The strong interaction at neutron-rich extremes

Achim Schwenk

TECHNISCHE UNIVERSITÄT DARMSTADT

EMMI

HELMHOLTZ | ASSOCIATION

Helmholtz Alliance
Extremes of Density and Temperature: Cosmic Matter in the Laboratory

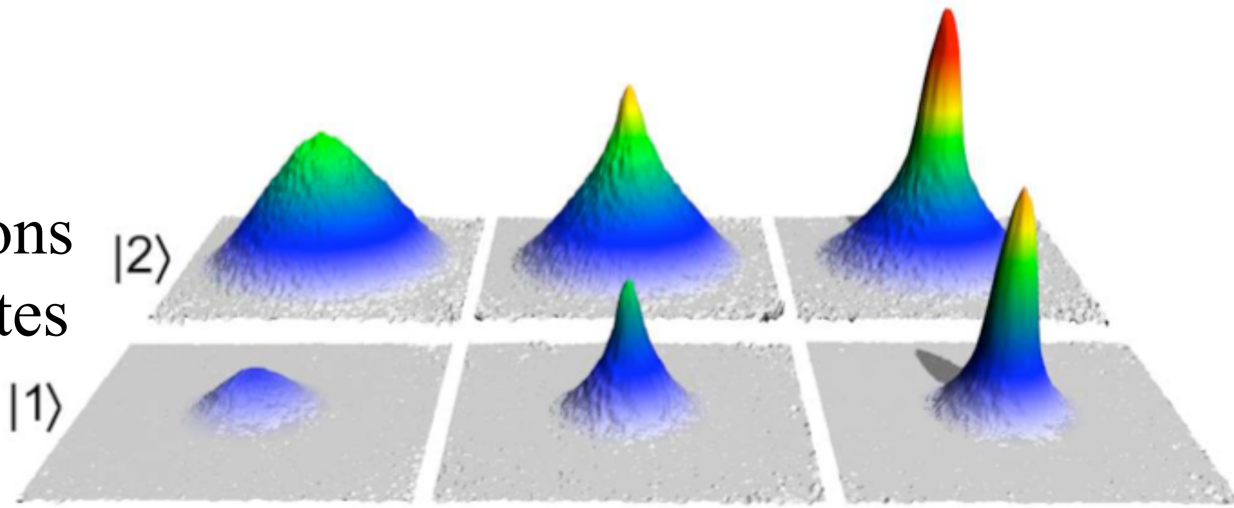
ExtreMe Matter Institute EMMI

EMMI Physics Days 2010

GSI, Darmstadt, Germany
November 4 - 5, 2010

The strong interaction at extreme low densities: Universal properties of neutrons and cold atoms

^{6}Li fermions
2 spin states



from M. Zwierlein

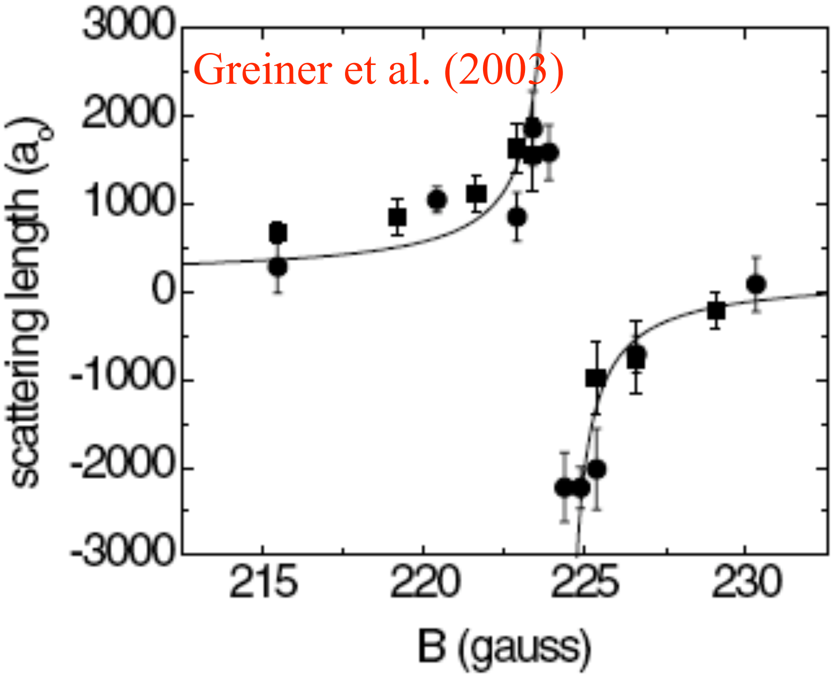
neutrons with same density and temperature
have the same properties!

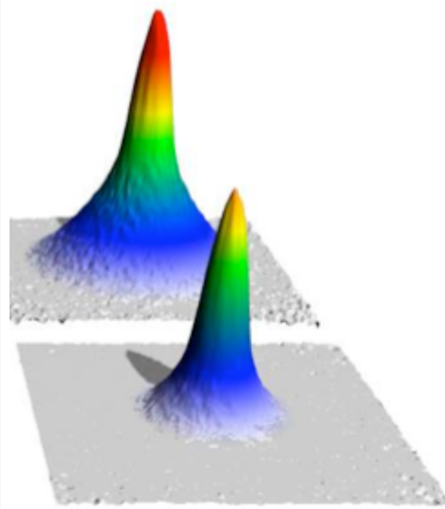
Helmholtz Alliance
Extremes of Density and Temperature: Cosmic Matter in the Laboratory

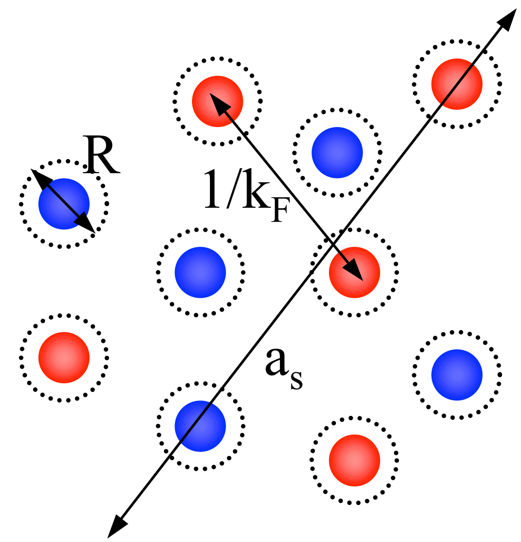
ExtreMe Matter Institute EMMI

EMMI Physics Days 2010

Large scattering lengths: Universal properties at low densities





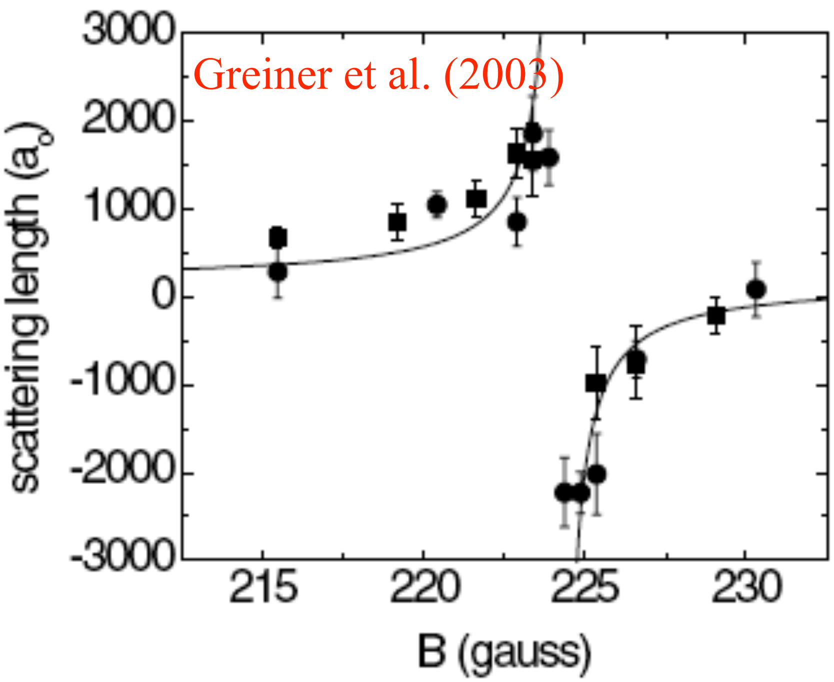


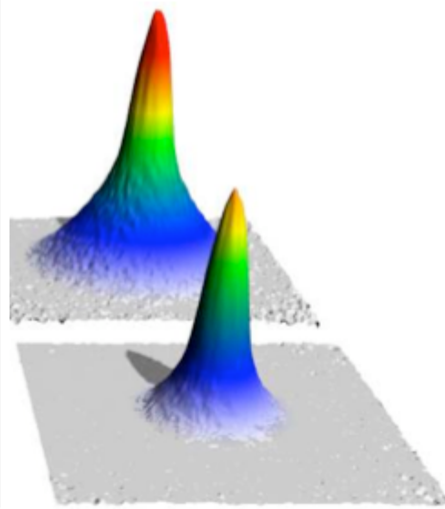
$$a_{\rm nn} = -18.5 \pm 0.3\,{\rm fm}$$

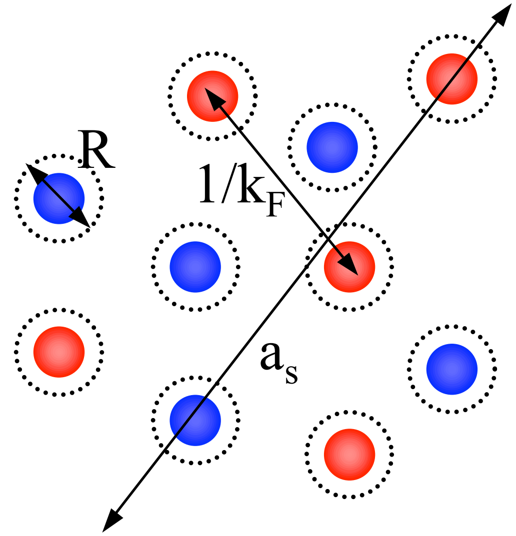
strong interactions via Feshbach resonances

large for neutrons

Large scattering lengths: Universal properties at low densities







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

strong interactions via Feshbach resonances

large for neutrons

dilute Fermi system with large scattering length has universal properties

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

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),…

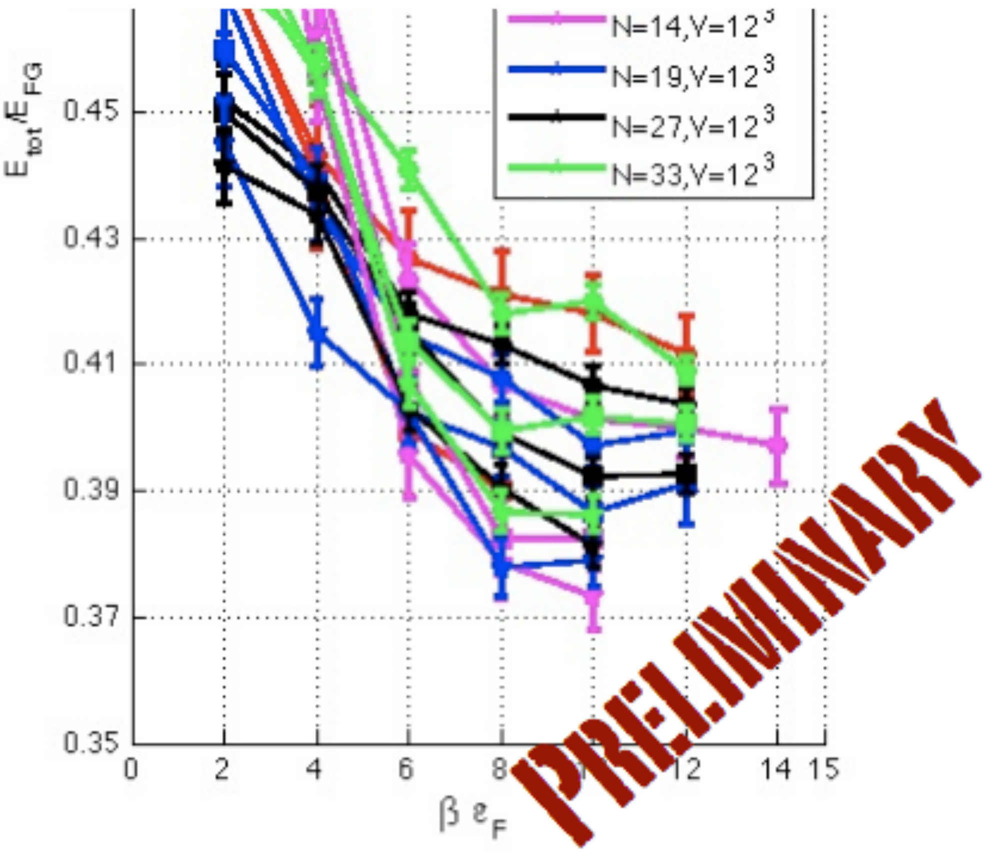
lattice: Auxiliary-Field Hybrid MC

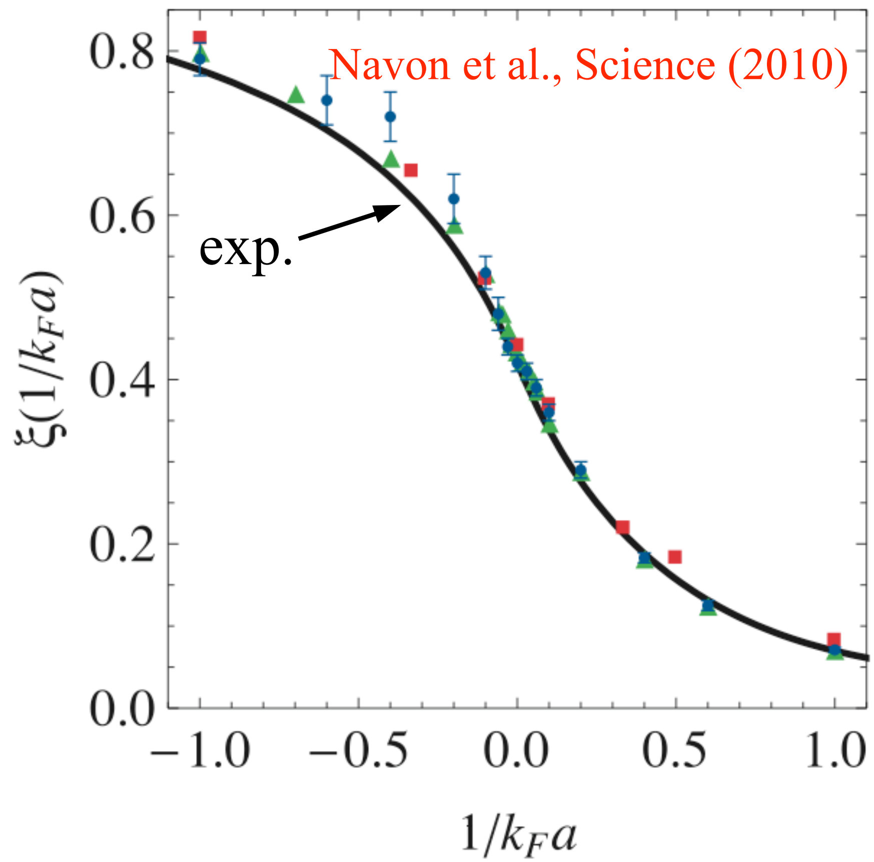
Drut, Gezerlis, Laehde @ 2010 UNEDF meeting

most precise results with ^{6}Li

ξ=0.39(2) and 0.41(2)

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





Large scattering lengths: Resonance superfluidity

phase transition to superfluid
with universal critical temperature $T_c \approx 0.15\text{-}0.2\ T_F$

Thomas et al., Science (2005),… Nascimbene et al., Nature (2010)

and universal pairing gap $\Delta \approx 0.45\ \varepsilon_F$

Schirotzek et al. (2009), Carlson, Reddy (2008)

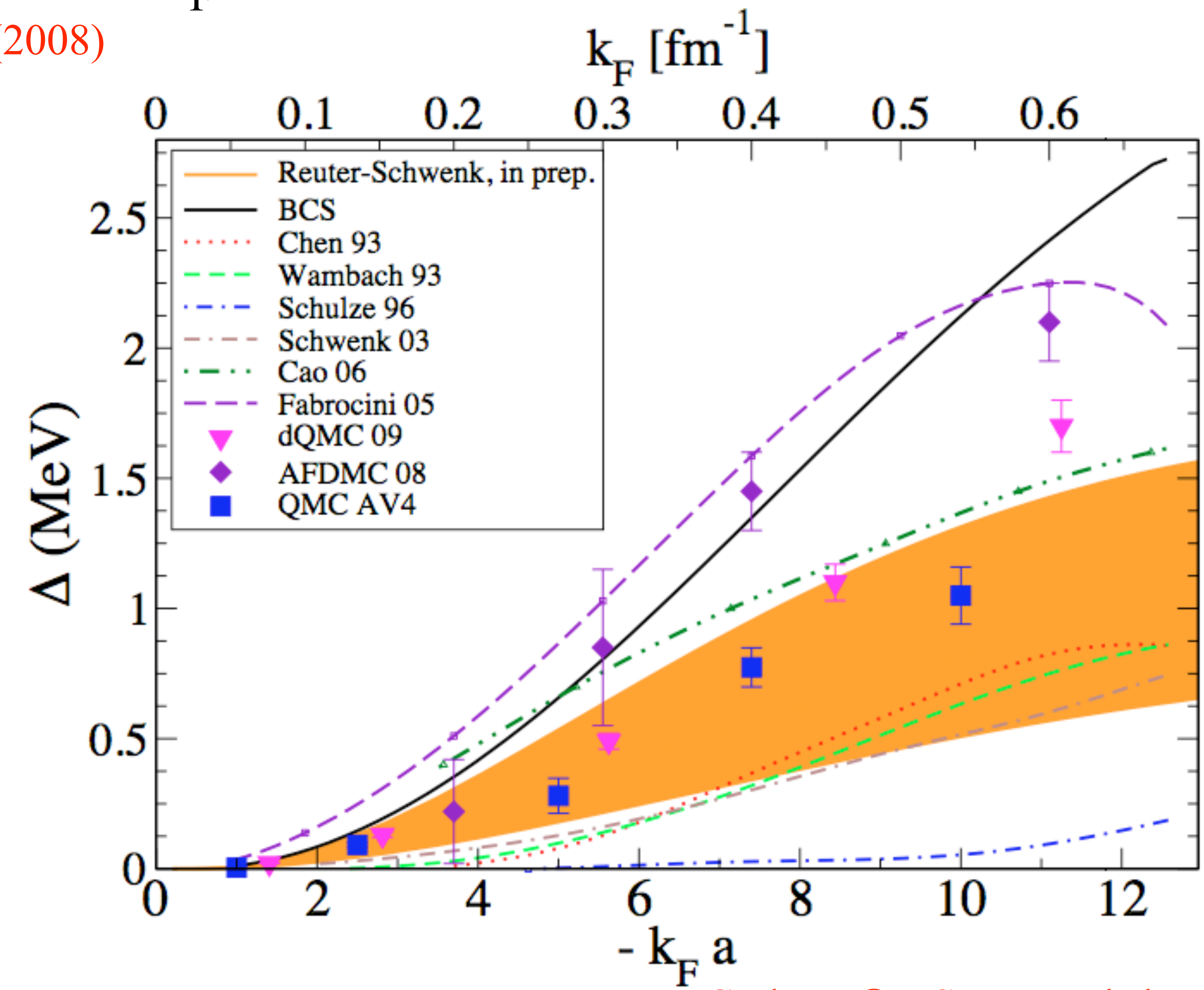
Superfluid pairing gap for low-density neutron matter

Progress from MC and other calculations

Differences to cold atoms:

effective range $k_F r_e \sim 2$

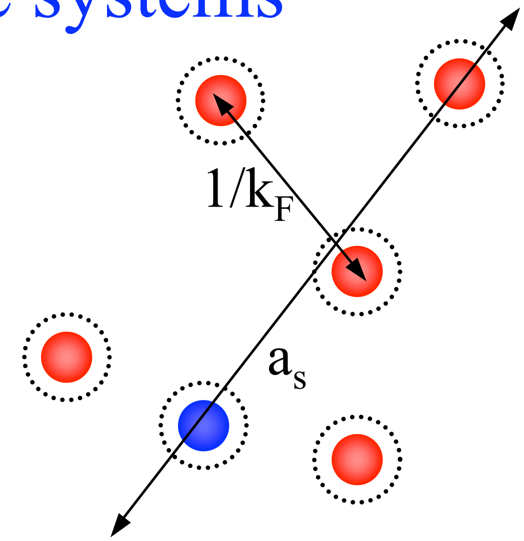
(weak shell effects for resonant interactions)



Carlson @ ESNT Workshop

Large scattering lengths: Asymmetric systems

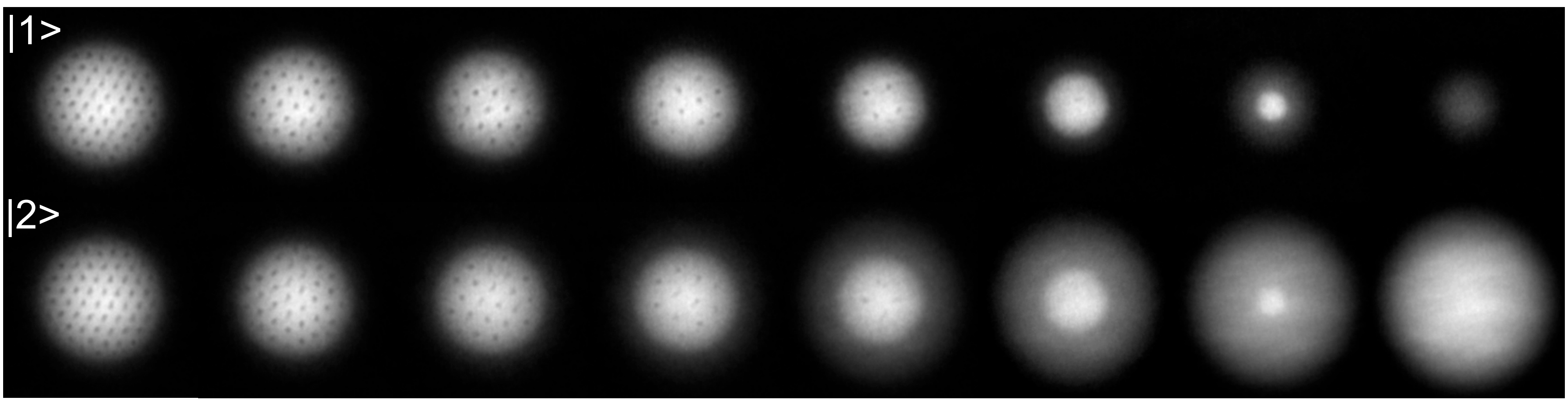
polaron binding = $\eta\varepsilon_F$ with $\eta\approx$-0.6



determines critical polarization of superfluidity
(superfluid energy ξ vs. normal energy η)

Chevy (2006), Bulgac, Forbes (2007),…

predicts critical polarization in traps $P_c \sim 70\%$

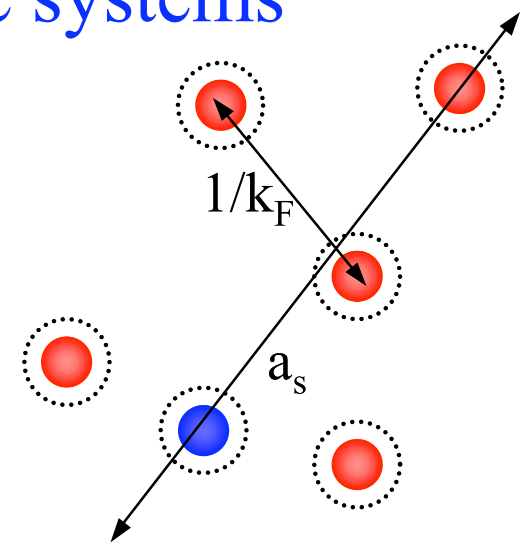


0% 6% 12% 22% 30% 56% 90% 94%

Zwierlein et al., Science (2006)

Large scattering lengths: Asymmetric systems

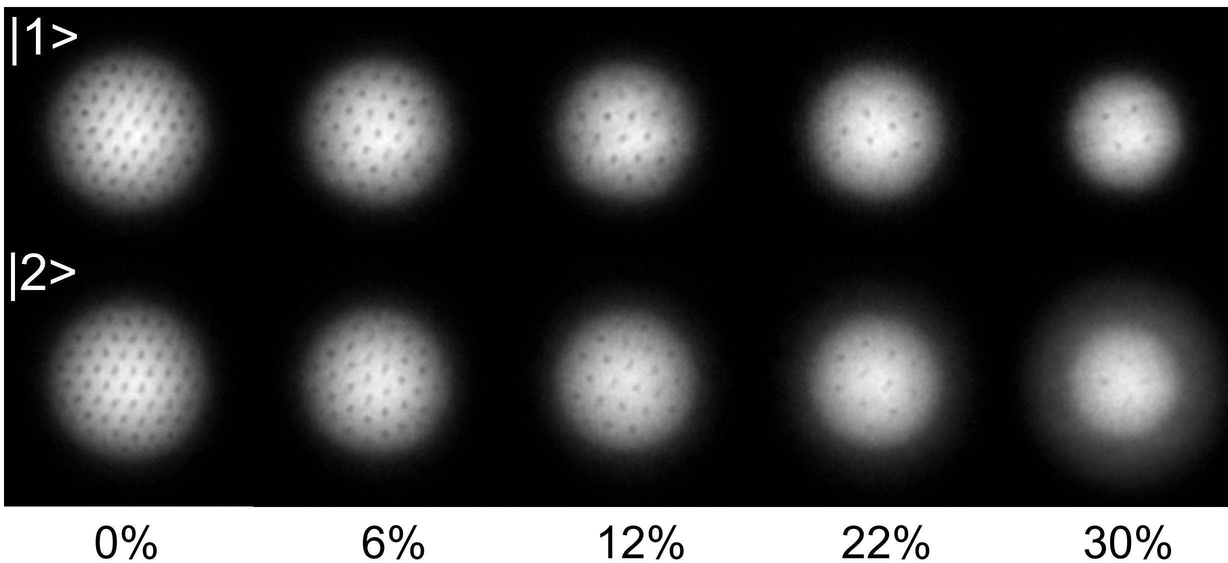
polaron binding = $\eta\varepsilon_F$ with $\eta \approx -0.6$



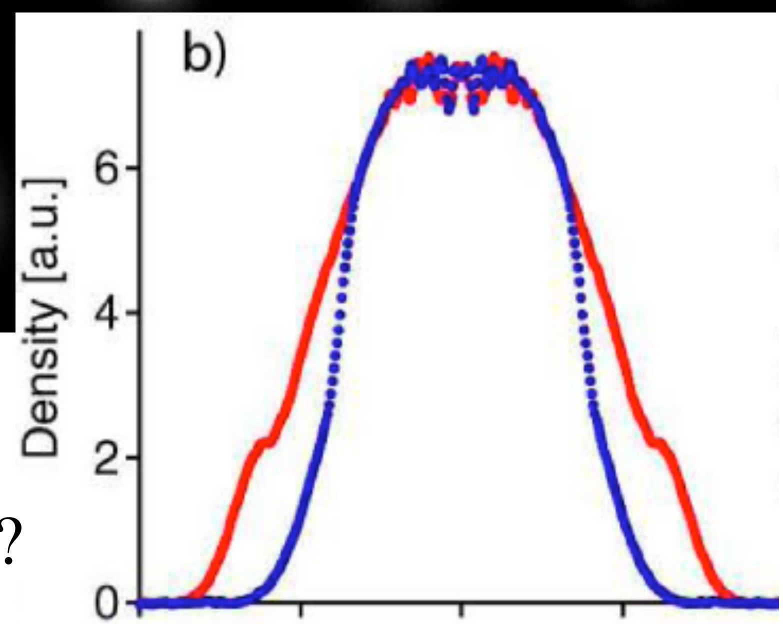
determines critical polarization of superfluidity
(superfluid energy ξ vs. normal energy η)

Chevy (2006), Bulgac, Forbes (2007),…

predicts critical polarization in traps $P_c \sim 70\%$



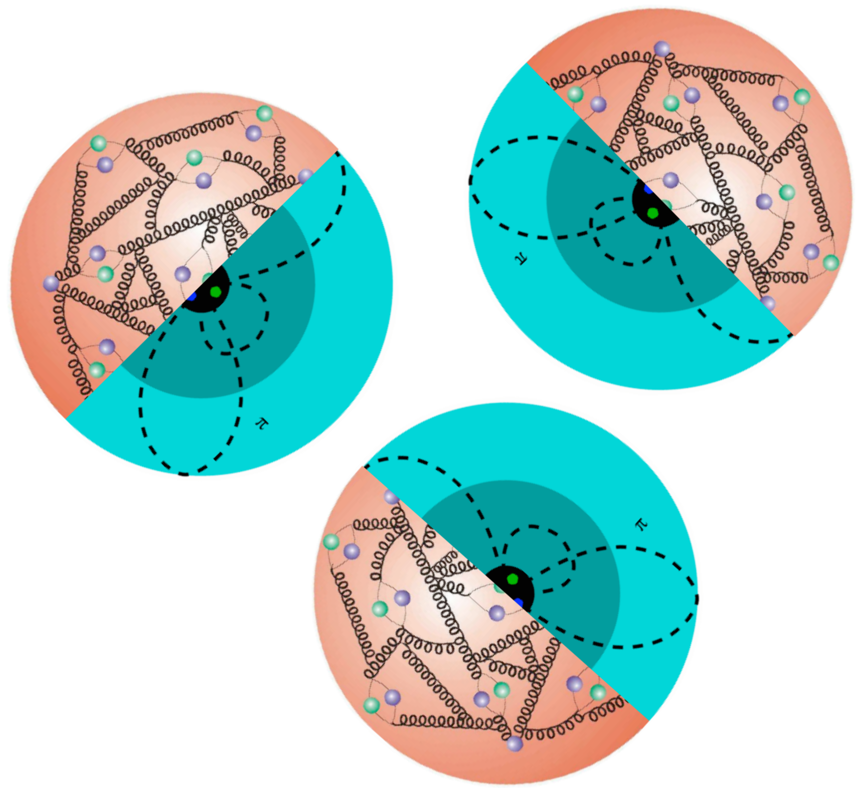
Zwierlein et al., Science (2006)



Are cold atom skins similar to neutron skins?

Shin et al., (2006)

The nuclear forces frontier –
beyond universal large scattering length physics



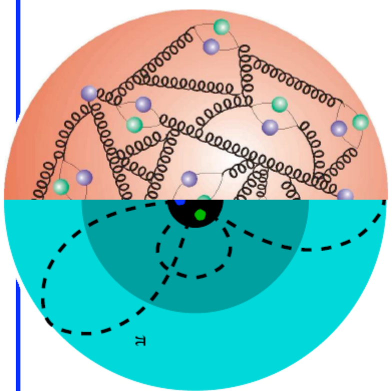
Helmholtz Alliance
Extremes of Density and Temperature: Cosmic Matter in the Laboratory

ExtreMe Matter Institute EMMI

EMMI Physics Days 2010

Λ / Resolution dependence of nuclear forces

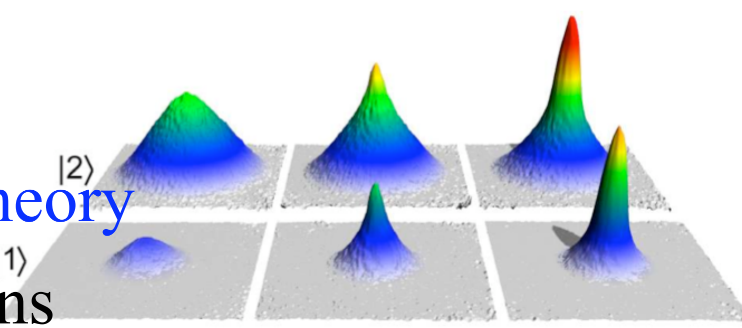
with high-energy probes:
quarks+gluons



$\Lambda_{\text{pionless}}$

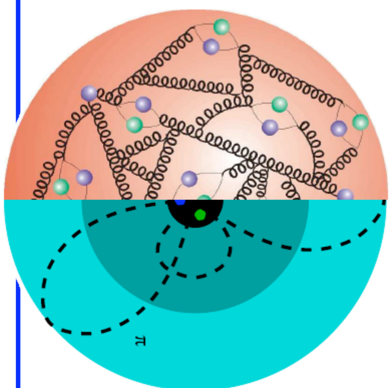
momenta $Q \ll m_\pi$: pionless effective field theory

large scattering length physics and corrections



Λ / Resolution dependence of nuclear forces

with high-energy probes:
quarks+gluons



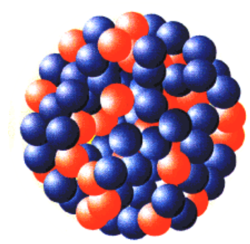
Effective theory for NN, 3N, many-N interactions and electroweak operators: resolution scale/Λ-dependent

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

Λ_{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



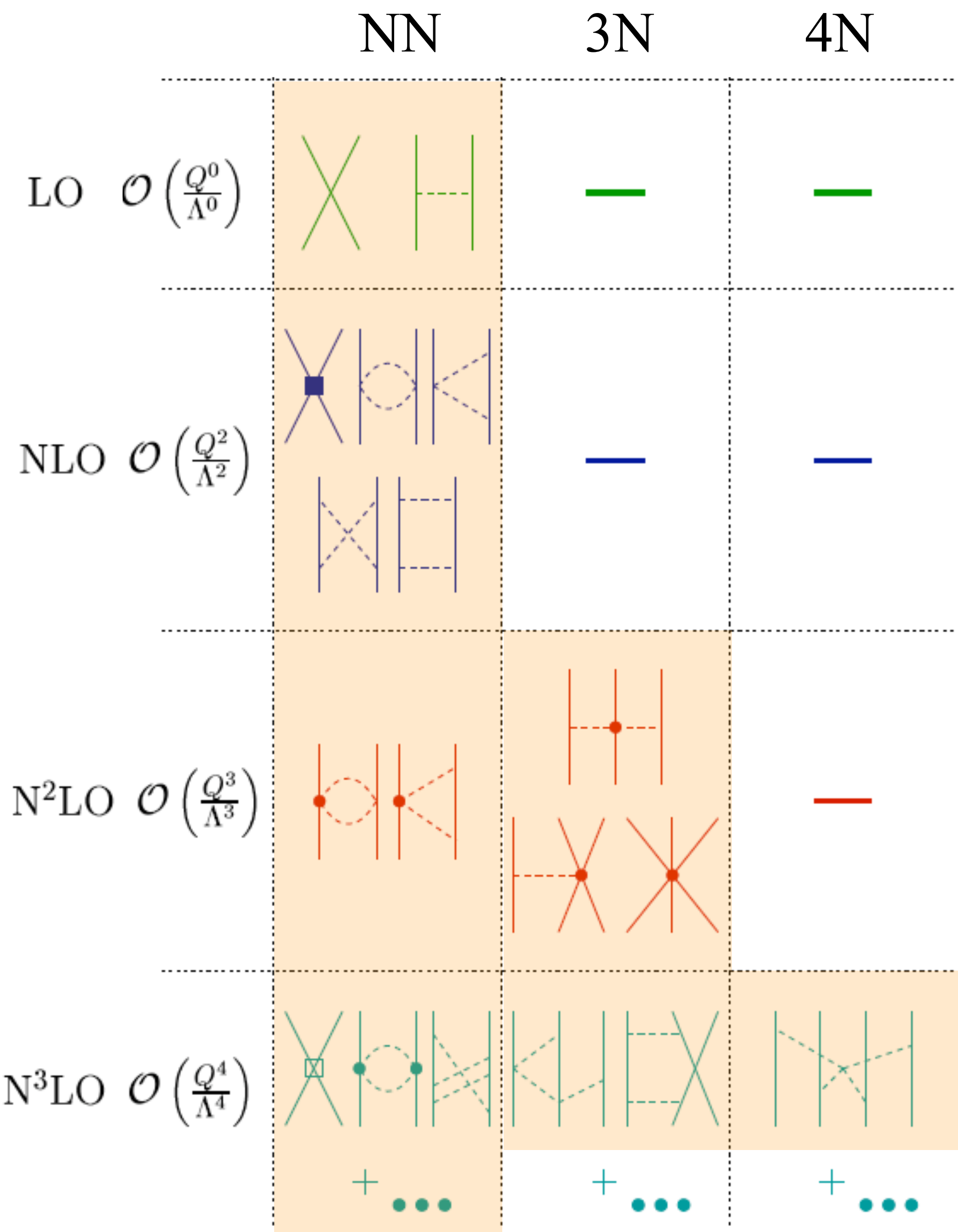
typical momenta in nuclei $\sim m_\pi$

$\Lambda_{\text{pionless}}$

$Q \ll m_\pi$

Chiral Effective Field Theory for nuclear forces

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



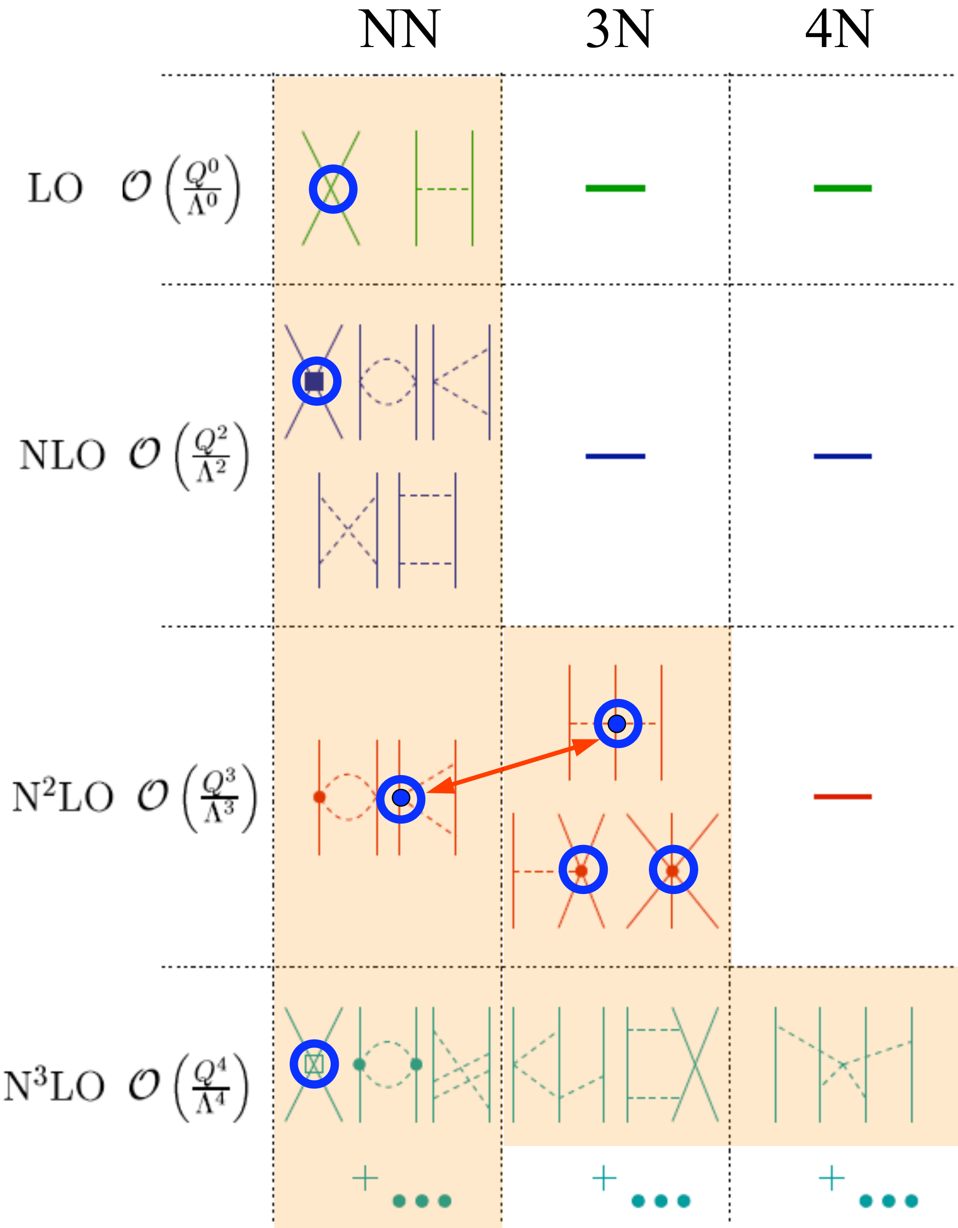
limited resolution at low energies, can expand in powers $(Q/\Lambda_b)^n$

expansion parameter ~ 1/3

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

Chiral Effective Field Theory for nuclear forces

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



include long-range pion physics

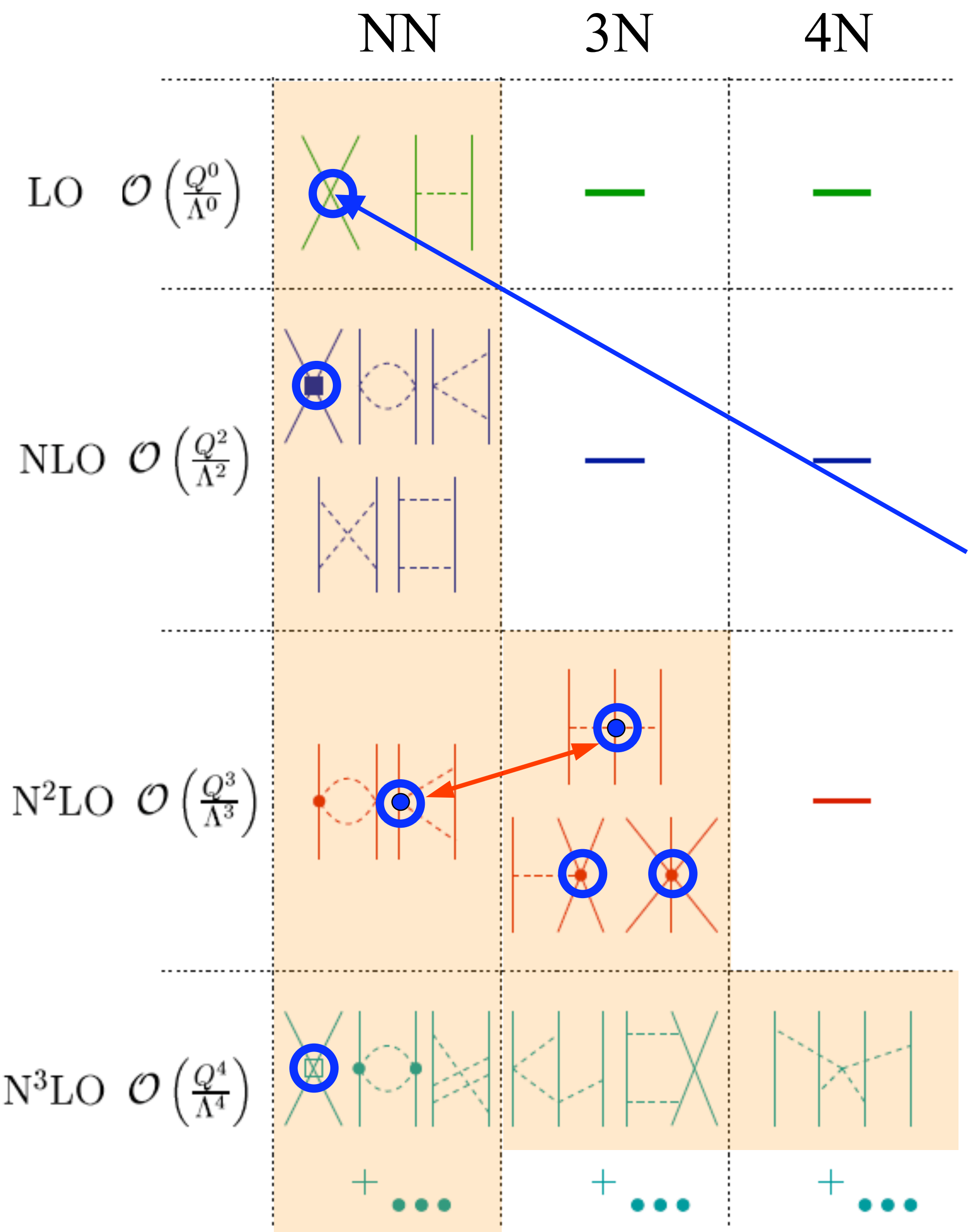
details at short distance not resolved

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

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

Chiral Effective Field Theory for nuclear forces

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



include long-range pion physics

details at short distance not resolved

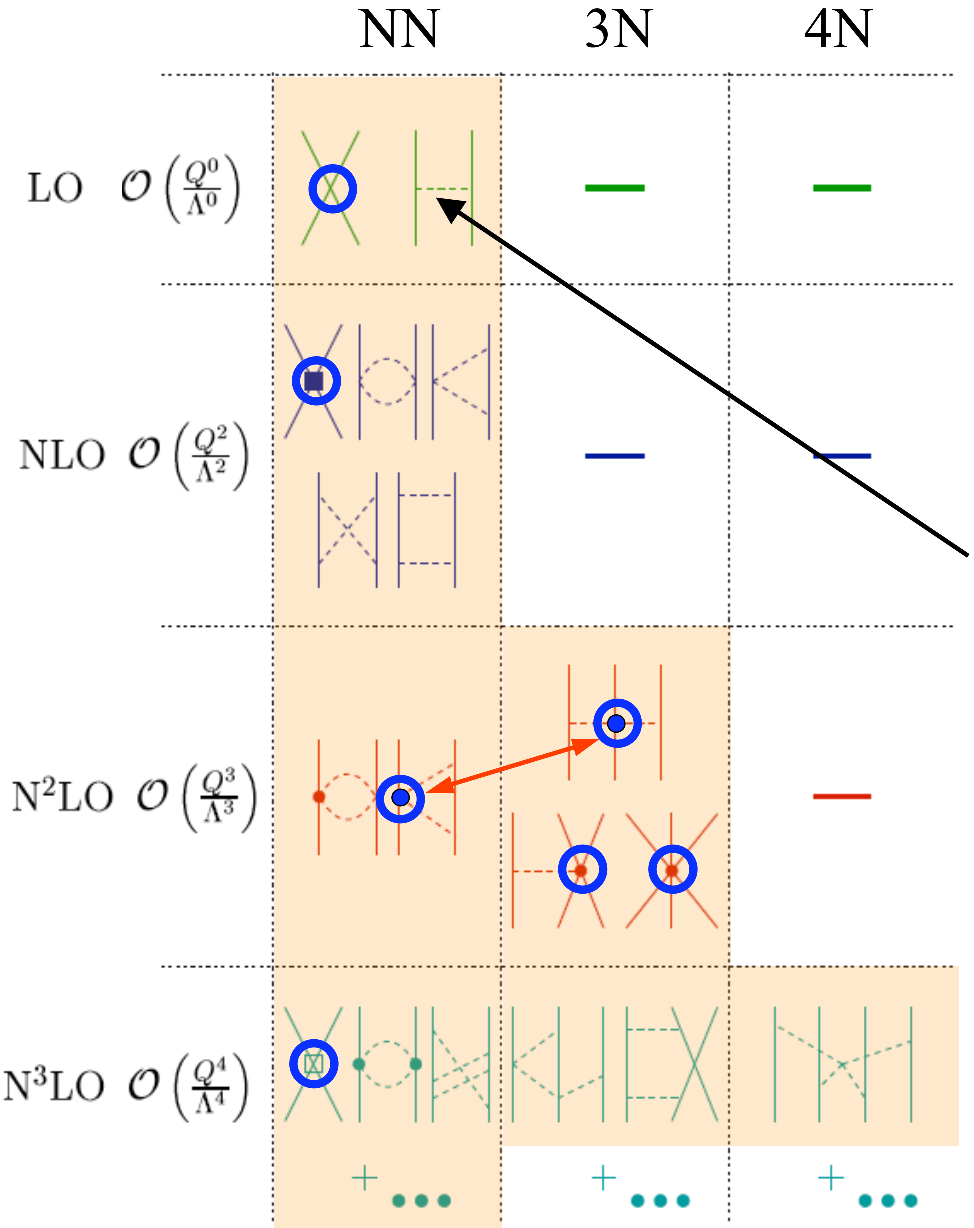
capture in few short-range couplings, fit to experiment once, Λ-dependent

large scattering length physics

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

Chiral Effective Field Theory for nuclear forces

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



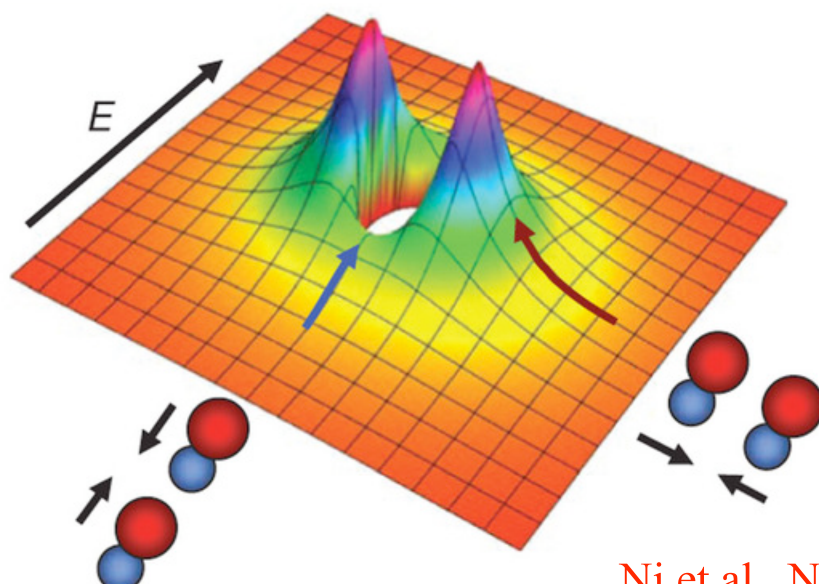
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelb

include long-range pion physics

details at short distance not resolved

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

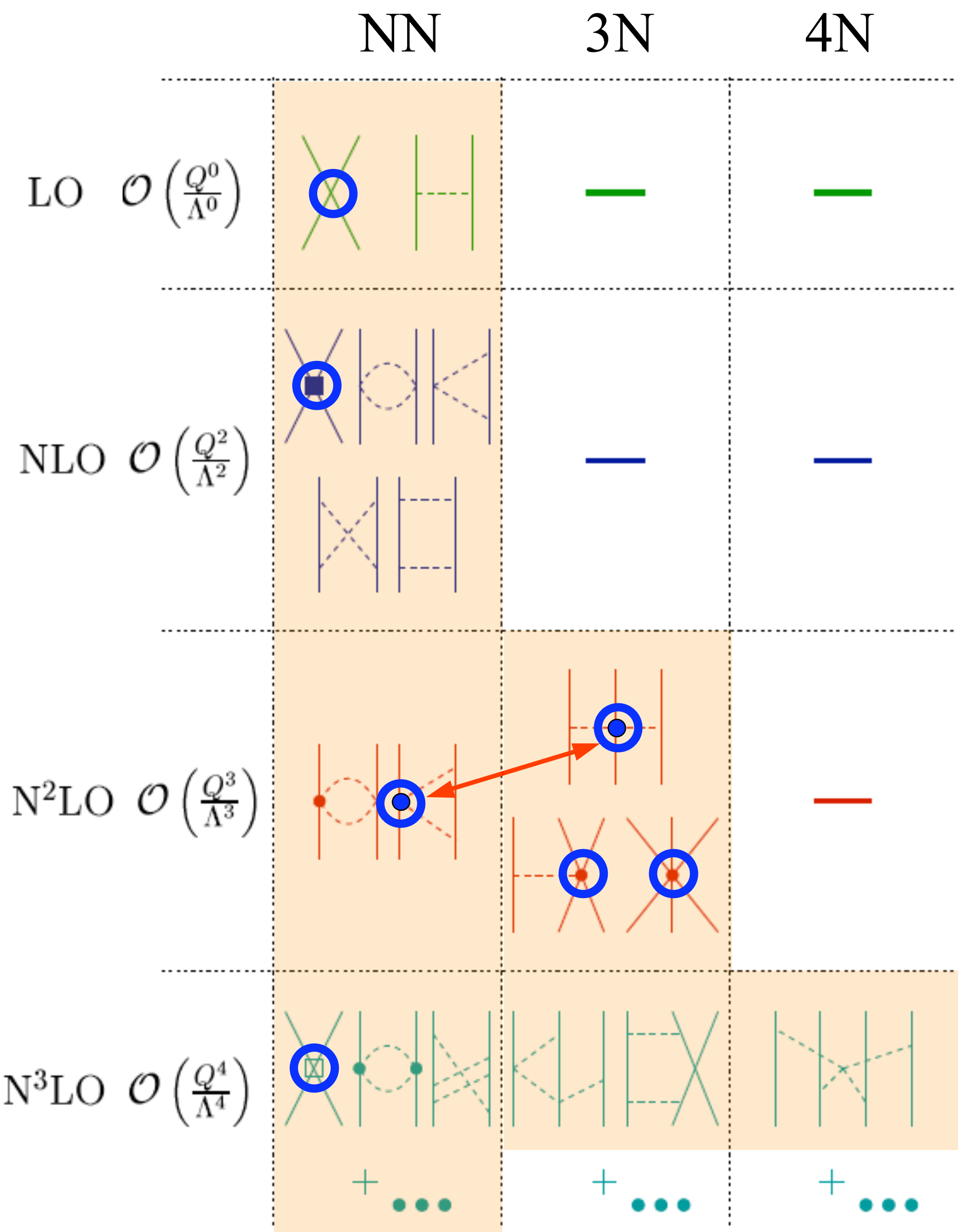
pion tensor/dipole interactions, compare to cold polar molecules



Ni et al., Nature (2010)

Chiral Effective Field Theory for nuclear forces

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



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

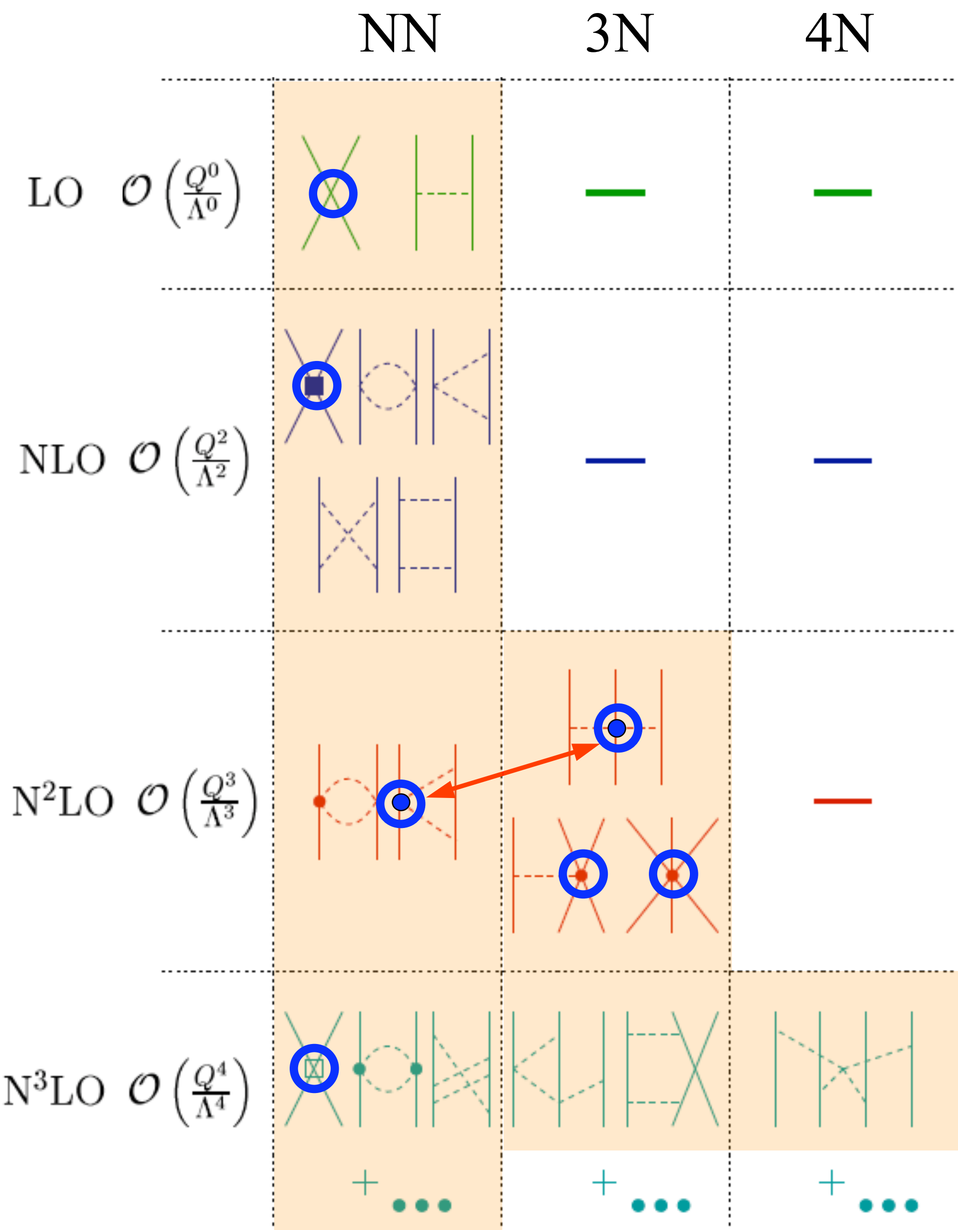
can connect to lattice QCD

several open problems regarding renormalization and power counting

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

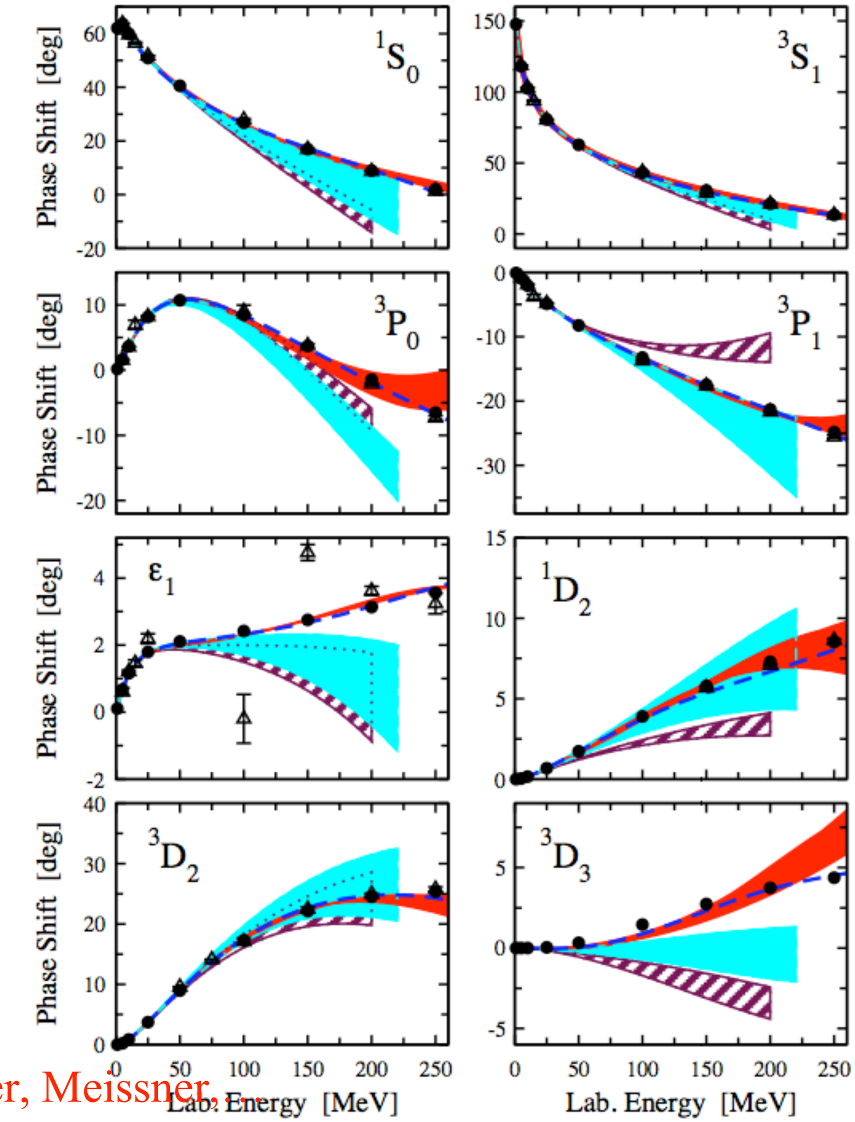
Chiral Effective Field Theory for nuclear forces

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



accurate reproduction of

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

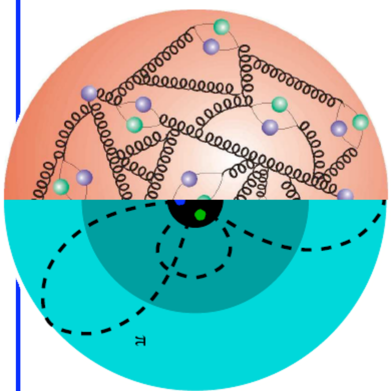


Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Meissner,...

Nuclear forces and the Renormalization Group (RG)

RG evolution to lower resolution/cutoffs

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



Λ_{chiral}

Λ ↓

Nuclear forces and the Renormalization Group (RG)

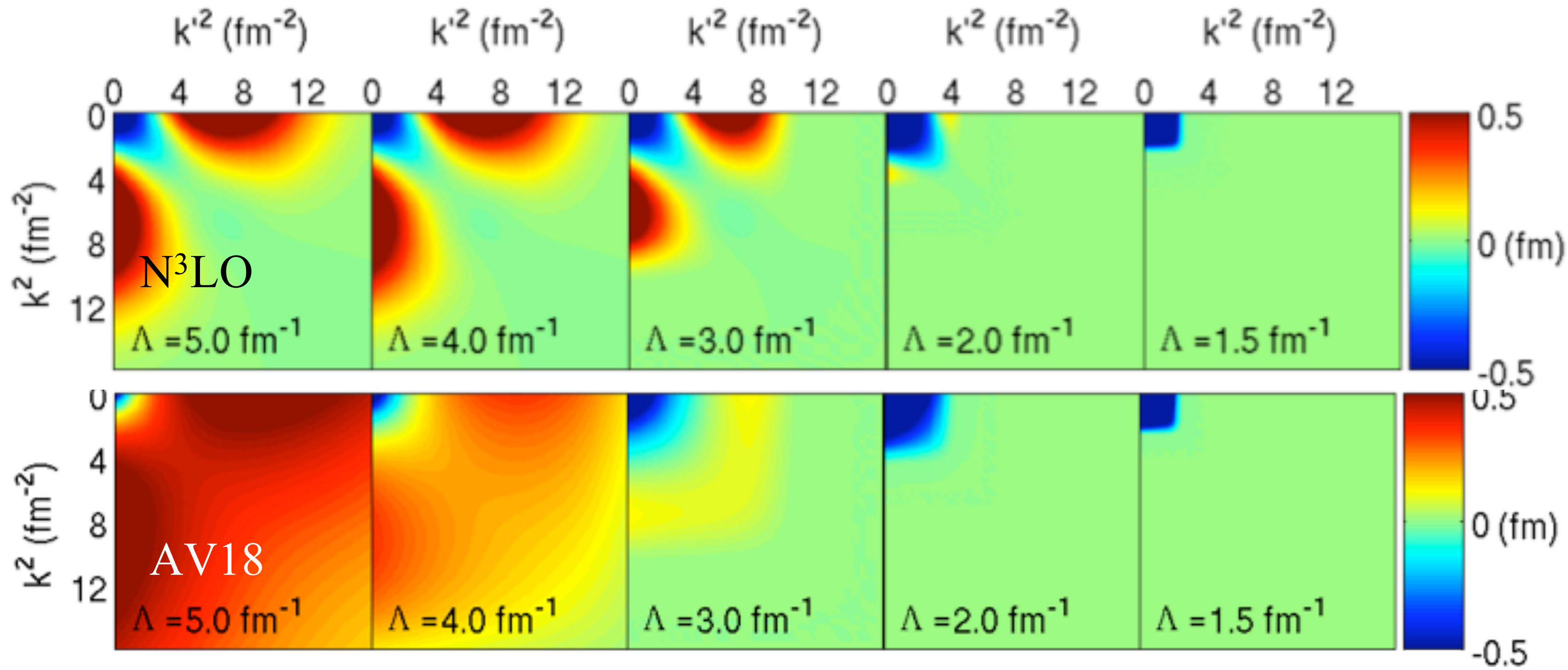
RG evolution to lower resolution/cutoffs

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

for NN interactions
(preserves NN observables)

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

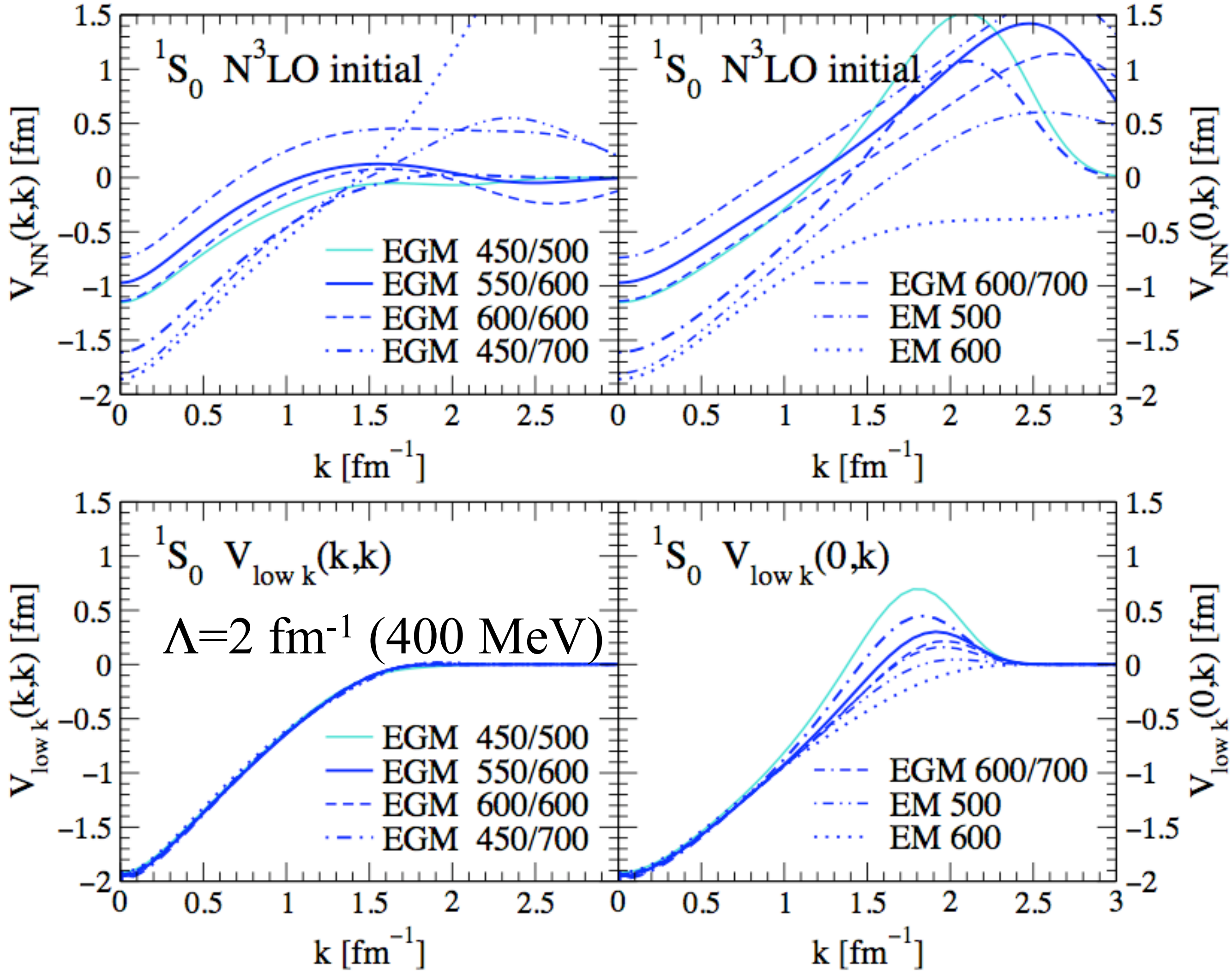
Bogner, Kuo, AS, Furnstahl,…



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

RG decouples low-momentum physics from high momenta

Low-momentum universality



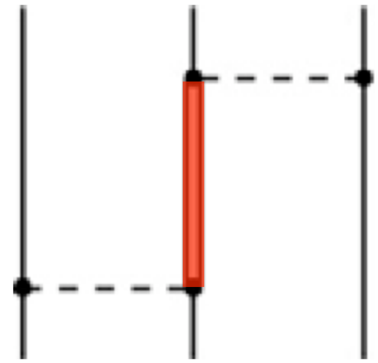
≈ universality from different chiral N^3LO potentials

A similar NN universality can also be found in many-body systems, especially for properties involving neutrons.

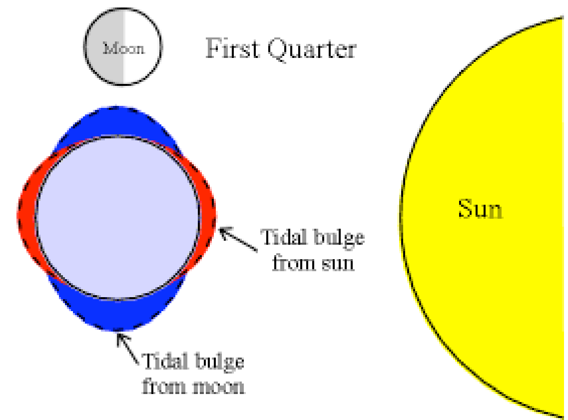
Why are there three-nucleon (3N) forces?

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

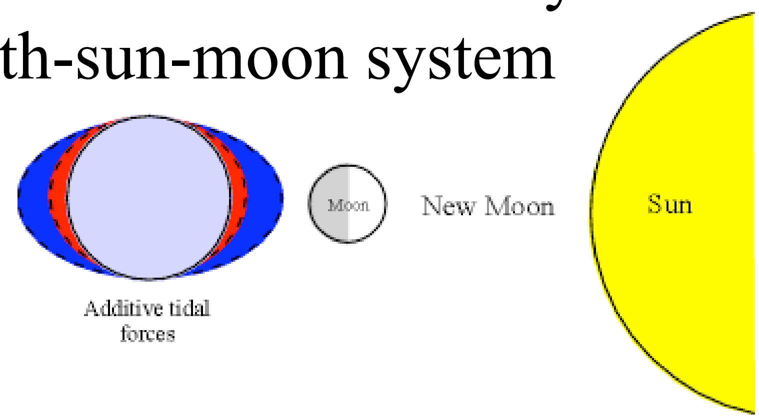
dominant contribution from Δ(1232 MeV)

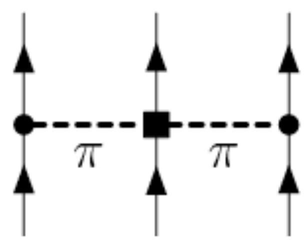


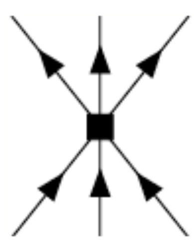
+ many shorter-range parts



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

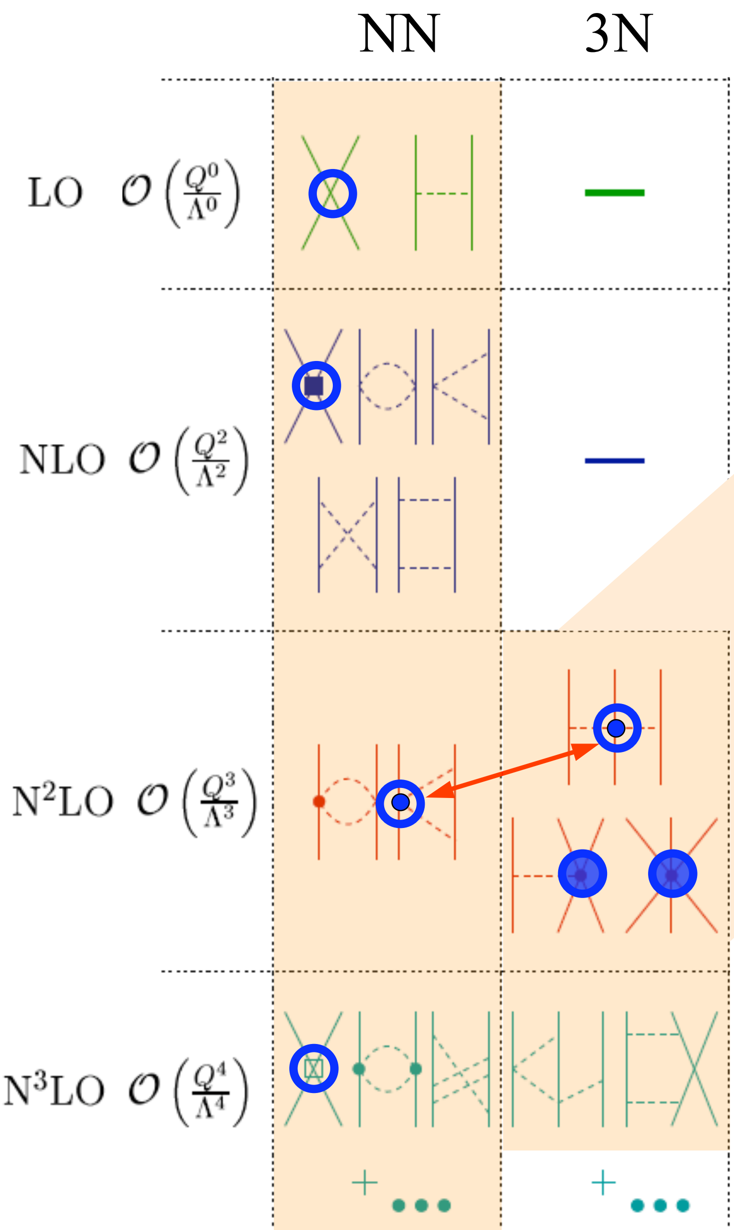


in chiral EFT (Delta-less):  + shorter-range parts

in pionless EFT:  + higher-order parts

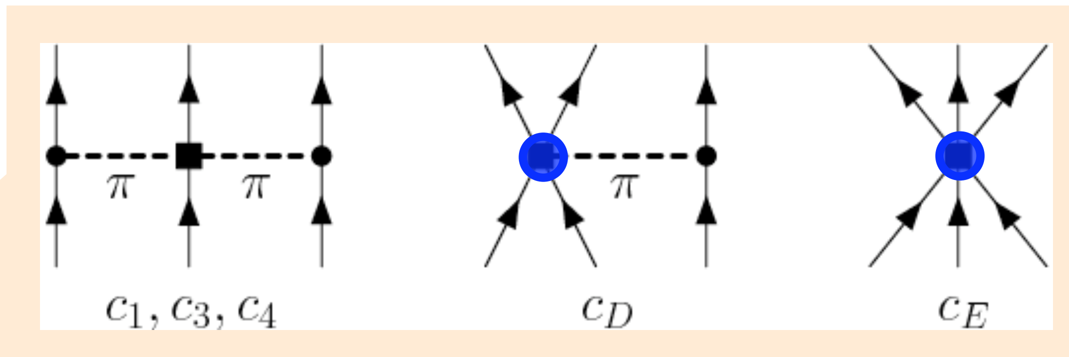
Chiral Effective Field Theory for nuclear forces

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^3LO



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

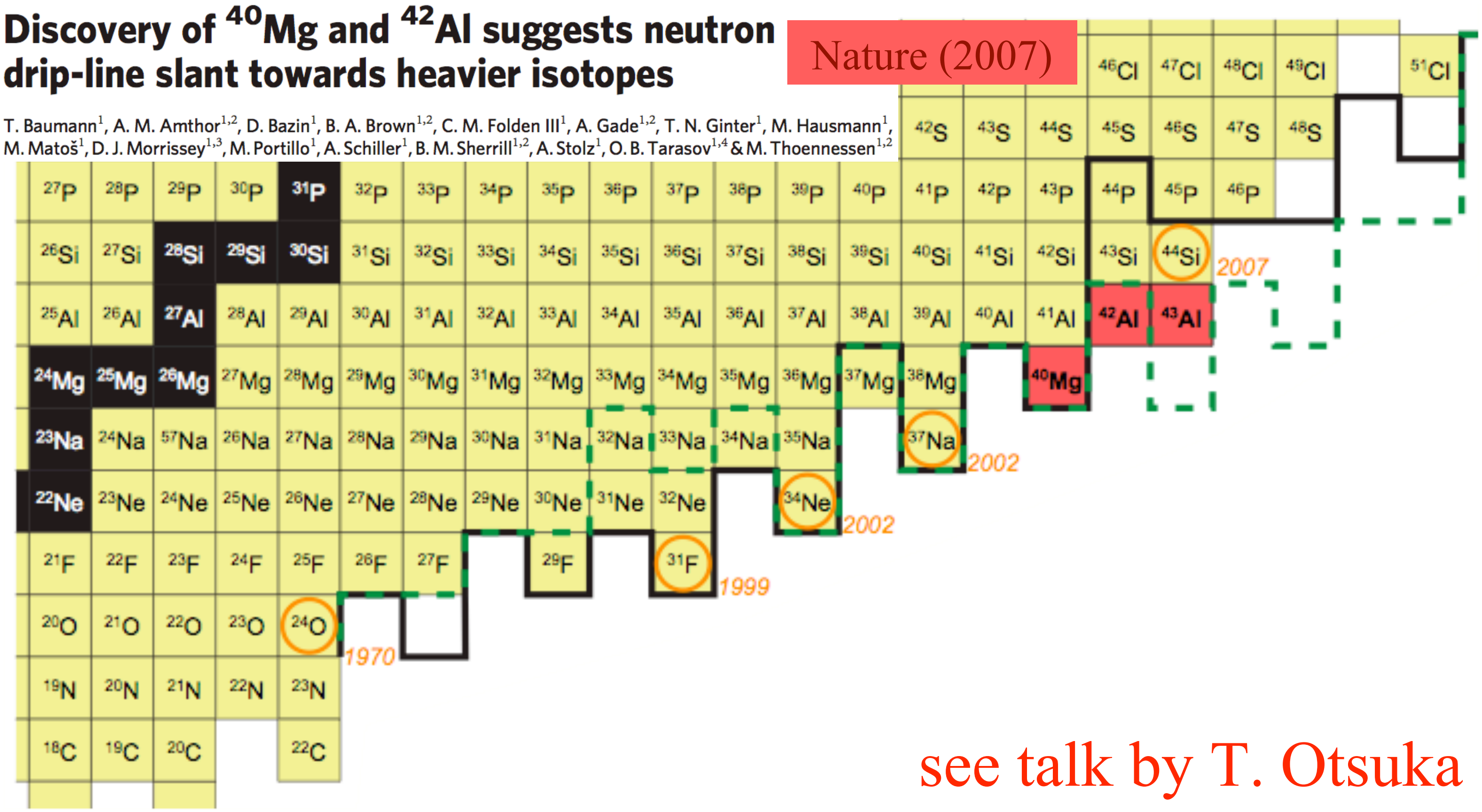
$$c_1 = -0.9^{+0.2}_{-0.5}\,,\; c_3 = -4.7^{+1.2}_{-1.0}\,,\; c_4 = 3.5^{+0.5}_{-0.2}$$

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

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

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

Towards the limits of existence - the neutron drip-line



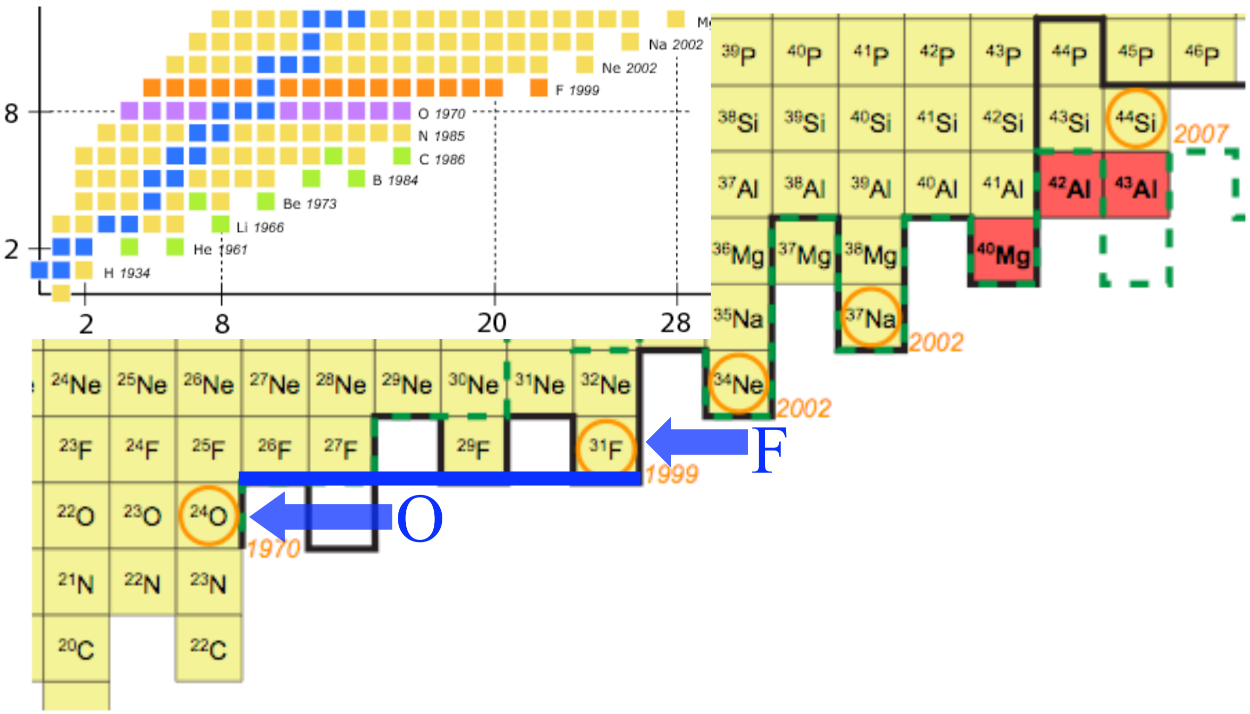
see talk by T. Otsuka

Helmholtz Alliance
Extremes of Density and Temperature: Cosmic Matter in the Laboratory

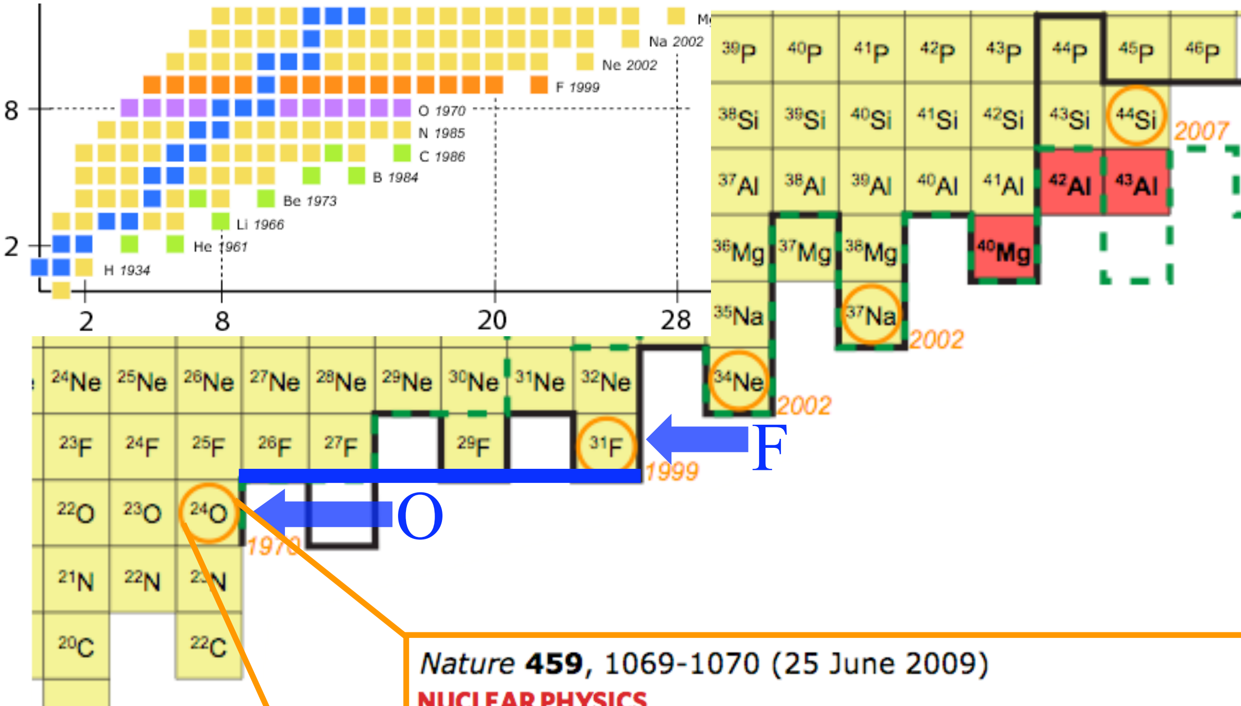
ExtreMe Matter Institute EMMI

EMMI Physics Days 2010

The oxygen anomaly



The oxygen anomaly



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

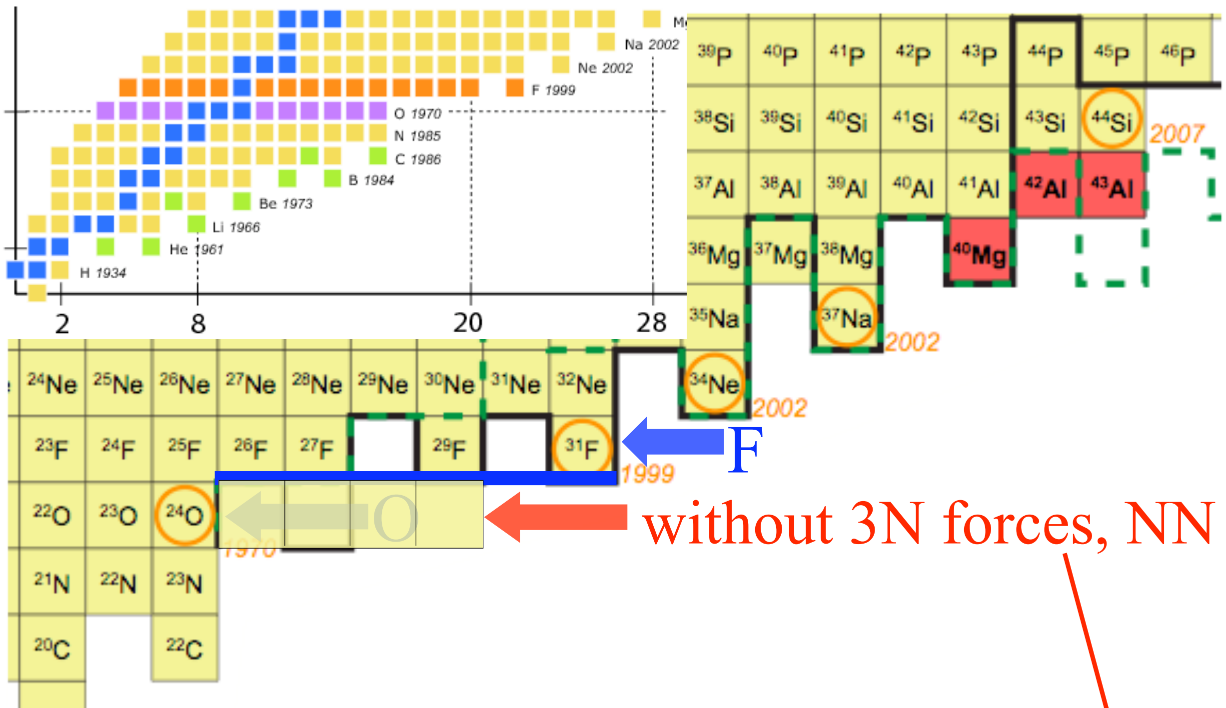
NUCLEAR PHYSICS

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.

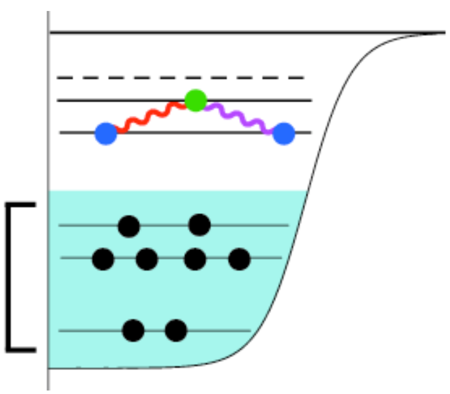
The oxygen anomaly - not reproduced without 3N forces



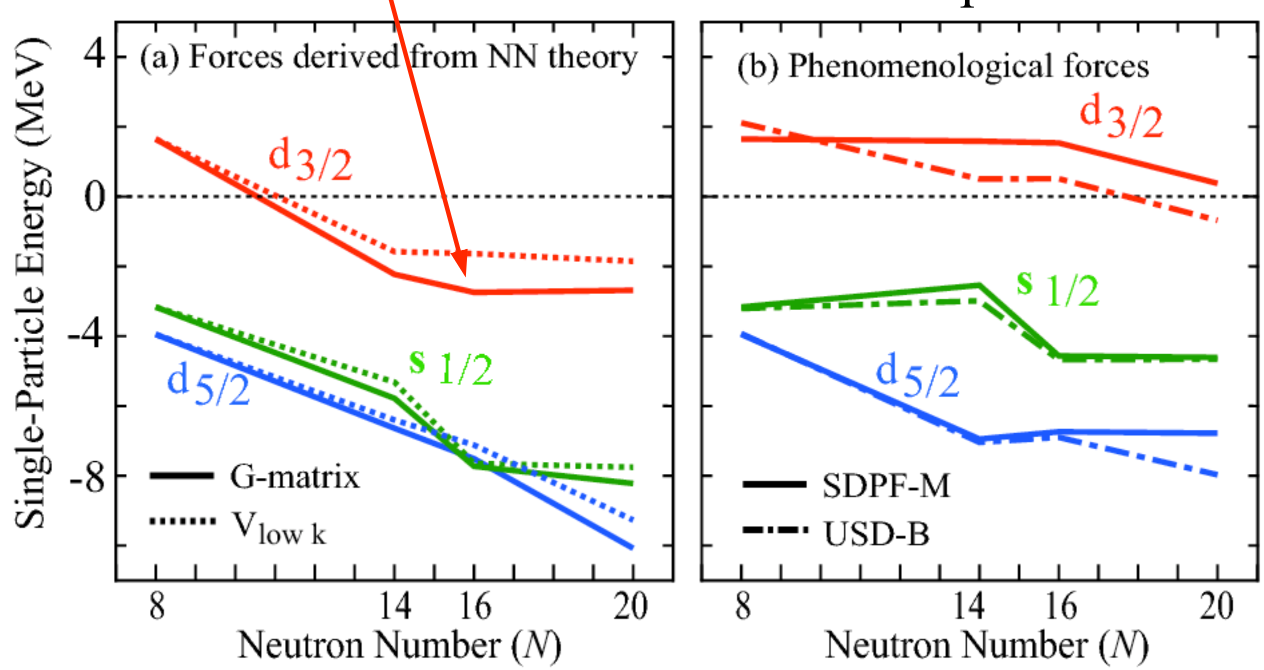
without 3N forces, NN interactions too attractive

many-body theory based on two-nucleon forces:

drip-line incorrect at ^{28}O



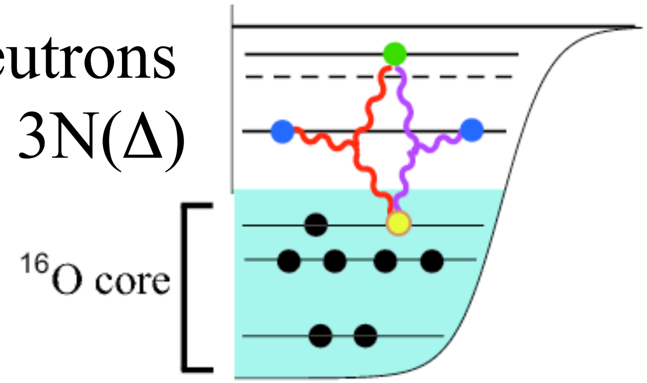
fit to experiment



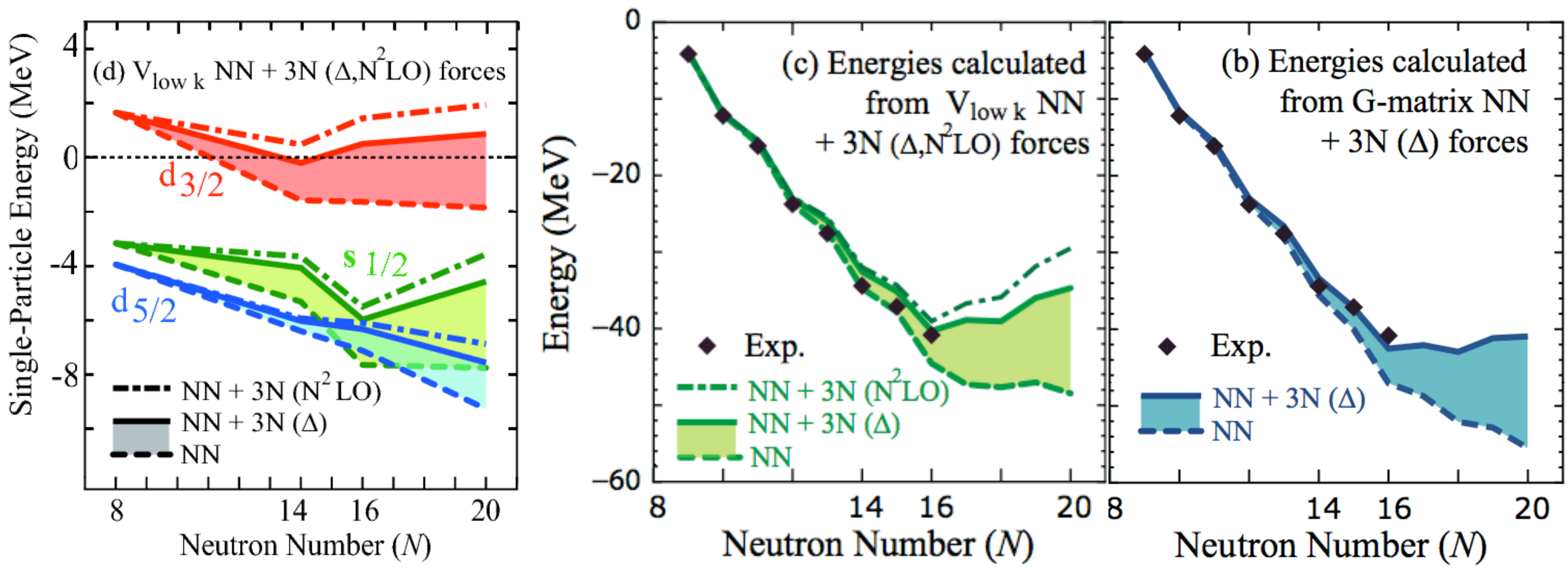
The oxygen anomaly - impact of 3N forces

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 for 3N(Δ)



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



first microscopic explanation of the oxygen anomaly

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

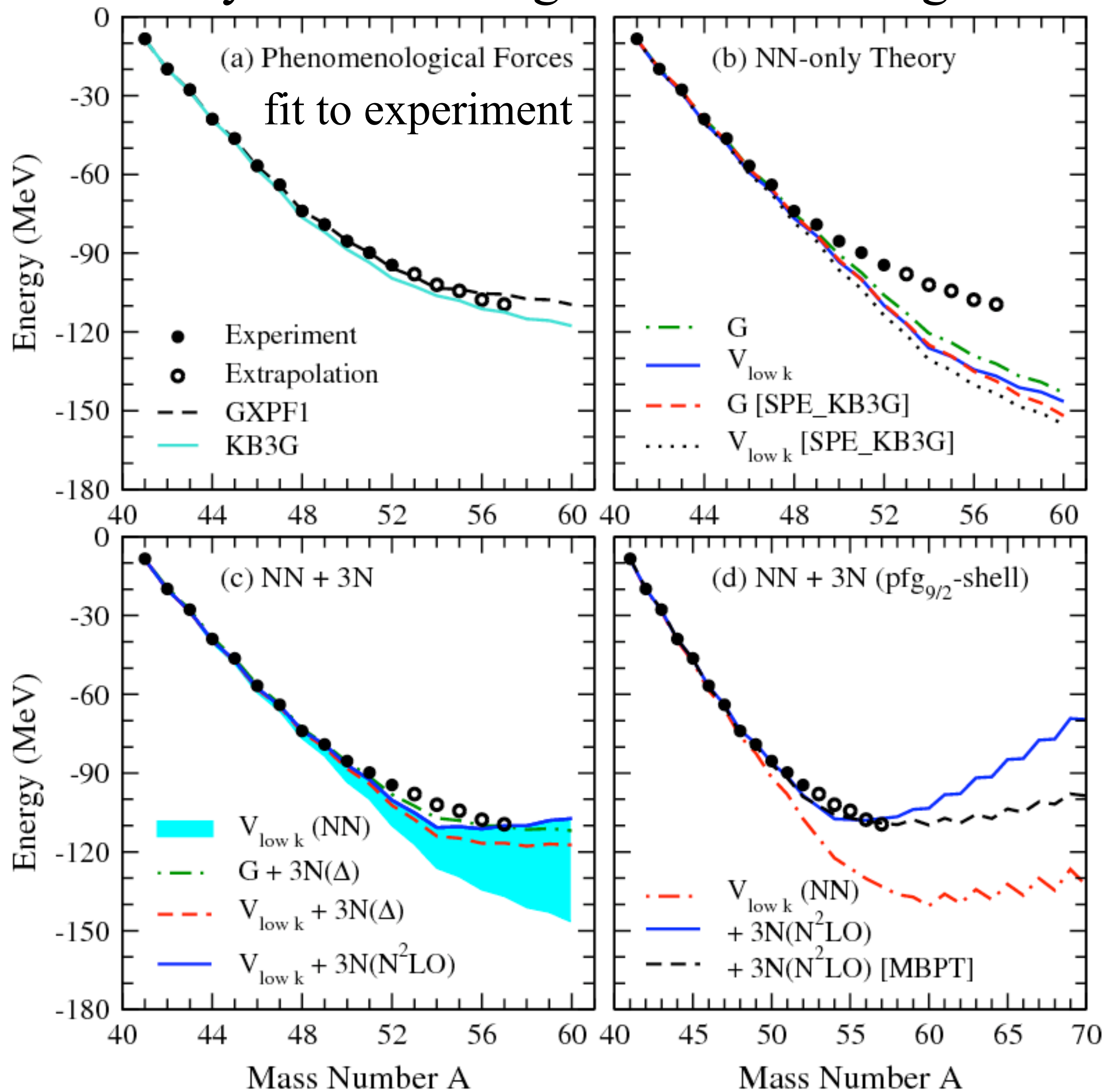
Evolution to neutron-rich calcium isotopes

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

Holt, Otsuka, AS, Suzuki (2010)

mass measured to ^{52}Ca

shown to exist to ^{58}Ca



Evolution to neutron-rich calcium isotopes

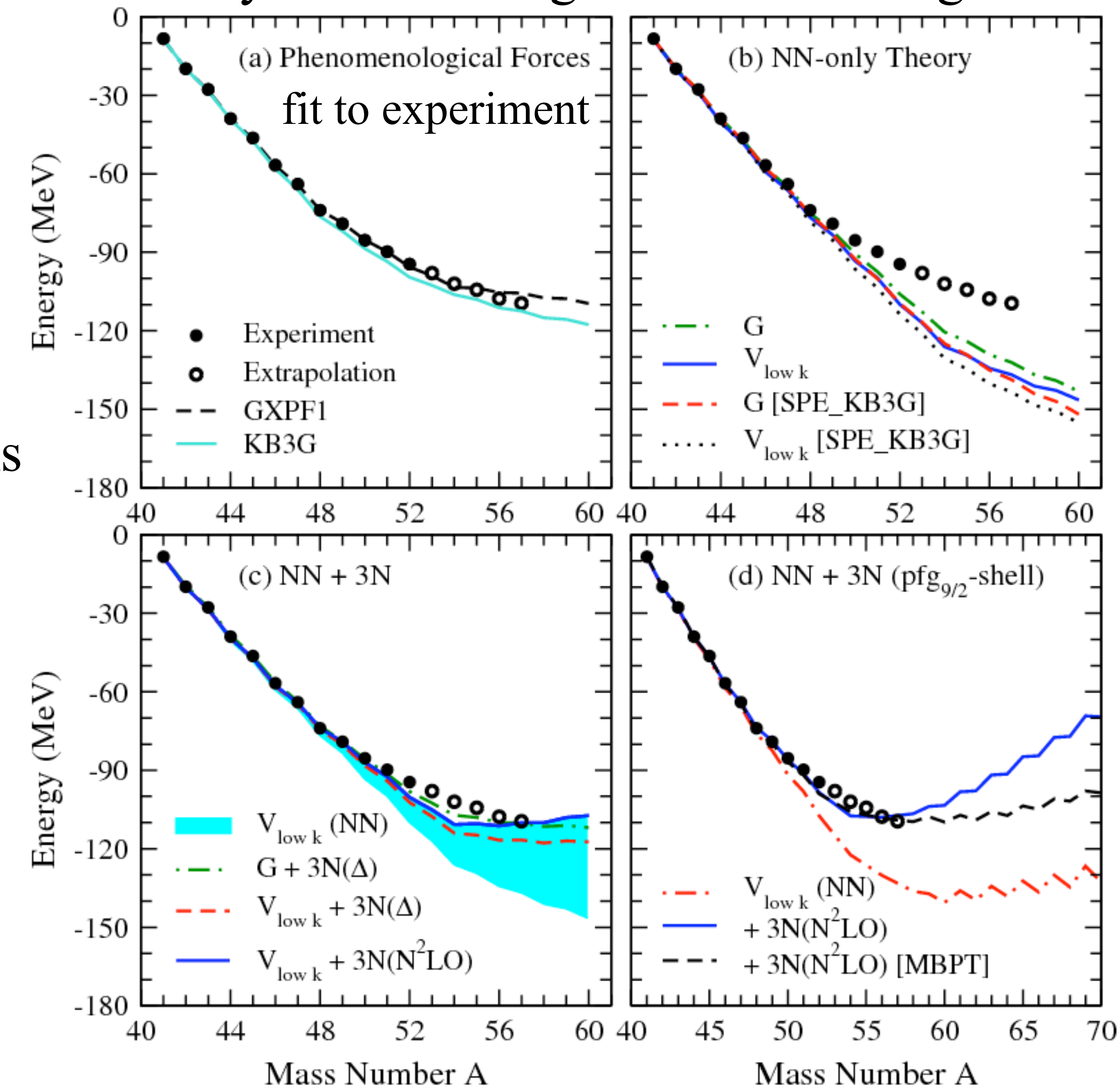
repulsive 3N contributions also key for calcium ground-state energies

Holt, Otsuka, AS, Suzuki (2010)

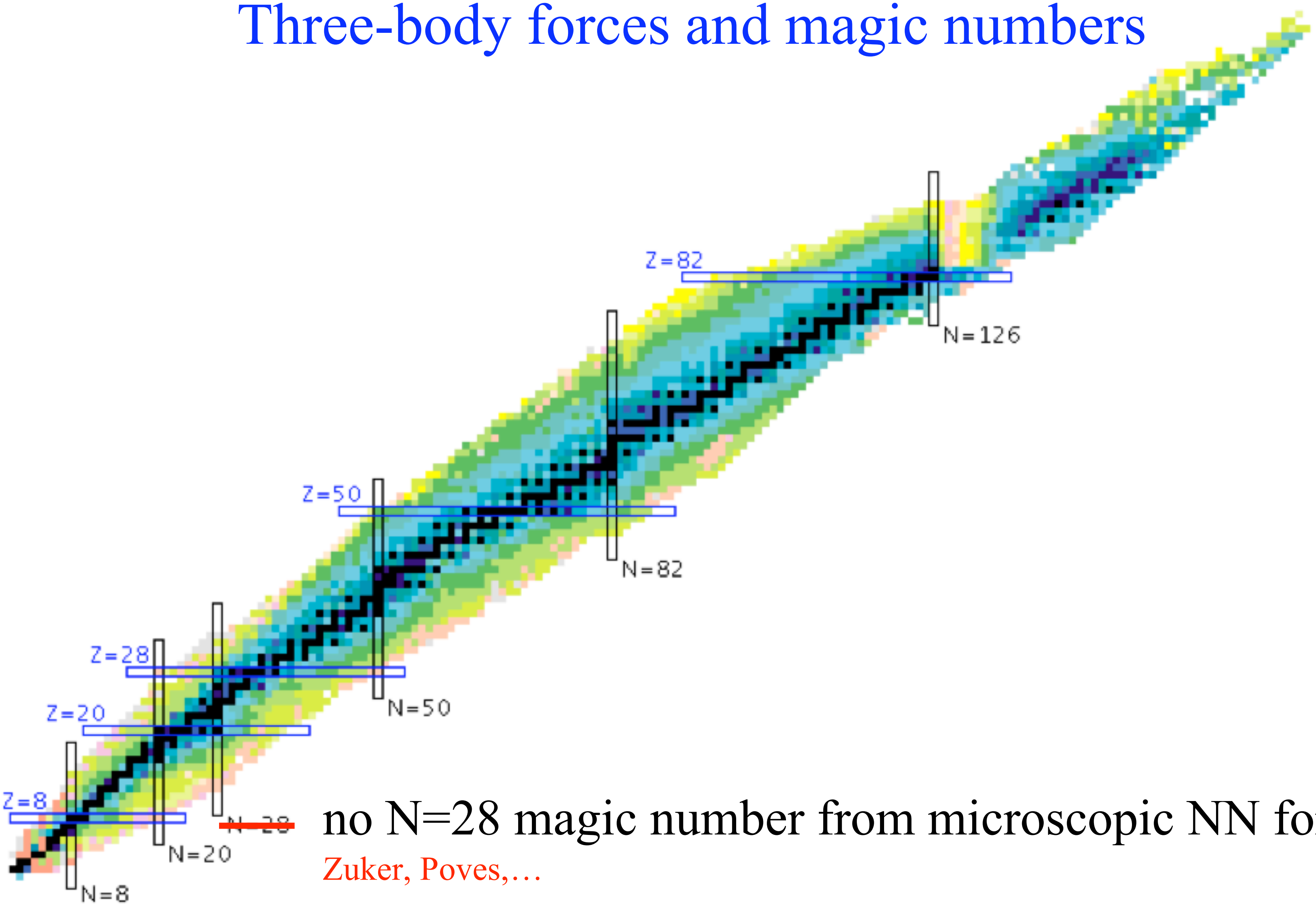
mass measured to ^{52}Ca
shown to exist to ^{58}Ca

predict drip-line
around ^{60}Ca

continuum contributions
need to be included



Three-body forces and magic numbers



no N=28 magic number from microscopic NN forces

Zuker, Poves,…

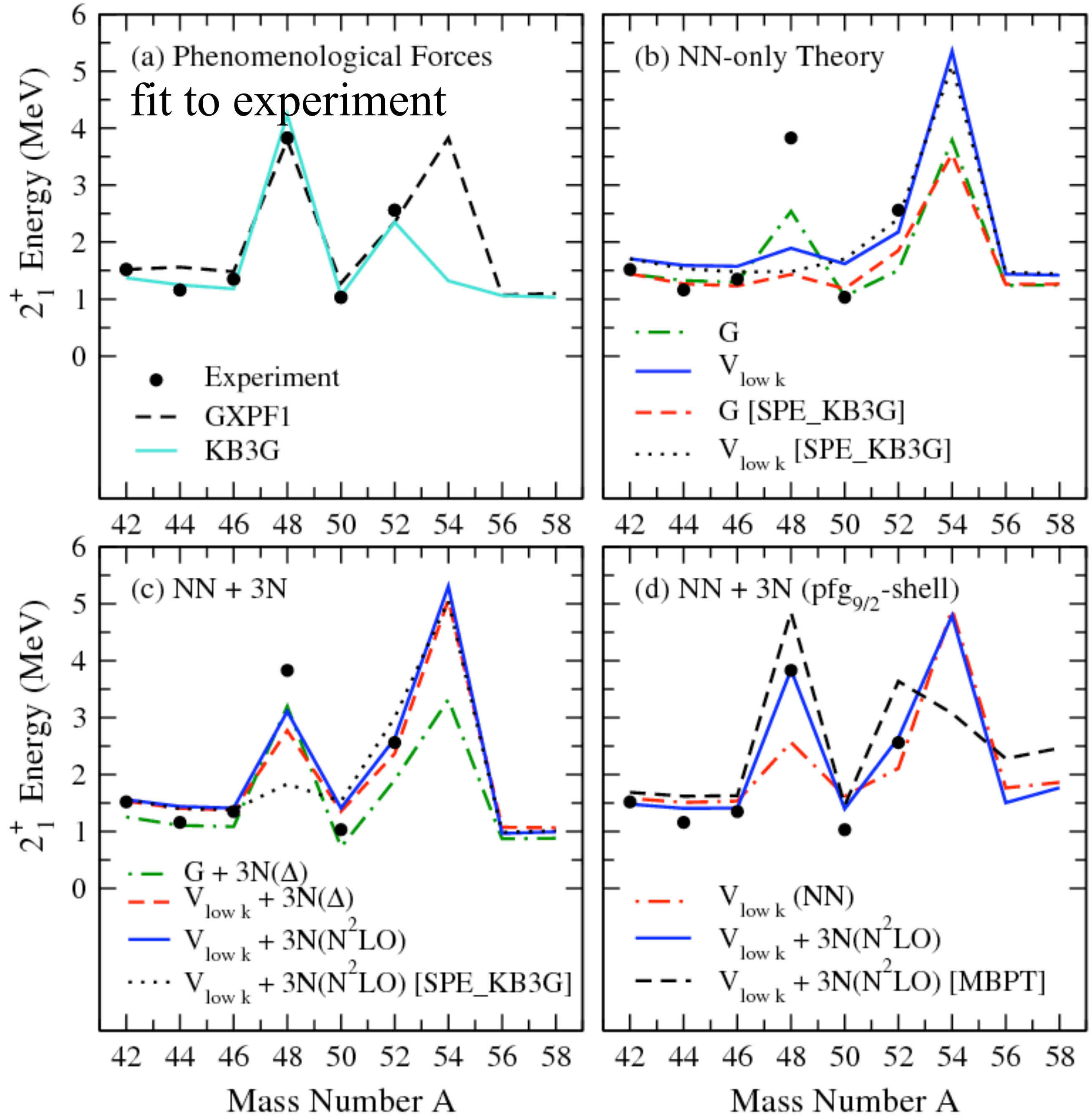
Three-body forces and magic numbers

3N mechanism important for shell structure

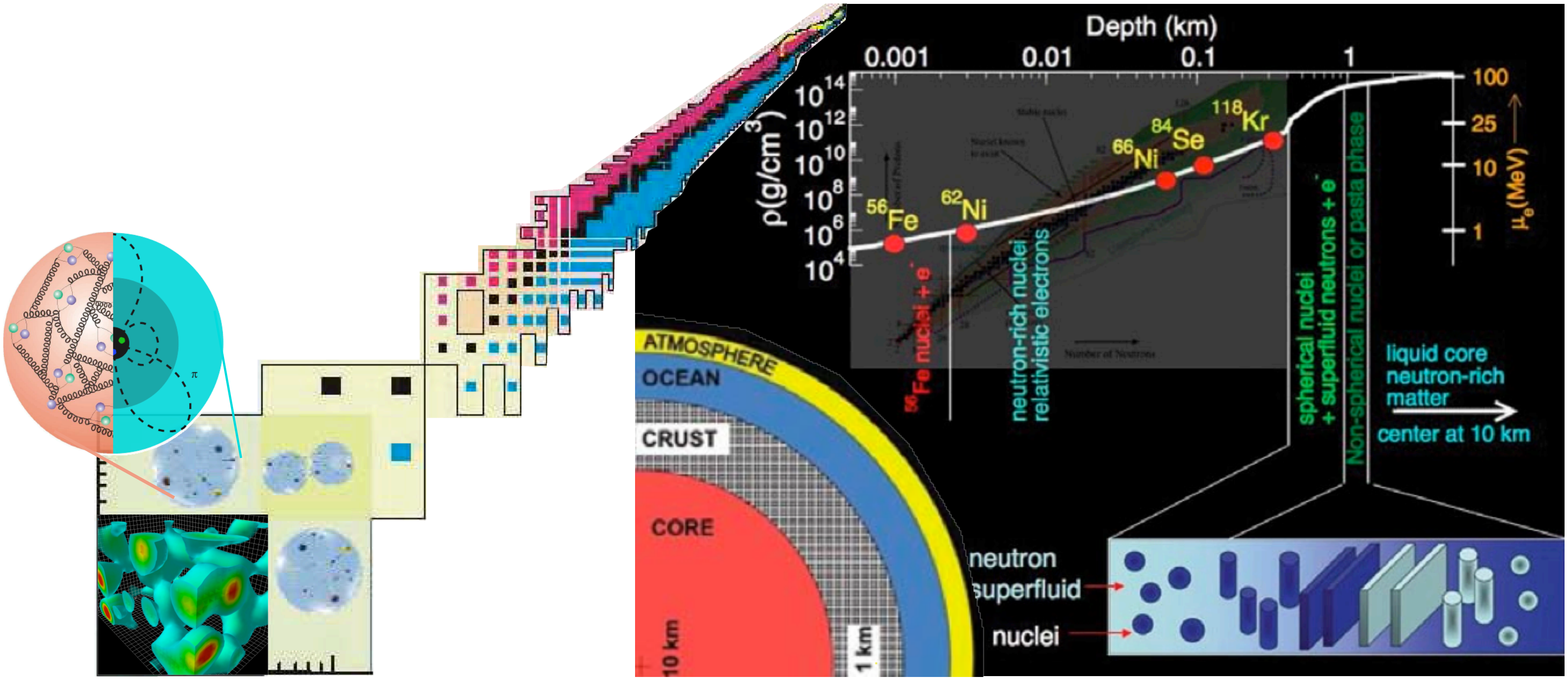
Holt, Otsuka, AS, Suzuki (2010)

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



Extreme neutron-rich matter in stars



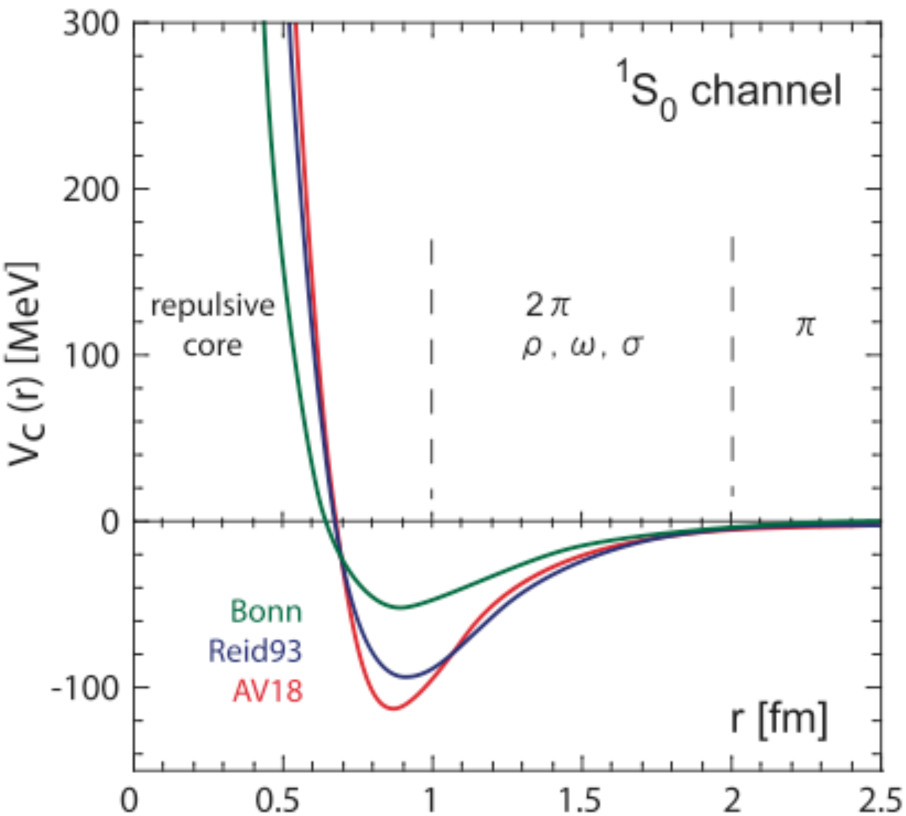
Helmholtz Alliance
Extremes of Density and Temperature: Cosmic Matter in the Laboratory

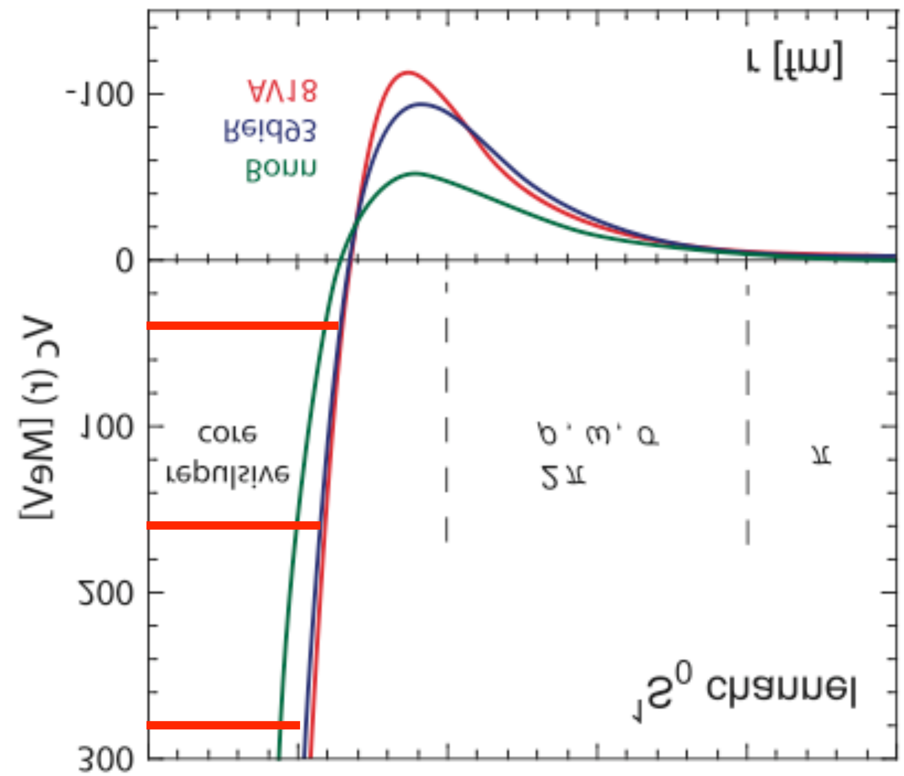
ExtreMe Matter Institute EMMI

EMMI Physics Days 2010

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



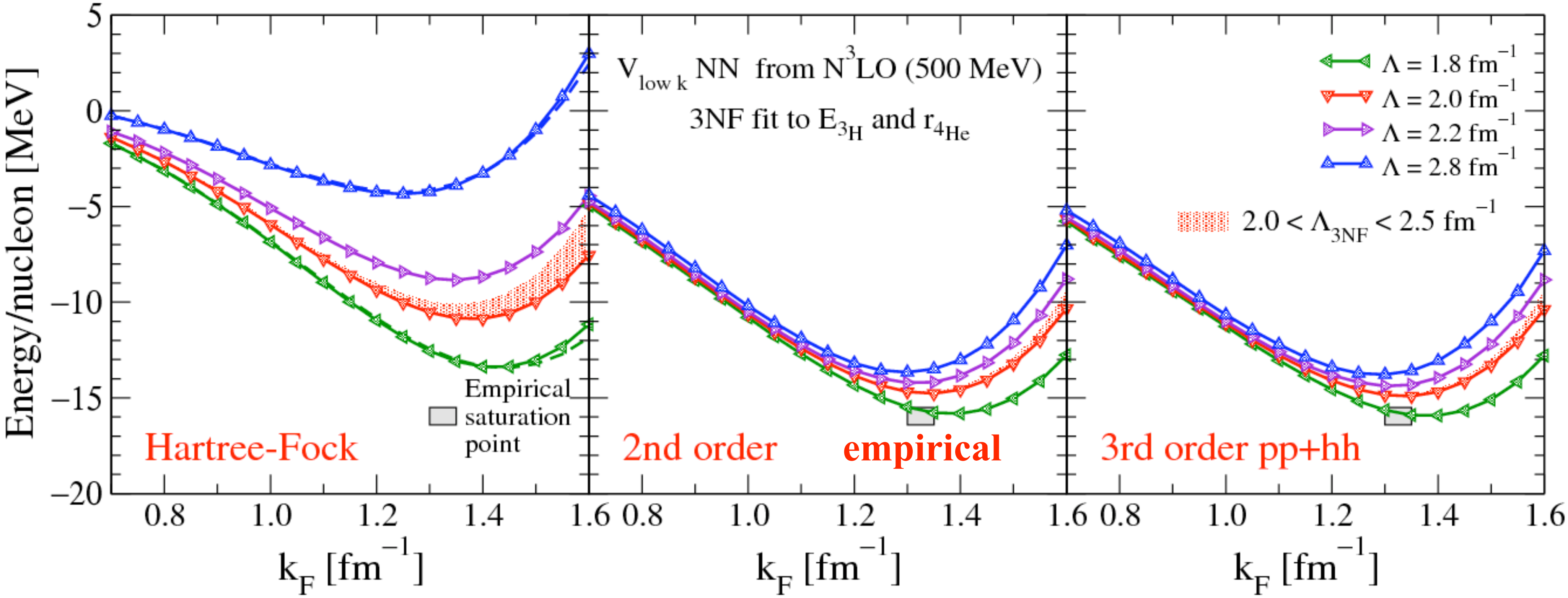


Weinberg eigenvalue analysis: two-body scattering becomes perturbative after RG evolution, except in channels with bound states

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?



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

exciting: empirical saturation with theoretical uncertainties

improved 3N treatment see also Holt, Kaiser, Weise (2010)

input to develop a universal energy density functional for all nuclei

UNEDF SciDAC Collaboration

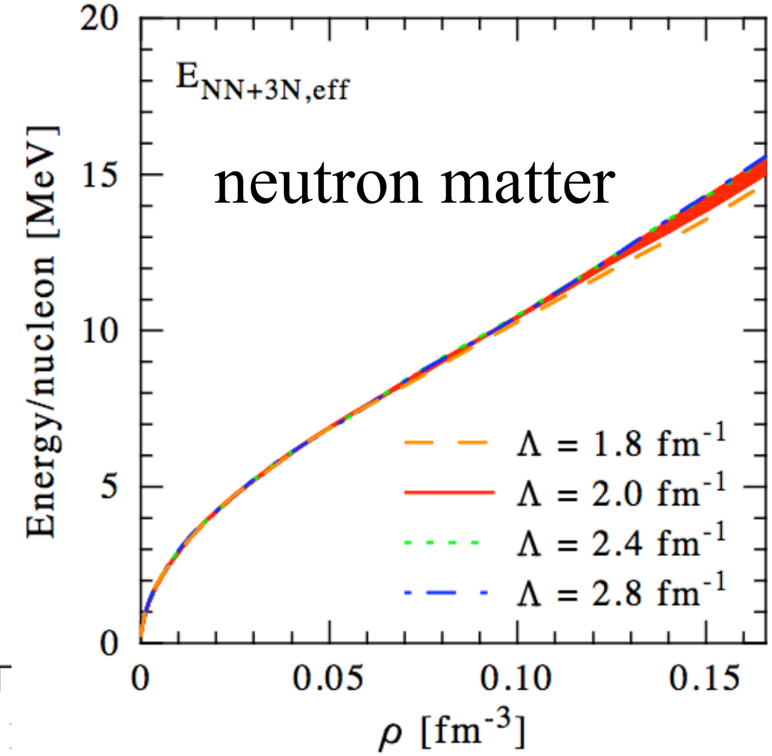
Universal Nuclear Energy Density Functional

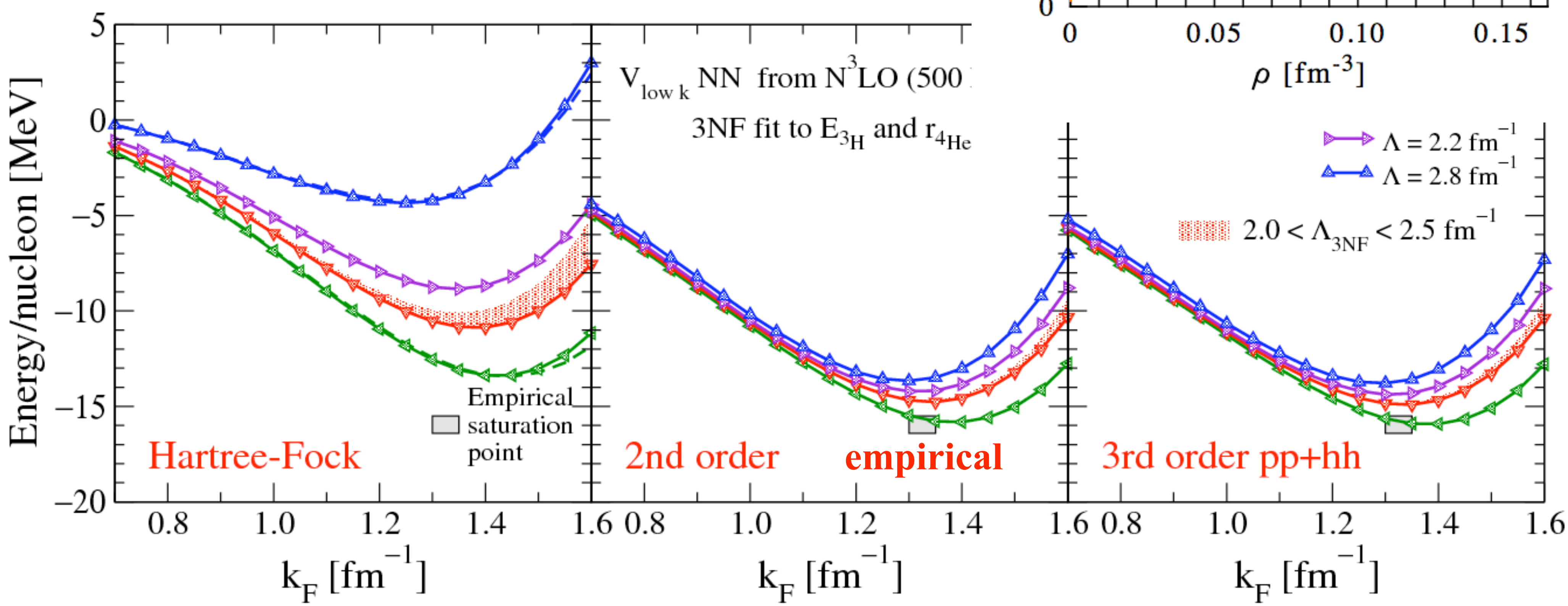
Impact of 3N forces on neutron matter

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

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

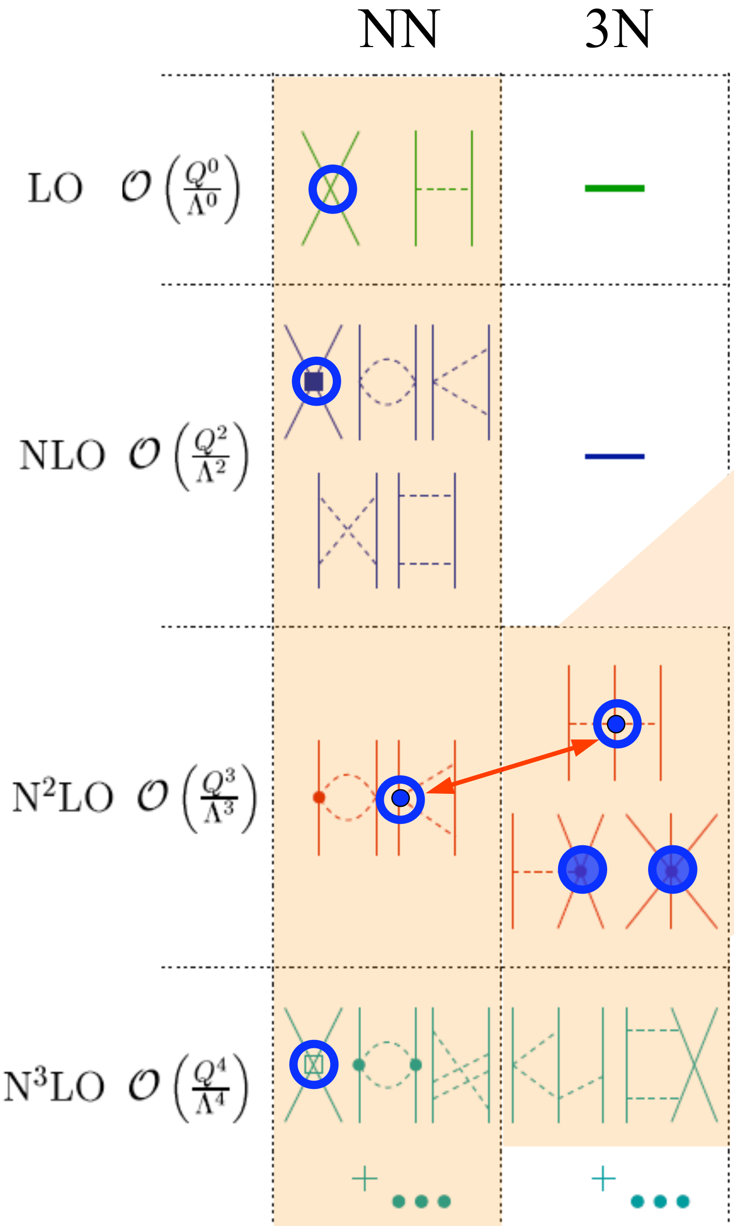
neutron matter: no new parameters in many-body forces to N^{3}LO!





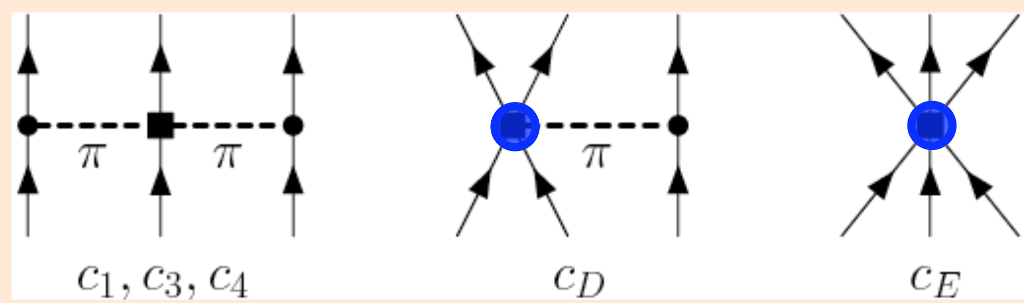
Chiral Effective Field Theory for nuclear forces

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 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: $c_1=0$, $c_3=-c_4/2=-3\ \text{GeV}^{-1}$

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

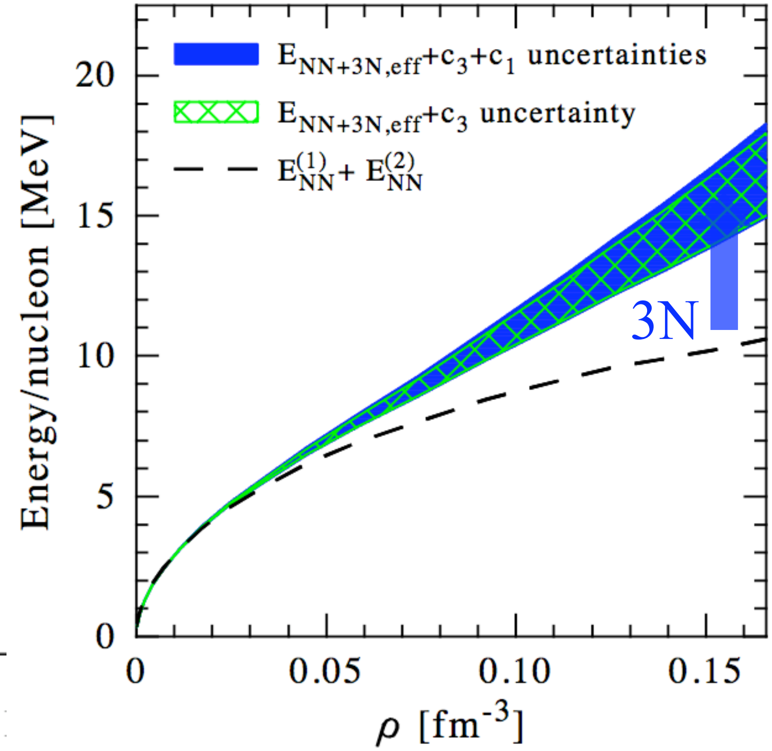
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Meissner,…

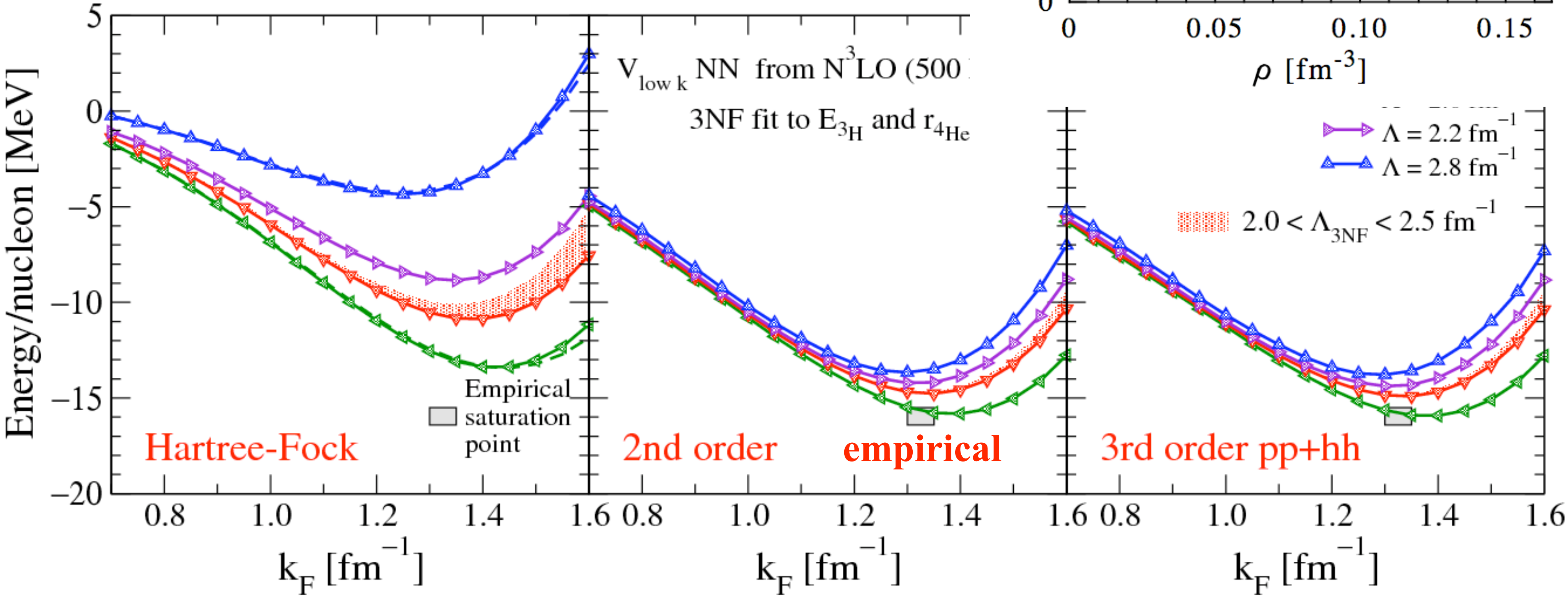
Impact of 3N forces on neutron matter

Hebeler, AS (2009); 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





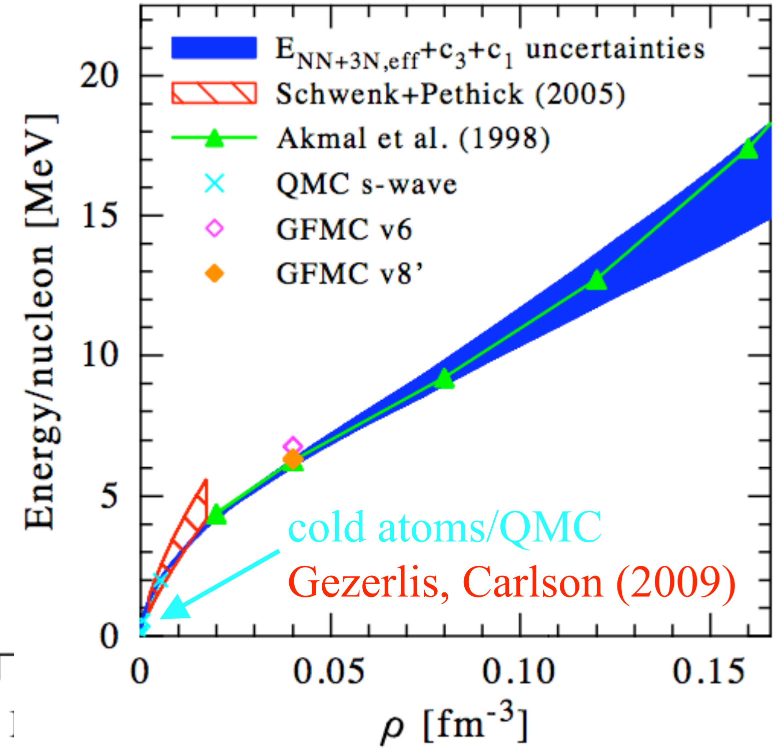
Impact of 3N forces on neutron matter

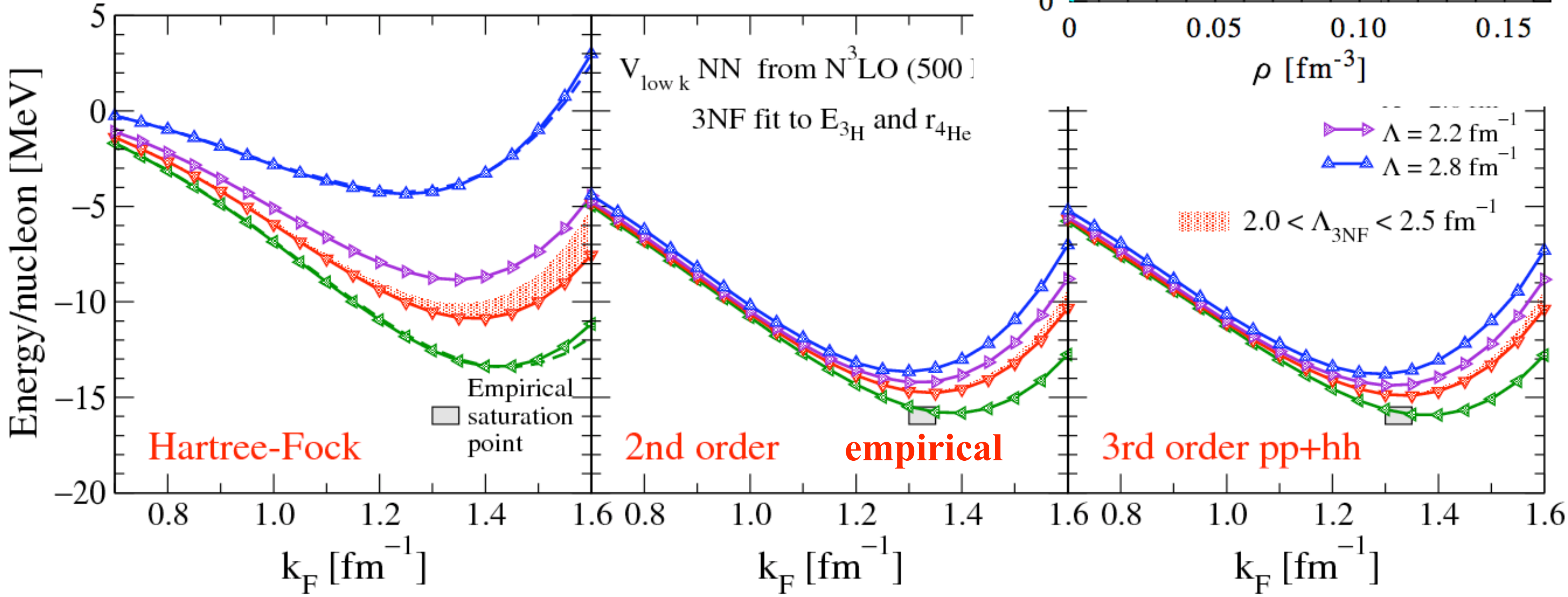
Hebeler, AS (2009); Tolos, Friman, AS (2007)

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

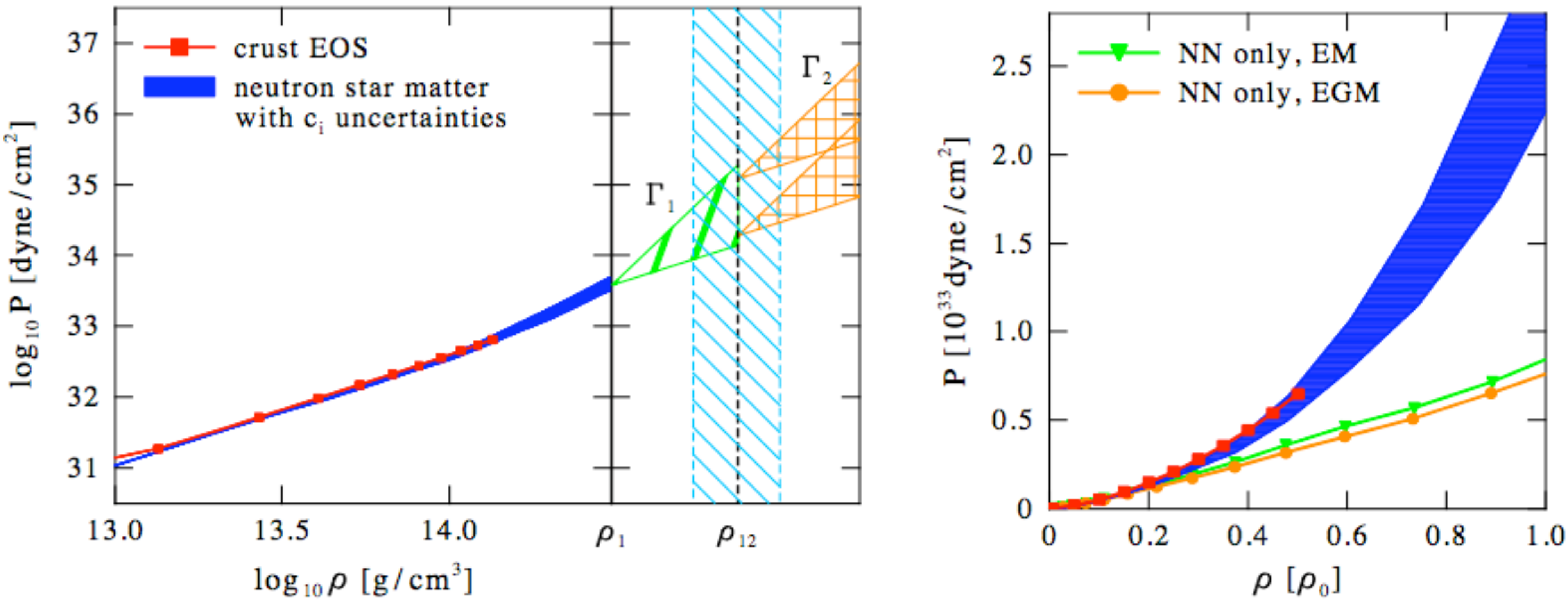
uncertainties dominated by c_3 coupling

microscopic calculations within band





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

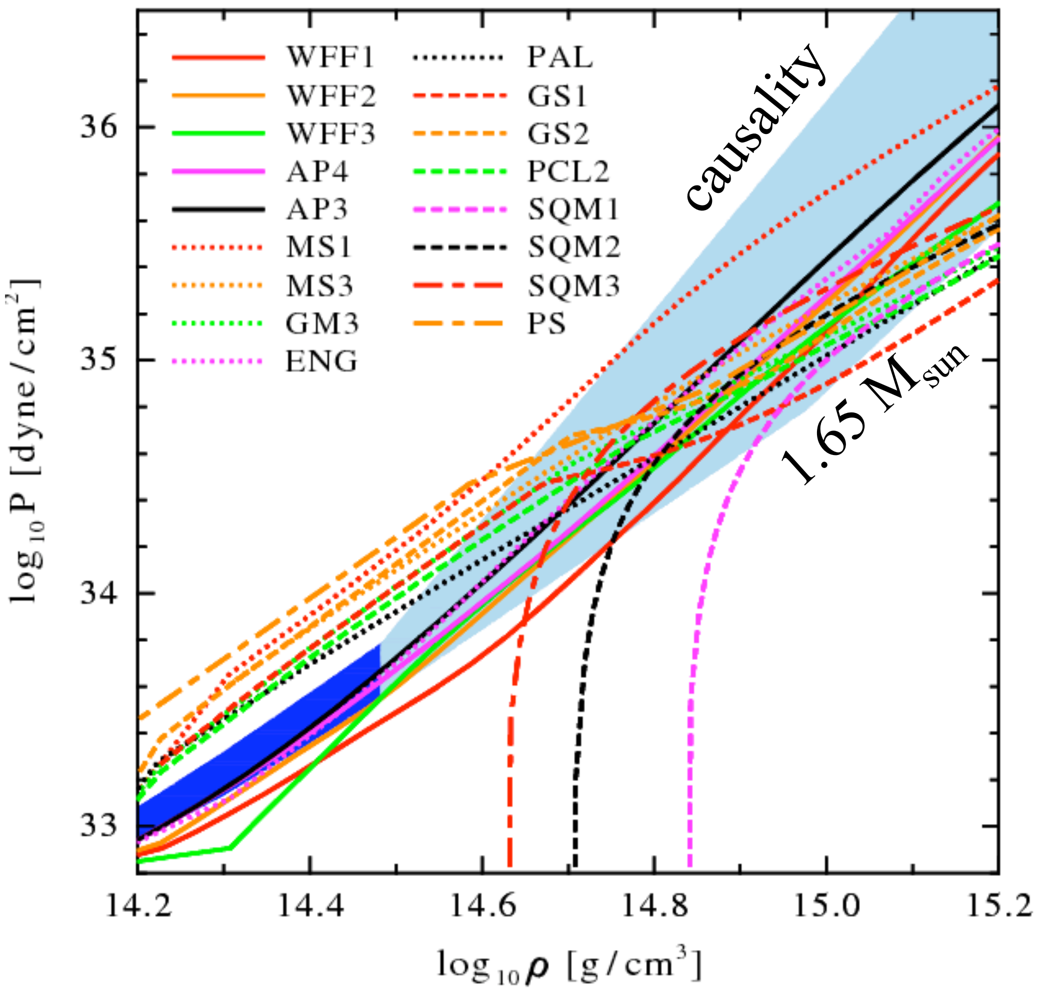


pressure below nuclear densities agrees with standard crust EOS only after 3N forces are included

extend uncertainty band to higher densities using piecewise polytropes

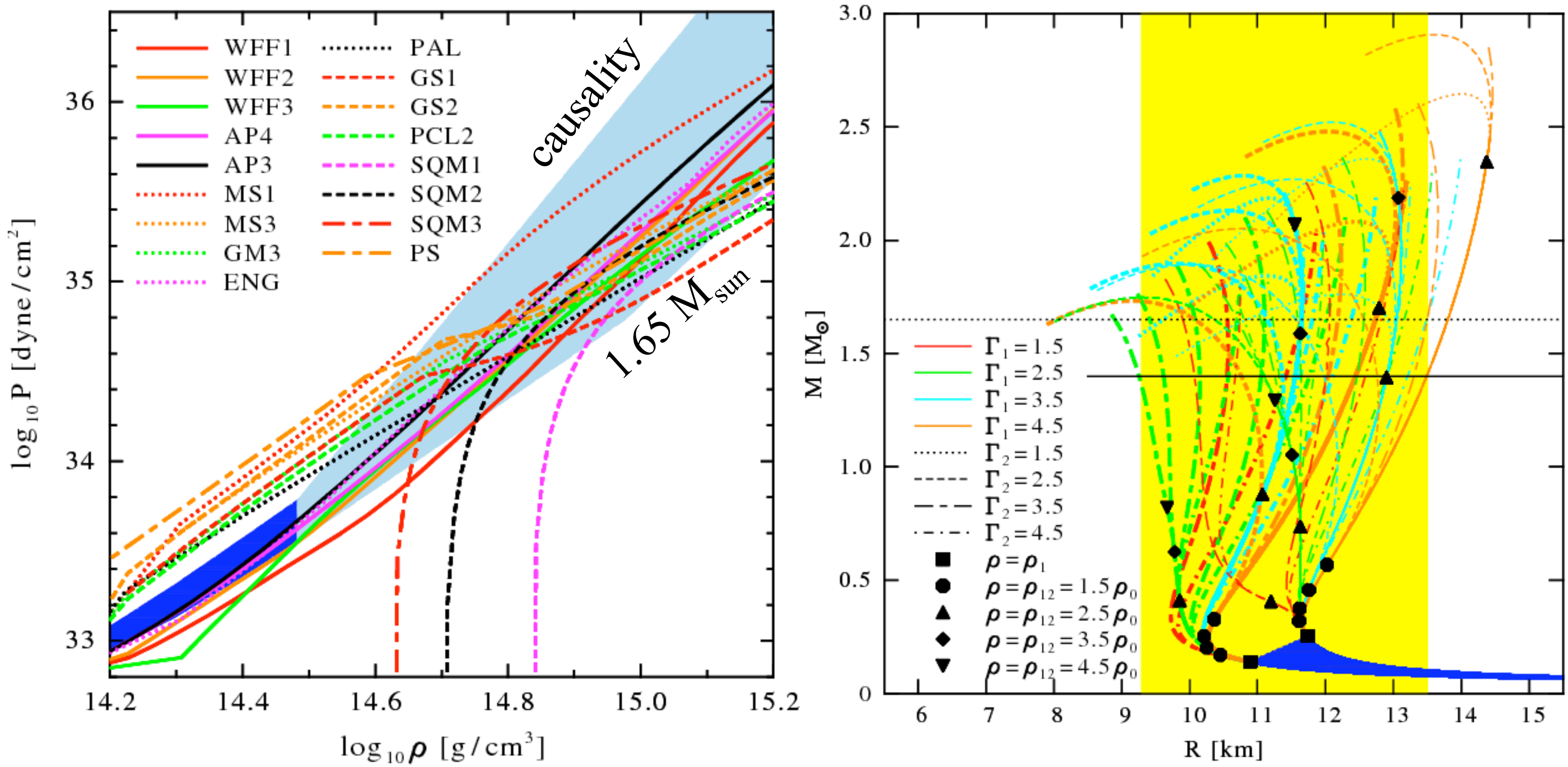
constrain polytropes by causality and require to support 1.65 M_{sun} star

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



low-density pressure sets scale, our results reduce spread at nuclear densities in current neutron star modeling from factor 6 to ±25%

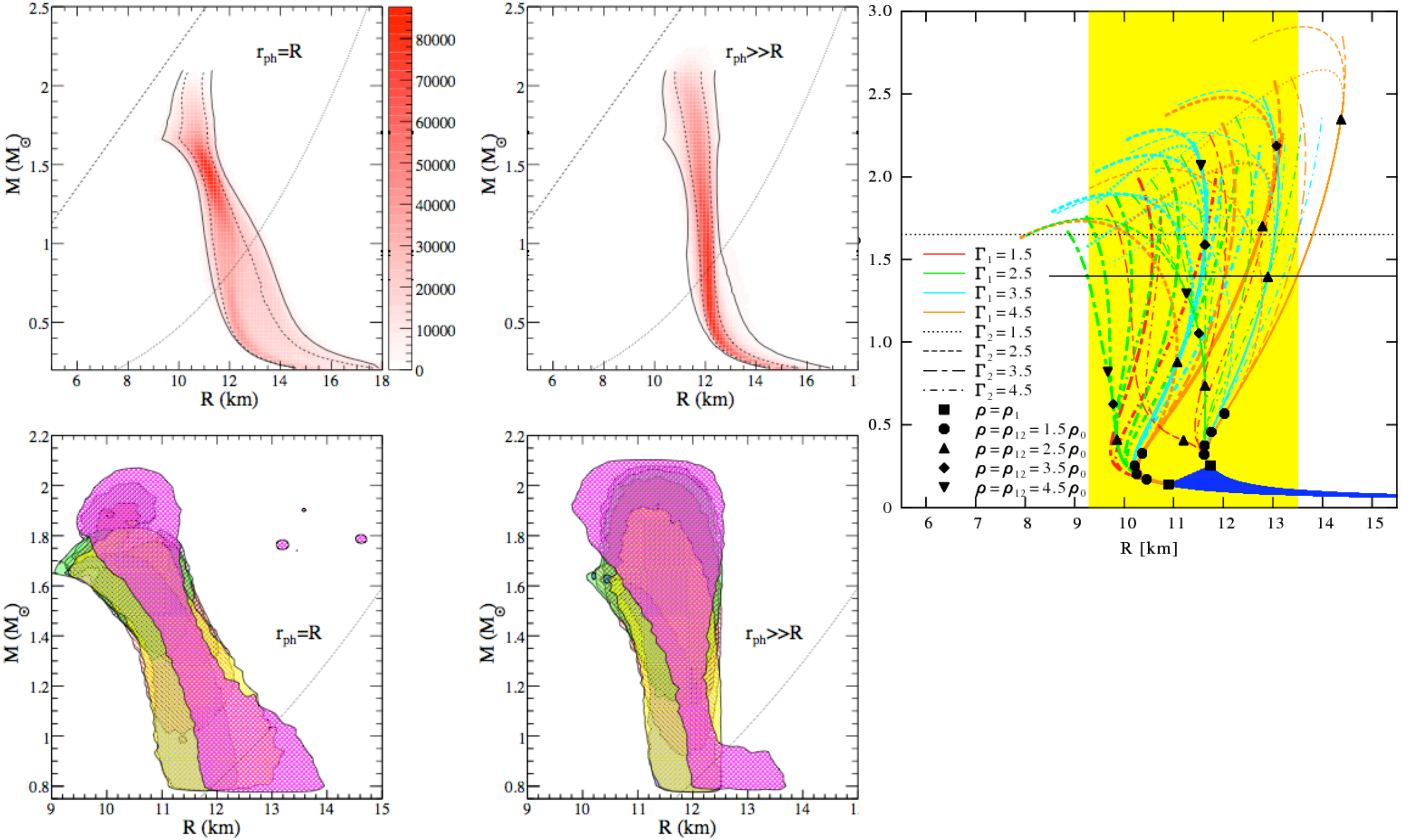
Impact on neutron stars Hebeler, Lattimer, Pethick, AS (2010)



low-density pressure sets scale, our results reduce spread at nuclear densities in current neutron star modeling from factor 6 to ±25%

constrains neutron star radius to 9.7-13.9 km for $M=1.4\ M_{sun}$

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



constrains neutron star radius to 9.7-13.9 km for M=1.4 M_{sun}

consistent with modeling of X-ray burst sources Steiner, Lattimer, Brown (2010)

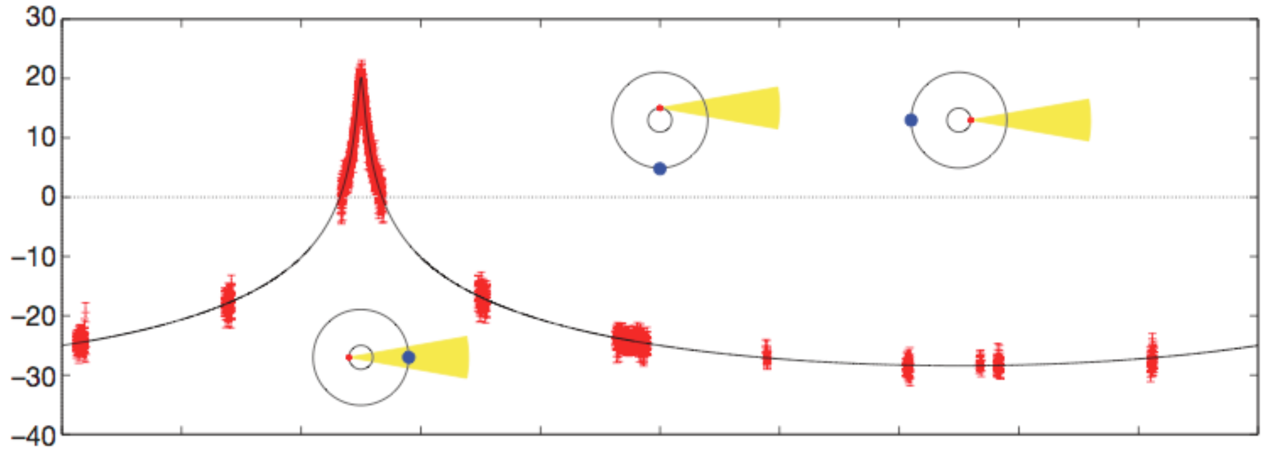
doi:10.1038/nature09466

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

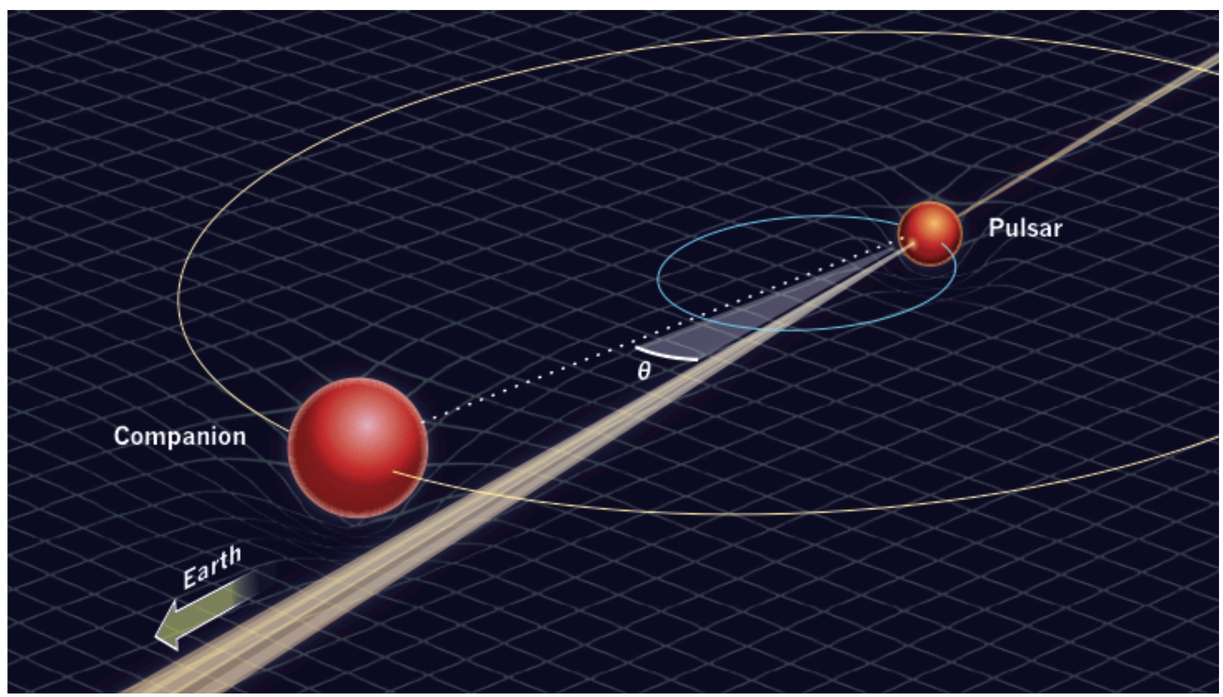
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

Nature, Oct. 28, 2010

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

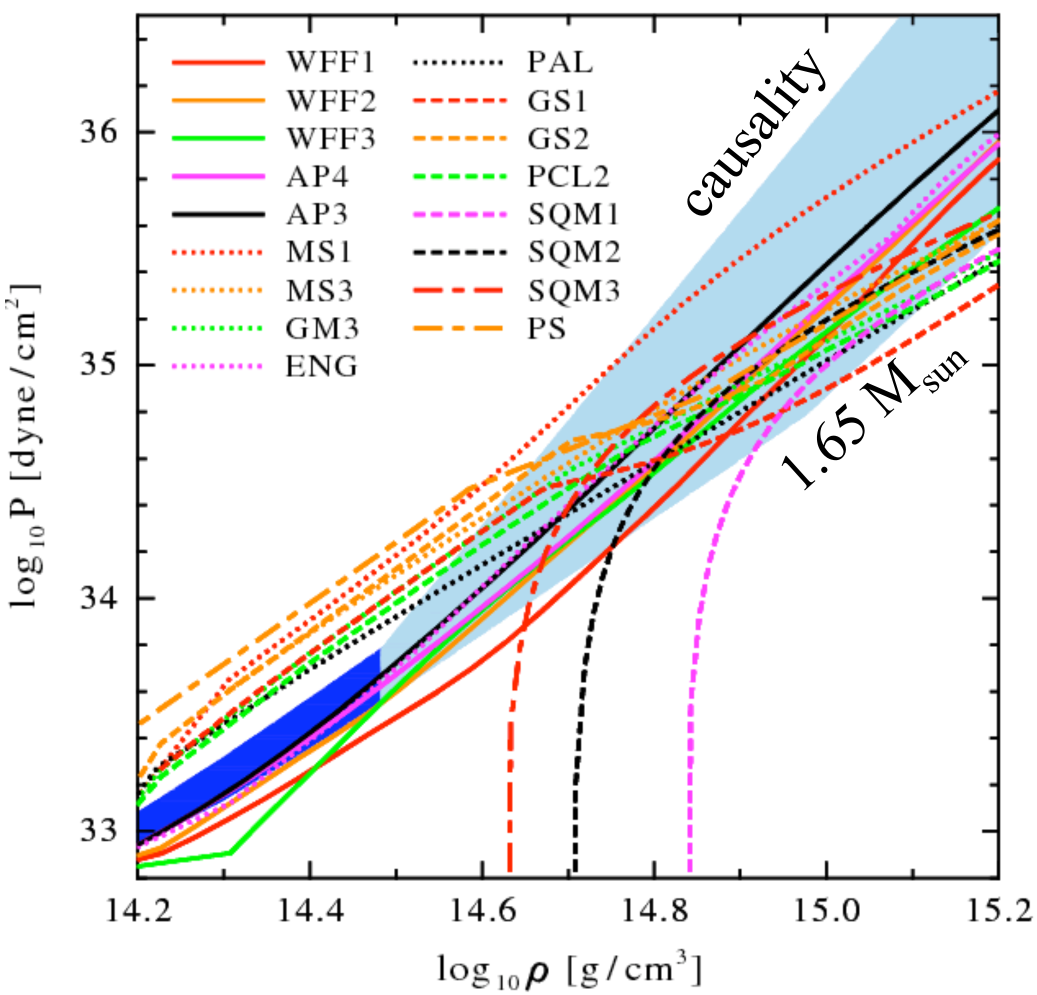


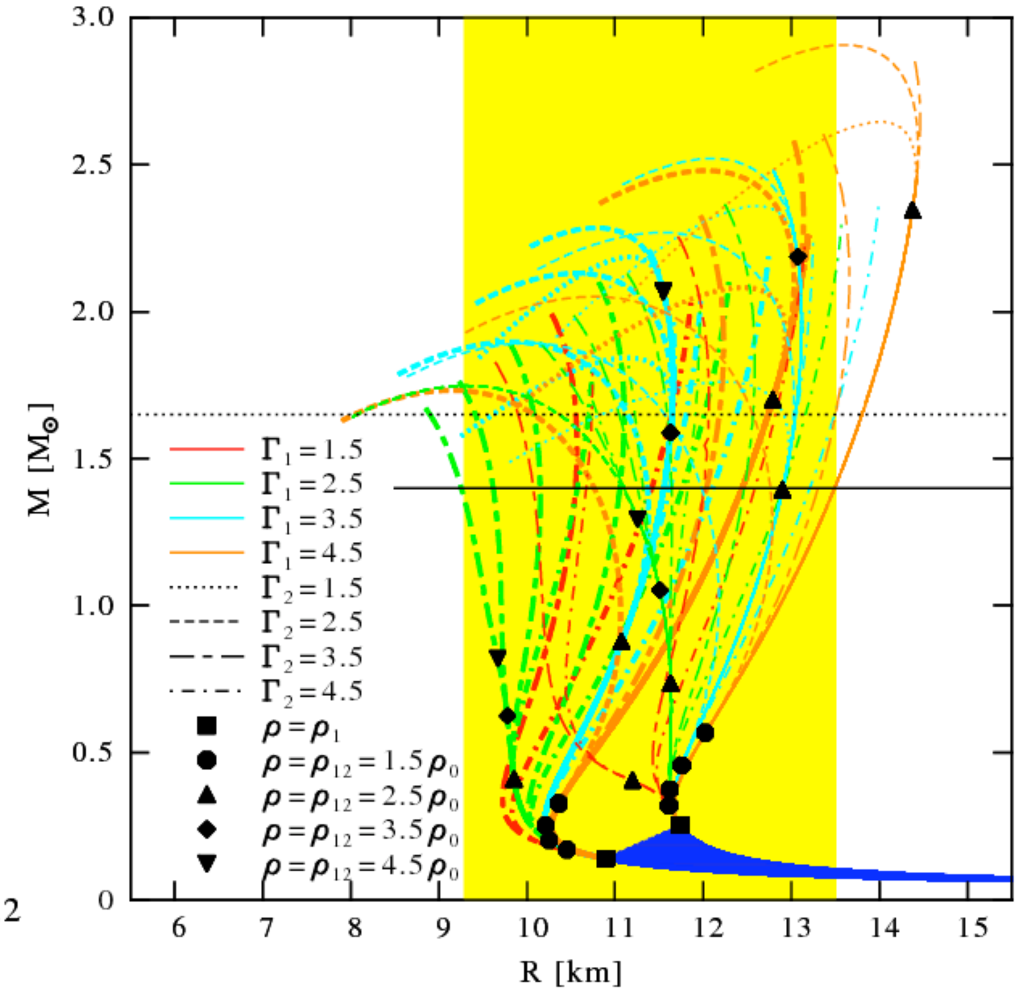
J1614-2230
most edge-on binary pulsar known (89.17°)
+ massive white dwarf companion (0.5 M_{sun})



heaviest neutron star with 1.97±0.04 M_{sun}

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





low-density pressure sets scale, our results reduce spread at nuclear densities in current neutron star modeling from factor 6 to ±25%

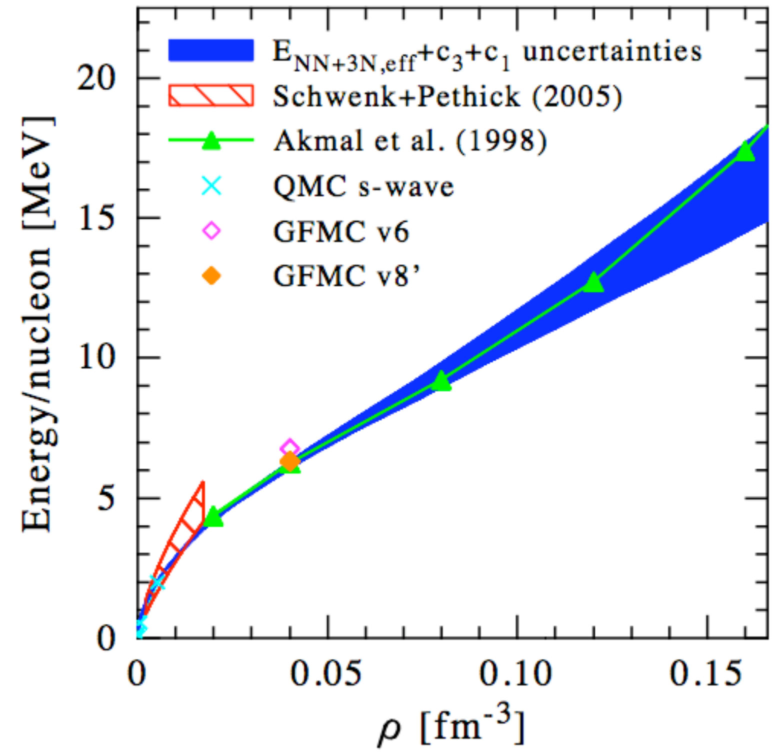
constrains neutron star radius to 9.7-13.9 km for M=1.4 M$_{sun}$

using 2.0 M$_{sun}$ constraint: 10.9-13.9 km (12% uncertainty!)

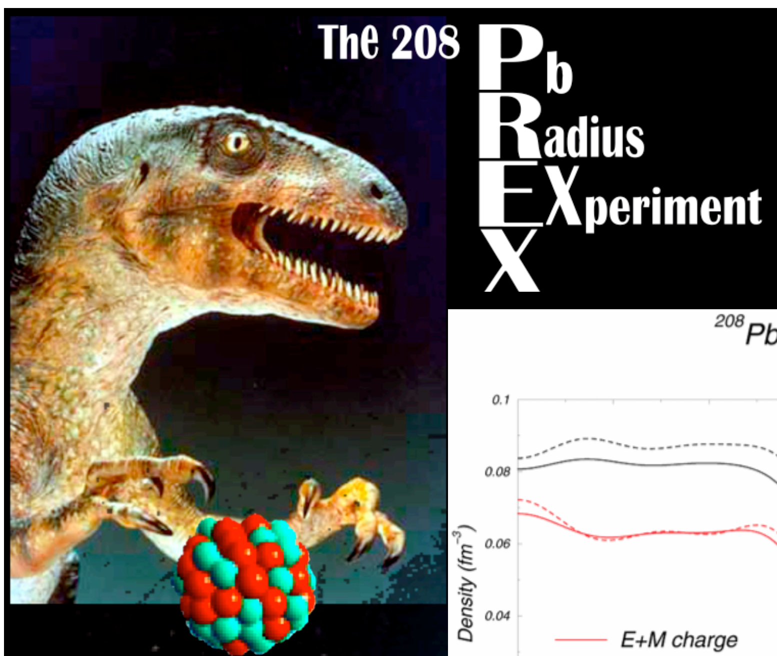
Symmetry energy and neutron skin Hebeler, Lattimer, Pethick, AS (2010)

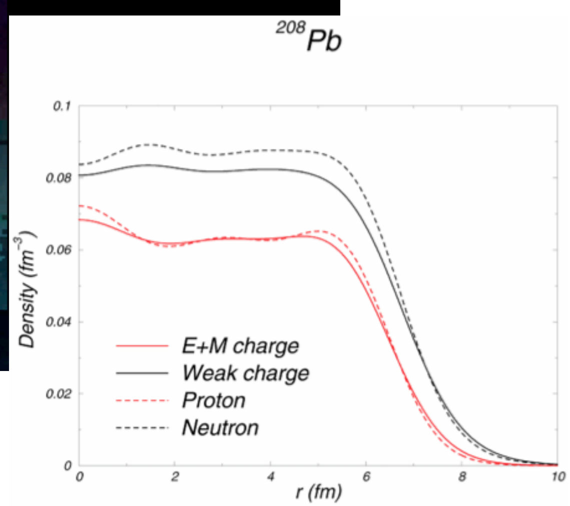
neutron matter band predicts range for symmetry energy 30.1-34.3 MeV

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 uncertainty goal of PREX @ JLAB

Thanks to collaborators!

J. Menendez

S.K. Bogner

R.J. Furnstahl,
K. Hebeler

A. Nogga

J.D. Holt

T. Otsuka

T. Suzuki

Y. Akaishi

C.J. Pethick

J.M. Lattimer

D. Gazit

Summary: From universal properties to neutron-rich extremes

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

universal properties and strong-interaction physics (corrections?)

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

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

N=28 magic number in calcium

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

intersections with atomic, condensed-matter, particle and astrophysics