Neutrinoless double-beta decay operator from chiral EFT

Achim Schwenk

TRIUMF Double Beta-Decay Workshop

May 12, 2016

Outline

Advances in nuclear forces and nuclear structure

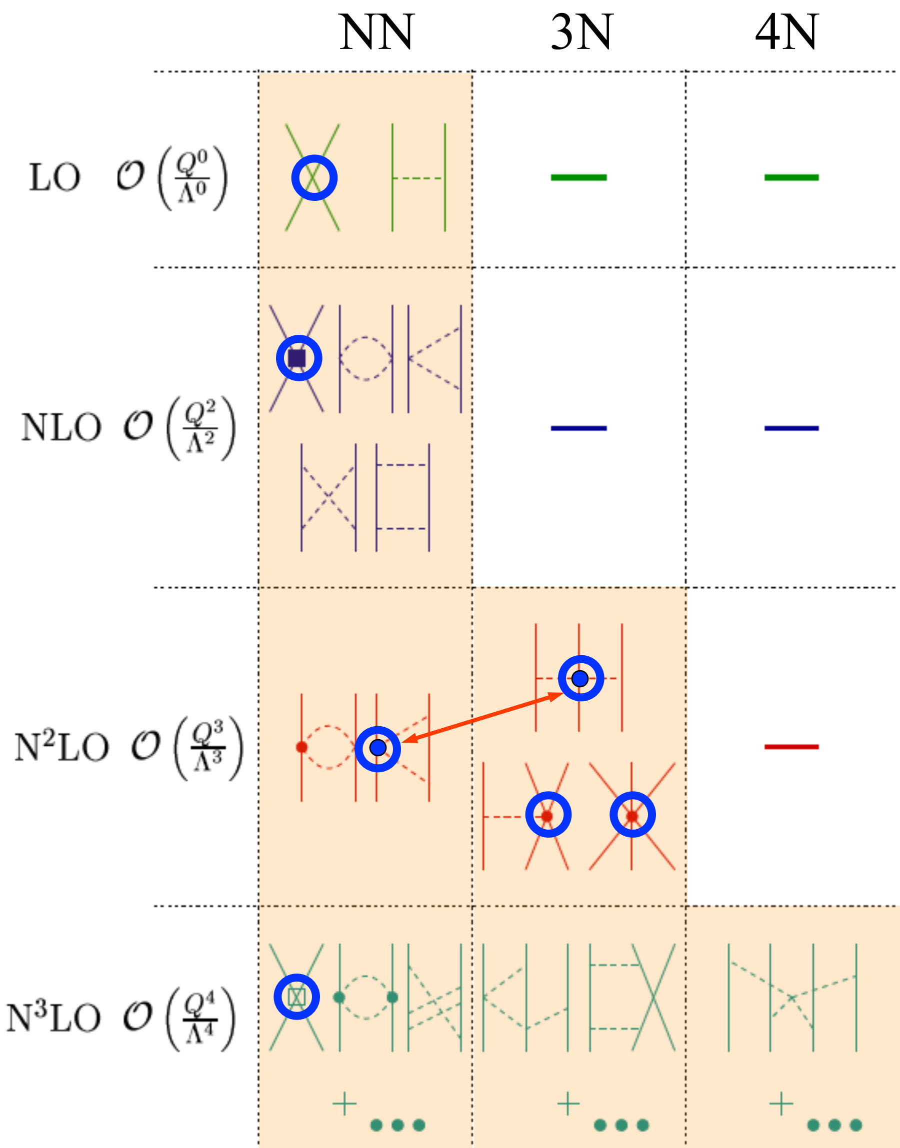
Theoretical uncertainties from chiral EFT

An issue fitting low-energy couplings to ^{3}H beta decay

$0\nu\beta\beta$ operator from chiral EFT

Chiral effective field theory for nuclear forces

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



include long-range pion physics

short-range couplings, fit to experiment once

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

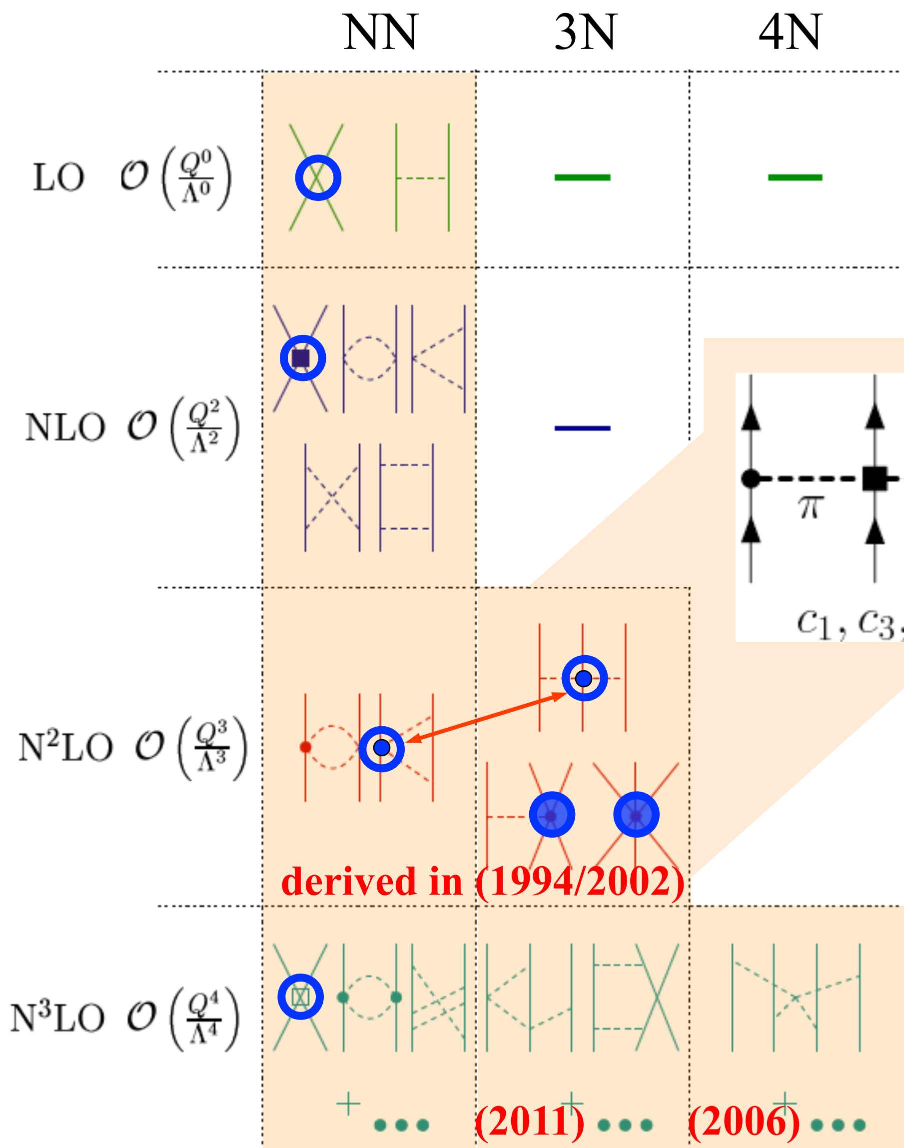
consistent **electroweak interactions** and **matching to lattice QCD**

new developments in power counting, uncertainty quantification, optimization Ektröm, Forssen, Furnstahl,...

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

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

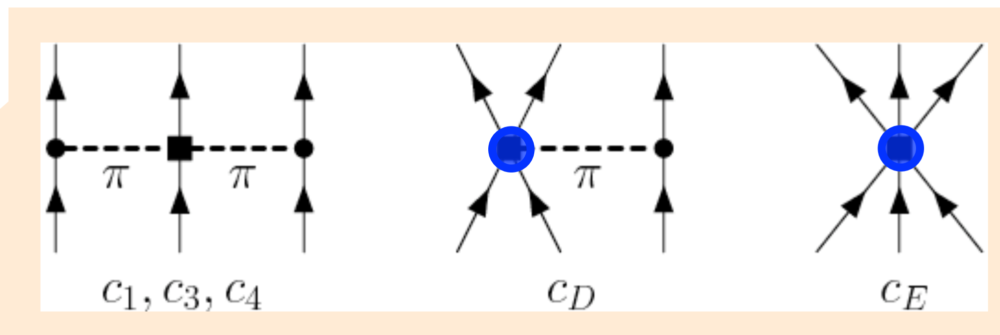
Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale ~500 MeV



consistent NN-3N-4N interactions

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

+ no new couplings for neutrons



c_i from πN and NN Meissner, LAT 2005

$$c_1 = -0.9^{+0.2}_{-0.5}\,, \quad c_3 = -4.7^{+1.2}_{-1.0}\,, \quad c_4 = 3.5^{+0.5}_{-0.2}$$

c_D, c_E fit to light nuclei only

N^{2}LOsat fit to nuclei up to A=24

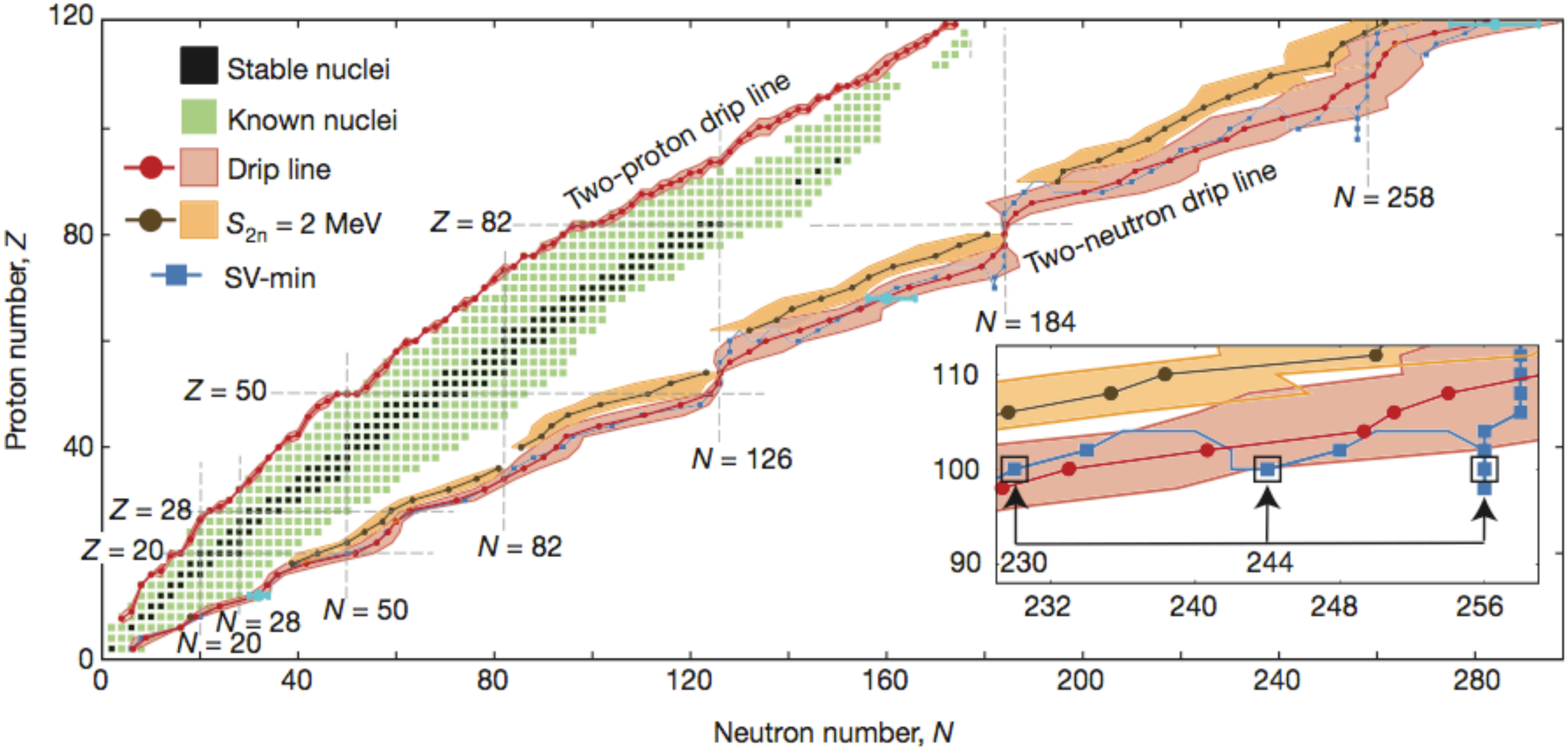
Weinberg, van Kolck, Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Machleidt, Meissner,…

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]‡

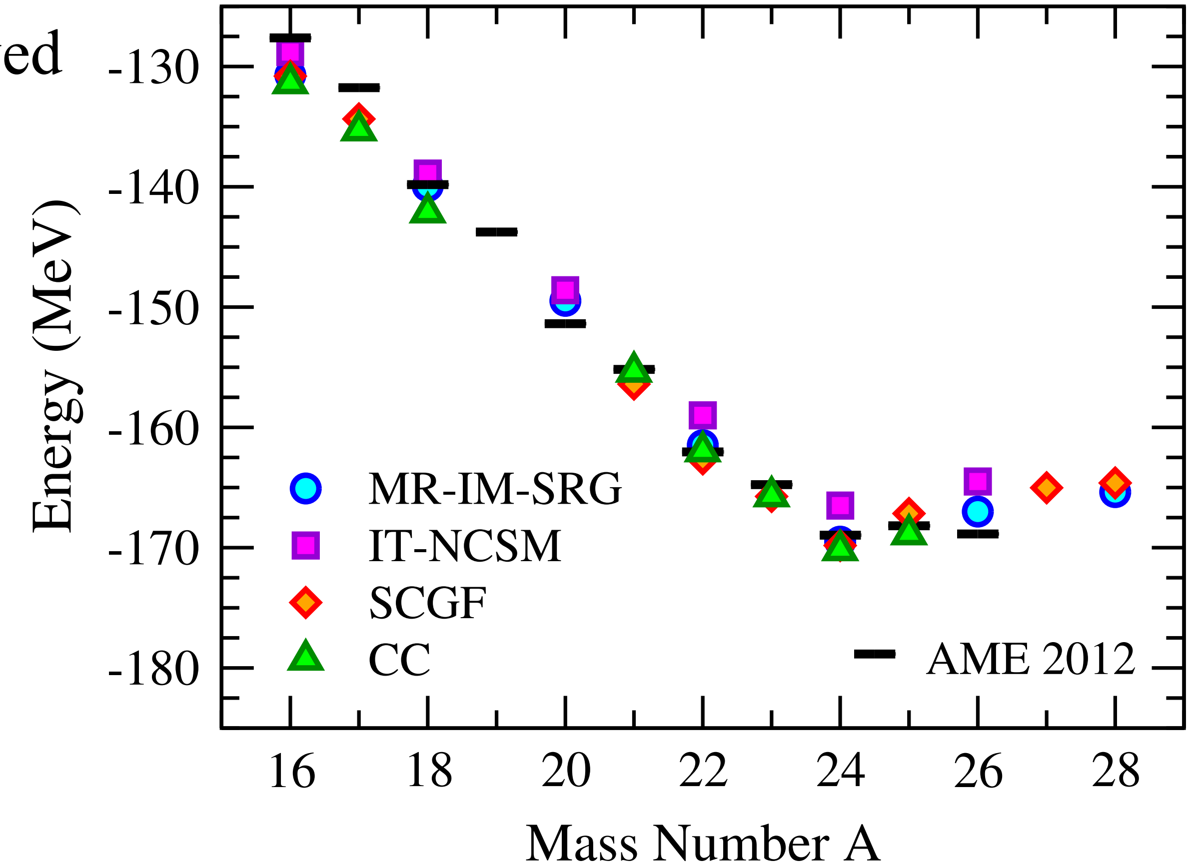


How does the nuclear chart emerge from chiral EFT?

Ab initio calculations of neutron-rich oxygen isotopes

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

based on same SRG-evolved 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)

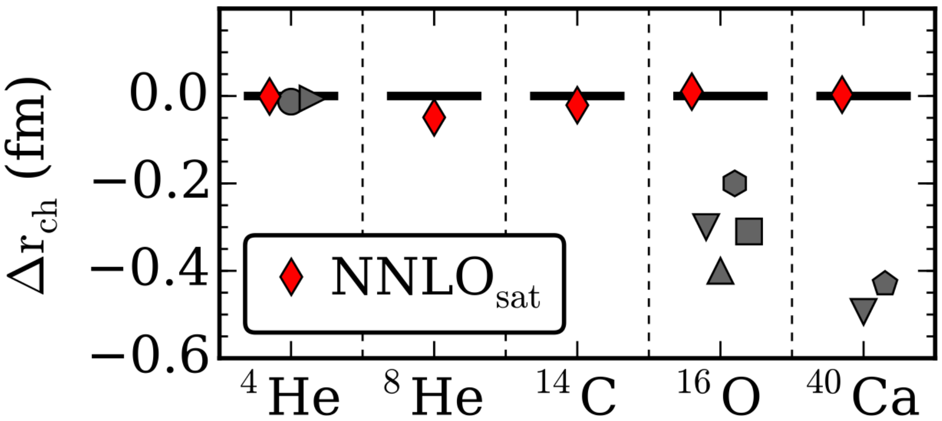
Self-Consistent Green's Function methods Cipollone et al., PRL (2013)

Resolution of radius problems

good saturation properties essential for radii

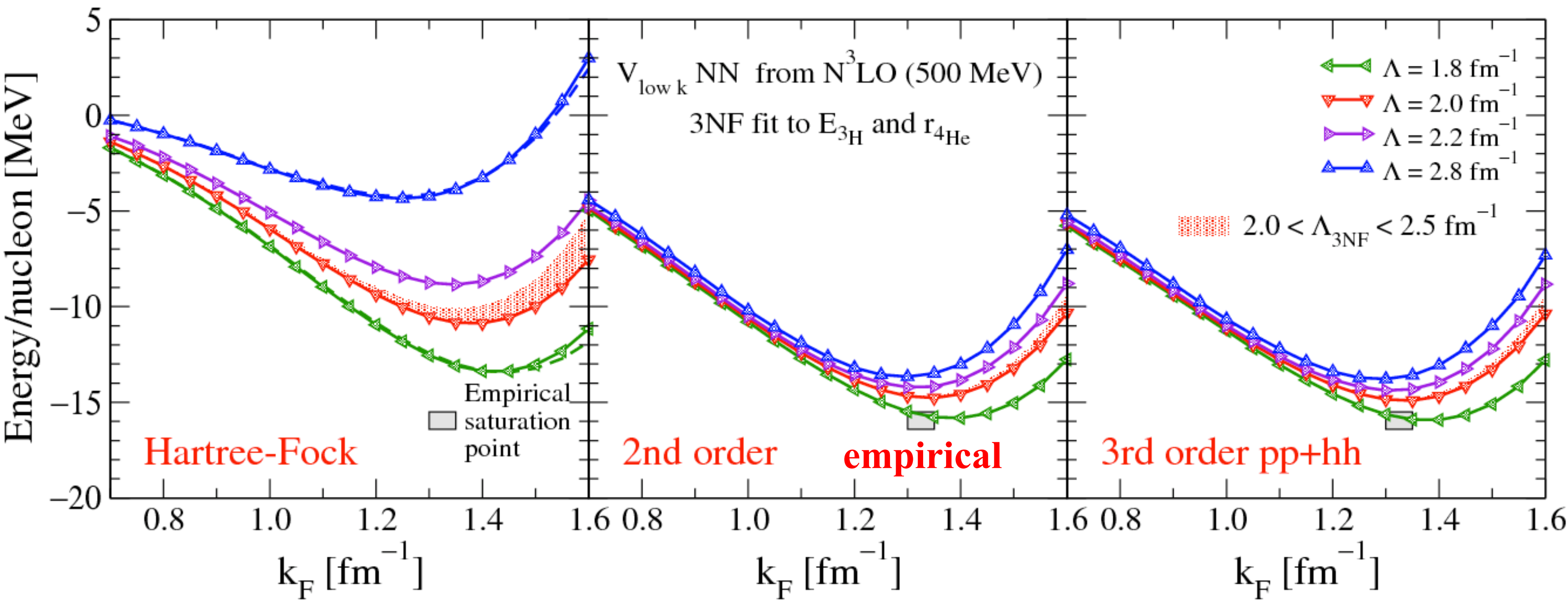
N^2LOsat potential fit to nuclei up to A=24

Ekström et al., PRC (2015)



Nuclear forces and nuclear matter

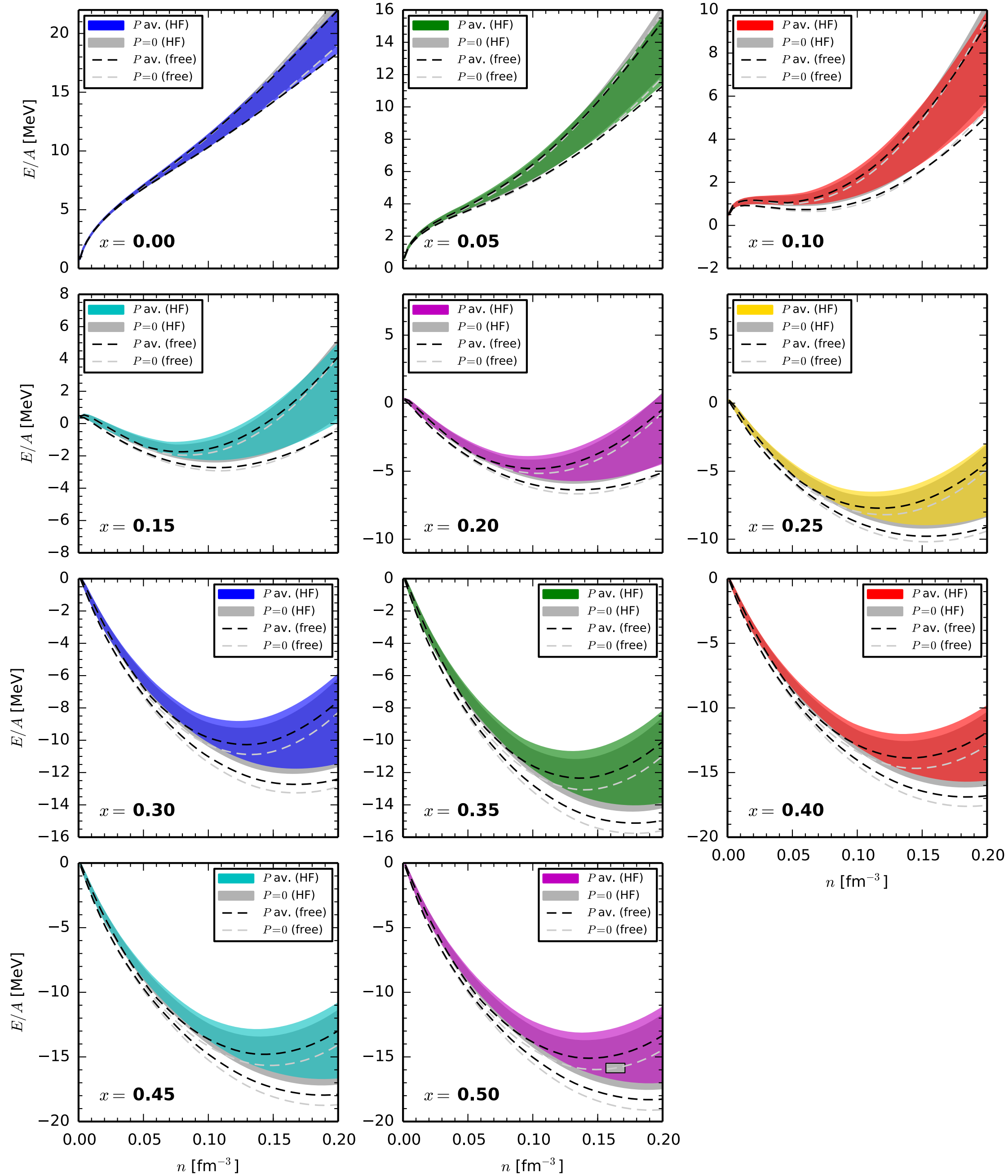
chiral 3N forces fit to light nuclei predict nuclear matter saturation with theoretical uncertainties Hebeler et al., PRC (2011), Bogner et al., NPA (2005)



Nuclear forces and nuclear matter

first results for asymmetric matter with improved treatment of 3N forces

Drischler, Hebeler, AS, PRC (2016)
see also Holt, Kaiser, Weise, Wellenhofer



Resolution of radius problems

good saturation properties essential for radii

N^2LOsat potential fit to nuclei up to A=24

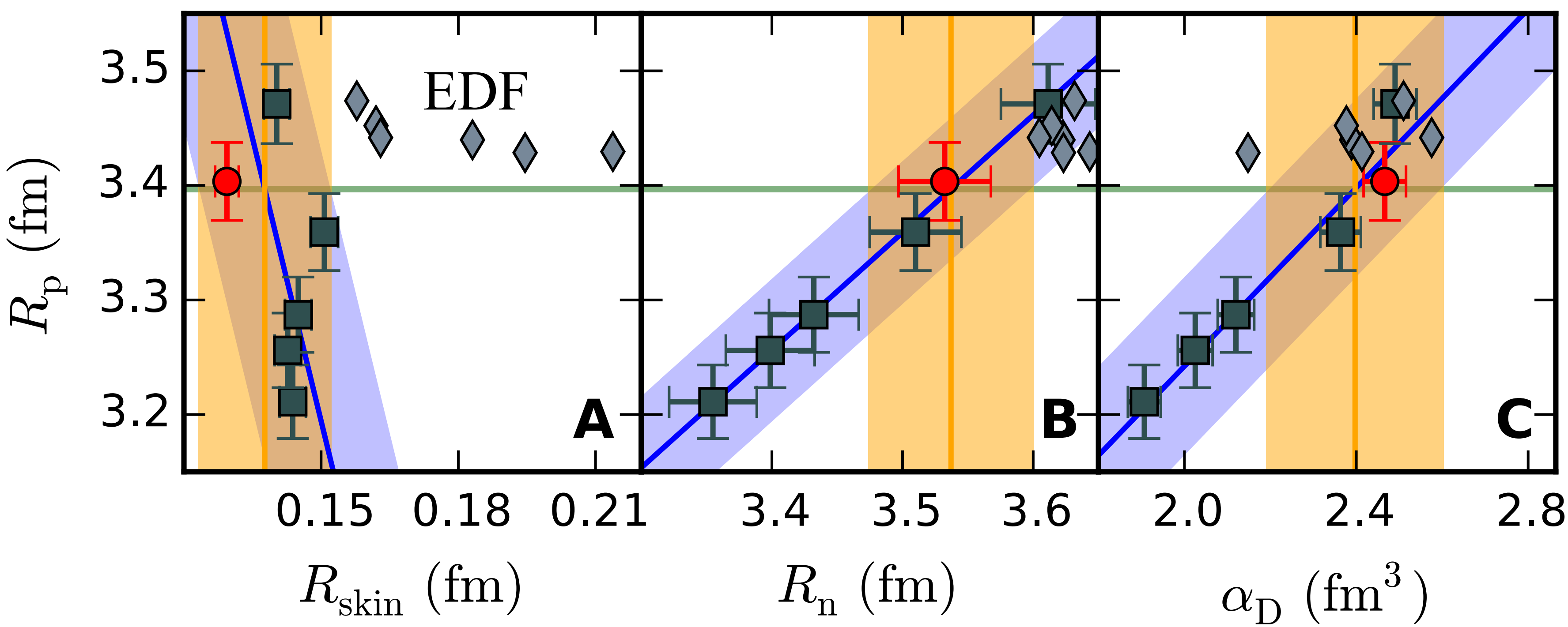
Ekström et al., PRC (2015)

NN+3N interactions that predict nuclear matter saturation

Hebeler et al., PRC (2011) only fit to light nuclei, but nonlocal 3N regulators

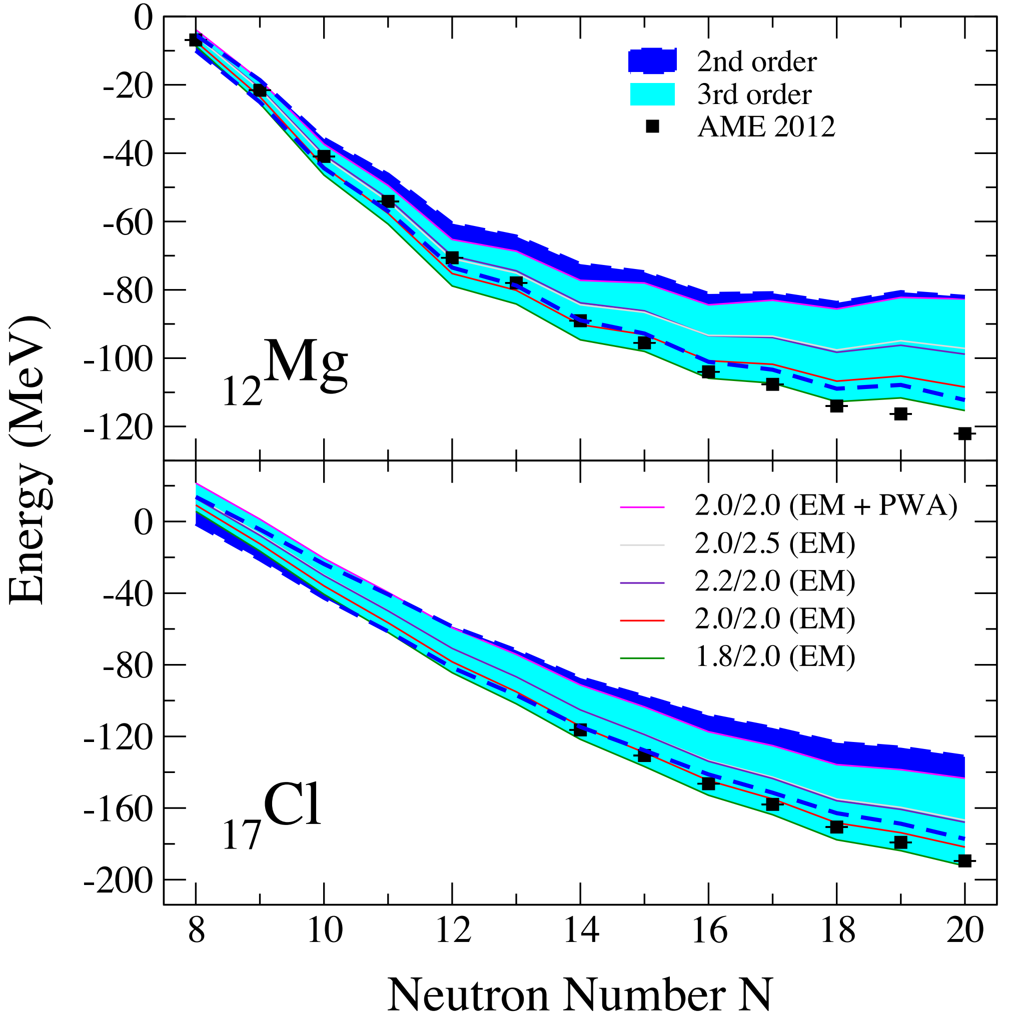
lead to radii consistent with experiment for ^{48}Ca Hagen et al., Nature Phys. (2015)

predict small neutron skin, dipole polarizability, and weak formfactor



Towards theoretical uncertainties Simonis et al., PRC (2016)

based on NN+3N interactions (sd shell)
that predict nuclear matter saturation within uncertainties



Theoretical uncertainties dominated by uncertainties in nuclear forces!

Frontier of ab initio calculations at A~50

doi:10.1038/nature12226

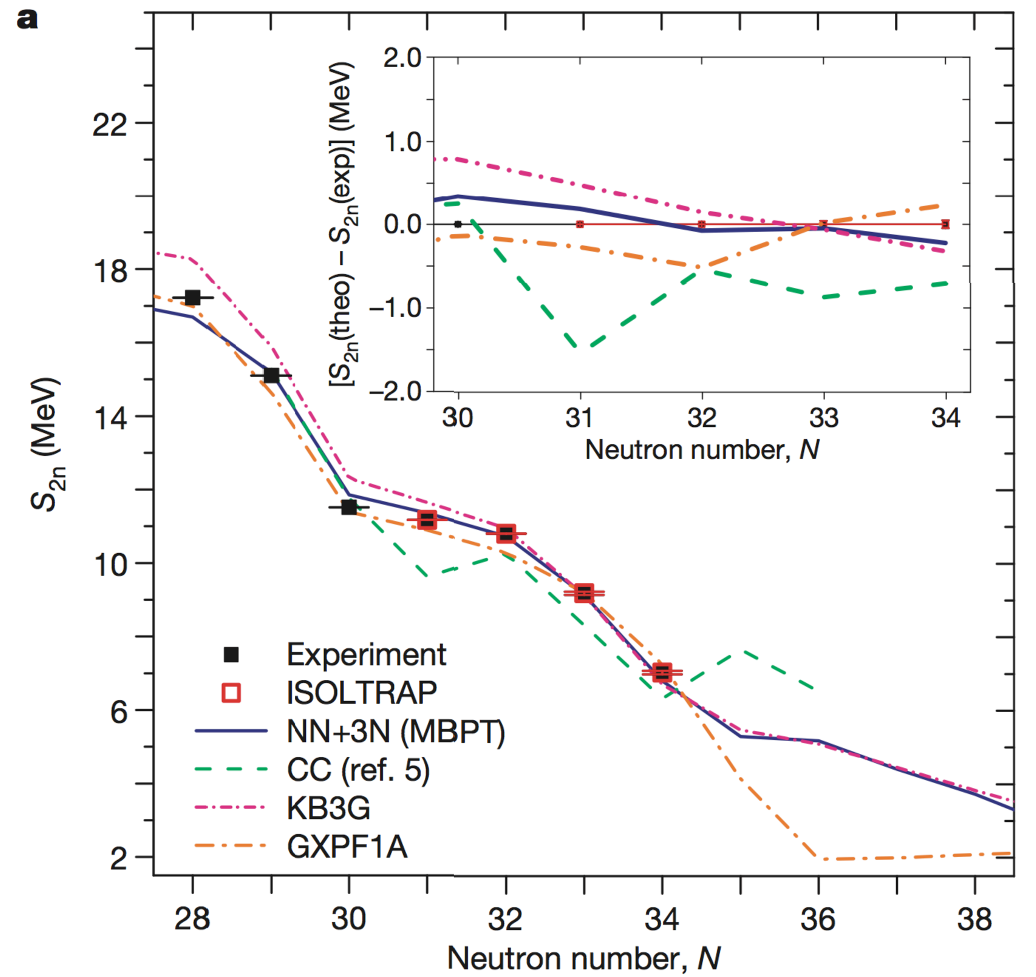
Masses of exotic calcium isotopes pin down nuclear forces

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



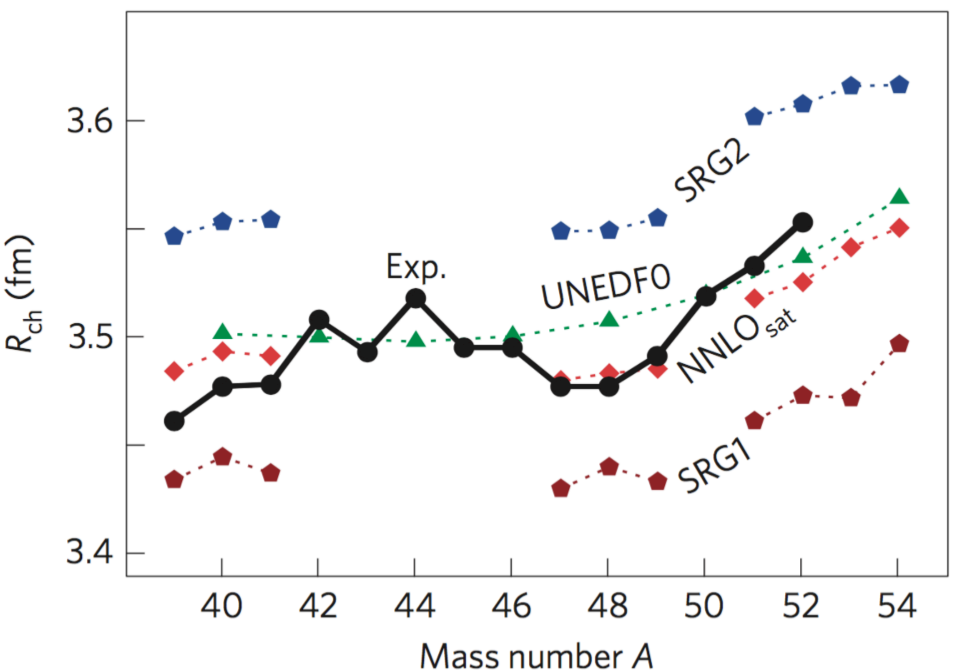
nature physics

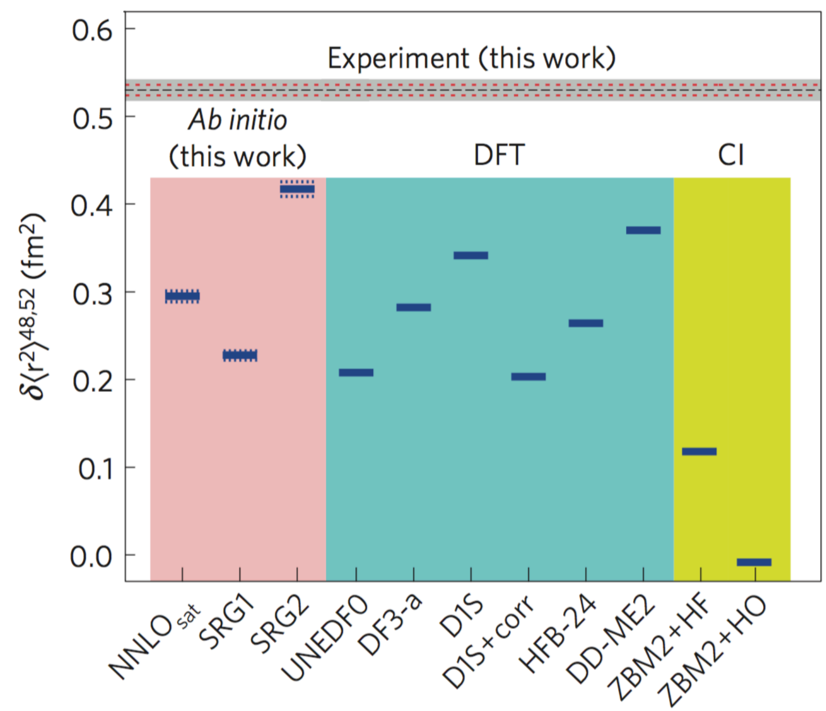
ARTICLES

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

Unexpectedly large charge radii of neutron-rich calcium isotopes

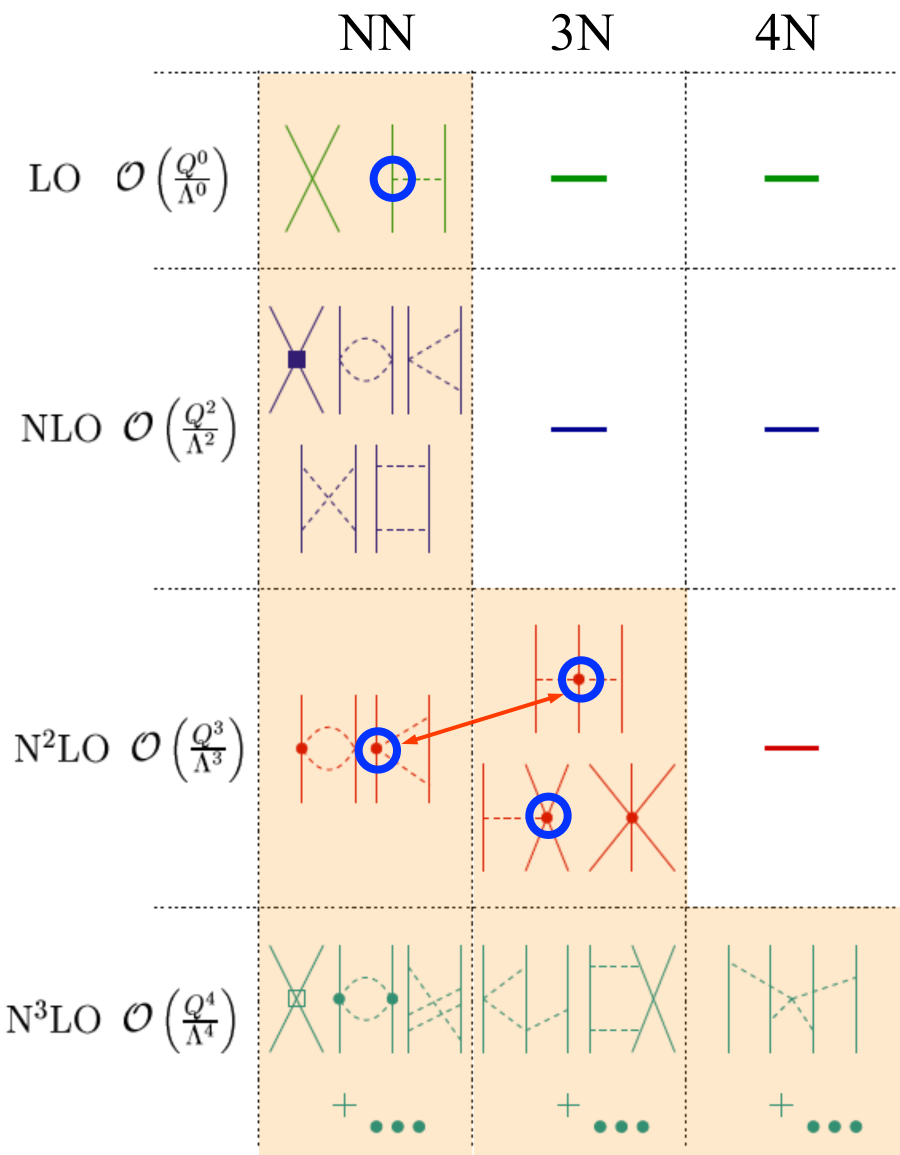
R. F. Garcia Ruiz[1*], M. L. Bissell[1,2], K. Blaum[3], A. Ekström[4,5], N. Frömmgen[6], G. Hagen[4], M. Hammen[6], K. Hebeler[7,8], J. D. Holt[9], G. R. Jansen[4,5], M. Kowalska[10], K. Kreim[3], W. Nazarewicz[4,11,12], R. Neugart[3,6], G. Neyens[1], W. Nörtershäuser[6,7], T. Papenbrock[4,5], J. Papuga[1],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



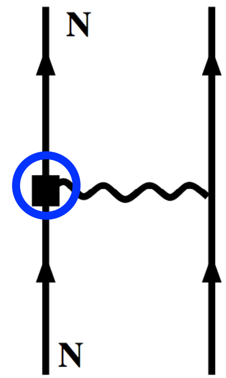


Chiral EFT for weak currents in nuclei

Park et al., Gazit, Epelbaum, Klos, Kölling, Pastore, Piarulli, …

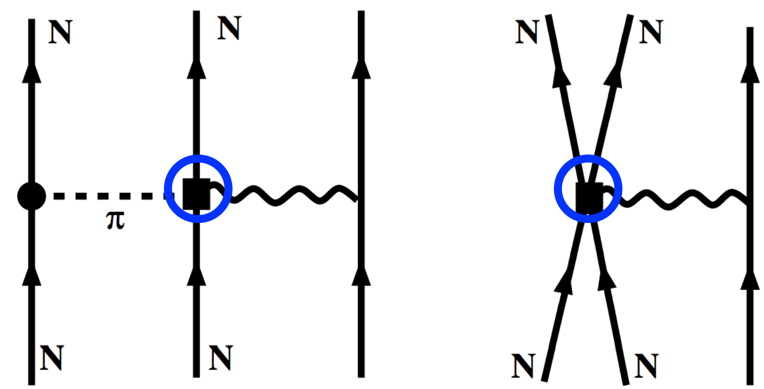


one-body currents at Q^0 and Q^2



one-body currents similar to pheno. currents

+ two-body currents at Q^3

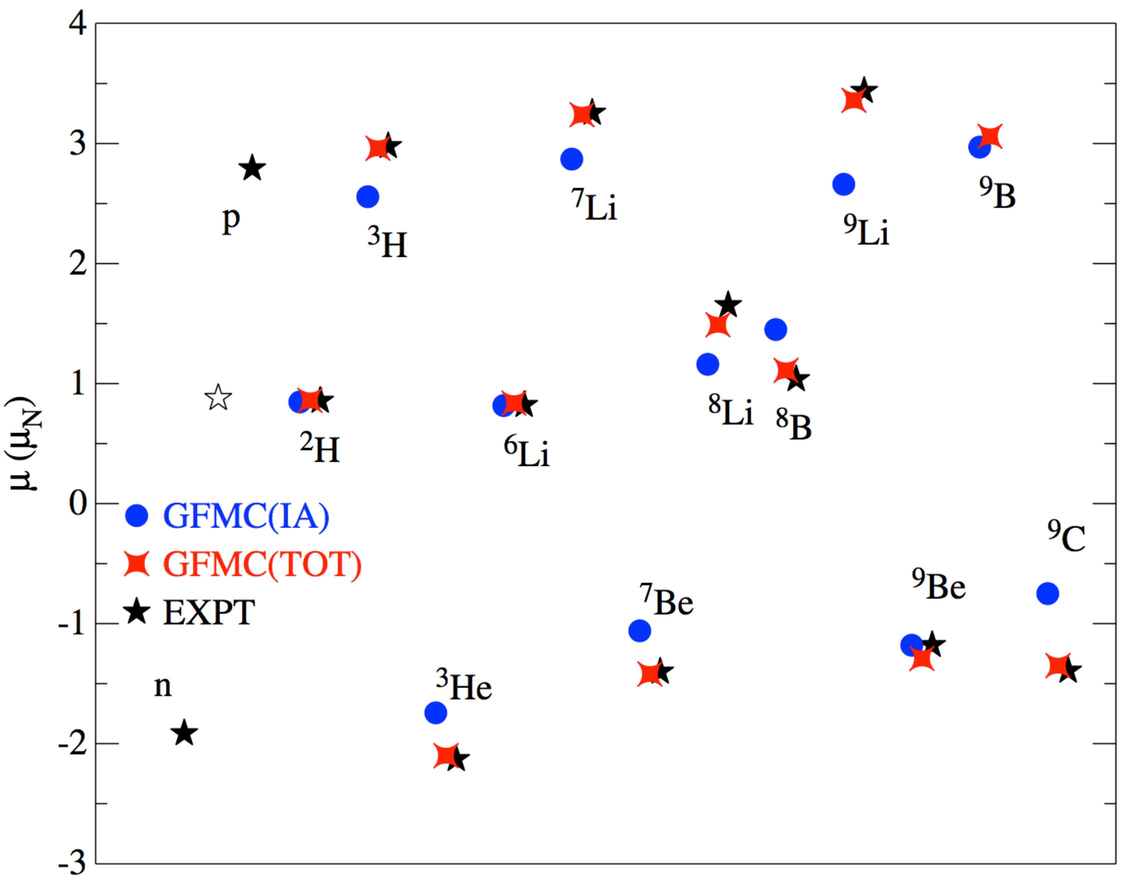


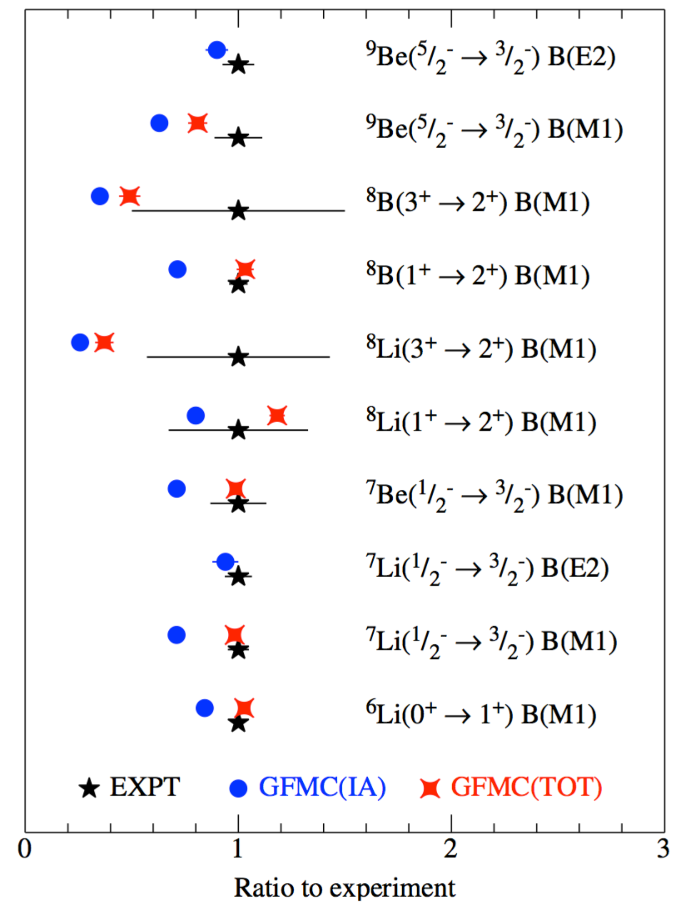
same couplings in forces and currents!

Chiral EFT for electromagnetic currents

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!



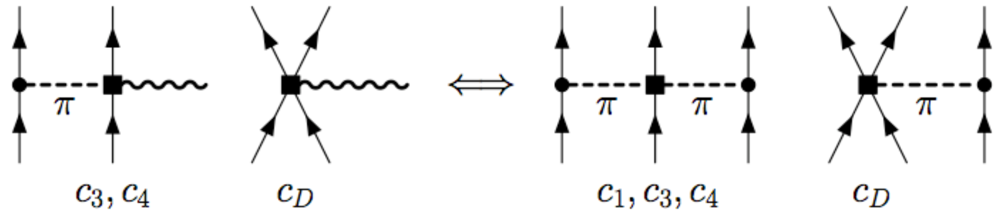


Axial-vector currents and 3N forces

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 pioneering study to determine c_D

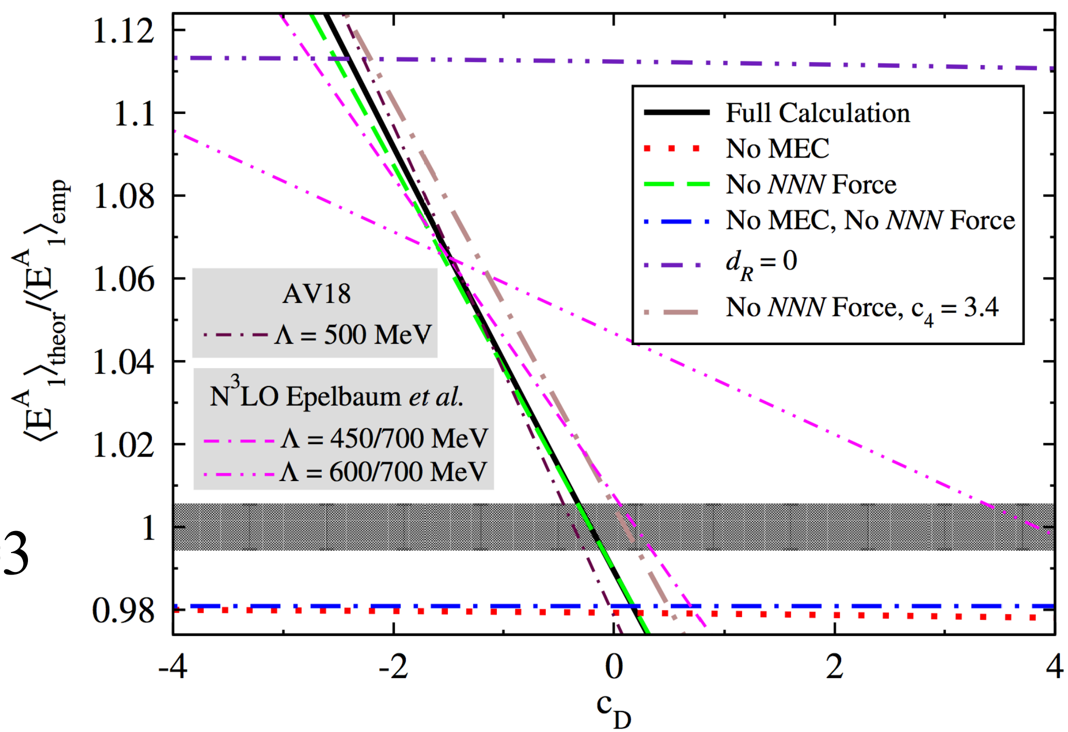
Gazit, Quaglioni, Navratil, PRL (2009)

very attractive because:

^{3}H half-life precisely known,

uncorrelated with ^{3}H energy

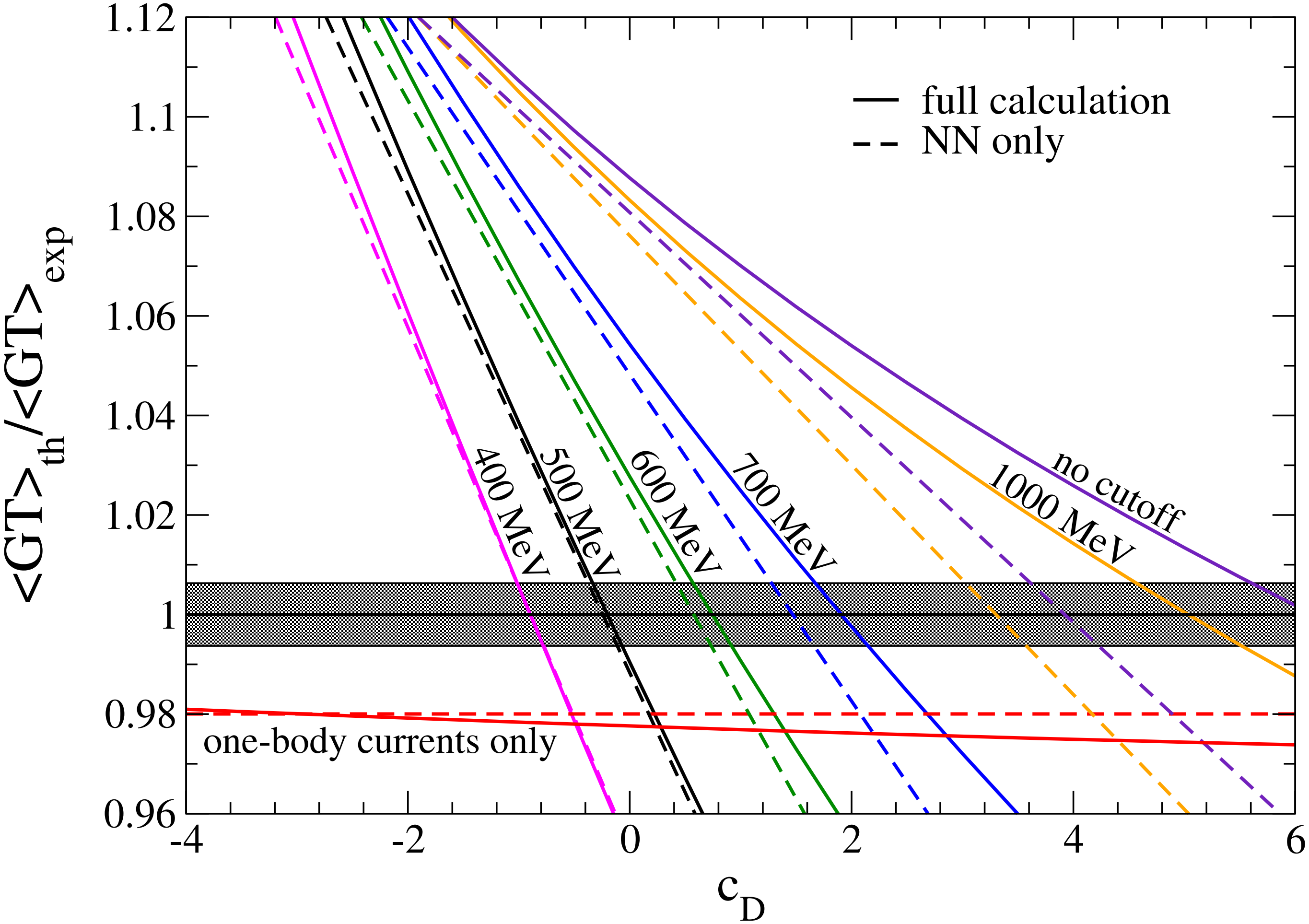
c_D, c_E fully determined from A=3



Axial-vector currents and 3N forces Klos et al., in prep.

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

Consider different cutoffs!



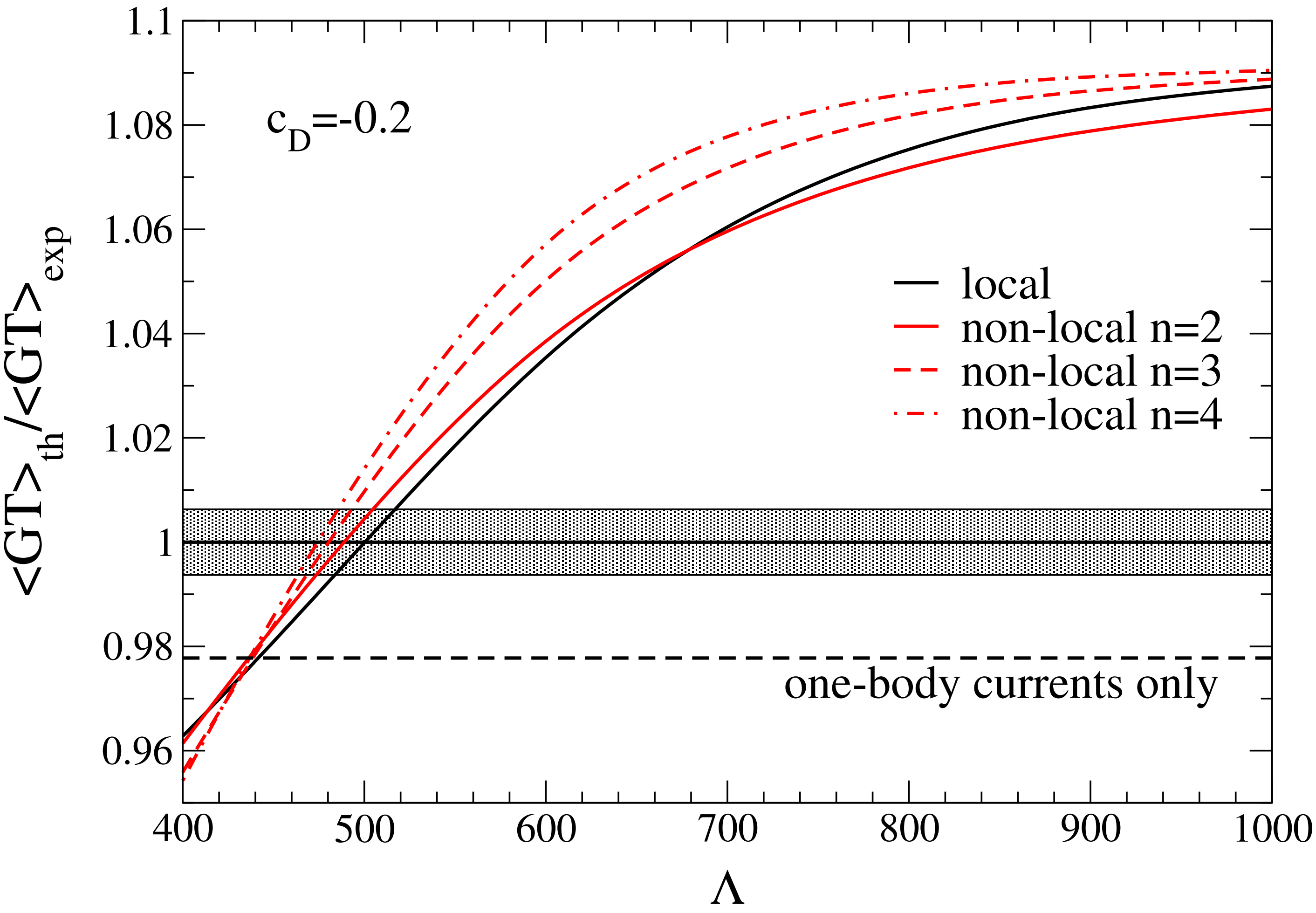
Cutoff dependence significant

obtained c_D value depends on cutoff in currents

cutoff in currents effects 3N forces!?

Axial-vector currents and 3N forces Klos et al., in prep.

Cutoff dependence in two-body currents can be significant/larger than two-body-current contribution



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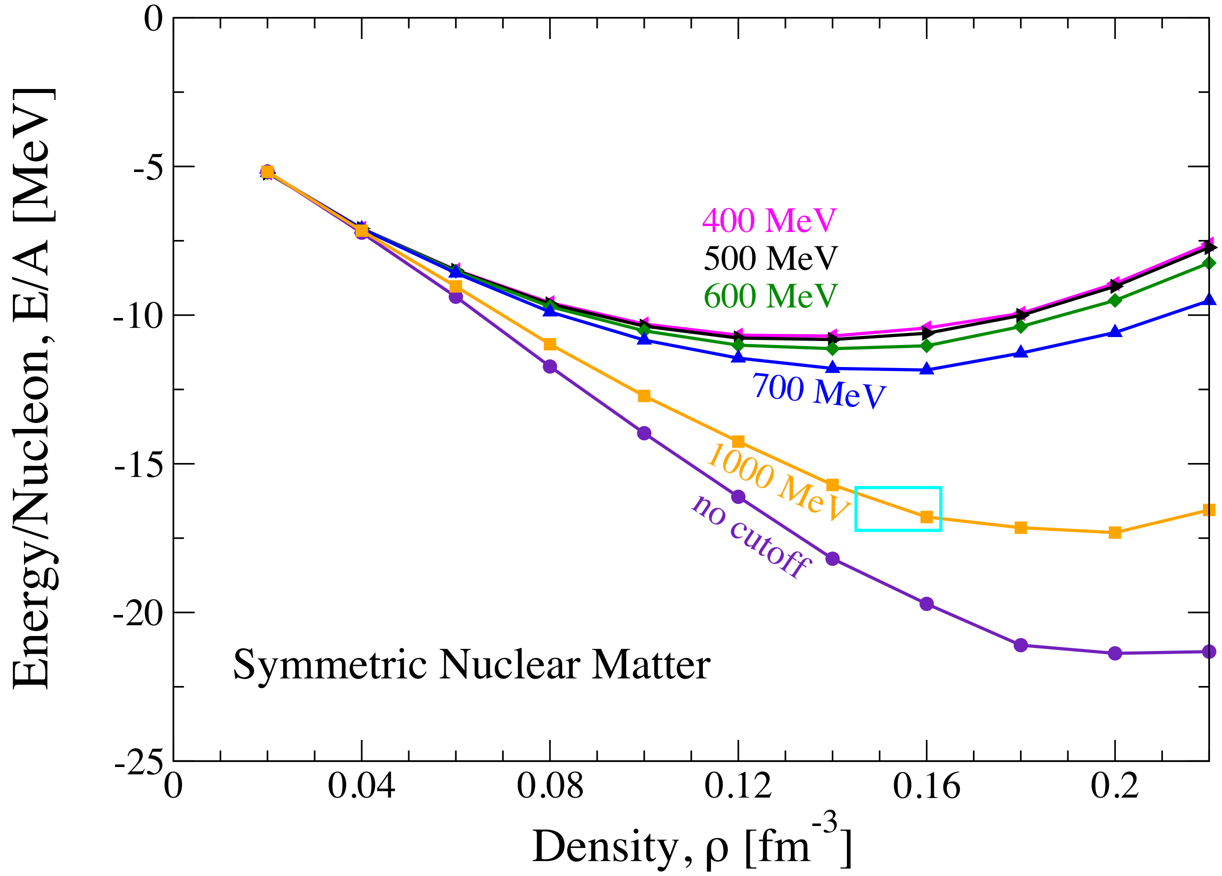
Impact on nuclear matter

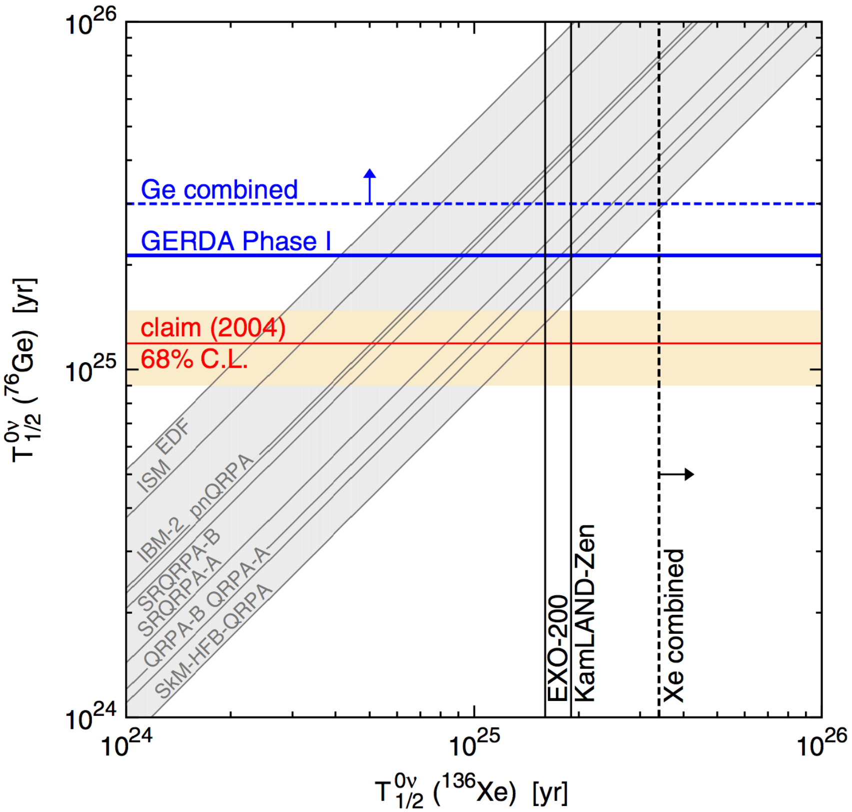
results from A. Carbone



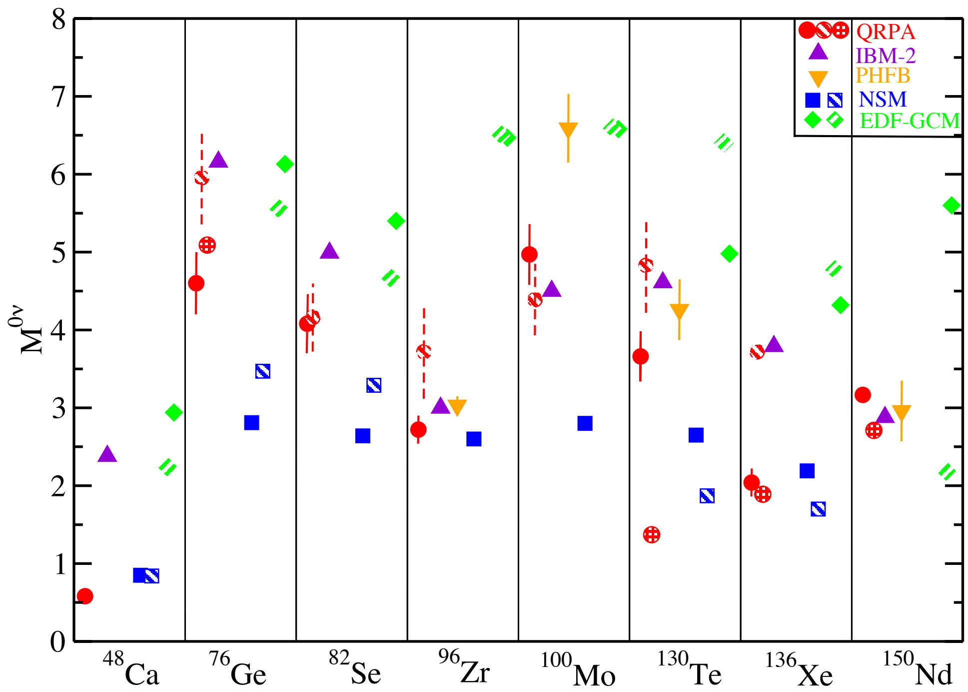
EFT uncertainties are important for electroweak operators

Neutrinoless double-beta decay

different NME calculations result in large spread



GERDA Collaboration (2013)



EMMI-RRTF (2014)

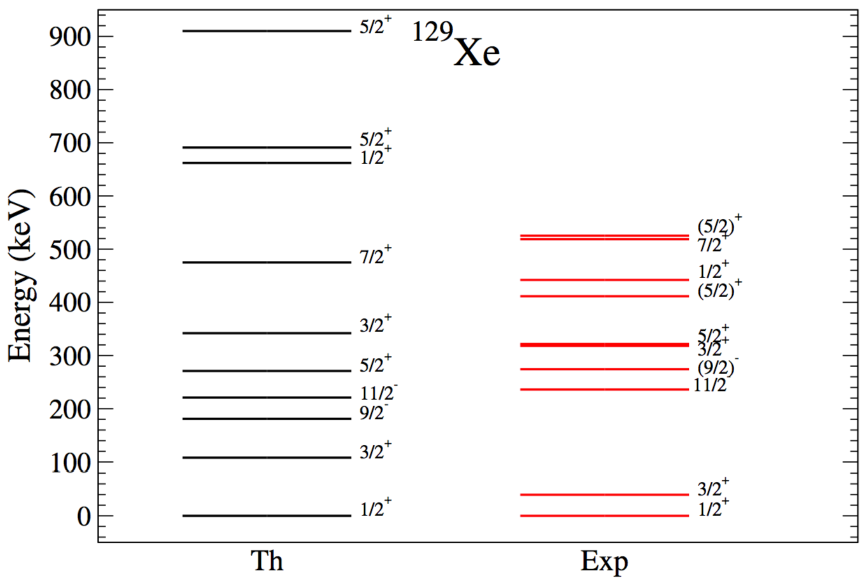
Can we understand the differences in nuclear structure?

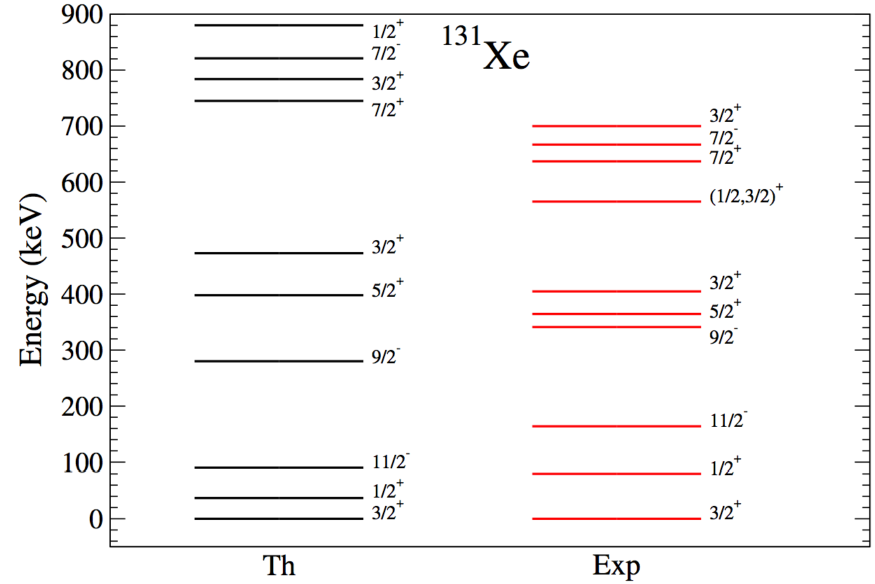
None of the calculations use consistent operators.

Contributions from two-body currents?

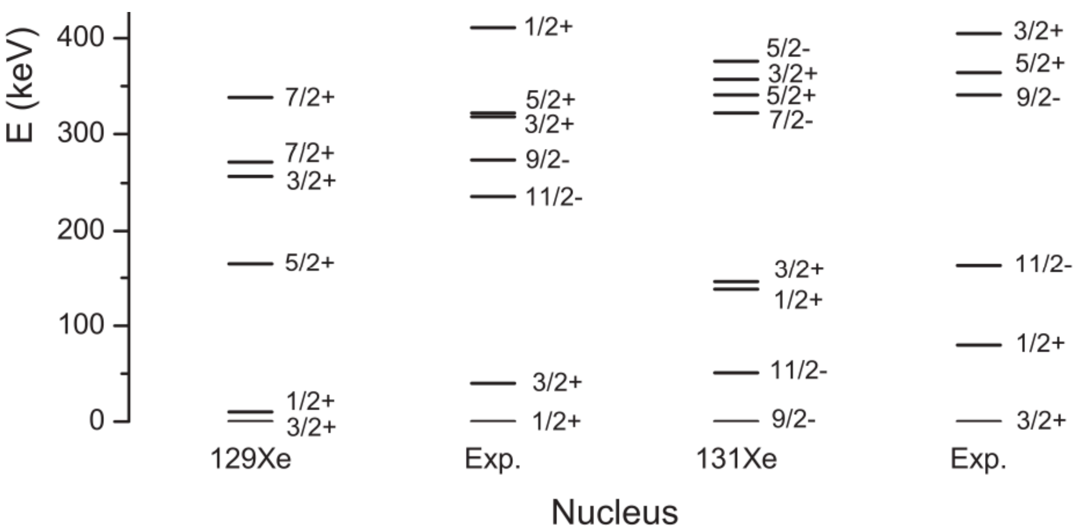
An example from WIMP-nucleus scattering

shell model calculation based on the same interactions as for $0\nu\beta\beta$
very good agreement for spectra, ordering and grouping well reproduced





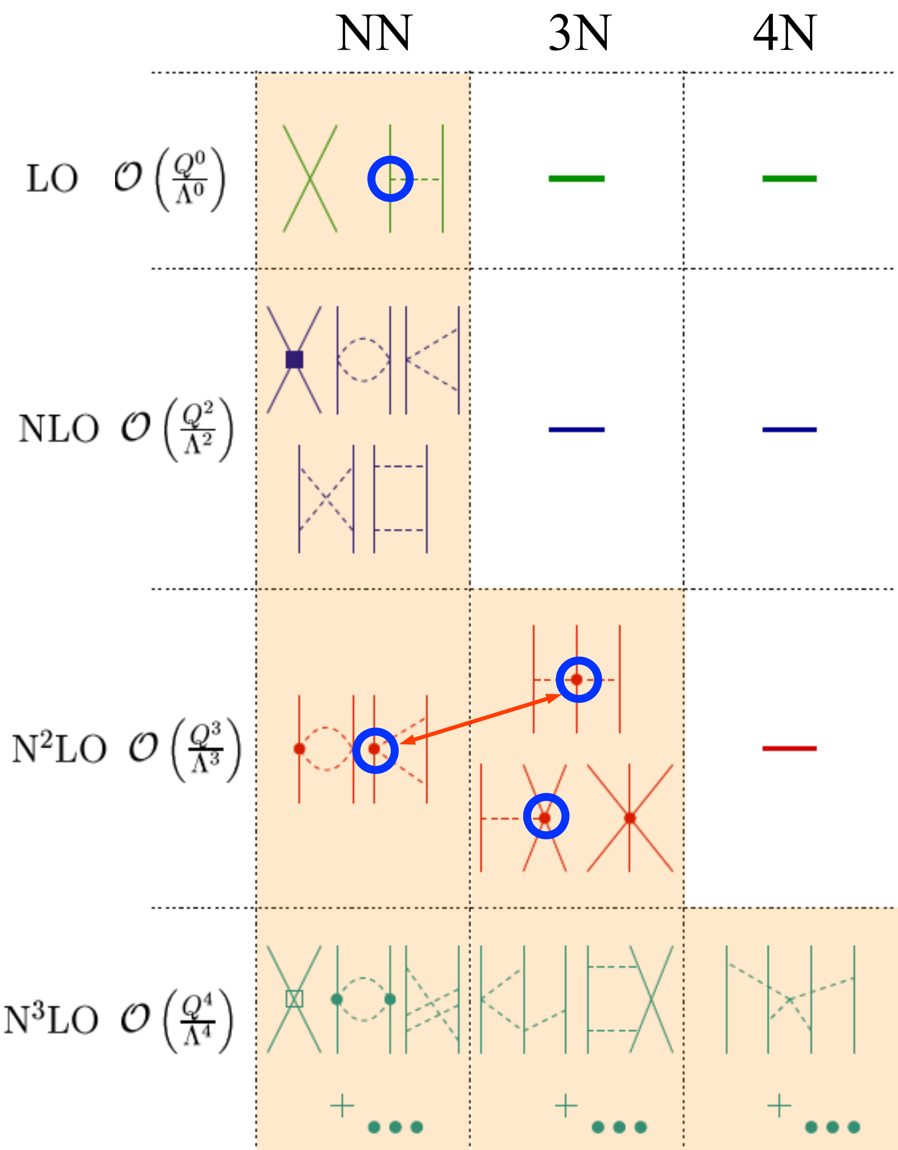
Menéndez, Gazit, AS (2012)



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

Chiral EFT for weak currents in nuclei

Park et al., Gazit, Epelbaum, Klos, Kölling, Pastore, Piarulli, …



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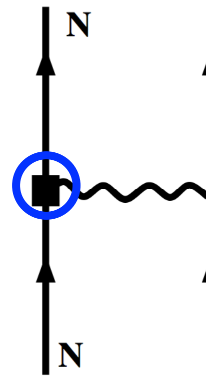

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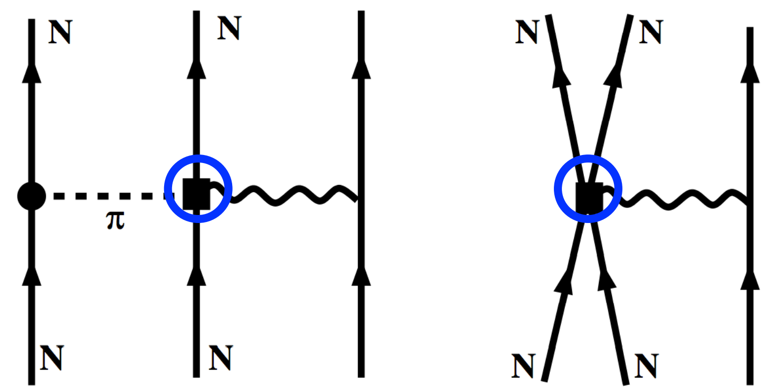
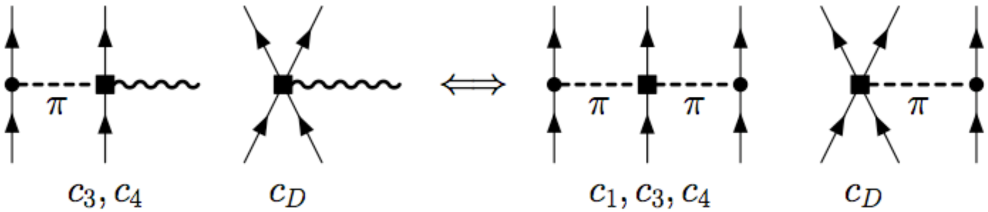


ci from πN and NN Meissner, LAT 2005

$$c_1 = -0.9^{+0.2}_{-0.5}\,,\ c_3 = -4.7^{+1.2}_{-1.0}\,,\ \ c_4 = 3.5^{+0.5}_{-0.2}$$

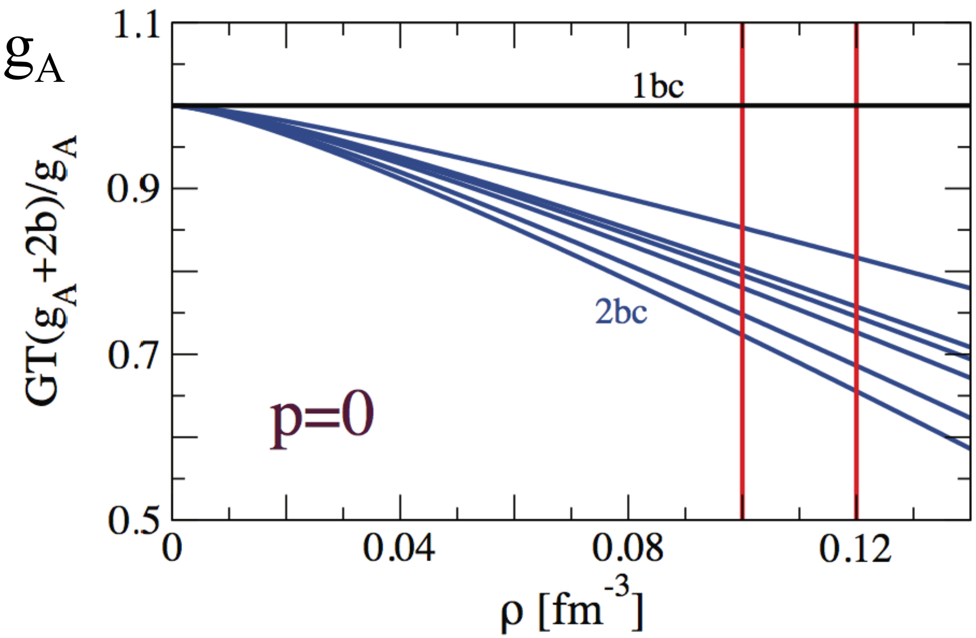
Electroweak interactions and 3N forces



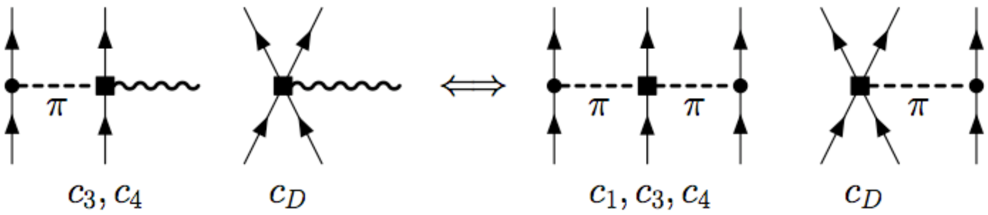
3N couplings predict quenching of g_A needed in beta decay calculations

Menendez, Gazit, AS (2011)

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



Electroweak interactions and 3N forces



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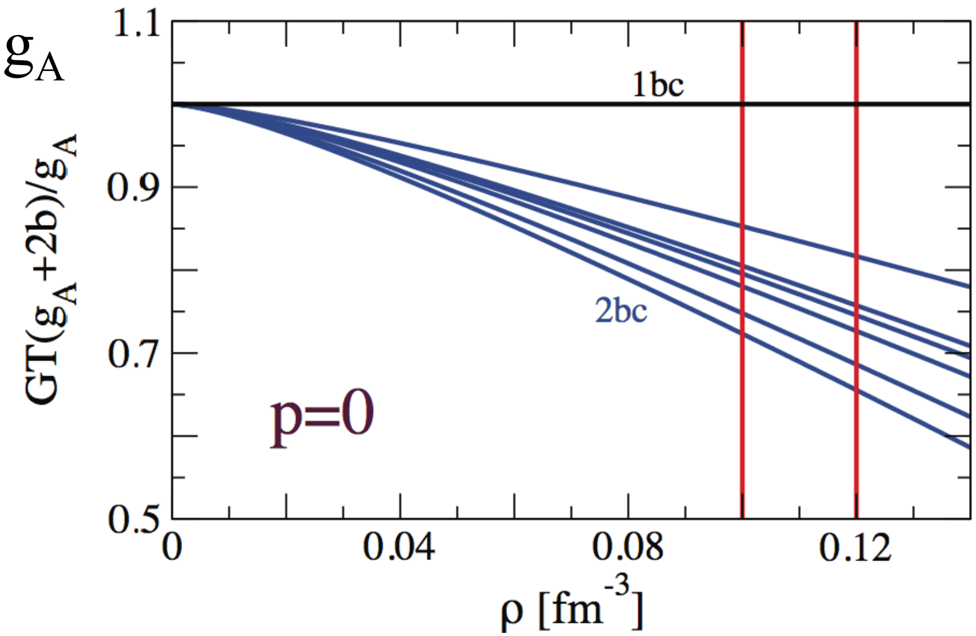
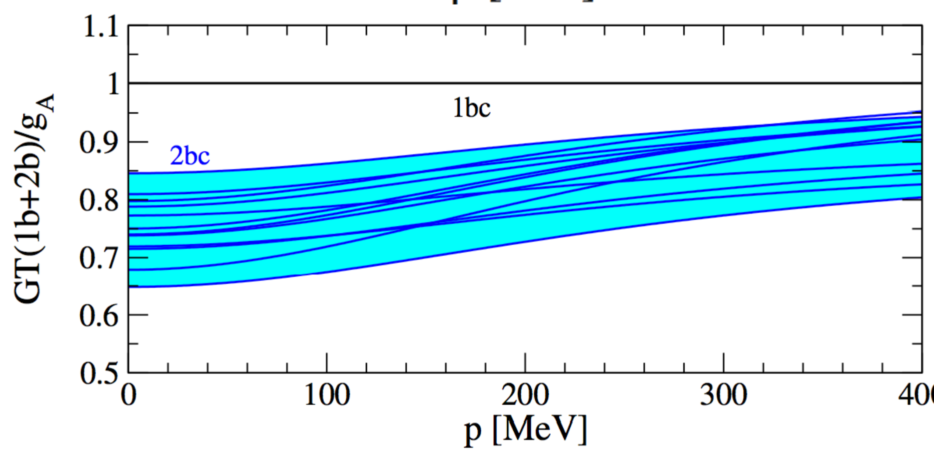


comparable to empirical q ~ 0.75 for β, 2νββ decays

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



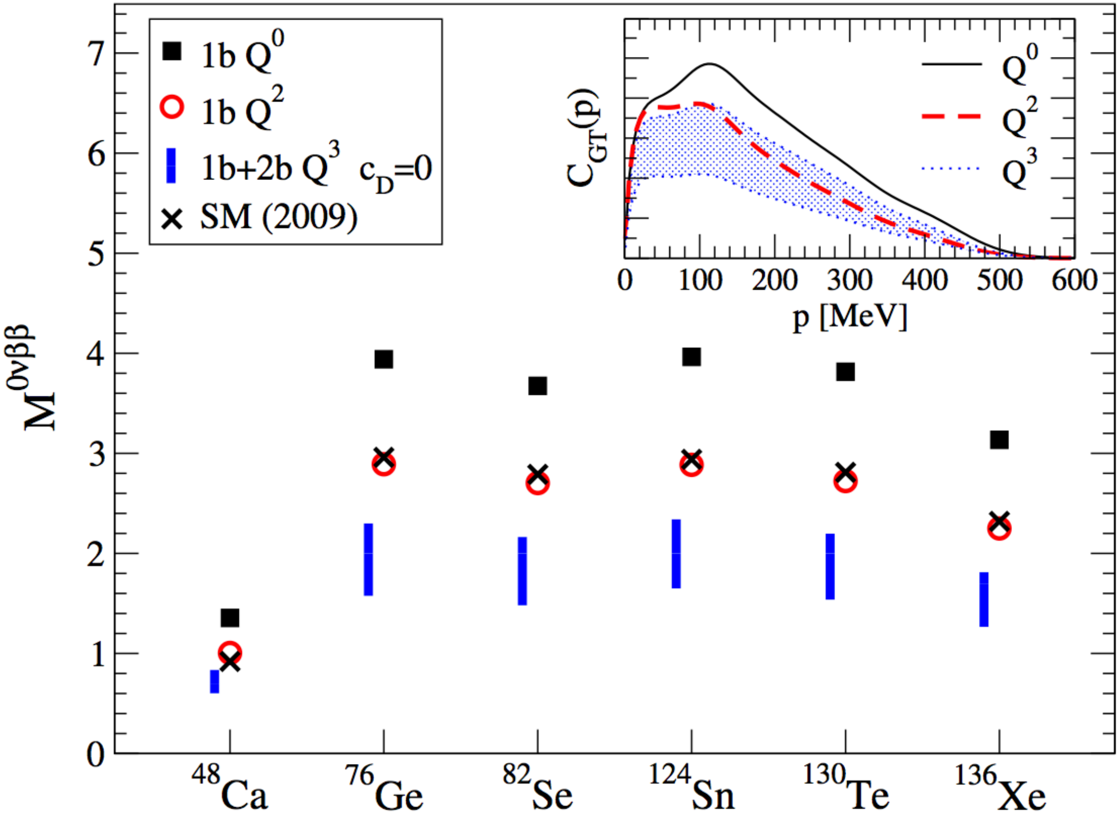
less quenching for 0νββ for p ~ m_π

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

Chiral EFT and $0\nu\beta\beta$ decay

NMEs for $0\nu\beta\beta$ decay based on chiral EFT operator

Menendez, Gazit, AS (2011)



modest quenching because $0\nu\beta\beta$ decay probes higher momentum transfer

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

Chiral EFT and $0\nu\beta\beta$ decay

NMEs for $0\nu\beta\beta$ decay based on chiral EFT operator

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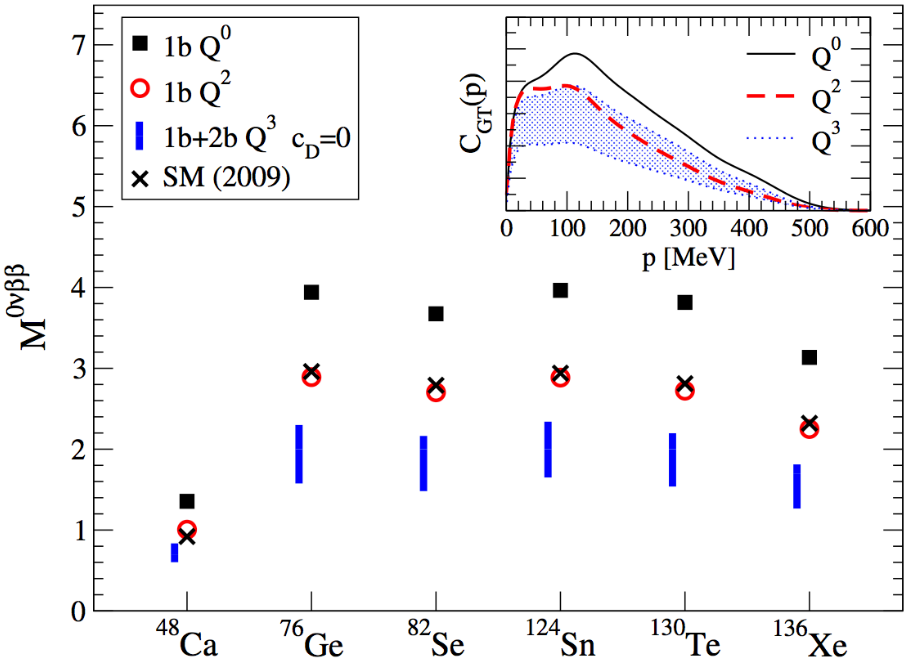

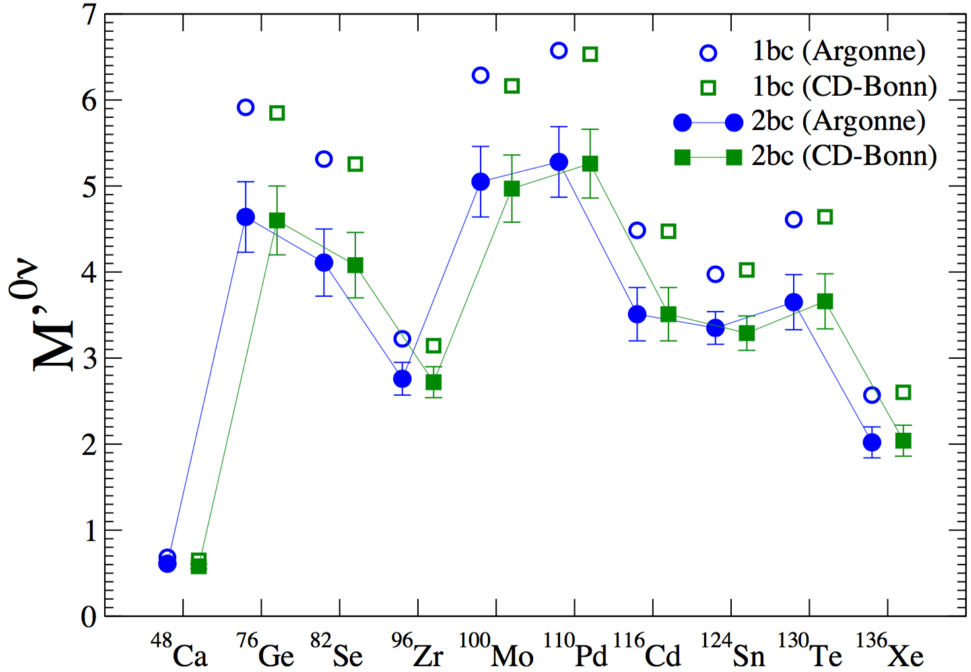

Engel, Simkovic ,Vogel (2014)

modest quenching because $0\nu\beta\beta$ decay probes higher momentum transfer

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

Summary

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

theo. uncertainties dominated by uncert. in nuclear forces
need to explore reg. scheme and long-range physics (e.g., c_i's)

calculation of **0νββ operator in chiral EFT**
less quenching compared to β, 2νββ decays

important to explore uncertainties in new calculations of NMEs