Neutron-rich nuclei, neutron matter and constraints on neutron star structure from chiral effective field theory interactions

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TECHNISCHE UNIVERSITÄT DARMSTADT

EMMI

HELMHOLTZ ASSOCIATION

EMMI Workshop, GSI, July 15, 2010

Thanks to collaborators and main message

TECHNISCHE UNIVERSITÄT DARMSTADT, EMMI — J. Menendez

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MICHIGAN STATE UNIVERSITY — S.K. Bogner

THE OHIO STATE UNIVERSITY — R.J. Furnstahl

Forschungszentrum Jülich in der Helmholtz-Gemeinschaft — A. Nogga

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東京大学 THE UNIVERSITY OF TOKYO — T. Otsuka

日本大学 — T. Suzuki

RIKEN NISHINA CENTER — Y. Akaishi

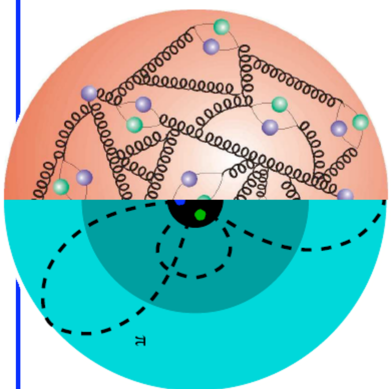
NORDITA, Niels Bohr Institutet — C.J. Pethick

STONY BROOK — J.M. Lattimer

3N forces are a frontier:
impact the structure and existence
of neutron-rich nuclei and
neutron-rich matter in astrophysics

Λ / Resolution dependence of nuclear forces

with high-energy probes:
quarks+gluons



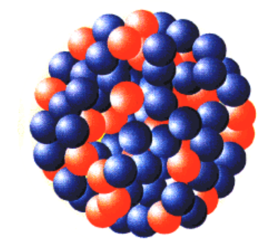
Effective theory for NN, 3N, many-N interactions and electroweak operators: resolution scale/Λ-dependent

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

$\Lambda_{\rm chiral}$

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

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



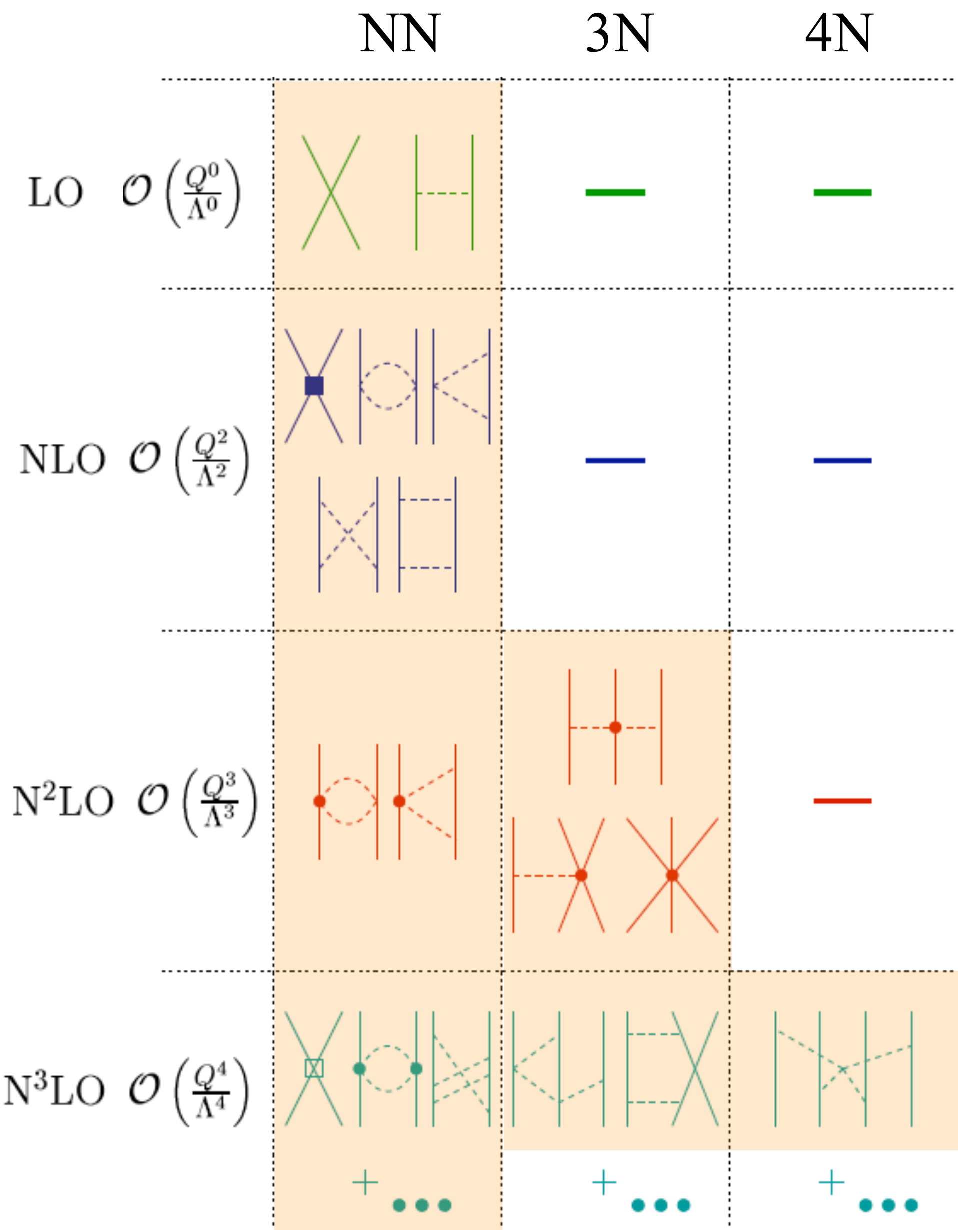
typical momenta in nuclei $\sim m_\pi$

$\Lambda_{\rm pionless}$

$Q \ll m_\pi$

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 $(Q/\Lambda_b)^n$

expansion parameter ~ 1/3

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

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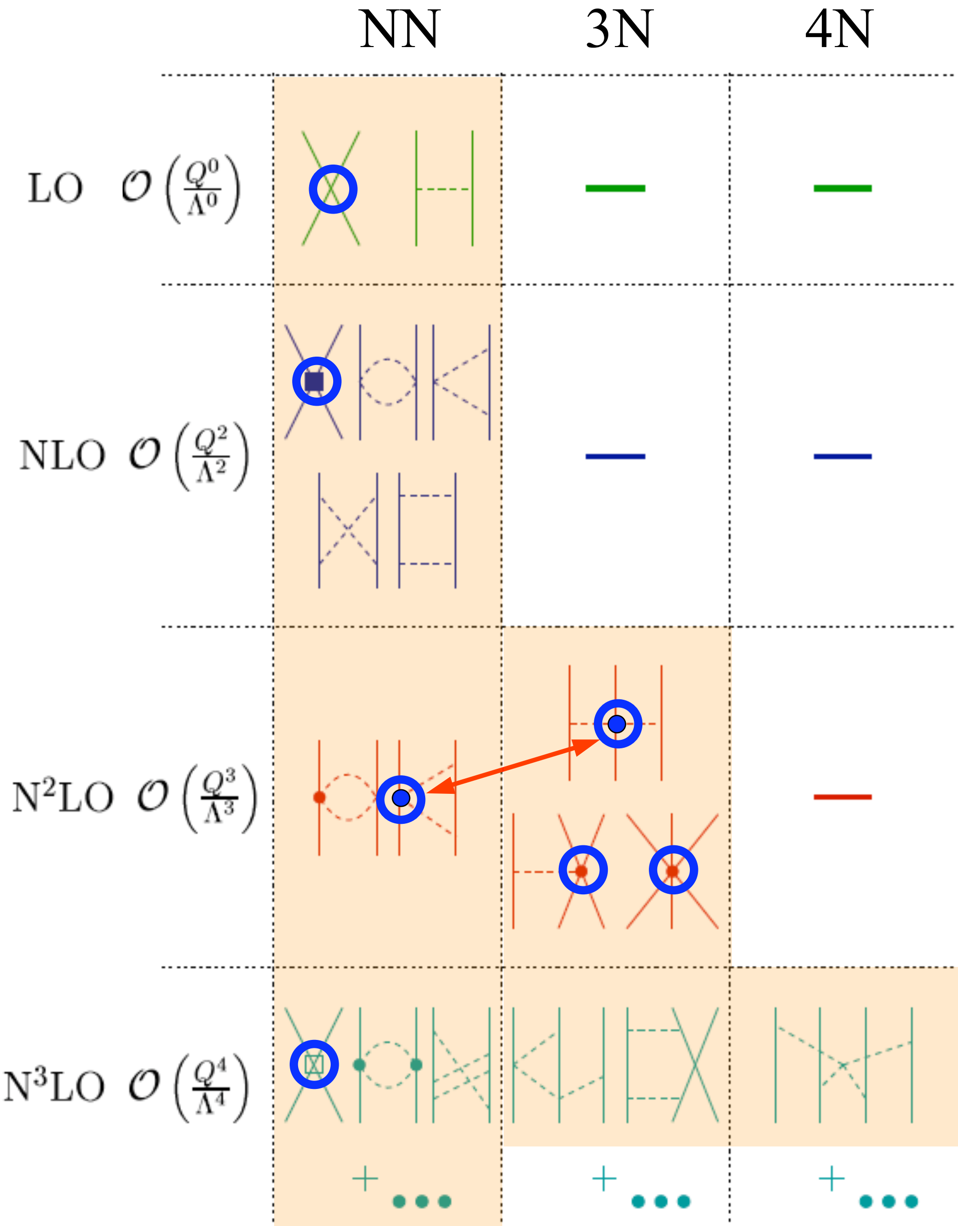

include long-range pion physics

details at short distance not resolved

capture in few short-range couplings, fit to experiment once, Λ-dependent

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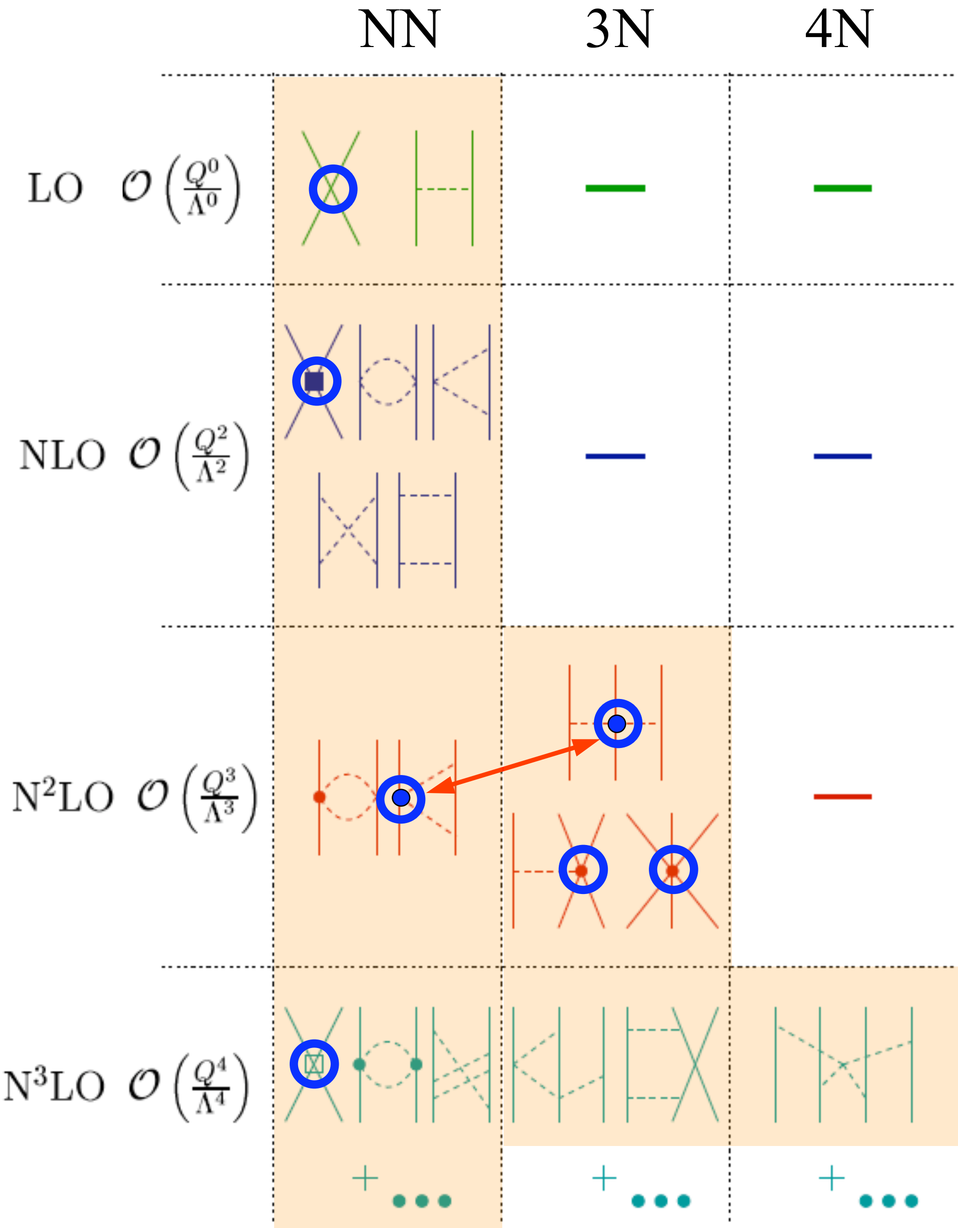

include long-range pion physics

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

can connect to lattice QCD

several open problems regarding renormalization and power counting

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

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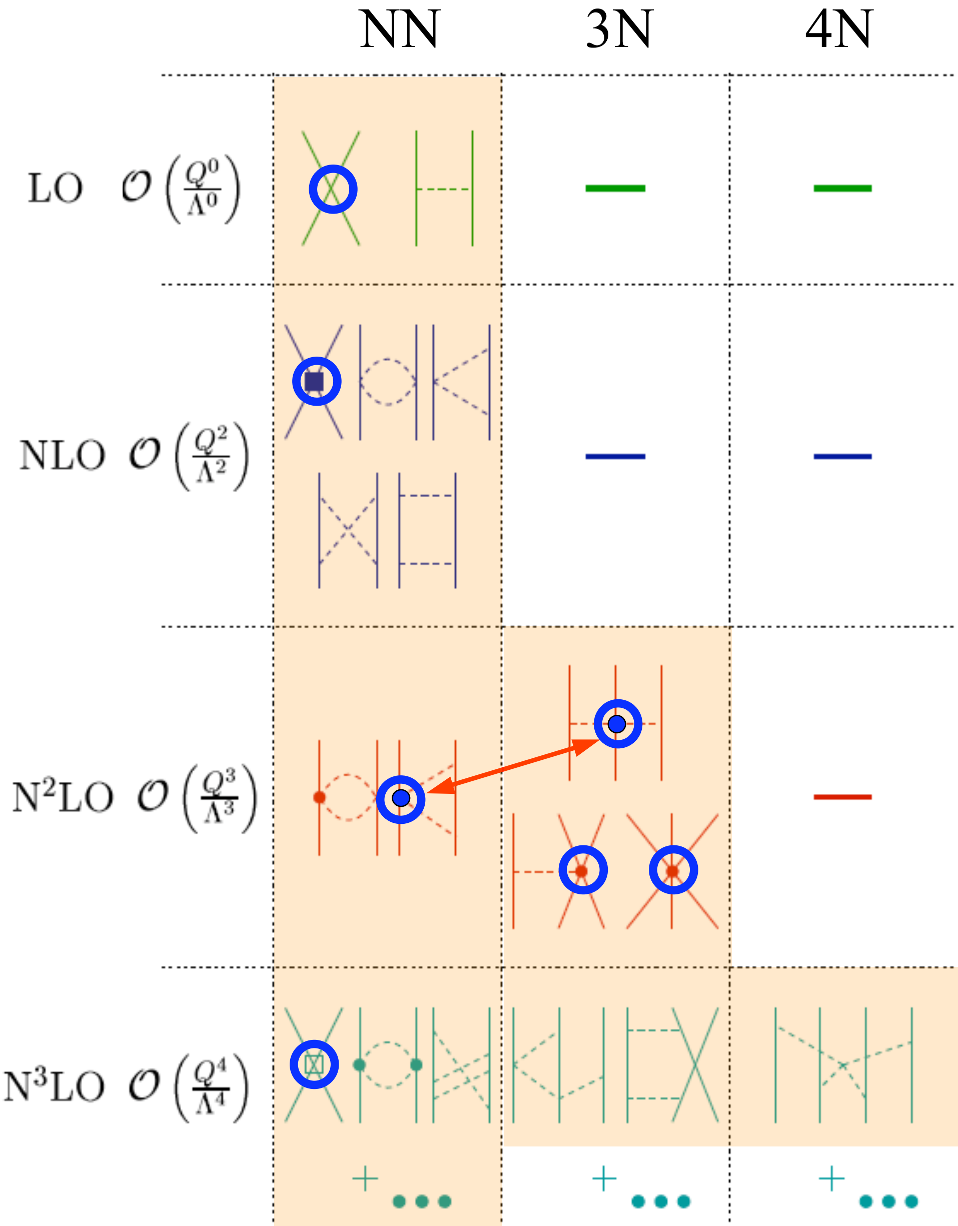
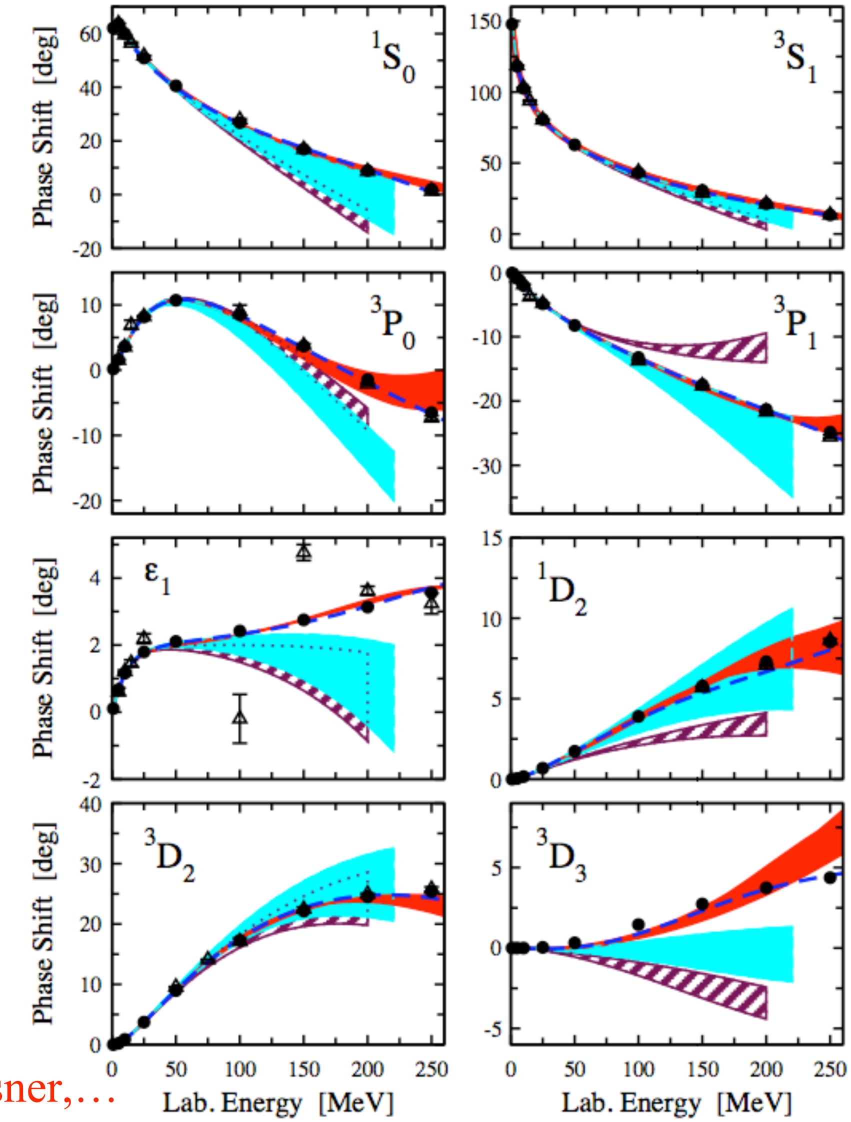


accurate reproduction of
low-energy NN scattering at N^{3}LO



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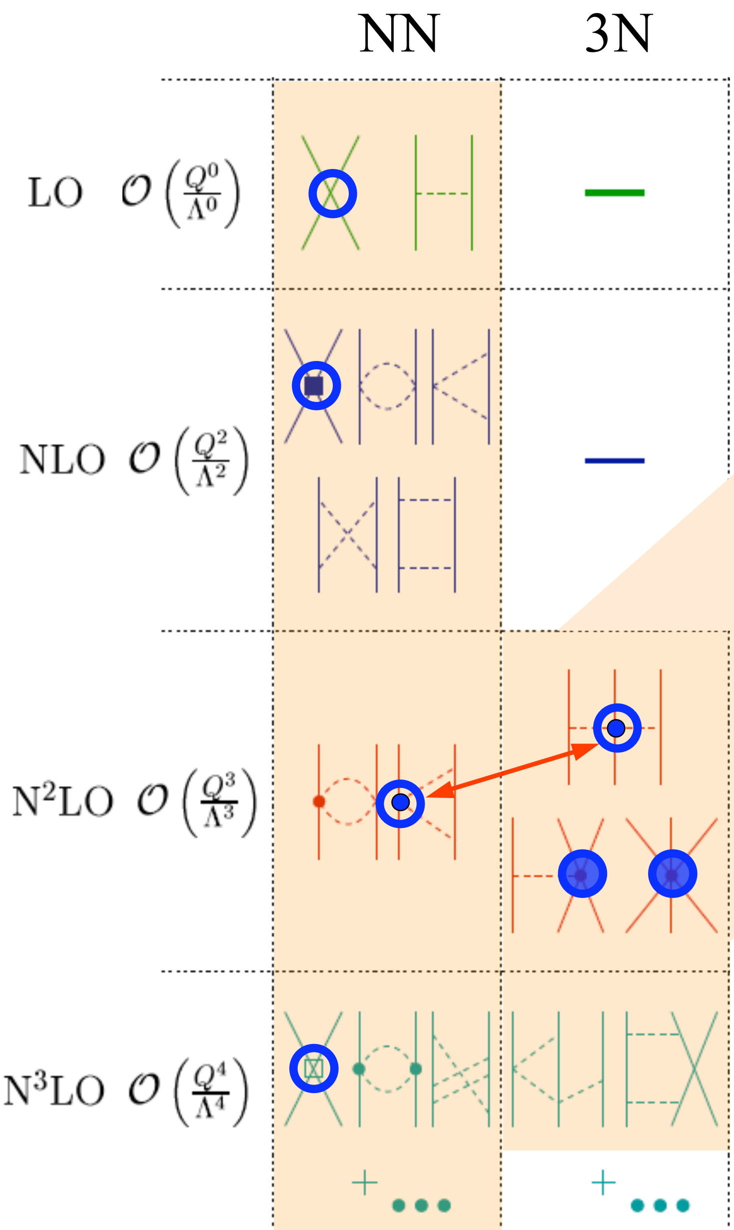
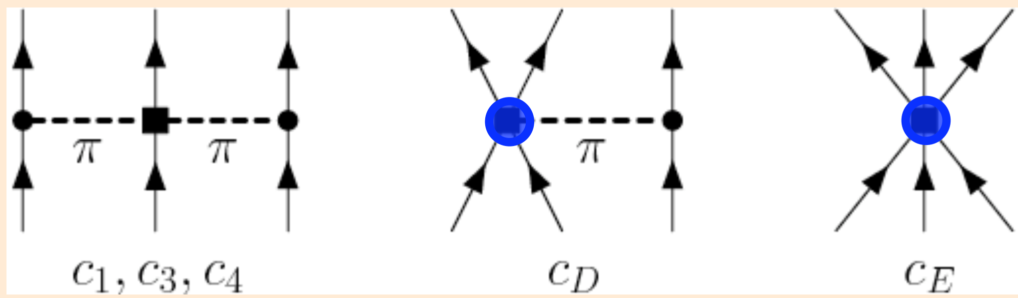


consistent NN-3N interactions

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 = particular c_i values

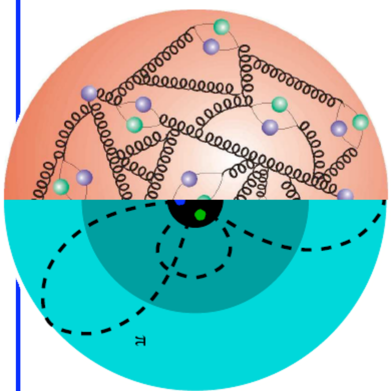
c_D, c_E fit to ^{3}H binding energy and ^{4}He radius (or ^{3}H beta decay half-life)

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

Nuclear forces and the Renormalization Group (RG)

RG evolution to lower resolution/cutoffs

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



$\Lambda_{\mathrm{chiral}}$

Λ ↓

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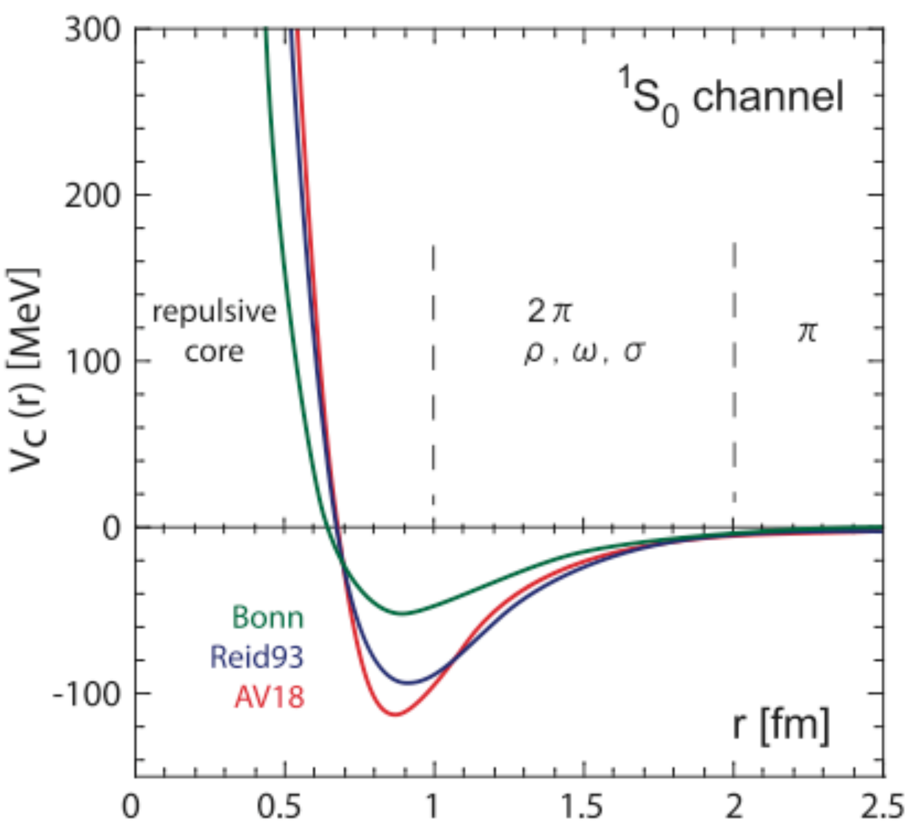
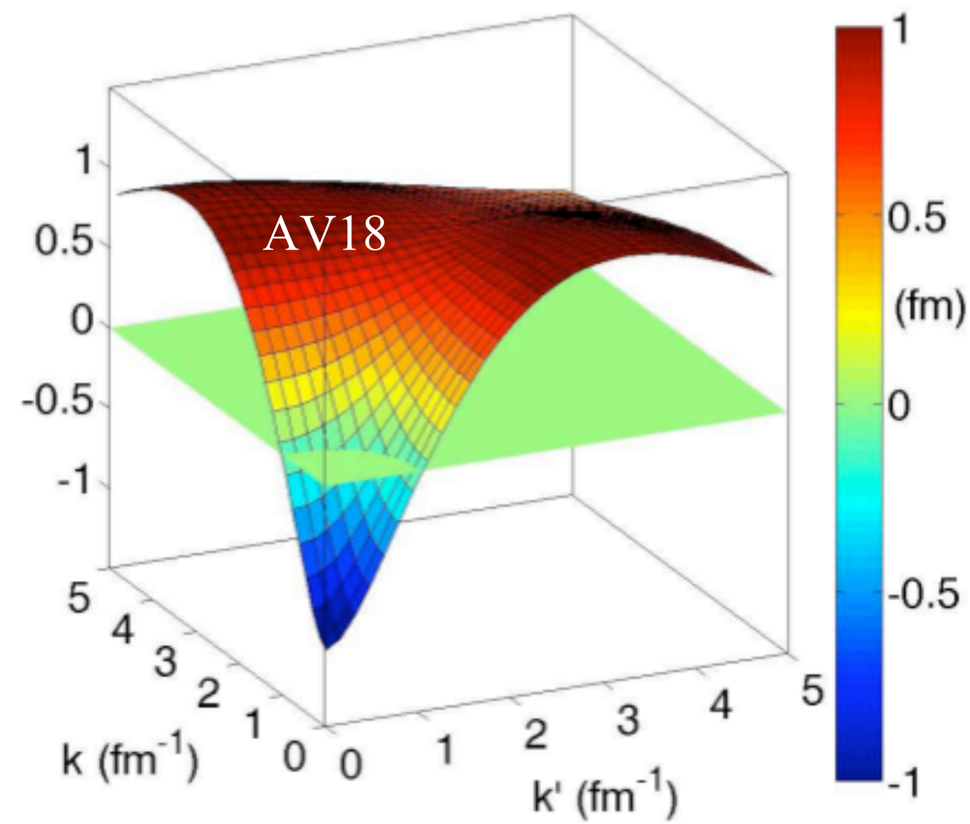
for NN interactions
(preserves NN observables)

$$\frac{d}{d\Lambda} V_{{\rm low}\,k}(k',k) = \frac{2}{\pi} \frac{V_{{\rm low}\,k}(k',\Lambda)\, T_{{\rm low}\,k}(\Lambda,k;\Lambda^2)}{1-(k/\Lambda)^2}$$

Bogner, Kuo, AS, Furnstahl,…





red = short-range repulsion

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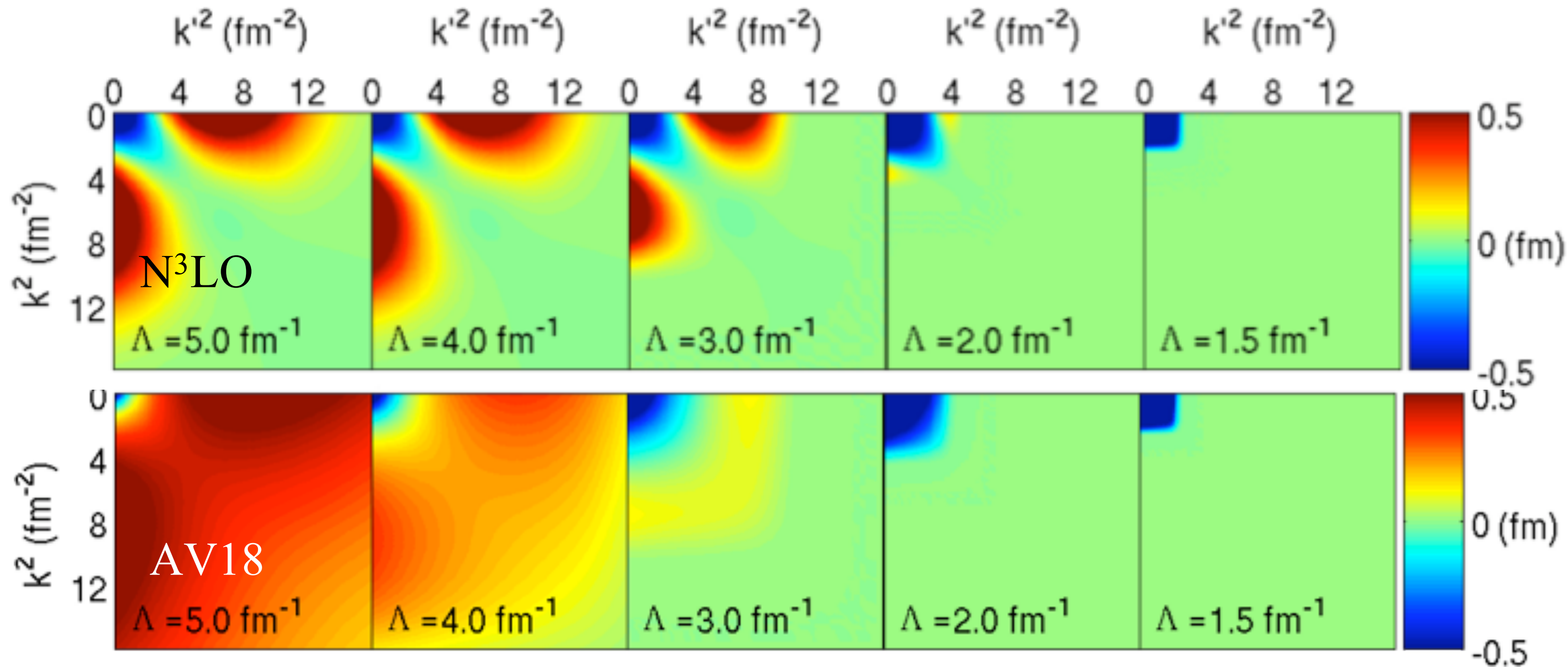
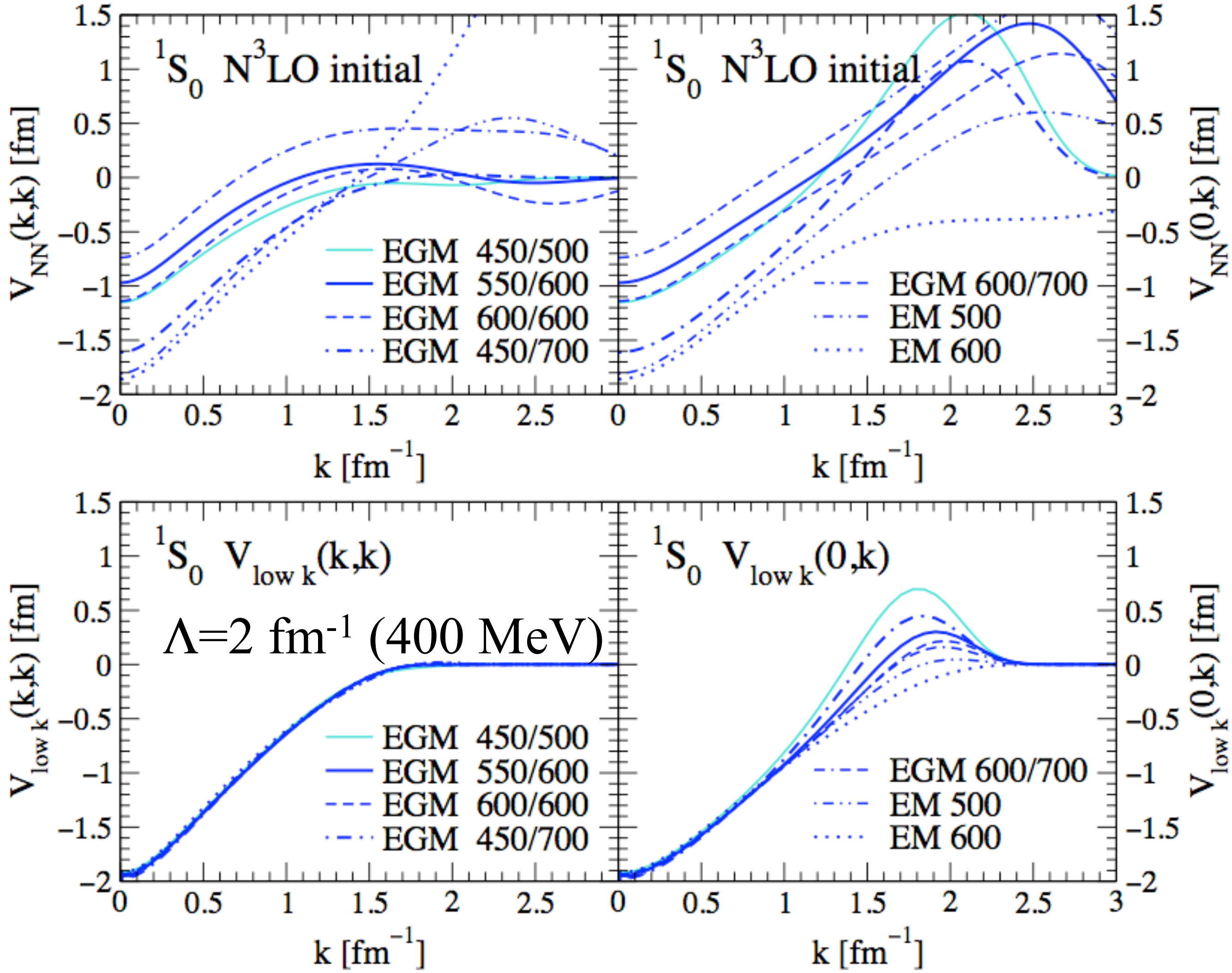


low-momentum interactions $V_{{\rm low}\,k}(\Lambda)$ with sharp or smooth regulators

decouples low-momentum physics from high momenta

Low-momentum universality

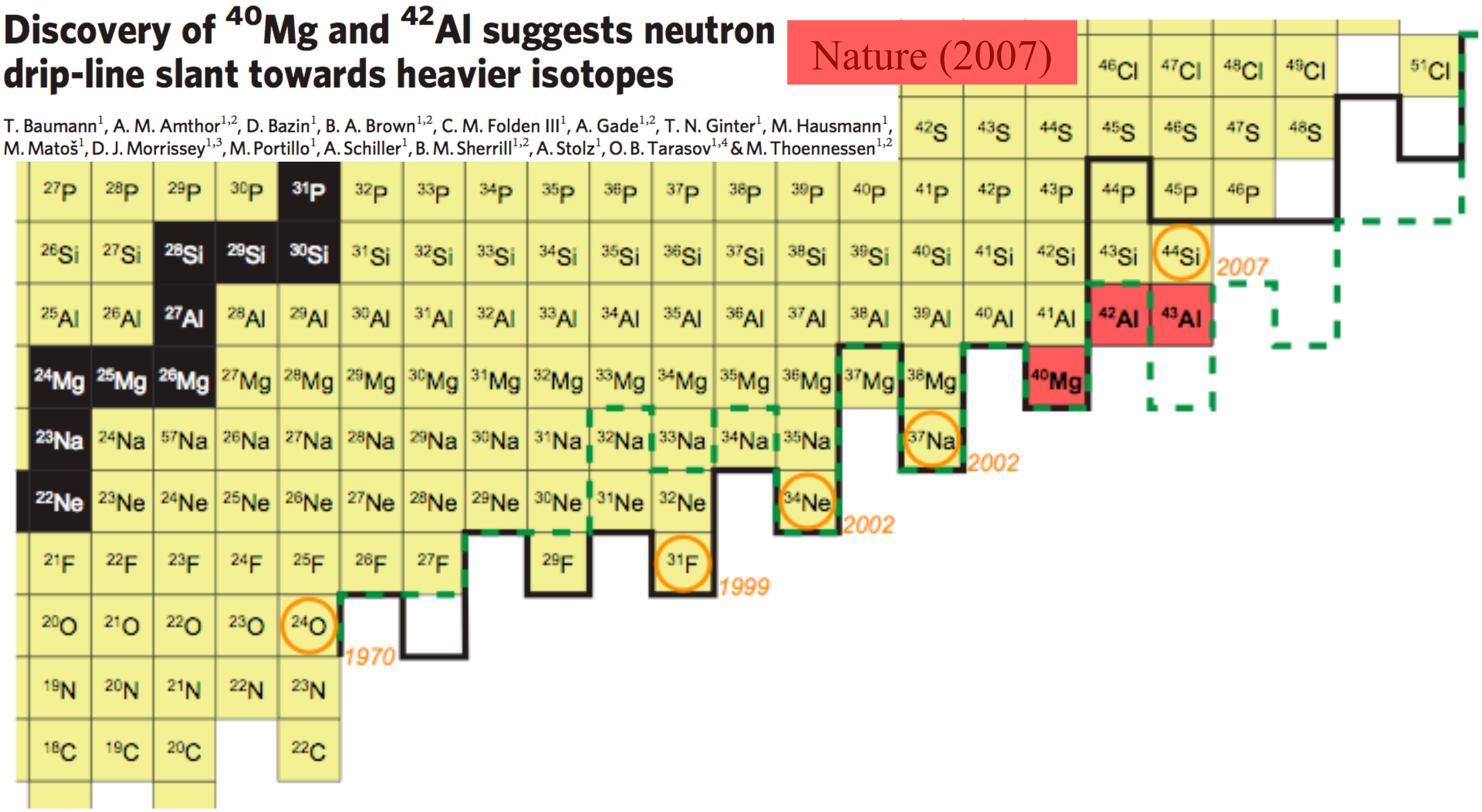


≈ universality from different chiral N^3LO potentials

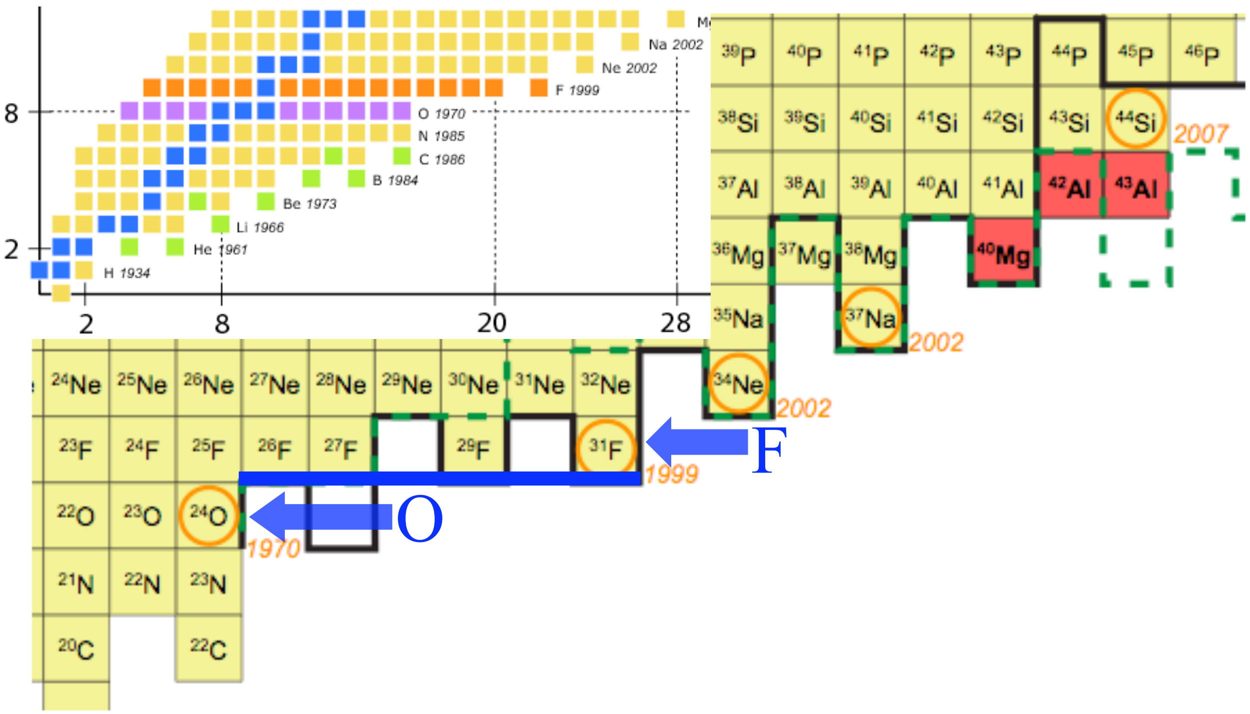
RG preserves NN observables and long-range parts

decouples low-momentum physics from high momenta

Towards the limits of existence - the neutron drip-line



The oxygen anomaly



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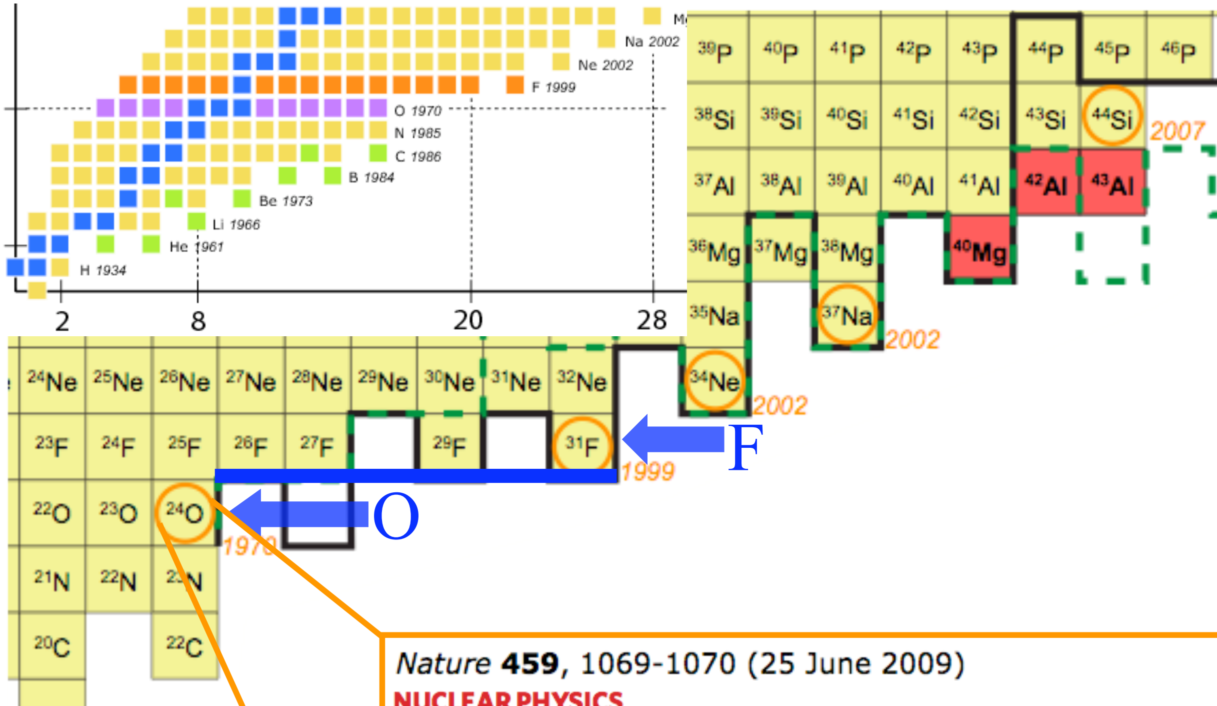


Nature **459**, 1069-1070 (25 June 2009)

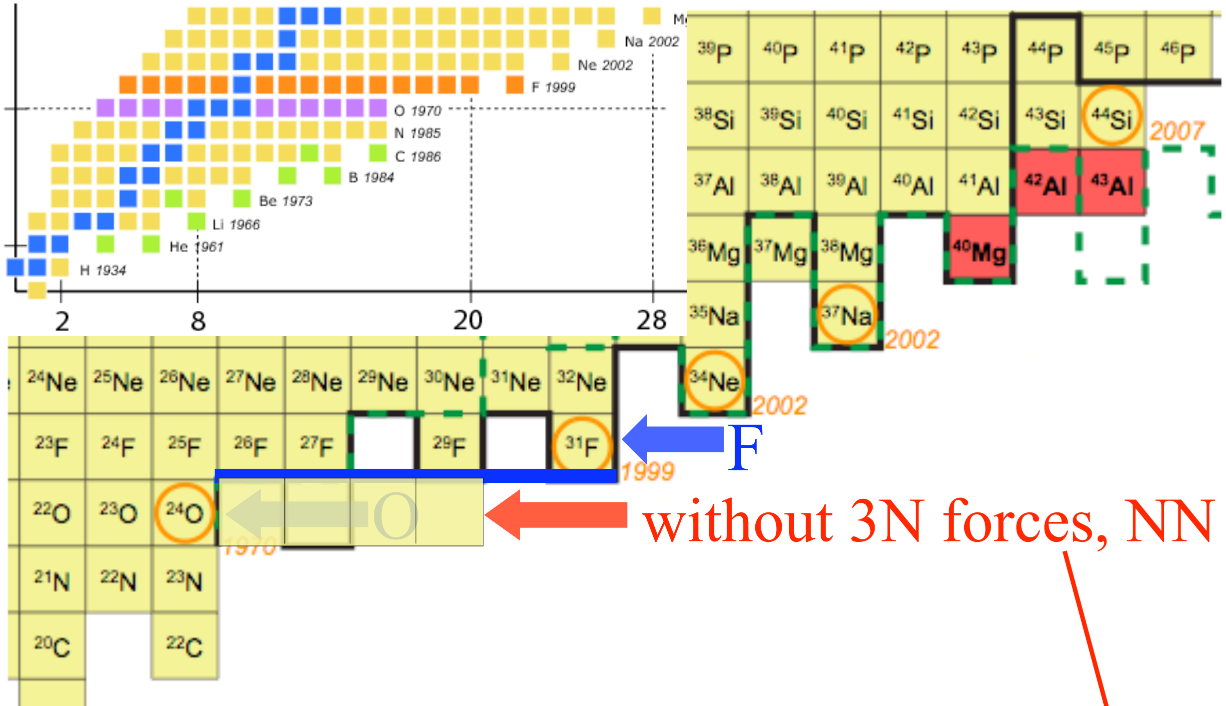
NUCLEAR PHYSICS

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.

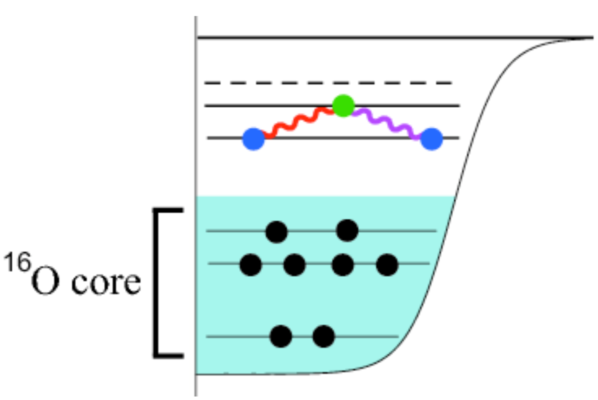
The oxygen anomaly - not reproduced without 3N forces

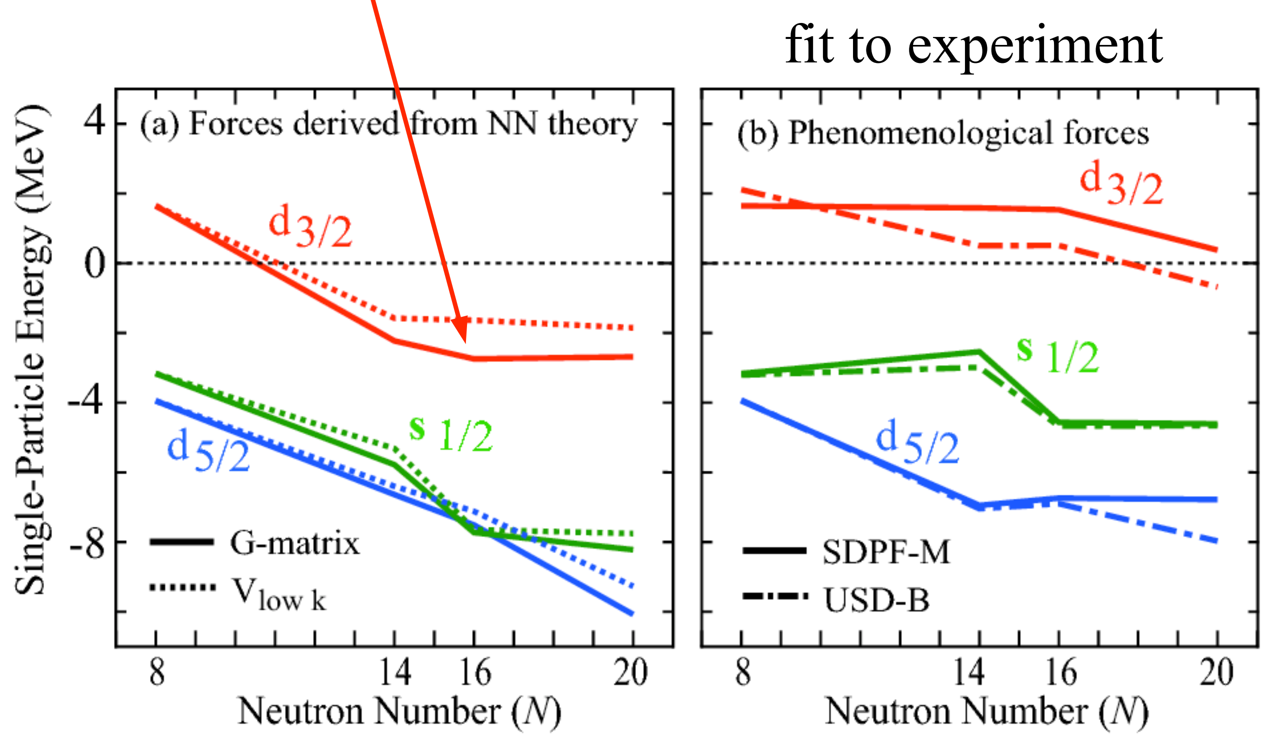


without 3N forces, NN interactions too attractive

many-body theory based on two-nucleon forces:

drip-line incorrect at ^{28}O

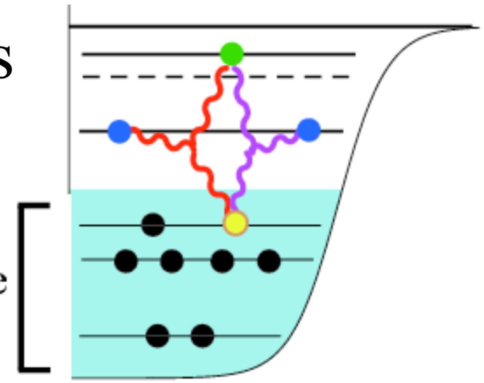




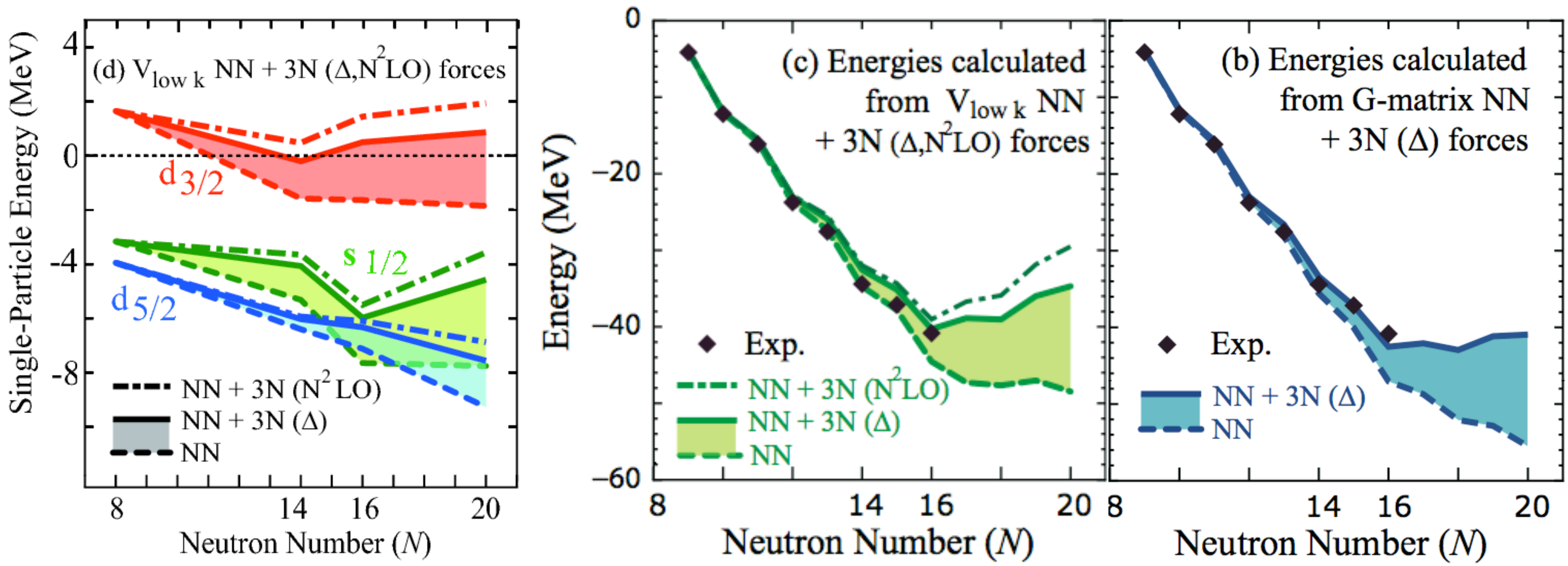
The oxygen anomaly - impact of 3N forces

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

leads to repulsive interactions between valence neutrons
(can understand partly based on Pauli principle)



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



first microscopic explanation of the oxygen anomaly

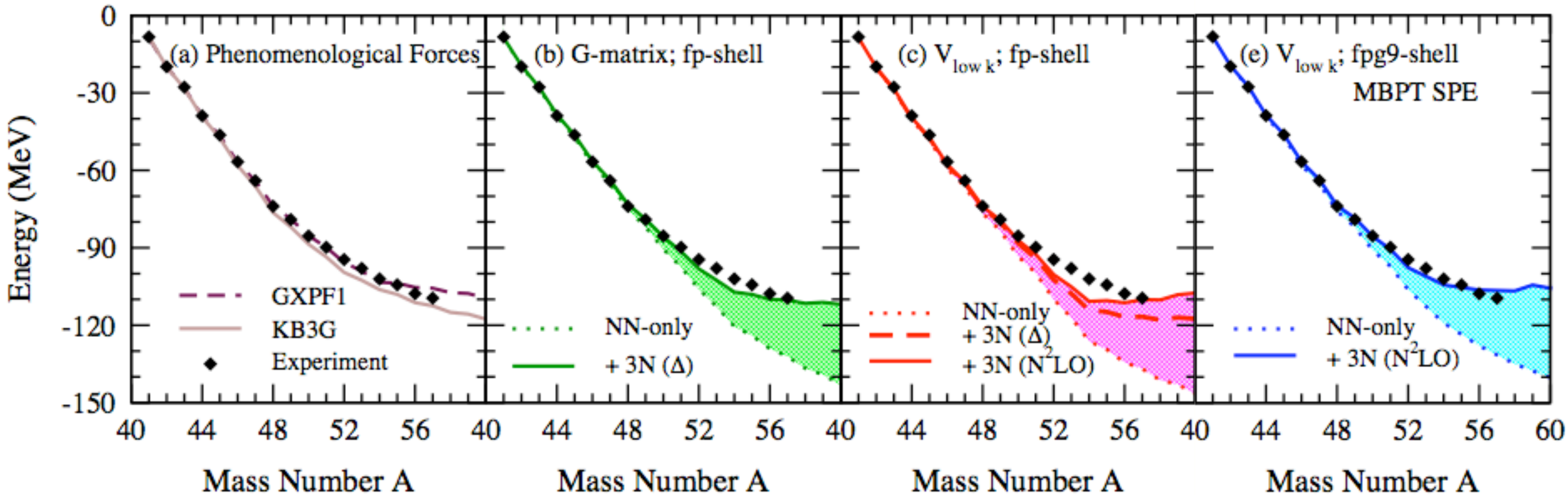
Otsuka, Suzuki, Holt, AS, Akaishi (2010)

Evolution to neutron-rich calcium isotopes

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

Holt, Otsuka, AS, Suzuki, in prep.

fit to experiment



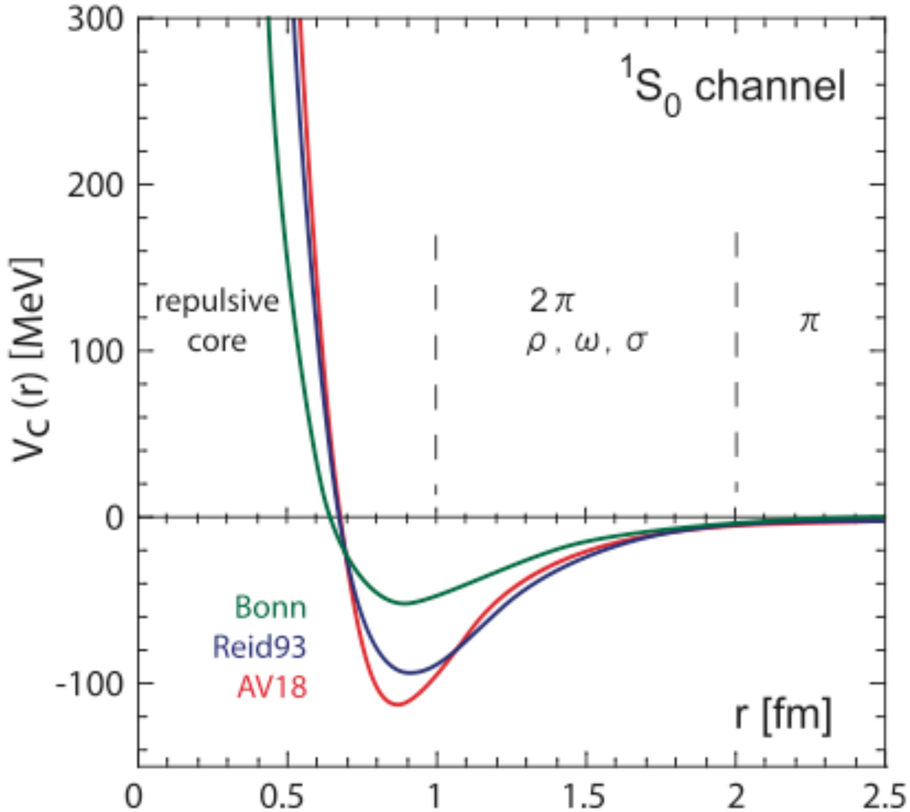
3N mechanism important for shell structure (e.g., N=28 and ^{48}Ca)

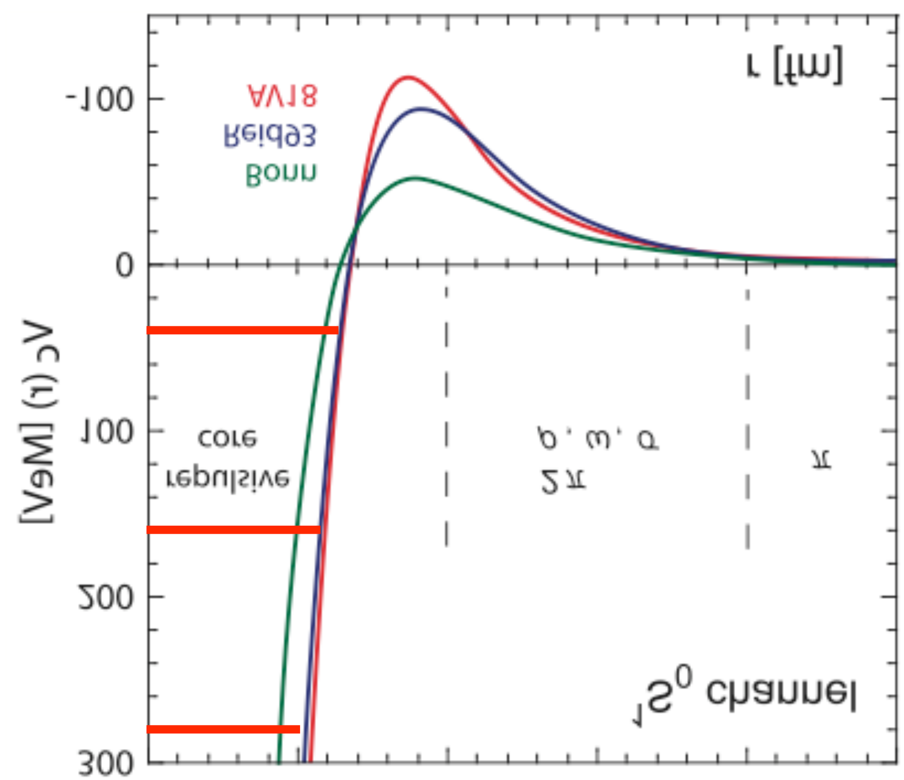
changes due to 3N forces amplified and testable in neutron-rich nuclei

impact on energy-density-functional based ground-state properties?

Convergence with low-momentum interactions

large cutoffs lead to flipped-potential bound states, even for small $-\lambda V$
requires nonperturbative expansion, leads to slow convergence for nuclei



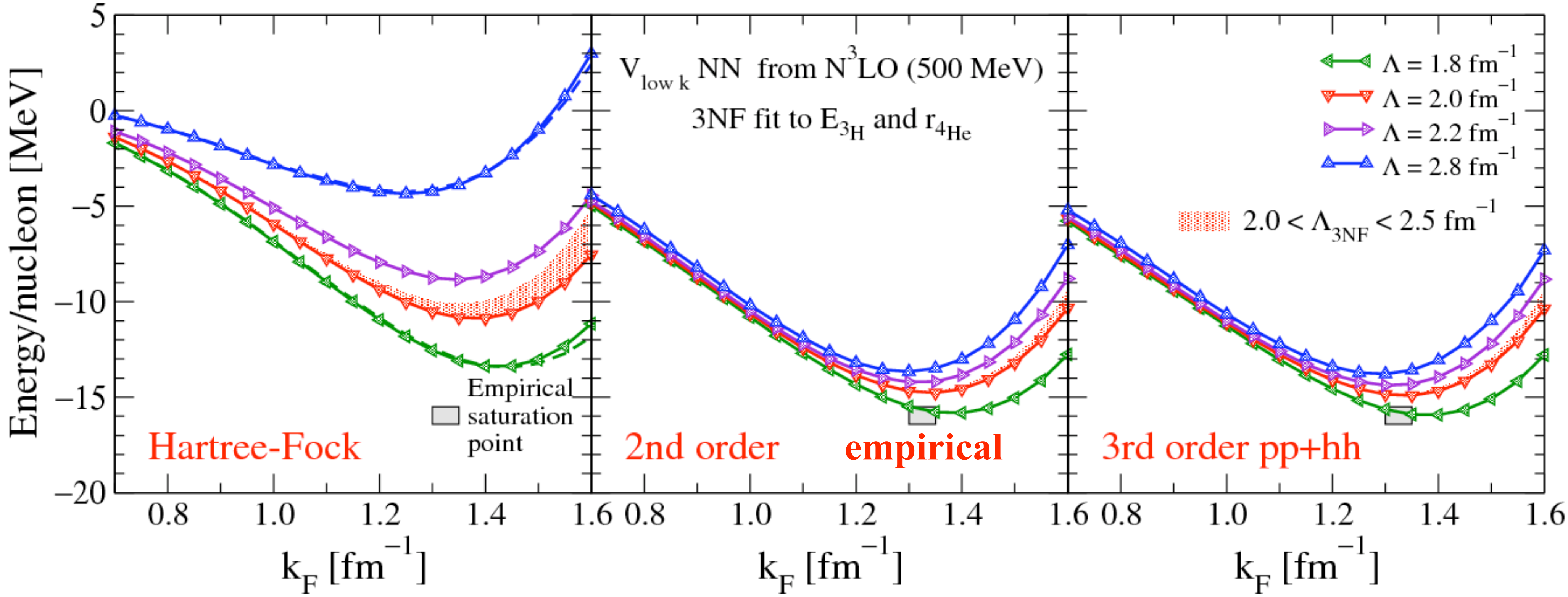


Weinberg eigenvalues show: two-body scattering becomes perturbative after RG evolution, except in channels with bound states

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?



Bogner, Furnstahl, Hebeler, Nogga, AS, in prep. and (2009)

exciting: empirical saturation with theoretical uncertainties
improved 3N improvements

input to develop a universal energy density functional for all nuclei

UNEDF SciDAC Collaboration
Universal Nuclear Energy Density Functional

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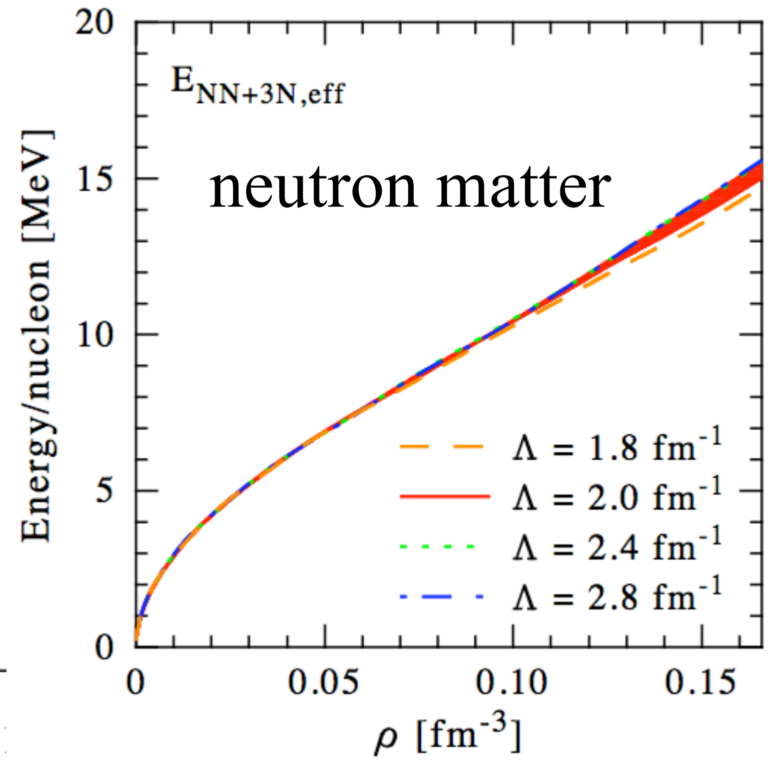
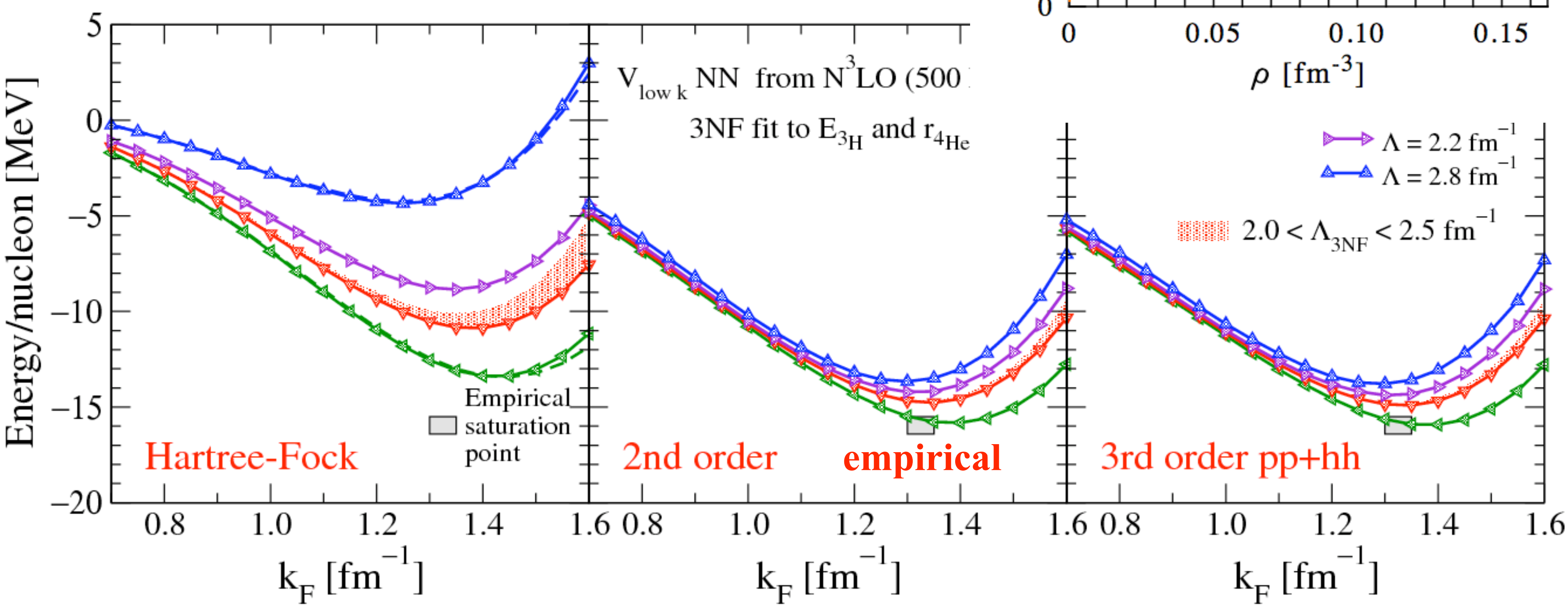
Hebeler, AS (2009); Tolos, Friman, AS (2007)

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





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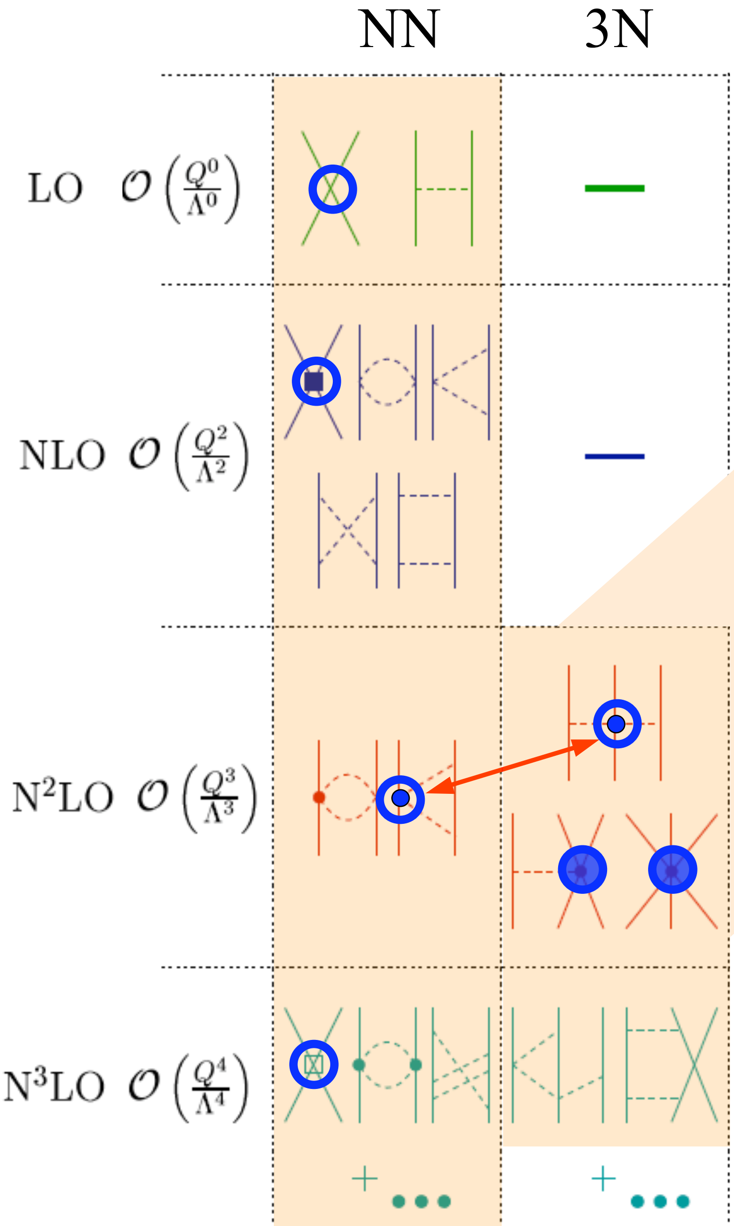

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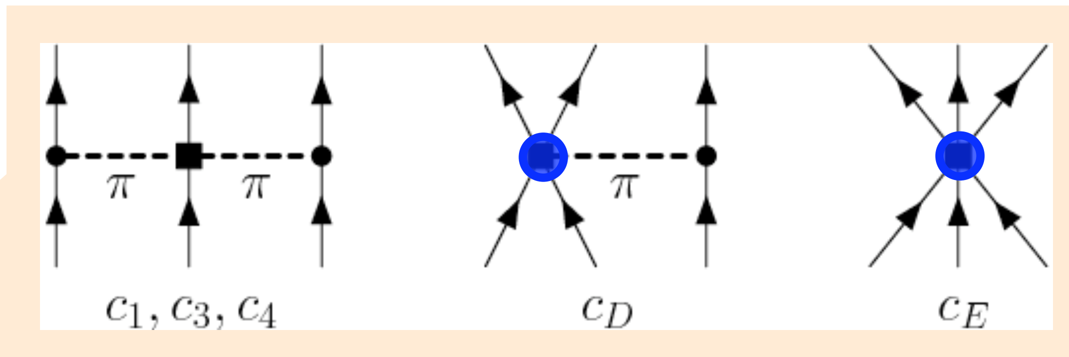

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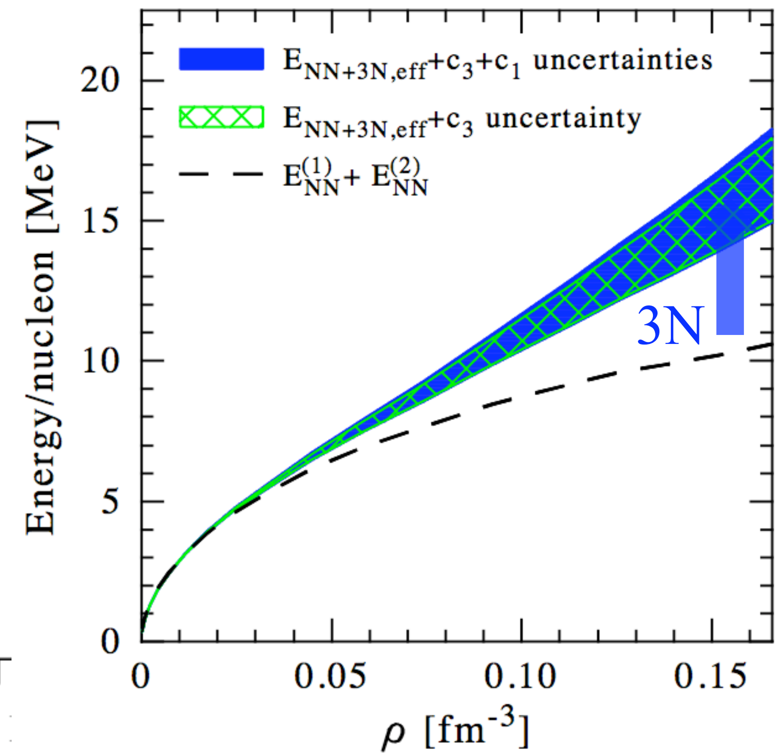
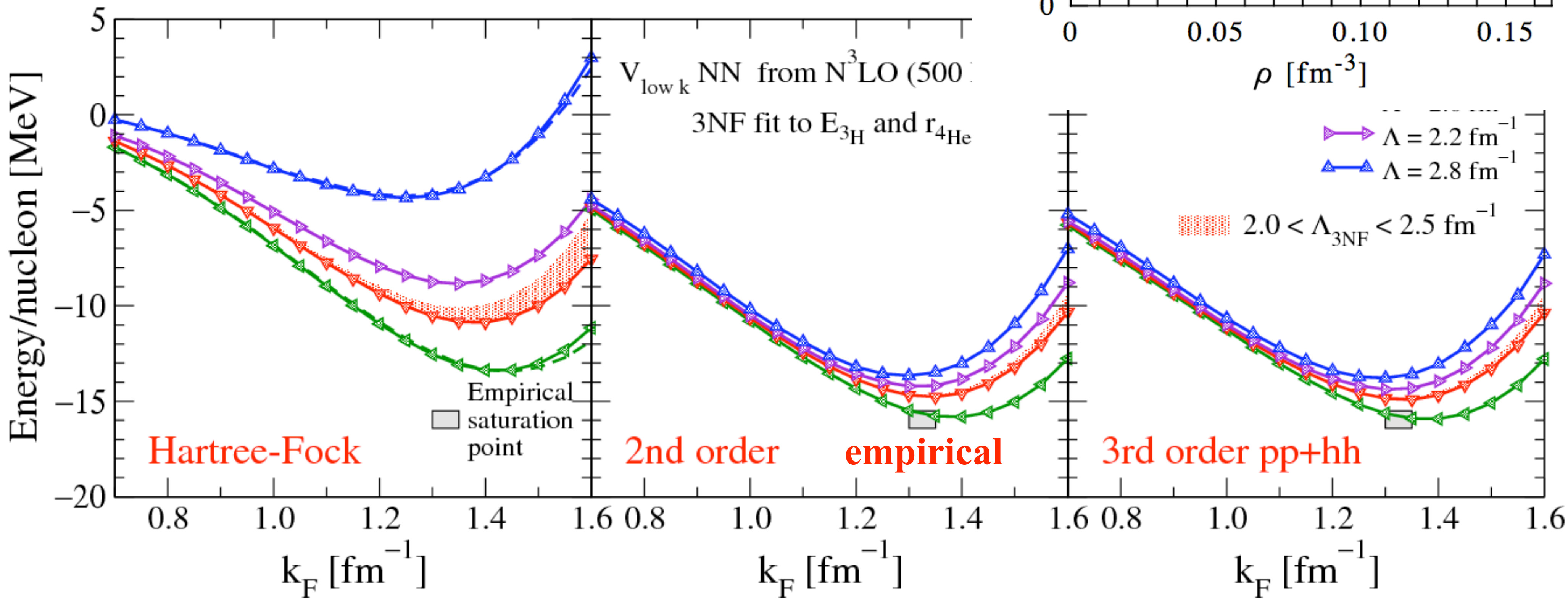
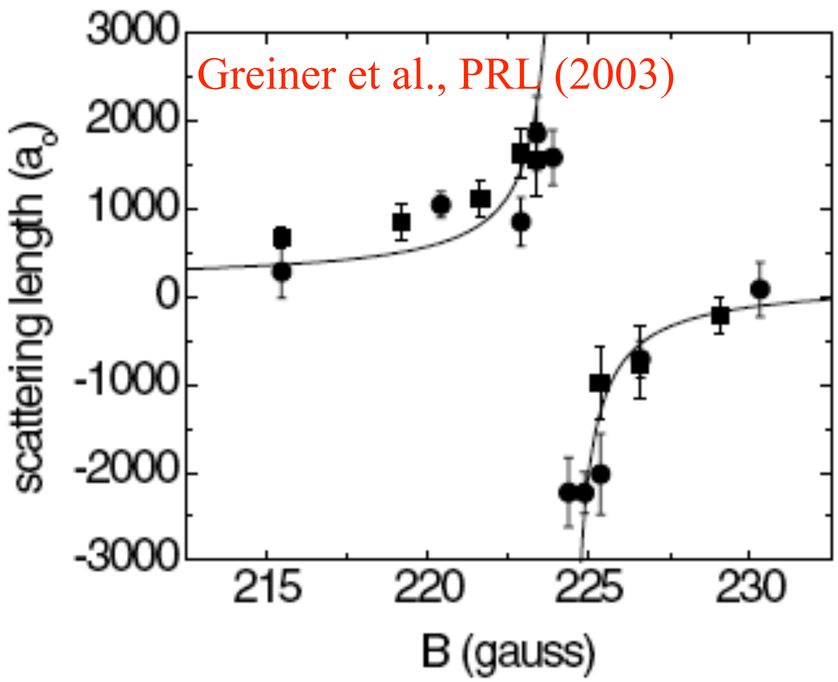
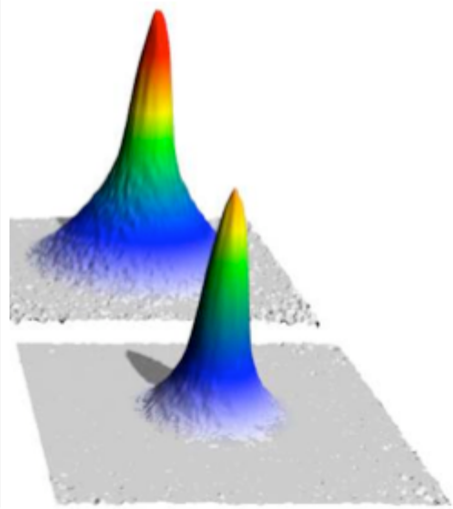
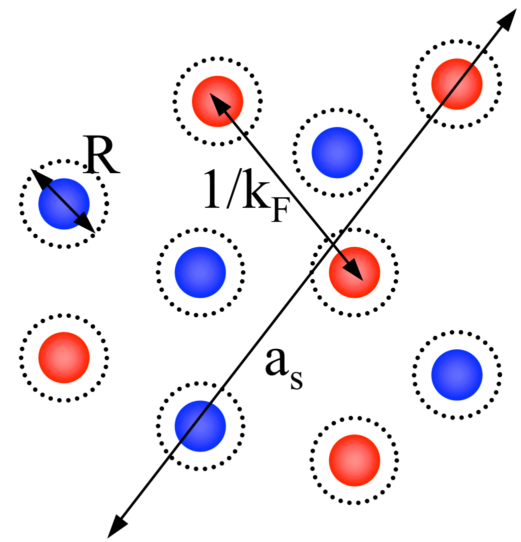




Large scattering lengths: Universal properties at low densities







$$a_{nn} = -18.5 \pm 0.3\,\text{fm}$$

strong interactions via Feshbach resonances

large for neutrons

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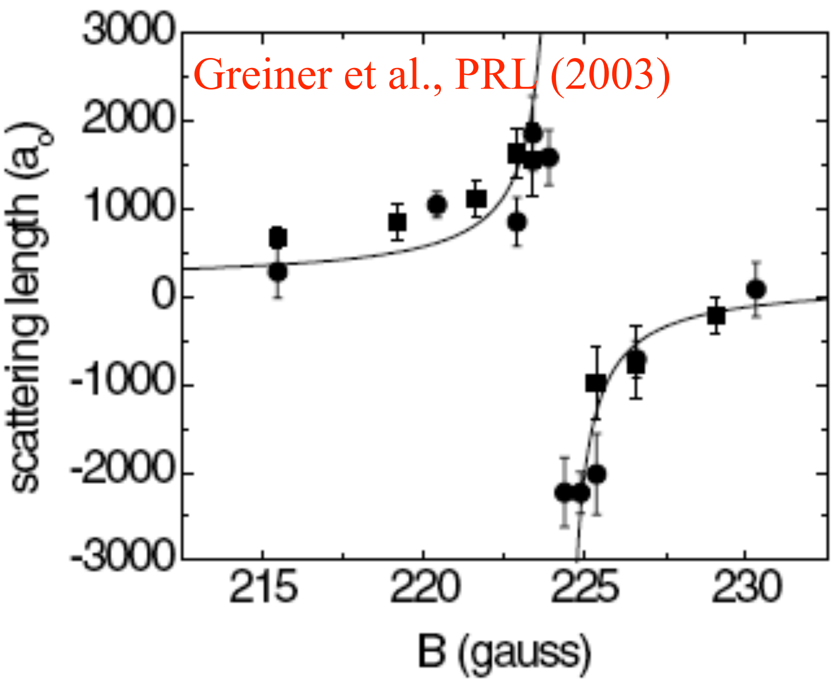

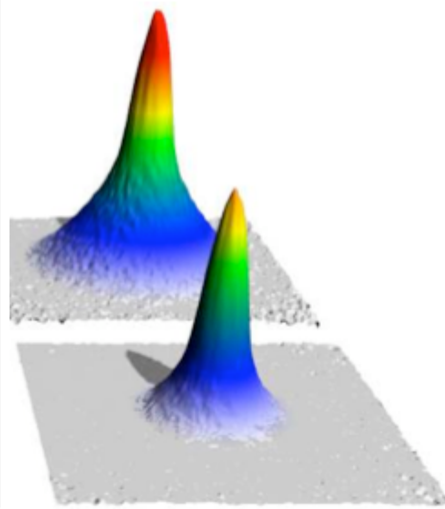

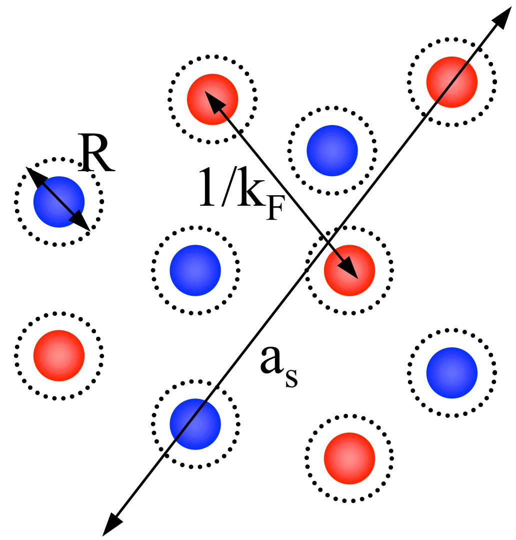

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dilute Fermi system with large scattering length has universal properties

$$0 \leftarrow 1/a_s \quad \ll \quad k_{\rm F} \quad \ll \quad 1/r_e \,, 1/R \,, \ldots \rightarrow \infty$$

strongly-interacting dilute

only Fermi momentum or density sets scale

physics is independent of interaction/system details:
from dilute neutron matter to resonant ^{6}Li or ^{40}K atoms in traps

Large scattering lengths: Universal thermodynamics

energy per particle $\frac{E}{N} = \xi \left(\frac{E}{N}\right)_{\text{free}} = \xi \, \frac{3k_{\text{F}}^2}{10m}$

with universal Bertsch parameter ξ

Quantum Monte Carlo: ξ=0.40(1)

Gezerlis, Carlson (2009),…

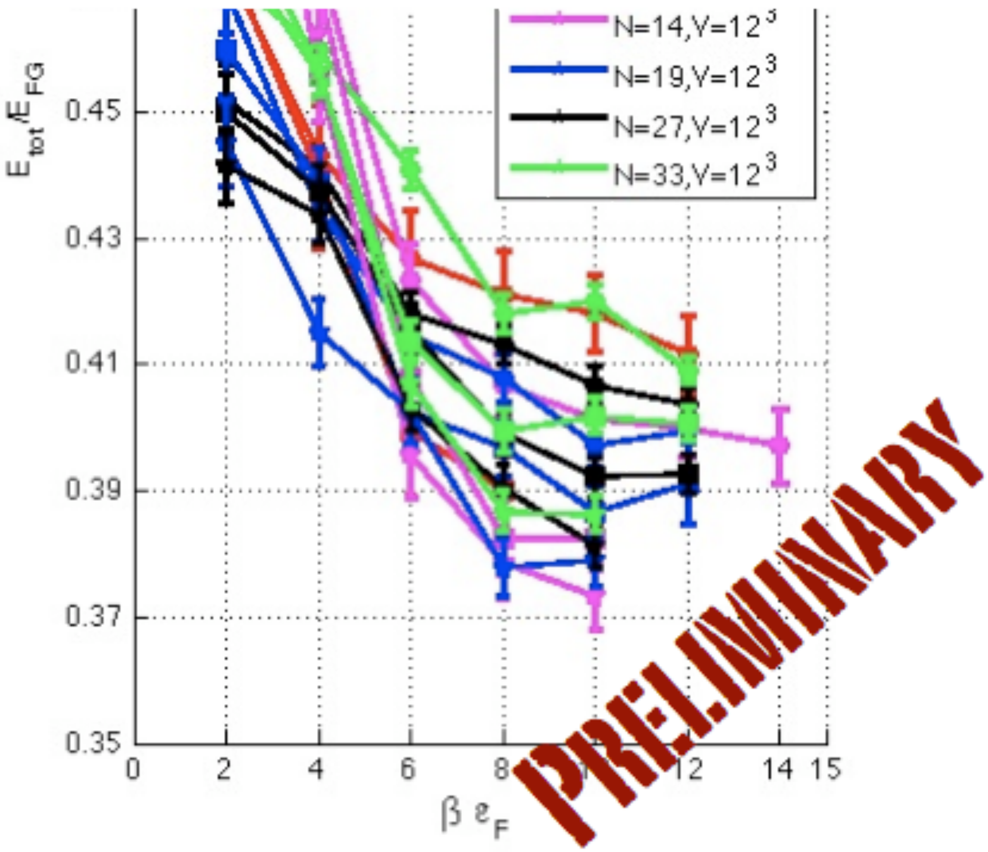
lattice: Auxiliary-Field Hybrid MC

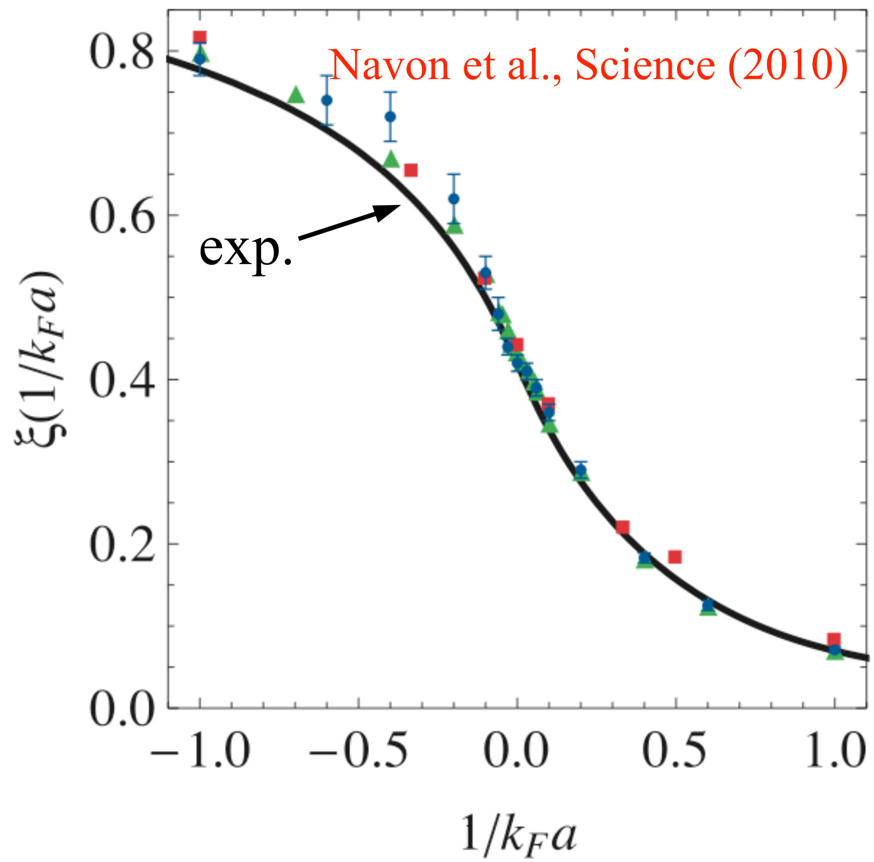
Drut, Gezerlis, Laehde @ 2010 UNEDF meeting

most precise results with ^{6}Li

ξ=0.39(2) and 0.41(2)

cloud size and E(S) Zuo, Thomas (2009)





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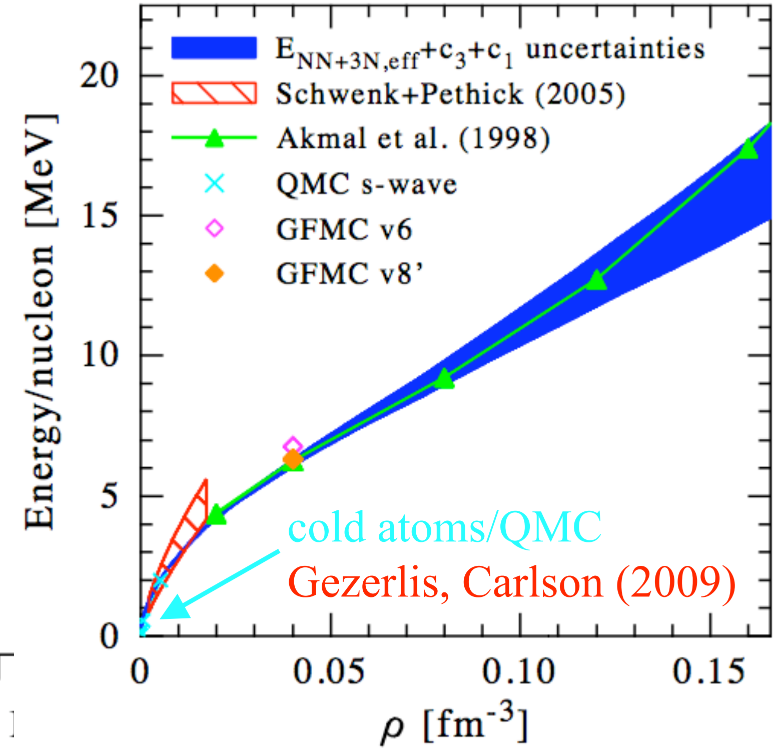
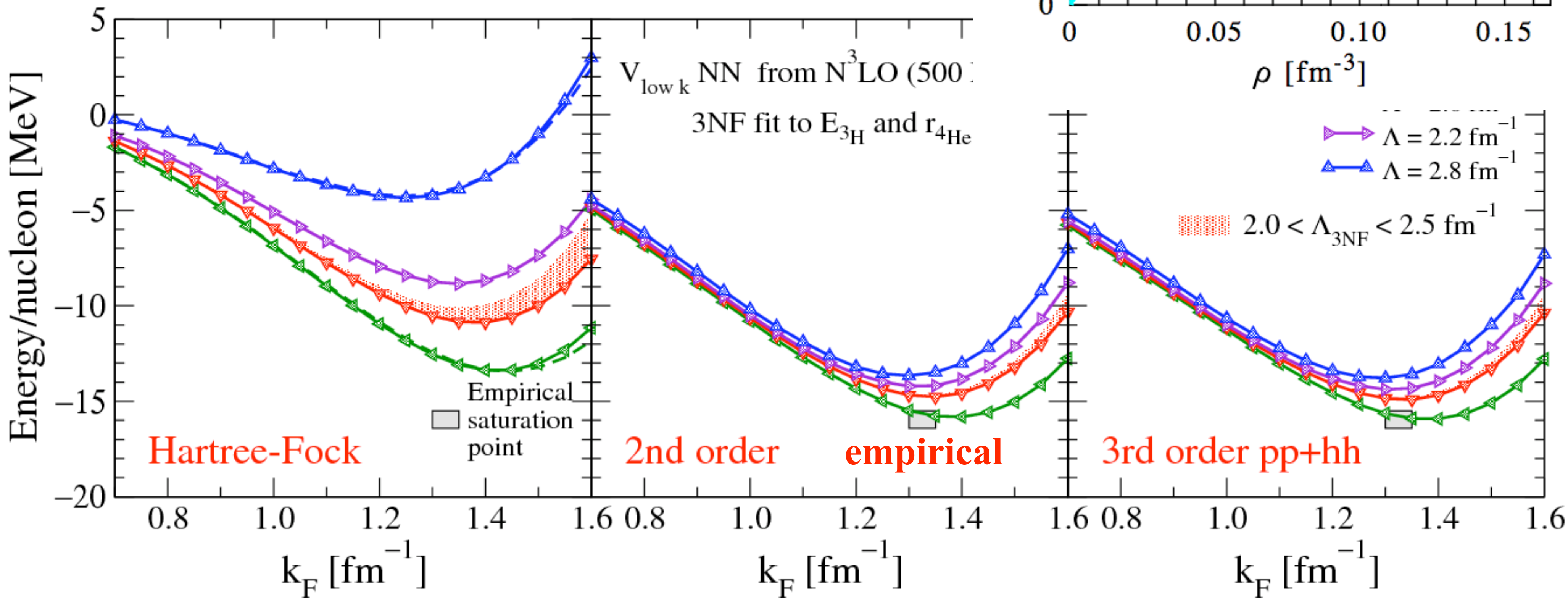
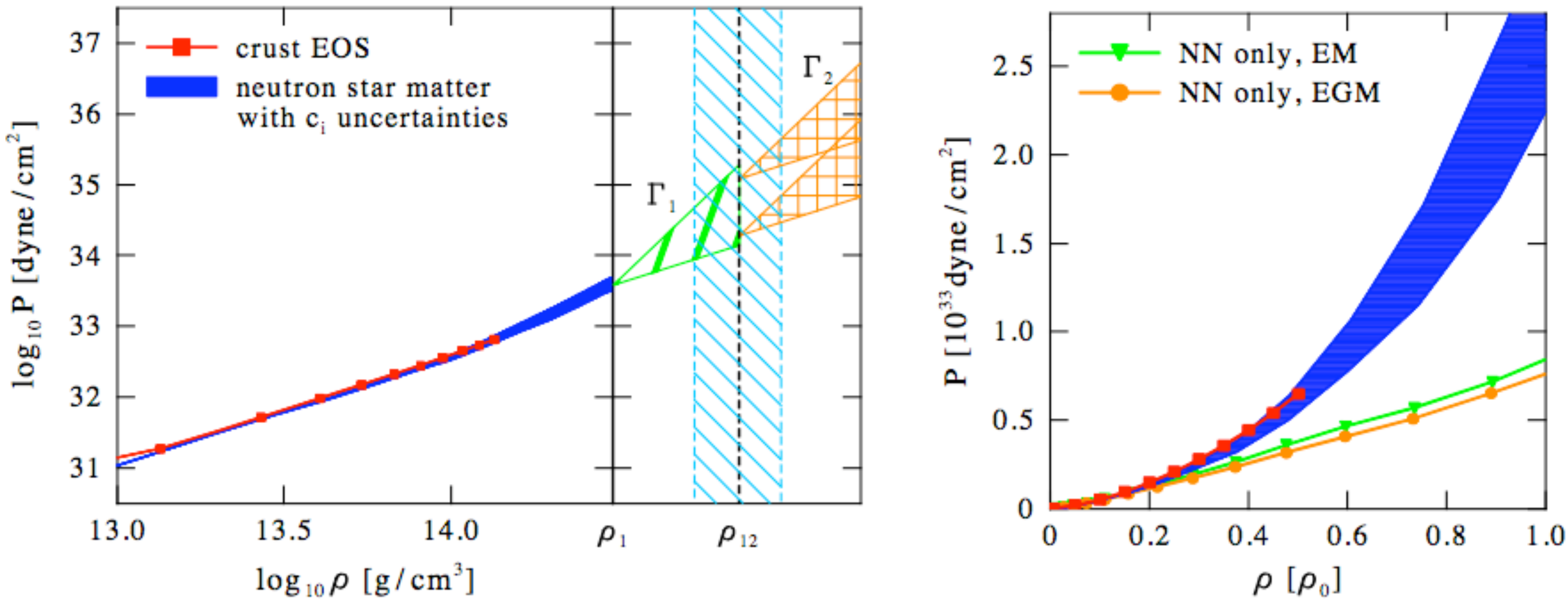




Impact on neutron stars Hebeler, Lattimer, Pethick, AS (2010)

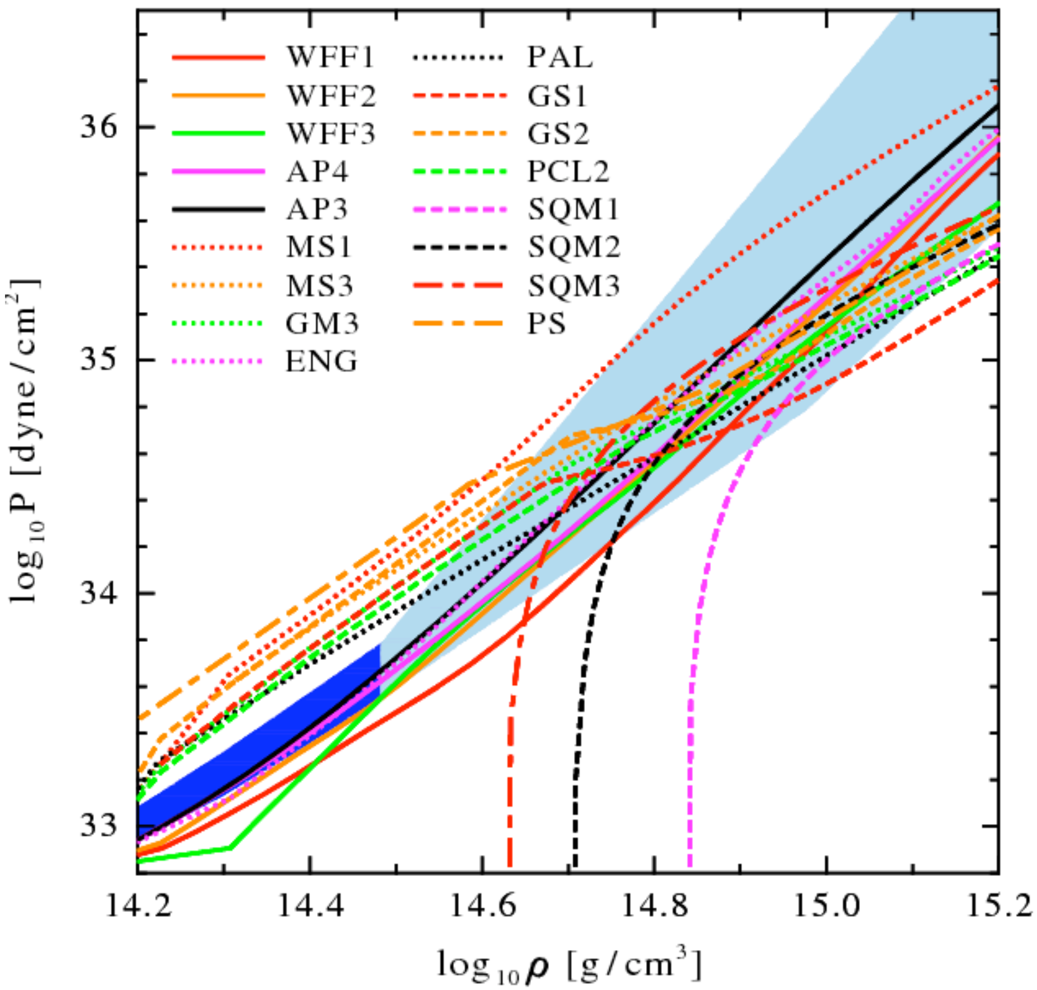


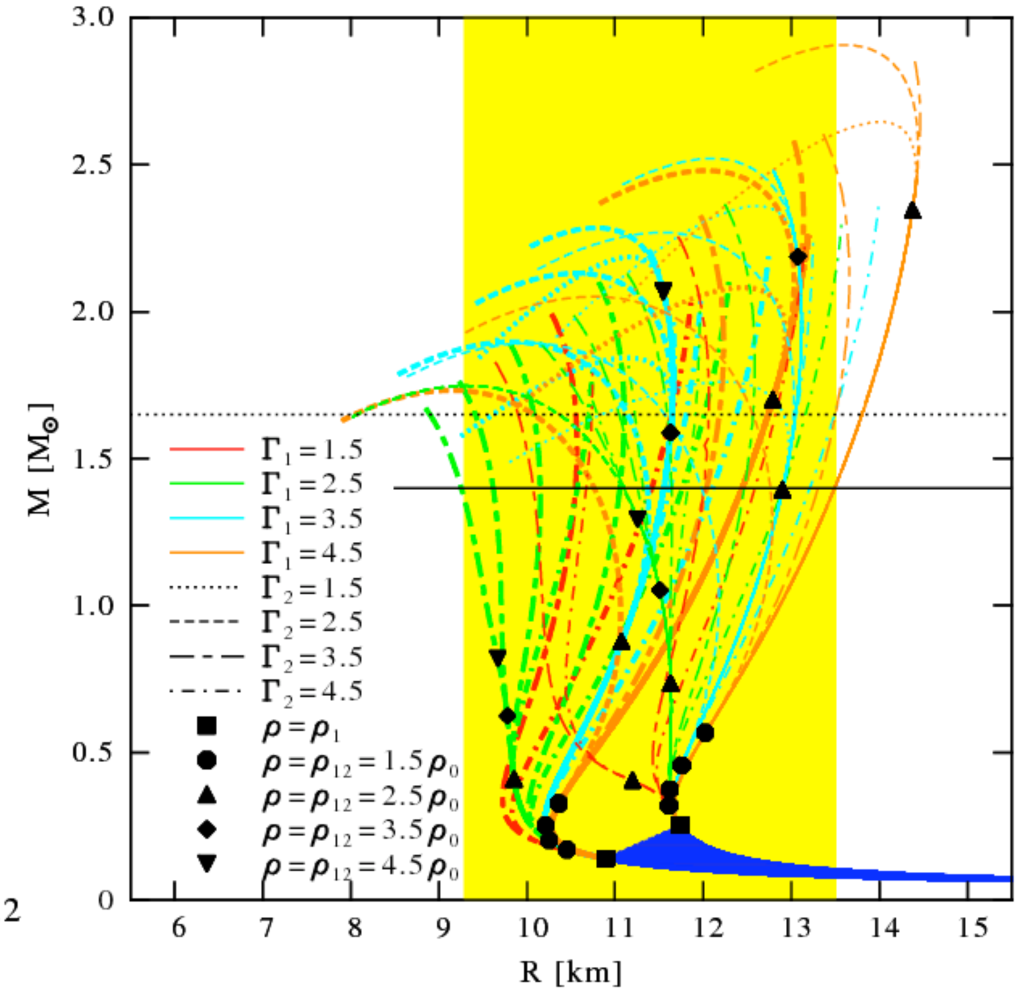
pressure below nuclear densities agrees with standard crust EOS only after 3N forces are included

extend uncertainty band to higher densities using piecewise polytropes

constrain polytropes by causality and require to support 1.65 M_{sun} star

Impact on neutron stars Hebeler, Lattimer, Pethick, AS (2010)





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constrains neutron star radius to 11.8±2.1 km for M=1.4 M_{sun}

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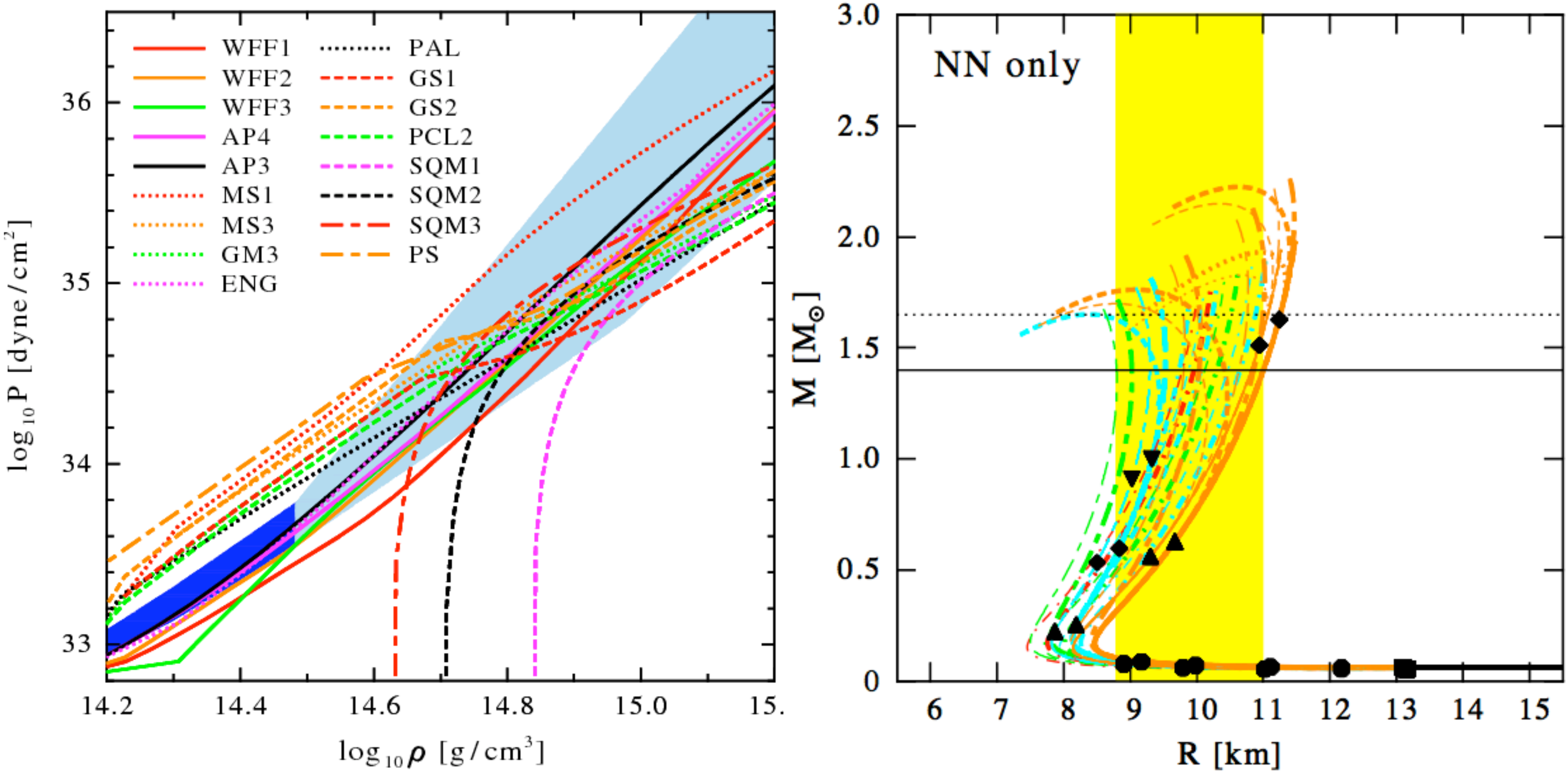

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9.9±1.1 km without 3N forces

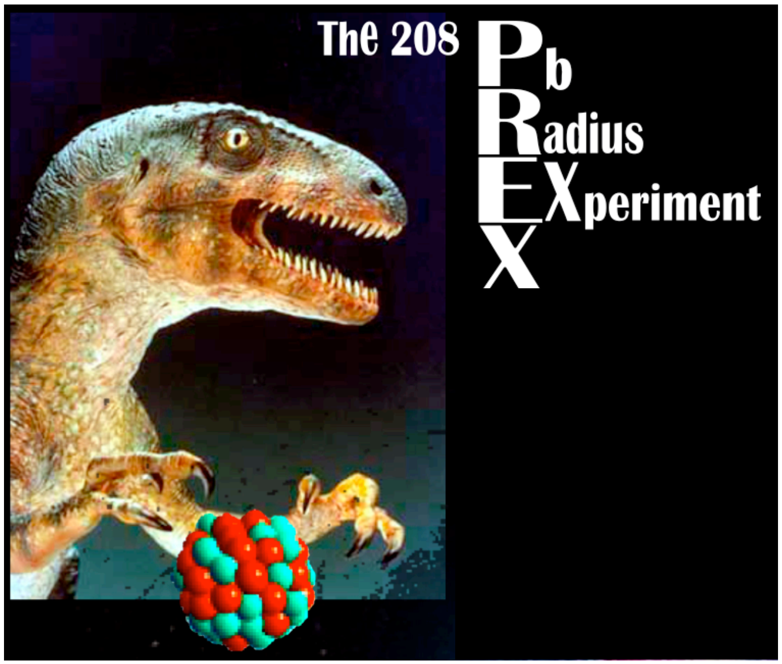
PREX - Neutron radius of lead

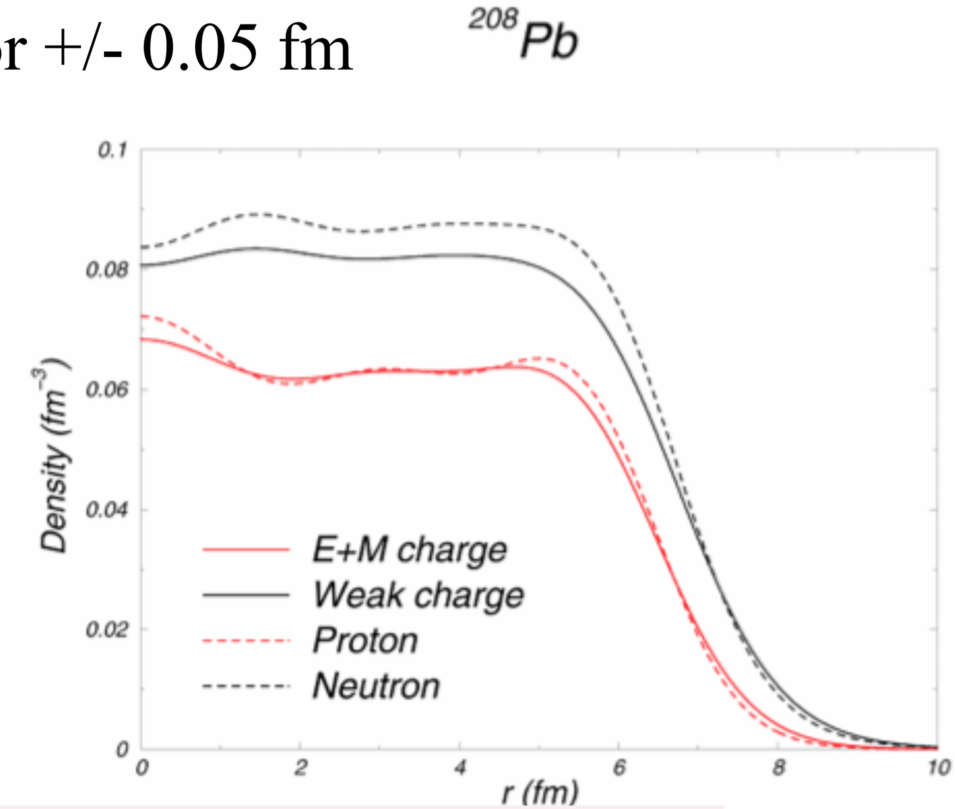
P.A. Souder, G.M. Urciuoli, R. Michaels

parity-violating electron-scattering at JLAB, scheduled for spring 2010

Z-boson couples preferentially to neutrons

will measure neutron radius to 1% or +/- 0.05 fm





	up-quark	down-quark	proton	neutron
γ-coupling	$+2/3$	$-1/3$	$+1$	0
Z_0-coupling	$\approx +1/3$	$\approx -2/3$	≈ 0	-1

$$g_v = 2t_z - 4Q\sin^2\theta_W \approx 2t_z - Q$$

Neutron matter band predicts the neutron skin of lead to 0.17±0.03 fm

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:

in chiral EFT for nuclear forces (and in RG evolution)

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

expect to be important for extrapolations towards neutron drip line

dominant uncertainty for pressure of neutron star matter below nuclear densities, important for radii and for comparison to standard crust EOS