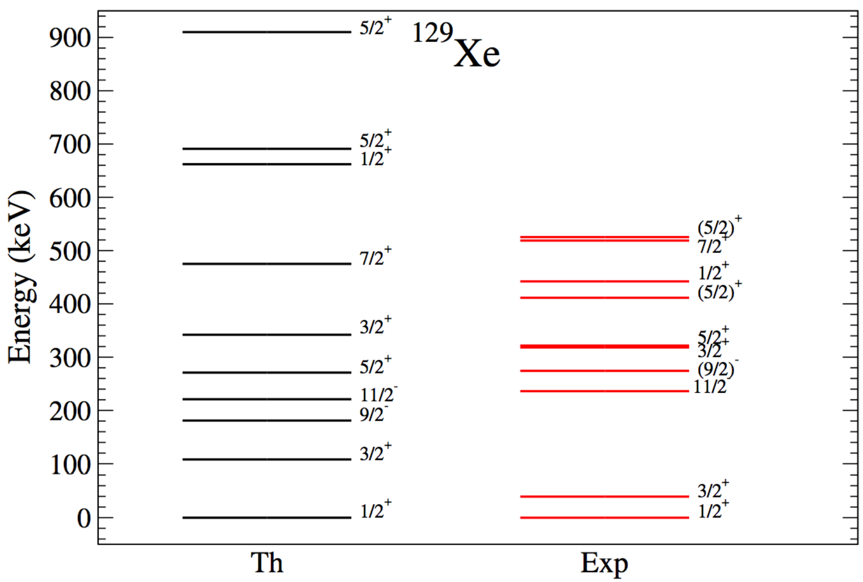
GFMC calculations of magnetic moments in light nuclei Pastore et al. (2012-)
2-body currents (meson-exchange currents=MEC) are key!

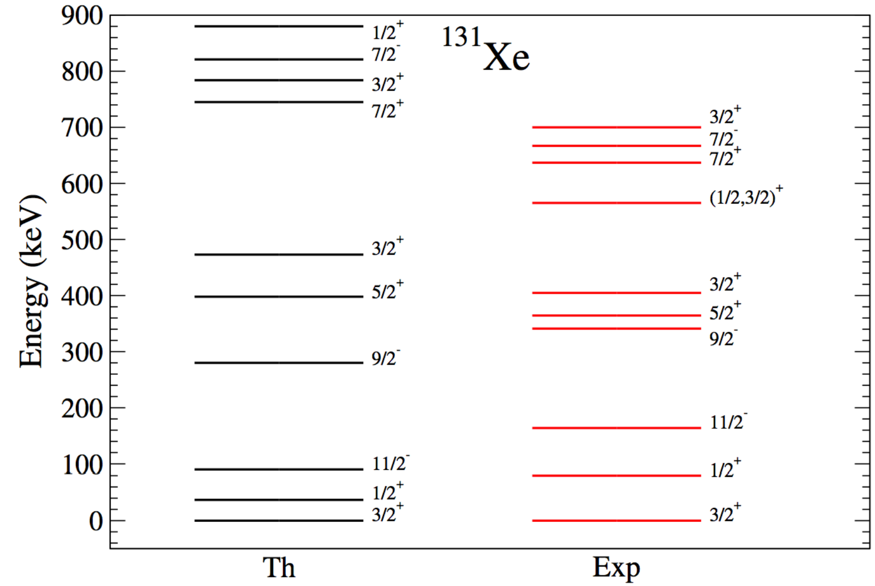


Nuclear structure for direct detection

valence-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

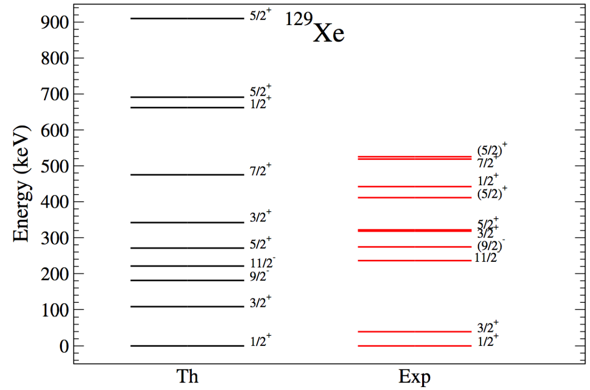
Menendez, Gazit, AS, PRD (2012)

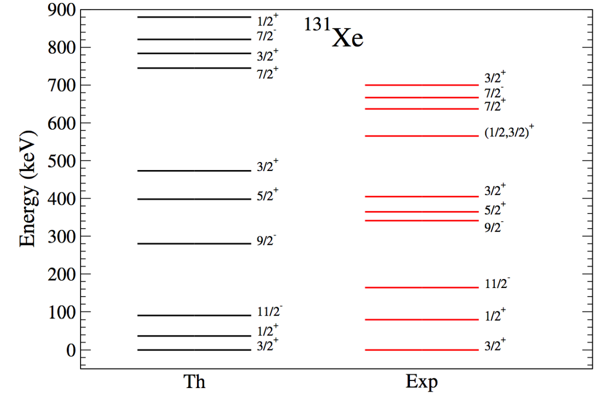
connects WIMP direct detection with double-beta decay

Nuclear structure for direct detection

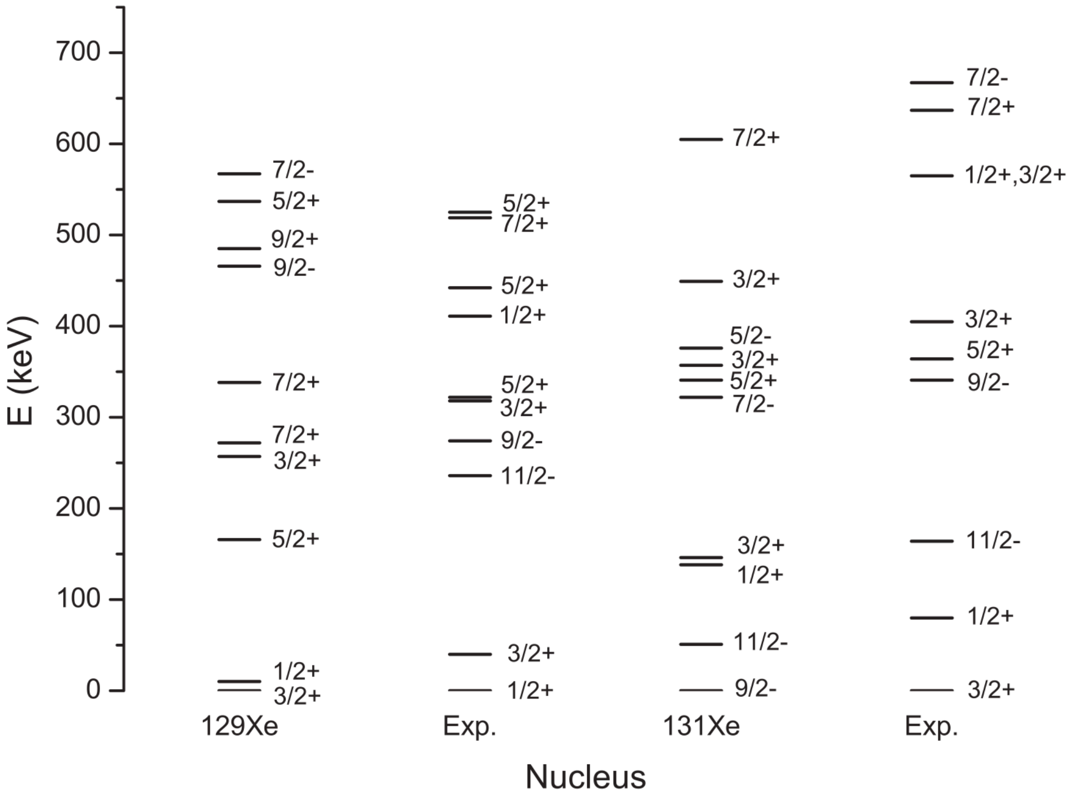
very good agreement for spectra; ordering and grouping well reproduced

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)

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

decompose into longitudinal, transverse electric and transverse magnetic

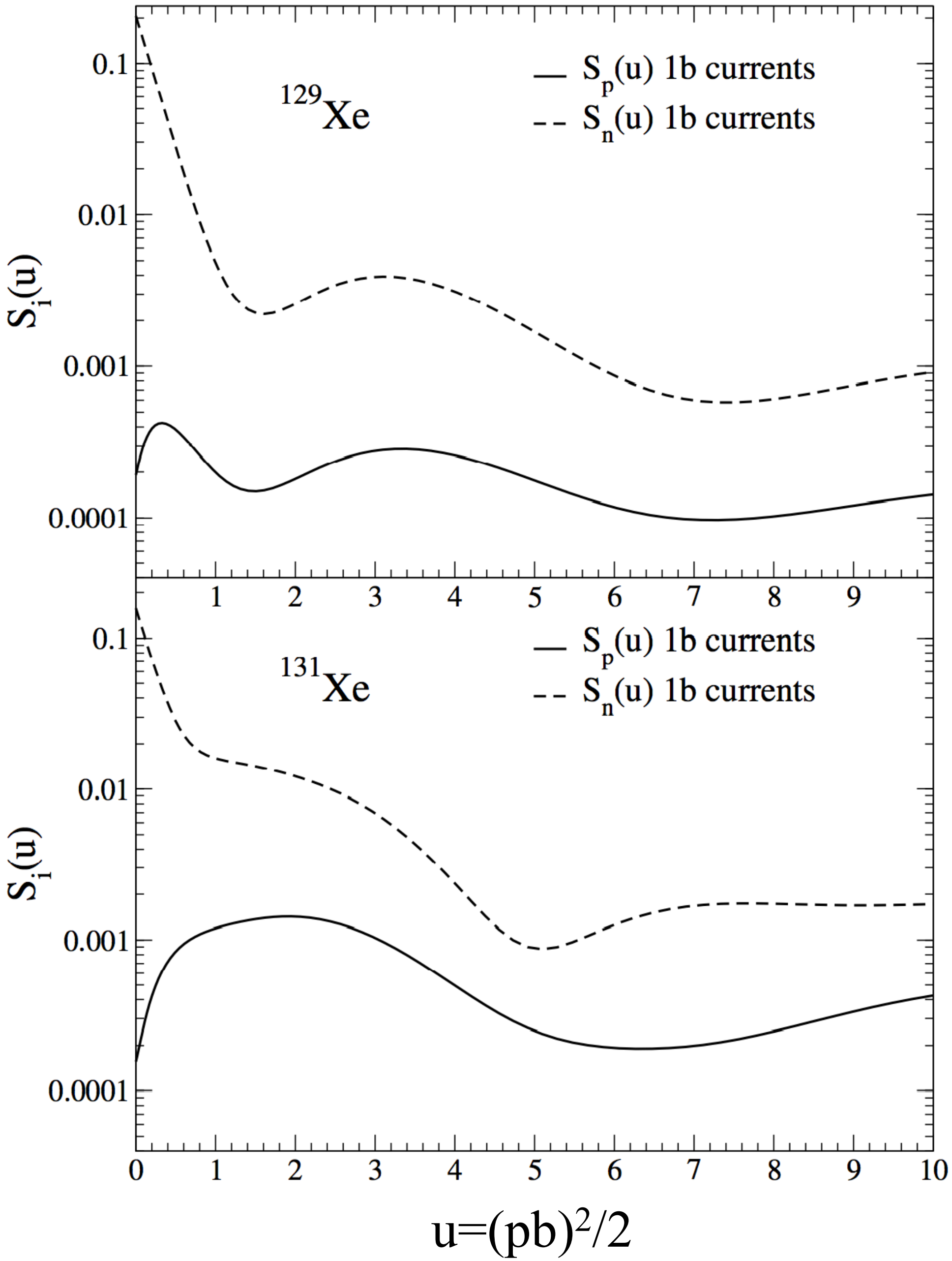
$$S_A(p) = \sum_{L \geqslant 0} \left| \langle J_f || \mathcal{L}_L^5 || J_i \rangle \right|^2 + \sum_{L \geqslant 1} \left(\left| \langle J_f || \mathcal{T}_L^{\mathrm{el}5} || J_i \rangle \right|^2 + \left| \langle J_f || \mathcal{T}_L^{\mathrm{mag}5} || J_i \rangle \right|^2 \right)$$

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

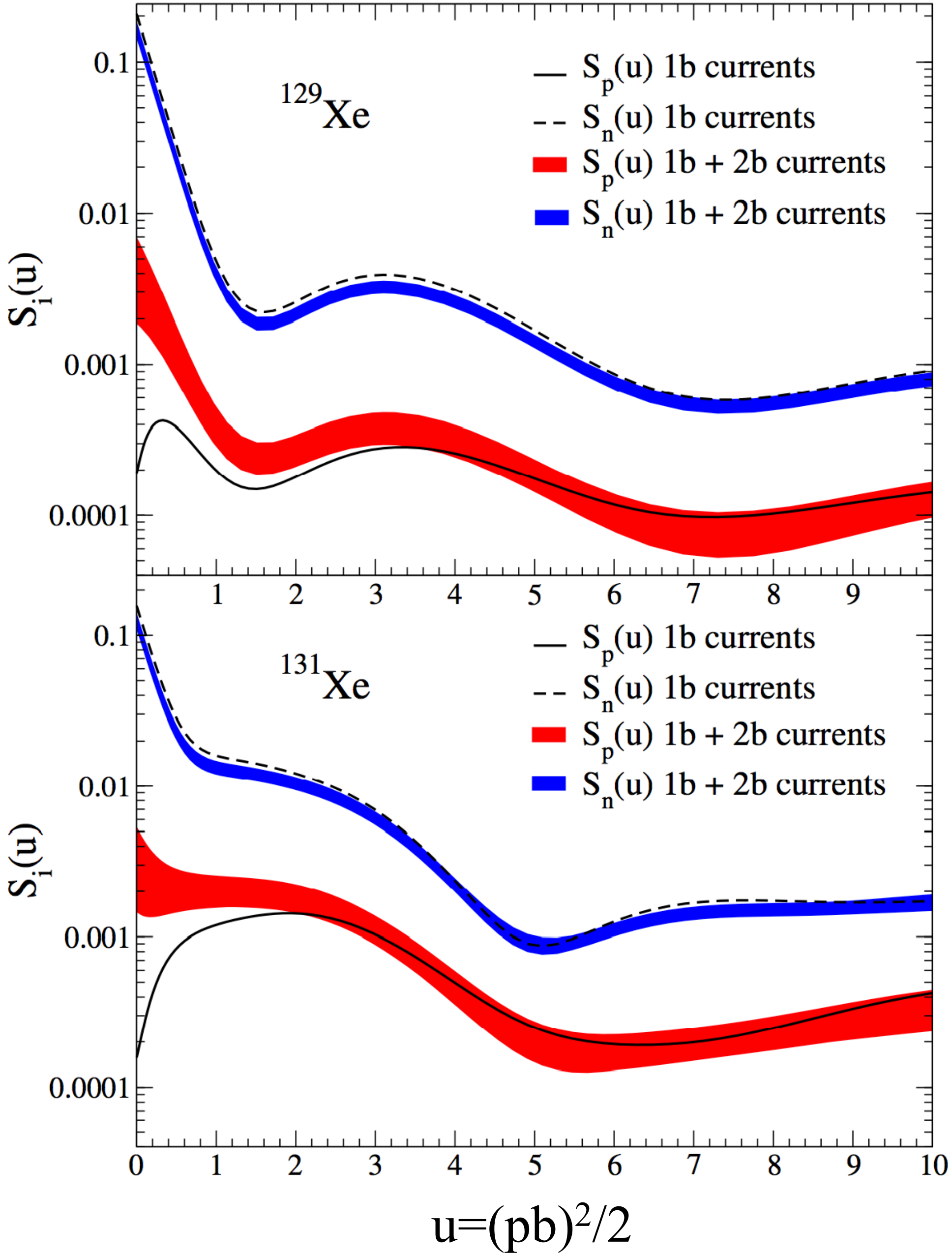


^{129,131}Xe are even Z, odd N,
spin is carried mainly by neutrons

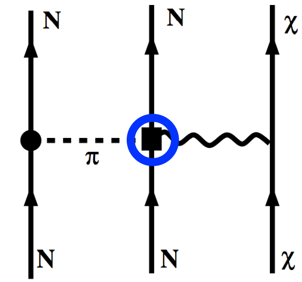
at p=0 structure factors
at the level of one-body currents
dominated by "neutron"-only

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

Xenon response with 1+2-body currents



two-body currents due to strong interactions among nucleons



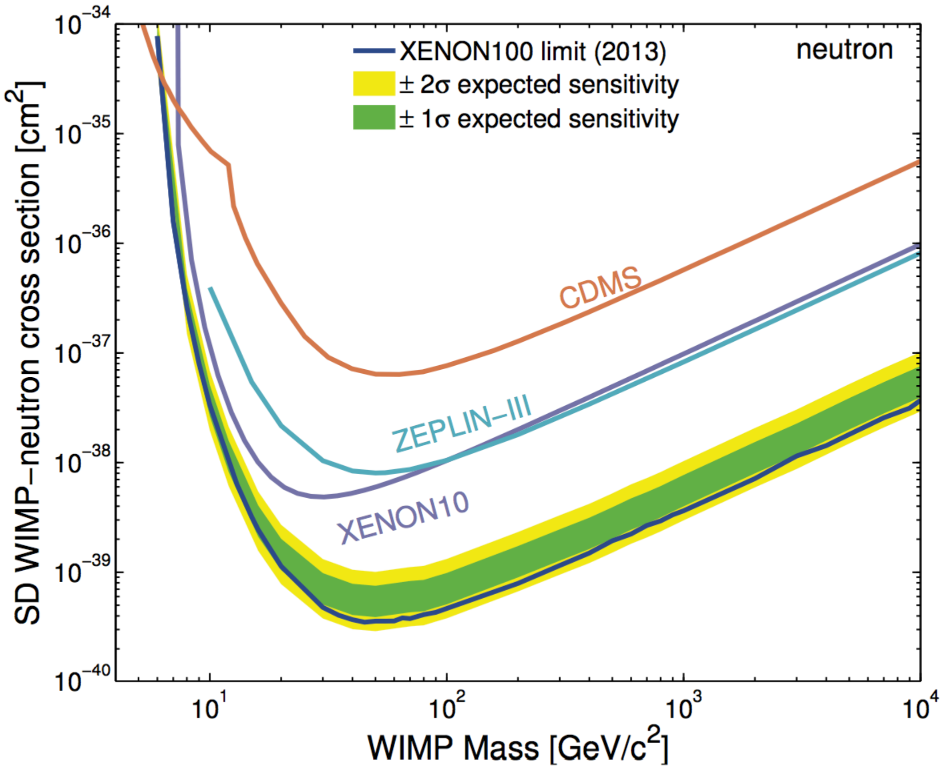
WIMPs couple to neutrons and protons at the same time

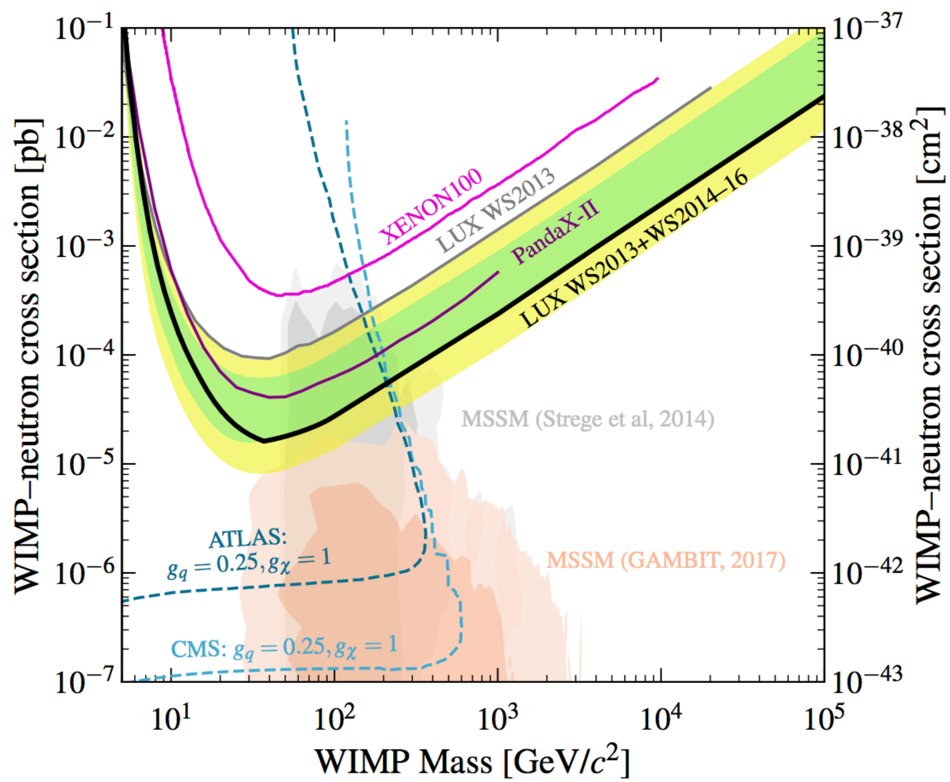
enhances coupling to even species in all cases (protons for Xe)

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)

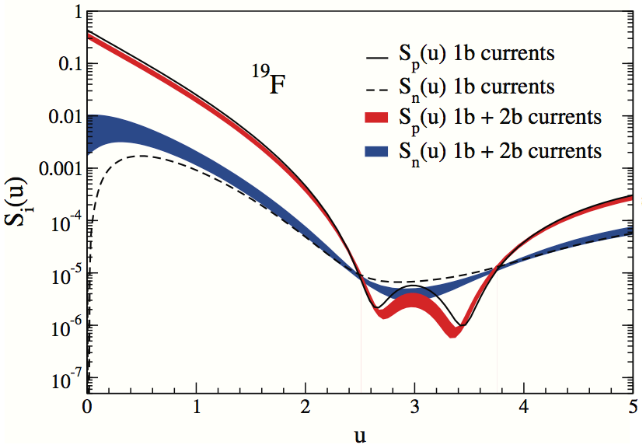
used our calculations with uncertainty bands for WIMP currents in nuclei



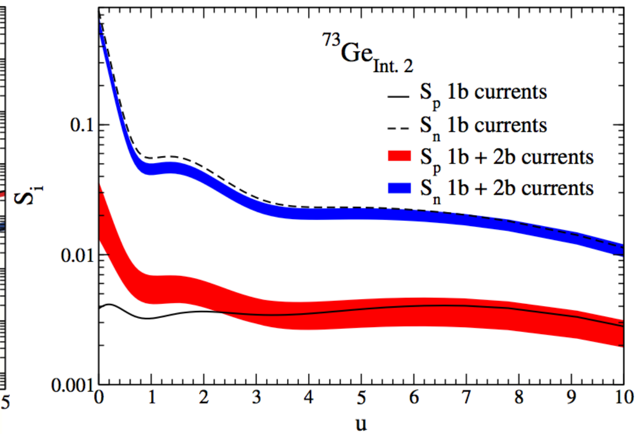


Spin-dependent WIMP-nucleus response for ^{19}F, ^{23}Na, ^{27}Al, ^{29}Si, ^{73}Ge, ^{127}I

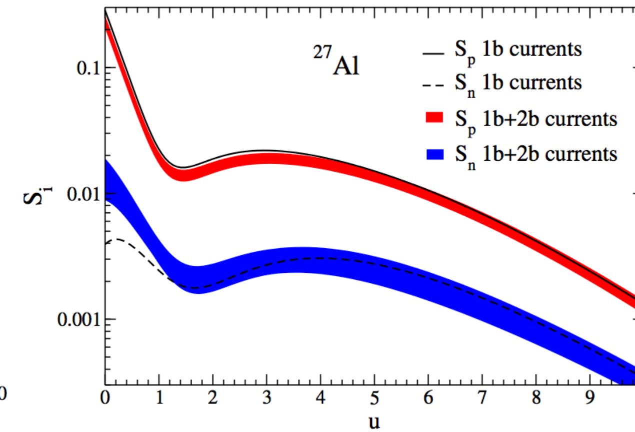
Klos, Menéndez, Gazit, AS, PRD (2013) includes structure factor fits for all isotopes



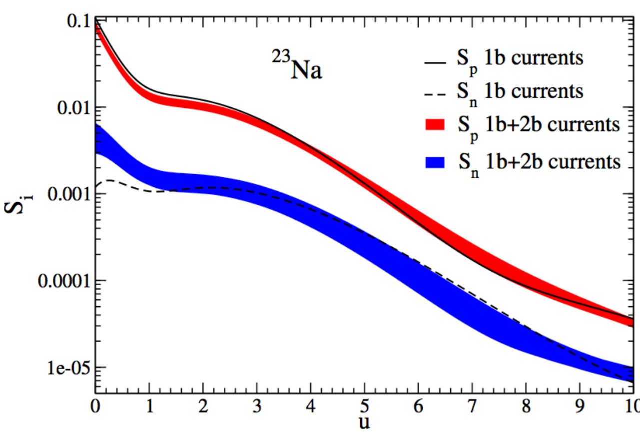
PICASSO, COUPP, SIMPLE



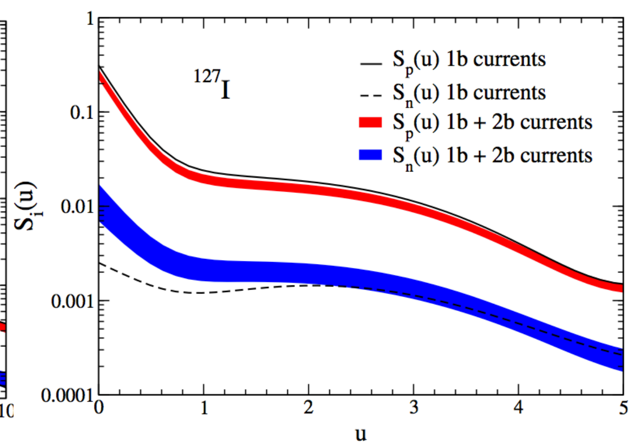
CDMS, EDELWEISS, EURECA



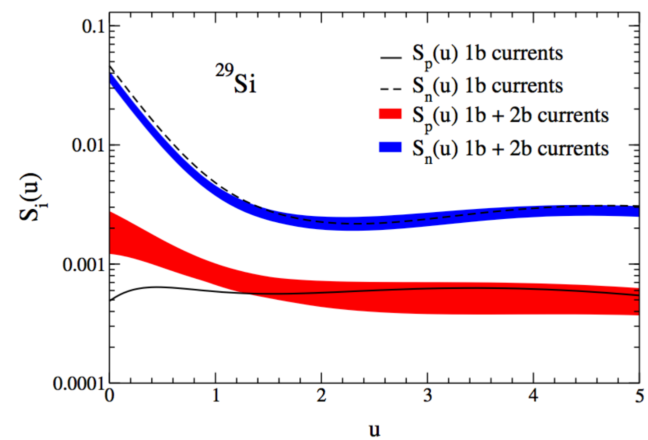
CRESST



DAMA, ANAIS, DM-Ice



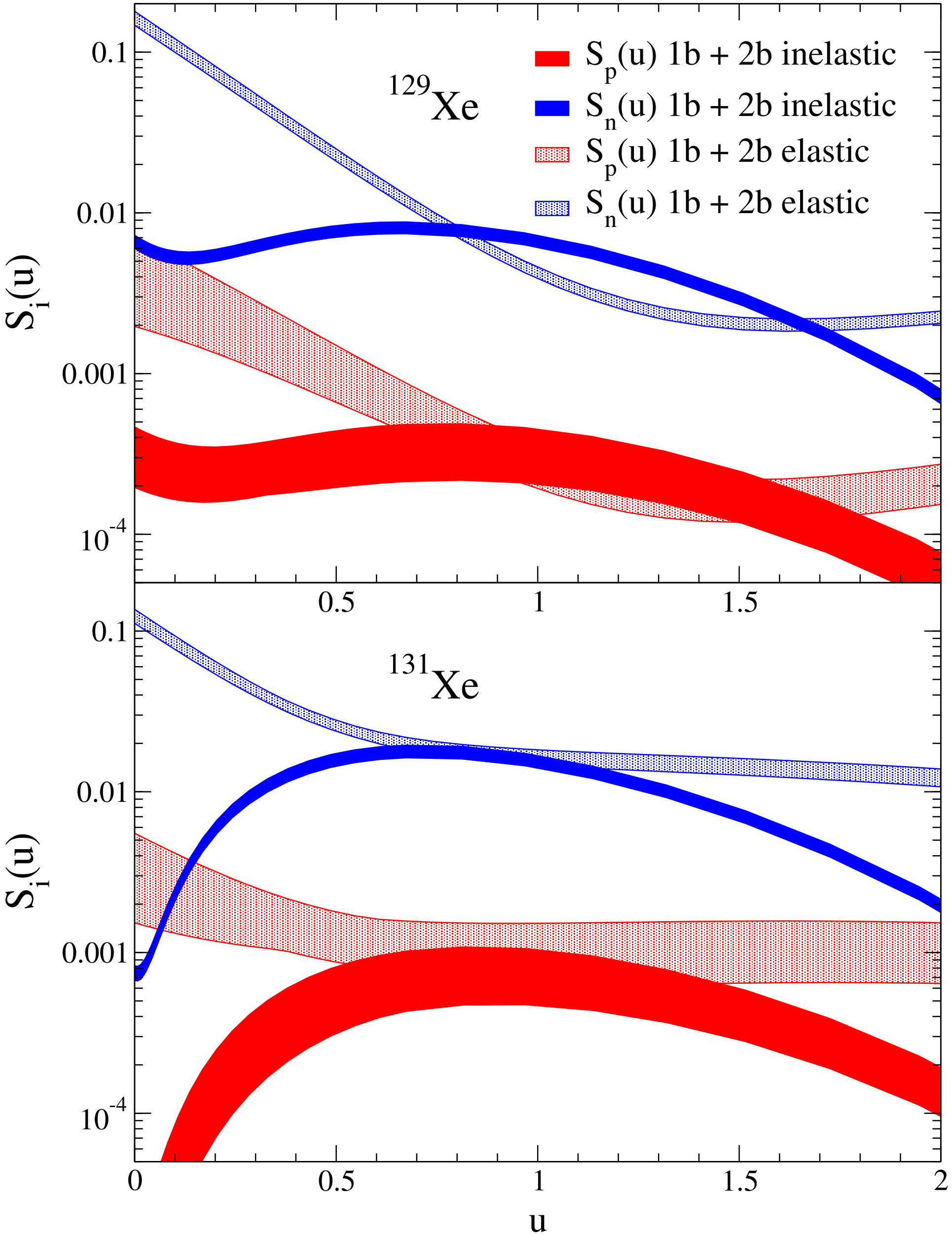
DAMA, ANAIS, DM-Ice, KIMS



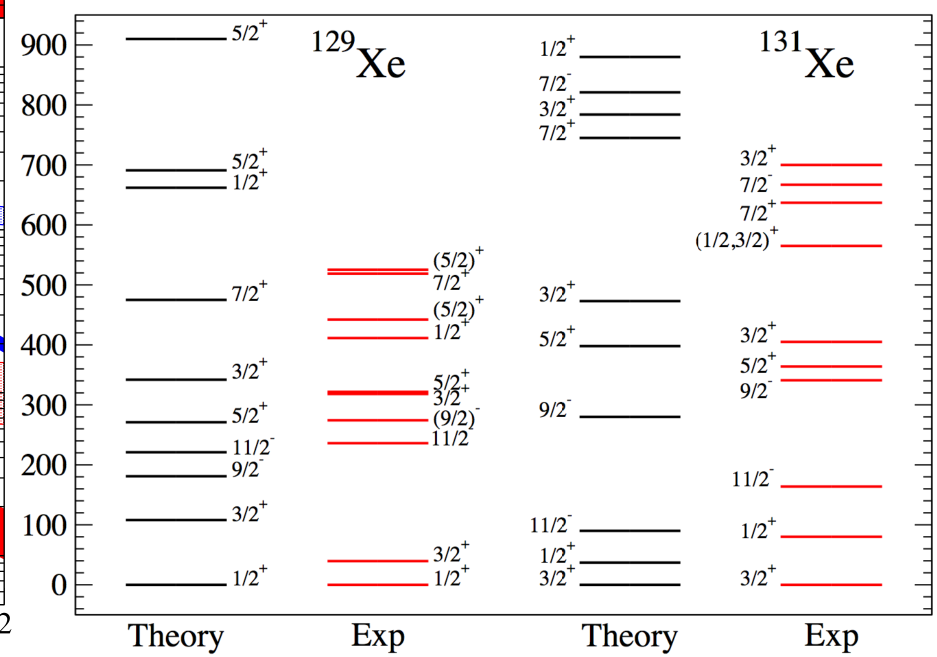
CDMS-II

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

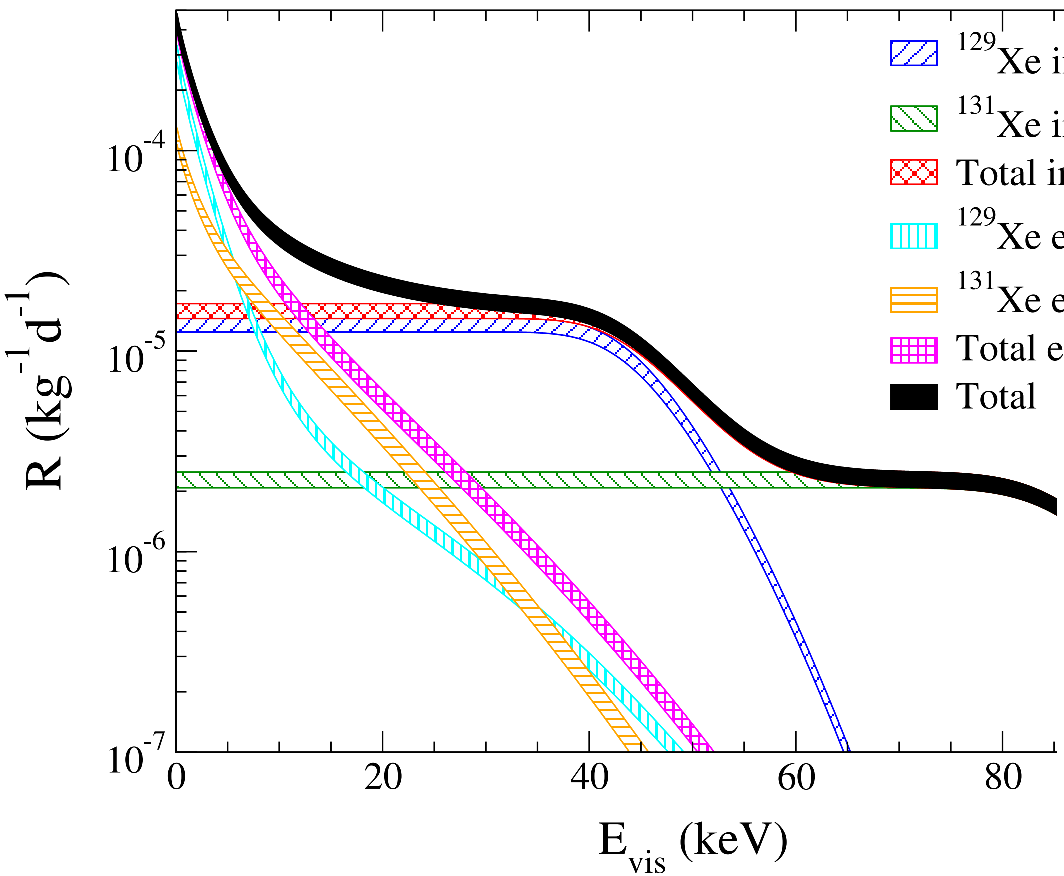


Signatures for **inelastic** WIMP scattering

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

Chiral EFT for general WIMP-nucleon interactions

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WIMP	Nucleon	V: t	V: $\mathbf{x}$	A: t	A: $\mathbf{x}$
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V	2b	4	2 + 2	2	4 + 2
	2b NLO	–	–	5	3 + 2
	1b	0 + 2	1	2 + 2	0
A	2b	4 + 2	2	2 + 2	4
	2b NLO	–	–	5 + 2	3

WIMP	Nucleon	S	P
	1b	2	1
S	2b	3	5
	2b NLO	–	4
	1b	2 + 2	1 + 2
P	2b	3 + 2	5 + 2
	2b NLO	–	4 + 2

matching to non-relativistic EFT

Fitzpatrick et al., JCAP (2013)

without chiral physics

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

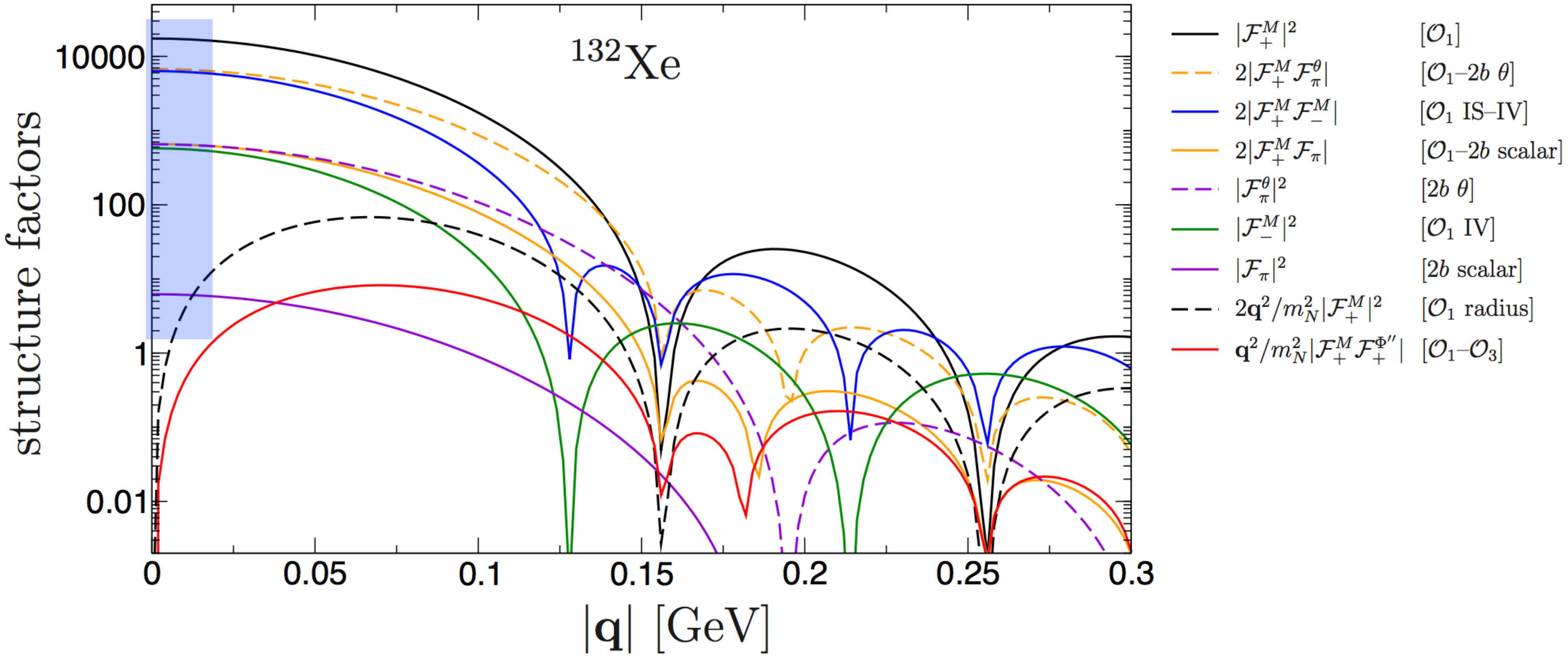
shows that NREFT operators are not linearly indep. (e.g., 4+6 are SD)

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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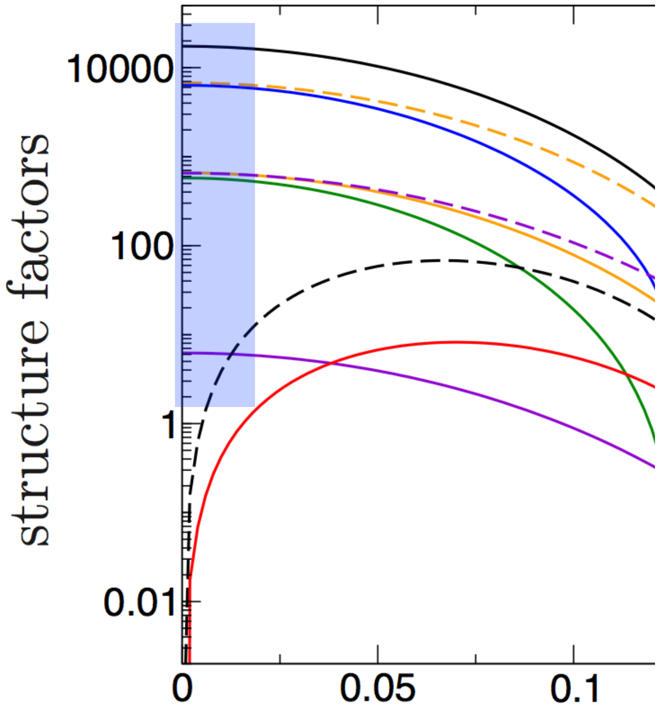

$$\mathcal{O}_1 = \mathbb{1}, \quad \mathcal{O}_2 = (\mathbf{v}^\perp)^2, \quad \mathcal{O}_3 = i\mathbf{S}_N \cdot (\mathbf{q} \times \mathbf{v}^\perp),$$
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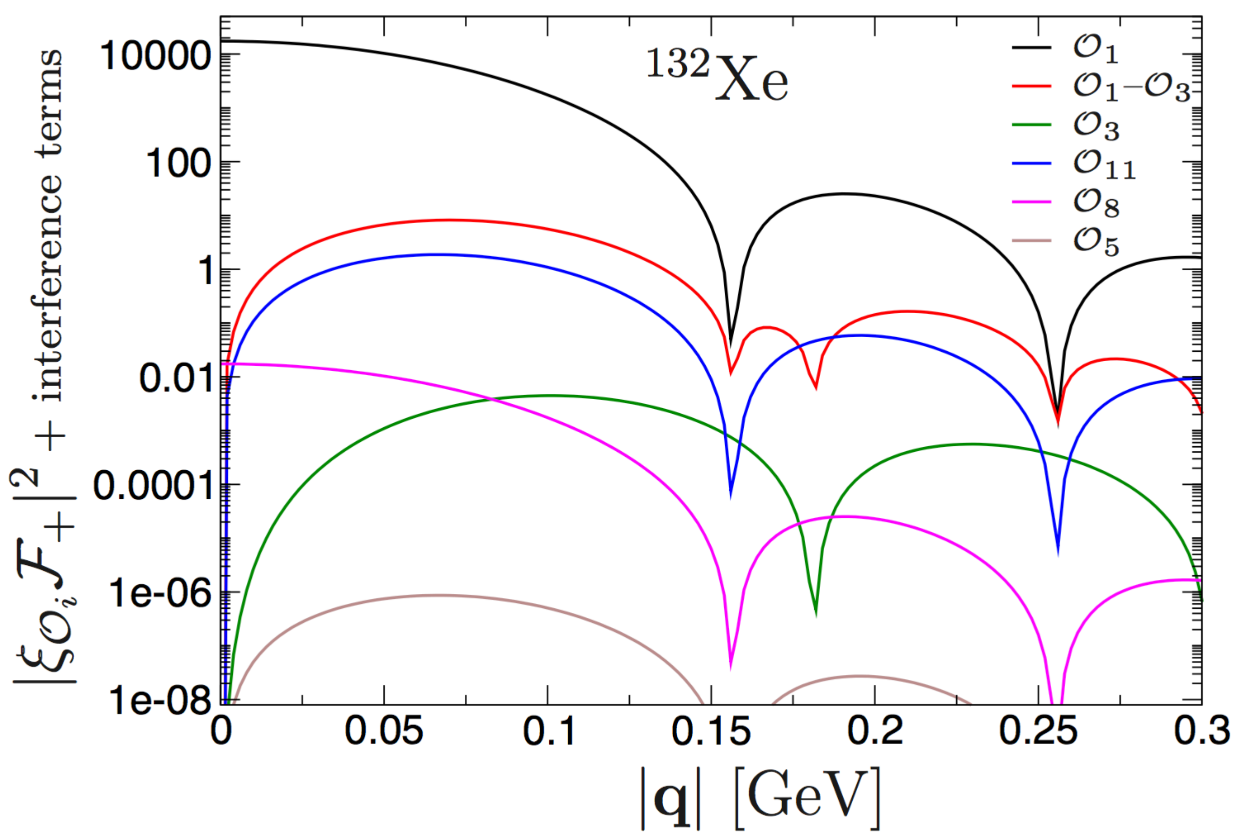
$$\mathcal{O}_{10} = i\mathbf{S}_N \cdot \mathbf{q}, \quad \mathcal{O}_{11} = i\mathbf{S}_\chi \cdot \mathbf{q},$$



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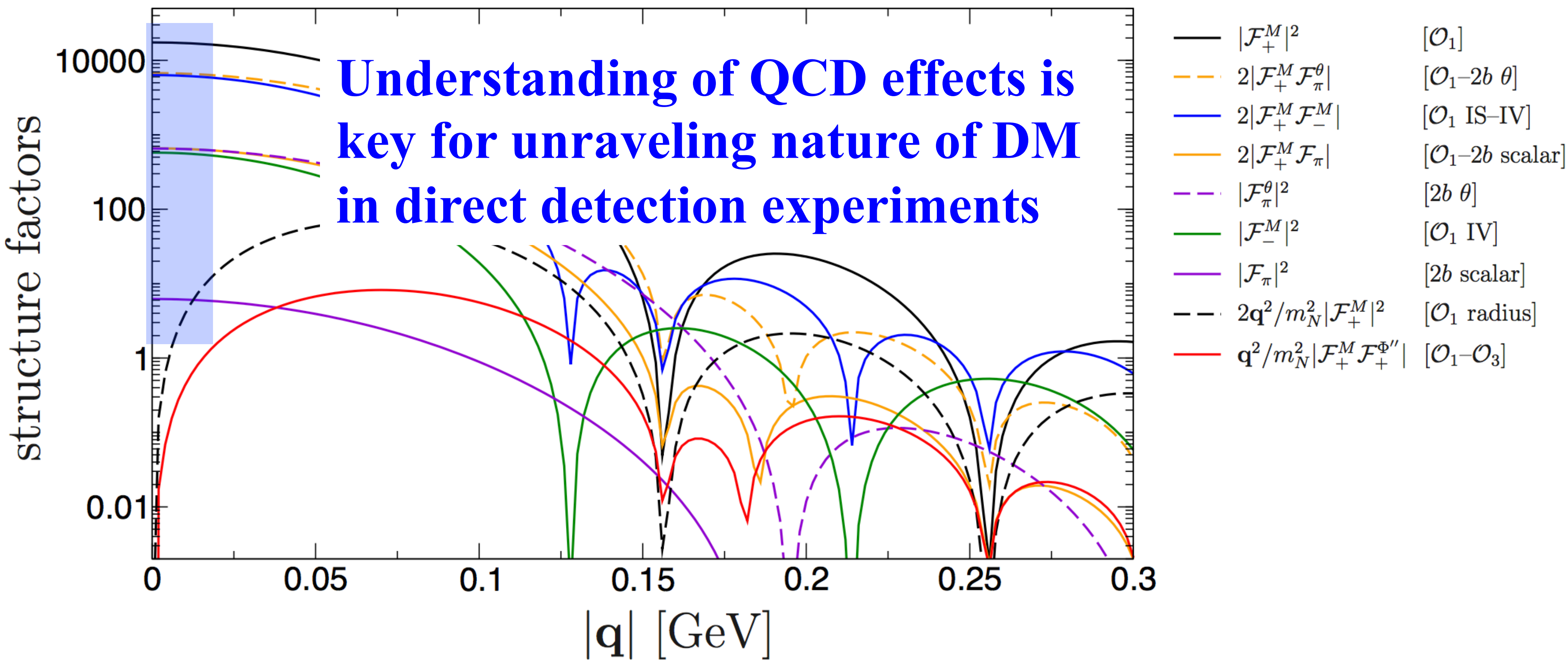

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Summary

Thanks to (chiral EFT for nuclei): **J. Simonis**, **R. Stroberg**, K. Hebeler, H. Hergert, J.D. Holt, S. Bogner, G. Hagen, T. Papenbrock,...
(... for WIMP interactions): **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