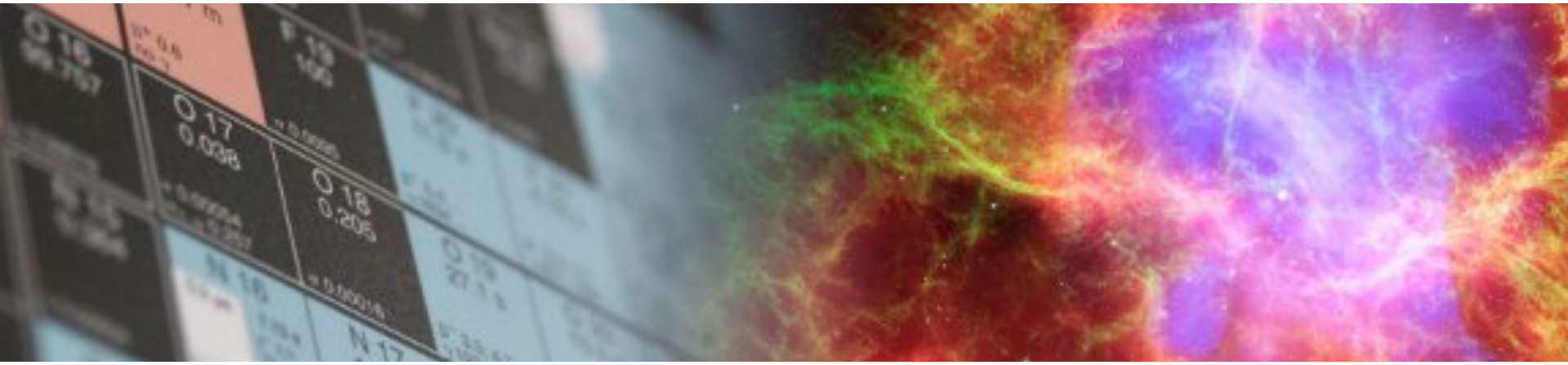
Medium-mass nuclei from nuclear forces

Achim Schwenk

TECHNISCHE UNIVERSITÄT DARMSTADT

EMMI



NUSTAR annual meeting, GSI, March 2, 2017

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Bundesministerium für Bildung und Forschung

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Nuclei bound by strong interactions

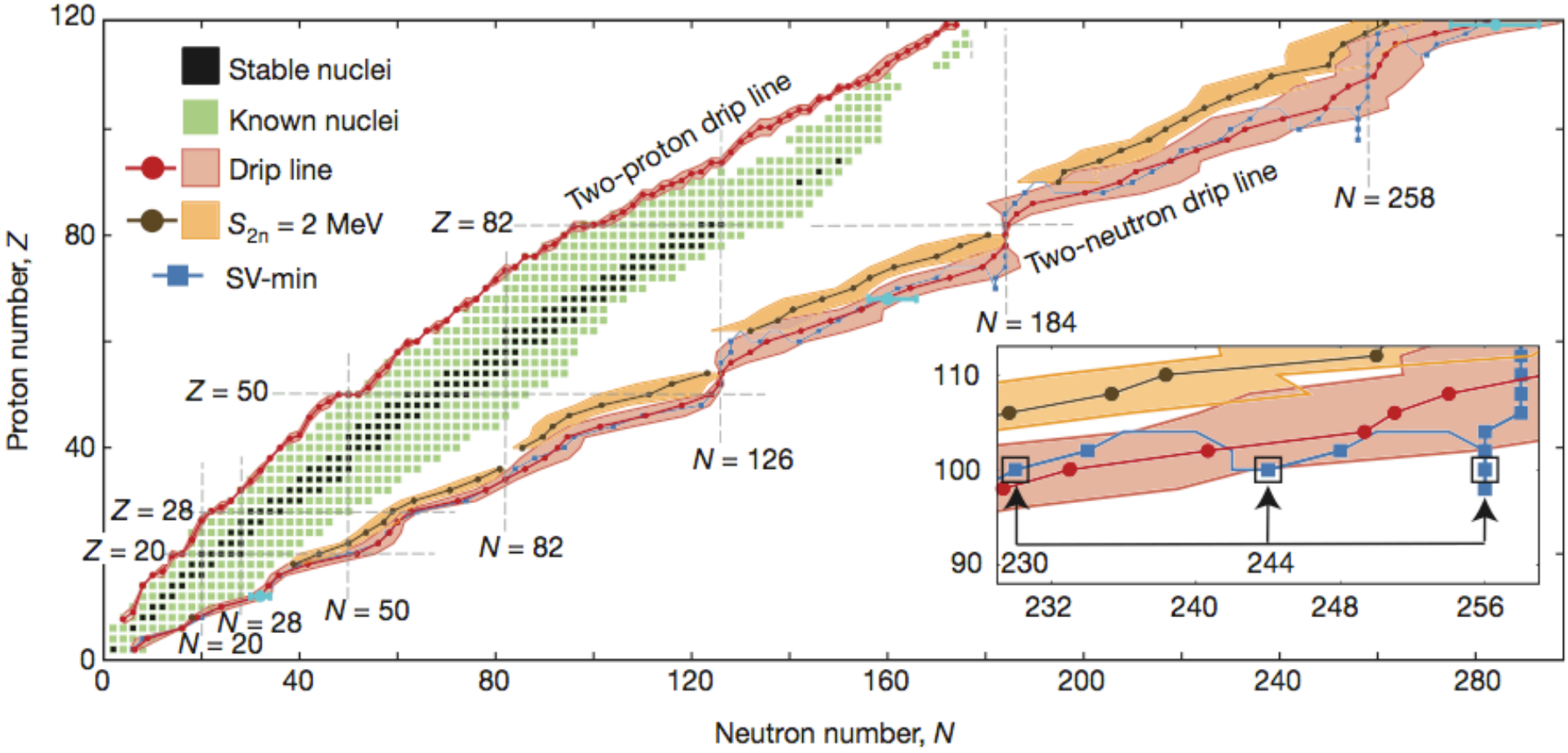
doi:10.1038/nature11188

The limits of the nuclear landscape

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

~ 3000 nuclei discovered (288 stable), 118 elements

~ 4000 nuclei unknown, extreme neutron-rich



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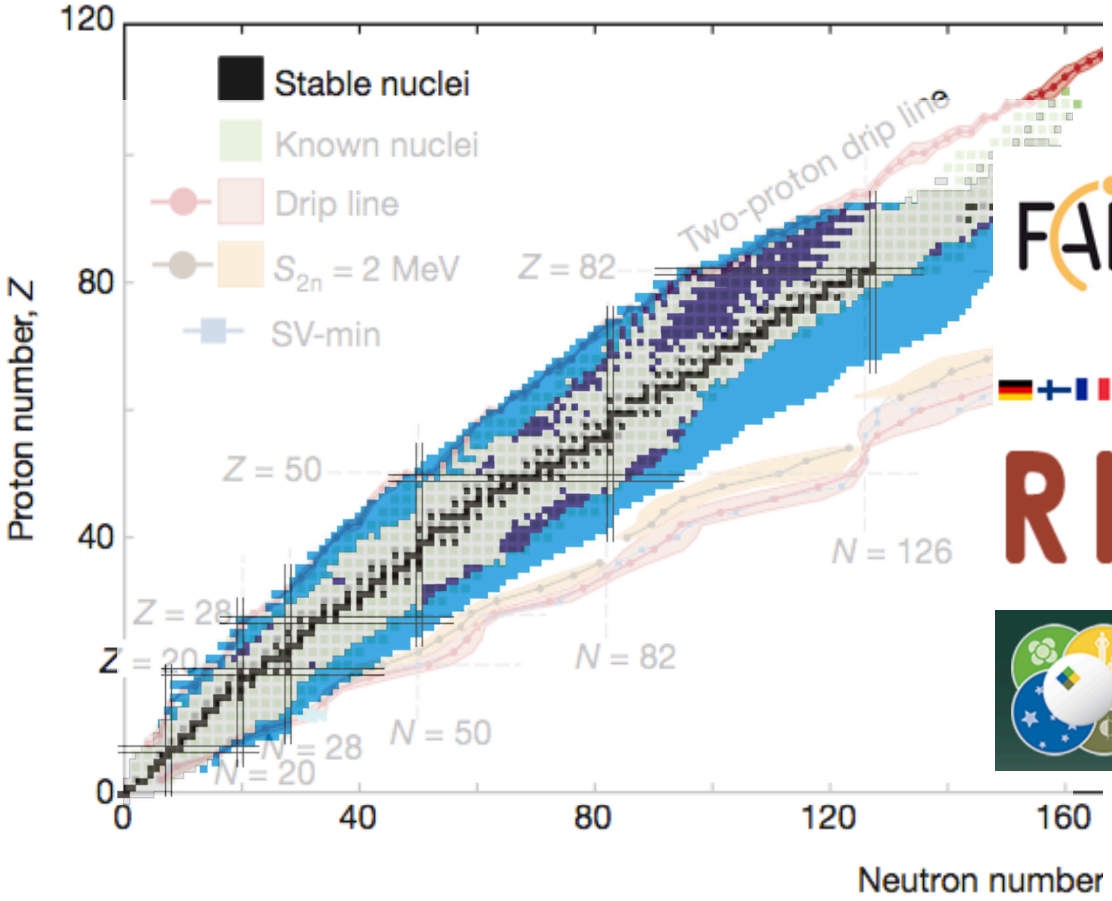

FAIR
Facility for Antiproton and Ion Research in Europe GmbH

RIBF

RIKEN NISHINA CENTER
RIKEN Nishina Center for Accelerator-Based Science

Facility for Rare Isotope Beams
at Michigan State University

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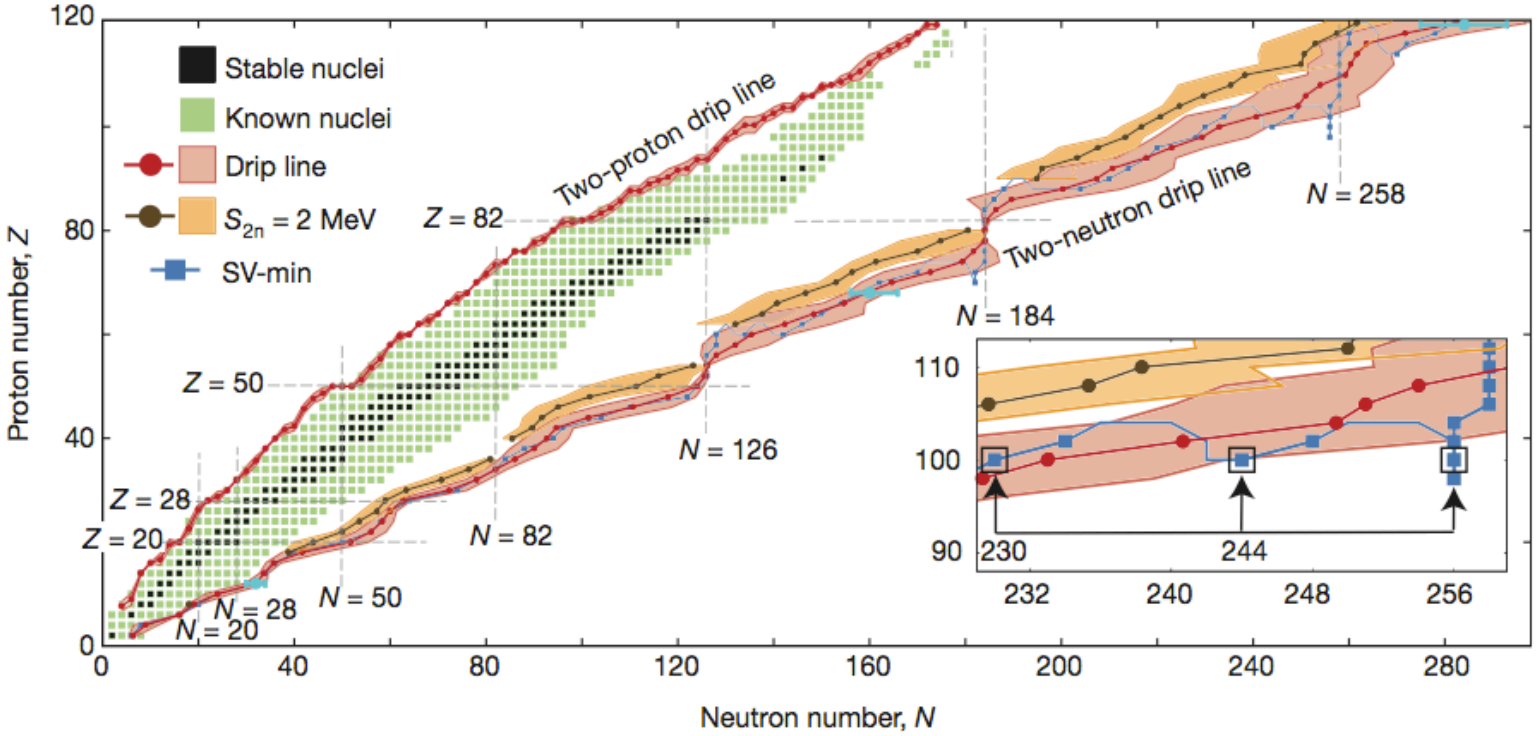


How does the nuclear chart emerge from quantum chromodynamics?

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

for few nucleons for all nuclei

Effective field theories of the strong interaction

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

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

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

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

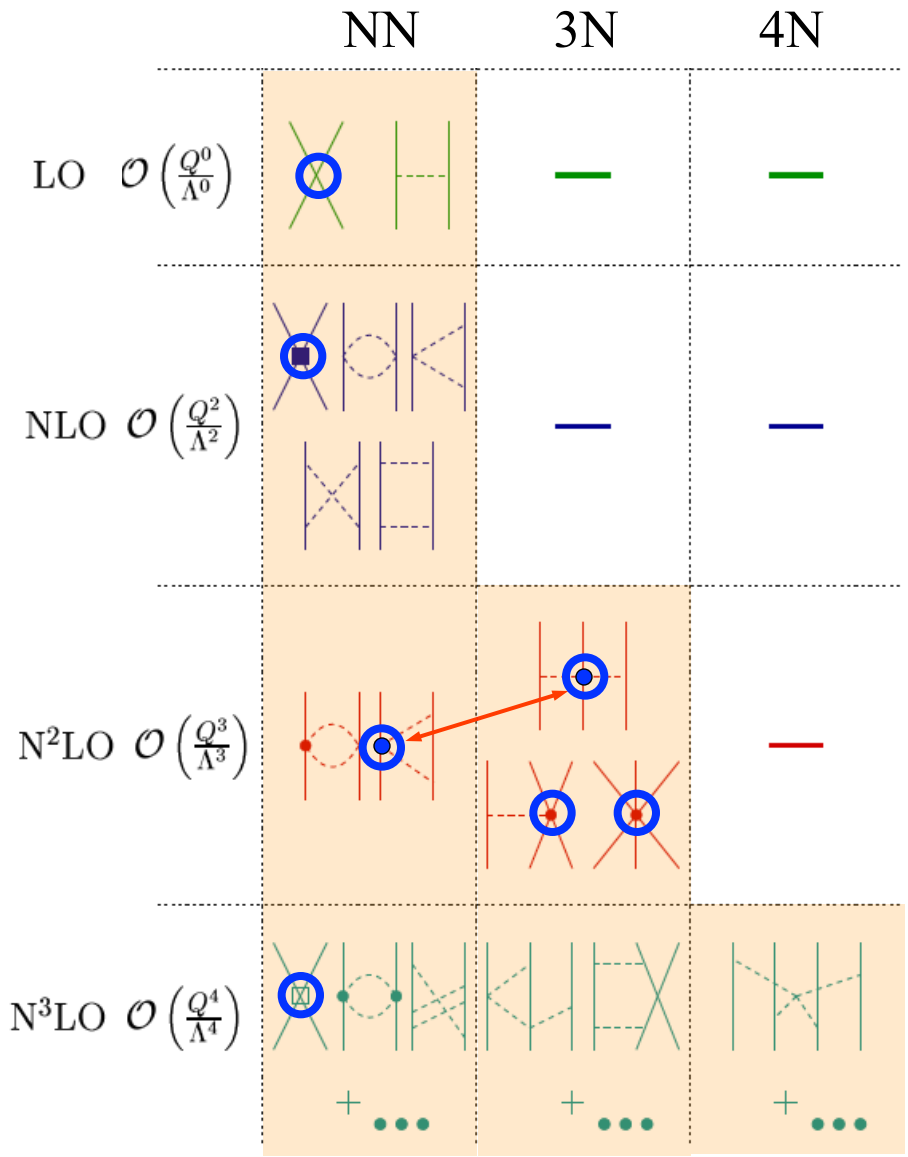
field theory enables **systematic coupling to photons and weak int.**

can **match between different theories**, e.g., match to halo EFT,
guide energy density functionals,…

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

Chiral effective field theory for nuclear forces

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



include long-range pion physics

short-range couplings, fit to experiment once

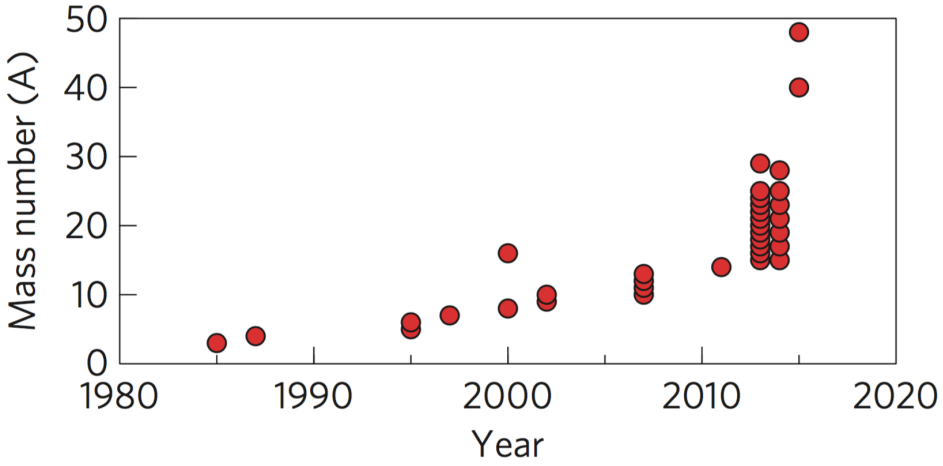
consistent NN-3N-4N interactions

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

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

Progress in ab initio calculations of nuclei

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



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

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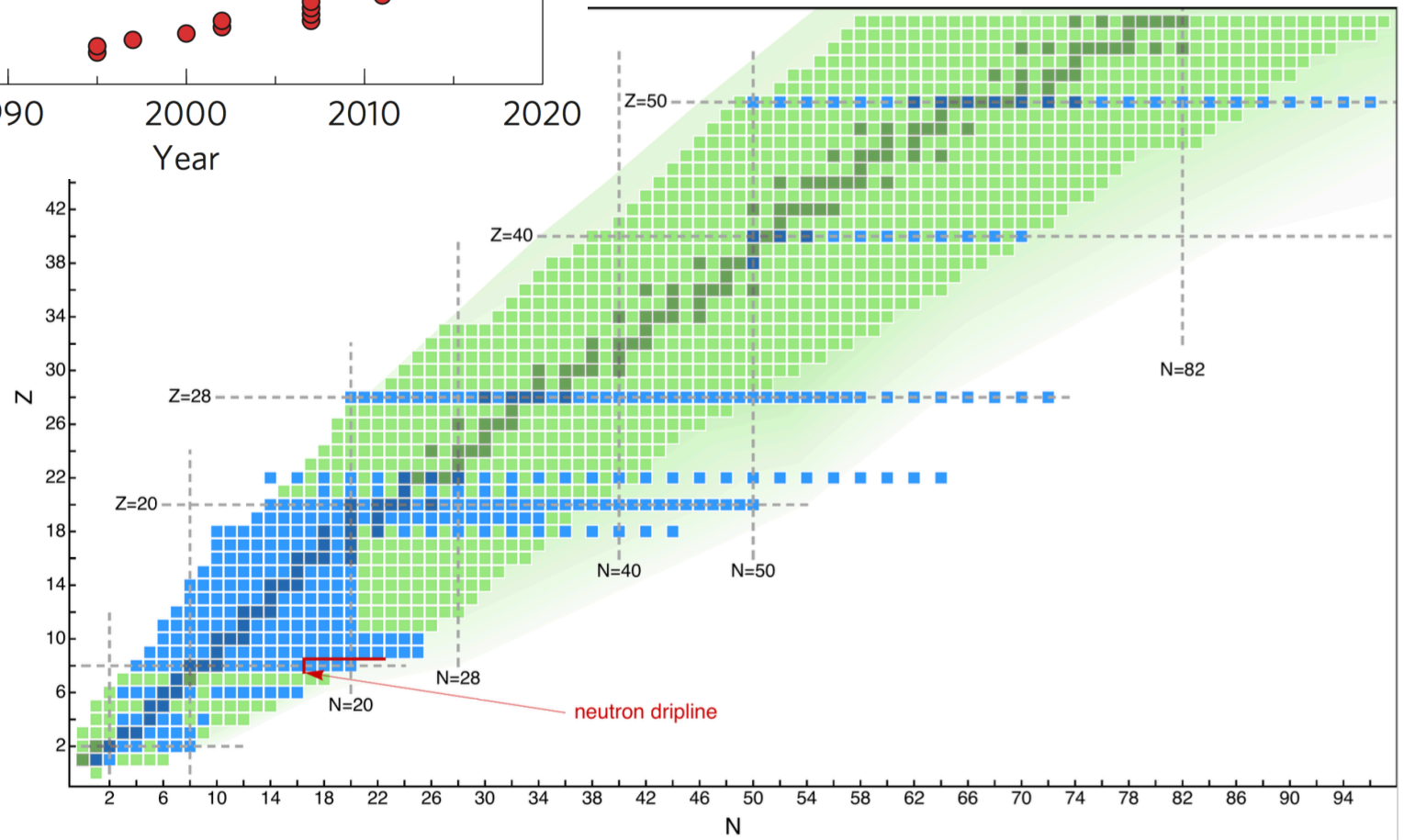

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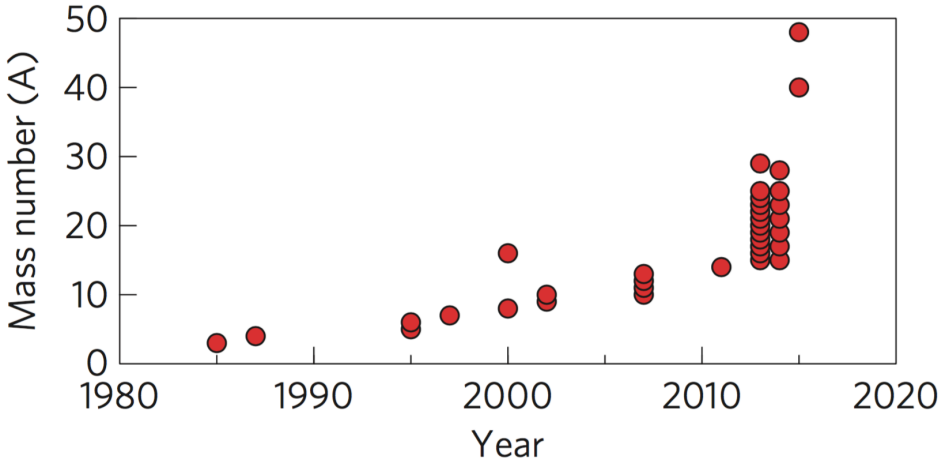

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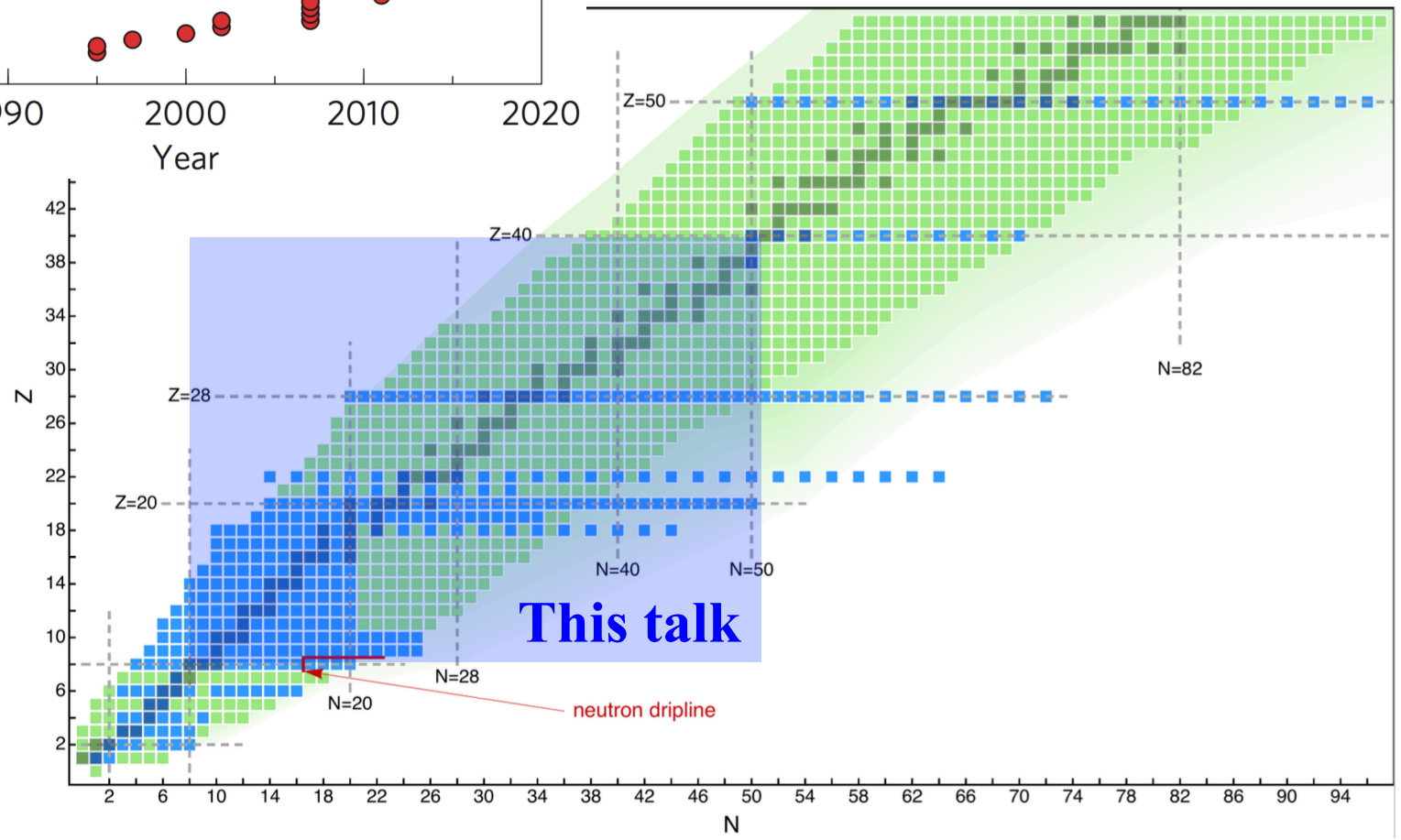


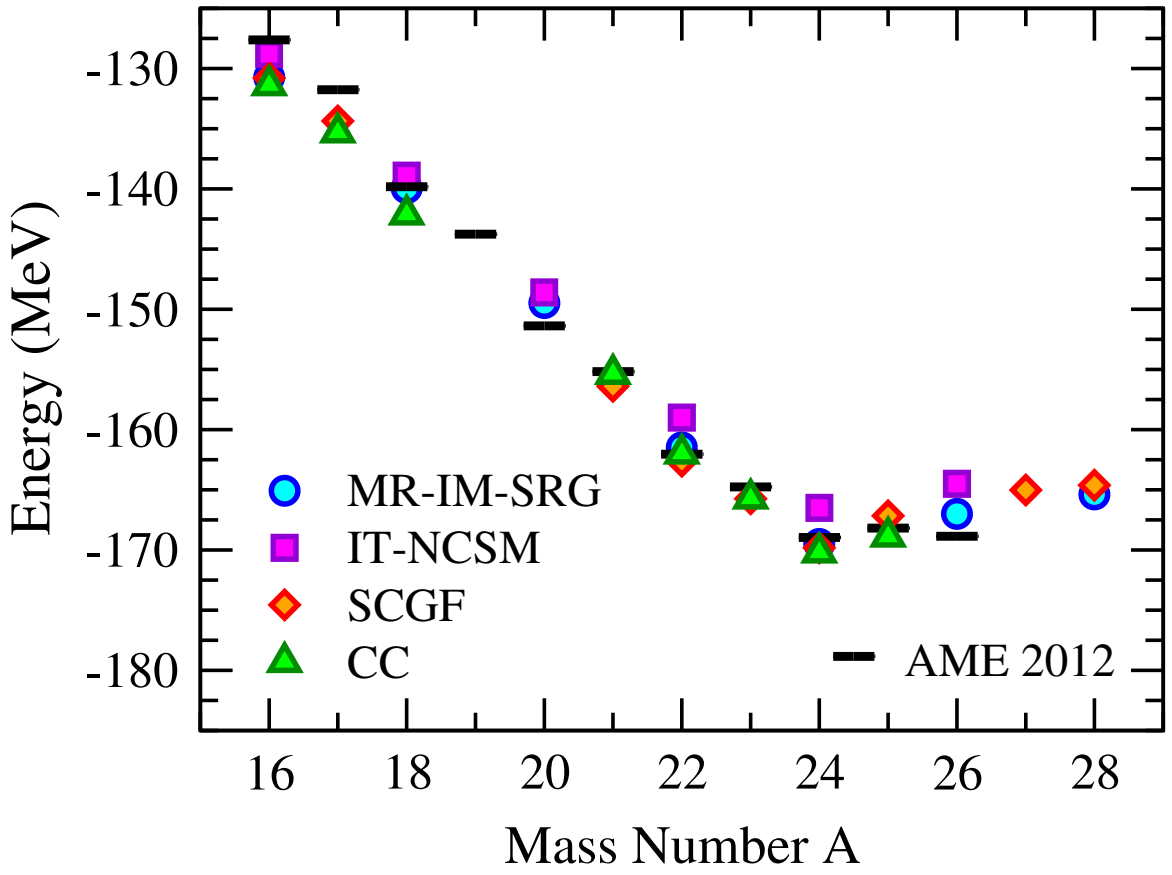
Ab initio calculations of neutron-rich oxygen isotopes

based on same NN+3N interactions with different many-body methods

CC 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 Functions
Cipollone et al., PRL (2013)



Many-body calculations of medium-mass nuclei have smaller uncertainty compared to uncertainties in nuclear forces!

Chiral effective field theory for nuclear forces

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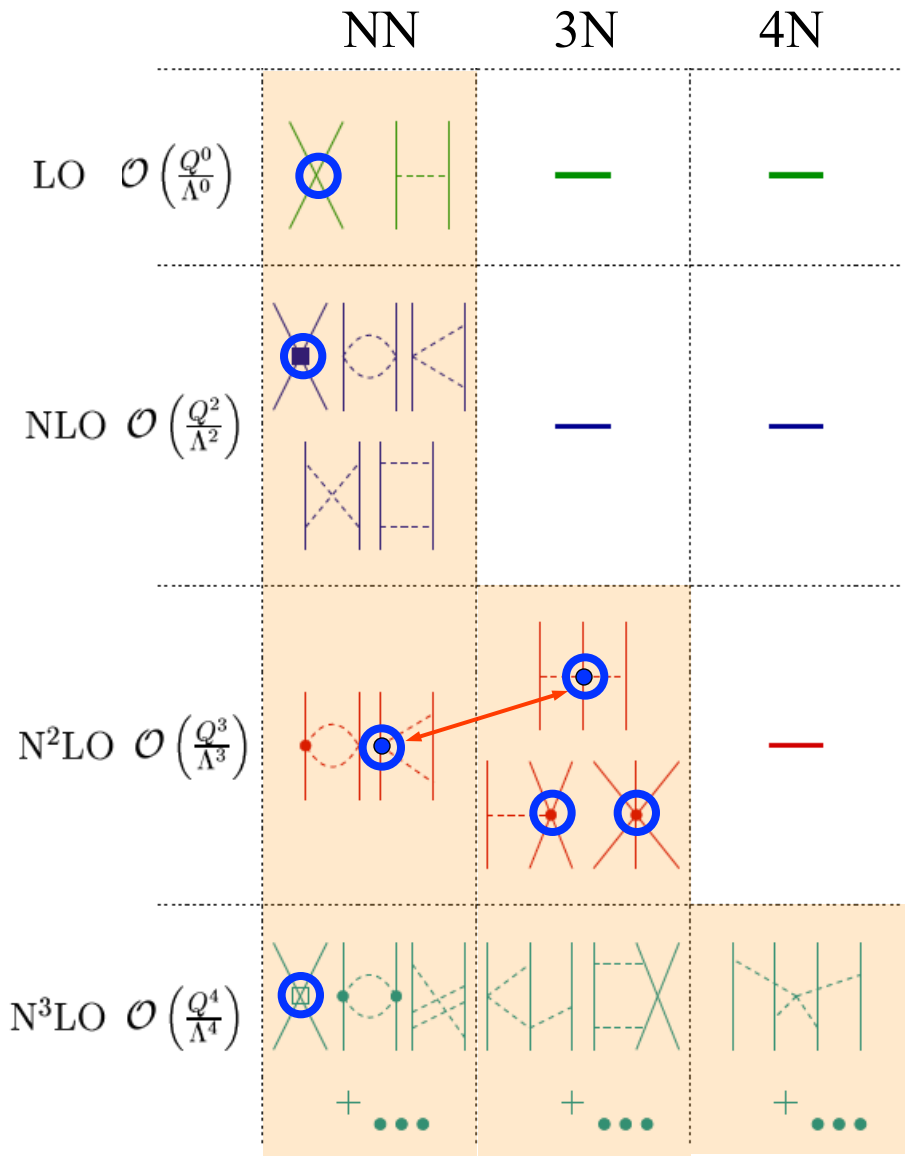

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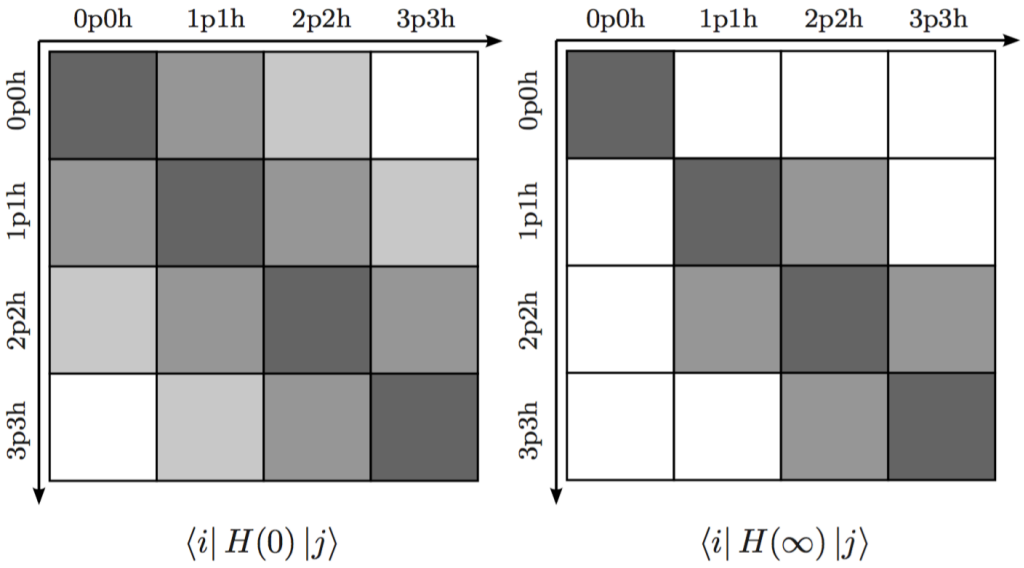
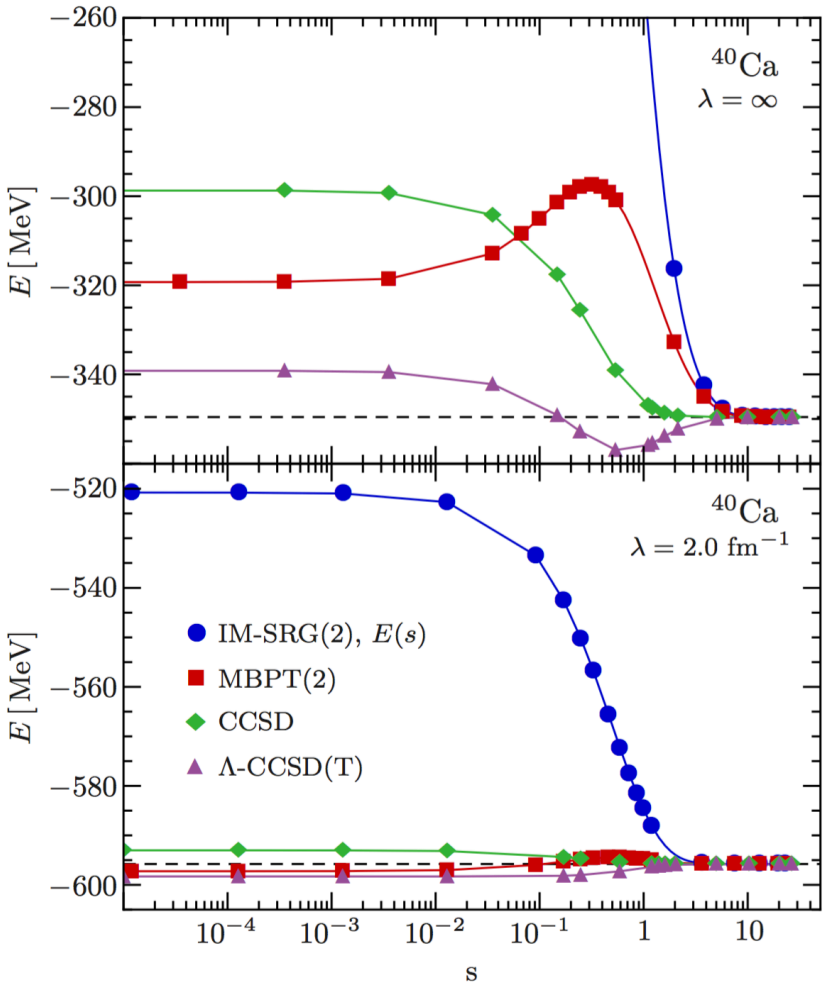
In-medium similarity renormalization group

flow equations to decouple higher-lying particle-hole states

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



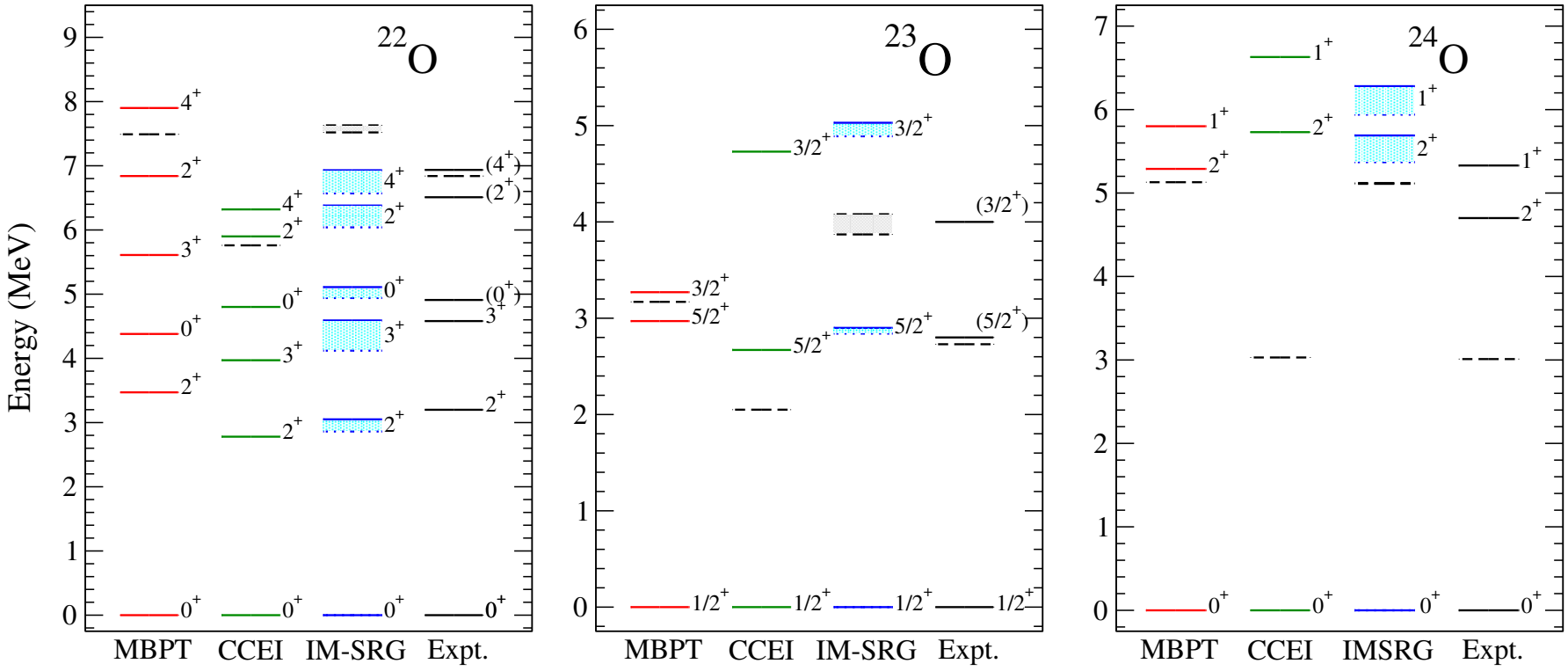


Ab initio calculations going open shell

In-Medium SRG to derive nonperturbative shell-model interactions

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

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



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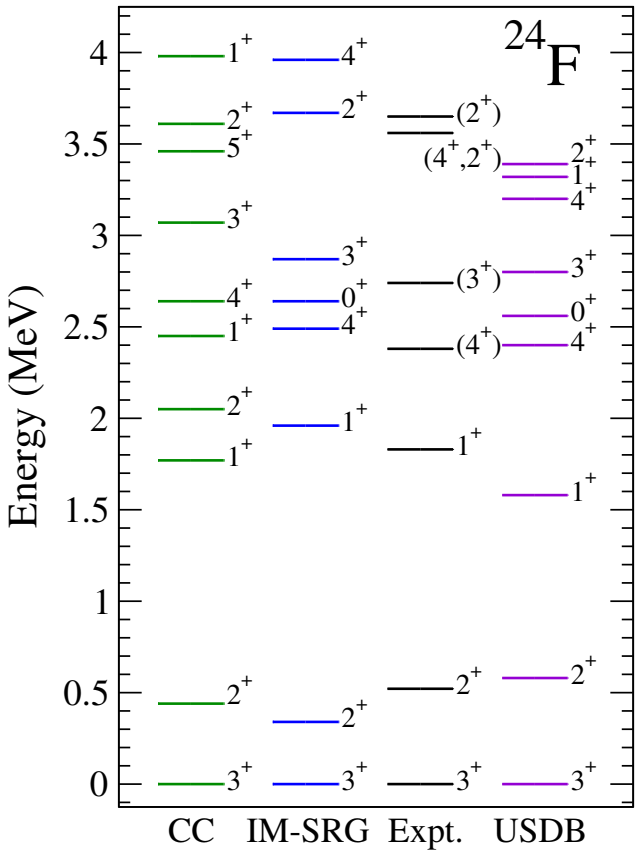
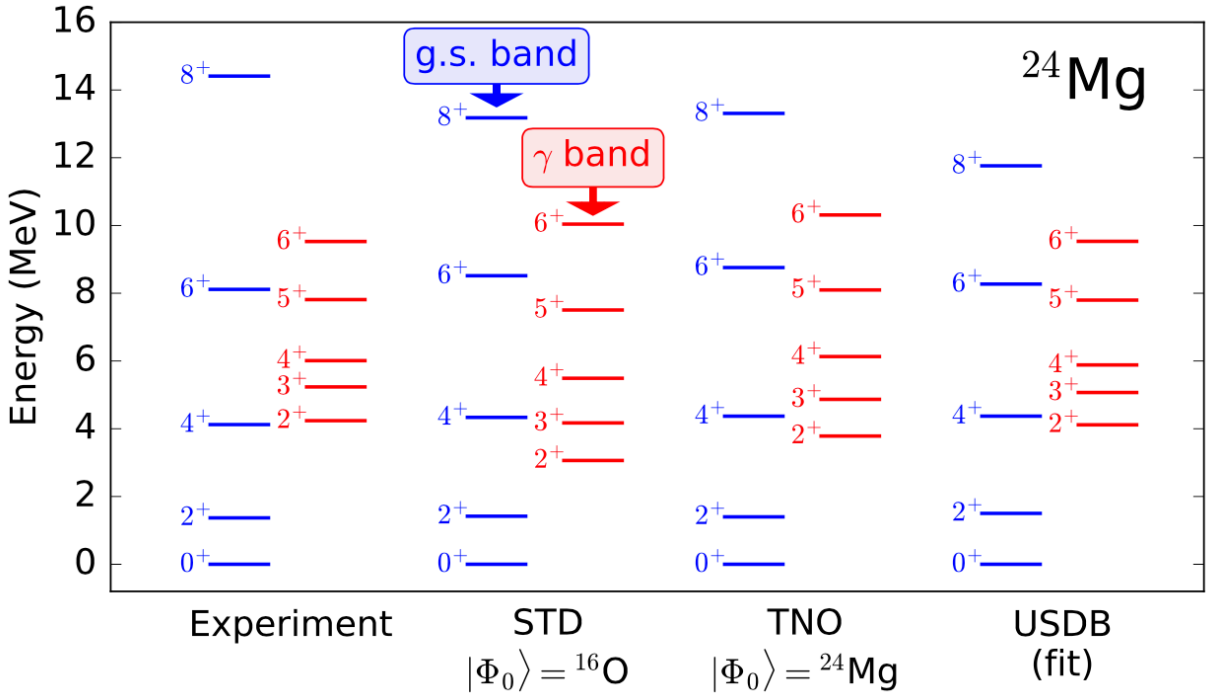


Cáceres et al., PRC (2015)



from R. Stroberg

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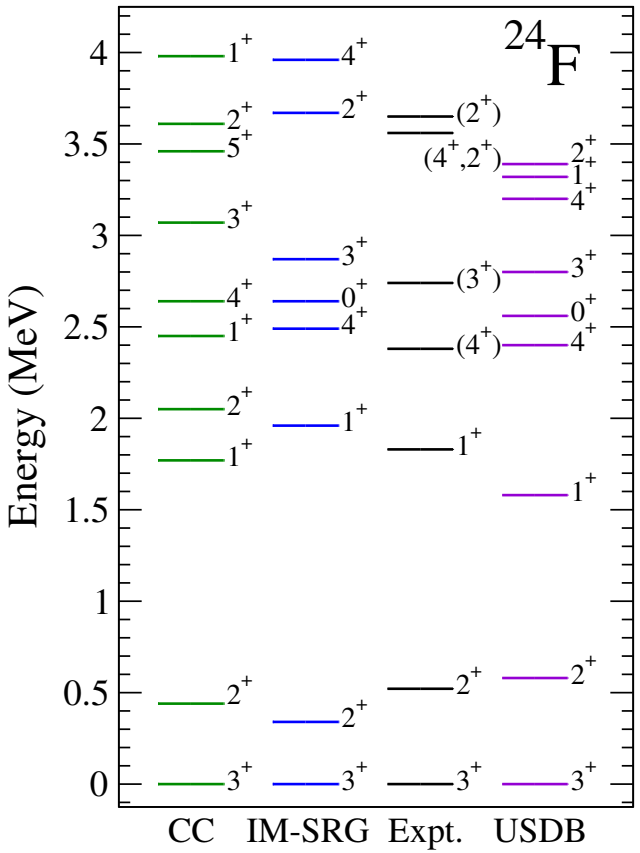

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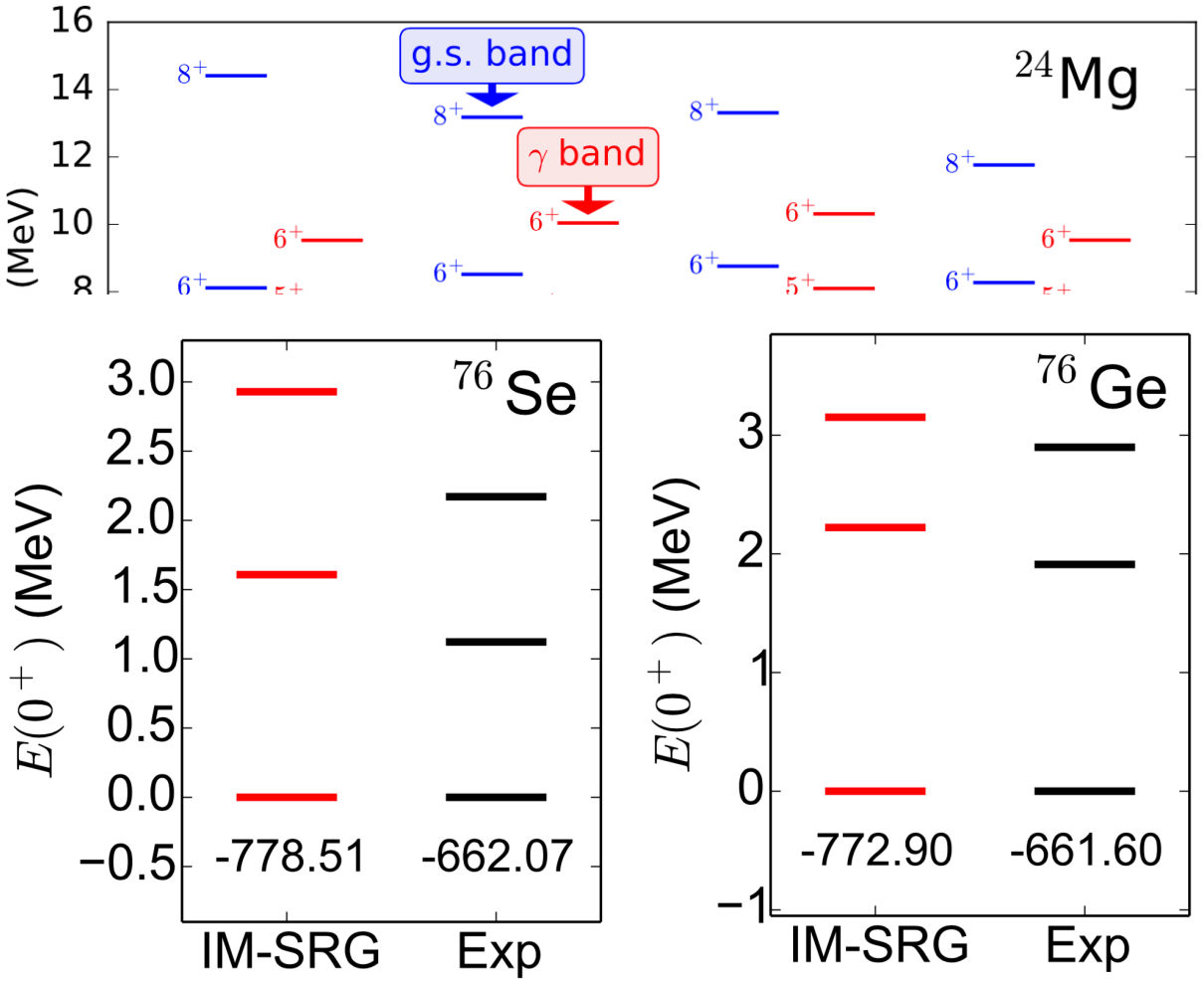
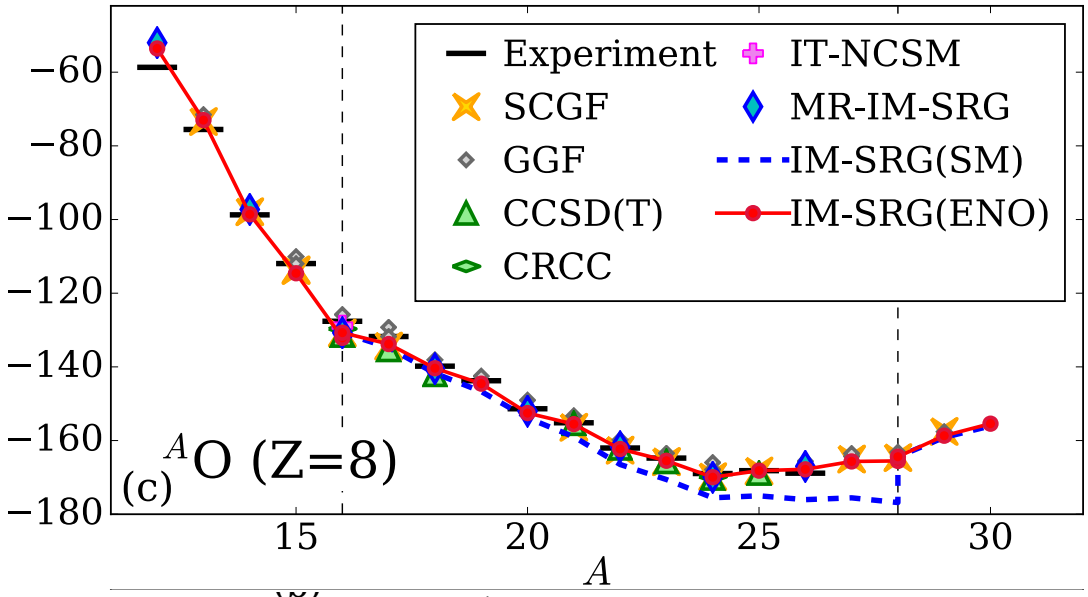
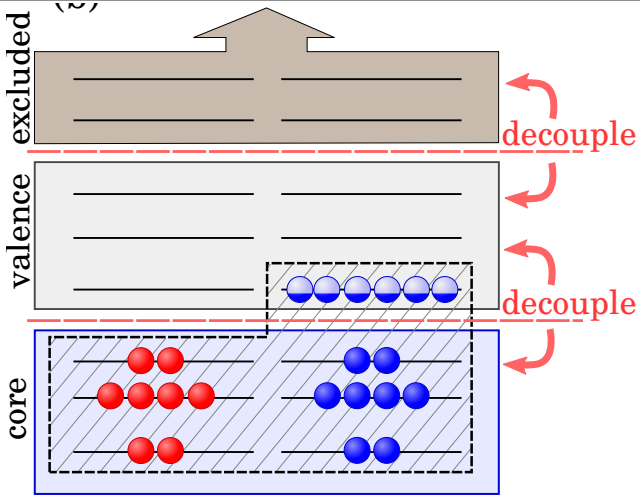


Future: IM-SRG for neutrinoless double-beta decay J.D. Holt, R. Stroberg, et al.

New targeted normal ordering Stroberg et al., PRL (2017)

use ensemble reference with fractional filling to include 3N forces





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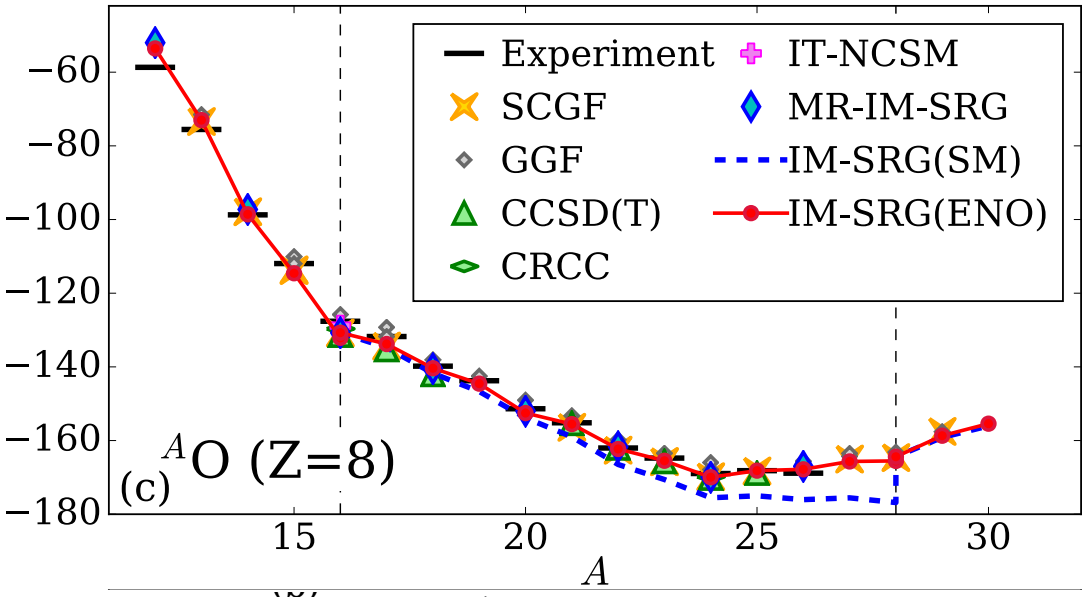
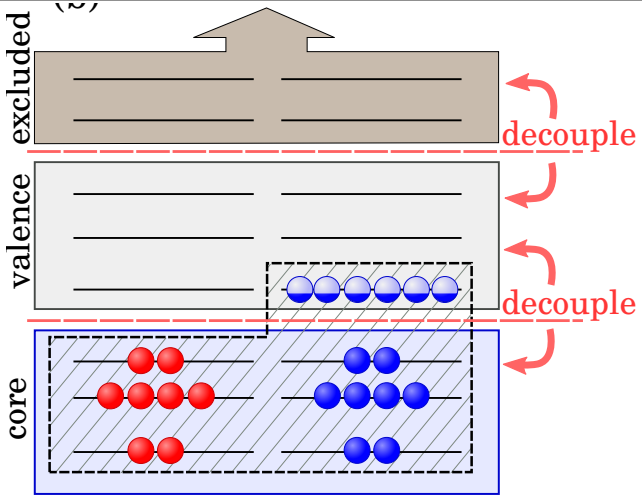
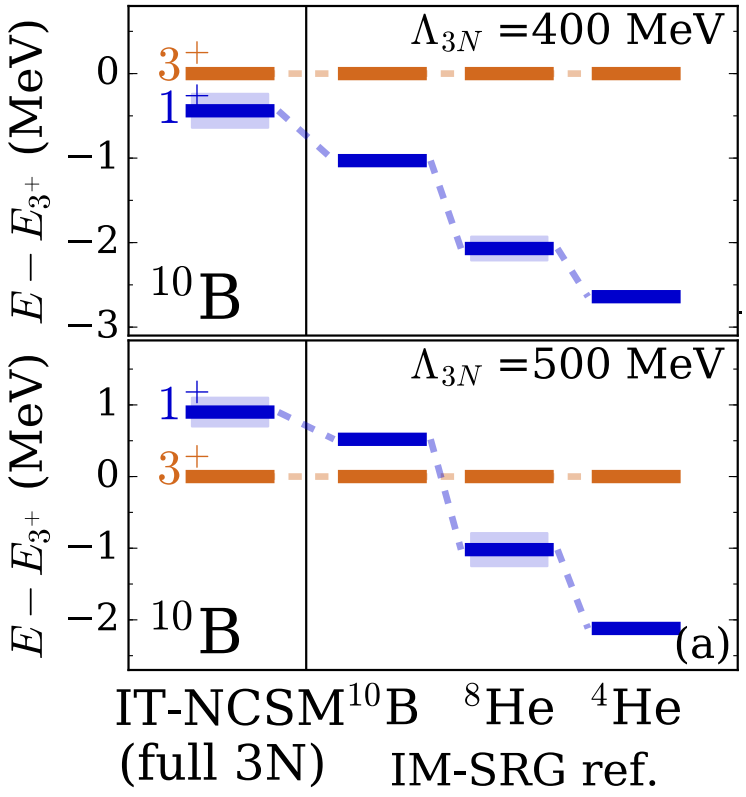
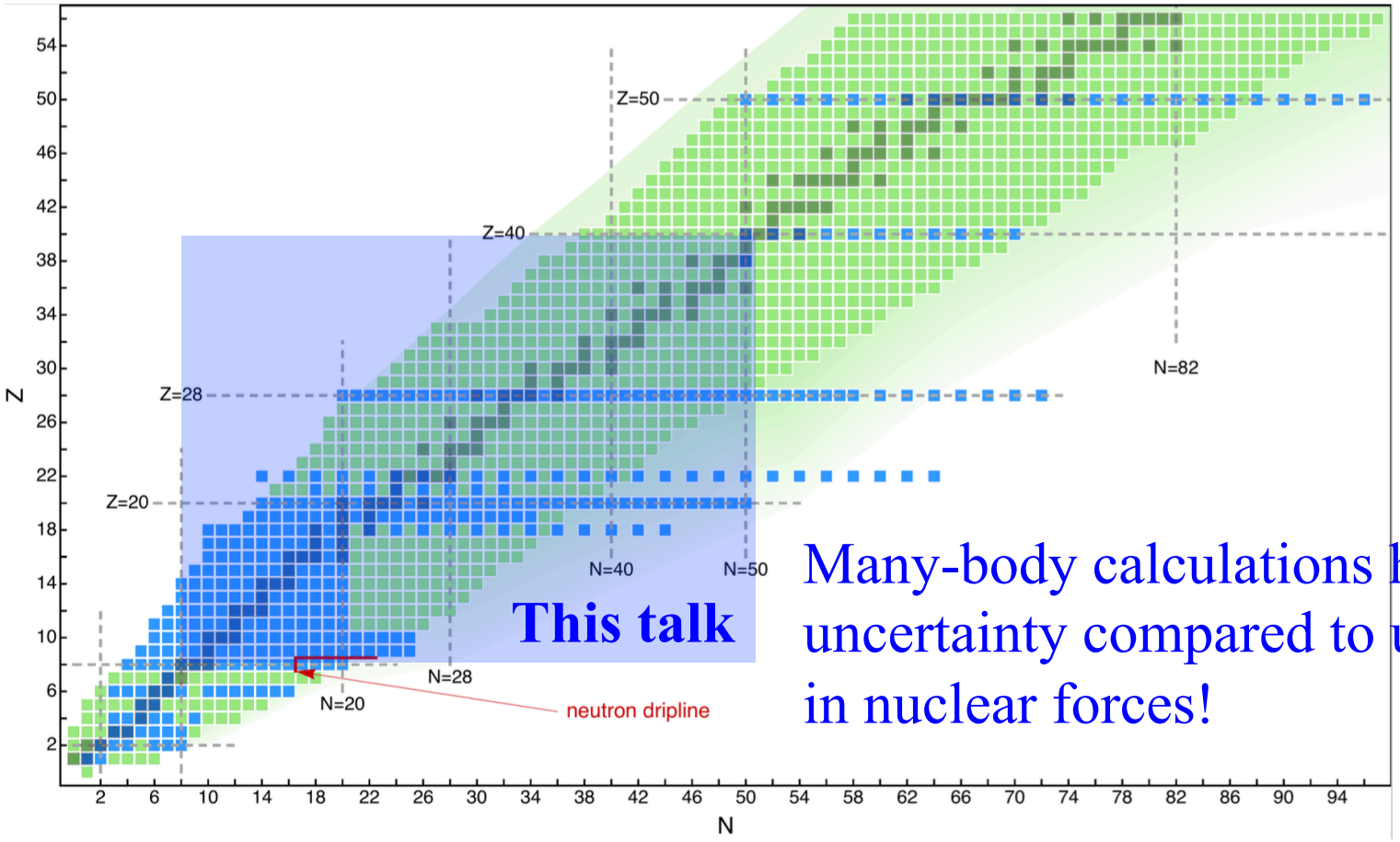






Many-body calculation versus input nuclear forces



Many-body calculations have smaller uncertainty compared to uncertainties in nuclear forces!

Important for medium-mass nuclei:

Consider nuclear forces with good (nuclear matter) saturation properties

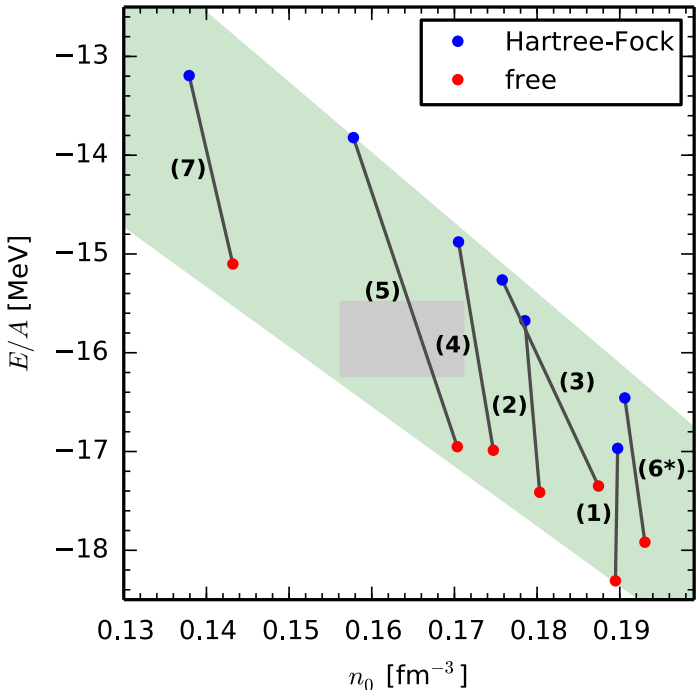
N^2LO_{sat} fit to selected nuclei up to A=24

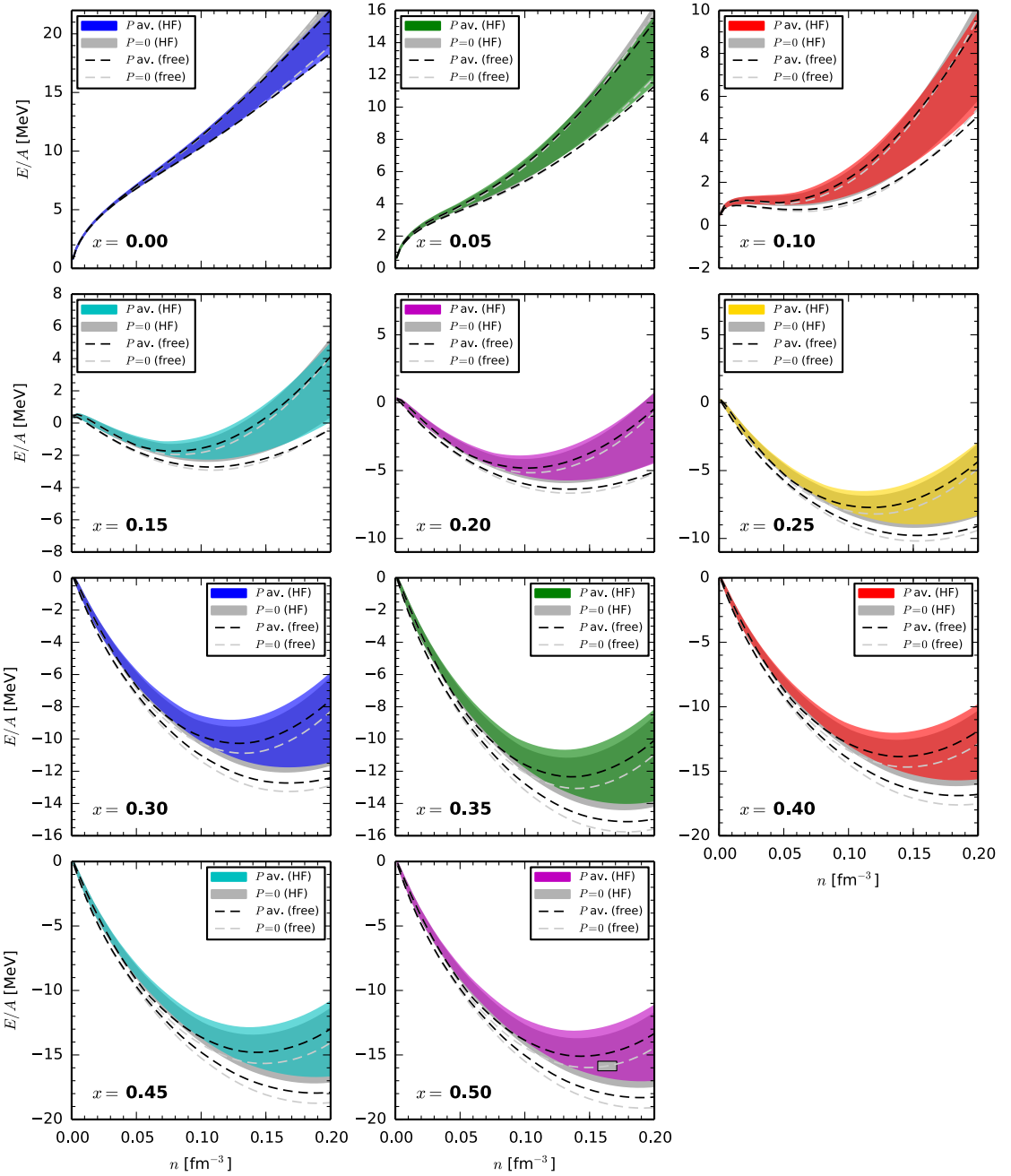
"Magnificent Seven": NN evolved + 3N fit to ^{3}H, ^{4}He

Nuclear forces and nuclear matter

asymmetric matter
with improved treatment
of 3N forces

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





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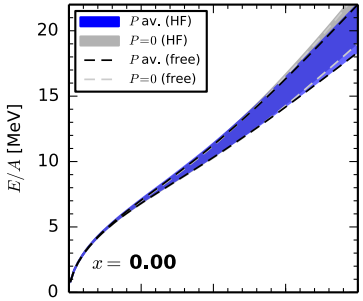
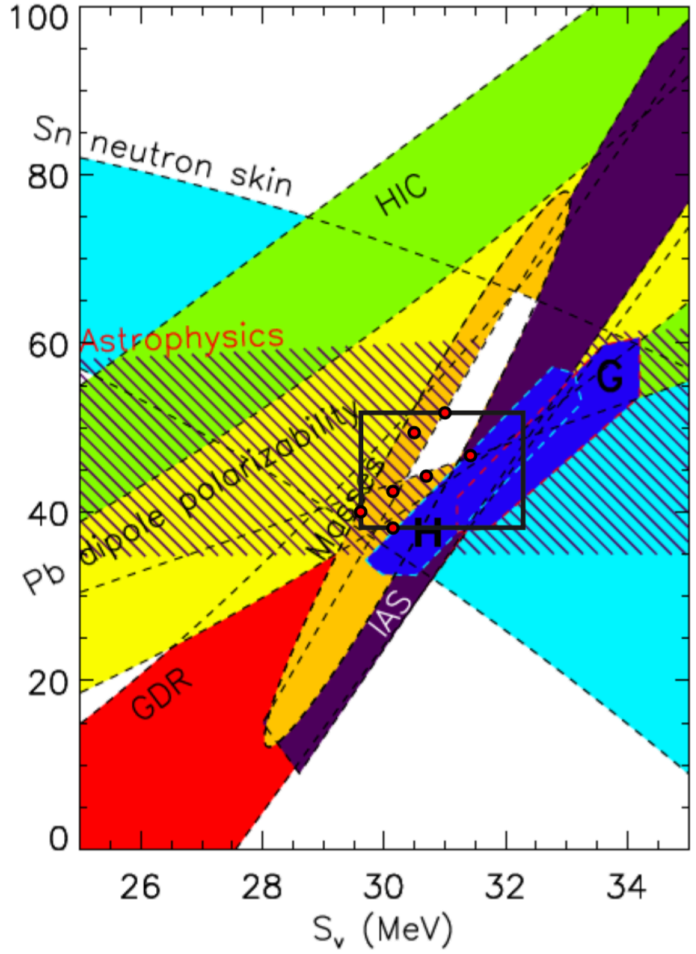
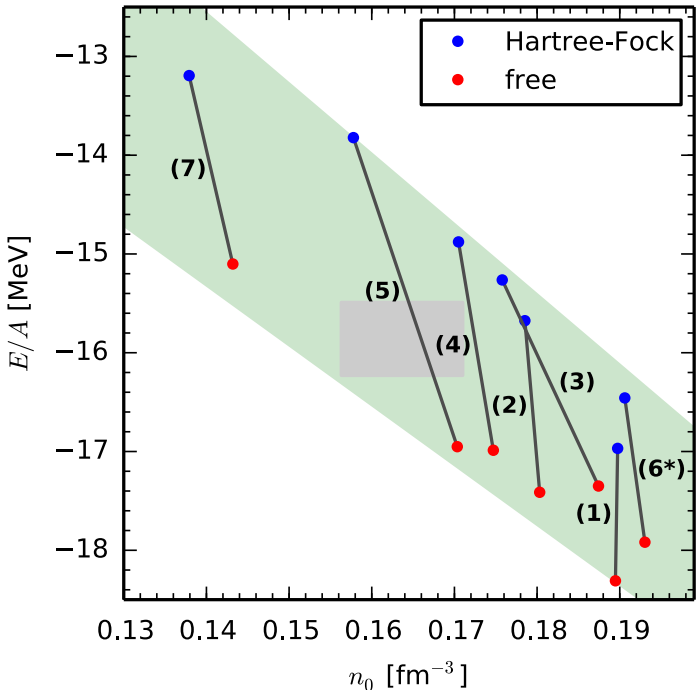
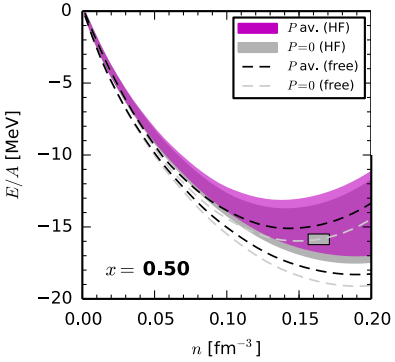








Neutron skin of ^{48}Ca

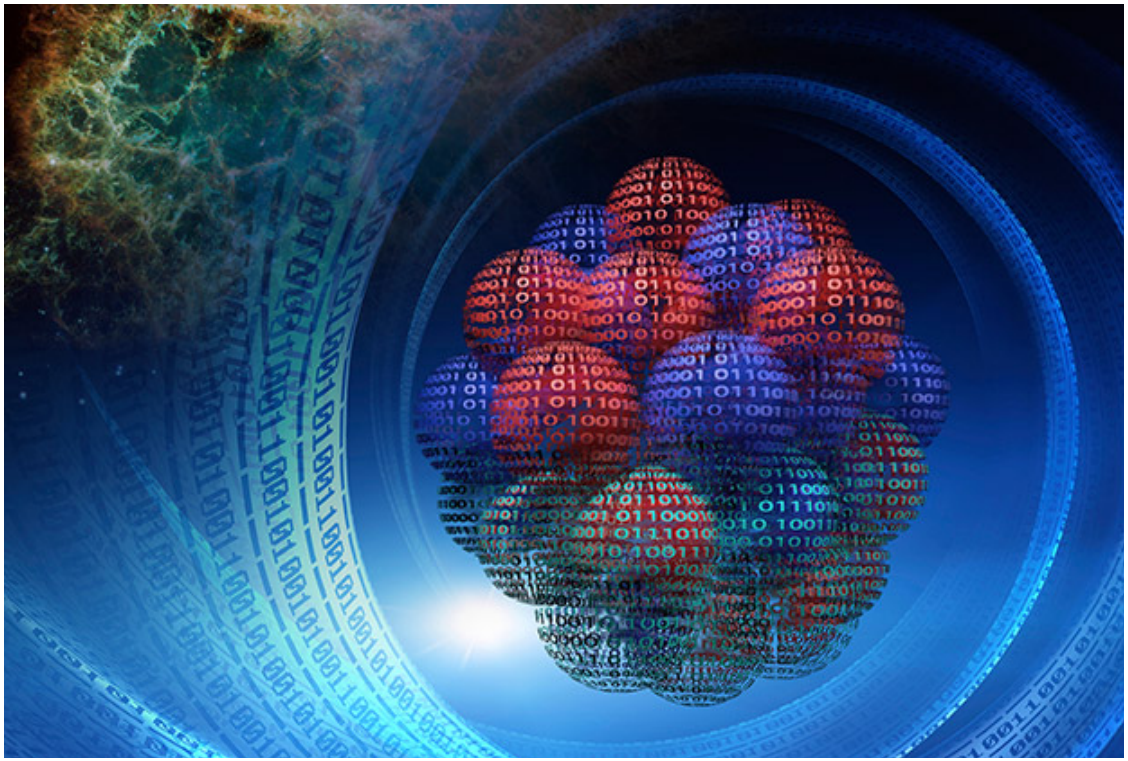
nature physics

ARTICLES

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

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

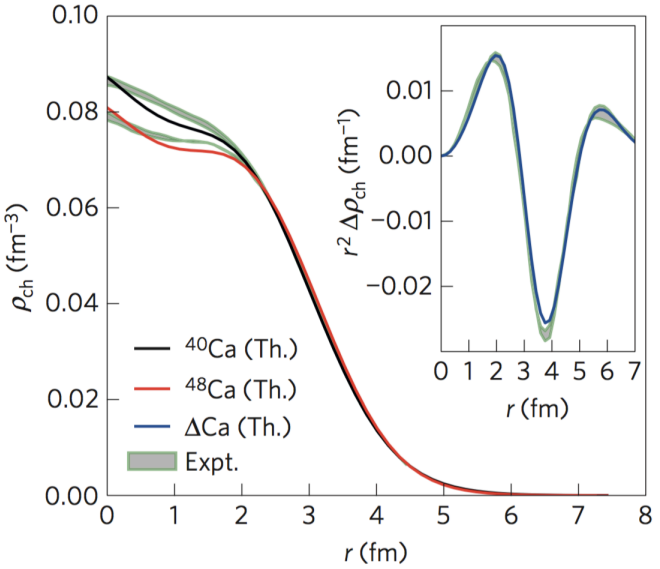
G. Hagen[1,2*], A. Ekström[1,2], C. Forssén[1,2,3], G. R. Jansen[1,2], W. Nazarewicz[1,4,5], T. Papenbrock[1,2], K. A. Wendt[1,2], S. Bacca[6,7], N. Barnea[8], B. Carlsson[3], C. Drischler[9,10], K. Hebeler[9,10], M. Hjorth-Jensen[4,11], M. Miorelli[6,12], G. Orlandini[13,14], A. Schwenk[9,10] and J. Simonis[9,10]

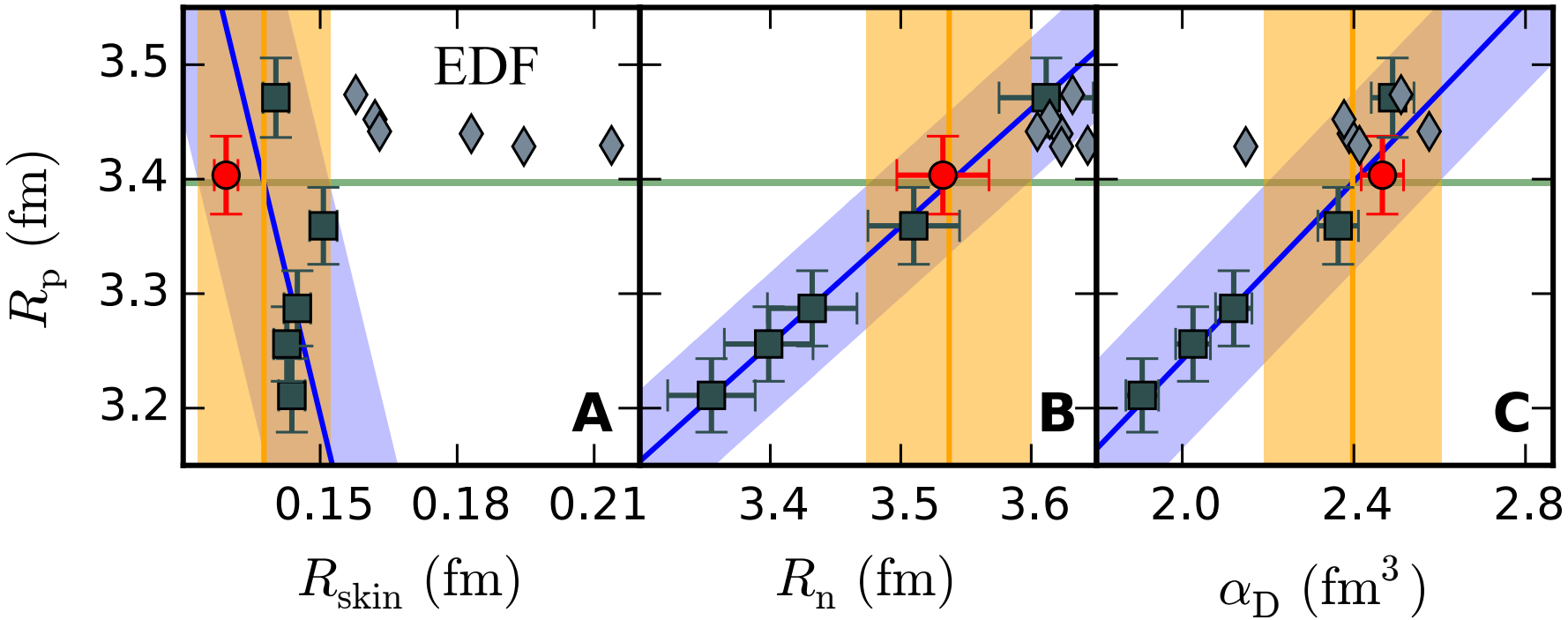


Neutron and weak-charge distributions of ^{48}Ca

ab initio calculations lead to charge distributions consistent with experiment

predict small neutron skin, dipole polarizability, and weak formfactor





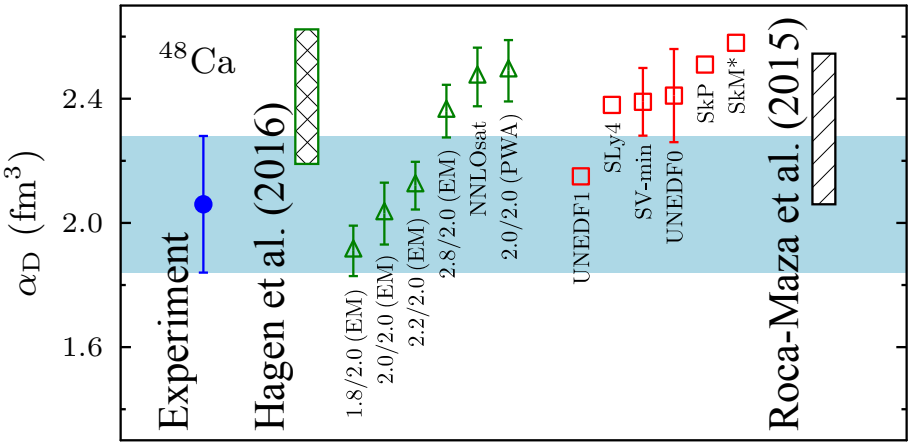
Dipole polarizability of ^{48}Ca

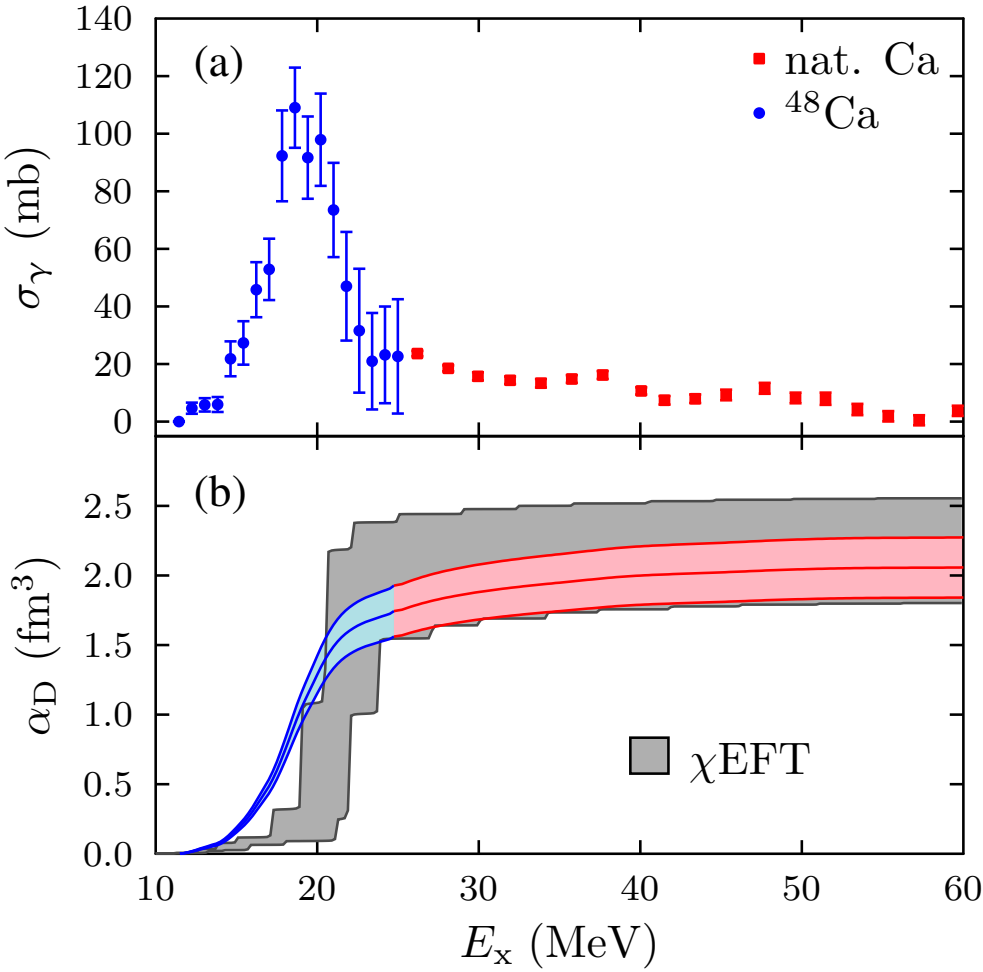
from photo-absorption cross section, measured at Osaka up to 25 MeV
Birkhan, von Neumann-Cosel, Richter, Tamii et al.

very similar to ^{40}Ca except for shift of giant dipole resonance

good agreement with
chiral EFT predictions
Miorelli, Bacca, Hagen et al.

theory comparison gives
$R_{skin} = 0.14\text{-}0.20$ fm





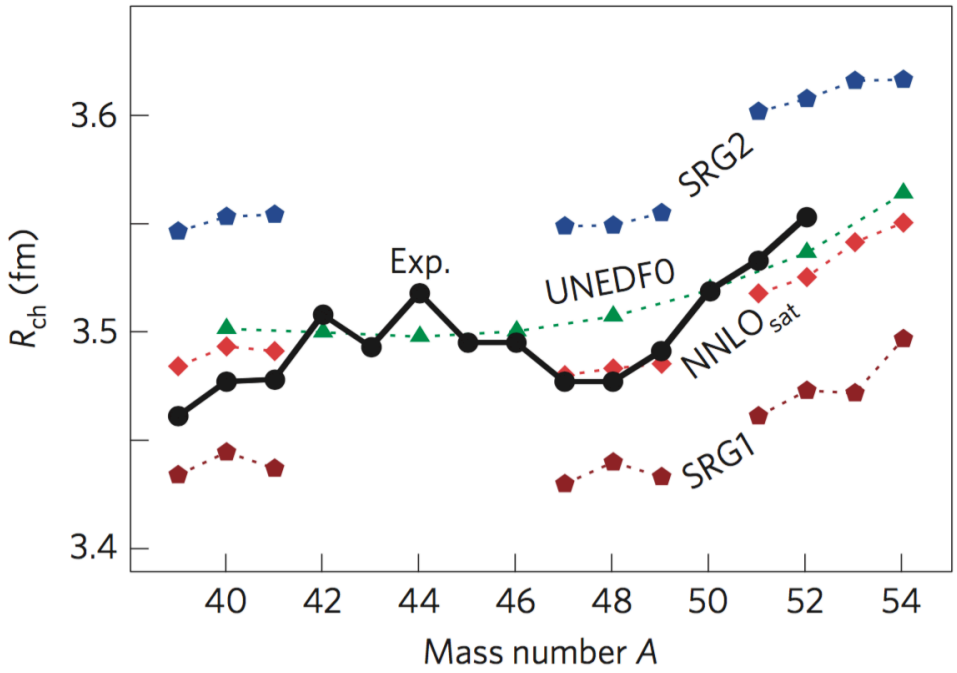
nature physics

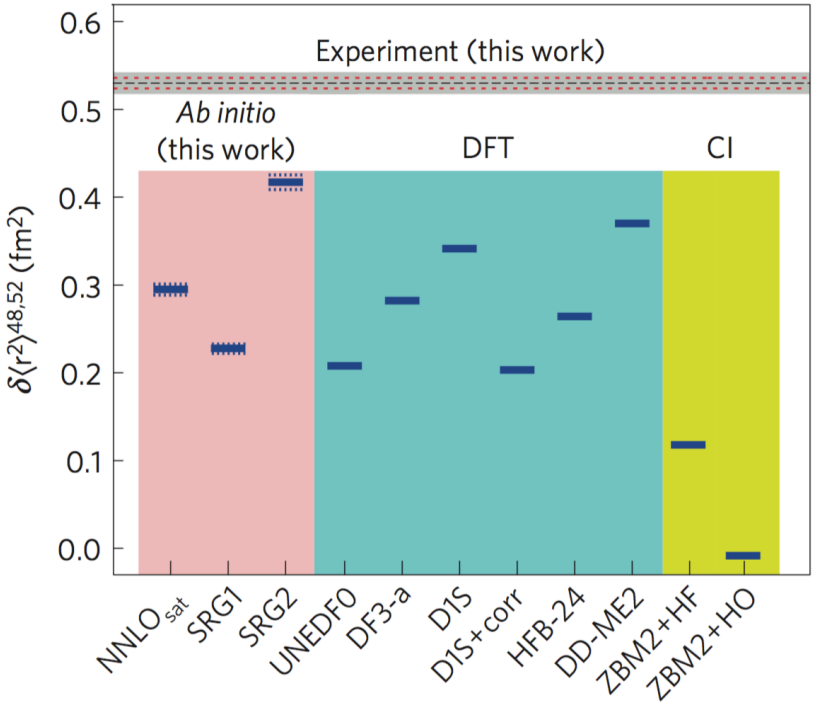
ARTICLES

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

Unexpectedly large charge radii of neutron-rich calcium isotopes

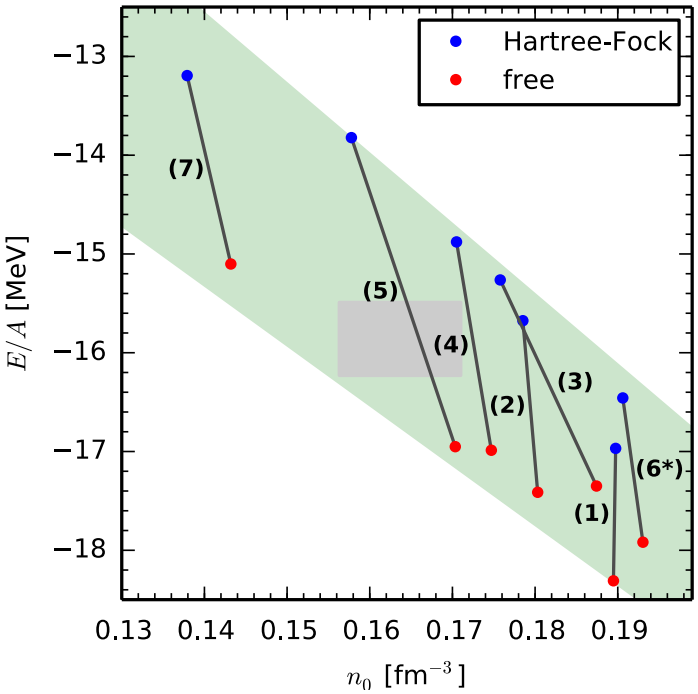
R. F. Garcia Ruiz[1*], M. L. Bissell[1,2], K. Blaum[3], A. Ekström[4,5], N. Frömmgen[6], G. Hagen[4], M. Hammen[6], K. Hebeler[7,8], J. D. Holt[9], G. R. Jansen[4,5], M. Kowalska[10], K. Kreim[3], W. Nazarewicz[4,11,12], R. Neugart[3,6], G. Neyens[1], W. Nörtershäuser[6,7], T. Papenbrock[4,5], J. Papuga[1],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

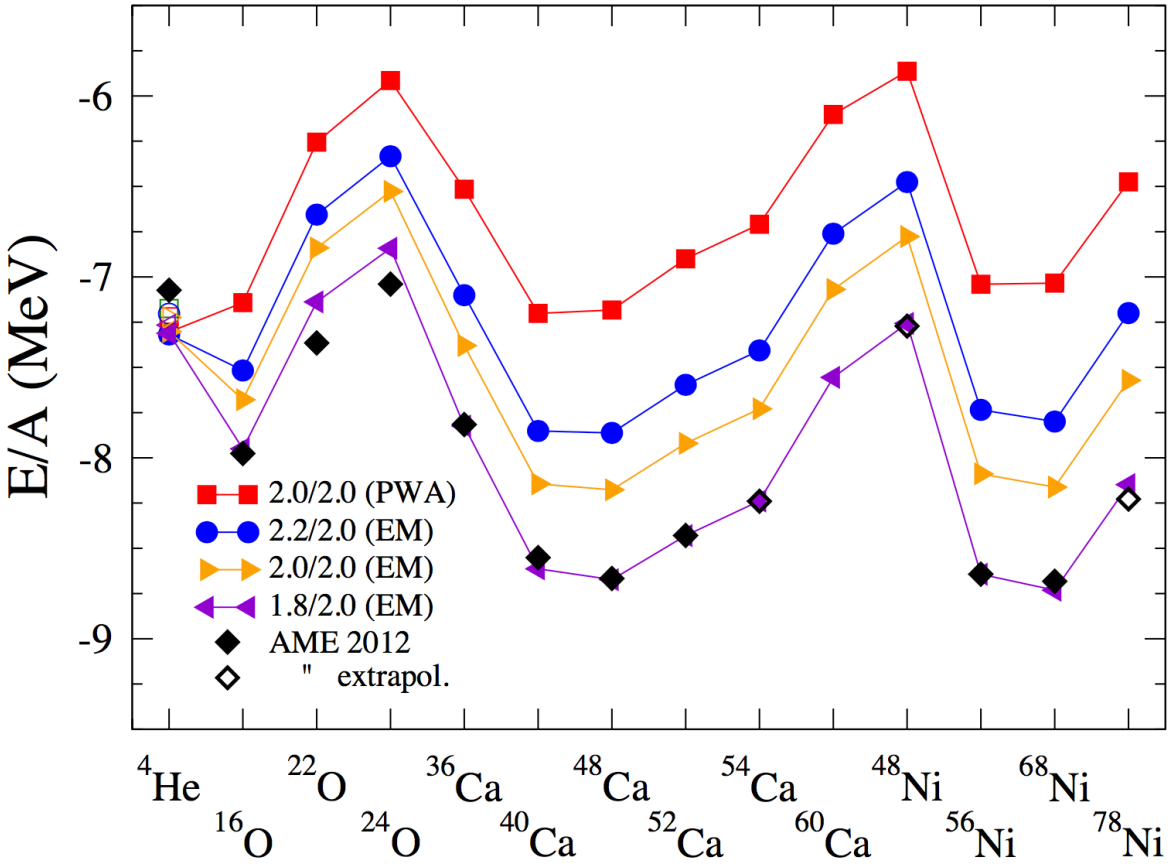




Importance of saturation for nuclear forces Simonis et al., in prep.

IM-SRG calculations of closed shell nuclei follow nuclear matter saturation systematics!





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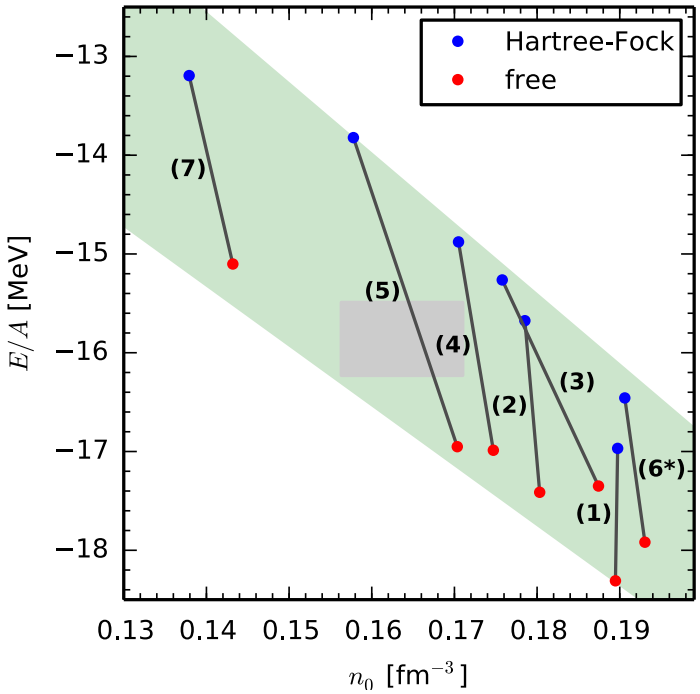
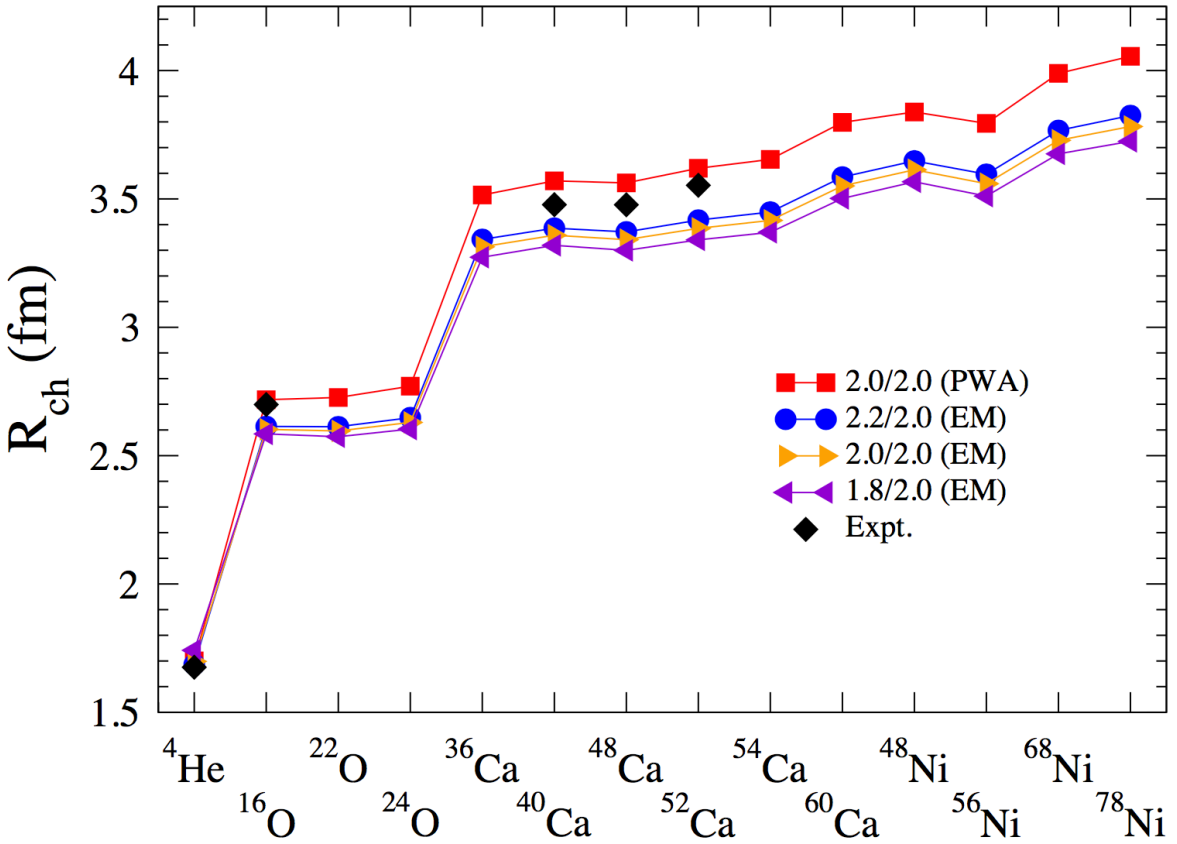
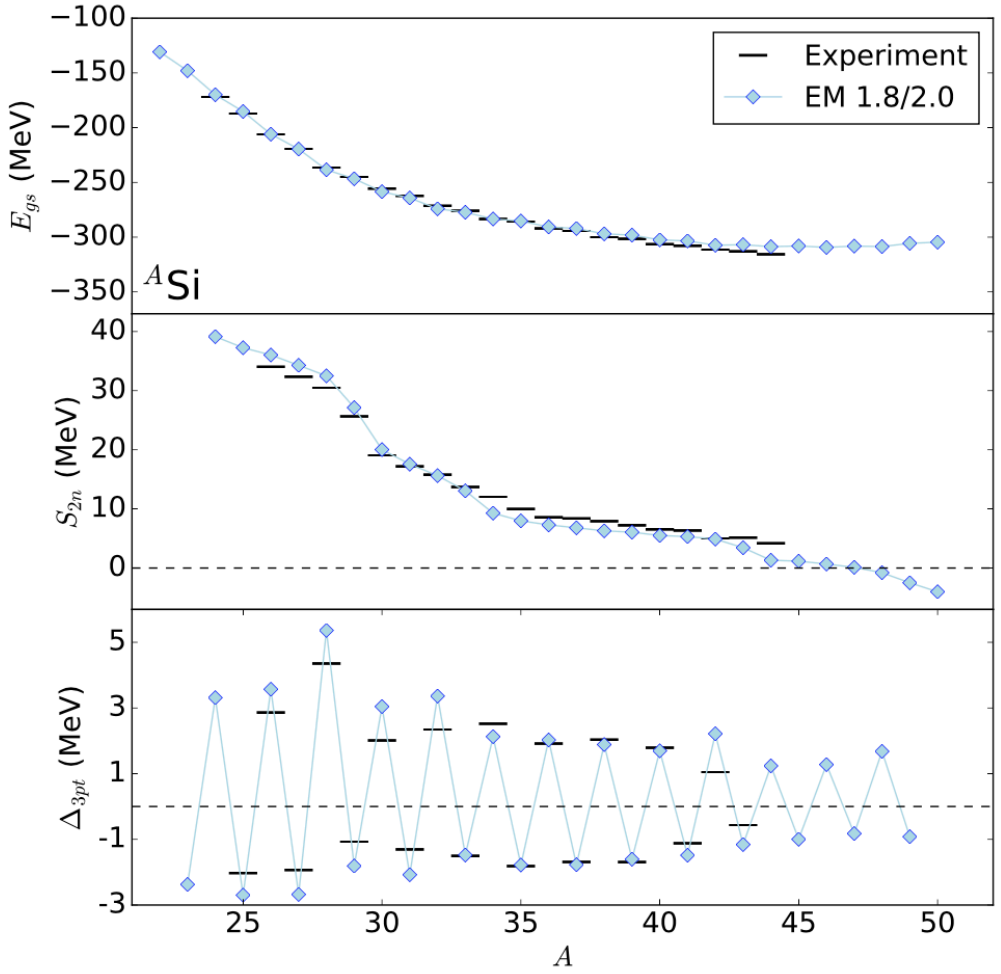
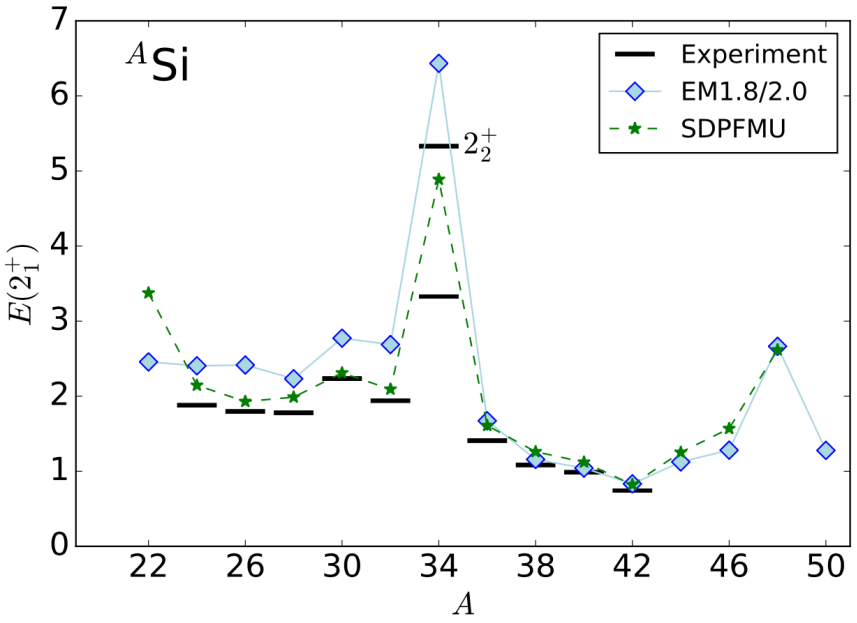


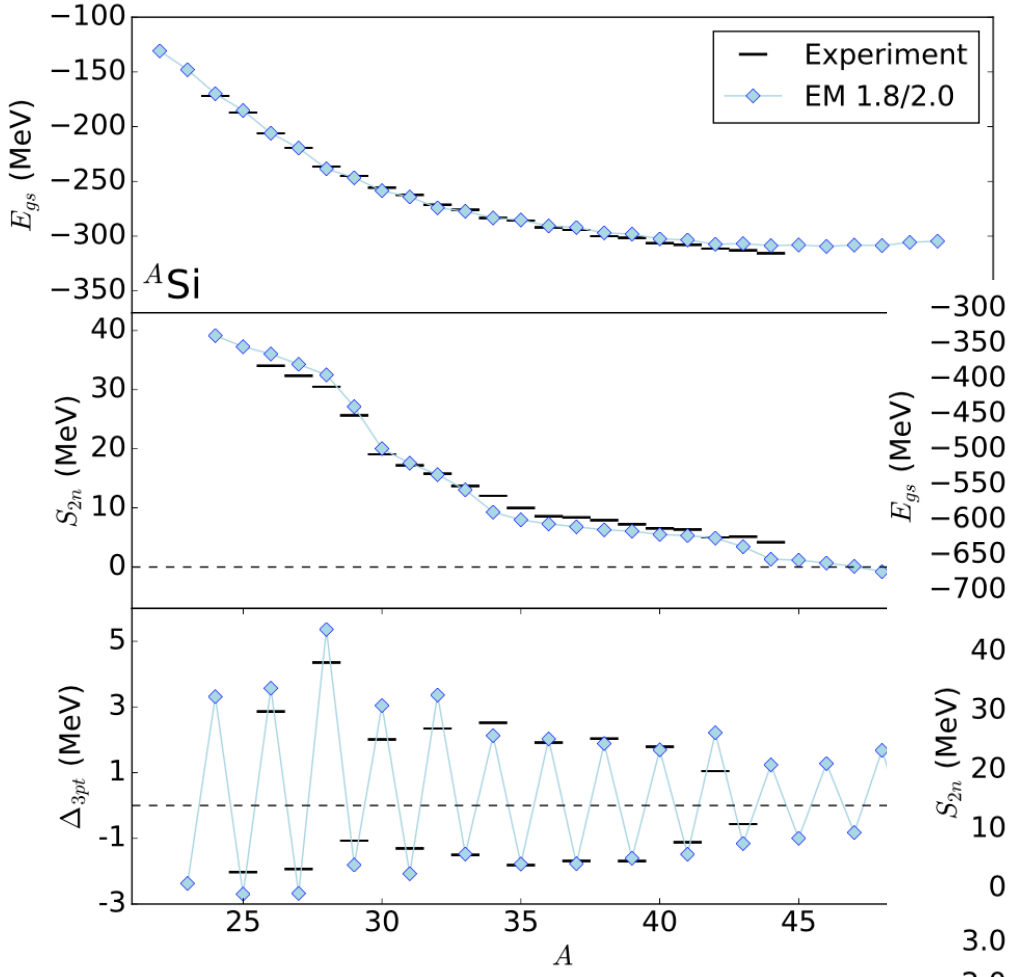


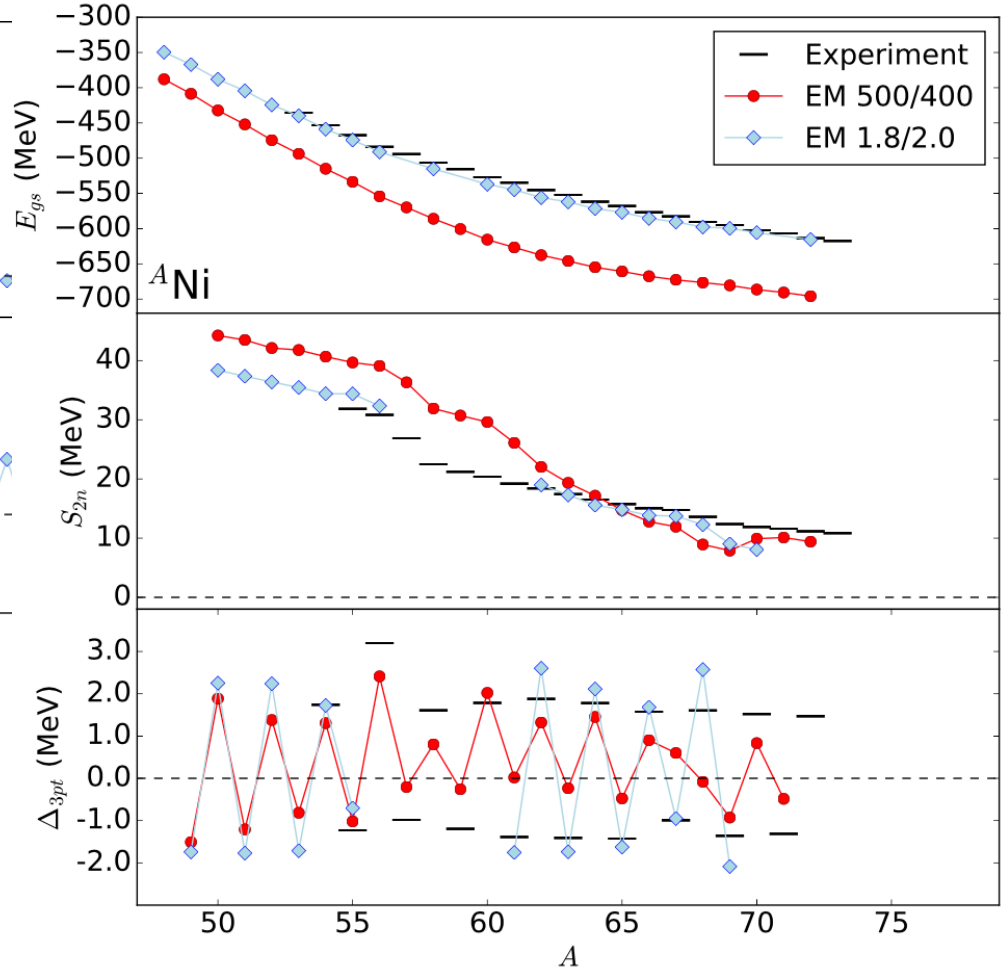
Great progress from medium to heavy nuclei Simonis et al., in prep.





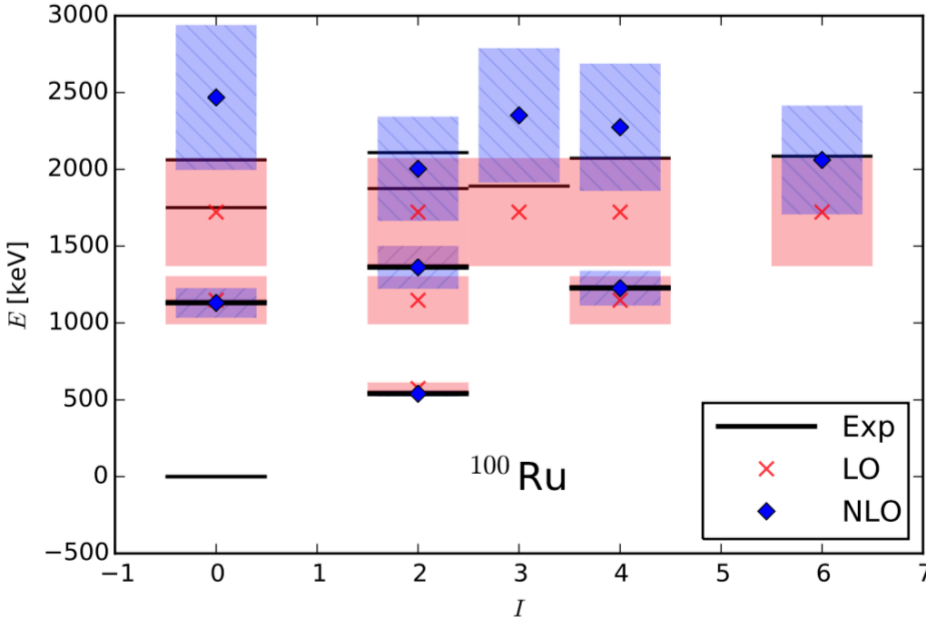
Great progress from medium to heavy nuclei Simonis et al., in prep.

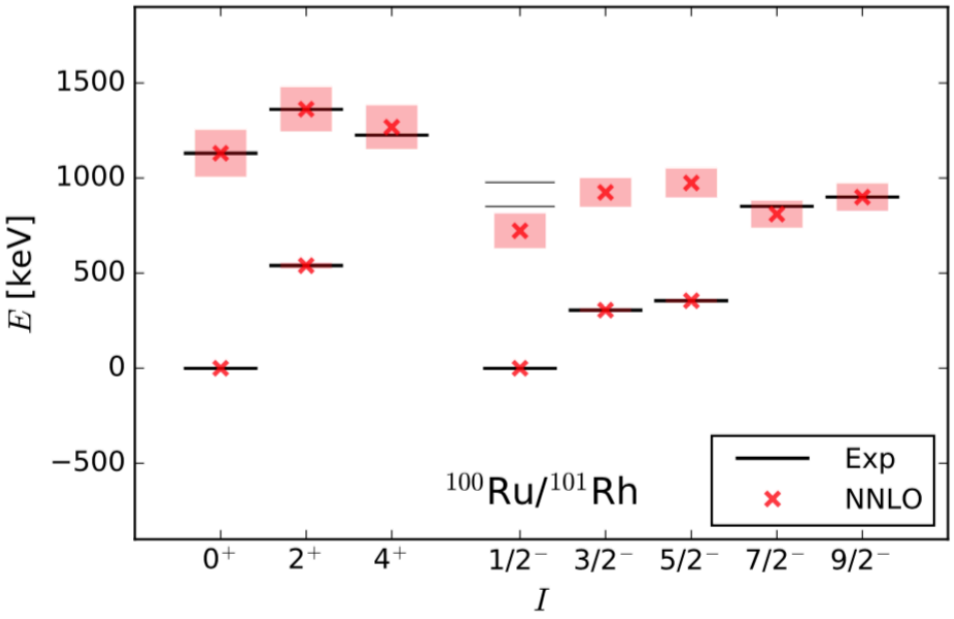




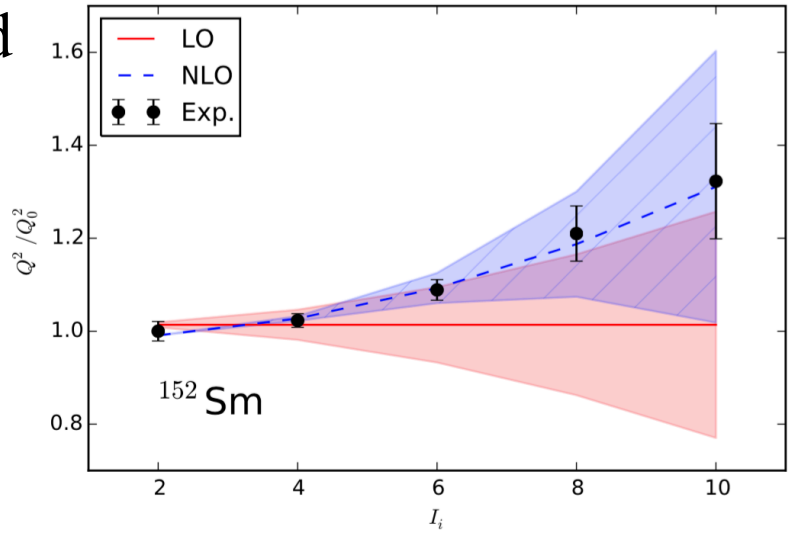
EFT for deformed nuclei Papenbrock, **Coello Perez**, Weidenmüller

EFT for vibrational excitations for even-even and even-odd nuclei



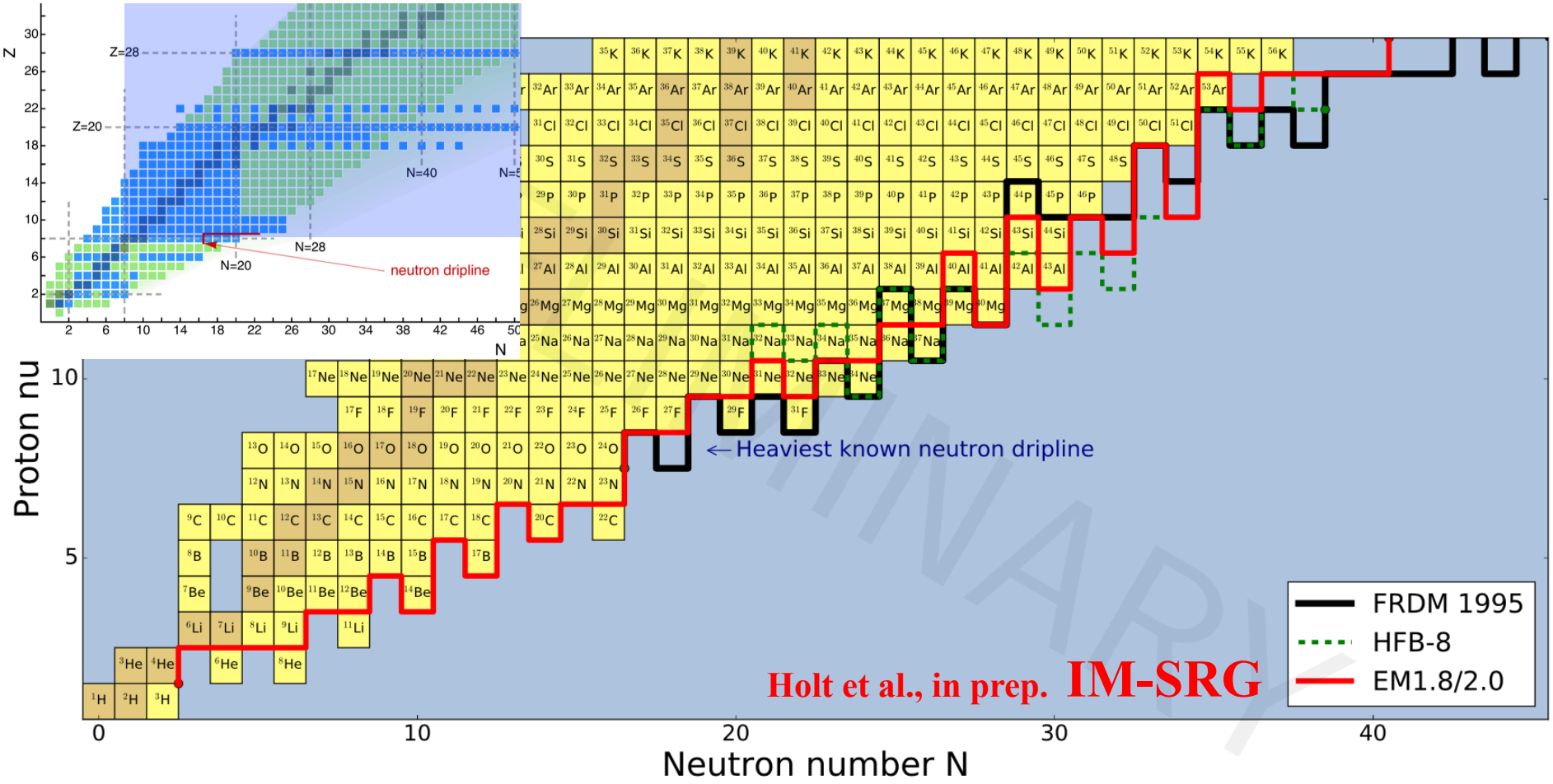


Quadrupole transitions in ground band



Exciting era in nuclear physics

EFTs of the strong interaction plus powerful many-body approaches



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