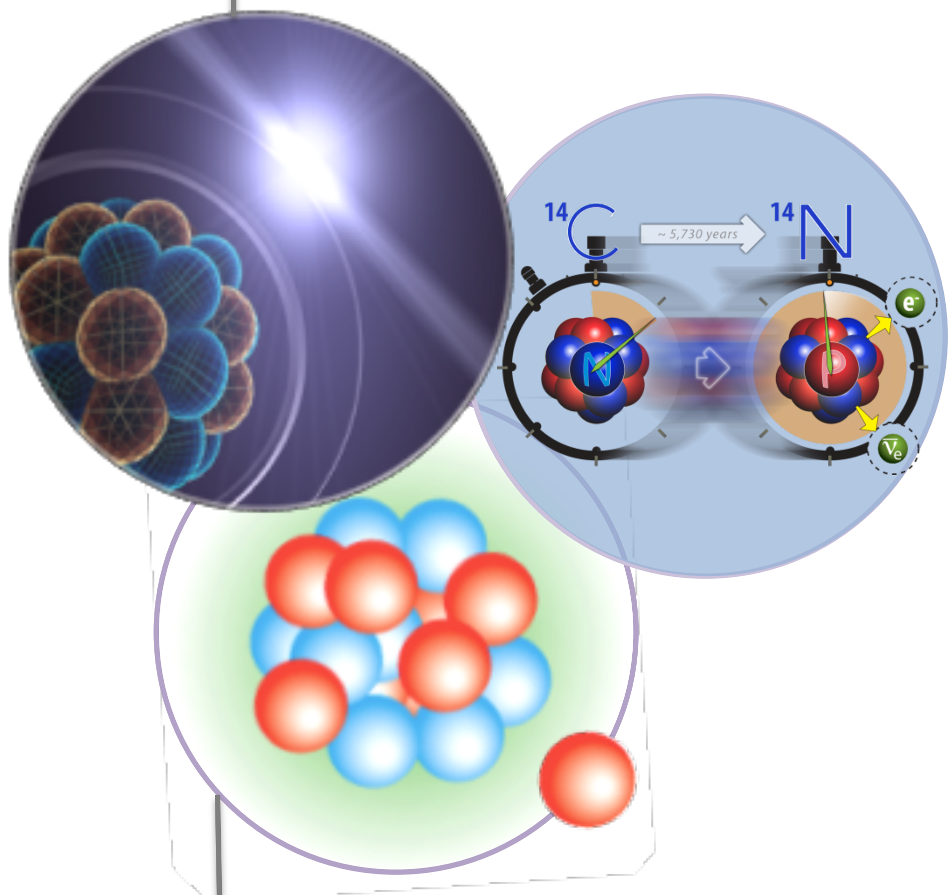
Current topics in nuclear structure theory:

Coupled-cluster computations of nuclei



Gaute Hagen

Oak Ridge National Laboratory

54th International Winter Meeting on Nuclear Physics

Bormio, Italy, January 27th, 2016

U.S. DEPARTMENT OF ENERGY

NUCLEI
Nuclear Computational Low-Energy Initiative

BSF
United States – Israel
Binational Science Foundation

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

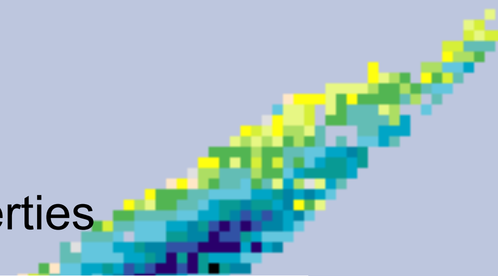
Outline

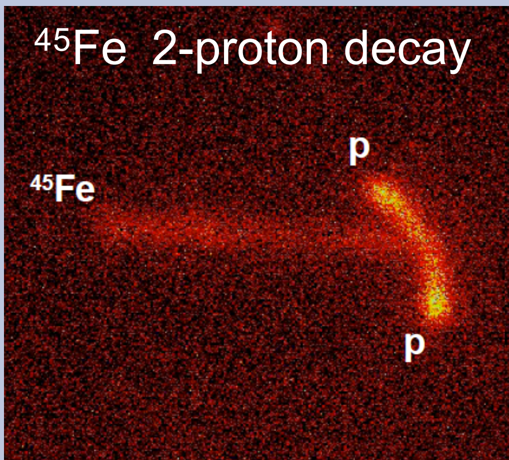
- Status of ab-initio computations of nuclei
- Accurate radii and binding energies from a chiral interaction
- The neutron radius and dipole polarizability of ^{48}Ca
- Coupled-cluster effective interactions with application to *sd*-shell nuclei
- Role of two-body currents and three-nucleon forces on quenching of Gamow-Teller strengths ^{14}C, $^{22,24}O$

Nuclei across the chart

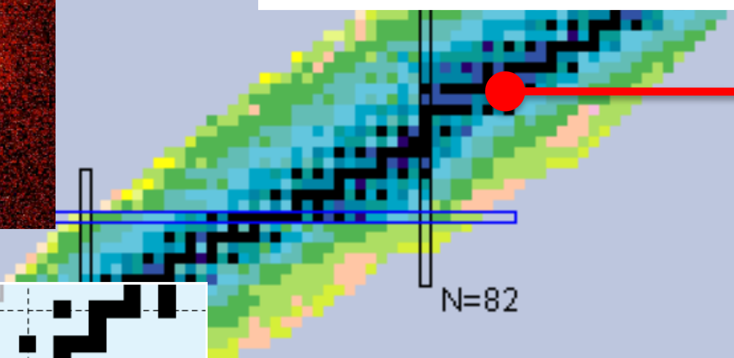
118 chemical elements (94 naturally found on Earth)
288 stable (primordial) isotopes

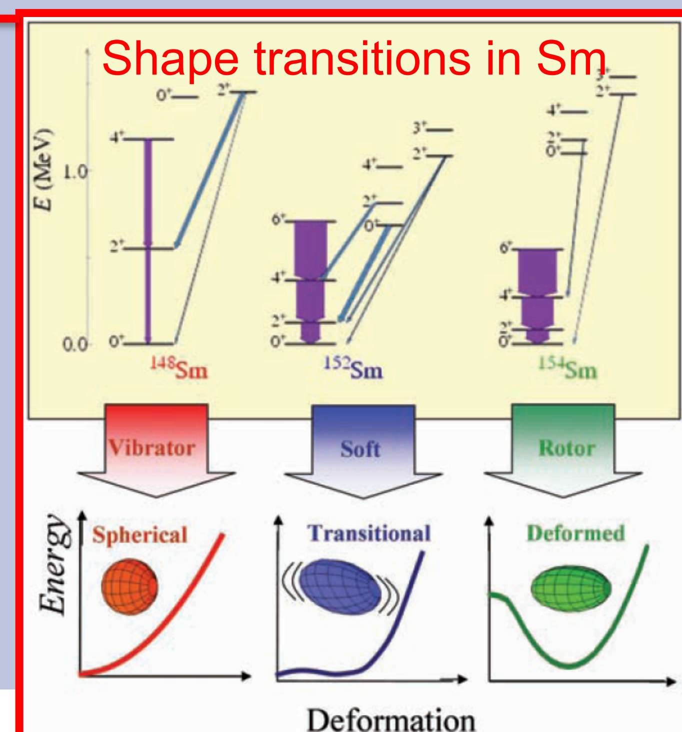
Thousands of short-lived isotopes – many with interesting properties

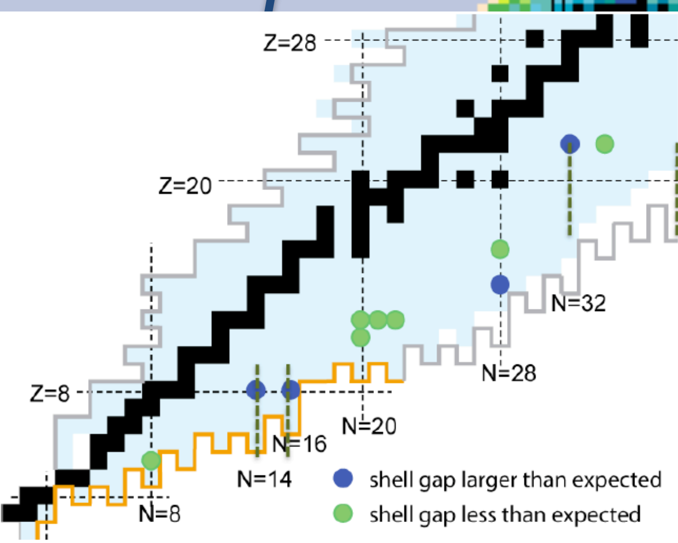


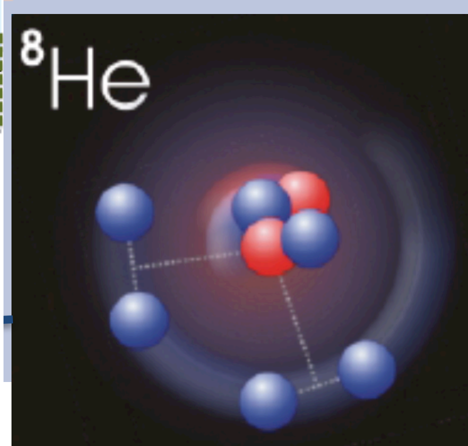


- Large isospin magnifies unknown physics
- Clustering behavior
- Novel evolution in structure
- Challenge for ab-initio theory









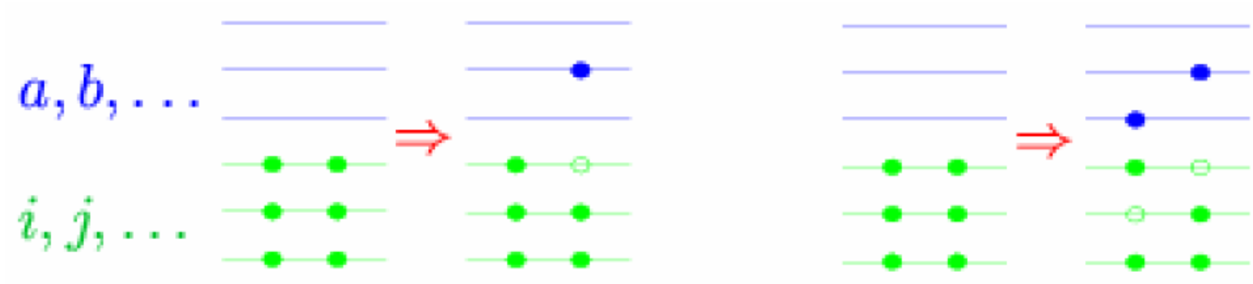
Coupled-cluster method (CCSD approximation)

Ansatz:

$$
\begin{aligned}
|\Psi\rangle &= e^{T}|\Phi\rangle \\
T &= T_1 + T_2 + \ldots \\
T_1 &= \sum_{ia} t_i^a a_a^\dagger a_i \\
T_2 &= \sum_{ijab} t_{ij}^{ab} a_a^\dagger a_b^\dagger a_j a_i
\end{aligned}
$$

- ☺ Scales gently (polynomial) with increasing problem size o^2u^4 .
- ☺ Truncation is the only approximation.
- ☺ Size extensive (error scales with A)
- ☹ Most efficient for closed (sub-)shell nuclei

Correlations are *exponentiated* 1p-1h and 2p-2h excitations. Part of np-nh excitations included!

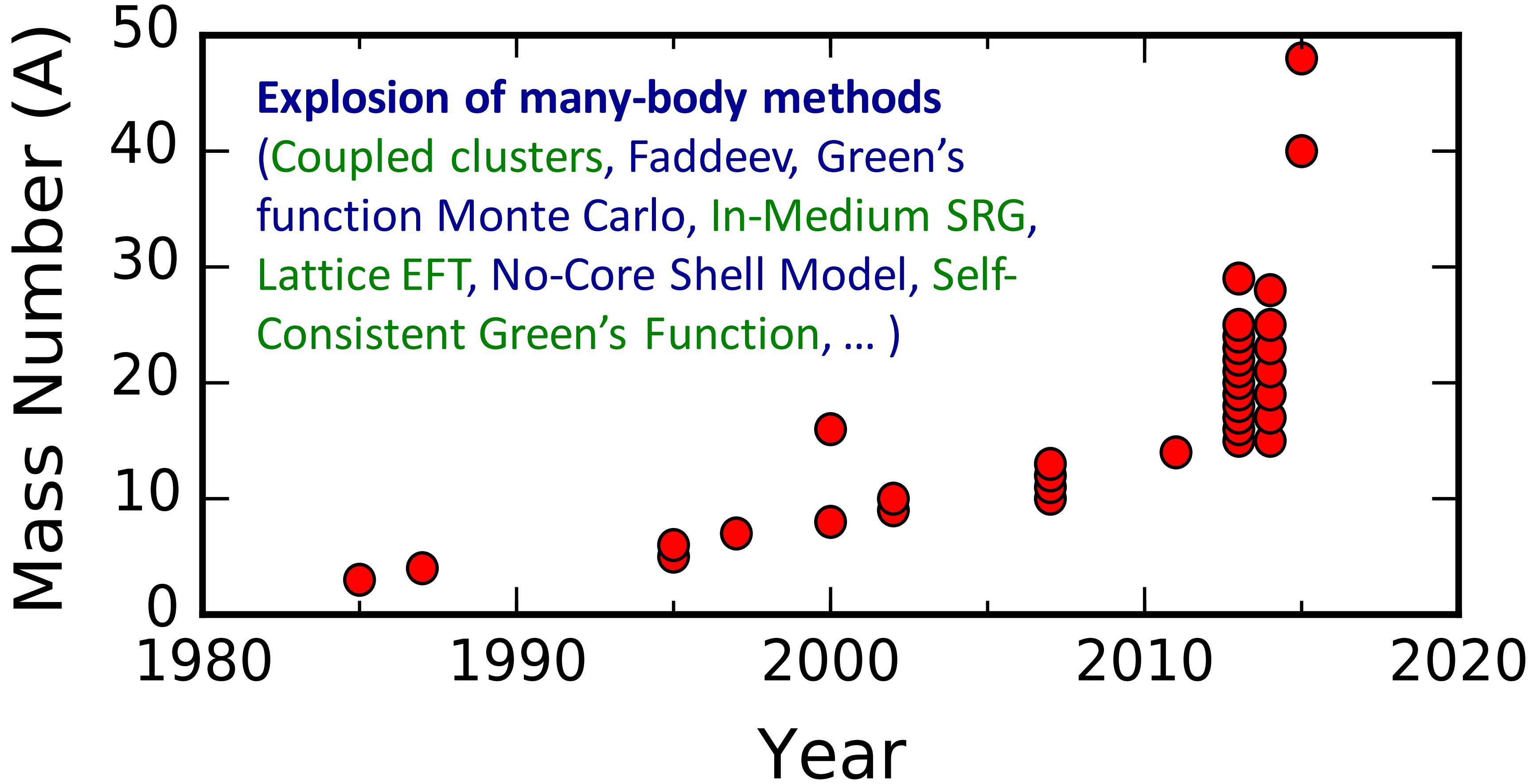


Coupled cluster equations

$$
\begin{aligned}
E &= \langle\Phi|\overline{H}|\Phi\rangle \\
0 &= \langle\Phi_i^a|\overline{H}|\Phi\rangle \\
0 &= \langle\Phi_{ij}^{ab}|\overline{H}|\Phi\rangle \\
\overline{H} &\equiv e^{-T}He^{T} = \left(He^{T}\right)_c = \left(H + HT_1 + HT_2 + \frac{1}{2}HT_1^2 + \ldots\right)_c
\end{aligned}
$$

Alternative view: CCSD generates similarity transformed Hamiltonian with no 1p-1h and no 2p-2h excitations.

Ab-initio calculations of nuclei

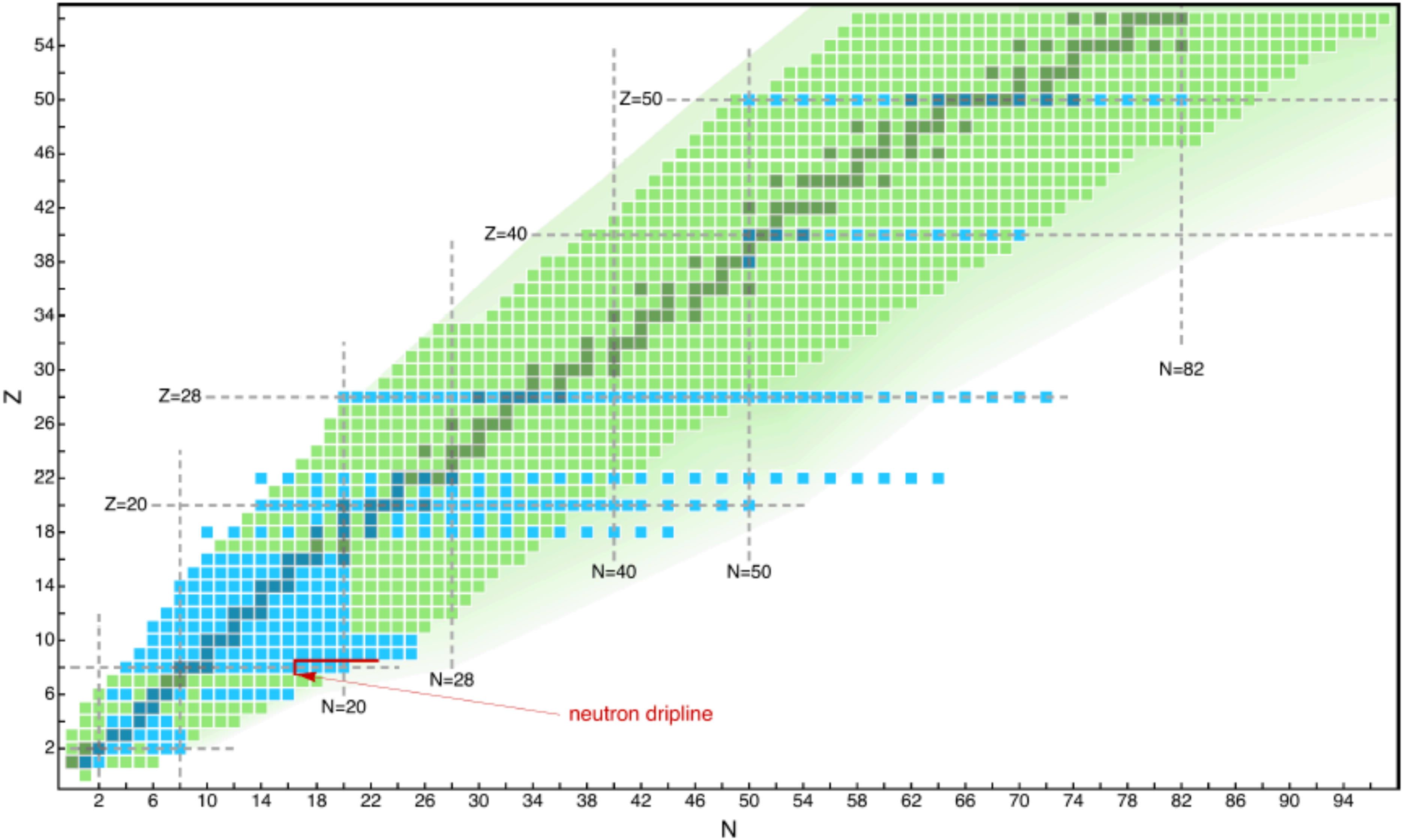


Computing power increases exponentially (Moore's law)

Algorithms with Exponential scaling in *A*

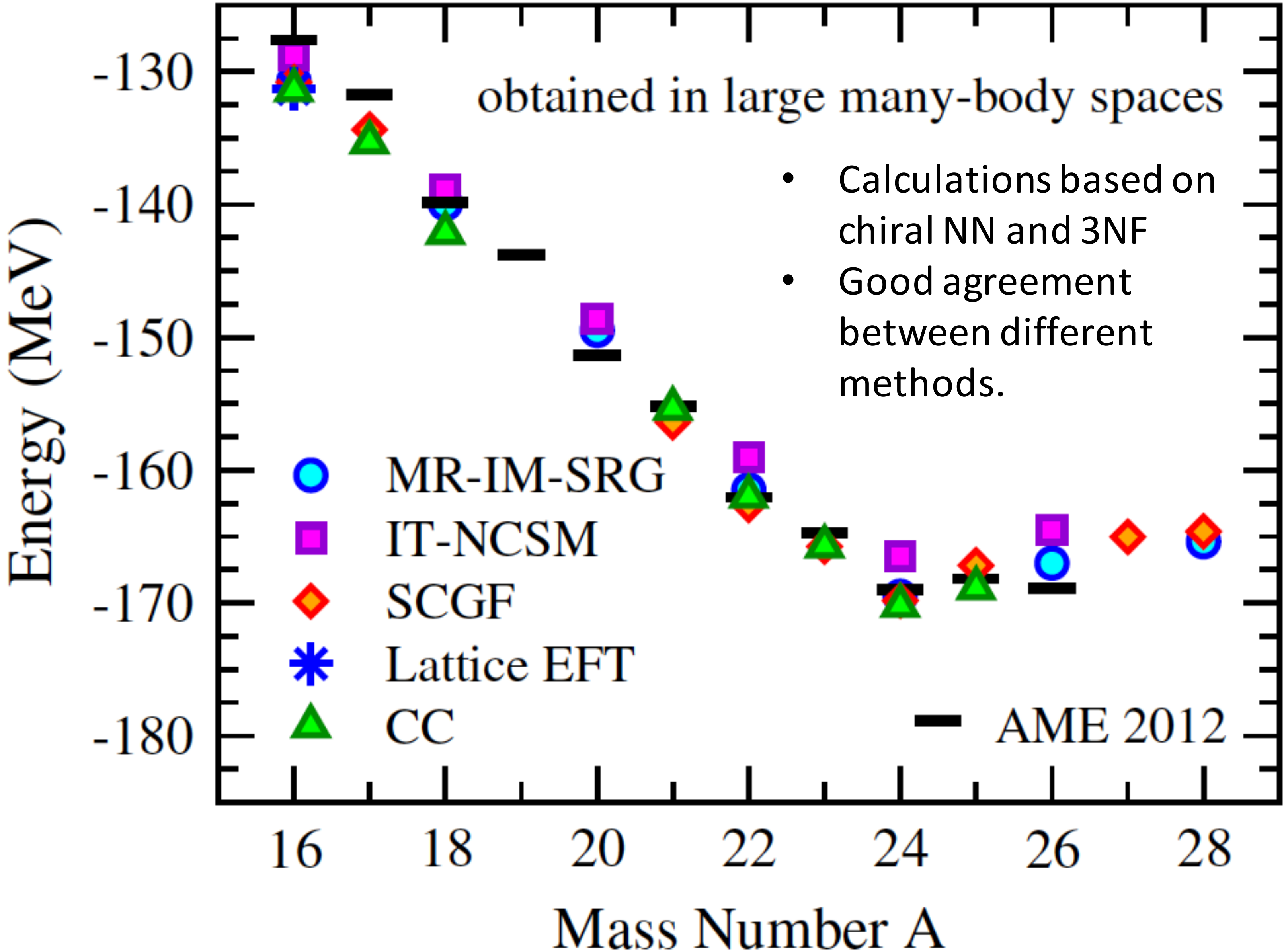
Algorithms with polynomial scaling in *A*

Reach of ab-initio calculations of nuclei



Nuclei for which ab-initio computations have been attempted.
H. Hergert *et al*, arXiv:1512.06956 (2015)

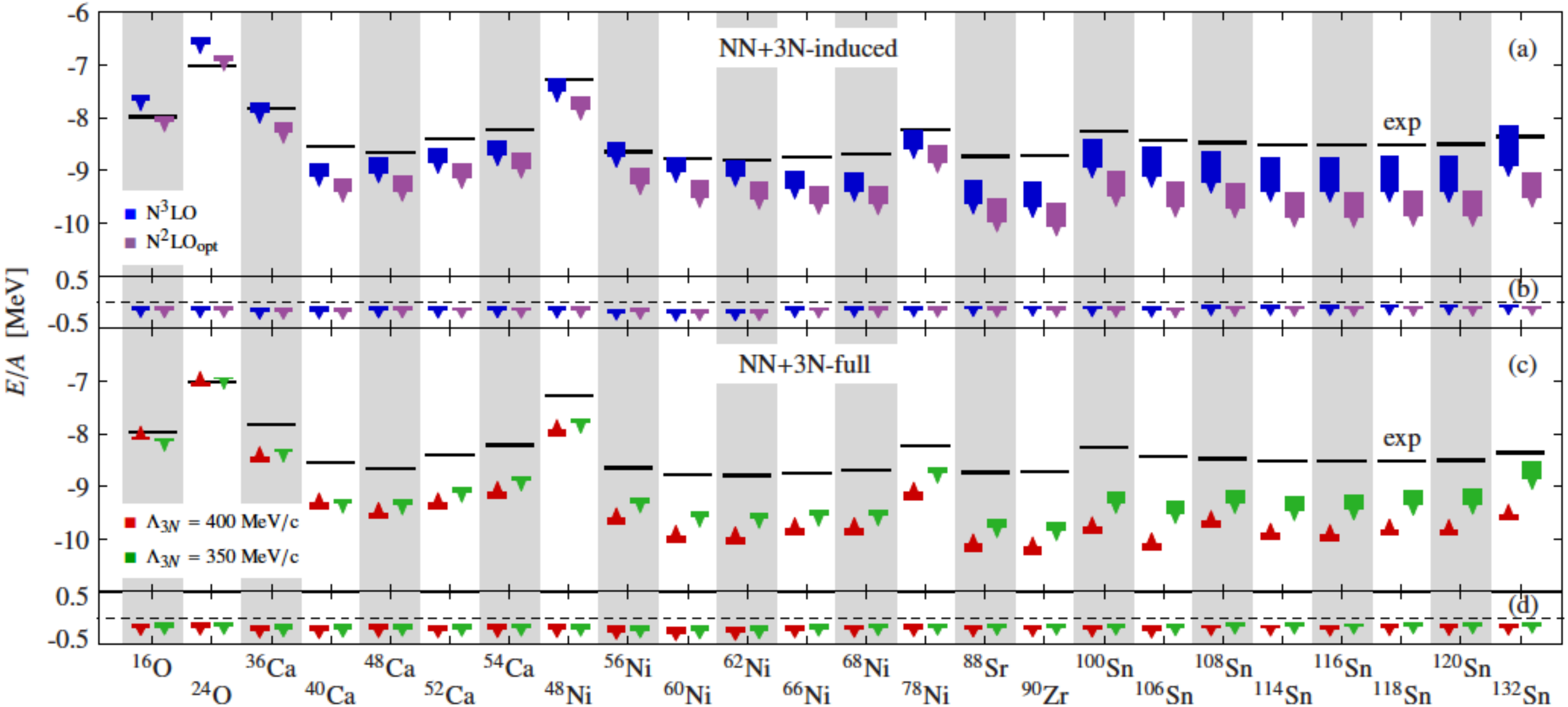
Oxgyen chain with interactions from chiral EFT



- Calculations based on chiral NN and 3NF
- Good agreement between different methods.

Hebeler, Holt, Menendez, Schwenk, Annu. Rev. Nucl. Part. Sci. 65, 457 (2015)

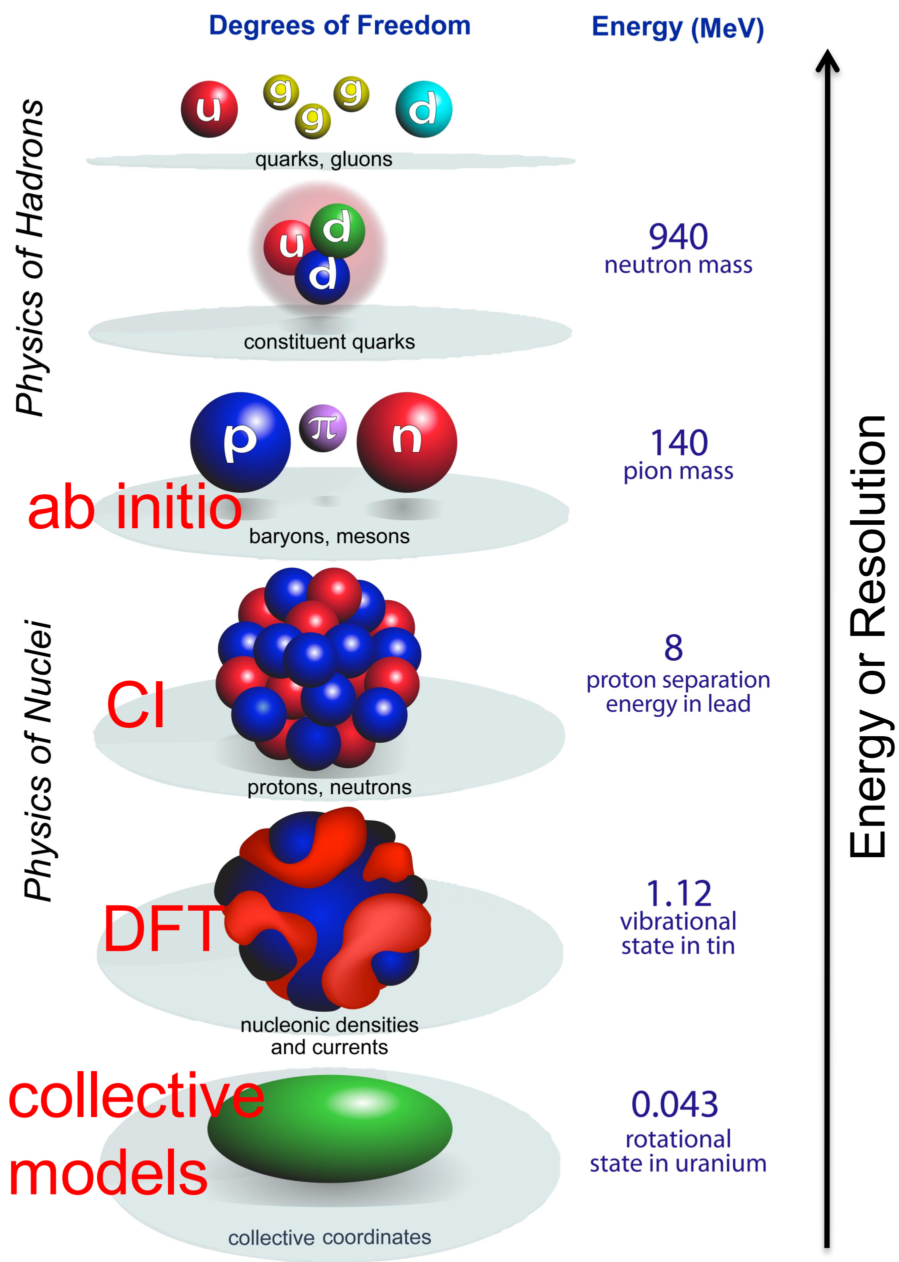
Ab-initio computations towards heavy nuclei



S. Binder et al, Physics Letters B 736 119, (2014)

- Overbinding of 1-2 MeV/A for increasing mass *A*
- **The challenge is now with the interactions**

Effective theories for nuclei



Effective theories provide us with model independent approaches to atomic nuclei

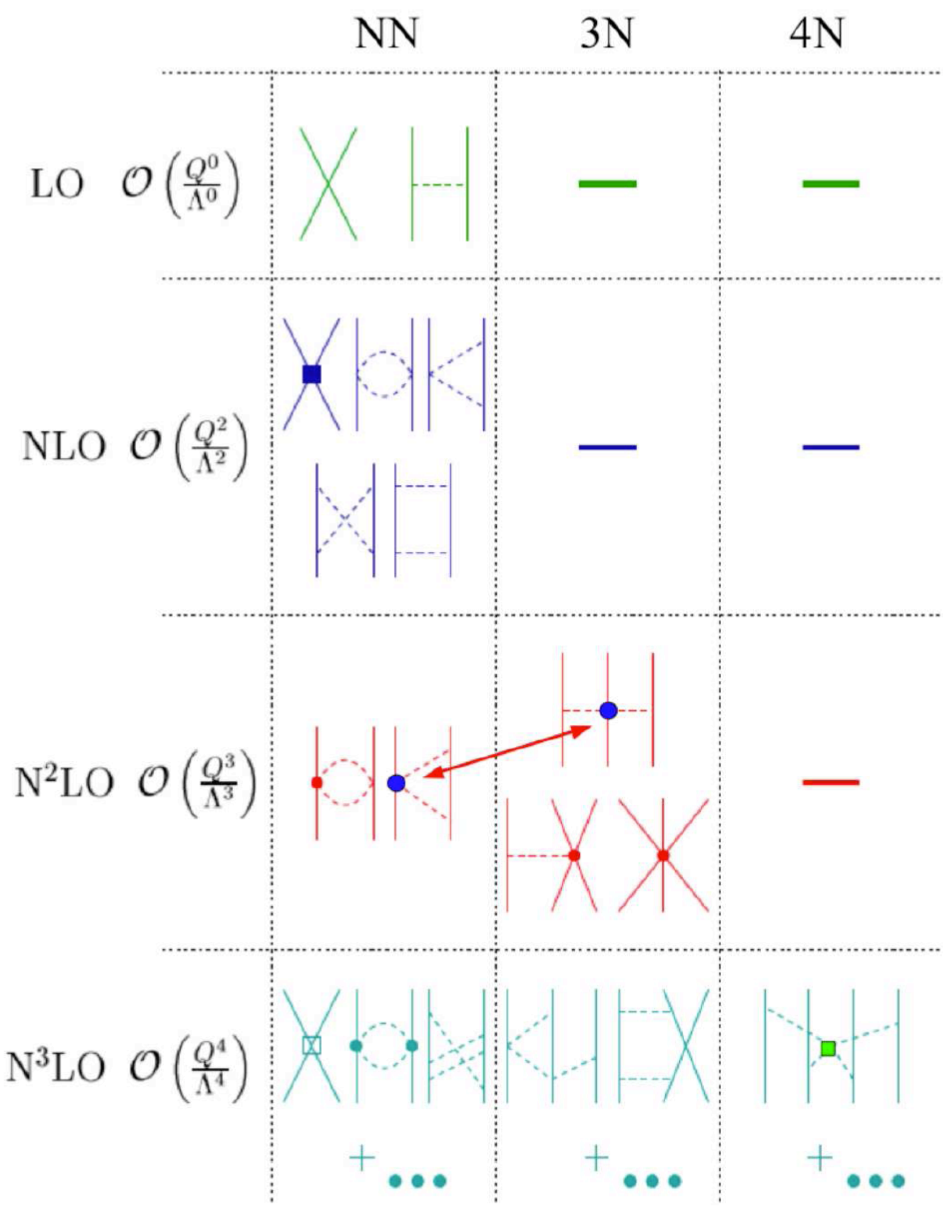
Key: Separation of scales

Ab-initio low-energy nuclear physics deals with nucleons and pions as dynamical degrees of freedom

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

Nuclear forces from chiral effective field theory

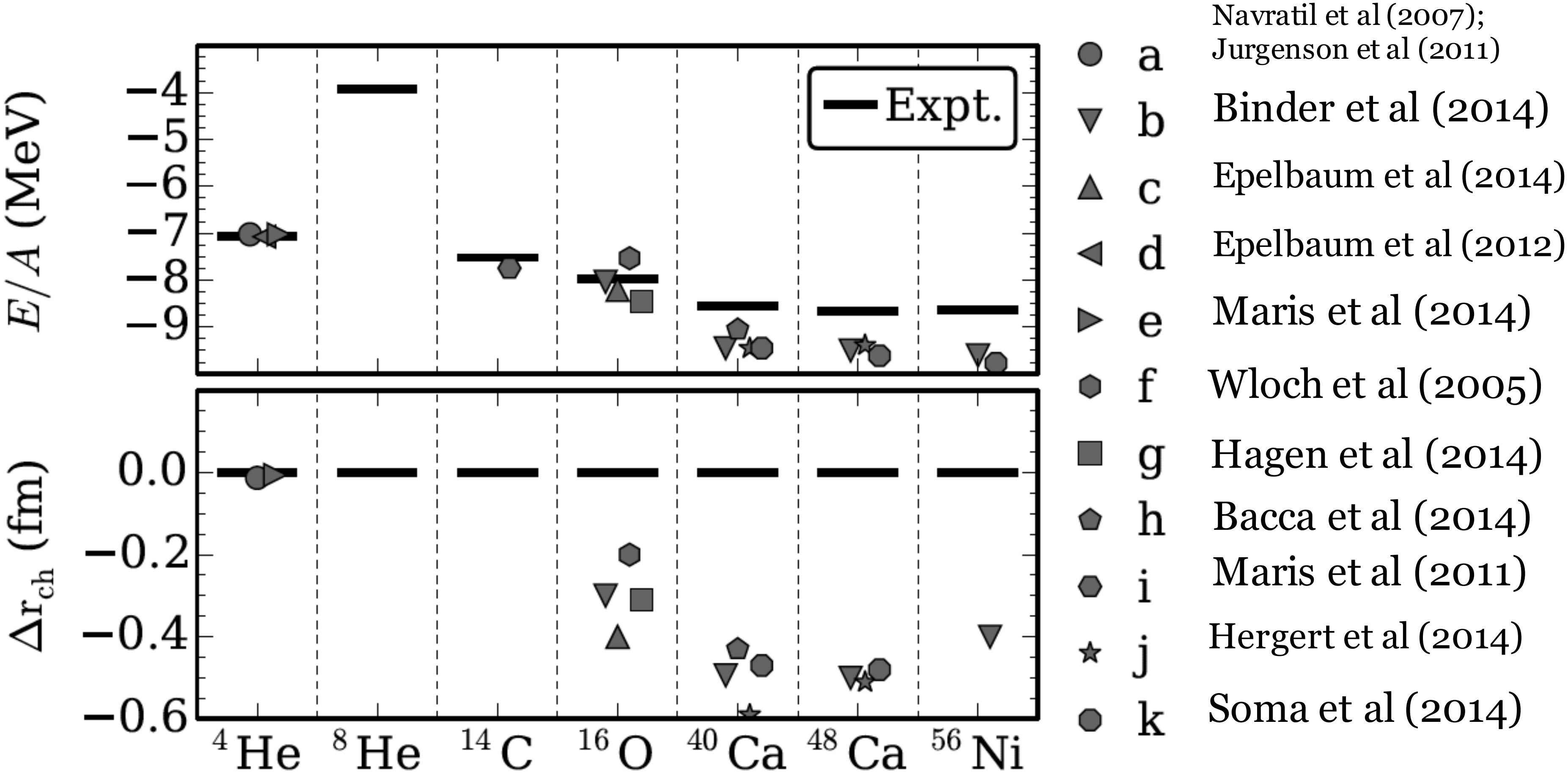
[Weinberg; van Kolck; Epelbaum *et al*.; Entem & Machleidt; …]



- 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 2013/2014]
- propagation of uncertainties on horizon [Navarro Perez 2014, Carlsson et al 2015]
- different optimization protocols [Ekström et al 2015]

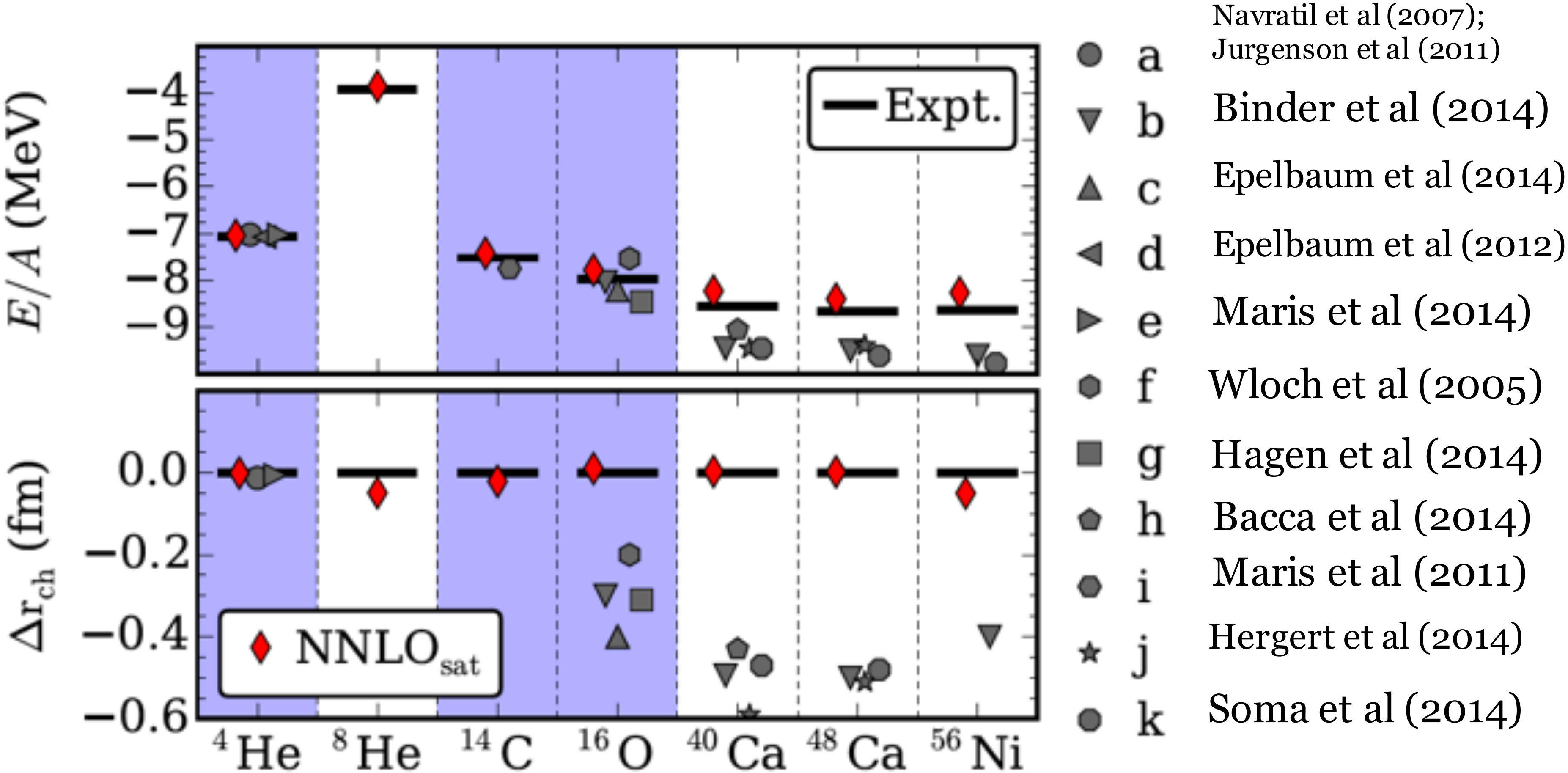
Much improved understanding and handling via renormalization group transformations [Bogner et al 2003; Bogner et al 2007]

Accurate nuclear binding energies and radii from a chiral interaction



- Chiral interactions have failed at describing both binding energies and radii of nuclei
- Predictive power does not go together with large extrapolations
- Nuclear saturation may be viewed as an emergent property

Accurate nuclear binding energies and radii from a chiral interaction



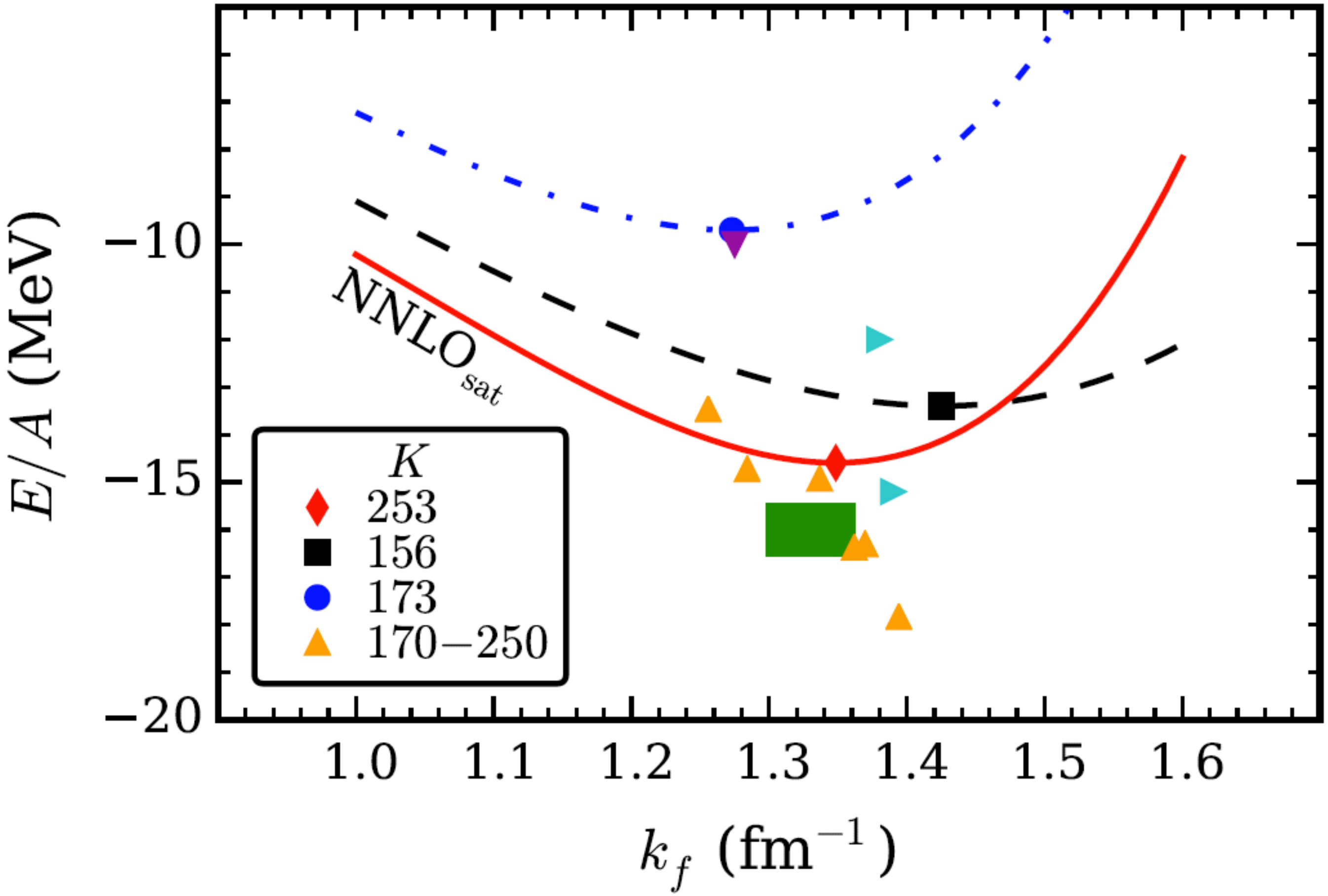
Solution: Simultaneous optimization of NN and 3NFs
Include charge radii and binding energies of ^{3}H, ^{3,4}He, ^{14}C, ^{16}O in the optimization ($NNLO_{sat}$)

A. Ekström *et al*, Phys. Rev. C **91**, 051301(R) (2015).

Critical ingredient:
Three-nucleon forces with non-local regulators

Nuclear matter from NNLO_{sat}

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



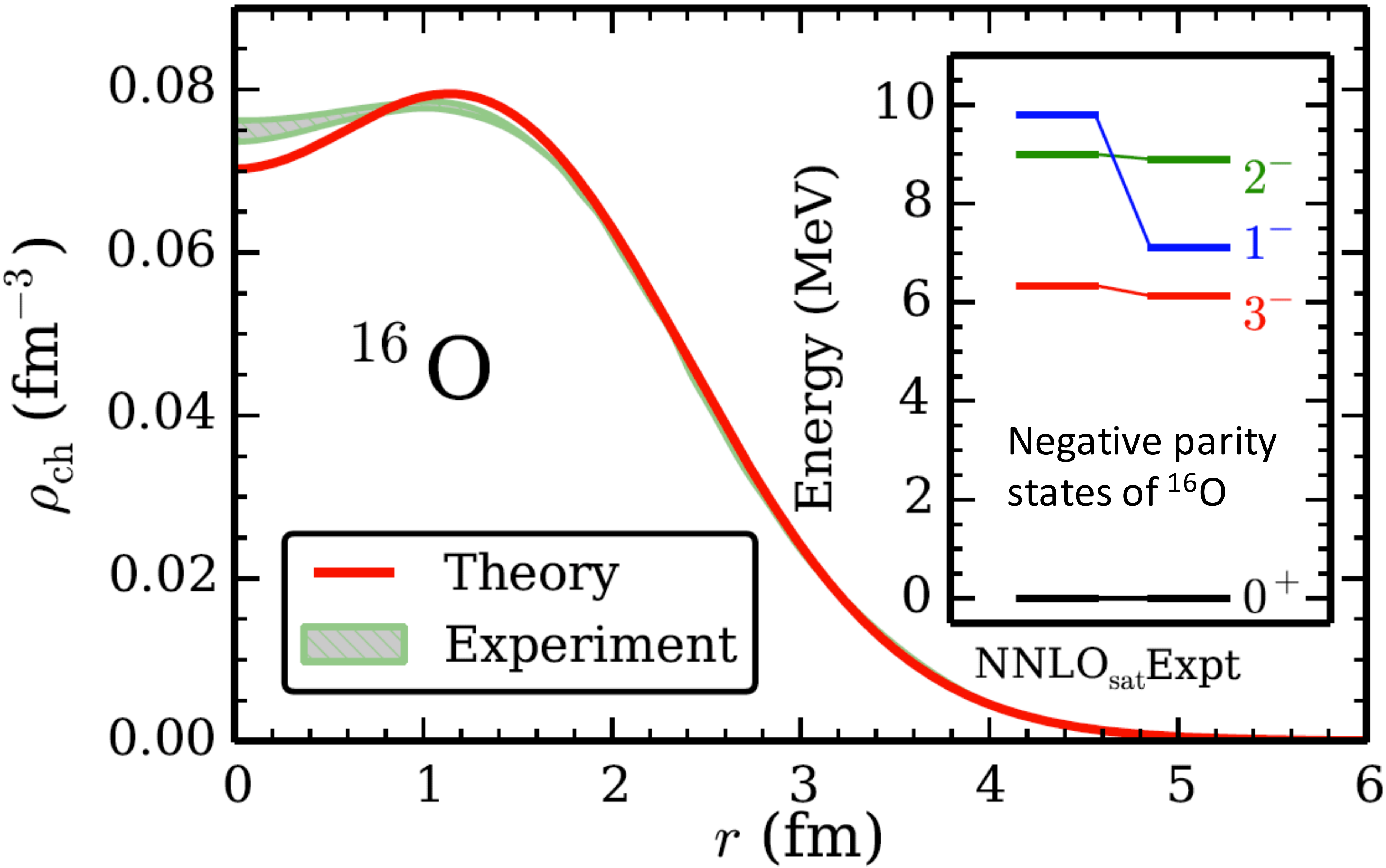
Nuclear matter saturation curves for NNLO_{sat} and other interactions.

Hagen et al (2014); Carbone et al (2013); Coraggio et al 2014;

Hebeler *et al* PRC 2011.

- Interactions from Hebeler *et al* not constrained by heavier nuclei.
- They reproduce binding energy and radii of few-body systems
- Non-local regulators in the 3NF important for saturation

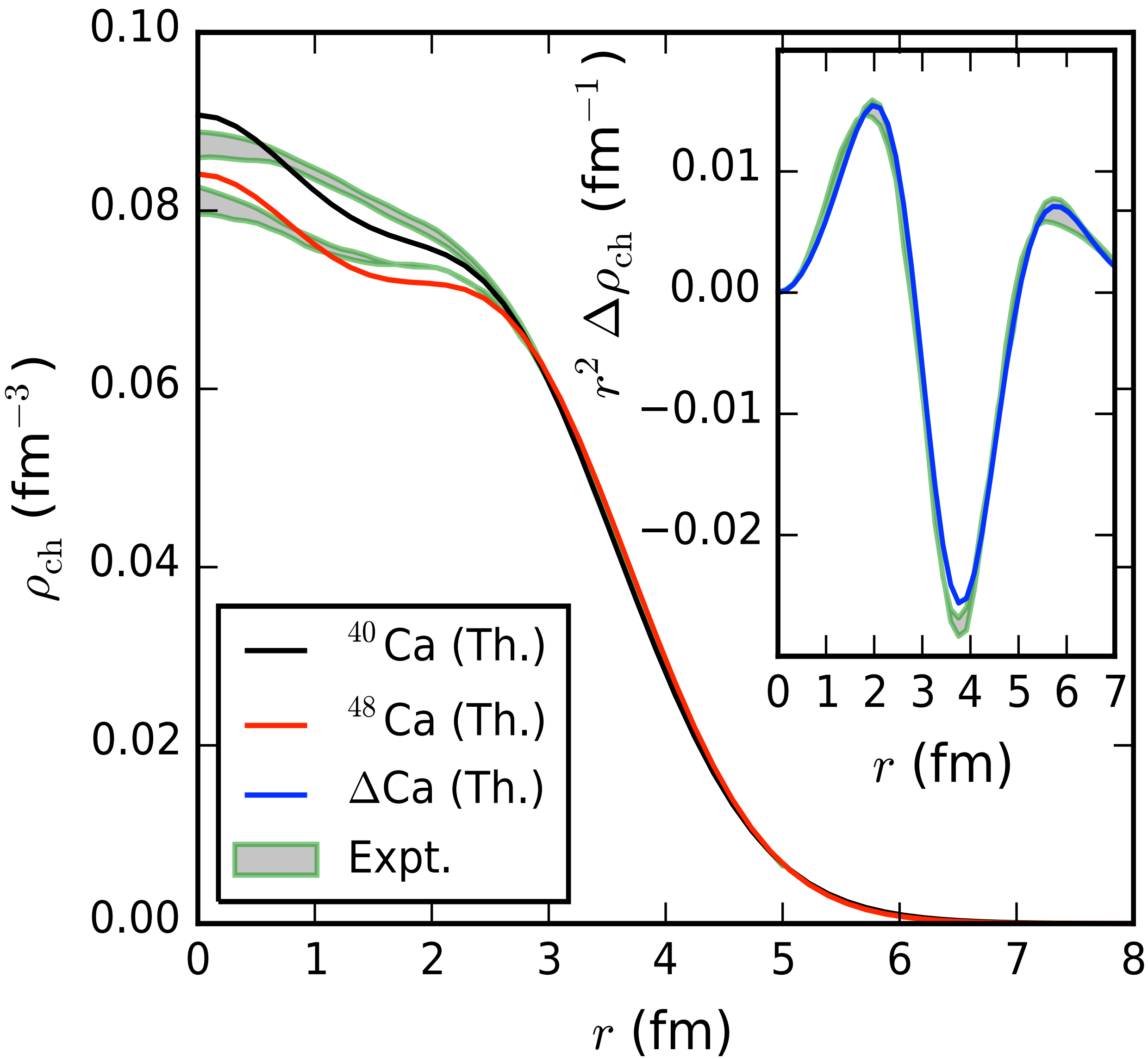
Charge density of ^{16}O from $NNLO_{sat}$



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

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

G. Hagen *et al*, Nature Physics (2015) doi:10.1038/nphys3529



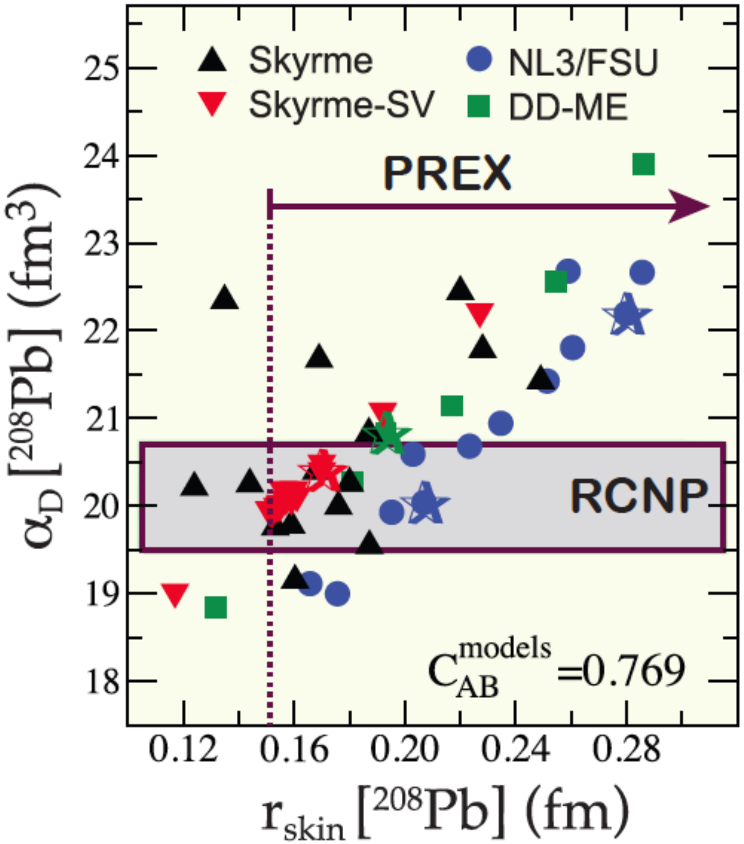
Electric charge distributions have been a long-standing problem for *ab initio* theory.

BE(Th) = 404(3) MeV
BE(Exp) = 416 MeV

R_{Ch} (Th) = 3.48(3) fm
$R_{Ch.}$(Exp) = 3.477(2) fm

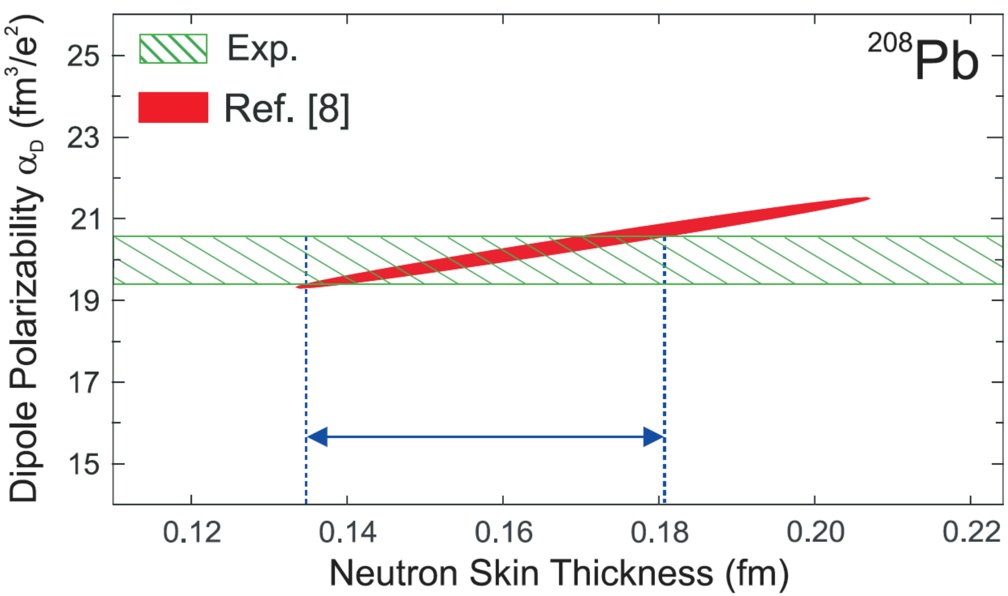
Neutron radii and dipole polarizability

J. Piekarewicz e al, PRC 85, 041302(R) (2012)



α_D: ^{208}Pb by Tamii et al, PRL 2011; ^{68}Ni by Rossi et al, PRL 2013; ^{120}Sn by Hashimoto et al. (2015); ^{48}Ca coming soon (Darmstadt/Osaka collaboration)

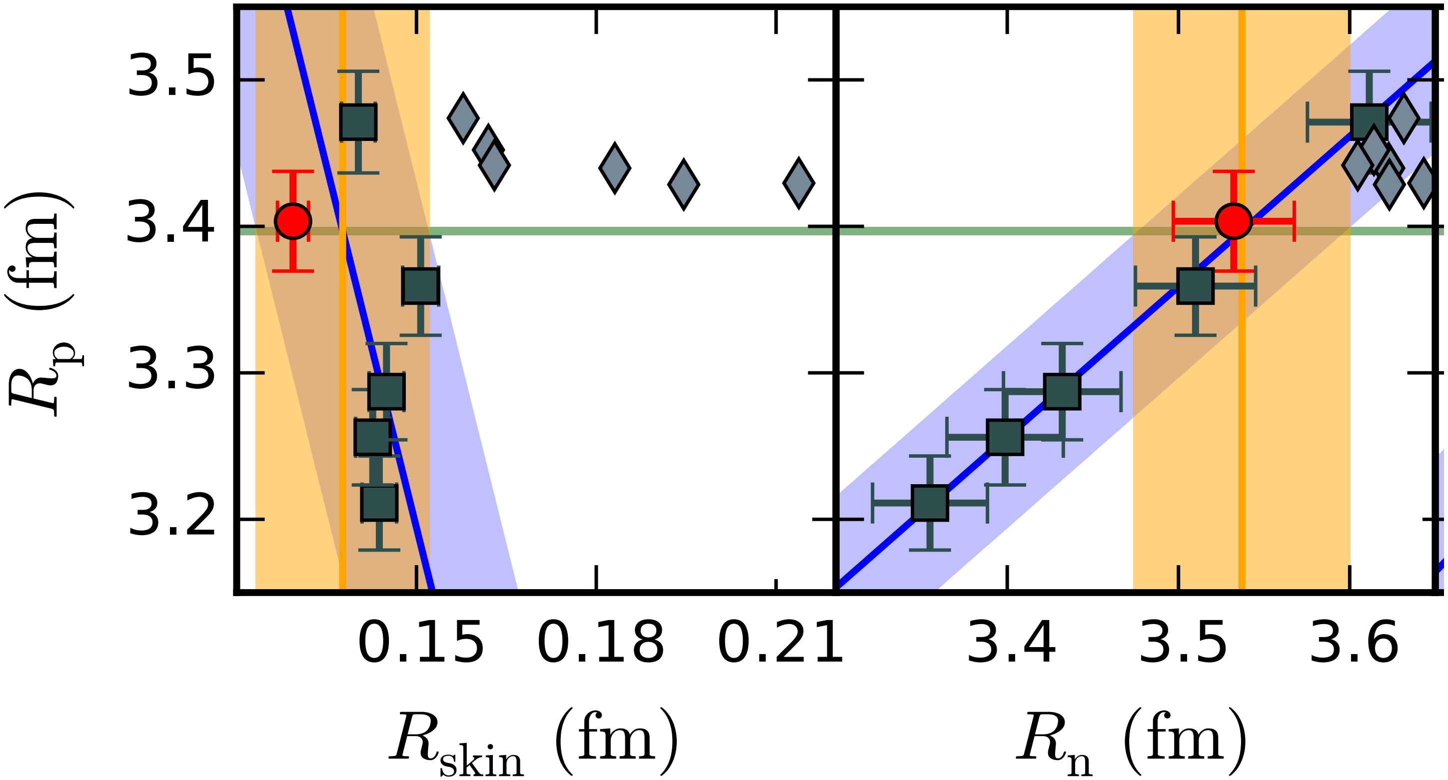
R_n: ^{208}Pb by Abrahamyan et al, PRL 2012; ^{48}Ca → CREX



- Our knowledge about neutron skins is so far mainly based on DFT models.
- What does ab-initio theory add to our knowledge of the neutron skin and size of nuclei?

Neutron radius and skin of ^{48}Ca

G. Hagen *et al*, Nature Physics (2015) doi:10.1038/nphys3529



Uncertainty estimates from family of chiral interactions.

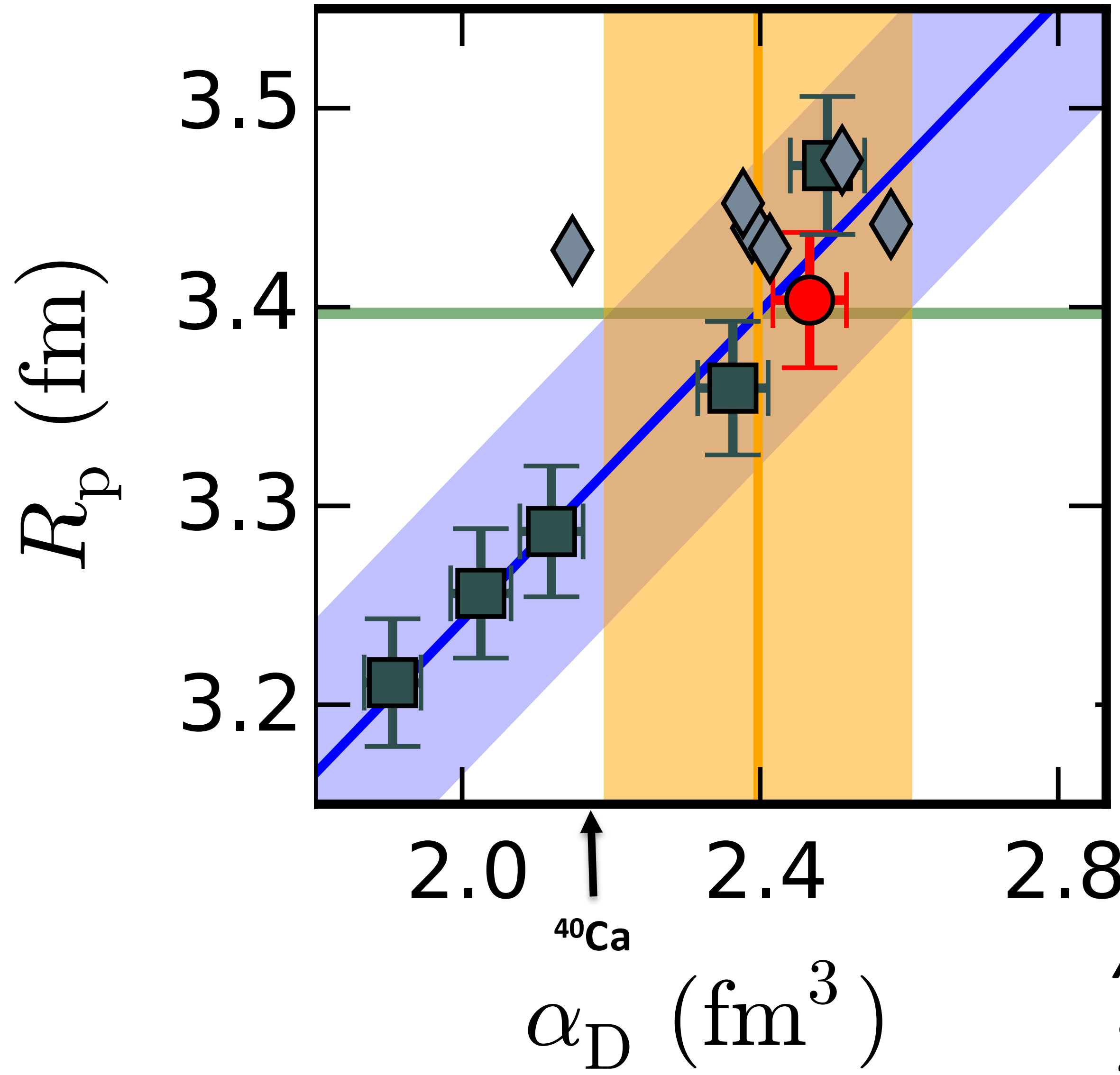
DFT: SkM*, SkP, Sly4, SV-min, UNEDF0, and UNEDF1

$0.12 \lesssim R_{skin} \lesssim 0.15$ fm **$3.47 \lesssim R_n \lesssim 3.60$ fm**

- Neutron skin significantly smaller than in DFT
- Neutron skin almost independent of the employed Hamiltonian
- Proton radii about 1% too large in DFT
- Ab-initio reproduce *N*=28 shell gap/DFT underestimates shell gaps

Dipole polarizability of ^{48}Ca

G. Hagen *et al*, Nature Physics (2015) doi:10.1038/nphys3529



DFT results are consistent and within band of ab-initio results

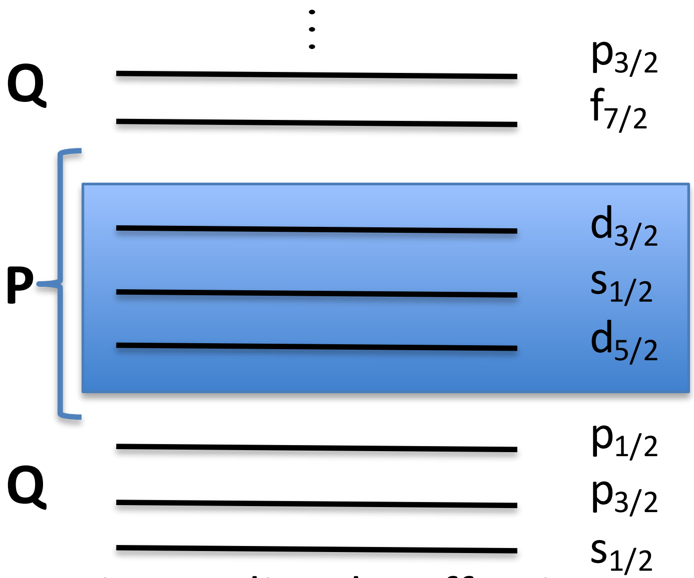
Data being analyzed by Osaka-Darmstadt collaboration

Ab-initio prediction:
$2.19 \lesssim \alpha_D \lesssim 2.60$ fm^3

Coupled-cluster effective interactions (CCEI)

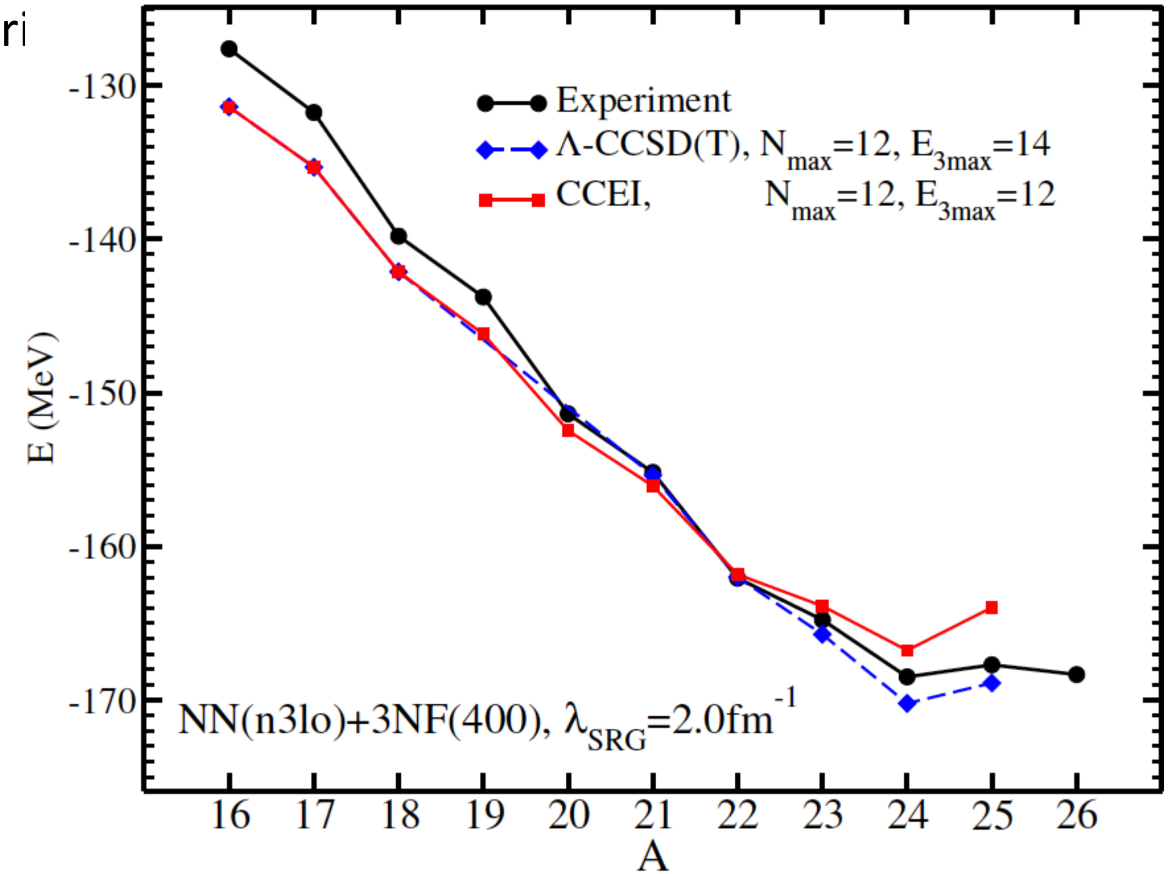
G. R. Jansen, J. Engel, GH, P. Navratil, A. Signoracci, Phys. Rev. Lett. **113**, 142502 (2014).

- Start from chiral NN+3NFs
- Solve for A, A+1 and A+2 using CC.
- Project A+1 and A+2 CC wave functions onto the *s-d* model space using Lee-Suzuki similari transformation.

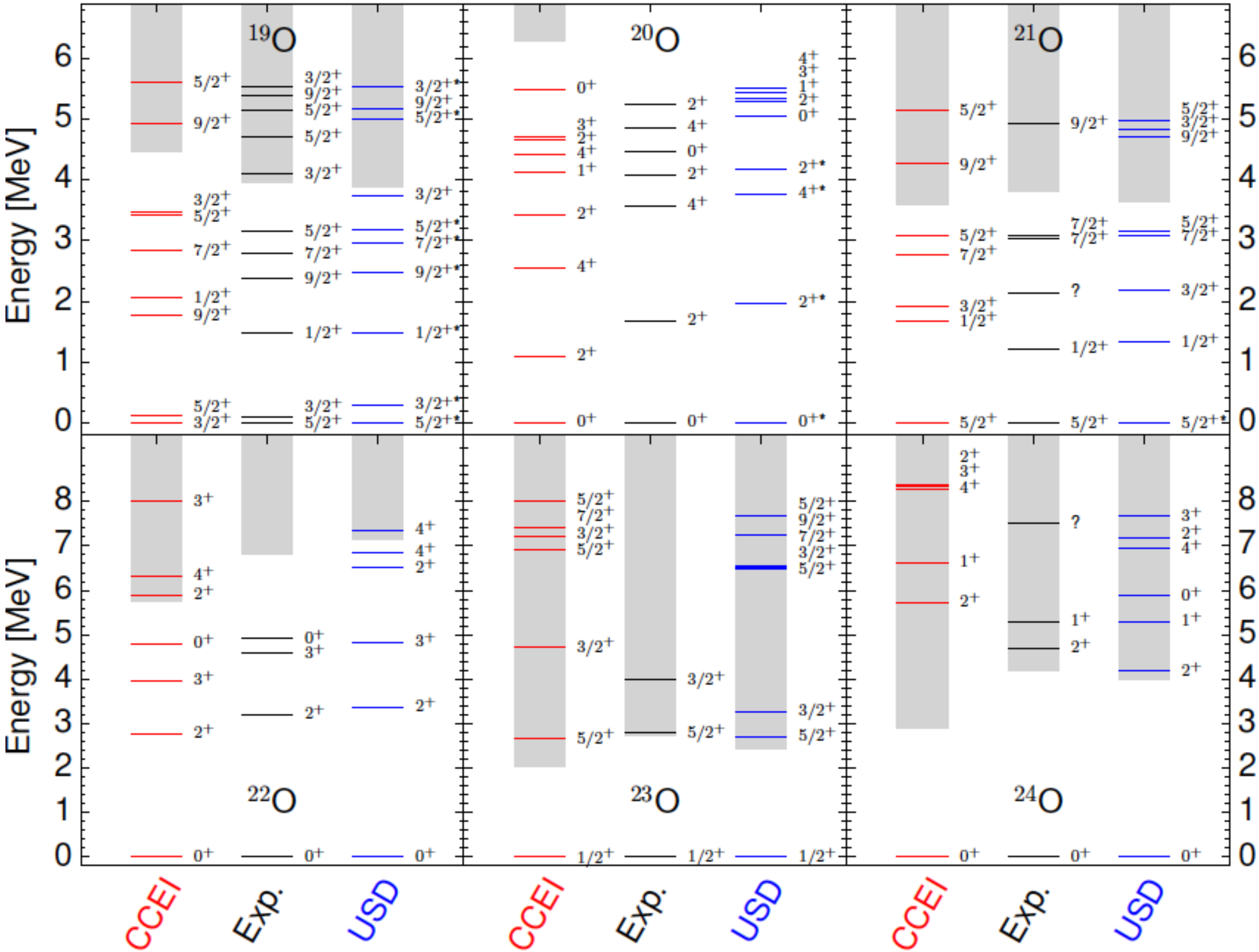


- Diagonalize the effective hamiltonian in the valence space.

Comparison between coupled-cluster effective interaction (CCEI) and "exact" coupled-cluster calculation with inclusion of perturbative triples (Λ-CCSD(T))

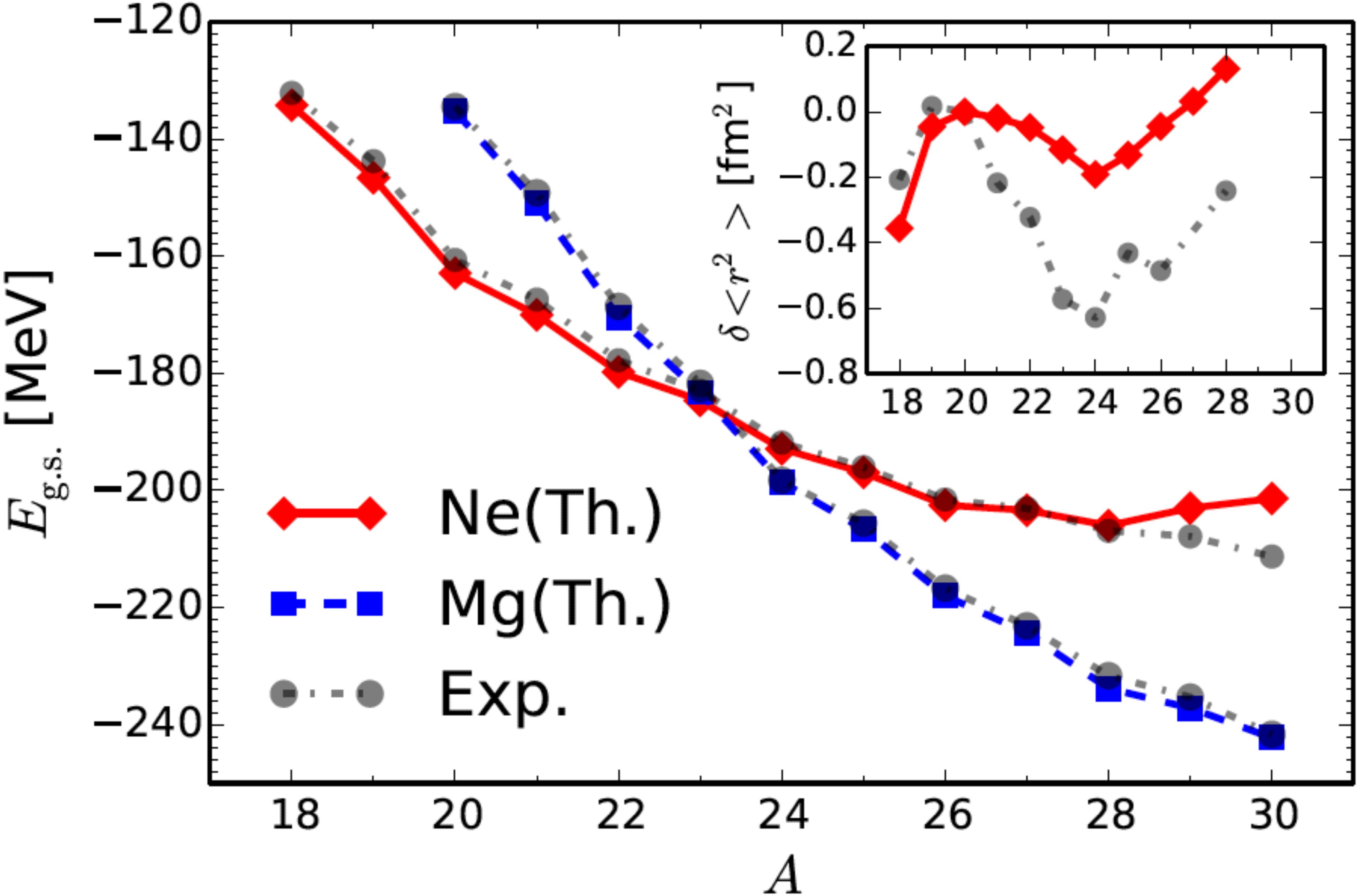


Coupled-cluster effective interactions for the shell model: Oxygen isotopes



Deformed sd-shell nuclei from first principles

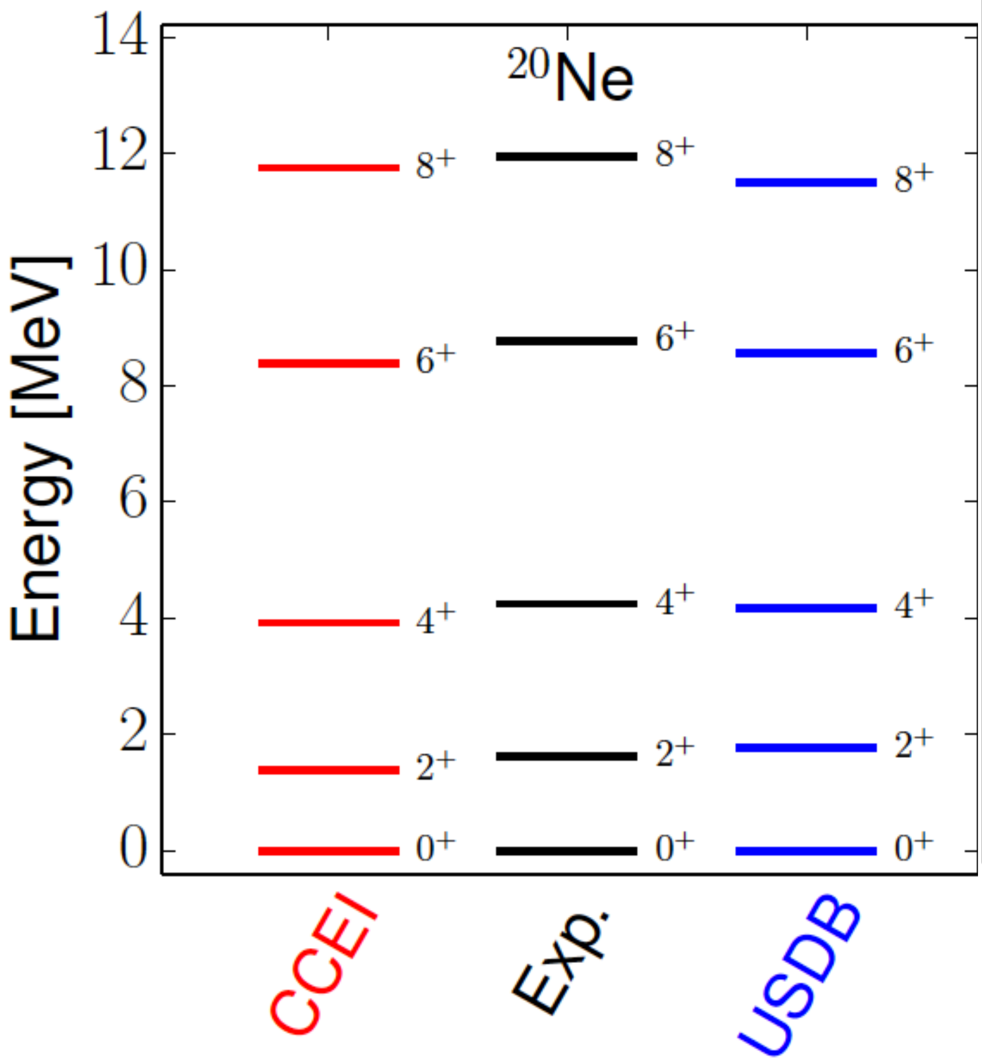
G. R. Jansen, A. Signoracci, GH, P. Navratil arXiv:1511.00757 (2015).

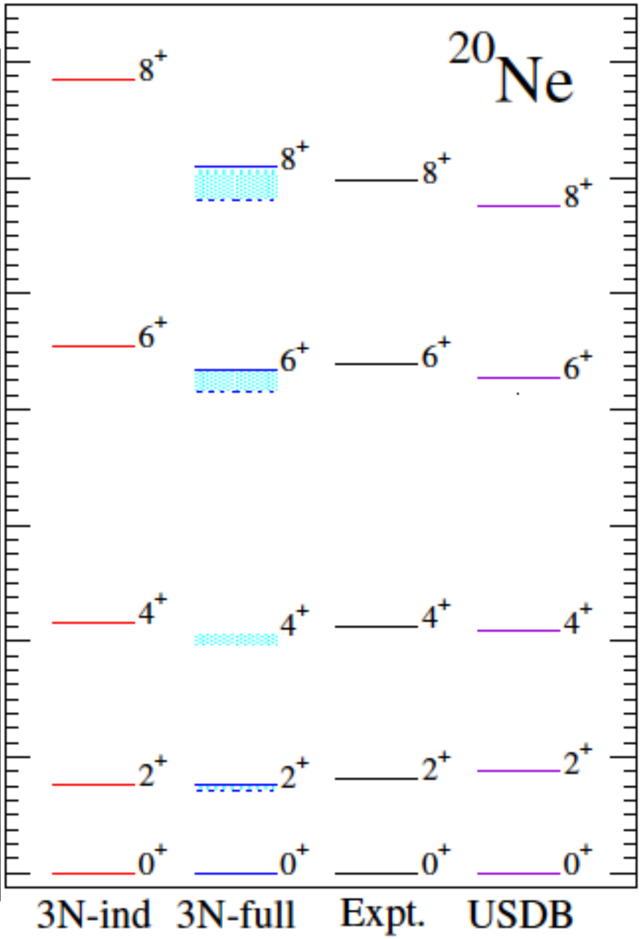


Deformed sd-shell nuclei from first principles

G. R. Jansen, A. Signoracci, GH, P. Navratil arXiv:1511.00757 (2015).

S. R. Stroberg et al, arXiv:1511.02802 (2015).



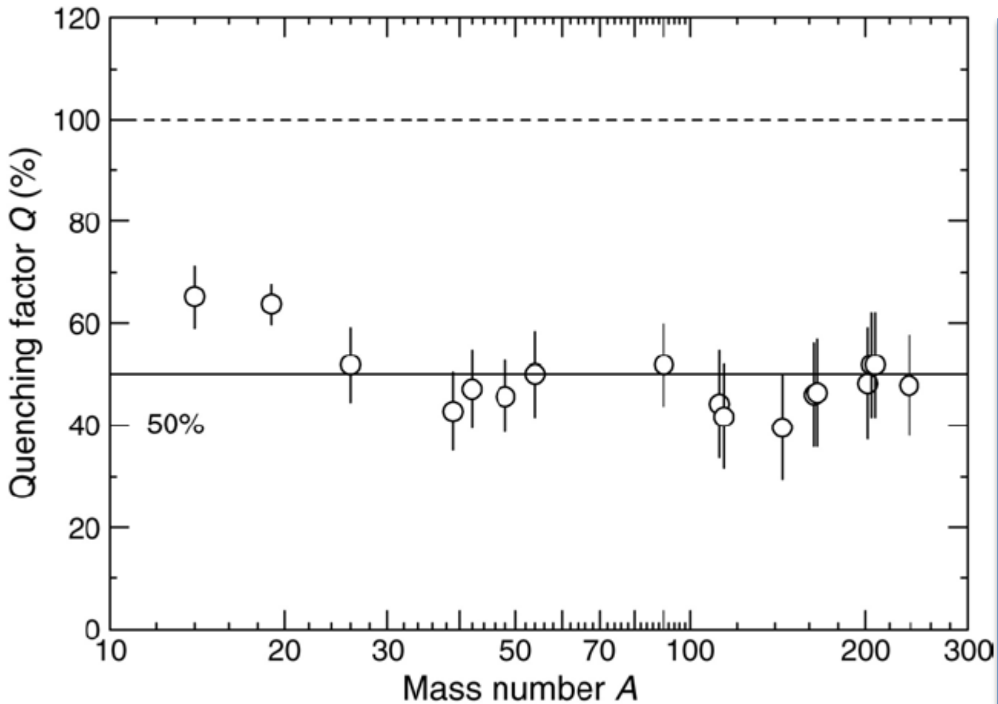


Quenching of Gamow-Teller strength in nuclei

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?

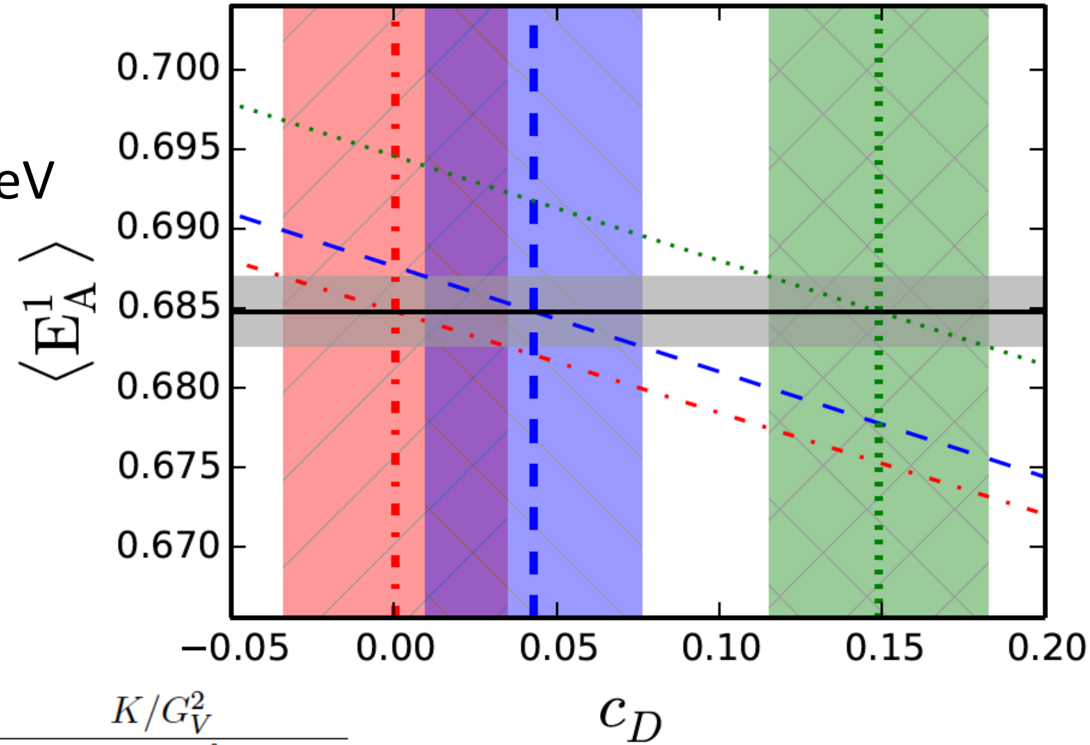
- **What does two-body currents and three-nucleon forces add to this long-standing problem?**

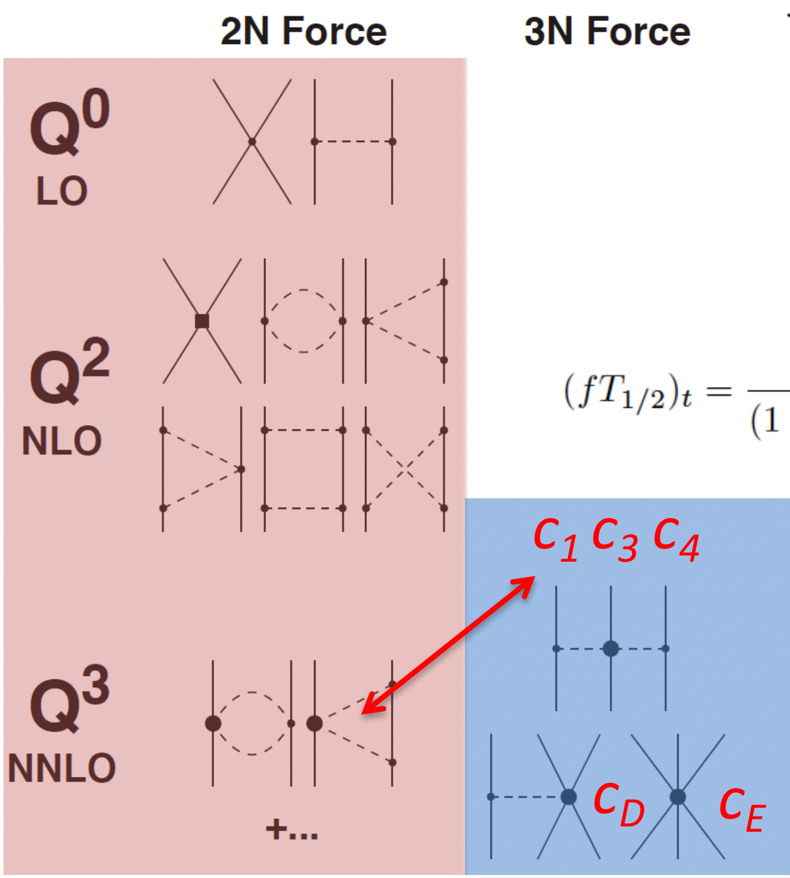
Weak decays from first principles

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

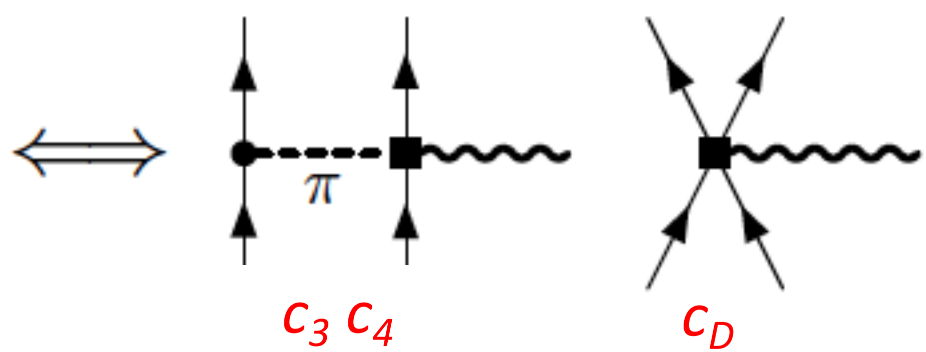
c_D - c_E fit of A=3 binding energies and the ^{3}H half life at NNLO for chiral cutoffs Λ = 450,500,550 MeV

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





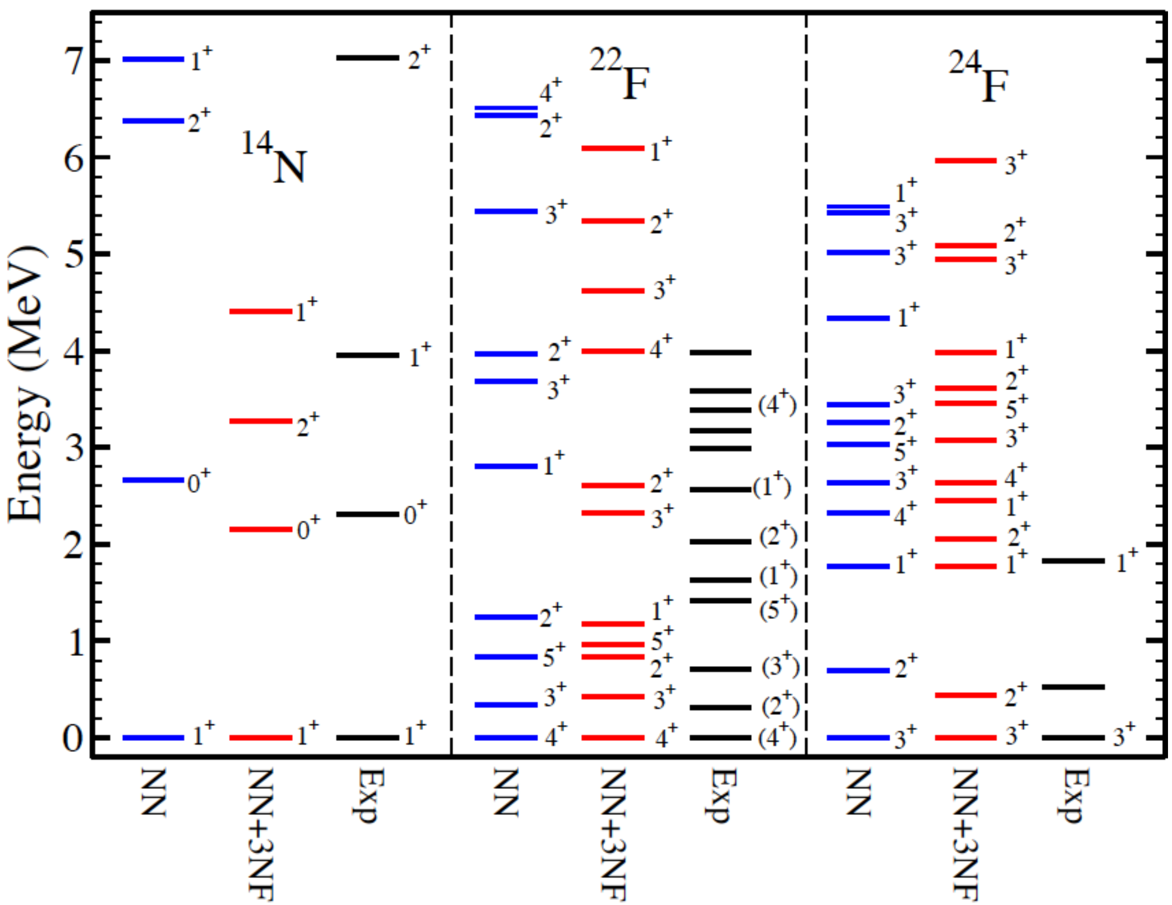
$$(fT_{1/2})_t = \frac{K/G_V^2}{(1-\delta_c) + 3\pi \frac{f_A}{f_V} \langle E_1^A \rangle^2}$$



Charge-exchange coupled cluster method for odd-odd nuclei

Diagonalize $\overline{H} = e^{-T} H_N e^{T}$ via charge-exchange 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

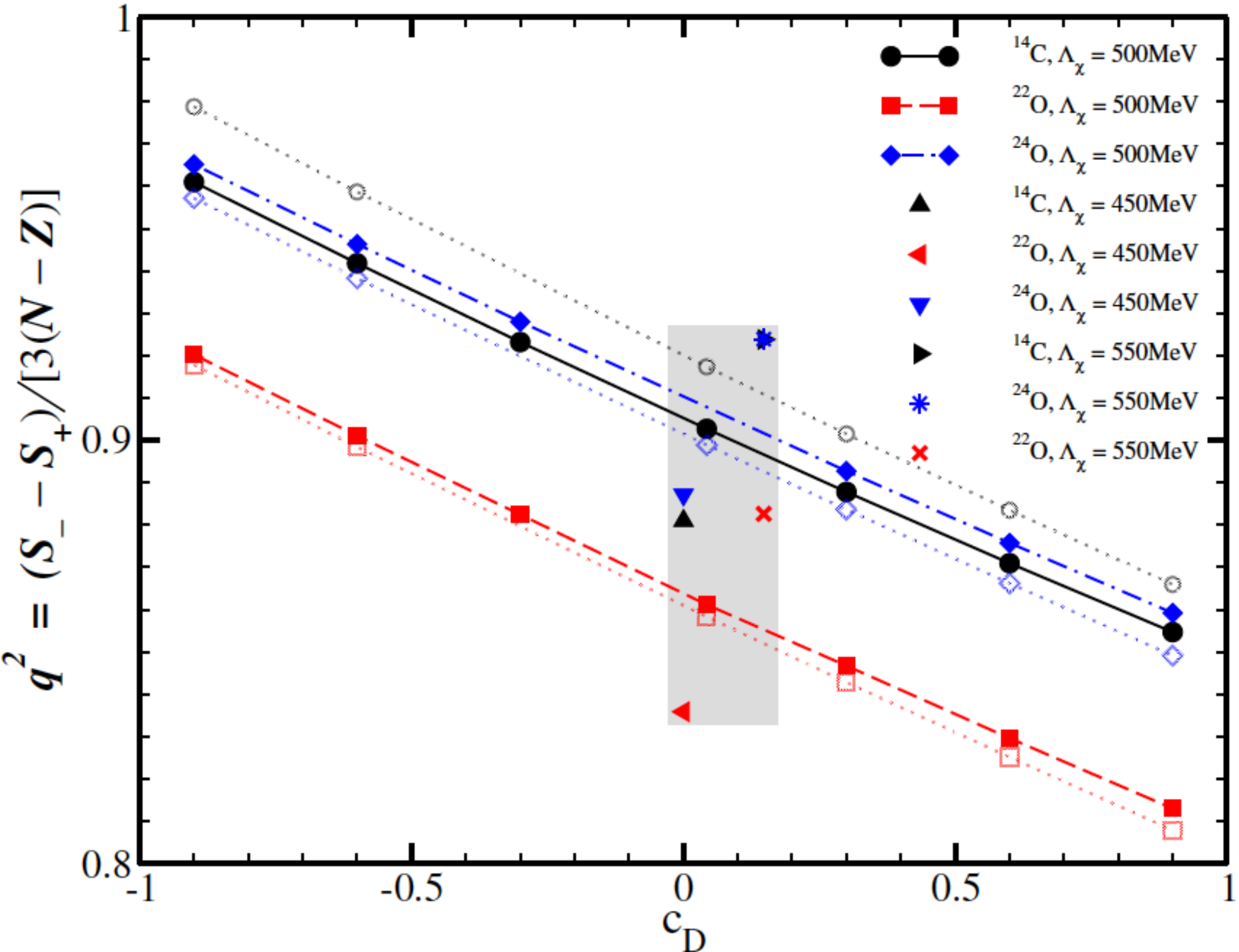
A. Ekström, G. Jansen, K. Wendt et al, PRL 113 262504 (2014)

Gamow-Teller matrix element:

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

Total GT strength functions:

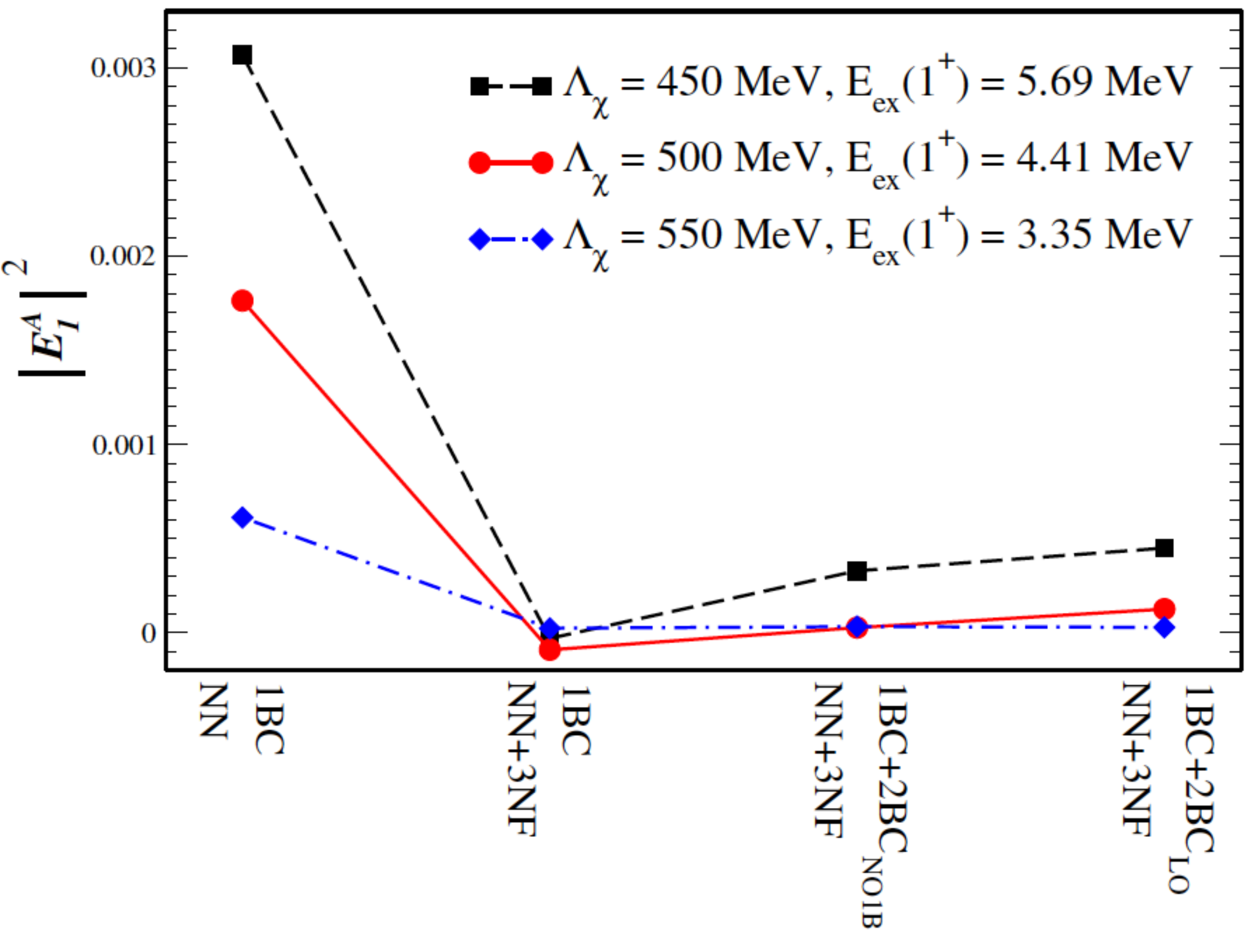
$$S_- = \langle\Lambda|\overline{\hat{O}^\dagger_{\mathrm{GT}}} \cdot \overline{\hat{O}_{\mathrm{GT}}}|\mathrm{HF}\rangle$$
$$S_+ = \langle\Lambda|\overline{\hat{O}_{\mathrm{GT}}} \cdot \overline{\hat{O}^\dagger_{\mathrm{GT}}}|\mathrm{HF}\rangle$$



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

Anomalous life-time of ^{14}C revisited

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



- 3NFs decrease the transition matrix element significantly
- 2BC counter the effect of 3NFs to some degree.
- The matrix element depends on the first excited 1^+ state in ^{14}N.

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

Summary

- Accurate radii and binding energies from a chiral interactions at NNLO
- Predictions for weak charge form-factor and distribution and dipole polarizability of ^{48}Ca
- Developed non-perturbative shell-model interactions for the shell-model with application to deformed nuclei
- Quenching of Gamow-Teller strength in selected nuclei due to two-body currents

Collaborators

@ ORNL / UTK: **A. Ekström**, T. Papenbrock, G. R. Jansen, L. Platter

@ MSU: W. Nazarewicz

@ Chalmers: **B. Carlsson**, C. Forssén

@ Hebrew U: N. Barnea, D. Gazit

@ MSU/ U Oslo: M. Hjorth-Jensen

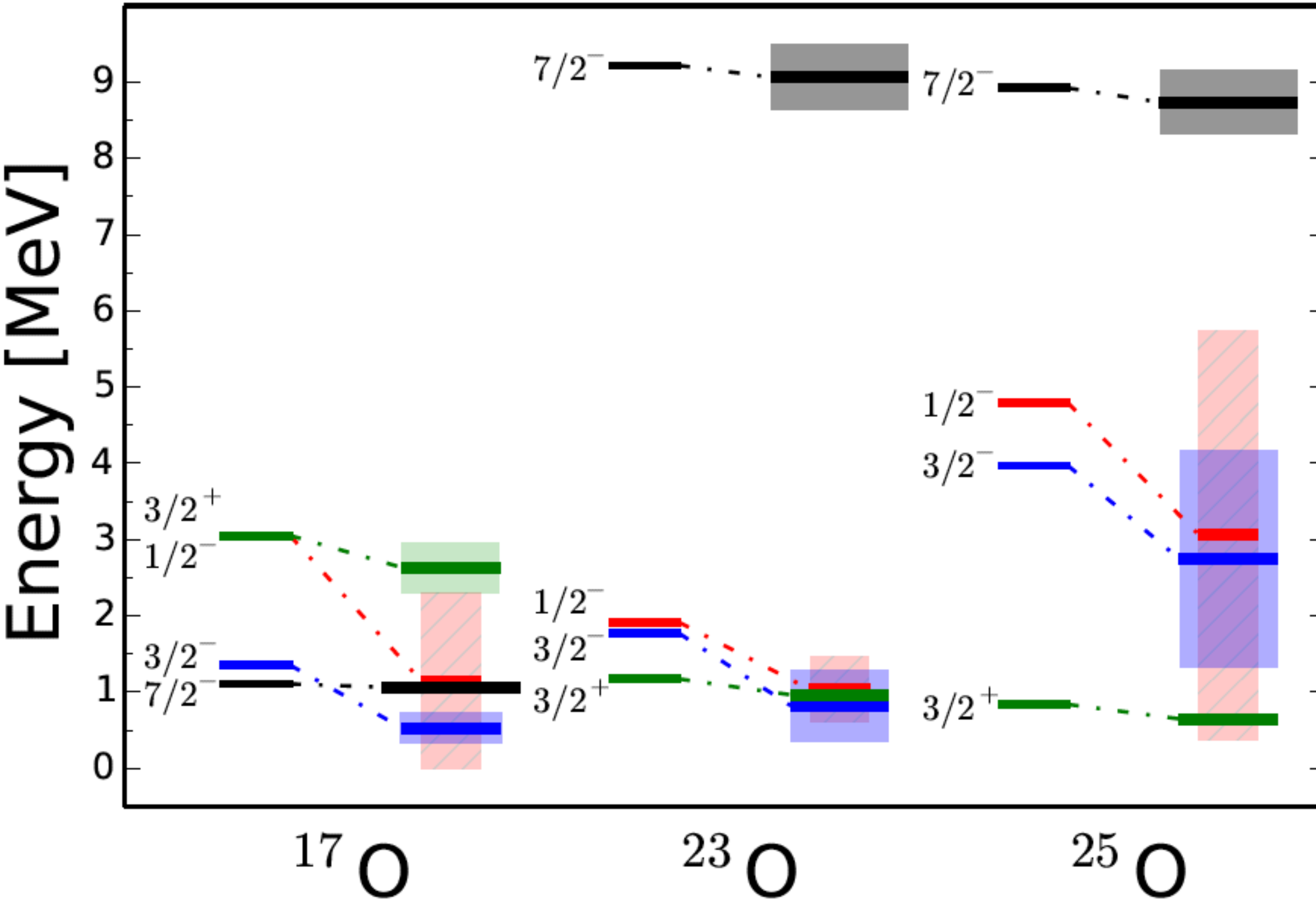
@ U. Idaho: R. Machleidt

@ Trento: G. Orlandini

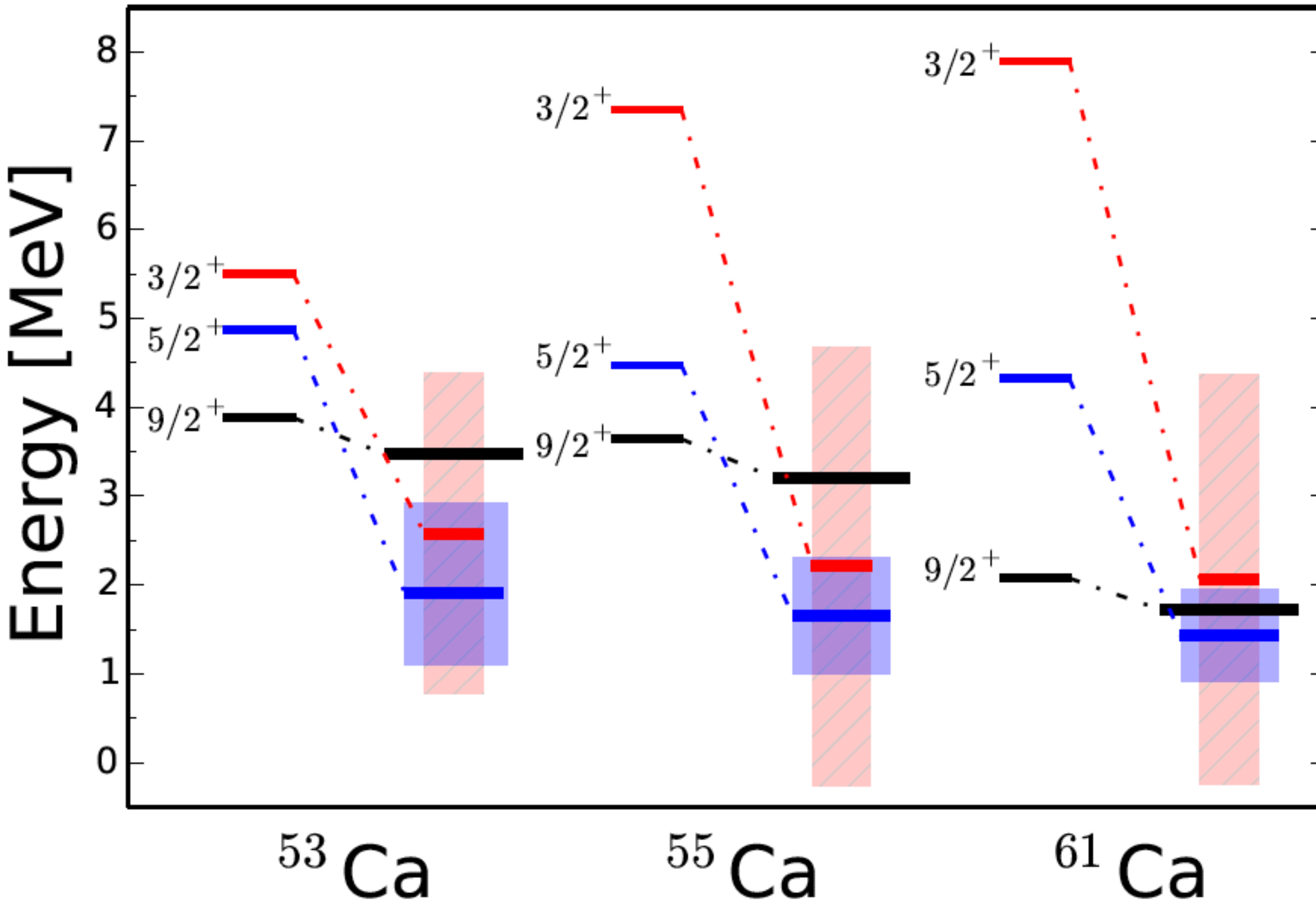
@ TRIUMF: S. Bacca, **M. Miorelli**, P. Navratil

@ TU Darmstadt: **C. Drischler**, H.-W. Hammer, K. Hebeler, A. Schwenk, **J. Simonis, K. Wendt**

Role of continuum on unbound states in oxygen isotopes



Role of continuum on unbound states in neutron rich calcium



Benchmarking different methods: Spectra in $^{22,23,24}O$

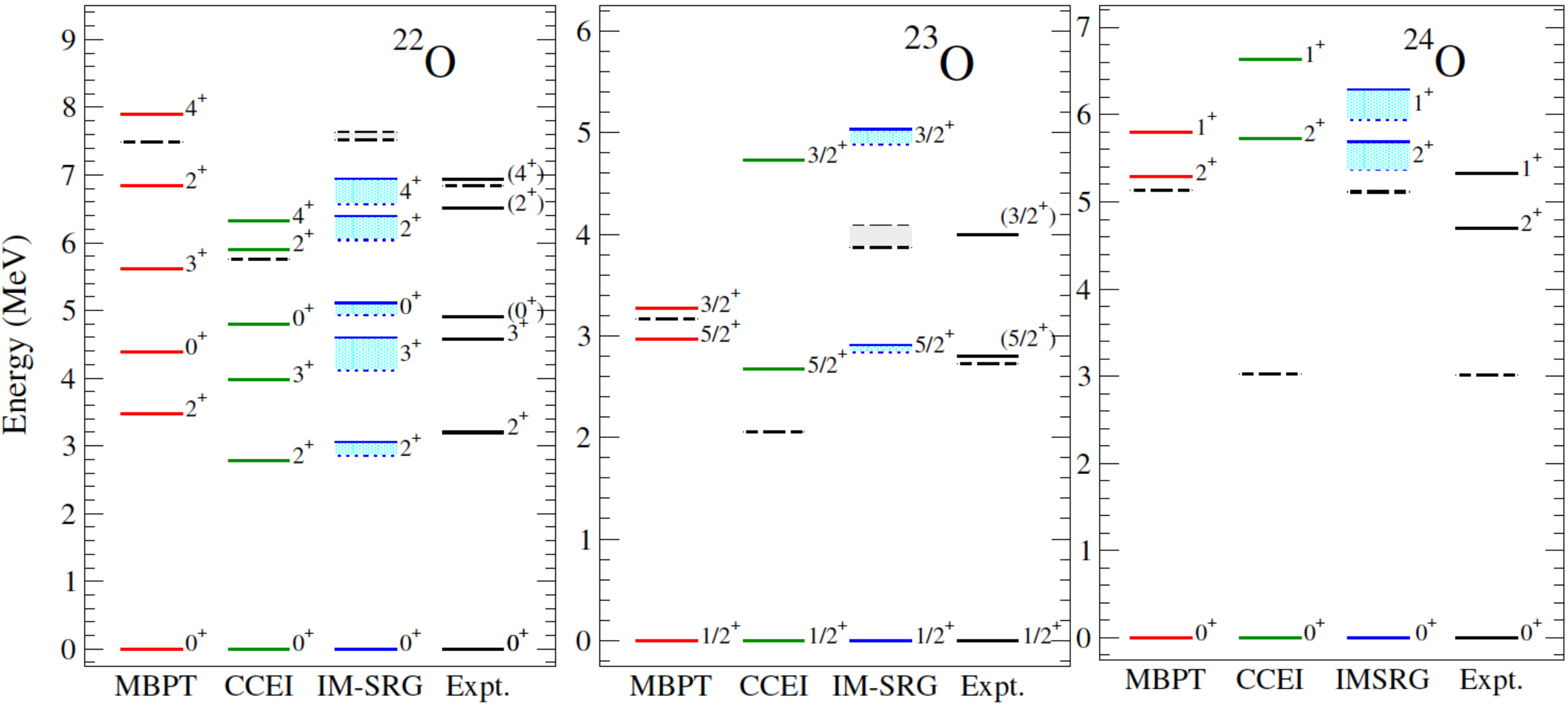
In-medium SRG

S. Bogner et al, Phys. Rev. Lett. 113, 142501 (2014)

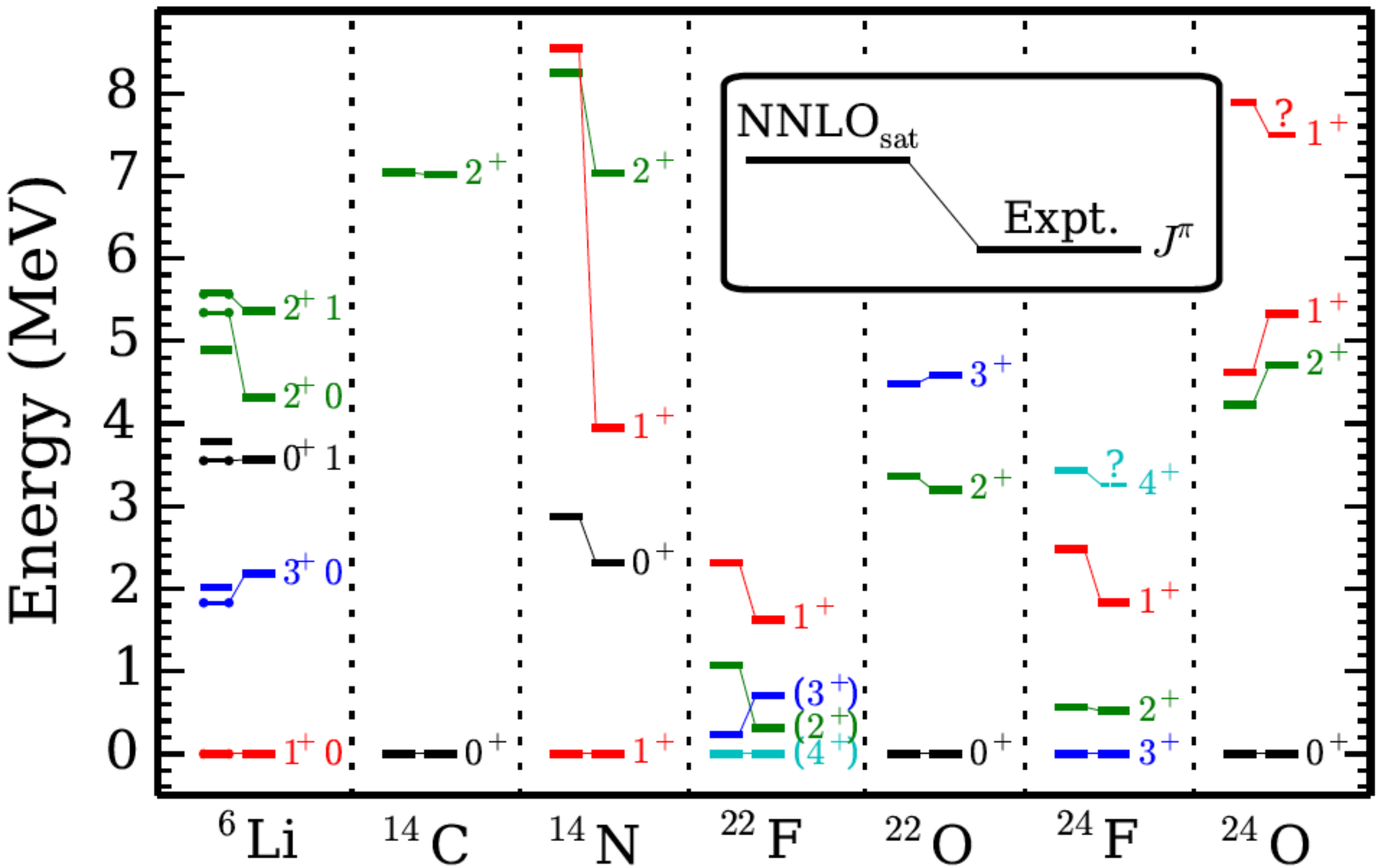
Hebeler, Holt, Menendez, Schwenk, Ann. Rev. Nucl. Part. Sci. in press (2015)

Coupled-Cluster Effective Interactions

G. R. Jansen et al, Phys. Rev. Lett. 113, 142502 (2014)



Spectra with NNLO$_{sat}$

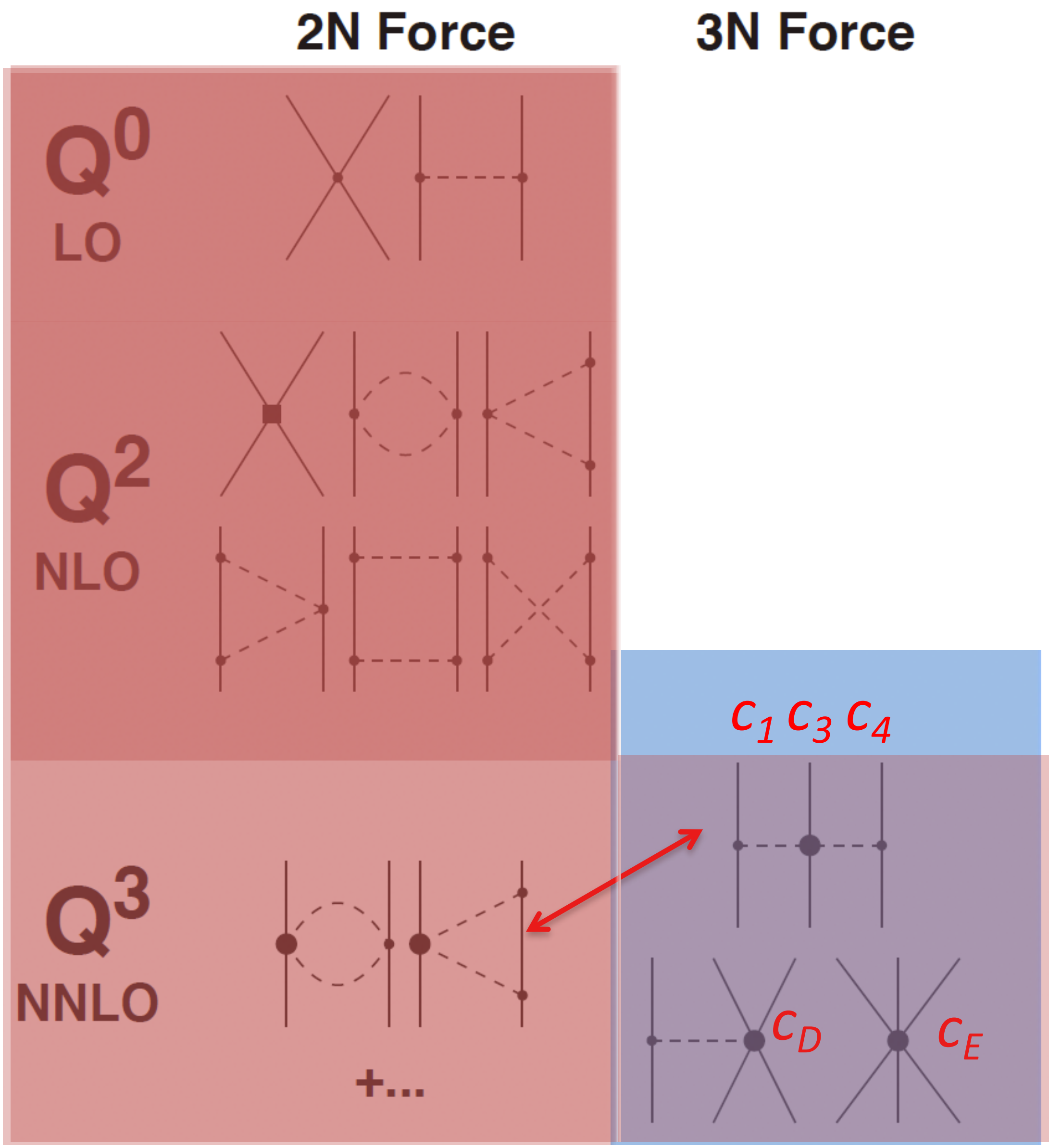


Other deficiencies: ^{17,18}O (1/2$^+$ too high, 2$^+$ too low)

Overall NNLO$_{sat}$ spectra comparable to other chiral interactions

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

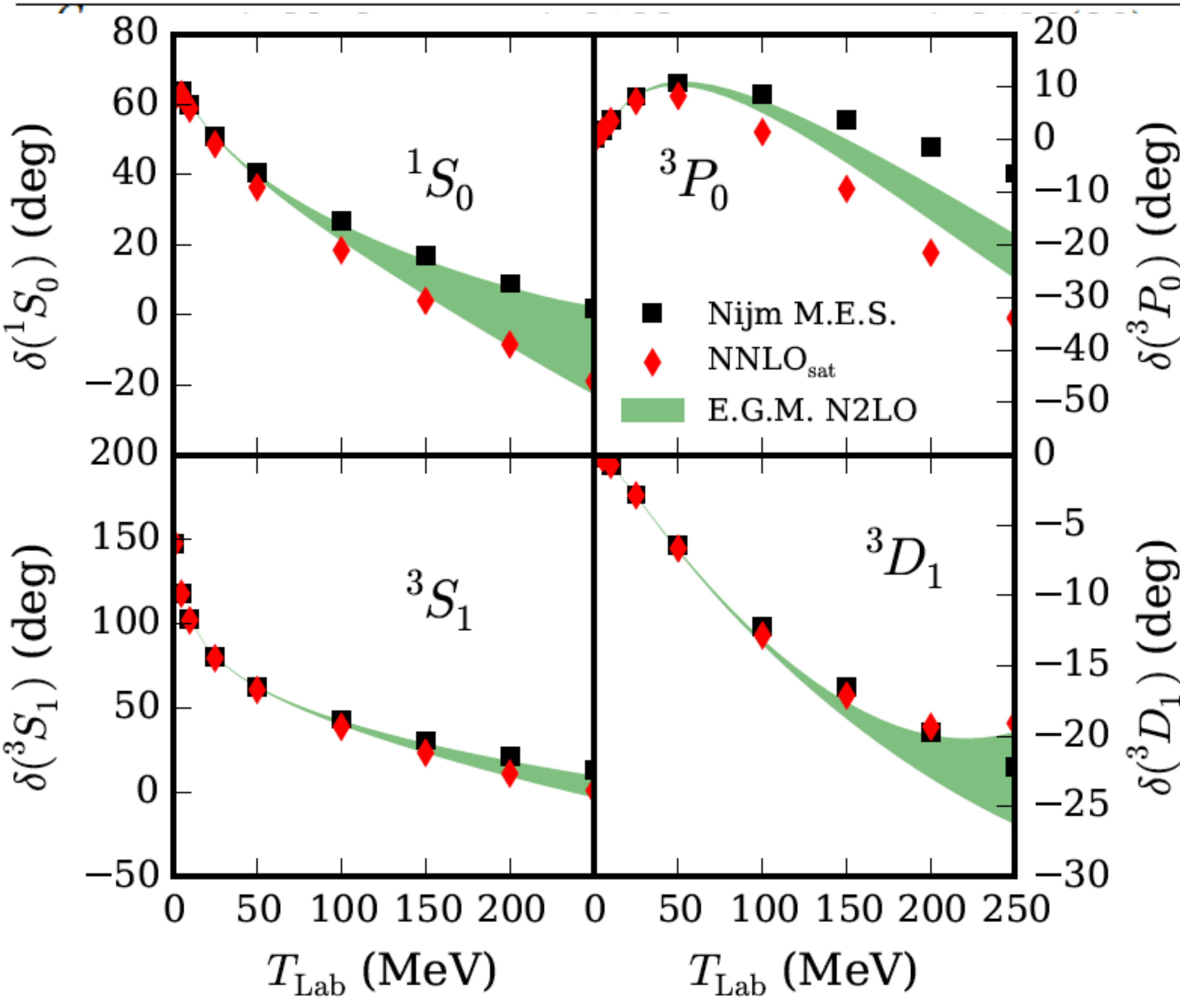
New approach:

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

Optimizing $NNLO_{sat}$

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

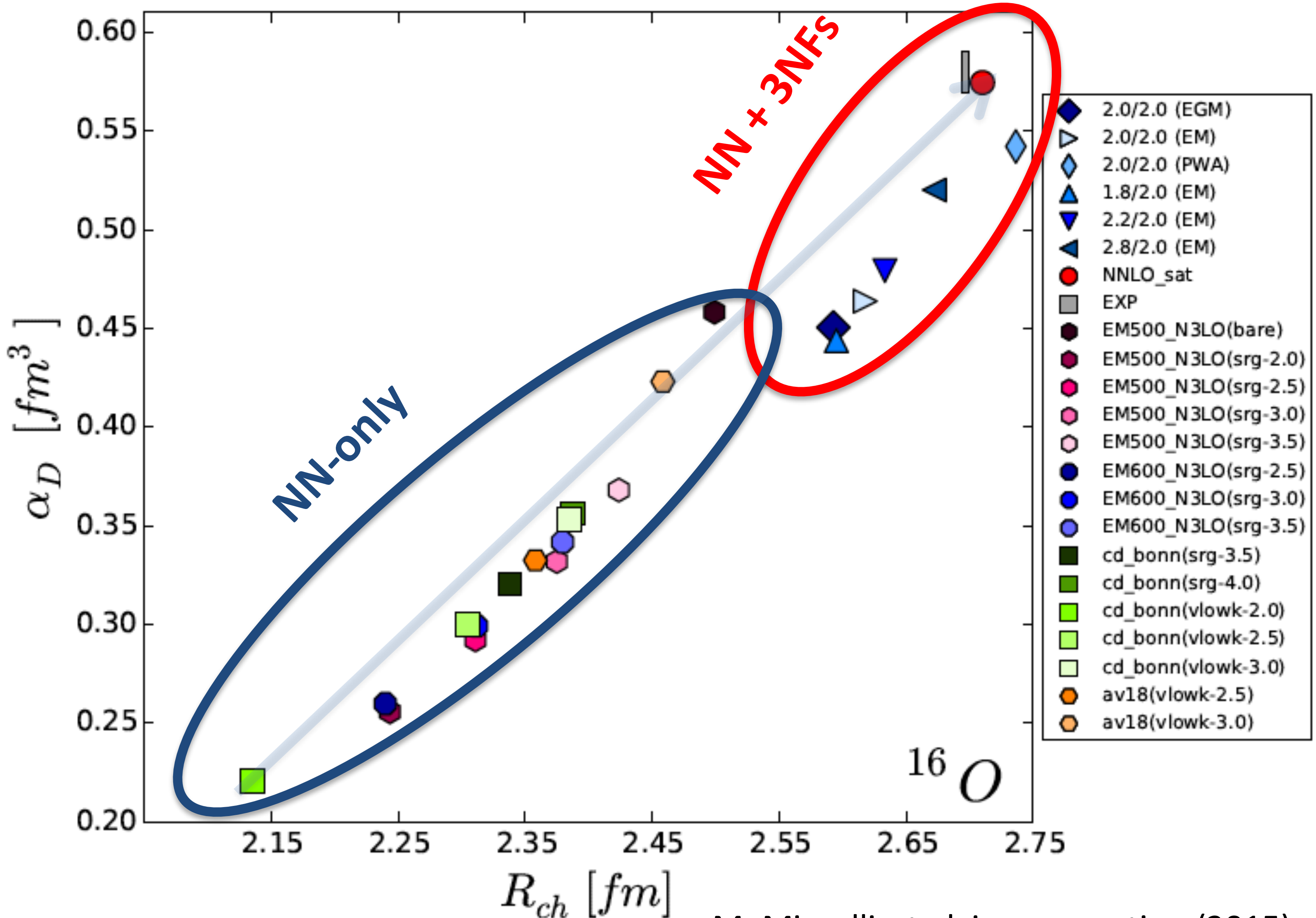
	$NNLO_{sat}$	N^3LO_{EM} [49]	Exp.
^{24}O	168.1	168.96(12)	
^{25}O	167.4	168.18(10)	



Objective function:

- Chi square optimization using POUNDerS
- Include BEs and radii in light nuclei and selected carbon and oxygen isotopes
- NN scattering data is included up to scattering energies of 35MeV
- Phase shifts are at the limit of expectations one can have at NNLO

Dipole polarizability of ^{16}O: The role of three-nucleon forces



M. Miorelli et al, in preparation (2015)

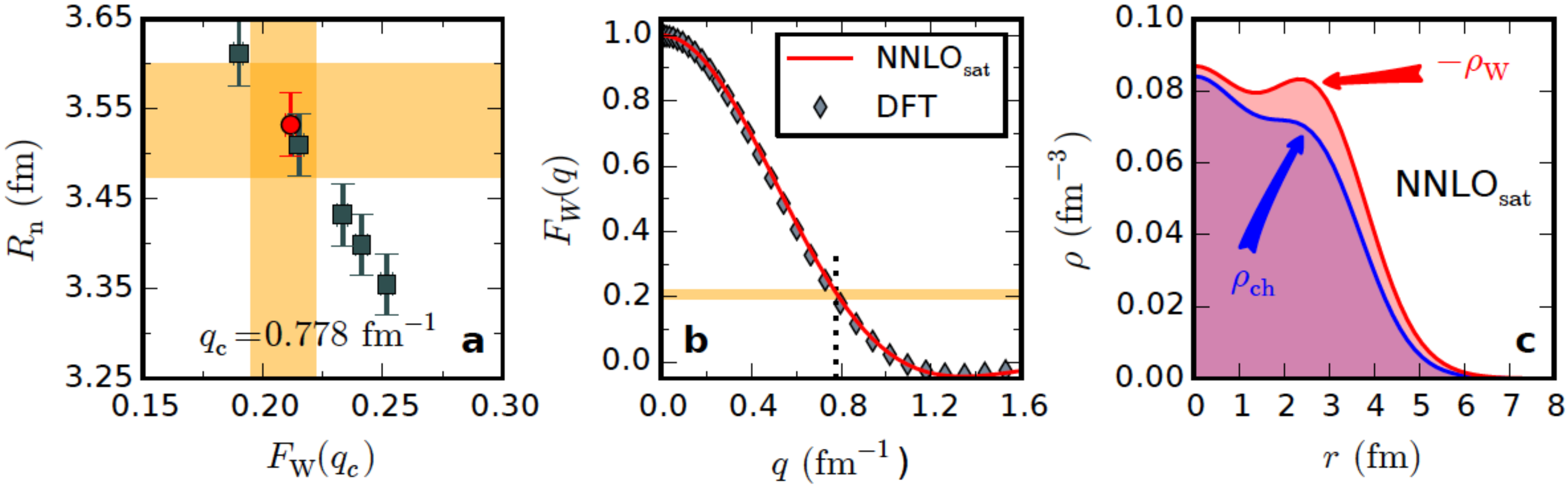
Family of chiral interactions

G. Hagen et al, in preparation (2015)

Interaction	BE	S_n	Δ	R_{ch}	R_W	S_v	L
$NNLO_{sat}$	404(3)	9.5	2.69	3.48	3.65	26.9	40.8
1.8/2.0 (EM)	420(1)	10.1	2.69	3.30	3.47	33.3	48.6
2.0/2.0 (EM)	396(2)	9.3	2.66	3.34	3.52	31.4	46.7
2.2/2.0 (EM)	379(2)	8.8	2.61	3.37	3.55	30.2	45.5
2.8/2.0 (EM)	351(3)	8.0	2.41	3.44	3.62	28.5	43.8
2.0/2.0 (PWA)	346(4)	7.8	2.82	3.55	3.72	27.4	44.0
Experiment	415.99	9.995	2.399	3.477			

Weak charge form-factor of ^{48}Ca

G. Hagen *et al*, Nature Physics (2015) doi:10.1038/nphys3529



***Ab-initio* predictions:**

$0.195 \lesssim F_{\rm W}(q_c) \lesssim 0.222$, $3.59 \lesssim R_{\rm W} \lesssim 3.71$ fm, $0.12 \lesssim R_{\rm skin} \lesssim 0.15$ fm

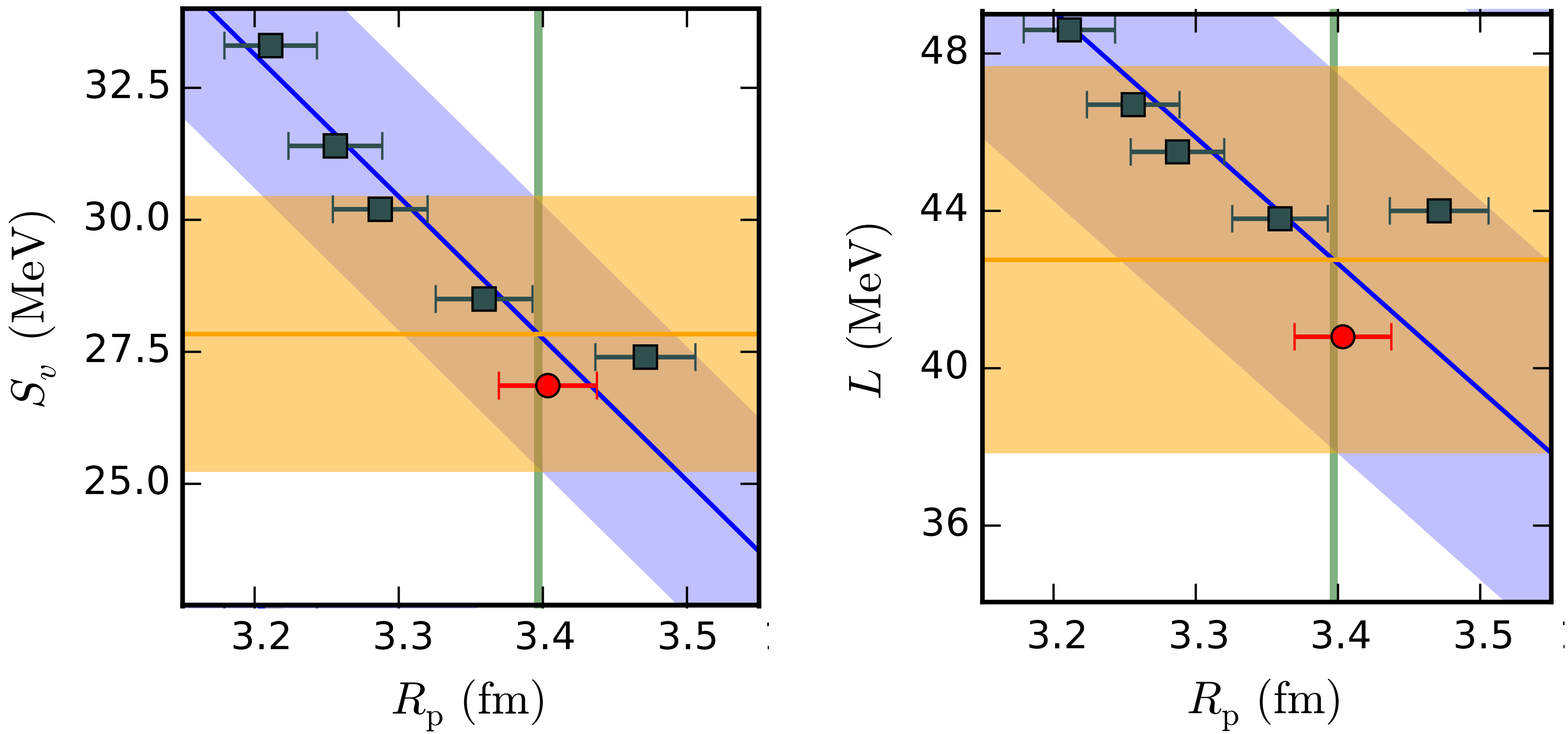
DFT predictions:

SV-min: $F_{\rm W}(q_C) = 0.1986$ $R_{\rm skin} = 0.1830$ fm

FSUBJ: $F_{\rm W}(q_C) = 0.205$ $R_{\rm skin} = 0.1925$ fm

Can we reliably extract the neutron skin from a single measurement?

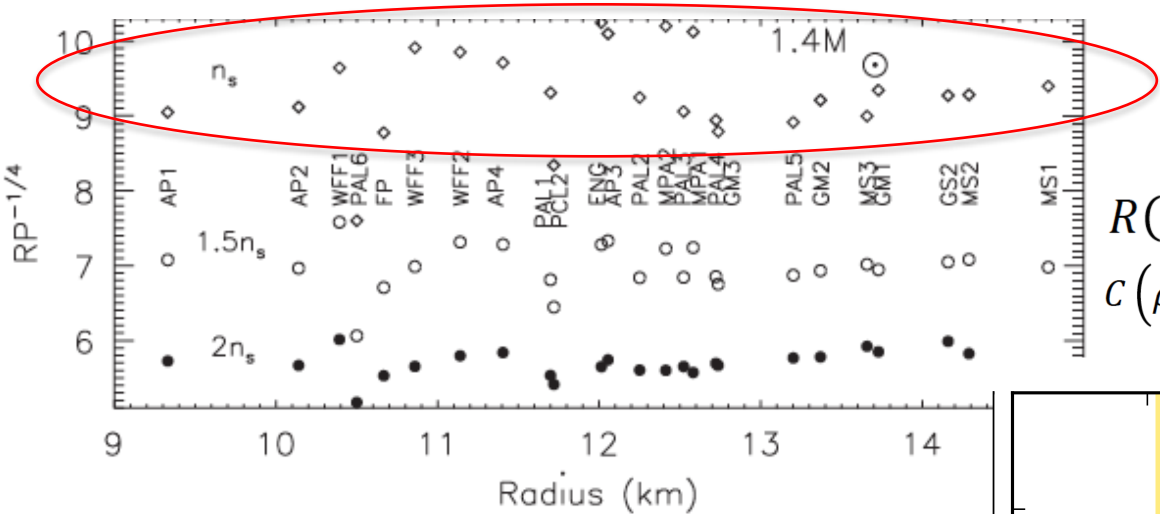
Symmetry energy and L from chiral EFT



- S_v and L correlates with dipole polarizability and proton radius
- Ab-initio prediction for S_v and L from chiral EFT:

  $25.2 \lesssim S_v \lesssim 30.4$ MeV, $37.8 \lesssim L \lesssim 47.7$ MeV
- Consistent with Lattimer and Lim:
- $29 \lesssim S_v \lesssim 32.7$ MeV and $40.5 \lesssim L \lesssim 61.9$ MeV

The radius of a 1.4M$_\odot$ neutron star



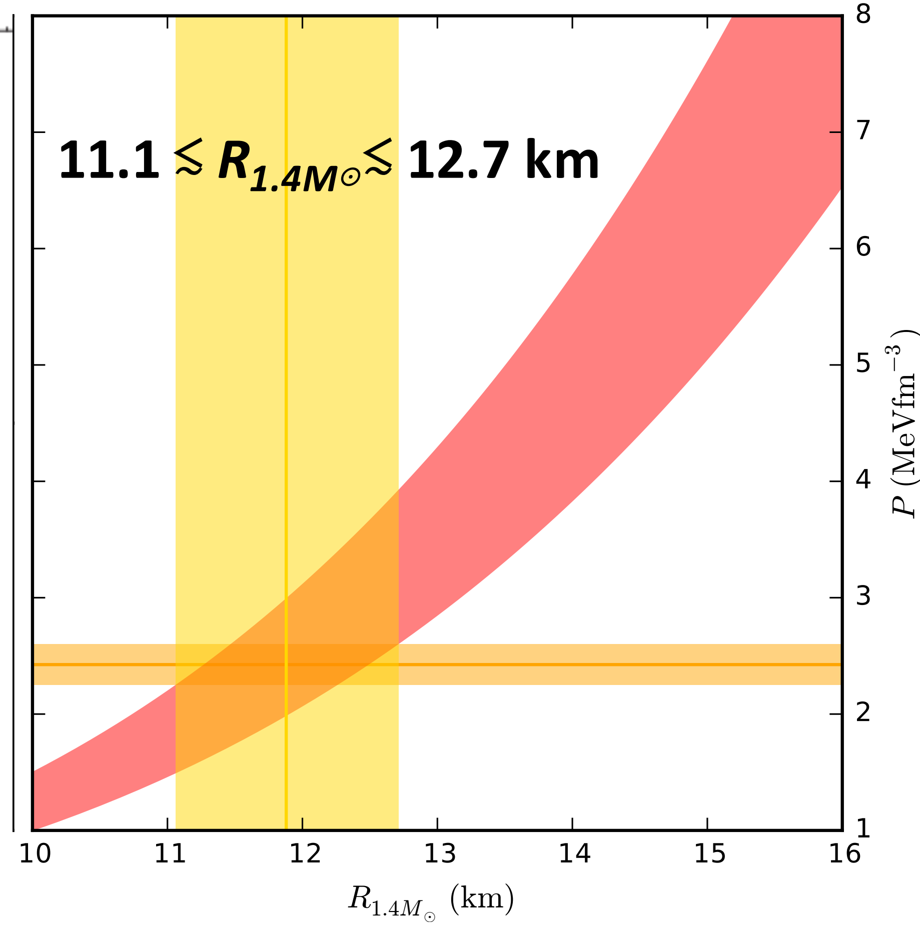
Lattimer and Prakash, Phys. Rep. 442, 109 (2007)

$$R(M) = C(\rho, M)(P(\rho)/\text{MeV fm}^{-3})^{1/4}$$

$$C\left(\rho = 0.16\ \text{fm}^{-3}, M = 1.4\ M_\odot\right) = 9.52 \pm 0.49\ \text{km}$$

- Use empirical power law that relates neutron-star radii to the pressure *P* at nuclear saturation density.
- *P* is strongly connected to S_v and *L*
- We correlate *P* with the charge radius of ^{48}Ca and get at an estimate: $2.3 \lesssim P \lesssim 2.6$ MeV fm^{-3}
- Ab-initio prediction consistent with Lattimer and Lim $10.7 \lesssim R_{1.4M_\odot} \lesssim 13.1$

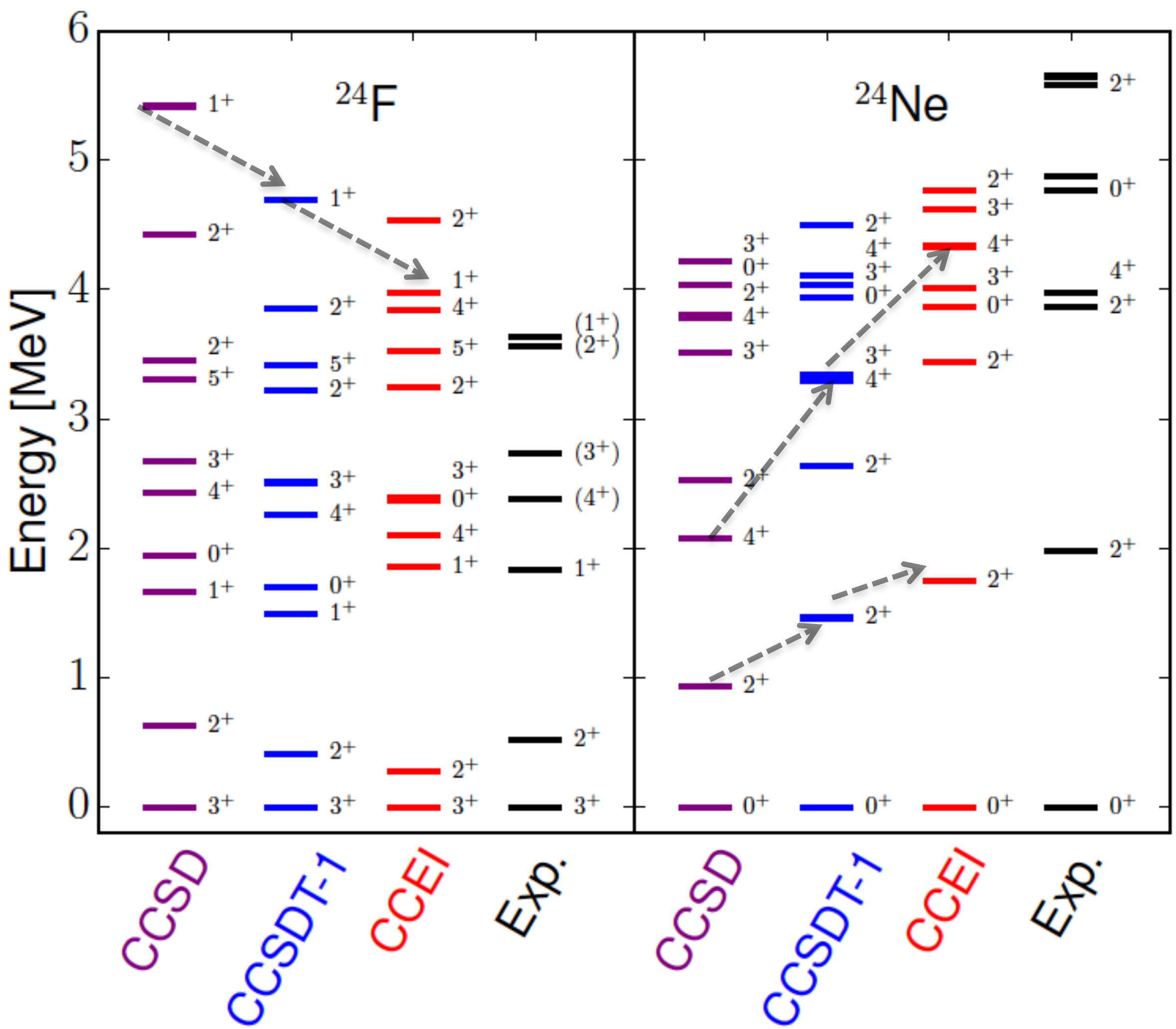
Lattimer and Lim Ap J. 771, 51 (2013)



Deformed sd-shell nuclei from first principles

G. R. Jansen, A. Signoracci, GH, P. Navratil arXiv:1511.00757 (2015).

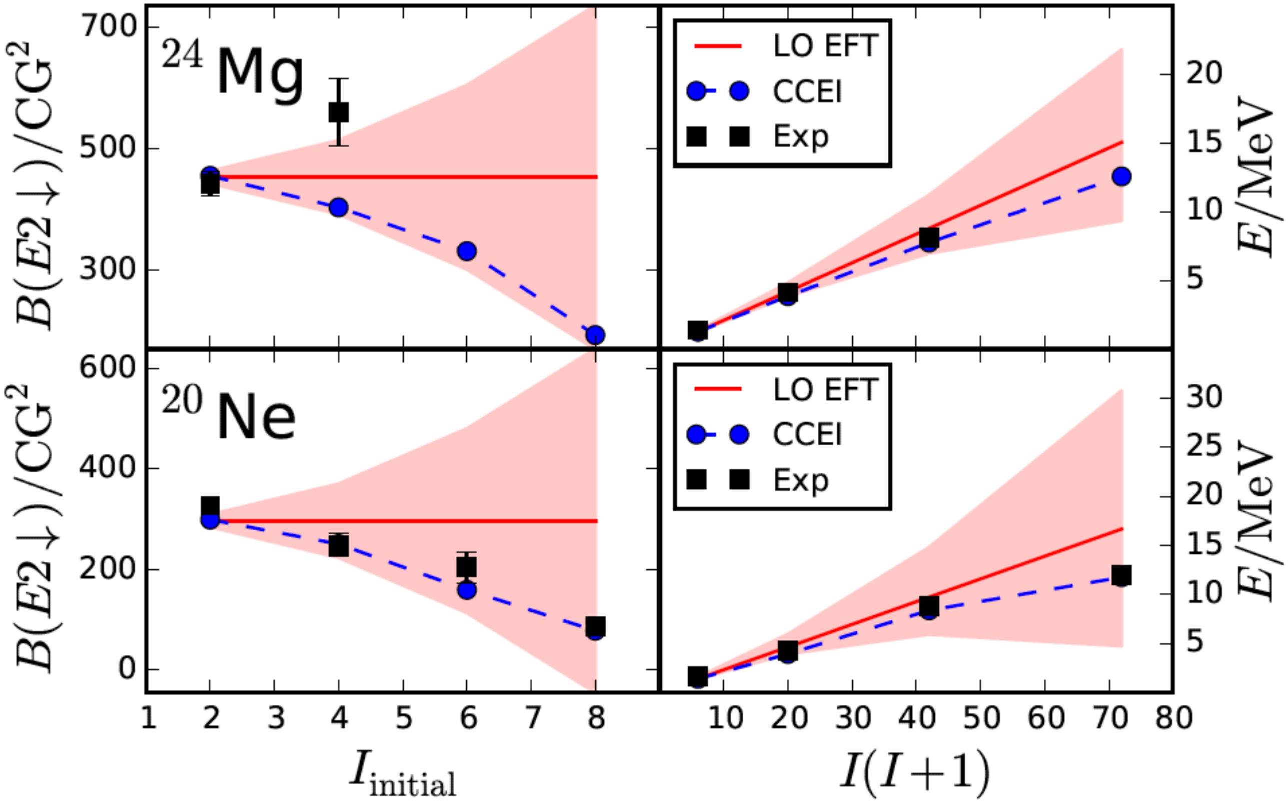
Single and double charge exchange equation-of-motion coupled cluster way to compute ground- and excited states of open-shell nuclei



- Good agreement between EOM-CCSD, EOM-CCSDT-1 and CCEI for excited states in ^{24}F
- Role of 3p-3h excitations small except for second 1^+ state
- For ^{24}Ne we find overall satisfactory agreement between EOM-CCSDT-1 and CCEI.
- Larger role of 3p-3h excitations and they overall improve the agreement with CCEI.

Deformed sd-shell nuclei from first principles

G. R. Jansen, A. Signoracci, GH, P. Navratil arXiv:1511.00757 (2015).



Rotational bands emerge from *ab-initio* calculations. CCEI results are within the uncertainties of EFT at LO.

Effective theory for deformed nuclei: E. A. Coello Perez and T. Papenbrock PRC 92, 014323 (2015)

LO EFT is straight line (rigid rotor). Error band from fit to first two excited states.

$$E(I) = \frac{I(I+1)}{2C_0} - \frac{C_2}{4C_0^4}\left(I(I+1)\right)^2$$

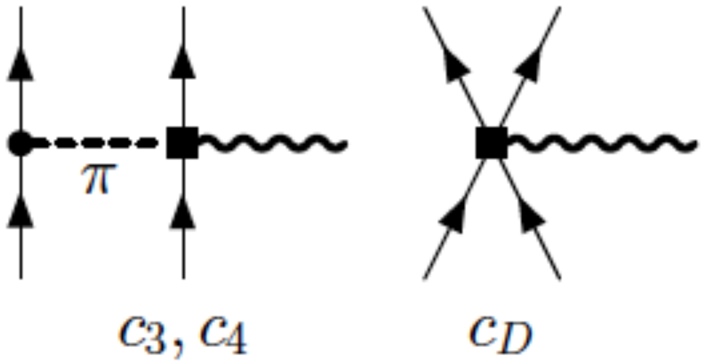
Within EFT, the B(E2) are that of a non-rigid rotor, and the deviation from the rigid rotor is as expected from the spectrum.

$$B(E2, i \to f) = \frac{(aqR)^2}{60}\left(C^{I_f 0}_{I_i 0 2 0}\right)^2\left[1 + \frac{b}{a} I_i(I_i - 1)\right]$$

Normal ordered one- and two-body current

Gamow-Teller matrix element:

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



Normal ordered operator:

$$\hat{O}_{\rm GT} = O_N^0 + O_N^1 + O_N^2$$

$$O_N^0 = \sum_{i\leq E_f}\langle i|O^{(1)}|i\rangle + \frac{1}{2}\sum_{i,j\leq E_f}\langle ij|O^{(2)}|ij\rangle$$

$$O_N^1 = \sum_{pq}\langle p|O^{(1)}|q\rangle\{p^\dagger q\} + \sum_{pq}\sum_{i\leq E_f}\langle pi|O^{(2)}|qi\rangle\{p^\dagger q\}$$

$$O_N^2 = \frac{1}{4}\sum_{pqrs}\langle pq|O^{(2)}|rs\rangle\{p^\dagger q^\dagger sr\}$$

One- and two-body currents and normal ordering in Coupled-Cluster

CCSD similarity transformed normal-ordered current operator: $T = T_1 + T_2$

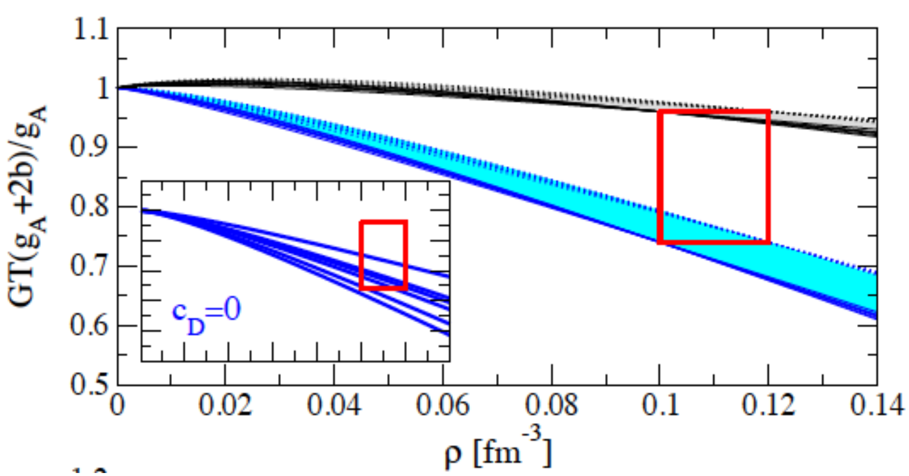
3-body terms 6-body terms

$$\overline{O_{\mathrm{GT}}} = e^{-T} O_N e^{T} = e^{-T} O_N^1 e^{T} + e^{-T} O_N^2 e^{T}$$

Normal ordered 1-body with Leading Order (LO) two-body contribution

Normal ordered 1-body approximation

$$e^{-T} O_N^2 e^{T} \approx \; O_N^2 = \frac{1}{4} \sum_{pqrs} \langle pq | O^{(2)} | rs \rangle \{ p^\dagger q^\dagger s r \}$$

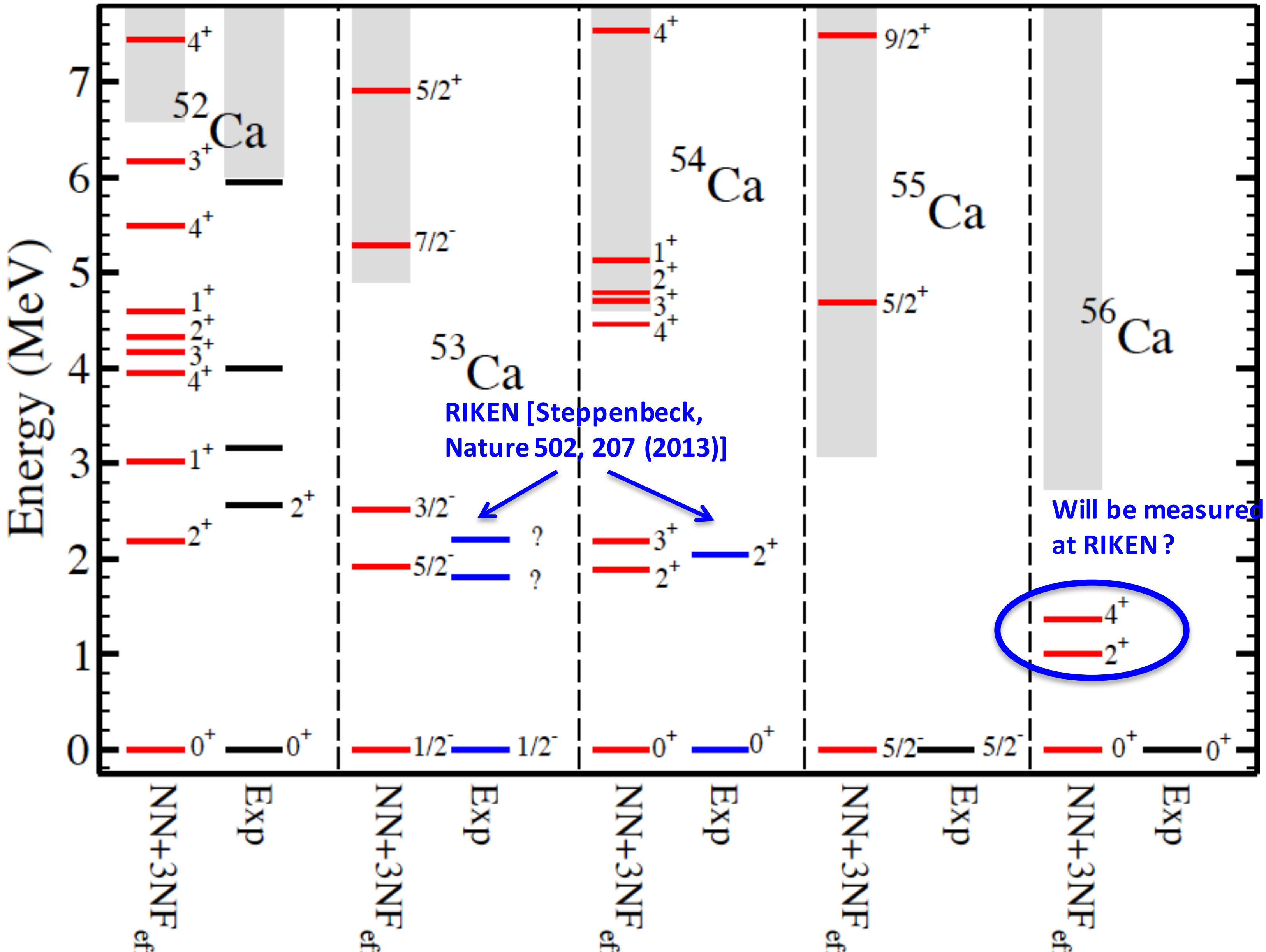


J. Menéndez, D. Gazit, A. Schwenk
PRL 107, 062501 (2011)

Normal order with respect to free Fermi gas. One-body normal ordered approximation gives quenching of g_A by a factor q = 0.74...0.96 for different set of couplings constants

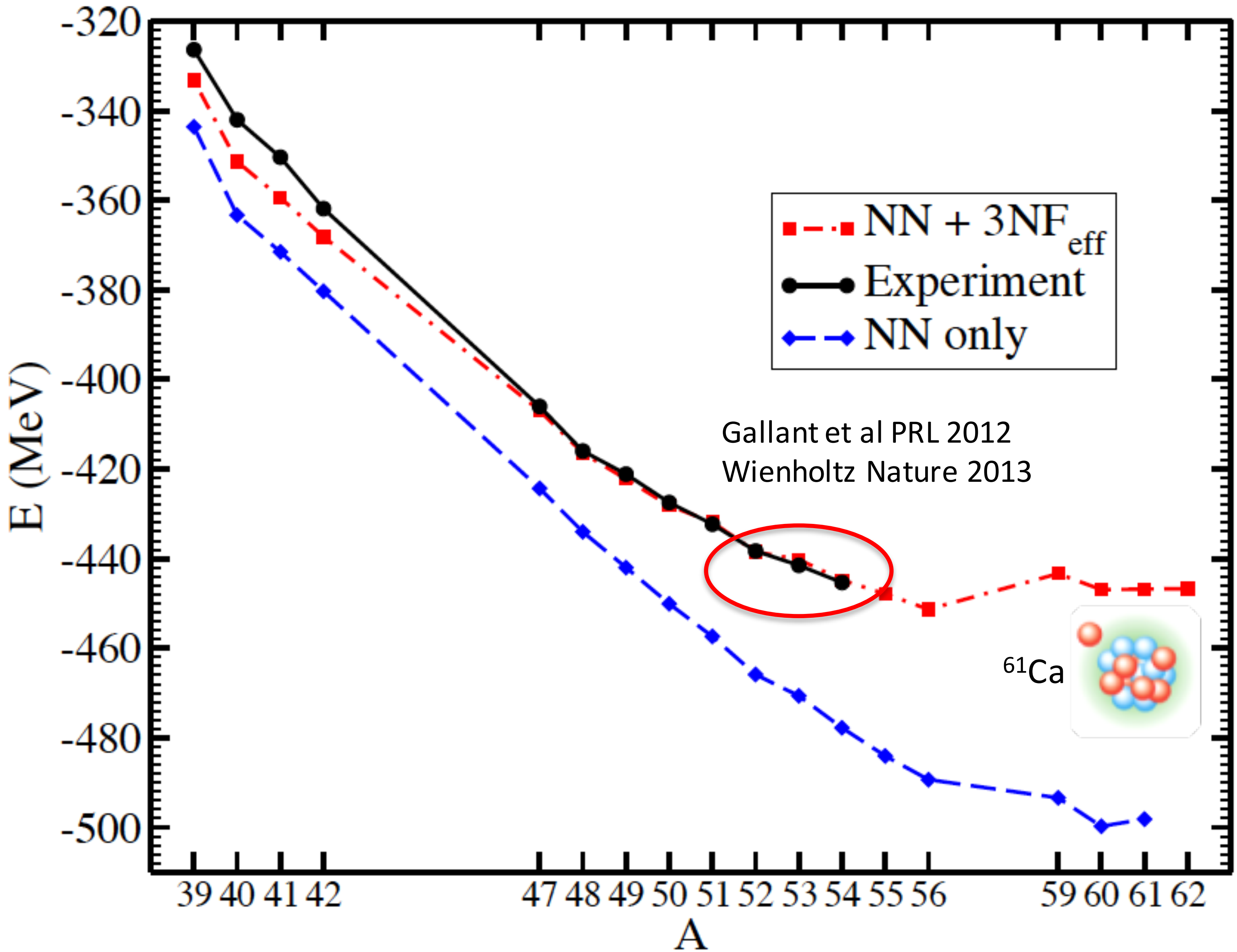
Spectra and shell evolution in Calcium isotopes

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

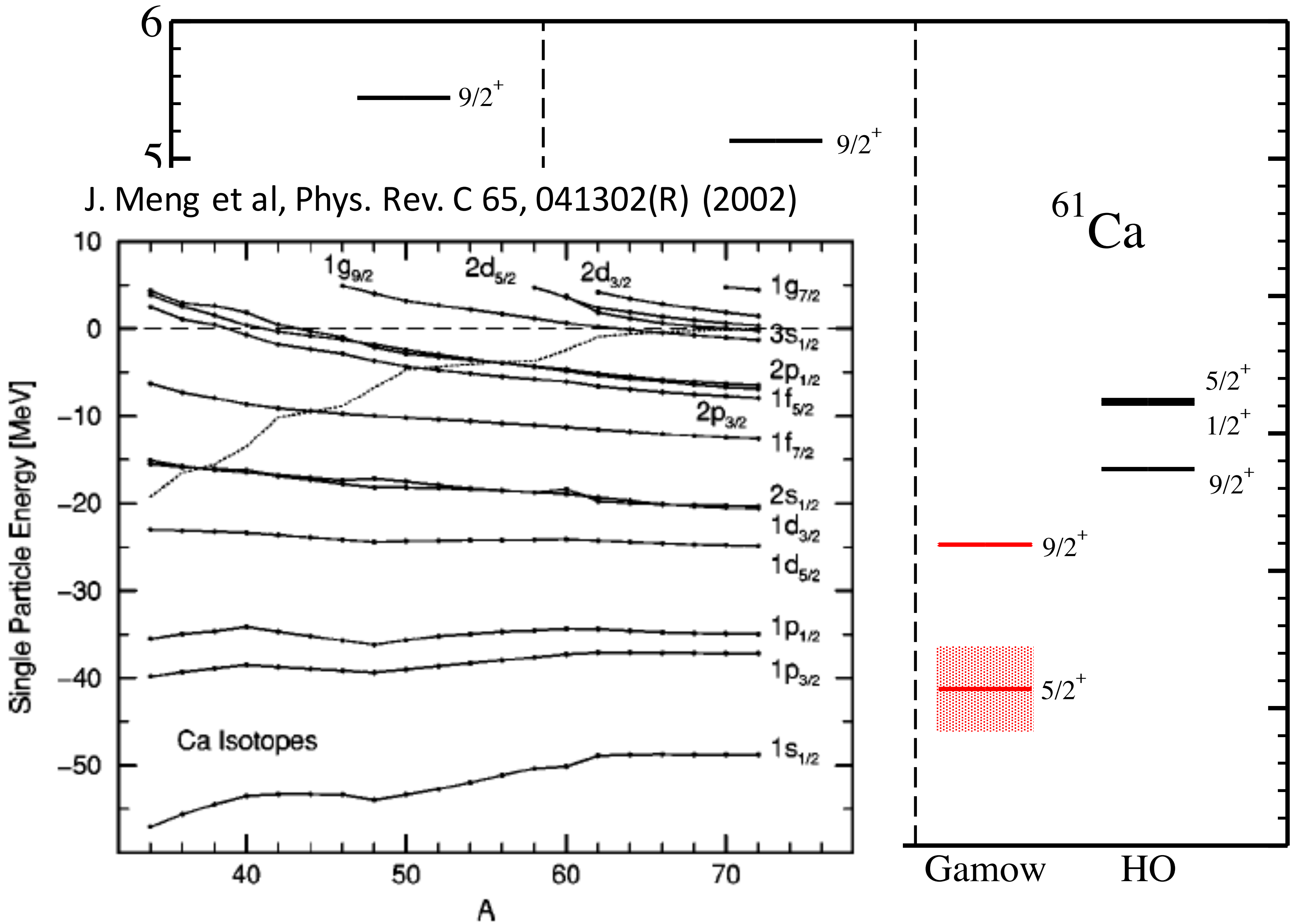


Calcium isotopes from chiral interactions

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

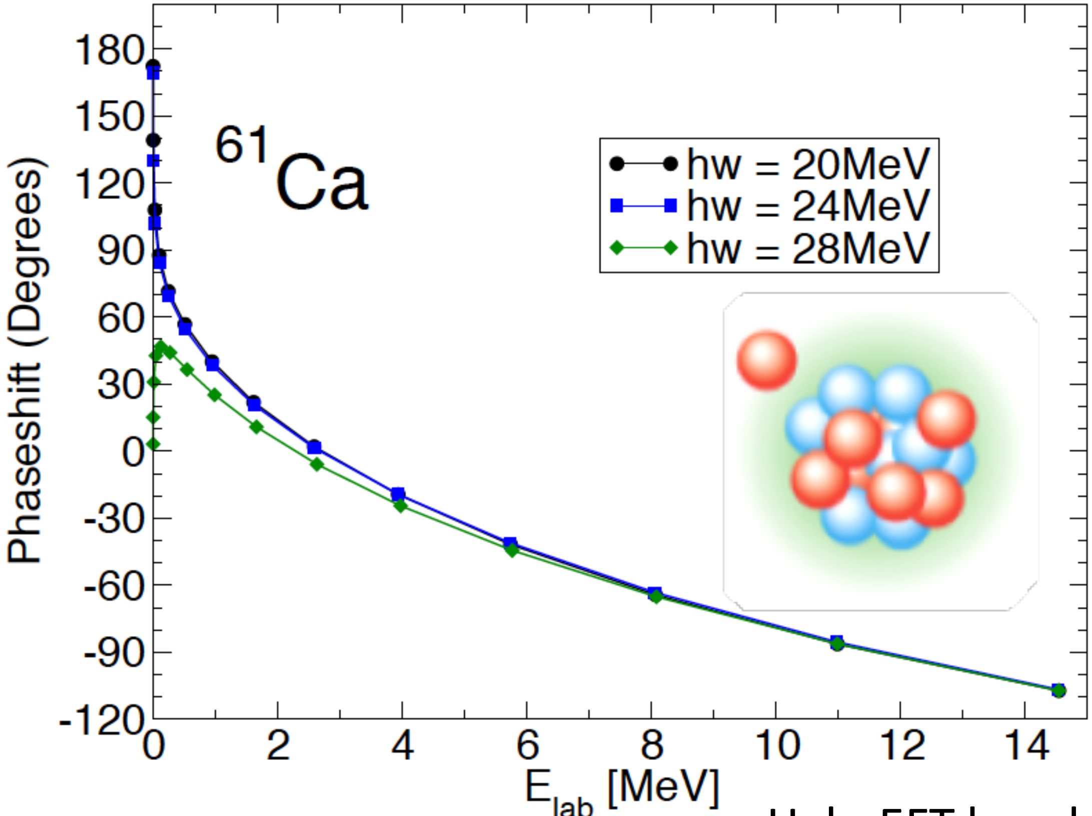


Effect of continuum on excited states in odd neutron rich Calcium isotopes



Efimov physics around neutron rich ^{60}Ca

G. Hagen, P. Hagen, H.-W. Hammer, and L. Platter, PRL 111, 132501 (2013)



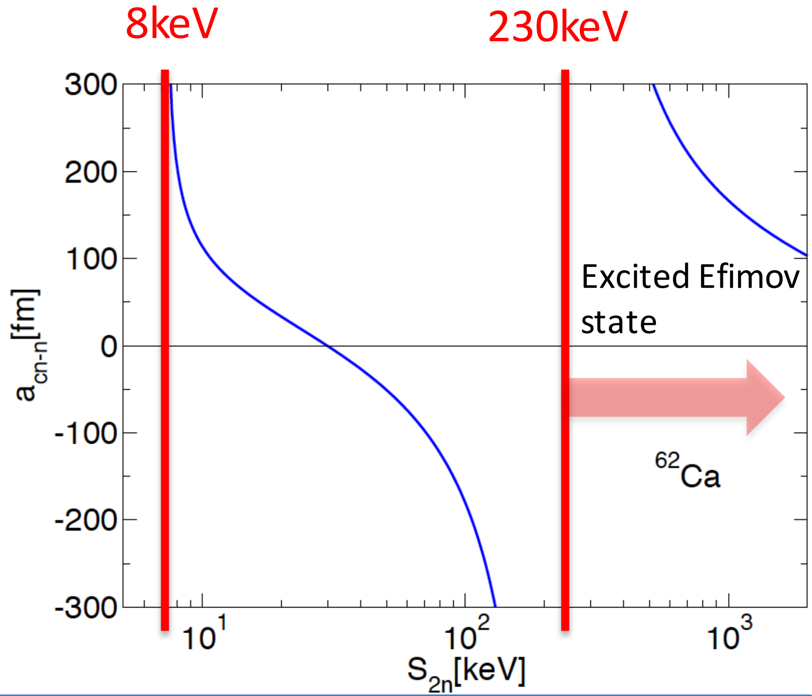
- Large S-wave scattering length in ^{61}Ca implies Halo phenomena
- Core-*n*-*n* are effective degrees of freedom
- New Approach: Merge halo-EFT and input from CC to study properties of ^{62}Ca

Halo EFT breakdown scale

$\hbar\omega$ [MeV]	a_{cn} [fm]	r_{cn} [fm]	S_n [keV]	S_{deep} [keV]
20	55.0	8.8	8.4	544
24	53.2	9.1	5.3	509
28	-26.1	10.8	-	361

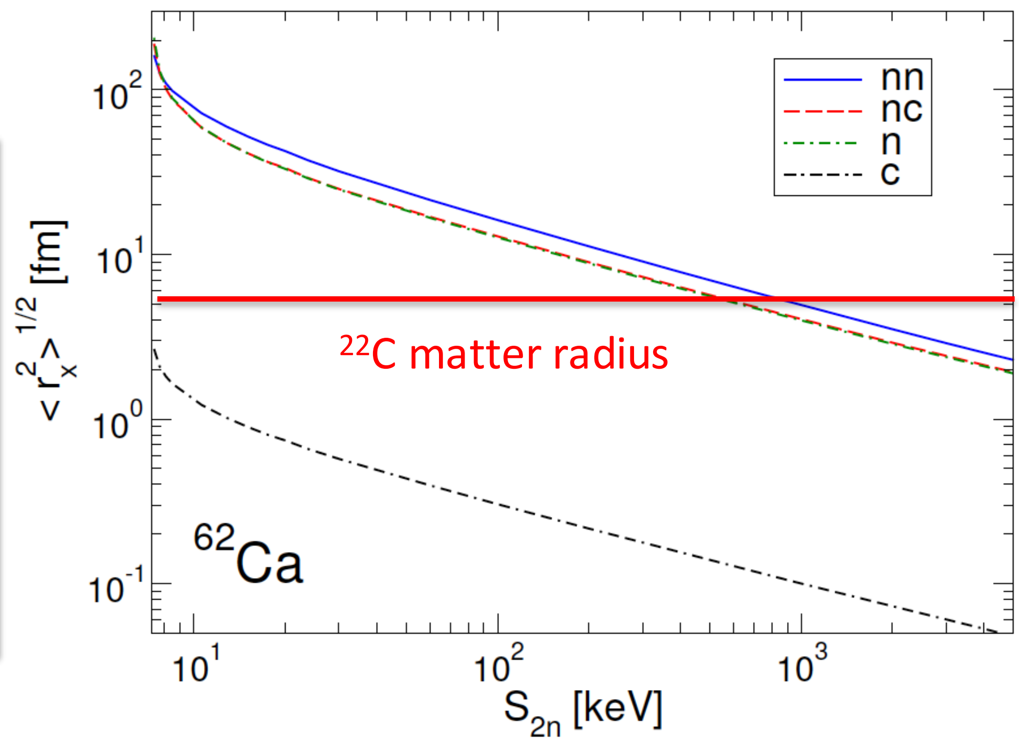
	^{53}Ca		^{55}Ca		^{61}Ca	
J^π	Re[E]	Γ	Re[E]	Γ	Re[E]	Γ
$5/2^+$	1.99	1.97	1.63	1.33	1.14	0.62
$9/2^+$	4.75	0.28	4.43	0.23	2.19	0.02

Efimov physics around neutron rich ^{60}Ca

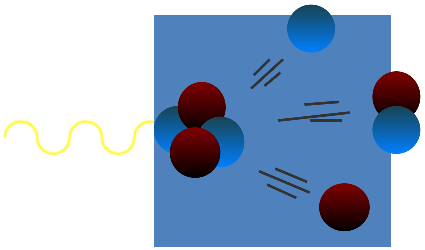


- For S_{2n} larger than ~ 230keV another state appears in the spectrum
- ^{62}Ca is likely to have an Efimov state (large halo)
- It is conceivable that ^{62}Ca displays an excited Efimov state

- ^{22}C is the largest known two-neutron halo R_{rms} ~5.4fm (Tanaka PRL 2010)
- Computed matter radii for ^{62}Ca indicates that it can be the largest and heaviest halo in the chart of nuclei so far.



Break-up observables for medium-mass nuclei



Cross section is related to the Response Function in the continuum

$$S(\omega) = \sum\!\!\!\!\!\!\int_f \left| \left\langle \psi_f \left| \hat{O} \right| \psi_0 \right\rangle \right|^2 \delta(E_f - E_0 - \omega)$$

Cannot be calculated beyond 3-body break-up even for A=4

Solution: Lorentz Integral Transform method
(Efros, Leidemann,Orlandini, Barnea, Bacca)

Efros *et al.*,J. Phys. G: Nucl. Part. Phys. 34 (2007)

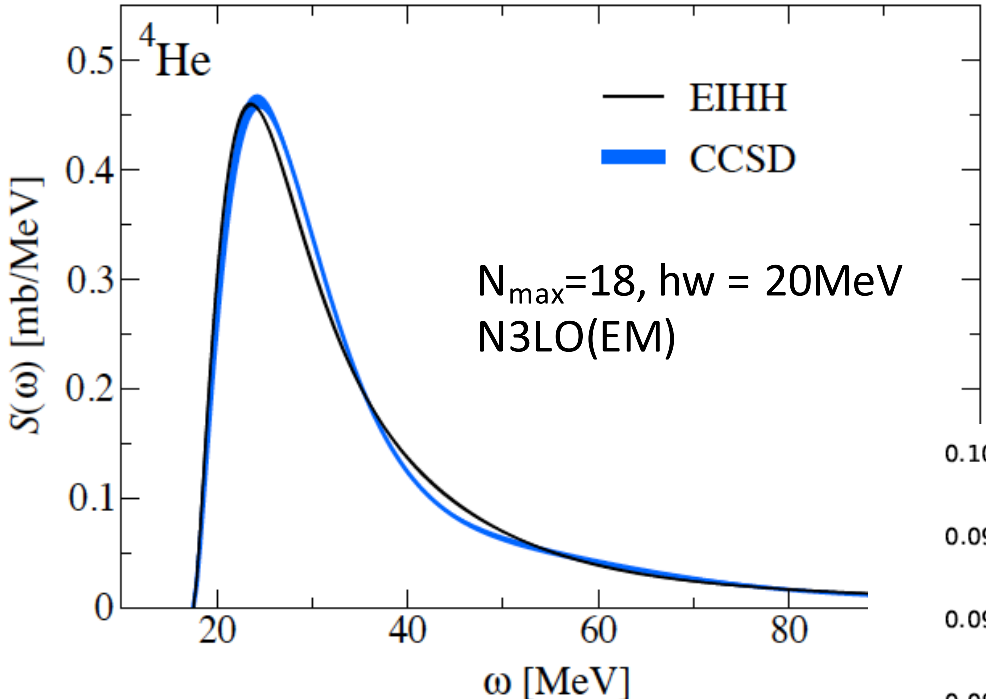
$$\mathcal{L}(\sigma, \Gamma) = \int d\omega \frac{S(\omega)}{(\omega - \sigma)^2 + \Gamma^2} = \langle \tilde{\Psi} | \tilde{\Psi} \rangle$$

$$(H - E_0 - \sigma + i\Gamma) \, |\tilde{\Psi}\rangle = O|\Psi_0\rangle$$

Bound-state-like object. Need bound state technique to calculate it

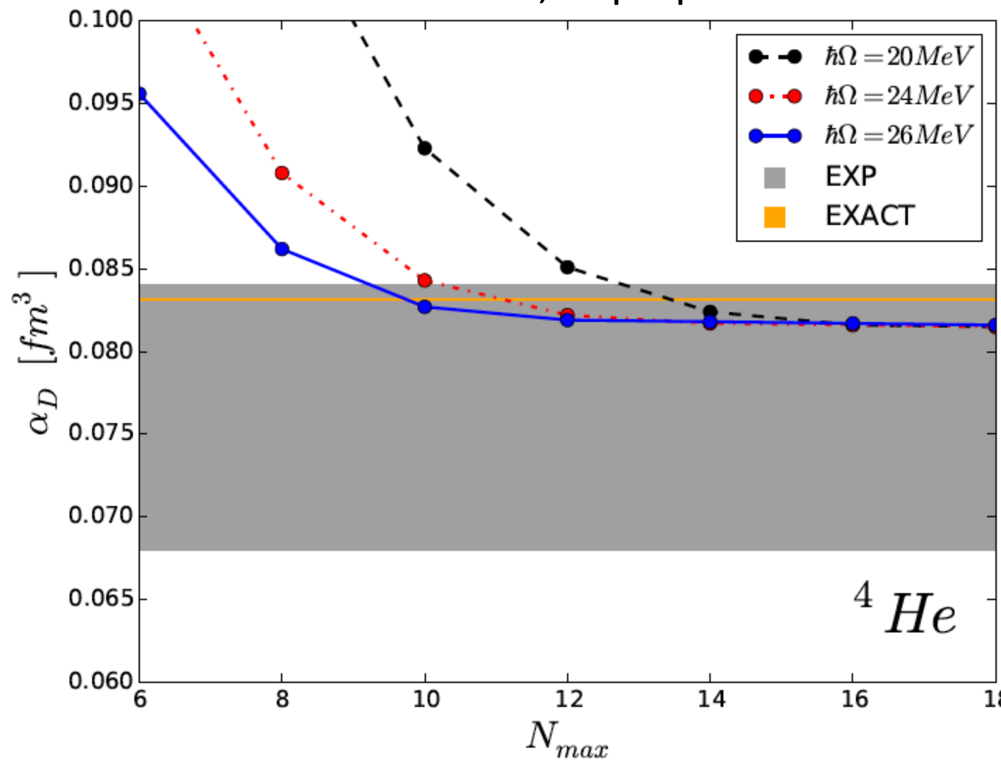
Dipole response in ^{4}He from coupled-cluster

S. Bacca, N. Barnea, G. Hagen, G. Orlandini, T. Papenbrock, PRL 111, 143402 (2013).
S. Bacca, N. Barnea, G. Hagen, M. Miorelli, G. Orlandini, T. Papenbrock, PRC 90, 064610 (2014)



Lorentz Integral transform from coupled-cluster benchmarked with "exact" hyper-spherical harmonics for ^{4}He

M. Miorelli *et al*, in preparation

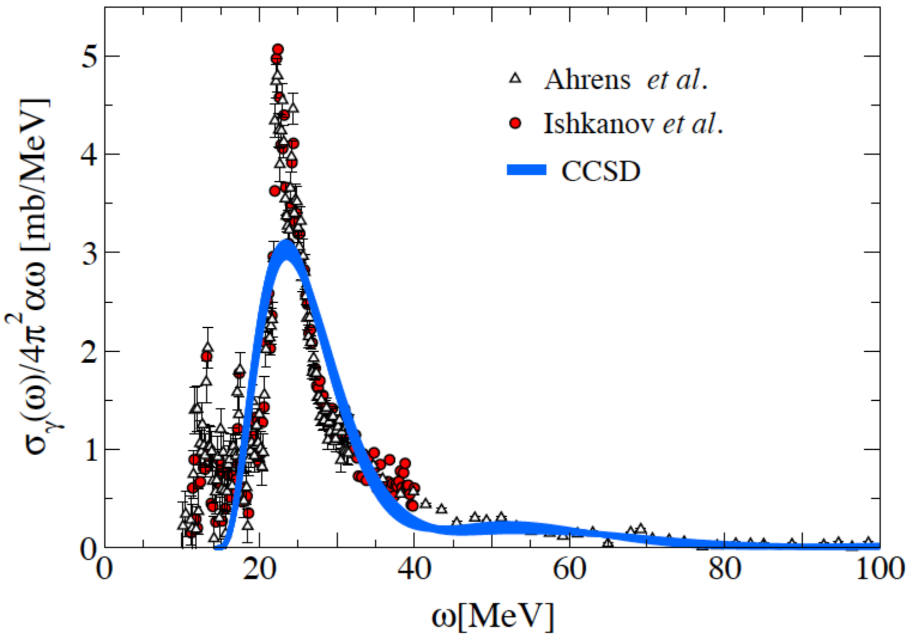


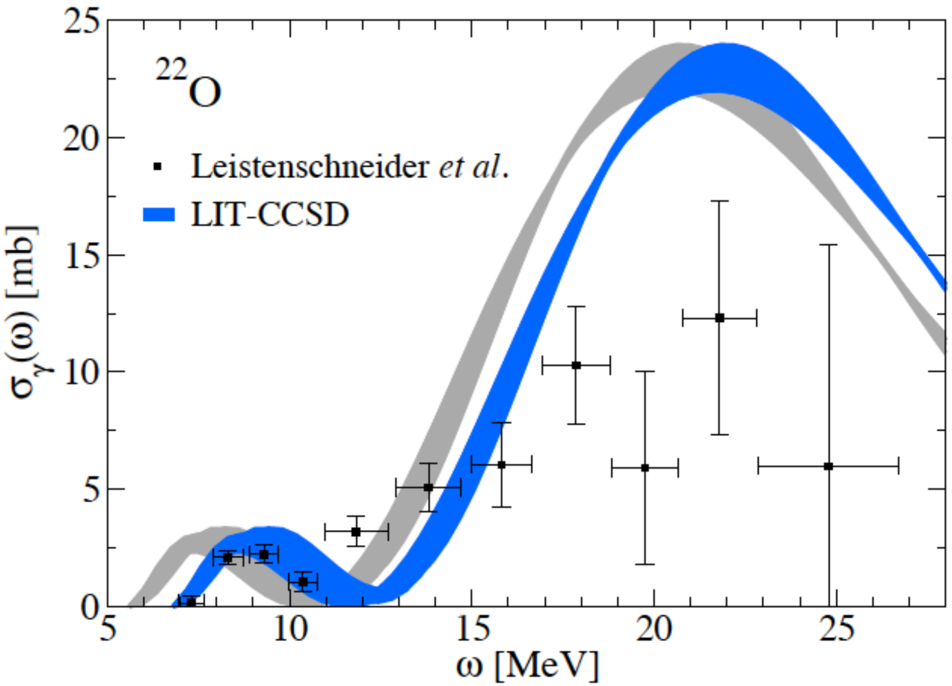
Dipole polarizability in ^{4}He from CCSD within 1% of exact Hyper-spherical harmonics

$$\alpha_D = 2\alpha \int_{\omega_{\rm th}}^{\infty} d\omega \frac{S(\omega)}{\omega}$$

Dipole response in $^{16,22}O$

We find low-lying dipole strength consistent with experiment
Total dipole strength is enhanced in ^{22}O as compared to ^{16}O which can be explained by the excess of neutrons in ^{22}O



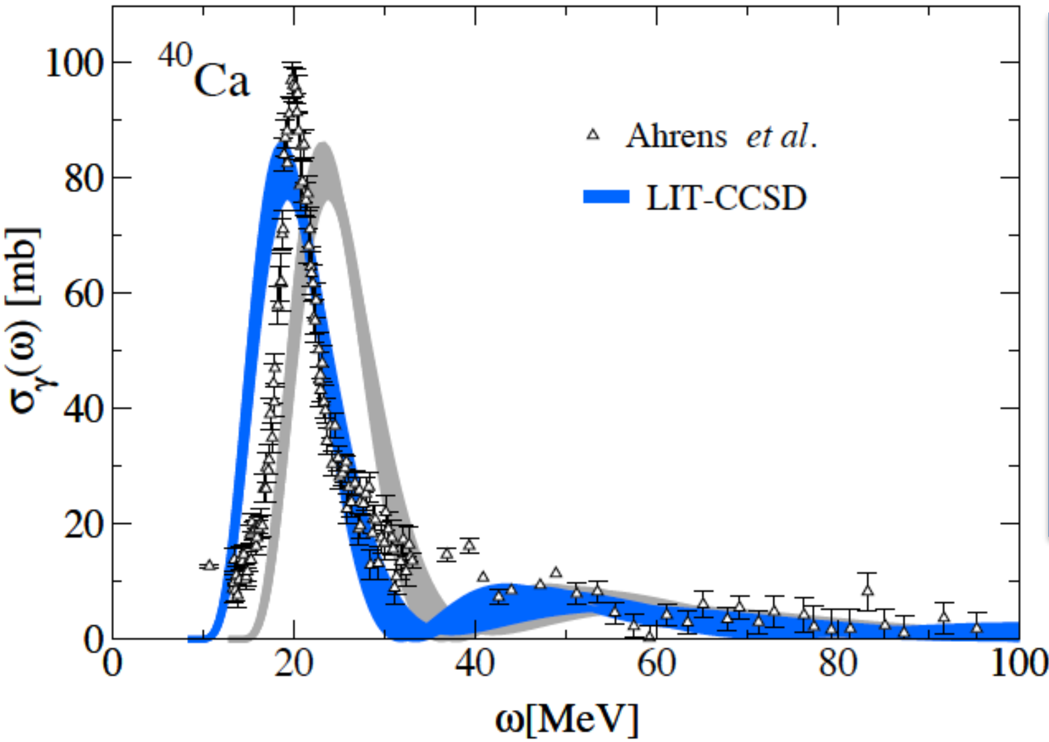


S. Bacca, N. Barnea, G. Hagen, G. Orlandini, T. Papenbrock, PRL 111, 143402 (2013).

S. Bacca, N. Barnea, G. Hagen, M. Miorelli, G. Orlandini, T. Papenbrock, PRC 90, 064610 (2014)

Dipole response and polarizability in ^{40}Ca

N^3LO Entem & Machleidt (NN only)



- Dipole response in ^{40}Ca compared to data.
- Dipole resonance at too high energy, implies too small electric dipole polarizability.

$$\alpha_D(\mathrm{Th}) = 1.47 \text{ fm}^3$$

$$\alpha_D(\mathrm{Exp}) = 2.23(3) \text{ fm}^3$$

$$R_{\mathrm{ch}}(\mathrm{Th}) = 3.05\mathrm{fm}$$

$$R_{\mathrm{ch}}(\mathrm{Exp}) = 3.48\mathrm{fm}$$

$$E(\mathrm{Th}) = 362\mathrm{MeV}$$

$$E(\mathrm{Exp}) = 342\mathrm{MeV}$$

Current chiral interactions do not have good saturation properties. Radii and binding energies are off the experimental target values

How to solve the problem of saturation?

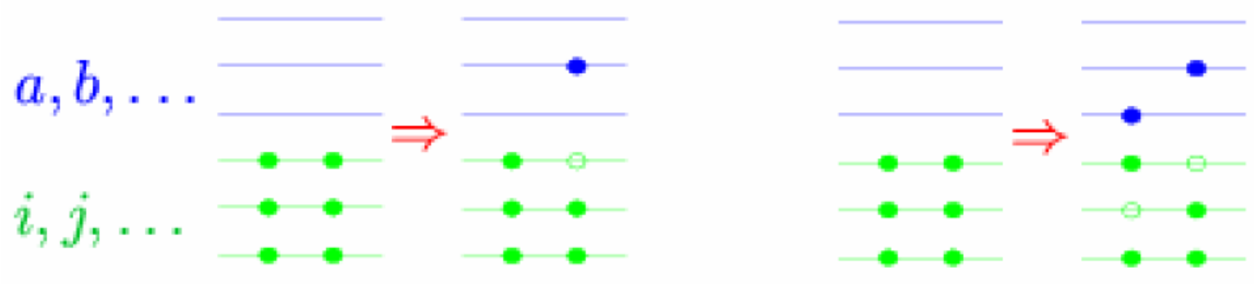
Coupled-cluster method (in CCSD approximation)

Ansatz:

$$|\Psi\rangle = e^T|\Phi\rangle$$
$$T = T_1 + T_2 + \ldots$$
$$T_1 = \sum_{ia} t_i^a a_a^\dagger a_i$$
$$T_2 = \sum_{ijab} t_{ij}^{ab} a_a^\dagger a_b^\dagger a_j a_i$$

- ☺ Scales gently (polynomial) with increasing problem size o^2u^4 .
- ☺ Truncation is the only approximation.
- ☺ Size extensive (error scales with A)
- ☹ Most efficient for closed (sub-)shell nuclei

Correlations are *exponentiated* 1p-1h and 2p-2h excitations. Part of np-nh excitations included!



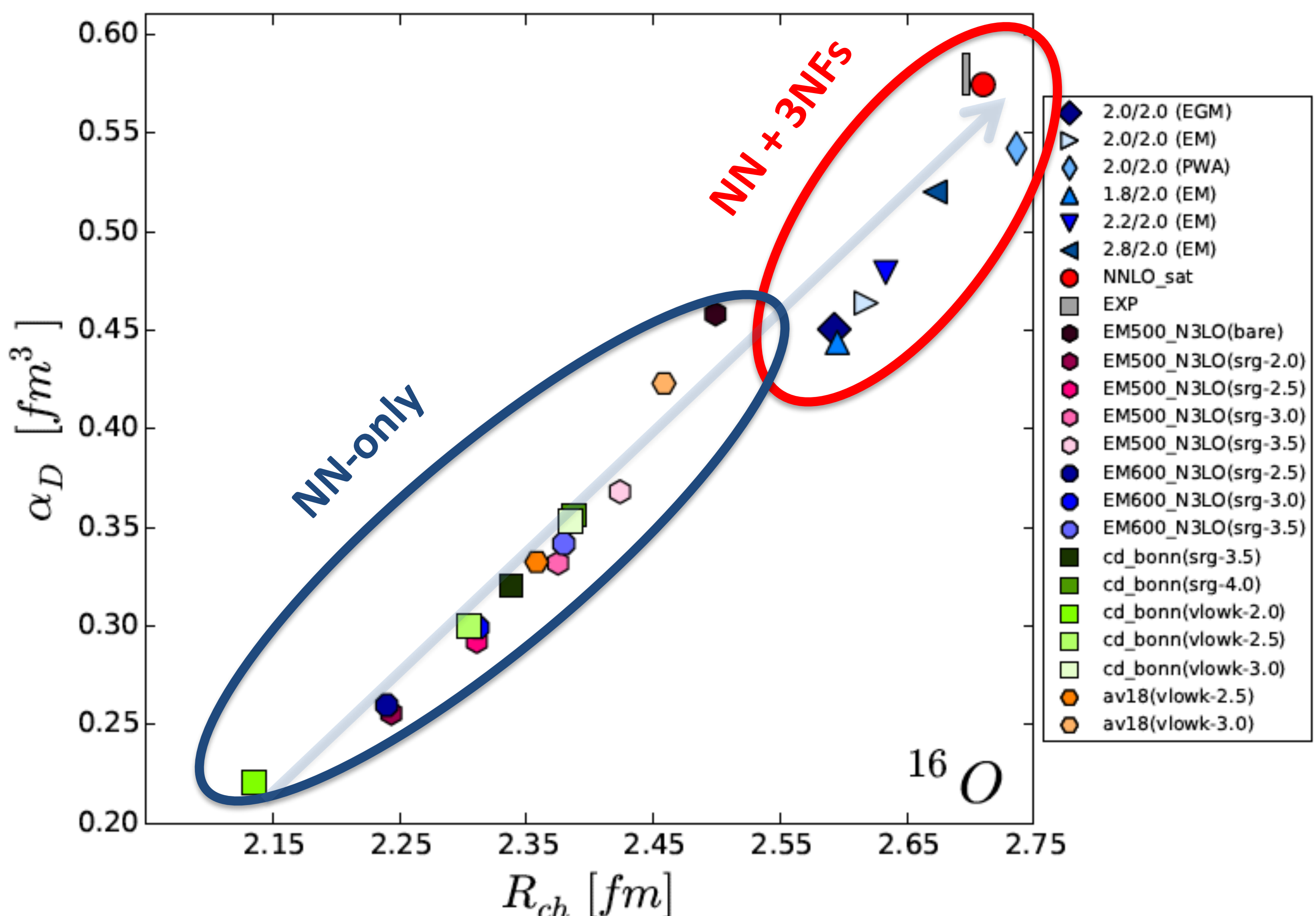
Coupled cluster equations

$$E = \langle\Phi|\overline{H}|\Phi\rangle$$
$$0 = \langle\Phi_i^a|\overline{H}|\Phi\rangle$$
$$0 = \langle\Phi_{ij}^{ab}|\overline{H}|\Phi\rangle$$

Alternative view: CCSD generates similarity transformed Hamiltonian with no 1p-1h and no 2p-2h excitations.

$$\overline{H} \equiv e^{-T}He^T = \left(He^T\right)_c = \left(H + HT_1 + HT_2 + \frac{1}{2}HT_1^2 + \ldots\right)_c$$

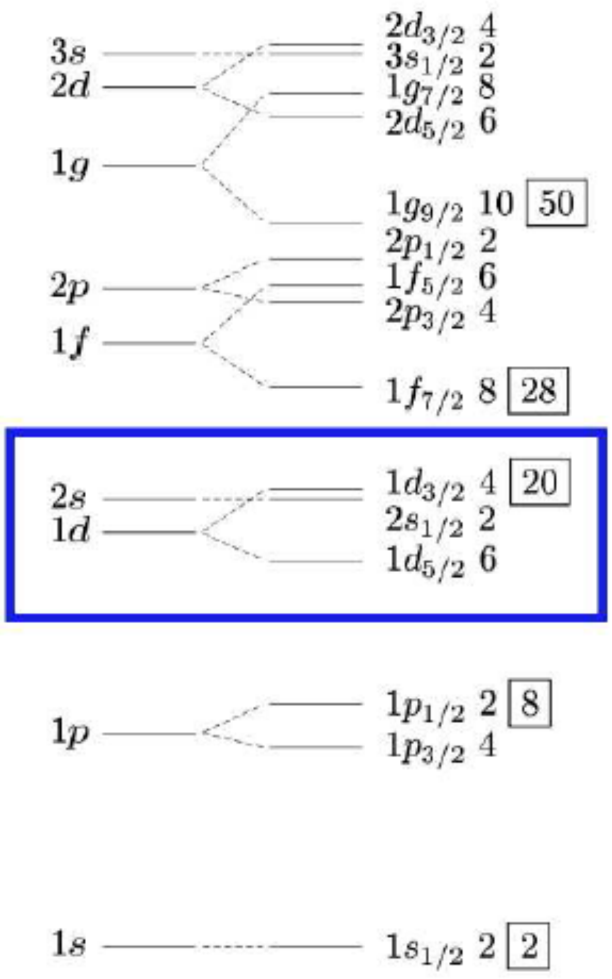
Dipole polarizability of ^{16}O



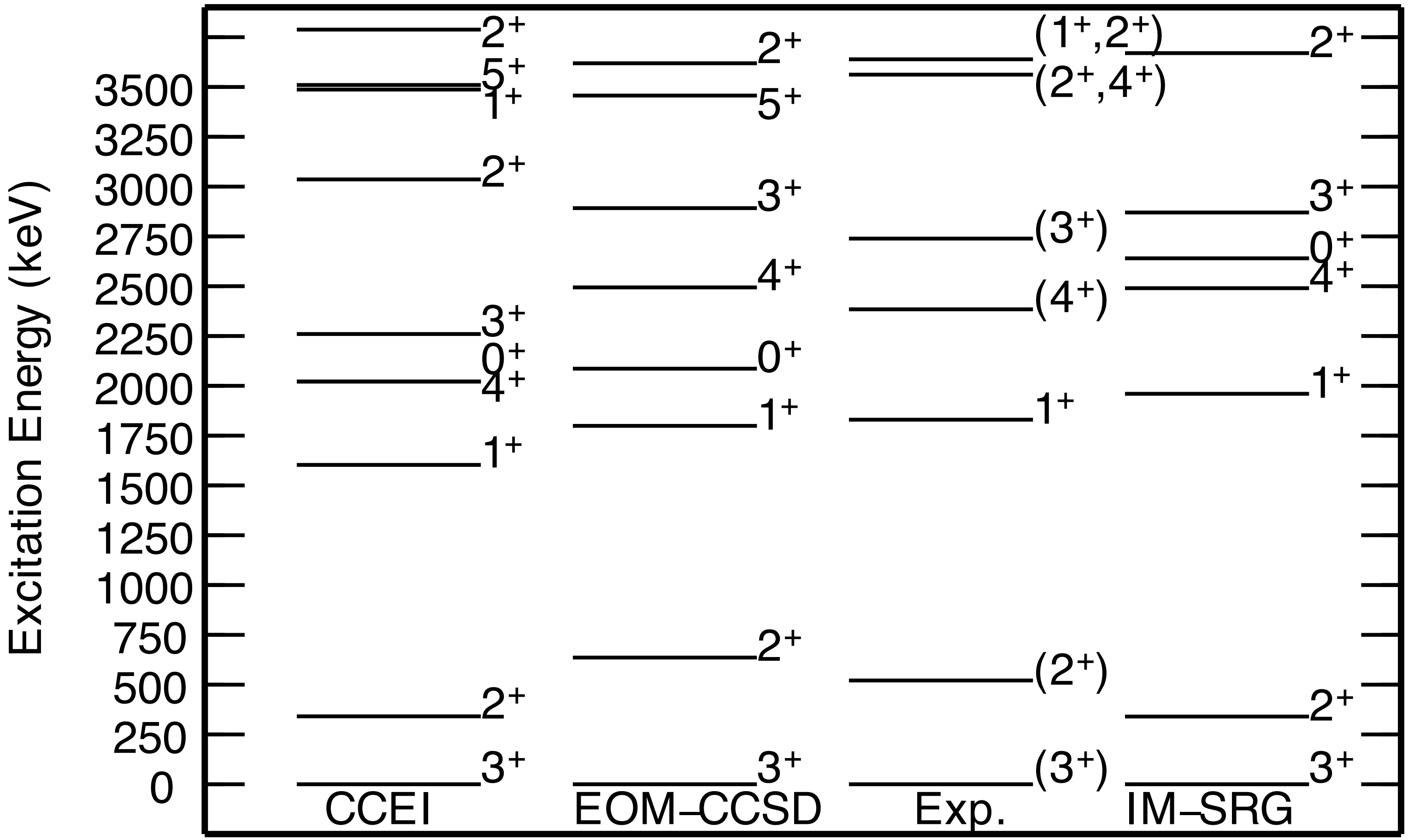
M. Miorelli et al, in preparation (2015)

Coupled-cluster effective interaction in practice

- Obtain excited states of A_c+ 1 and A_c+ 2 from **PA-EOMCCSD(2p1h)** and **2PA-EOMCCSD(3p1h)**
- The A_c+1 Hamiltonian is diagonal and given by the A_c+1 lowest eigenvalues
- Are results sensitive to the choice of left/right eigenvector projections for A+2?
- How do we choose the d “exact” A+2 wavefunctions?
  - ➢ Largest overlap with model space
  - ➢ Lowest energies



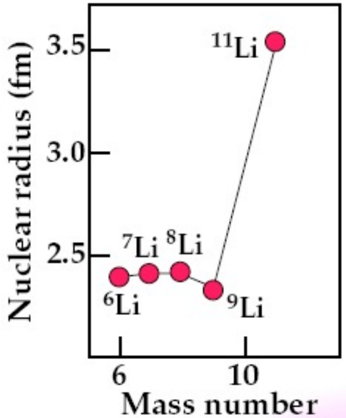
Benchmarking different methods in ^{24}F



^{24}F Level Scheme

IM-SRG: L. Caceres et al arXiv:1501.01166 (2015)

Physics of nuclei at the edges of stability



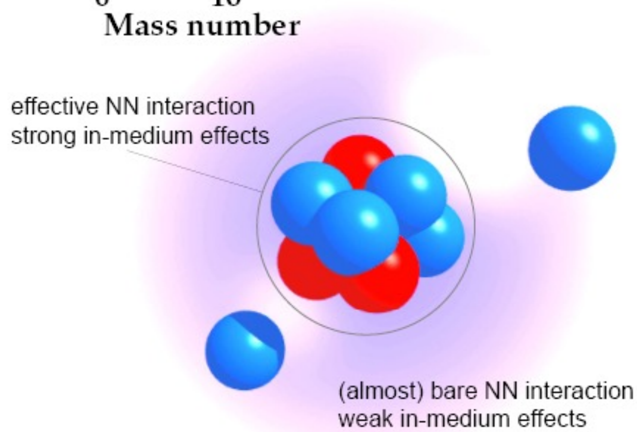
I. Tanihata et al.
Phys. Rev. Lett. 55, 2676 (1985)

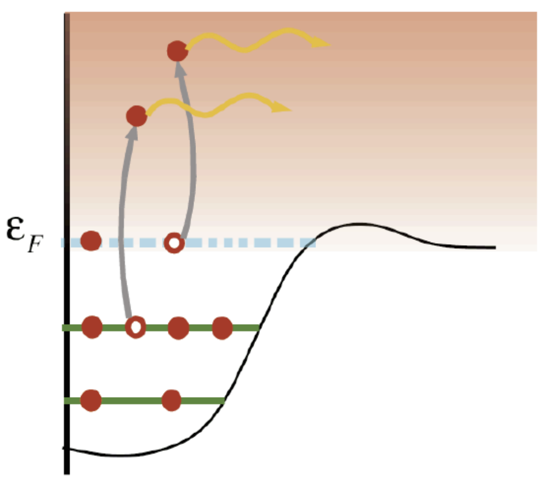
Interaction cross section measurements at Bevalac (790 MeV/u)

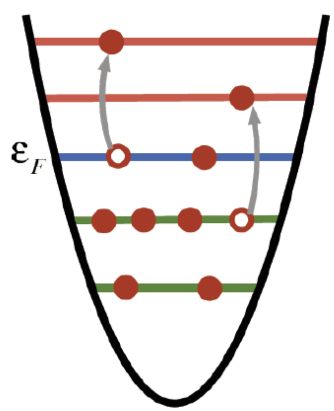
The Berggren completeness treats bound, resonant and scattering states on equal footing.

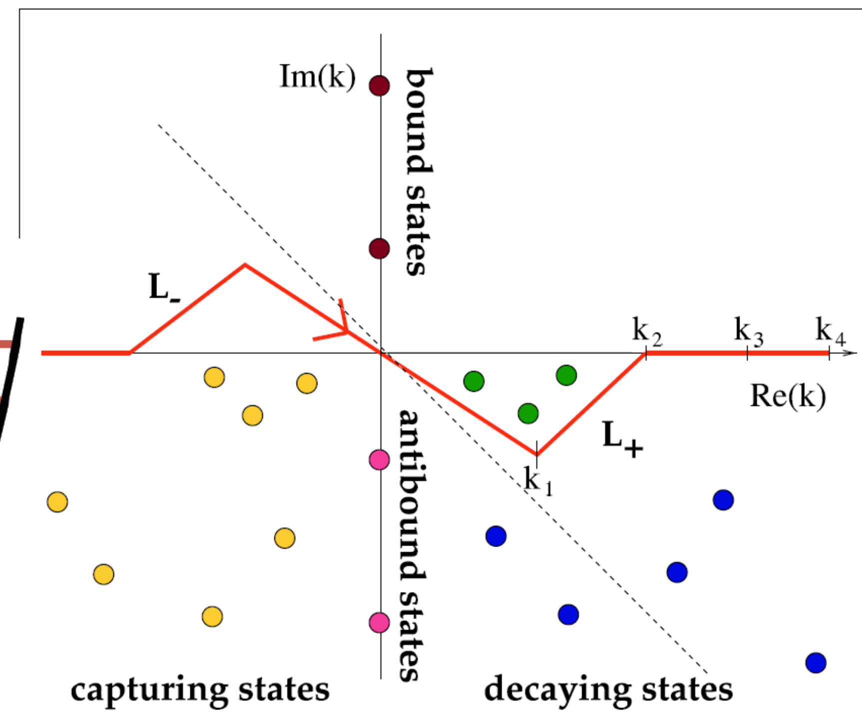
Has been successfully applied in the shell model in the complex energy plane to light nuclei. For a review see

N. Michel et al J. Phys. G 36, 013101 (2009).



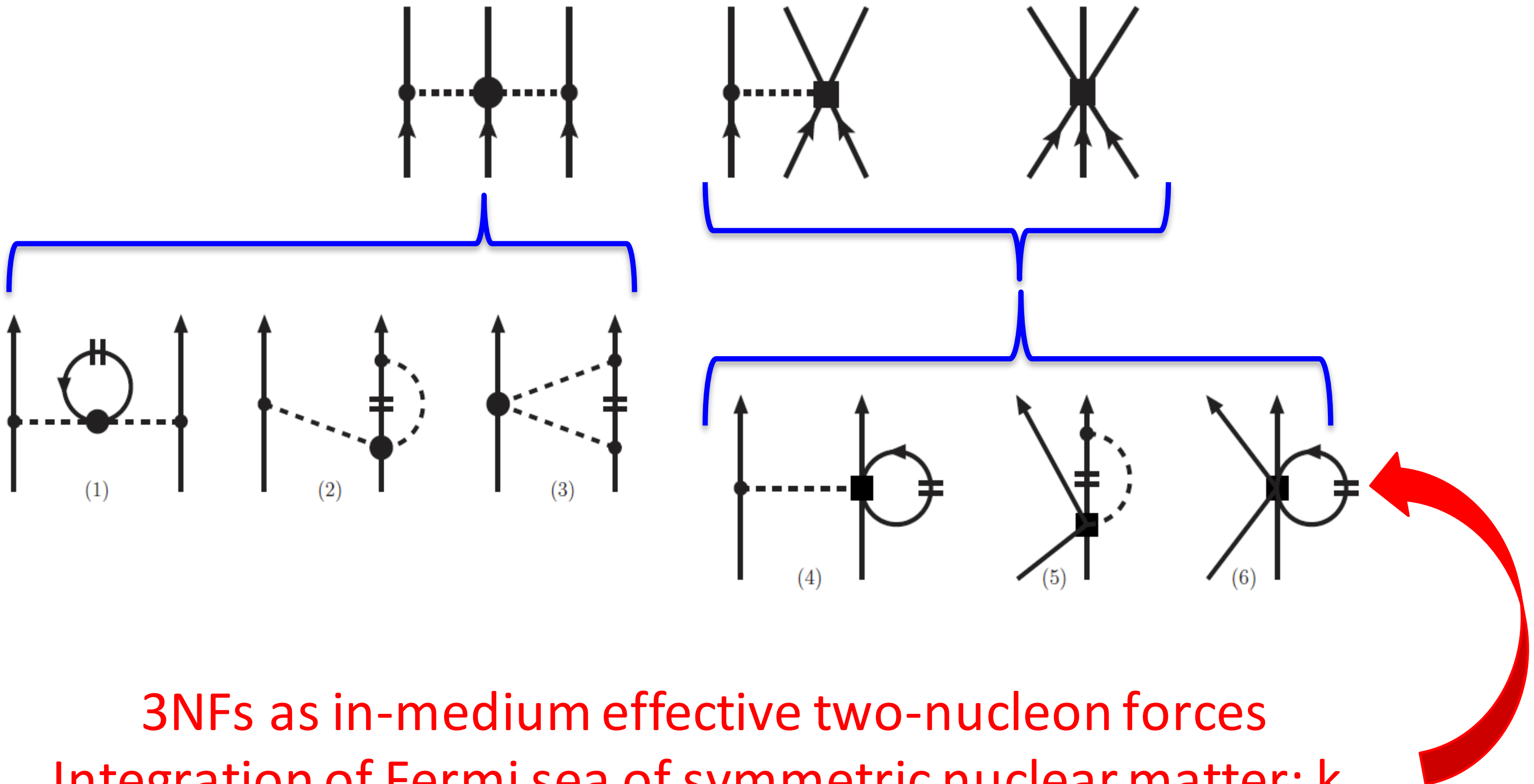






Including the effects of 3NFs (approximation!)

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



3NFs as in-medium effective two-nucleon forces

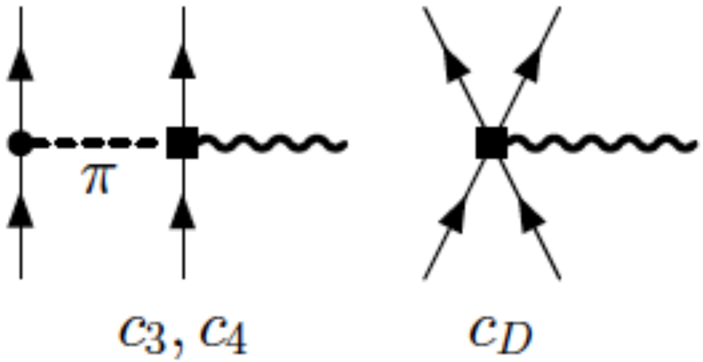
Integration of Fermi sea of symmetric nuclear matter: k_F

Parameters: For Calcium we use k_F = 0.95 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)

Normal ordered one- and two-body current

Gamow-Teller matrix element:

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



Normal ordered operator:

$$\hat{O}_{\mathrm{GT}} = O_N^0 + O_N^1 + O_N^2$$

$$O_N^0 = \sum_{i\leq E_f} \langle i|O^{(1)}|i\rangle + \frac{1}{2}\sum_{i,j\leq E_f}\langle ij|O^{(2)}|ij\rangle$$

$$O_N^1 = \sum_{pq}\langle p|O^{(1)}|q\rangle\{p^\dagger q\} + \sum_{pq}\sum_{i\leq E_f}\langle pi|O^{(2)}|qi\rangle\{p^\dagger q\}$$

$$O_N^2 = \frac{1}{4}\sum_{pqrs}\langle pq|O^{(2)}|rs\rangle\{p^\dagger q^\dagger sr\}$$

One- and two-body currents and normal ordering in Coupled-Cluster

CCSD similarity transformed normal-ordered current operator: $T = T_1 + T_2$

3-body terms

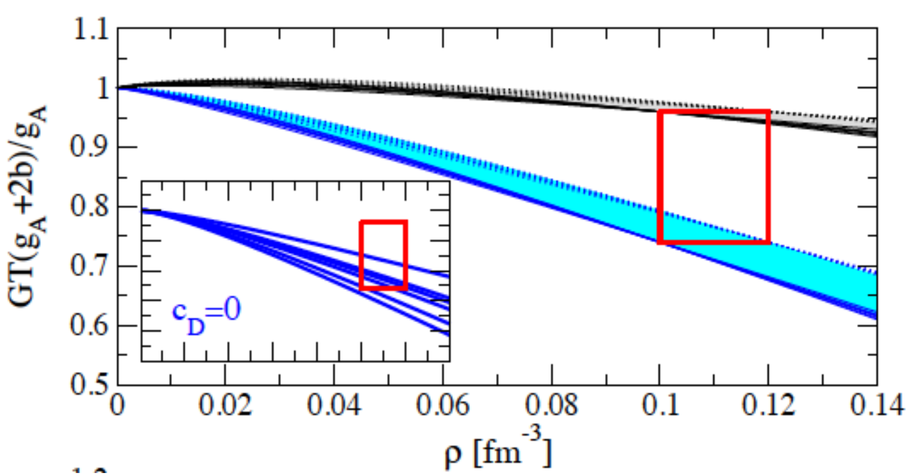
6-body terms

$$\overline{O_{\mathrm{GT}}} = e^{-T} O_N e^{T} = e^{-T} O_N^1 e^{T} + e^{-T} O_N^2 e^{T}$$

Normal ordered 1-body with Leading Order (LO) two-body contribution

Normal-ordered 1-body approximation

$$e^{-T} O_N^2 e^{T} \approx \ O_N^2 = \frac{1}{4} \sum_{pqrs} \langle pq | O^{(2)} | rs \rangle \{ p^\dagger q^\dagger s r \}$$

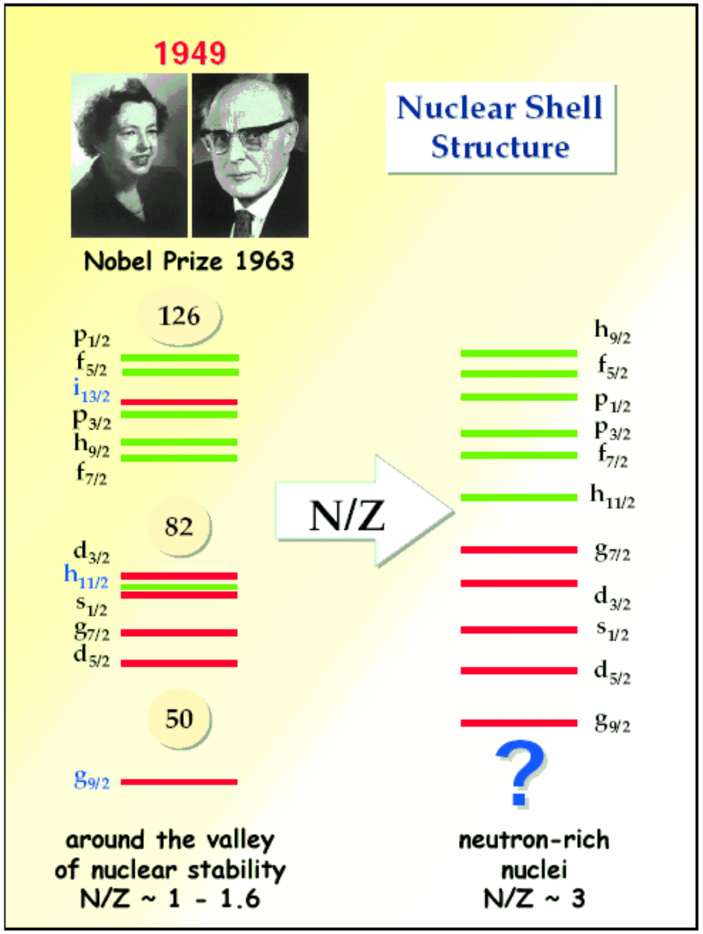


J. Menéndez, D. Gazit, A. Schwenk

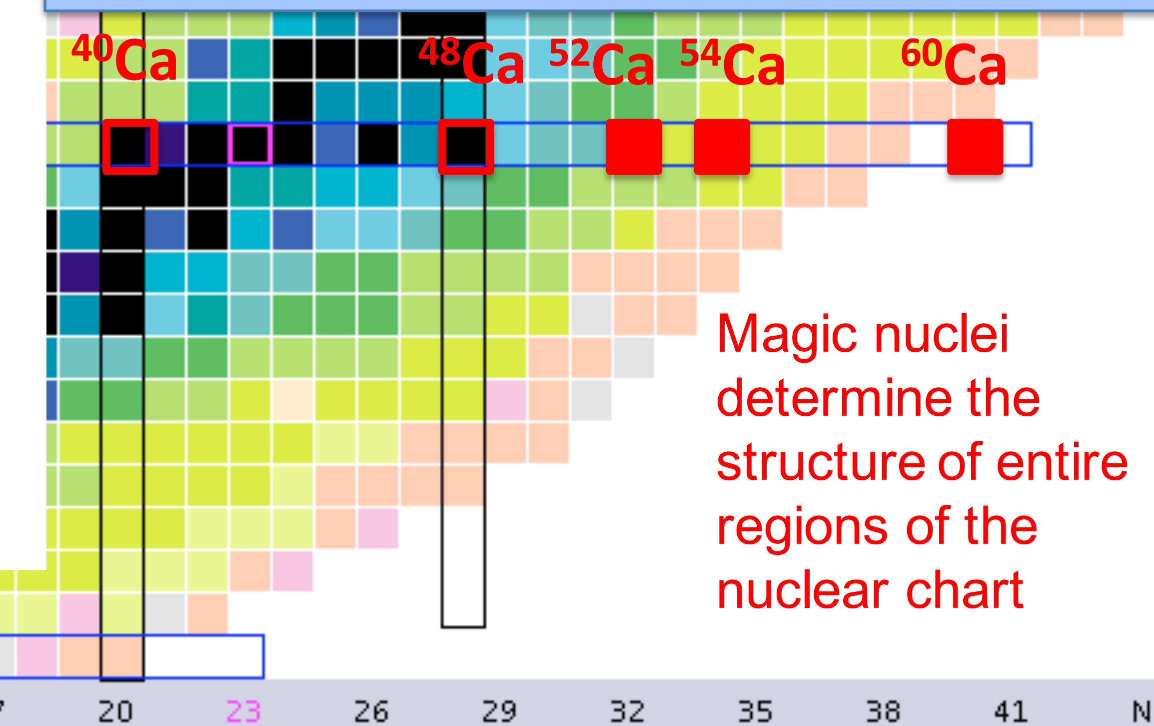
PRL 107, 062501 (2011)

Normal order with respect to free Fermi gas. One-body normal ordered approximation gives quenching of g_A by a factor q = 0.74…0.96 for different set of couplings constants

Evolution of shell structure in neutron rich Calcium



- How do shell closures and magic numbers evolve towards the dripline?
- Is the naïve shell model picture valid at the neutron dripline?
- What are the mechanisms for new shell structure?



Evolution of shell structure in neutron rich Calcium

- Effects of three-nucleon forces and continuum is essential to describe shell structure
- We predict an inversion of the *gds* shell-model orbitals
- Our prediction for excited states in ^{53}Ca and weak sub-shell closure in ^{54}Ca was verified by experiment at RIKEN (Nature 2013, D. Steppenbeck et al)

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