Three-nucleon forces and neutron-rich nuclei

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TECHNISCHE UNIVERSITÄT DARMSTADT

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S-DALINAC

DFG

HELMHOLTZ ASSOCIATION

Minerva Stiftung

Bundesministerium für Bildung und Forschung

Outline

Understanding nuclear forces

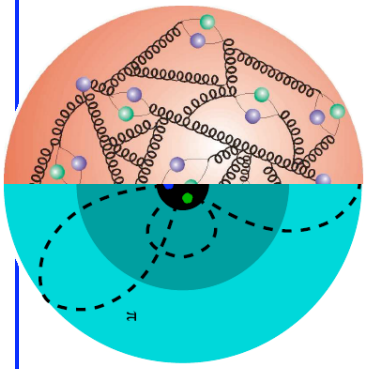
Three-nucleon forces

Three-nucleon forces and neutron-rich nuclei

Chiral effective field theory and electroweak transitions

Three-nucleon forces and neutron matter

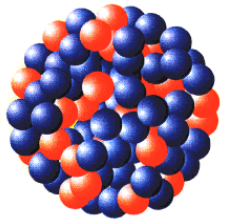
Λ / Resolution dependence of nuclear forces



Λ_{chiral}

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

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

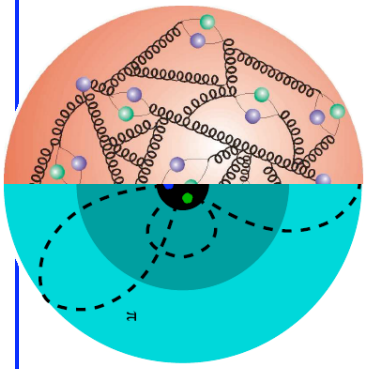


typical momenta in nuclei ~ m_π

$\Lambda_{pionless}$

momenta $Q \ll m_\pi$

Λ / Resolution dependence of nuclear forces



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

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

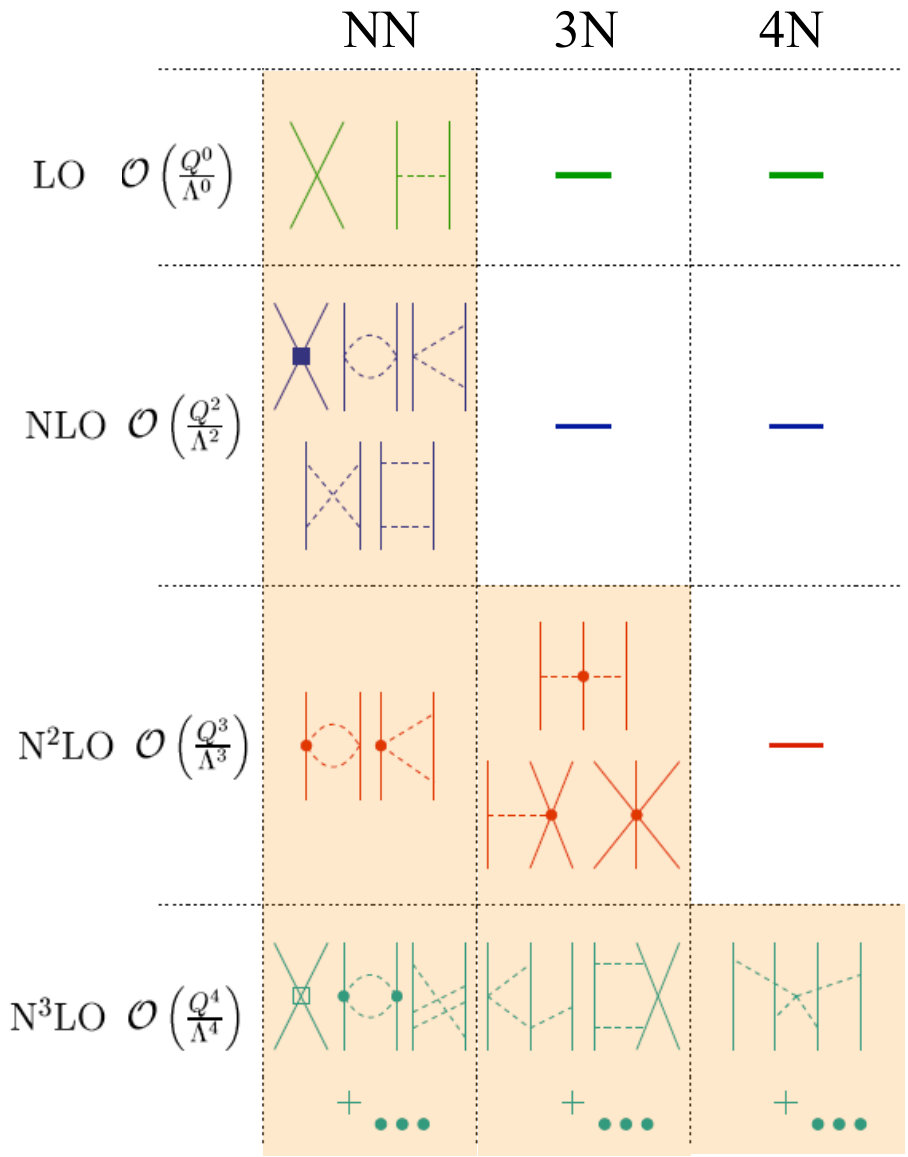
$\Lambda_{\rm chiral}$
momenta $Q \sim \lambda^{-1} \sim m_\pi$: chiral effective field theory

Λ ↓

$\Lambda_{\rm pionless}$
momenta $Q \ll m_\pi$

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 $(Q/\Lambda_b)^n$

LO, n=0 - leading order,
NLO, n=2 - next-to-leading order,…

expansion parameter ~ 1/3

(compare to multipole expansion for a charge distribution)

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

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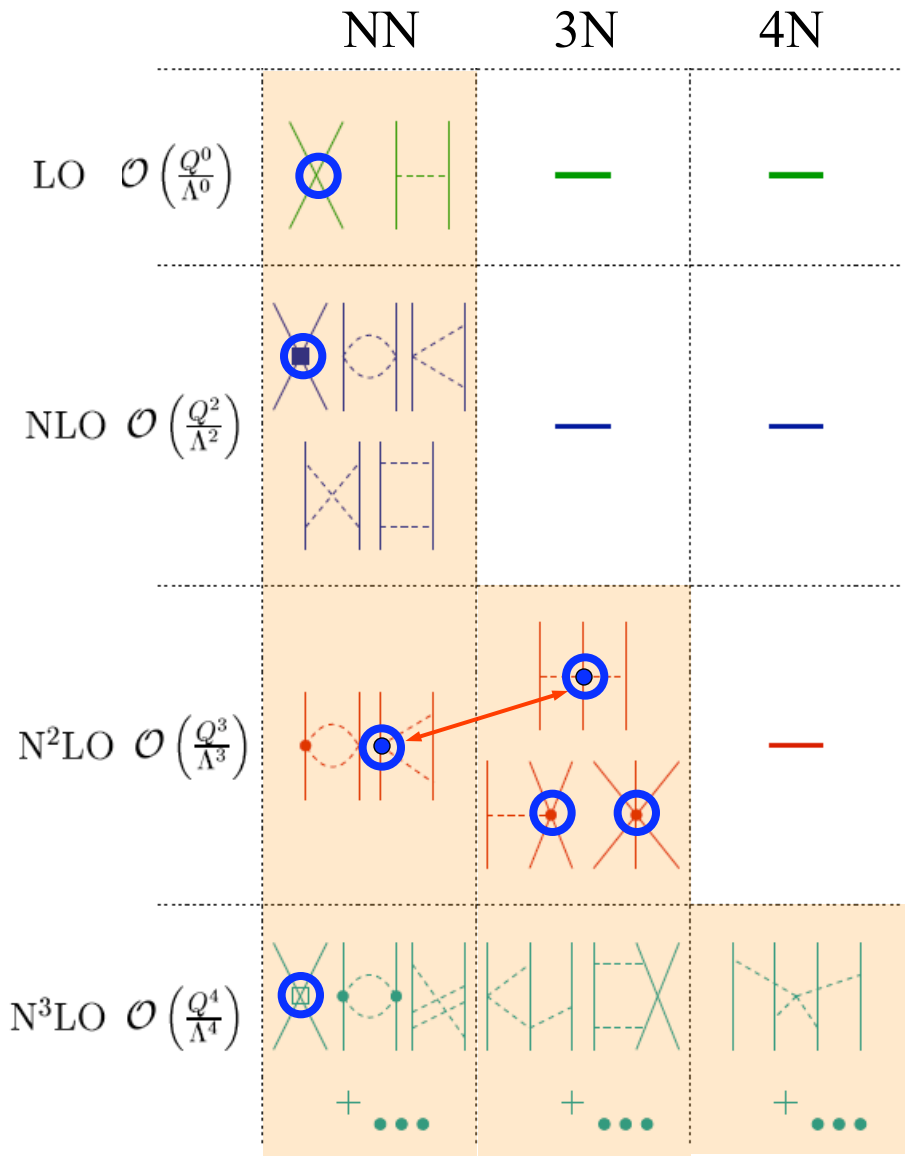


limited resolution at low energies, can expand in powers $(Q/\Lambda_b)^n$

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

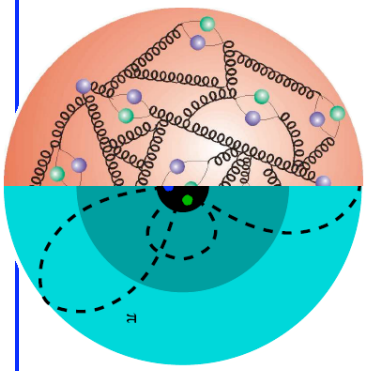
open problems: renormalization and power counting

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,…

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



$\Lambda_{\rm chiral}$

Λ ↓

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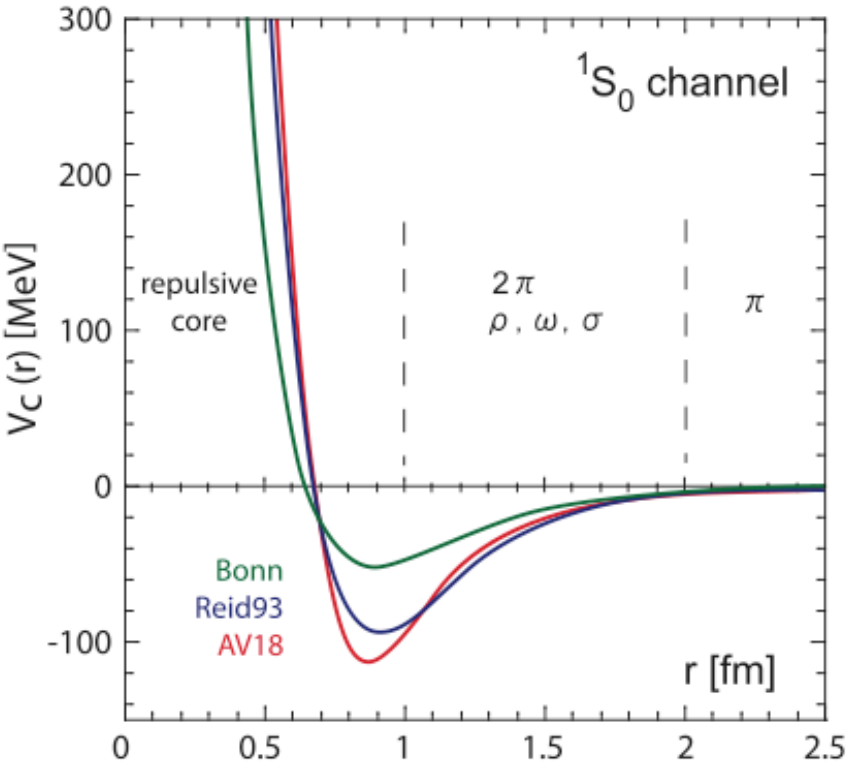
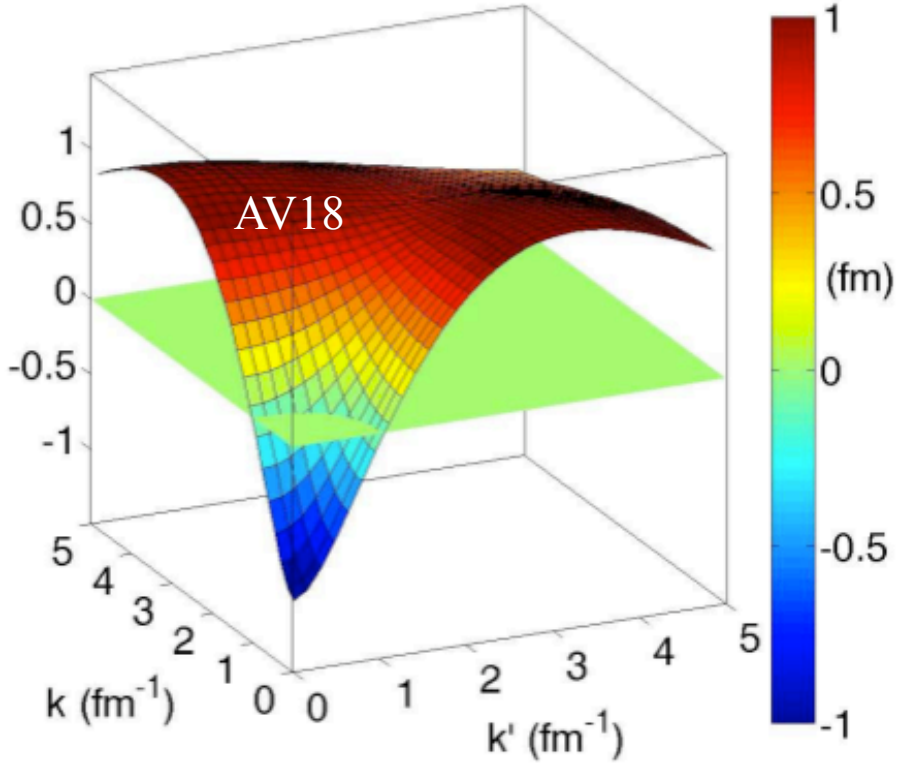
for NN interactions (preserves NN observables)





red = short-range repulsion

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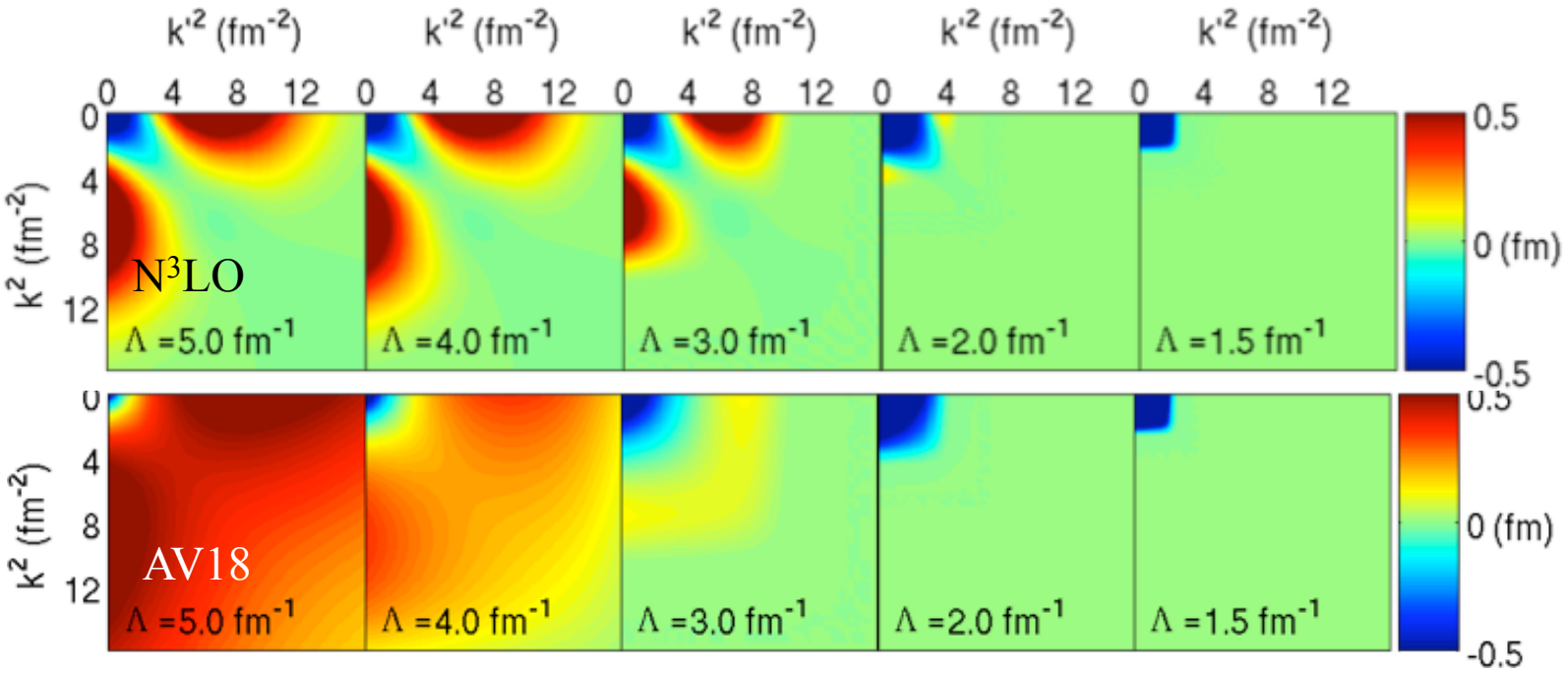
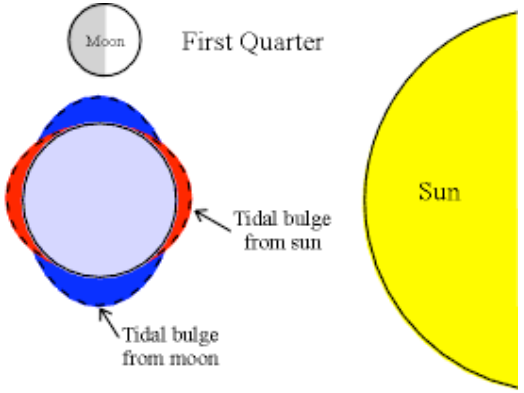


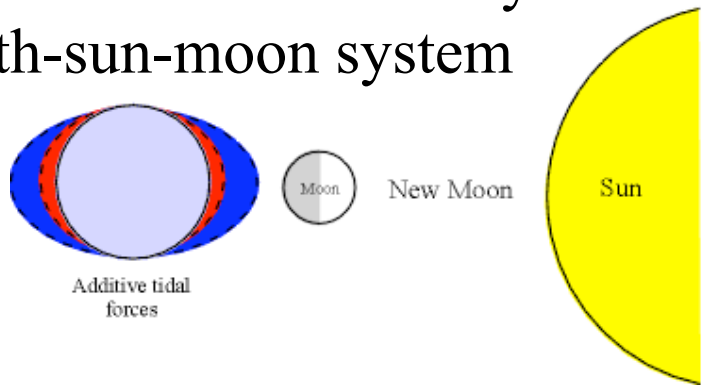
low-momentum interactions $V_{\text{low } k}(\Lambda)$

RG decouples low-momentum physics from high momenta

Why are there three-body forces?



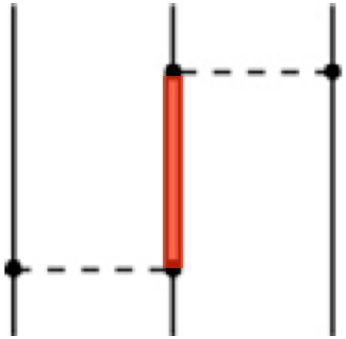
tidal effects lead to 3-body forces in earth-sun-moon system



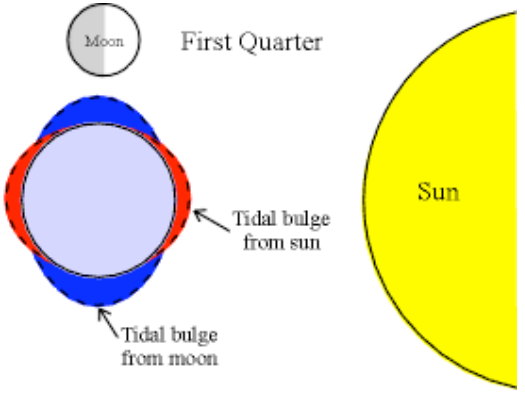
Why are there three-nucleon (3N) forces?

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

dominant contribution from Δ(1232 MeV)



+ many shorter-range parts



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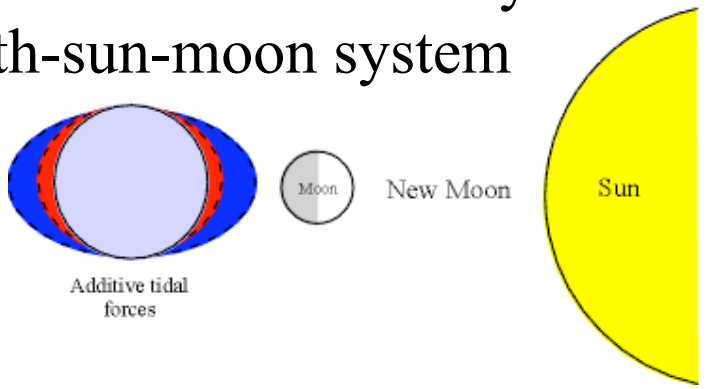
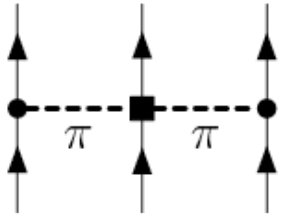
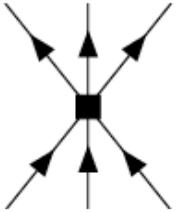


in chiral EFT (Delta-less):  + shorter-range parts

in pionless EFT:  + higher-order parts

Chiral Effective Field Theory for nuclear forces

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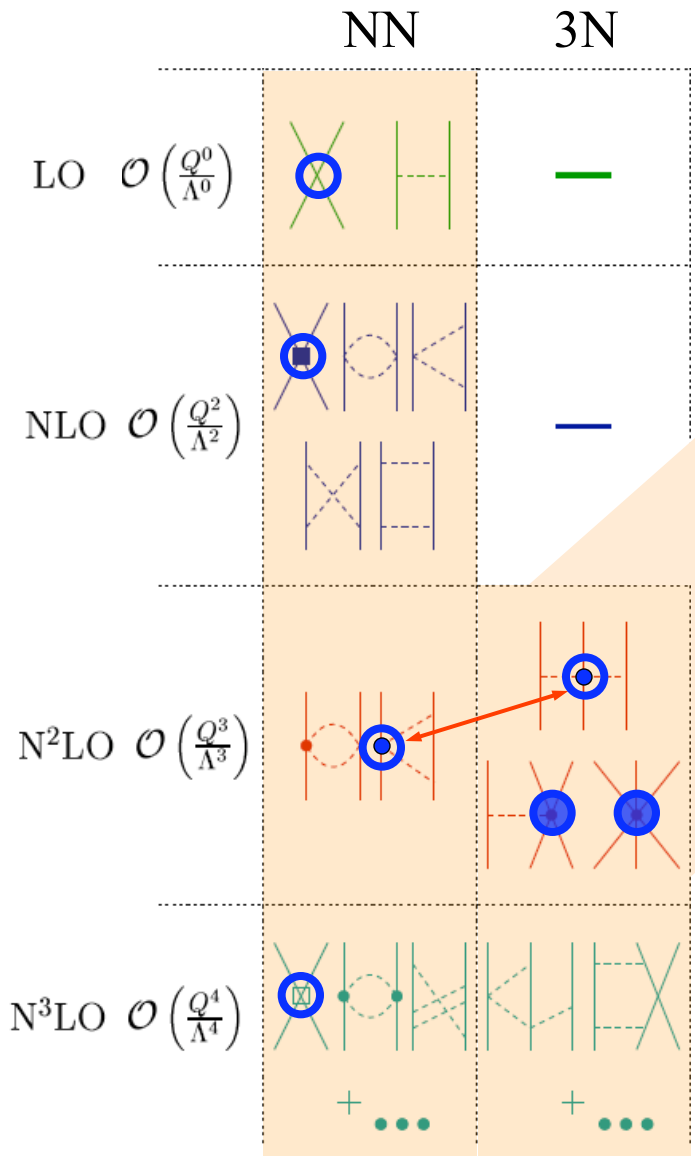
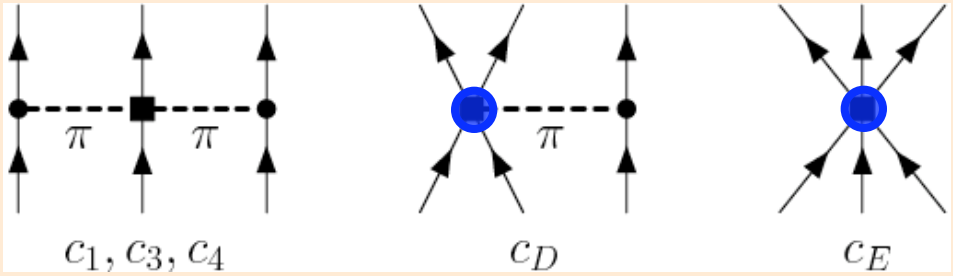


consistent NN-3N interactions

3N,4N: only 2 new couplings to N³LO



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)

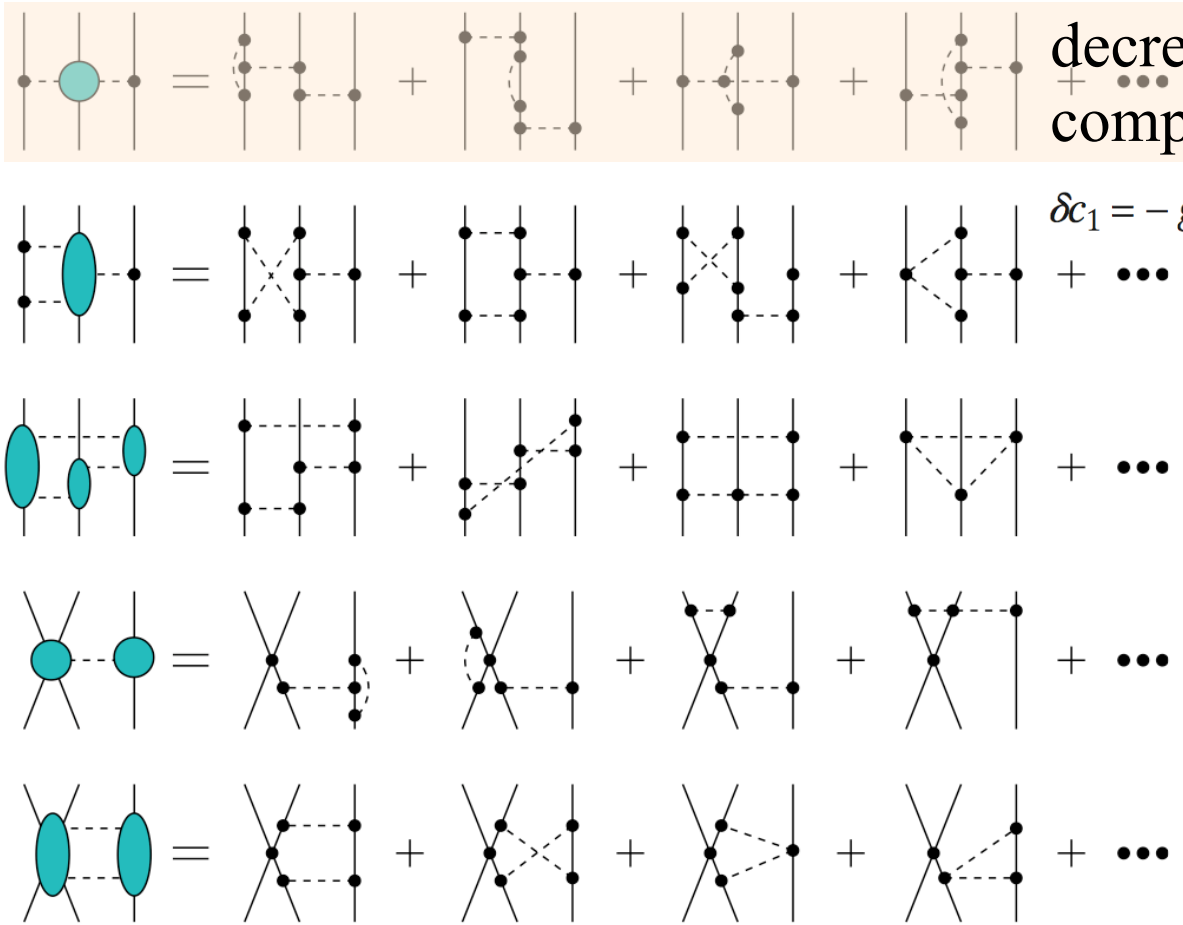
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

Subleading chiral 3N forces

parameter-free N^{3}LO 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^{2}LO uncertainty

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

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

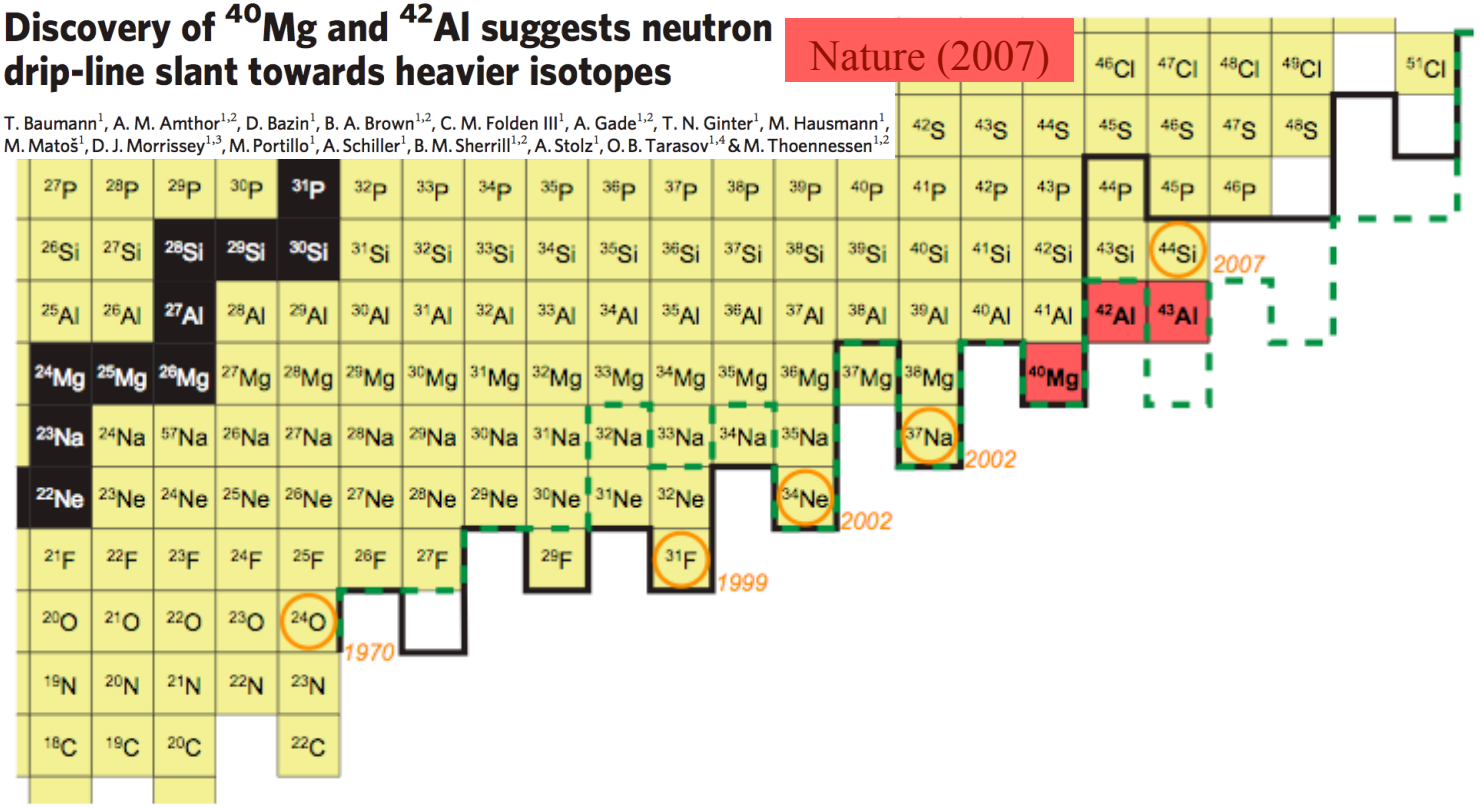
1/m corrections: spin-orbit parts, interesting for A_y puzzle

Towards the limits of existence - the neutron drip-line

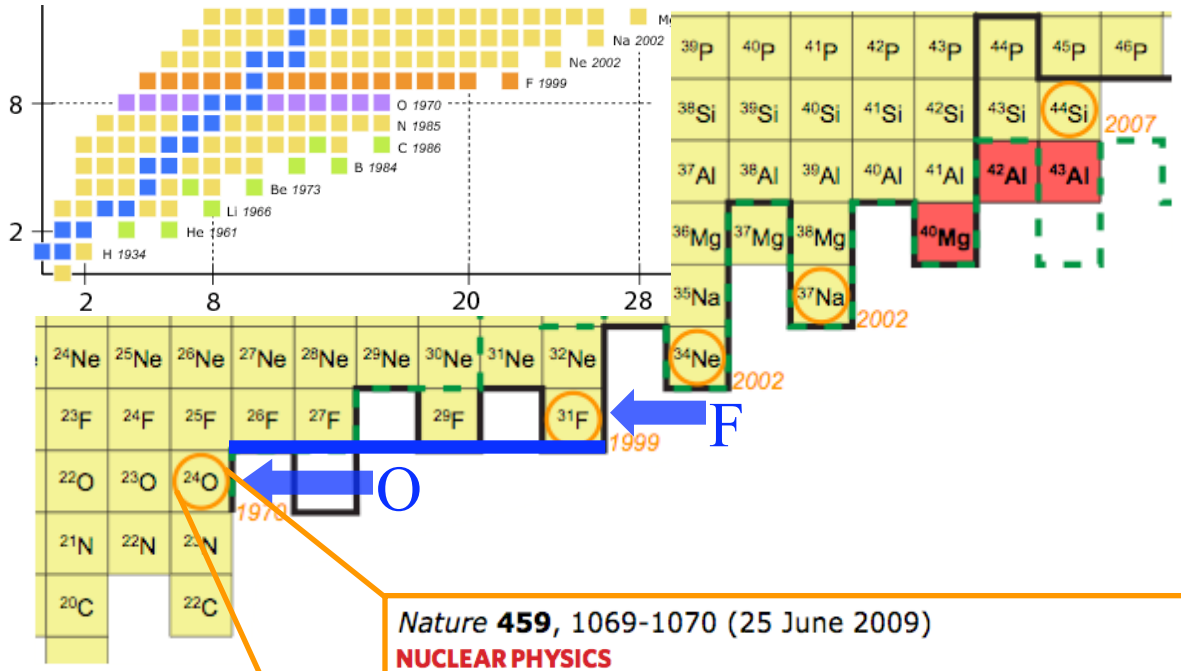
Discovery of ^{40}Mg and ^{42}Al suggests neutron drip-line slant towards heavier isotopes

Nature (2007)

T. Baumann[1], A. M. Amthor[1,2], D. Bazin[1], B. A. Brown[1,2], C. M. Folden III[1], A. Gade[1,2], T. N. Ginter[1], M. Hausmann[1], M. Matoš[1], D. J. Morrissey[1,3], M. Portillo[1], A. Schiller[1], B. M. Sherrill[1,2], A. Stolz[1], O. B. Tarasov[1,4] & M. Thoennessen[1,2]



The oxygen anomaly



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

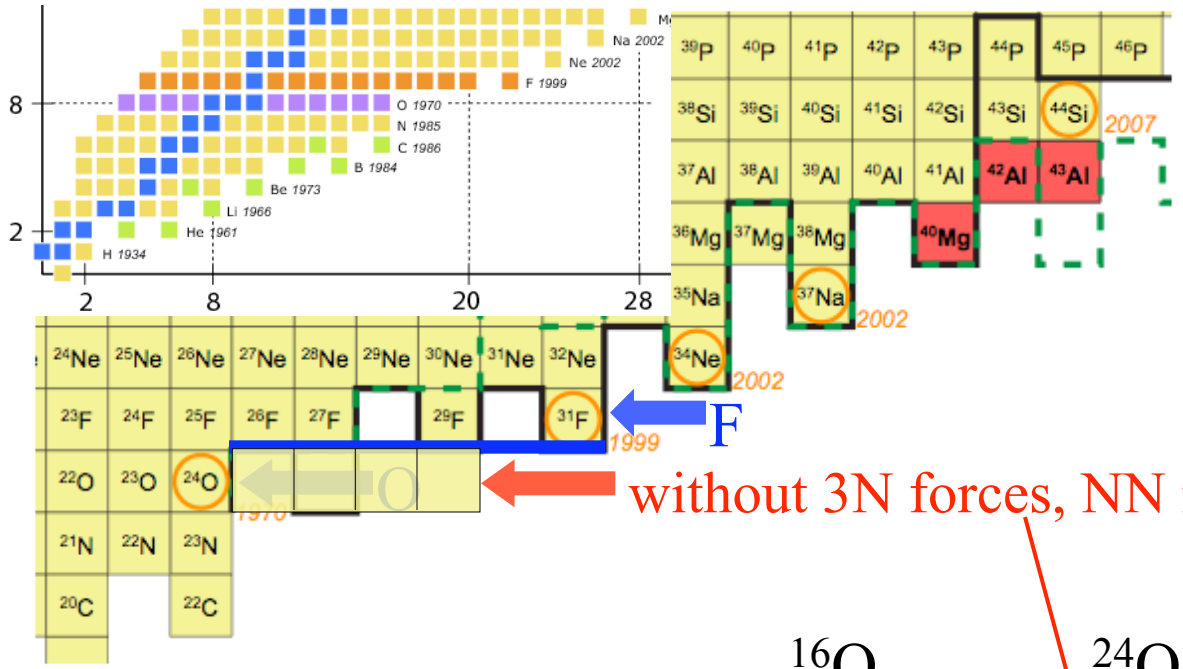
NUCLEAR PHYSICS

Unexpected doubly magic nucleus

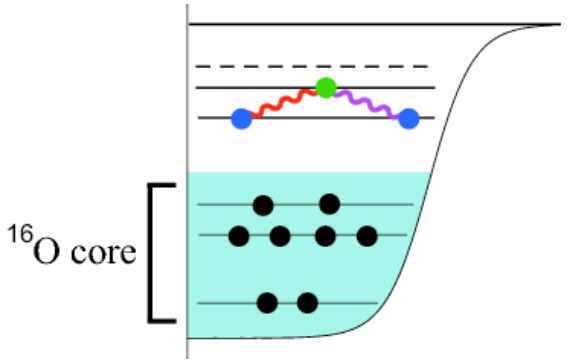
Robert V. F. Janssens

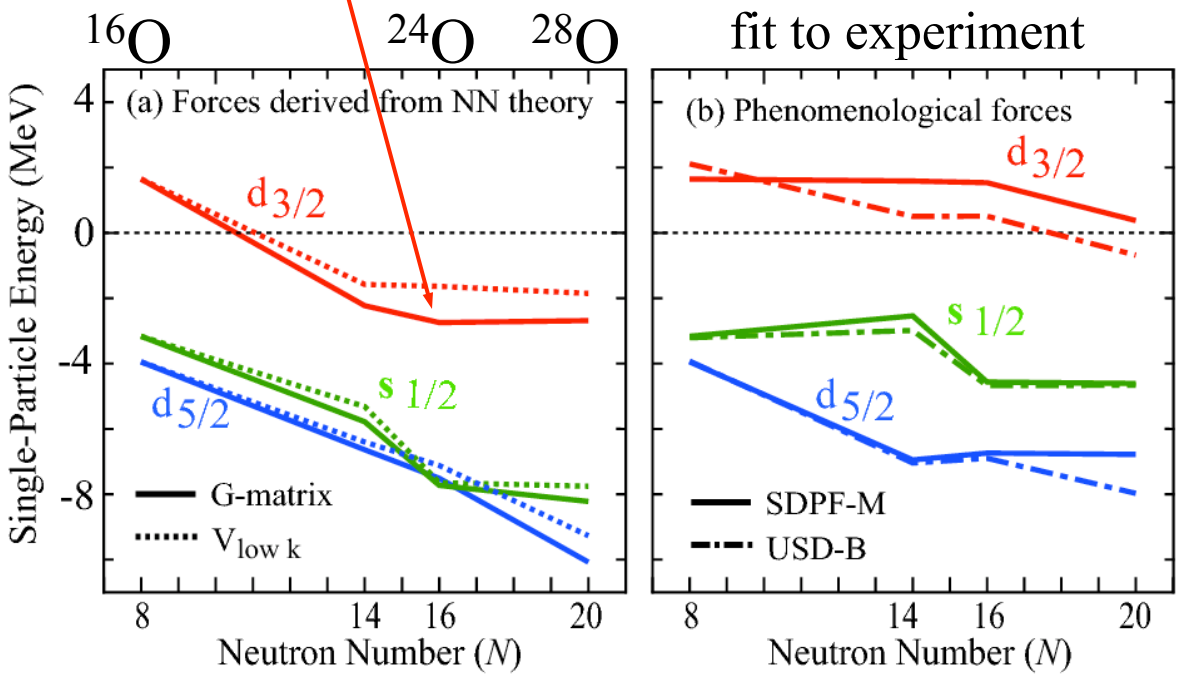
Nuclei with a 'magic' number of both protons and neutrons, dubbed doubly magic, are particularly stable. The oxygen isotope ^{24}O has been found to be one such nucleus — yet it lies just at the limit of stability.

The oxygen anomaly - not reproduced without 3N forces



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





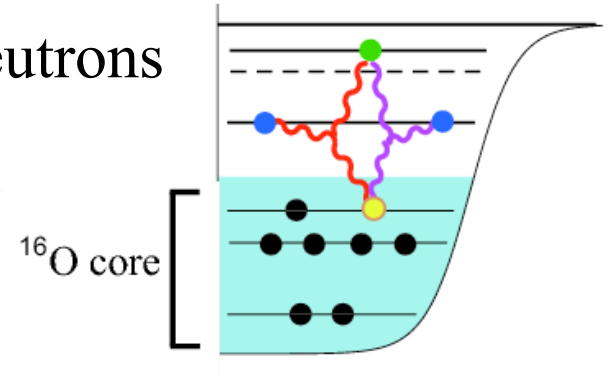
The oxygen anomaly - impact of 3N forces

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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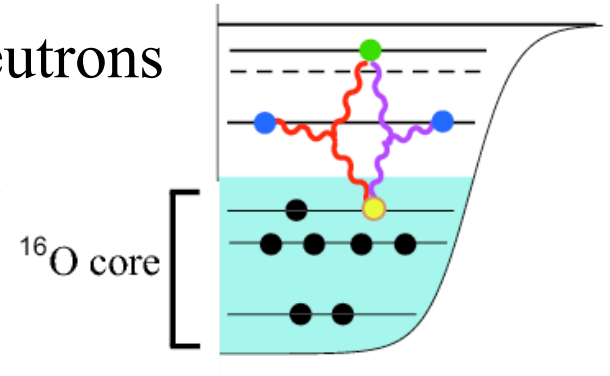
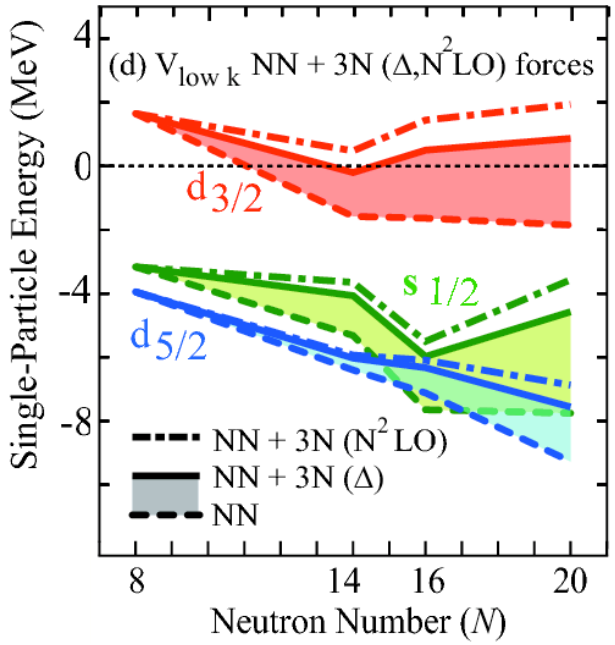
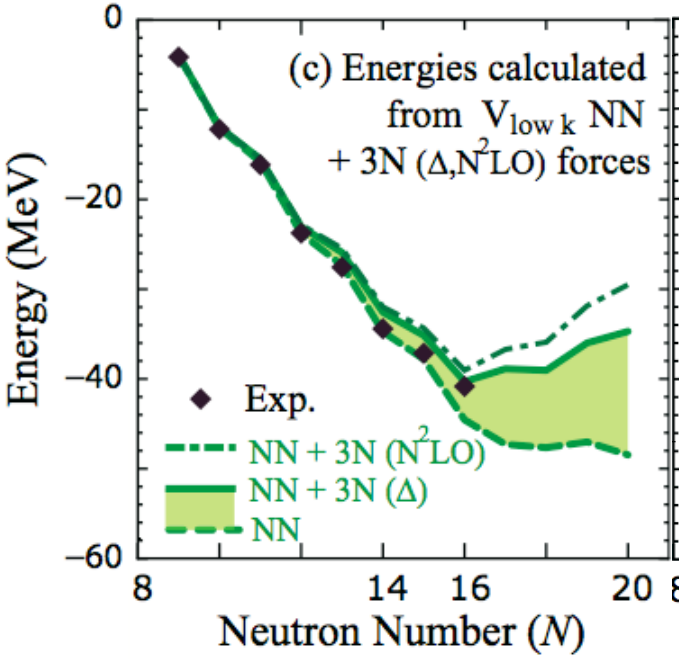
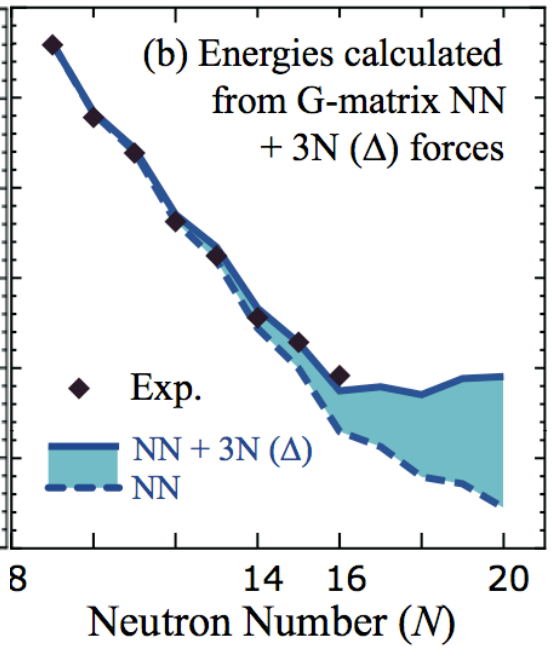


$d_{3/2}$ orbital remains unbound from ^{16}O to ^{28}O

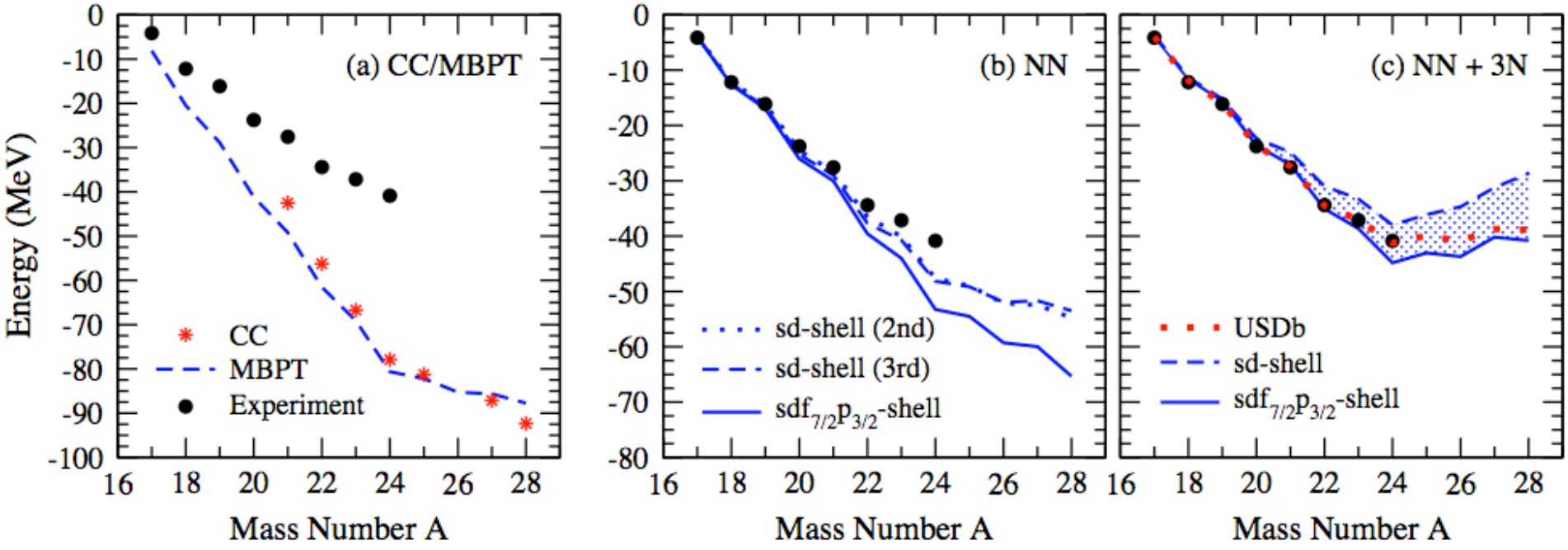






microscopic explanation of the oxygen anomaly Otsuka et al., PRL (2010)

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

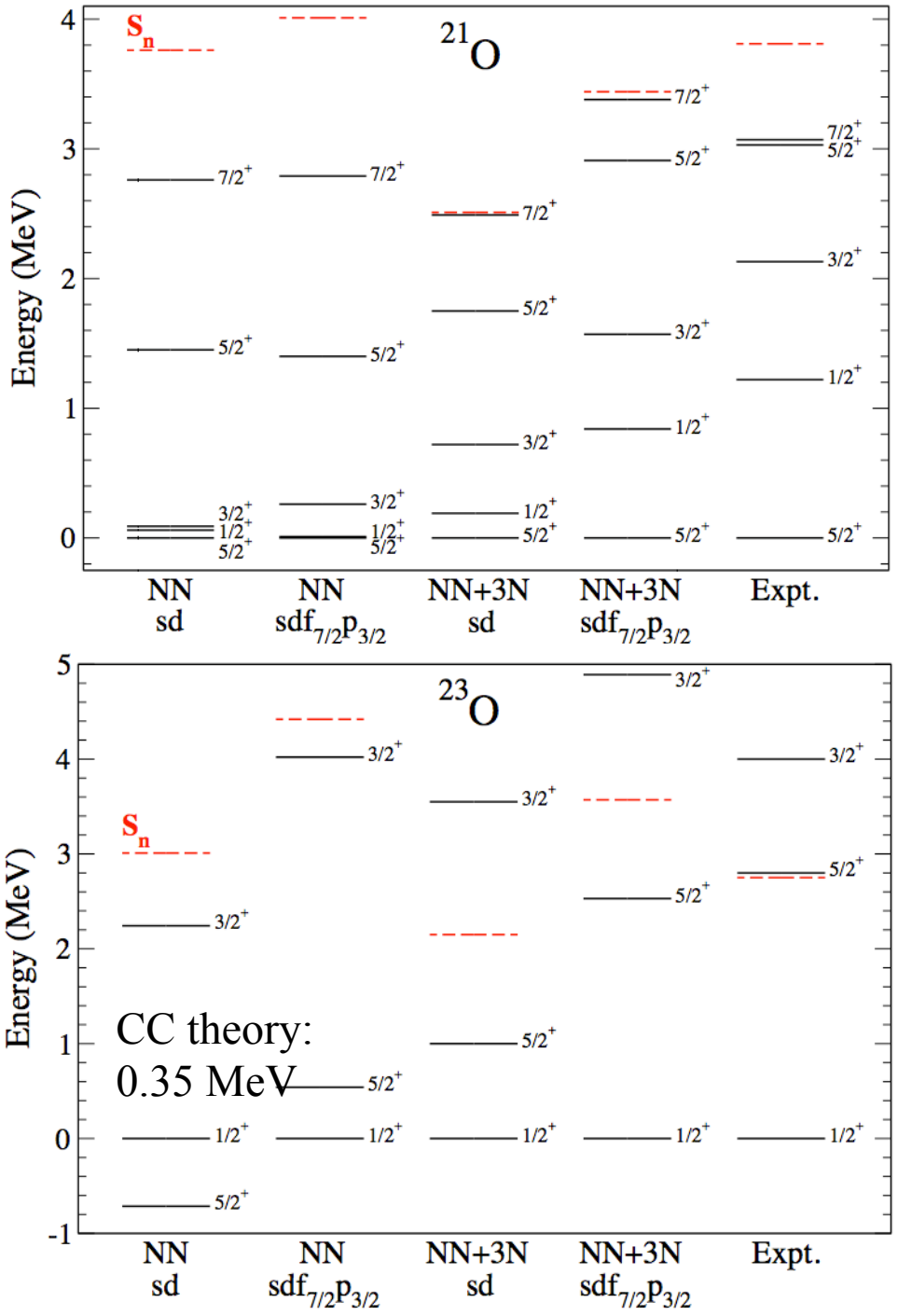
Oxygen spectra

focused on bound excited states

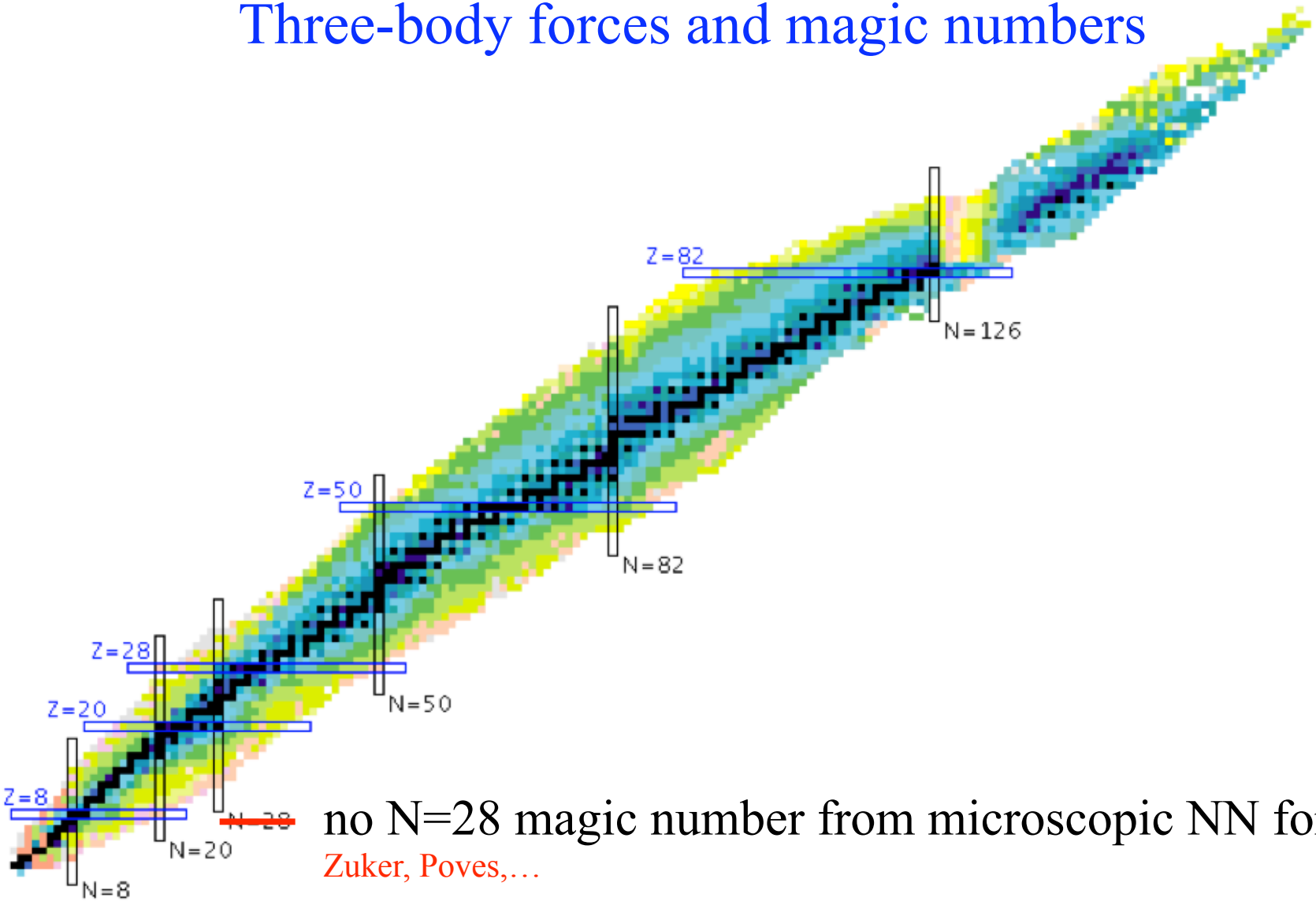
Holt, AS, arXiv:1108.2680.

NN only too compressed

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



Three-body forces and magic numbers



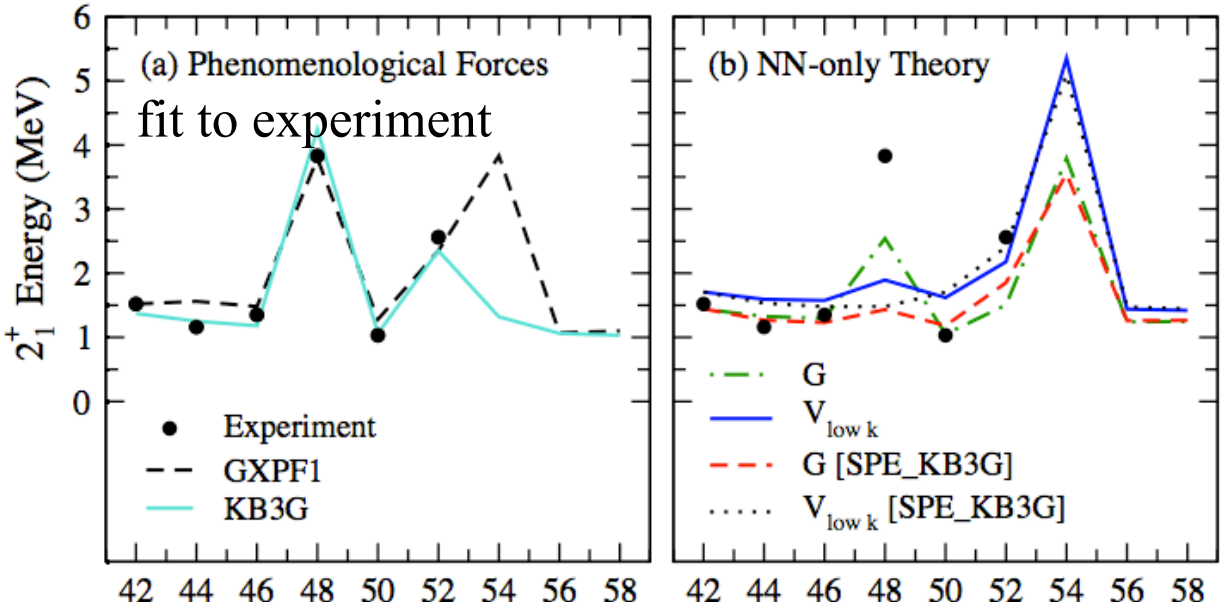
no N=28 magic number from microscopic NN forces

Zuker, Poves,…

Three-body forces and magic numbers

3N mechanism important for shell structure

Holt et al., arXiv:1009:5984



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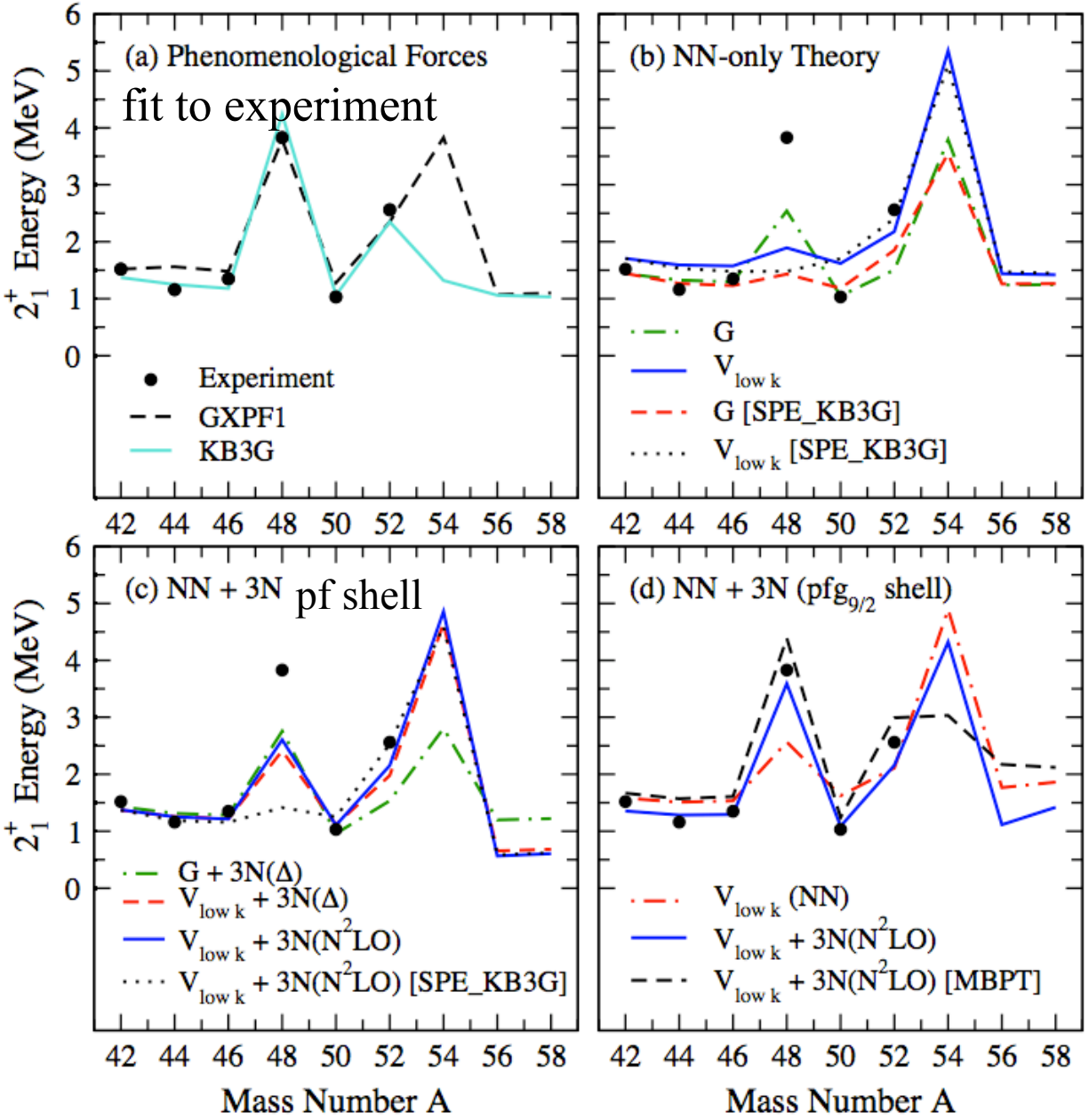
N=28 shell closure due to 3N forces and single-particle effects (^{41}Ca)

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



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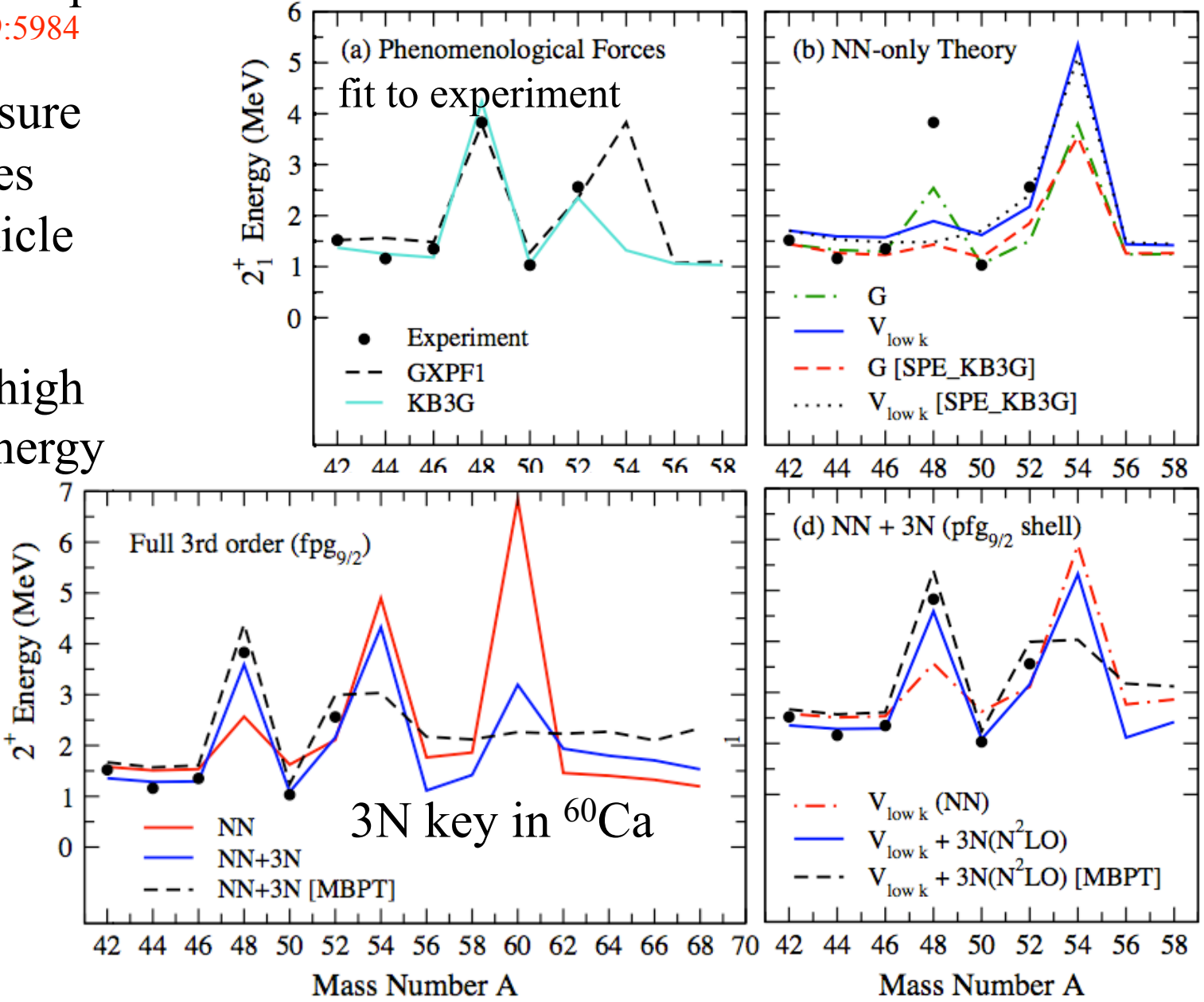

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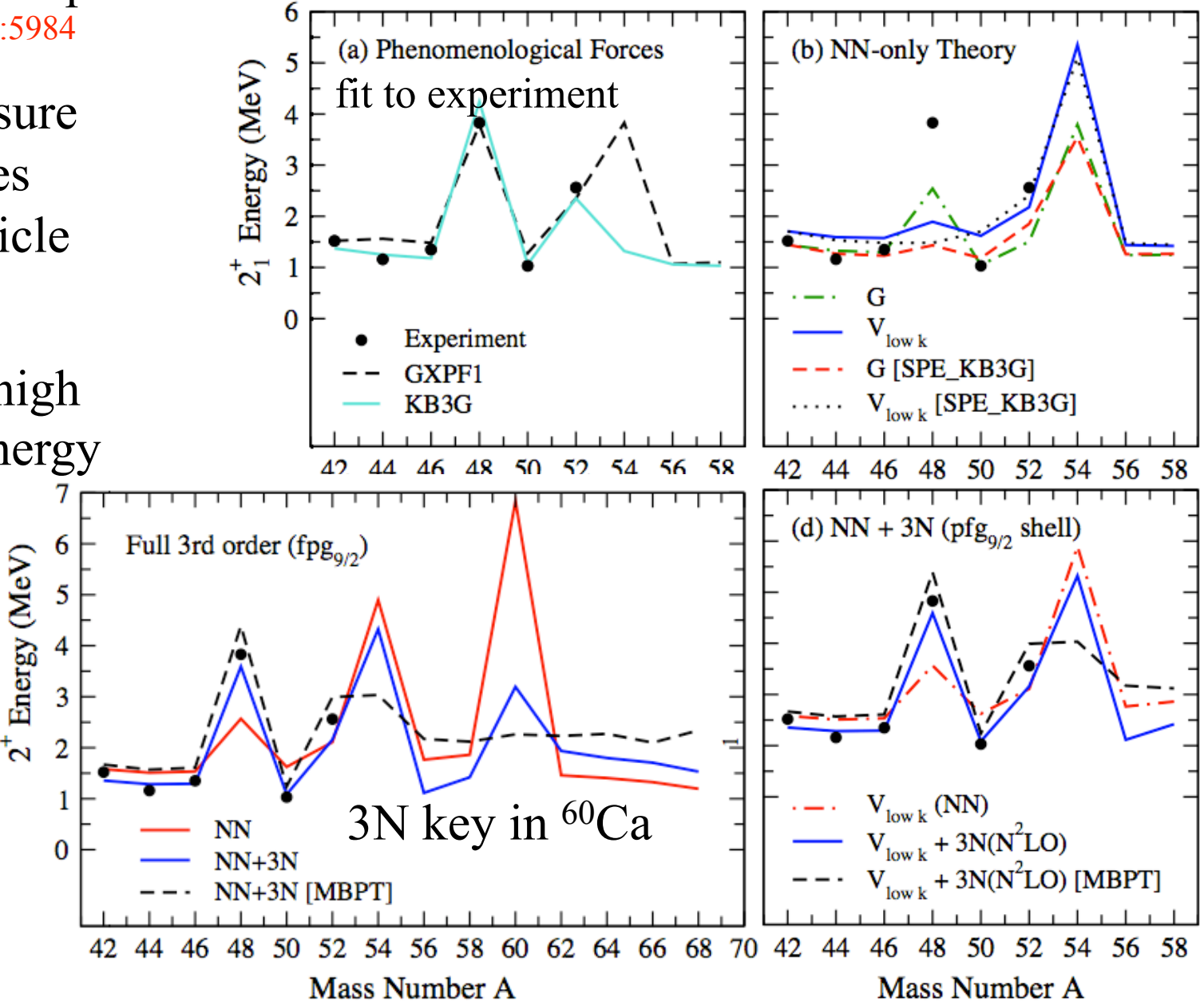
N=34: predict high 2^+ excitation energy

masses of N=34 isotones at ISOLDE

S. Kreim et al.

INTC-P-317



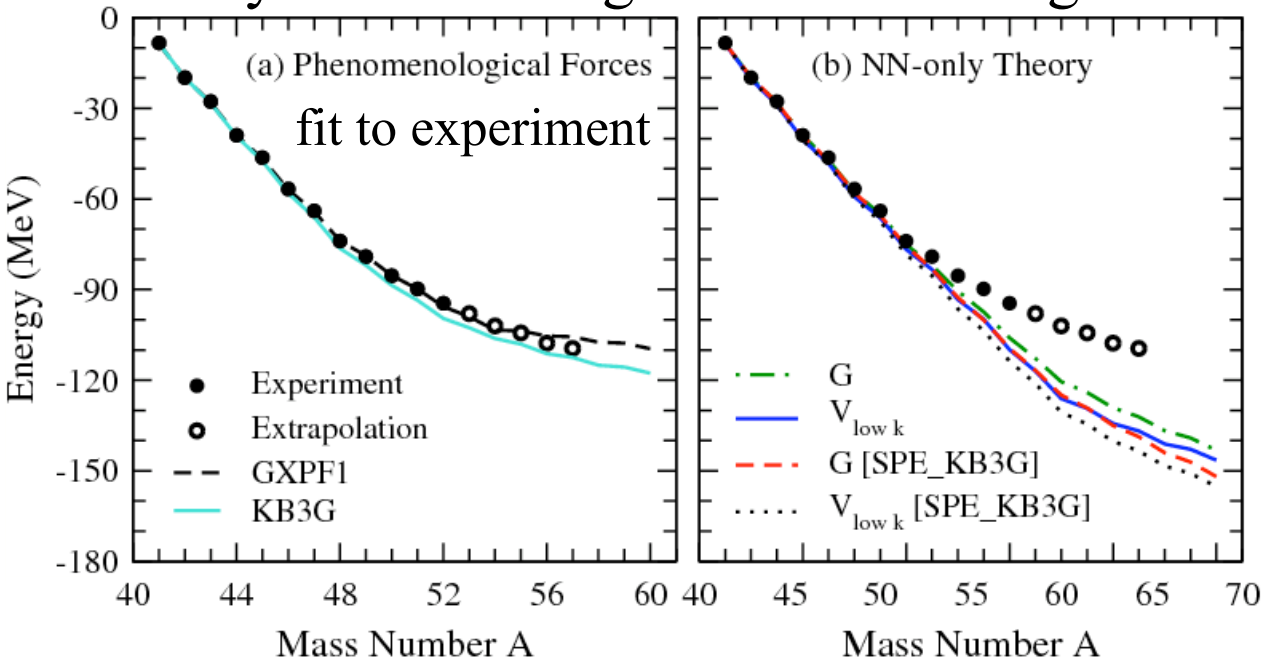
Evolution to neutron-rich calcium isotopes

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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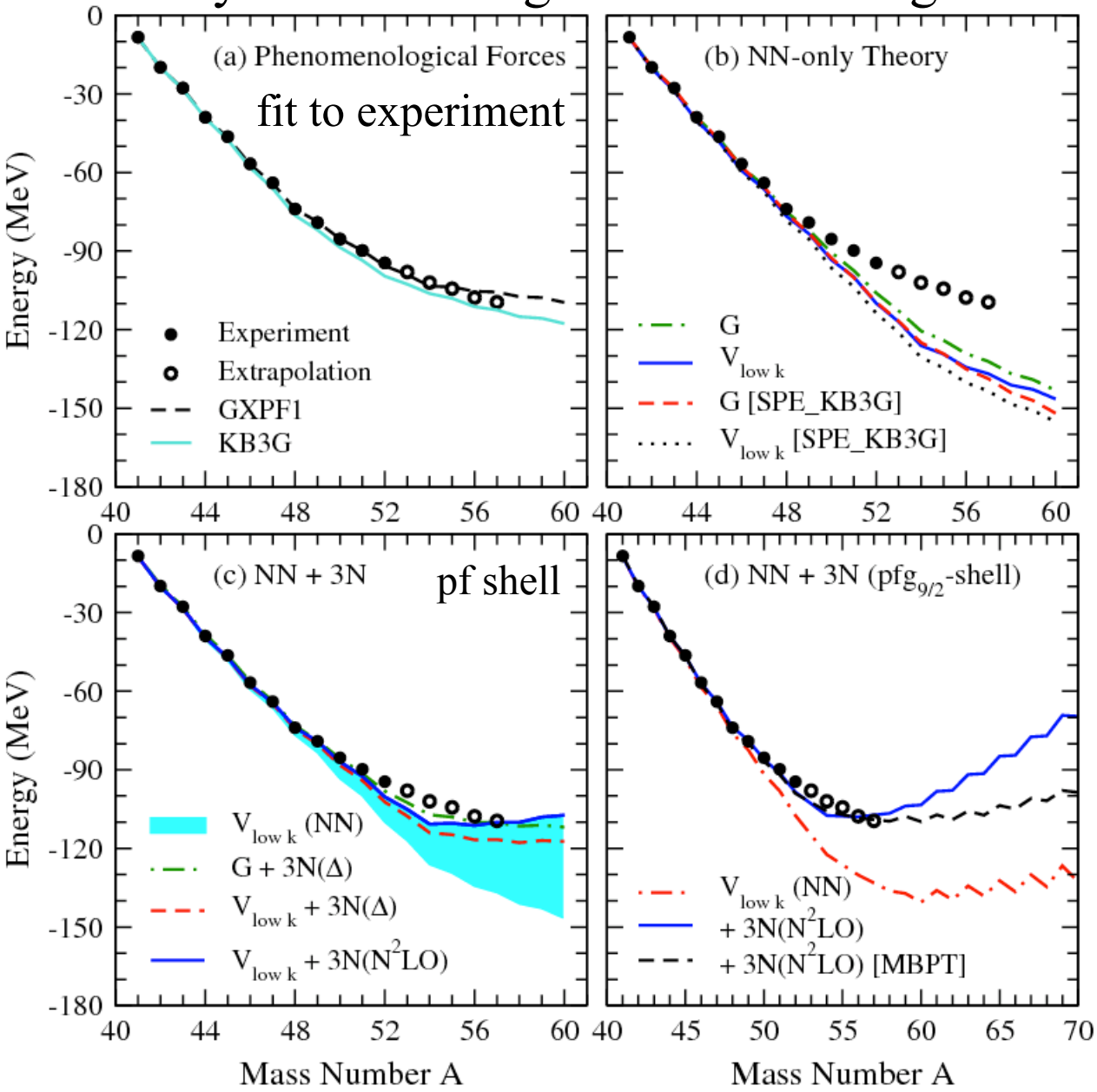
shown to exist to ^{58}Ca

predict drip-line
around ^{60}Ca

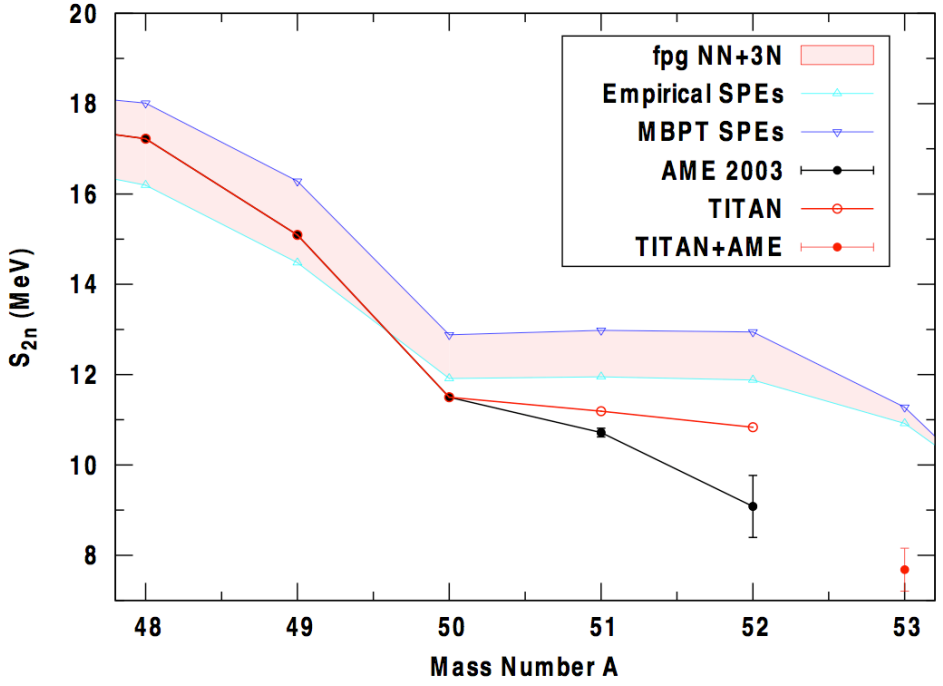


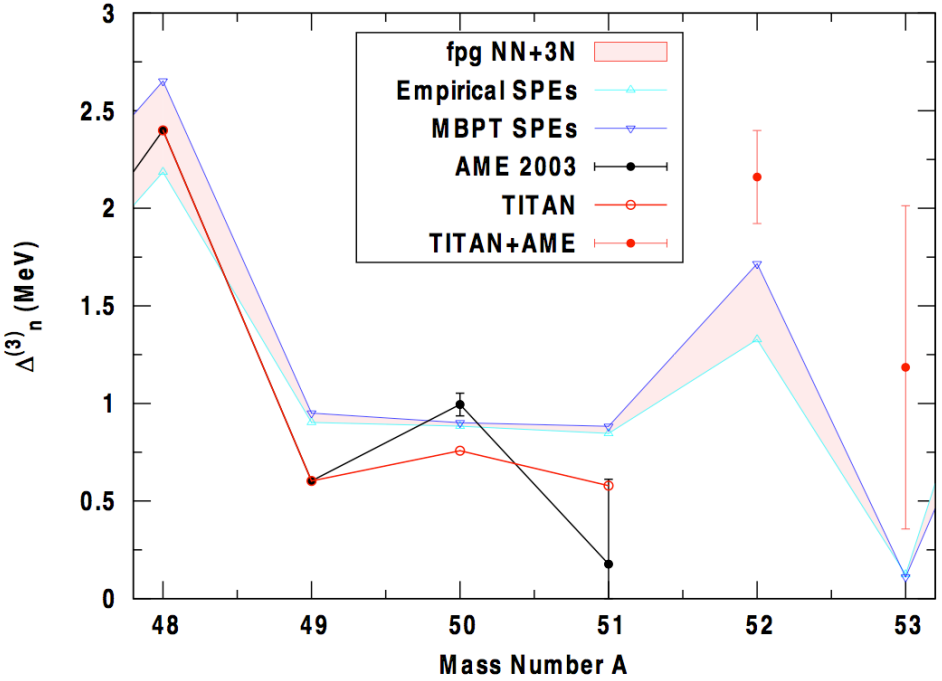
Evolution to neutron-rich calcium isotopes

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

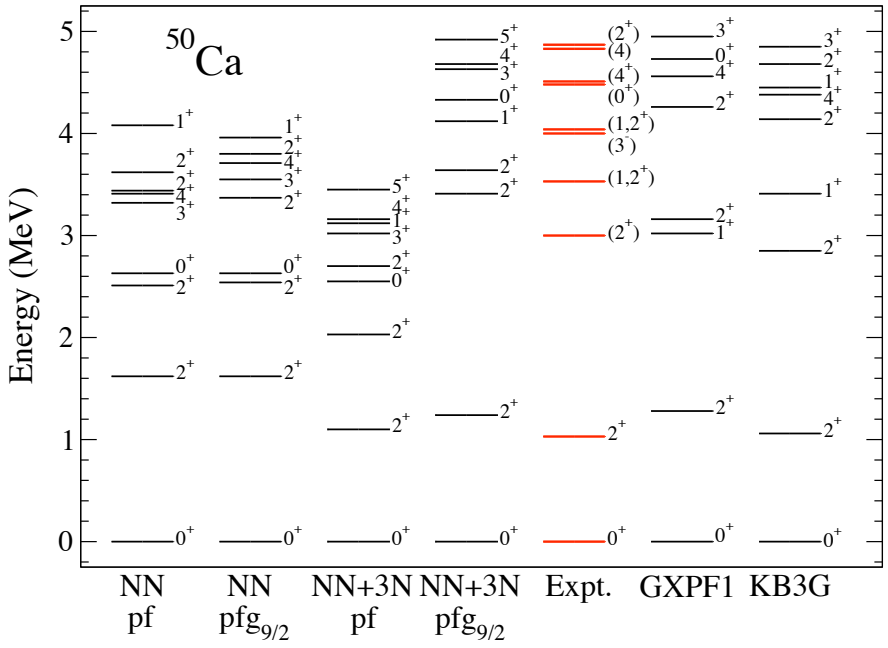
^{52}Ca is 1.75 MeV more bound compared to atomic mass evaluation (AME)!

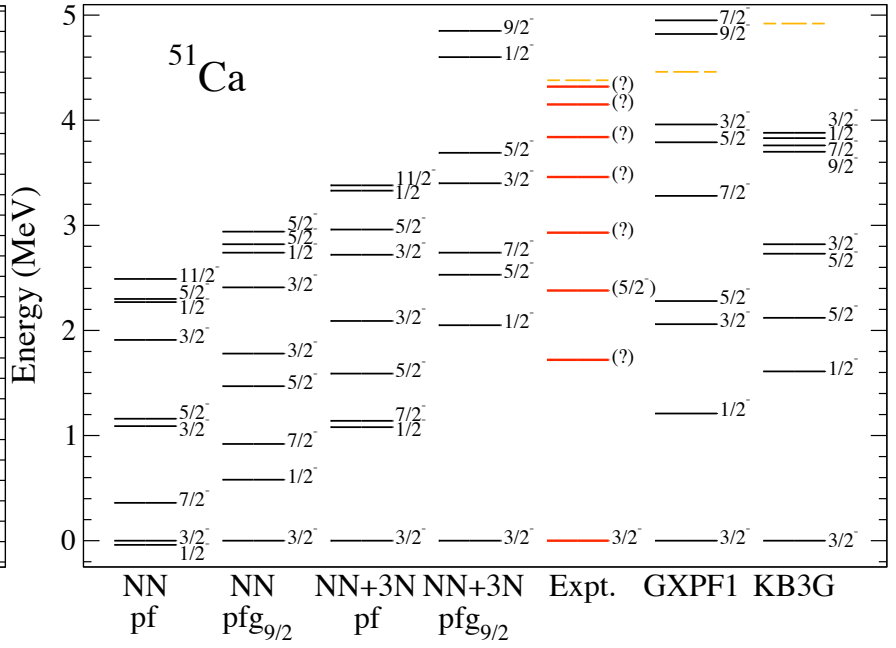
behavior of S_{2n} and Δ_n agrees with NN+3N calculations

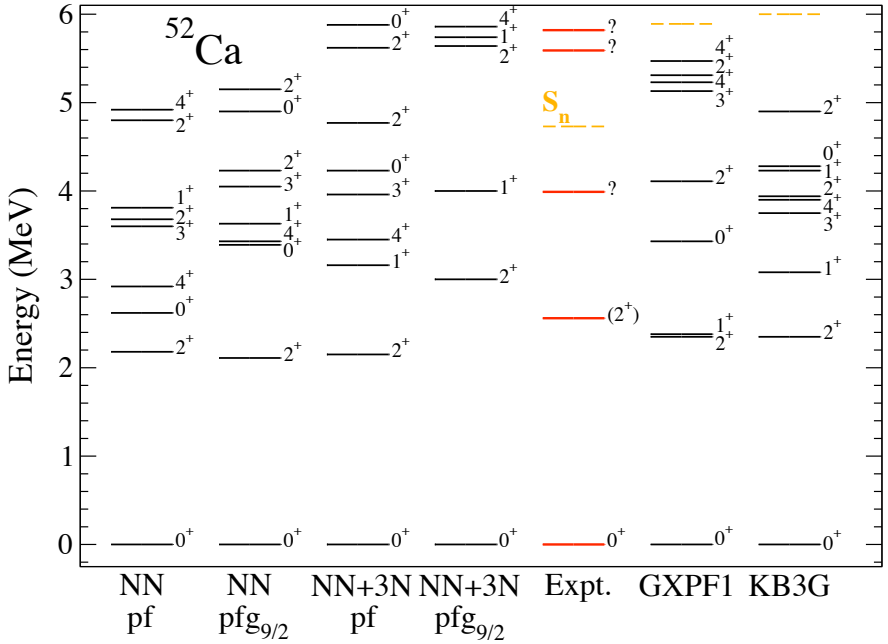


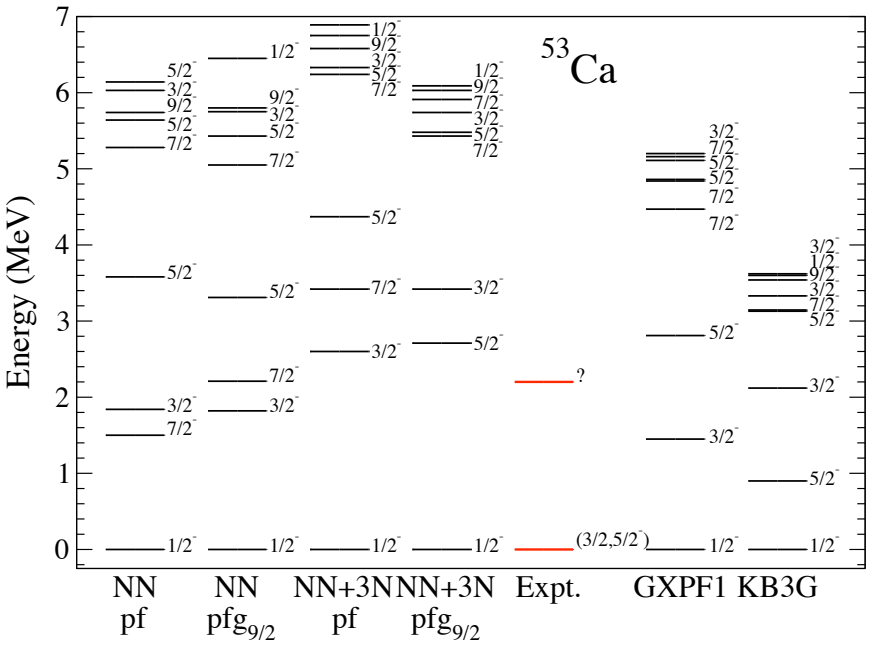


Spectra of neutron-rich calcium isotopes Holt, Menendez, AS, in prep.





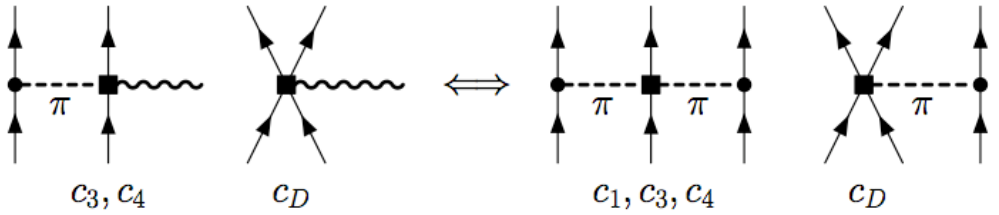




Chiral EFT for electroweak transitions Menendez, Gazit, AS (2011).

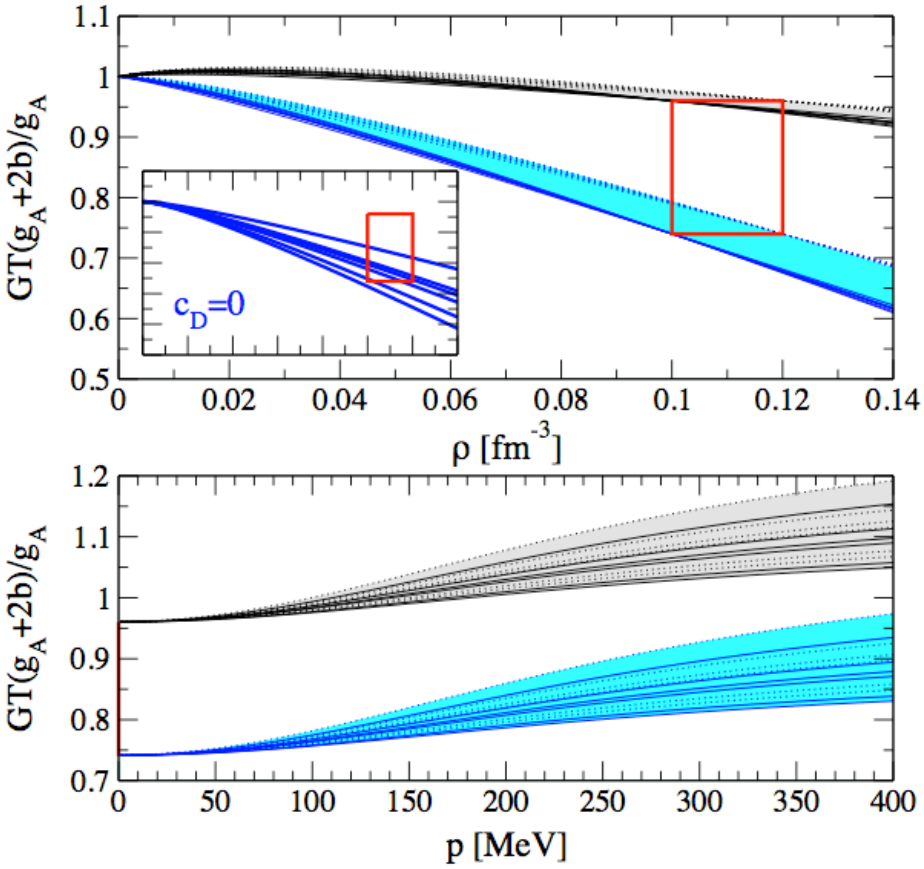
two-body currents lead to important contributions in nuclei (Q~100 MeV) especially for Gamow-Teller transitions

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



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

+ predict momentum dependence (weaker quenching for larger p: 0νββ decay, muon capture,…)



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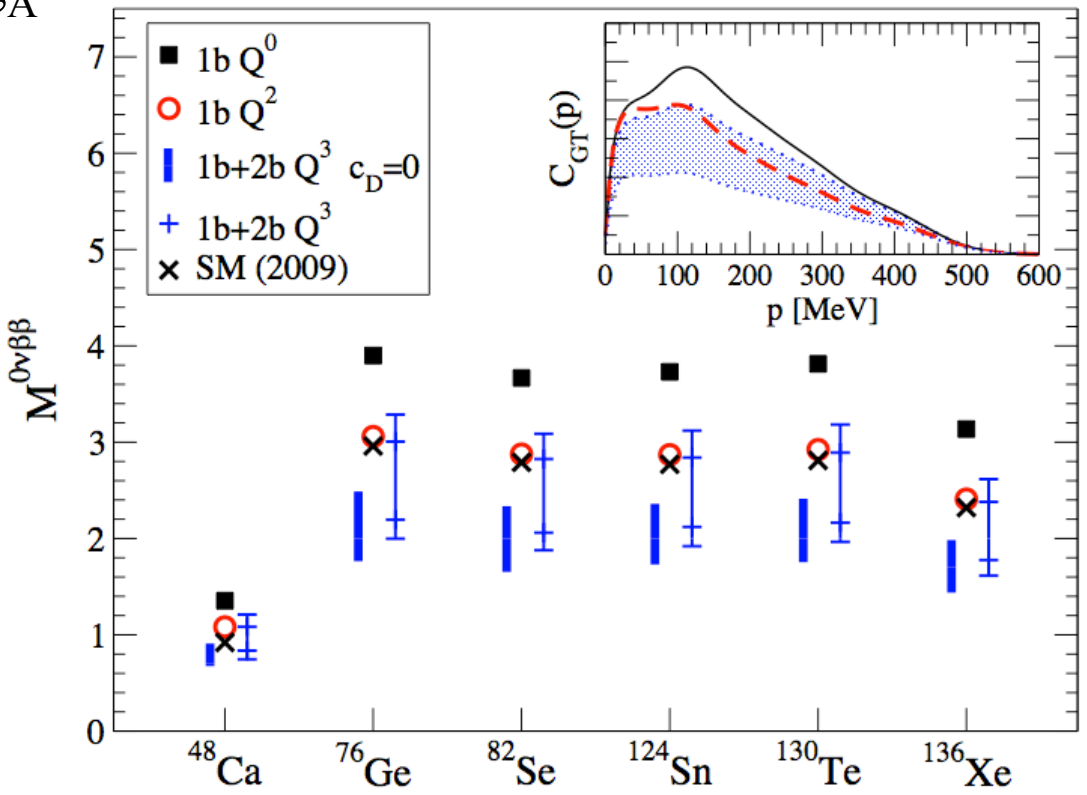
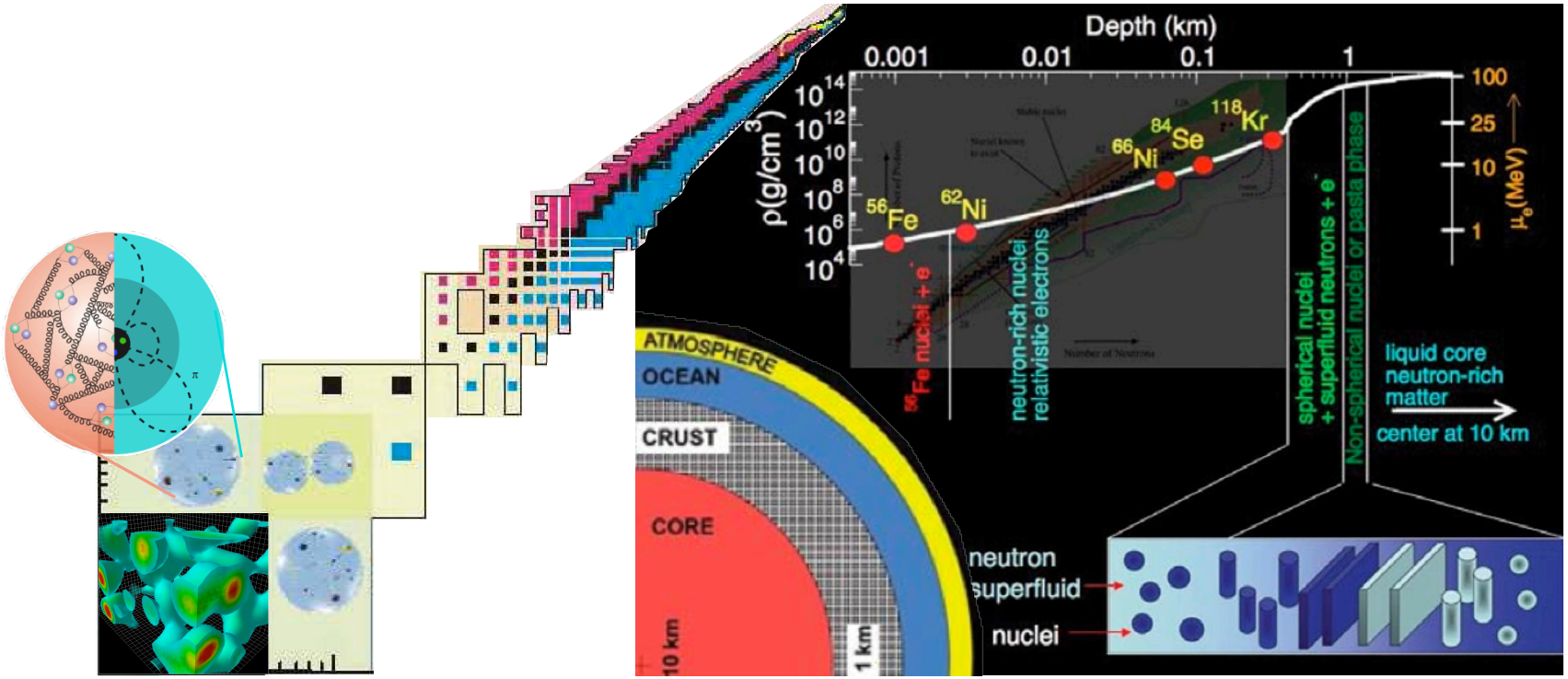
+ predict mom. dependence

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



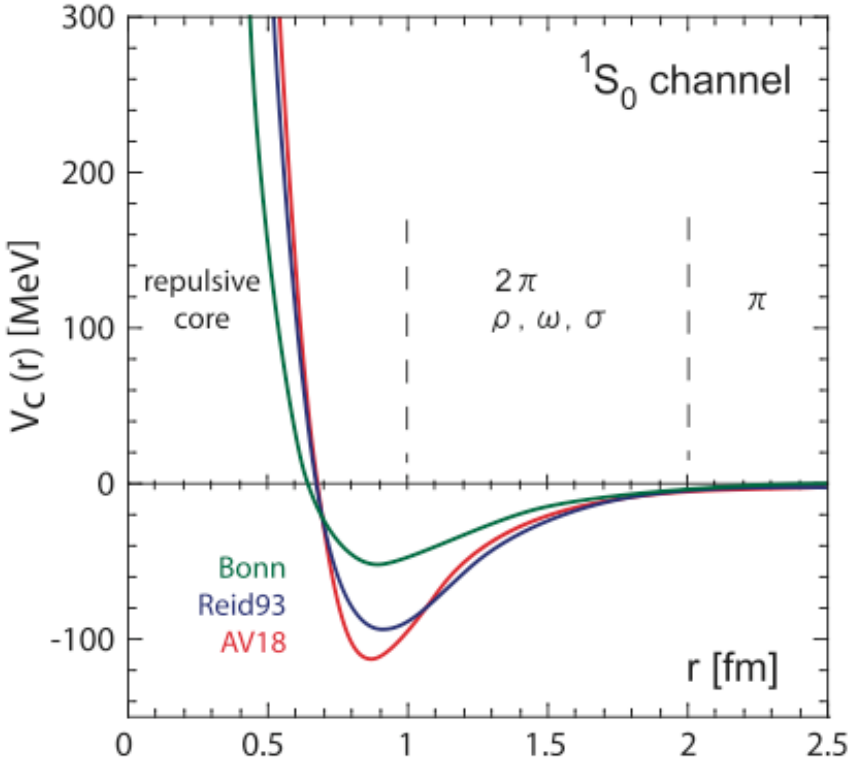
Neutron matter and neutron stars

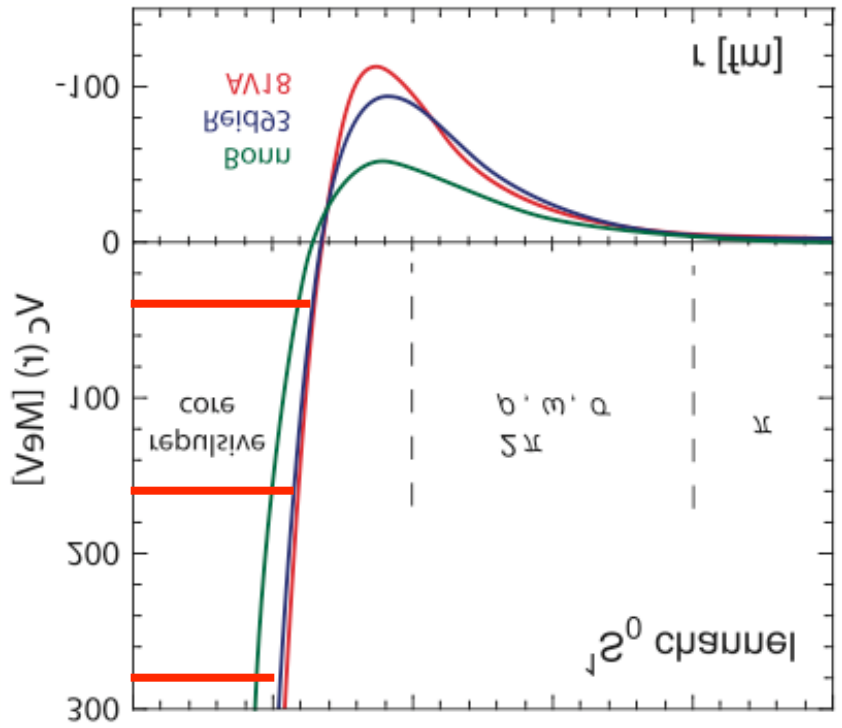


Convergence with low-momentum interactions

large cutoffs lead to flipped-potential bound states, even for small -λV

requires nonperturbative expansion, leads to slow convergence for nuclei



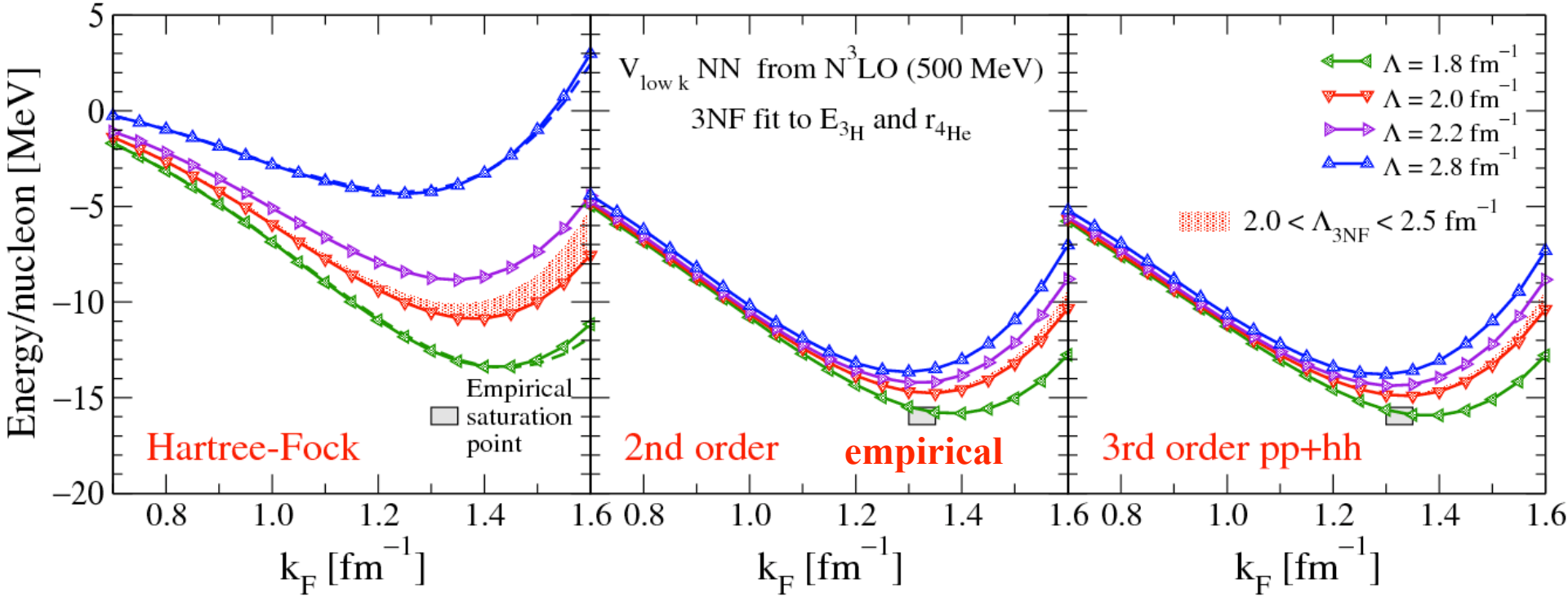


Weinberg eigenvalue analysis: two-body scattering becomes perturbative after RG evolution, except in channels with bound states

EFT and RG leads to improved convergence for nuclei and nuclear matter

Advances in nuclear matter theory

Is nuclear matter perturbative with chiral EFT and RG evolution?



Hebeler et al. (2009, 2010)

exciting: empirical saturation with theoretical uncertainties

input to develop a universal energy density functional for all nuclei

UNEDF SciDAC Collaboration

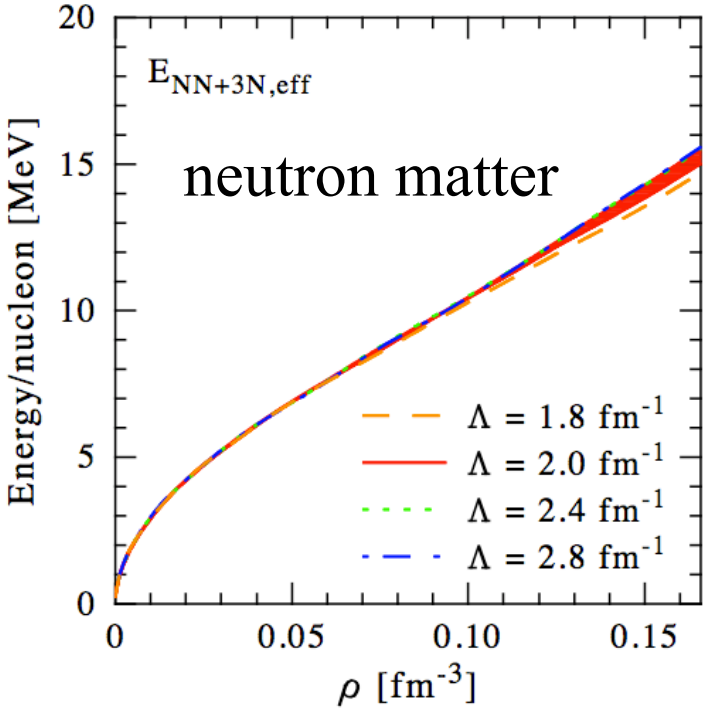
Universal Nuclear Energy Density Functional

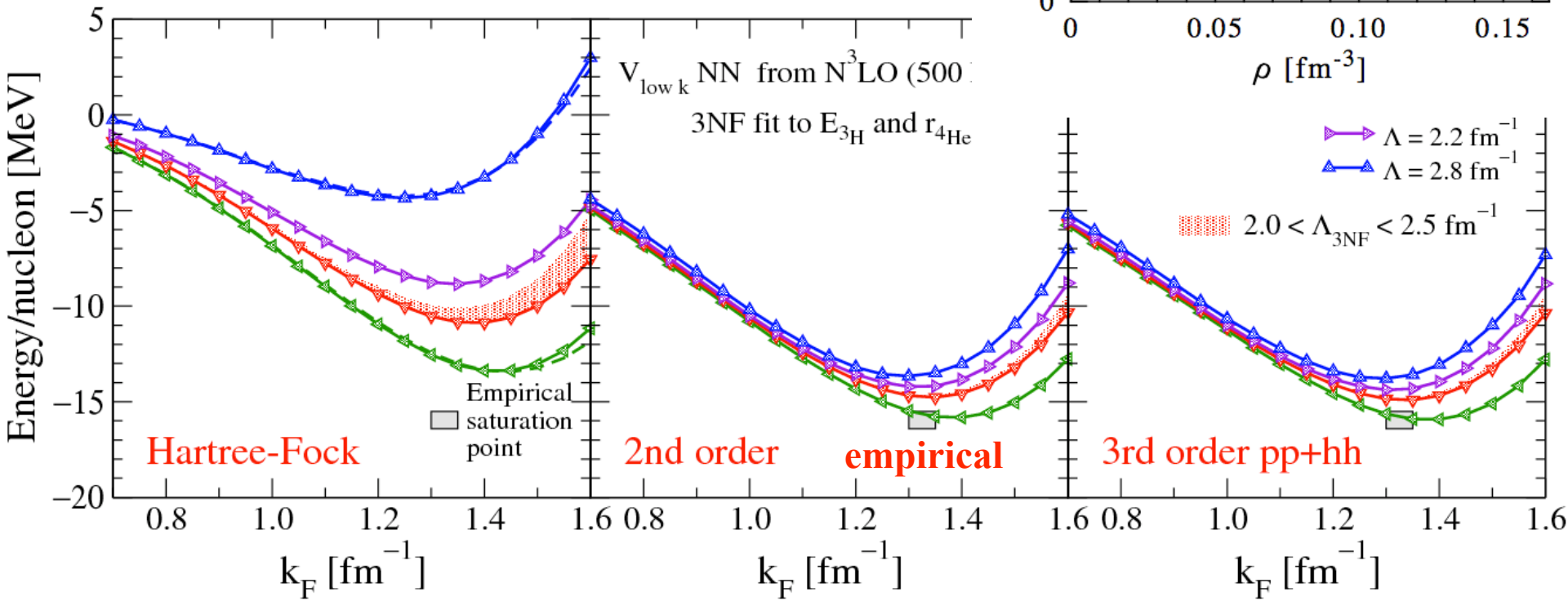
Impact of 3N forces on neutron matter

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

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

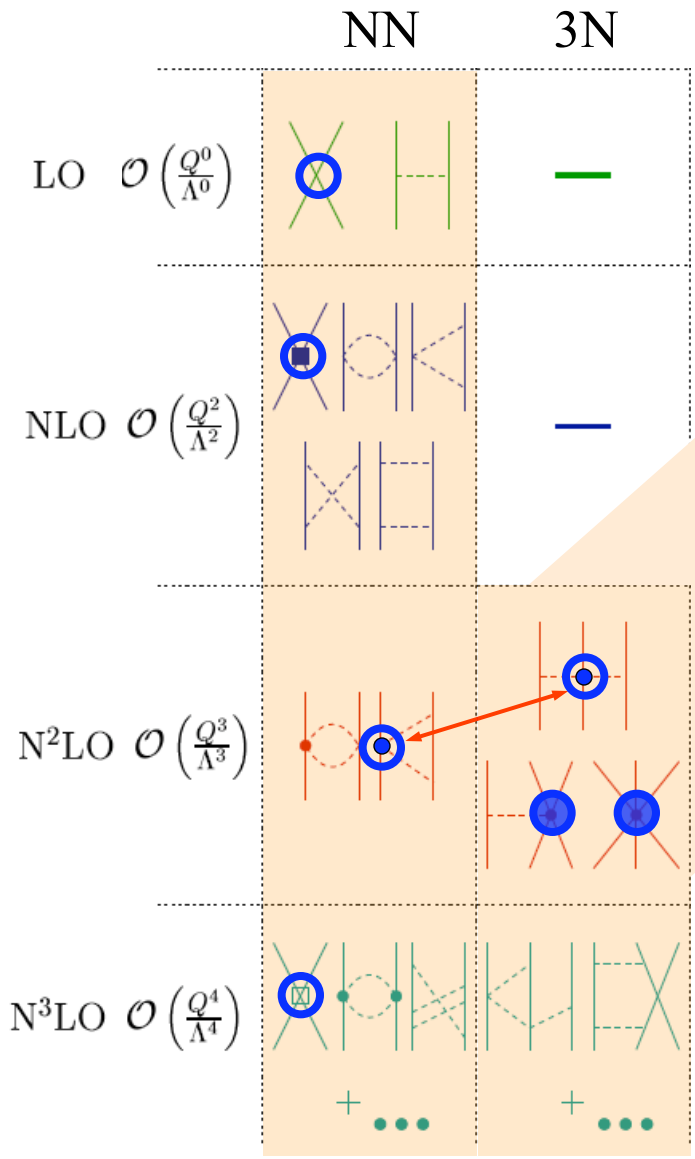
neutron matter: many-body forces are predicted to N^{3}LO!





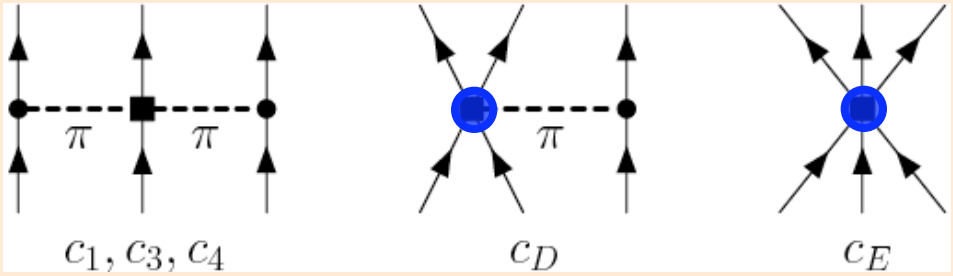
Chiral Effective Field Theory for nuclear forces

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 N³LO



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}

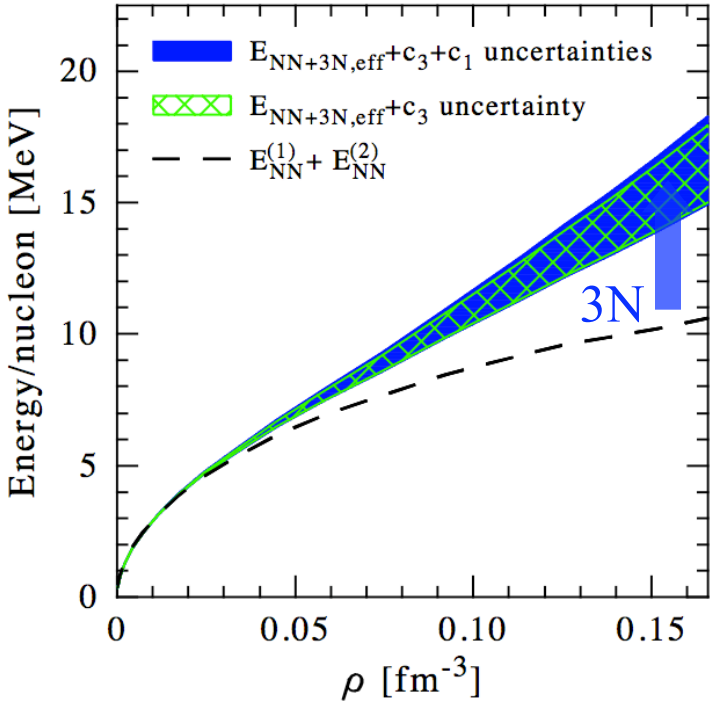
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Meissner,…

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



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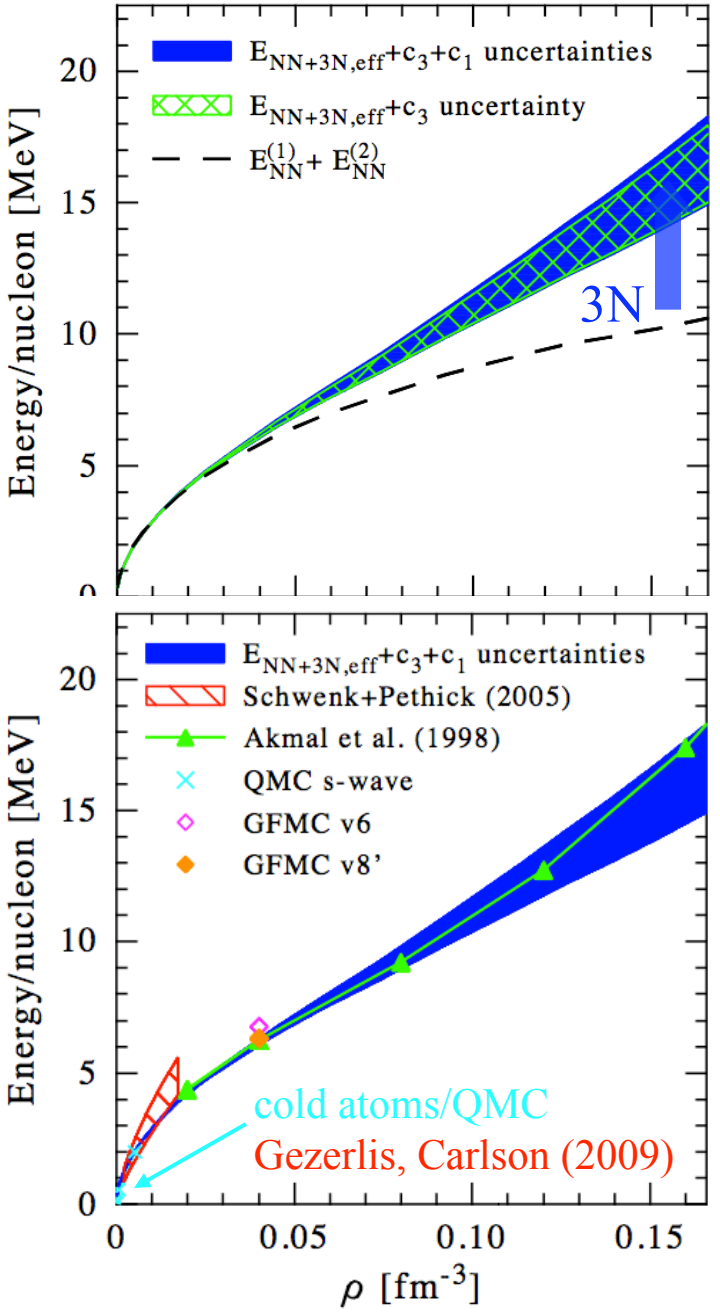
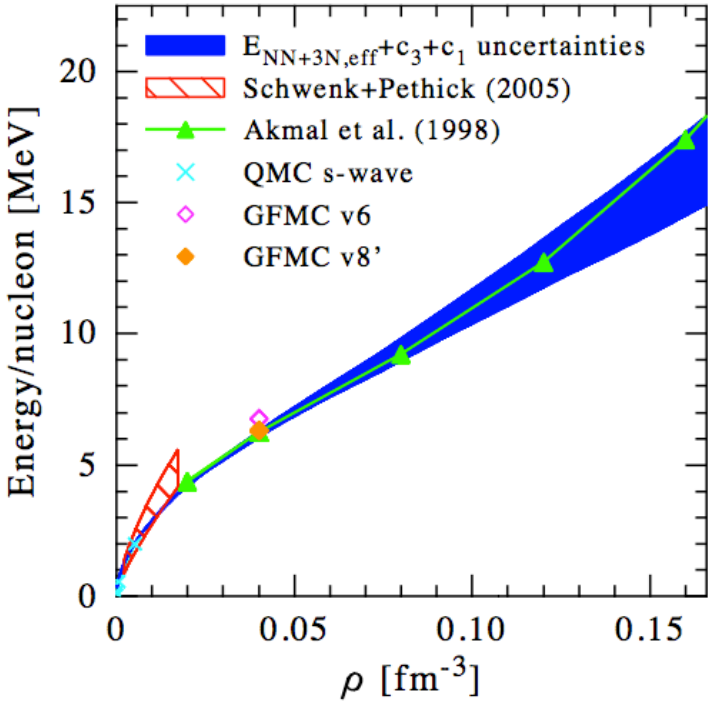
microscopic calculations within band



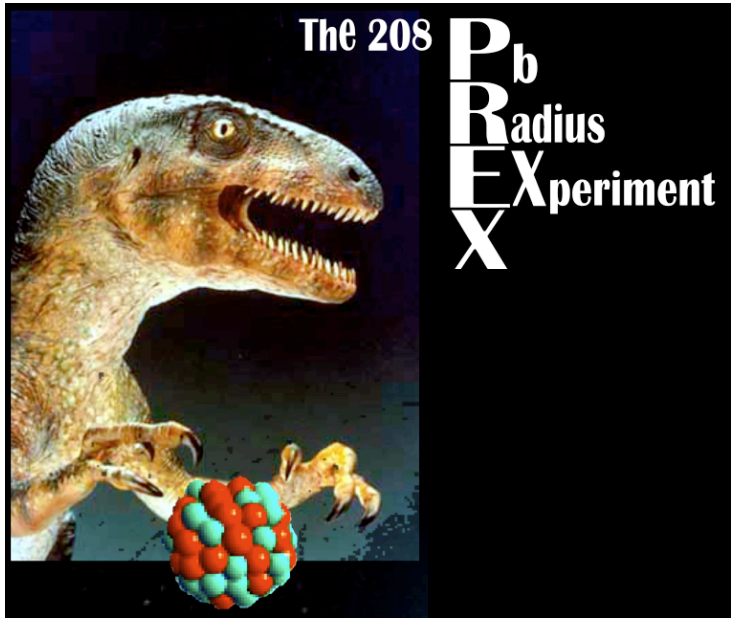
Symmetry energy and neutron skin Hebeler et al. (2010)

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).

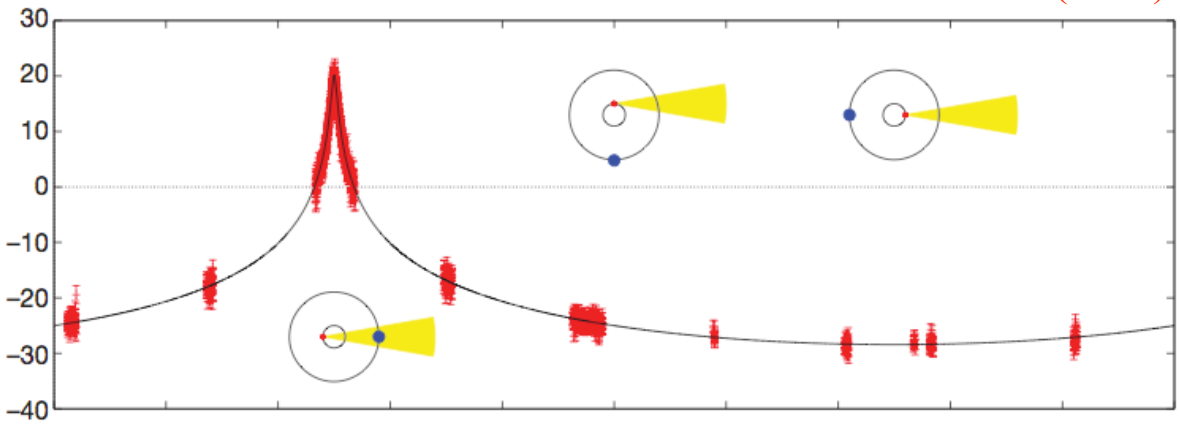
Discovery of the heaviest neutron star

A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

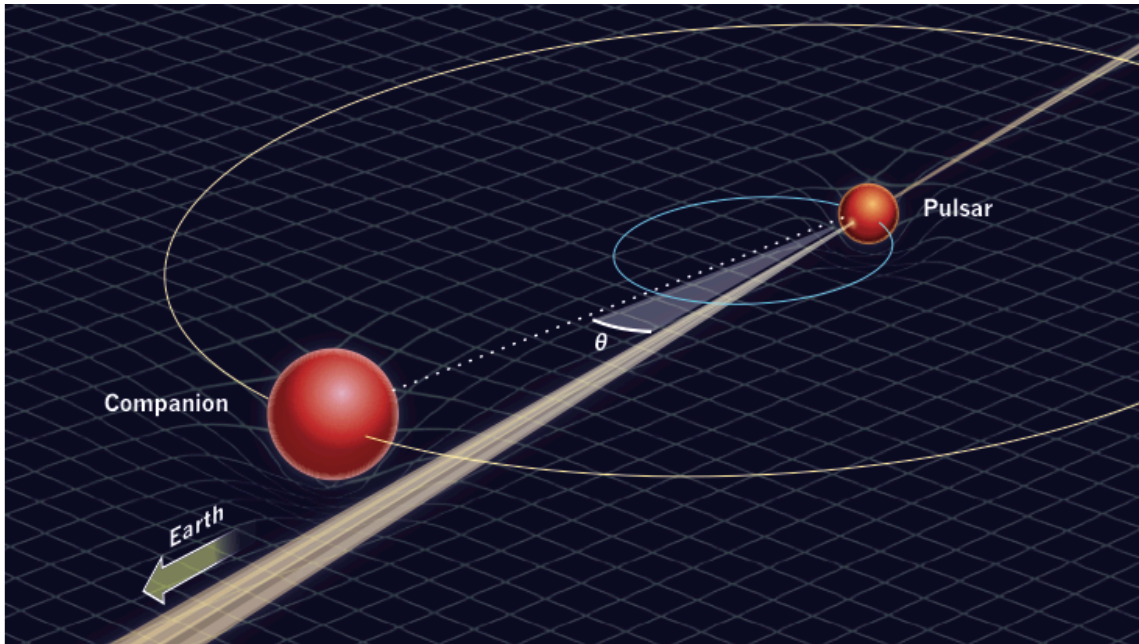
Nature (2010)

direct measurement of neutron star mass from increase in signal travel time near companion



J1614-2230
most edge-on binary pulsar known (89.17°)
+ massive white dwarf companion (0.5 M_{sun})

heaviest neutron star with 1.97±0.04 M_{sun}

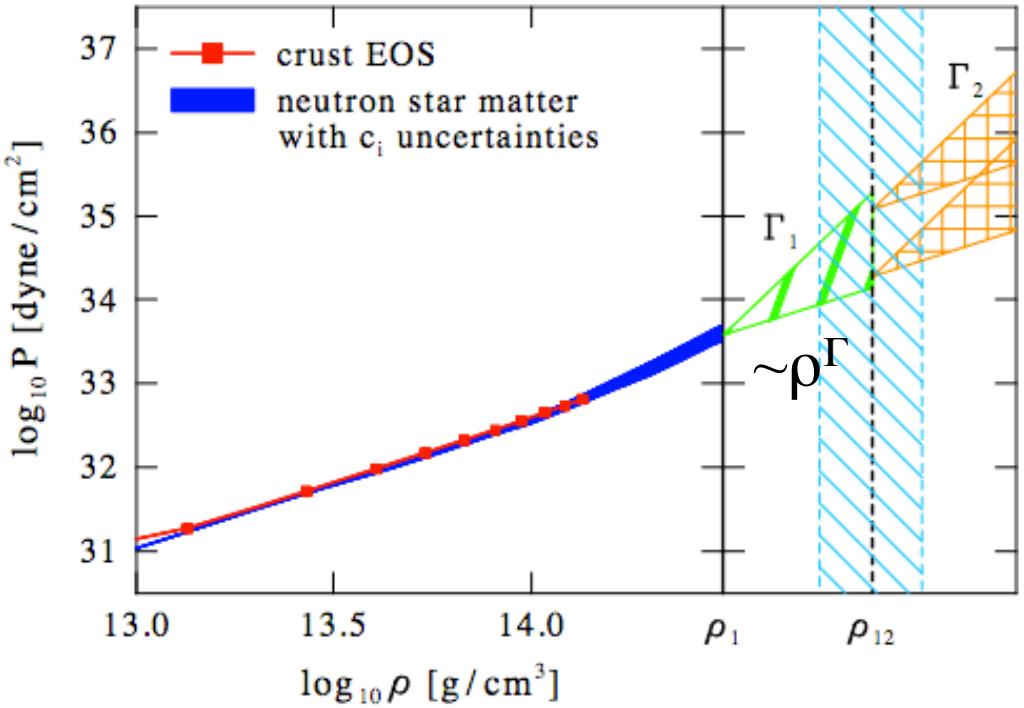


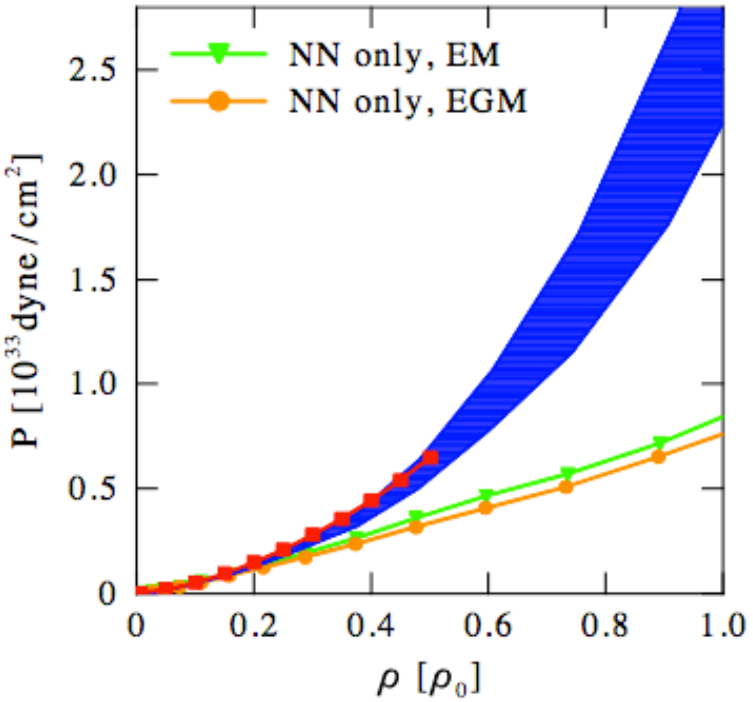
Impact on neutron stars

Neutron star structure determined by Tolman-Oppenheimer-Volkov eqn

$$\frac{dP}{dr} = -\frac{GM\epsilon}{r^2}\left[1+\frac{P}{\epsilon c^2}\right]\left[1+\frac{4\pi r^3 P}{Mc^2}\right]\left[1-\frac{2GM}{c^2 r}\right]^{-1}$$

with equation of state/pressure for neutron-star matter Hebeler et al., (2010)



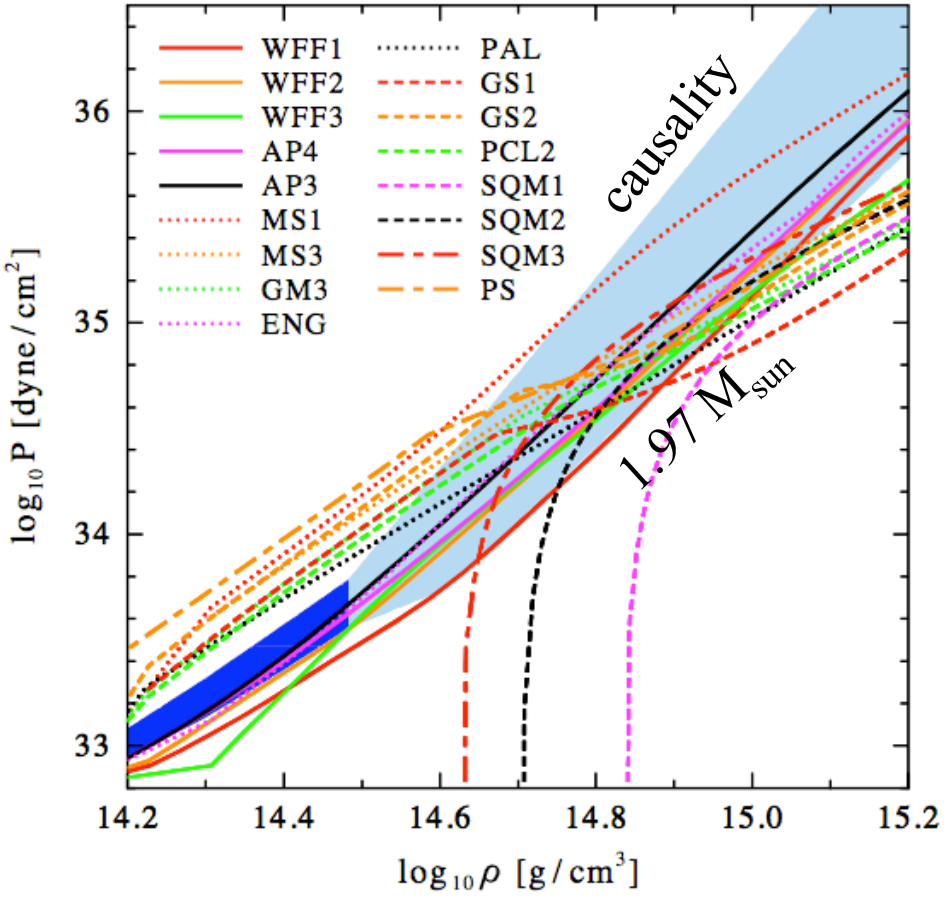


pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

extend uncertainty band to higher densities using piecewise polytropes

Pressure of neutron star matter Hebeler et al. (2010)

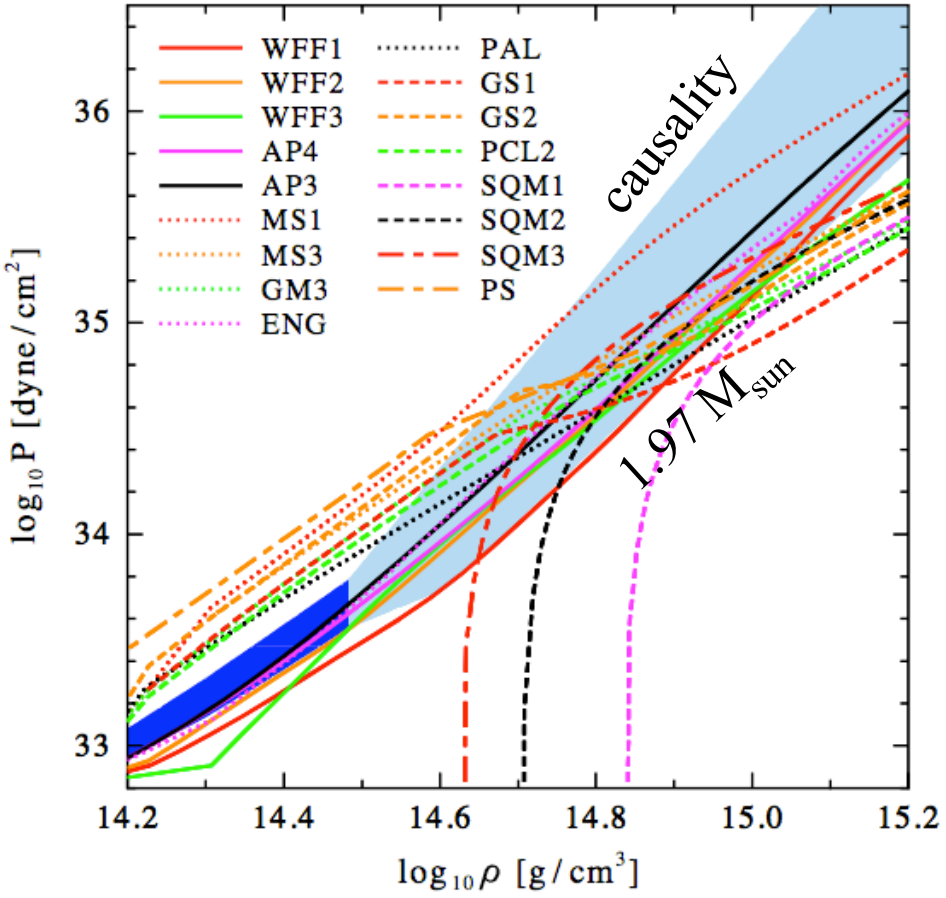
constrain polytropes by causality and require to support 1.97 M_{sun} star

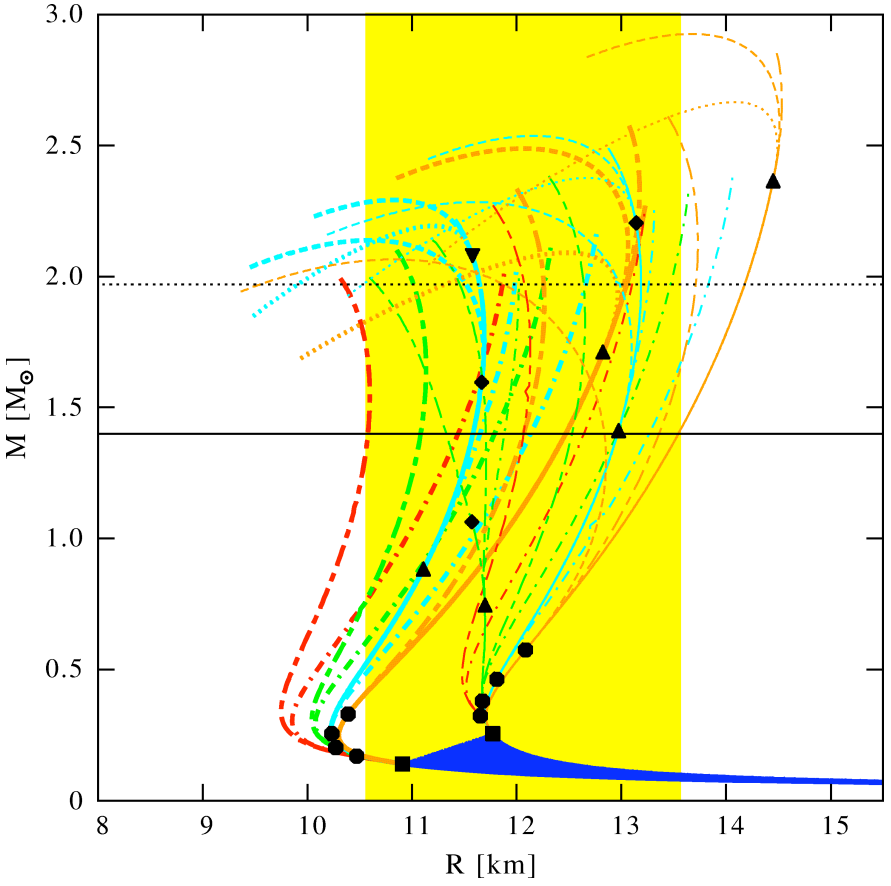


low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

Neutron star radius constraints Hebeler et al. (2010)

constrain polytropes by causality and require to support 1.97 M_{sun} star





low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

constrains neutron star radius: 10.9-13.9 km for M=1.4 M_{sun} (±12% !)

Thanks to collaborators!

A. Bartl, T. Krüger, J. Menendez,
J. Simonis, V. Soma, I. Tews

K. Hebeler

J.D. Holt

T. Otsuka

T. Suzuki

Y. Akaishi

C.J. Pethick

J.M. Lattimer

D. Gazit

Summary

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

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

key for neutron-rich nuclei: Ca isotopes, N=28 and shell evolution

next steps: full sd and pf shell (Ca to Ni)

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

impact of 3N forces and global mass predictions?

exciting interactions with experiments and observations!