Three-Nucleon Forces and Exotic Oxygen and Calcium Isotopes

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Drip Lines and Magic Numbers: The Nuclear Landscape Toward the Extremes

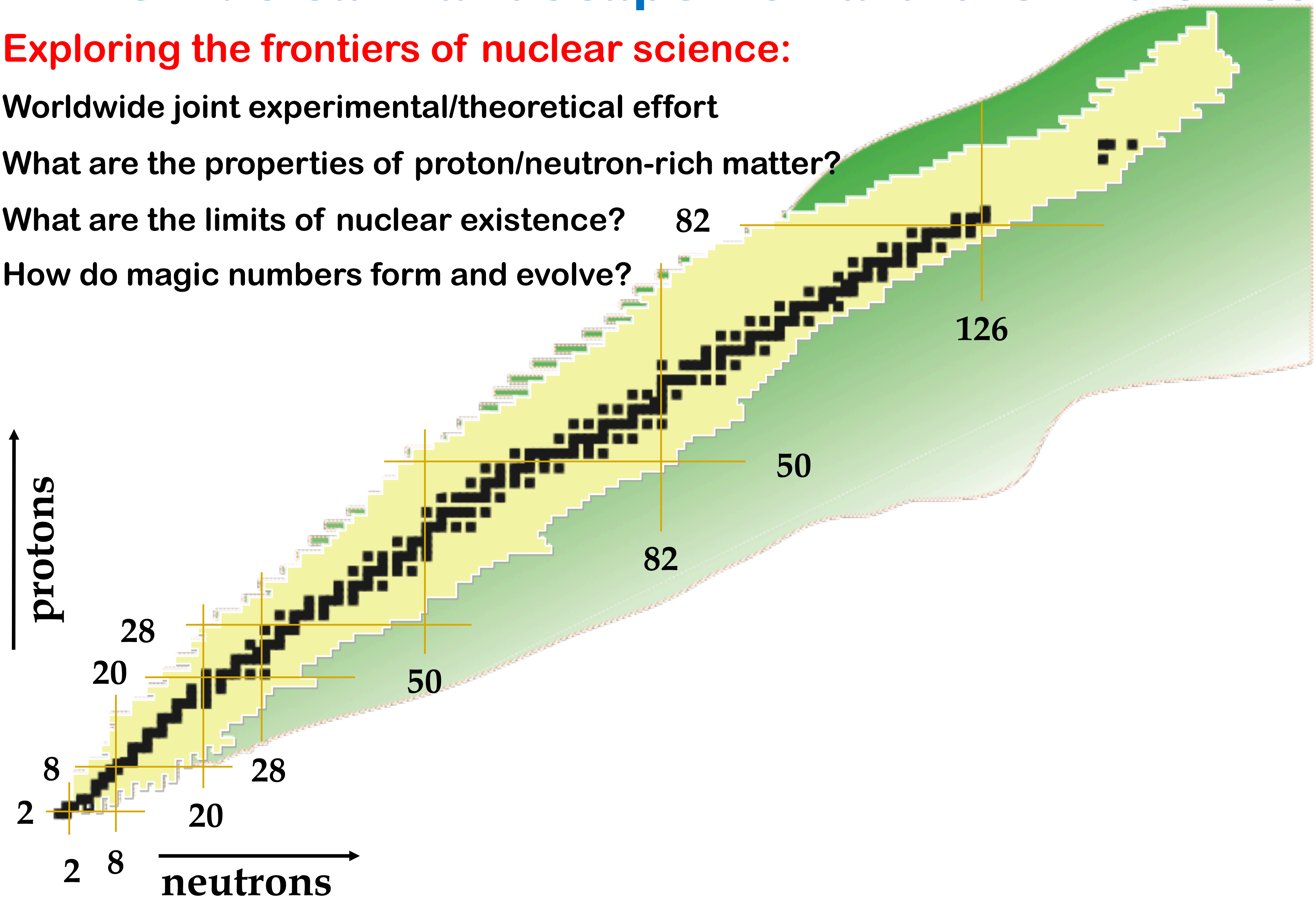
Exploring the frontiers of nuclear science:

Worldwide joint experimental/theoretical effort

What are the properties of proton/neutron-rich matter?

What are the limits of nuclear existence?

How do magic numbers form and evolve?



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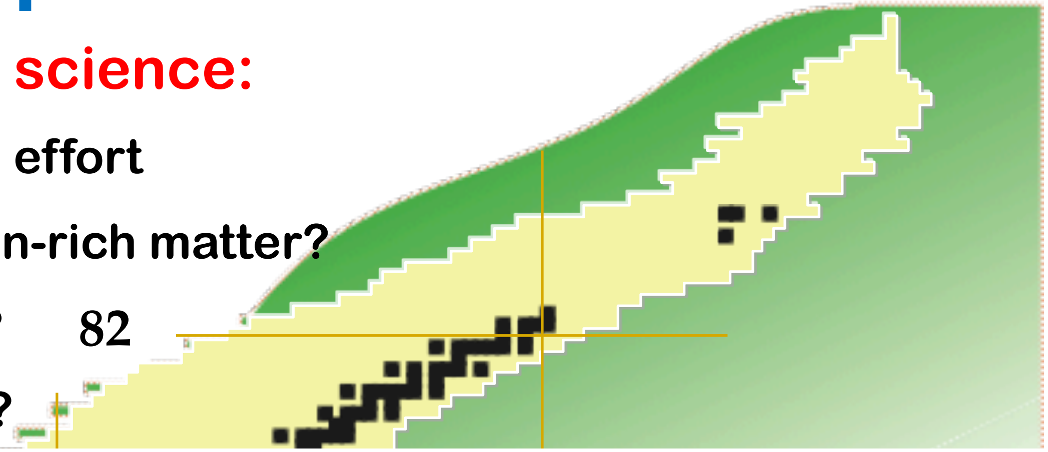

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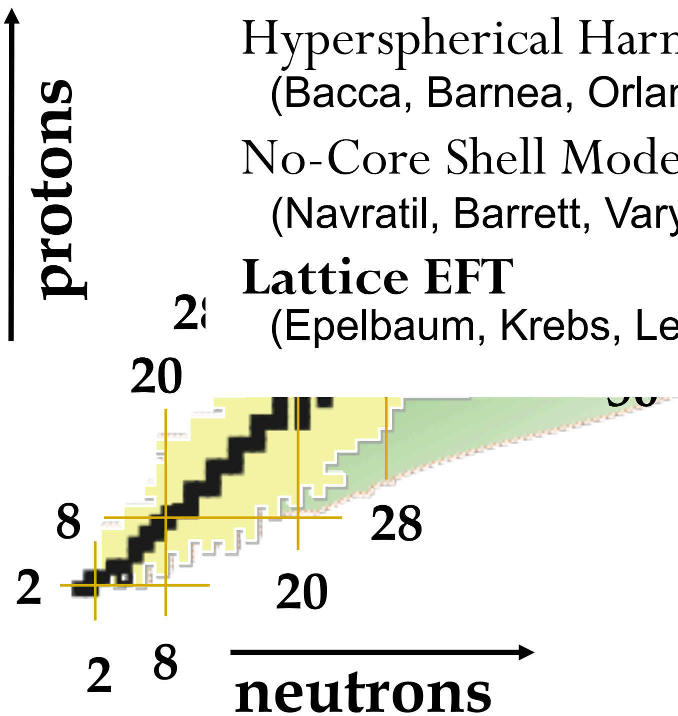
Advances in many-body methods

Green's Function Monte Carlo
(Gezerlis, Carlson, Peiper, Wiringa)

Hyperspherical Harmonics
(Bacca, Barnea, Orlandini)

No-Core Shell Model
(Navratil, Barrett, Vary, Roth)

Lattice EFT
(Epelbaum, Krebs, Lee, Meissner)



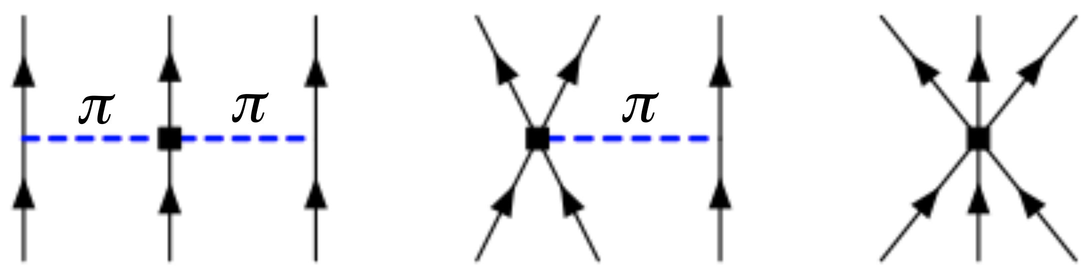
Coupled Cluster
(Hagen, Papenbrock, Dean, Roth)

In-Medium SRG
(Bogner, Hergert, JDH, Schwenk)

Many-Body Perturbation Theory
(JDH, Hjorth-Jensen, Schwenk)

Self-Consistent Green's Function
(Barbieri, Soma, Duguet)

3N forces essential for exotic nuclei



Drip Lines and Magic Numbers: 3N Forces in Medium-Mass Nuclei

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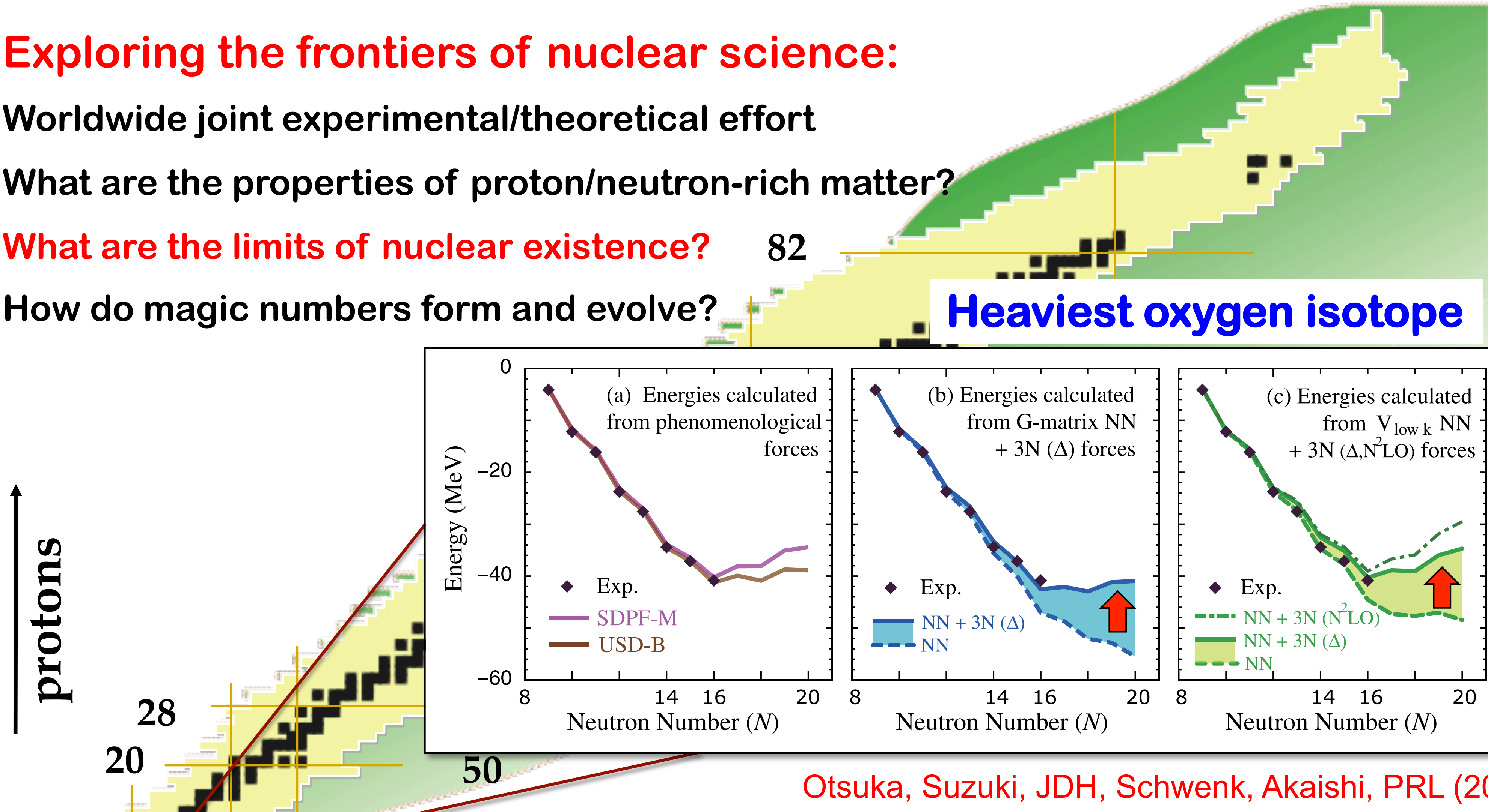
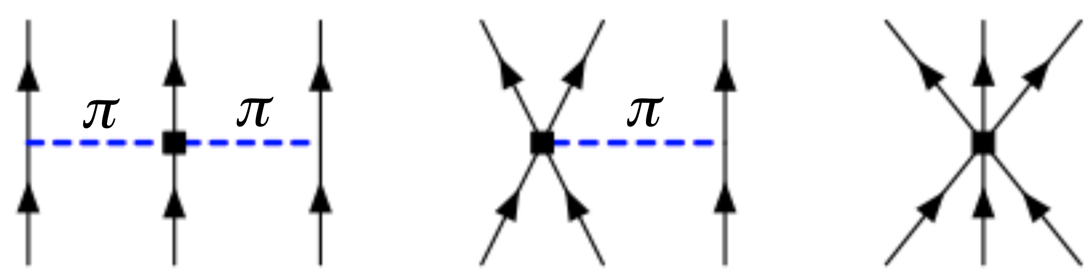
Heaviest oxygen isotope



Otsuka, Suzuki, JDH, Schwenk, Akaishi, PRL (2010)



Drip Lines and Magic Numbers:
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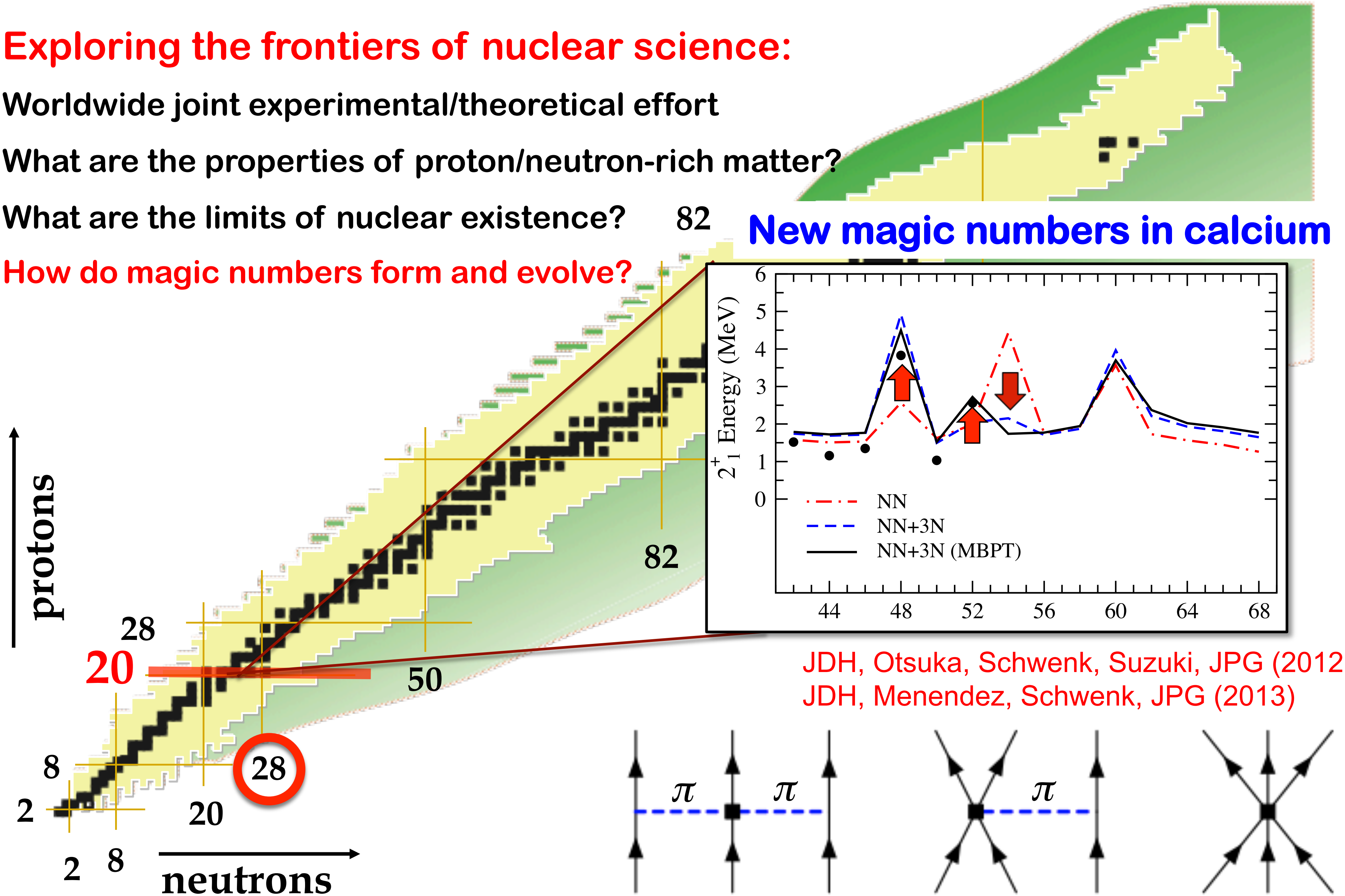
New magic numbers in calcium



JDH, Otsuka, Schwenk, Suzuki, JPG (2012)

JDH, Menendez, Schwenk, JPG (2013)

Oxygen Isotopes

Exploring the frontiers of nuclear science:

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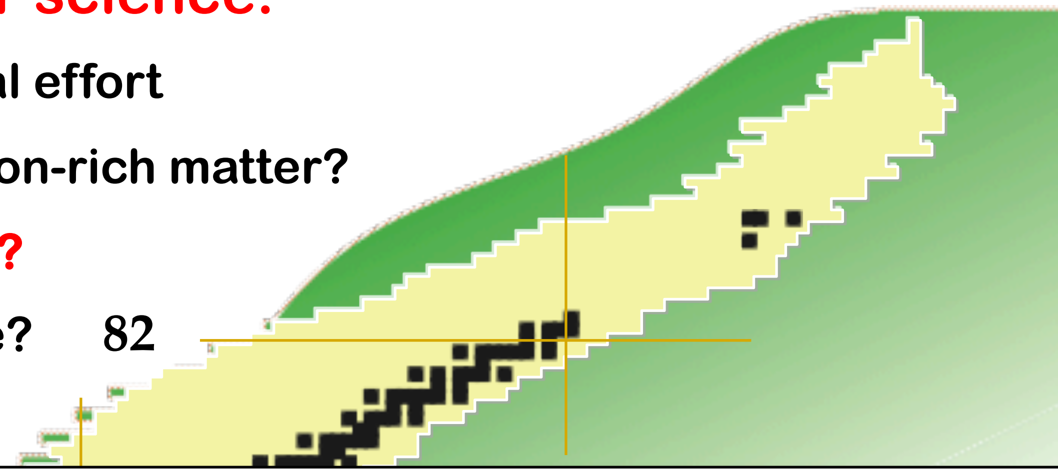
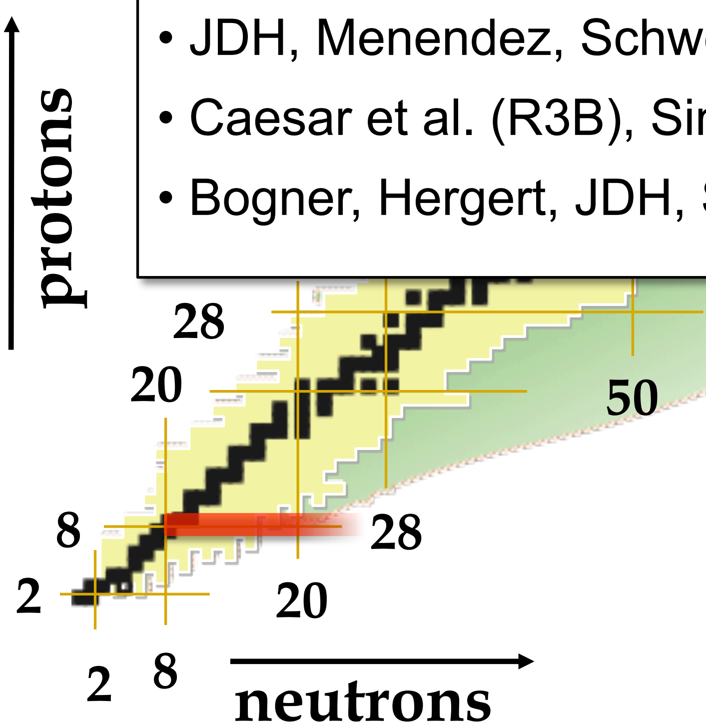


References

- Otsuka, Suzuki, JDH, Schwenk, Akaishi PRL **105**, 032501 (2010)
- JDH, Menendez, Schwenk, EPJA **49**, 39 (2013)
- Caesar et al. (R3B), Simonis, JDH, Menendez, Schwenk PRC **88**, 034313 (2013)
- Bogner, Hergert, JDH, Schwenk et al., PRL, **113**, 142501 (2014)



Key physics problems:

- Location of dripline
- Properties of new closed-shell nuclei $^{22,24}O$
- Physics beyond the neutron dripline

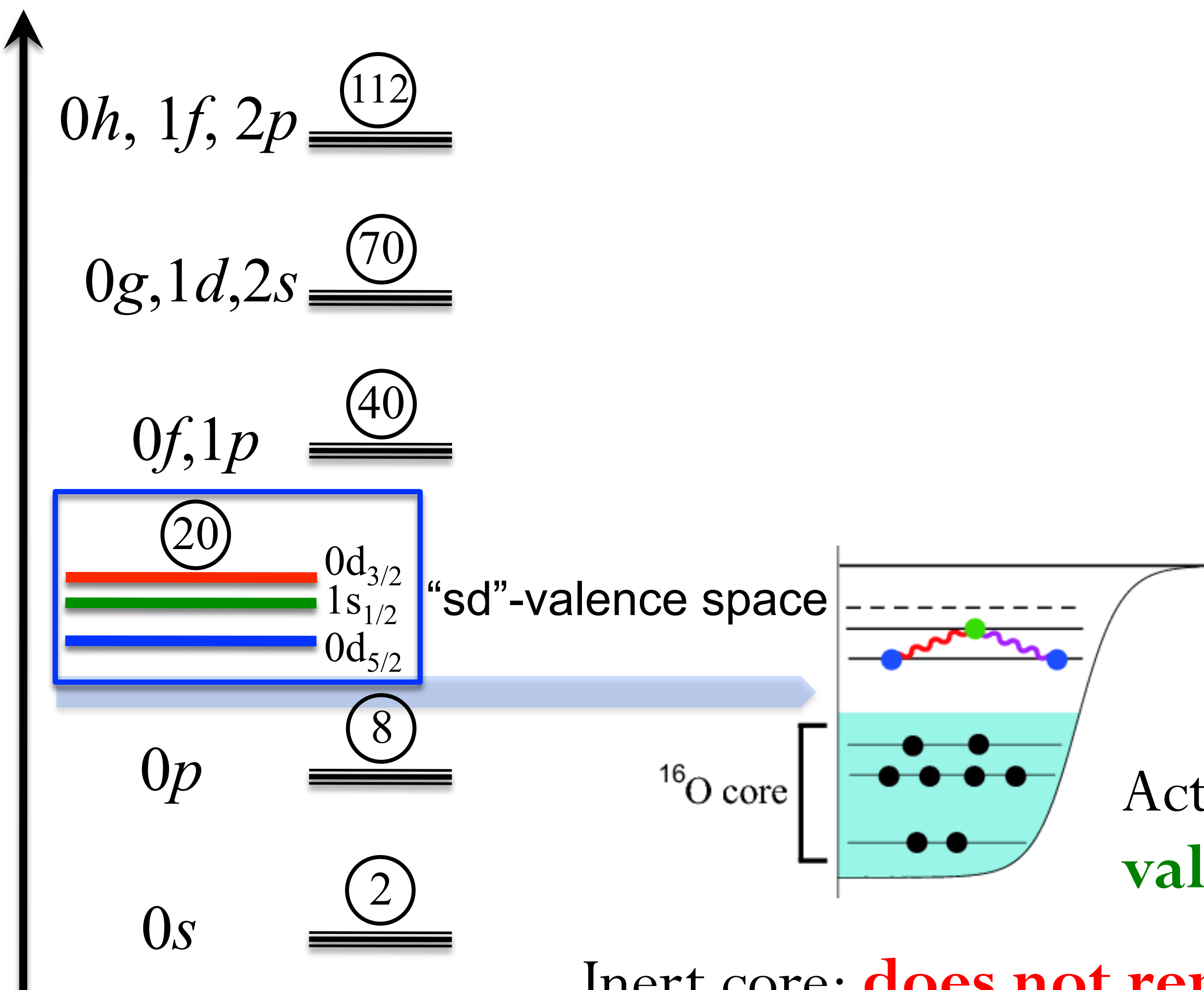
The Nuclear Many-Body Problem

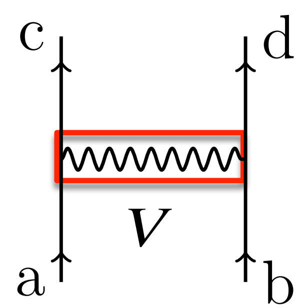
Nuclei understood as many-body system starting from closed shell, add nucleons

Calculate **valence-space** Hamiltonian inputs from nuclear forces

Interaction matrix elements

Single-particle energies (SPEs)





Active nucleons occupy **valence space**

Inert core: **does not reproduce experiment**

The Nuclear Many-Body Problem

Nuclei understood as many-body system starting from closed shell, add nucleons

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Interaction matrix elements

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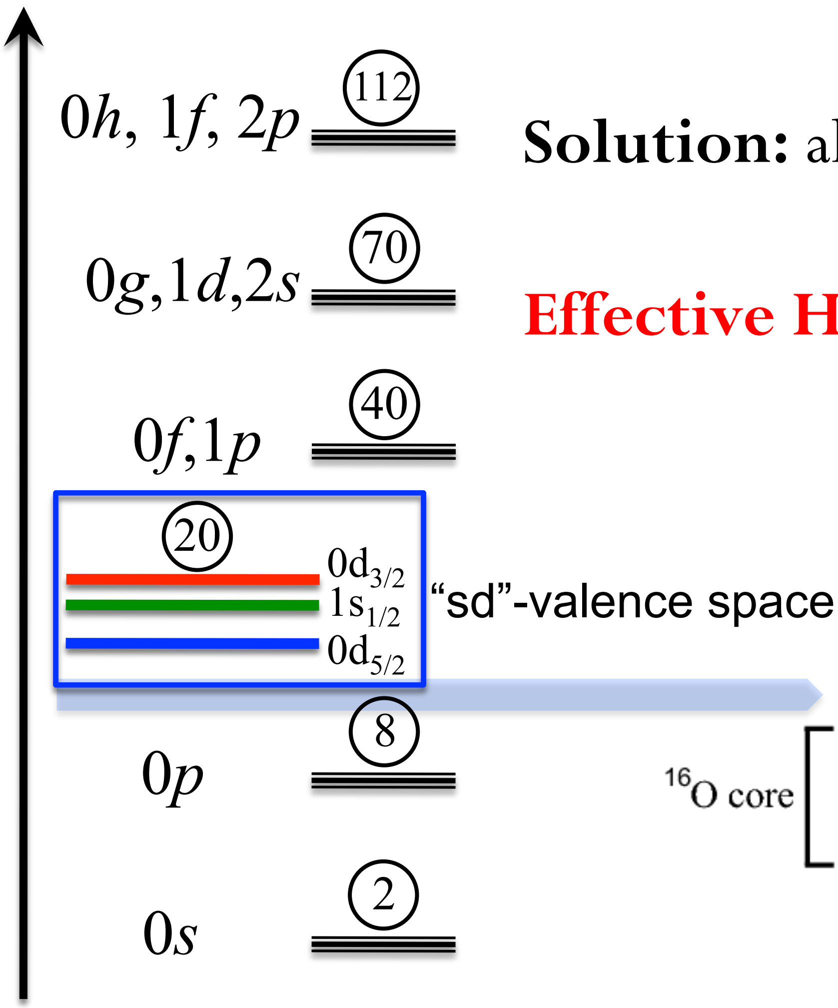
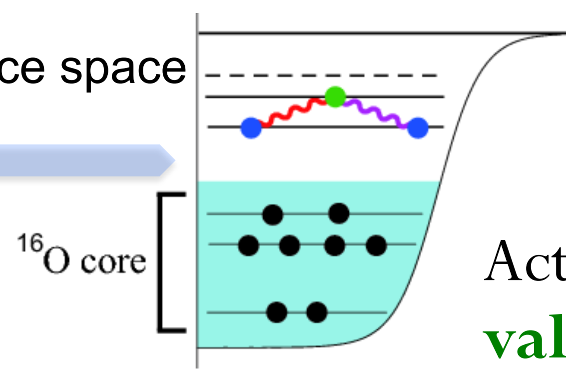
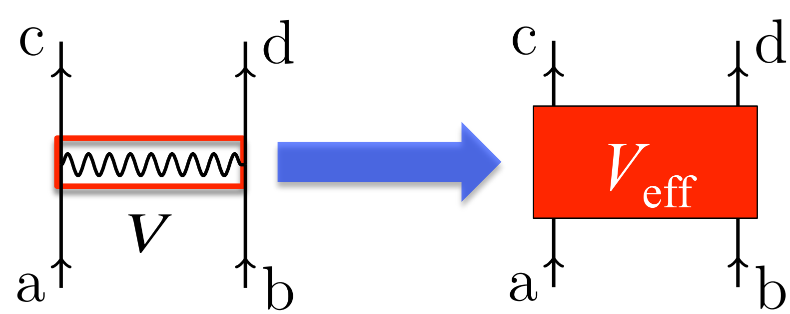


Solution: allow breaking of core

Effective Hamiltonian for valence nucleons





Active nucleons occupy **valence space**

Perturbative Valence-Space Strategy

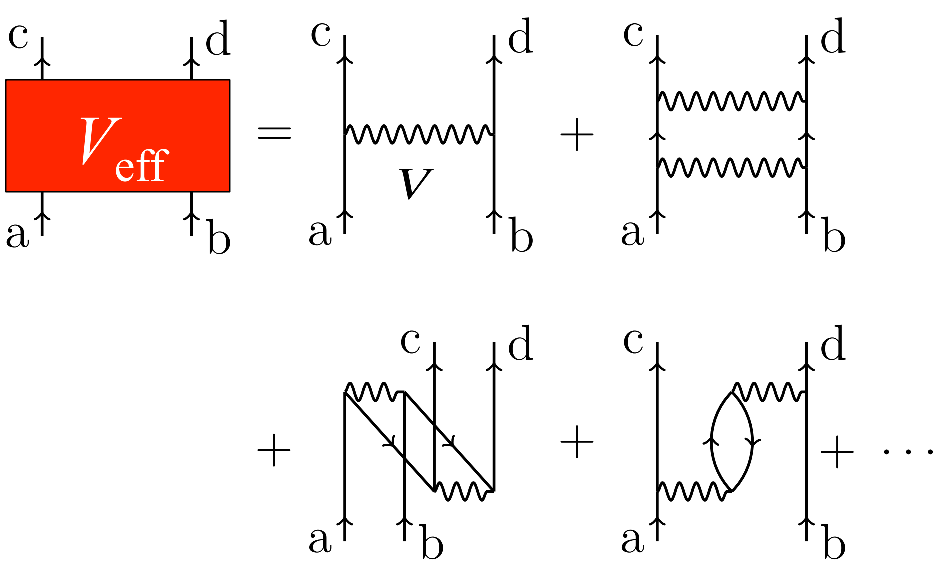
★1) Effective interaction: sum excitations outside valence space to **3rd order**

★2) Single-particle energies calculated self consistently

3) Harmonic-oscillator basis of 13-15 major shells: **converged**

4) NN and 3N forces from chiral EFT – to 3rd-order MBPT

5) Explore extended valence spaces



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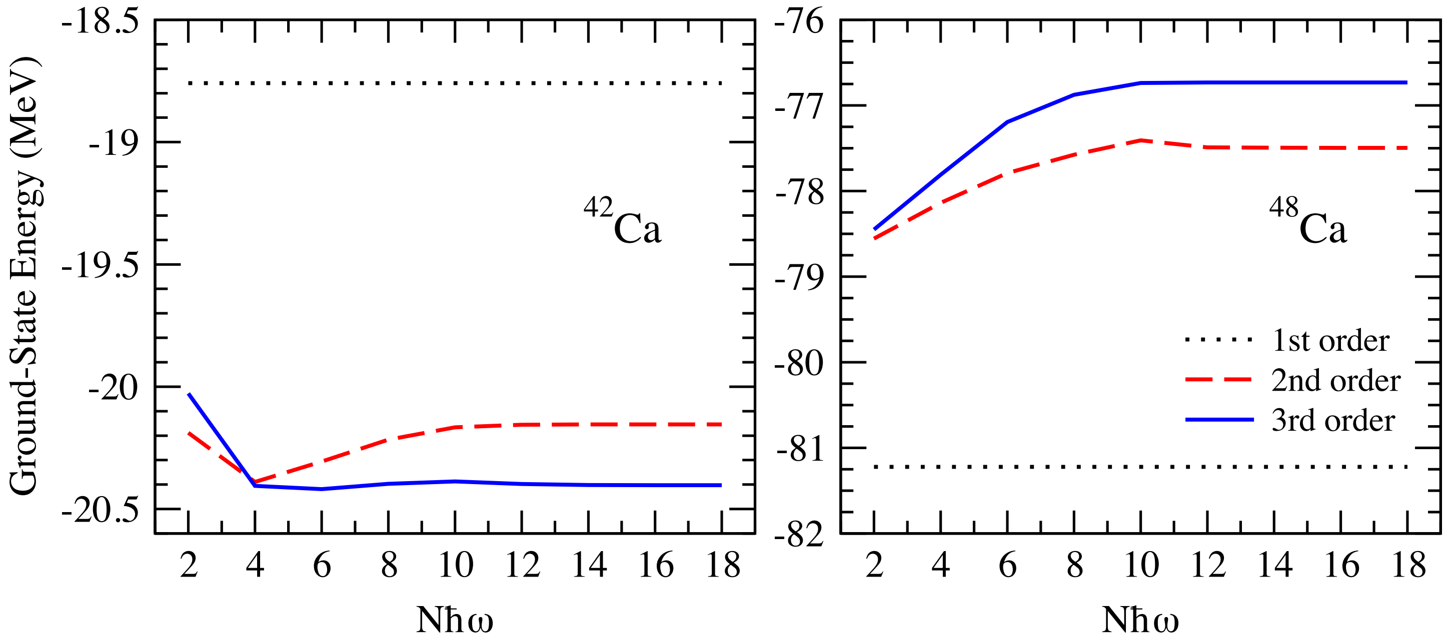

Clear convergence with HO basis size

Promising order-by-order behavior

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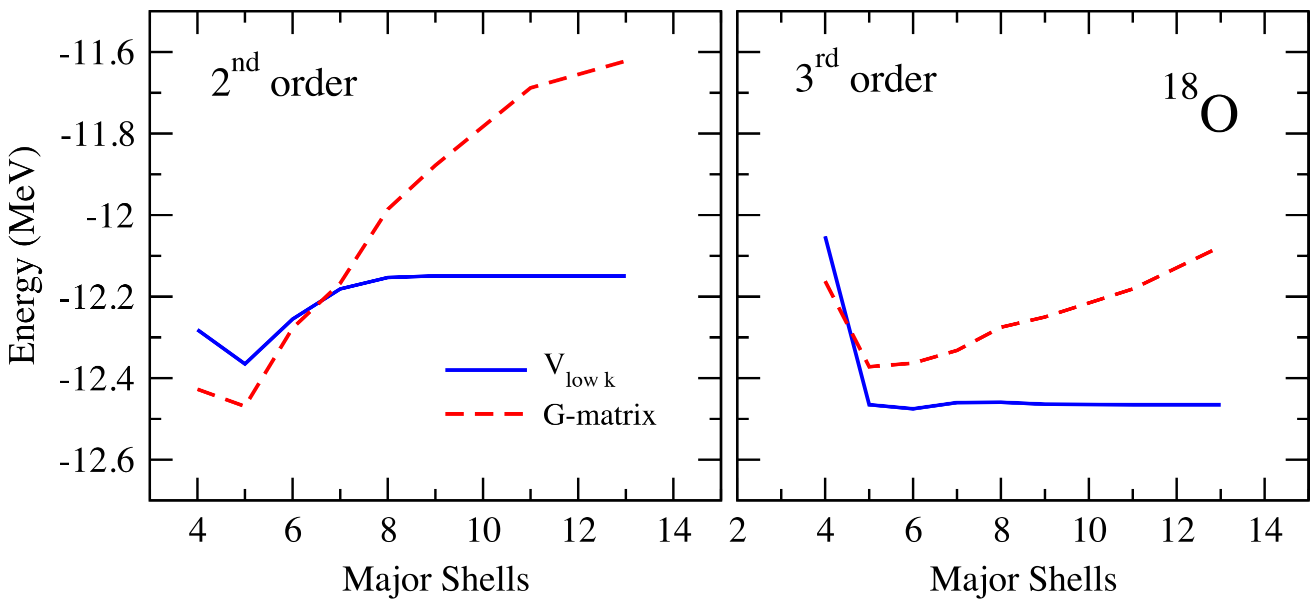
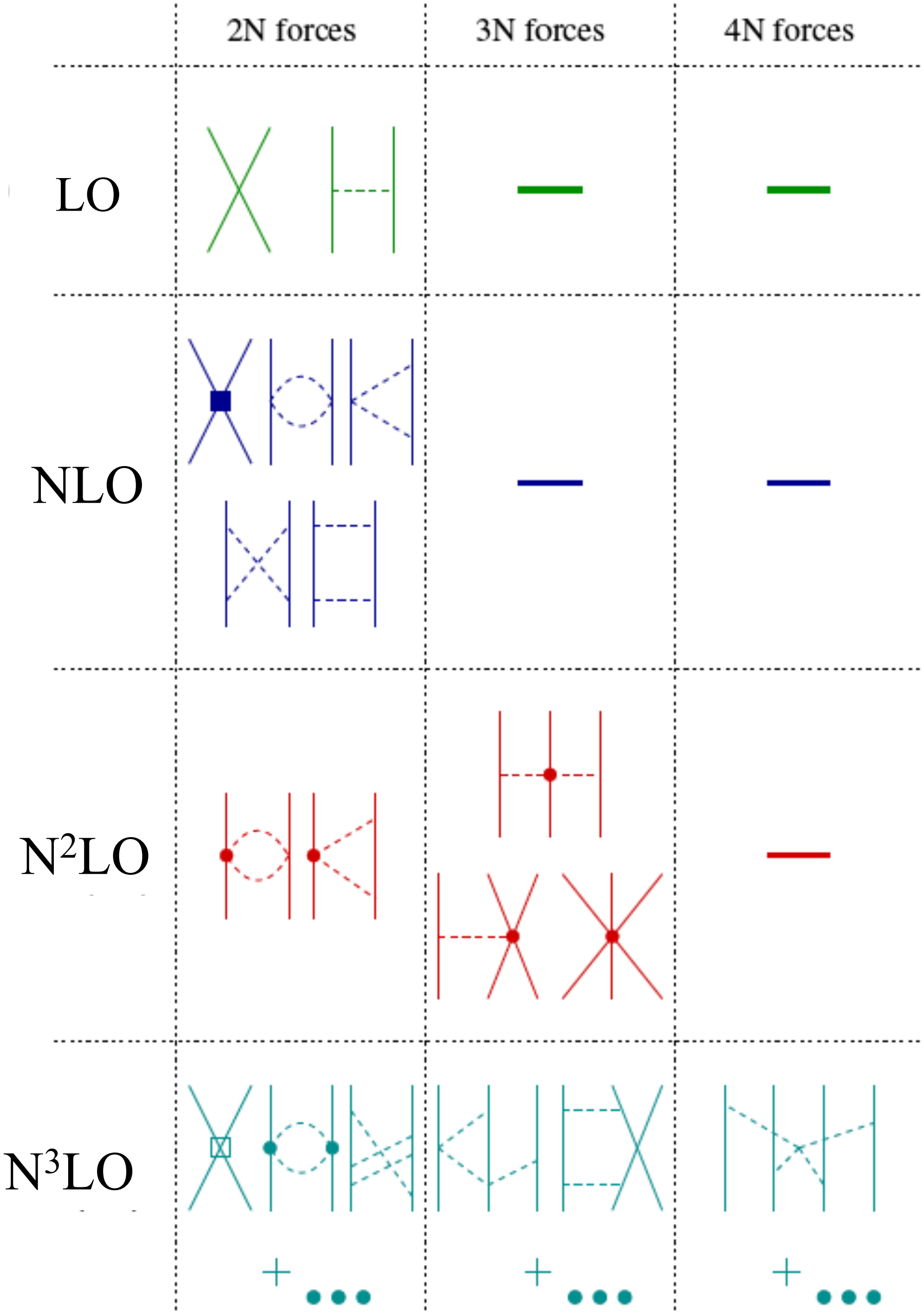


G-matrix – no signs of convergence (similar in pf-shell)

Chiral Effective Field Theory: Nuclear Forces



Nucleons interact via pion exchanges and contact interactions

Consistent treatment of NN, 3N,…

3N couplings fit to properties of light nuclei at low momentum

Improve convergence of many-body methods:

$$V_{\text{low } k} \quad \text{or} \quad V_{\text{SRG}}$$

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

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5) Explore extended valence spaces

NN matrix elements

- Chiral N^3LO (Machleidt, $\Lambda_{NN} = 500\text{MeV}$); smooth-regulator $V_{\text{low }k}(\Lambda)$

3N force contributions

- Chiral N^2LO

  c_D, c_E fit to properties of light nuclei with $V_{\text{low }k}$ $(\Lambda = \Lambda_{3N} = 2.0\text{fm}^{-1})$

- Included to 5 major HO shells

Perturbative Valence-Space Strategy

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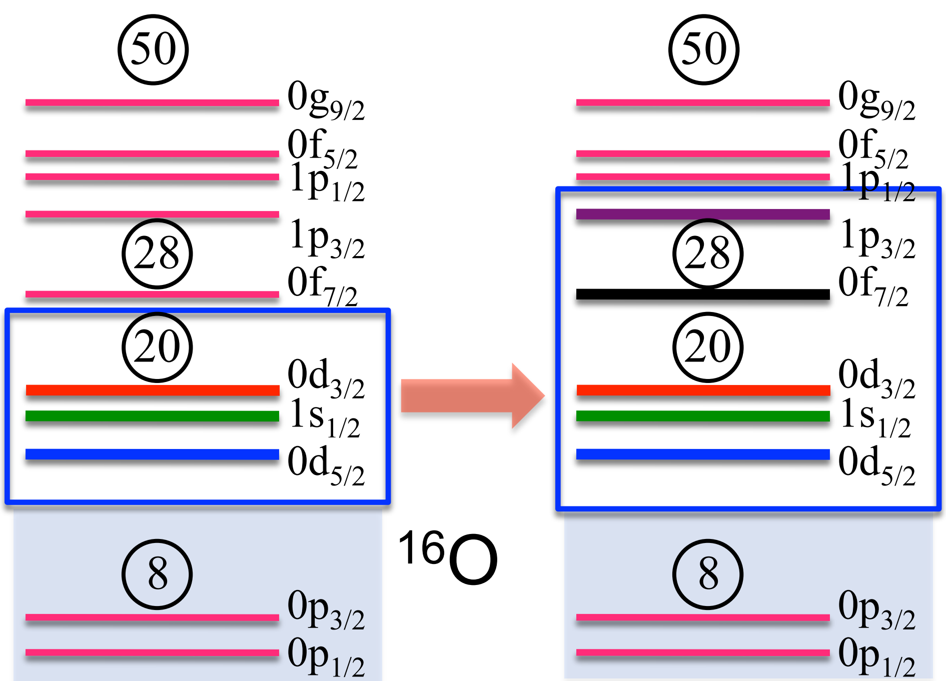
★ 5) Explore **extended valence spaces**

Philosophy: diagonalize in largest possible valence space (where orbits relevant)



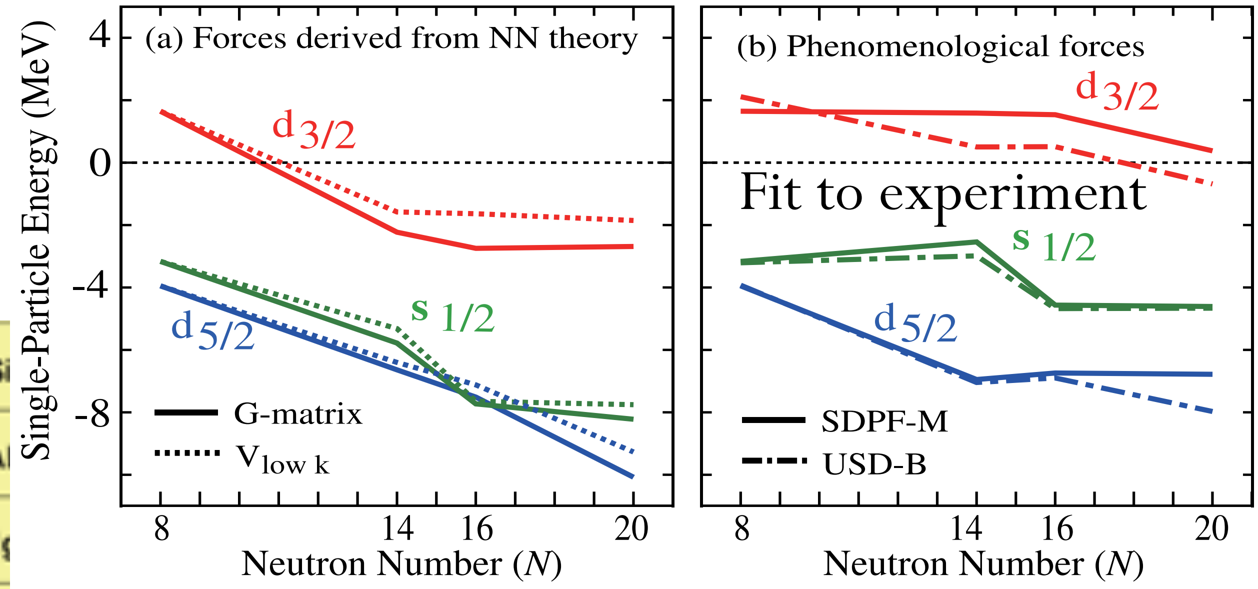
Treats higher orbits nonperturbatively

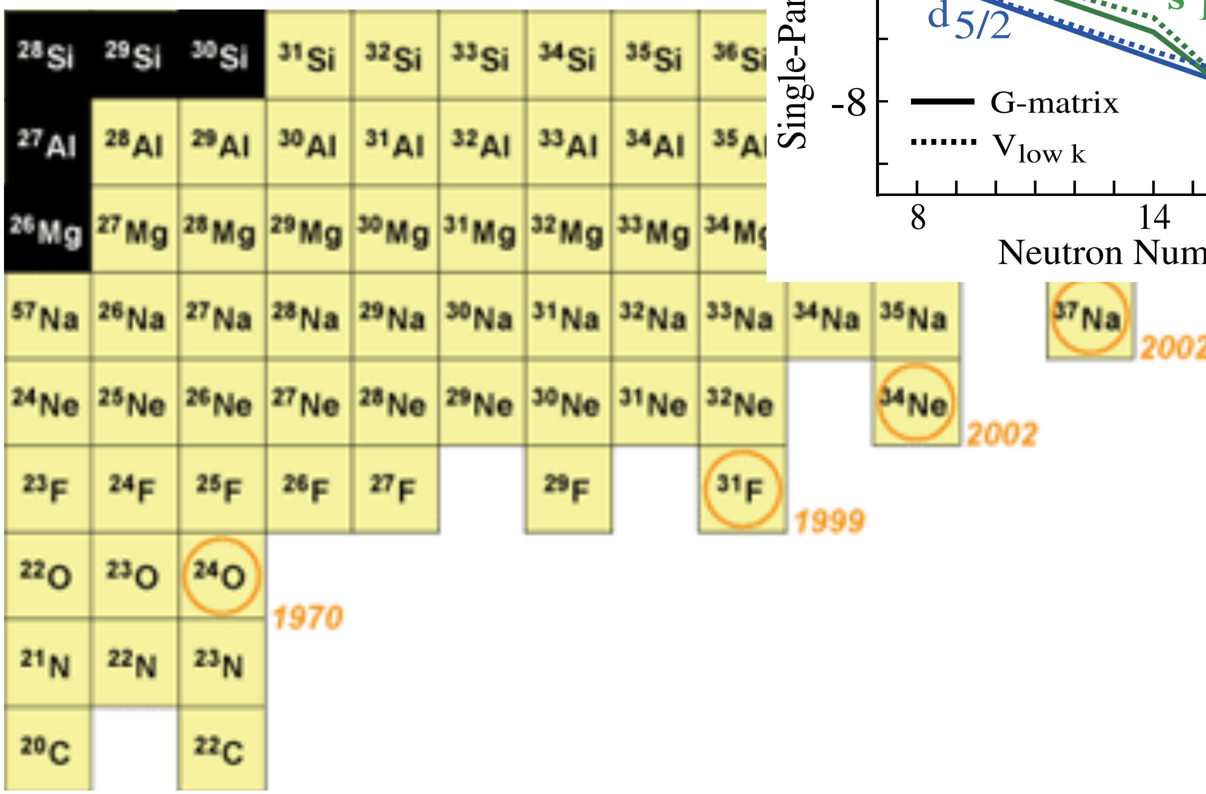
When important for exotic nuclei?

Limits of Nuclear Existence: Oxygen Anomaly

Microscopic picture:

NN-forces too attractive





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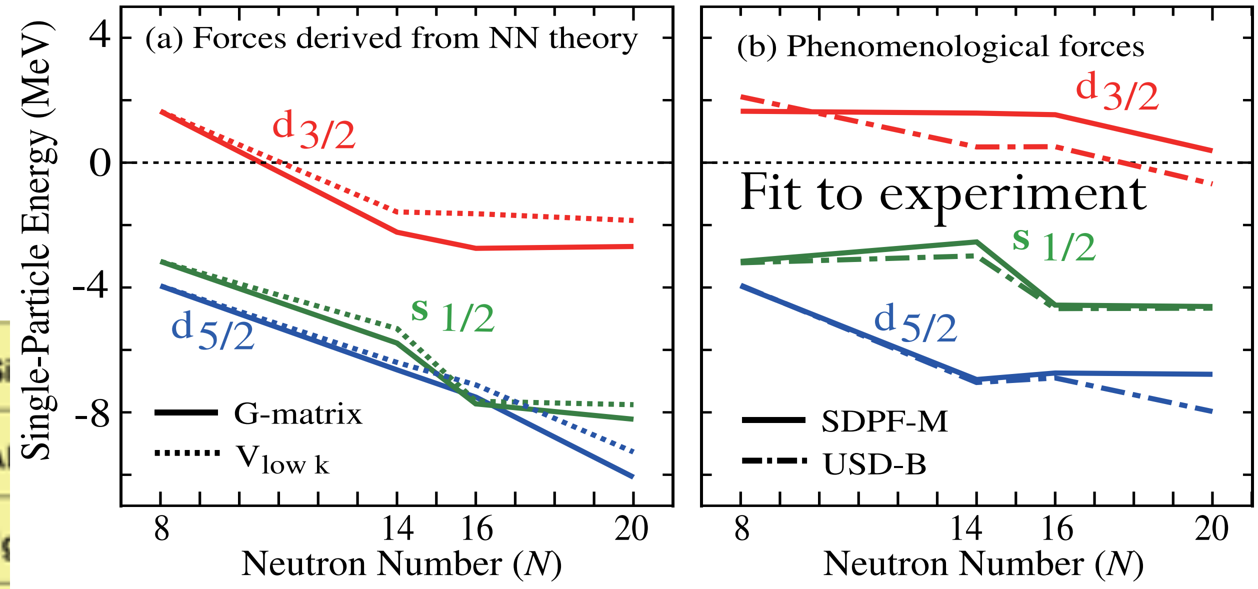
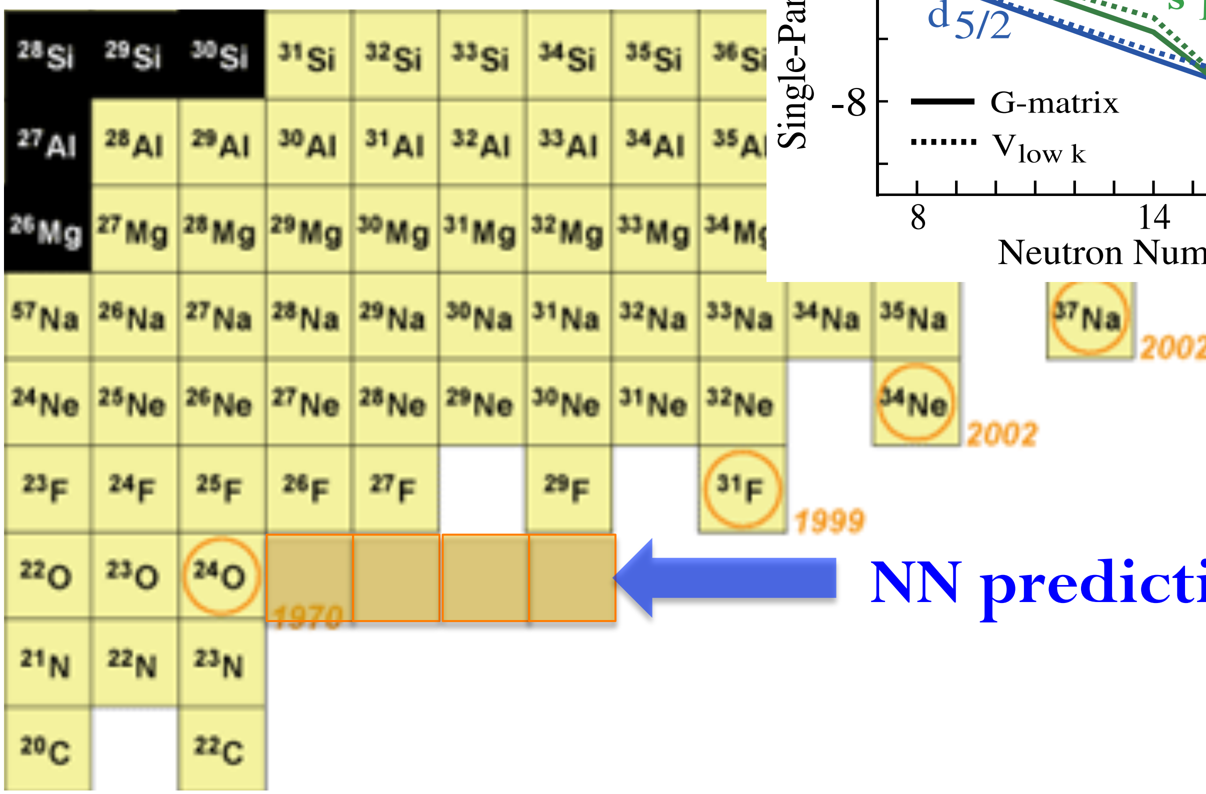
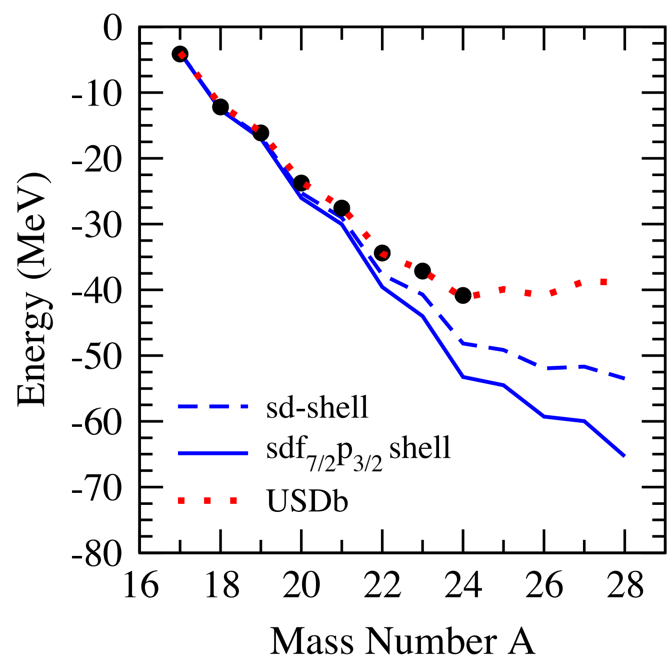




NN prediction



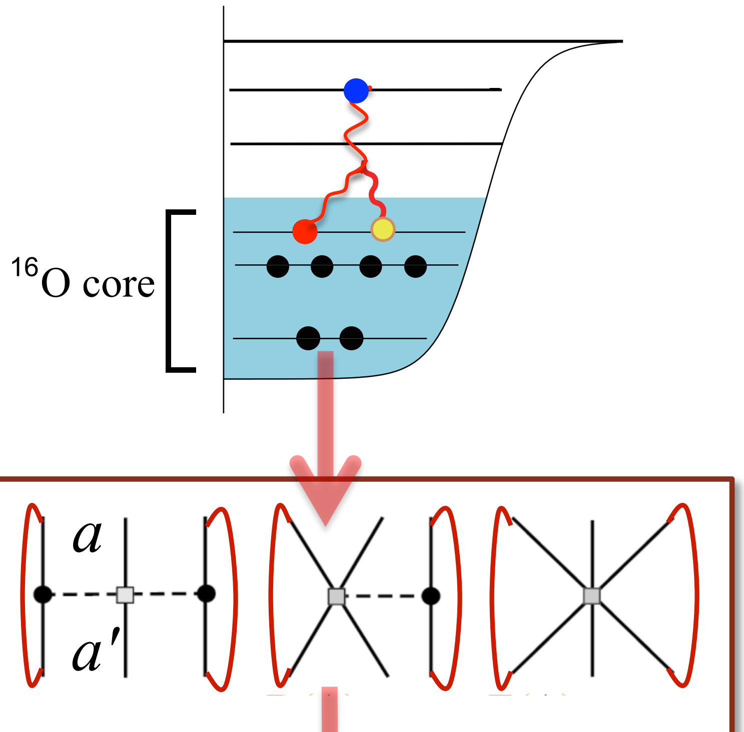
Incorrect prediction of oxygen dripline

Extended-space – more binding

3N Forces for Valence-Shell Theories

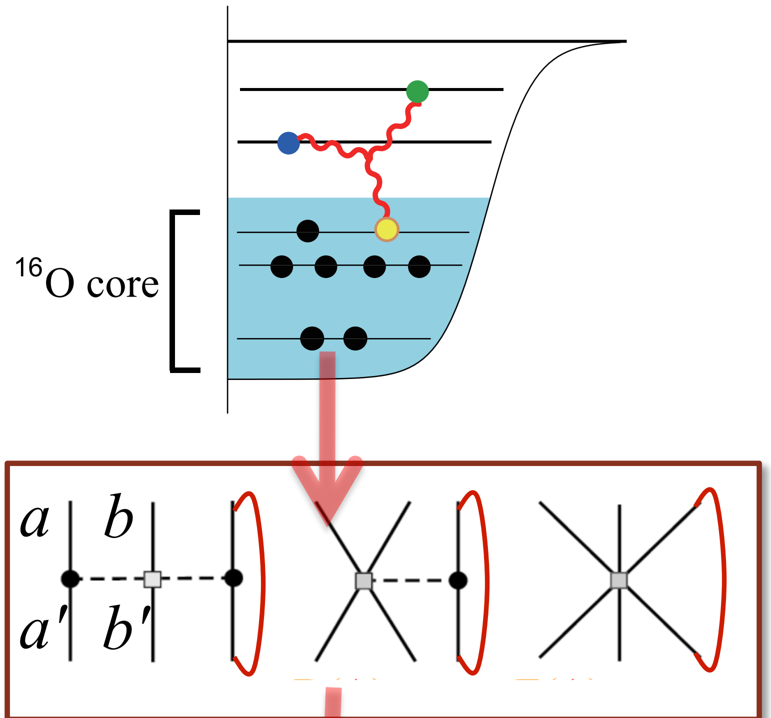
Normal-ordered 3N: contribution to valence-space Hamiltonian

Effective one-body



$$\langle a | V_{3N,\mathrm{eff}} | a' \rangle = \frac{1}{2} \sum_{\alpha\beta = core} \langle \alpha\beta a | V_{3N} | \alpha\beta a' \rangle$$

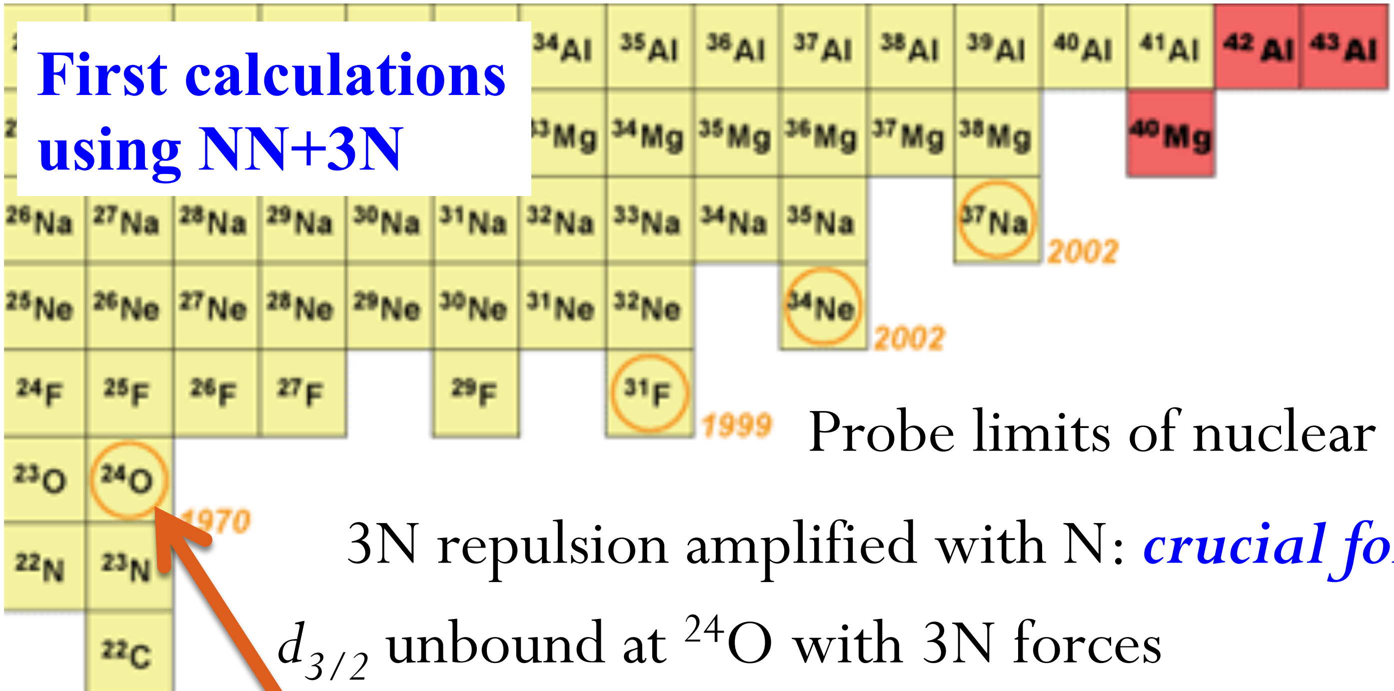
Effective two-body



$$\langle ab | V_{3N,\mathrm{eff}} | a'b' \rangle = \sum_{\alpha = core} \langle \alpha ab | V_{3N} | \alpha a'b' \rangle$$

Combine with NN (**Third Order**): no empirical adjustments

Oxygen Anomaly

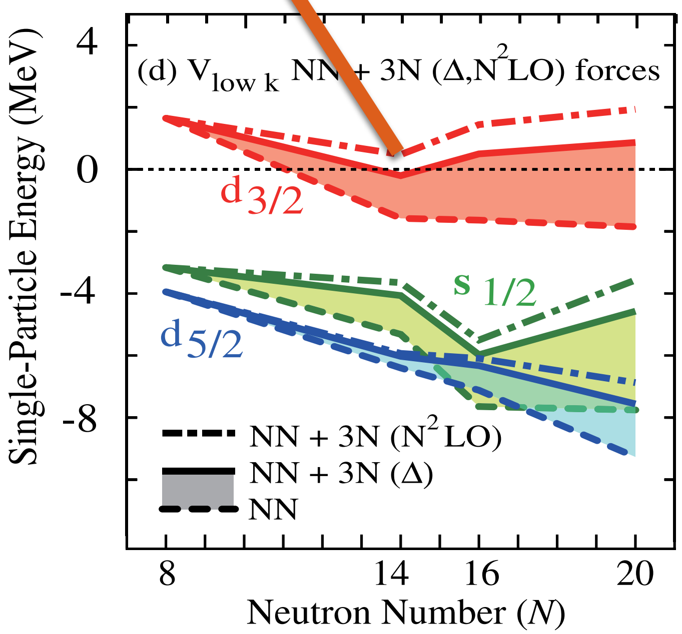


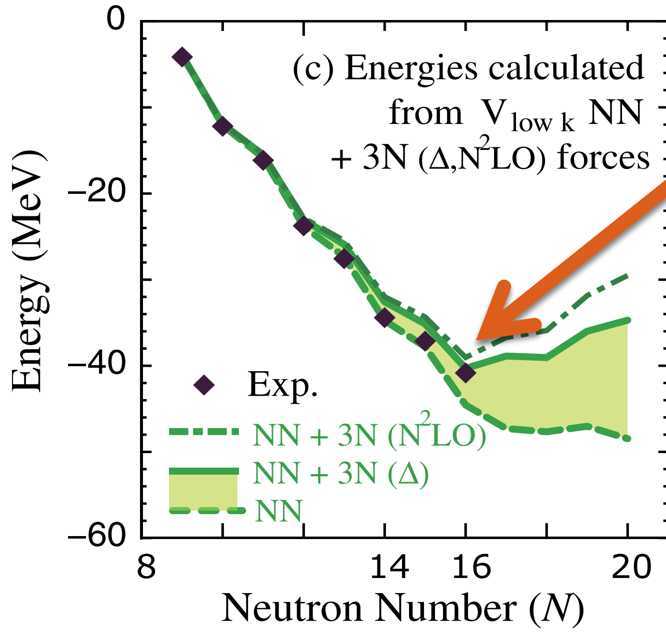
First calculations using NN+3N

Probe limits of nuclear existence with 3N forces

3N repulsion amplified with N: ***crucial for neutron-rich nuclei***

$d_{3/2}$ unbound at ^{24}O with 3N forces





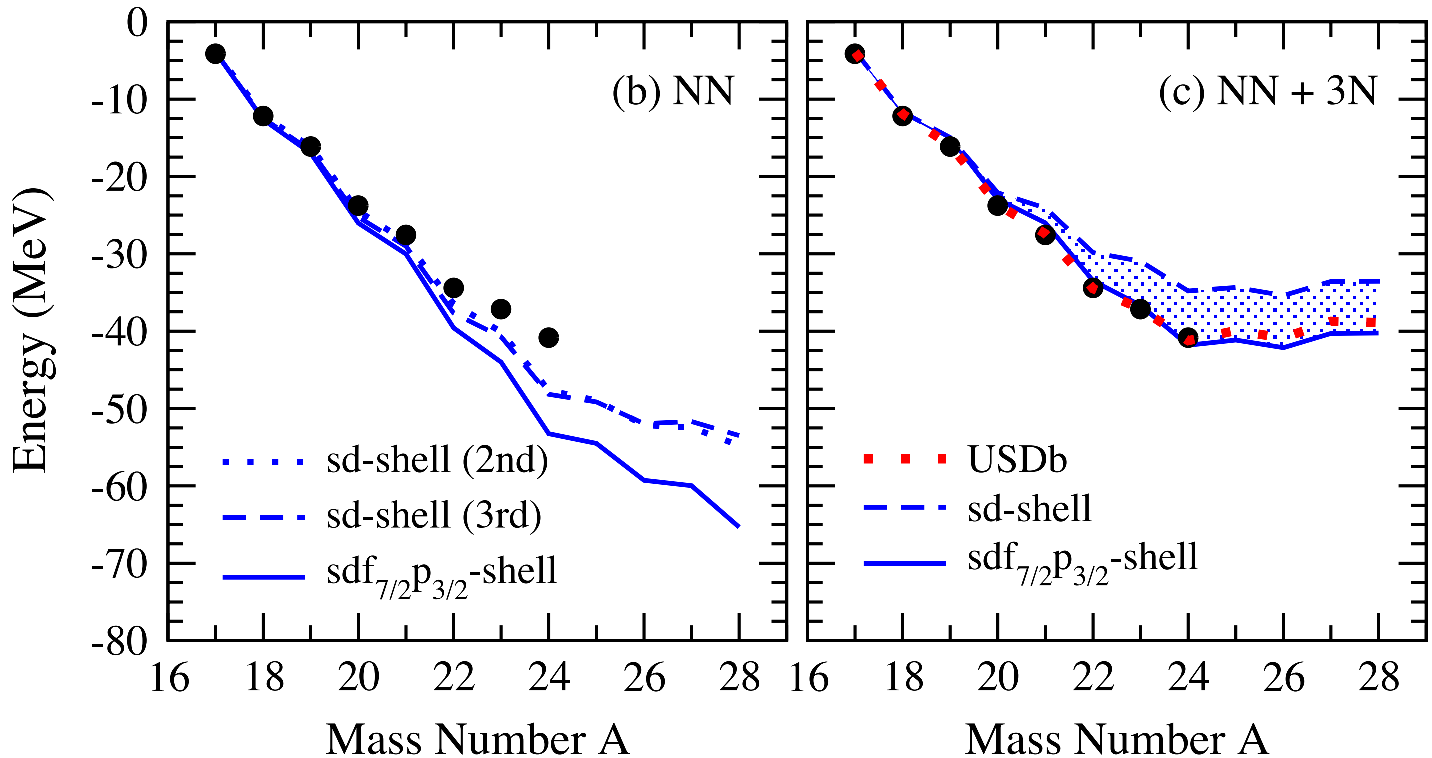
Isotopes unbound beyond ^{24}O

First microscopic explanation of oxygen anomaly

Otsuka, Suzuki, JDH, Schwenk, Akaishi, PRL (2010)

Ground-State Energies of Oxygen Isotopes

Valence-space interaction and SPEs from NN+3N



JDH, Menendez, Schwenk, EPJA (2013)

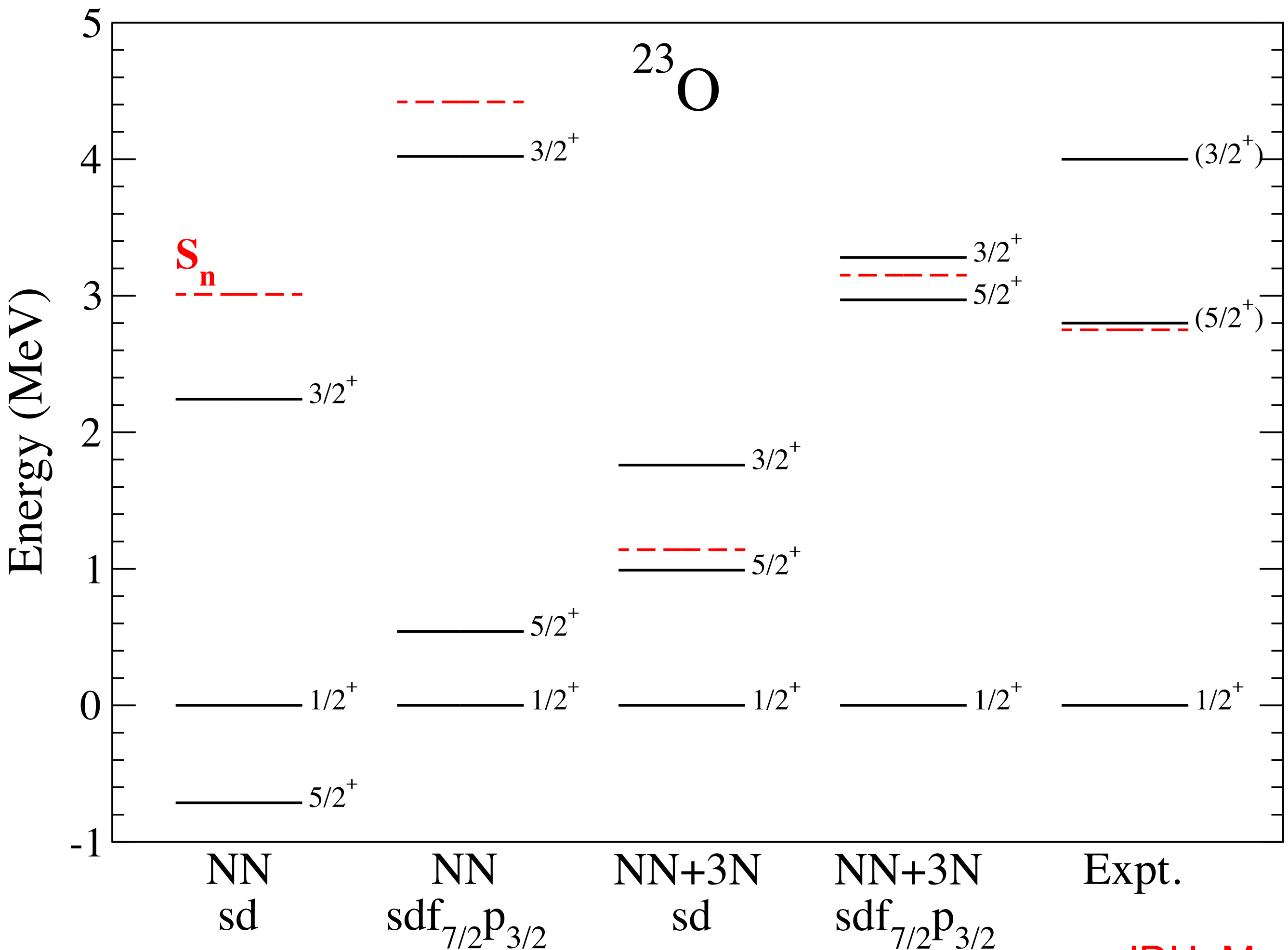
Repulsive character improves agreement with experiment

sd-shell results underbound; improved in **extended space**

Impact on Spectra: ^{23}O

Neutron-rich oxygen spectra with NN+3N

$5/2^+$, $3/2^+$ energies reflect ^{22,24}O shell closures



***sd*-shell NN only**

Wrong ground state

$5/2^+$ too low

$3/2^+$ bound

NN+3N

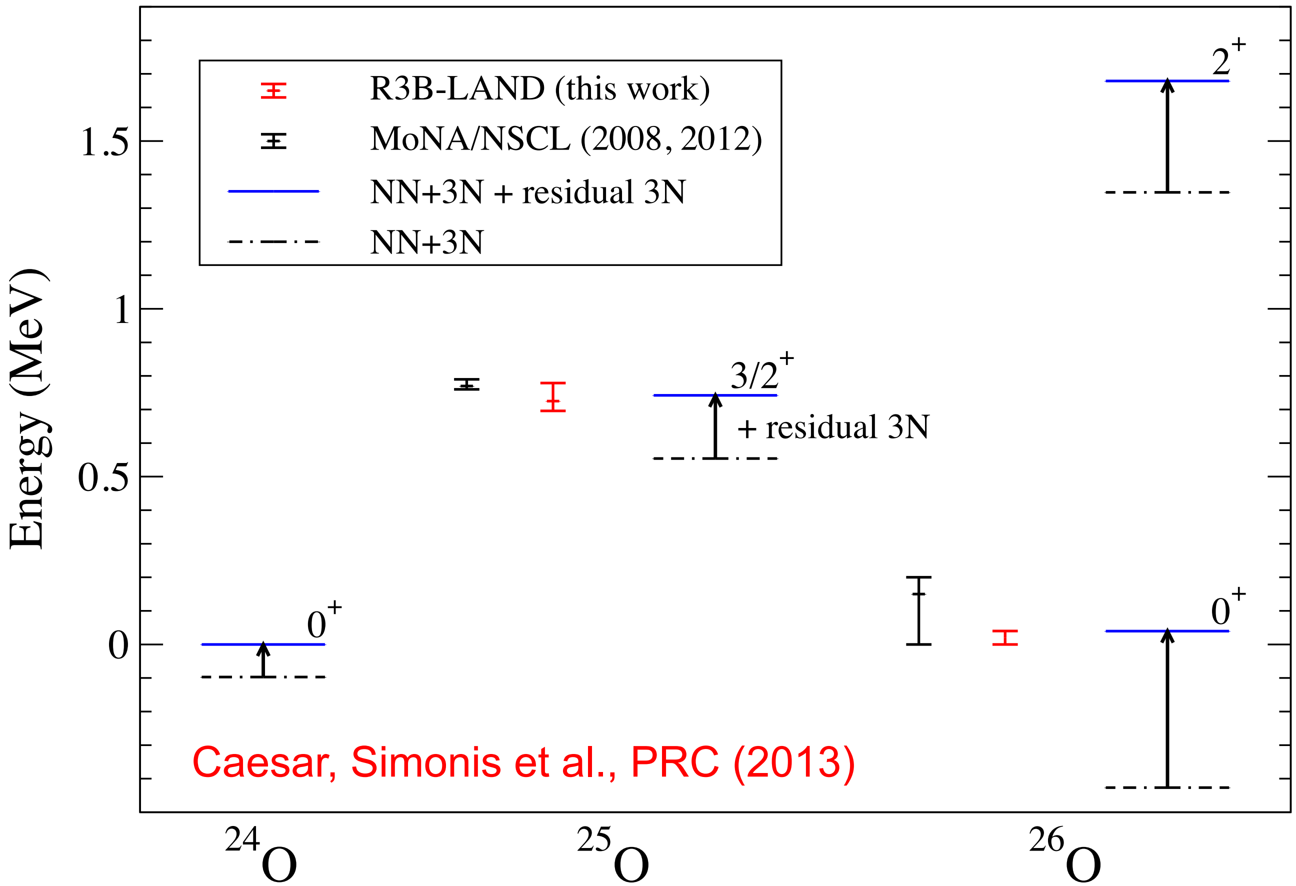
Clear improvement in extended valence space

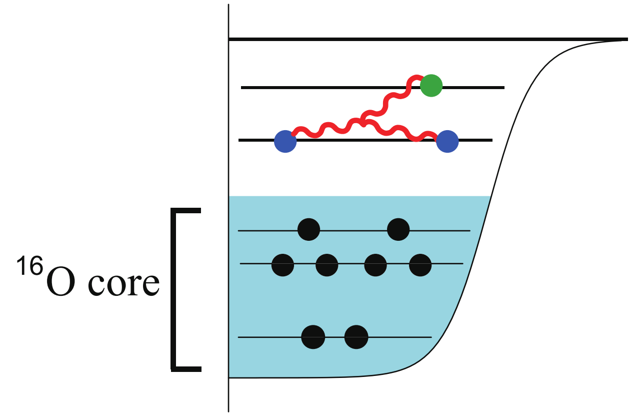
JDH, Menendez, Schwenk, EPJA (2013)

Experimental Connection: Beyond the Dripline

Hoffman, Kanungo, Lunderberg… PRLs (2008+)

Valence-space Hamiltonian from NN + 3N + **residual 3N**





	MBPT	Exp.
$S_n(^{25}O)$	742 keV	770 keV

	MBPT	Exp.
$S_{2n}(^{26}O)$	40 keV	<120 keV

Repulsion more pronounced for neutron-rich systems: 400 keV at ^{26}O

Improved agreement with new data beyond ^{24}O dripline

Future: include coupling to continuum

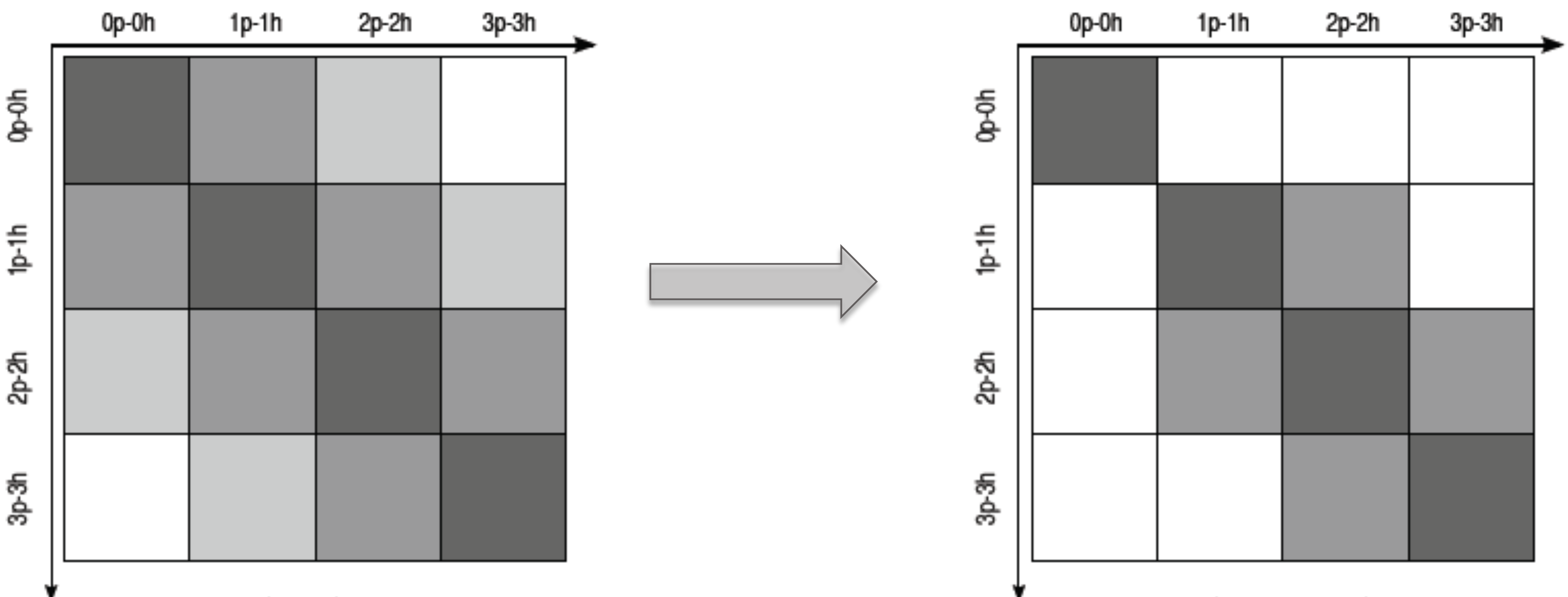
In-Medium SRG: Basics

In-Medium SRG applies continuous unitary transformation to drive off-diagonal physics to zero

Tsukiyama, Bogner, Schwenk, PRL (2011)

$$H(s) = U(s)HU^{\dagger}(s) \equiv H^{\mathrm{d}}(s) + H^{\mathrm{od}}(s) \rightarrow H^{\mathrm{d}}(\infty)$$

Decouples reference state from excitations $\langle npnh | H(\infty) | \Phi_c \rangle = 0$



$\langle i | H | j \rangle$ $\langle i | H(\infty) | j \rangle$

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$$H(s) = U(s)HU^{\dagger}(s) \equiv H^{\mathrm{d}}(s) + H^{\mathrm{od}}(s) \rightarrow H^{\mathrm{d}}(\infty)$$

Where U is defined by the generator:

$$\eta(s) \equiv \left(\mathrm{d}U(s)/\mathrm{d}s\right)U^{\dagger}(s)$$ chosen for desired decoupling behavior

Taking

$$\eta(s) = \left[H^{\mathrm{d}}(s), H(s)\right] = \left[H^{\mathrm{d}}(s), H^{\mathrm{od}}(s)\right]$$

Drives H^{od} to 0 (Wegner, 1994)

Closed-shell reference state: drives all n-particle n-hole couplings to 0

$$\frac{\mathrm{d}H(s)}{\mathrm{d}s} = \left[\eta(s), H(s)\right] \qquad \left\langle npnh \middle| H(\infty) \middle| \Phi_c \right\rangle = 0$$

IM-SRG for Valence-Space Hamiltonians

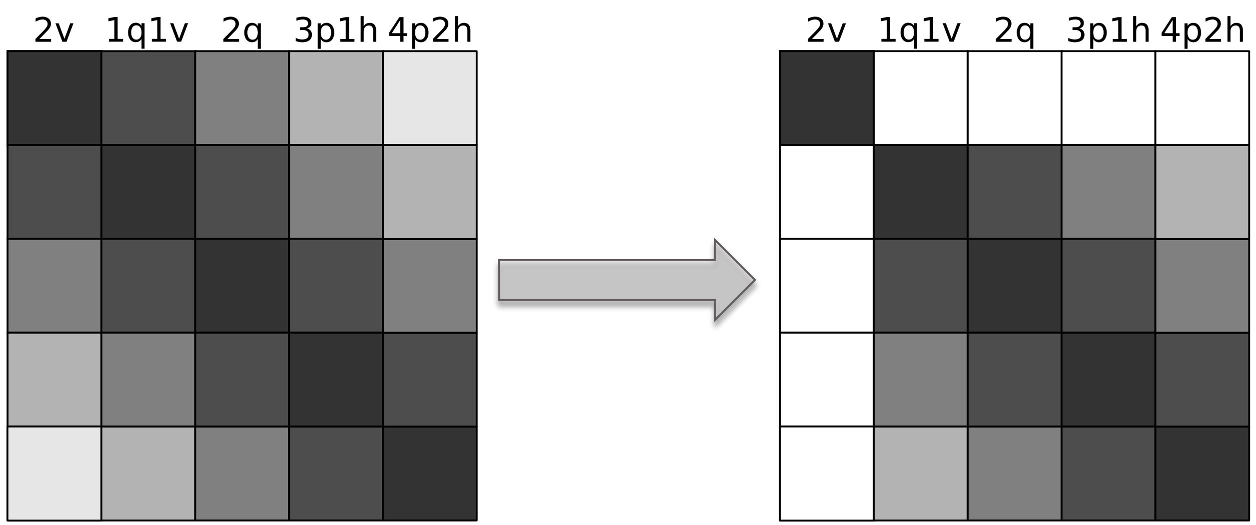
In-Medium SRG applies continuous unitary transformation to drive off-diagonal physics to zero

Tsukiyama, Bogner, Schwenk, PRC (2012)

Open shell systems:

split particle states into valence states, v, and those above valence space, q

Redefine "off-diagonal" to exclude valence particles



$$H(s=0) \rightarrow H(\infty)$$

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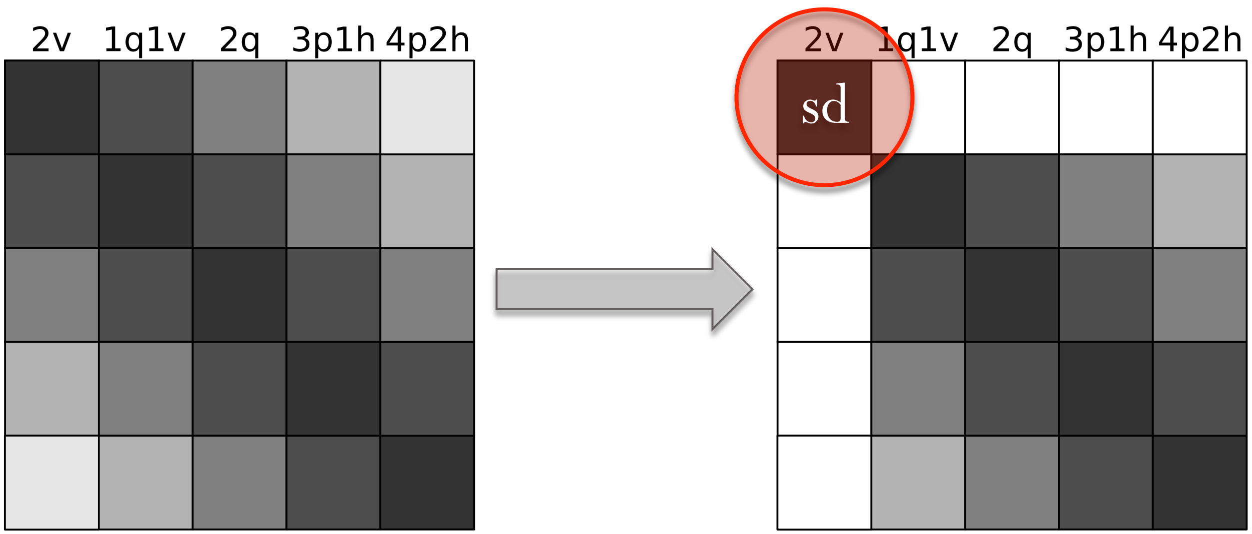


$$H(s=0) \rightarrow H(\infty)$$

Defines new effective valence-space Hamiltonian H_{eff}

States outside valence space are decoupled

Nonperturbative Valence-Space Strategy

1) Effective interaction: nonperturbative from IM-SRG

2) Single-particle energies: nonperturbative from IM-SRG

3) Hartree-Fock basis of $e_{\max} = 2n + l = 14$ **converged**

★ 4) NN and 3N forces from chiral EFT

5) Explore extended valence spaces – in progress

NN matrix elements

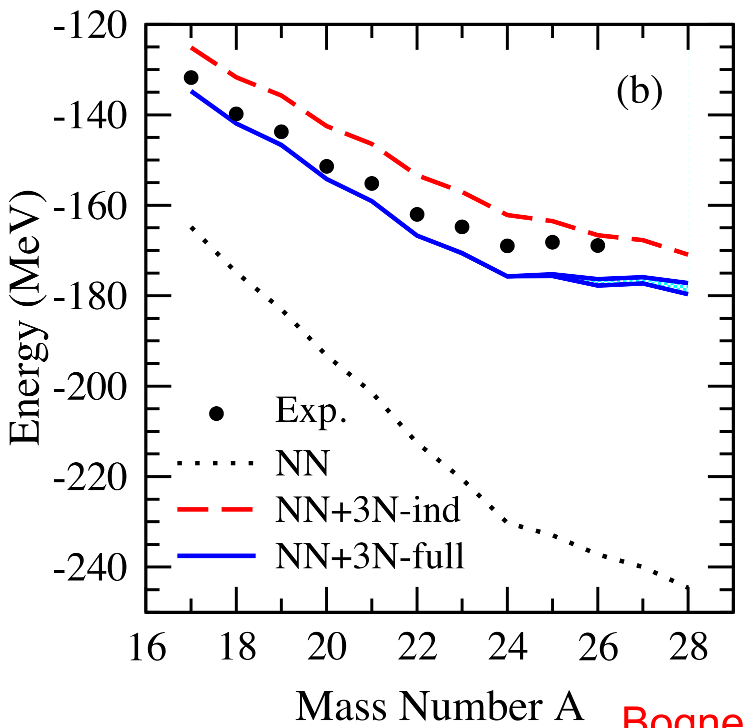
- Chiral N^3LO (Machleidt, $\Lambda_{NN} = 500\text{MeV}$); free-space SRG evolution
- Cutoff variation $\lambda_{SRG} = 1.88 - 2.24\text{fm}^{-1}$
- Vary $\hbar\omega = 20 - 24\text{MeV}$
- Consistently include 3N forces induced by SRG evolution (**NN+3N-ind**)

Initial 3N force contributions

- Chiral N^2LO $\Lambda_{3N} = 400\text{MeV}$ (**NN+3N-full**)
- Included with cut: $e_1 + e_2 + e_3 \leq E_{3\max} = 14$

IM-SRG Oxygen Ground-State Energies

Valence-space interaction and SPEs from IM-SRG in *sd* shell



Bogner et al., PRL (2014)

NN+3N-induced reproduce exp well, not dripline

NN+3N-full modestly overbound – good behavior past dripline

Good dripline properties

Very weak $\hbar\omega$ dependence

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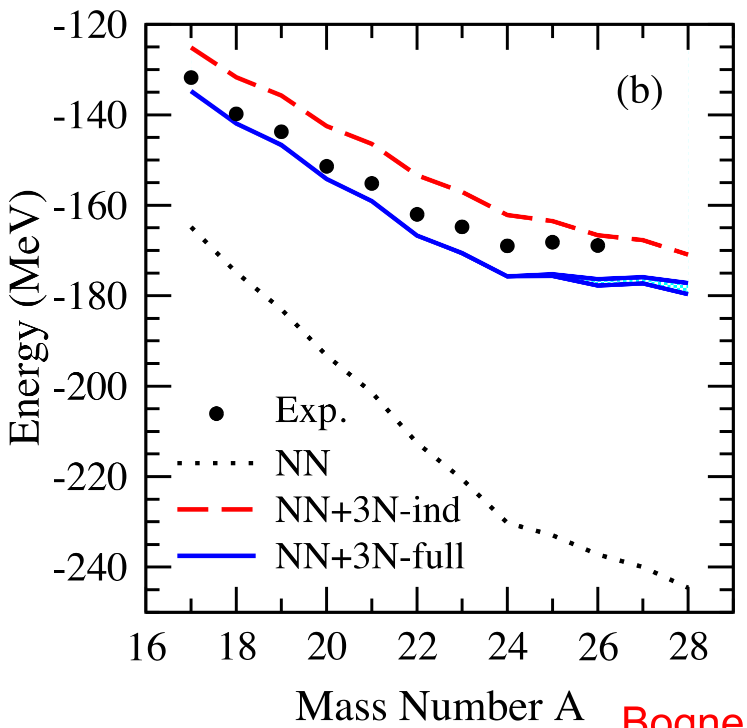
Valence-space interaction and SPEs from IM-SRG in *sd* shell



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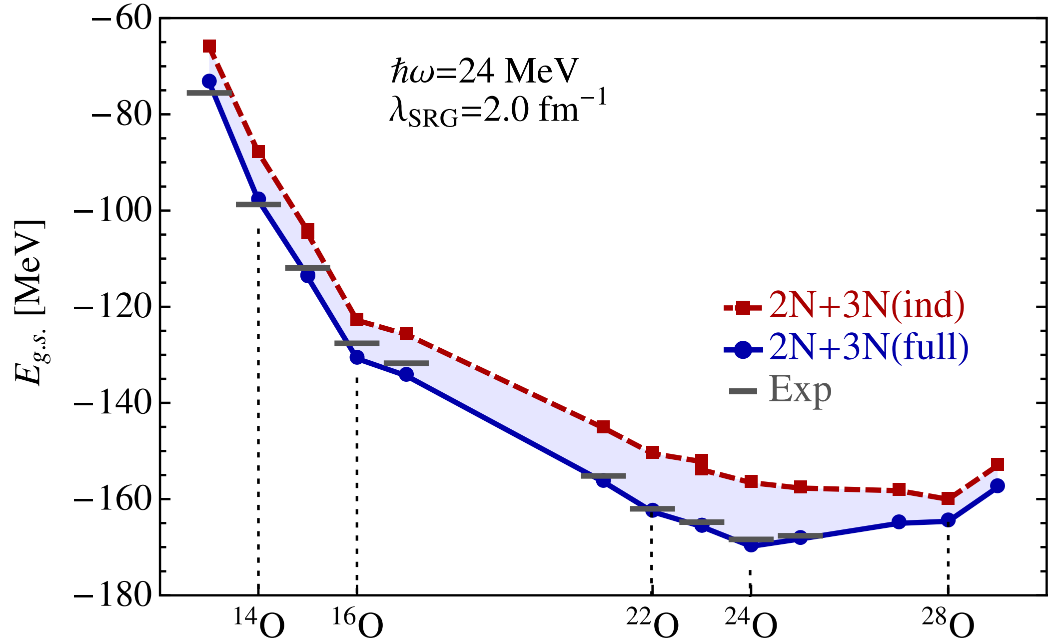

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NN+3N-full modestly overbound – good behavior past dripline

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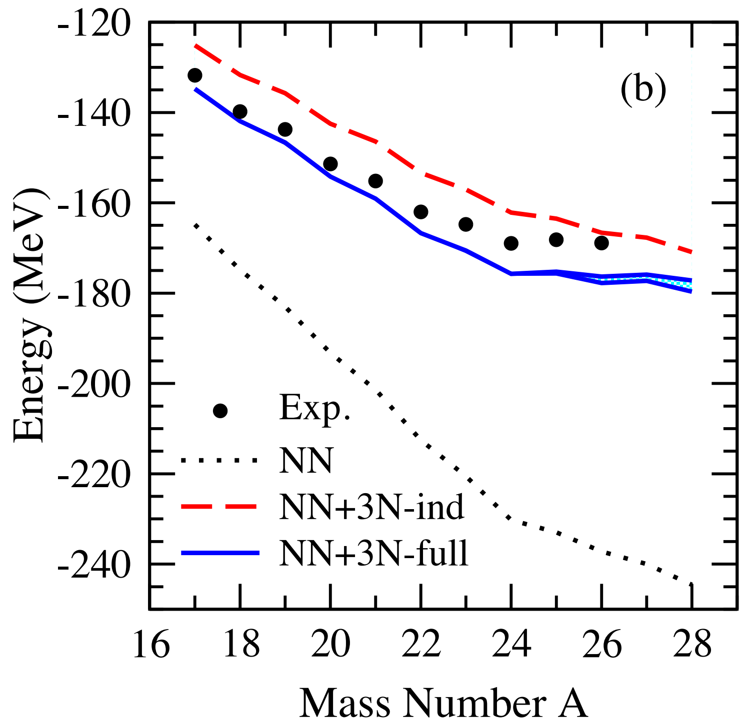
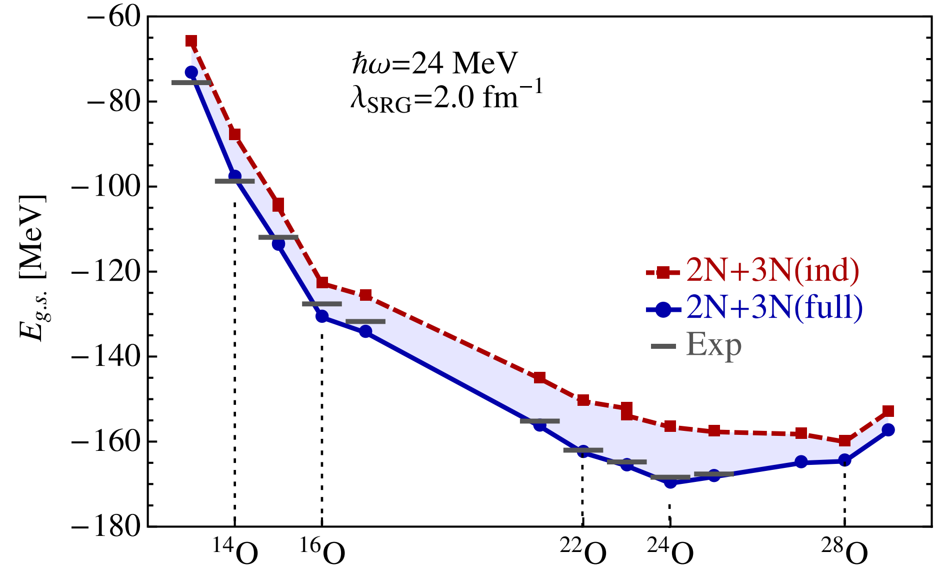
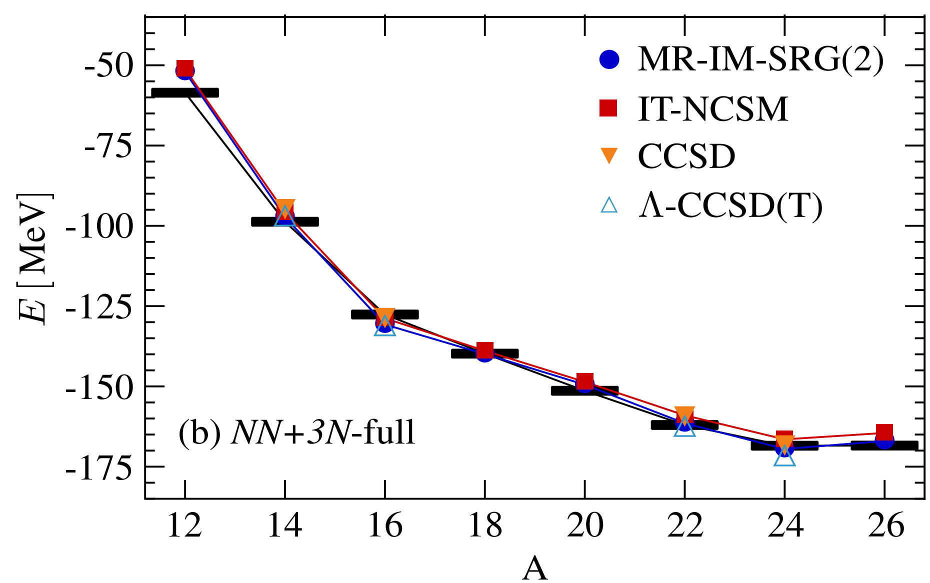
Comparison with Large-Space Methods

Large-space methods with same SRG-evolved NN+3N forces





Cipollone, Barbieri, Navratil, PRL (2013)



Hergert et al., PRL (2013)

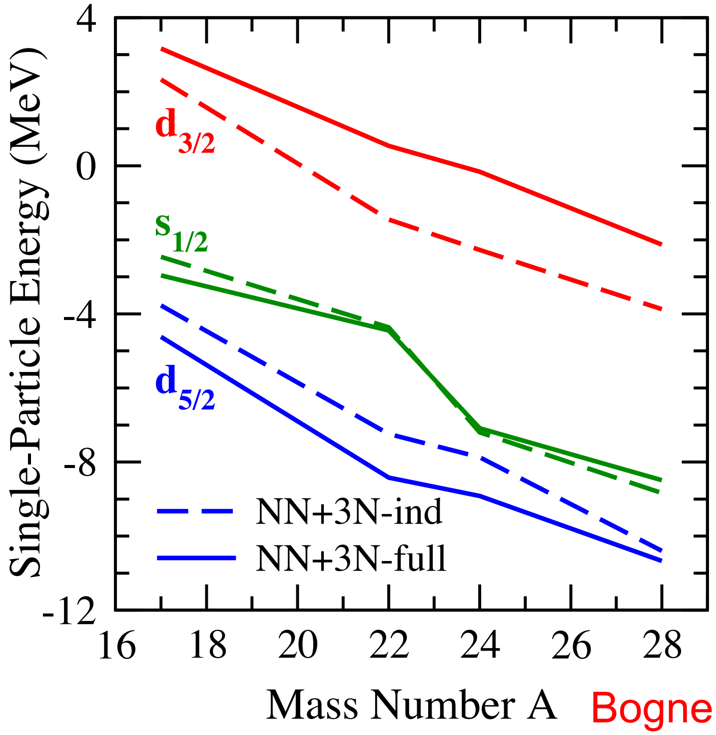
Clear improvement with full NN+3N

Confirms valence-space results

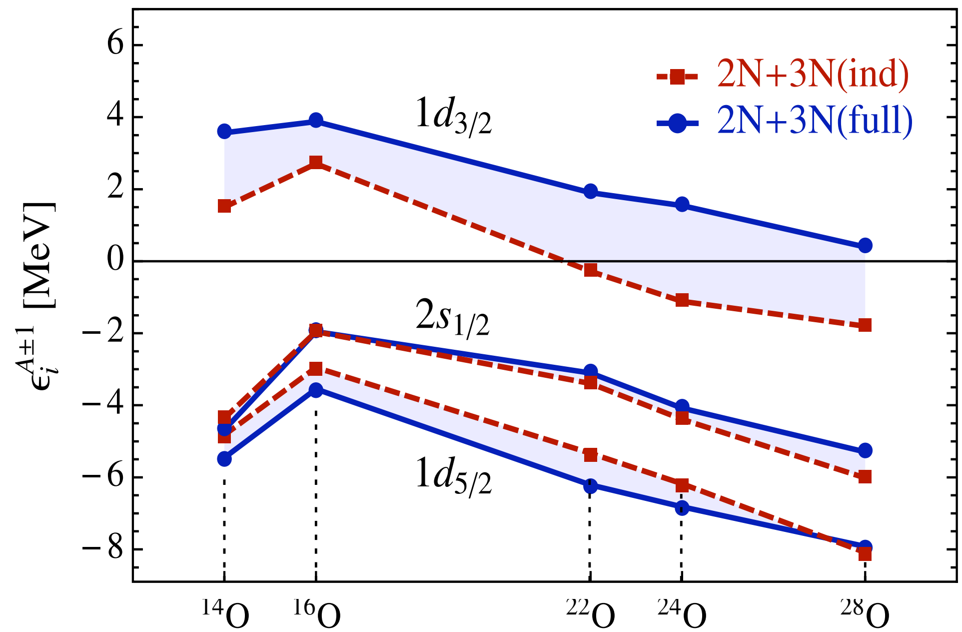
Remarkable agreement with same forces

Dripline Mechanism

Compare to large-space methods with same SRG-evolved NN+3N forces



Bogner et al., PRL (2014)



Cipollone, Barbieri, Navratil, PRL (2013)

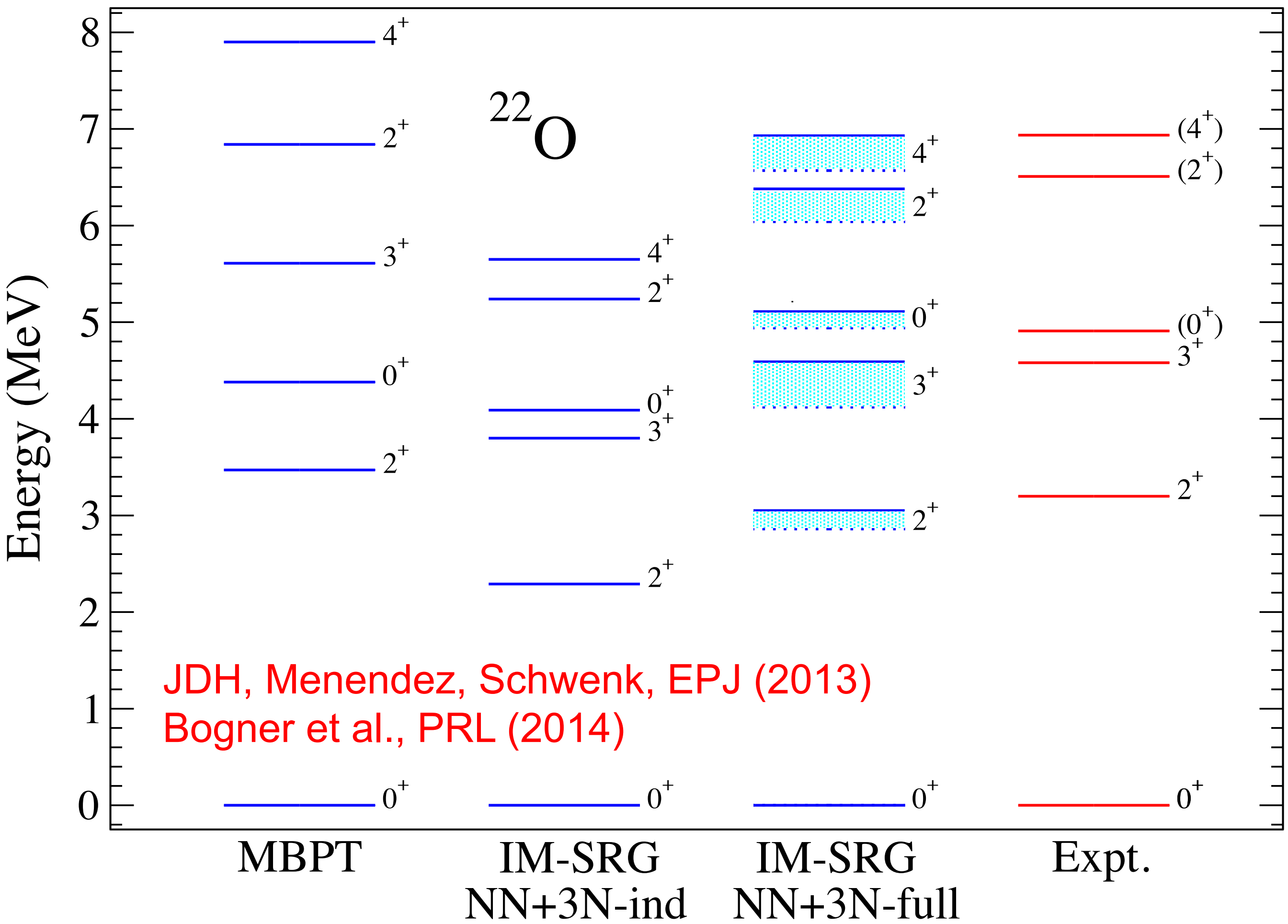
Robust mechanism driving dripline behavior

3N repulsion raises $d_{3/2}$, lessens decrease across shell

Similar to initial MBPT NN+3N calculations in oxygen

IM-SRG Oxygen Spectra

Oxygen spectra: extended-space MBPT and IM-SRG

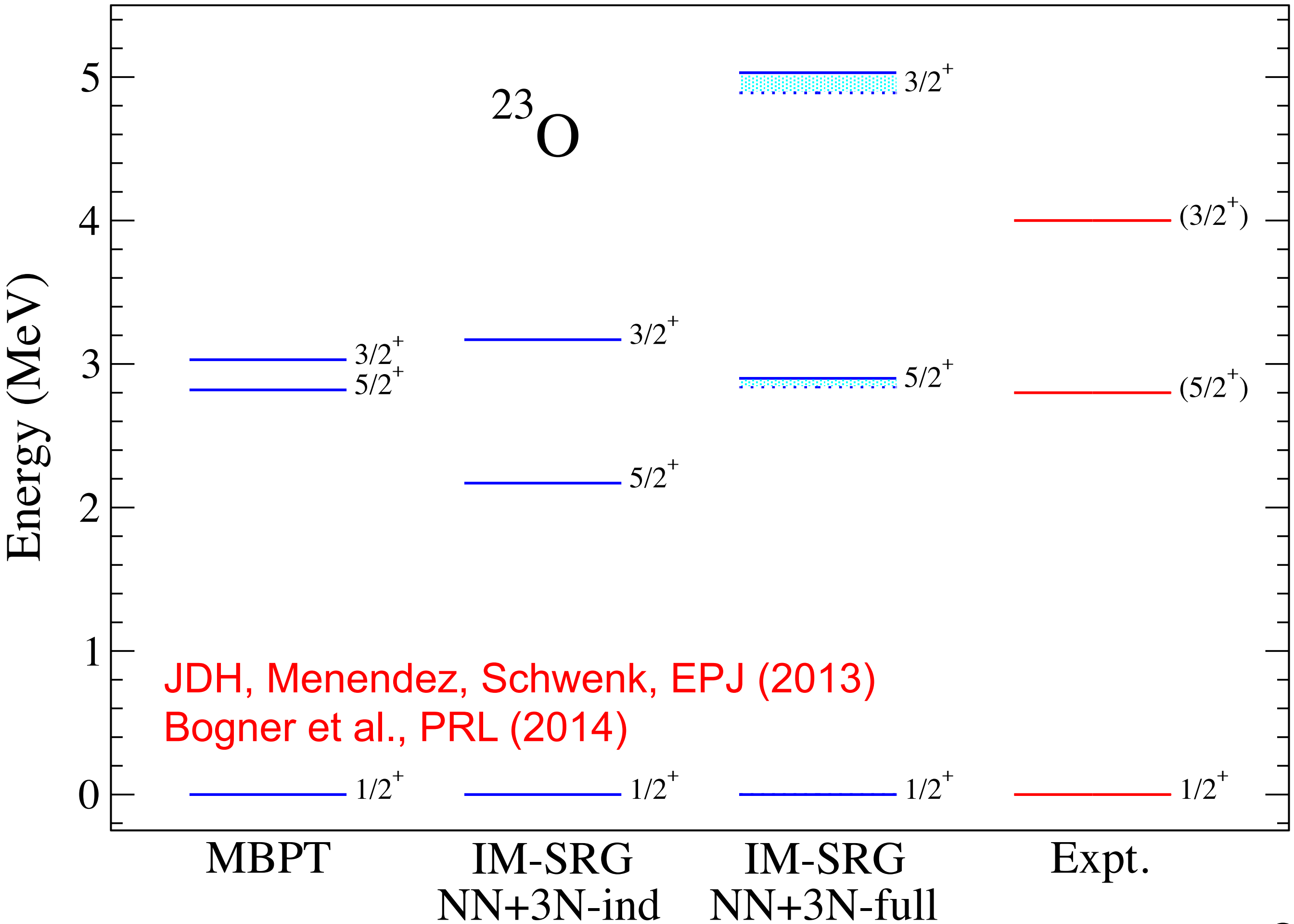


Clear improvement with NN+3N-full

IM-SRG: comparable with phenomenology

IM-SRG Oxygen Spectra

Oxygen spectra: extended-space MBPT and IM-SRG



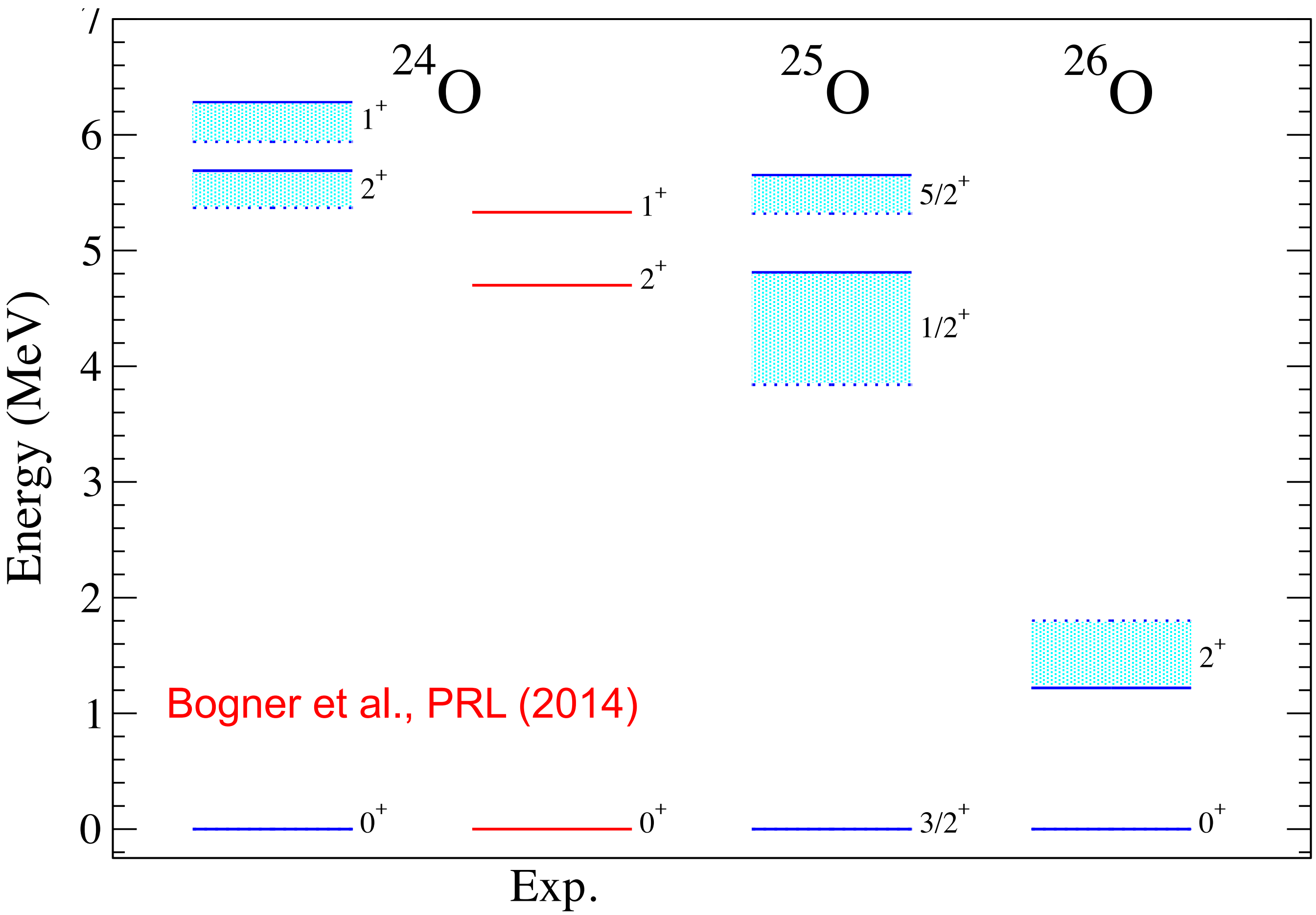
Similar CC valence-space results:
G. Jansen et al., arXiv:1402.2563

Clear improvement with NN+3N-full

Continuum neglected: expect to lower $d_{3/2}$

IM-SRG Oxygen Spectra

Oxygen spectra: IM-SRG predictions beyond the dripline



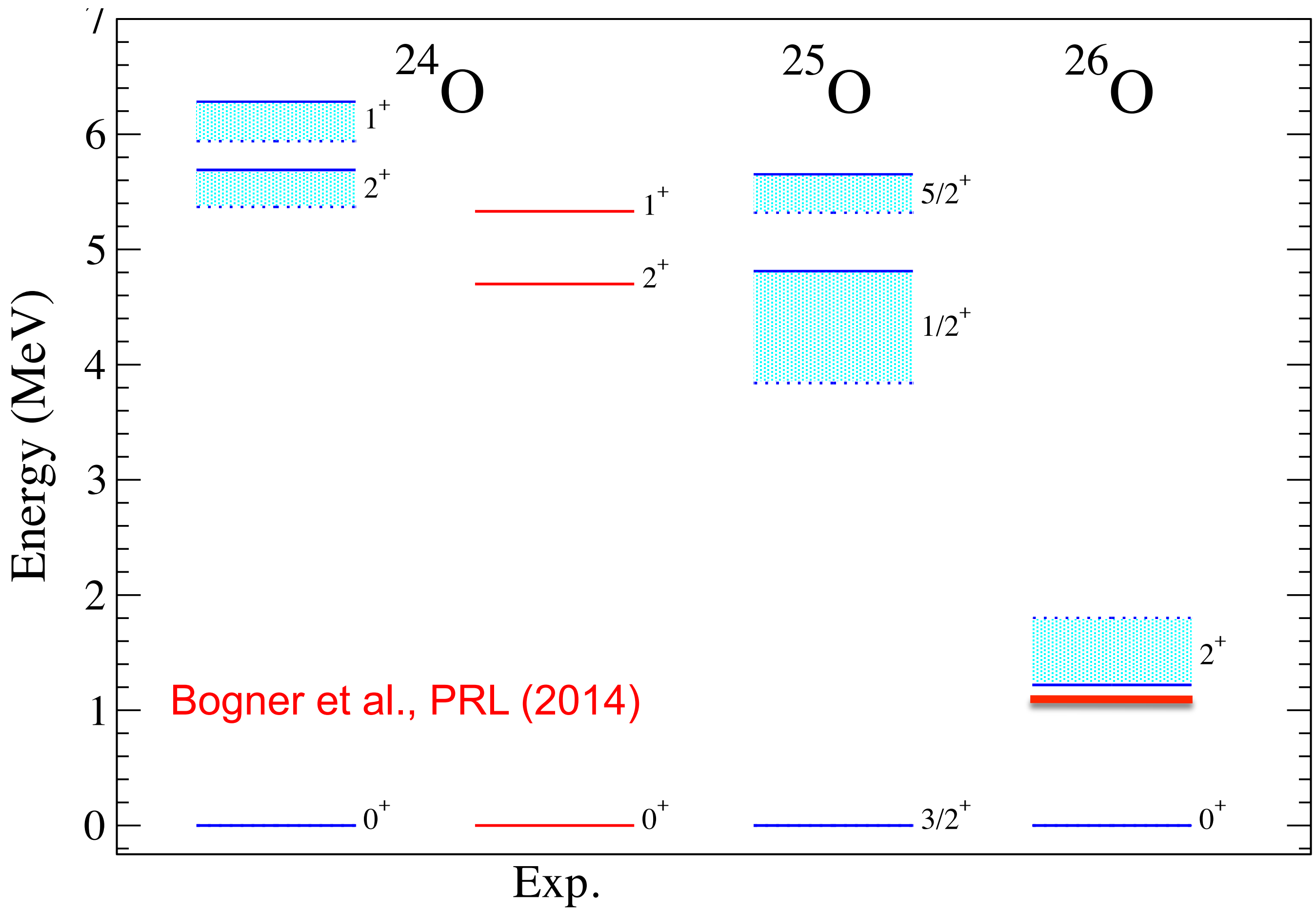
^{24}O closed shell (too high 2^+)

Continuum neglected: expect to lower spectrum

Only one excited state in ^{26}O below 6.5MeV

Experimental Connection: ^{26}O Spectrum

Oxygen spectra: IM-SRG predictions beyond the dripline



Kondo et al., PRELIMINARY

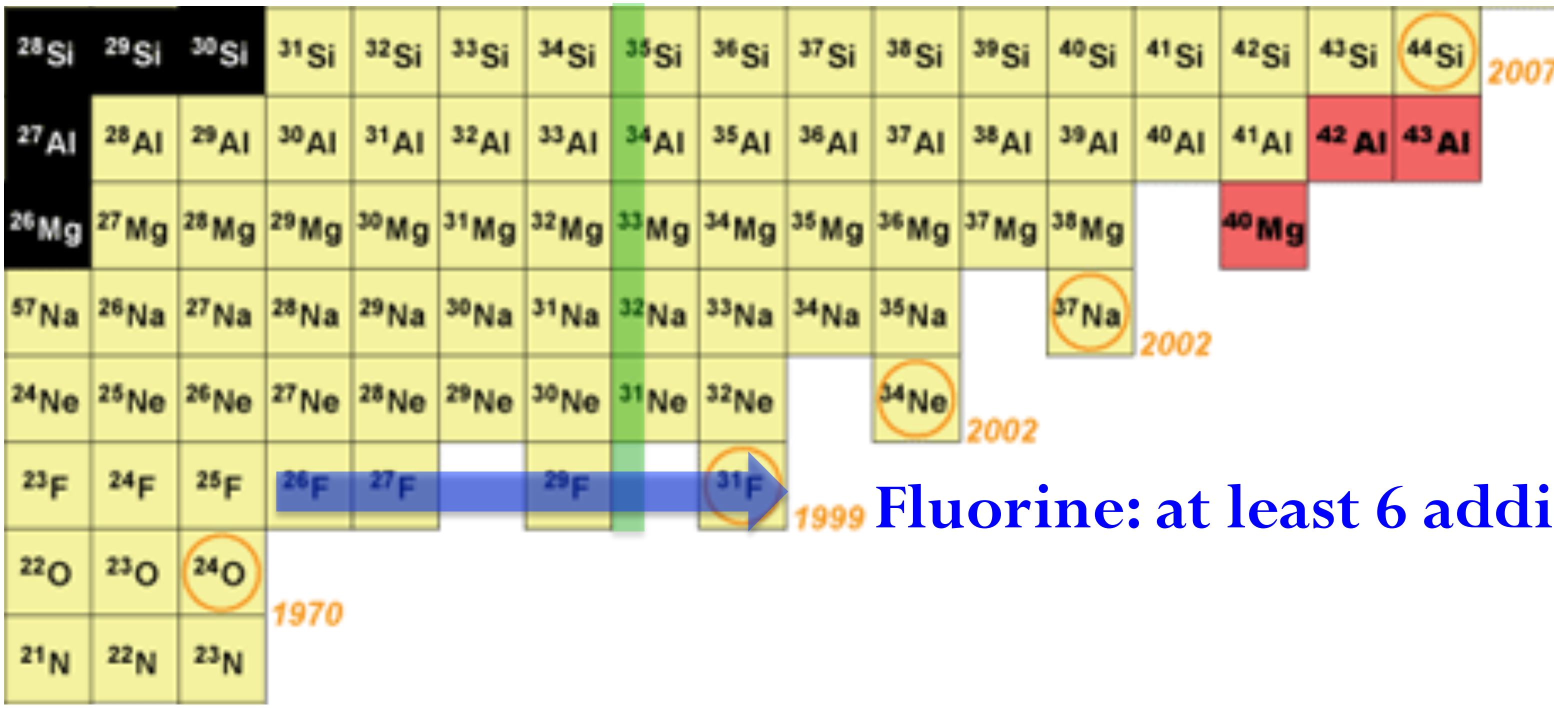
New measurement at RIKEN on excited states in ^{26}O

Existence of excited state "just over 1.0 MeV" (uncertainty not finalized)

Towards Full sd-Shell with MBPT: Fluorine

Next challenge: **valence protons + neutrons**

Neutron-rich fluorine and neon



Fluorine: at least 6 additional neutrons

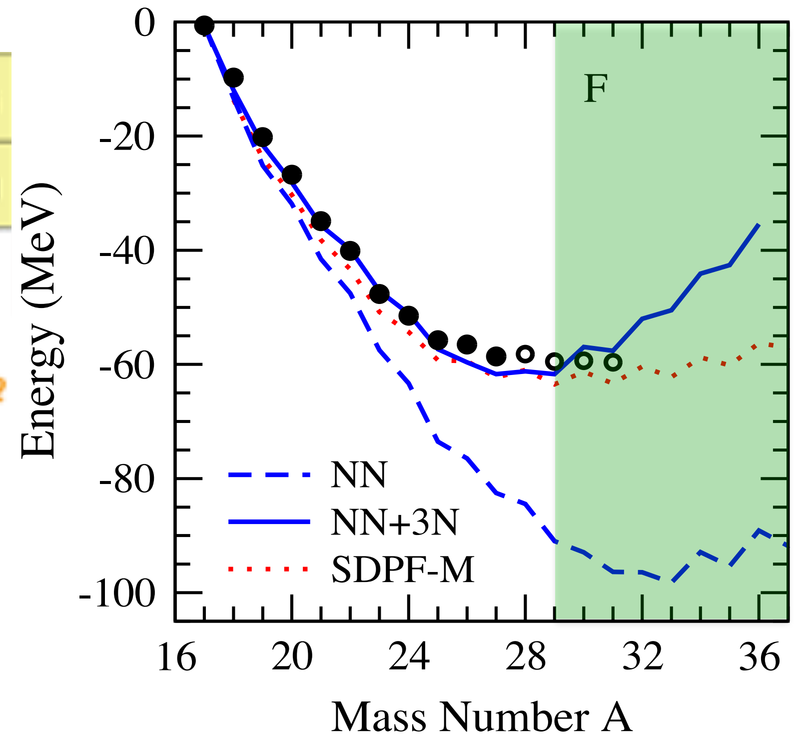
sd shell filled at ^{29}F/^{30}Ne

Need extended-space orbits

Towards Full sd-Shell with MBPT: Fluorine

Next challenge: **valence protons + neutrons**

Neutron-rich fluorine and neon



JDH, Menendez, Simonis, Schwenk, in prep.

NN only: severe overbinding

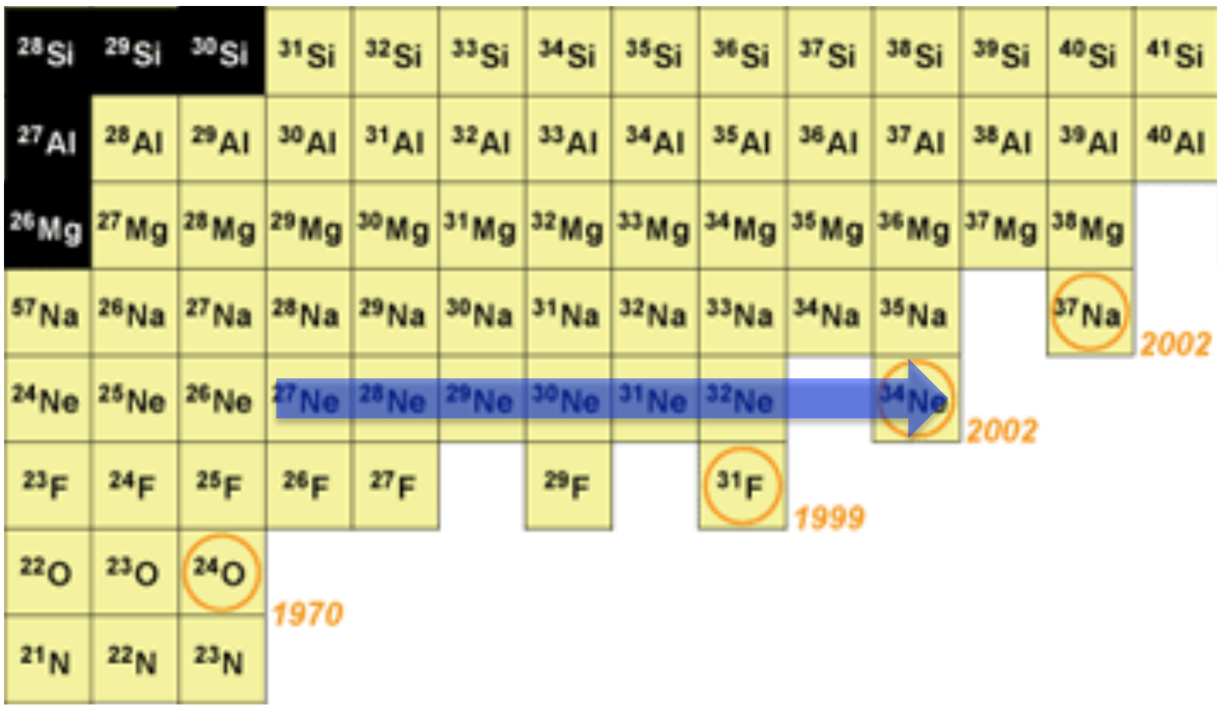
NN+3N: good experimental agreement through ^{29}F

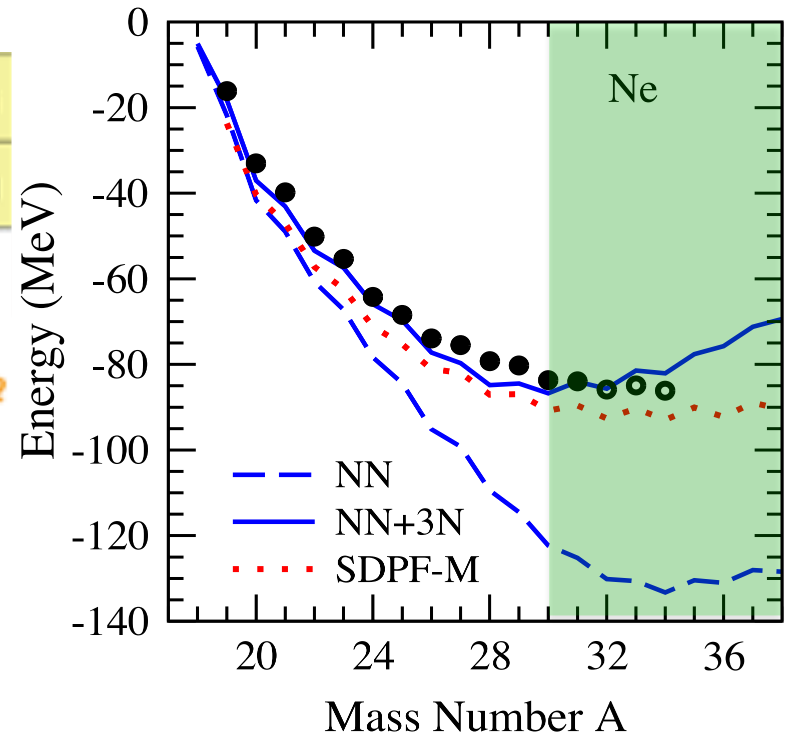
Sharp increase in ground-state energies beyond ^{29}F: incorrect dripline

Towards Full sd-Shell with MBPT: Neon

Next challenge: **valence protons + neutrons**

Neutron-rich fluorine and neon





JDH, Menendez, Simonis, Schwenk, in prep.

Similar behavior in Neon isotopes

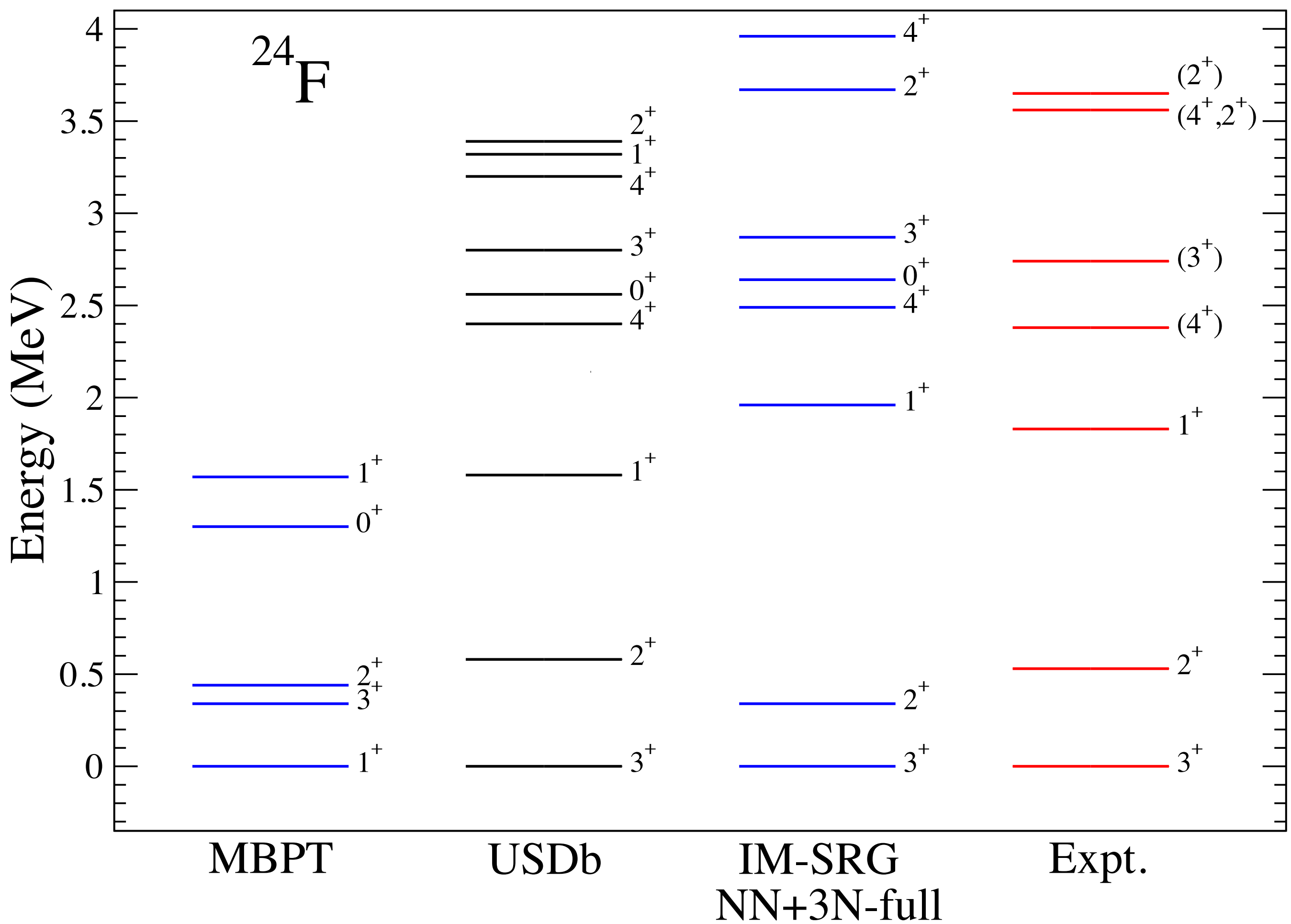
Revisit cross-shell valence space theory – **non-degenerate valence spaces**

Tsunoda, Hjorth-Jensen, Otsuka

IM-SRG energies overbound in F/Ne

Experimental Connection: ^{24}F Spectrum

Fluorine spectra: extended-space MBPT and (sd-shell) IM-SRG



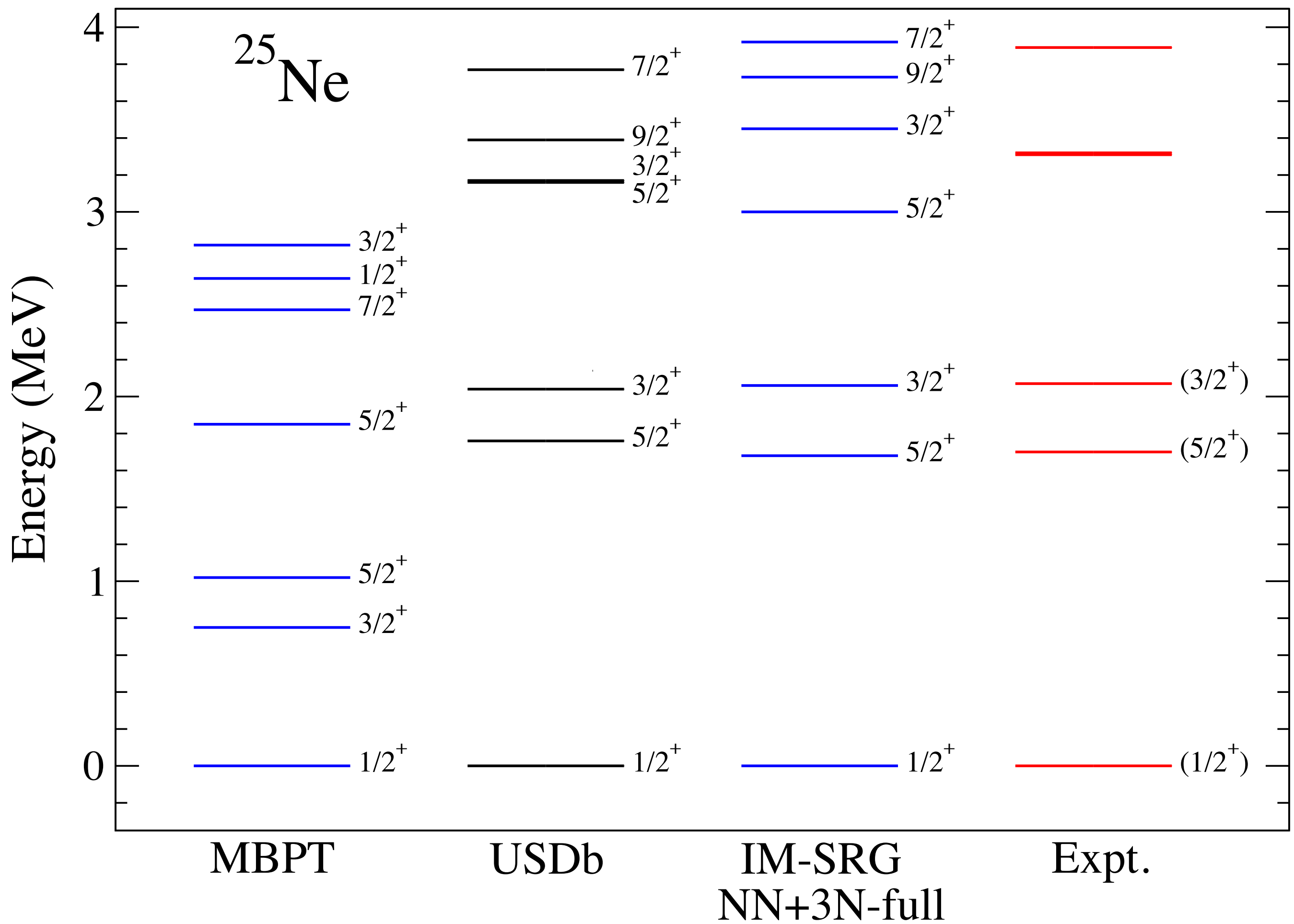
Caceres et al., in prep.

New measurements from GANIL

IM-SRG: comparable with phenomenology in good agreement with new data

^{25}Ne Spectrum

Neon spectra: extended-space MBPT and (sd-shell) IM-SRG



Bogner, Hergert, JDH, Schwenk, in prep

Limited experimental data

IM-SRG: comparable with phenomenology, good agreement with data

Calcium Isotopes

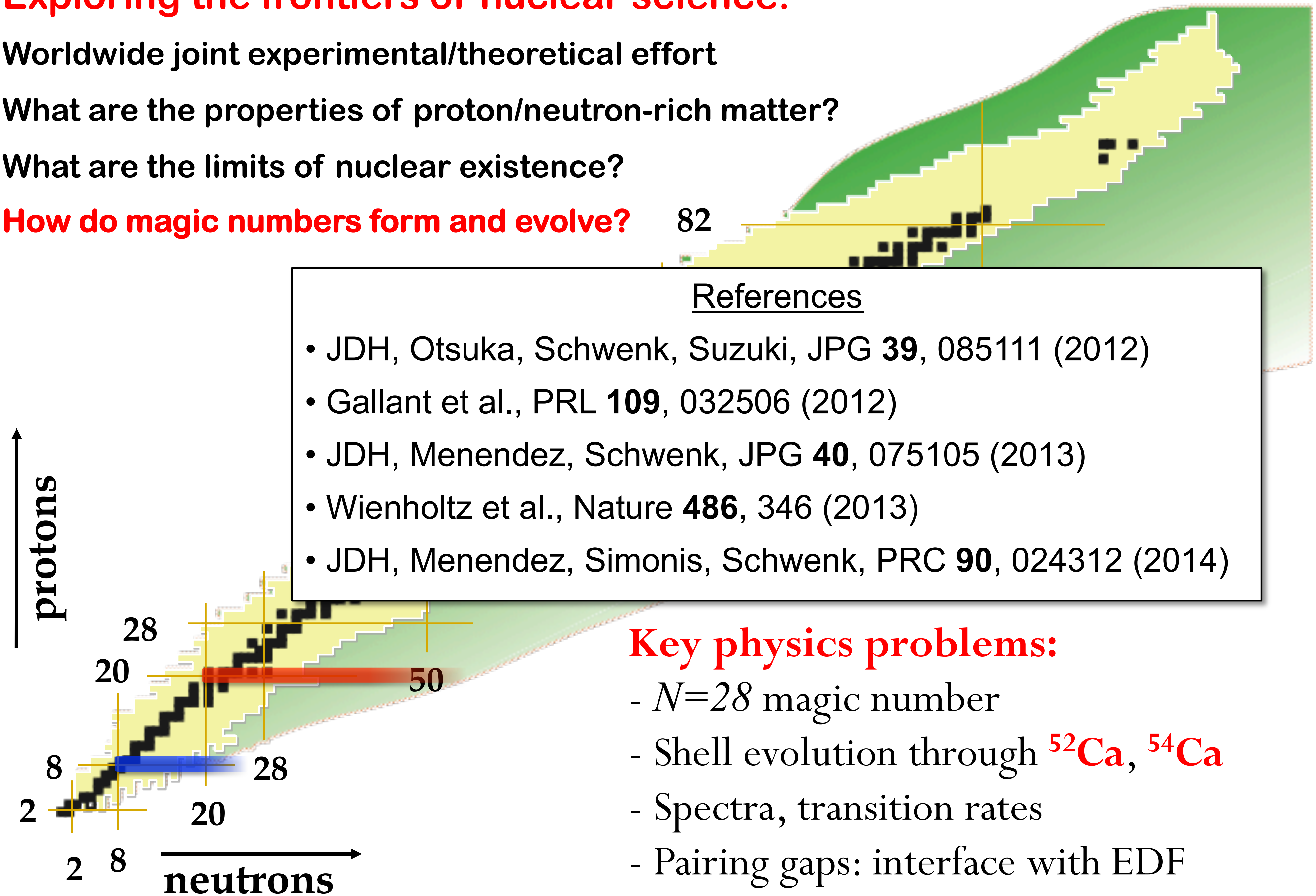
Exploring the frontiers of nuclear science:

Worldwide joint experimental/theoretical effort

What are the properties of proton/neutron-rich matter?

What are the limits of nuclear existence?

How do magic numbers form and evolve?



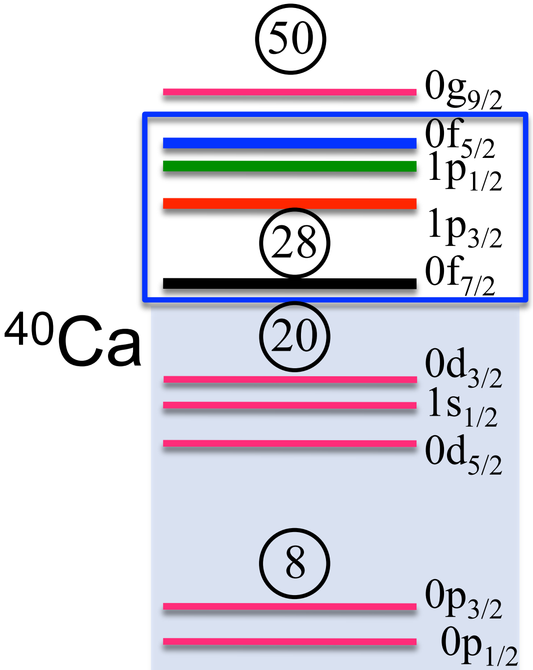
References

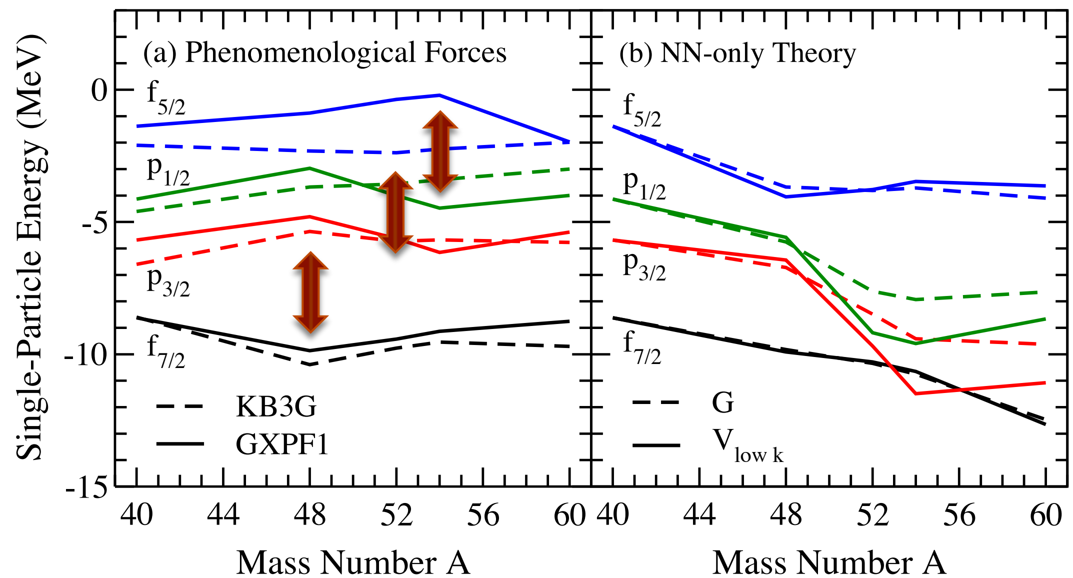
- JDH, Otsuka, Schwenk, Suzuki, JPG **39**, 085111 (2012)
- Gallant et al., PRL **109**, 032506 (2012)
- JDH, Menendez, Schwenk, JPG **40**, 075105 (2013)
- Wienholtz et al., Nature **486**, 346 (2013)
- JDH, Menendez, Simonis, Schwenk, PRC **90**, 024312 (2014)

Key physics problems:

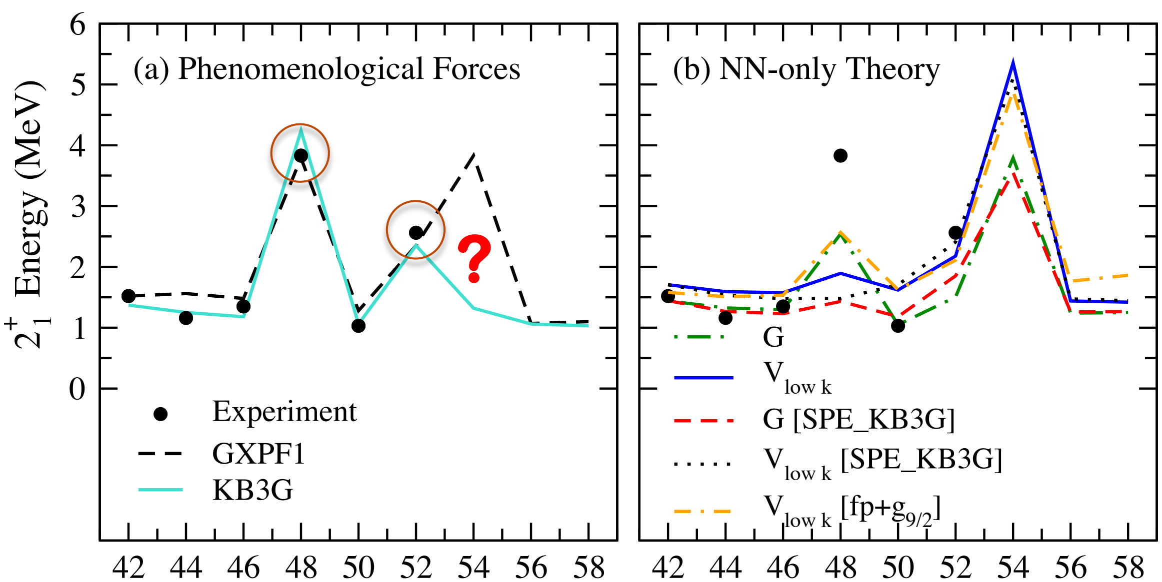
- $N=28$ magic number
- Shell evolution through ^{52}Ca, ^{54}Ca
- Spectra, transition rates
- Pairing gaps: interface with EDF

Calcium Isotopes: Magic Numbers





GXPF1: Honma, Otsuka, Brown, Mizusaki (2004)
KB3G: Poves, Sanchez-Solano, Caurier, Nowacki (2001)



Phenomenological Forces

Large gap at ^{48}Ca

Discrepancy at $N=34$

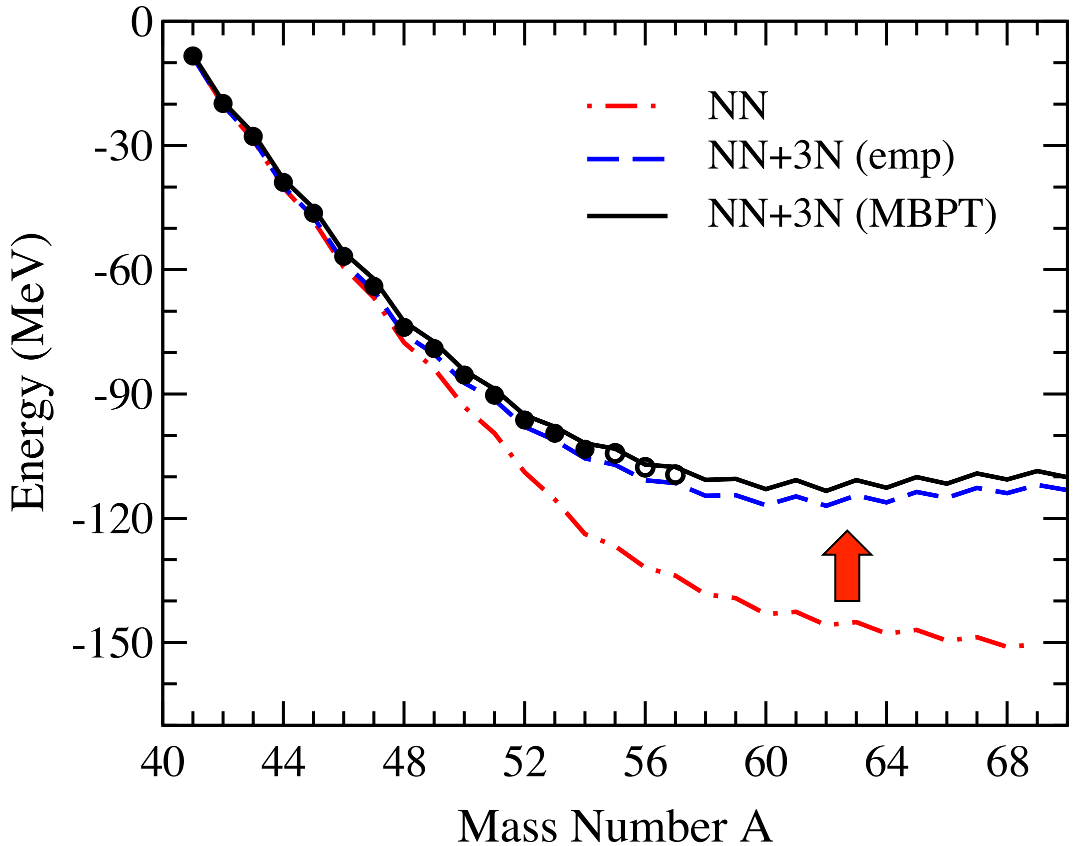
Microscopic NN Theory

Small gap at ^{48}Ca

N=28: first standard magic number not reproduced in microscopic NN theories

Calcium Ground State Energies and Dripline

Signatures of shell evolution from ground-state energies?



Holt, Otsuka, Schwenk, Suzuki, JPG (2012)

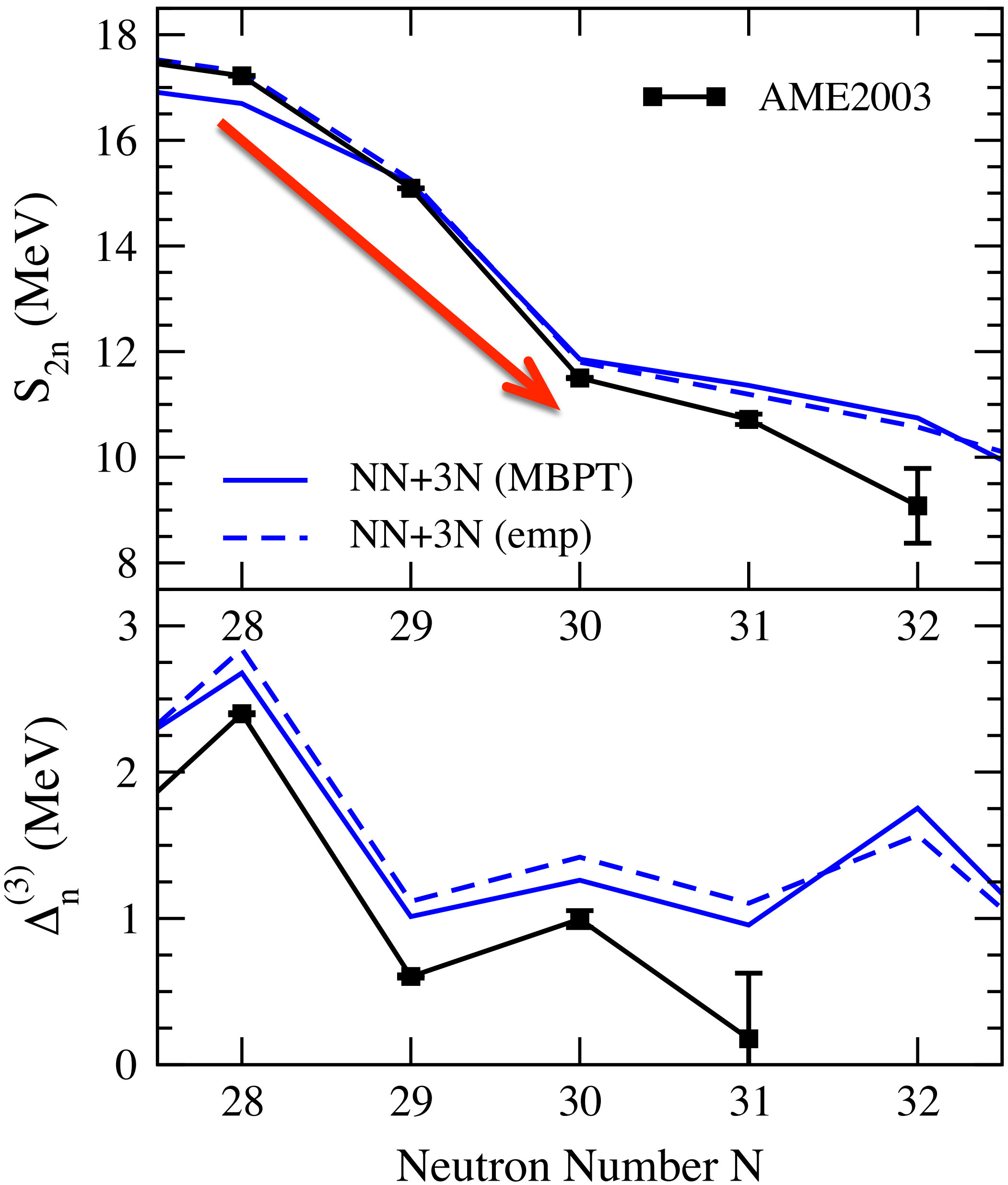
No clear dripline; flat behavior past ^{54}Ca – **Halos beyond ^{60}Ca?**

$S_{2n} = -\left[BE(N,Z) - BE(N-2,Z)\right]$ **sharp decrease indicates shell closure**

$\Delta_n^{(3)} = \frac{(-1)^N}{2}\left[BE(N+1,Z) + BE(N-1,Z) - 2BE(N,Z)\right]$ **peak indicates shell closure**

Two-Neutron Separation Energies: Mass of ^{52}Ca

Compare with AME2003 data



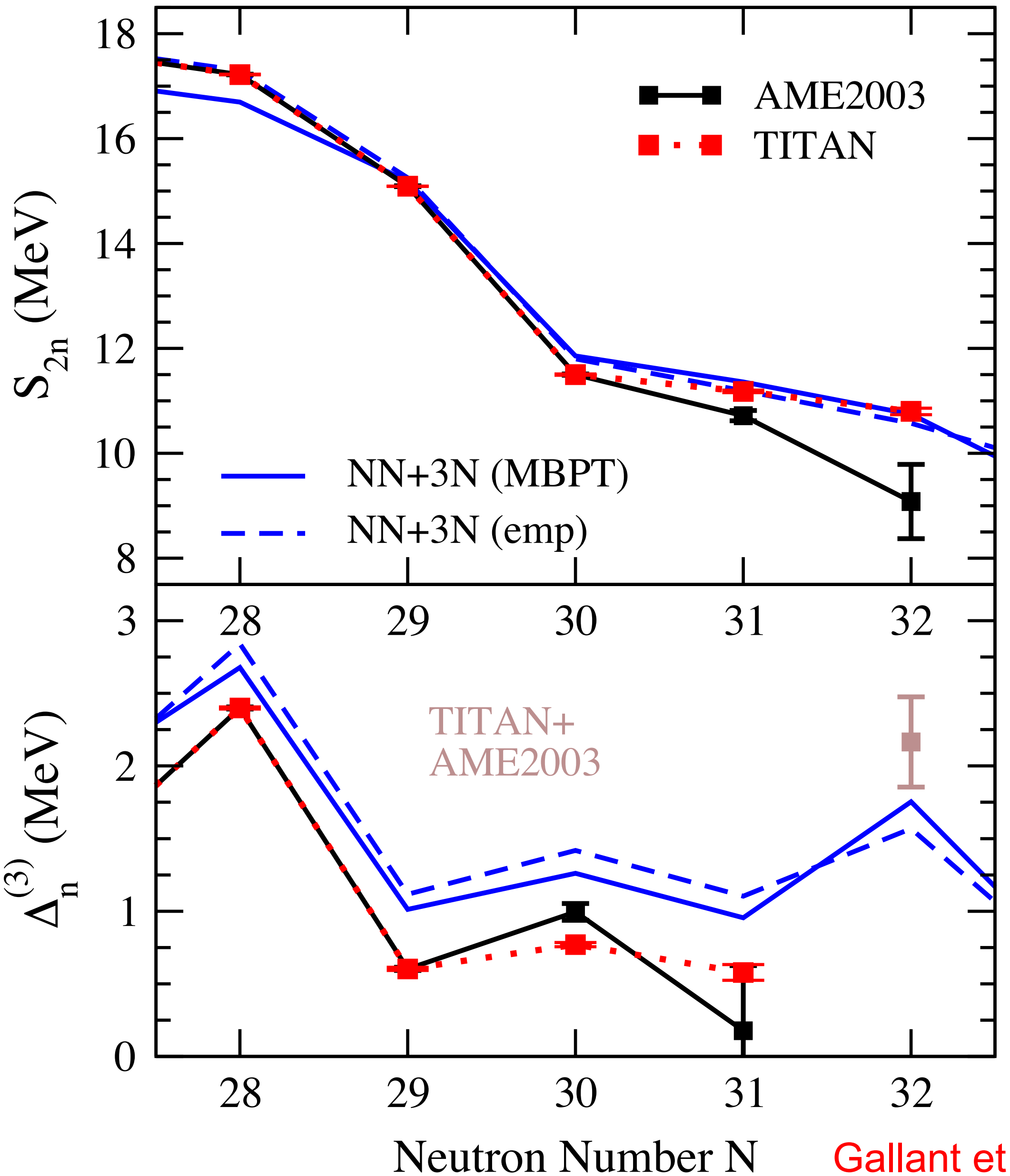
NN+3N Predictions

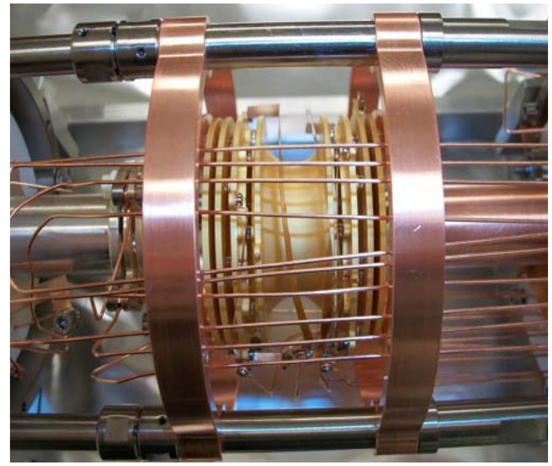
Reproduce ^{48}Ca shell closure

Predictions too bound past ^{50}Ca

Experimental Connection: Mass of ^{52}Ca

New mass measurements of ^{51,52}Ca at **TITAN**: Penning trap experiment





TRIUMF

TITAN Measurement

^{52}Ca mass 1.75MeV ***more*** bound than AME2003 value

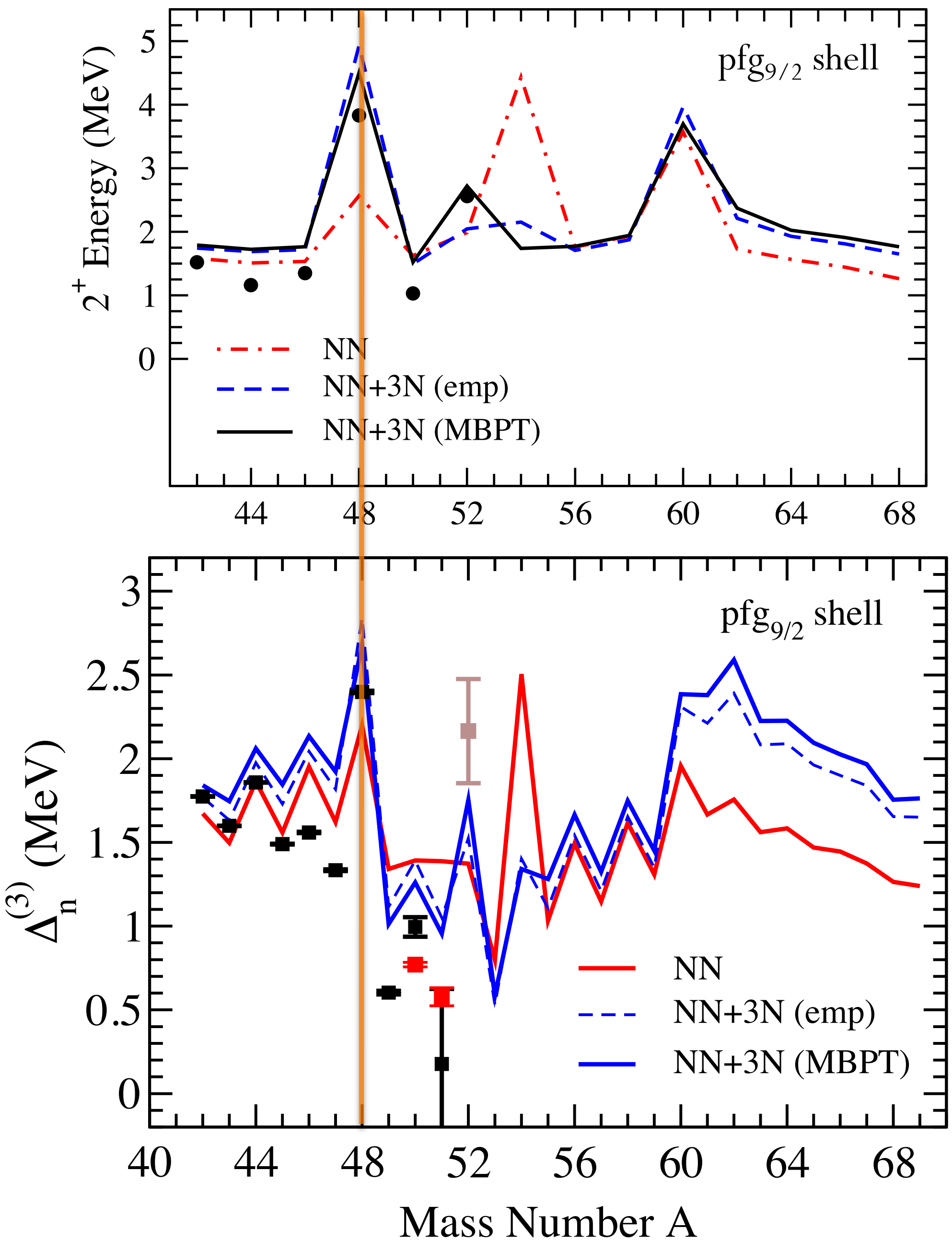
NN+3N Predictions

Confirmed with new measurements

Good reproduction of pairing gaps

Gallant et al., PRL (2012)

Pairing for Shell Evolution N=28



Peak in pairing gaps: complementary signature for shell closure

Compare with 2^+ energies for Ca

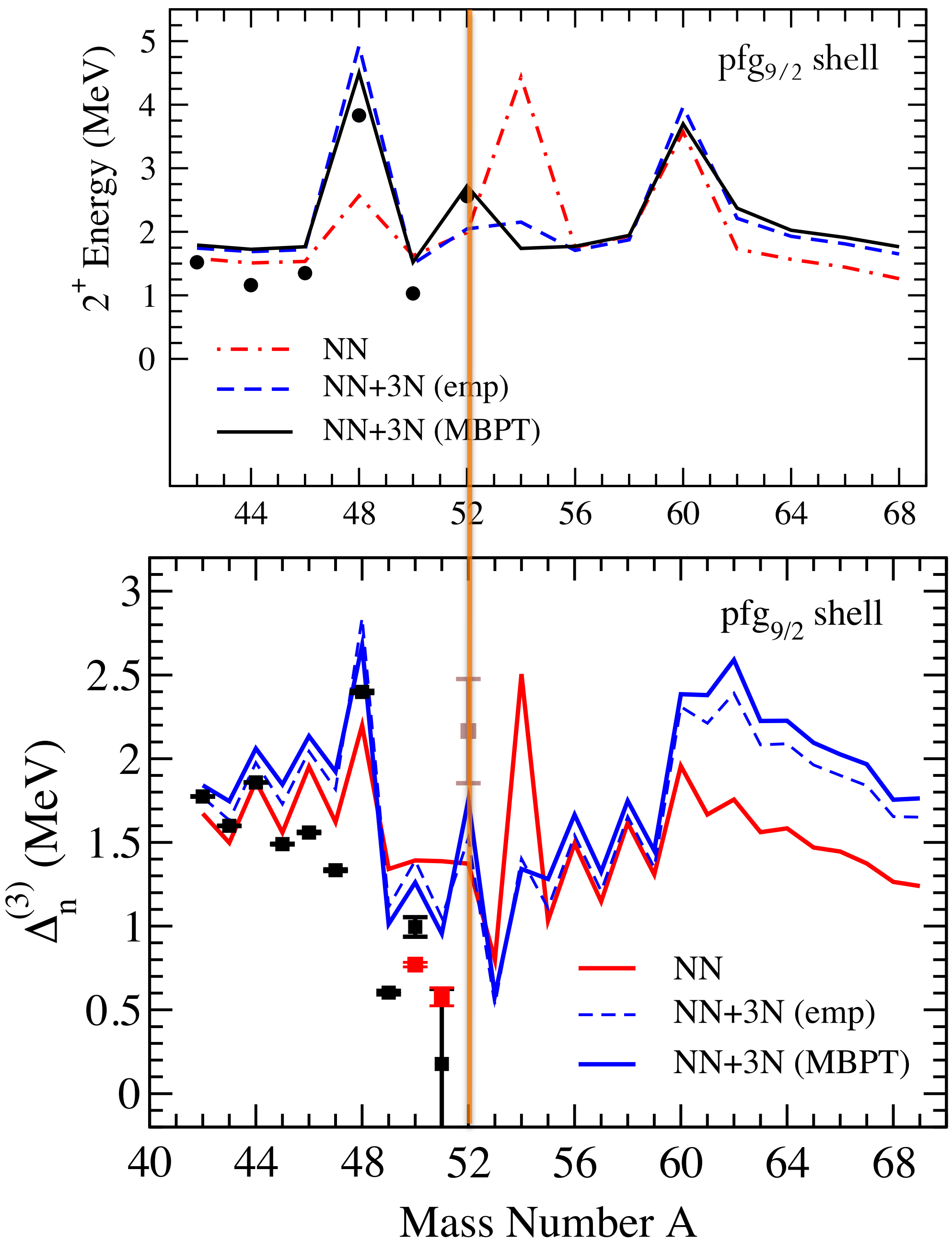
Agreement with CC throughout chain

Hagen et al. PRL (2012)

N=28 strong peak

JDH, Menendez, Schwenk, JPG (2013)

Pairing for Shell Evolution N=32



Peak in pairing gaps: complementary signature for shell closure

Compare with 2^+ energies for Ca

Agreement with CC throughout chain

Hagen et al. PRL (2012)

N=28 strong peak

N=32 moderate peak

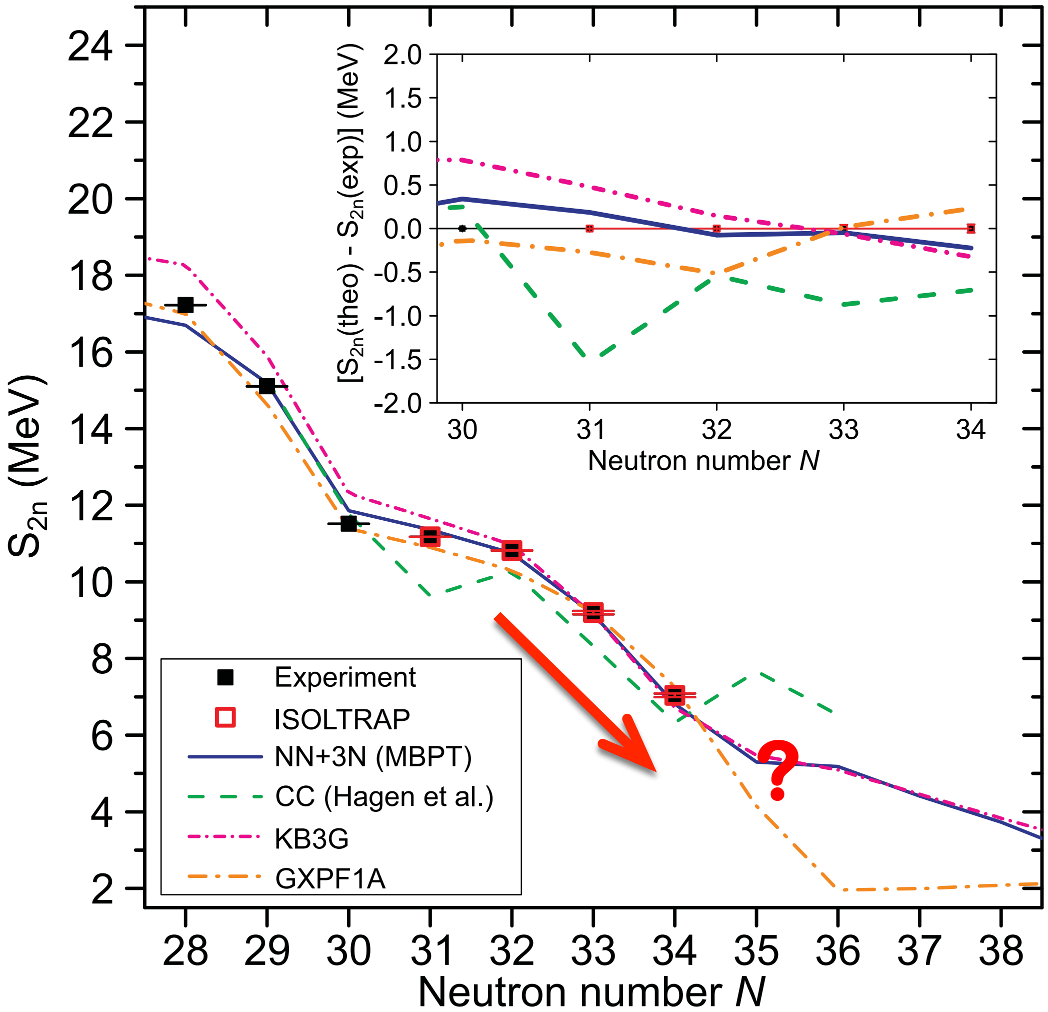
Close to data with new TITAN value

Experimental measurement of ^{53}Ca mass needed to reduce uncertainty

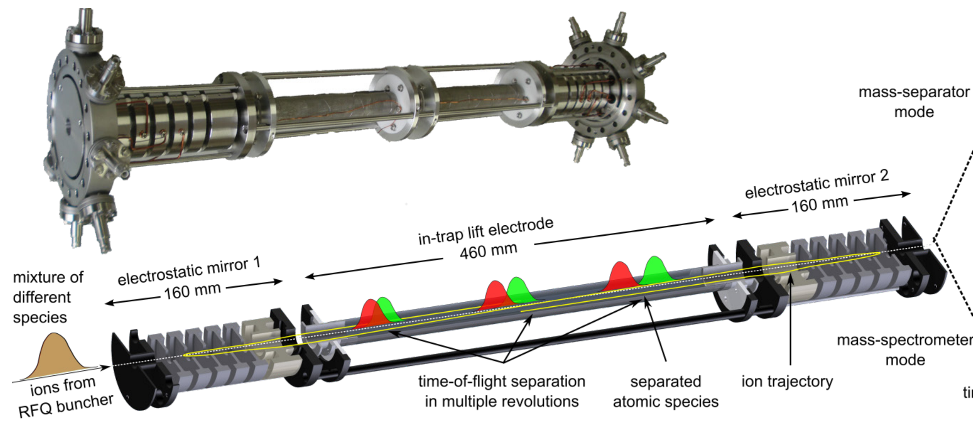
JDH, Menendez, Schwenk, JPG (2013)

Experimental Connection: Mass of ^{54}Ca

New precision mass measurement of ^{53,54}Ca at **ISOLTRAP**: multi-reflection ToF



Wienholtz et al., Nature (2013)



ISOLTRAP *Measurement*

Sharp decrease past ^{52}Ca

Unambiguous closed-shell ^{52}Ca

Test predictions of various models

MBPT NN+3N

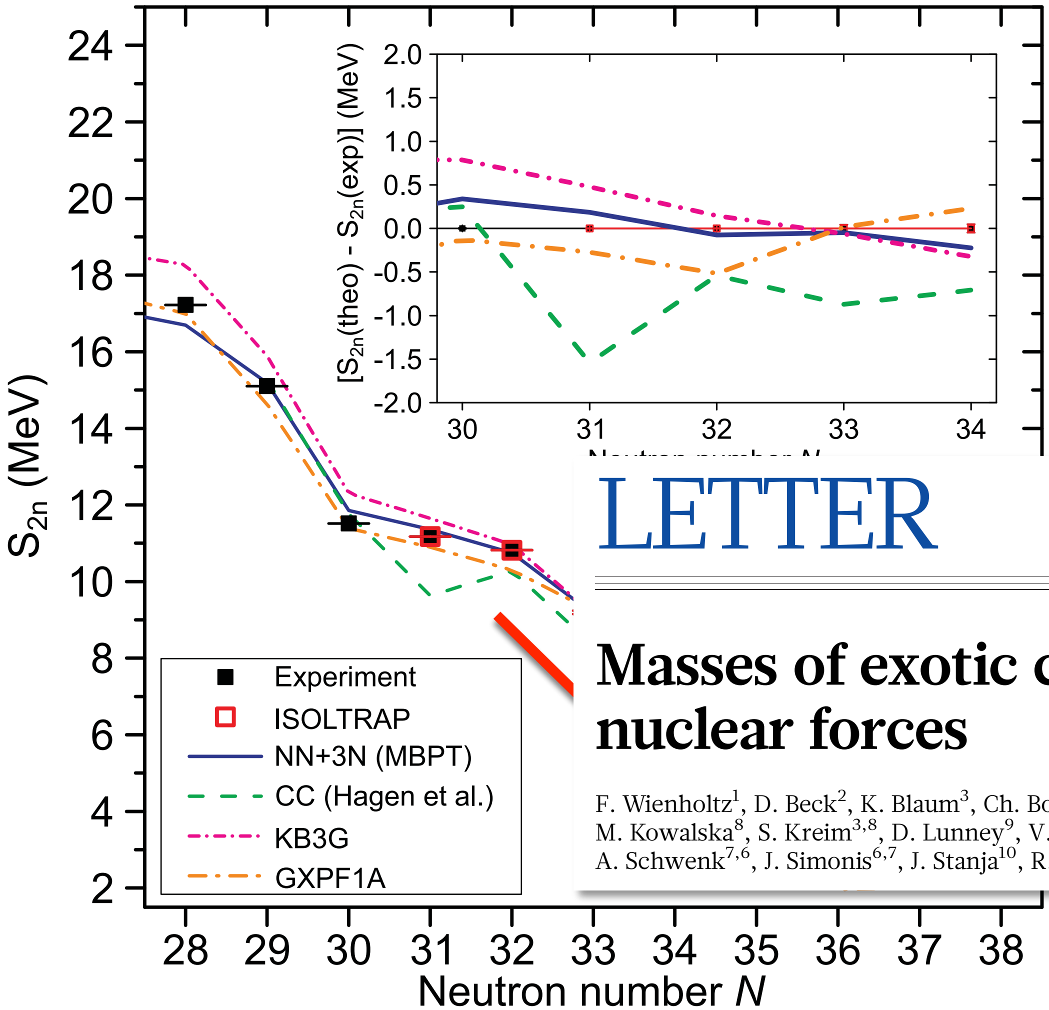
Excellent agreement with new data

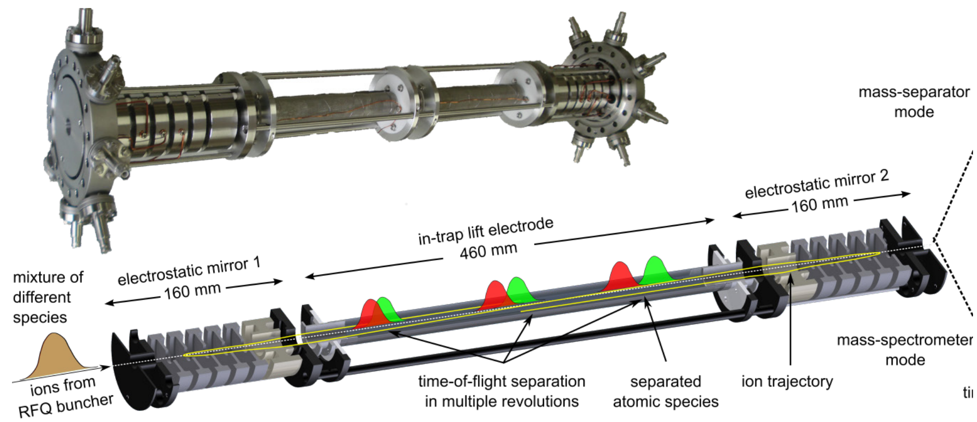
Reproduces closed-shell ^{48,52}Ca

Weak closed sell signature past ^{54}Ca

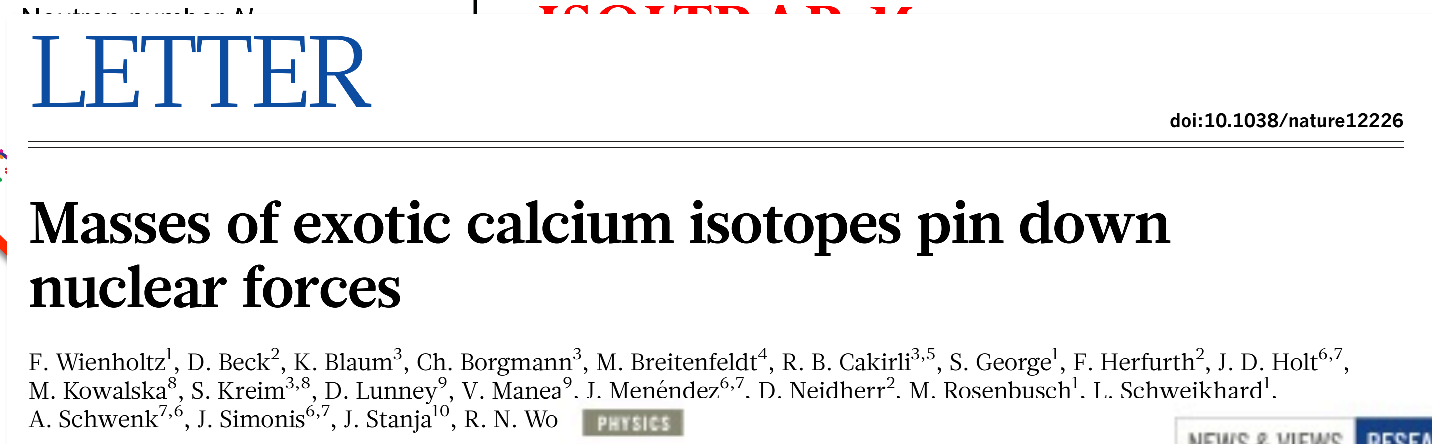
Experimental Connection: Mass of ^{54}Ca

New precision mass measurement of ^{53,54}Ca at **ISOLTRAP**: multi-reflection ToF





Wienholtz et al., Nature (2013)

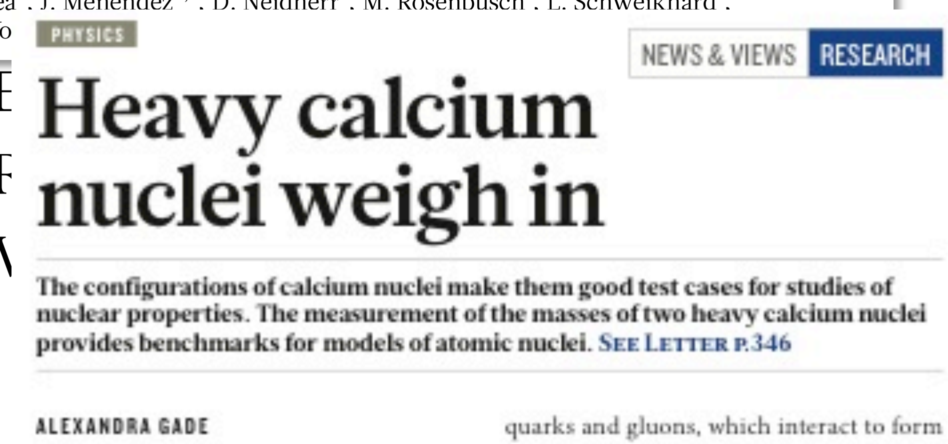


LETTER

doi:10.1038/nature12226

Masses of exotic calcium isotopes pin down nuclear forces

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



PHYSICS

NEWS & VIEWS RESEARCH

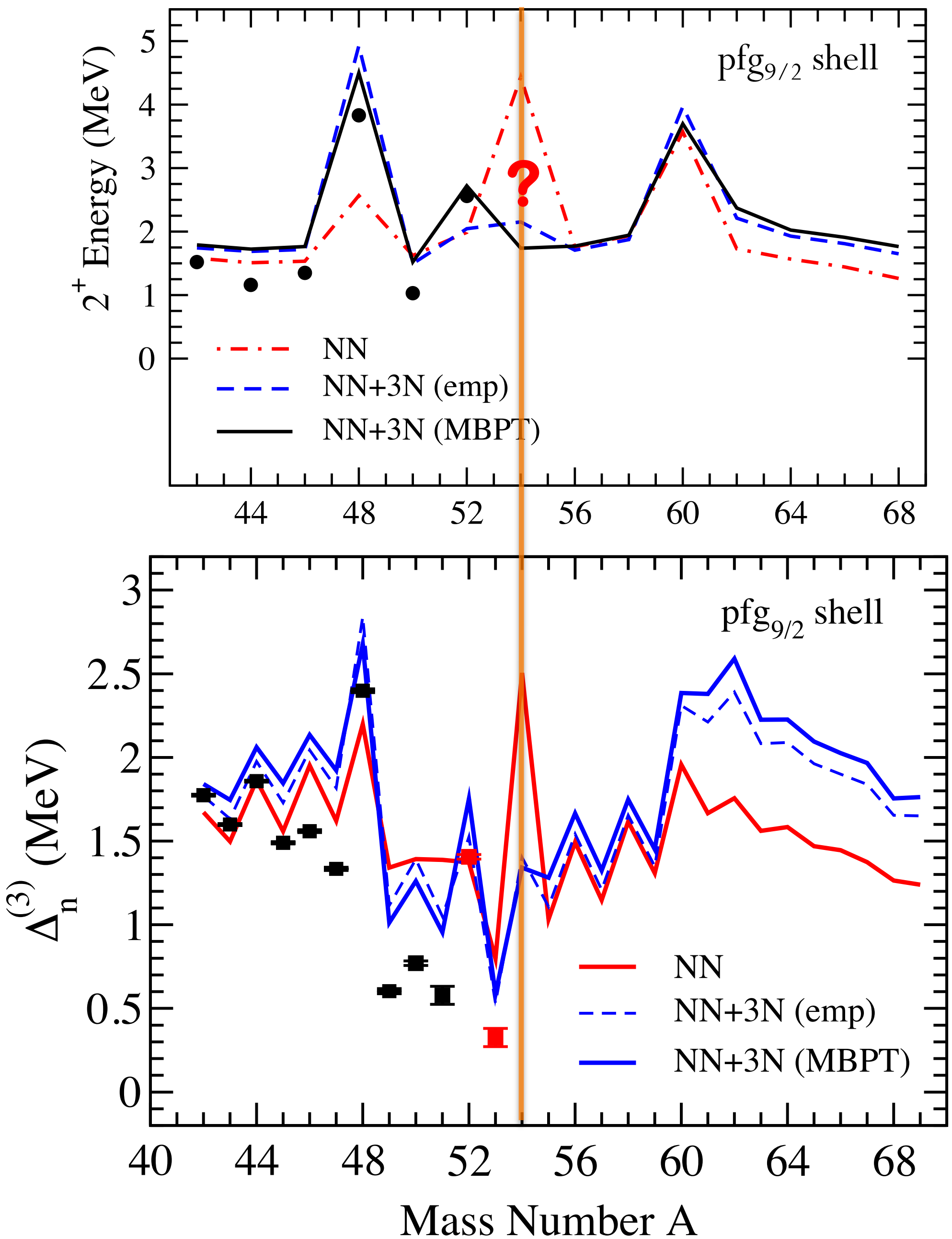
Heavy calcium nuclei weigh in

The configurations of calcium nuclei make them good test cases for studies of nuclear properties. The measurement of the masses of two heavy calcium nuclei provides benchmarks for models of atomic nuclei. SEE LETTER P.346

ALEXANDRA GADE

quarks and gluons, which interact to form

Pairing for Shell Evolution N=34



Peak in pairing gaps: complementary signature for shell closure

Compare with 2^+ energies for Ca

Agreement with CC throughout chain

Hagen et al. PRL (2012)

N=28 strong peak

N=32 moderate peak

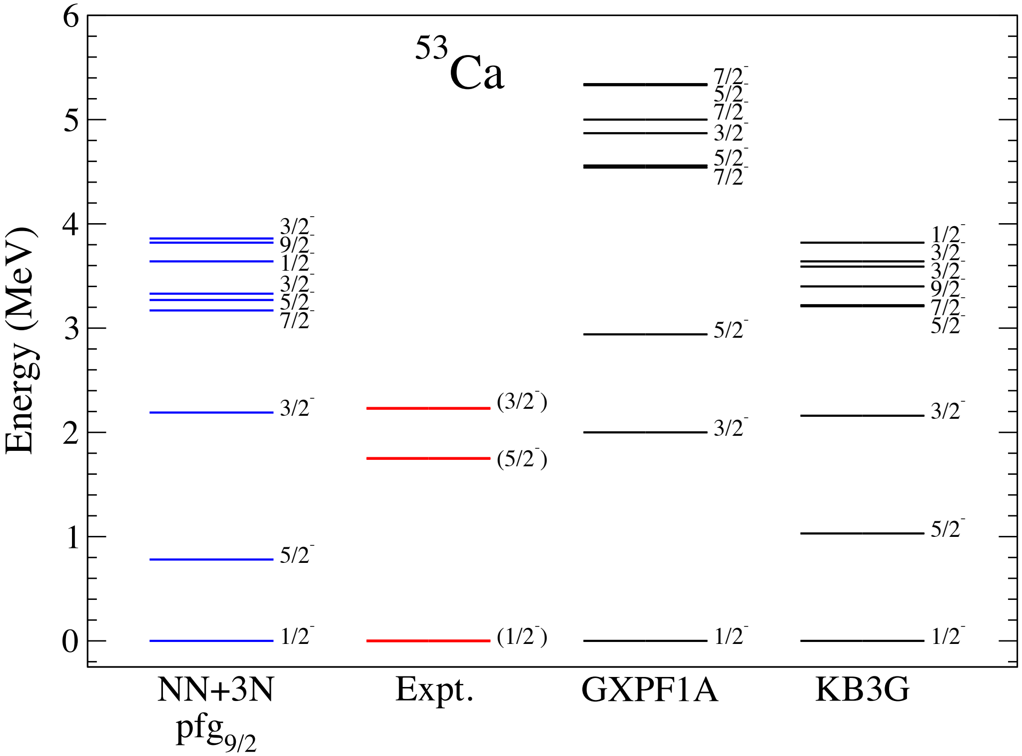
N=34 weak signature

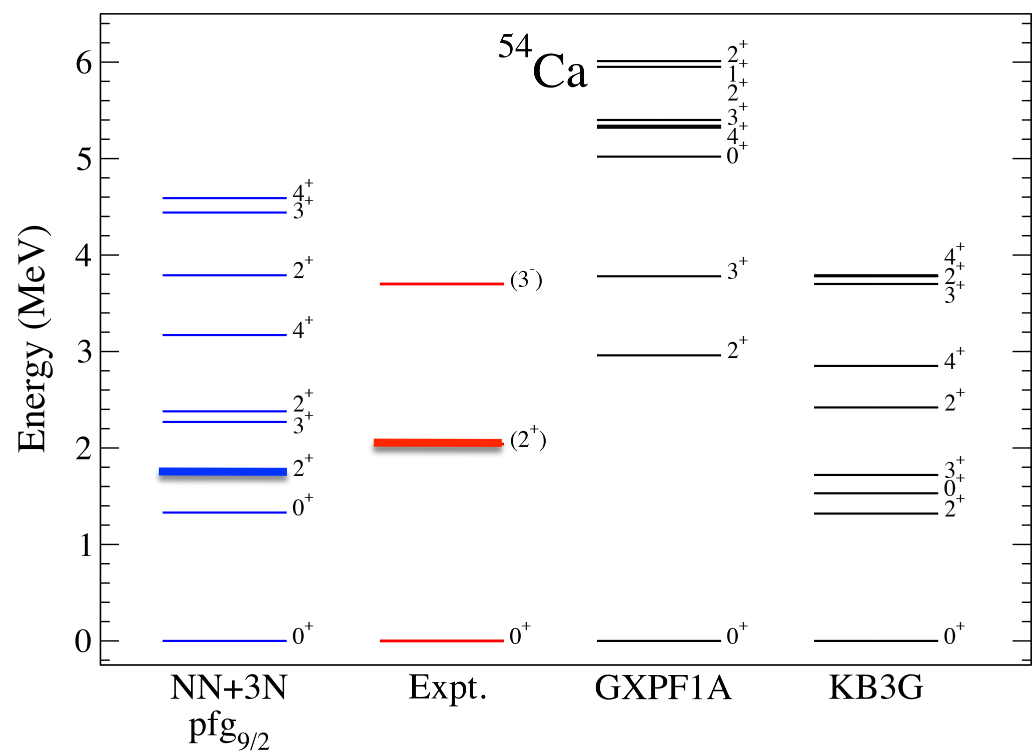
3N forces suppress closed-shell feature

JDH, Menendez, Schwenk, JPG (2013)

Neutron-Rich Ca Spectra Near N=34

Neutron-rich calcium spectra with NN+3N





JDH, Menendez, Schwenk, JPG (2013)
JDH, Menendez, Simonis, Schwenk, PRC (2014)

Phenomenology: inconsistent predictions

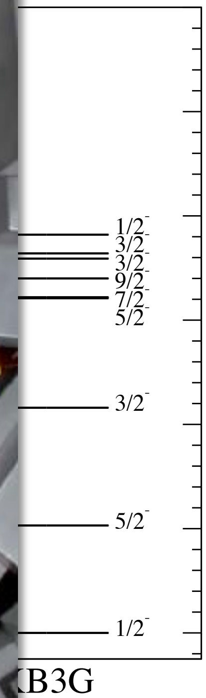
NN+3N: signature of new *N=34* magic number (also predicted in CC theory)

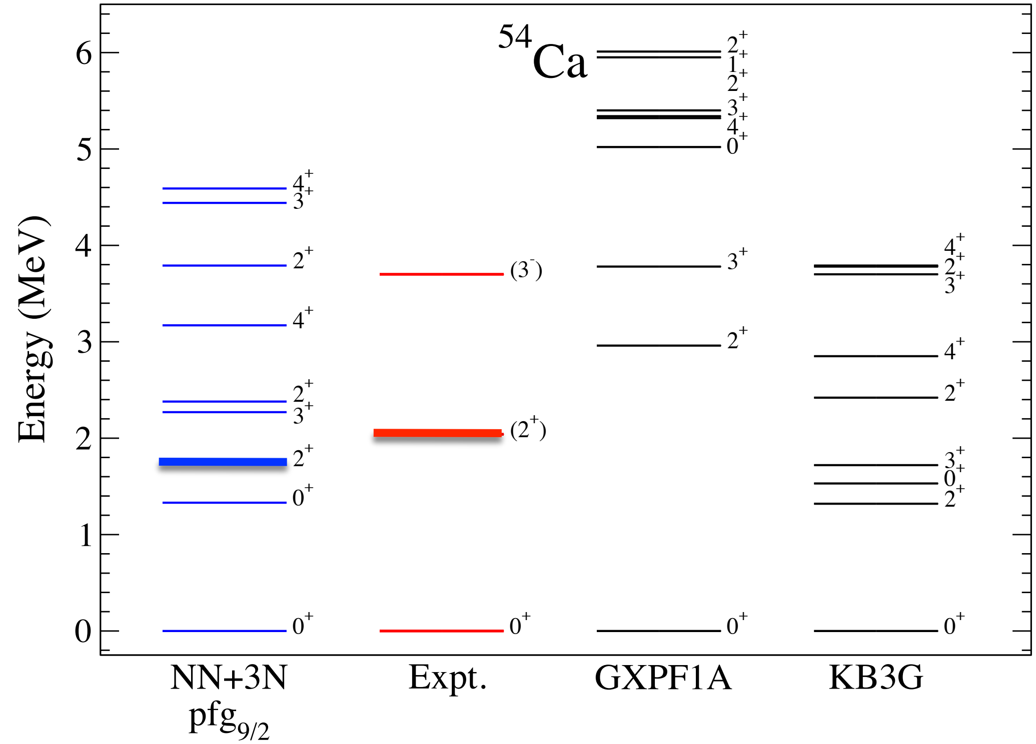
Agrees with new measurements from RIKEN

Steppenbeck et al., Nature (2013)

Neutron-Rich Ca Spectra Near N=34

Neutron-rich calcium spectra with NN+3N





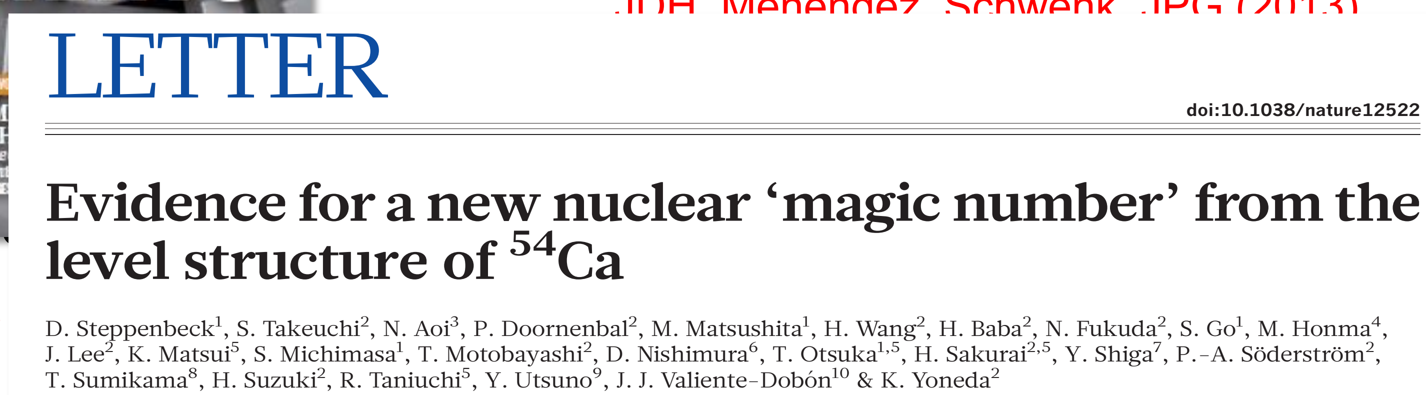
JDH, Menendez, Schwenk, JPG (2013)

2014)

NN+3N: signature

)

Agrees with new



LETTER

doi:10.1038/nature12522

Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

Steppenbeck et al., Nature (2013)

New Directions and Outlook

Heavier semi-magic chains: Nickel and Tin

Ab initio valence-shell Hamiltonians
- Towards full sd- and pf-shells
- Revisit cross-shell theory

Moving beyond stability
- Continuum effects near driplines

Islands of inversion in sd/pf regions
- Exotic cores

Map driplines in sd region?

Fundamental symmetries
- Non-empirical calculation of $0\nu\beta\beta$ decay
- Effective electroweak operators
- WIMP-nucleus scattering