Nuclear forces constraints of neutron-rich matter

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EMMI

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Outline

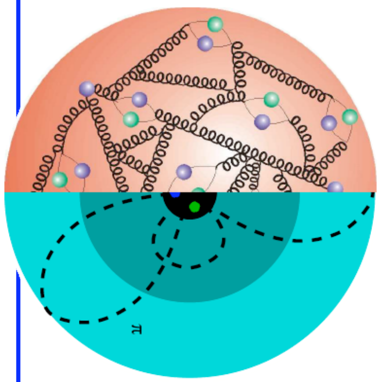
Chiral effective field theory and renormalization group
for nuclear forces

Three-nucleon forces and neutron-rich nuclei

Chiral effective field theory and electroweak transitions

Three-nucleon forces and neutron matter
(see colloquium)

Λ / Resolution dependence of nuclear forces



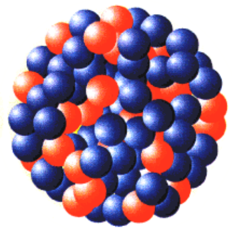
Effective theory for NN, 3N, many-N interactions and electroweak operators: resolution scale/Λ-dependent

$$H(\Lambda) = T + V_{\mathrm{NN}}(\Lambda) + V_{\mathrm{3N}}(\Lambda) + V_{\mathrm{4N}}(\Lambda) + \ldots$$

$\Lambda_{\mathrm{chiral}}$

momenta $Q \sim \lambda^{-1} \sim m_\pi$=140 MeV: chiral effective field theory

neutrons and protons interacting via pion exchanges
and shorter-range contact interactions



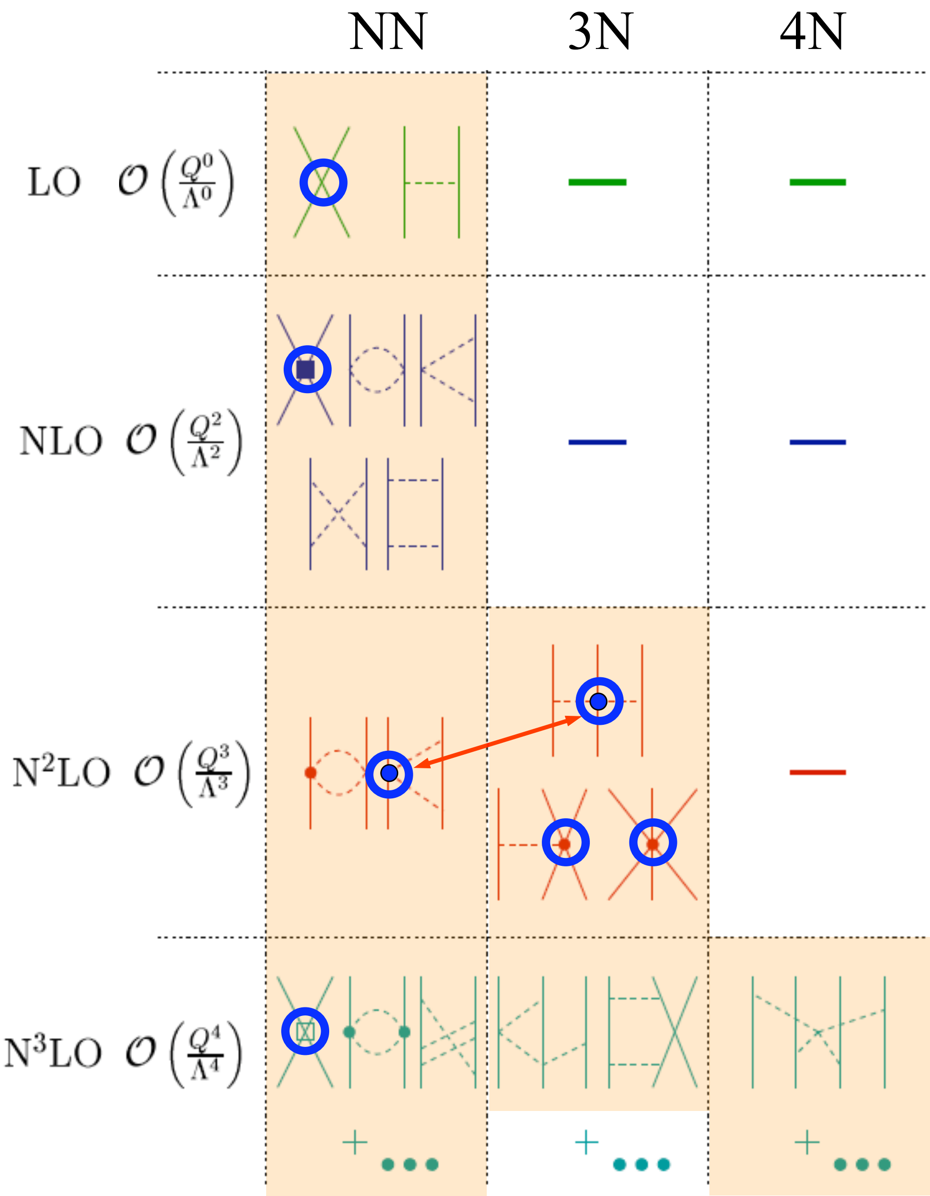
typical momenta in nuclei $\sim m_\pi$

$\Lambda_{\mathrm{pionless}}$

$Q << m_\pi$

Chiral Effective Field Theory 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 $(Q/\Lambda_b)^n$

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

open problems: renormalization and power counting

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

Nuclear forces and the Renormalization Group (RG)

RG evolution to lower resolution/cutoffs Bogner, Kuo, AS, Furnstahl,…

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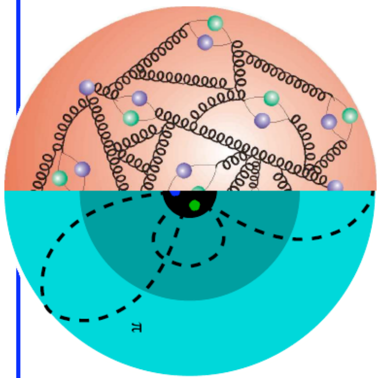

$\Lambda_{\mathrm{chiral}}$

Λ

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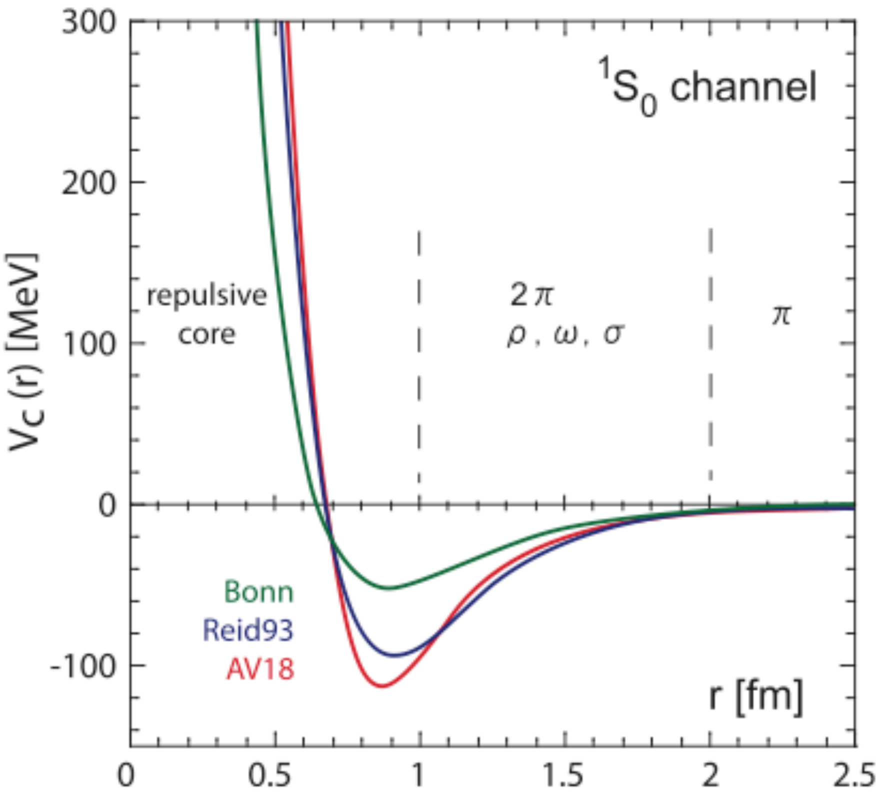
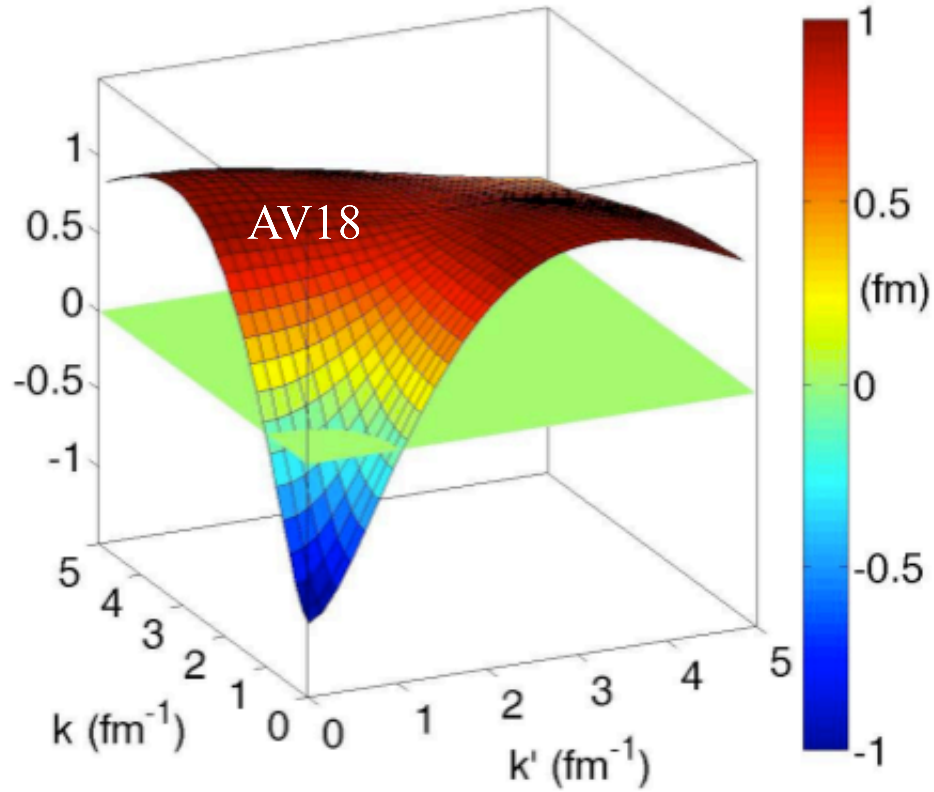
for NN interactions (preserves NN observables)





red = short-range repulsion

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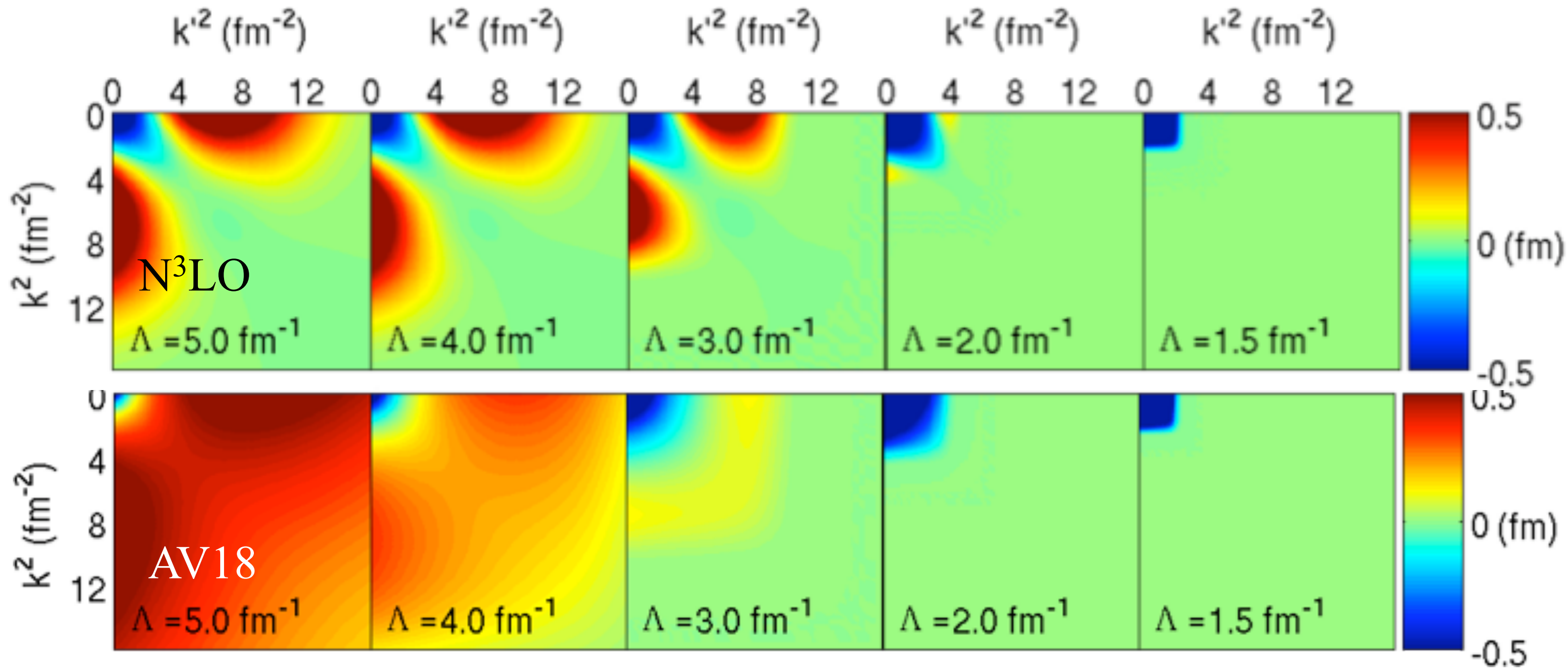


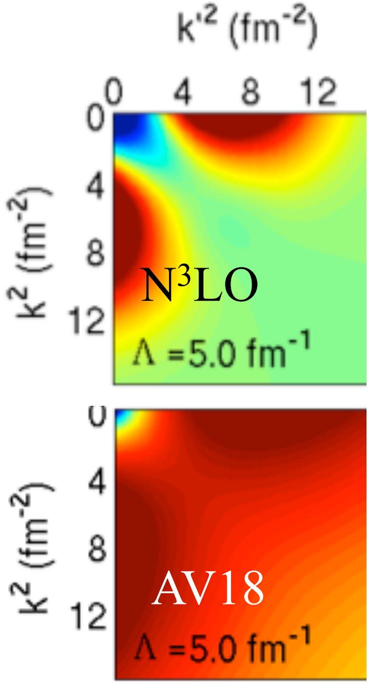
low-momentum interactions $V_{\mathrm{low}\,k}(\Lambda)$

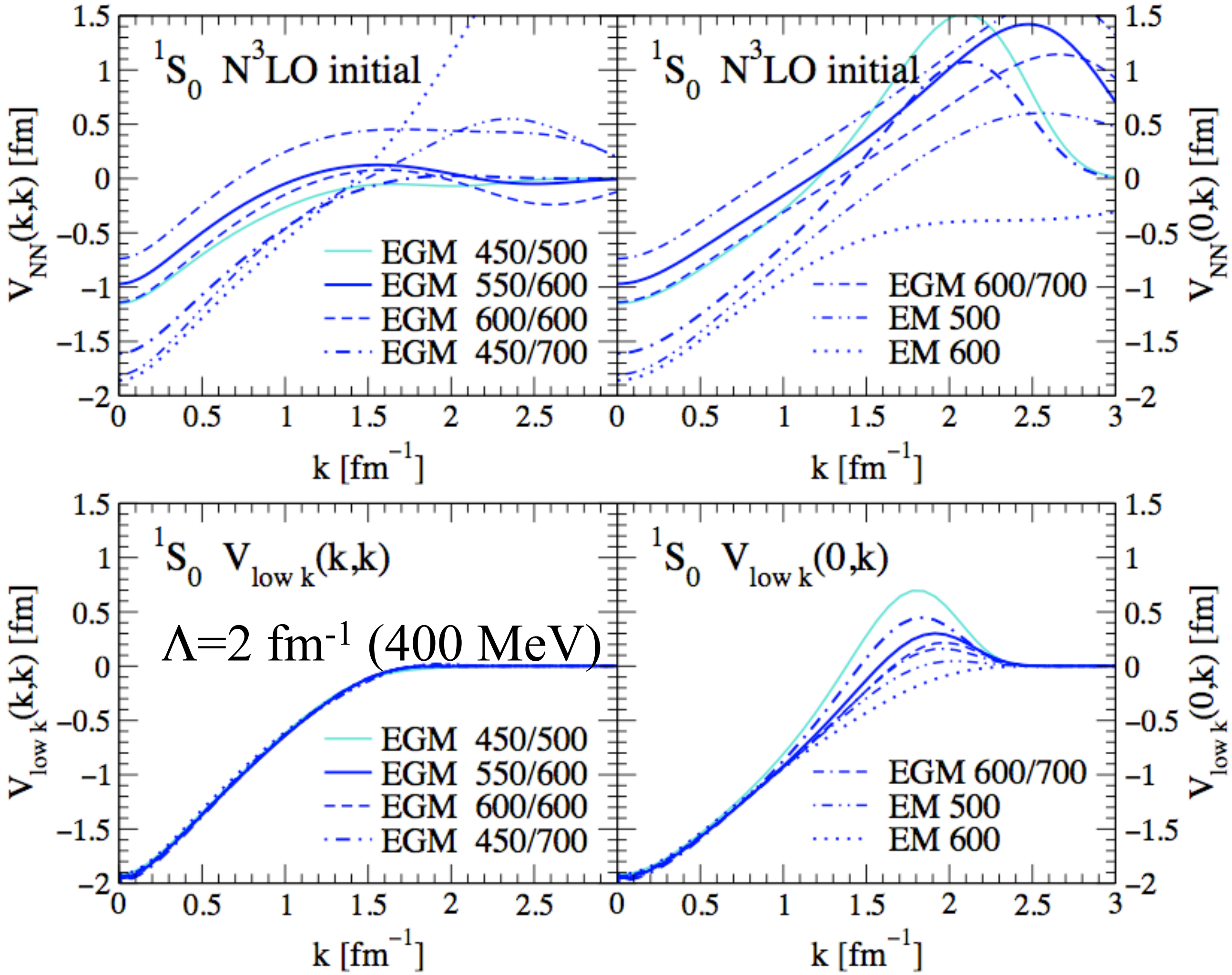
RG decouples low-momentum physics from high momenta

Nuclear forces and the Renormalization Group (RG)

RG evolution to lower resolution/cutoffs Bogner, Kuo, AS, Furnstahl,…

$$H(\Lambda) = T + V_{\mathrm{NN}}(\Lambda) + V_{3\mathrm{N}}(\Lambda) + V_{4\mathrm{N}}(\Lambda) + \ldots$$





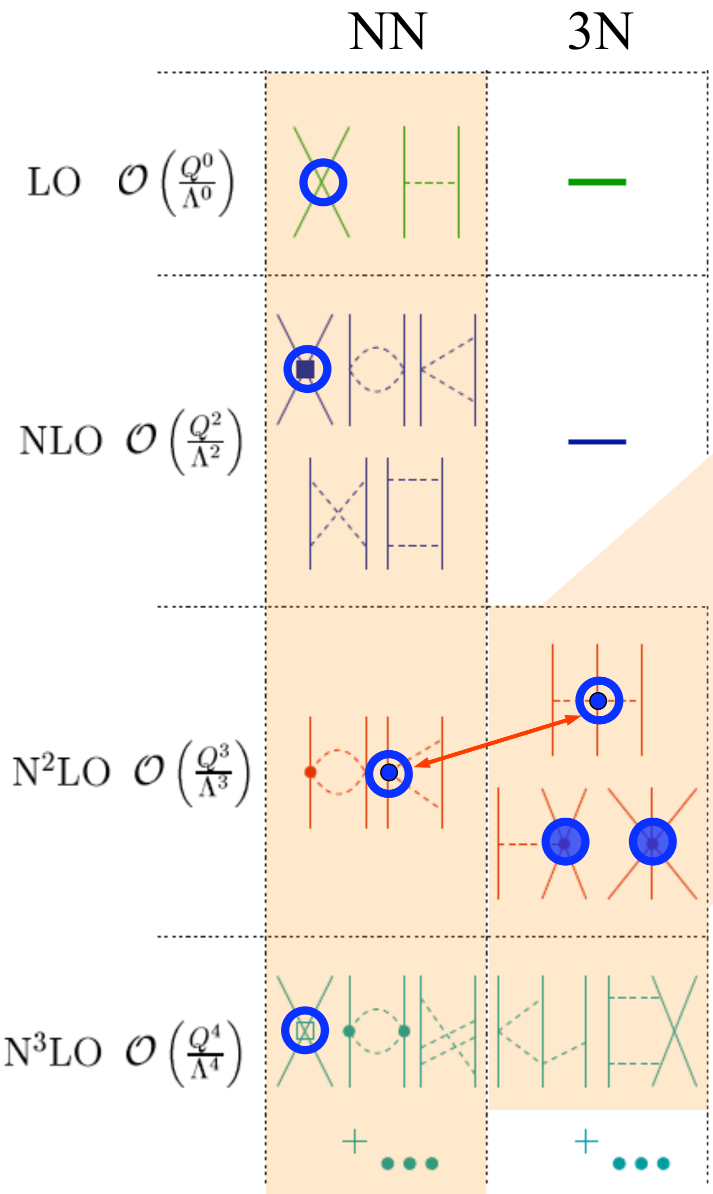
low-momentum i

RG decouples lov

low-momentum universality from different chiral N^3LO potentials

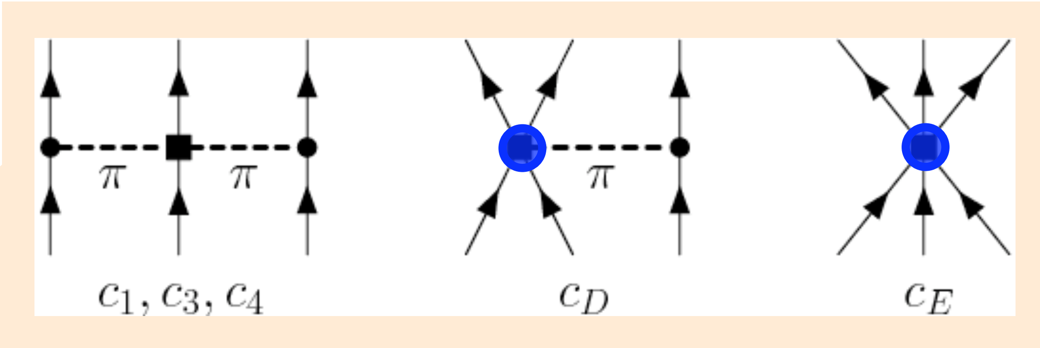
Chiral Effective Field Theory for nuclear forces

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}

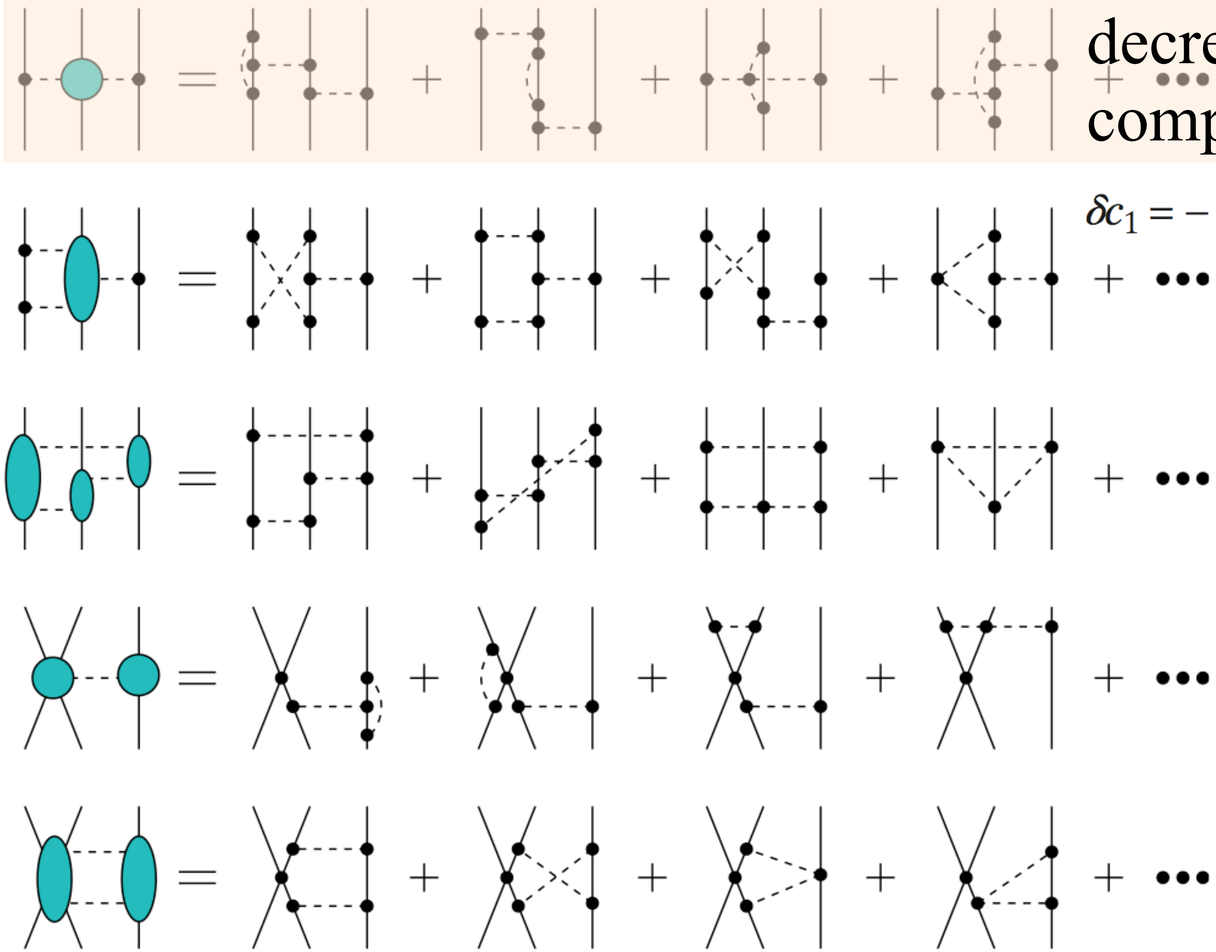
c_D, c_E fit to ^{3}H binding energy and ^{4}He radius (or ^{3}H beta decay half-life)

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

Subleading chiral 3N forces

parameter-free N^3LO from Epelbaum et al.; Bernard et al. (2007), 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

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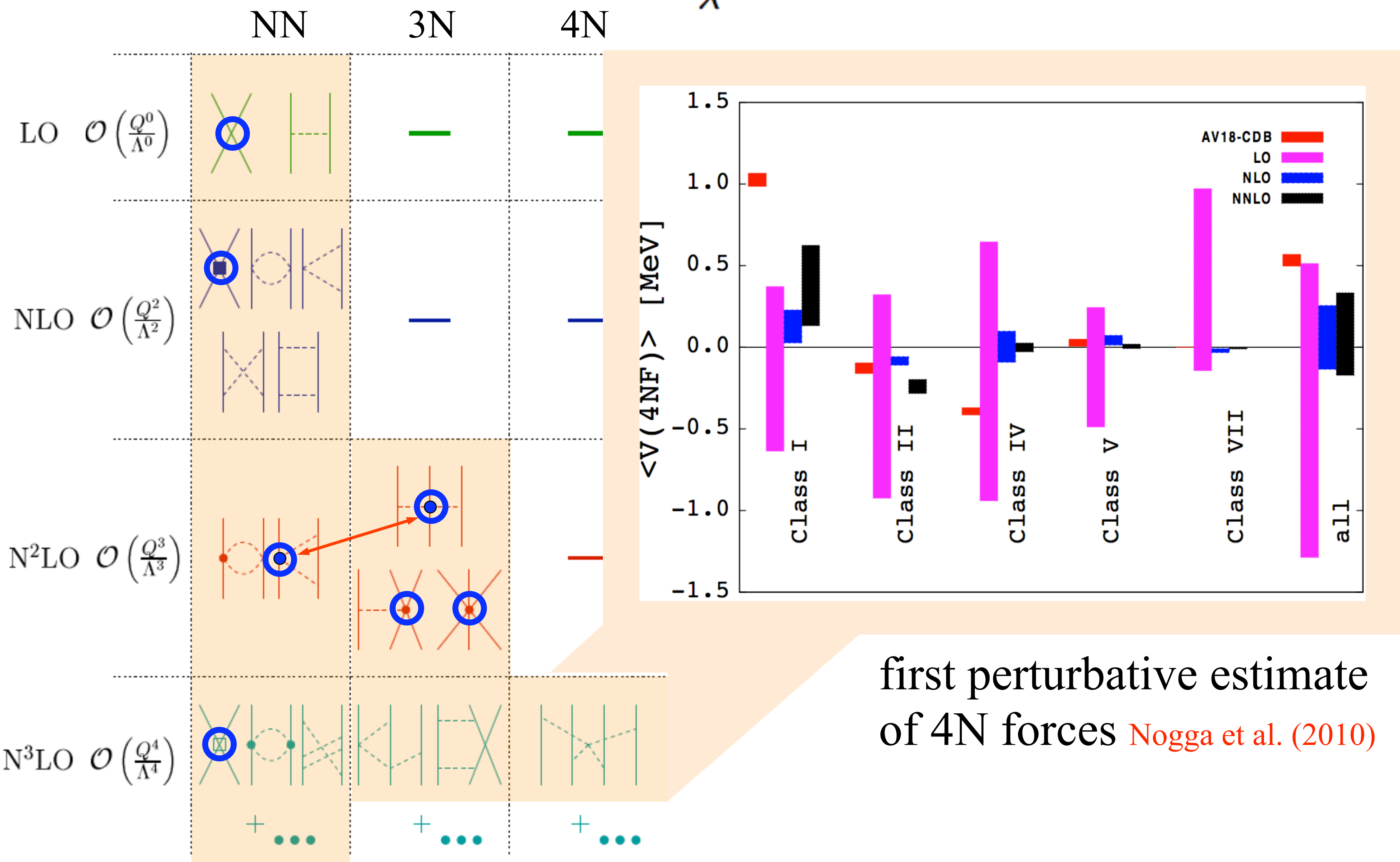
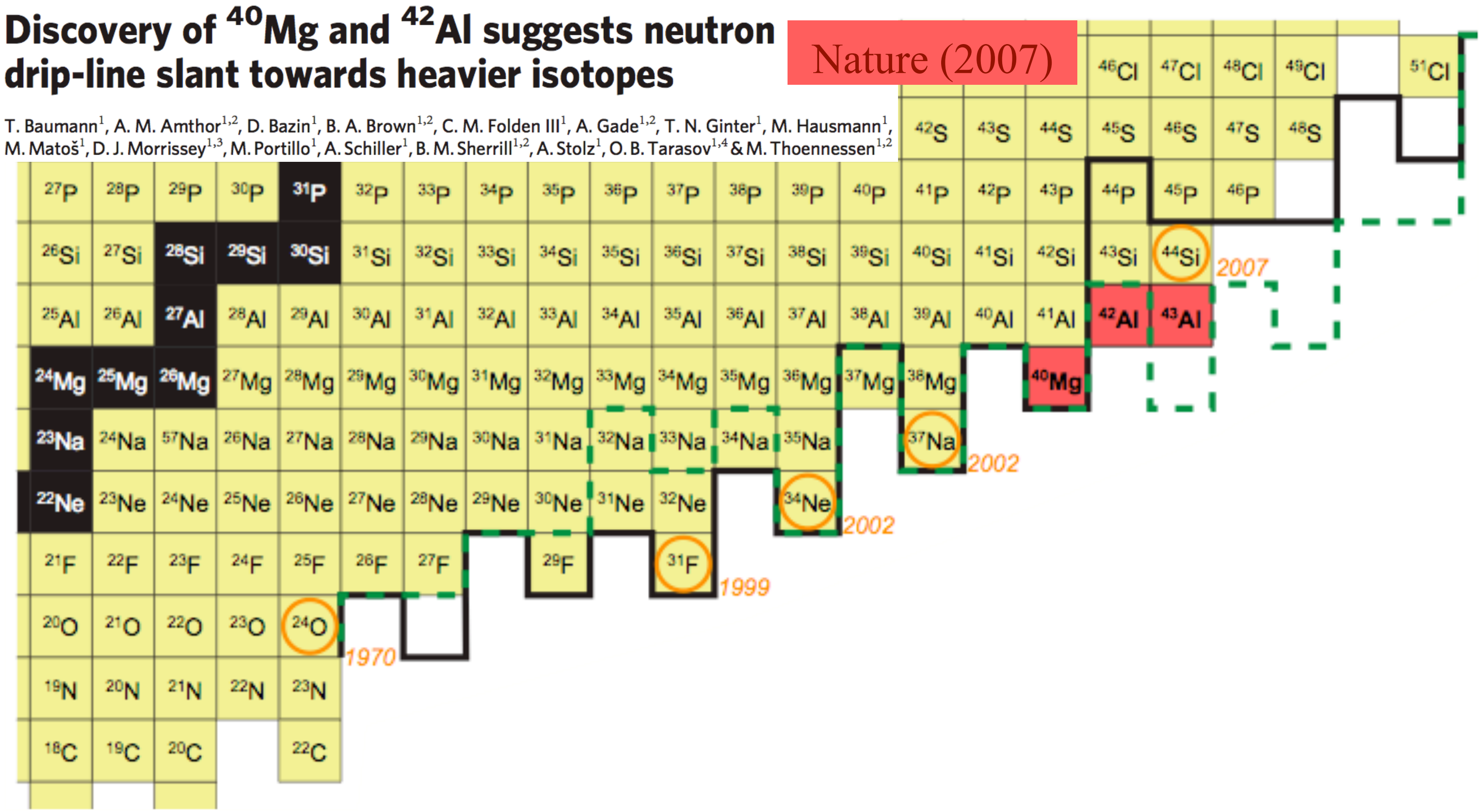


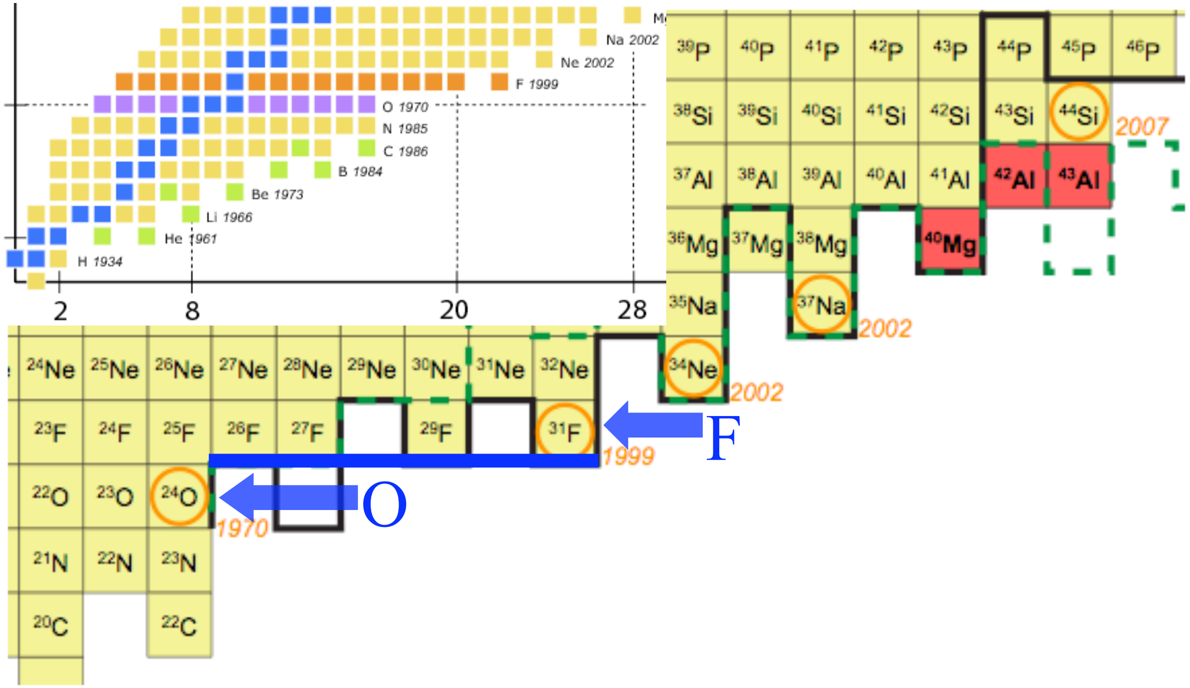
first perturbative estimate of 4N forces Nogga et al. (2010)

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

Towards the limits of existence - the neutron drip-line



The oxygen anomaly



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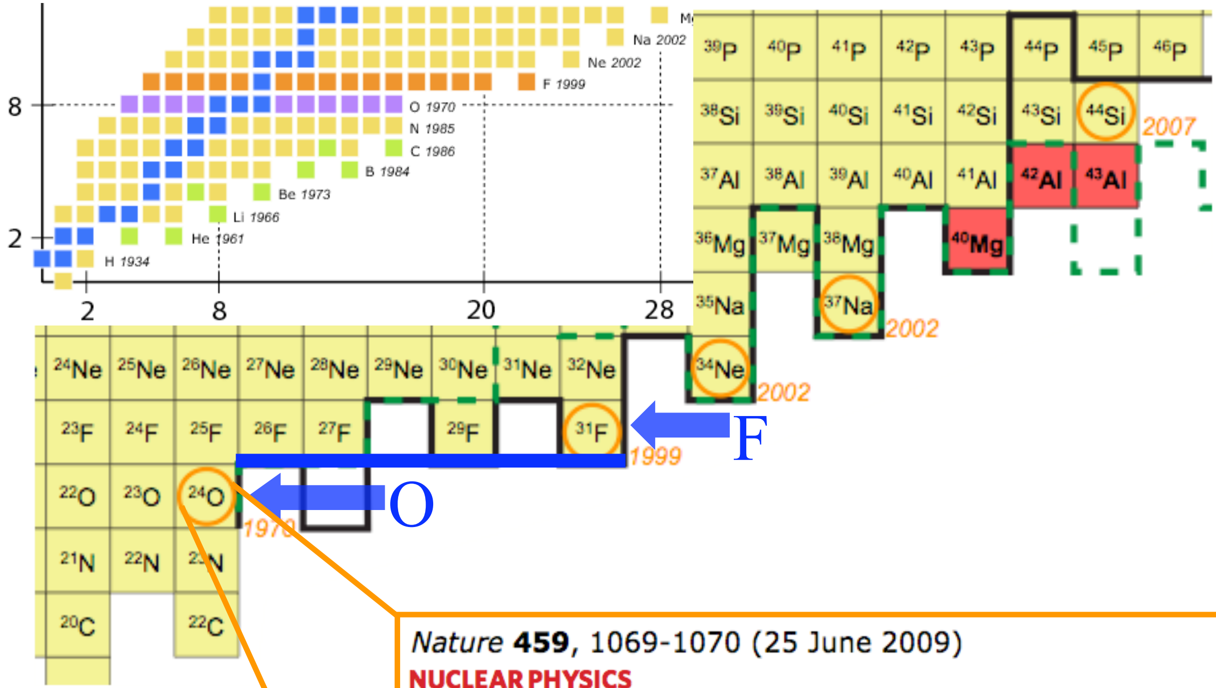


Nature **459**, 1069-1070 (25 June 2009)

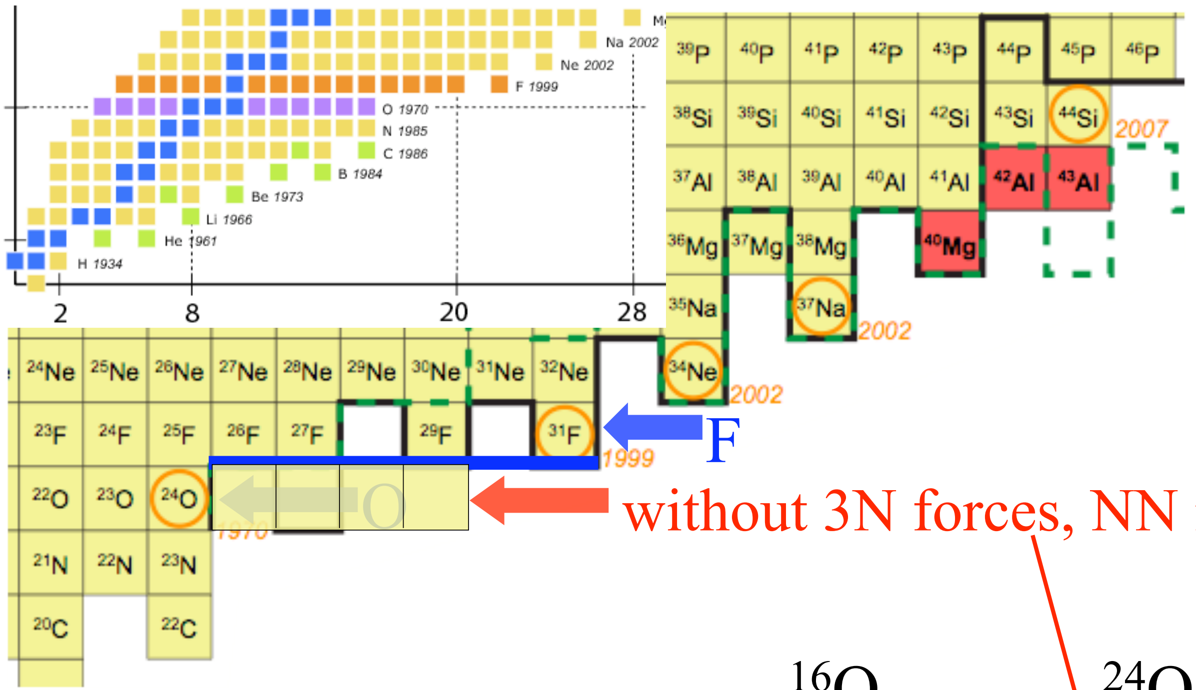
NUCLEAR PHYSICS

Unexpected doubly magic nucleus

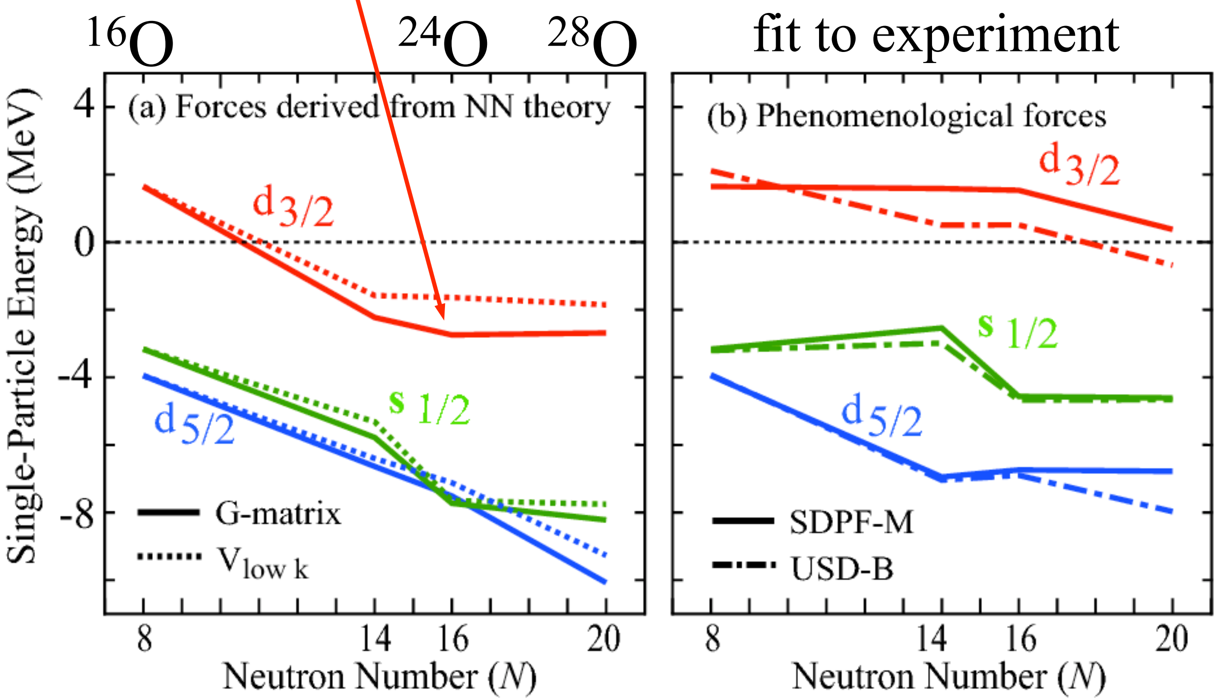
Robert V. F. Janssens

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

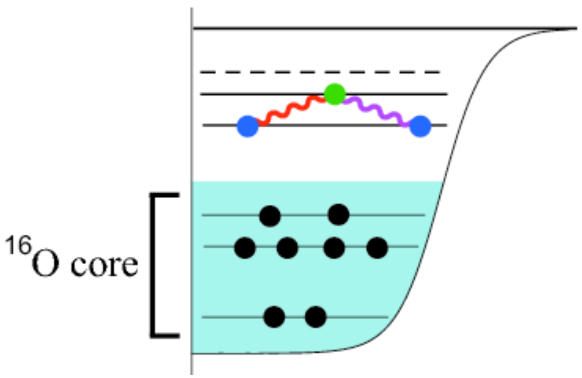


without 3N forces, NN interactions too attractive



many-body theory based on two-nucleon forces:

drip-line incorrect at ^{28}O



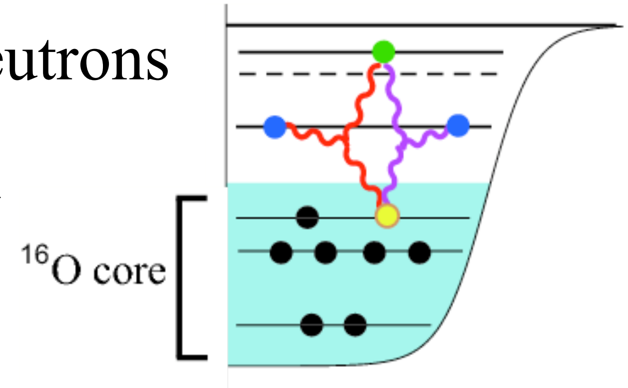
The oxygen anomaly - impact of 3N forces

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 $E_{ex}/E_F \sim N_{valence}/N_{core}$

Friman, AS, arXiv:1101.4858.



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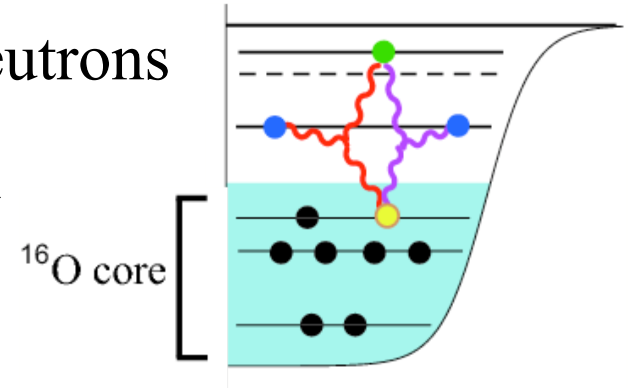
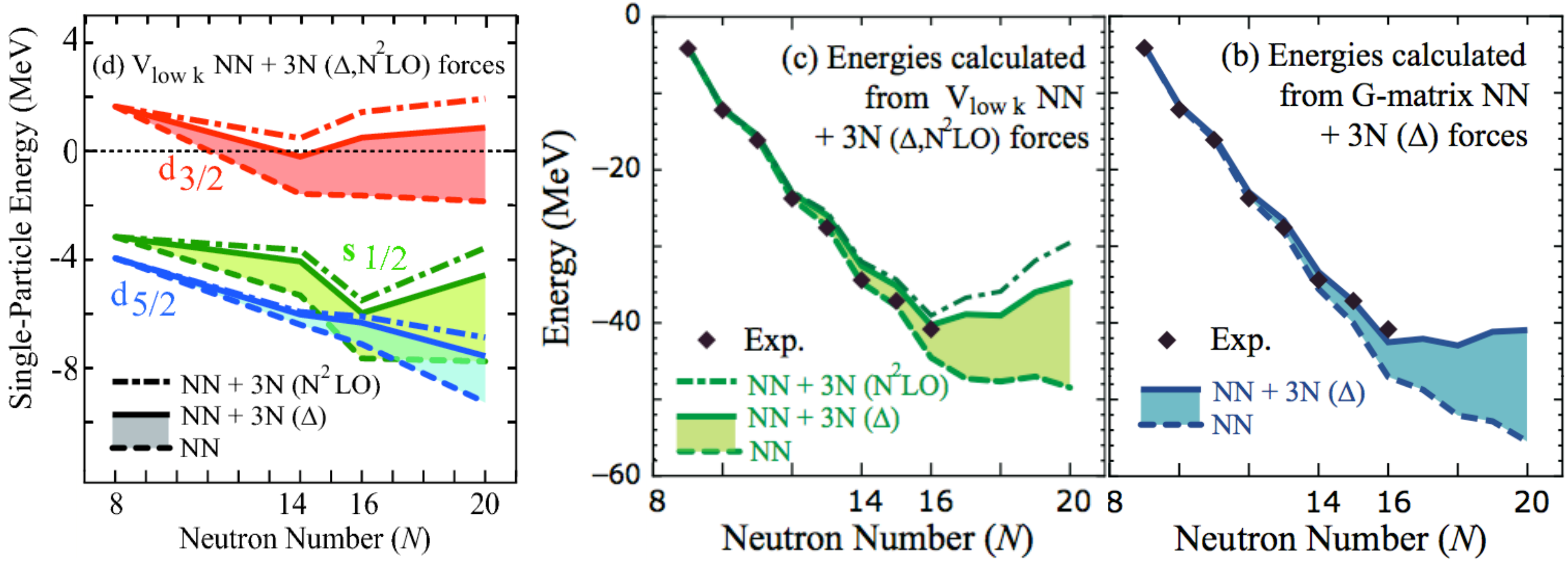
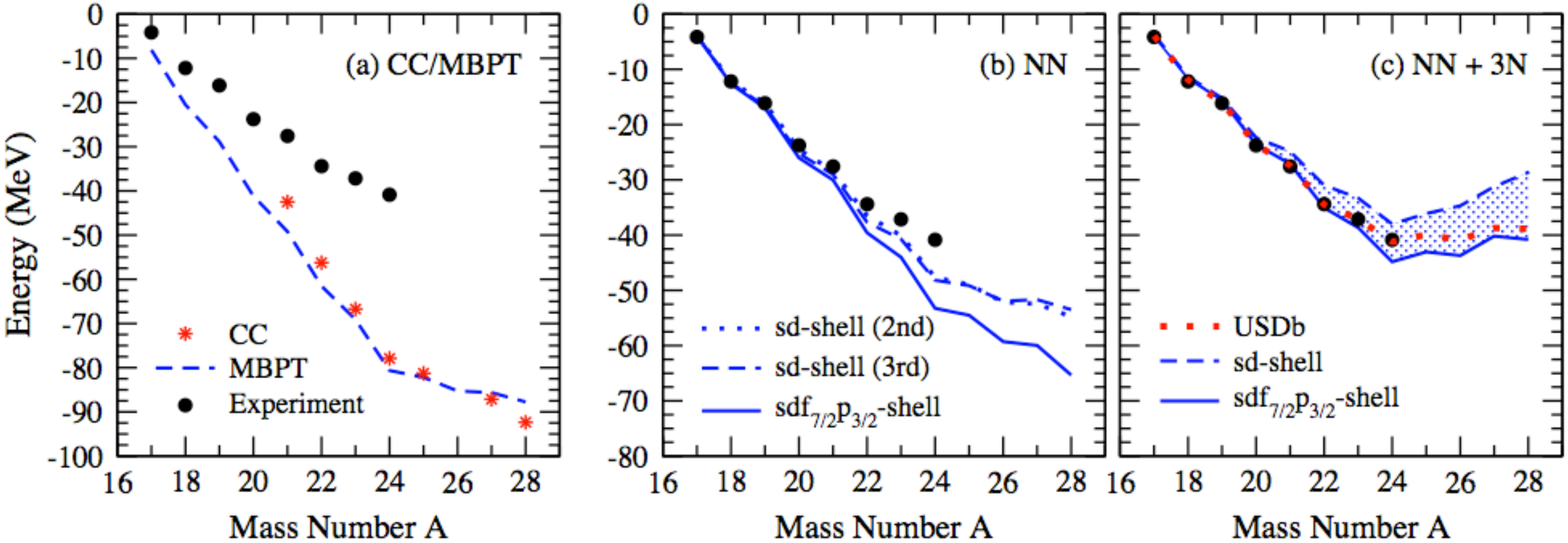


$d_{3/2}$ orbital remains unbound from ^{16}O to ^{28}O



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 ($sdf_{7/2}p_{3/2}$) is important for neutron-rich extremes

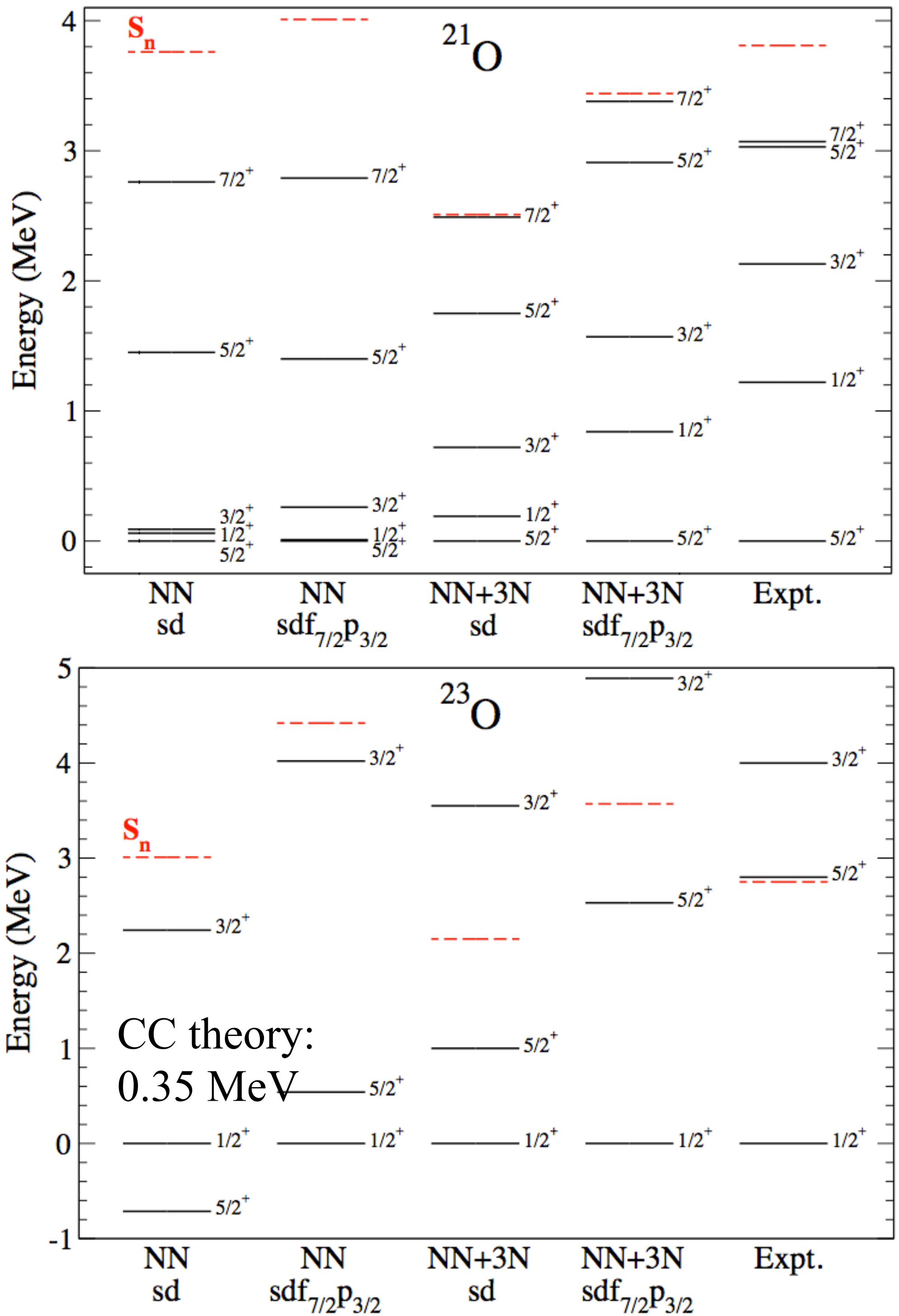
Oxygen spectra

focused on bound excited states

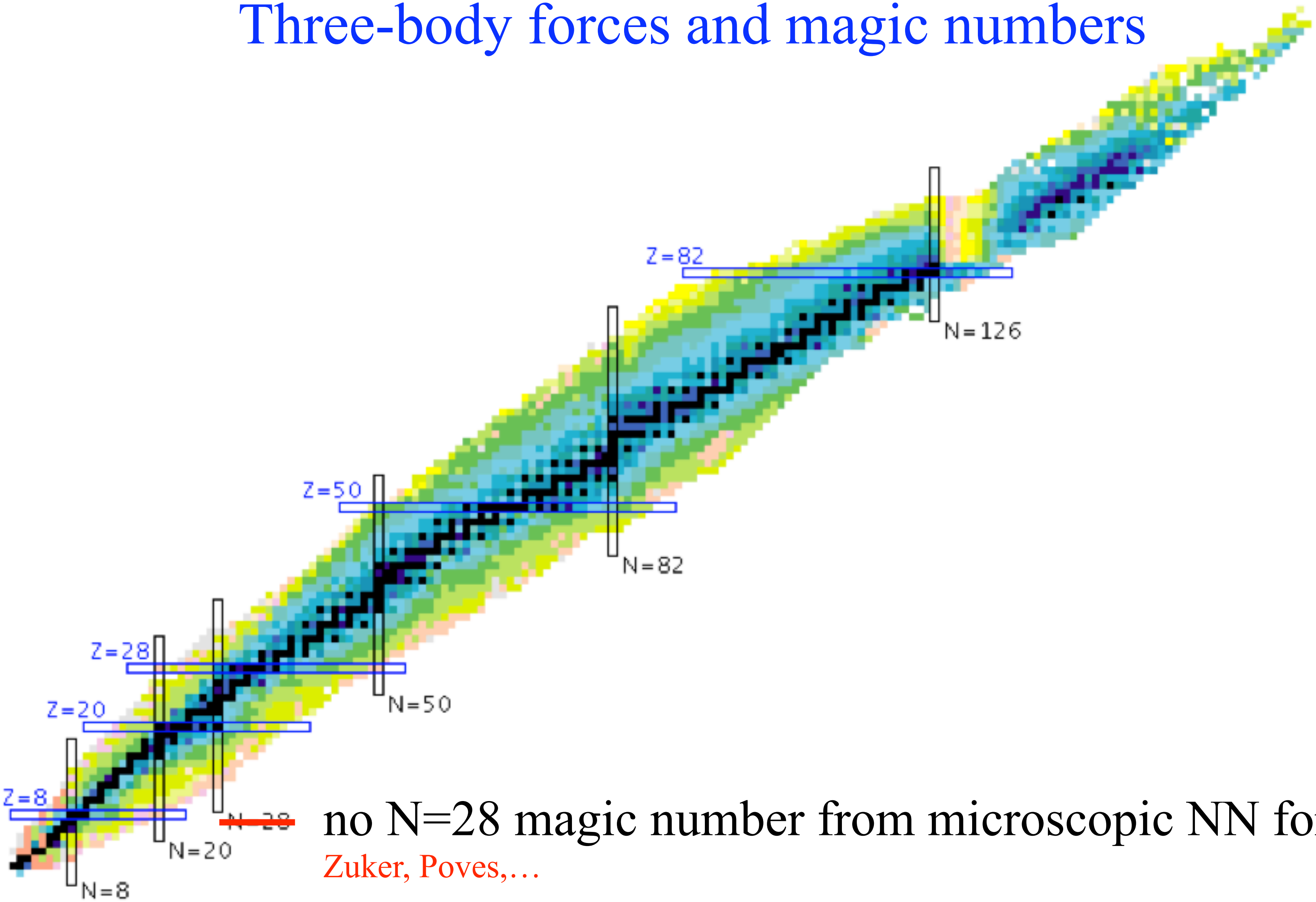
Holt, AS, arXiv:1108.2680.

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,…

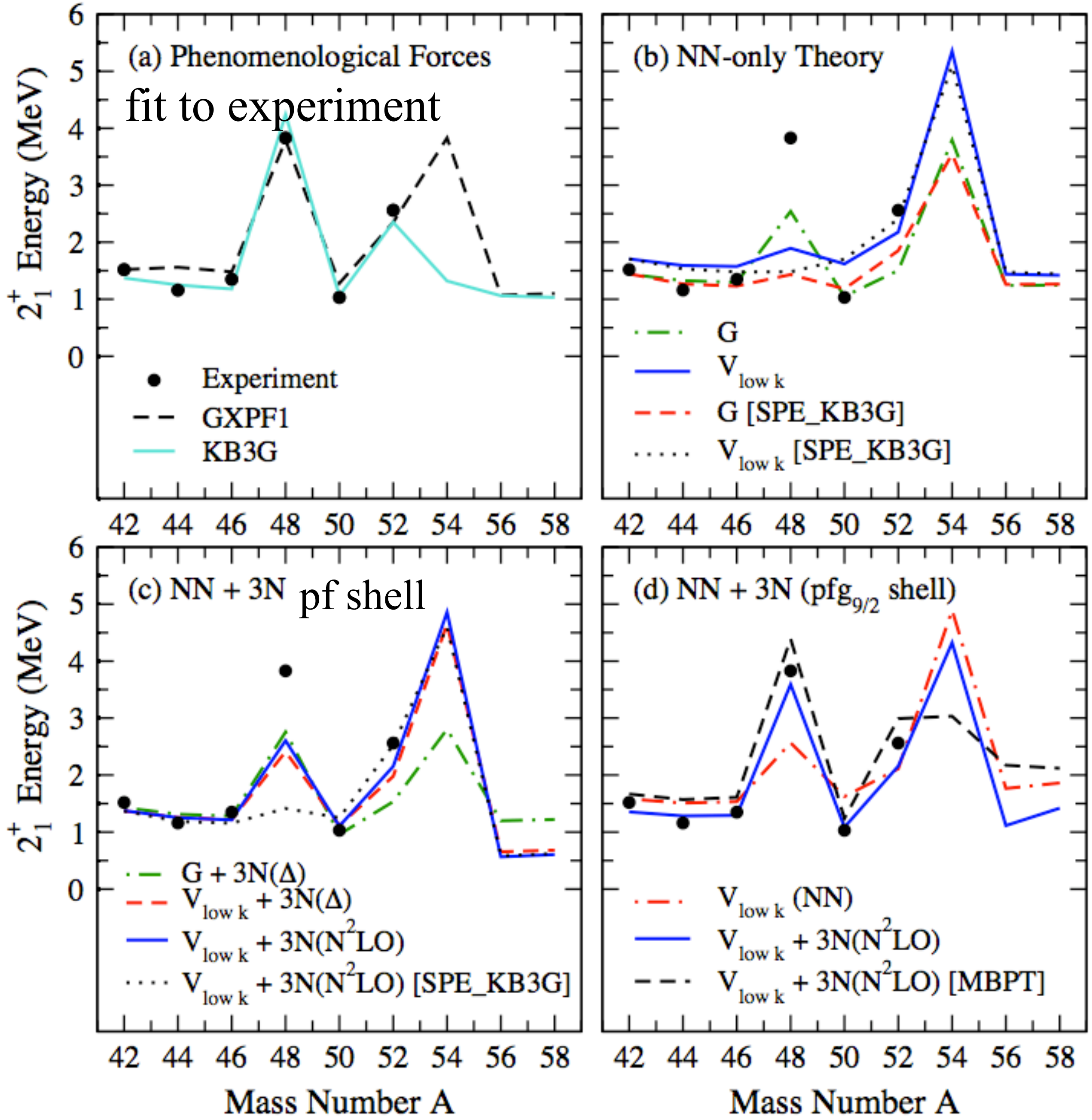
Three-body forces and magic numbers

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



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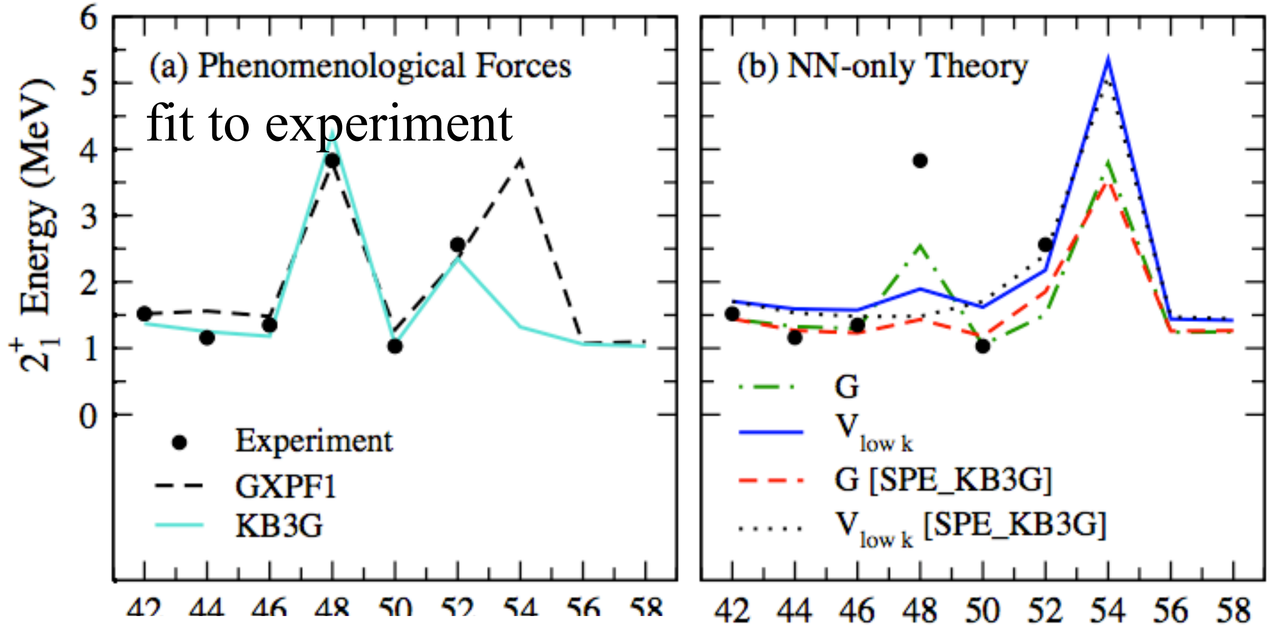
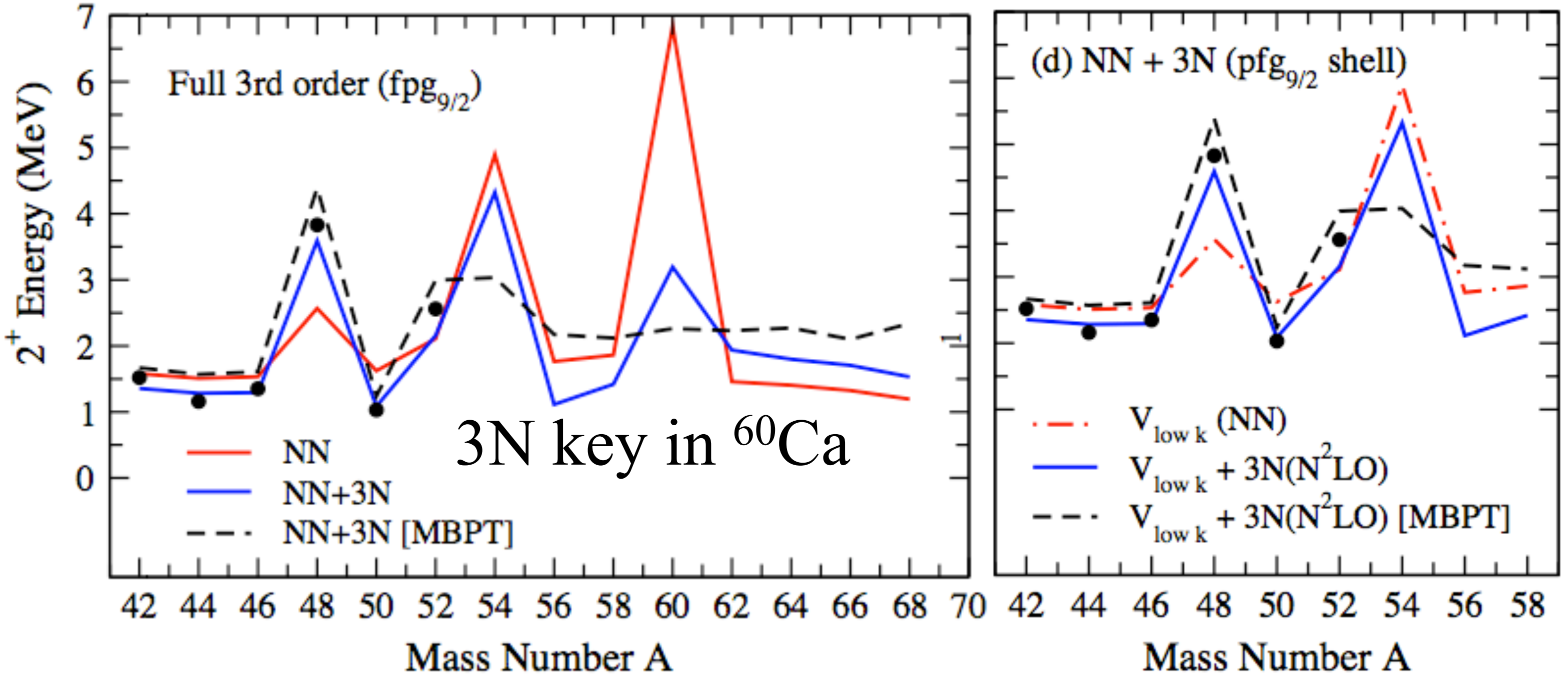
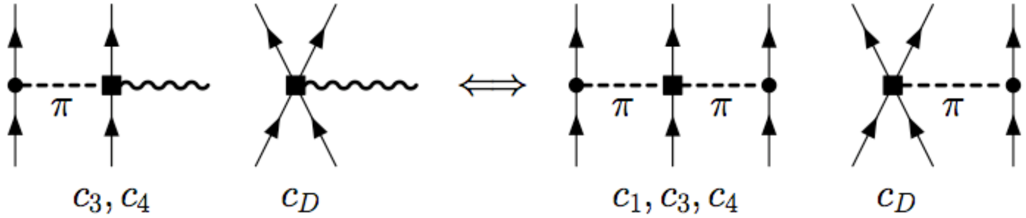




Chiral EFT for electroweak transitions Menendez, Gazit, AS (2011).

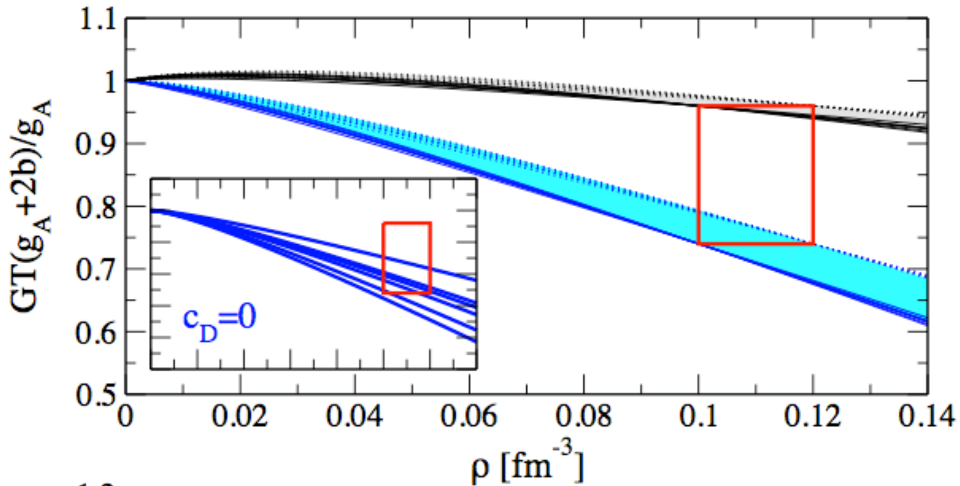
two-body currents lead to important contributions in nuclei (Q~100 MeV) especially for Gamow-Teller transitions

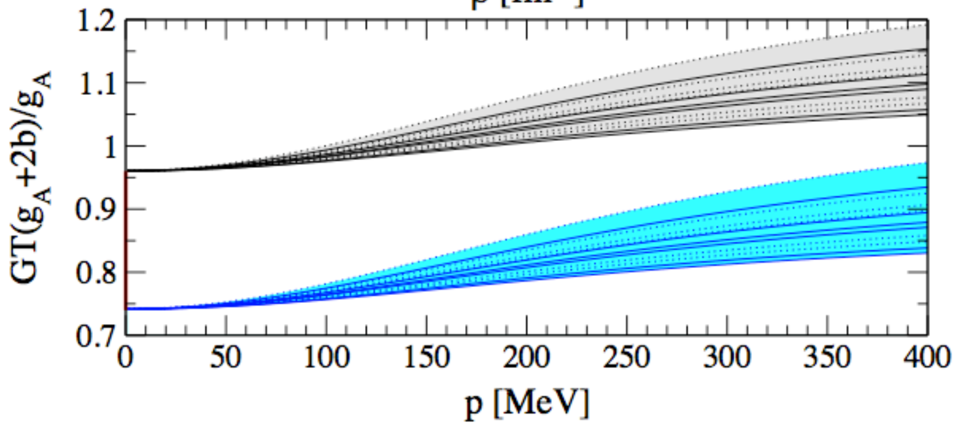
two-body currents determined by NN, 3N couplings to N^3LO
Park et al., Phillips,…



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

+ predict momentum dependence (weaker quenching for larger p)





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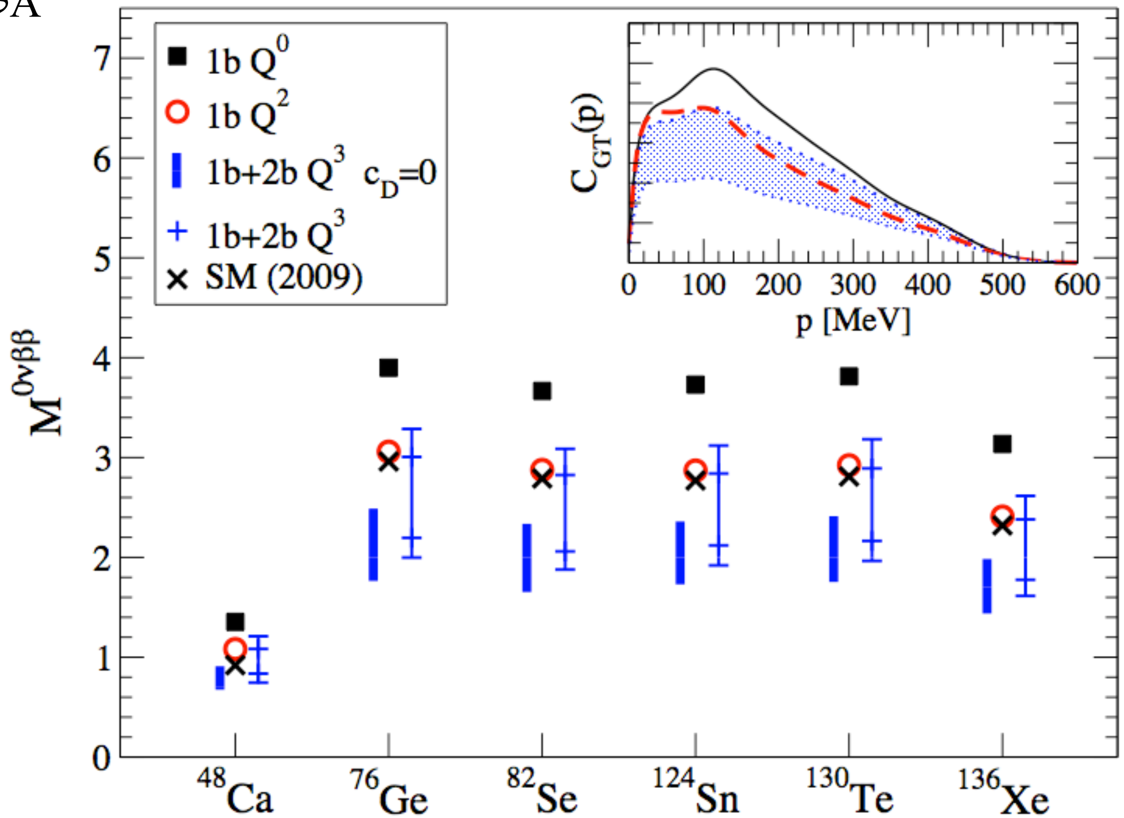
explains part of quenching of g_A

+ predict mom. dependence

+ nuclear matrix elements for 0νββ decay based on chiral EFT operator



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S.K. Bogner

R.J. Furnstahl,
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A. Nogga

J.D. Holt

T. Otsuka

T. Suzuki

Y. Akaishi

C.J. Pethick

J.M. Lattimer

D. Gazit

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!