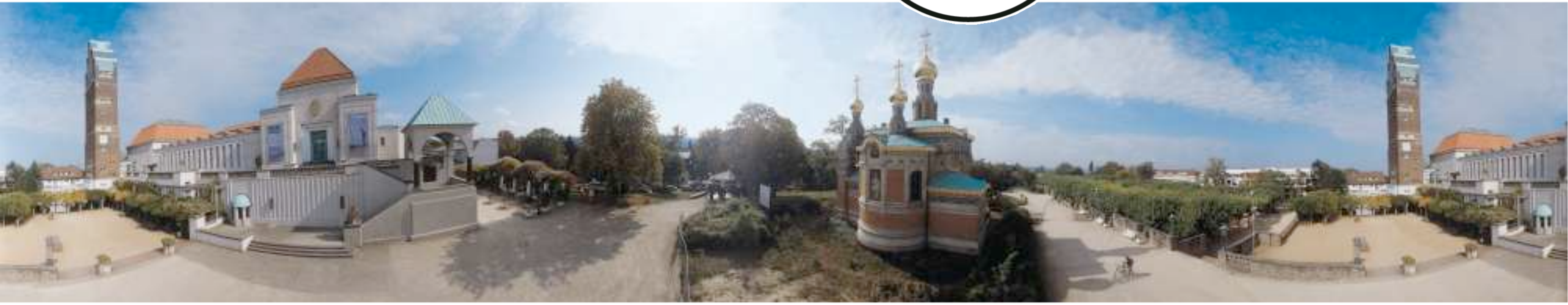
Three-nucleon forces and neutron-rich nuclei

Achim Schwenk

TECHNISCHE UNIVERSITÄT DARMSTADT

EMMI



Facets of Strong Interaction Physics

Hirschegg 40 + Bengt 60, Jan. 18, 2012

S-DALINAC

DFG

HELMHOLTZ ASSOCIATION

Minerva Stiftung

Bundesministerium für Bildung und Forschung

Happy Birthday Bengt!

Outline

Understanding three-nucleon forces

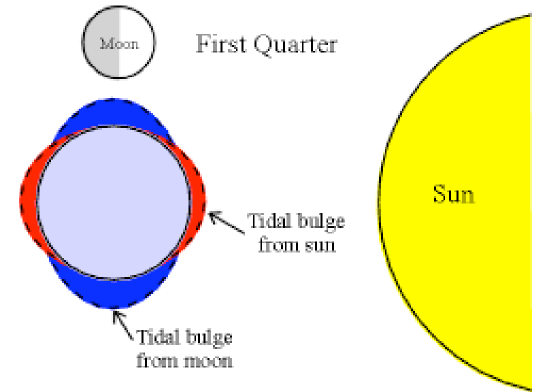
Three-body interactions and normal Fermi systems
with B. Friman

3N forces and neutron-rich nuclei
with J.D. Holt, J. Menendez, T. Otsuka, T. Suzuki

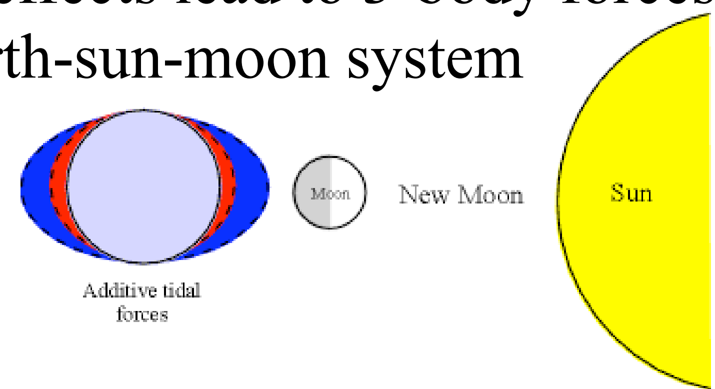
Electroweak interactions and 3N forces
with J. Menendez, D. Gazit

Three-nucleon forces and neutron matter
with K. Hebeler, J.M. Lattimer, C.J. Pethick

Why are there three-body forces?

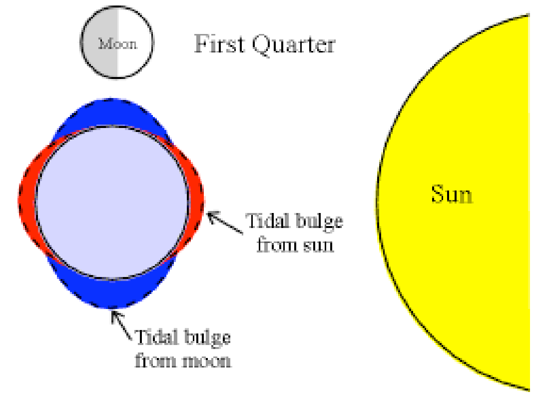


tidal effects lead to 3-body forces
in earth-sun-moon system

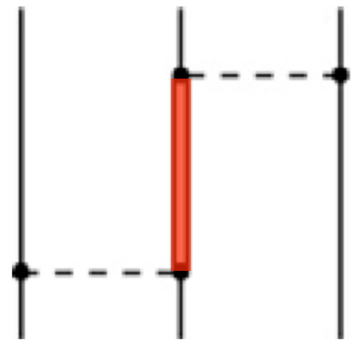


Why are there three-nucleon (3N) forces?

Nucleons are finite-mass composite particles, can be excited to resonances

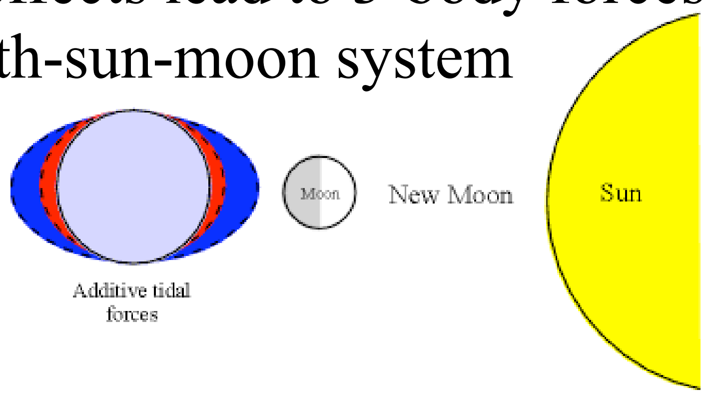


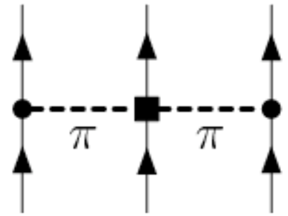
dominant contribution from Δ(1232 MeV)



+ many shorter-range parts

tidal effects lead to 3-body forces in earth-sun-moon system



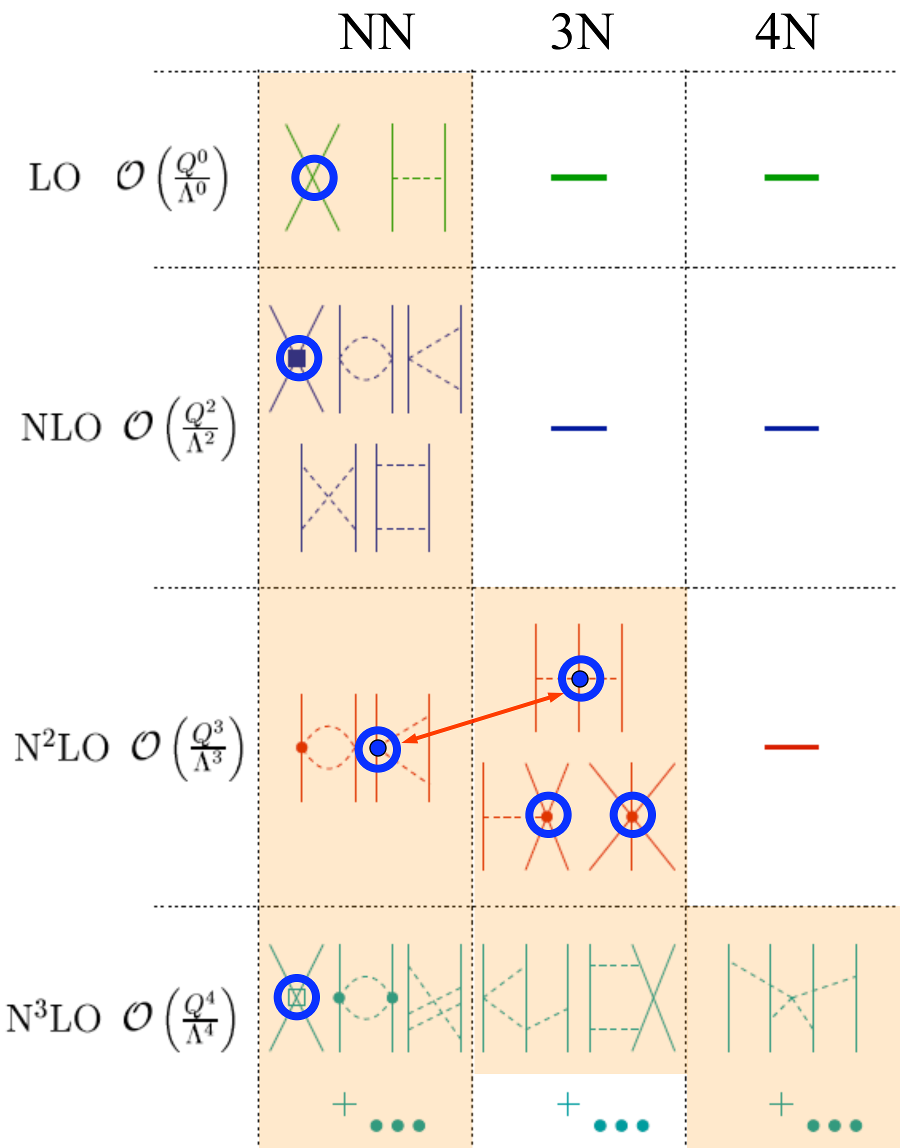
in chiral EFT (Delta-less): 

+ shorter-range parts

EFT provides a systematic and powerful approach to organize 3N forces

Chiral EFT for nuclear forces

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



limited resolution at low energies, can expand in powers $(Q/\Lambda_b)^n$

expansion parameter ~ 1/3

include long-range pion physics

details at short distance not resolved, capture in few short-range couplings, fit to experiment once, Λ-dependent

systematic: can work to desired accuracy and obtain error estimates from truncation order and Λ variation

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

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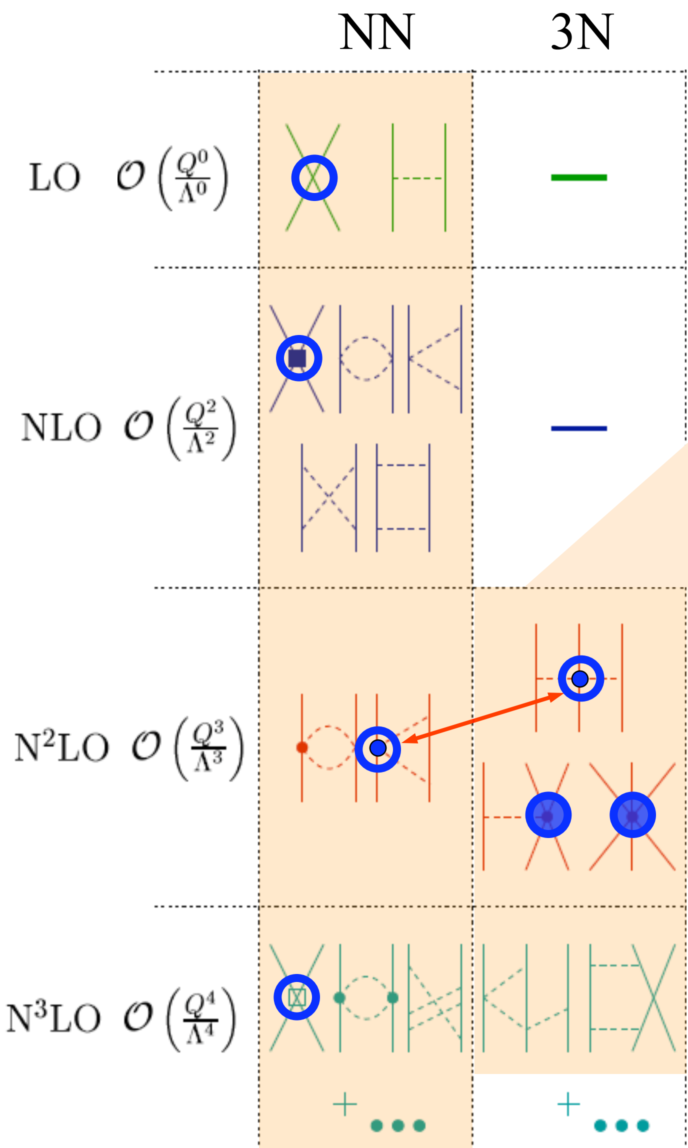
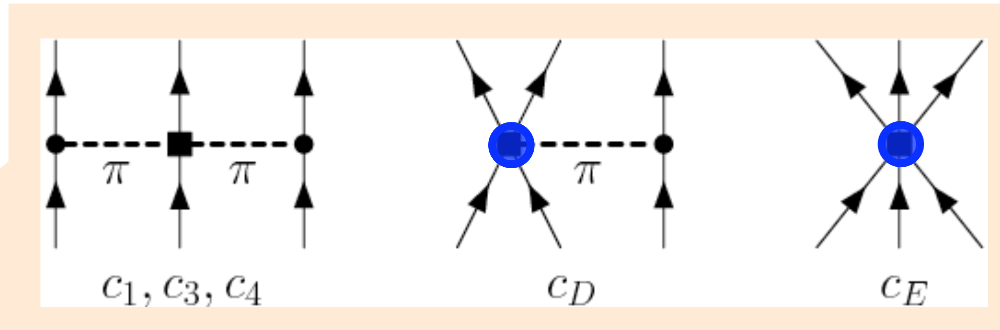


consistent NN-3N interactions

3N,4N: only 2 new couplings to N^3LO



c_i from πN and NN Meissner et al. (2007)

$$c_1 = -0.9^{+0.2}_{-0.5}\,,\; c_3 = -4.7^{+1.2}_{-1.0}\,,\; c_4 = 3.5^{+0.5}_{-0.2}$$

single-Δ: c_1=0, c_3=-c_4/2=-3 GeV^{-1}

c_D, c_E fit to few-body data:
^{3}H energy, half-life, ^{4}He radius,…

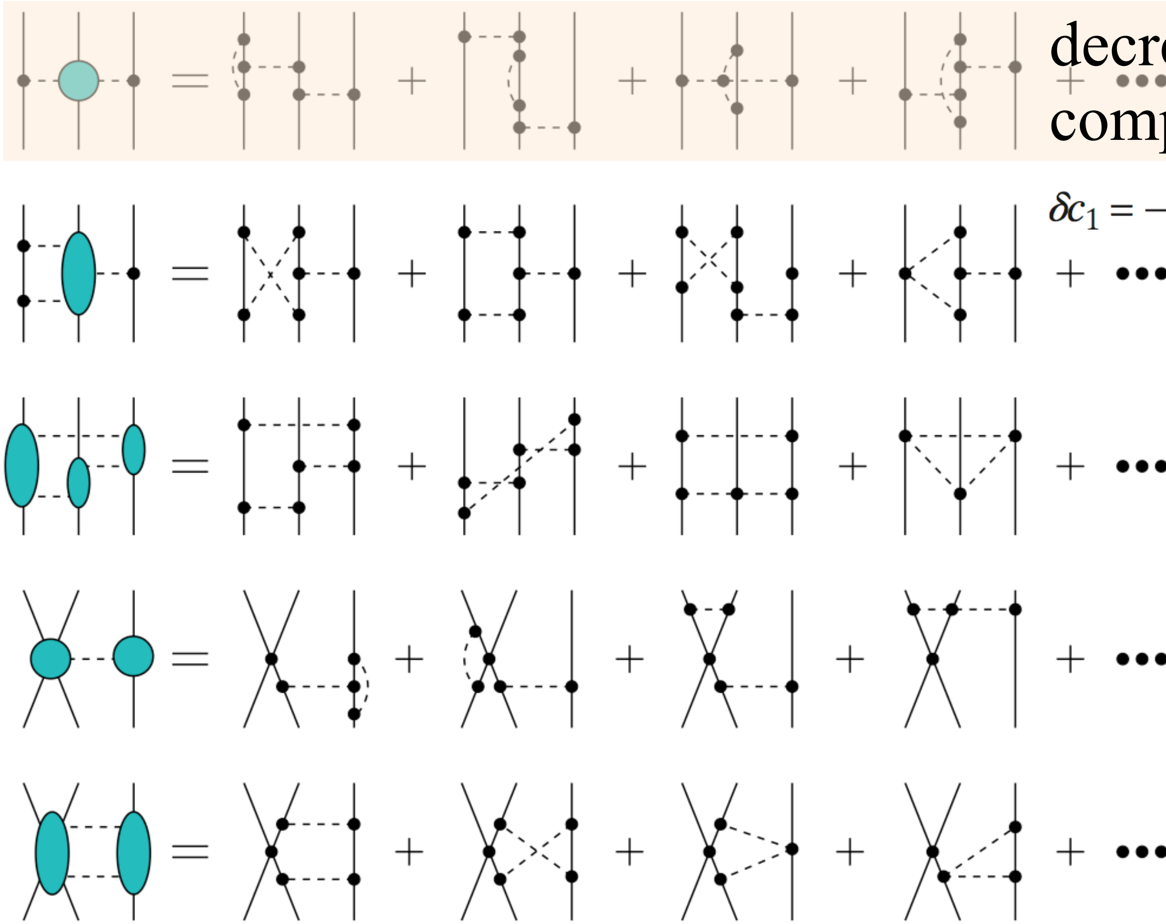
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

Subleading chiral 3N forces

parameter-free N^3LO Bernard et al. (2007, 2011), Ishikawa, Robilotta (2007)

one-loop contributions:

2π-exchange, 2π-1π-exchange, rings, contact-1π-, contact-2π-exchange



decrease c_i strengths
comparable to N^2LO uncertainty

$\delta c_1 = -\, g_A^2 M_\pi / 64\pi F_\pi^2,\ \delta c_3 = -\,\delta c_4 = g_A^4 M_\pi / 16\pi F_\pi^2$

$\delta c_3 = -\delta c_4 = 1\ \mathrm{GeV}^{-1}$

1/m corrections: spin-orbit parts, interesting for A_y puzzle

Chiral EFT for nuclear forces

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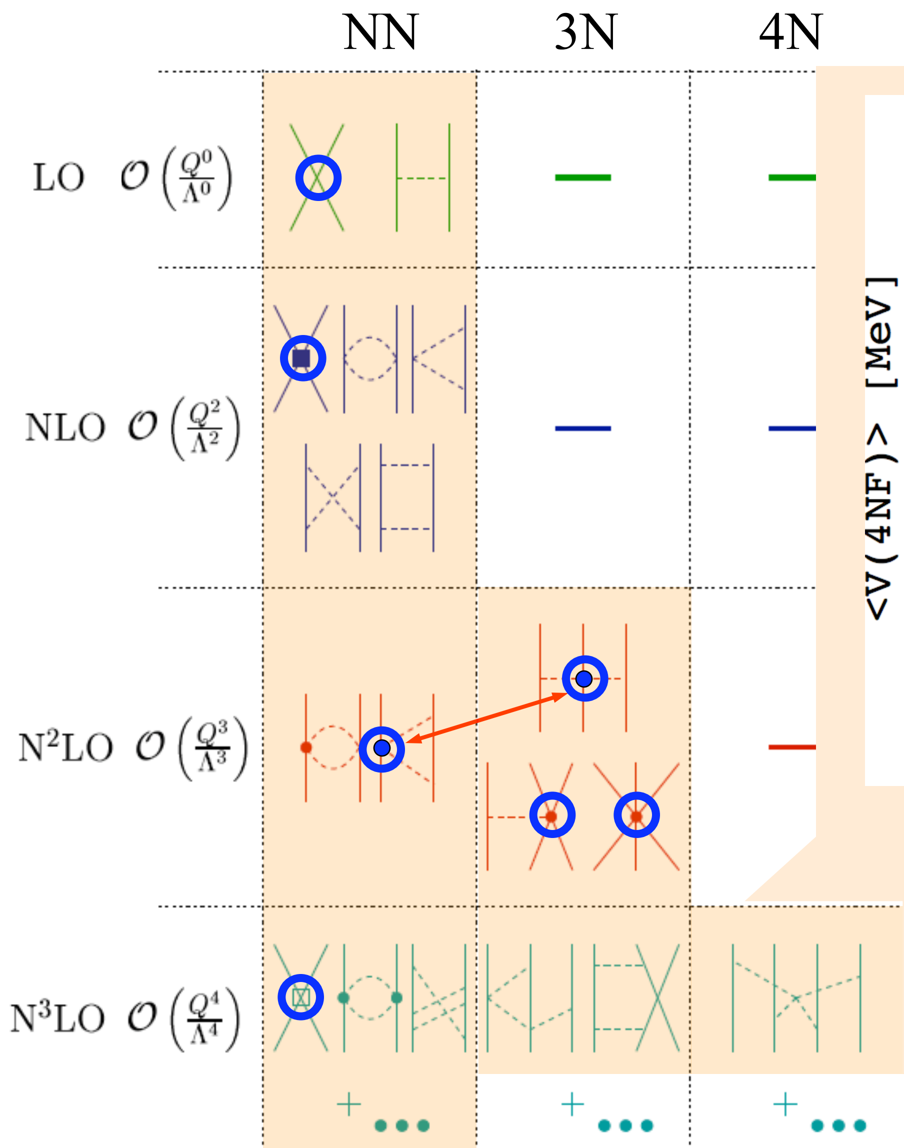

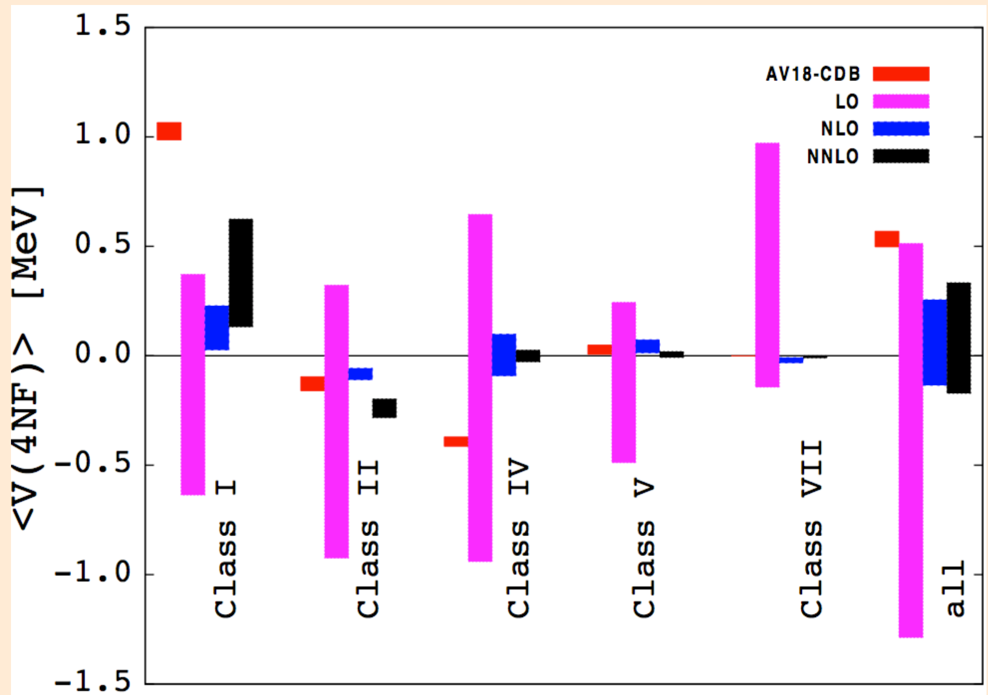

first perturbative estimate of 4N forces Nogga et al. (2010)

nuclear matter estimate small Fiorilla et al. (2011)

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

Three-body interactions and normal Fermi systems

3N forces important, but why residual 3-body contributions small?

no 3-body Fermi liquid parameters needed in liquid ^{3}He

no evidence of residual 3-body forces in the shell model (I. Talmi)

Three-body interactions and normal Fermi systems

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no 3-body Fermi liquid parameters needed in liquid ^{3}He

no evidence of residual 3-body forces in the shell model (I. Talmi)

can be understood in Fermi liquid theory Friman, AS, arXiv:1101.4858.

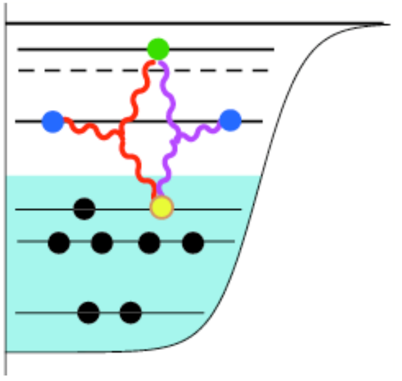
$$\delta E = \sum_1 \varepsilon_1^0 \, \delta n_1 + \frac{1}{2V} \sum_{1,2} f^{(2)}_{1,2} \, \delta n_1 \, \delta n_2 + \frac{1}{6V^2} \sum_{1,2,3} f^{(3)}_{1,2,3} \, \delta n_1 \, \delta n_2 \, \delta n_3$$

contributions from residual 3-body interactions suppressed by E_{ex}/E_F

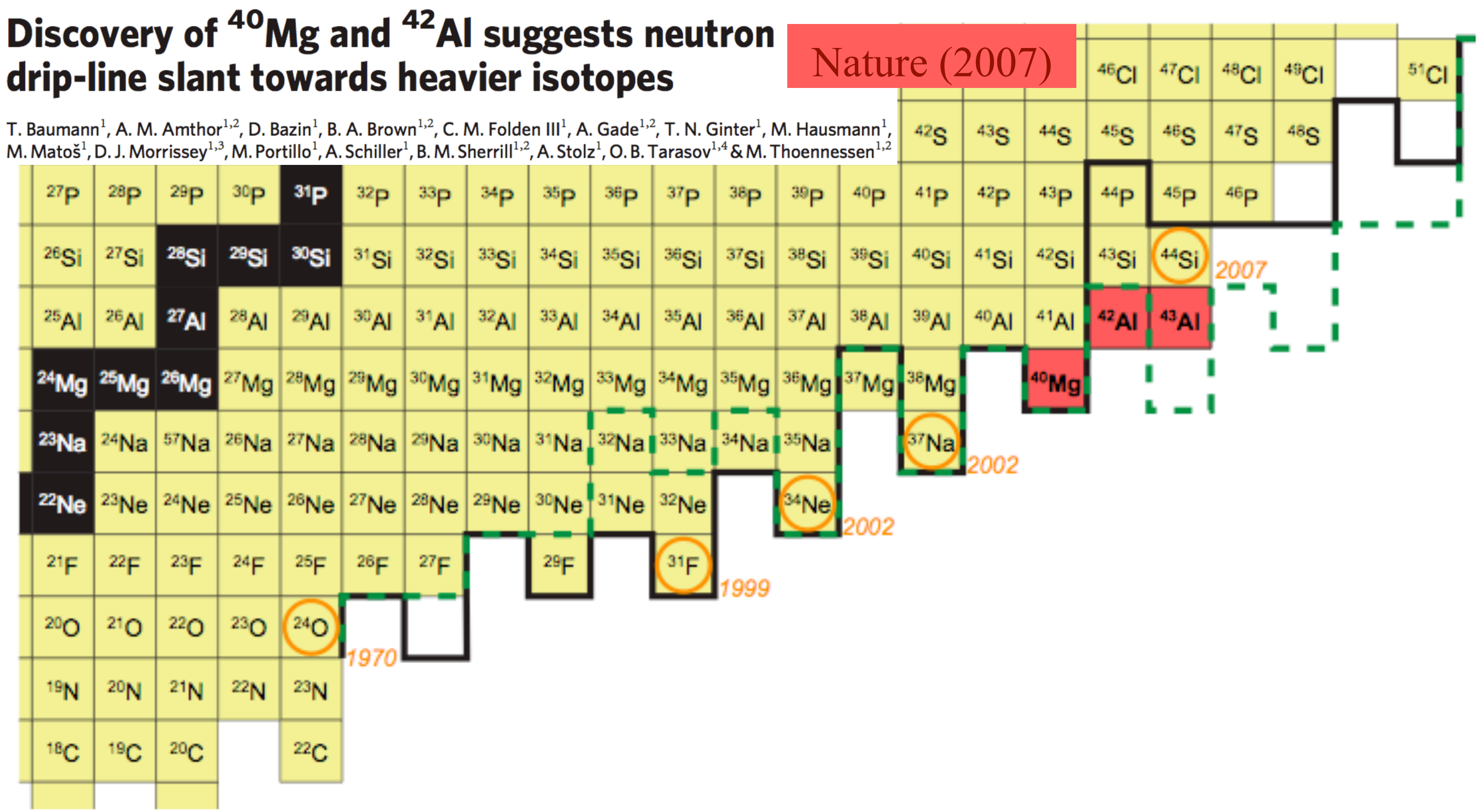
$$\frac{1}{2V} \sum_{1,2} f^{(2)}_{1,2} \, \delta n_1 \, \delta n_2 \sim \frac{1}{V} \langle f^{(2)} \rangle \left(\frac{N\Delta}{\mu} \right)^2 \sim \langle F^{(2)} \rangle \, \frac{N\Delta^2}{\mu}$$

$$\frac{1}{6V^2} \sum_{1,2,3} f^{(3)}_{1,2,3} \, \delta n_1 \, \delta n_2 \, \delta n_3 \sim \frac{n^2}{\mu} \langle f^{(3)} \rangle \, \frac{N\Delta^3}{\mu^2} \sim \langle F^{(3)} \rangle \, \frac{N\Delta^3}{\mu^2}$$

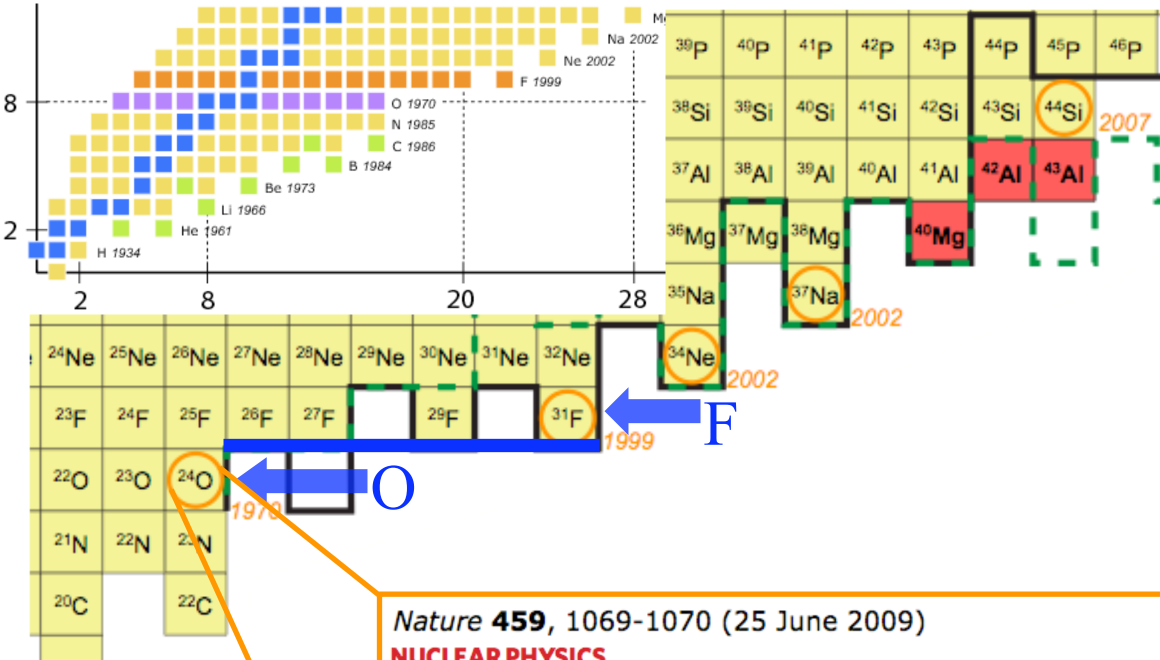
very helpful guiding principle for nuclei



Towards the limits of existence - the neutron drip-line



The oxygen anomaly



Nature **459**, 1069-1070 (25 June 2009)

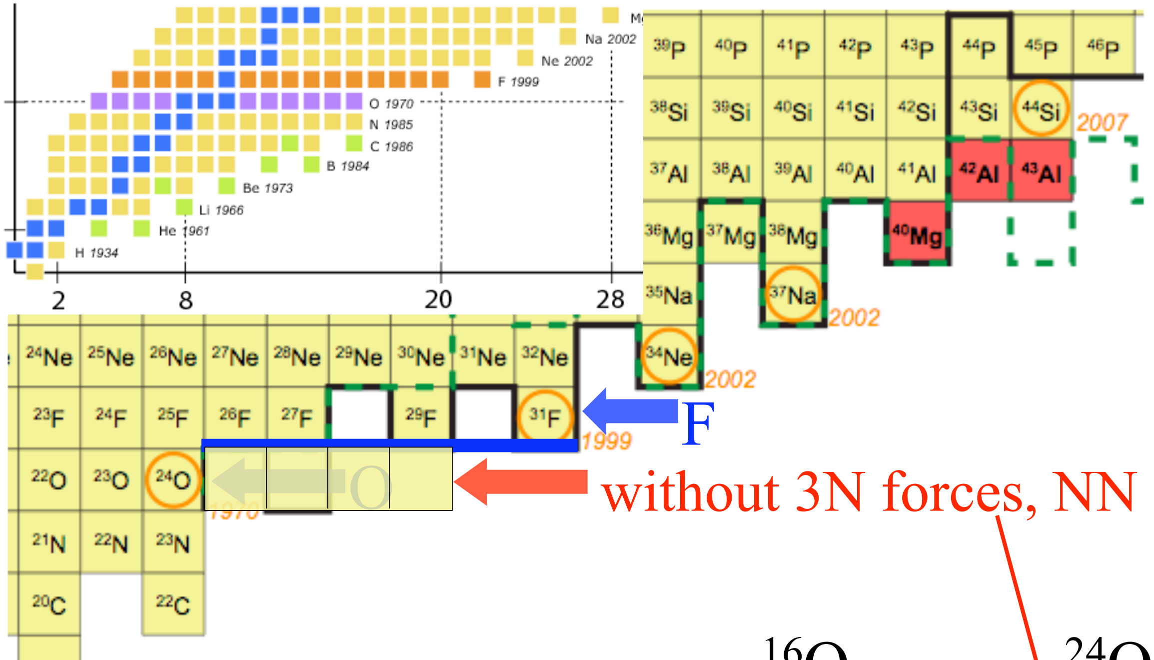
NUCLEAR PHYSICS

Unexpected doubly magic nucleus

Robert V. F. Janssens

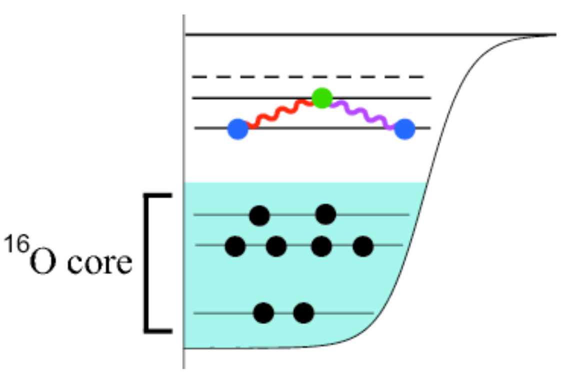
Nuclei with a 'magic' number of both protons and neutrons, dubbed doubly magic, are particularly stable. The oxygen isotope ^{24}O has been found to be one such nucleus — yet it lies just at the limit of stability.

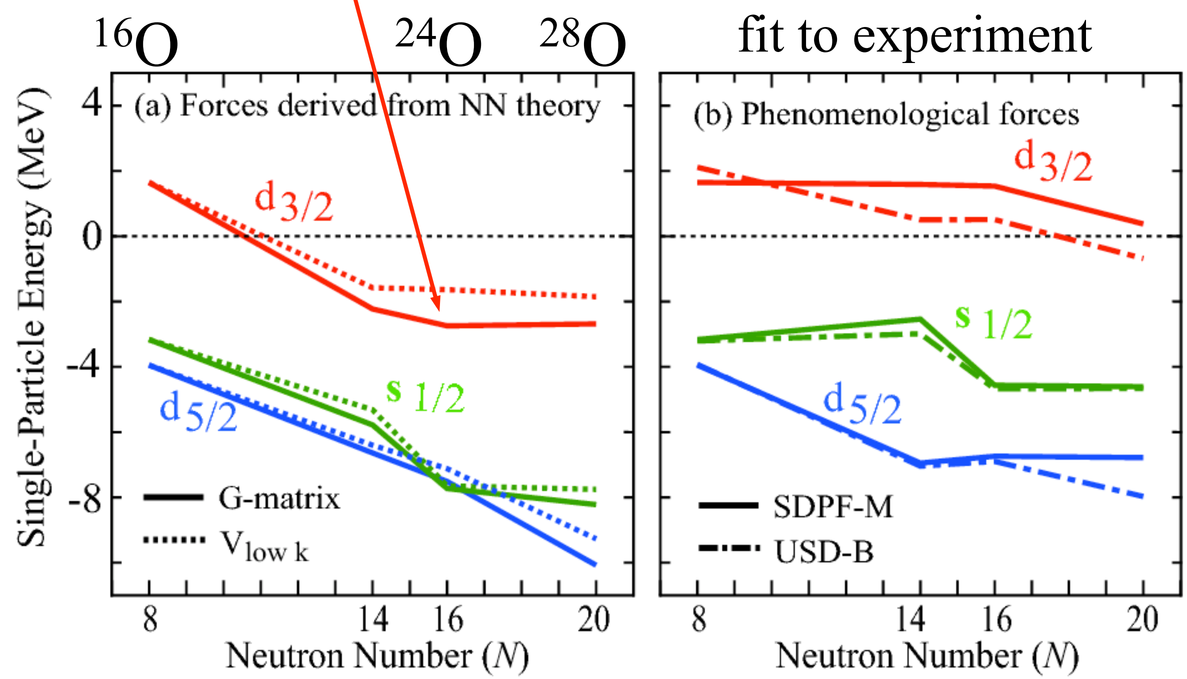
The oxygen anomaly - not reproduced without 3N forces



without 3N forces, NN interactions too attractive

many-body theory based on two-nucleon forces:
drip-line incorrect at ^{28}O

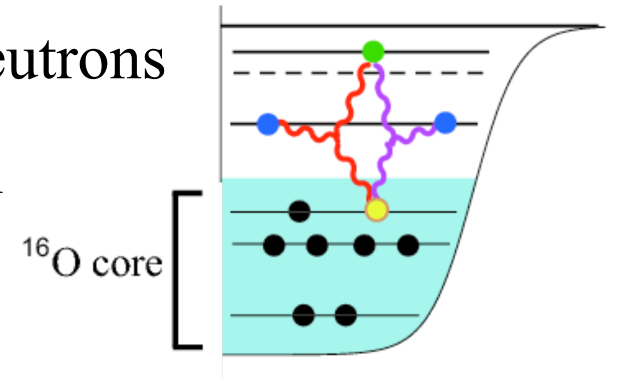




The oxygen anomaly - impact of 3N forces

include ‘normal-ordered’ 2-body part of 3N forces (enhanced by core A)

leads to repulsive interactions between valence neutrons



contributions from residual three valence-nucleon interactions suppressed by $E_{ex}/E_F \sim N_{valence}/N_{core}$

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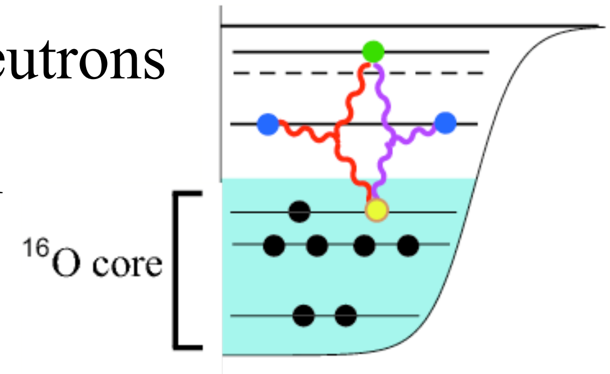
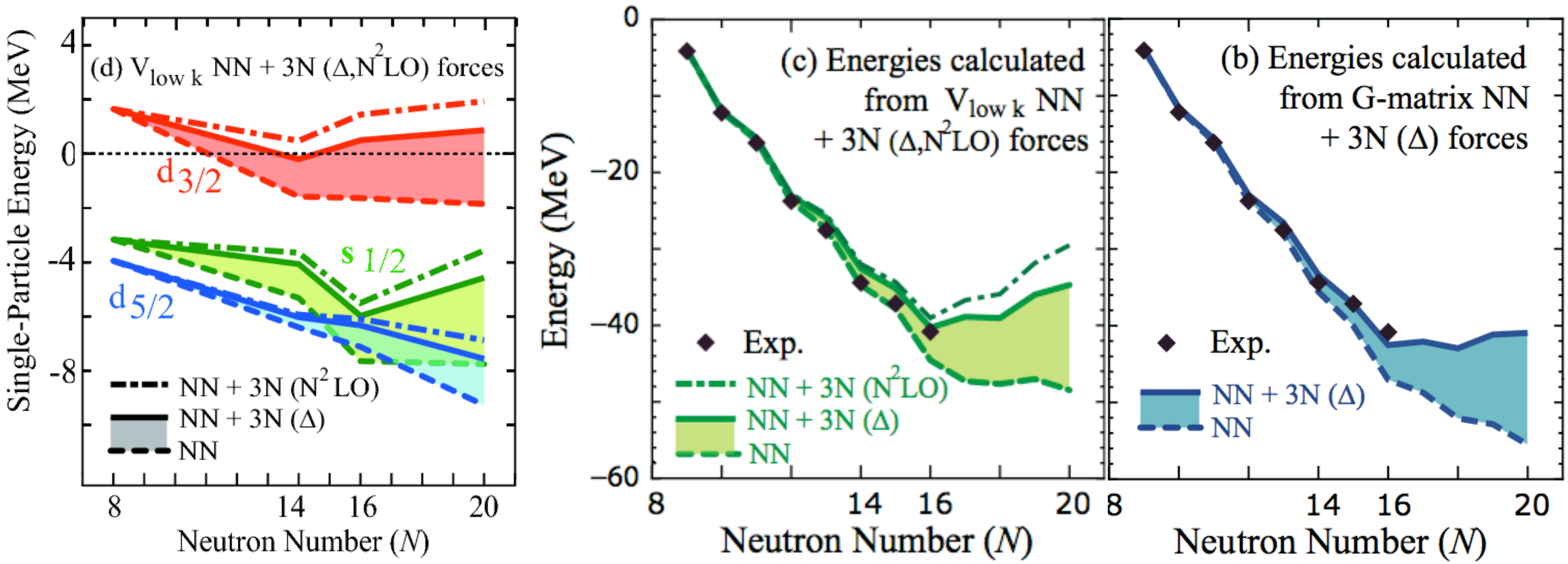
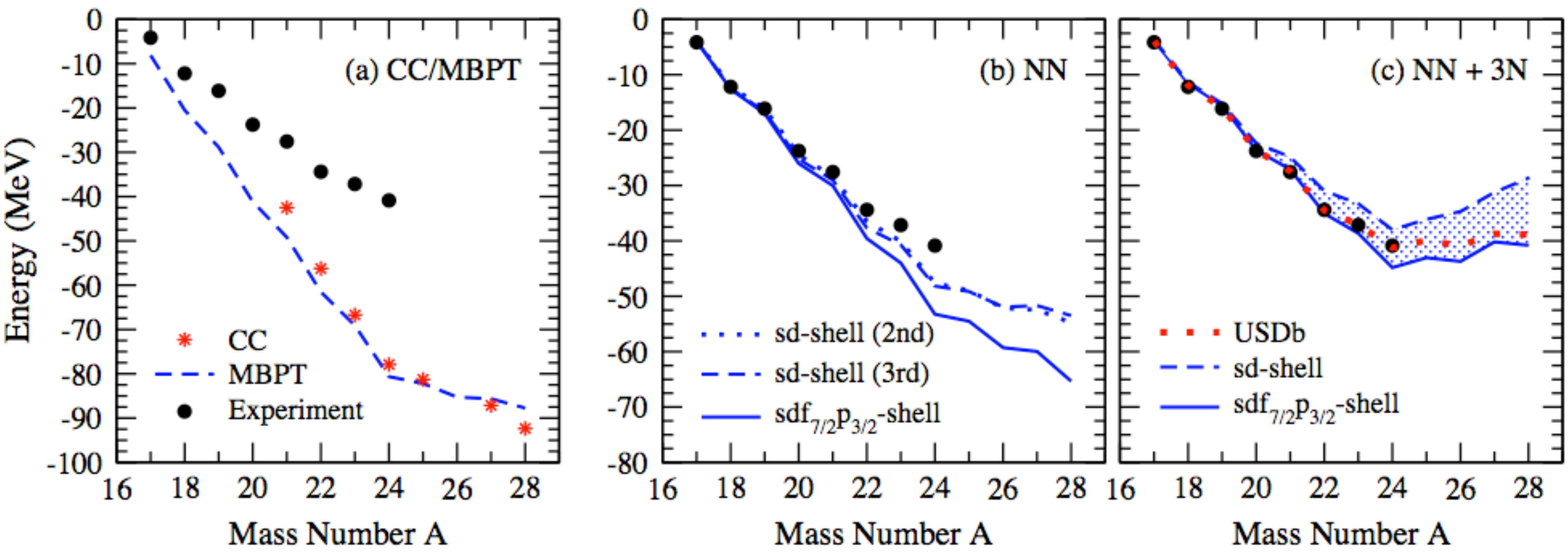


$d_{3/2}$ orbital remains unbound from ^{16}O to ^{28}O



microscopic explanation of the oxygen anomaly Otsuka et al., PRL (2010)

Calculational improvements and benchmark Holt, AS, arXiv:1108.2680.



good agreement with CC calculations (based on same NN interaction and CC single-particle energies)

3rd order MBPT well converged compared to other uncertainties

extended valence space (sd$f_{7/2}p_{3/2}$) is important for neutron-rich extremes

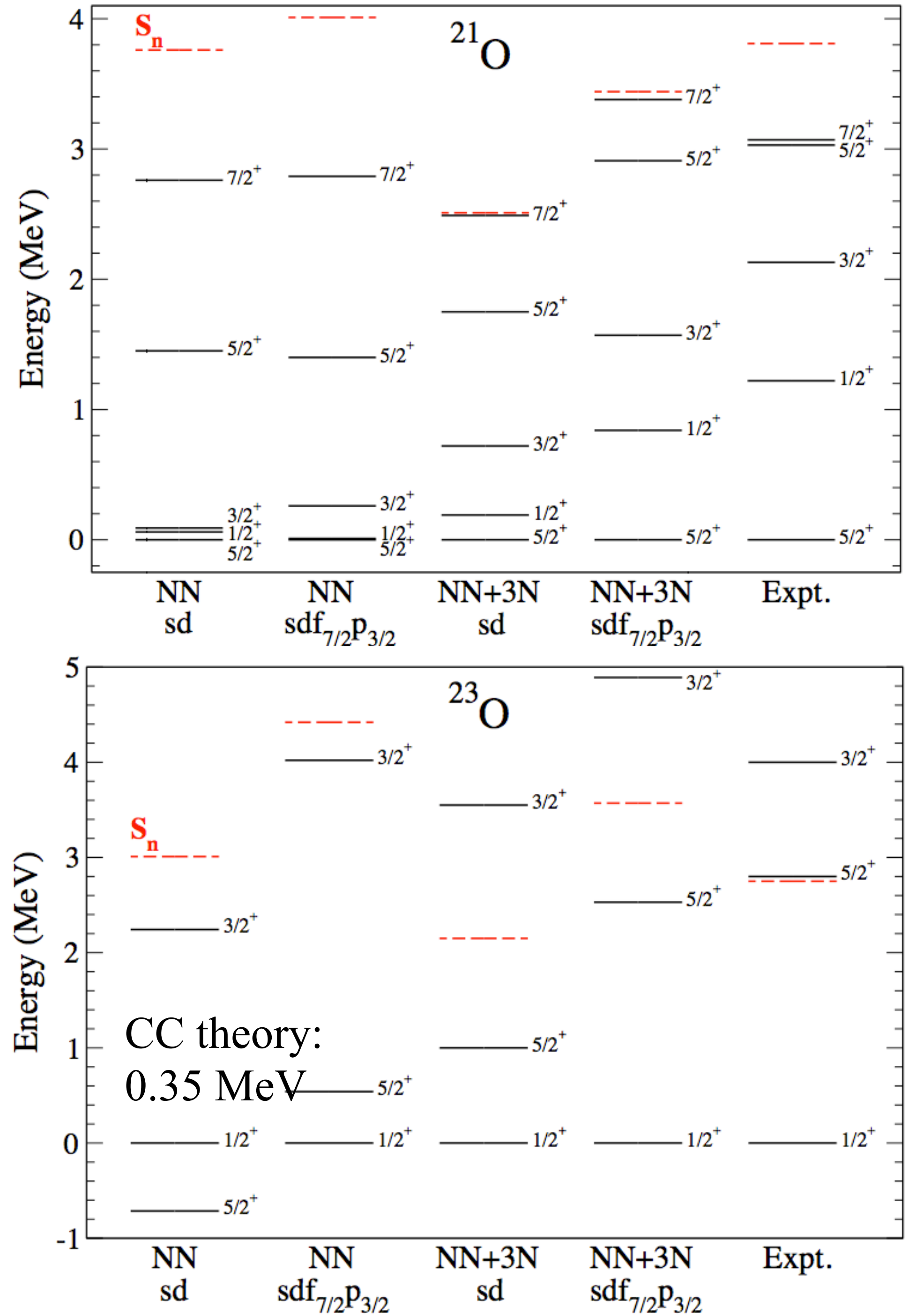
Oxygen spectra

focused on bound excited states

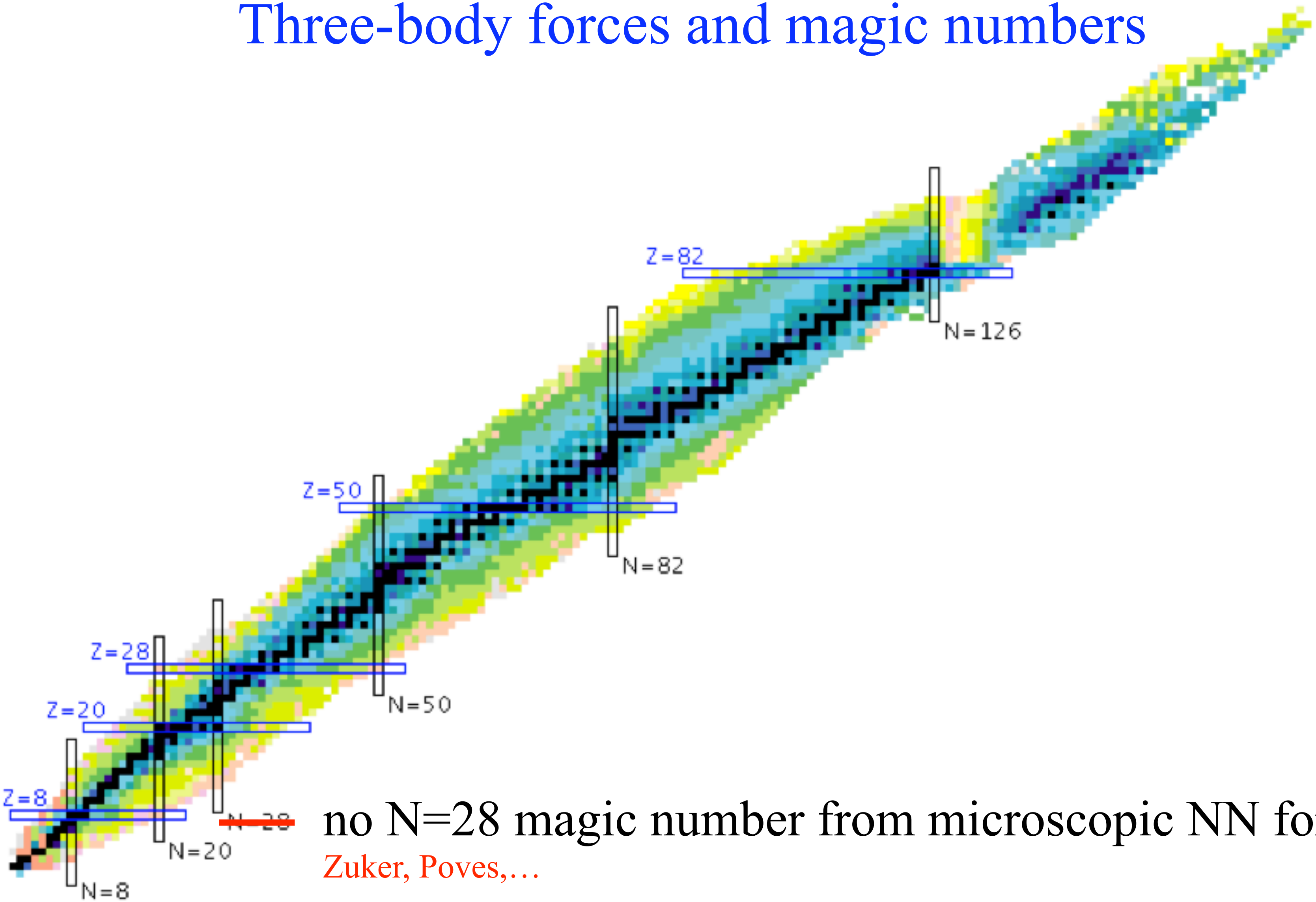
Holt, AS, arXiv:1108.2680.

NN only too compressed

3N contributions and extended valence space are key to reproduce excited states



Three-body forces and magic numbers



no N=28 magic number from microscopic NN forces

Zuker, Poves,…

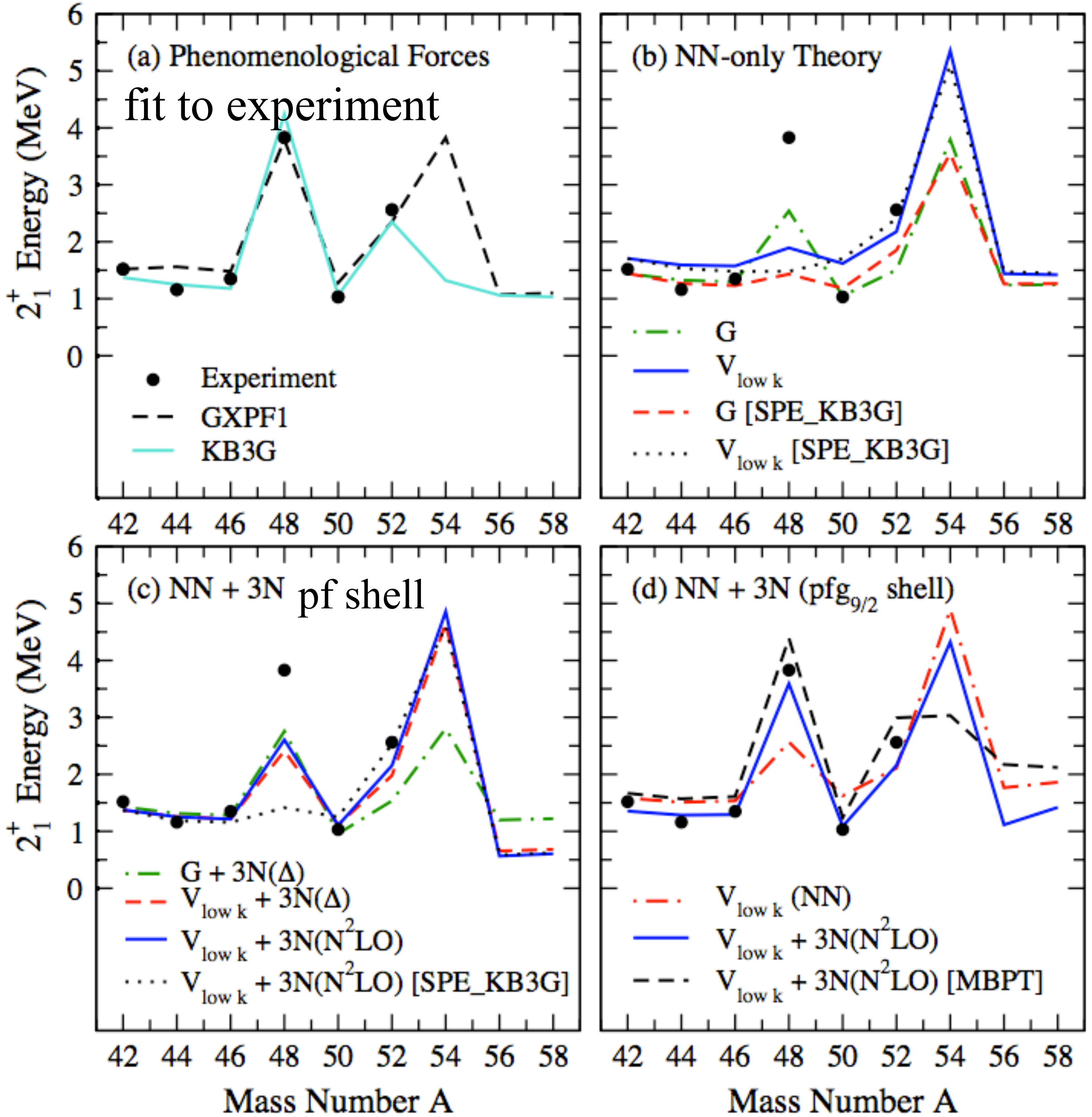
Three-body forces and magic numbers

3N mechanism important for shell structure

Holt et al., arXiv:1009:5984

N=28 shell closure due to 3N forces and single-particle effects (^{41}Ca)

N=34: predict high 2^+ excitation energy in ^{54}Ca at 3-5 MeV



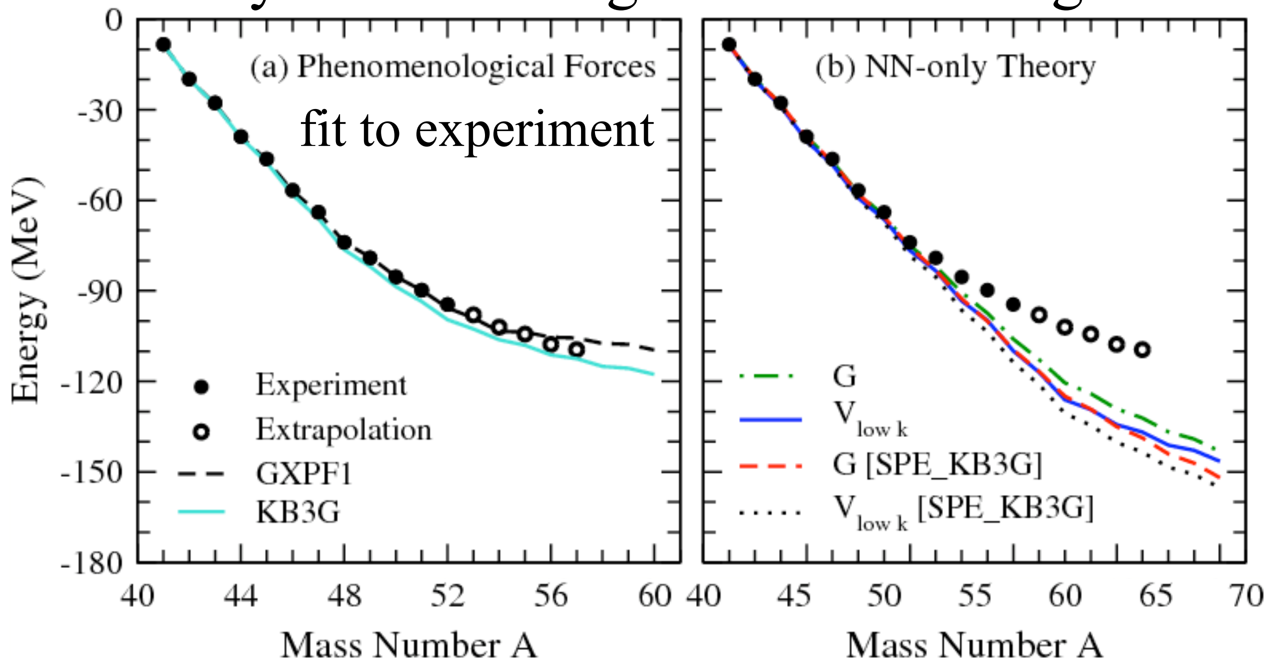
Evolution to neutron-rich calcium isotopes

repulsive 3N contributions also key for calcium ground-state energies

Holt et al., arXiv:1009:5984

mass measured to ^{52}Ca

shown to exist to ^{58}Ca



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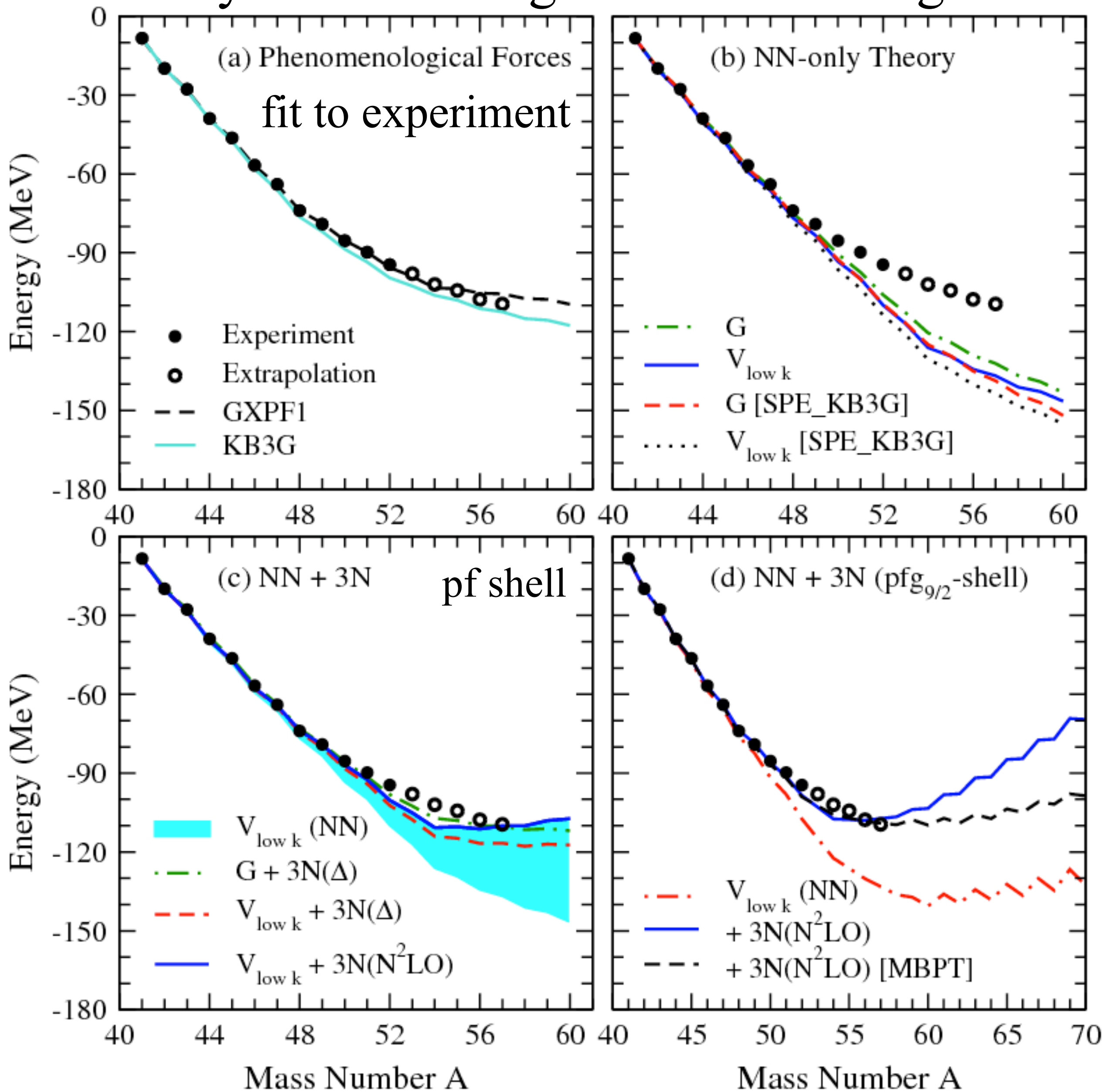
repulsive 3N contributions also key for calcium ground-state energies

Holt et al., arXiv:1009:5984

mass measured to ^{52}Ca
shown to exist to ^{58}Ca

predict drip-line
around ^{60}Ca

estimate of residual
3-body forces
~5 MeV in ^{60}Ca

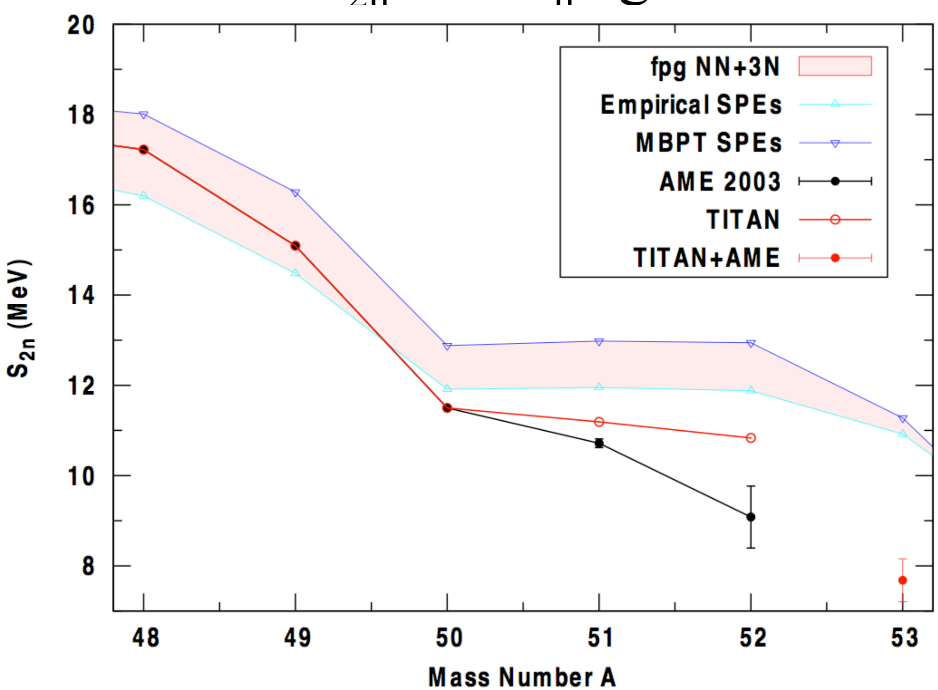


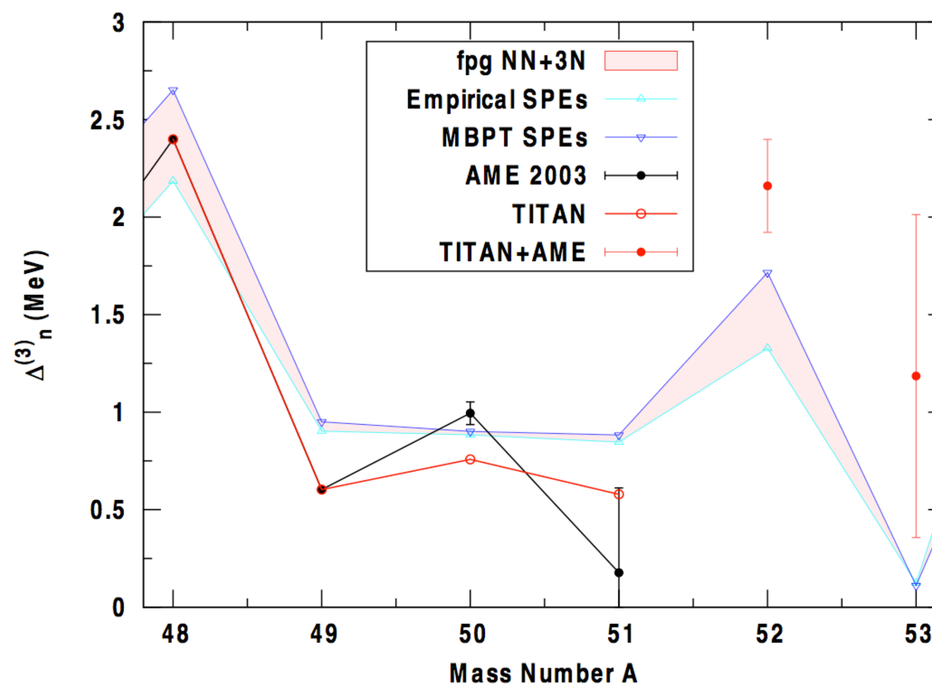
Evolution to neutron-rich calcium isotopes

new ^{51,52}Ca TITAN measurements:
J. Dilling et al. preliminary

^{52}Ca is 1.75 MeV more bound compared to atomic mass evaluation (AME)!

behavior of S_{2n} and Δ_n agrees with NN+3N calculations



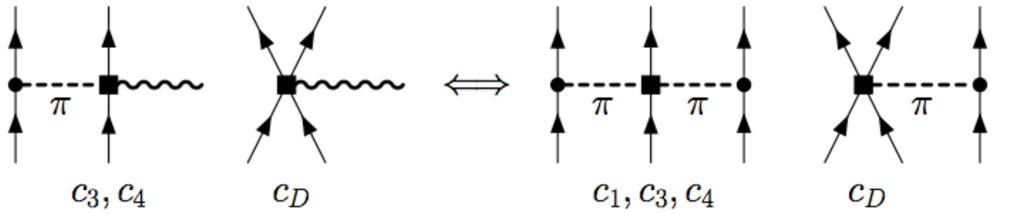


Chiral EFT for electroweak transitions Menendez, Gazit, AS (2011).

two-body currents lead to important contributions in nuclei (Q~100 MeV) especially for Gamow-Teller transitions

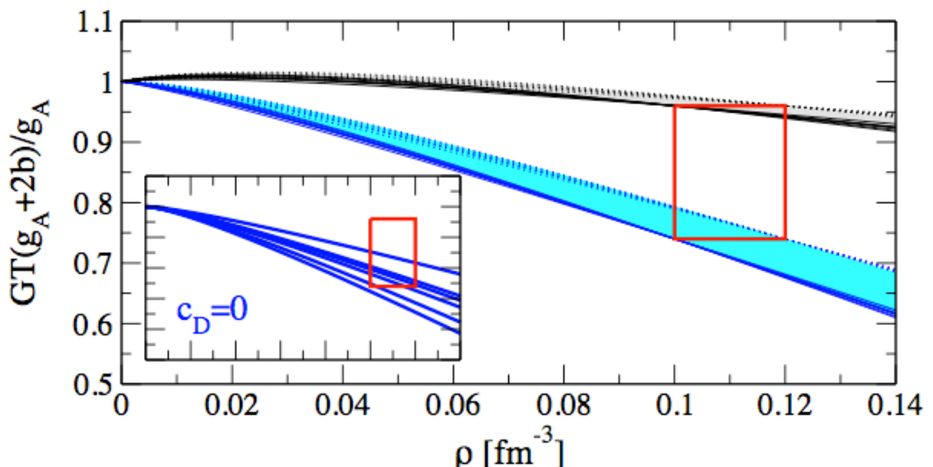
two-body currents determined by NN, 3N couplings to N^3LO

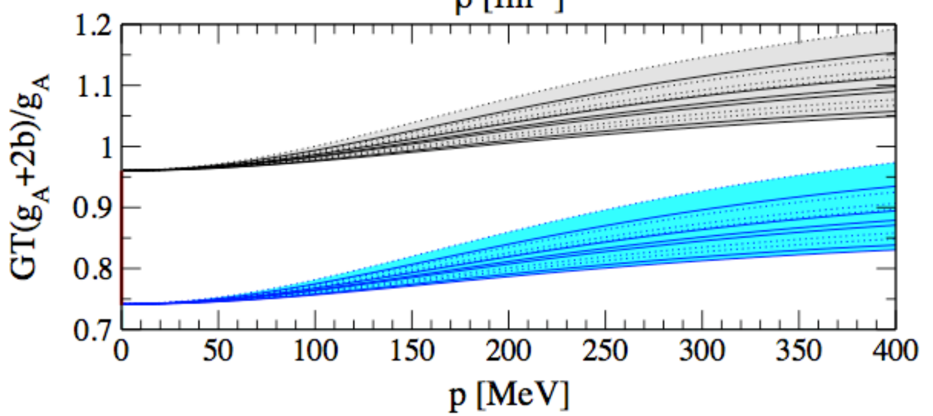
Park et al., Phillips,…



explains part of quenching of g_A (dominated by long-range part)

+ predict momentum dependence (weaker quenching for larger p)





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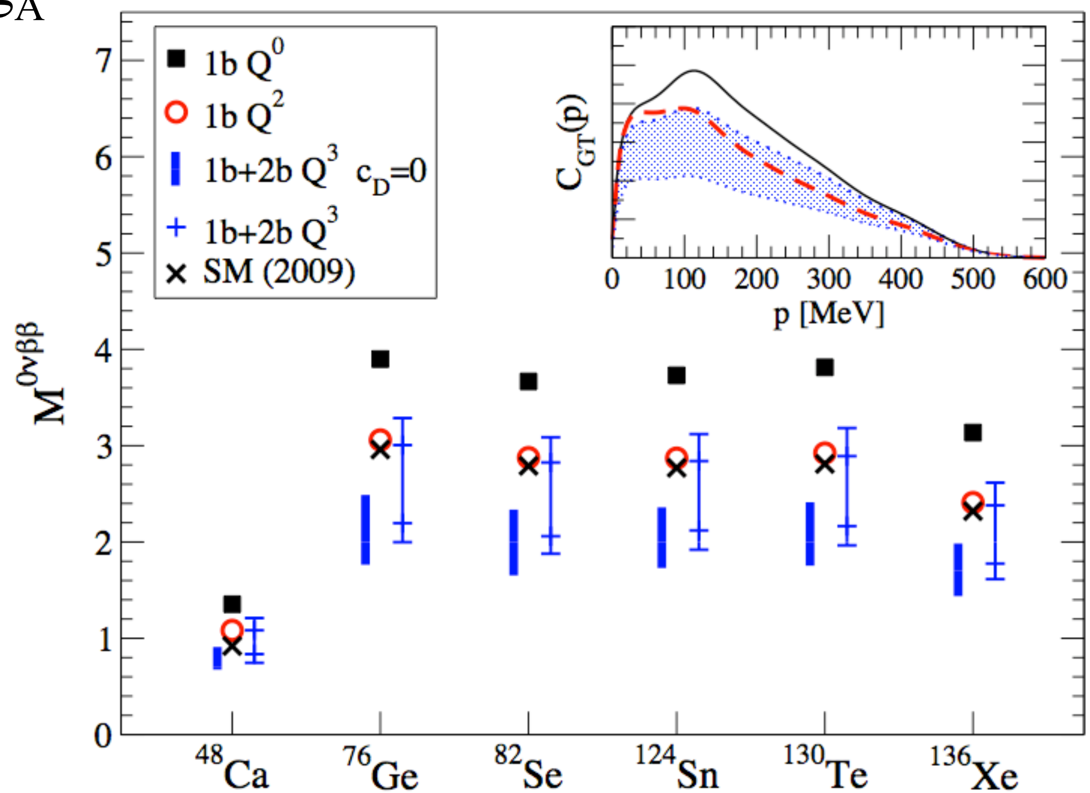
Park et al., Phillips,…

explains part of quenching of g_A

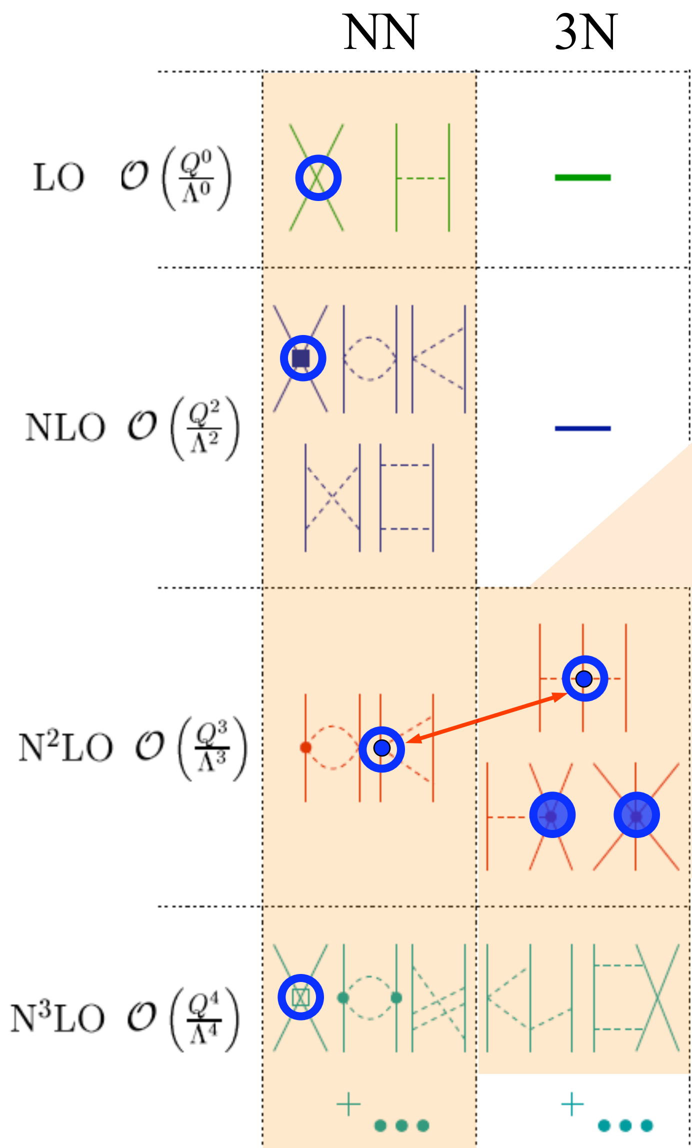
+ predict mom. dependence

+ nuclear matrix elements for $0\nu\beta\beta$ decay based on chiral EFT operator



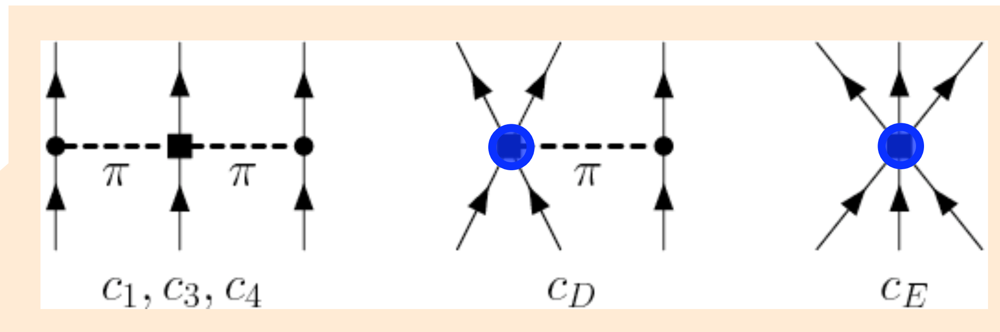
Chiral Effective Field Theory for nuclear forces

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



consistent NN-3N interactions

3N,4N: only 2 new couplings to N^{3}LO



c_i from πN and NN Meissner et al. (2007)

$$c_1 = -0.9^{+0.2}_{-0.5}\,,\ c_3 = -4.7^{+1.2}_{-1.0}\,,\ \ c_4 = 3.5^{+0.5}_{-0.2}$$

single-Δ: c_1=0, c_3=-c_4/2=-3 GeV^{-1}

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

Impact of 3N forces on neutron matter

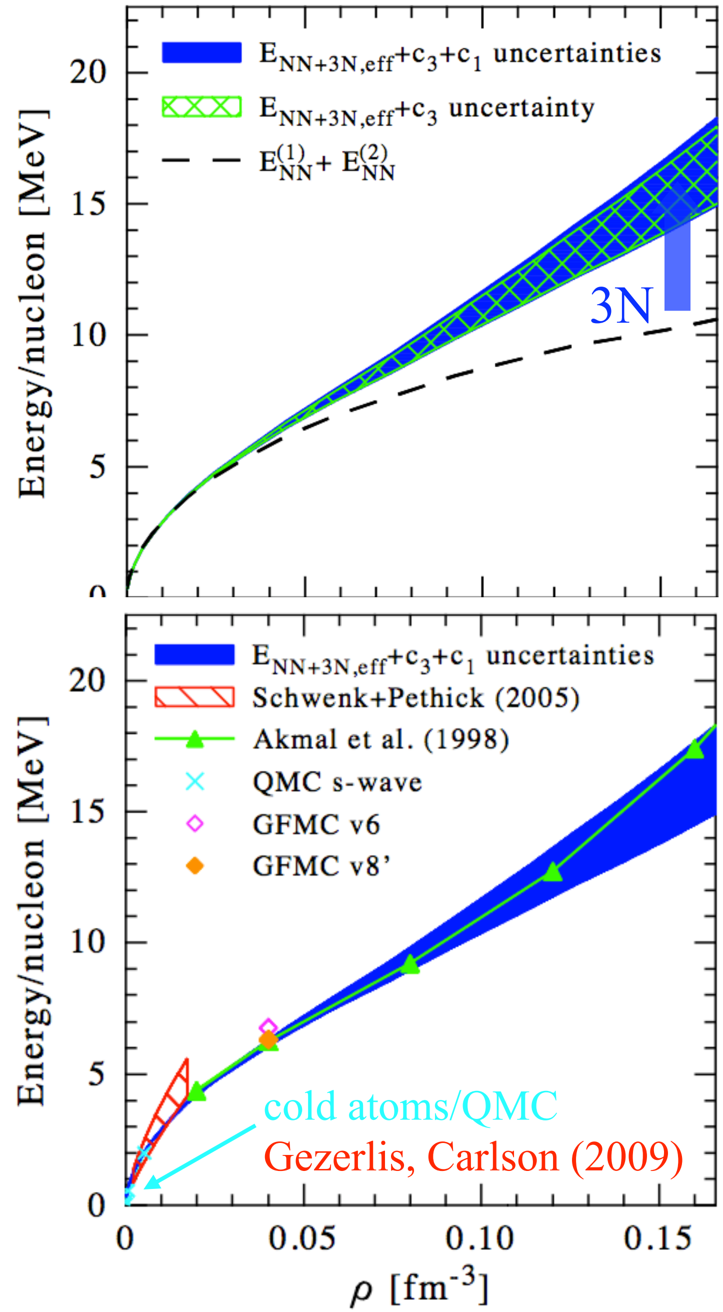
Hebeler, AS (2010); Tolos, Friman, AS (2007)

only long-range parts of 3N forces contribute to neutron matter (c_1 and c_3)

uncertainties dominated by c_3 coupling

repulsive contribution as for heavier neutron-rich nuclei

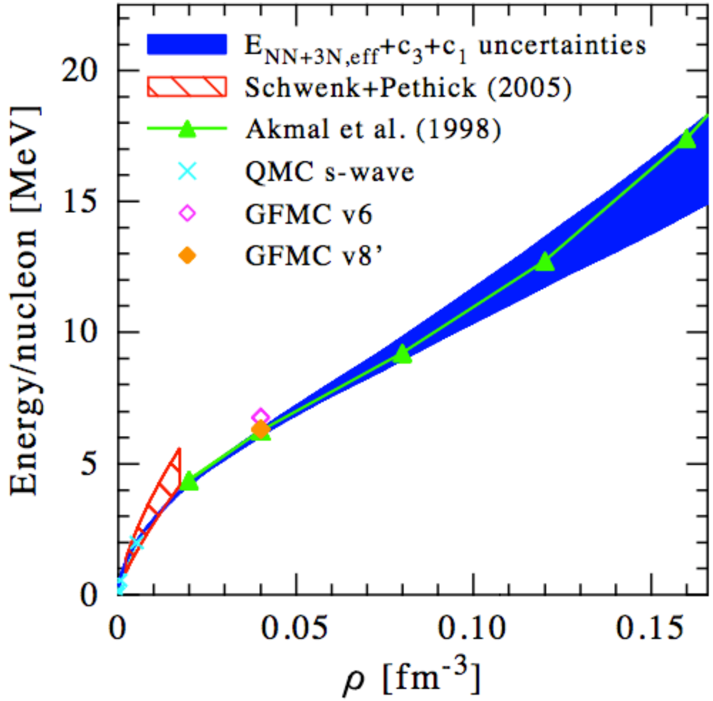
microscopic calculations within band



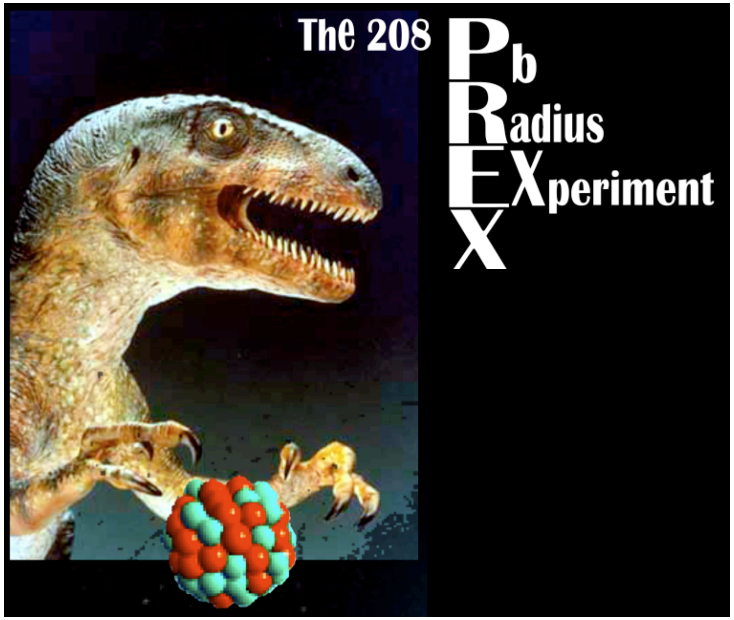
Symmetry energy and neutron skin Hebeler et al. (2010)

neutron matter band predicts range for symmetry energy 30.1-34.4 MeV

c_1 [GeV^{-1}]	c_3 [GeV^{-1}]	$\overline{S}_2$ [MeV]
−0.7	−2.2	30.1
−1.4	−4.8	34.4
NN-only EM		26.5
NN-only EGM		25.6



and neutron skin of ^{208}Pb to 0.17±0.03 fm

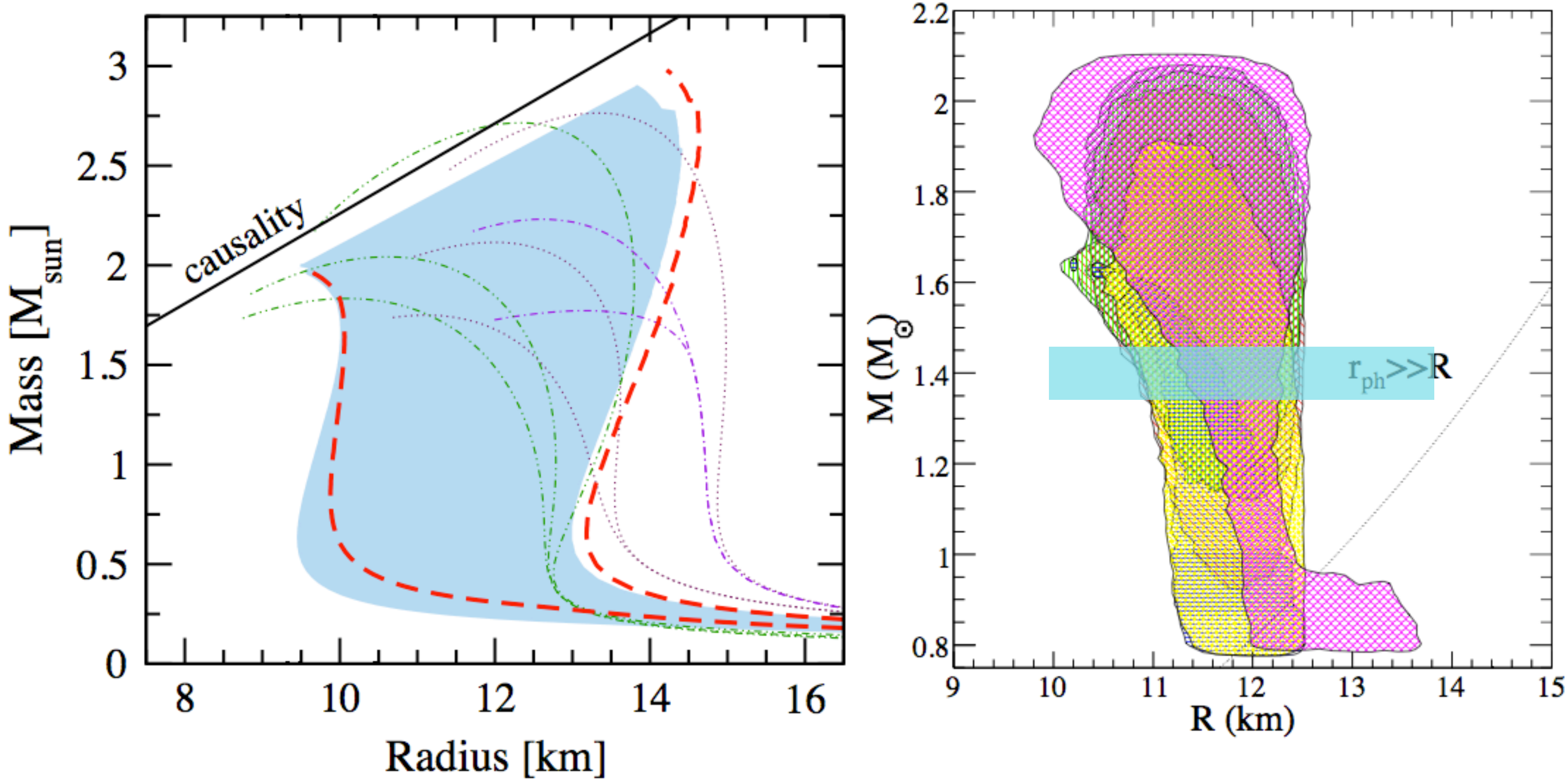


compare to ±0.05 fm future PREX goal
first result: 0.34+0.15-0.17 fm

from complete E1 response
0.156+0.025-0.021 fm Tamii et al., PRL (2011).

3N forces and neutron stars

uncertainty from many-body forces and general extrapolation



constrains neutron star radius: 9.9-13.8 km for M=1.4 M_{sun} (±15% !)

consistent with extraction from X-ray burst sources Steiner et al., ApJ (2010)

provides important constraints for EOS for core-collapse supernovae

Summary

Exciting era with advances on many fronts:
development of effective field theory and the renormalization group

enables a unified description from nuclei to matter in astrophysics

3N forces are a frontier for neutron-rich nuclei/matter:

key to explain why ^{24}O is the heaviest oxygen isotope

Ca isotopes (and N=28 magic number), key for neutron-rich nuclei

dominant uncertainty of neutron (star) matter below nuclear densities,
constraints on neutron star radii

exciting interactions with experiments and observations