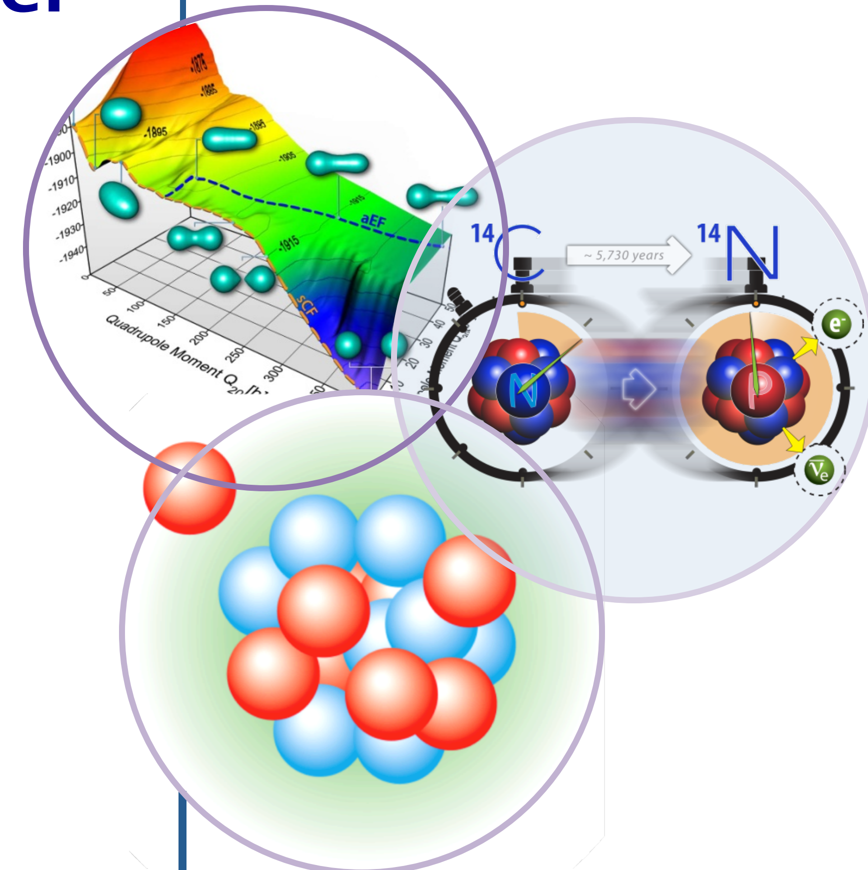
Ab-initio structure and the role of three-nucleon forces in nucleonic matter

Gaute Hagen (ORNL)



Lecture 3, TALENT school

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Outline

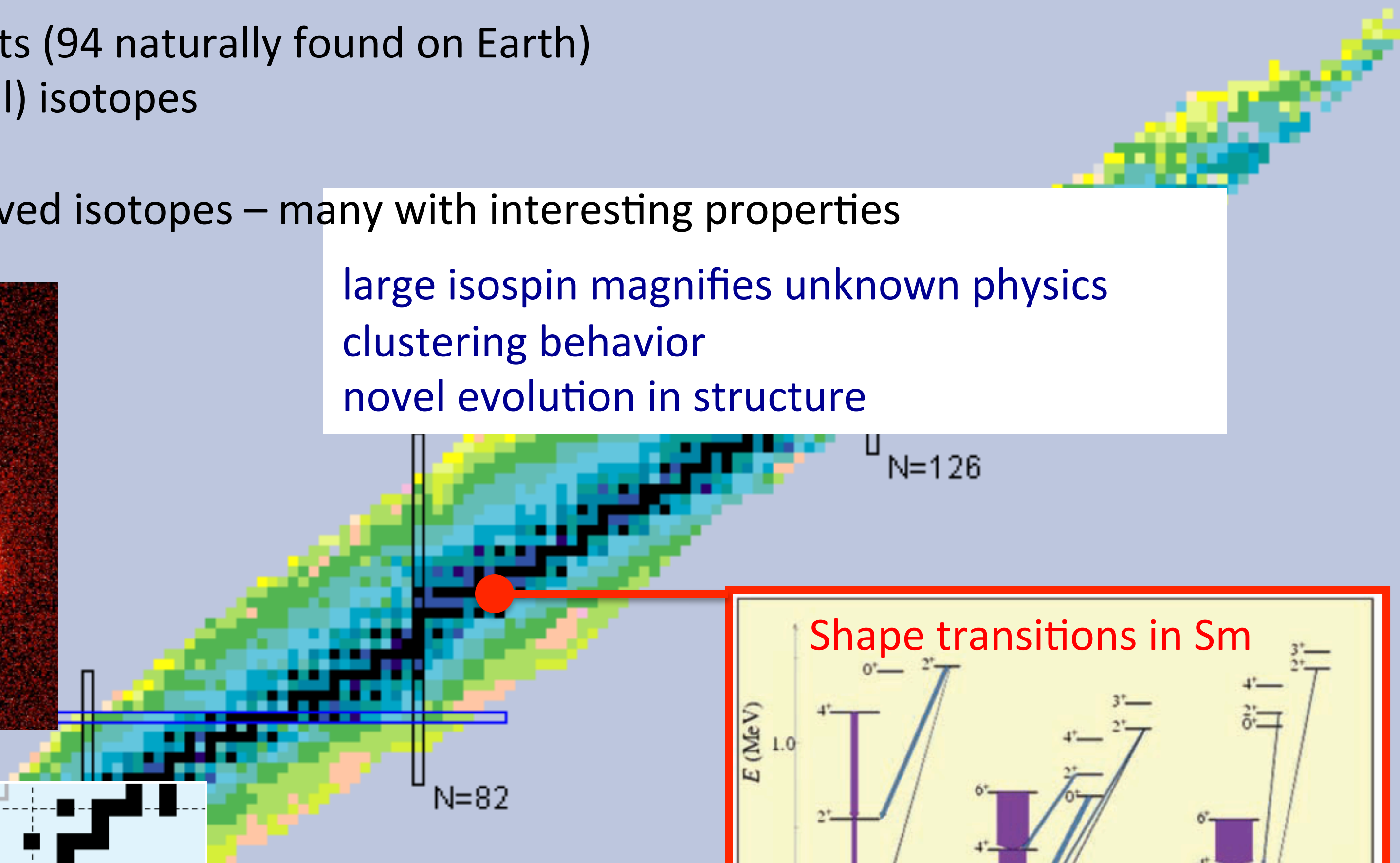
- Nuclei across the chart and status of *ab initio* calculations with three-nucleon forces (3NFs)
- Chiral effective field theory – Why 3NFs?
  - SRG evolution of chiral interactions
- Role of 3NFs on spectra of light nuclei
- Role of 3NFs on weak decays and quenching of axial coupling in nuclei
- The oxygen dripline and 3NFs
- Evolution of shell structure in neutron calcium isotopes
- The problem of saturation and overbinding in nuclei from chiral interactions
  - Simultaneous Optimization of chiral forces with input from nuclei selected nuclei up to A ~ 25
  - Accurate binding energies and radii from a chiral interaction ($NNLO_{sat}$)
- Impact of 3NFs in infinite nucleonic matter

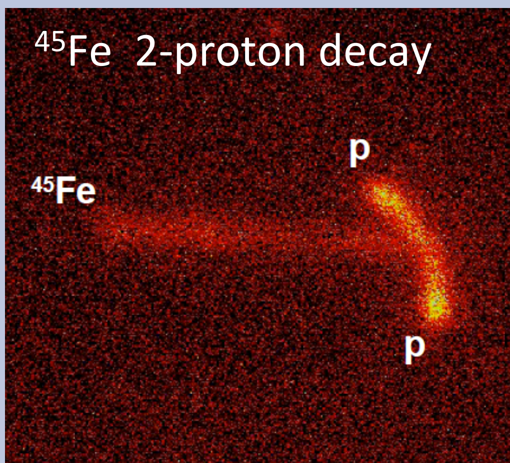
Nuclei across the chart

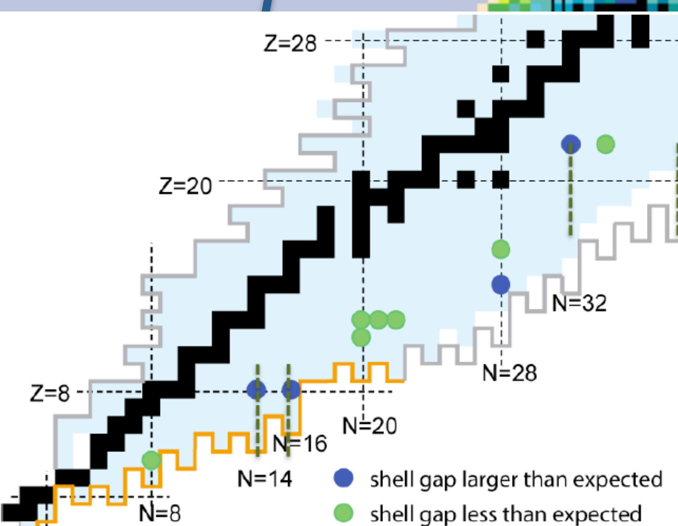
118 chemical elements (94 naturally found on Earth)
288 stable (primordial) isotopes

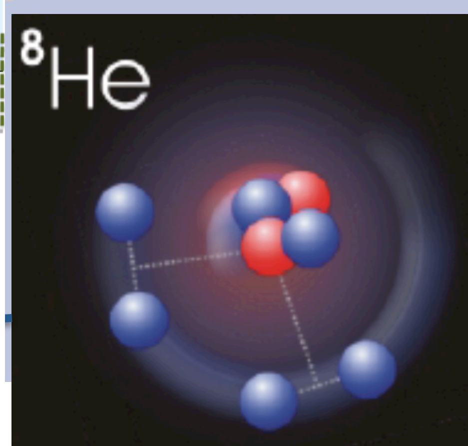
Thousands of short-lived isotopes – many with interesting properties

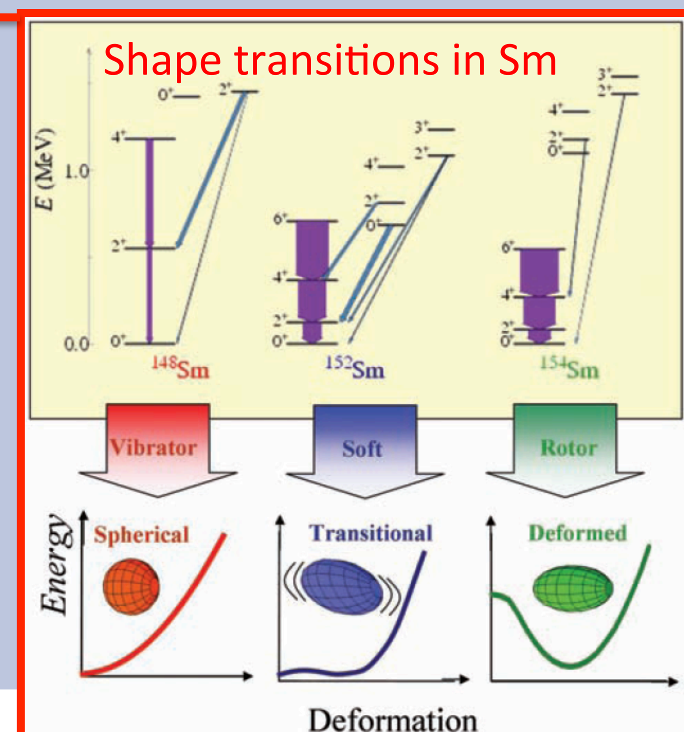
large isospin magnifies unknown physics
clustering behavior
novel evolution in structure





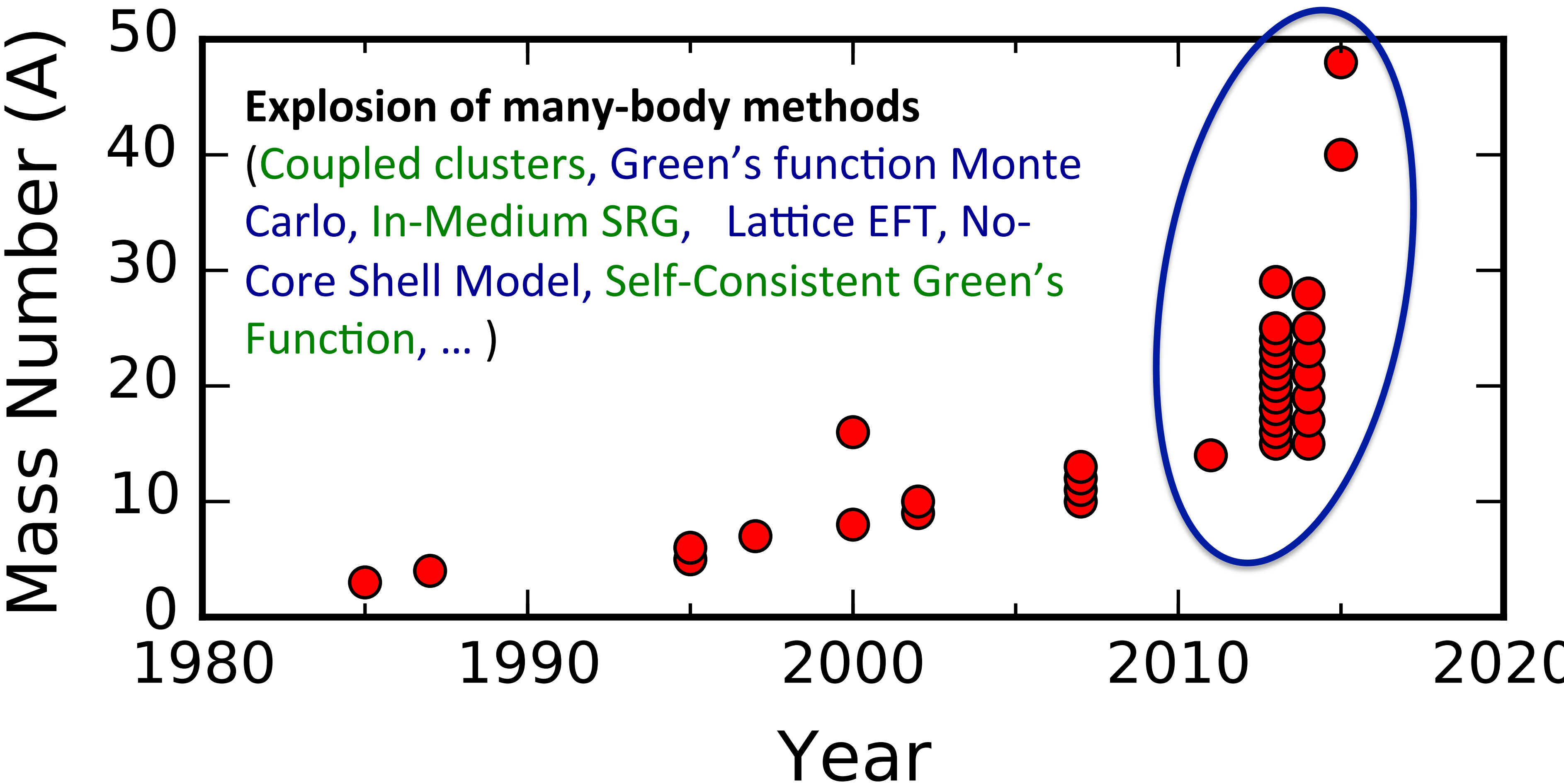




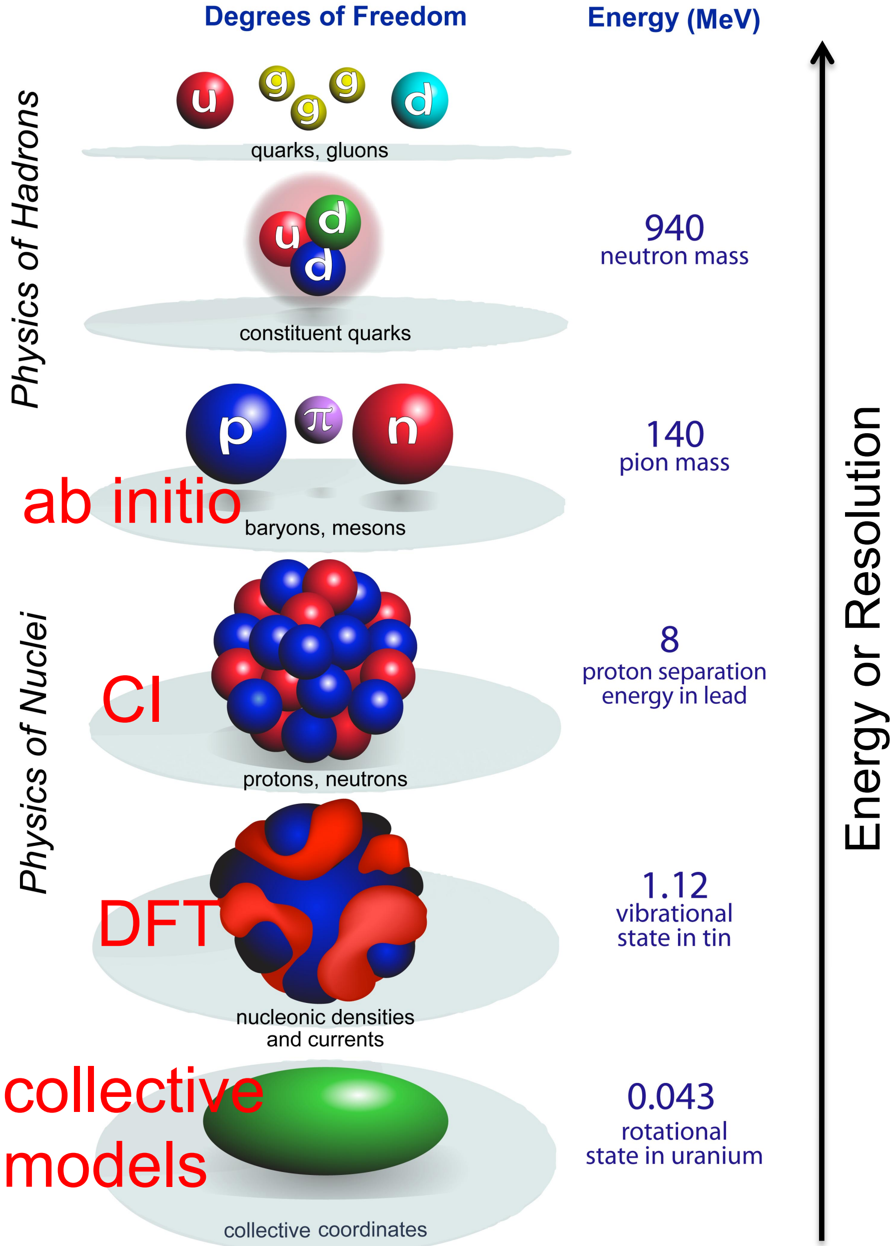


Reach of realistic *ab initio* calculations

(realistic meaning that binding energies are within 5% of experimental values)



Energy scales and relevant degrees of freedom



Chiral symmetry is broken

Pion is Nambu-Goldstone boson

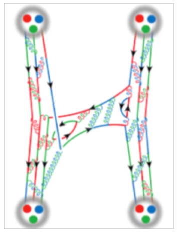
Tool: Chiral effective field theory

Effective theories provide us with model independent approaches to atomic nuclei

Key: Separation of scales

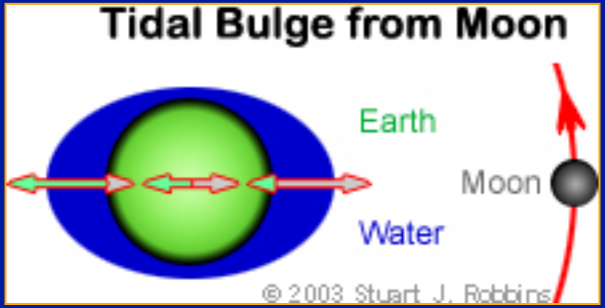
Fig.: Bertsch, Dean, Nazarewicz, SciDAC review (2007)

Three-nucleon forces – Why?

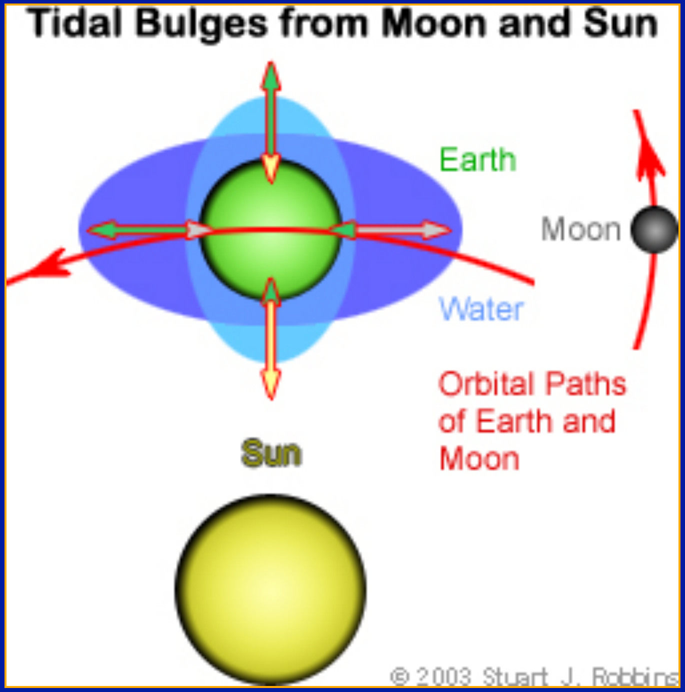


- Nucleons are not point particles (i.e. not elementary).
- We neglected some internal degrees of freedom (e.g. Δ-resonance, "polarization effects", …), and unconstrained high-momentum modes.

Example from celestial mechanics:
Earth-Moon system: point masses and modified two-body interaction



Other tidal effects cannot be included in the two-body interaction! Three-body force unavoidable for point masses.



The question is not: Do three-body forces enter the description?
The (only) question is: How large are three-body forces?

Three–body forces cont'd

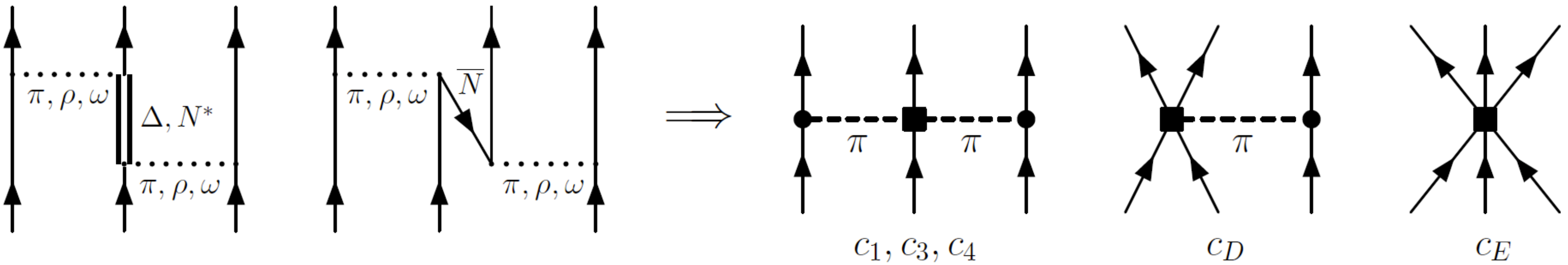


Figure 23: Eliminating degrees of freedom leads to three-body forces.

(taken from Bogner, Furnstahl, Schwenk, arXiv:0912.3688)

Leading three-nucleon force

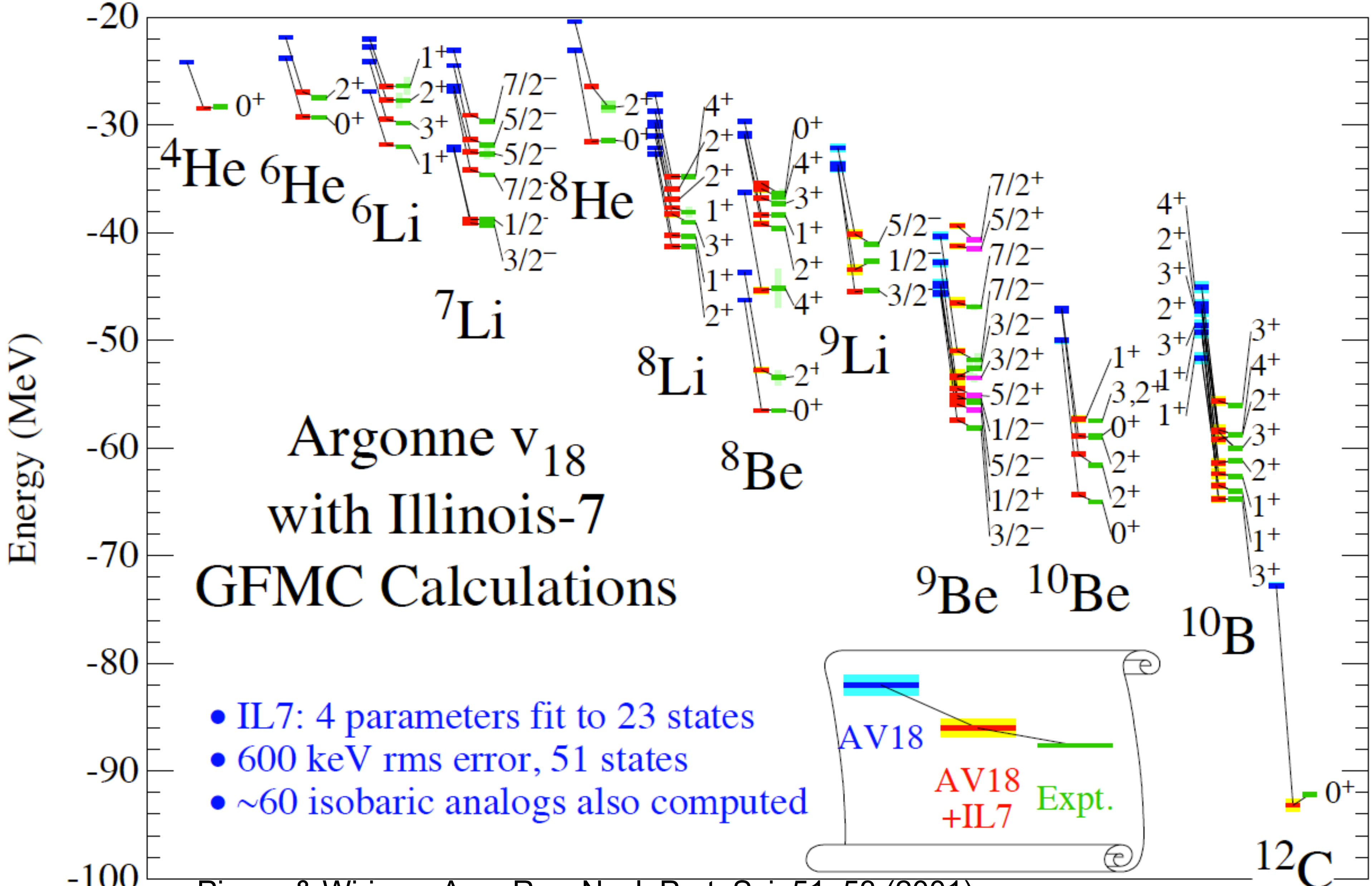
1. Long-ranged two-pion term (Fujita & Miyazawa …)
2. Intermediate-ranged one-poin term
3. Short-ranged three-nucleon contact

The question is not: Do three-body forces enter the description?

The (only) question is: How large are three-body forces?

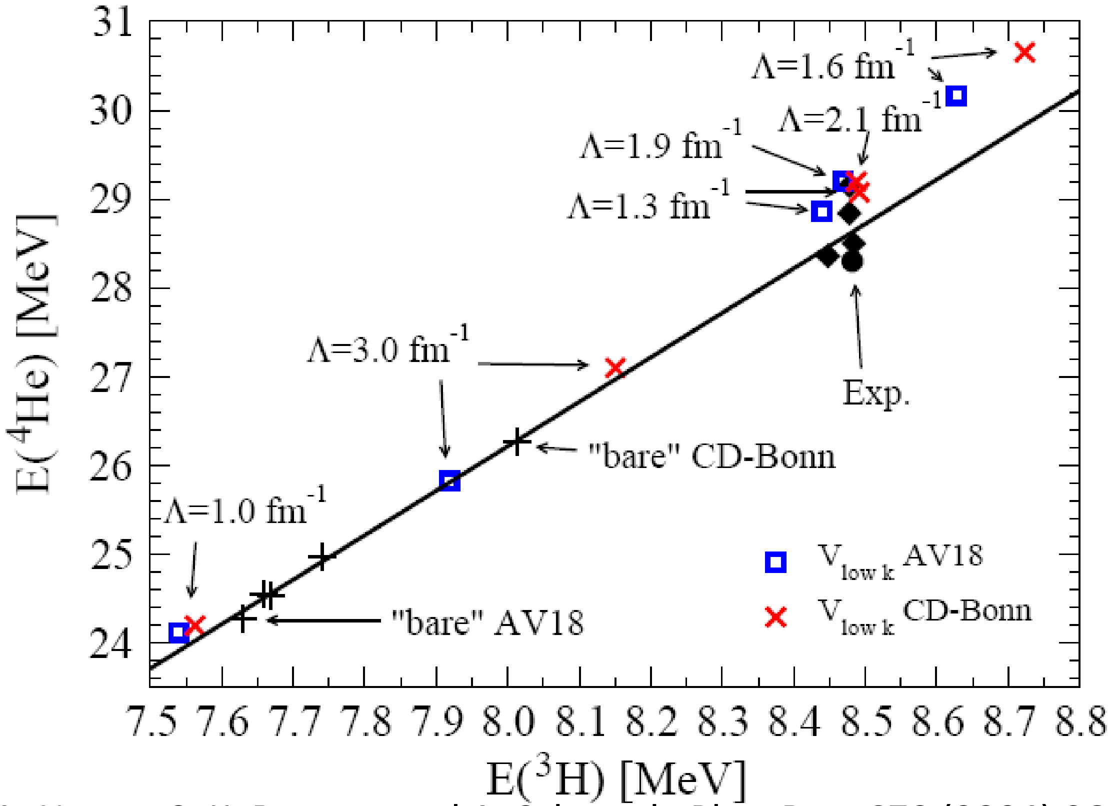
Green's function Monte Carlo computations

Demonstration that light nuclei can be build from scratch



Pieper & Wiringa, Ann. Rev. Nucl. Part. Sci. 51, 53 (2001)

Non-uniqueness of three-nucleon forces



A. Nogga, S. K. Bogner, and A. Schwenk, Phys.Rev. C70 (2004) 061002

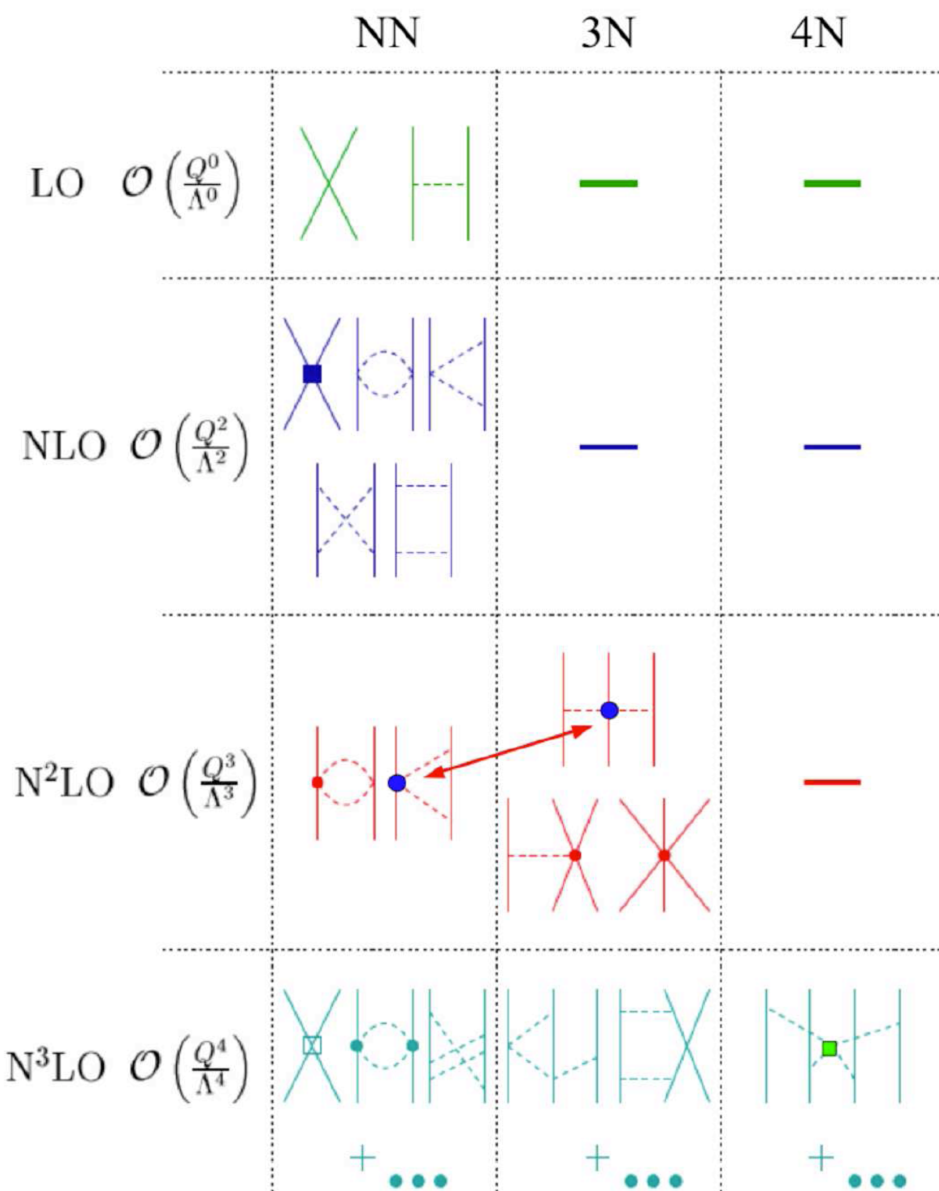
As cutoff Λ is varied, motion along "Tjon line".

Addition of Λ-dependent three-nucleon force yields (almost) agreement with experiment. **Q: What's missing?**

A: The complete description of ^{4}He would require four-nucleon forces!

Nuclear forces from chiral effective field theory

[Weinberg; van Kolck; Epelbaum *et al*.; Entem & Machleidt; …]



- developing higher orders and higher rank (3NF, 4NF) [Epelbaum 2006; Bernard et al 2007; Krebs et al 2012; Hebeler et al 2015; …]
- implemented in continuum and on lattice [Borasoy et al 2007]
- local / non-local formulations [Gezerlis et al 2013]
- propagation of uncertainties on horizon [Navarro Perez 2014]
- different optimization protocols [Ekström et al 2013]

Much improved understanding and handling via renormalization group transformations [Bogner et al 2003; Bogner et al 2007]

Similarity renormalization group (SRG) transformation

Glazek, & Wilson, PRD **48** (1993) 5863; **49** (1994) 4214; Wegner, Ann. Phys. **3** (1994) 77; Perry, Bogner, & Furnstahl (2007)

Main idea: decouple low from high momenta via a (unitary) similarity transformation

Unitary transformation

$$\hat{H}(s) = U(s)\hat{H}U^\dagger(s) = U(s)\left(\hat{T}+\hat{V}\right)U^\dagger(s)$$

Evolution equation

$$\frac{d\hat{H}(s)}{ds} = \left[\eta(s), \hat{H}(s)\right] \qquad \text{with} \qquad \eta(s) \equiv \frac{dU(s)}{ds}U^\dagger(s) = -\eta^\dagger(s)$$

Choice of unitary transformation through (one does not need to construct U explicitly).

$$\eta(s) = \left[\hat{T}, \hat{H}(s)\right]$$

yields scale-dependent potential that becomes more and more diagonal

$$\hat{H}(s) = \hat{T} + \hat{V}(s)$$

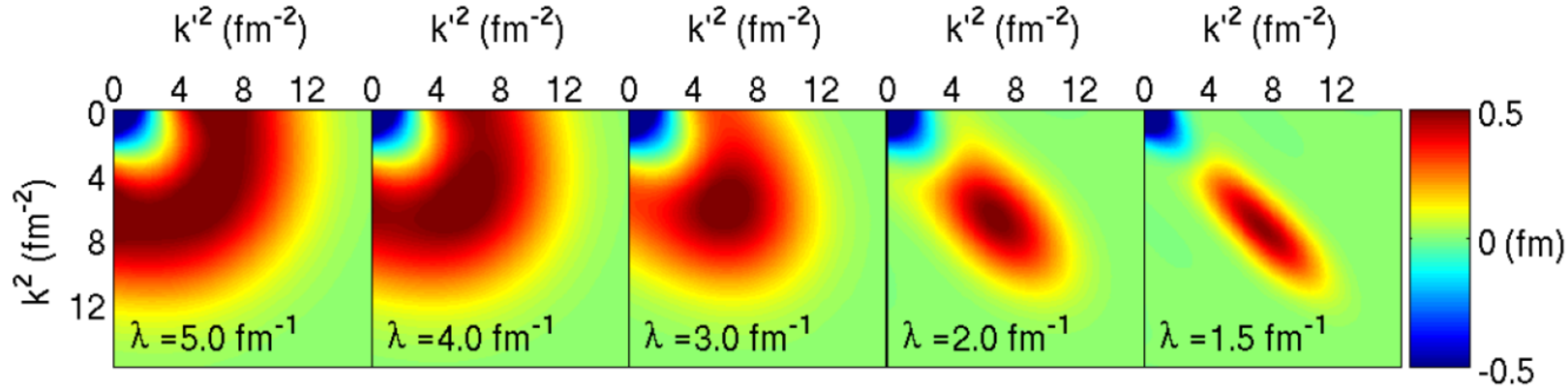
Note: Baker-Campbell-Hausdorff expansion implies that SRG of 2-body force generates many-body forces

$$e^{-\eta}\hat{H}e^{\eta} = \hat{H} + \left[\hat{H}, \eta\right] + \frac{1}{2!}\left[\left[\hat{H}, \eta\right], \eta\right] + \ldots$$

SRG evolution of a chiral potential

(use cutoff $\lambda \equiv s^{-1/4}$ as evolution variable)

$^1S_0$ from N^{3}LO (500 MeV) of Entem/Machleidt



$^3S_1$ from N^{3}LO (500 MeV) of Entem/Machleidt

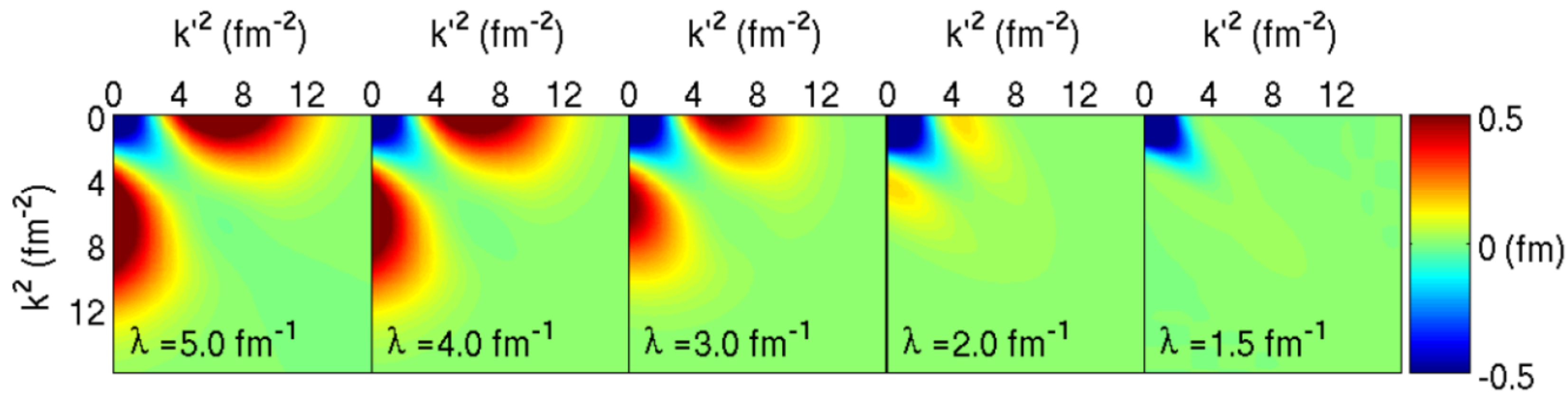


Fig.: Bogner & Furnstahl. See http://www.physics.ohio-state.edu/~ntg/srg

Understanding SRGs

Question: Which statement is correct?

1. The SRG is a unitary transformation, and no information is lost.
2. The SRG is only accurate up to the cutoff.

Understanding SRGs

Question: Which statement is correct?

1. The SRG is a unitary transformation, and no information is lost. ✔
2. The SRG is only accurate up to the cutoff.

When performing the SRG, up to A-body forces are created in an A-body system ("no free lunch theorem"). In practice, one hopes (with view to the chiral power counting) that the computation of 2-body and 3-body forces might be sufficient.

Q: How can we check in practice, that keeping 2-body and 3-body forces is sufficient?

1. Perform a computation with and without SRG an compare.
2. Check how results in the A-body system depend on the cutoff/evolution parameter

Understanding SRGs

Question: Which statement is correct?

1. The SRG is a unitary transformation, and no information is lost. ✔
2. The SRG is only accurate up to the cutoff.

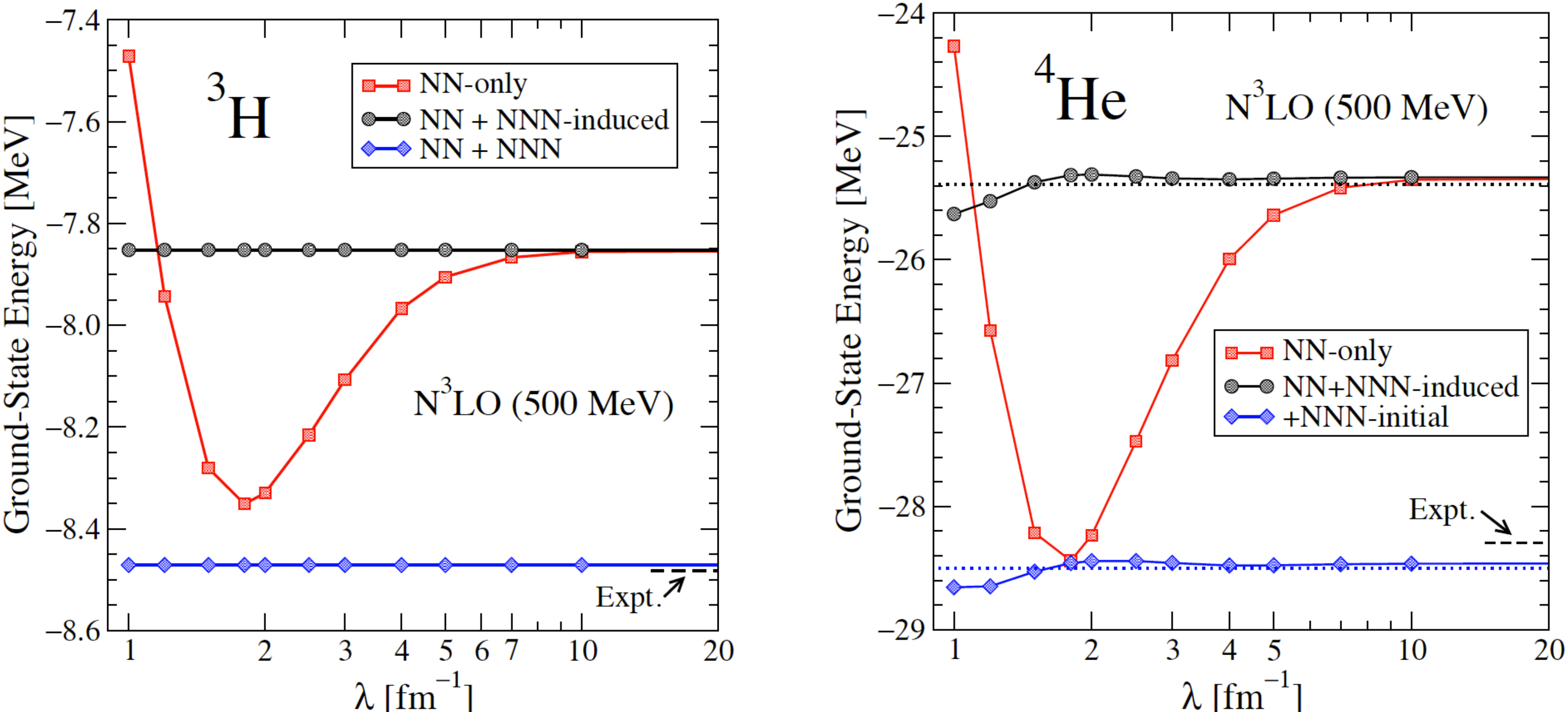
When performing the SRG, up to A-body forces are created in an A-body system ("no free lunch theorem") . In practice, one hopes (with view to the chiral power counting) that the computation of 2-body and 3-body forces might be sufficient.

Q: How can we check in practice, that keeping 2-body and 3-body forces is sufficient?

1. Perform a computation with and without SRG an compare.
2. Check how results in the A-body system depend on the cutoff/evolution parameter ✔

Of course: Any observable other than the Hamiltonian also needs to be transformed.

Solution of ^{3}H and ^{4}He with induced and initial 3NF



Jurgenson, Navratil & Furnstahl, Phys. Rev. Lett. 103, 082501 (2009), arXiv:0905.1873

Q: What is the effect of (omitted) 4NF and forces of even higher rank?

A: In ^{4}He, (short ranged) 4NF yield about 200 keV (see energies at small momentum)
Note: This is consistent with deviation from experiment!

Second quantized normal-ordered Hamiltonian:

$$H_N = \sum_{pq} \langle \mathbf{k}_p | f | \mathbf{k}_q \rangle : a_p^\dagger a_q :$$
$$+ \frac{1}{4} \sum_{pqrs} \langle \mathbf{k}_p \mathbf{k}_q | v | \mathbf{k}_r \mathbf{k}_s \rangle : a_p^\dagger a_q^\dagger a_s a_r :$$
$$+ \frac{1}{36} \sum_{pqrstu} \langle \mathbf{k}_p \mathbf{k}_q \mathbf{k}_r | w | \mathbf{k}_s \mathbf{k}_t \mathbf{k}_u \rangle : a_p^\dagger a_q^\dagger a_r^\dagger a_u a_t a_s :$$

Note: all two-body matrix elements are here assumed to be anti-symmetric

Second quantized normal-ordered Hamiltonian:

The vacuum energy:

$$
\begin{aligned}
E_0 &= \langle \Phi_0 | H | \Phi_0 \rangle \\
&= \sum_i \langle \mathbf{k}_i | f | \mathbf{k}_i \rangle + \frac{1}{2} \sum_{i,j} \langle \mathbf{k}_i \mathbf{k}_j | v | \mathbf{k}_i \mathbf{k}_j \rangle \\
&\quad + \frac{1}{6} \sum_{ijk} \langle \mathbf{k}_i \mathbf{k}_j \mathbf{k}_l | w | \mathbf{k}_i \mathbf{k}_j \mathbf{k}_l \rangle
\end{aligned}
$$

The normal-ordered one-body part is given by

$$
\begin{aligned}
\langle \mathbf{k}_p | f | \mathbf{k}_q \rangle &= \langle \mathbf{k}_p | t | \mathbf{k}_q \rangle + \sum_i \langle \mathbf{k}_p \mathbf{k}_i | V_{\mathrm{N}N} | \mathbf{k}_q \mathbf{k}_i \rangle \\
&\quad + \frac{1}{2} \sum_{ij} \langle \mathbf{k}_p \mathbf{k}_i \mathbf{k}_j | V_{3\mathrm{NF}} | \mathbf{k}_q \mathbf{k}_i \mathbf{k}_j \rangle \, .
\end{aligned}
$$

The normal-ordered two-body part is given by:

$$
\begin{aligned}
\langle \mathbf{k}_p \mathbf{k}_q | v | \mathbf{k}_r \mathbf{k}_s \rangle &= \langle \mathbf{k}_p \mathbf{k}_q | V_{\mathrm{N}N} | \mathbf{k}_r \mathbf{k}_s \rangle \\
&\quad + \sum_i \langle \mathbf{k}_p \mathbf{k}_q \mathbf{k}_i | V_{3\mathrm{NF}} | \mathbf{k}_i \mathbf{k}_r \mathbf{k}_s \rangle
\end{aligned}
$$

The normal-ordered three-body part is given by:

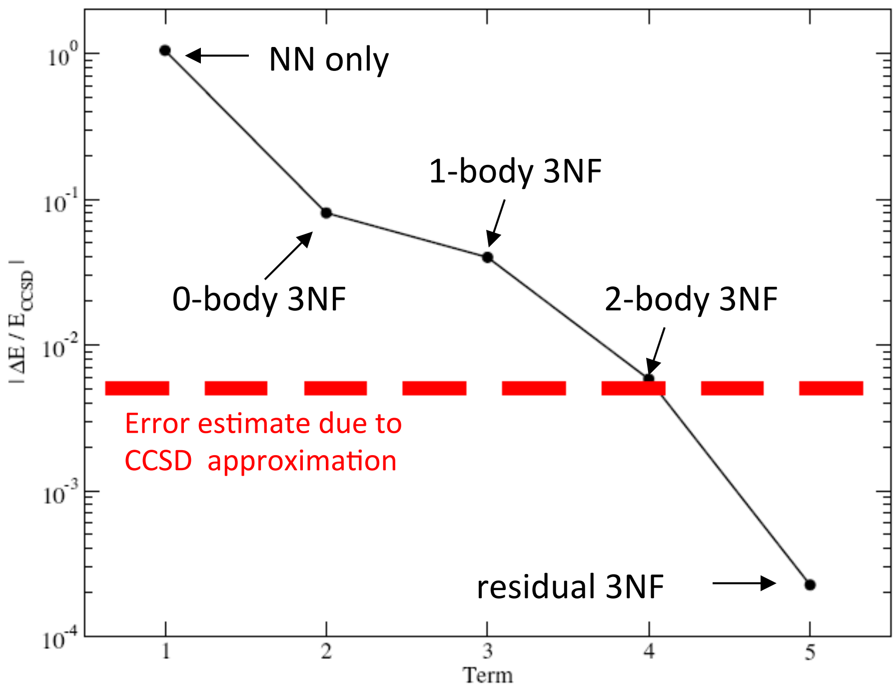
$$
\langle \mathbf{k}_p \mathbf{k}_q \mathbf{k}_r | w | \mathbf{k}_s \mathbf{k}_t \mathbf{k}_u \rangle = \langle \mathbf{k}_p \mathbf{k}_q \mathbf{k}_r | V_{3\mathrm{NF}} | \mathbf{k}_s \mathbf{k}_t \mathbf{k}_u \rangle
$$

Normal-ordered Hamiltonian at the two-body level (approximation)

$$H_N = \sum_{pq} \langle \mathbf{k}_p | f | \mathbf{k}_q \rangle : a_p^\dagger a_q :$$
$$+ \frac{1}{4} \sum_{pqrs} \langle \mathbf{k}_p \mathbf{k}_q | v | \mathbf{k}_r \mathbf{k}_s \rangle : a_p^\dagger a_q^\dagger a_s a_r :$$
$$\cancel{+ \frac{1}{36} \sum_{pqrstu} \langle \mathbf{k}_p \mathbf{k}_q \mathbf{k}_r | w | \mathbf{k}_s \mathbf{k}_t \mathbf{k}_u \rangle : a_p^\dagger a_q^\dagger a_r^\dagger a_u a_t a_s :}$$

Can we neglect the residual three-body term of the normal ordered Hamiltonian?
If so, we can re-use all the formalism developed for two-nucleon forces!

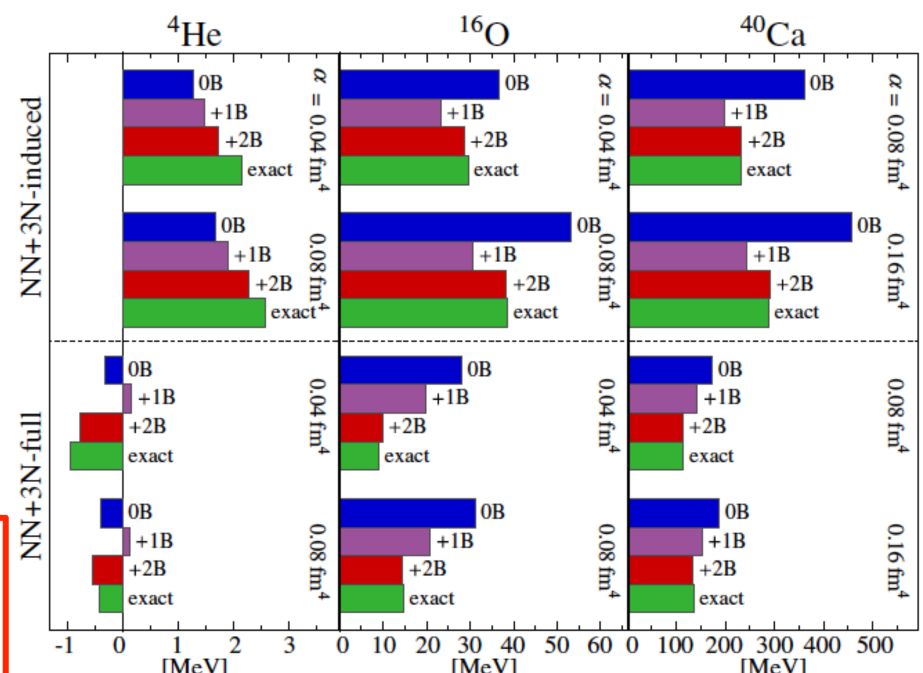
What's the role of three-nucleon forces?



Contributions to binding of ^{4}He. [Hagen, Papenbrock, Dean, Schwenk, Nogga, Wloch, Piecuch, PRC 76, 034302 (2007)]

$$\hat{H}_3 = \frac{1}{6}\sum_{ijk}\langle ijk||ijk\rangle + \frac{1}{2}\sum_{ijpq}\langle ijp||ijq\rangle\{\hat{a}_p^\dagger\hat{a}_q\} + \frac{1}{4}\sum_{ipqrs}\langle ipq||irs\rangle\{\hat{a}_p^\dagger\hat{a}_q^\dagger\hat{a}_s\hat{a}_r\} + \cancel{\hat{h}_3},$$

Contributions to binding of ^{4}He, ^{16}O, and ^{40}Ca. R. Roth et al, Phys Rev. Lett. 109, 052501 (2012)



Residual normal-ordered 3N term can safely be neglected in finite nuclei with forces from chiral EFT

Light nuclei from chiral NN and 3NFs with no-core shell model

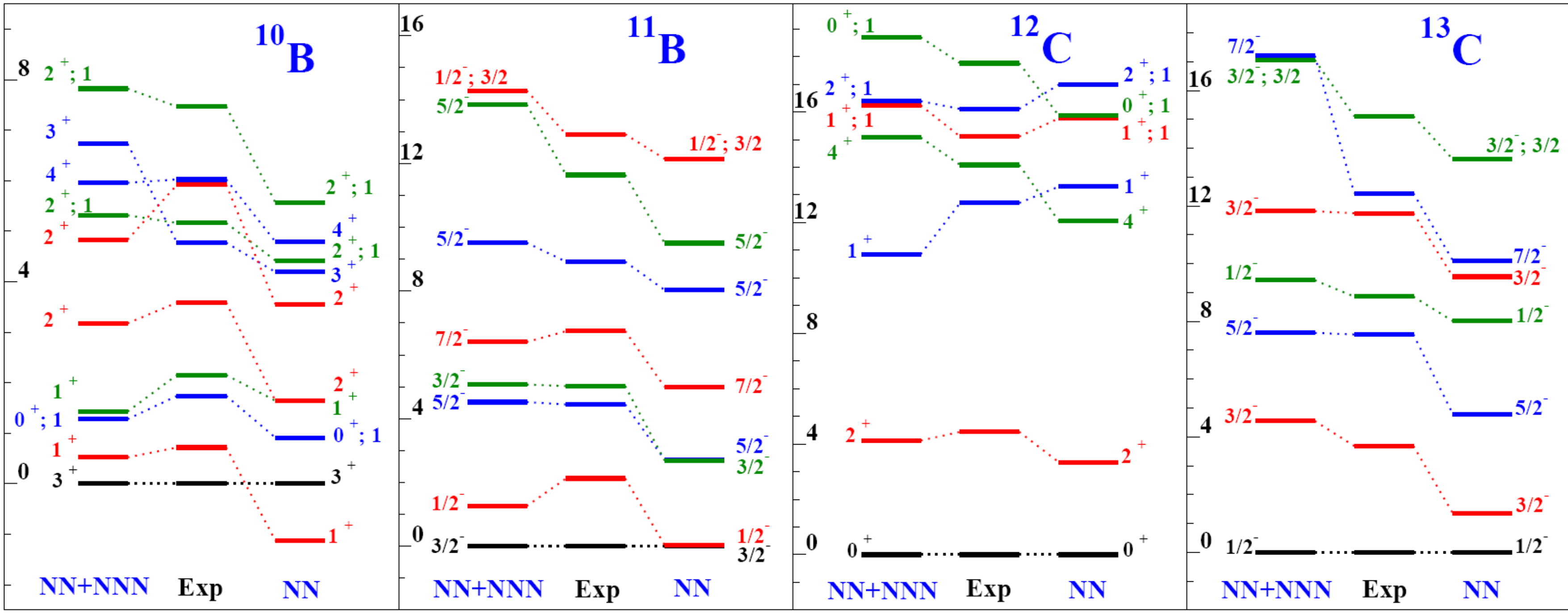


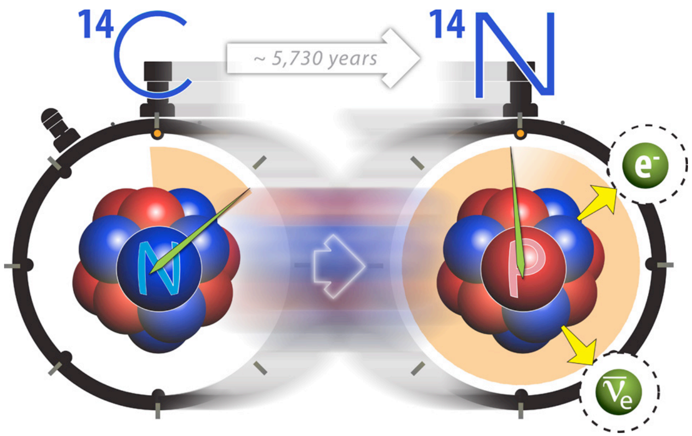
Figure 5. States dominated by p-shell configurations for ^{10}B, ^{11}B, ^{12}C, and ^{13}C calculated at $N_{\max} = 6$ using $\hbar\Omega = 15$ MeV (14 MeV for ^{10}B). Most of the eigenstates are isospin T=0 or 1/2, the isospin label is explicitly shown only for states with T=1 or 3/2. The excitation energy scales are in MeV.

P. Navratil et al., Phys. Rev. Lett. 99, 042501 (2007), nucl-th/0701038.

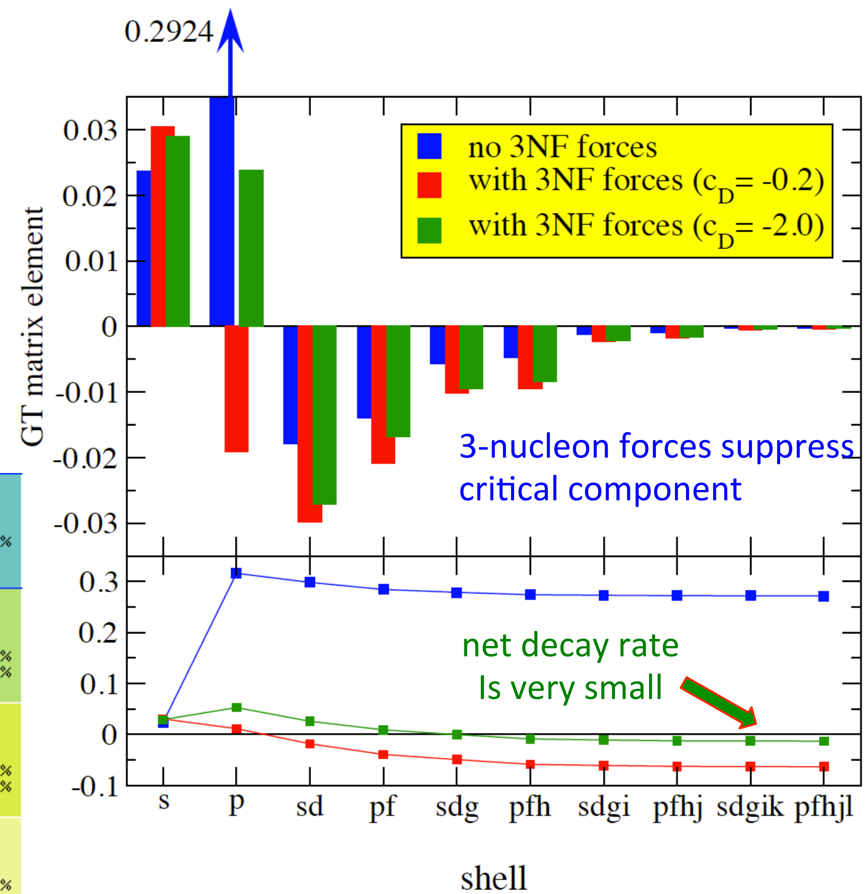
Review: Navratil, Quaglioni, Stetcu, Barrett, J. Phys. G 36, 083101 (2009); arXiv:0904.0463.

Anomalous Long Lifetime of Carbon-14

Anomalous long lifetime of Carbon-14 (used in carbon dating) explained by ab-initio CI calculations using NN and NNN forces. Three-nucleon forces yield suppression of transition matrix element.



Z	12O 0.40 MeV P	13O 8.58 MS εp: 100.00% ε: 100.00%	14O 70.620 S ε: 100.00%	15O 122.24 S ε: 100.00%	16O STABLE 99.757%	17O STABLE 0.038%	18O STABLE 0.205%	19O 26.88 S β-: 100.00%	20O 13.51 S β-: 100.00%
7	11N 0.83 MeV P: 100.00%	12N 11.000 MS ε: 100.00%	13N 9.965 M ε: 100.00%	14N STABLE 99.636%	15N STABLE 0.364%	16N 7.13 S β-: 100.00% β-α: 1.2E-3%	17N 4.173 S β-: 100.00% β-n: 95.1%	18N 620 MS β-: 100.00% β-α: 12.20%	19N 336 MS β-: 100.00% β-n: 41.80%
6	10C 19.308 S ε: 100.00%	11C 20.334 M ε: 100.00%	12C STABLE 98.93%	13C STABLE 1.07%	14C 5700 Y β-: 100.00%	15C 2.449 S β-: 100.00%	16C 0.747 S β-: 100.00% β-n: 99.00%	17C 193 MS β-: 100.00% β-n: 32.00%	18C 92 MS β-: 100.00% β-n: 31.50%
5	9B 0.54 KeV 2α: 100.00% P: 100.00%	10B STABLE 19.9%	11B STABLE 80.1%	12B 20.20 MS β-: 100.00% B3A: 1.58%	13B 17.33 MS β-: 100.00%	14B 12.5 MS β-: 100.00%	15B 9.93 MS β-: 100.00% β-n: 93.60%	16B <190 PS N	17B 5.08 MS β-: 100.00% β-n: 63.00%
4	8Be 5.57 eV α: 100.00%	9Be STABLE 100.%	10Be 1.387E+6 Y β-: 100.00%	11Be 13.81 S β-: 100.00% β-α: 3.1%	12Be 21.49 MS β-: 100.00% β-n≤ 1.00%	13Be 2.7E-21 S N	14Be 4.35 MS β-: 100.00% β-n: 81.00%	15Be <200 NS N	16Be <200 NS 2N
	4	5	6	7	8	9	10	11	N



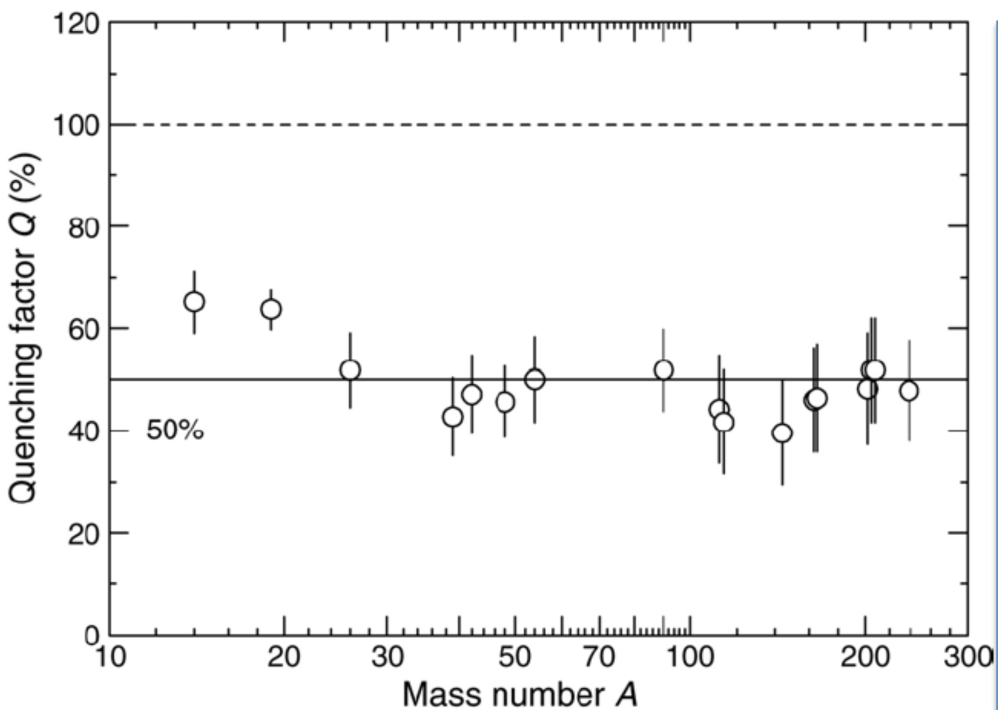
Maris, Vary, Navrátil, Ormand, Nam, Dean,
Phys. Rev. Lett. 106, 202502 (2011)

Quenching of Gamow–Teller strength in nuclei

The Ikeda sum-rule $S^{\mathrm{N}}(\mathrm{GT}) = S^{\mathrm{N}}(\mathrm{GT}^{-}) - S^{\mathrm{N}}(\mathrm{GT}^{+}) = 3(N-Z)$

Long-standing problem: Experimental beta-decay strengths quenched compared to theoretical results.

$$Q = \frac{S^{-}_{\mathrm{GT}}(\omega^{-}_{\mathrm{top}}) - S^{+}_{\mathrm{GT}}(\omega^{+}_{\mathrm{top}})}{3(N-Z)}$$



Surprisingly large quenching Q (50%) obtained from (p,n) experiments. The excitation energies were just above the giant Gamow-Teller resonance ~10-15MeV (Gaarde 1983).

- Measurement of GT strengths to high energies (Sasano et al 2009, Yako et al 2005),suggests a much smaller quenching Q =0.88-0.92

- Renormalizations of the Gamow-Teller operator?
- Missing correlations in nuclear wave functions?
- Model-space truncations?

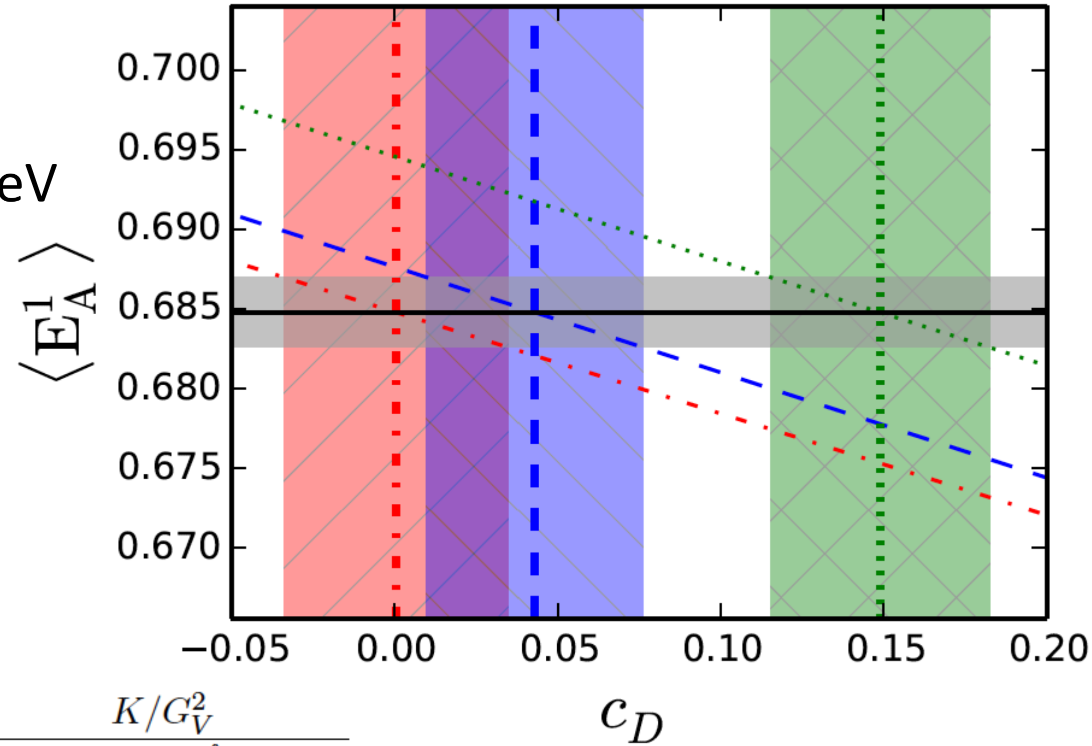
- **What does two-body currents and three-nucleon forces add to this long-standing problem?**

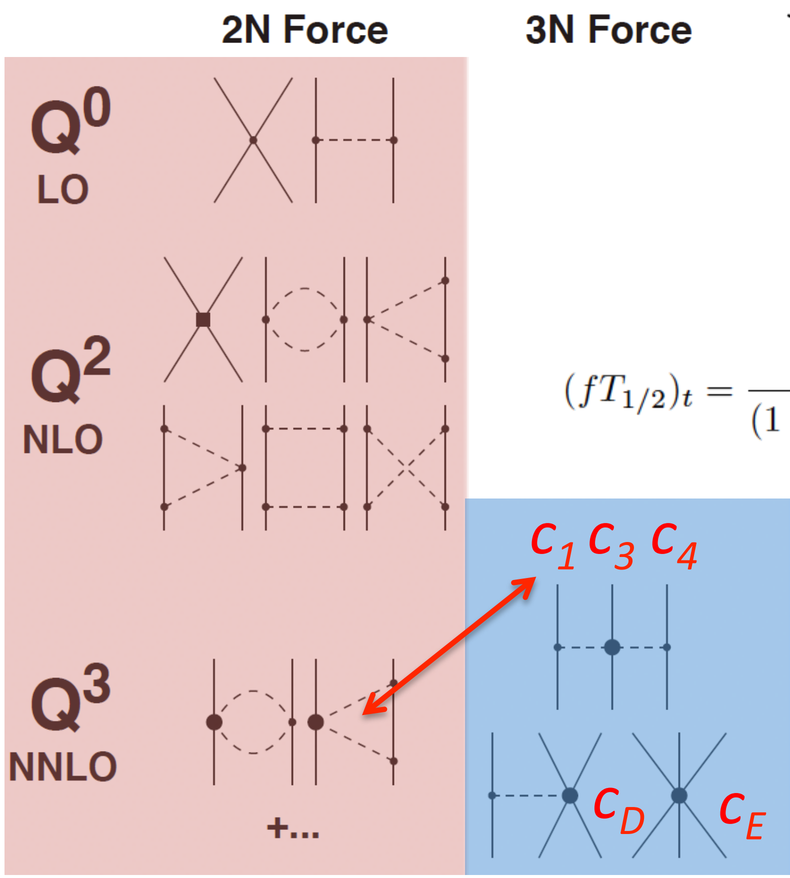
Optimization of chiral interactions currents at NNLO

A. Ekström, G. Jansen, K. Wendt et al, PRL 113 262504 (2014)

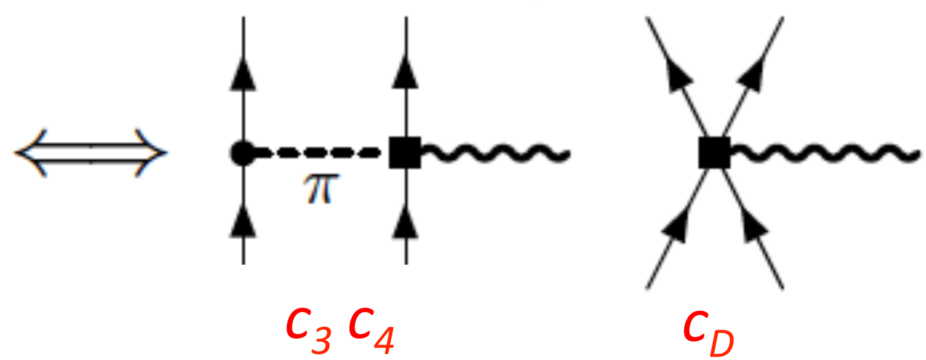
c_D - c_E fit of A=3 binding energies and the ^{3}H half life at NNLO for chiral cutoffs Λ = 450,500,550 MeV

$[c_D, c_E] = [0.043, -0.501]$





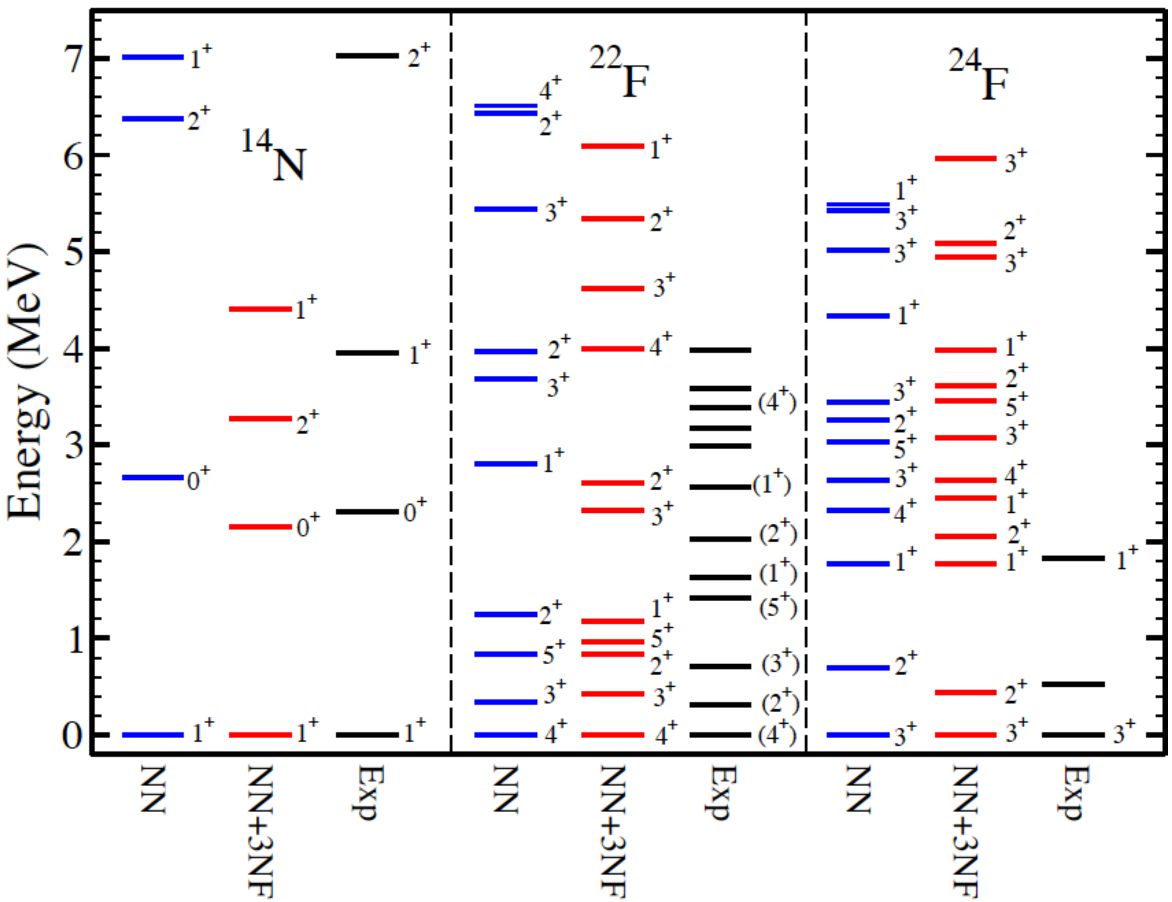
$$(fT_{1/2})_t = \frac{K/G_V^2}{(1-\delta_c) + 3\pi \frac{f_A}{f_V} \langle E_1^A \rangle^2}$$



Coupled cluster calculations of odd-odd nuclei

Diagonalize $\overline{H} = e^{-T} H_N e^T$ via a novel equation-of-motion technique:

$$R \equiv \sum_{ia} r_i^a p_a^\dagger n_i + \frac{1}{4} \sum_{ijab} r_{ij}^{ab} p_a^\dagger N_b^\dagger N_j n_i$$



- Compute spectra of daughter nuclei as beta decays of mother nuclei
- Level densities in daughter nuclei increase slightly with 3NF
- Predict several states in neutron rich Fluorine

Quenching of Gamow-Teller strength in nuclei

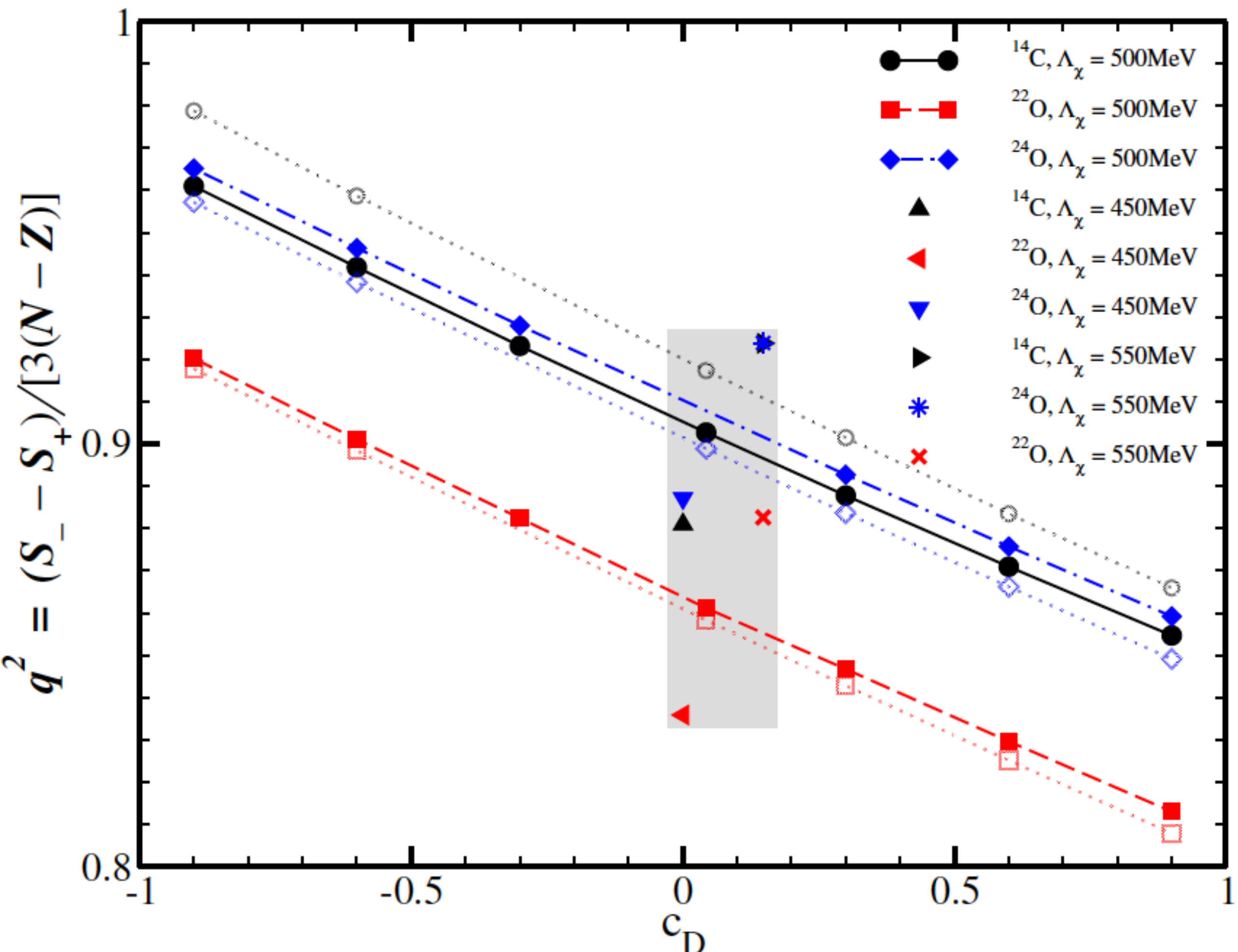
A. Ekström, G. Jansen, K. Wendt et al, PRL 113 262504 (2014)

Gamow-Teller matrix element:

$$\hat{O}_{\mathrm{GT}} \equiv \hat{O}_{\mathrm{GT}}^{(1)} + \hat{O}_{\mathrm{GT}}^{(2)} \equiv g_A^{-1}\sqrt{3\pi}E_1^A$$

The Gamow-Teller strength functions:

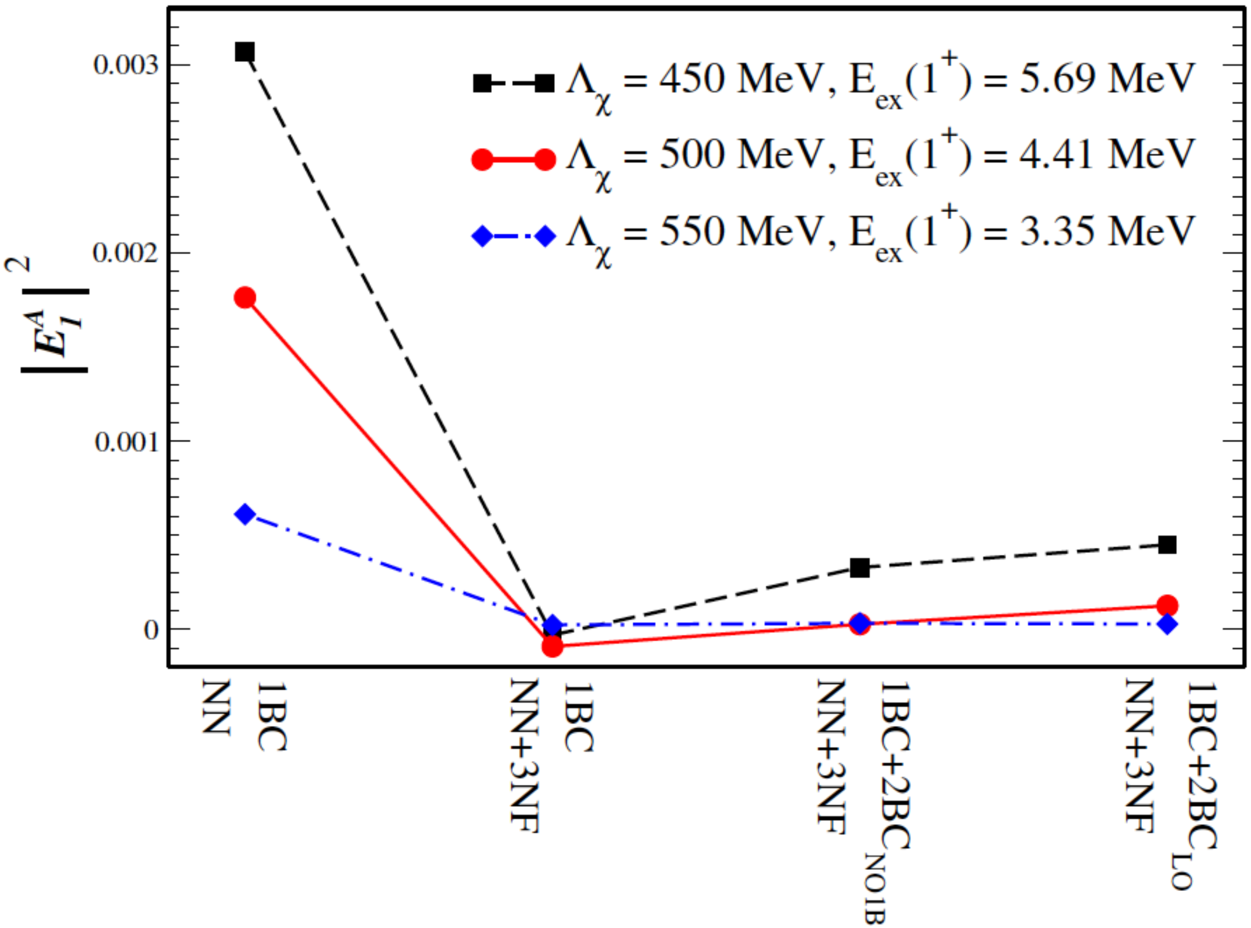
$$S_- = \langle\Lambda|\overline{\hat{O}_{\mathrm{GT}}^\dagger} \cdot \overline{\hat{O}_{\mathrm{GT}}}|\mathrm{HF}\rangle$$
$$S_+ = \langle\Lambda|\overline{\hat{O}_{\mathrm{GT}}} \cdot \overline{\hat{O}_{\mathrm{GT}}^\dagger}|\mathrm{HF}\rangle$$



- Quenching of the Ikeda sum rule in ^{14}C and ^{22,24}O for different cutoffs. q = 0.92…0.96
- Grey area is region which reproduce triton half-life
- The quenching q^2 is about 8-16% and agrees with estimates in ^{90}Zr

Anomalous life-time of ^{14}C revisited

A. Ekström, G. Jansen, K. Wendt et al, PRL 113 262504 (2014)



E_1^A varies between 5x10^{-3} to 2x10^{-2} which is more than one order of magnitude larger than the empirical value ~6x10^{-4} extracted from the 5700 a half life of ^{14}C

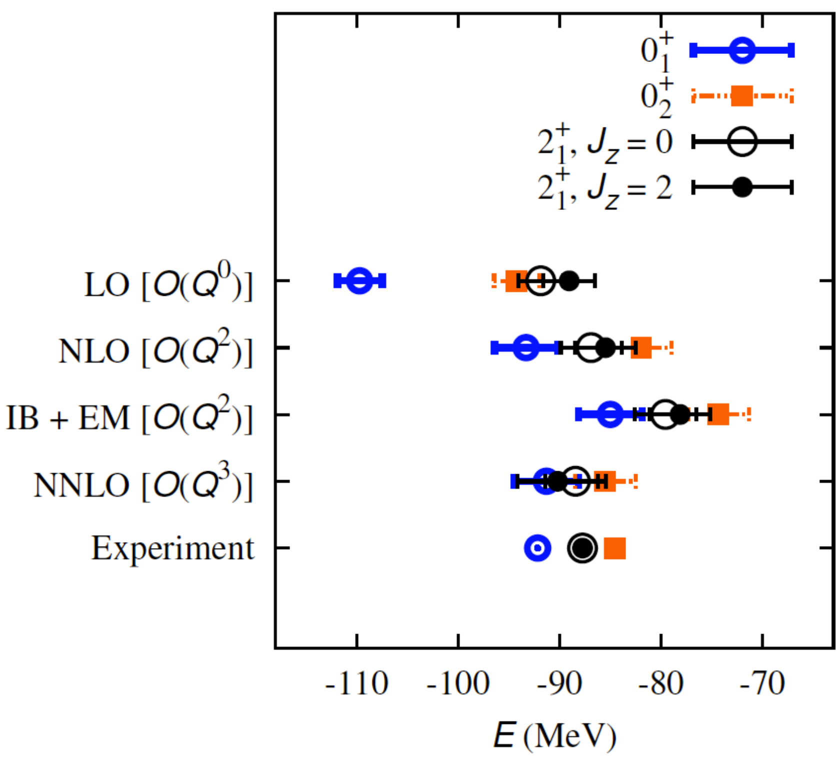
The life time of ^{14}C depends in a complicated way on 3NFs, 2BCs and the energy of the first excited 1^+ state in ^{14}N.

- 3NFs decrease the transition matrix element significantly
- 2BC counter the effect of 3NFs to some degree.
- Note that 2BCs increases the strength to the first 1^+ state in ^{14}N but overall quenches the Ikeda sum rule.

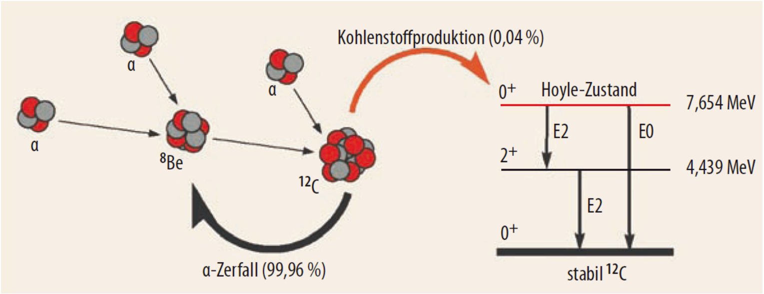
Computation of the Hoyle state

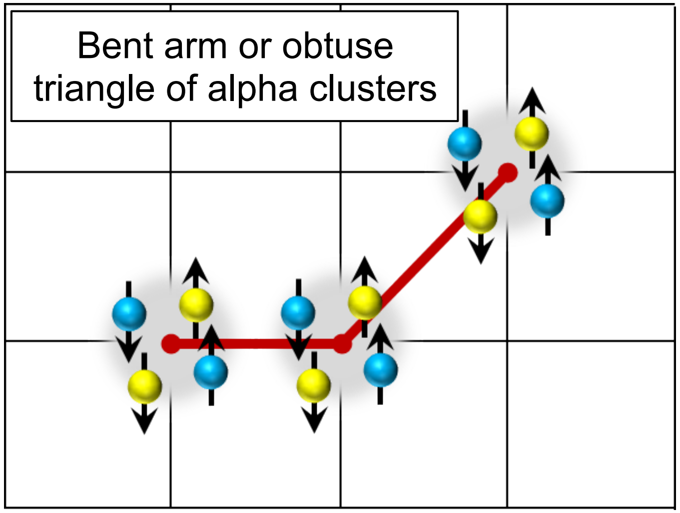
The Hoyle state (postulated in 1954) explains the abundance of ^{12}C in stars.

Nuclear Lattice Effective Field Theory Collaboration



Epelbaum, Krebs, Lee, Meißner,
Phys. Rev. Lett. 106, 192501 (2011)



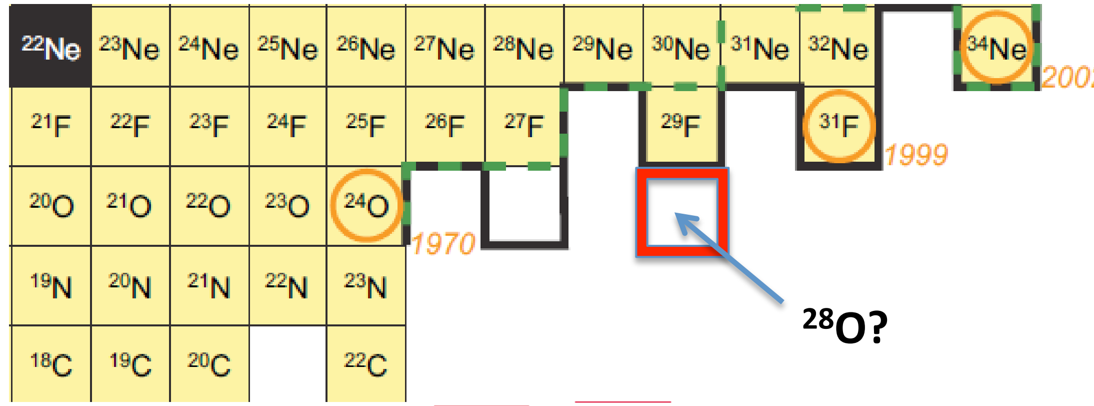


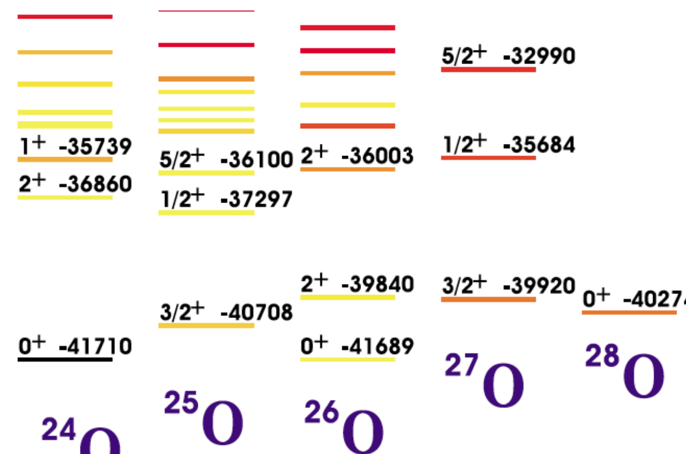
Epelbaum, Krebs, Lähde, Lee, Meißner,
Phys. Rev. Lett. 109, 252501 (2012)

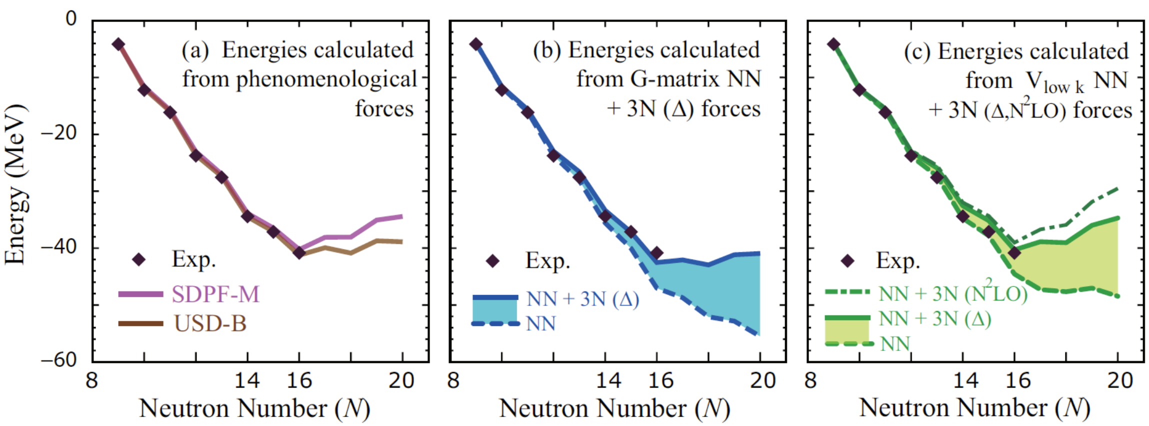
Is ^{28}O a bound nucleus?

Experimental situation

- “Last” stable oxygen isotope ^{24}O
- ^{25,26}O unstable (Hoffman et al 2008, Lunderberg et al 2012)
- ^{28}O not seen in experiments
- ^{31}F exists (adding on proton shifts drip line by 6 neutrons!?)



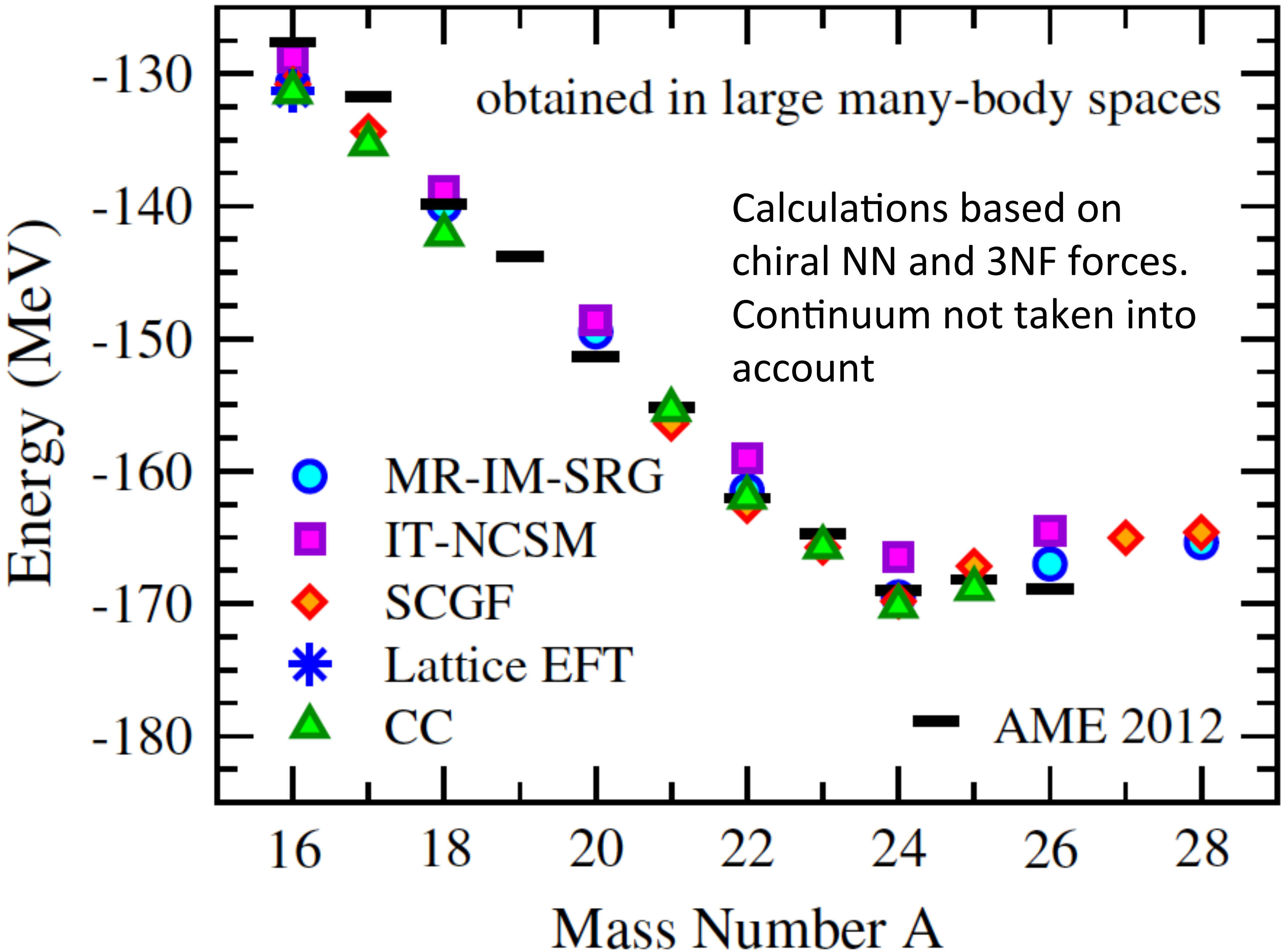




Continuum shell model with HBUSD interaction predict ^{28}O unbound. A. Volya and V. Zelevinsky PRL (2005)

Shell model (sd shell) with monopole corrections based on three-nucleon force predicts 2nd O as last stable isotope of oxygen. [Otsuka, Suzuki, Holt, Schwenk, Akaishi, PRL (2010), arXiv:0908.2607]

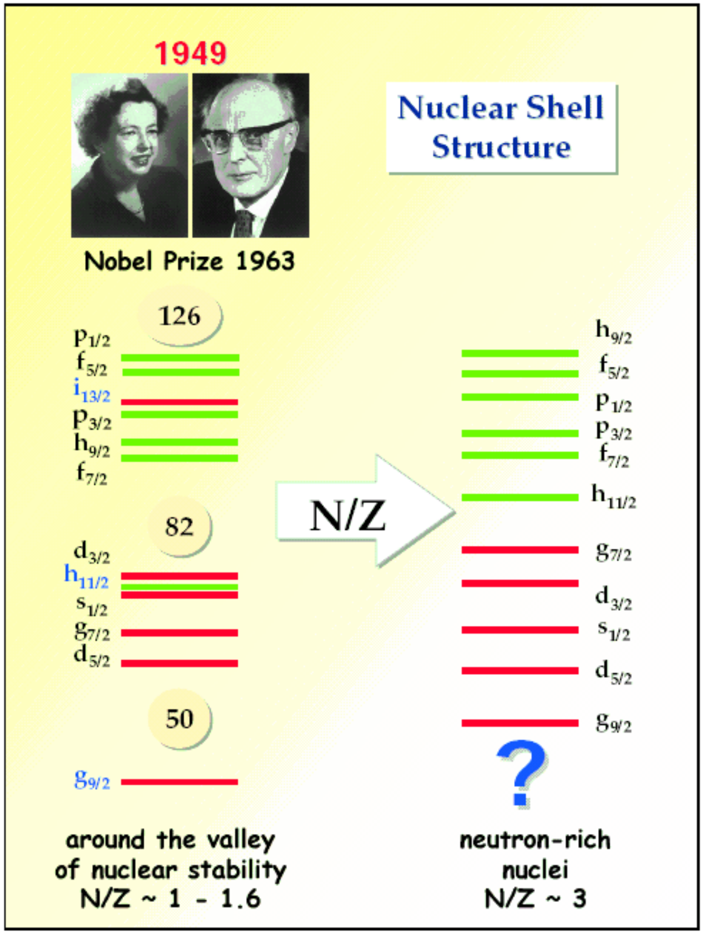
Benchmarking different ab-initio methods in the oxgyen chain

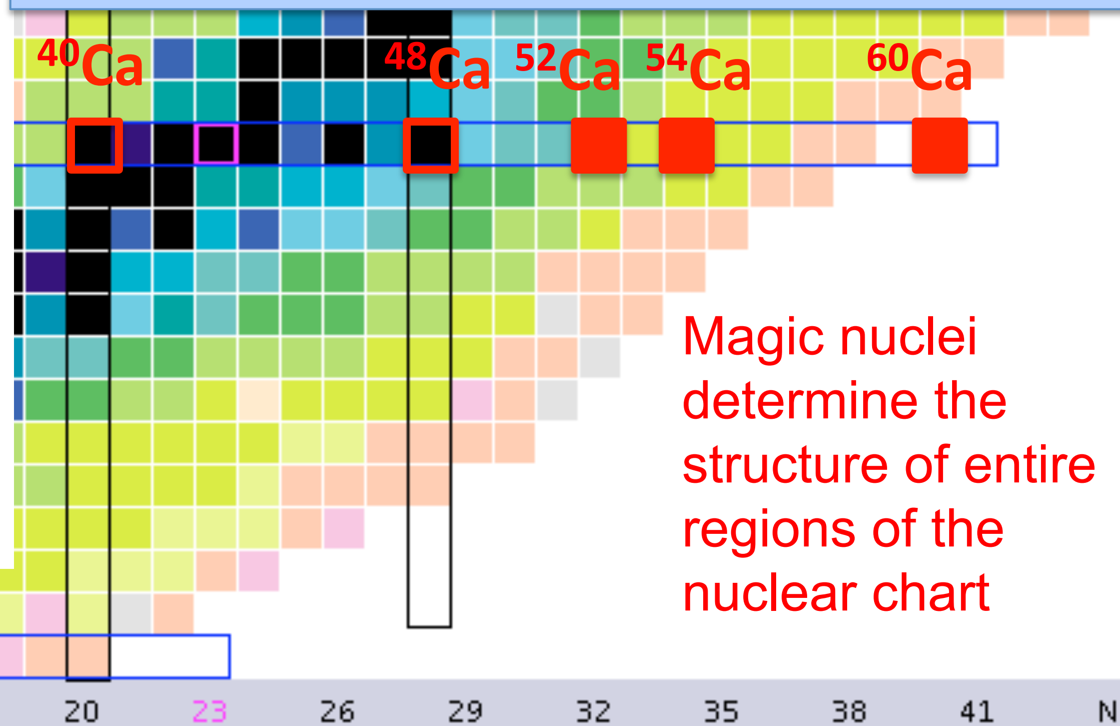


Hebeler, Holt, Menendez, Schwenk, Ann. Rev. Nucl. Part. Sci. in press (2015)

Evolution of shell structure in neutron rich Calcium

- How do shell closures and magic numbers evolve towards the dripline?
- What are the underlying mechanisms and how do we identify new shell structure?

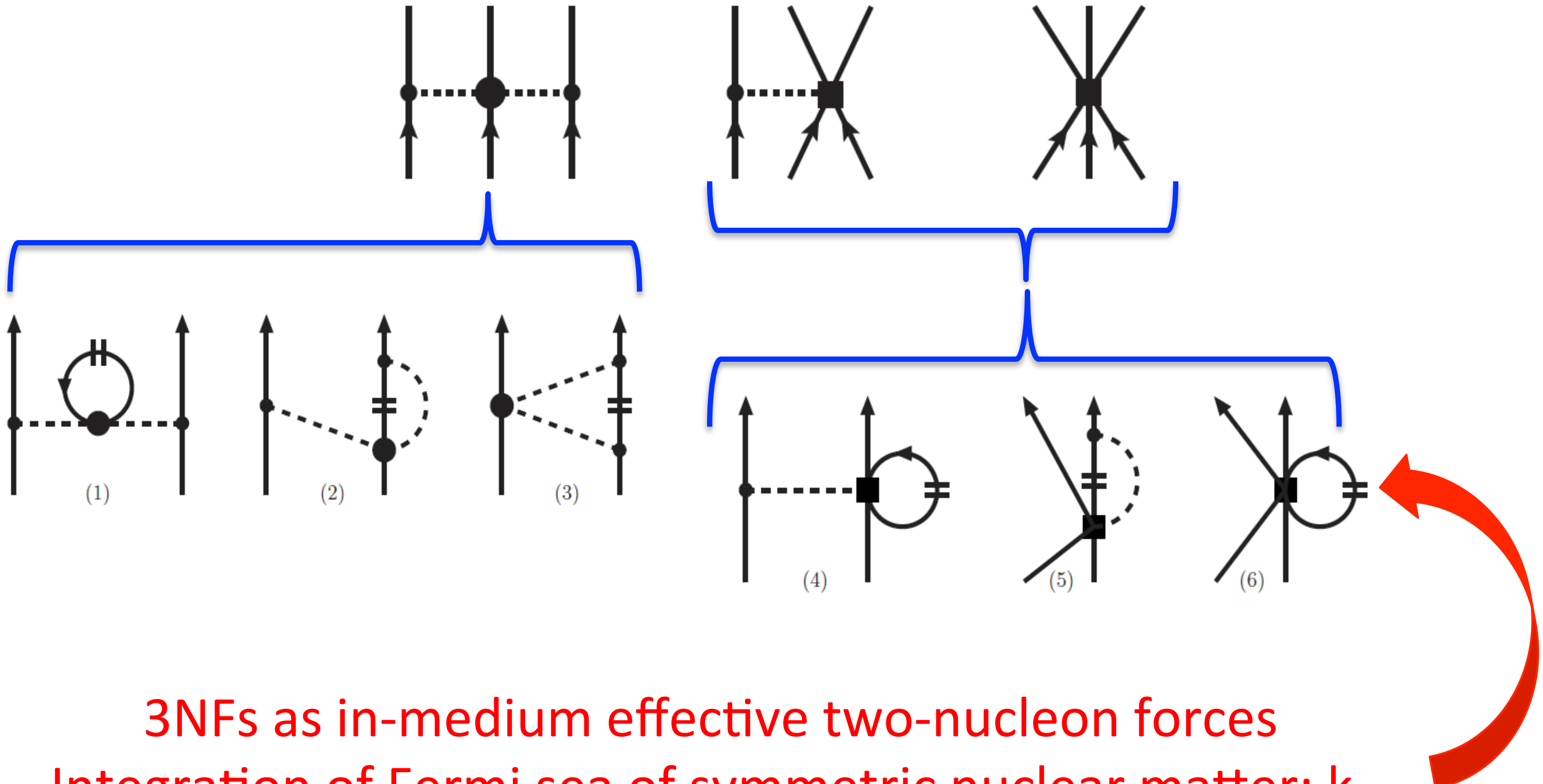




Magic nuclei determine the structure of entire regions of the nuclear chart

Including the effects of 3NFs (approximation!)

[J.W. Holt, Kaiser, Weise, PRC 79, 054331 (2009); Hebeler & Schwenk, PRC 82, 014314 (2010)]



3NFs as in-medium effective two-nucleon forces

Integration of Fermi sea of symmetric nuclear matter: k_F

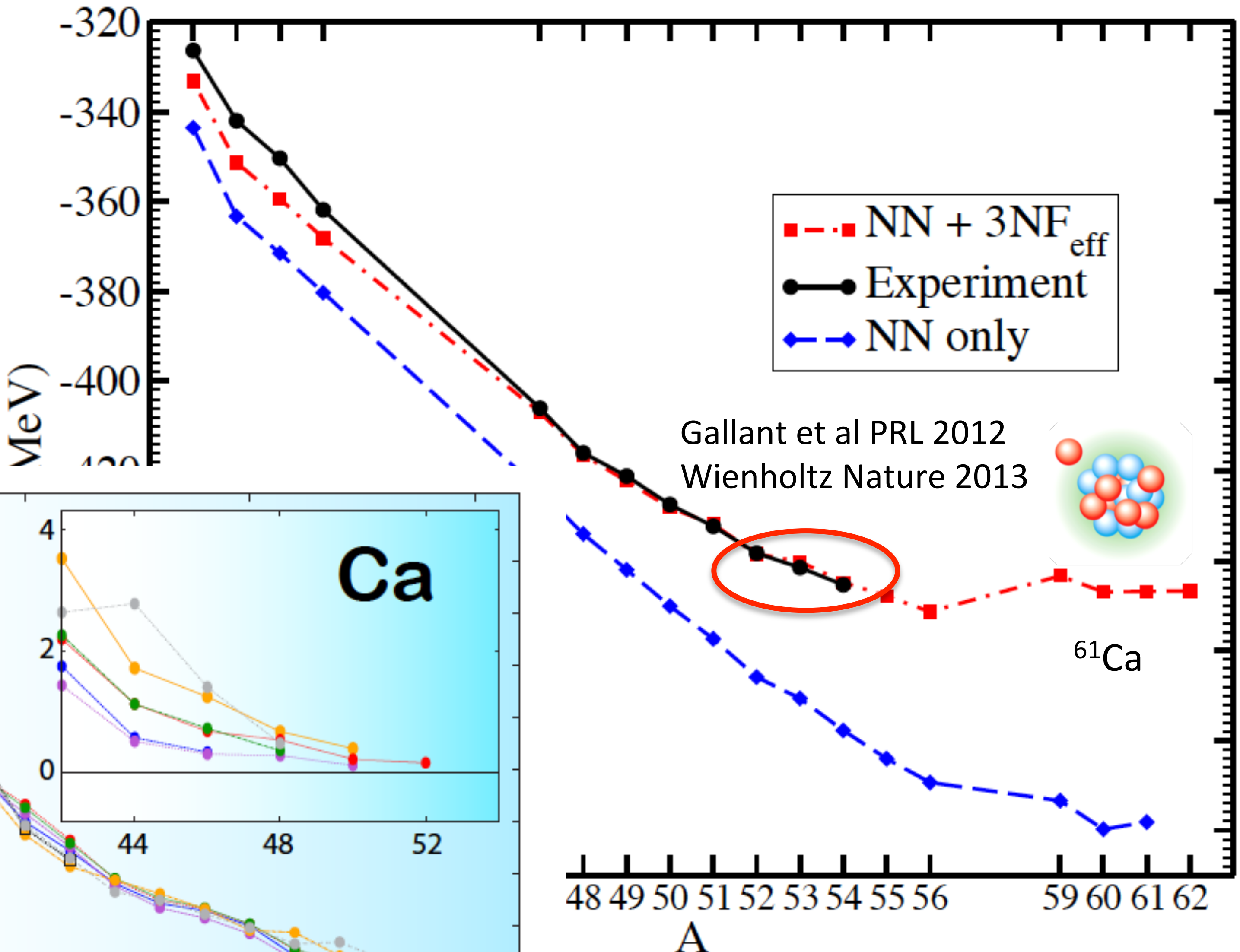
Parameters: For Calcium we use $k_F = 0.95\ \mathrm{fm}^{-1}$, $c_E = 0.735$, $c_D = -0.2$ from binding energy of ^{40}Ca and ^{48}Ca (The parameters c_D, c_E differ from values proposed for light nuclei)

Neutron rich calcium isotopes

Hagen, Hjorth-Jensen, Jansen, Machleidt, Papenbrock, Phys. Rev. Lett. 109, 032502 (2012).

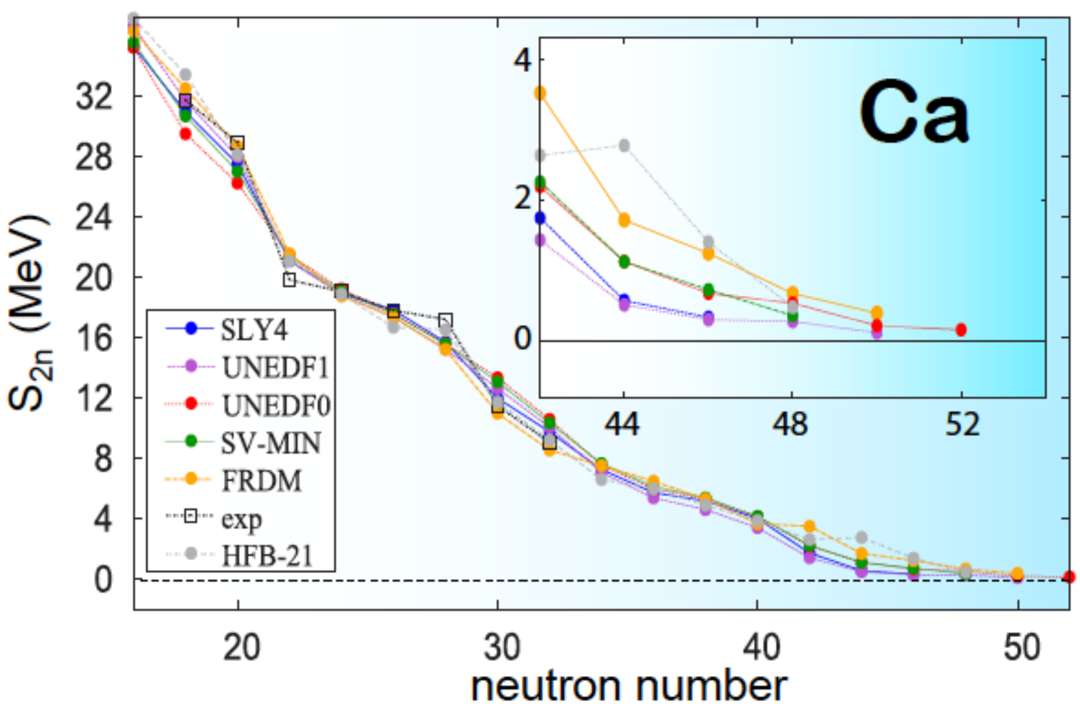
C Forssén et al
Phys. Scr. 014022 (2013)

Erler et al., Nature 486, 509 (2012)

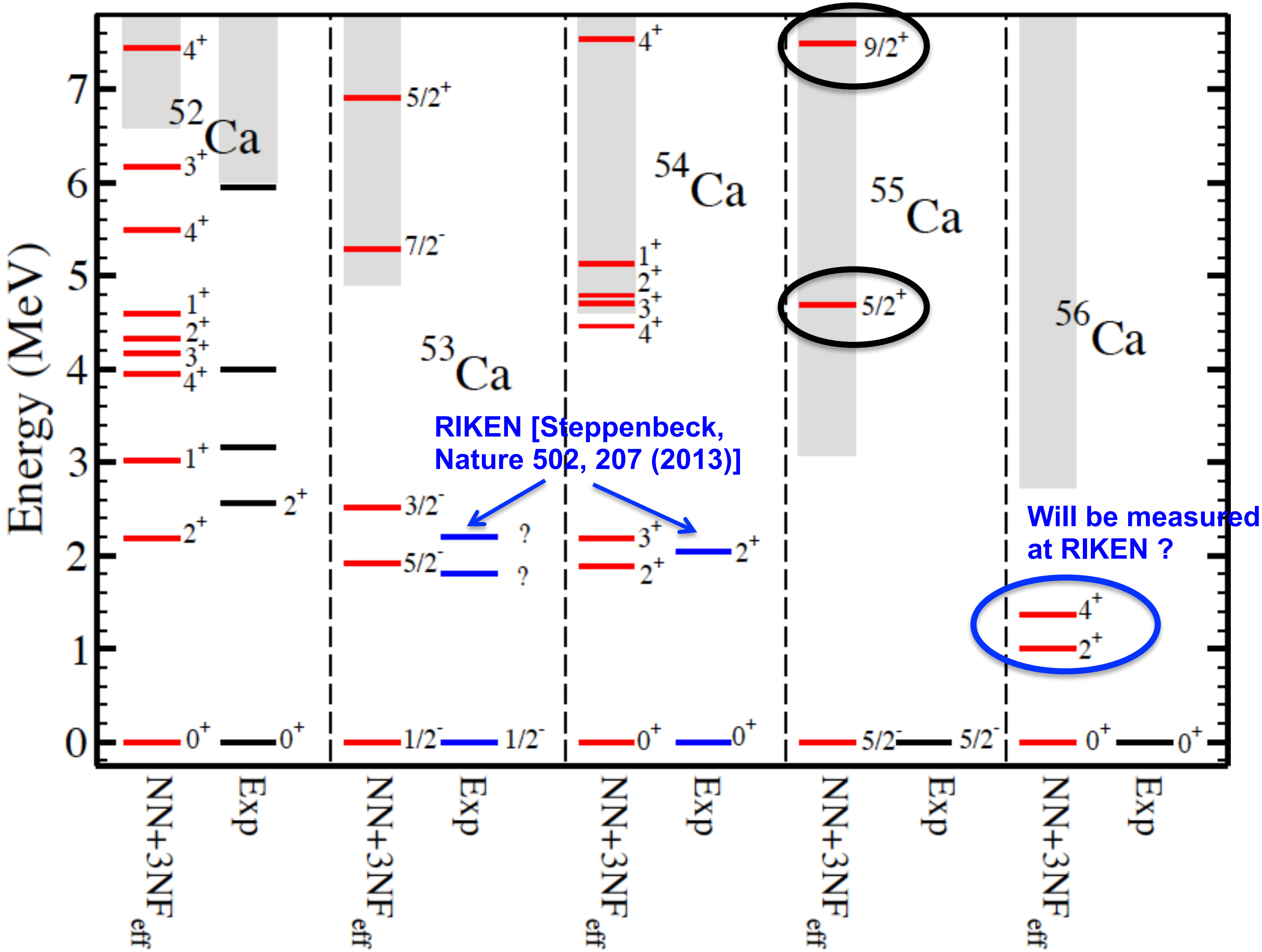


Gallant et al PRL 2012
Wienholtz Nature 2013

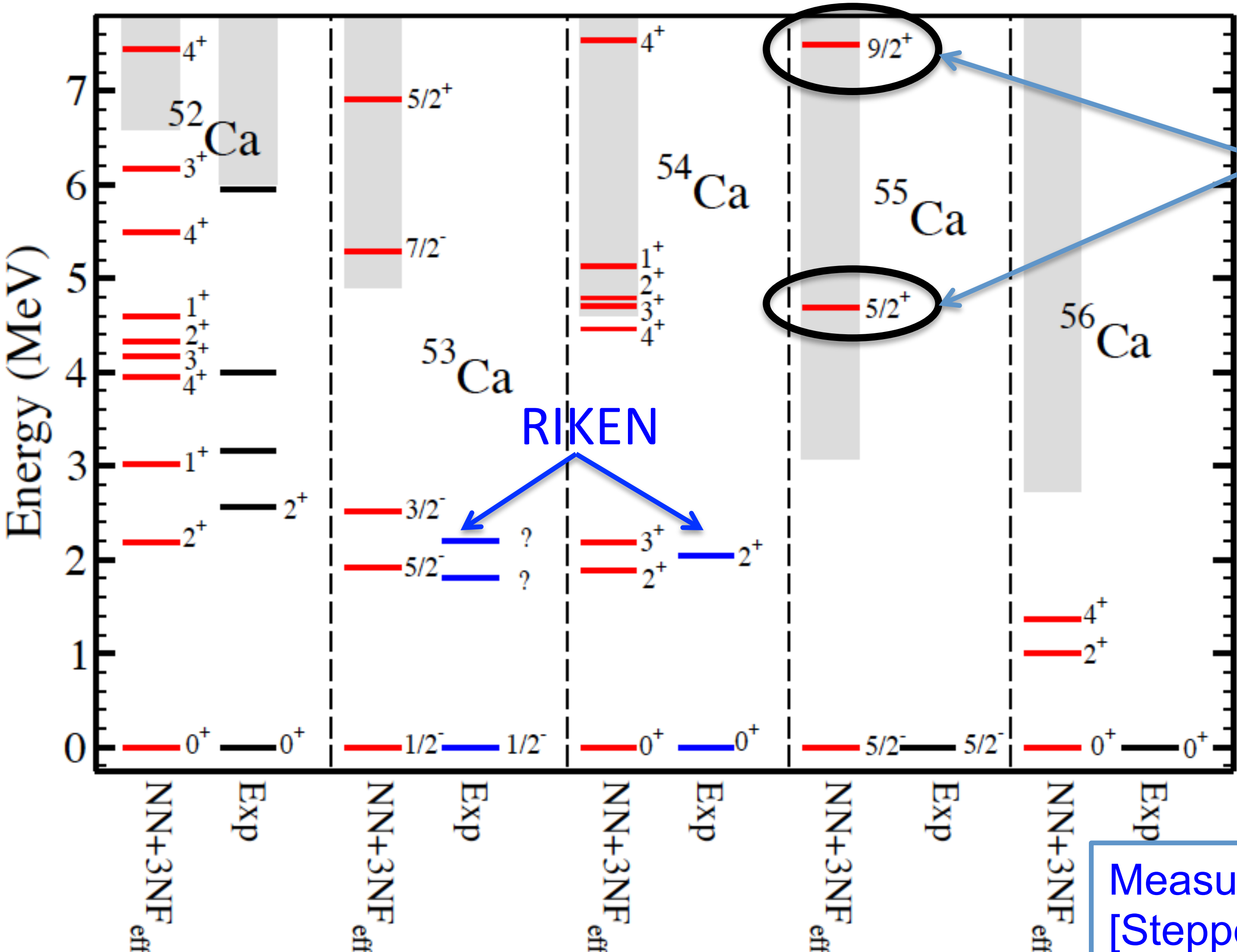
^{61}Ca



Spectra and shell evolution in Calcium isotopes



Spectra and shell evolution in Calcium isotopes

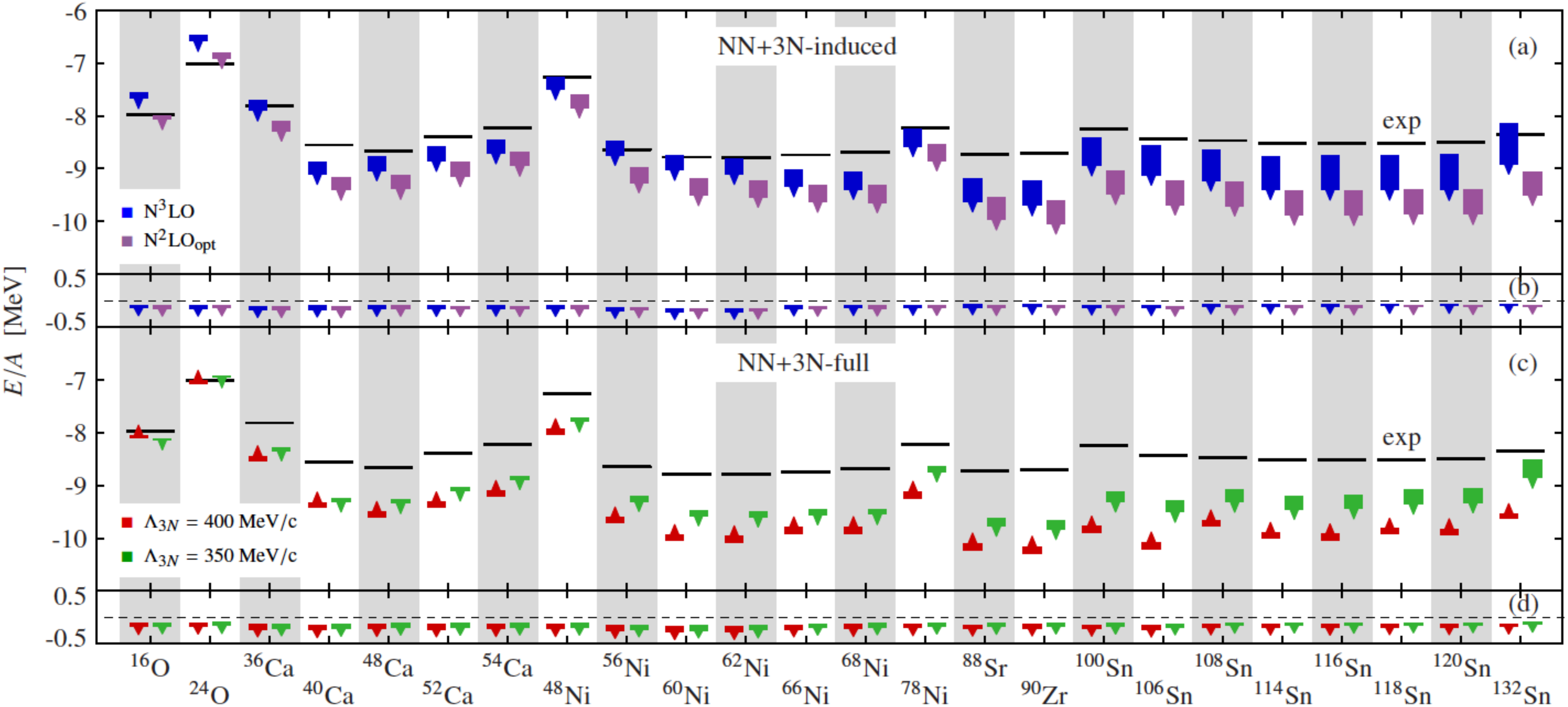


1. Our prediction for excited 5/2⁻ and ½⁻ states in ^{53}Ca seen at RIKEN
2. Inversion of 9/2⁺ and 5/2⁺ states in neutron rich calcium isotopes
3. Harmonic oscillator gives the naïve shell model order

Measurement at RIKEN [Steppenbeck et al., J. Phys. G 2013; Nature 502, 207 (2013);] confirms our prediction.

Continuum coupling crucial for level ordering

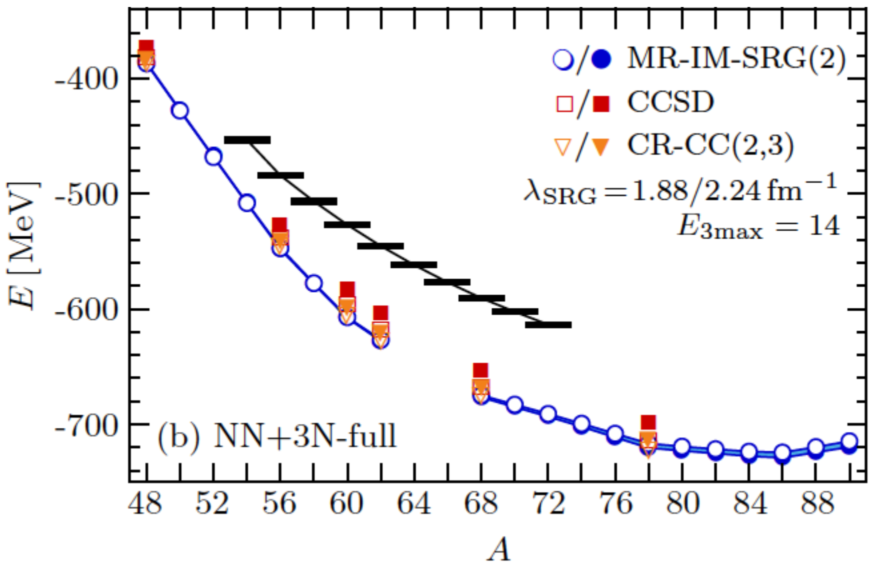
Chiral NN + 3NFs overbind and give to small radii in medium mass and heavy nuclei



S. Binder et al. PLB 736 (2014) 119-123

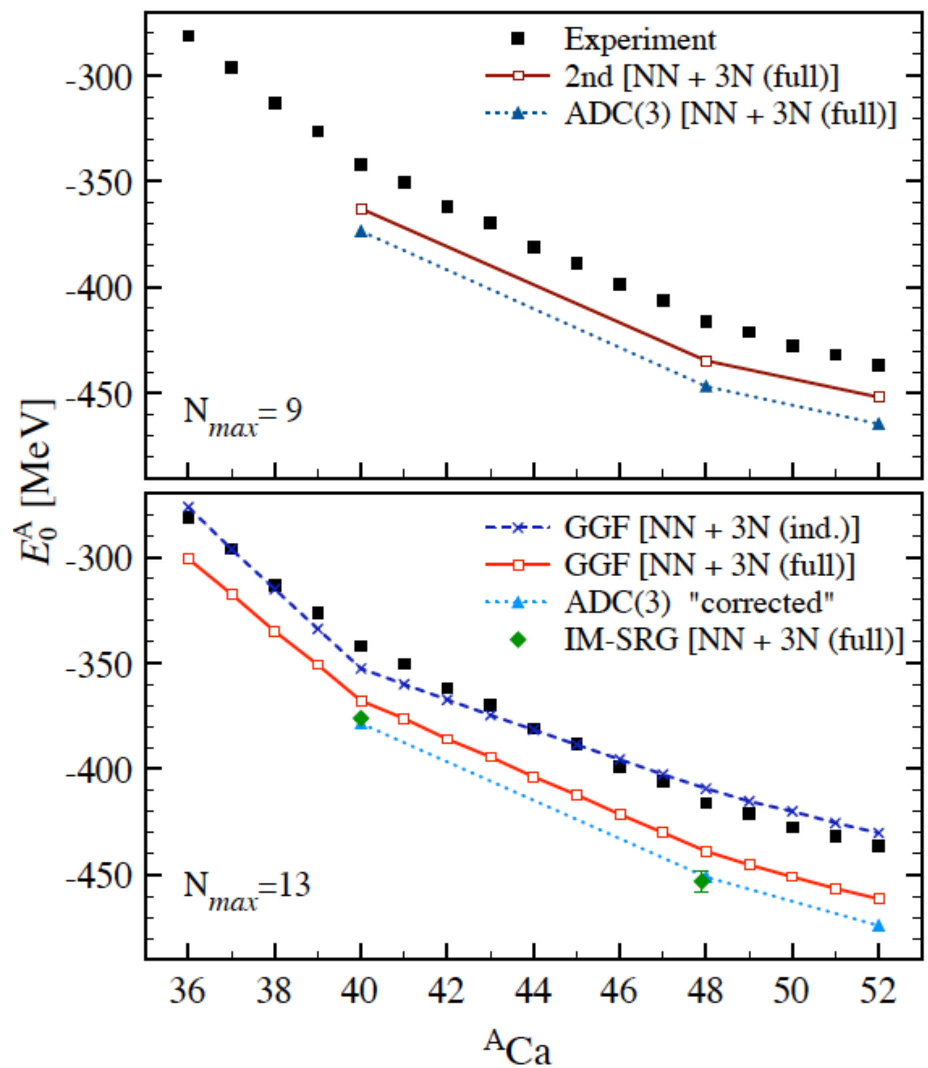
Chiral NN + 3NFs and the problem of saturation

H. Hergert et al Phys. Rev. C 90, 041302 (2014)

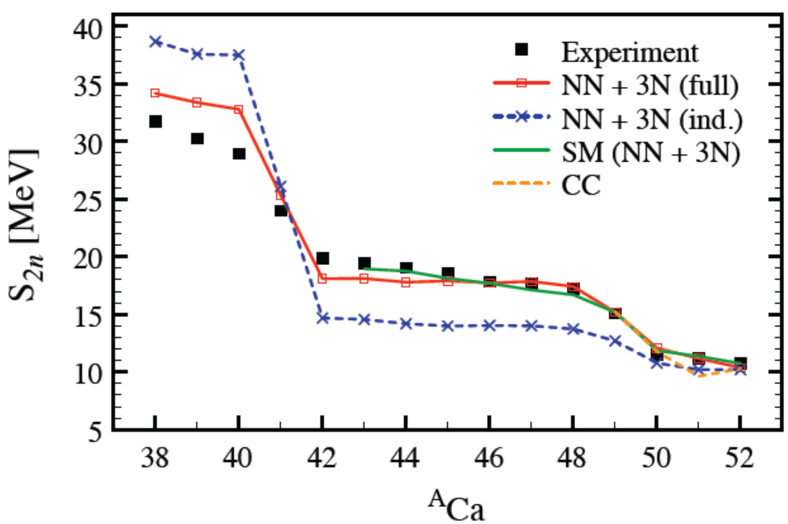


Significant overbinding is found in calcium and nickel isotopes using chiral NN and 3NFs

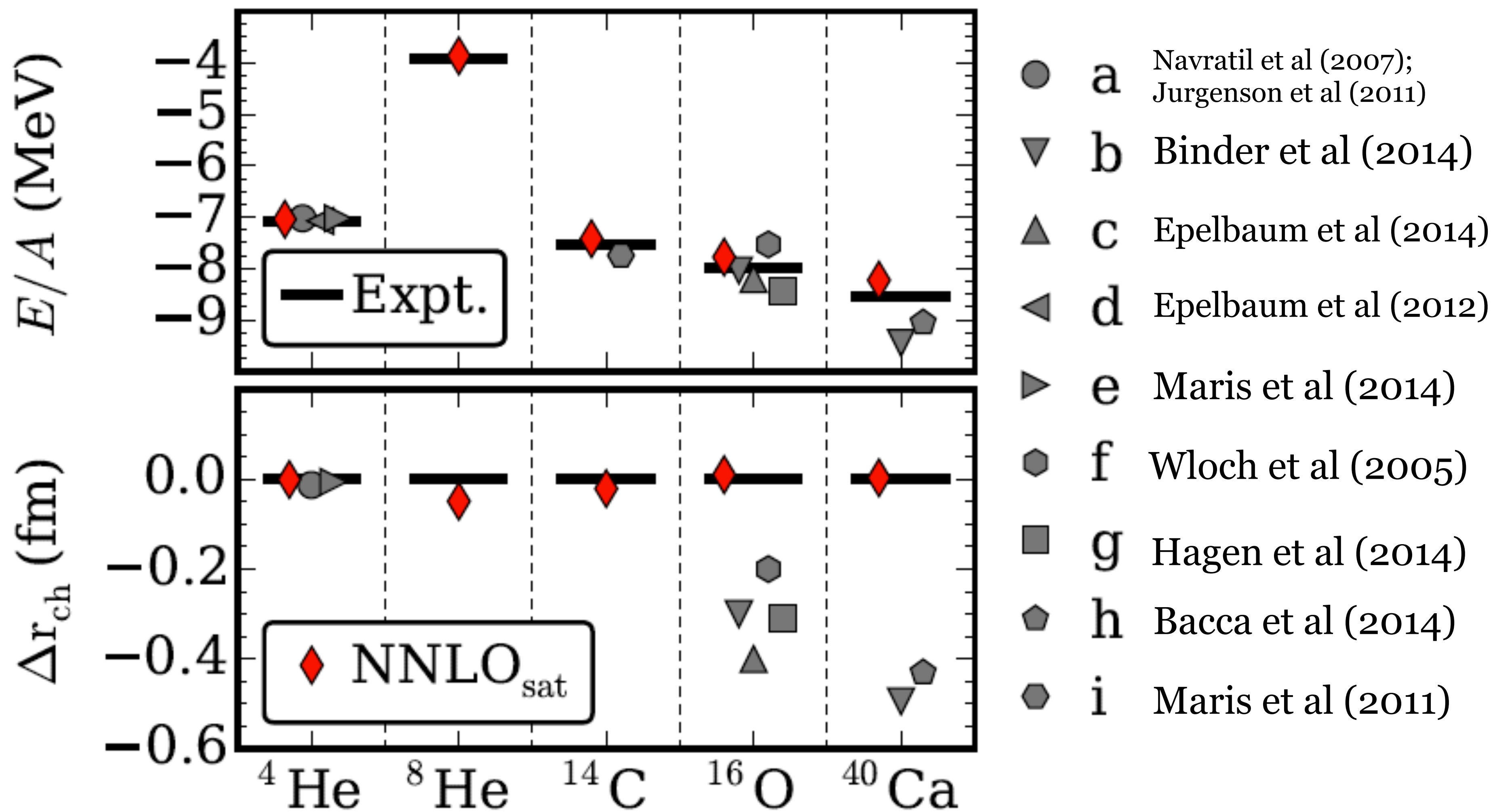
V. Soma et al Phys. Rev. C 89, 061301 (2014)



Energy differences such as two-neutron separation energies are better reproduced

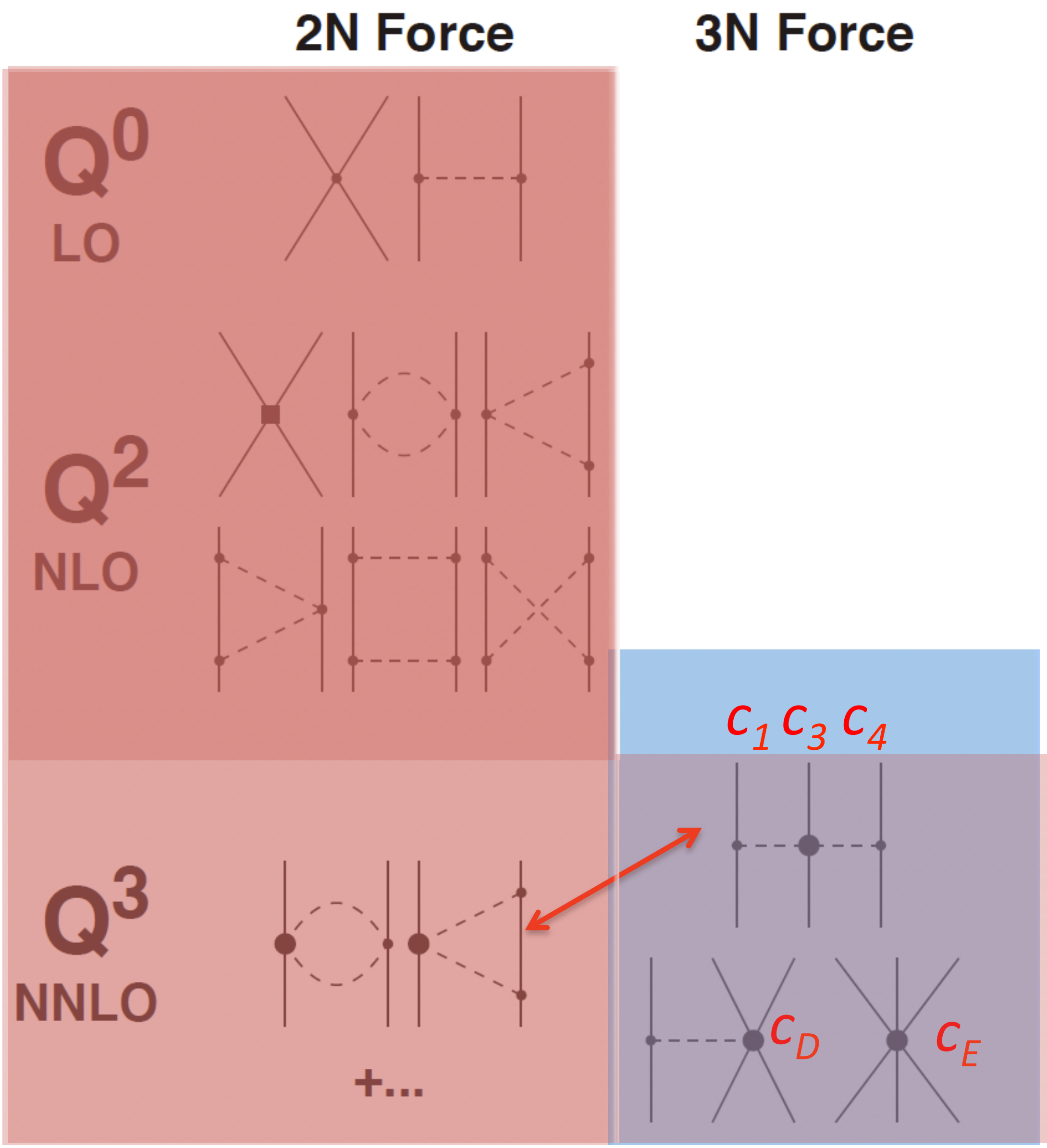


Accurate nuclear binding energies and radii from a chiral interaction



Our solution: simultaneous optimization of NN and 3NFs with input from selected nuclei up to A ~ 25 ($\mathrm{NNLO_{sat}}$). A. Ekström *et al*, Phys. Rev. C **91**, 051301(R) (2015)

Simultaneous optimization of NN and 3NFs



Traditional approach:

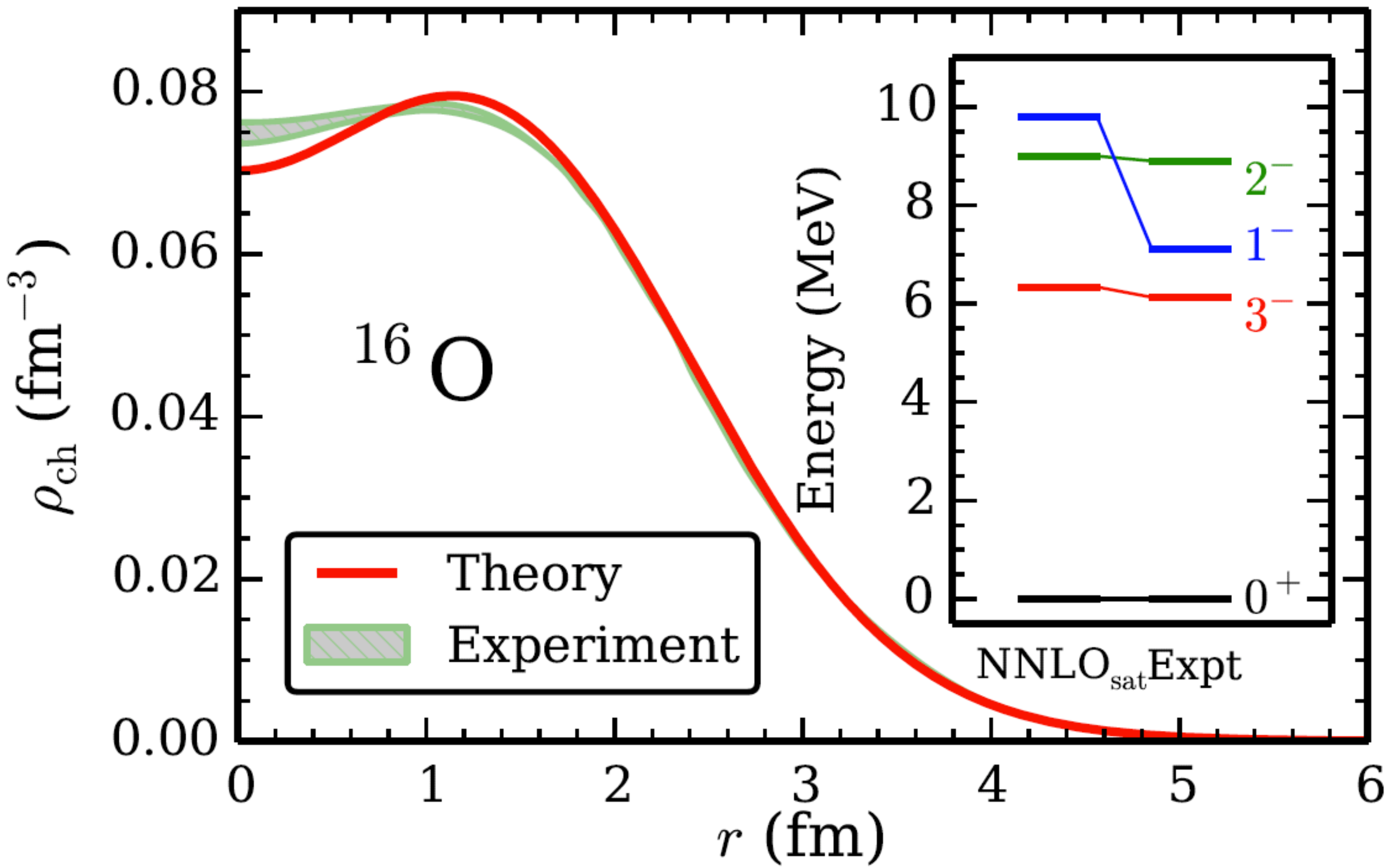
- Fit interactions nucleon by nucleon
- Fit to NN scattering data up to ~350MeV
- cE and cD fit to A=3,4

Our approach:

- Simultaneous optimization of NN and 3NFs
- Fit to few-body data and BEs/radii in nuclei with *A* ~ 25

Not new: GFMC with AV18 and Illinois-7 are fit to 23 levels in nuclei with A <10

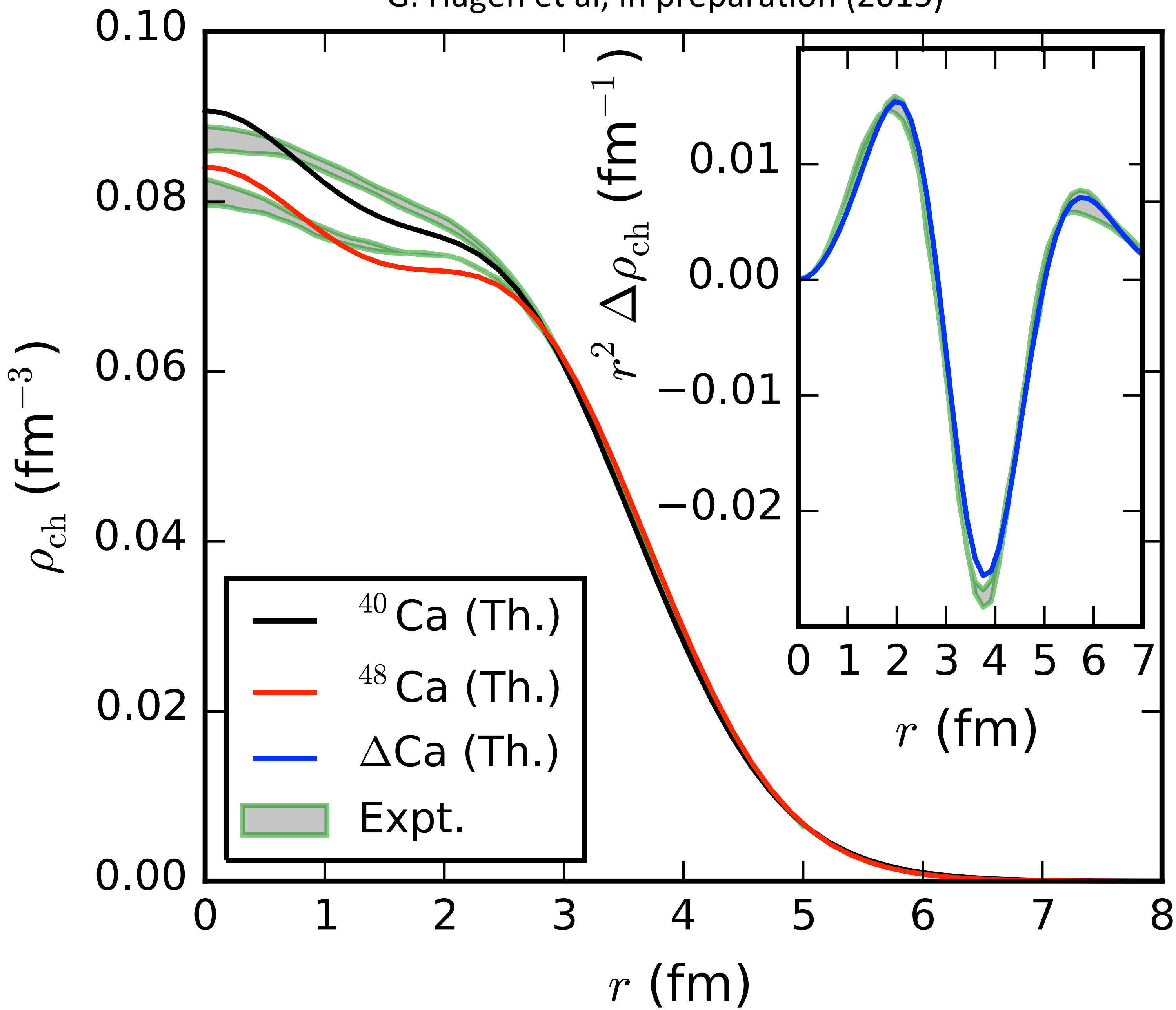
Charge density and negative parity states of ^{16}O



A. Ekström, G. Jansen, K. Wendt et al, PRC 91, 051301 2015

Charge densities of ^{40,48}Ca with NNLO$_{sat}$

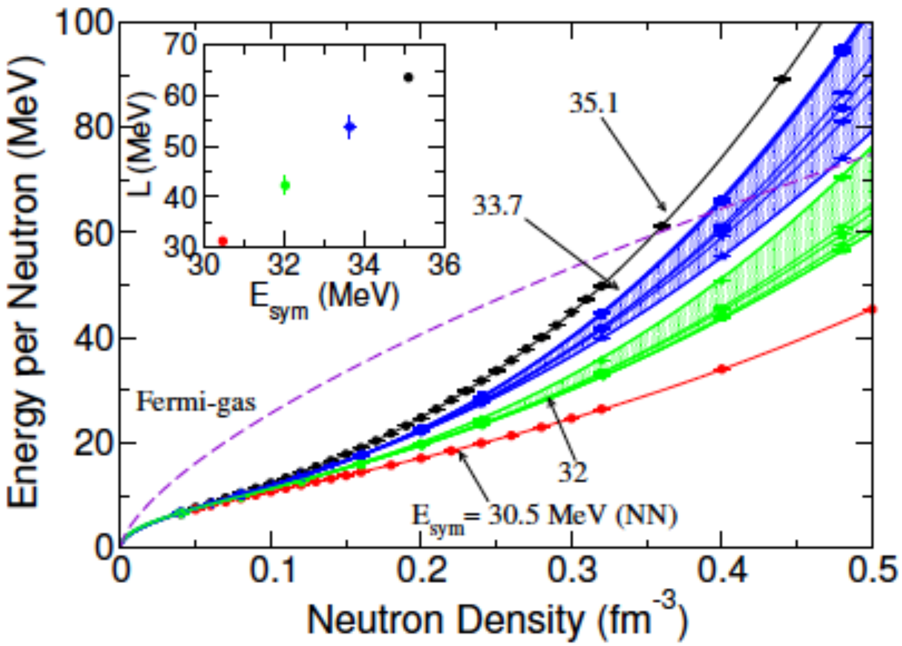
G. Hagen et al, in preparation (2015)



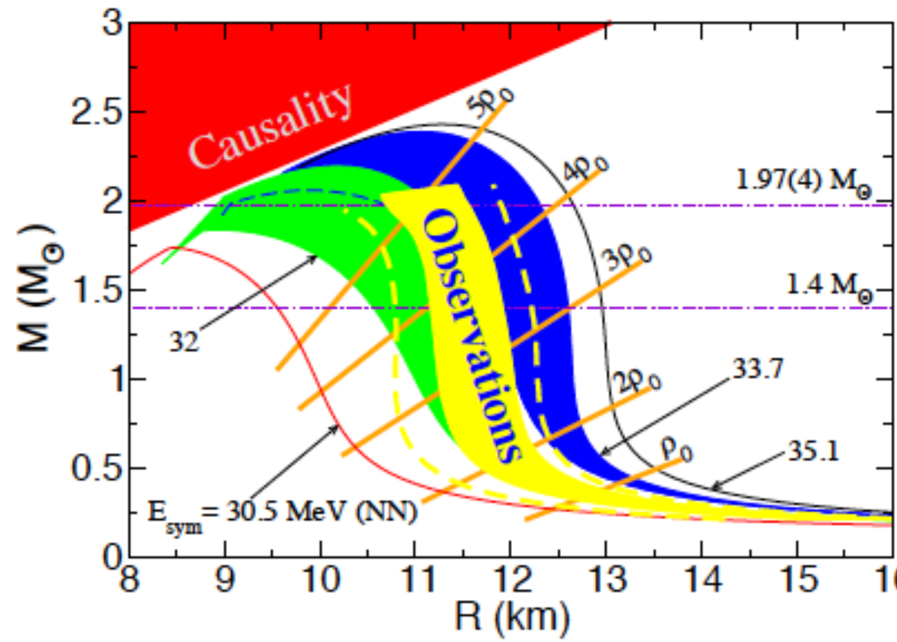
Effects of 3NFs in neutron matter and neutron star structure

Auxiliary Field Diffusion Quantum Monte Carlo calculations of neutron matter and equation of state with Argonne and Urbana/Illinois NN + NNN forces.

Constraining the maximum mass and radius of neutron stars and the nuclear symmetry energy

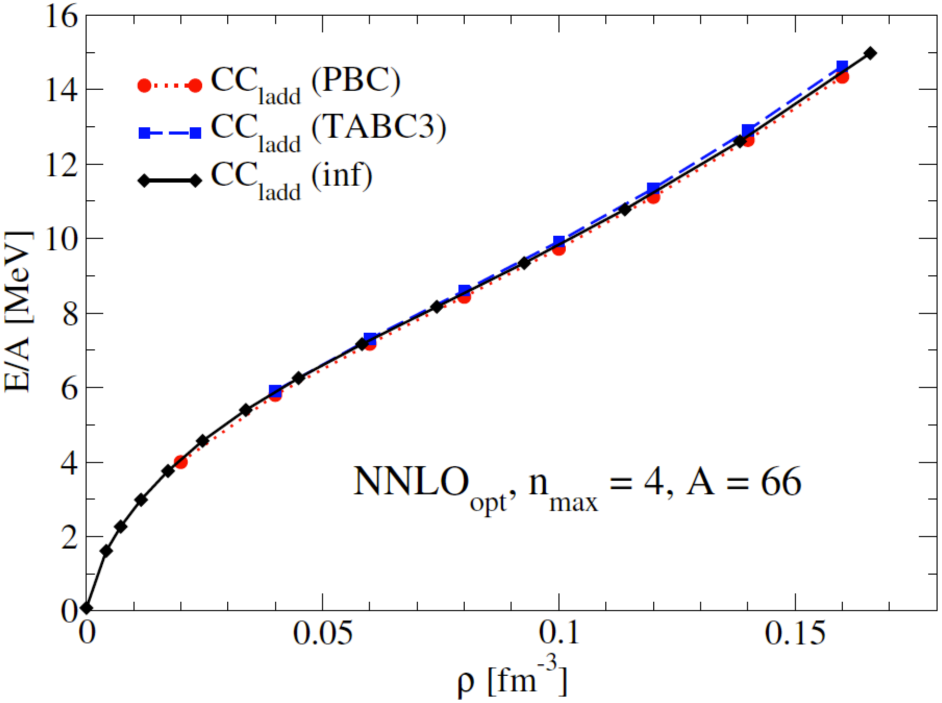


Gandolfi, Carlson, Reddy, PRC 85, 032801 (2012)

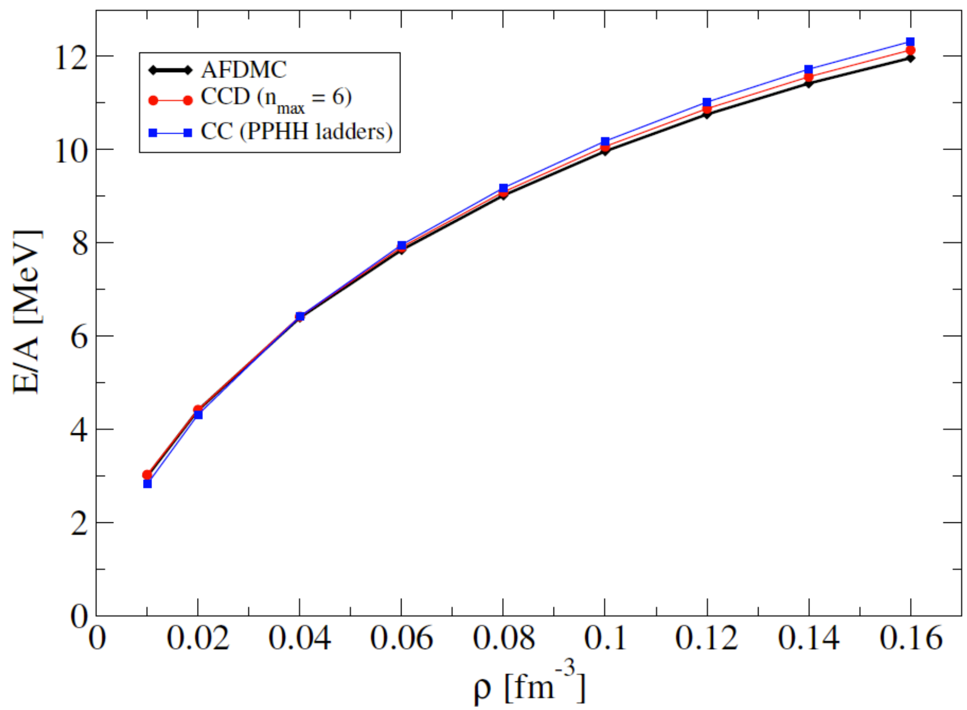


adapted from
Steiner, Gandolfi, PRL 108, 081102 (2012)

Benchmark calculations of neutron matter



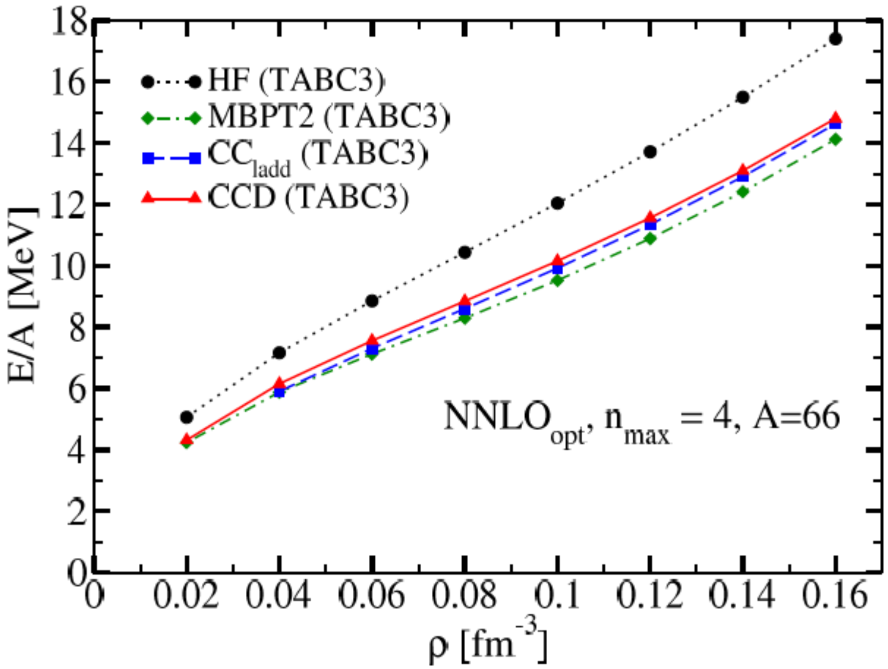
Comparison with continuum coupled-cluster method [Baardsen *et al.*, PRC (2013)]



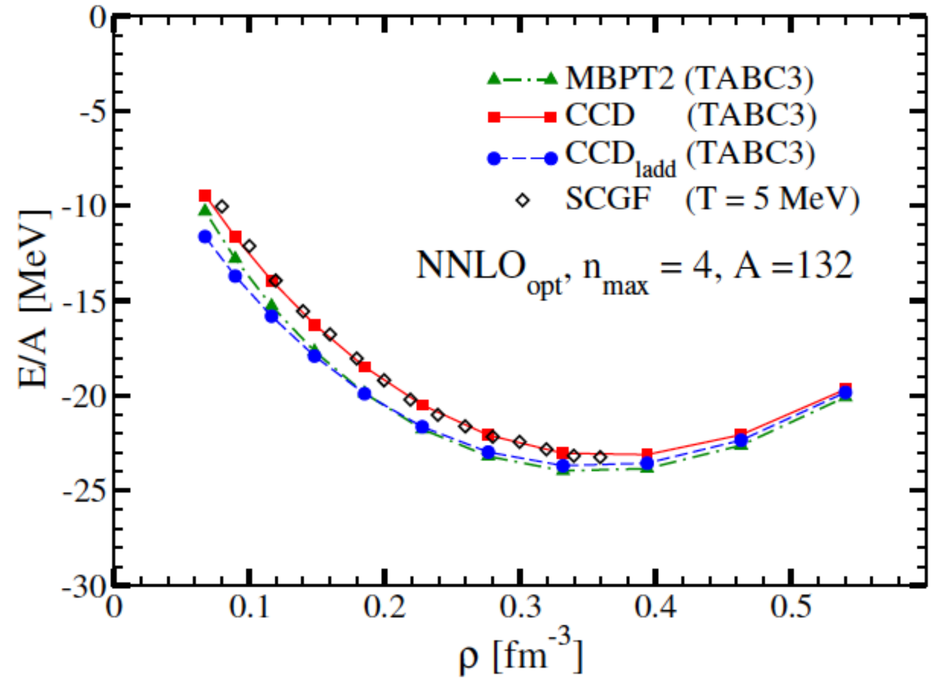
Comparison with auxiliary field diffusion Monte Carlo and Minnesota potential

Role of particle-hole excitations in nucleonic matter

Pure neutron matter (NN-only)



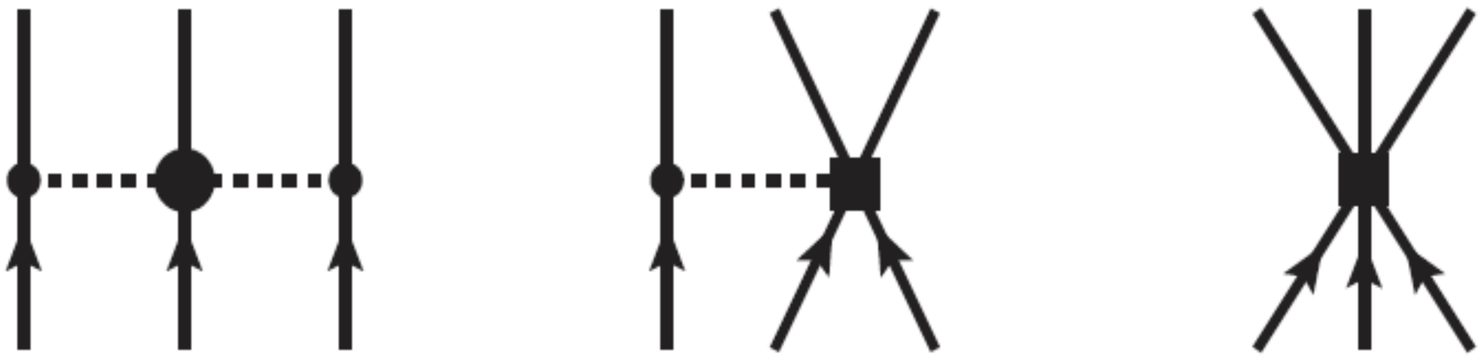
Symmetric nuclear matter (NN-only)



- Particle-hole and non-linear terms in CCD are small in pure neutron matter.
- MBPT2/CCD_{ladd}/CCD results agree within 500keV/A. Indicates that PNM is perturbative
- Particle-hole and non-linear terms play a larger role in symmetric nuclear matter.
- CCD_{ladd} and CCD results differ by up to 1.5MeV/A around saturation density.

Three nucleon force (3NF) and regulator dependence

van Kolck, Phys. Rev. C 49, 2934 (1994); Epelbaum et al., Phys. Rev. C 66, 064001 (2002)



$c_{1,2,3}$ c_D c_E

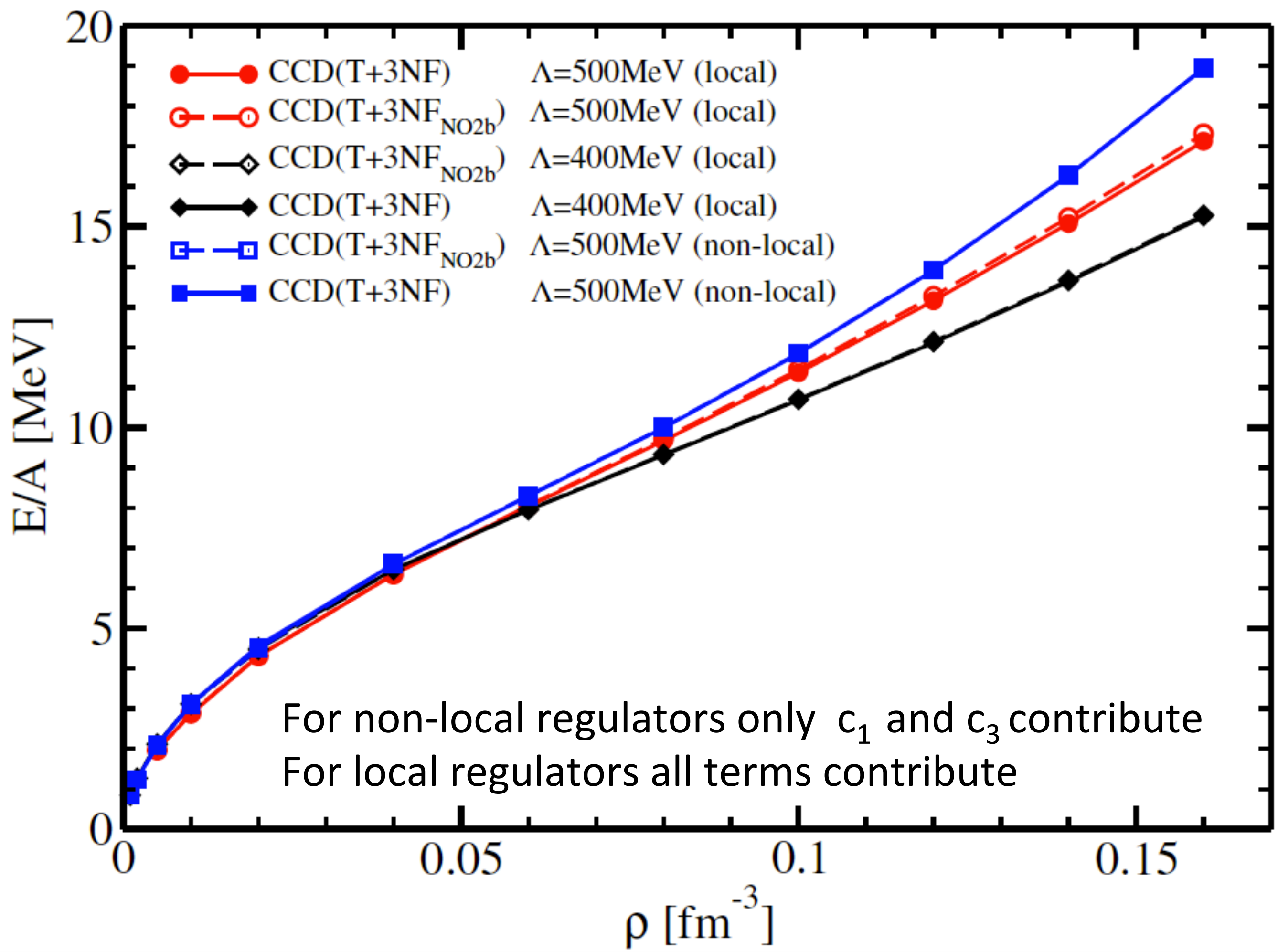
Nonlocal form of 3NF [Epelbaum et al. PRC (2002)]: Cutoff is in Jacobi momenta
Λ=500 MeV: c_D=-2, c_E=-0.791 (from A=3 binding energies)

Local form of 3NF [Navratil, Few Body Syst. (2007)]: Cutoff is in the momentum transfer

Λ=500 MeV: c_D=-0.39, c_E=-0.389 (from A=3,4 binding and ^{3}H $\tau_{1/2}$ (Gazit, Navratil, & Quaglioni)

Λ=400 MeV: c_D=-0.39, c_E=-0.27 (adjusted to ^{4}He)

Neutron matter

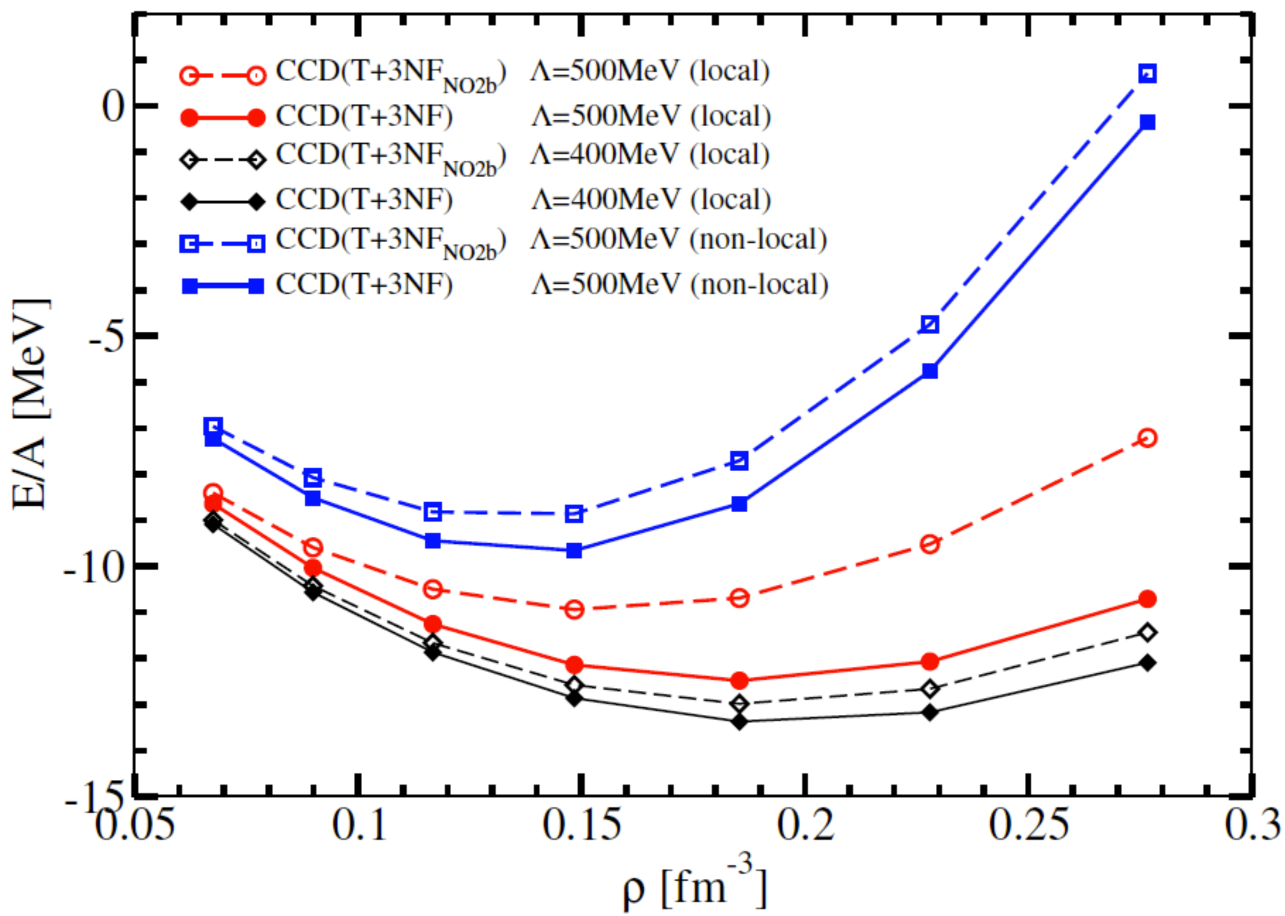


Neutron matter is perturbative (small differences between MBPT2 and coupled clusters

3NFs act repulsively in neutron matter and $NNLO_{opt}$

Error bands from variation of cutoffs and level of sophistication in treating 3NFs

Symmetric nuclear matter

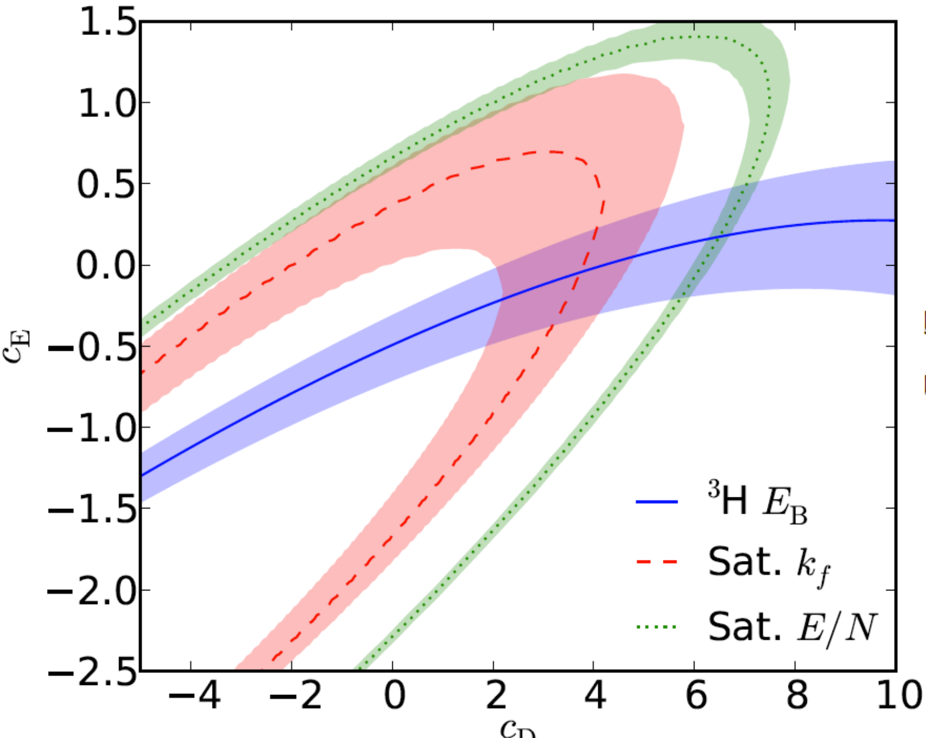


Nuclear matter is not perturbative (larger differences between MBPT2 and coupled clusters)

3NFs act repulsively in nuclear matter and NNLO$_{opt}$

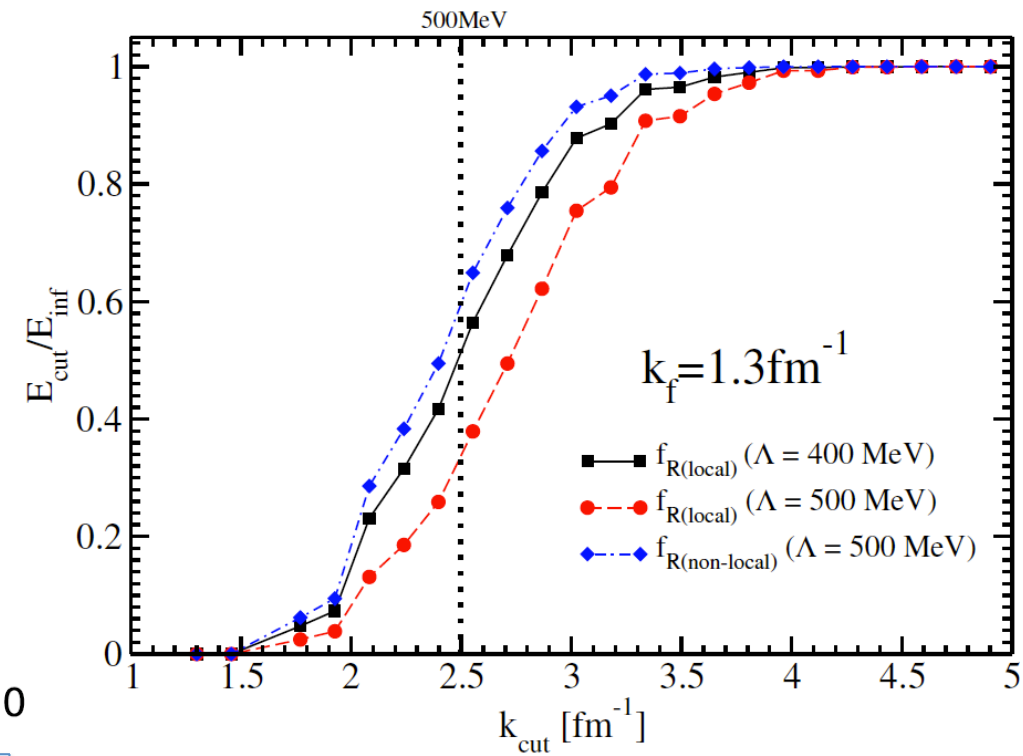
☹ Regularization scheme dependence of 3NF; sensitivity to sophistication in treatment of 3NFs

Understanding the 3NF at NNLO



5% error bands for saturation k_f, E/N and binding energy of ^{3}H

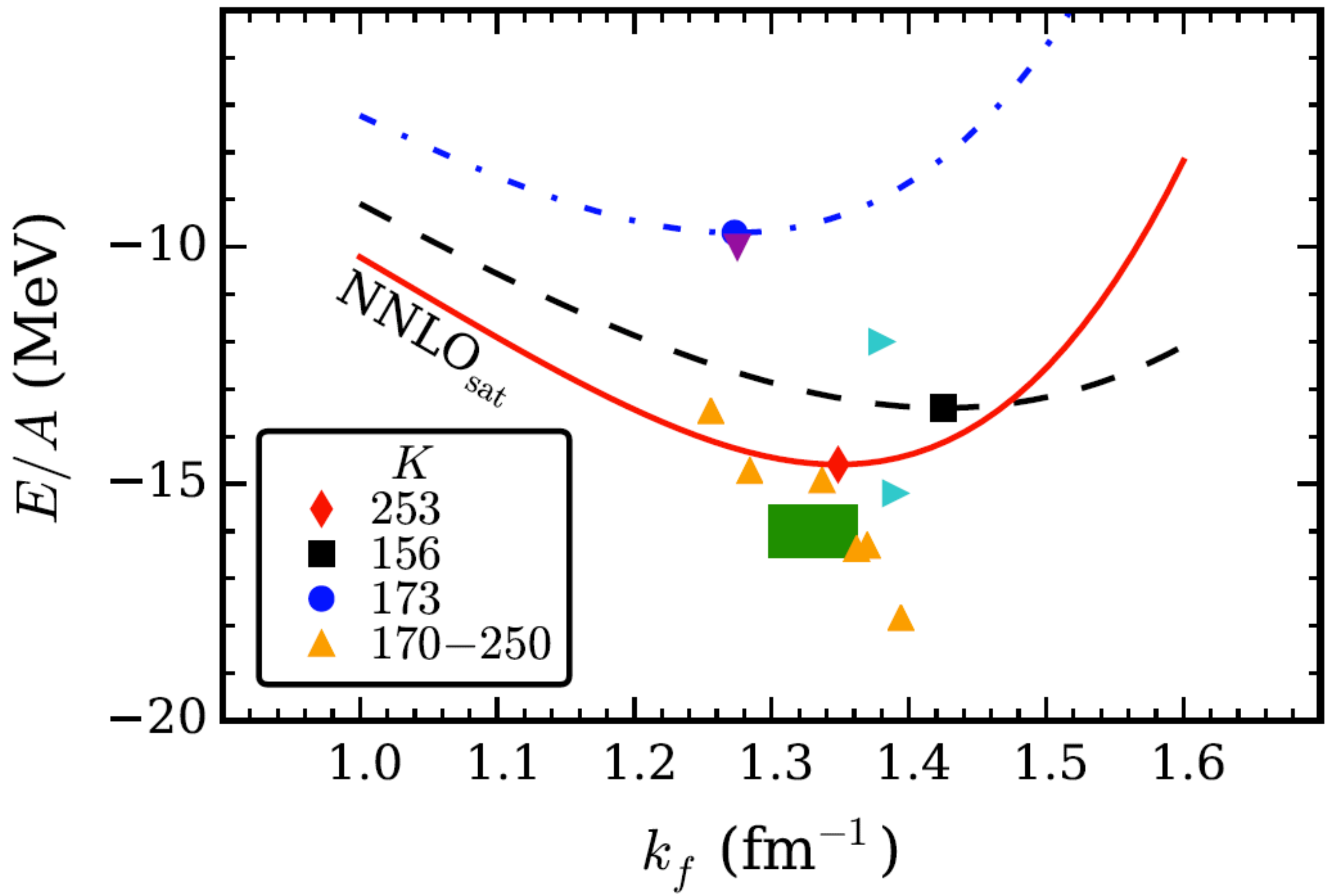
☹ Variation of c_D and c_E not sufficient to simultaneously bind light nuclei and nuclear matter



Cutoff dependent fraction of residual 3NF contribution to MBPT2 energy per particle in SNM around saturation density.

Local regulators converge slower than non-local regulators

Nuclear matter from chiral NN and 3NFs



Nuclear matter saturation curves for NNLO$_{sat}$ and other interactions. Hagen et al (2014); Carbone et al (2013); Coraggio et al 2014; **Hebeler *et al* PRC 2011.**

Question: Your favorite physics friend comes to you and suggests to determine the effects of the three-body force on the structure of your favorite nucleus. You reply

1. Let's do this. This will put us on the fast track to Stockholm.
2. This is difficult to disentangle. But it can be done in a three-body system such as ^3H.
3. Which interaction are you looking at?
4. Answers 2 & 3 are correct.

Question: Your favorite physics friend comes to you and suggests to determine the effects of the three-body force on the structure of your favorite nucleus. You reply

1. Let's do this. This will put us on the fast track to Stockholm.
2. This is difficult to disentangle. But it can be done in a three-body system such as ^3H.
3. Which interaction are you looking at? ✔
4. Answers 2 & 3 are correct.

The size and form of three-body forces depends on the cutoff, and the chosen renormalization scheme. Different schemes ("implementations of the EFT at order n") yield predictions that expected to agree within the error estimate $(Q/\Lambda)^{n+1}$. **Only the sum of interactions can be probed**.