Three-Nucleon Forces and the Structure of Exotic Nuclei

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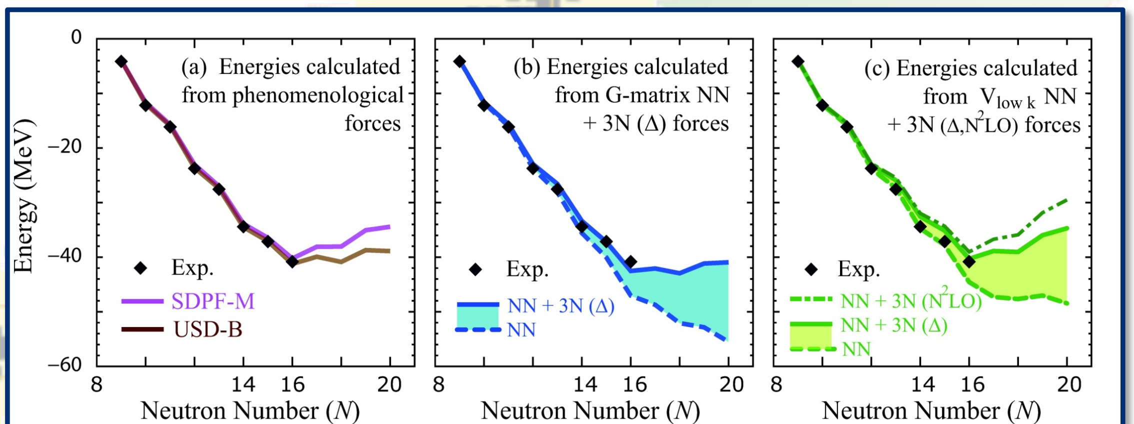
THE UNIVERSITY of TENNESSEE KNOXVILLE



OAK RIDGE NATIONAL LABORATORY

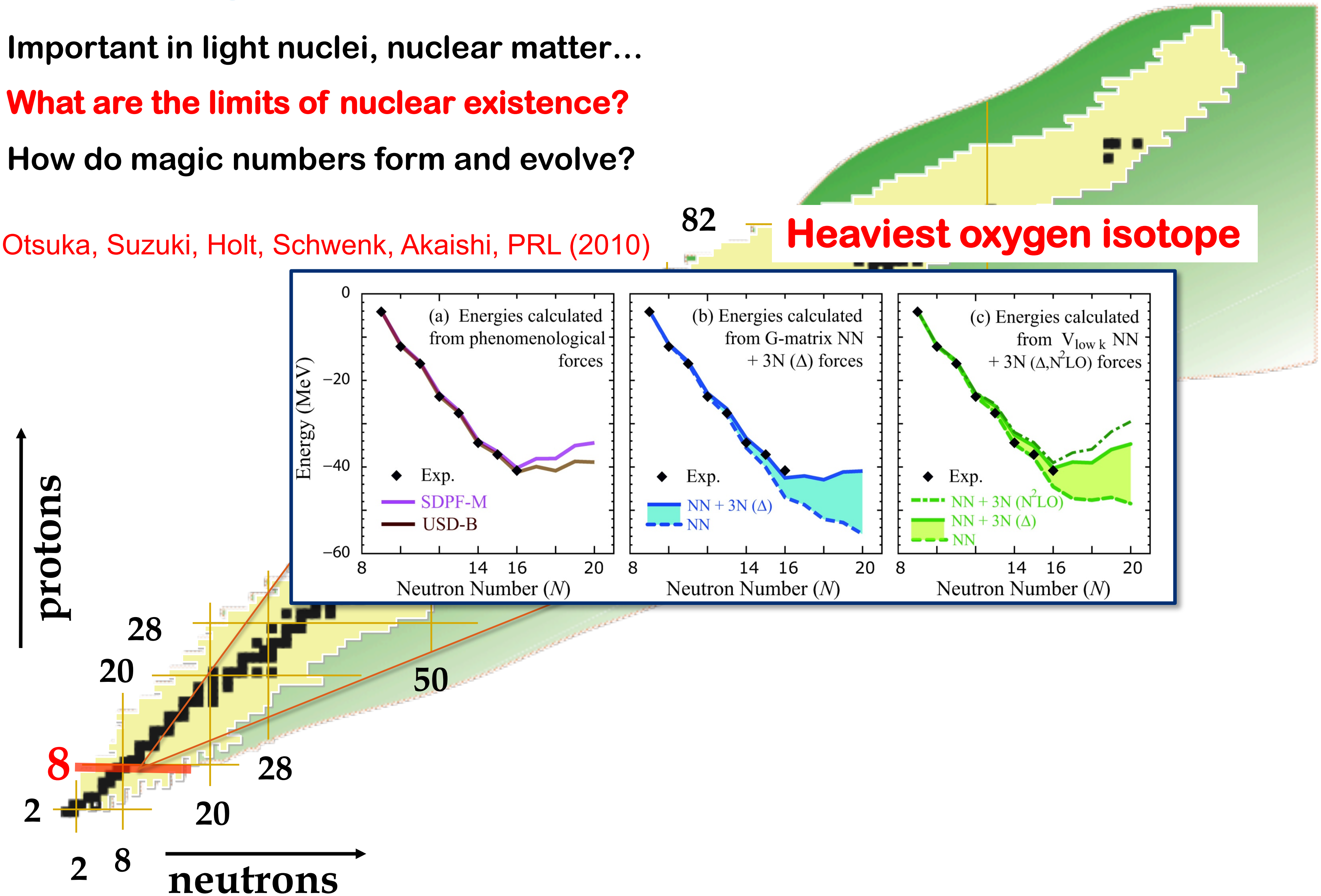
Drip Lines and Magic Numbers: 3N Forces in Medium-Mass Nuclei

Important in light nuclei, nuclear matter…

What are the limits of nuclear existence?

How do magic numbers form and evolve?

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



Drip Lines and Magic Numbers:
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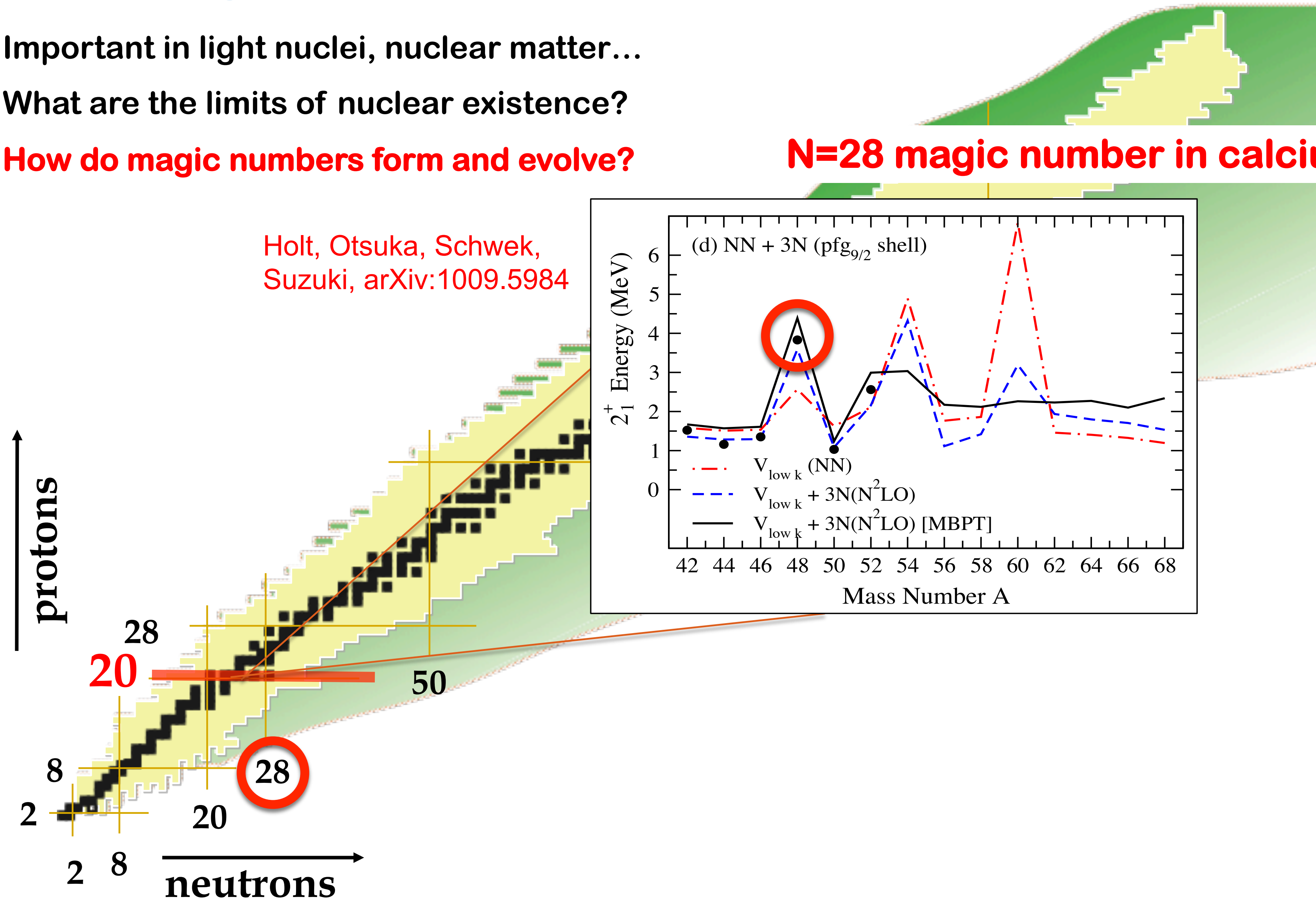
N=28 magic number in calcium

Holt, Otsuka, Schwek, Suzuki, arXiv:1009.5984



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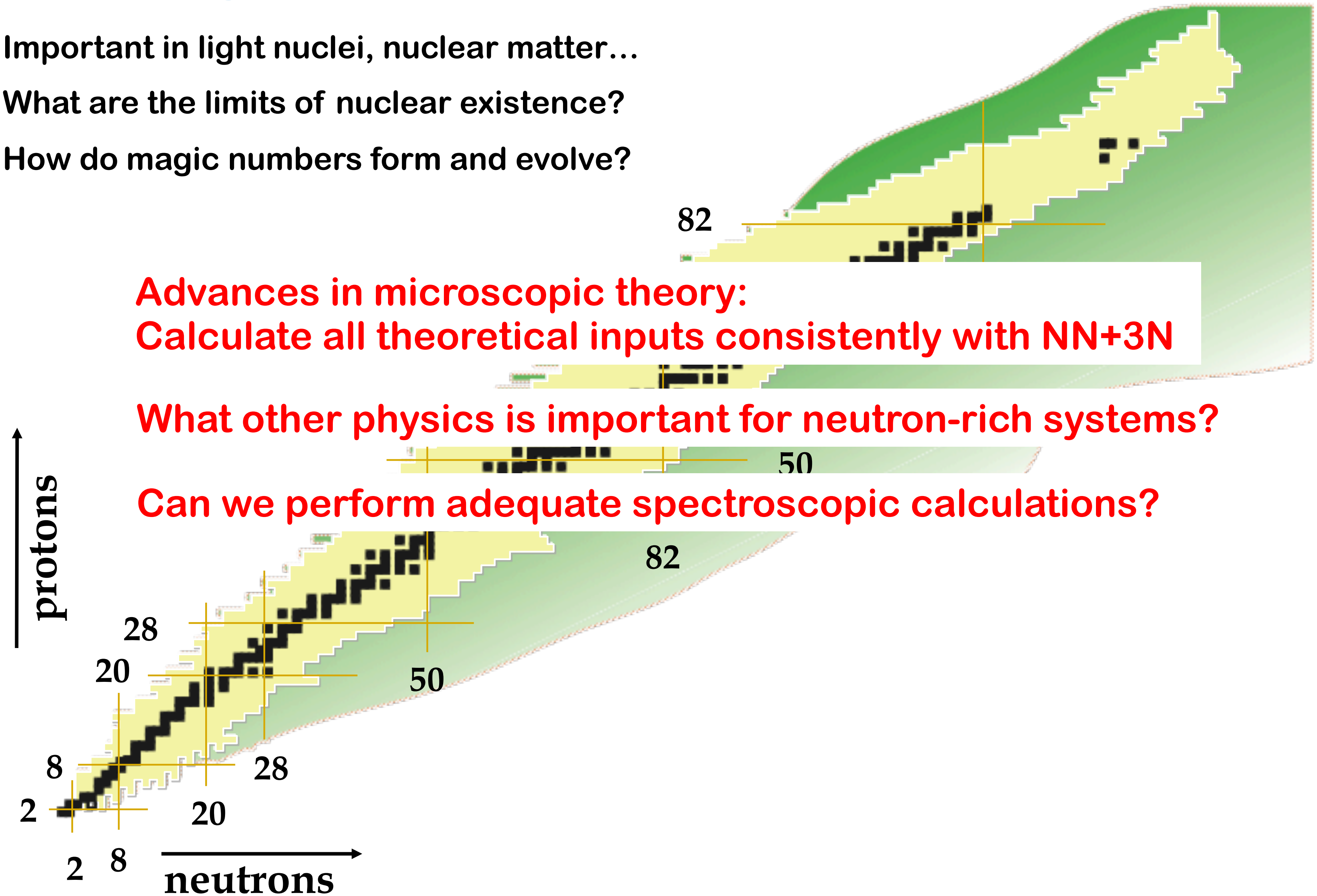


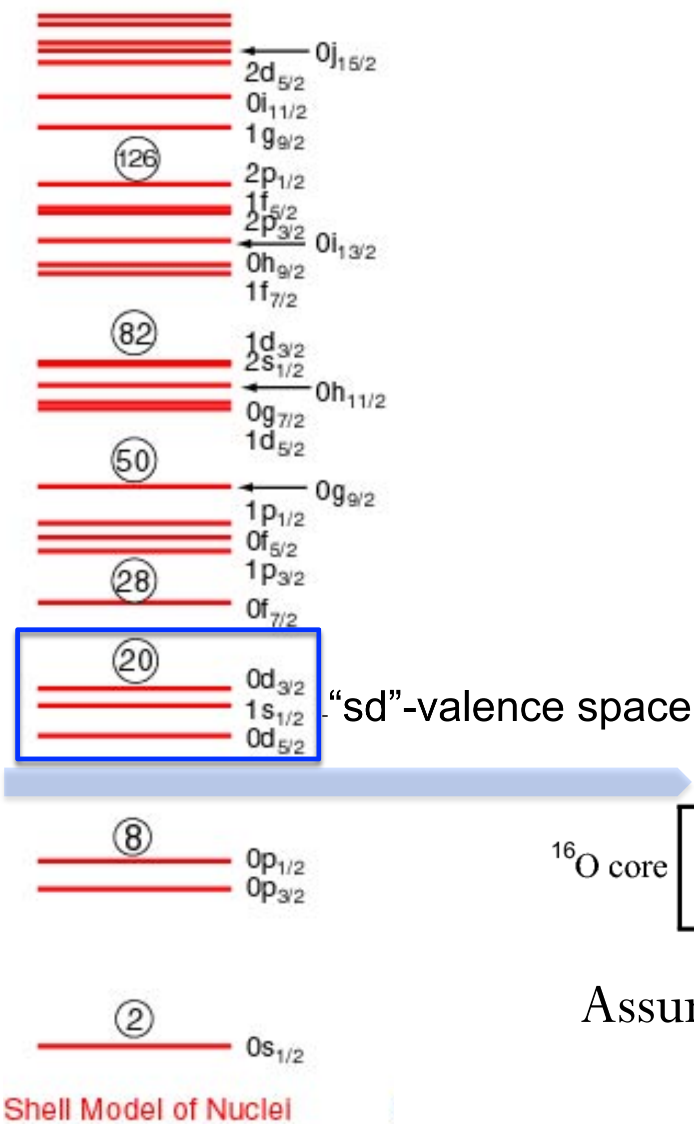
Advances in microscopic theory:
Calculate all theoretical inputs consistently with NN+3N

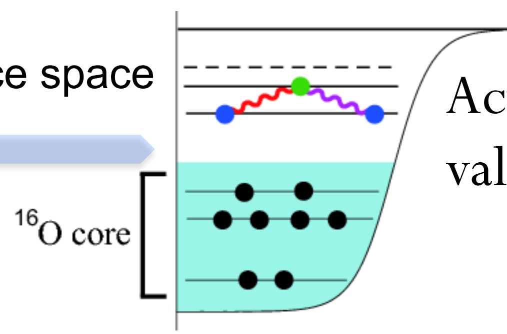
What other physics is important for neutron-rich systems?

Can we perform adequate spectroscopic calculations?

Solving the Nuclear Many-Body Problem

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





Active nucleons occupy valence space

Assume filled core

Solving the Nuclear Many-Body Problem

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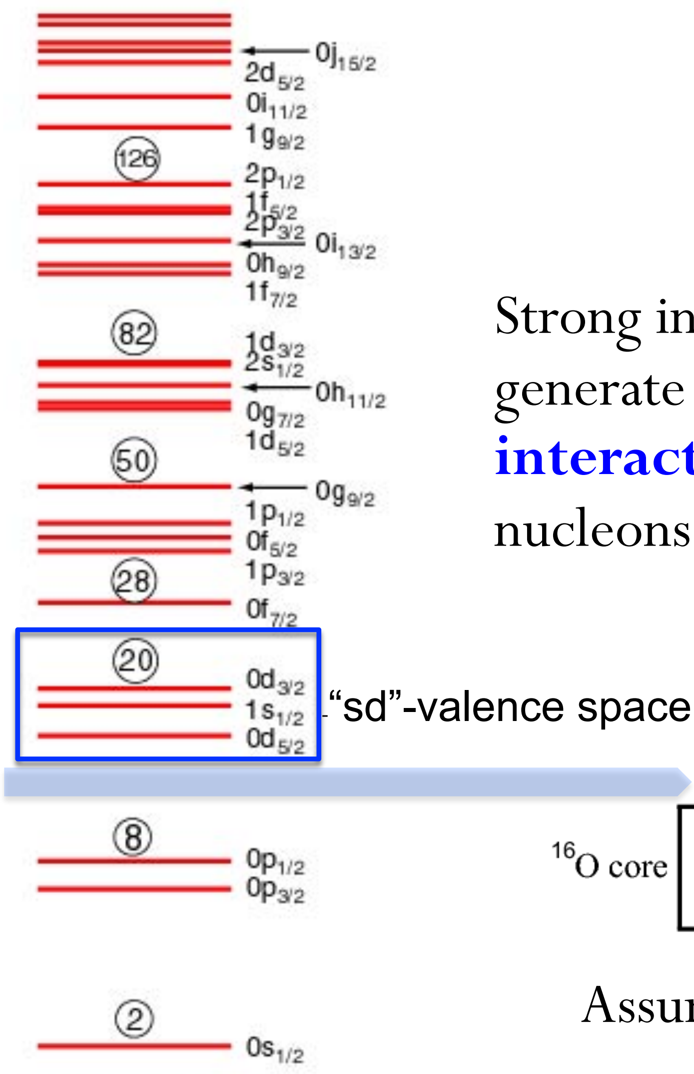
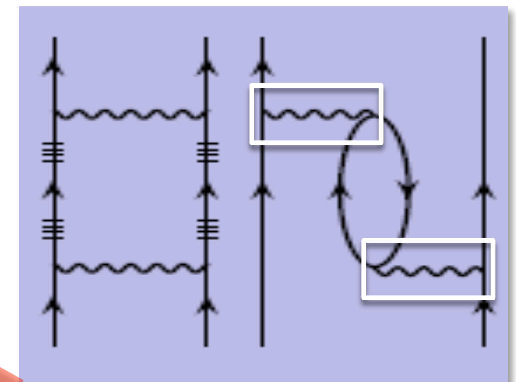
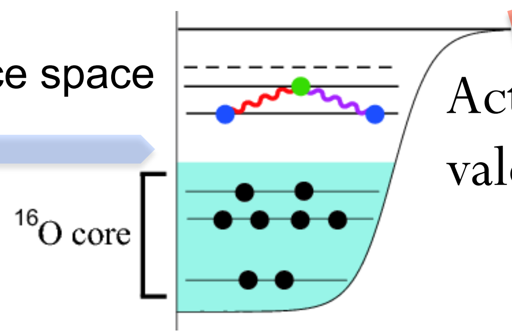


Shell Model of Nuclei

Strong interactions with core generate **effective interaction** between valence nucleons

Hjorth-Jensen, Kuo, Osnes (1995)





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Assume filled core

Solving the Nuclear Many-Body Problem

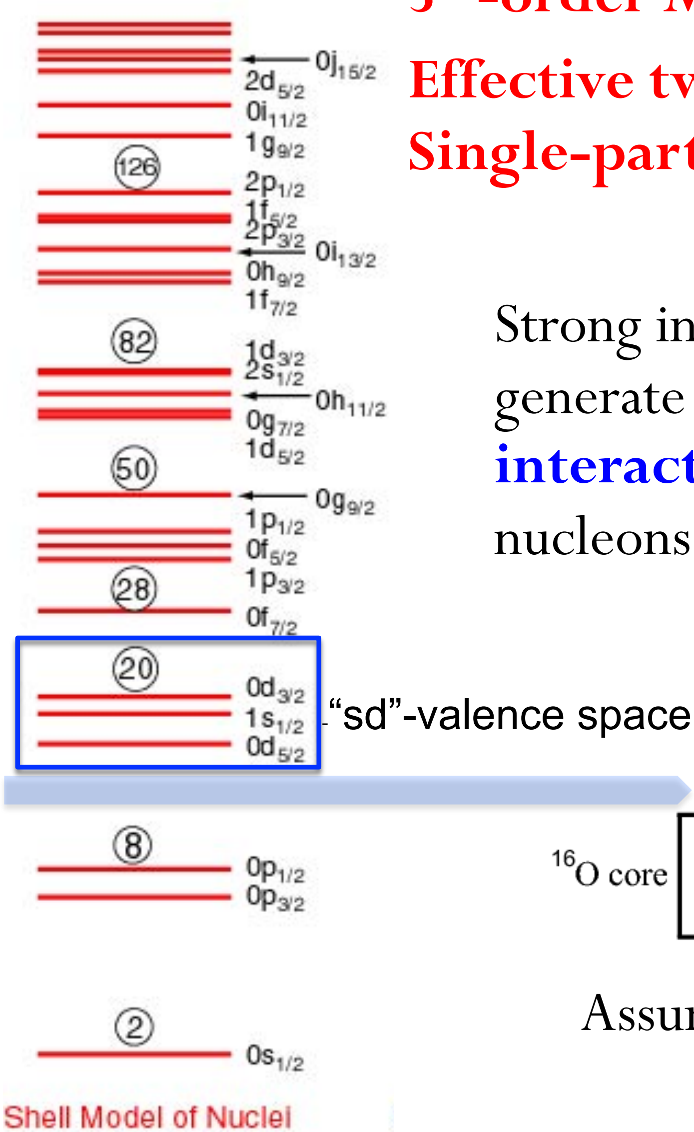
Nuclei understood as many-body system starting from closed shell, add nucleons

3rd-order MBPT: intermediate states to 13 major shells

Effective two-body interaction

Single-particle energies (SPEs)

Hjorth-Jensen, Kuo, Osnes (1995)



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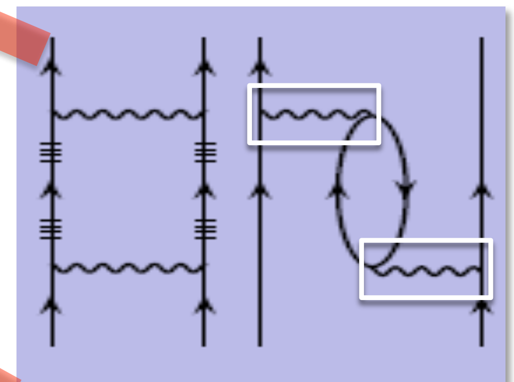
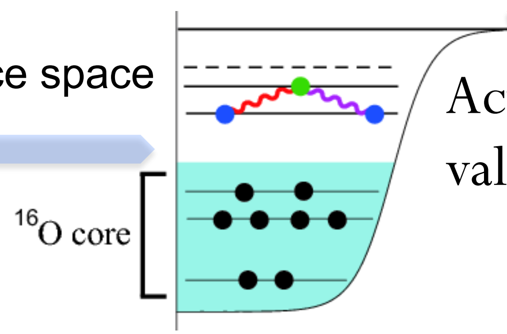




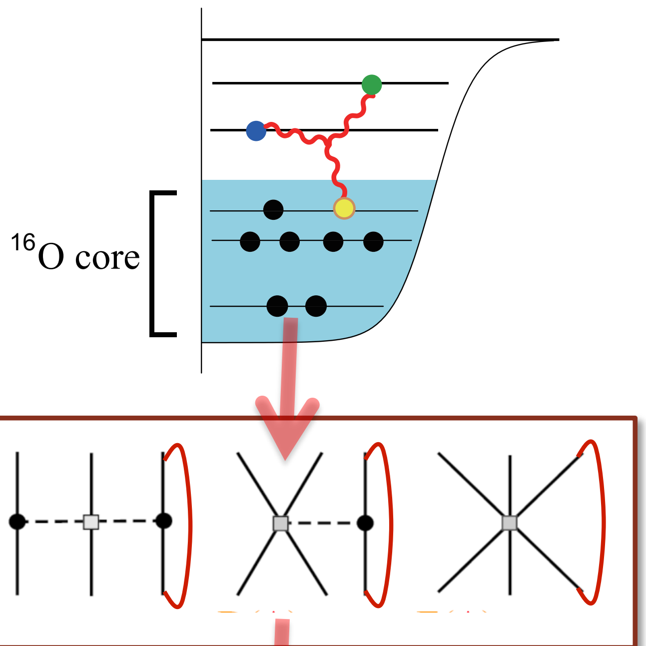
Active nucleons occupy valence space

Assume filled core

3N Forces for Valence-Shell Theories

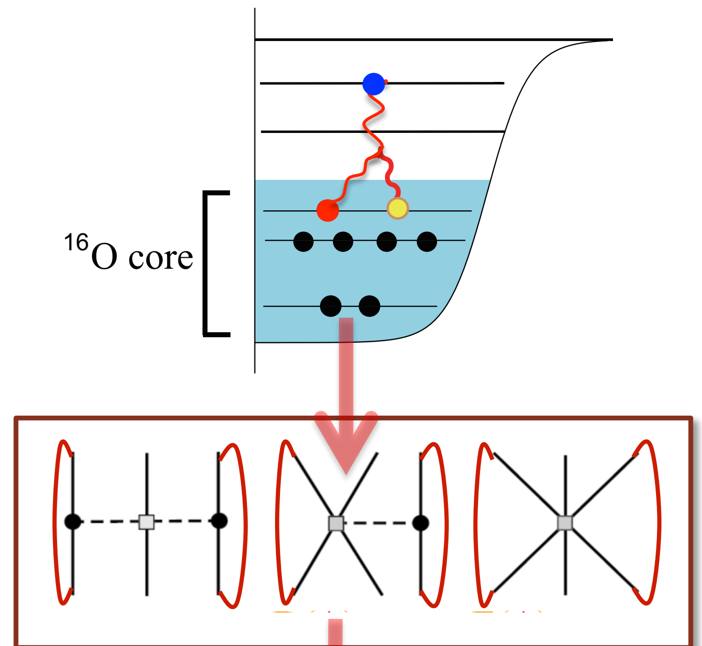
Normal-ordered 3N: contribution to valence neutron interactions

Effective two-body



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

Effective one-body

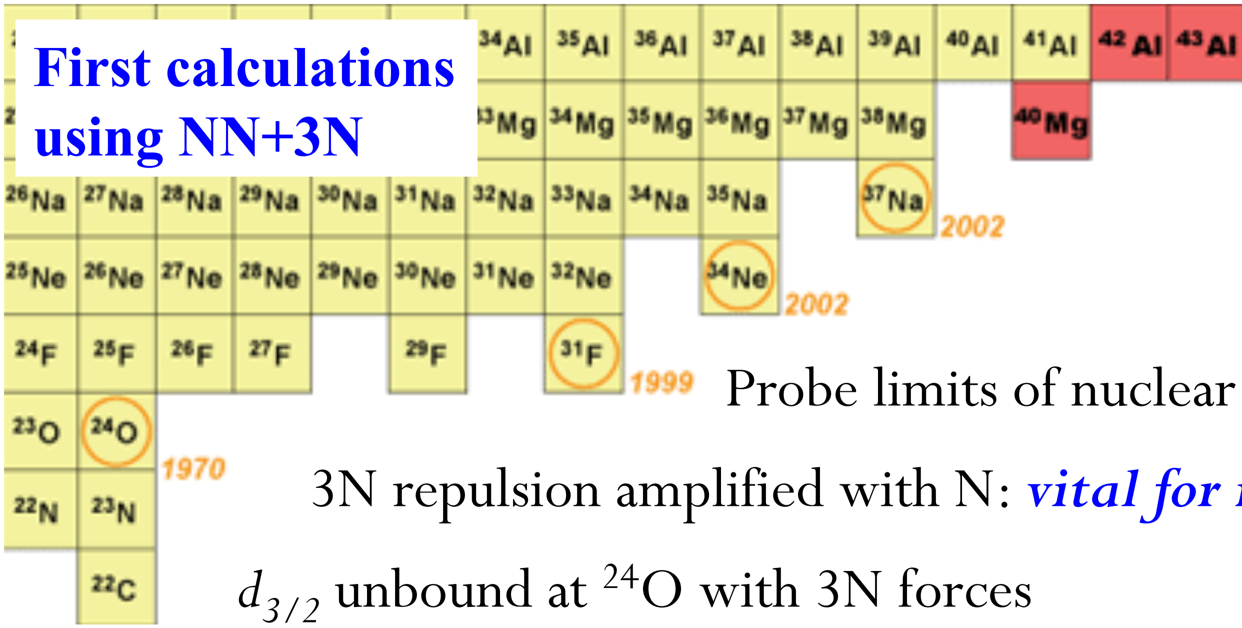


$$\langle a | V_{3N,\text{eff}} | a' \rangle = \frac{1}{2} \sum_{\alpha\beta=core} \langle \alpha\beta a | V_{3N} | \alpha\beta a' \rangle$$

Combine with microscopic NN: eliminate empirical adjustments

Oxygen Anomaly

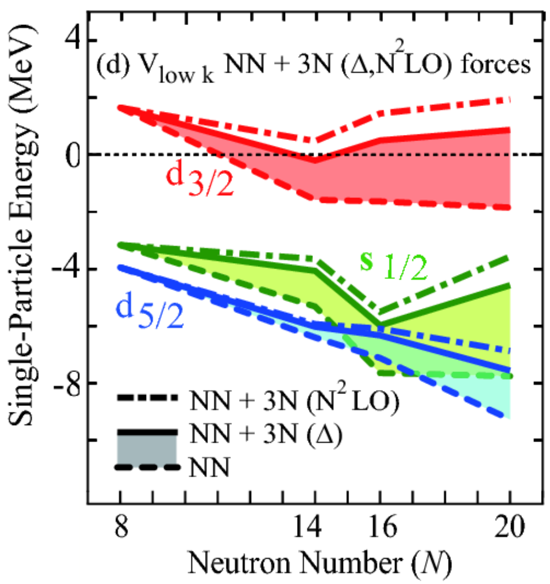
First calculations using NN+3N

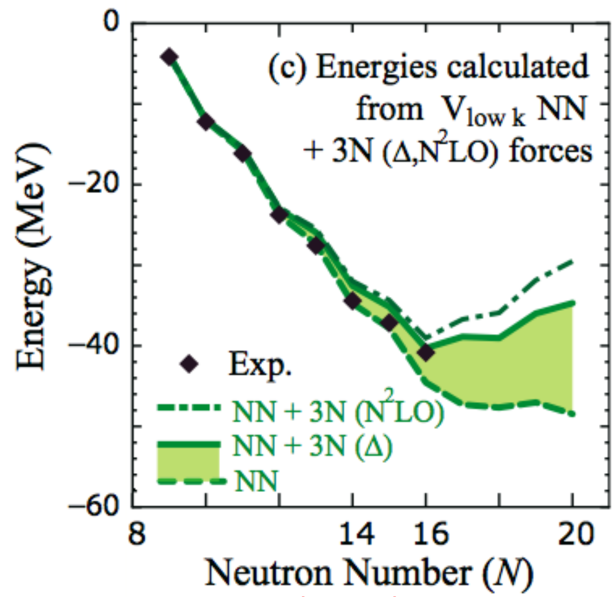


Probe limits of nuclear existence with 3N forces

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

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





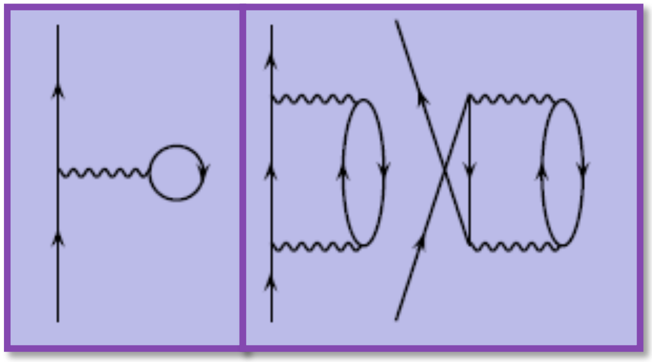
Isotopes unbound beyond ^{24}O

First microscopic explanation of oxygen anomaly

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

One-Body 3N: Single Particle Energies

NN-only microscopic SPEs yield poor results – rely on empirical adjustments



sd-shell: SPEs much too bound, unreasonable splitting

Orbit	"Exp"	USDb	$T+V_{NN}$
$d_{5/2}$	-4.14	-3.93	-5.43
$s_{1/2}$	-3.27	-3.21	-5.32
$d_{3/2}$	0.944	2.11	-0.97

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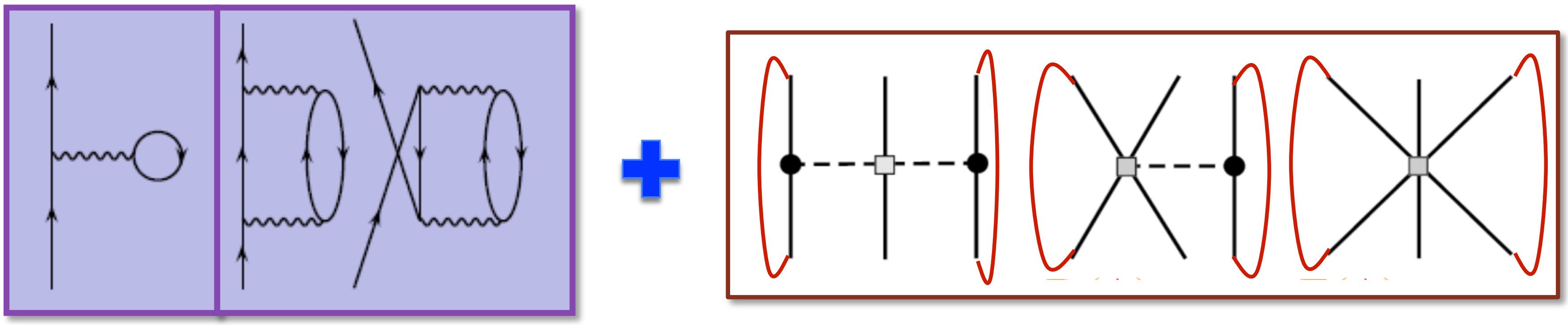


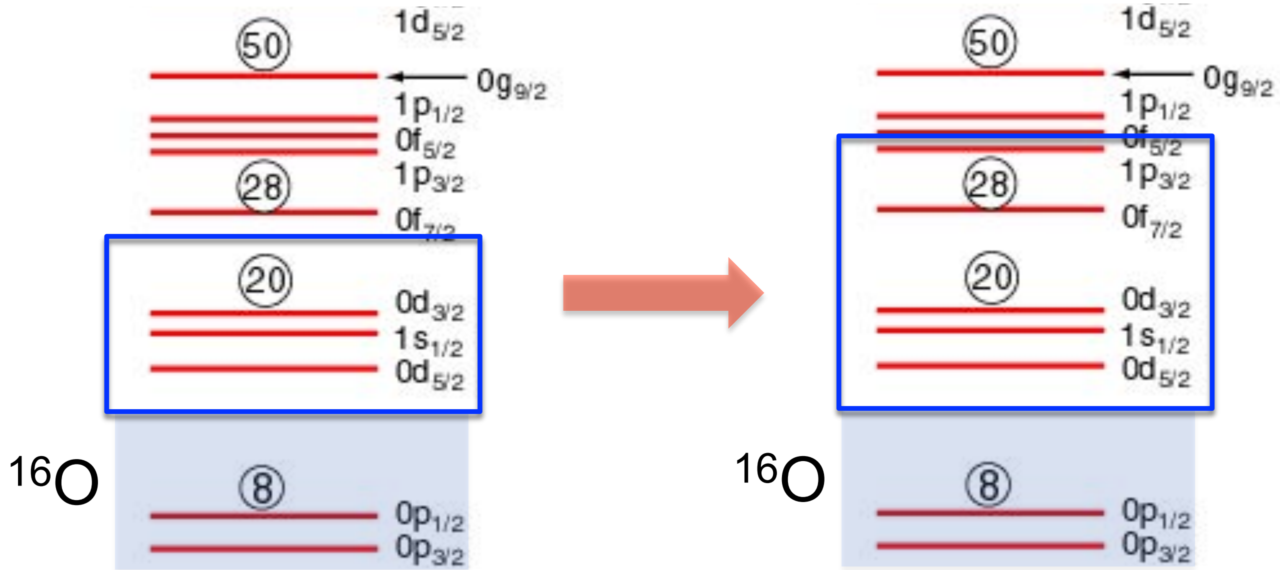
sd-shell: SPEs much too bound, unreasonable splitting

3N forces: additional repulsion – reasonable values!

Orbit	USDb	$T+V_{NN}+V_{3N}$
$d_{5/2}$	-3.93	-3.82
$s_{1/2}$	-3.21	-2.14
$d_{3/2}$	2.11	2.01

One-Body 3N: Single Particle Energies

Effects of correlations beyond one major oscillator shell:



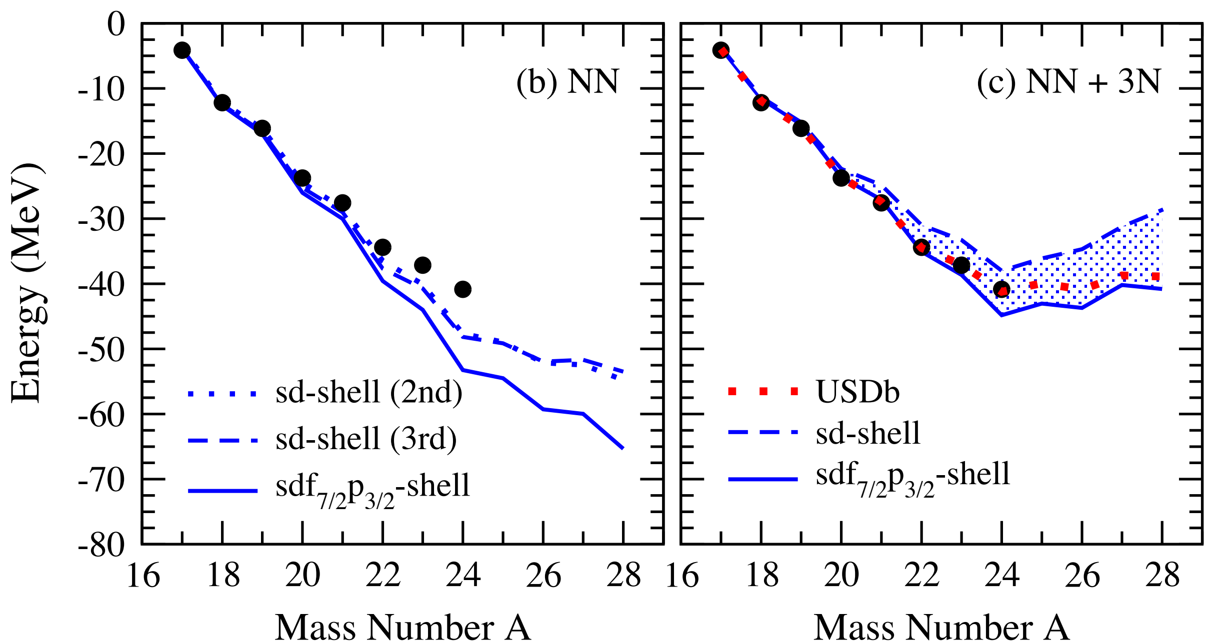
Orbit	USDb	$T+V_{NN}+V_{3N}$	SDPF-M	$T+V_{NN}+V_{3N}$
$d_{5/2}$	-3.93	-3.82	-3.95	-3.75
$s_{1/2}$	-3.21	-2.14	-3.16	-2.10
$d_{3/2}$	2.11	2.01	1.65	2.13
$f_{7/2}$			3.10	2.96
$p_{3/2}$			3.10	4.82

Fully microscopic framework and extended valence space

Fully-Microscopic Calculations

Interaction and self-consistent SPEs from NN+3N

Empirical SPEs for NN-only



Holt, Schwenk, arXiv:1108.2680

NN-only: dripline at ^{28}O

NN+3N: dripline at ^{24}O

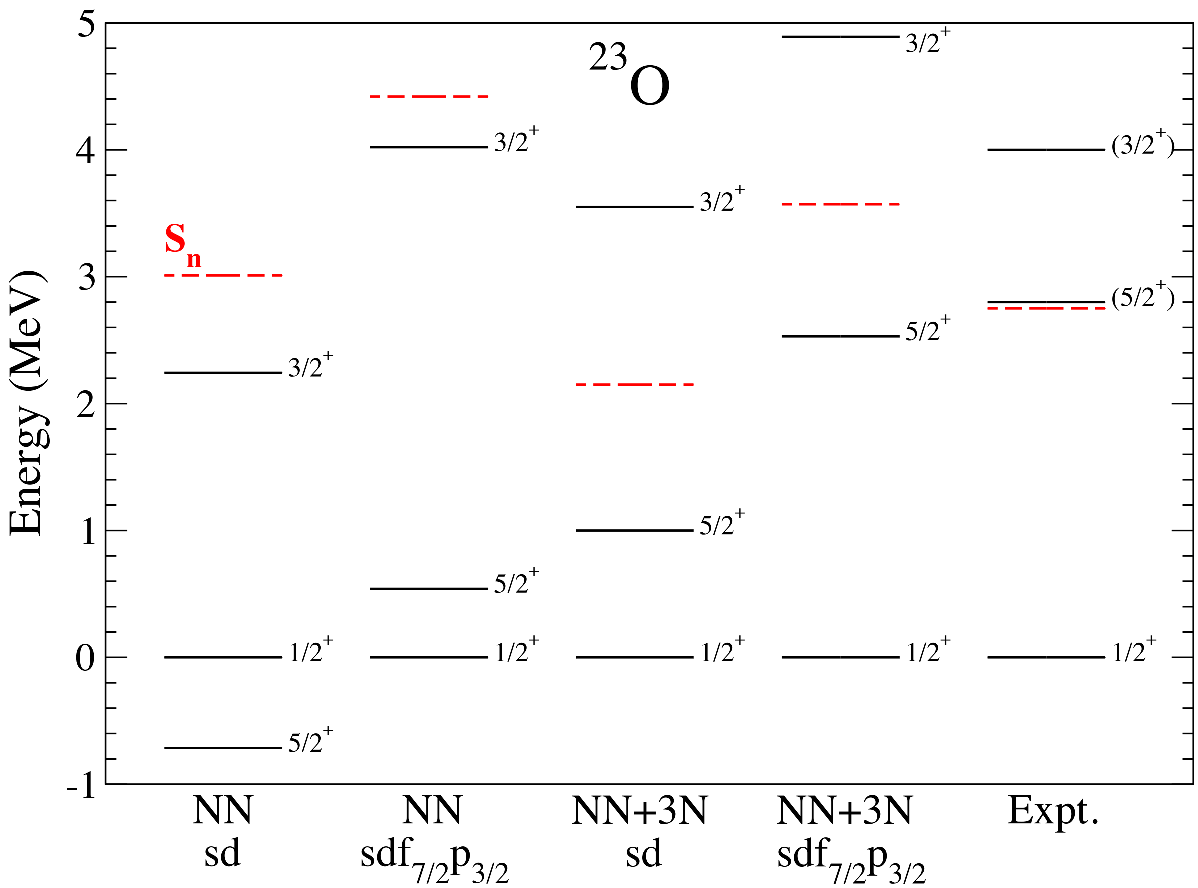
sd-shell results underbound; improved in $sdf_{7/2}\ p_{3/2}$

Continuum: ~300keV more binding beyond ^{24}O (from CC)

Impact on Spectra: ^{23}O

Neutron-rich oxygen spectra with NN+3N

$5/2^+$, $3/2^+$ indicate position of $d_{5/2}$ and $d_{3/2}$ orbits



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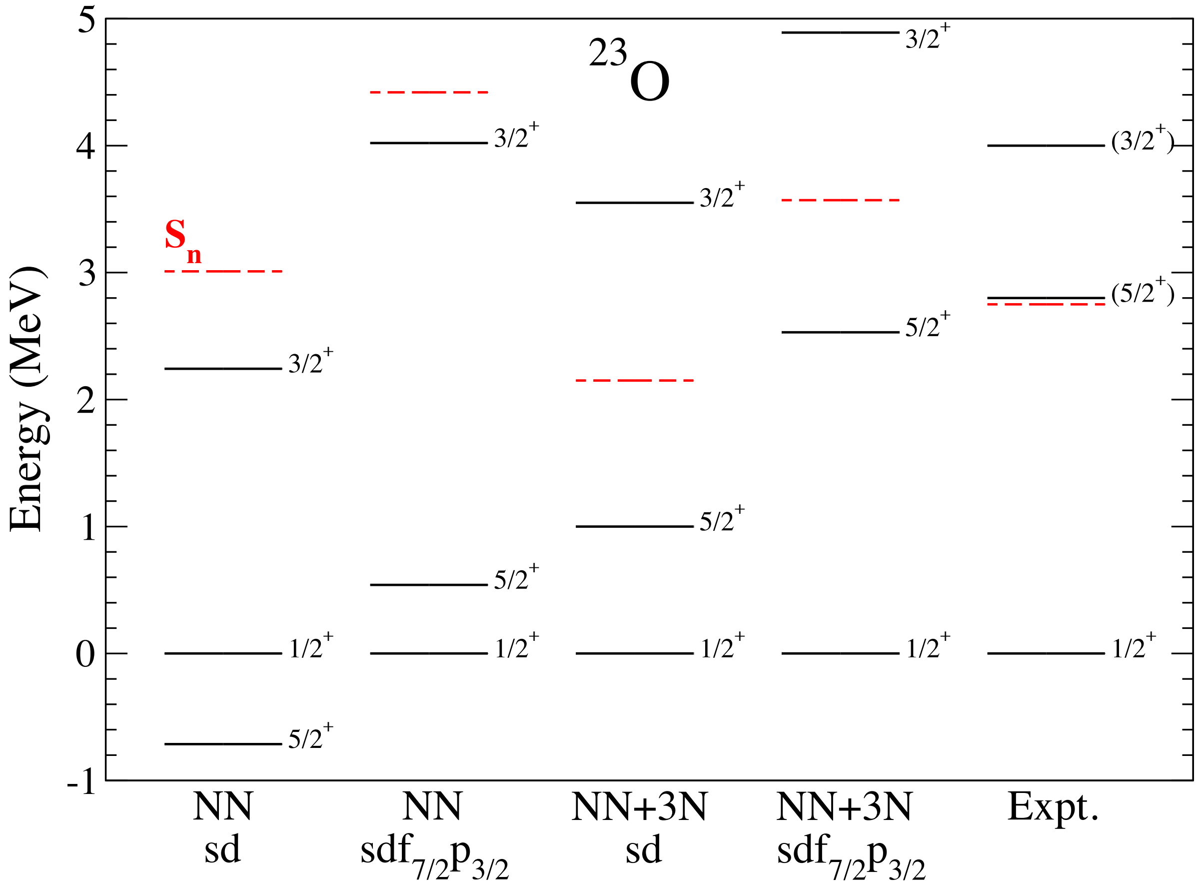

sd*-shell *NN-only

Wrong ground state!

$5/2^+$ too low

$3/2^+$ bound

Microscopic NN+3N

Great improvements in extended valence space!

Holt, Schwenk, arXiv:1108.2680

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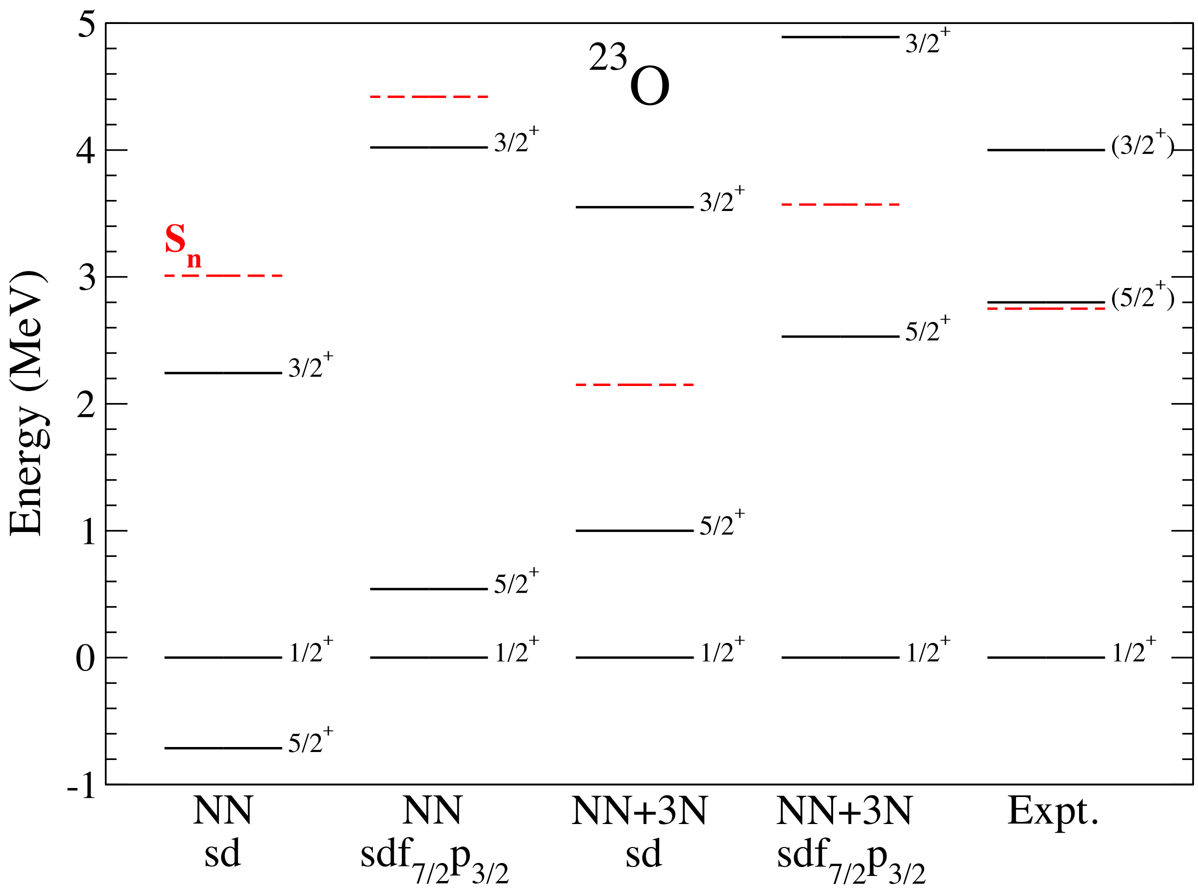

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Wrong ground state!

$5/2^+$ too low

$3/2^+$ bound

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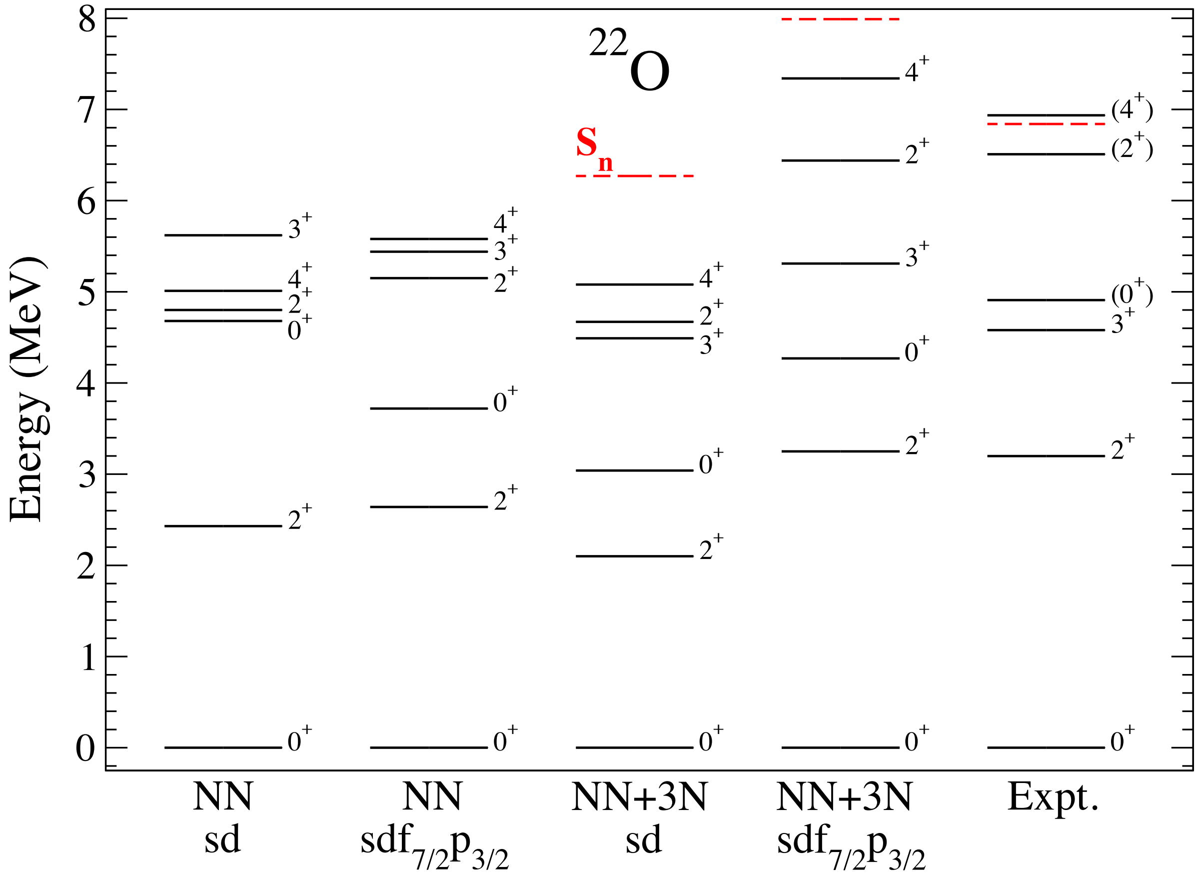
Holt, Schwenk, arXiv:1108.2680

Continuum effectively lowers $3/2^+$ - vital for $^{24\text{-}28}$O

Impact on Spectra: ^{22}O

Neutron-rich oxygen spectra with NN+3N

^{22}O: $N=14$ new magic number – not reproduced with NN



NN-only

2^+ 500 keV too low

Spectrum too compressed

Microscopic NN+3N

Extended space essential

Reproduces $N=14$ magic number

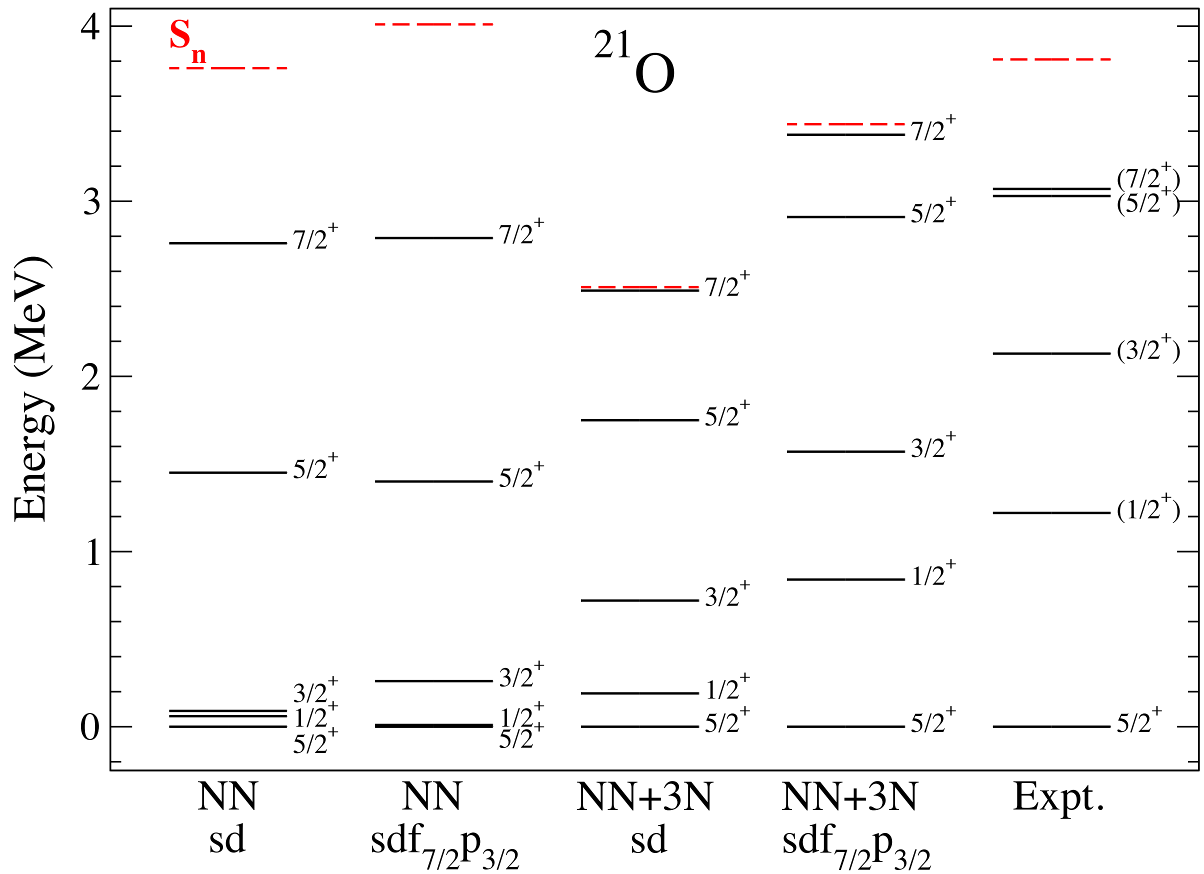
Holt, Schwenk, arXiv:1108.2680

Contributions from 3N and extended valence orbitals important

Impact on Spectra: ^{21}O

Neutron-rich oxygen spectra with NN+3N

Spectrum sensitive to $s_{1/2}$ shell closure



NN-only

Low-lying states too compressed

$7/2^+$-$5/2^+$ too wide

Microscopic NN+3N

Improvement in *sd*

Extended orbits essential

Improved spacing in all levels

Holt, Schwenk, arXiv:1108.2680

3N improvements largely due to higher calculated $s_{1/2}$ orbital

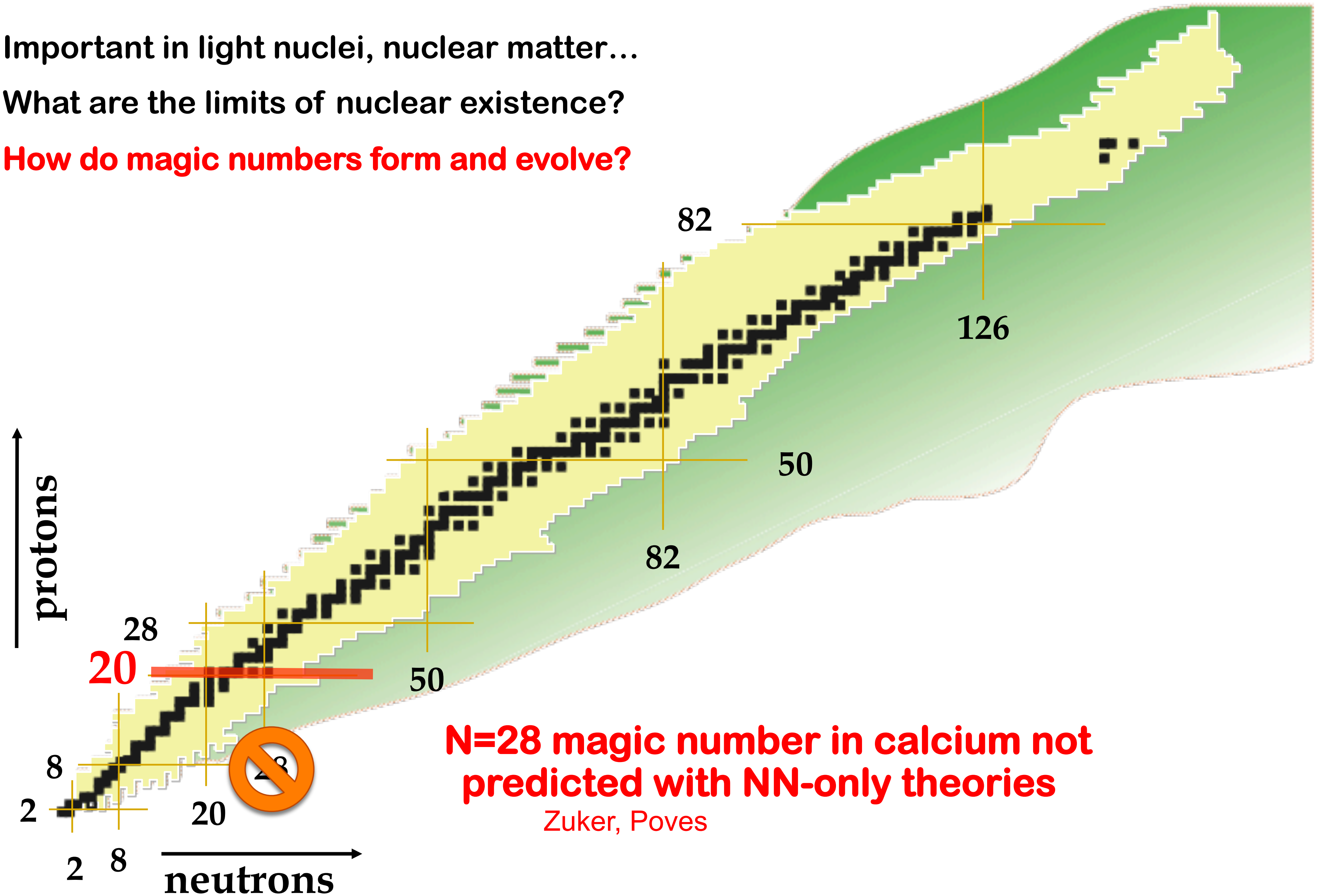
Need proper treatment of non-degenerate spaces

Shell Formation/Evolution in Calcium Isotopes

Important in light nuclei, nuclear matter…

What are the limits of nuclear existence?

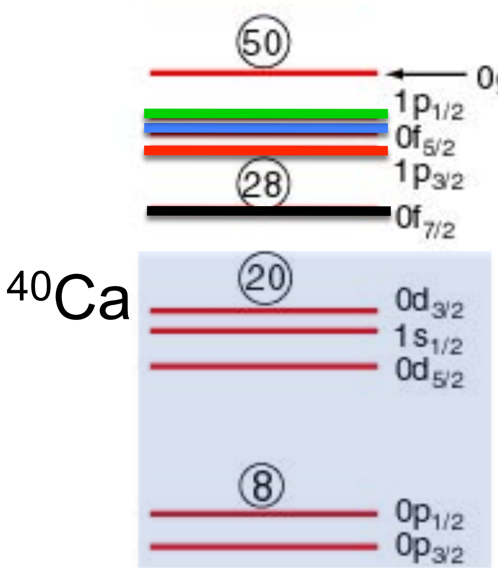
How do magic numbers form and evolve?

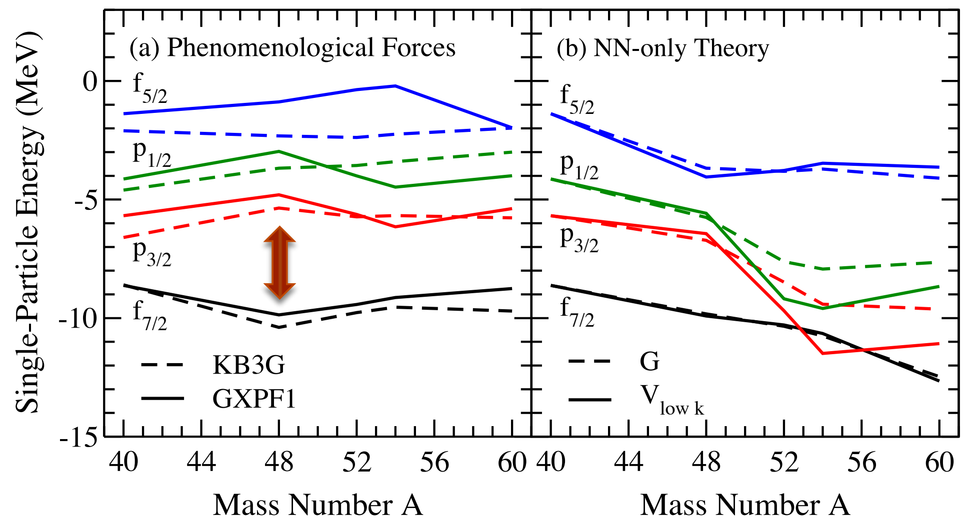


N=28 magic number in calcium not predicted with NN-only theories

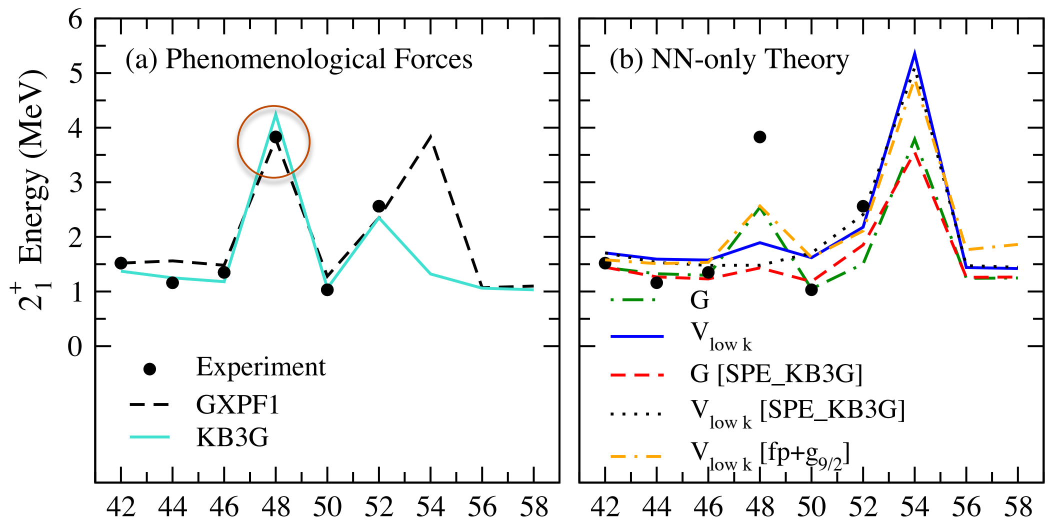
Zuker, Poves

Calcium Isotope Physics: 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

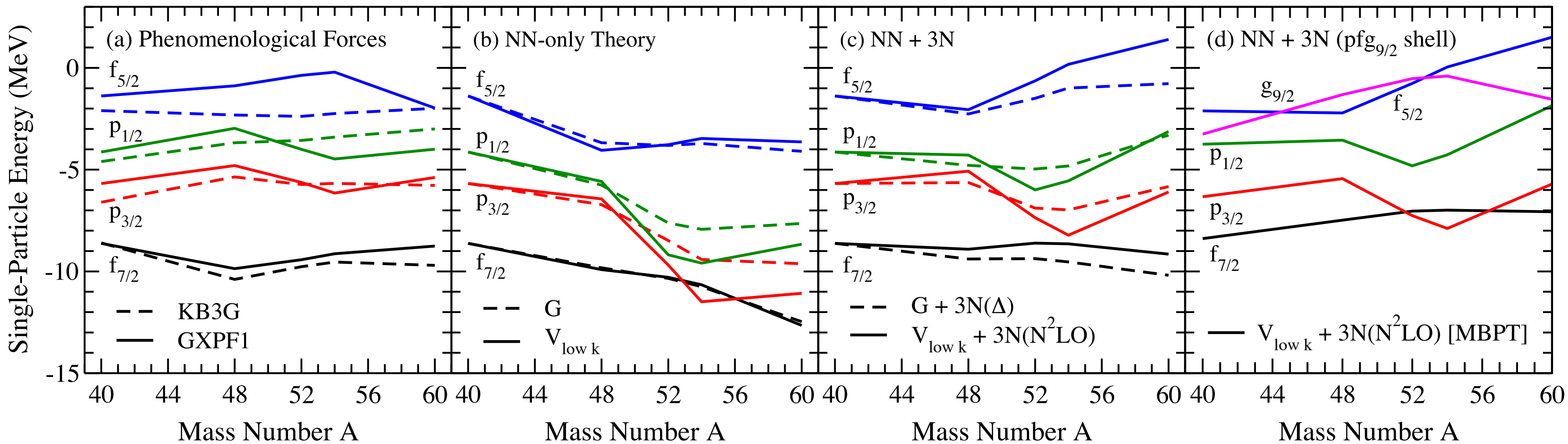
Microscopic NN Theory

Small gap at ^{48}Ca

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

Evolution of Shell Structure

SPE evolution with 3N forces in *pf* and $pfg_{9/2}$ spaces:



Holt, Otsuka, Schwenk, Suzuki arXiv:1009.5984

NN+3N *pf*-shell:

Trend across: improved binding energies

Increased gap at ^{48}Ca: enhanced closed-shell features

Include $g_{9/2}$ orbit, calculated SPEs

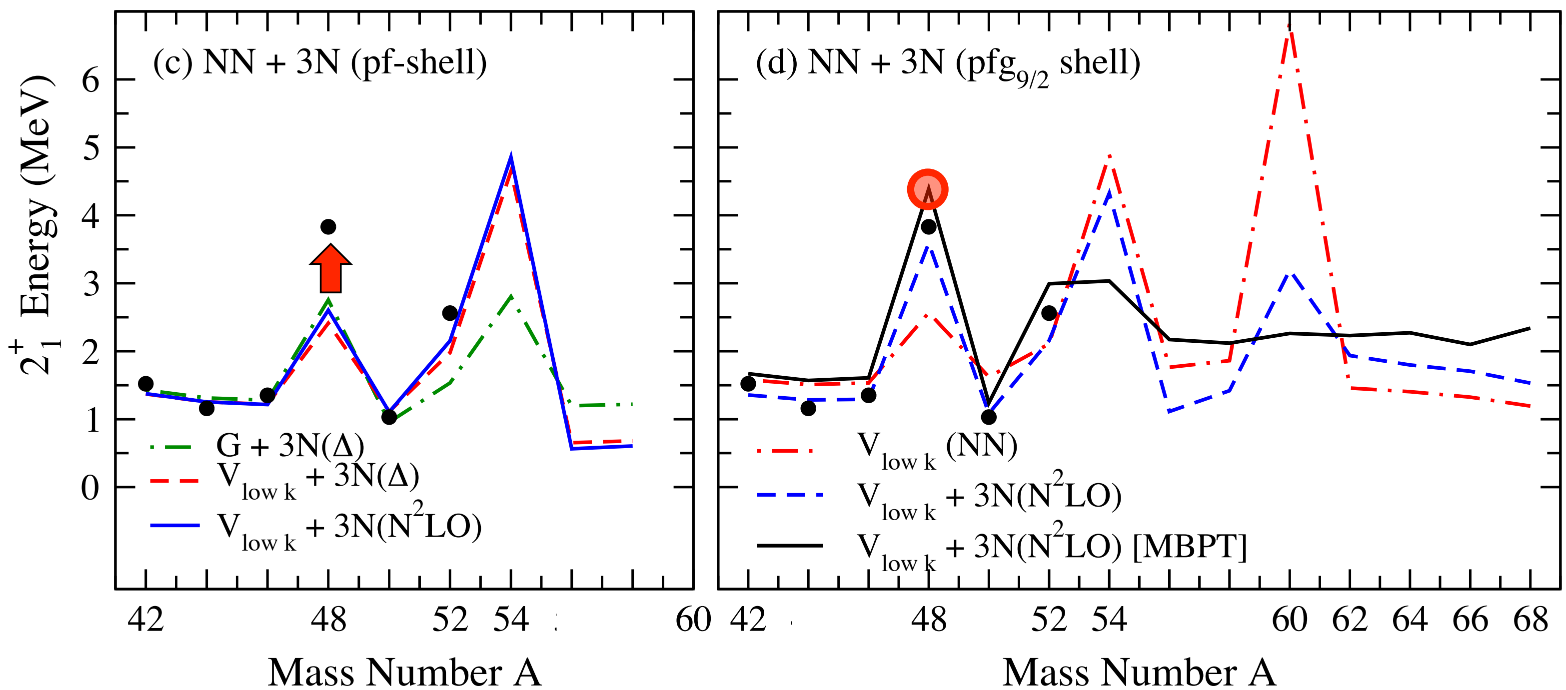
More modest N=34 gap

Different behavior of ESPEs

Small gap can give large 2^+ energy Duguet, Hagen, arXiv:1110.2468

N=28 Magic Number in Calcium

First excited 2^+ energies in calcium isotopes with NN+3N



Holt, Otsuka, Schwenk, Suzuki arXiv:1009.5984

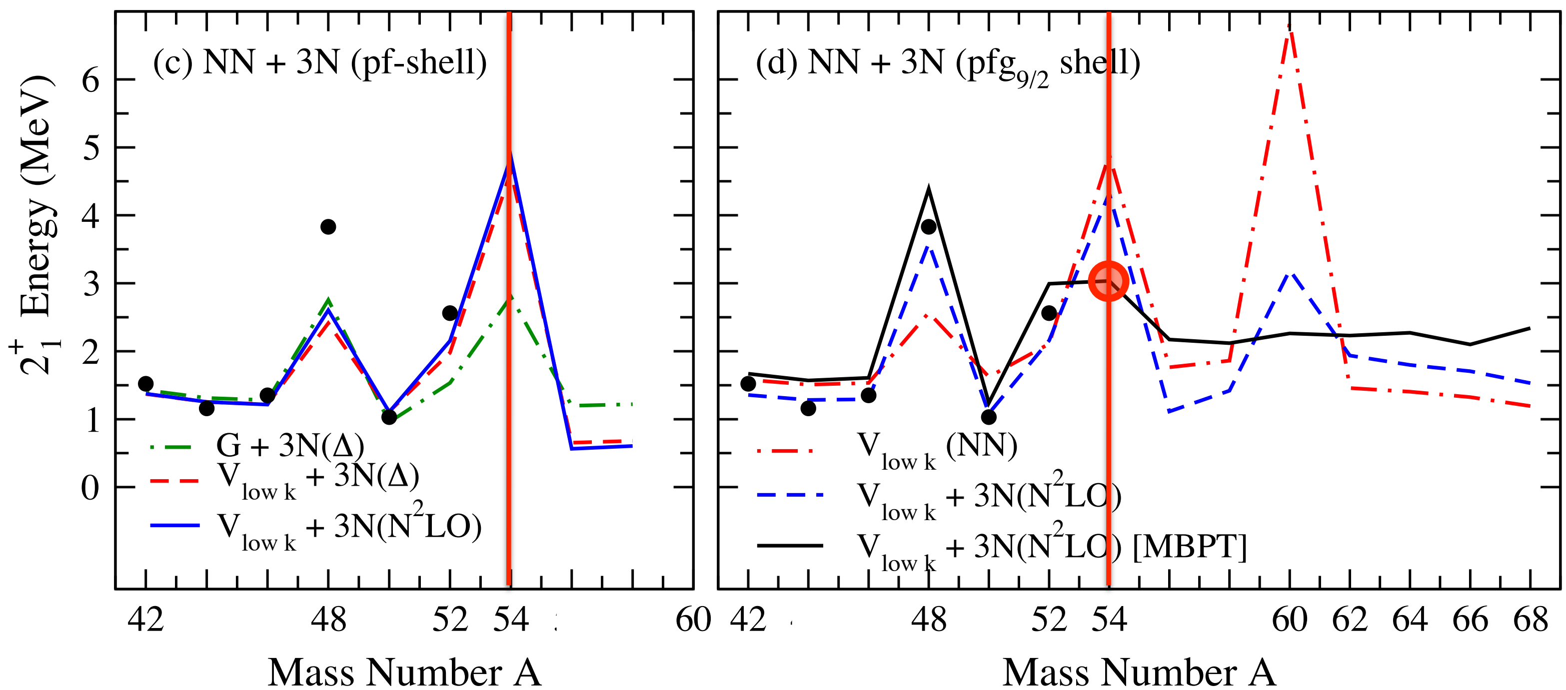
***pf*-shell**: robust but modest improvement in 2^+ energies, below experiment

***pfg*$_{9/2}$-shell**: reproduce experimental 2^+ in ^{48}Ca

Both 3N and extended space essential

Evolution of Magic Numbers: N=34

First excited 2^+ energies in calcium isotopes with NN+3N



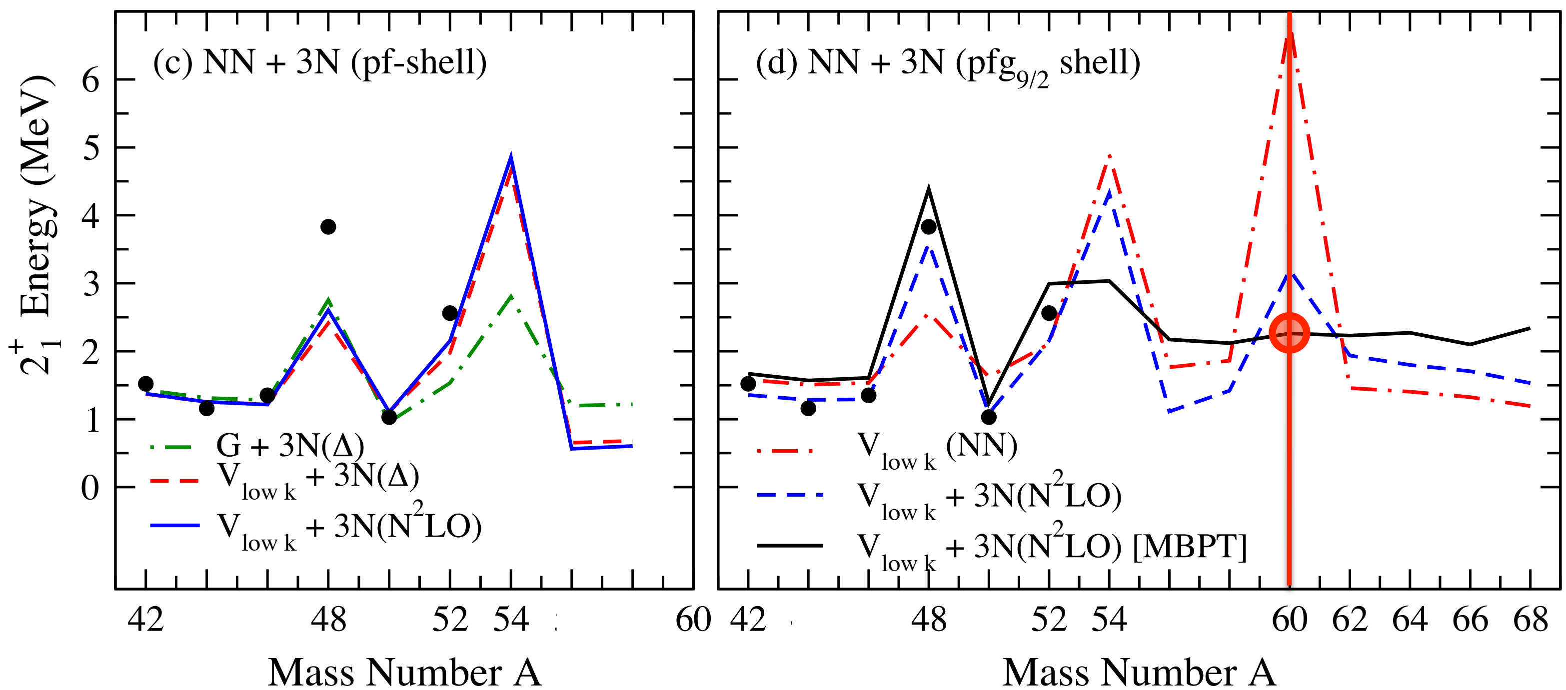
Holt, Otsuka, Schwenk, Suzuki arXiv:1009.5984

***pf*-shell**: Very pronounced closed-shell properties

***pfg*$_{9/2}$-shell**: More modest, similar to ^{52}Ca

Evolution of Magic Numbers: N=40

First excited 2^+ energies in calcium isotopes with NN+3N



Holt, Otsuka, Schwenk, Suzuki arXiv:1009.5984

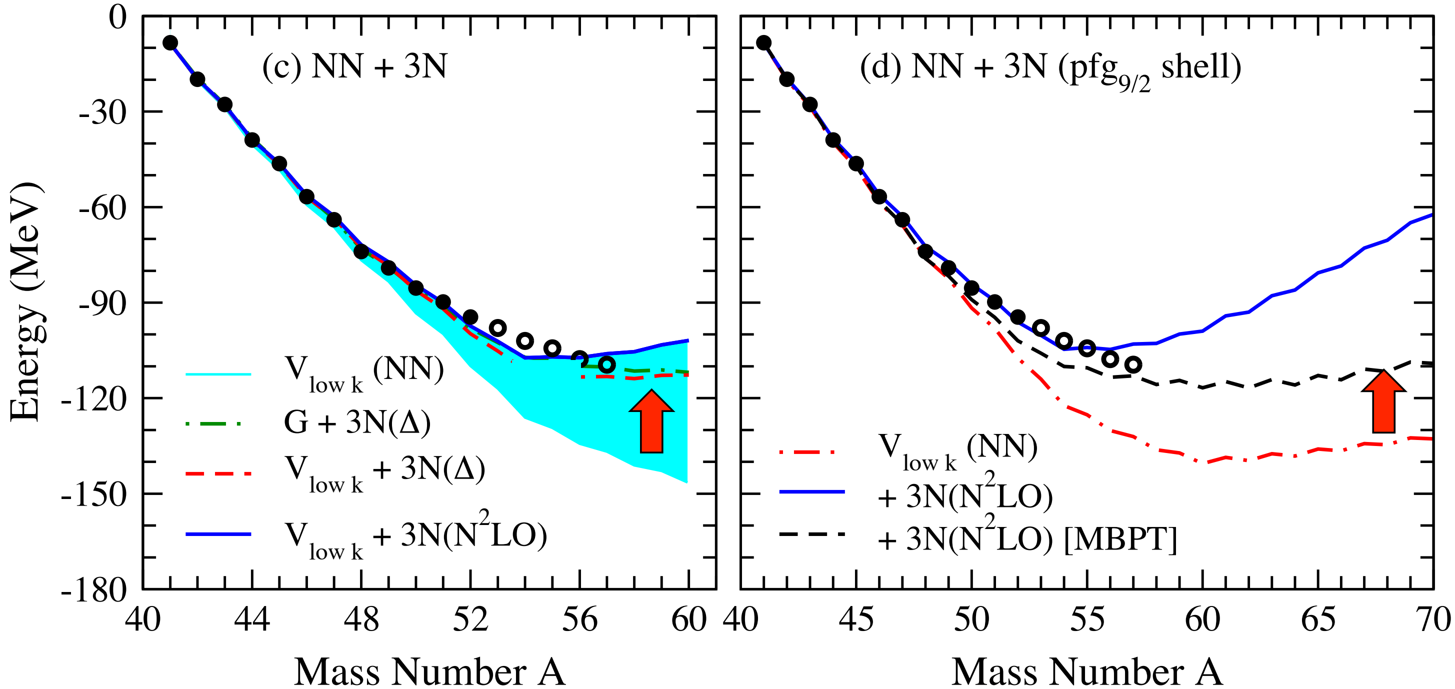
Extremely pronounced with NN-only

Dramatically quenched with NN+3N

Calcium Ground State Energies and Dripline

Ground state energies using NN+3N

NN-only: overbinds beyond ~ ^{46}Ca



Holt, Otsuka, Schwenk, Suzuki arXiv:1009.5984

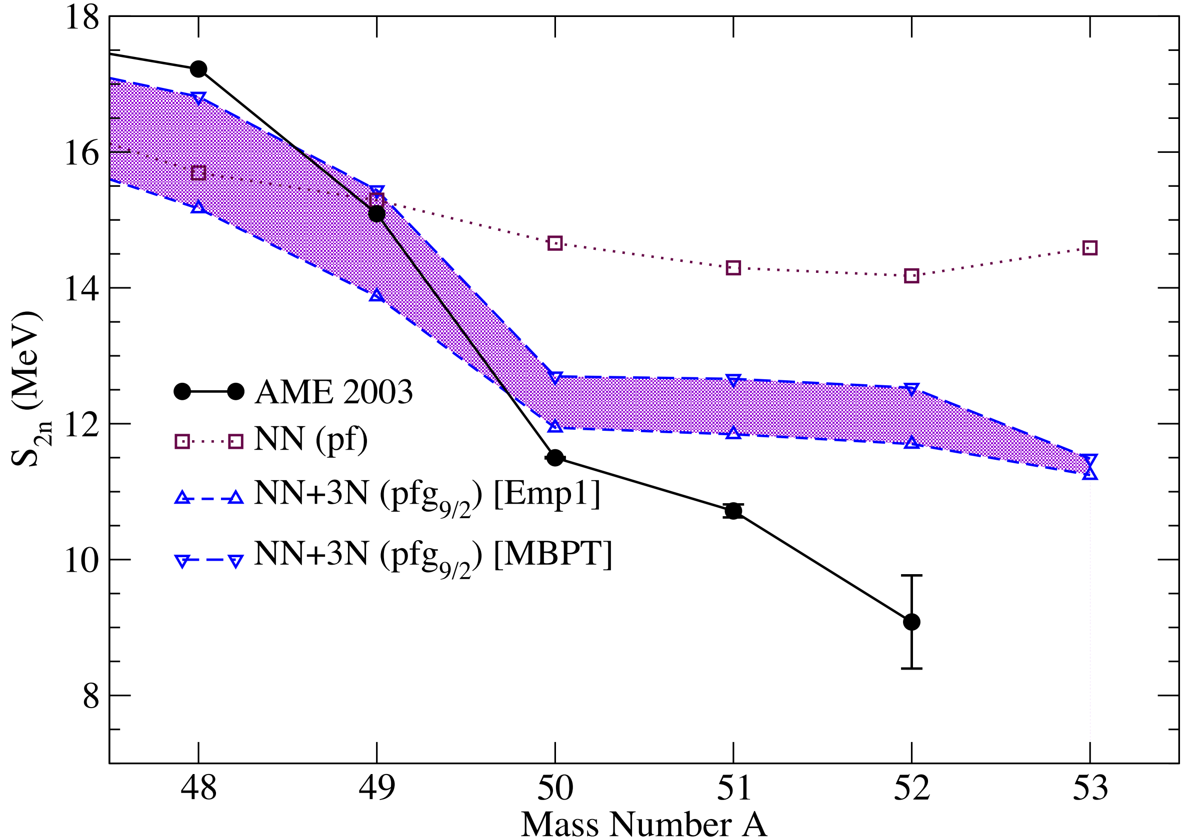
***pf*-shell**: 3N forces correct binding energies; good experimental agreement

***pfg*$_{9/2}$-shell**: calculate to ^{70}Ca; modest overbinding (as in oxygen)

Predict heaviest calcium isotope ~ $^{58\text{-}60}$Ca

Experimental Connection: Mass of ^{52}Ca

S_{2n} energies for exotic calcium isotopes:

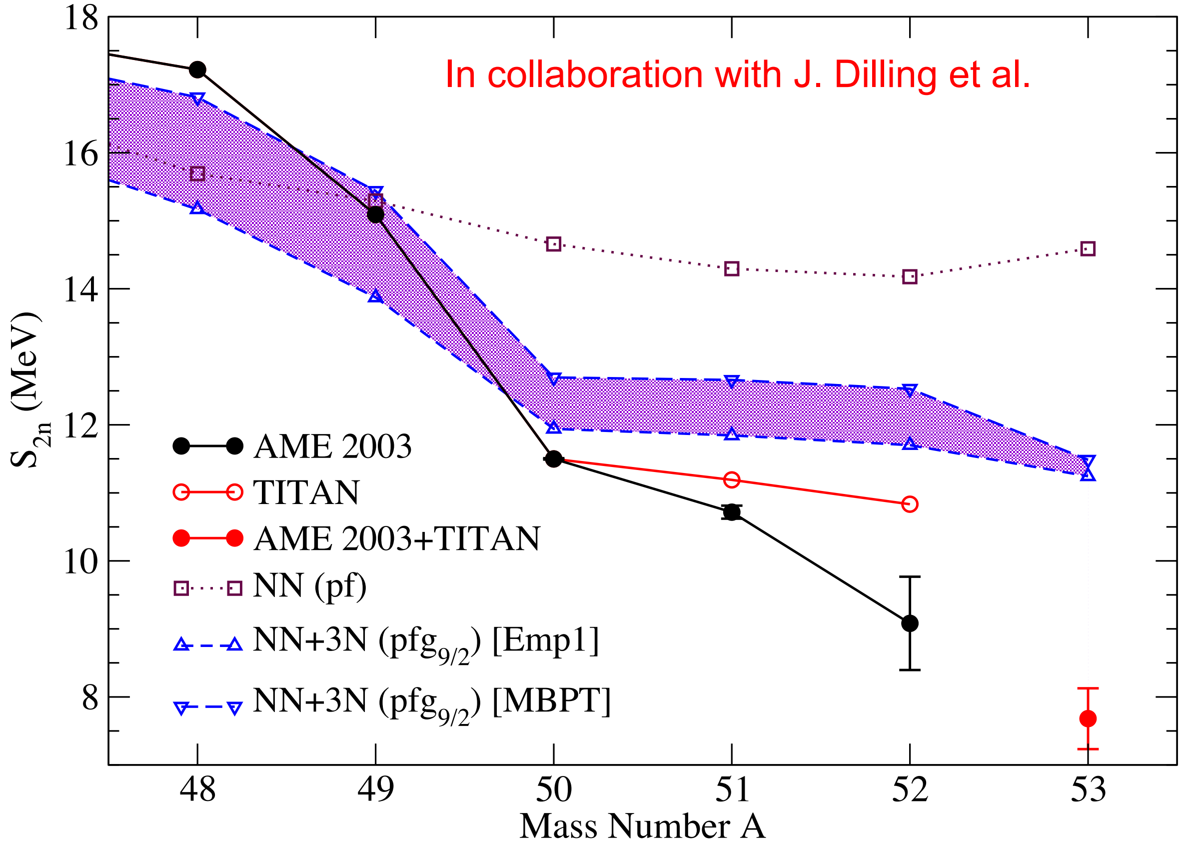


NN-only: poor agreement with experiment

NN+3N: reasonable improvement for lighter calcium, wrong behavior past ^{50}Ca

Experimental Connection: Mass of ^{52}Ca

New mass measurements of 51,52Ca at TITAN: Penning trap experiment at TRIUMF



TITAN Measurement

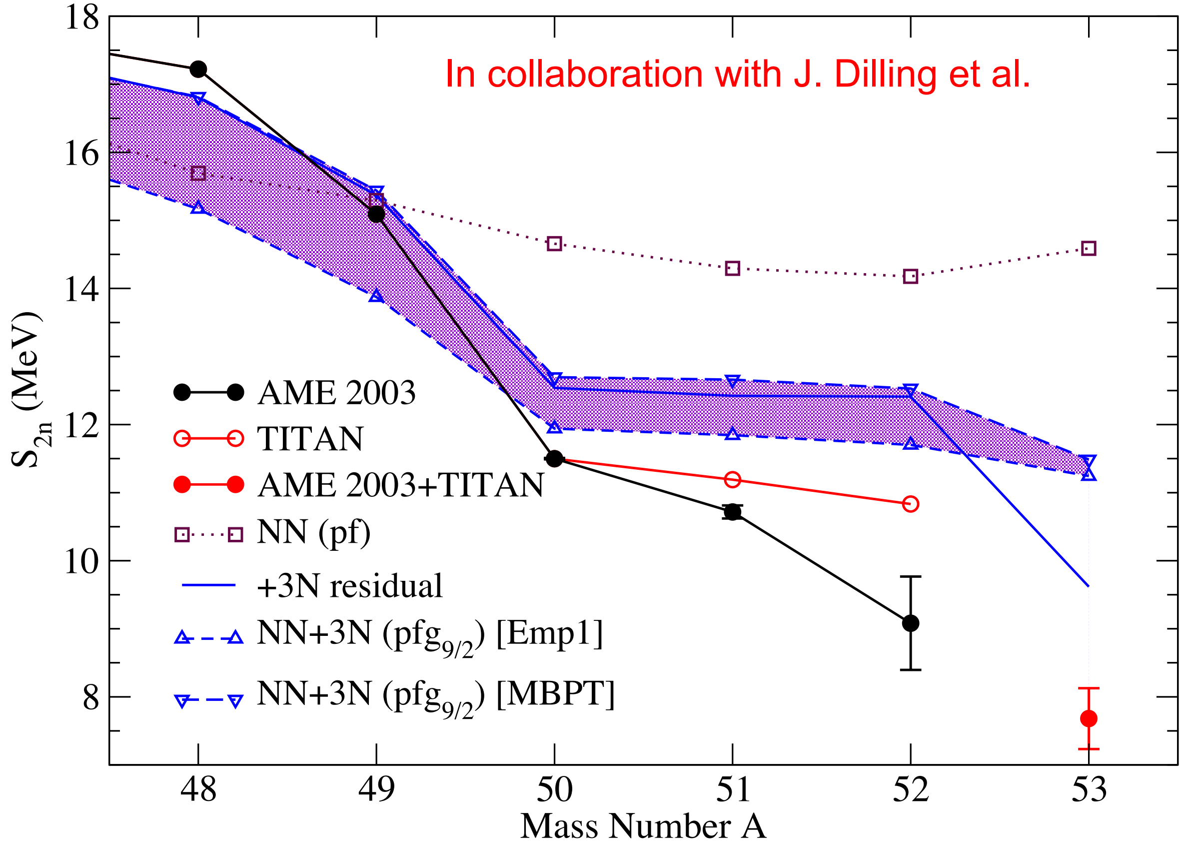
^{52}Ca mass 1.75MeV ***more*** bound than AME2003 value!

NN+3N: Now reasonable agreement with experiment from $^{50\text{-}52}$Ca

What about at ^{53}Ca? No sharp downward trend…

Experimental Connection: Mass of ^{52}Ca

New mass measurements of 51,52Ca at **TITAN**: Penning trap experiment at TRIUMF



TITAN Measurement

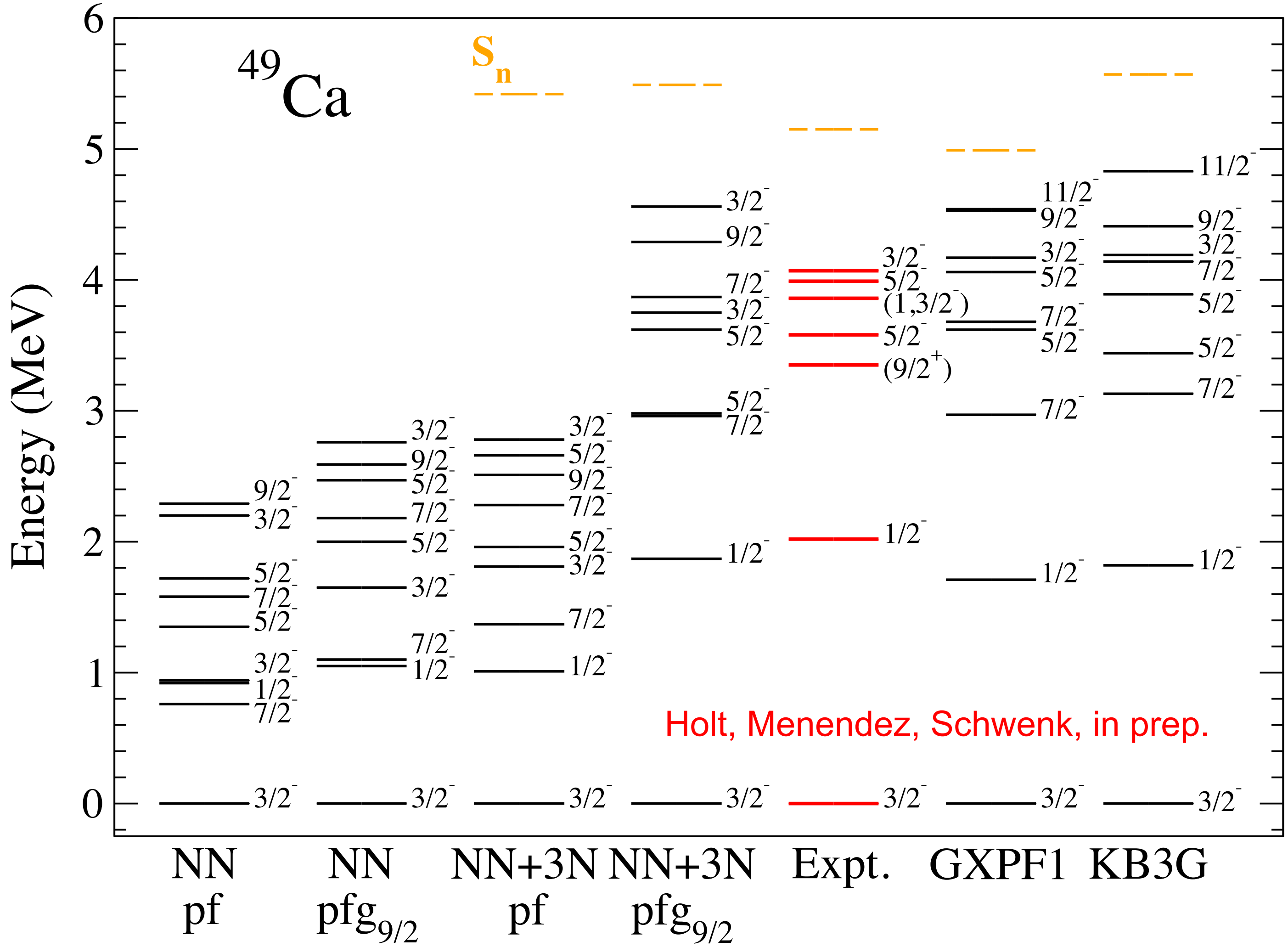
^{52}Ca mass 1.75MeV ***more*** bound than AME2003 value!

NN+3N: Now reasonable agreement with experiment from $^{50-52}$Ca

Adding approximated **residual 3N** important beyond ^{52}Ca: gives correct trend

Impact on Spectra: ^{49}Ca

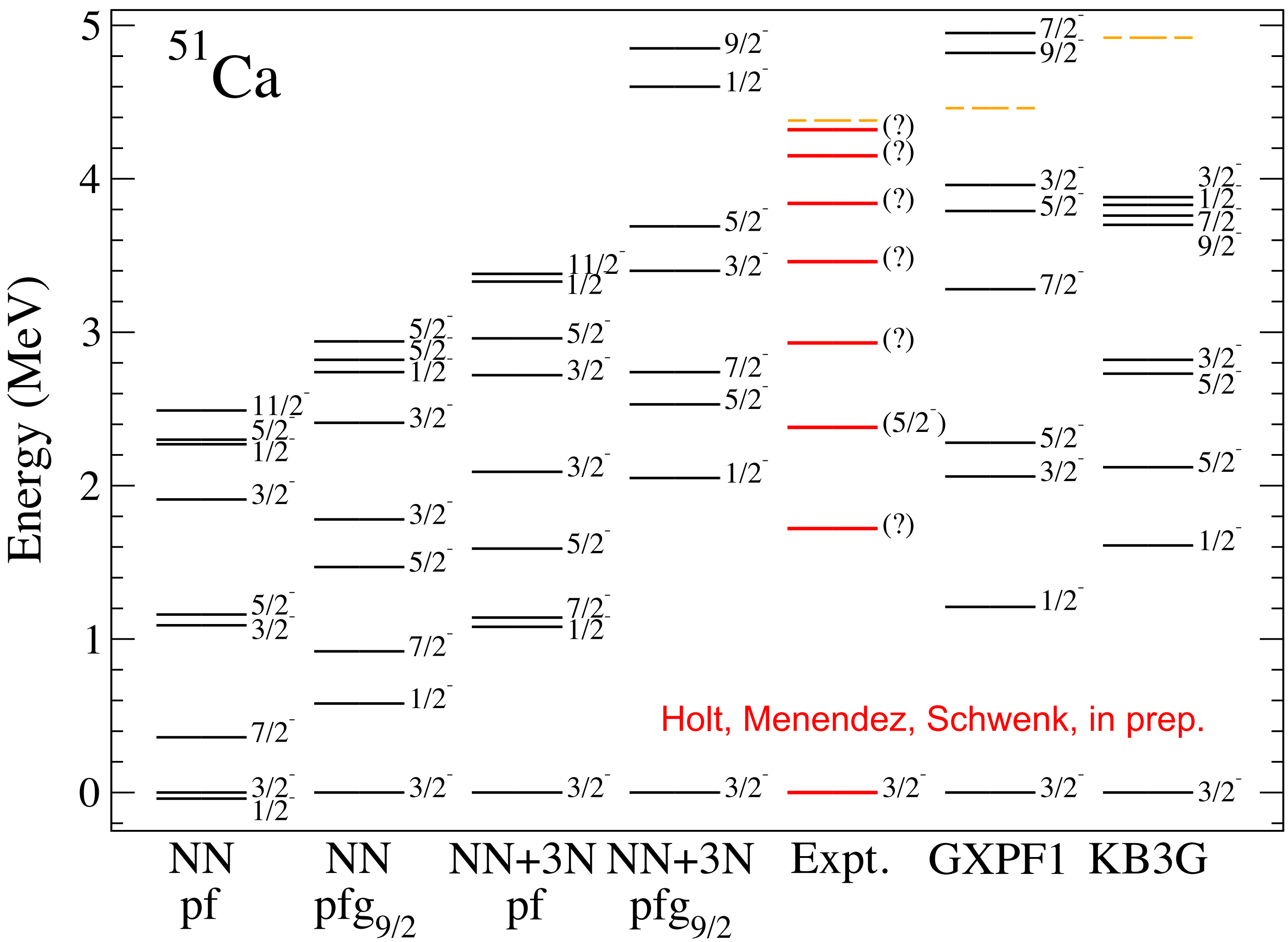
Neutron-rich calcium spectra with NN+3N



NN+3N in $pfg_{9/2}$ comparable to phenomenology (as for all lighter Ca isotopes)

Impact on Spectra: ^{51}Ca

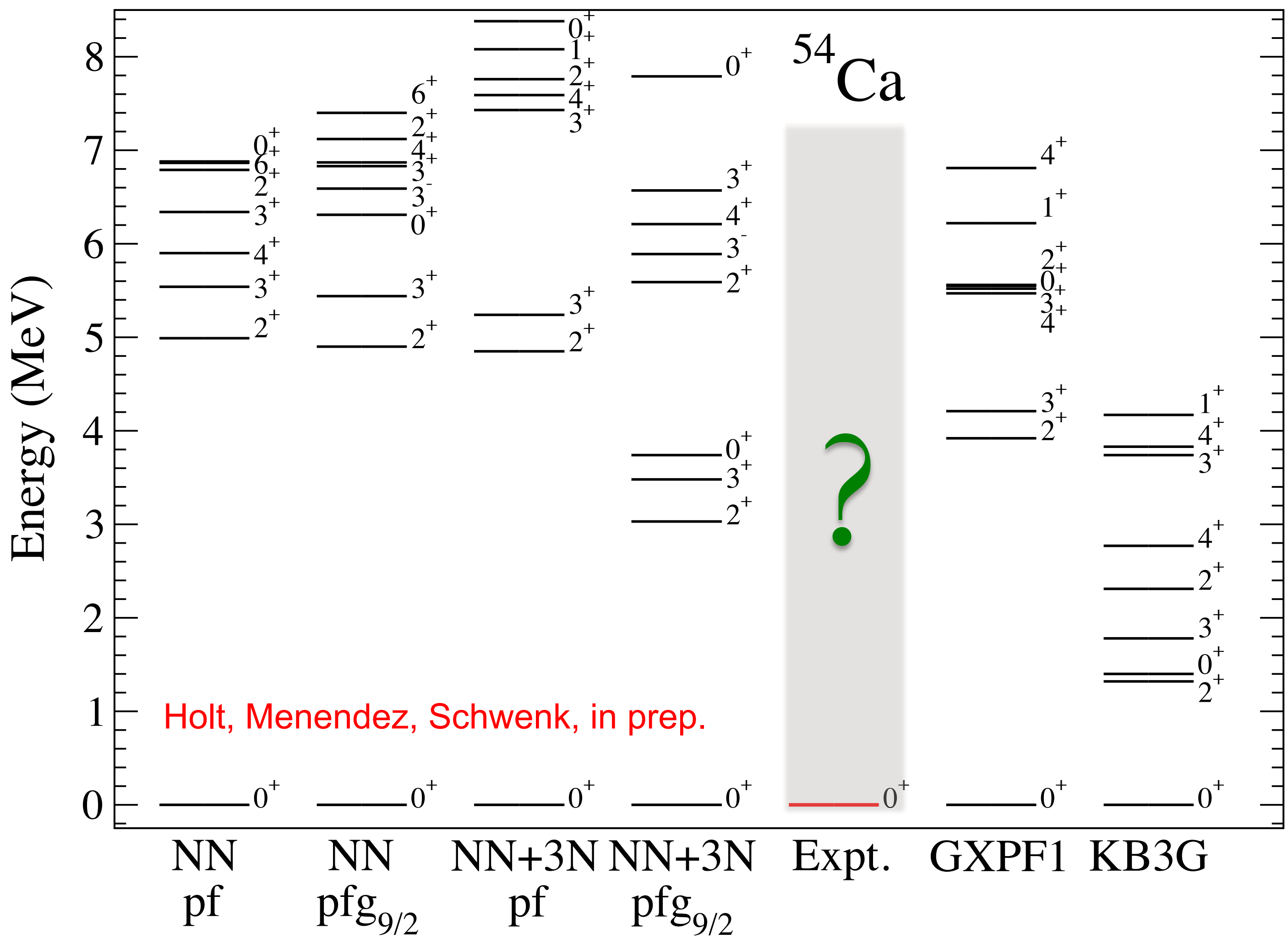
Neutron-rich calcium spectra with NN+3N



Different ordering from different models: gamma-ray spectroscopy needed!

Impact on Spectra: ^{54}Ca

Neutron-rich calcium spectra with NN+3N

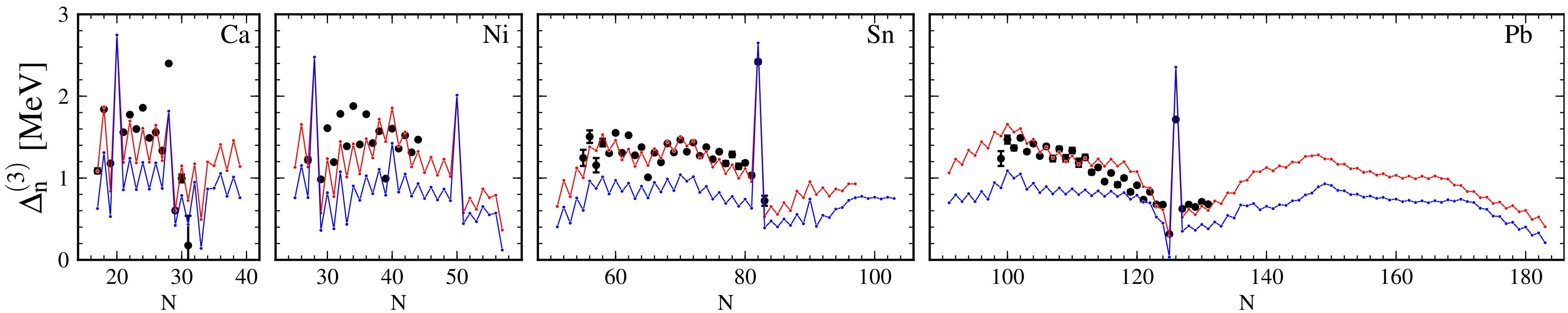


Microscopic prediction for ^{54}Ca spectrum

Pairing in EDF with 3N Forces

Calculations from Energy Density Functional with 3N forces

Lower gaps systematically:



Lesinski, Hebeler, Duguet, Schwenk, arXiv:1104.2955

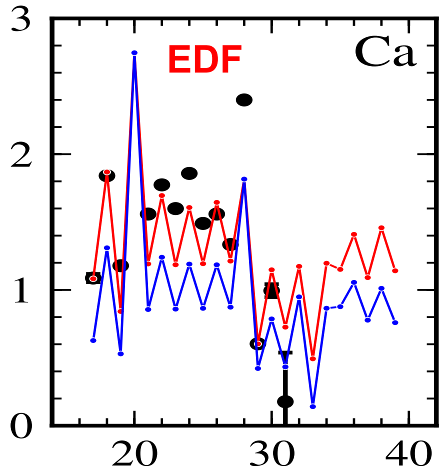
Improvement in theory – worse agreement with experiment

Due to neglected many-body effects?

Pairing in Calcium Isotopes

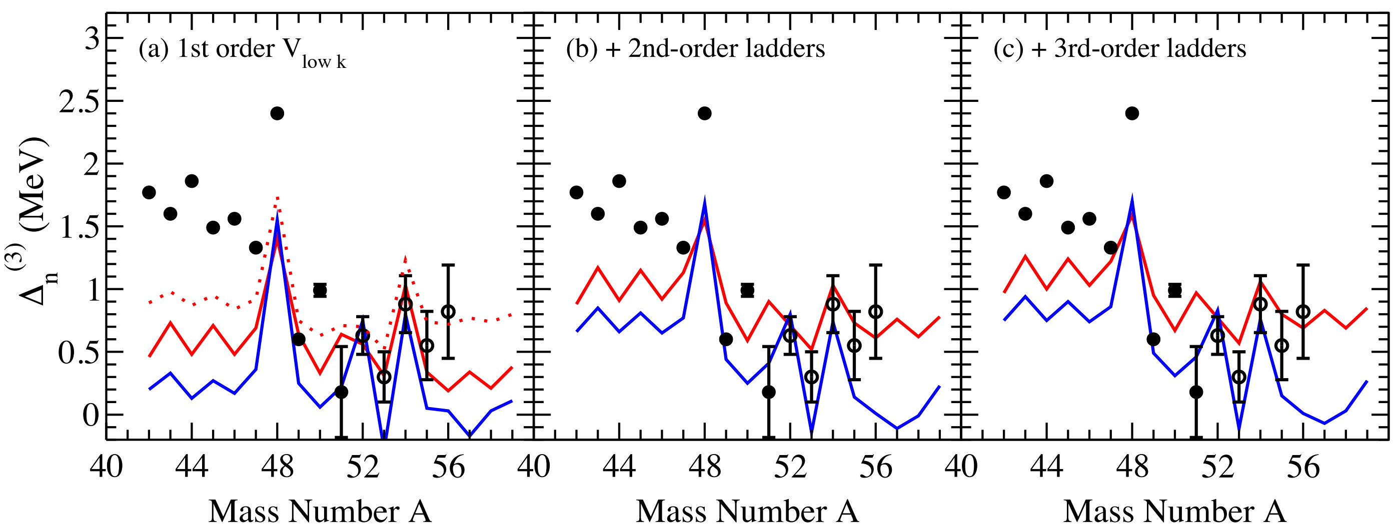
Compare with $\Delta_n^{(3)}$ calculated from microscopic NN+3N in calcium

Negative shift from 3N repulsion



Convergence in terms of order-by-order ladders

Holt, Menendez, Schwenk, in prep.



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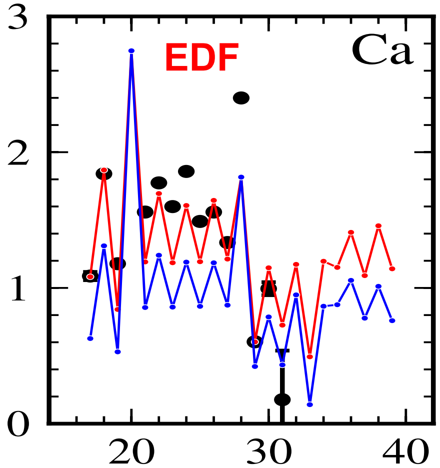
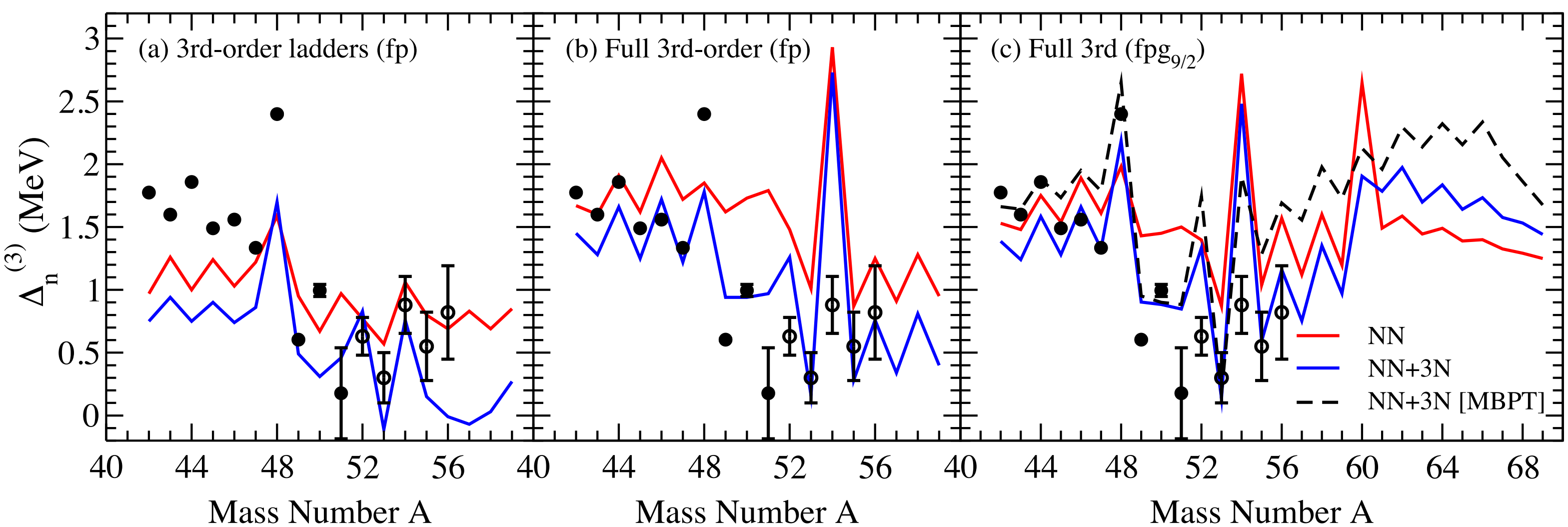


High order processes increase gaps - experimental agreement

Clear signature of shell closure in ^{48,54}Ca, quenching in ^{60}Ca

Holt, Menendez, Schwenk, in prep.



Conclusion

- Exciting era for nuclear structure – **experimentally and theoretically**
- Exploring frontiers of nuclear structure theory of medium-mass nuclei with 3N forces
- Discovered robust and general repulsive 3N mechanism for T=1 neutron-rich nuclei

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    - Cures NN-only failings: dripline, shell evolution, spectra in oxygen isotopes
- **Calcium isotopes** in *pf*- and $pfg_{9/2}$-shells:
    - First microscopic prediction of $N=28$ magic number in ^{48}Ca
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    - Dripline near ^{60}Ca
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    - NN+3N with higher many-body processes describe pairing without adjustments

Conclusion

- Exciting era for nuclear structure – **experimentally and theoretically**
- Exploring frontiers of nuclear structure theory of medium-mass nuclei with 3N forces
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- Clearly improvable upgrade path

Much to look forward to!

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