Neutrinoless double-beta decay and nuclear theory

Achim Schwenk

TECHNISCHE UNIVERSITÄT DARMSTADT

EMMI

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DFG SFB 1245 erc HELMHOLTZ ASSOCIATION Bundesministerium für Bildung und Forschung

Outline

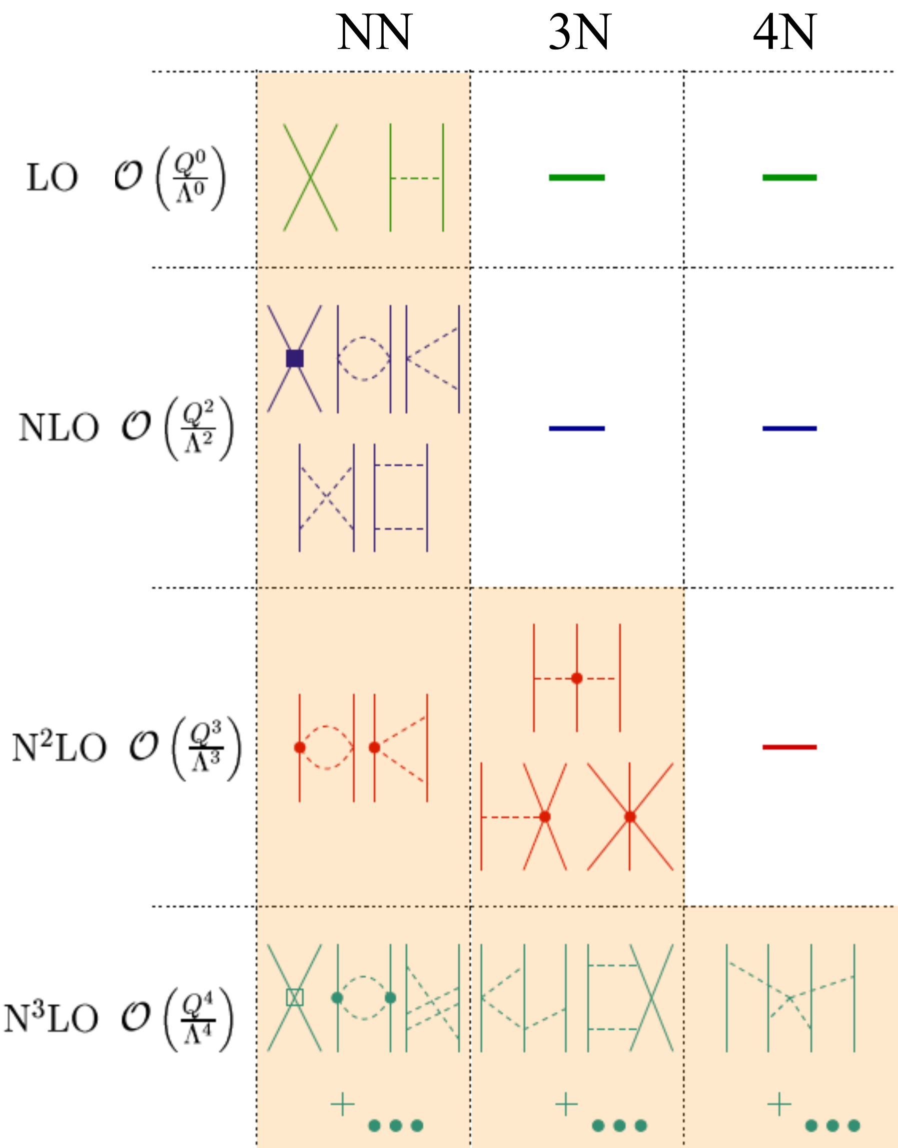
Advances in nuclear forces and nuclear structure

Progress in nuclear matrix elements for
neutrinoless double beta decay

Perspectives

Chiral effective field theory for nuclear forces

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



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

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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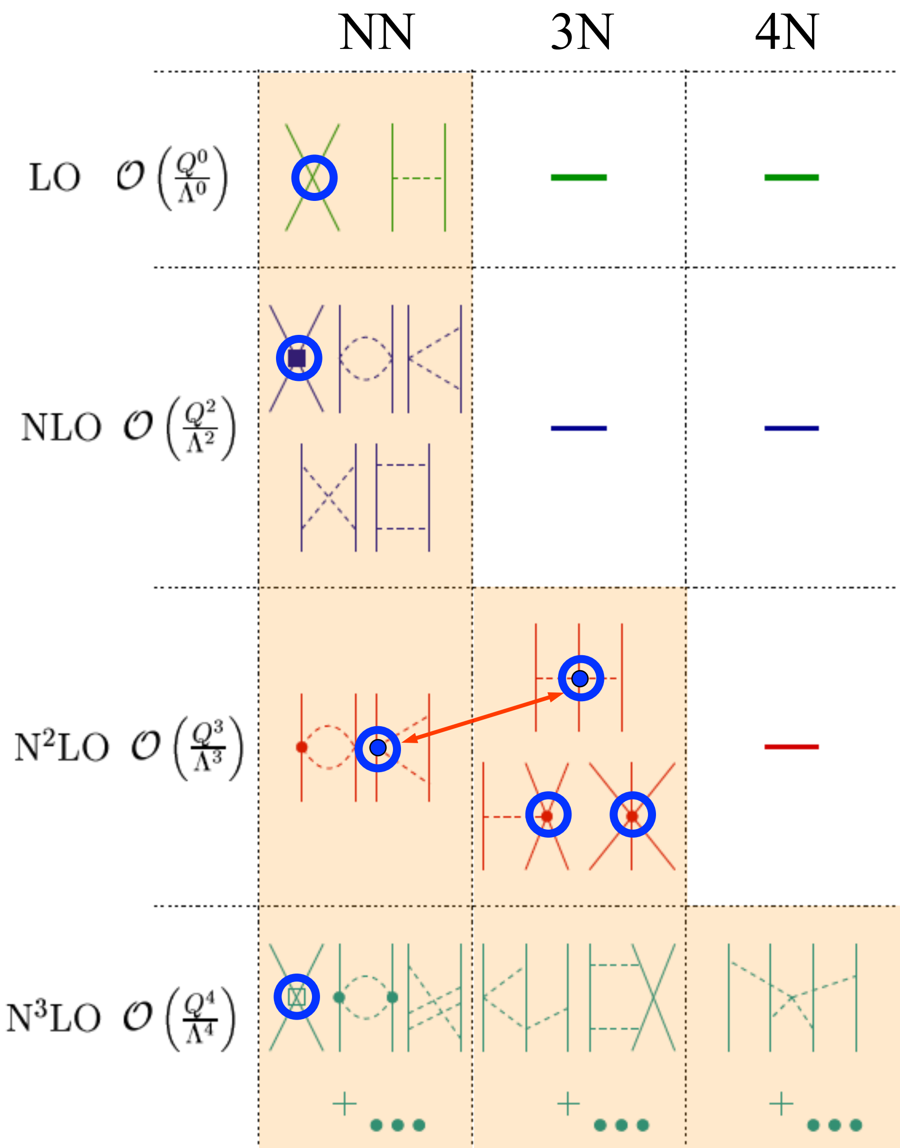

include long-range pion physics

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**

new developments in power counting, uncertainty quantification, optimization,… Ektröm et al., Furnstahl et al.

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

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

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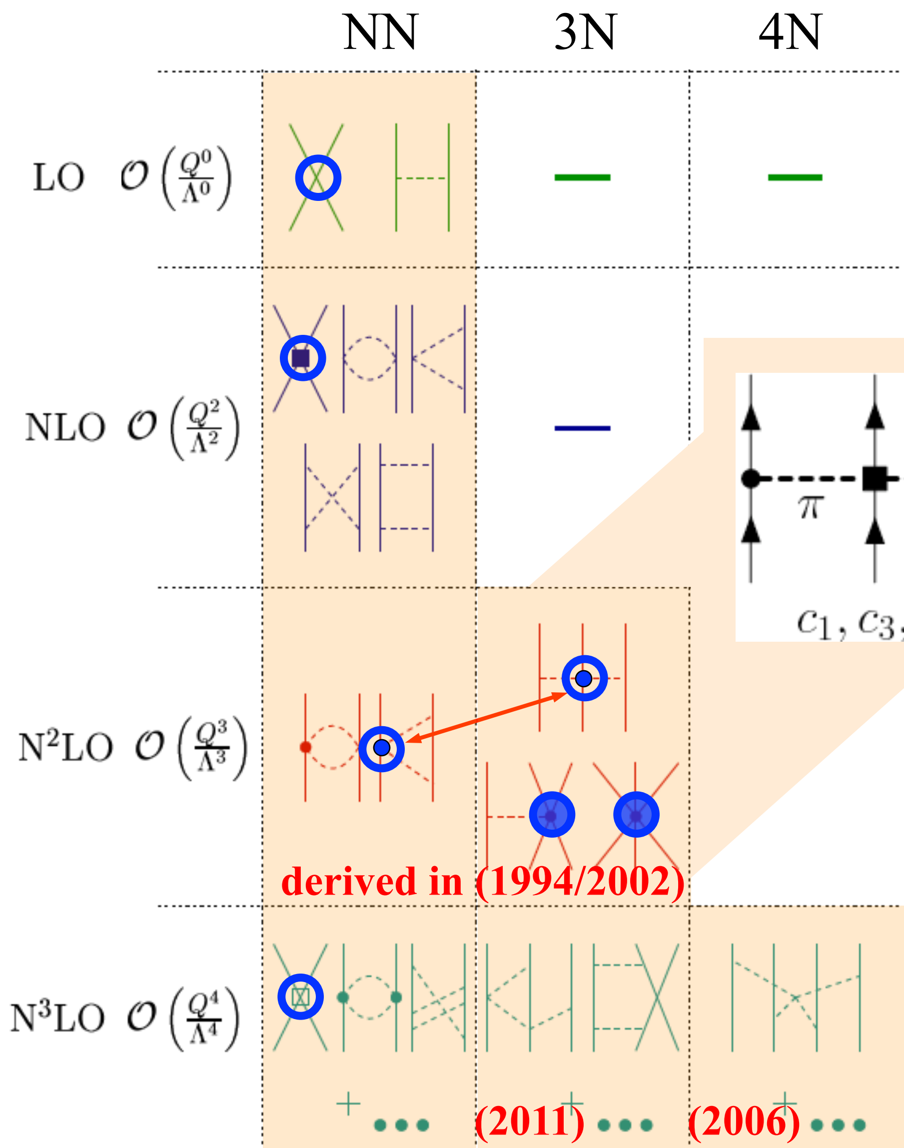
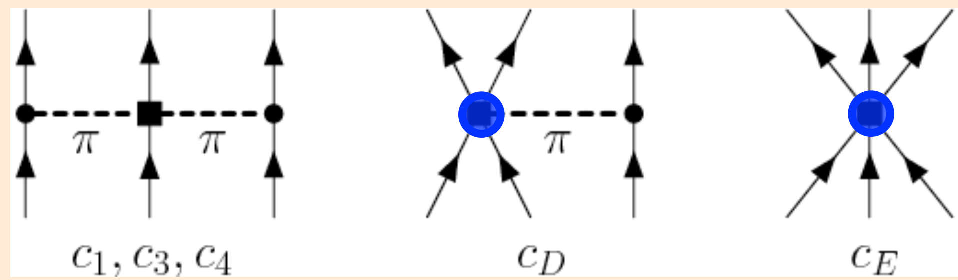


consistent NN-3N-4N interactions

3N,4N: **2 new couplings to N^{3}LO**

+ no new couplings for neutrons



c_i from πN and NN

c_D, c_E fit to light nuclei only

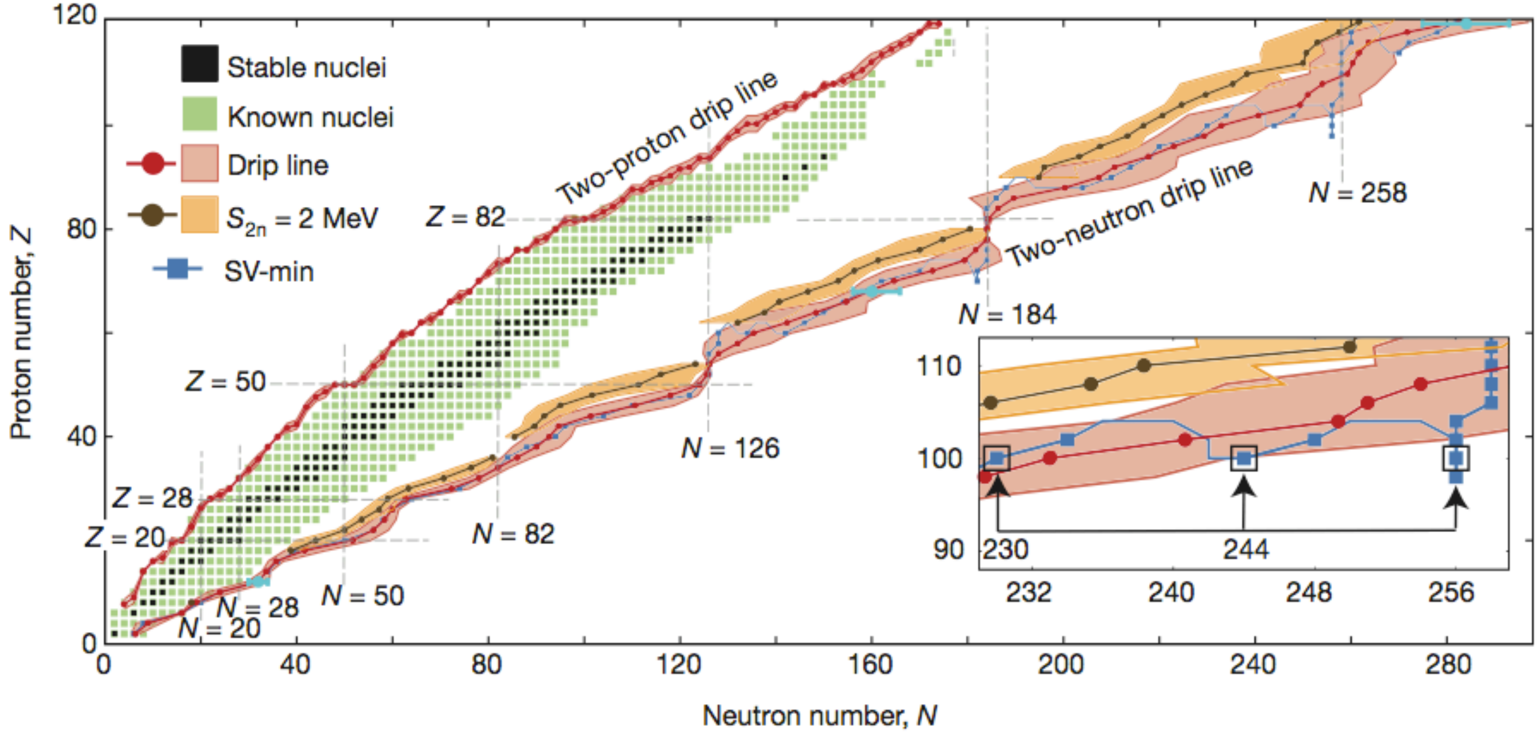
Weinberg, van Kolck, Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Machleidt, Meissner,…

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]‡

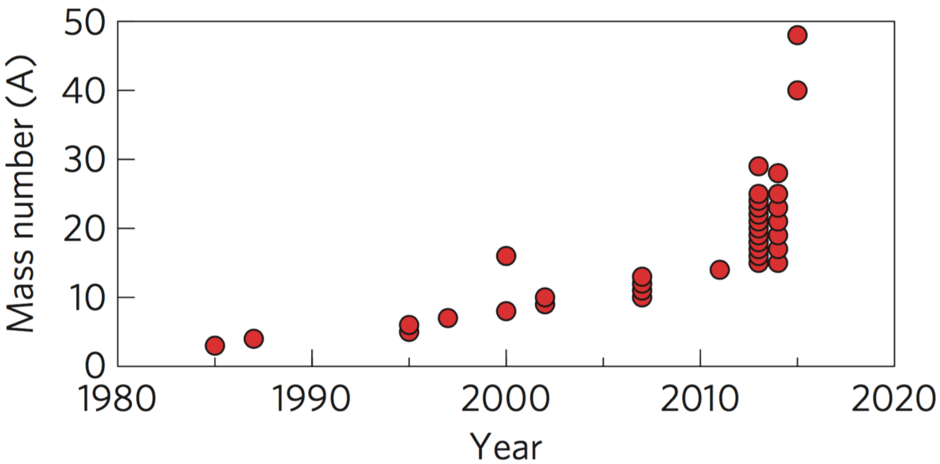


How does the nuclear chart emerge from quantum chromodynamics?

Lattice QCD and **effective field theories of QCD**

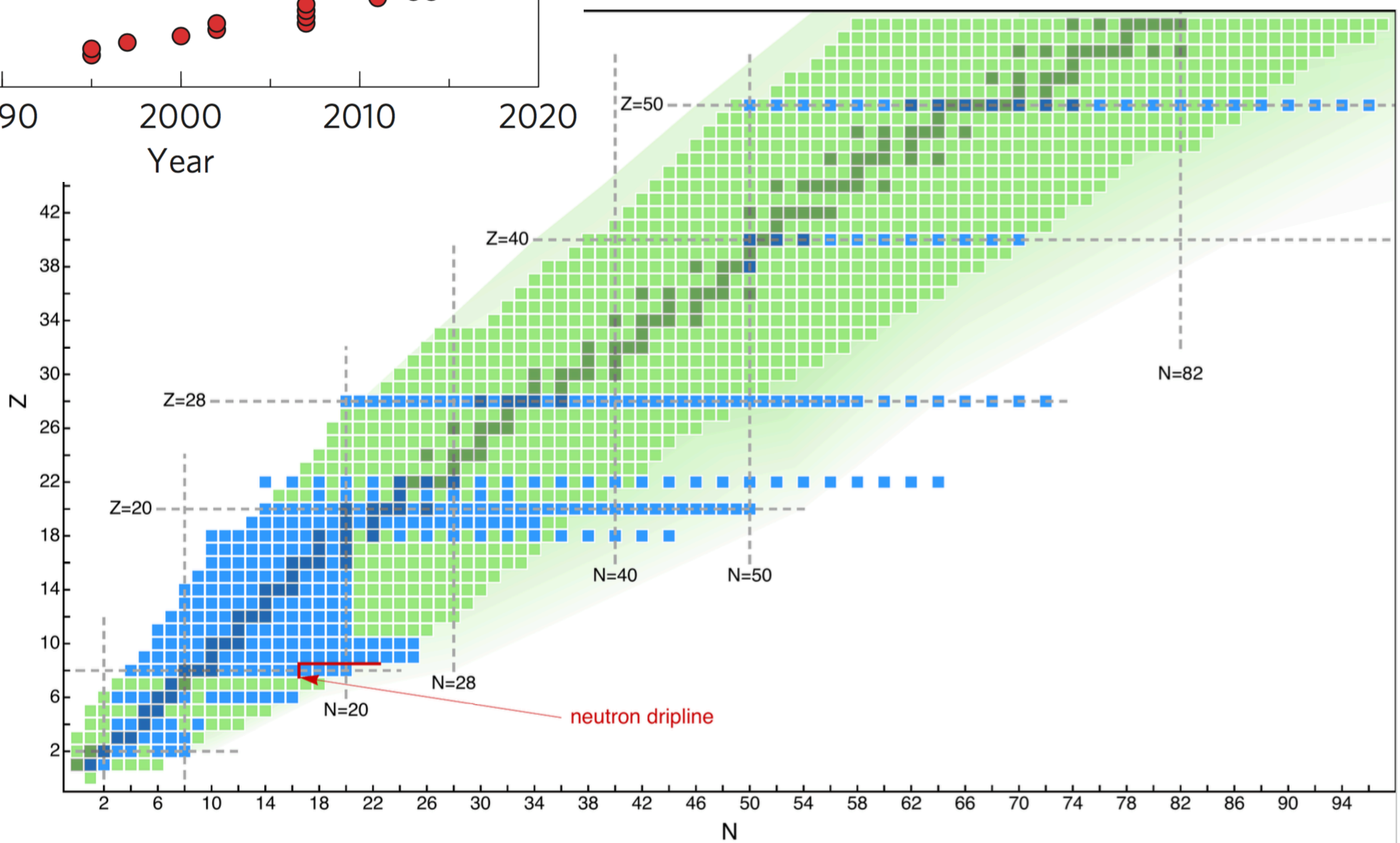
Progress in ab initio calculations of nuclei

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



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

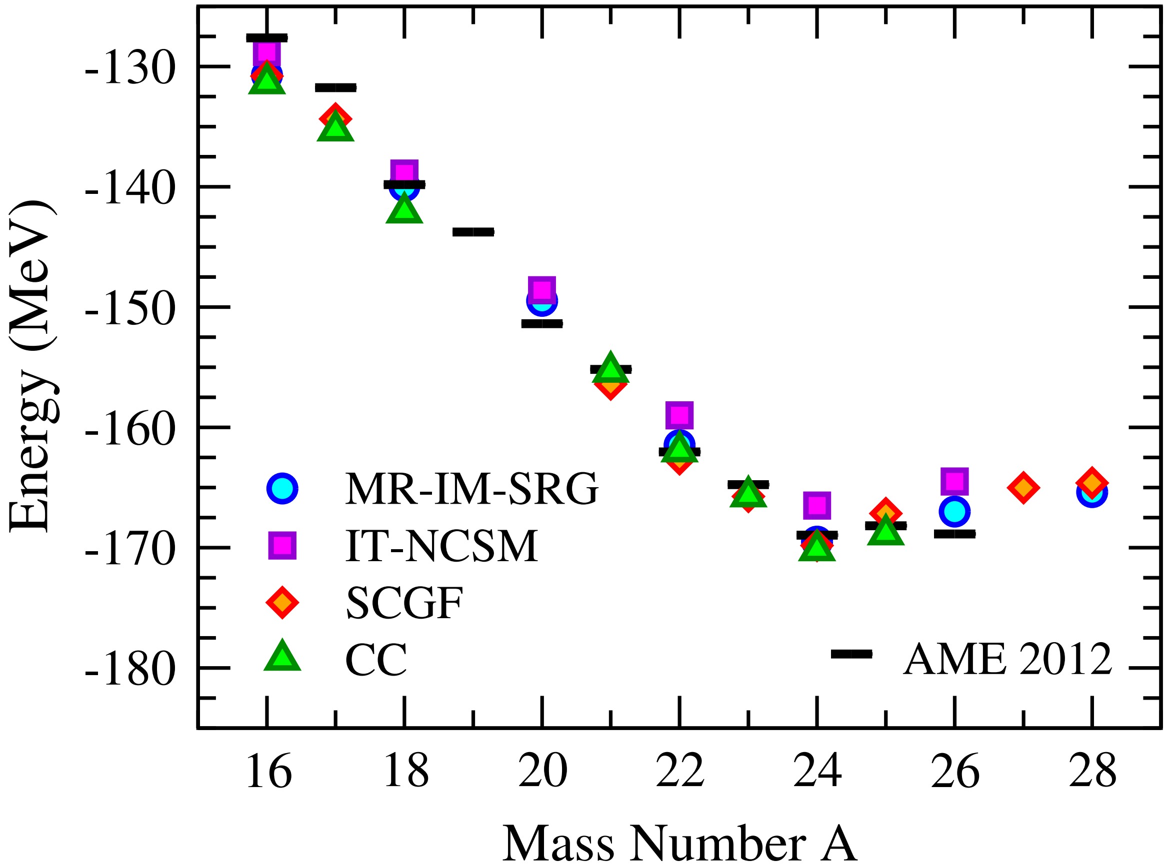
from Hergert et al., Phys. Rep. (2016)



Ab initio calculations of neutron-rich oxygen isotopes

impact of **3N forces key for neutron dripline** Otsuka et al., PRL (2010)

based on same NN+3N interactions



using different many-body methods:

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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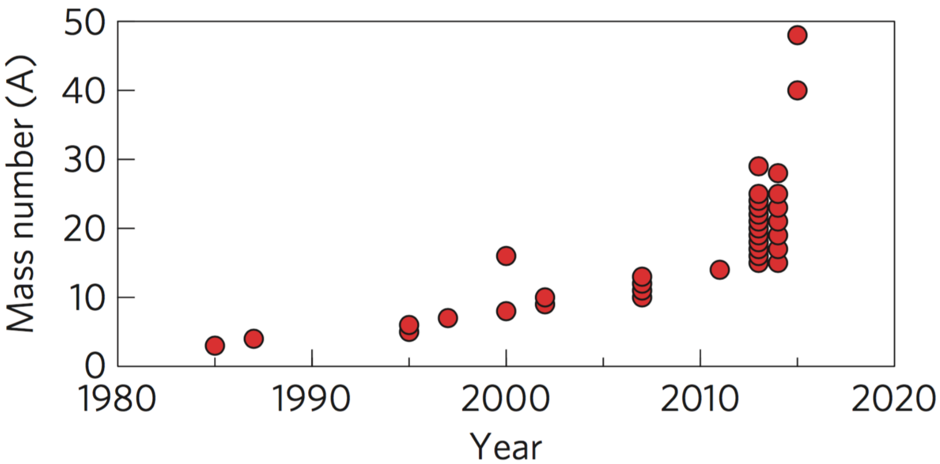

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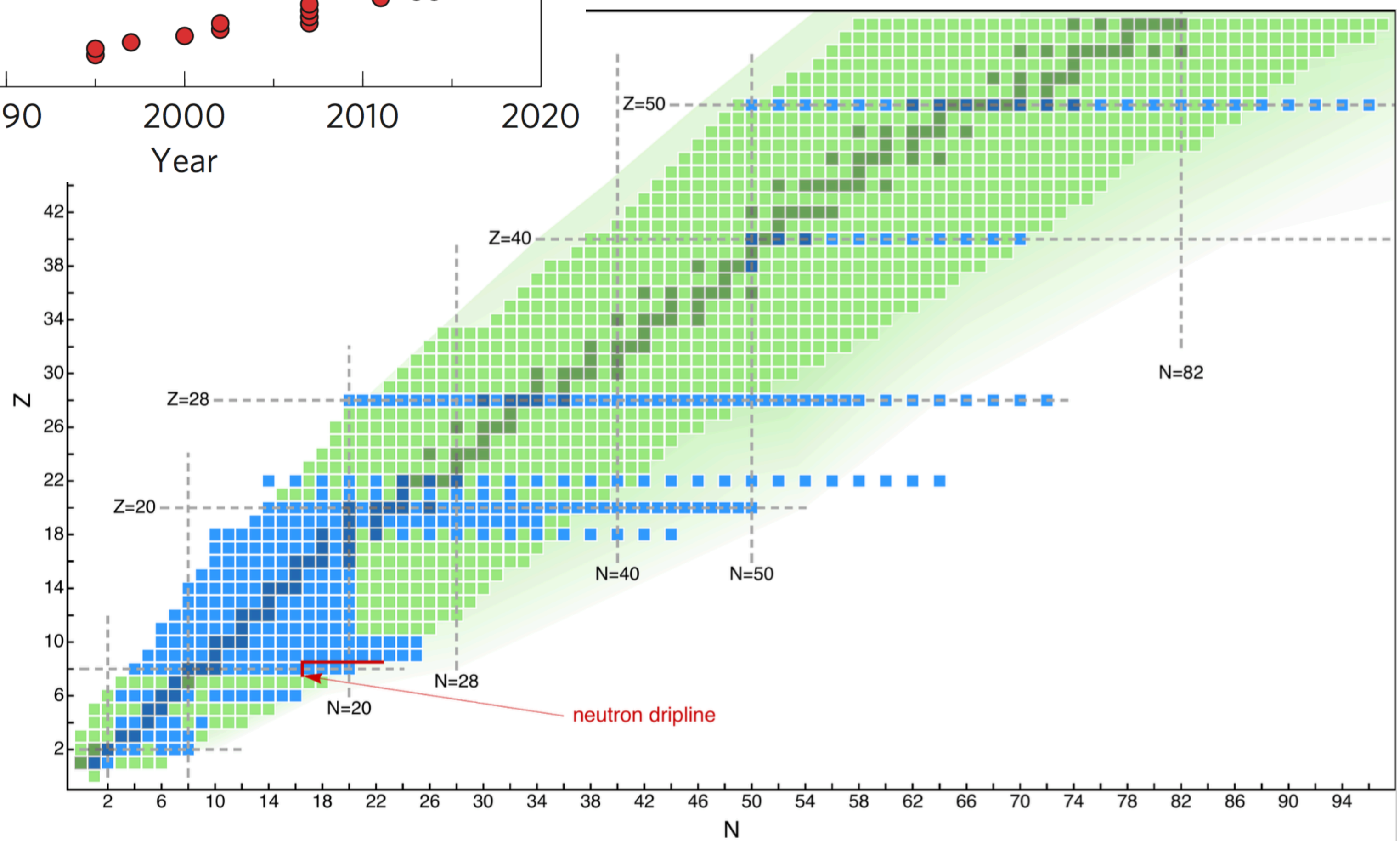
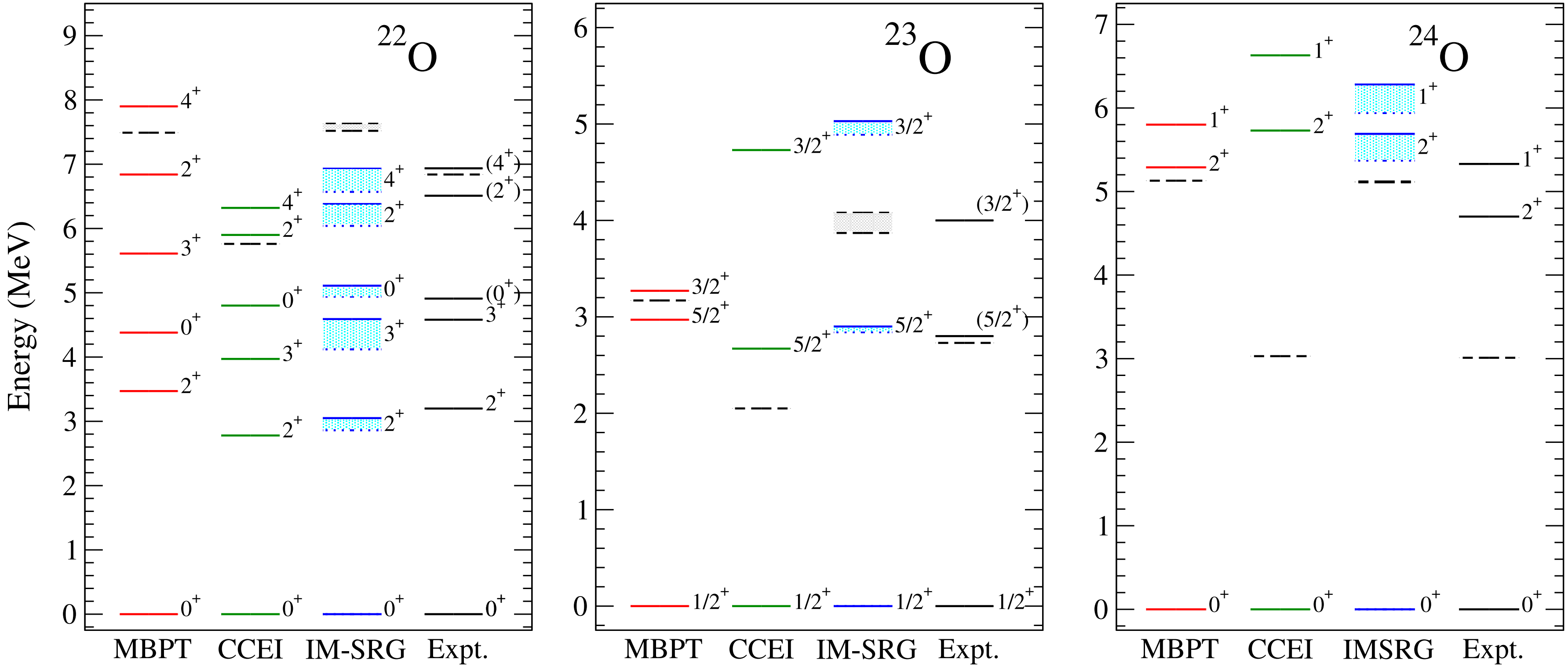


Ab initio calculations going open shell

In-Medium SRG to derive nonperturbative shell-model interactions

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

Coupled Cluster for effective interactions (CCEI) Jansen et al., PRL (2014)



Experiments at GANIL, GSI, NSCL, RIBF: ^{22}O and ^{24}O doubly magic

Ab initio calculations going open shell

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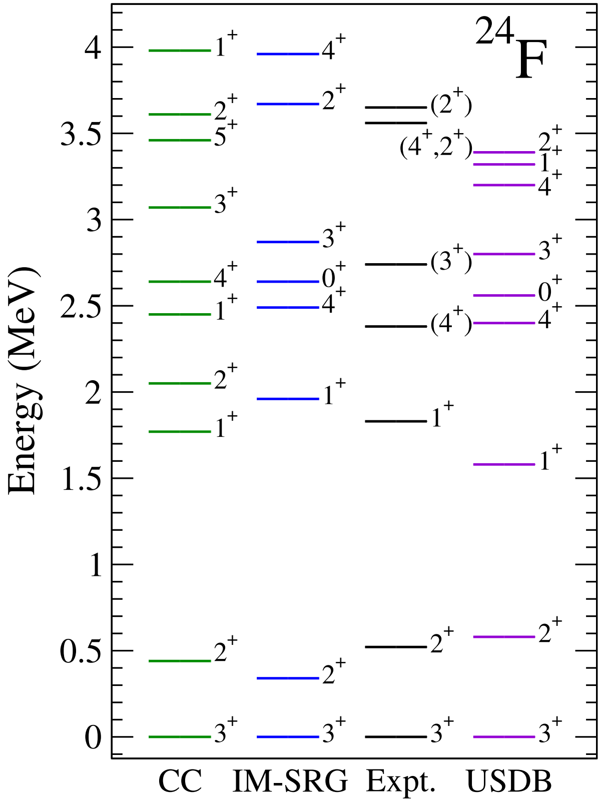
Spectrum of ^{24}F Cáceres et al., PRC (2015)

vs. new GANIL experiment



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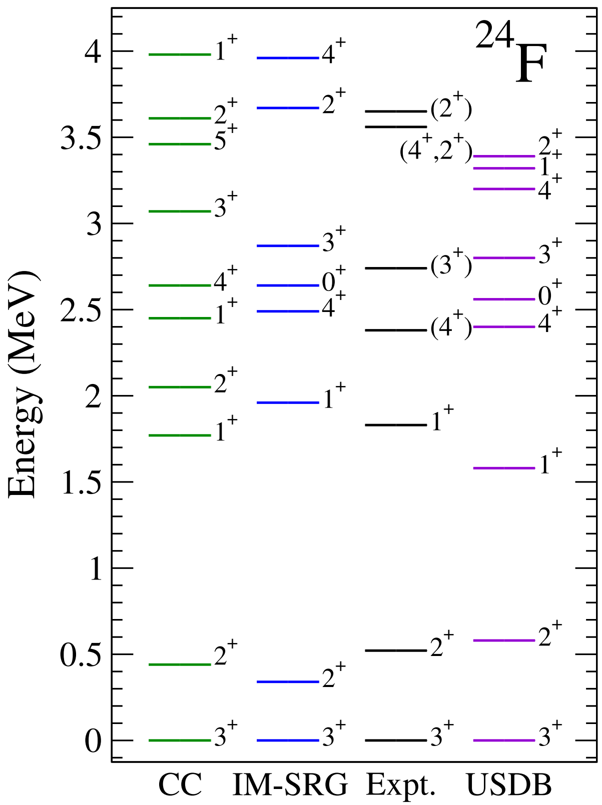
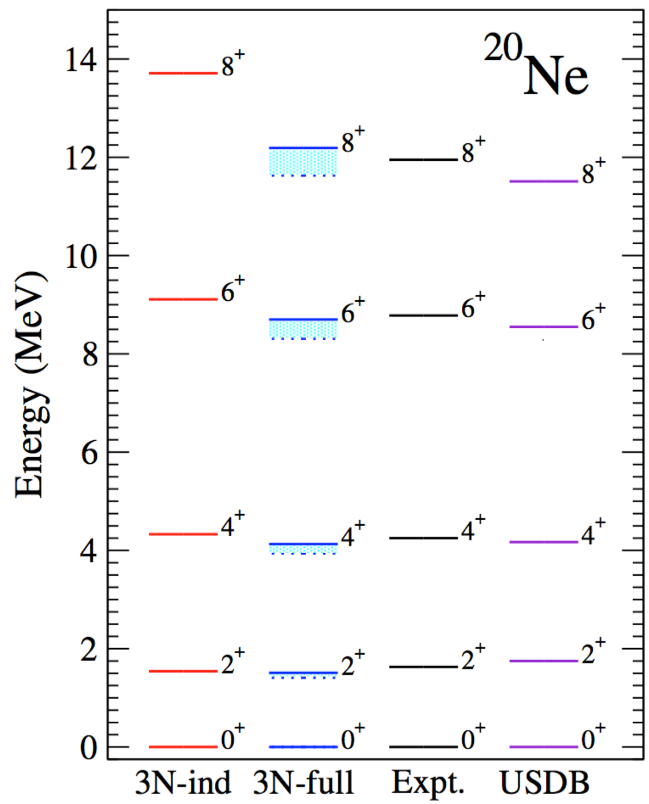
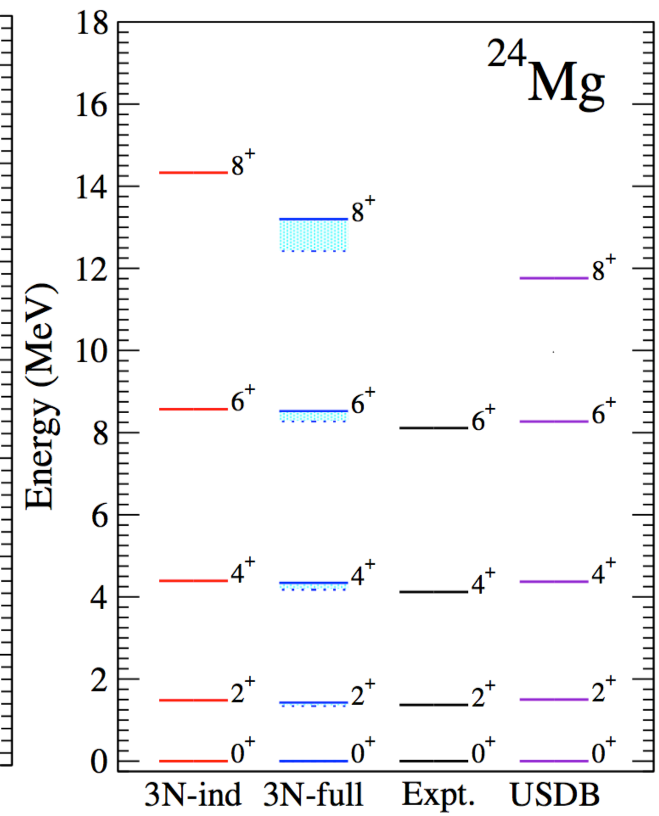
Spectrum of ^{24}F Cáceres et al., PRC (2015)
vs. new GANIL experiment

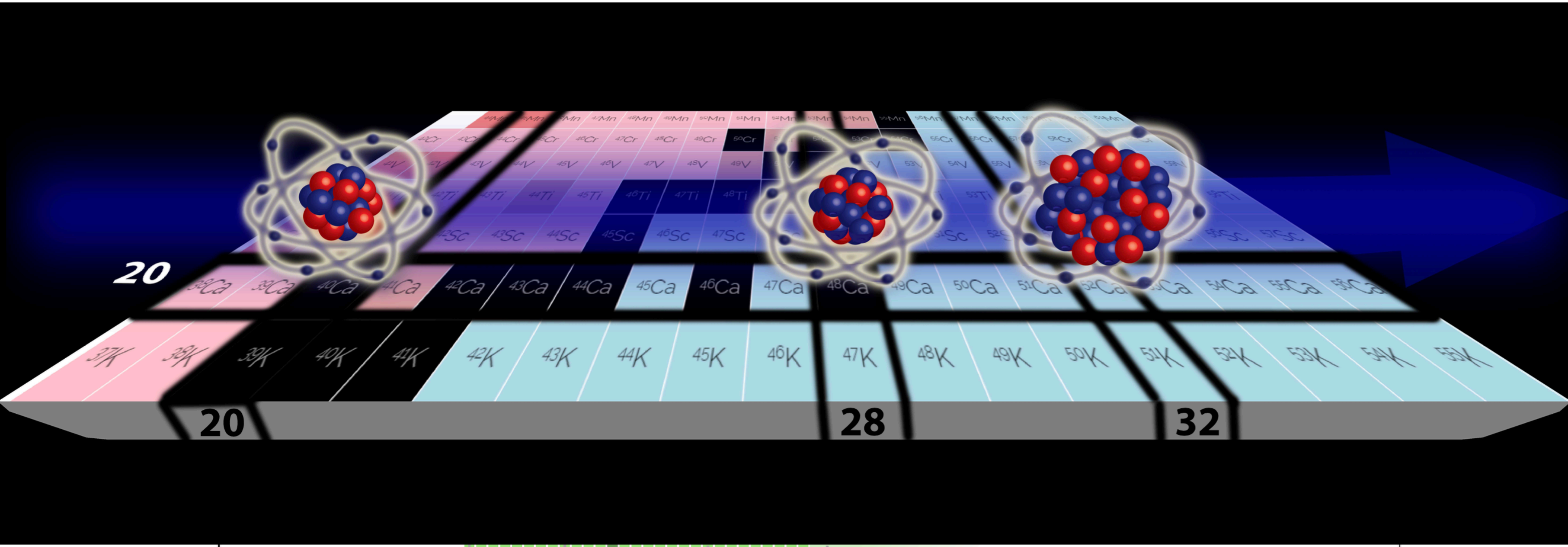
Deformed nuclei Stroberg et al., 1511.02802
CCEI Jansen et al., arXiv: 1511.00757

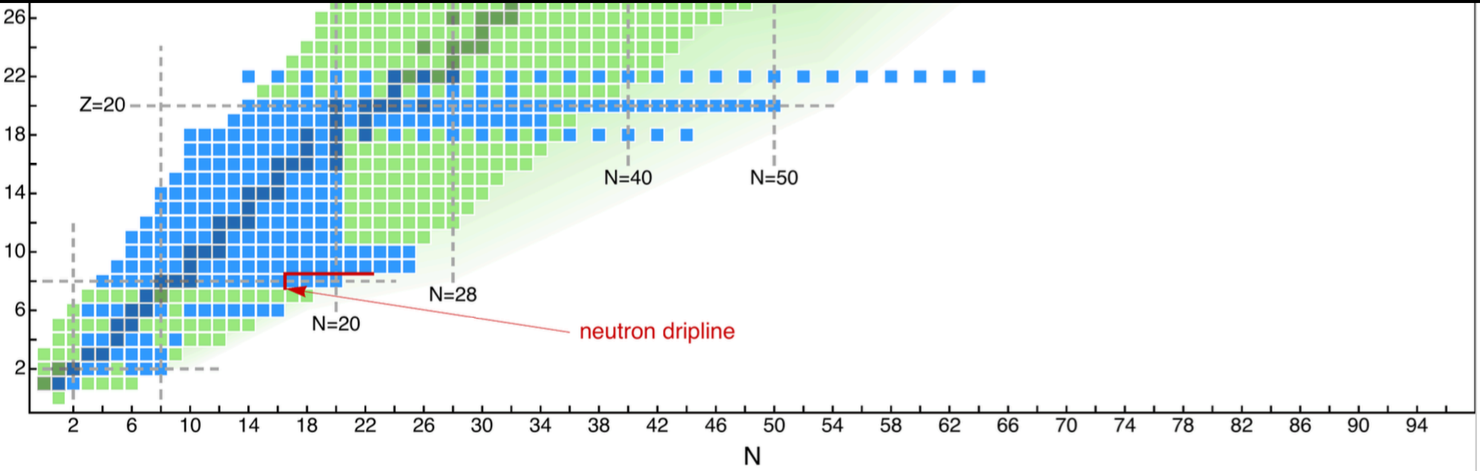






Neutron-rich calcium isotopes





Frontier of ab initio calculations at A~50

doi:10.1038/nature12226

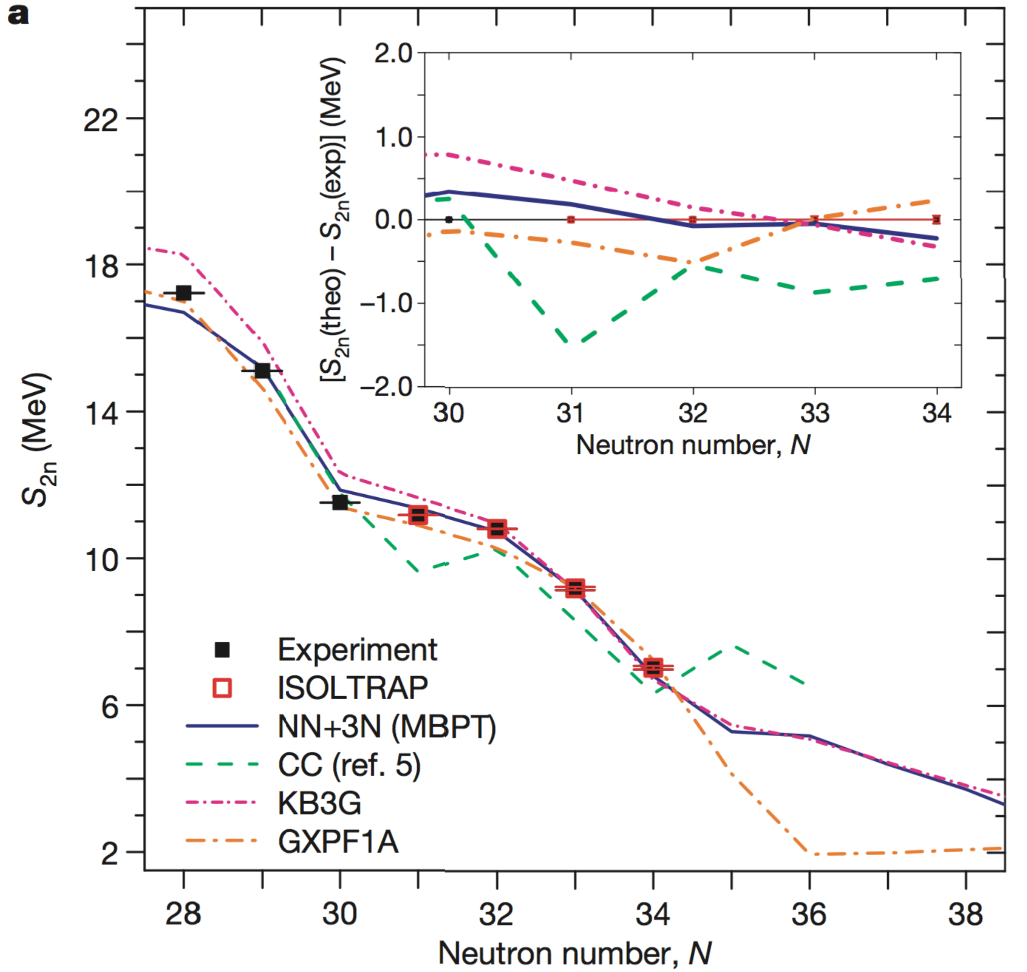
Masses of exotic calcium isotopes pin down nuclear forces

F. Wienholtz[1], D. Beck[2], K. Blaum[3], Ch. Borgmann[3], M. Breitenfeldt[4], R. B. Cakirli[3,5], S. George[1], F. Herfurth[2], J. D. Holt[6,7], M. Kowalska[8], S. Kreim[3,8], D. Lunney[9], V. Manea[9], J. Menéndez[6,7], D. Neidherr[2], M. Rosenbusch[1], L. Schweikhard[1], A. Schwenk[7,6], J. Simonis[6,7], J. Stanja[10], R. N. Wolf[1] & K. Zuber[10]

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

excellent agreement with theoretical NN+3N prediction

suggests N=32 shell closure



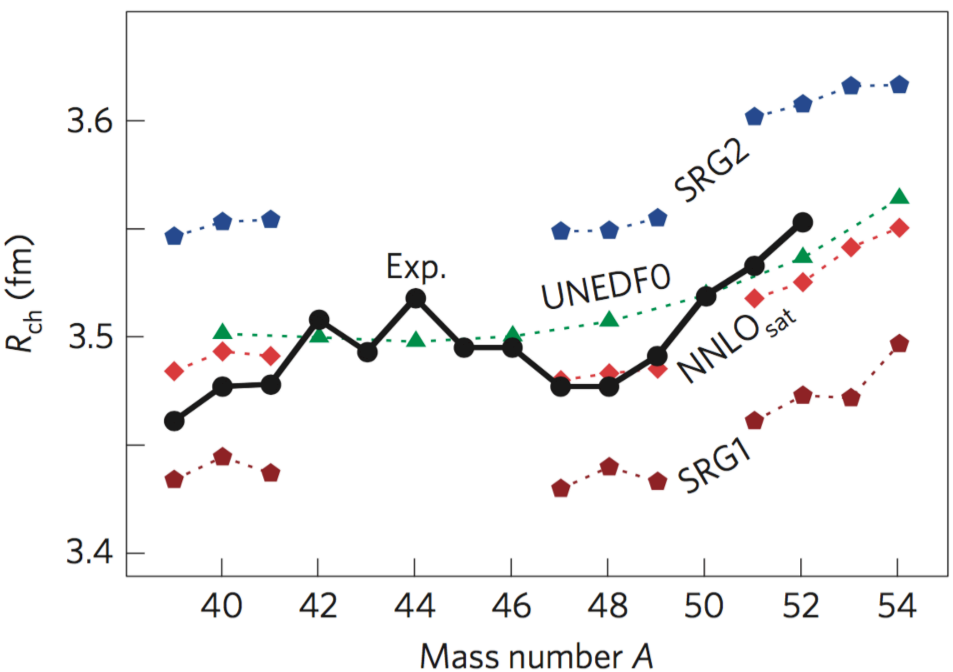
nature physics

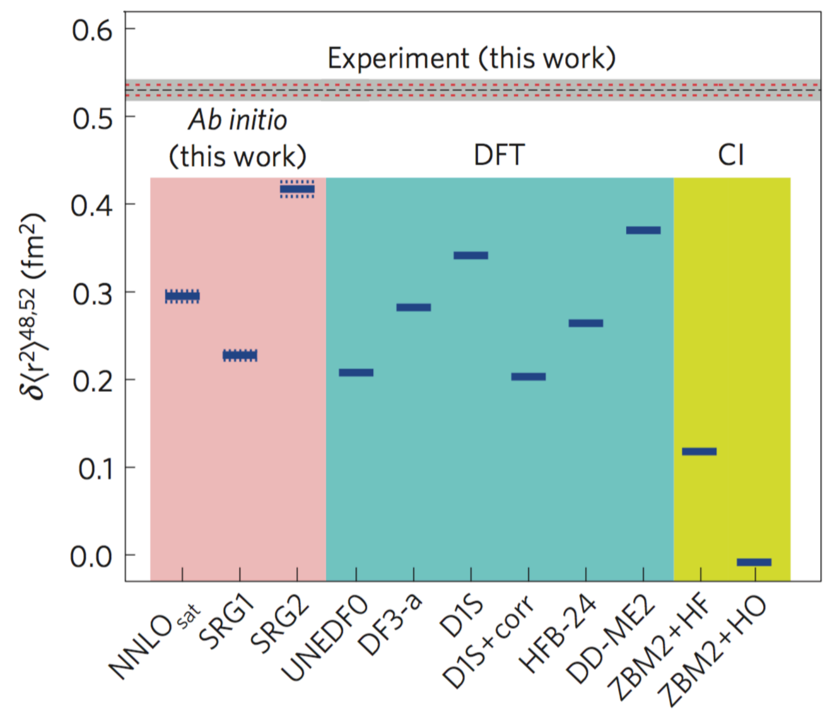
ARTICLES

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]





Neutron skin of ^{48}Ca

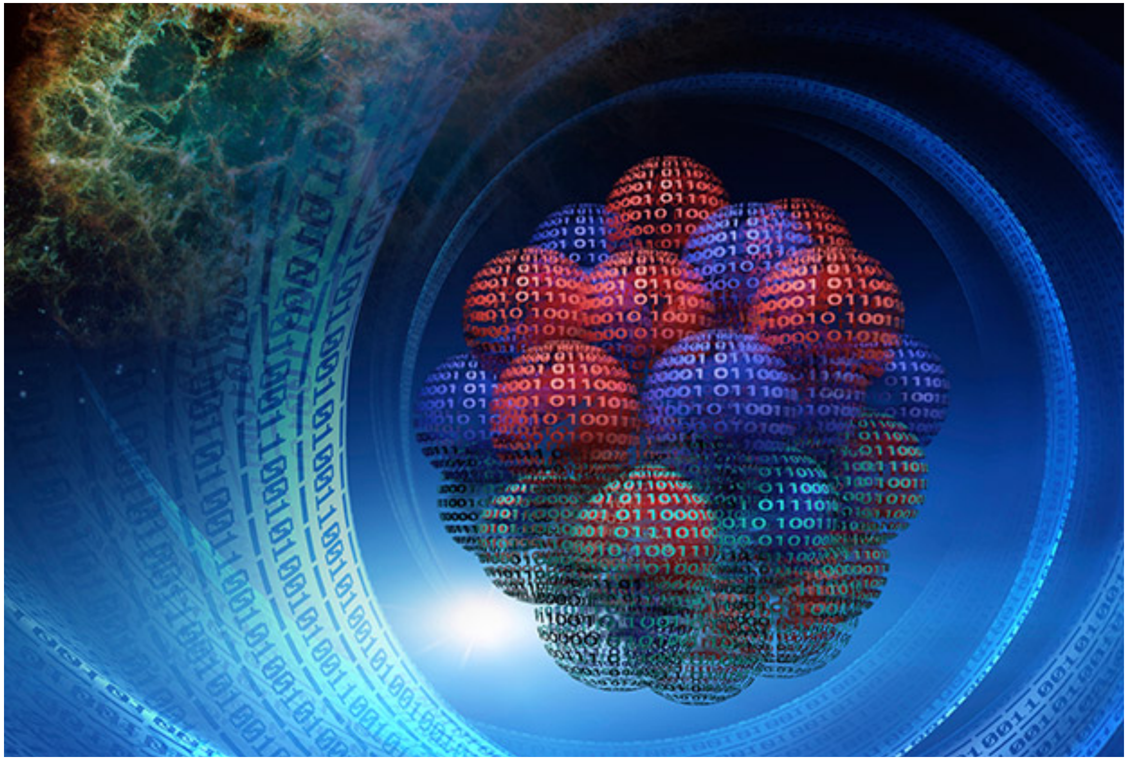
nature physics

ARTICLES

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

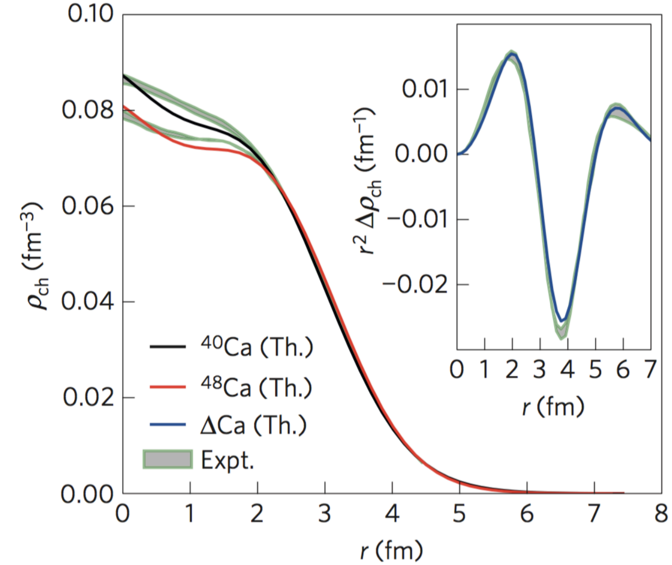
Neutron and weak-charge distributions of the ^{48}Ca nucleus

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]

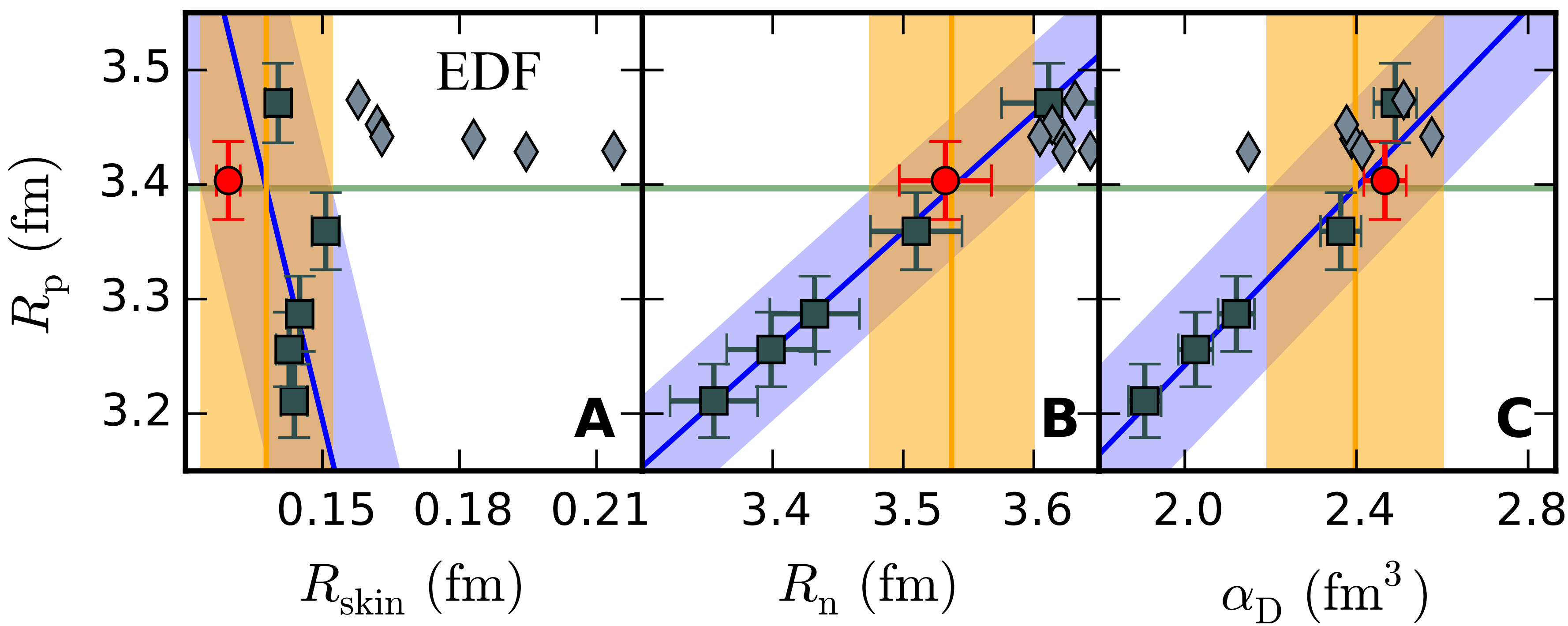


Neutron and weak-charge distributions of ^{48}Ca

ab initio calculations lead to charge distributions consistent with experiment



predict small neutron skin, dipole polarizability, and weak formfactor



Outline

Advances in nuclear forces and nuclear structure

- opens up ab initio calculations of $0\nu\beta\beta$ nuclei
- theoretical uncertainties from chiral EFT

Progress in nuclear matrix elements for neutrinoless double beta decay

Perspectives

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Advances in nuclear forces and nuclear structure

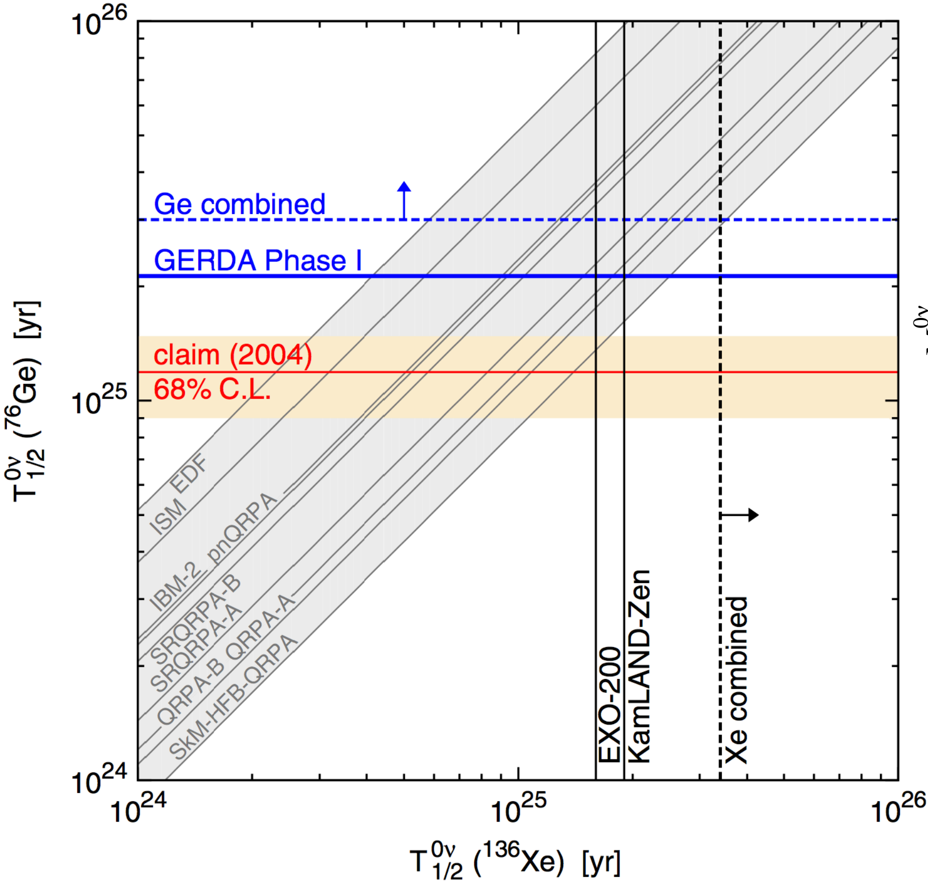
Progress in nuclear matrix elements for neutrinoless double beta decay

- state-of-the-art calculations (shell model)
  based on NN interactions + corrections
  to compensate for not including 3N forces
- calculation of $0\nu\beta\beta$ operator in chiral EFT

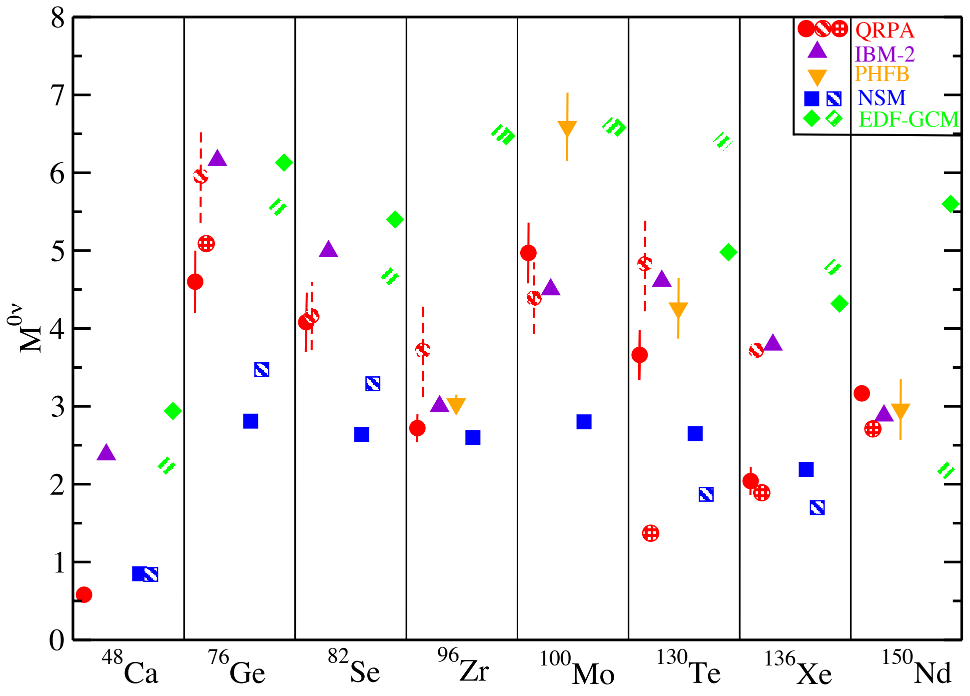
Perspectives

Range of nuclear matrix elements

different NME calculations result in large spread



GERDA Collaboration (2013)



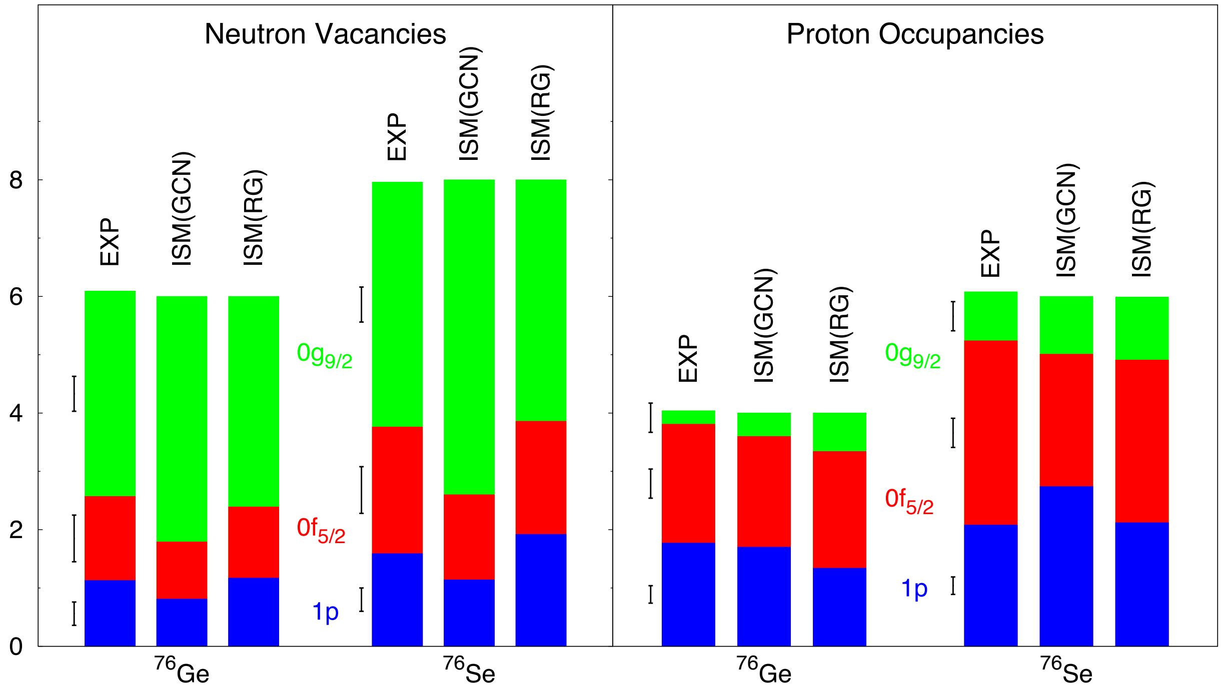
EMMI-RRTF (2014)

Can we understand the differences in nuclear structure?

Nuclear structure of 0νββ nuclei

shell model calculations: valence spaces and interactions successfully tested with experiment (spectra, occupancies)! largest spaces used

Experimental occupancies are well described!



Calculations using state-of-the-art ISM interactions and valence spaces (NATHAN code)

$M^{0\nu\beta\beta} =$
2.81 (GCN)
3.26 (RG)

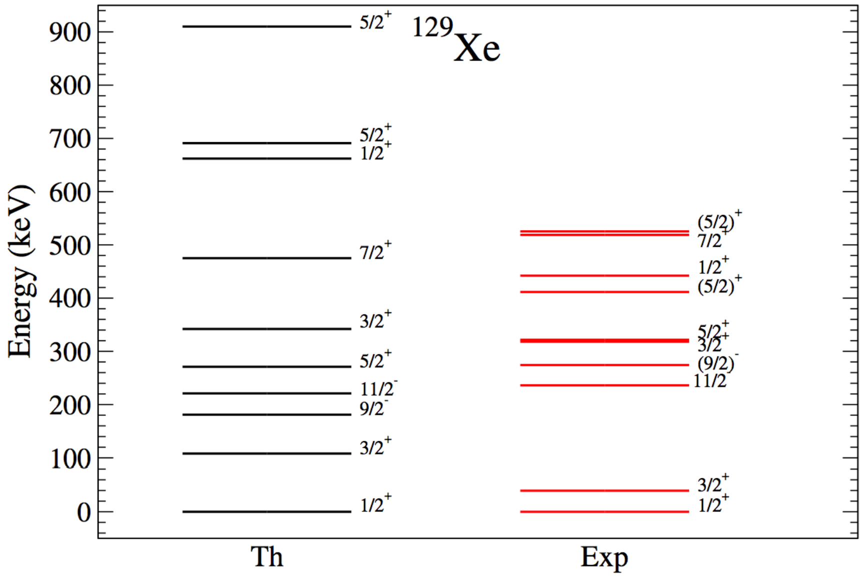
Experiment: Schiffer et al. PRL100 112501(2009), Kay et al. PRC79 021301(2009)
Theory: JM, Caurier, Nowacki, Poves PRC80 048501 (2009)

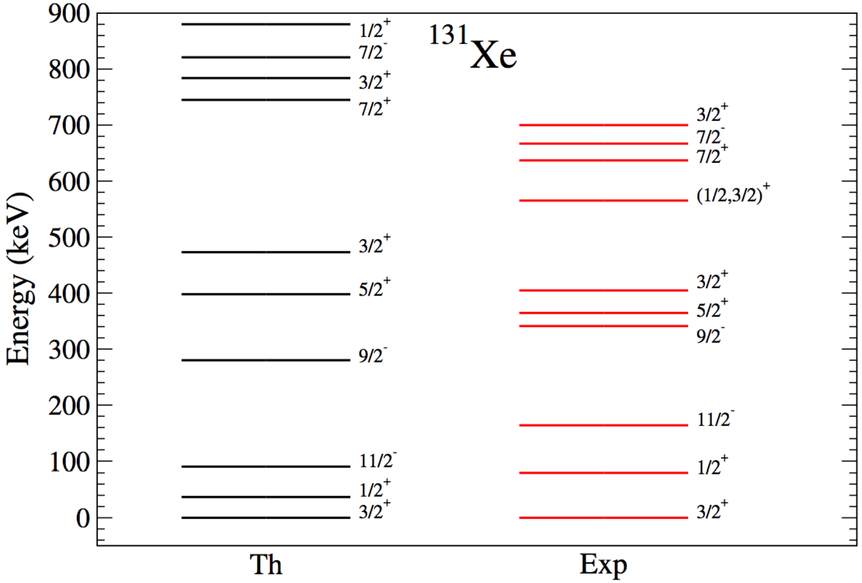
Other methods do not demonstrate that structure is well reproduced

An example from WIMP-nucleus scattering

shell model calculation based on the same interactions as for $0\nu\beta\beta$

very good agreement for spectra, ordering and grouping well reproduced





Menendez, Gazit, AS (2012)

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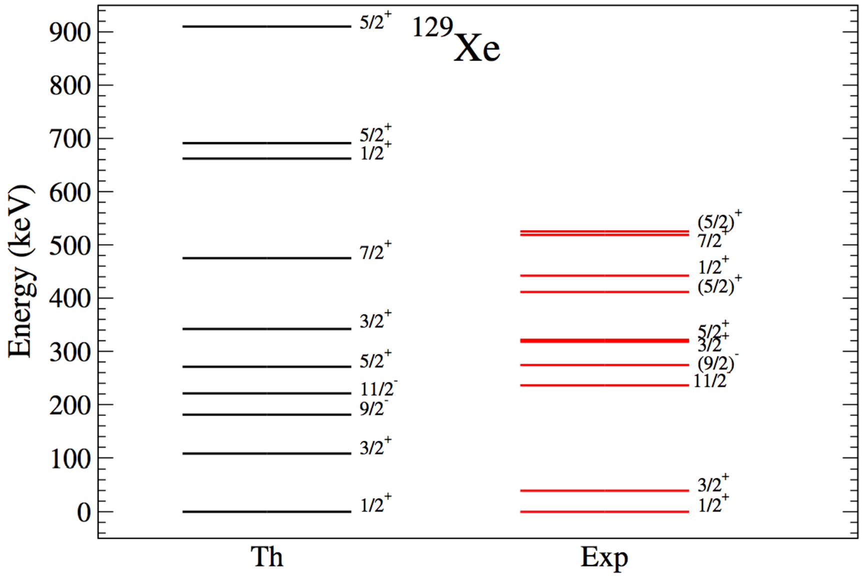

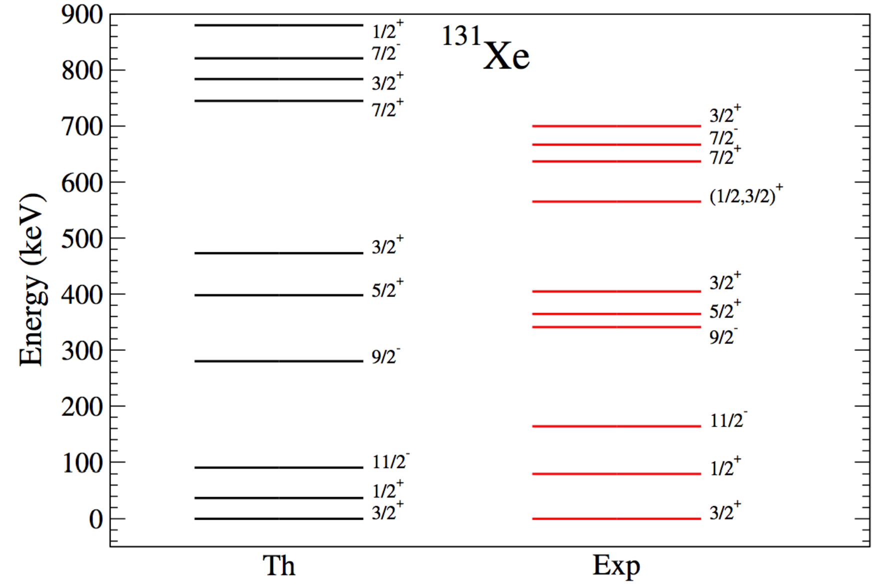

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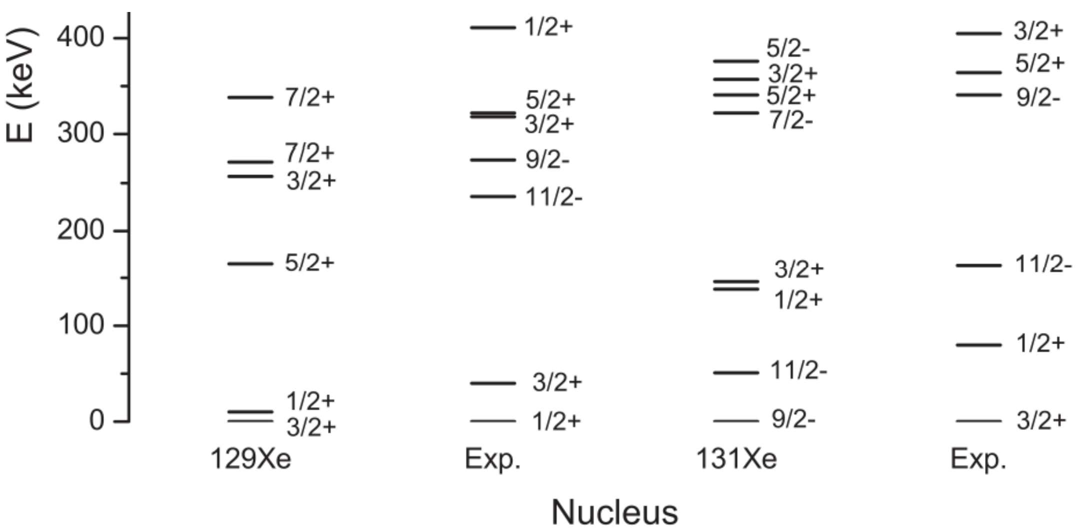
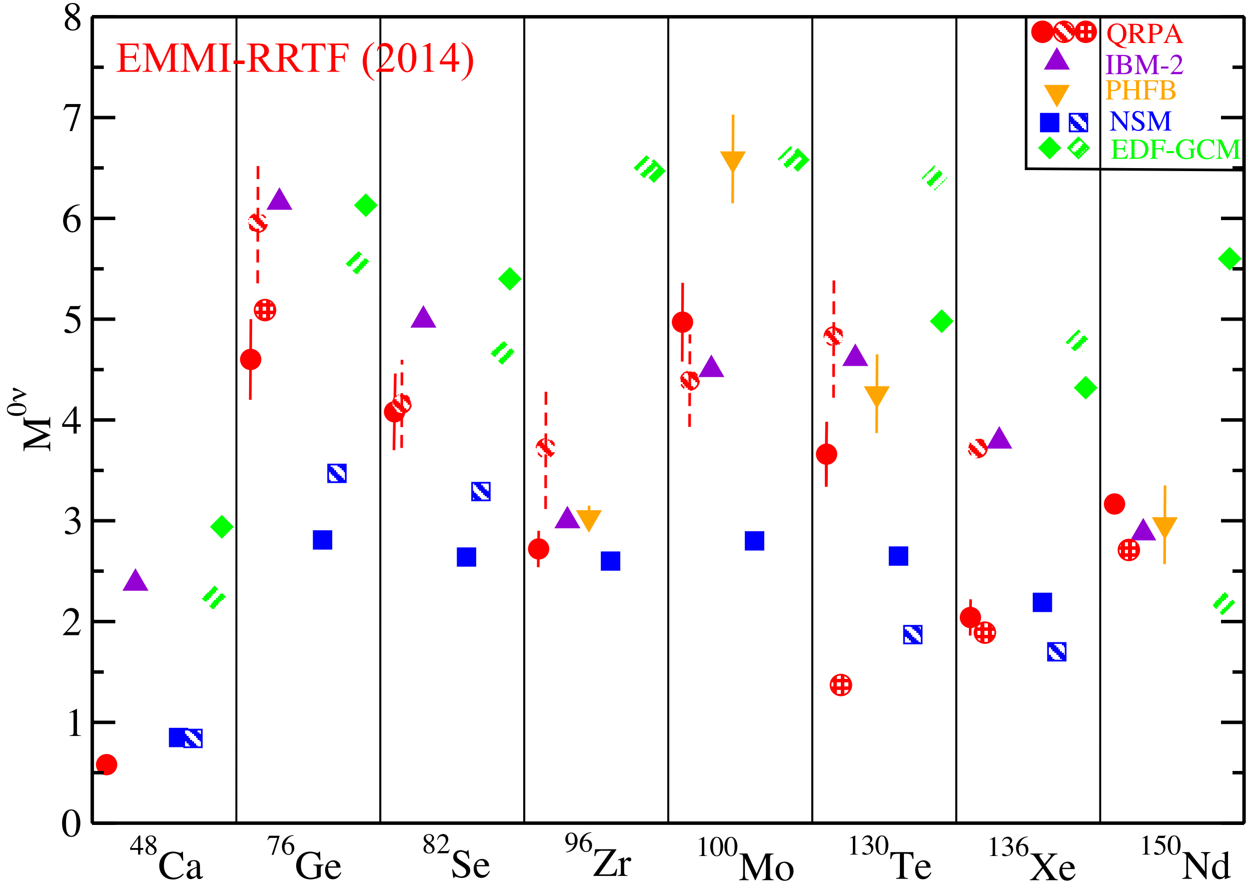


Previous “state-of-the-art” calculation… Toivanen et al. (2009)

Differences of nuclear matrix elements

NME differ by factor ~ 2 in Ge (range is not good measure of theo. uncertainty)



QRPA:
Fang et al., PRC (2010, 2011)
Kortelainen, Suhonen, PRC (2007)
Mustonen, Engel, PRC (2013)

IBM: Barea et al., PRC (2013)

PHFB: Rath et al., PRC (2013)

NSM:
Menéndez et al., NPA (2008), JPCS (2011)
Neascu, Horoi, PRC (2015)

EDF-GCM:
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Yao et al., PRC (2014)

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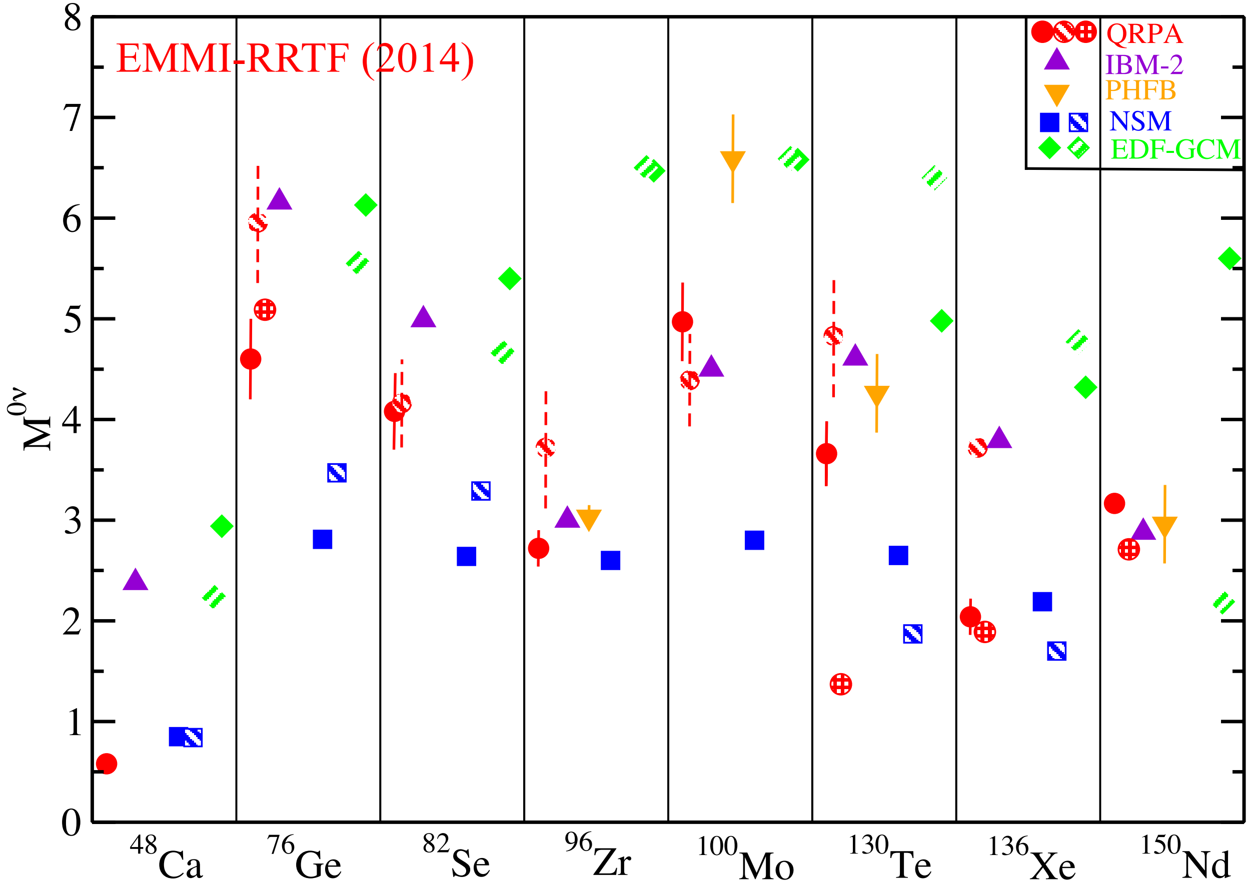

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Yao et al., PRC (2014)

largest difference: shell model (NSM) smaller than "mean-field results"
QRPA, PHFB, EDF-GCM

Can we trace this to missing correlations?

Pairing part of nuclear interactions

T=1, J=0 interactions included in all calculations,
T=0, J=1 channel only in shell model

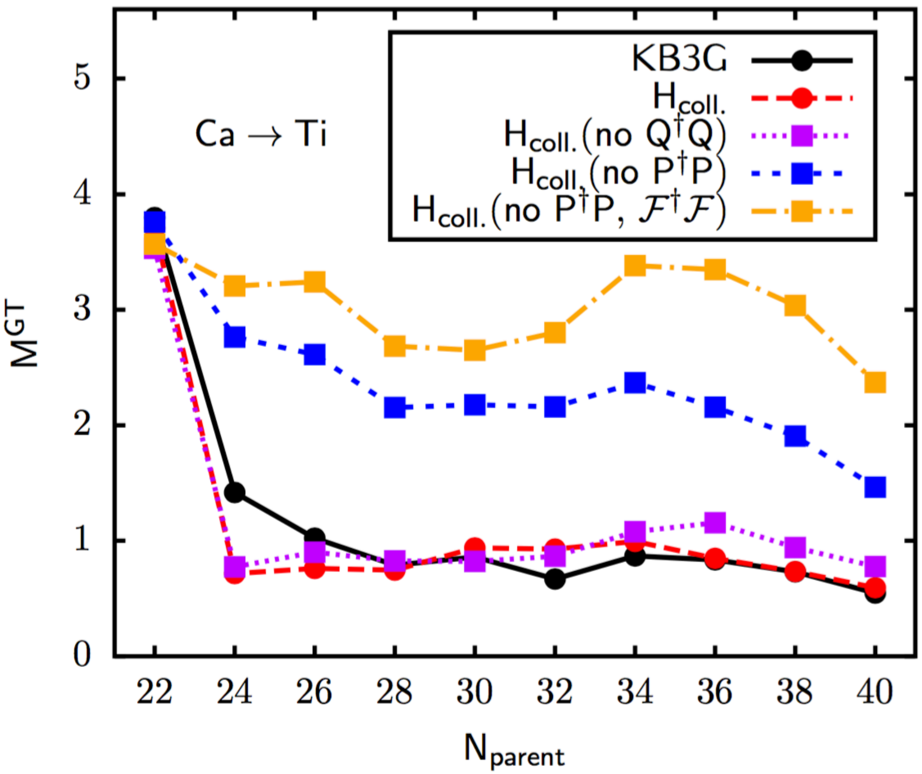
What about correlations due to T=0, J=1 interactions (np pairs)?

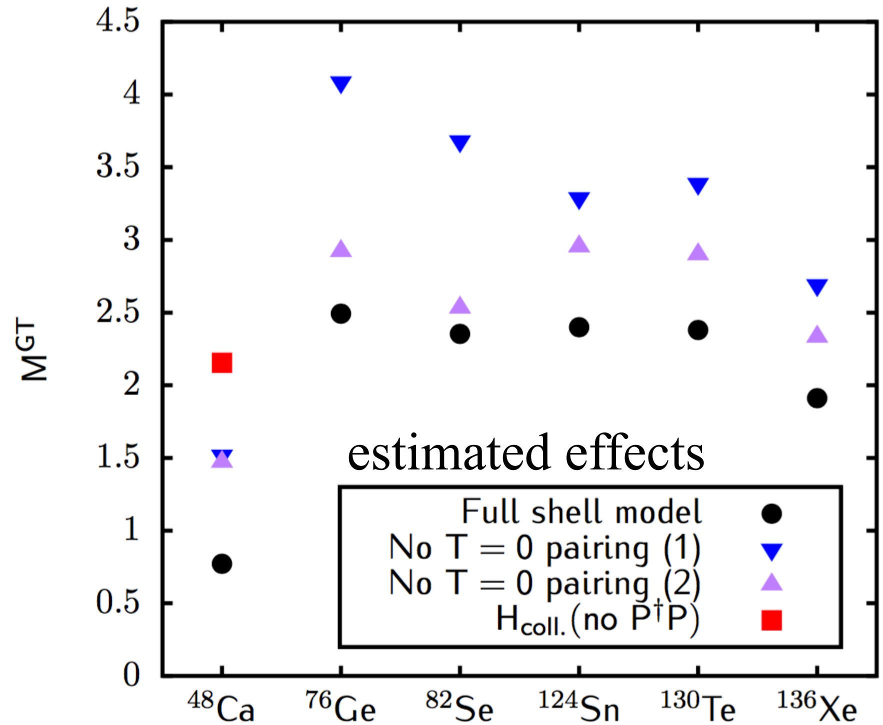
Pairing part of nuclear interactions

T=1, J=0 interactions included in all calculations,
T=0, J=1 channel only in shell model

What about correlations due to T=0, J=1 interactions (np pairs)?

consider Ca chain, without T=0 channel NMEs are factor ~ 2 smaller





Menéndez et al. (2016)

Pairing part of nuclear interactions

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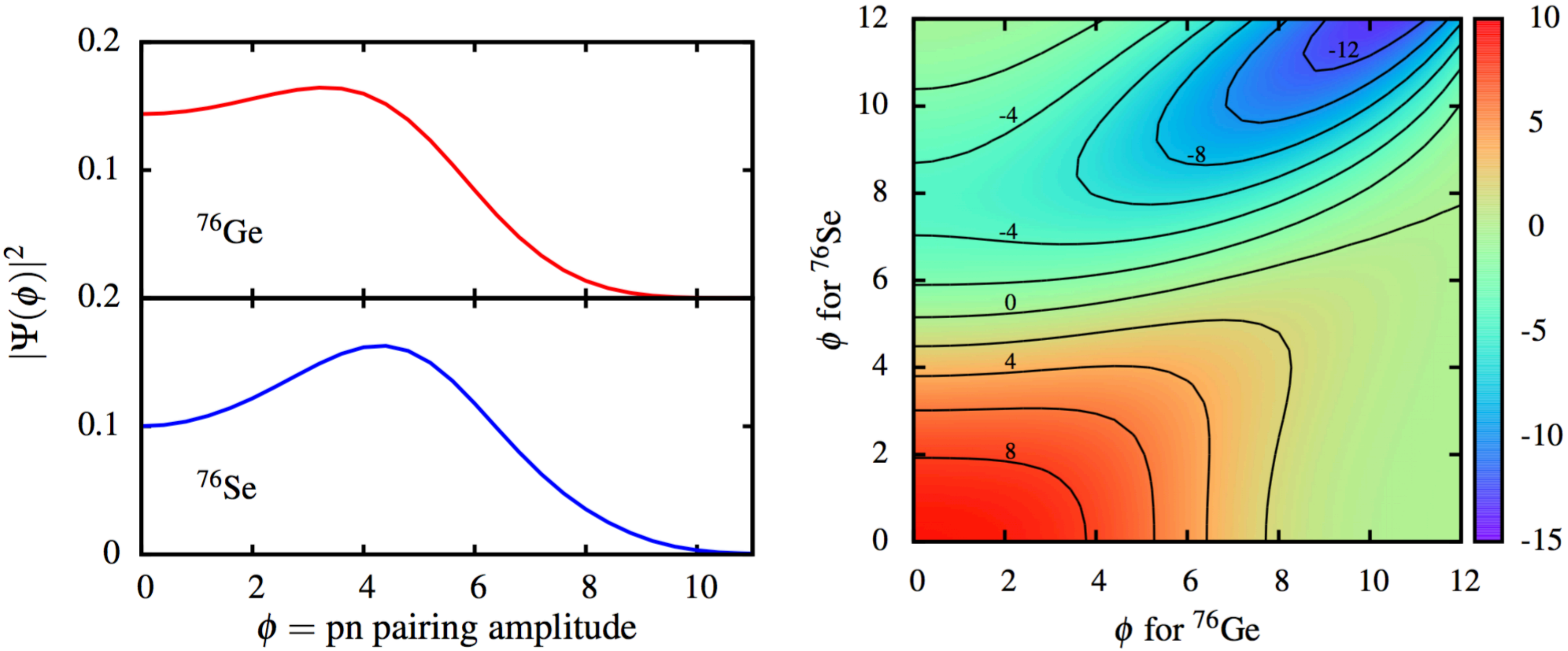
What about correlations due to T=0, J=1 interactions (np pairs)?

np pairing correlations in EDF-GCM also reduce NMEs



Hinohara, Engel (2014)

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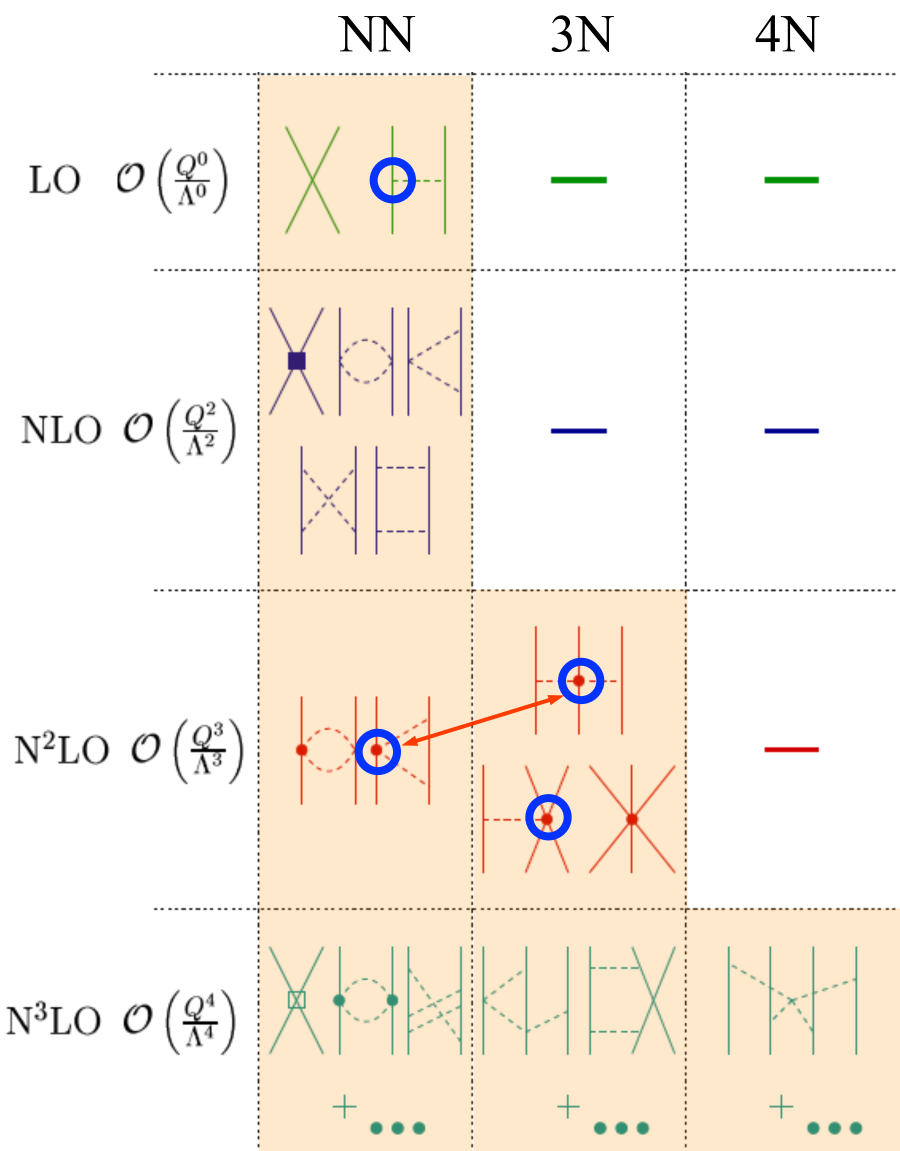
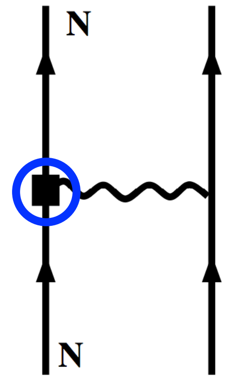
- calculation of $0\nu\beta\beta$ operator in chiral EFT

Perspectives

Chiral EFT for weak currents in nuclei

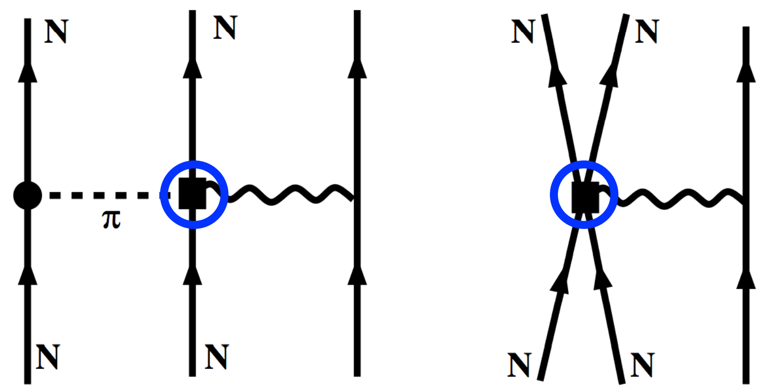


one-body currents at Q^0 and Q^2



one-body currents
similar to pheno currents
compared to Simkovic et al. (1999)

+ two-body currents at Q^3

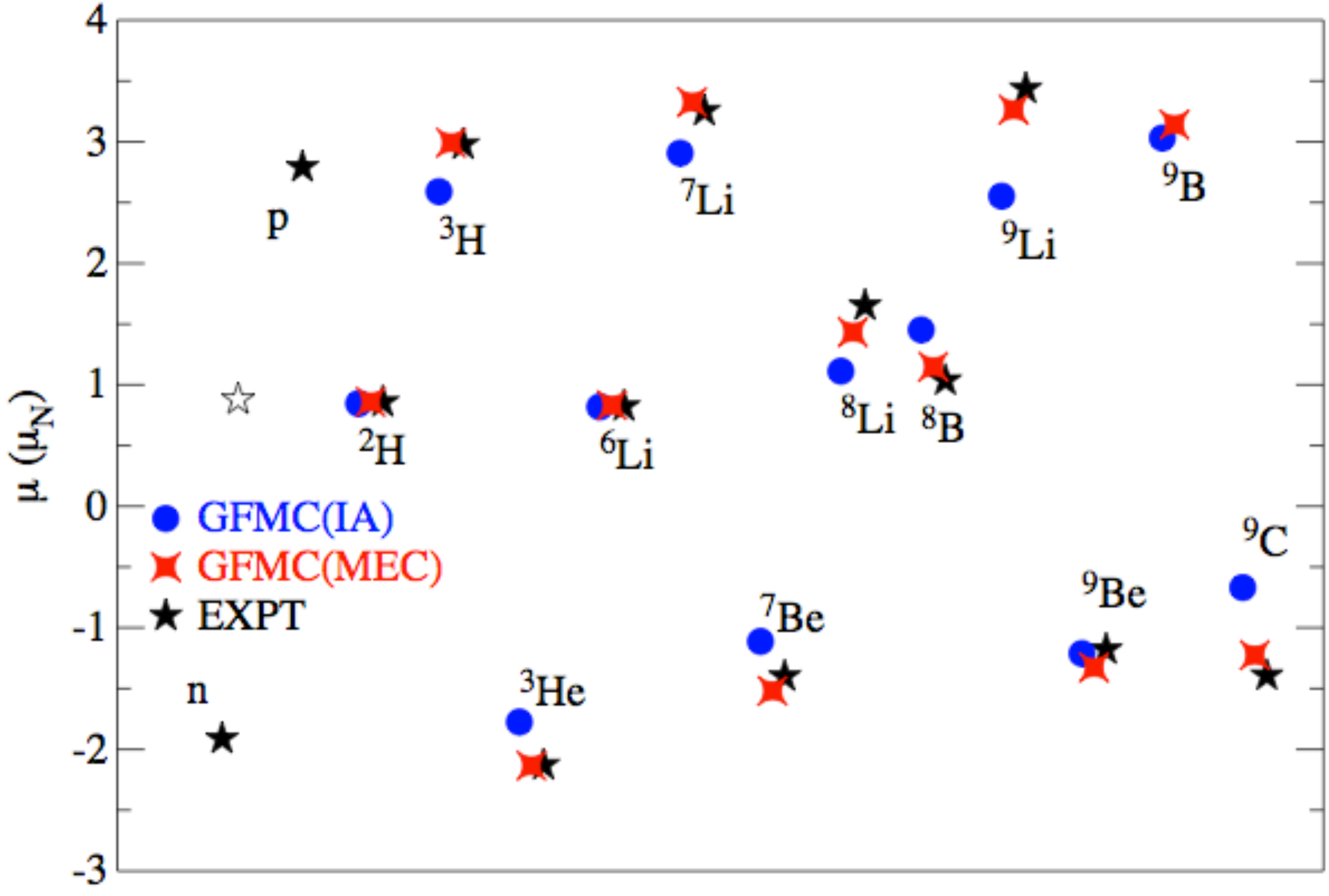


same couplings in forces and currents!

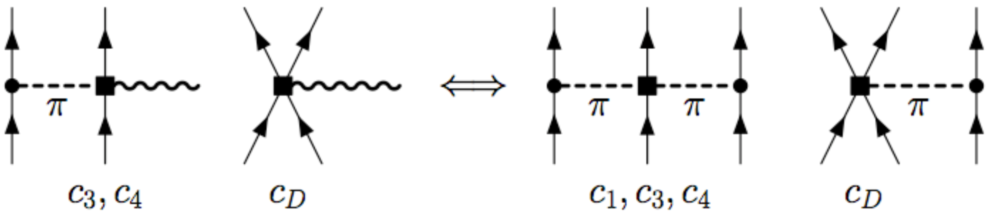
Chiral EFT currents and electromagnetic interactions

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!



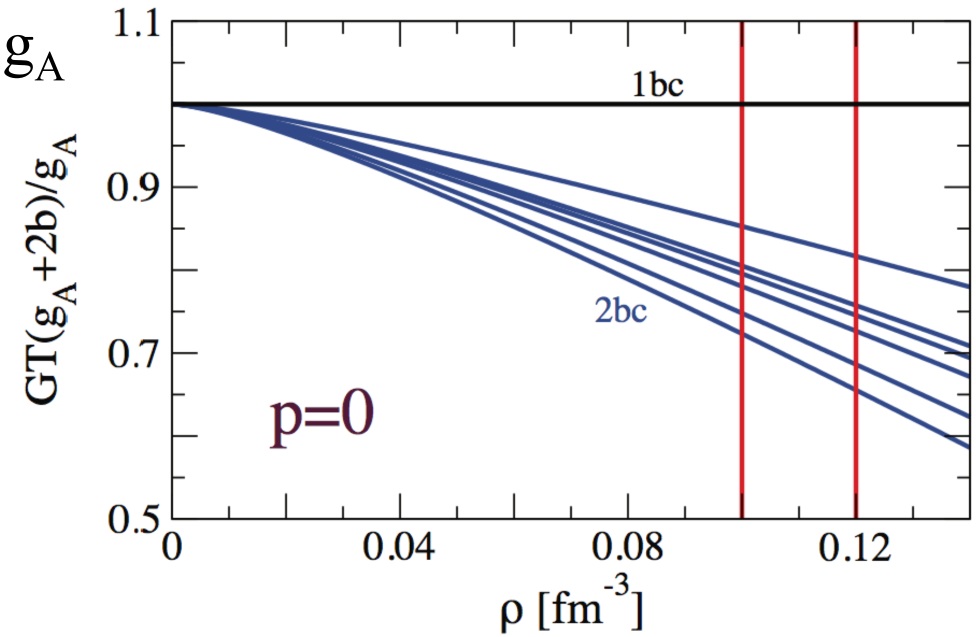
Electroweak interactions and 3N forces



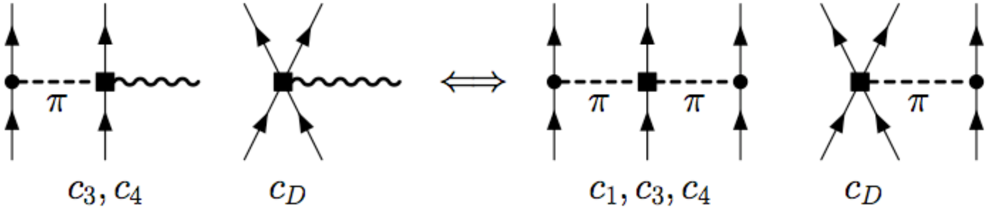
3N couplings predict quenching of g_A needed in beta decay calculations

Menendez, Gazit, AS (2011)

comparable to empirical q ~ 0.75 for β, 2νββ decays



Electroweak interactions and 3N forces



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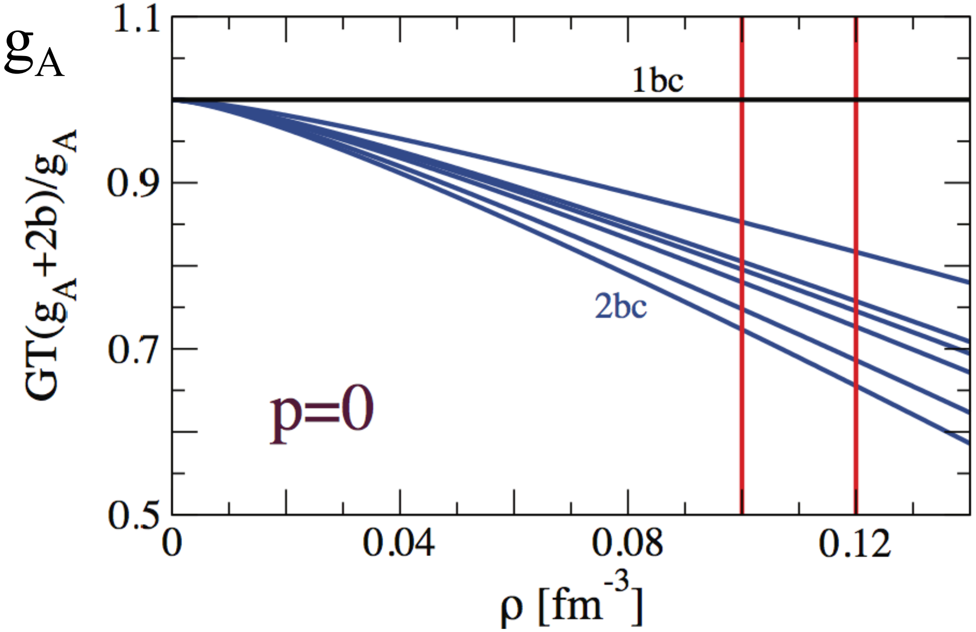
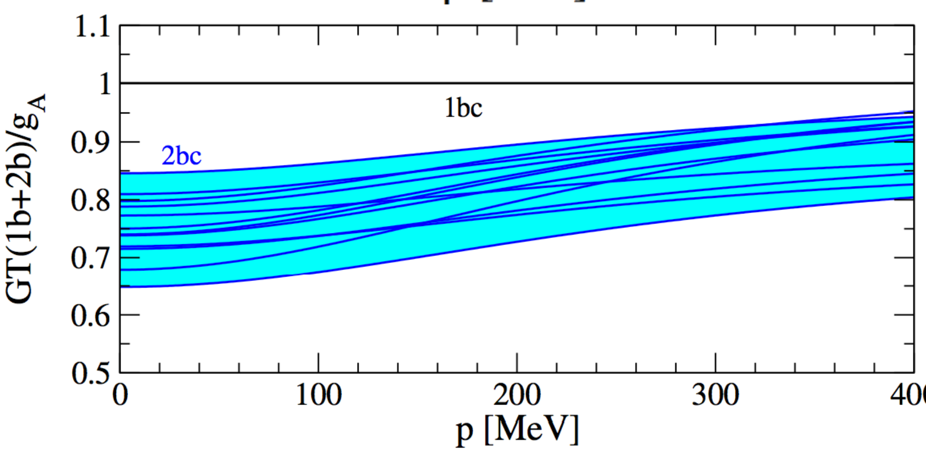


comparable to empirical q ~ 0.75 for β, 2νββ decays

predicts momentum dependence, weaker quenching for larger p
Menendez, Gazit, AS (2011)



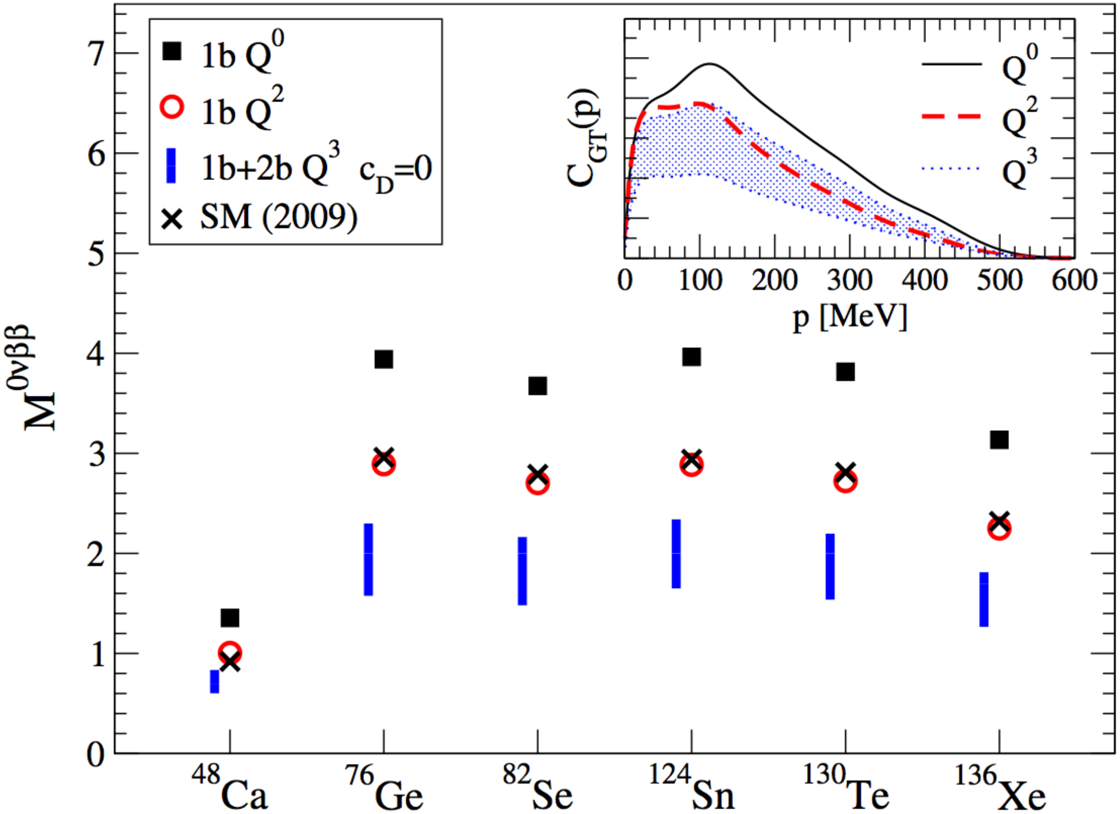
less quenching for 0νββ for p ~ m_π

$$M^{0\nu\beta\beta} \propto g_A^2 \Rightarrow \left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto g_A^4$$

Chiral EFT and 0νββ decay

NMEs for 0νββ decay based on chiral EFT operator

Menendez, Gazit, AS (2011)



modest quenching because 0νββ decay probes higher momentum transfer

two-body currents reduce NME by ~ 15% - 40%,
need to be included in all calculations of 0νββ decay

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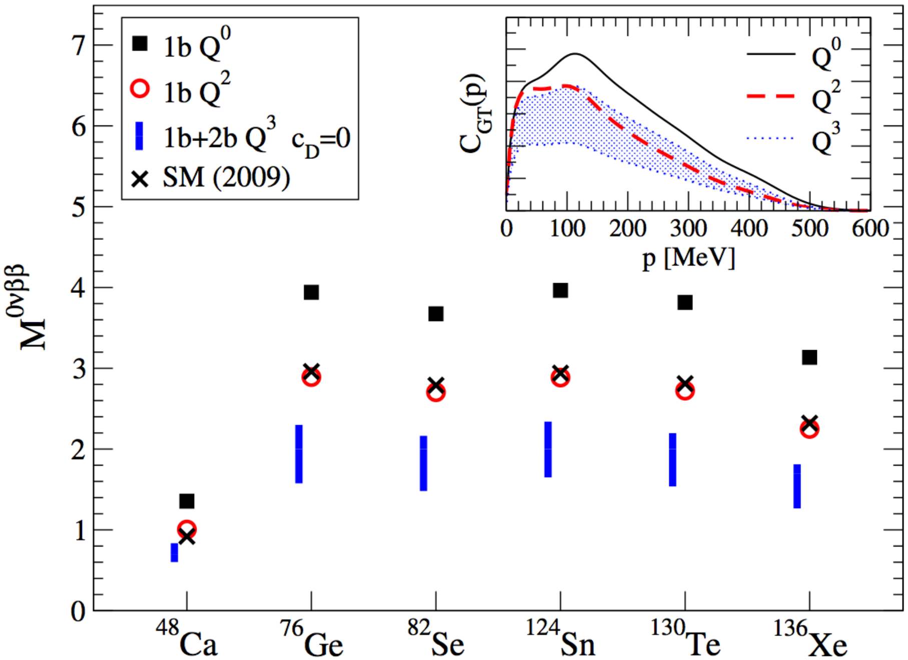

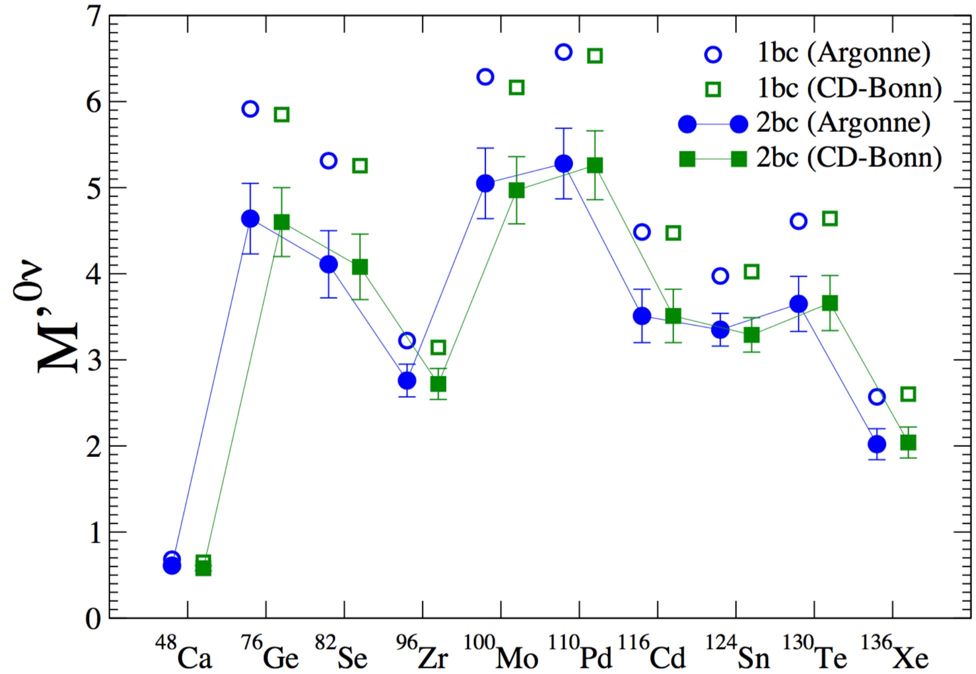

Engel, Simkovic ,Vogel (2014)

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Summary and perspectives

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

advances in ab initio calculations up to A ~ 50

progress in understanding **nuclear structure differences in NMEs**

first calculation of **$0\nu\beta\beta$ operator in chiral EFT**
less quenching compared to β, $2\nu\beta\beta$ decays

Future perspectives: ^{48}Ca NME ab initio calculation as benchmark

ab initio calculation of NMEs with consistent electroweak ints.

US-DOE topical collaboration lead by J. Engel (UNC), see CIPANP 1511.00074