Ultracold atoms and neutron-rich matter in nuclei and astrophysics

Achim Schwenk

NORDITA program “Pushing the boundaries with cold atoms”

Stockholm, Jan. 23, 2013

Outline

Advances in nuclear forces

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

3N forces and neutron matter/stars
with K. Hebeler, T. Krüger, I. Tews,
J.M. Lattimer, C.J. Pethick

Neutron polaron and density functionals
with M. Forbes, A. Gezerlis,
K. Hebeler, T. Lesinski

TECHNISCHE UNIVERSITÄT DARMSTADT
EMMI
東京大学 THE UNIVERSITY OF TOKYO
日本大学
THE OHIO STATE UNIVERSITY
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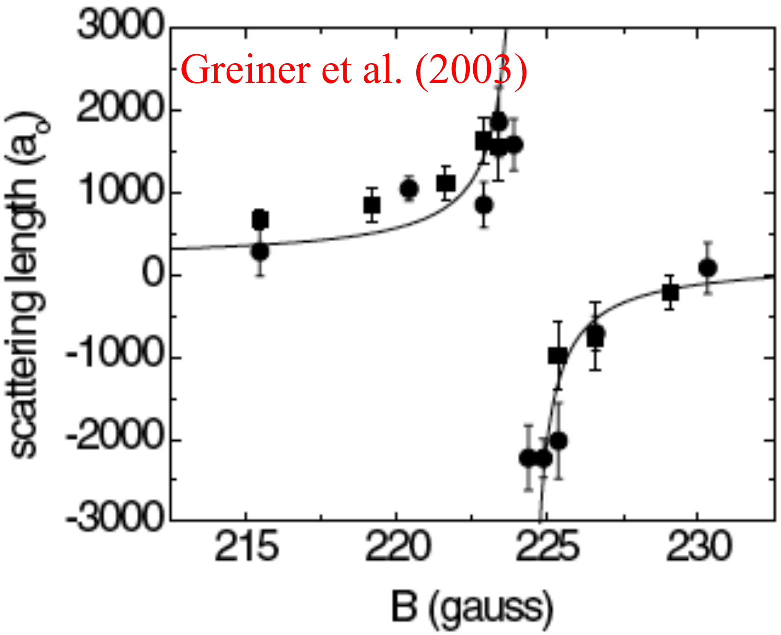
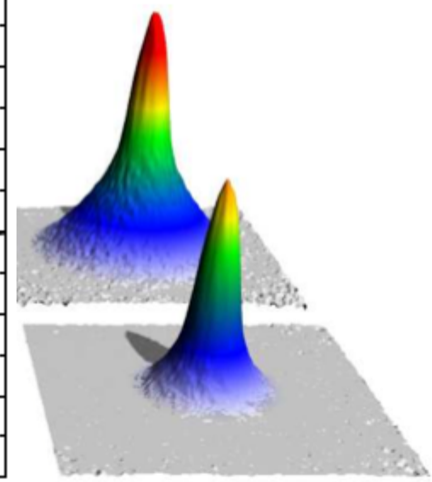
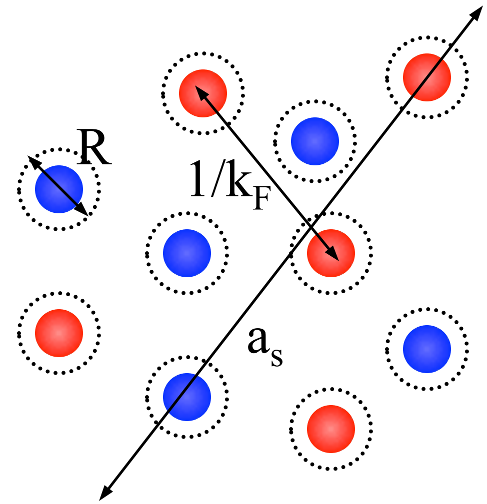
Large scattering lengths: Universal properties at low densities







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

strong interactions via Feshbach resonances — large for neutrons

dilute Fermi system with large scattering length has universal properties

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

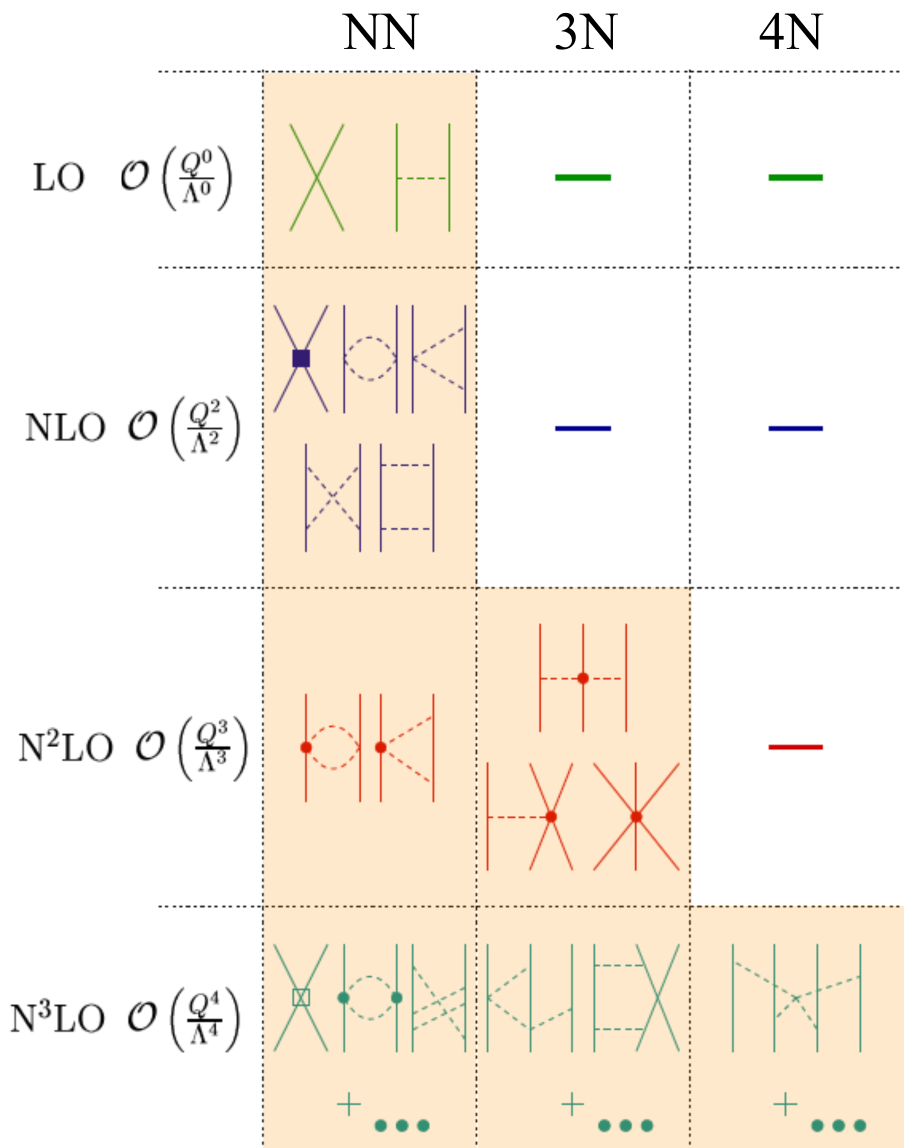
strongly-interacting — dilute

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

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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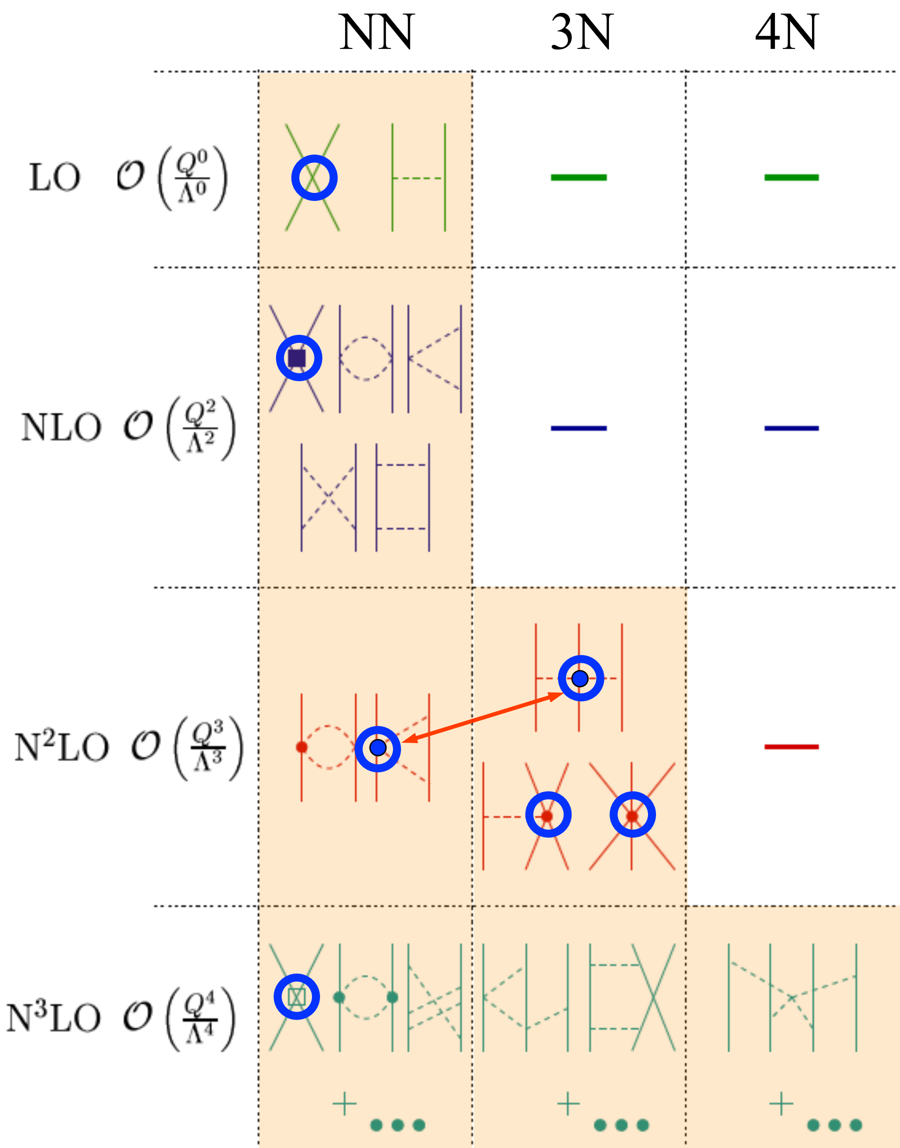

include long-range pion physics

few short-range couplings,
fit to experiment once

systematic: can work to desired accuracy and obtain **error estimates**

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

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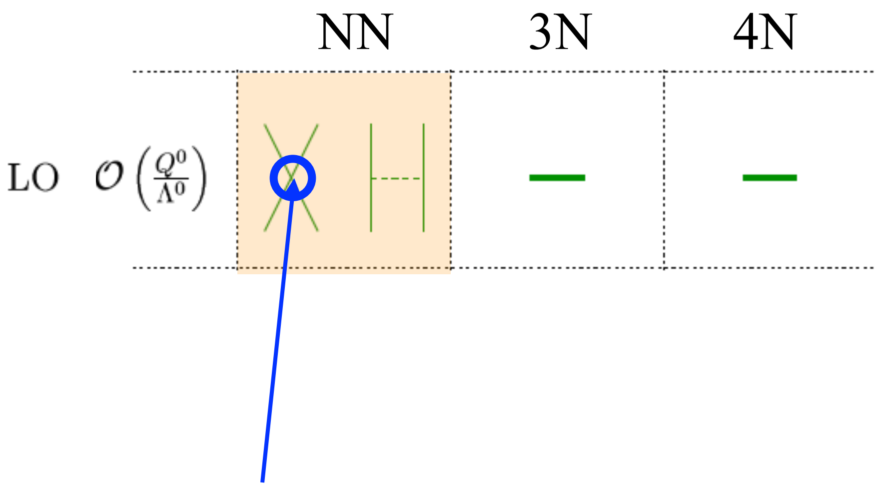
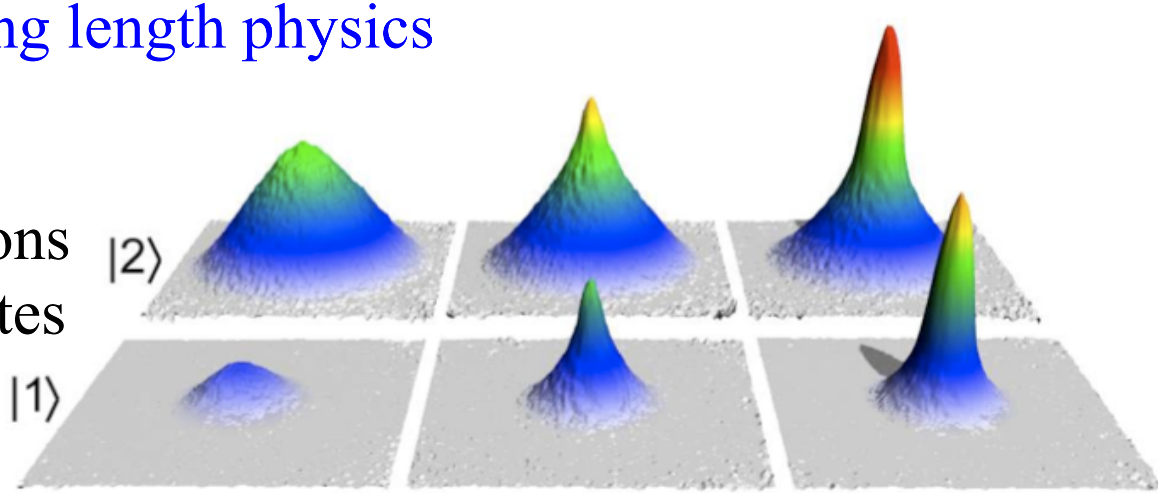


large scattering length physics

^{6}Li fermions
2 spin states



from M. Zwierlein

neutrons with same density, temperature and spin polarization
have the same properties!

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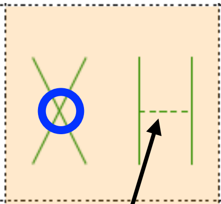
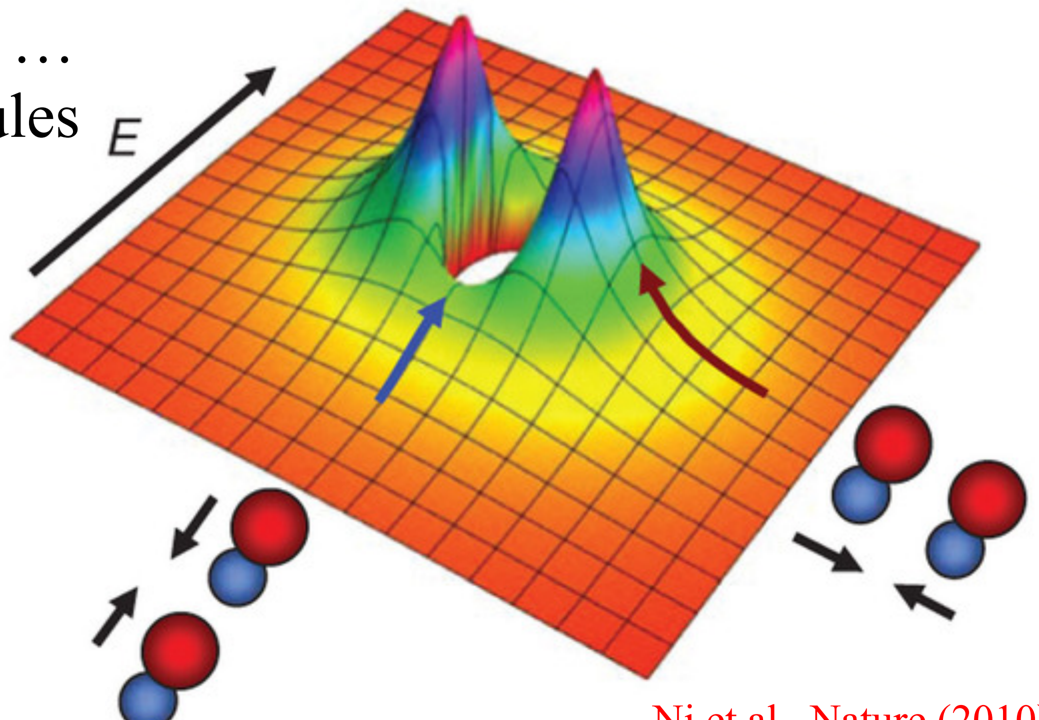
		NN	3N	4N
LO	$\mathcal{O}\left(\frac{Q^0}{\Lambda^0}\right)$		—	—

pion tensor/dipole interactions + …

→ compare to cold polar molecules



Ni et al., Nature (2010)

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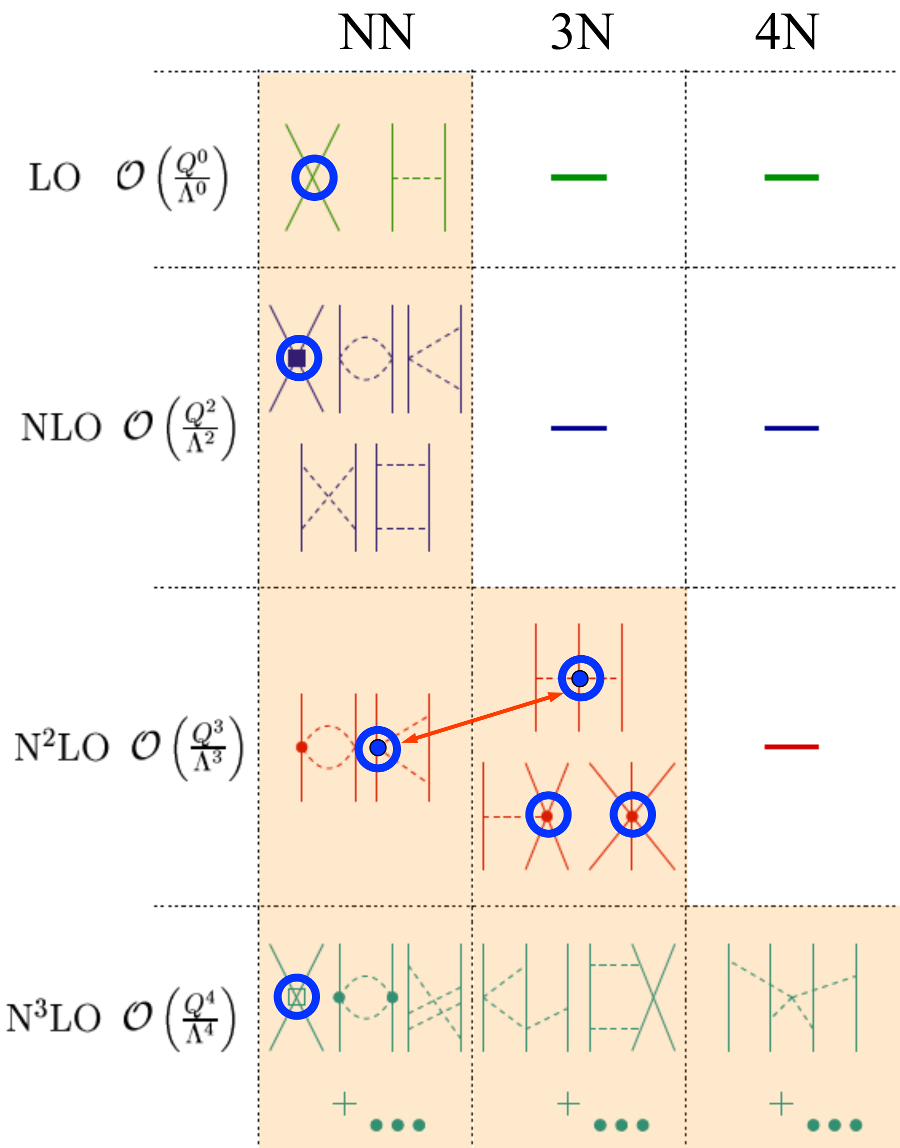

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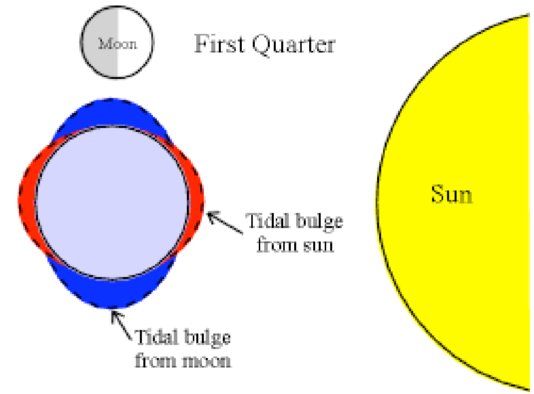
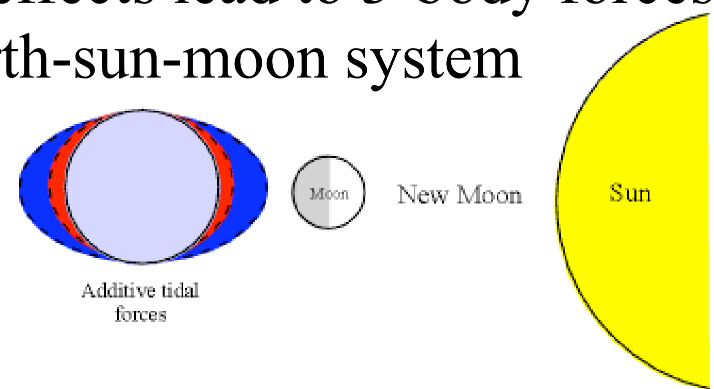
Why are there three-body forces?

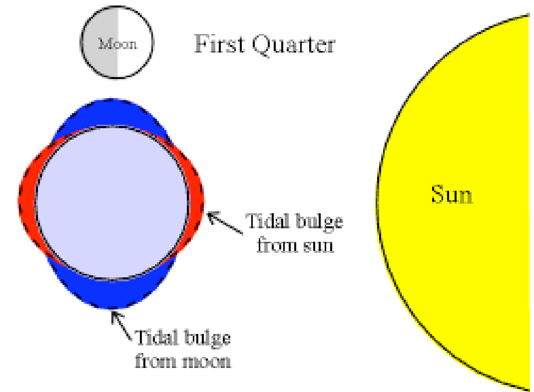


tidal effects lead to 3-body forces
in earth-sun-moon system

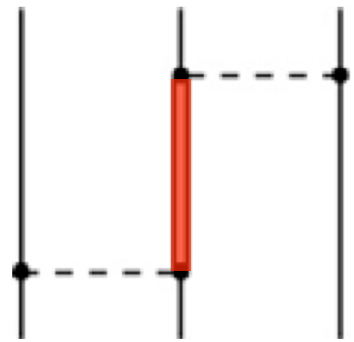


Why are there 3N forces?

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



dominant contribution from Δ(1232 MeV)



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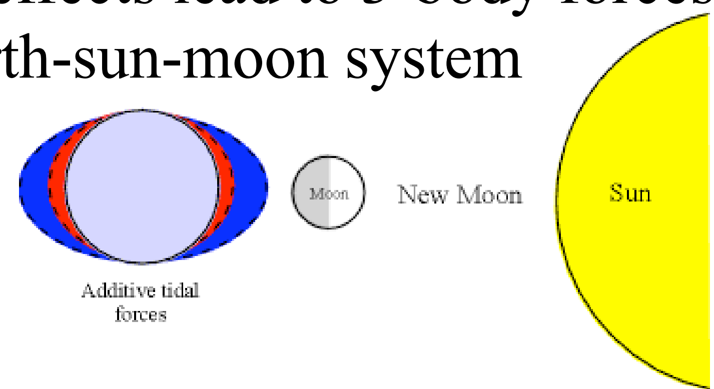
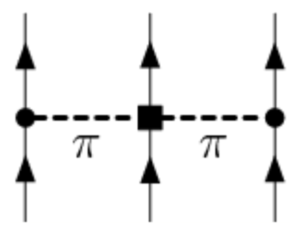


+ many shorter-range parts

chiral effective field theory (EFT)
Delta-less (Δ is treated as heavy):

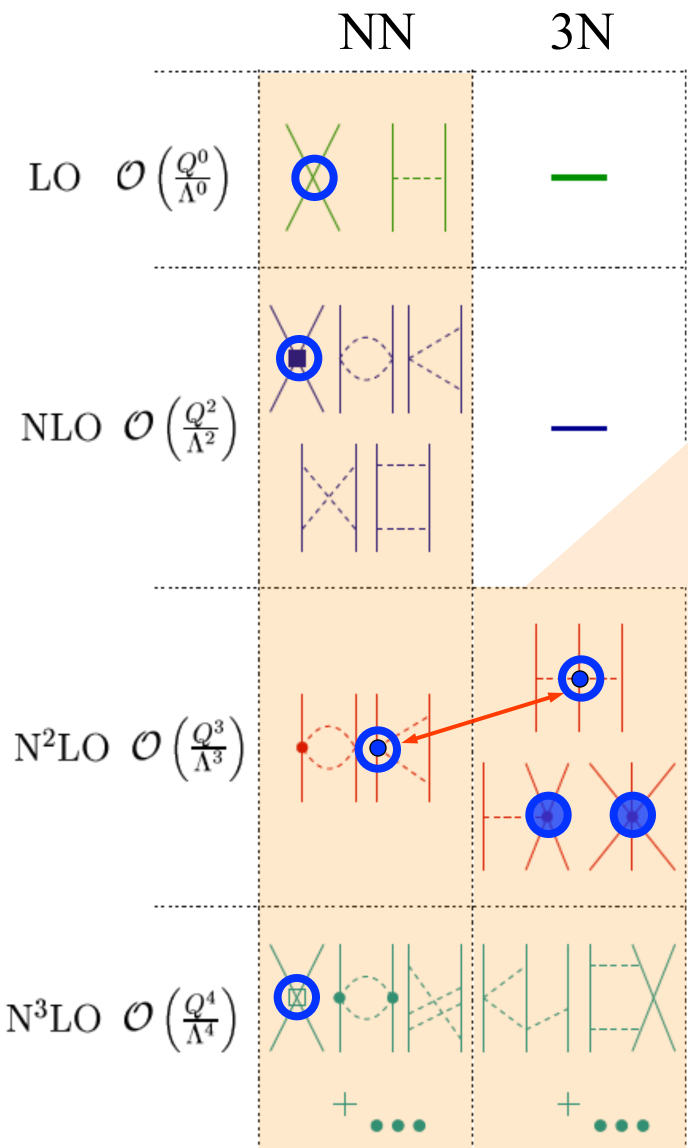


+ shorter-range parts

EFT provides a systematic and powerful approach for 3N forces

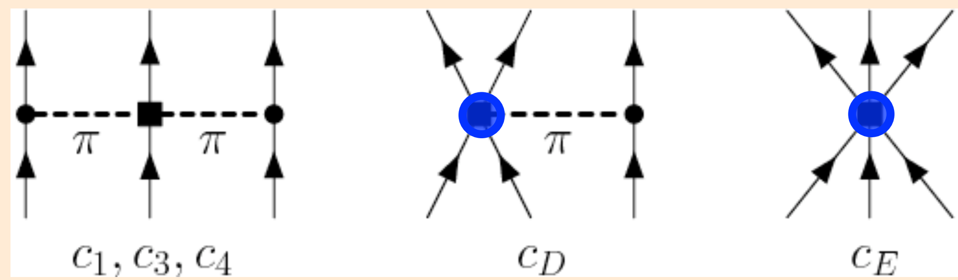
Chiral Effective Field Theory and many-body forces

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

c_D, c_E fit to ^{3}H, ^{4}He properties only

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

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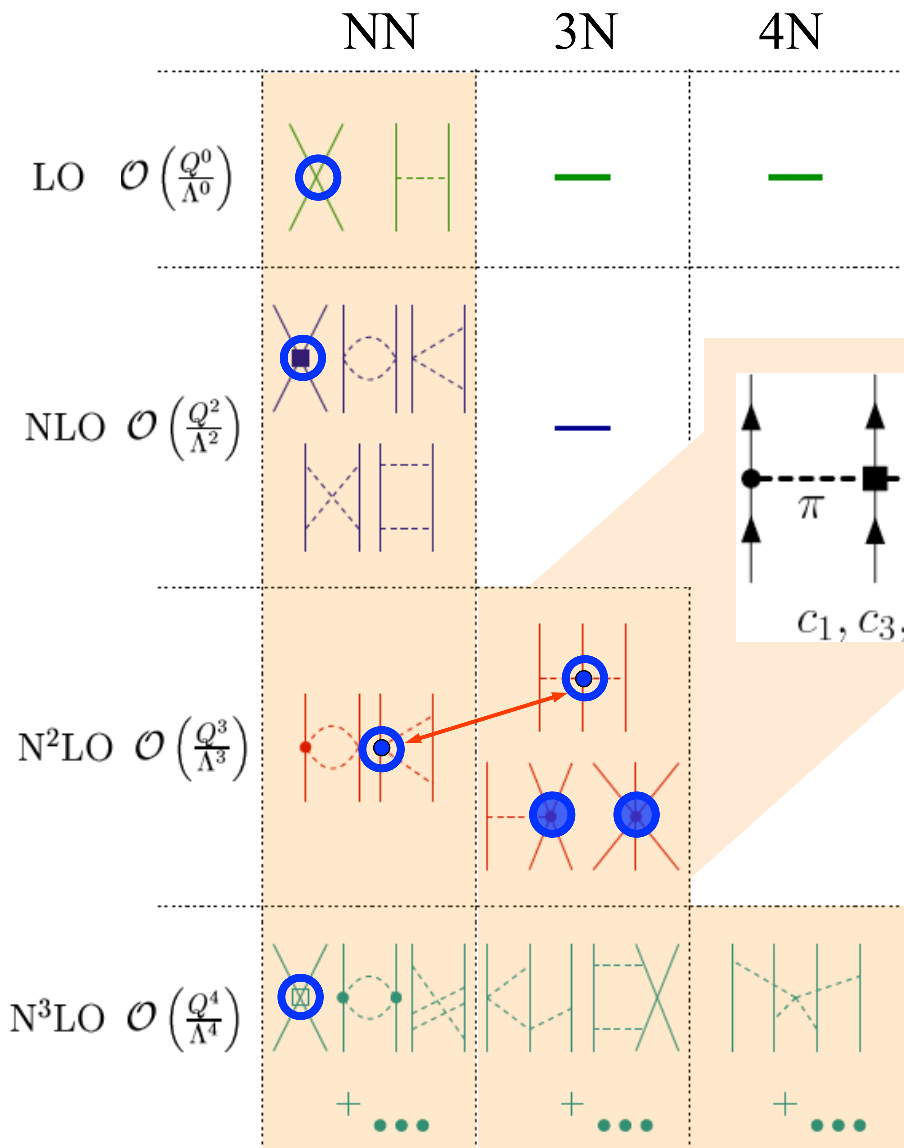
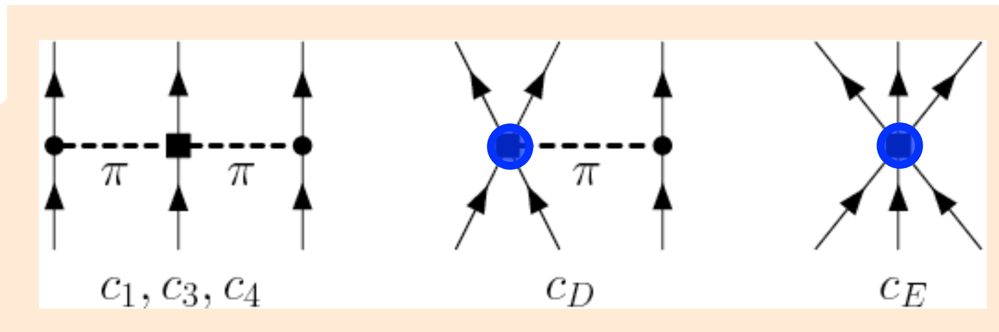


c_D, c_E don't contribute for neutrons because of Pauli principle and pion coupling to spin, also for c_4

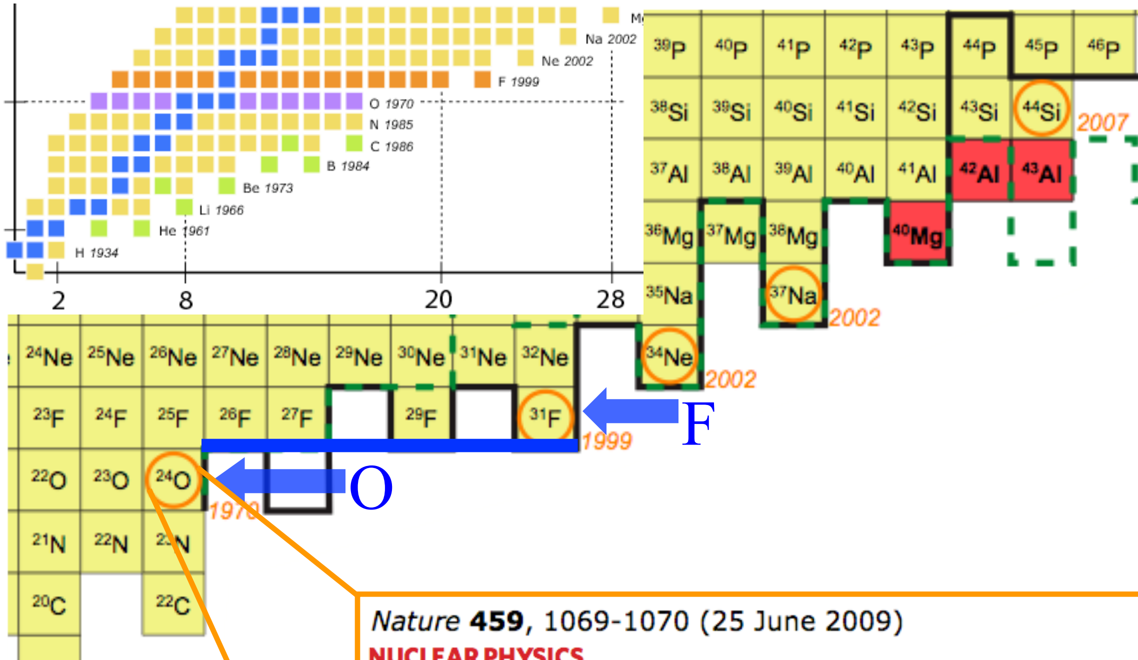
Hebeler, AS (2010)



all 3- and 4-neutron forces are predicted to N³LO!

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

The oxygen anomaly



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

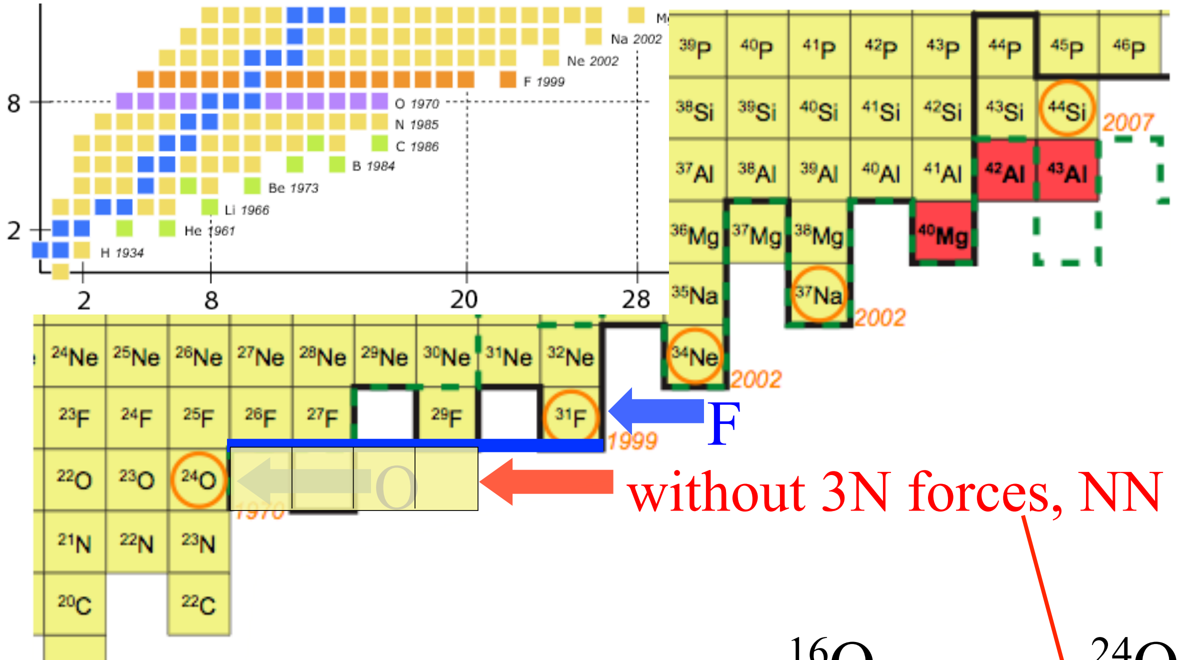
NUCLEAR PHYSICS

Unexpected doubly magic nucleus

Robert V. F. Janssens

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

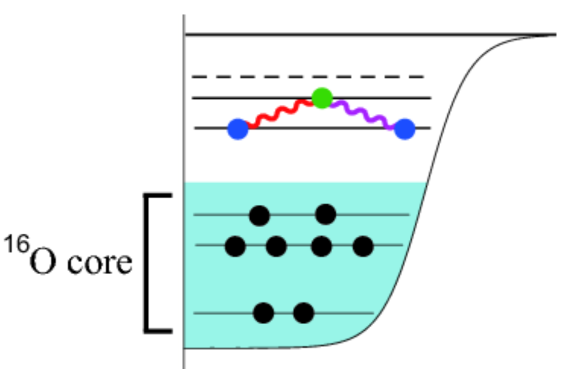
The oxygen anomaly - not reproduced without 3N forces

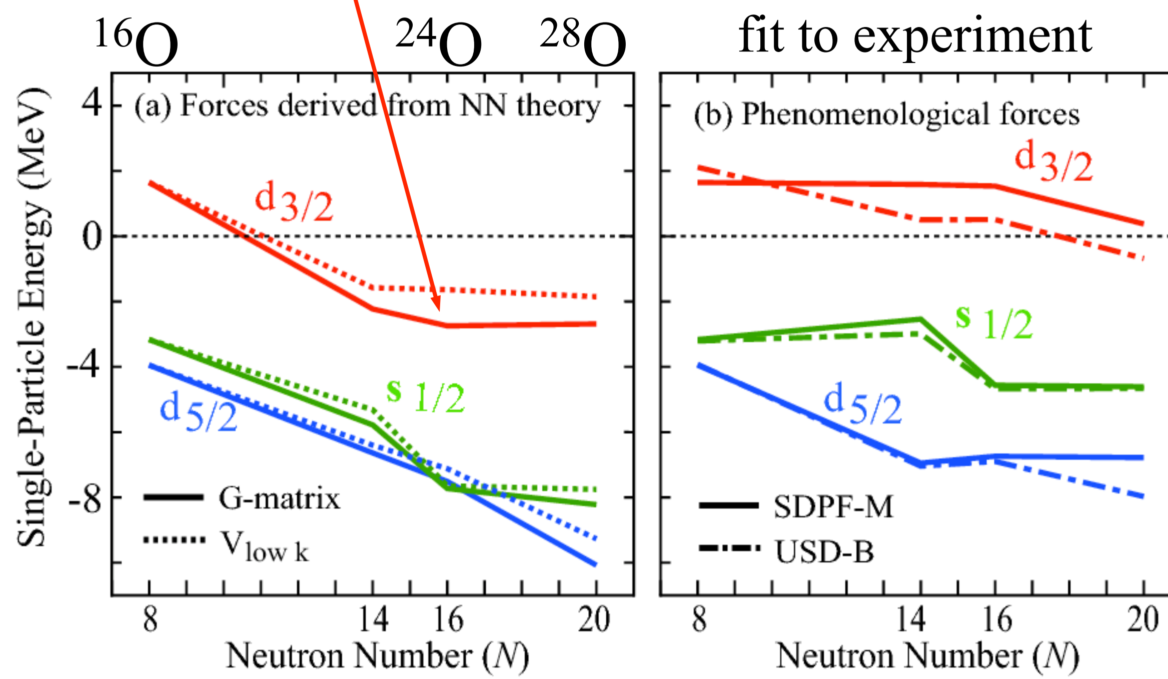


without 3N forces, NN interactions too attractive

many-body theory based on two-nucleon forces:

drip-line incorrect at ^{28}O





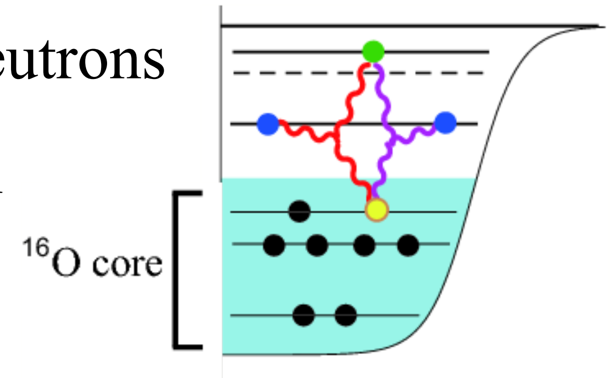
The shell model - impact of 3N forces

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 (2011)



Oxygen isotopes - impact of 3N forces

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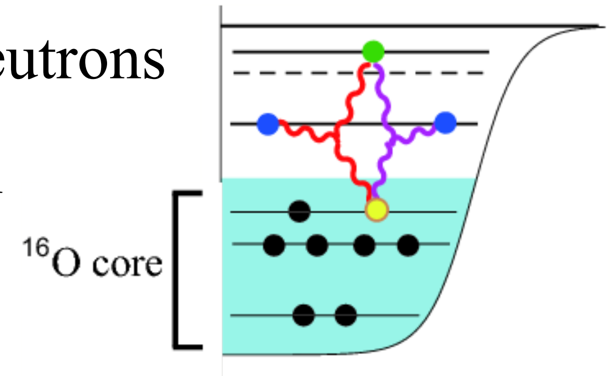
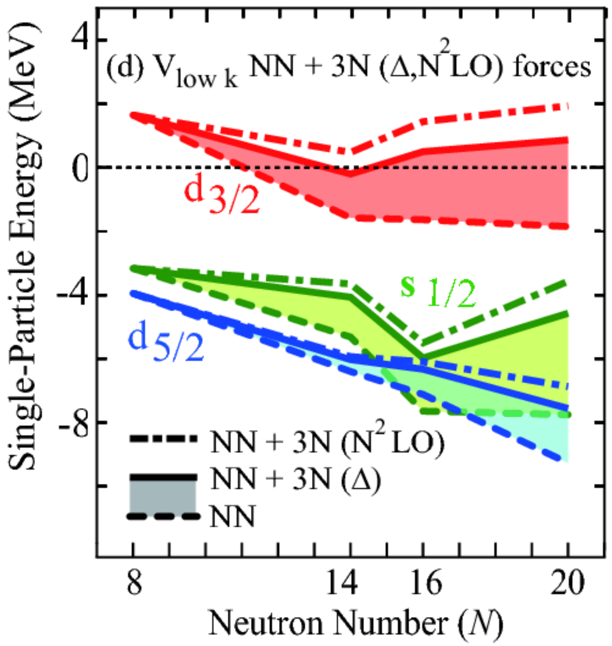
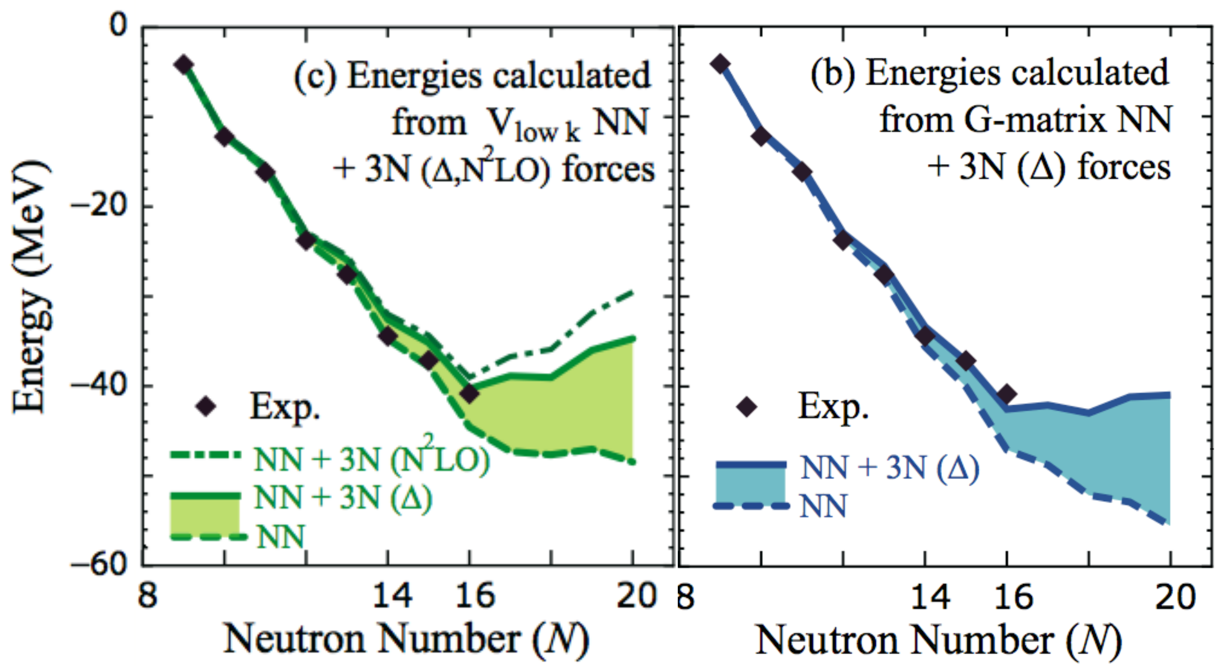


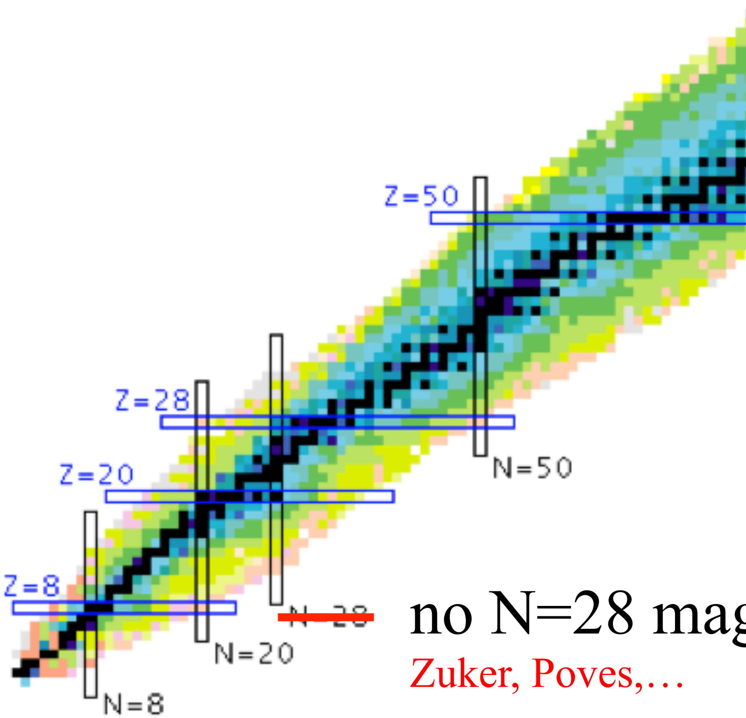
$d_{3/2}$ orbital remains unbound from ^{16}O to ^{28}O

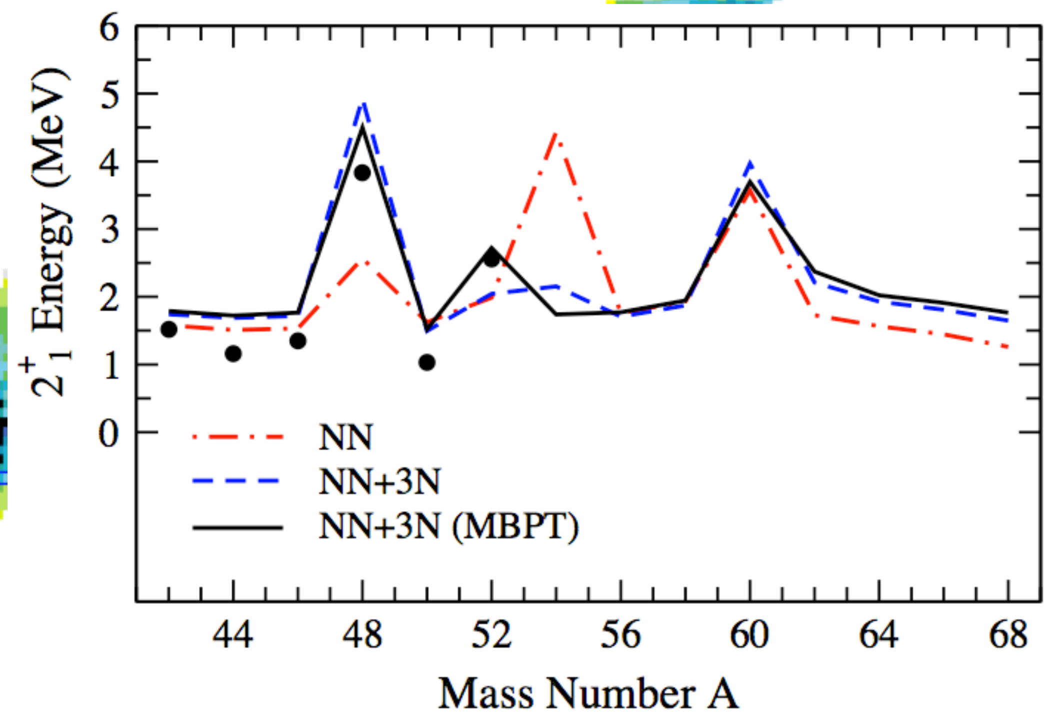




microscopic explanation of the oxygen anomaly Otsuka et al. (2010)

Three-body forces and magic numbers





Holt et al. (2010), Holt, Menendez, AS, in prep.

no N=28 magic number from microscopic NN forces

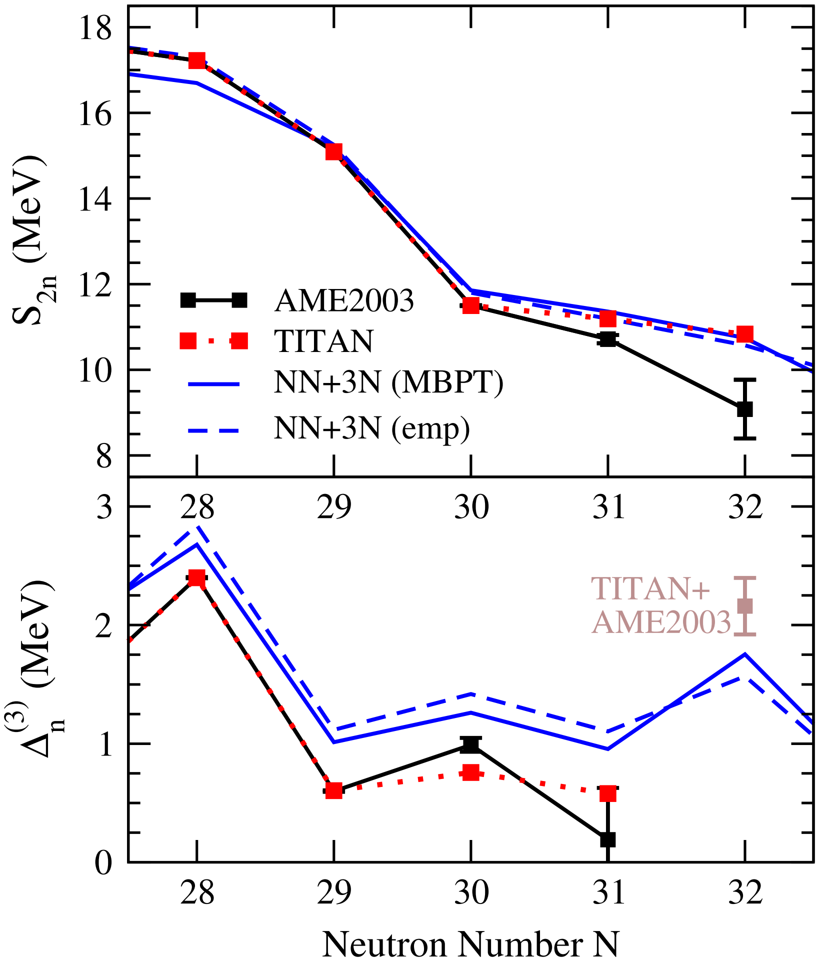
Zuker, Poves,…

new ^{51,52}Ca TITAN measurements

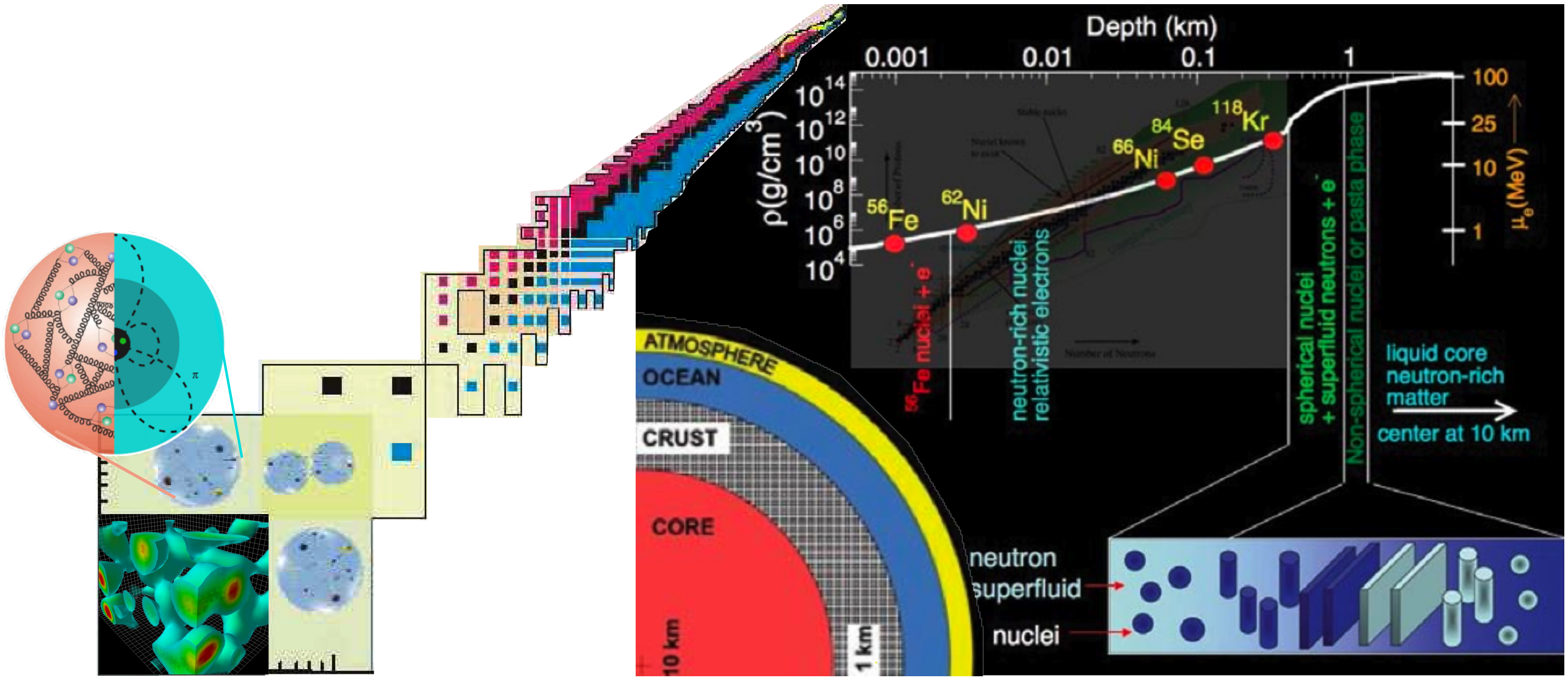
^{52}Ca is 1.75 MeV more bound compared to atomic mass evaluation

Gallant et al. (2012)

behavior of two-neutron separation energy S_{2n} and odd-even staggering Δ_n agrees with NN+3N predictions



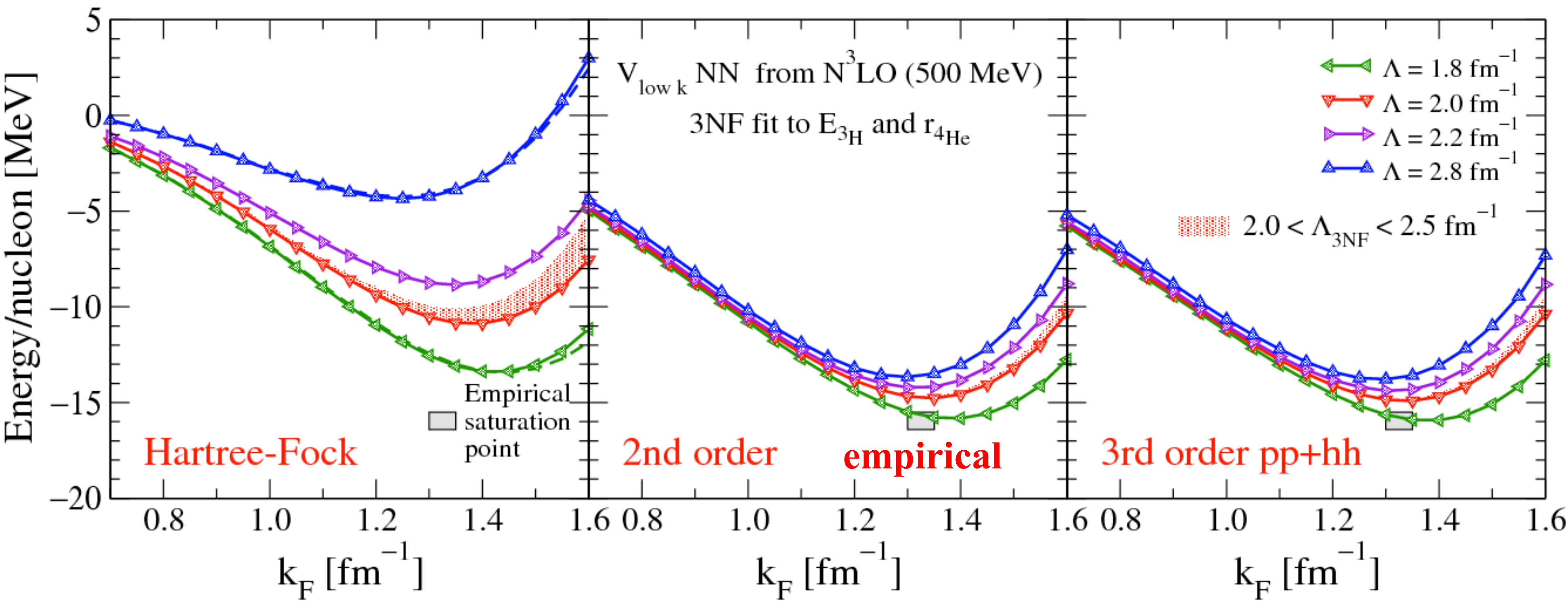
Neutron matter and neutron stars



Impact of 3N forces on nuclear matter

chiral 3N forces fit to light nuclei
predict nuclear matter saturation
with theoretical uncertainties

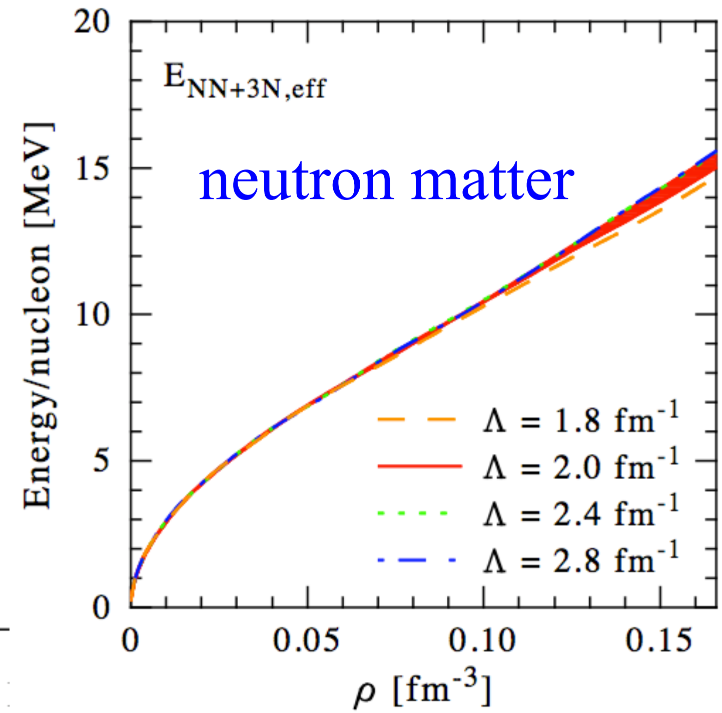
Hebeler et al. (2011), Bogner et al. (2005)

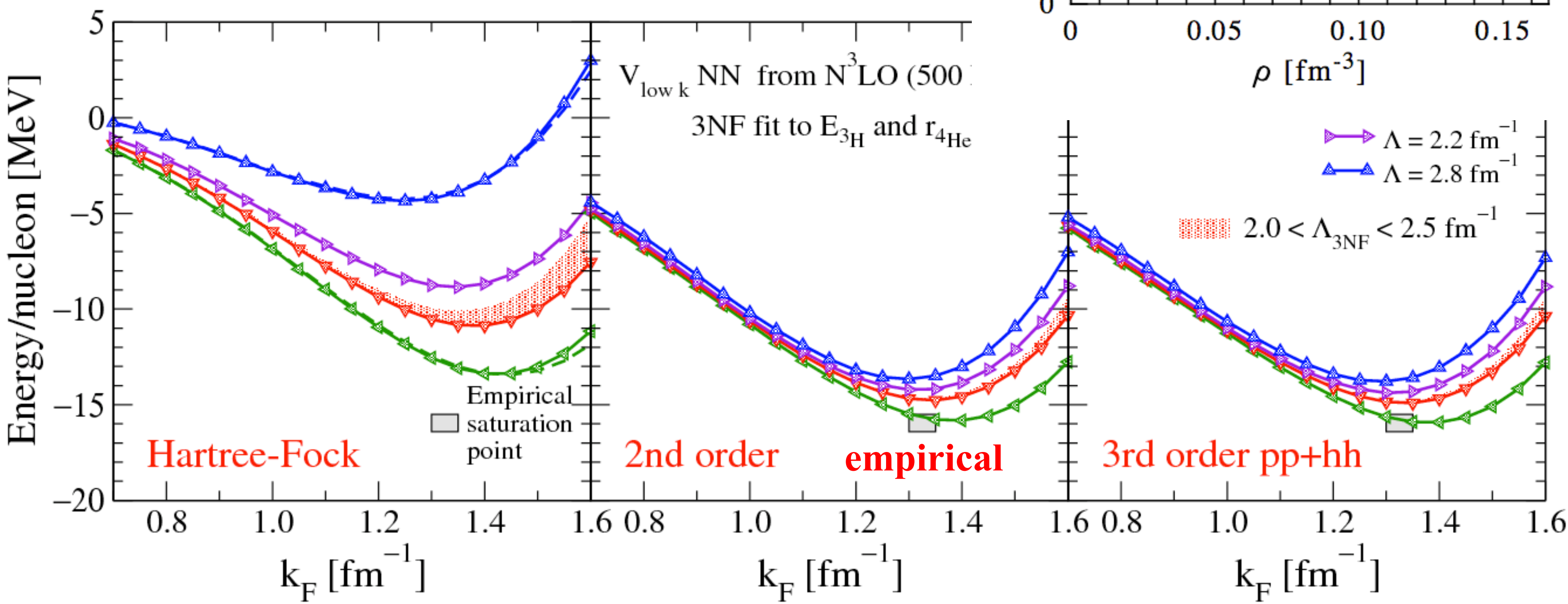


Impact of 3N forces on neutron matter

neutron matter is simpler system,
only long-range parts of 3N forces
contribute (c_1 and c_3)
Hebeler, AS (2010)

scales as in universal regime at low densities,
cold atoms provide anchor point





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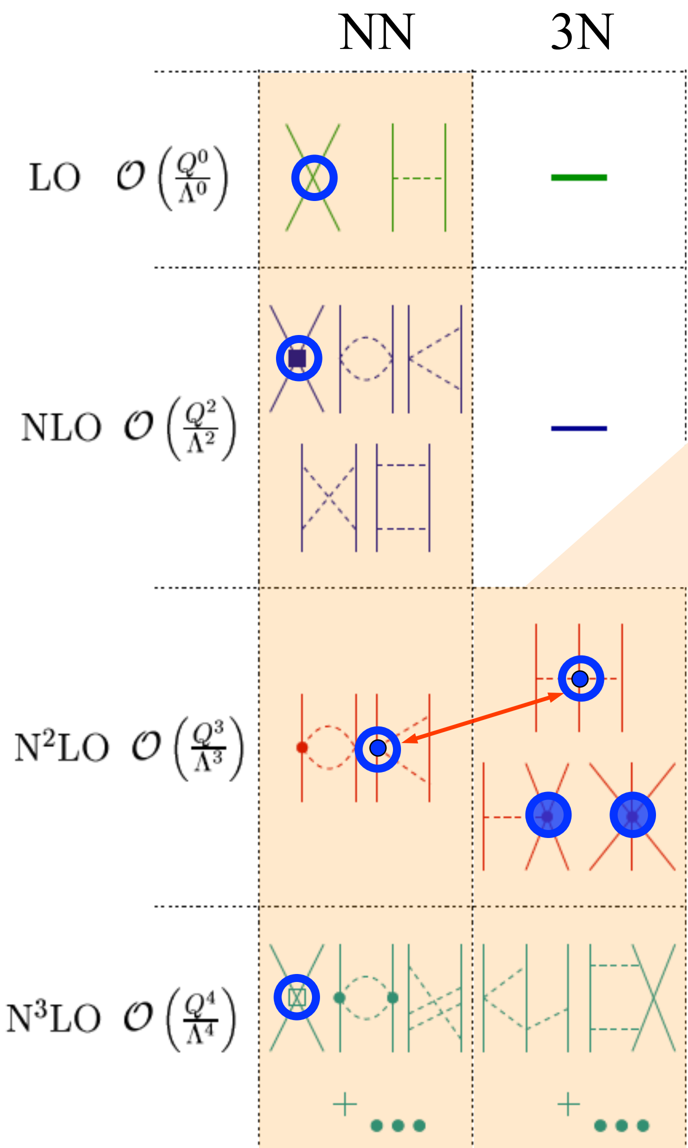

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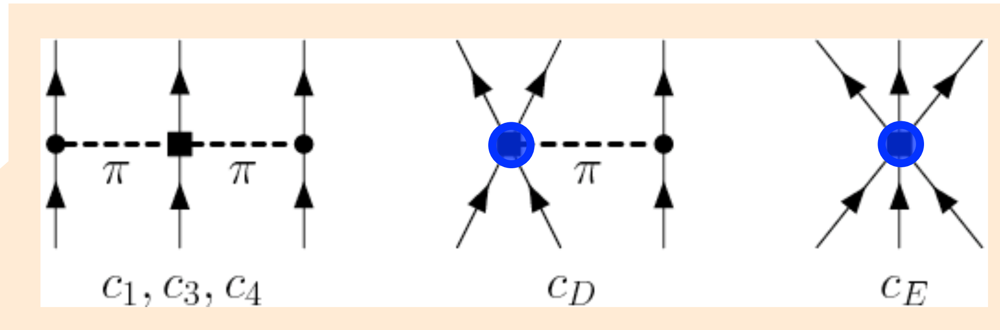

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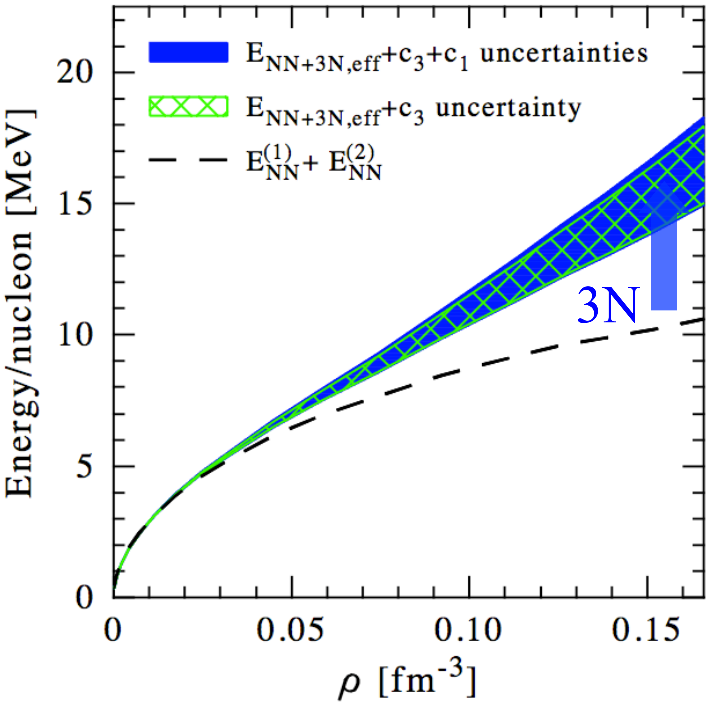
Impact of 3N forces on neutron matter

neutron matter uncertainties
dominated by 3N forces (c_3 coupling)

Hebeler, AS (2010)



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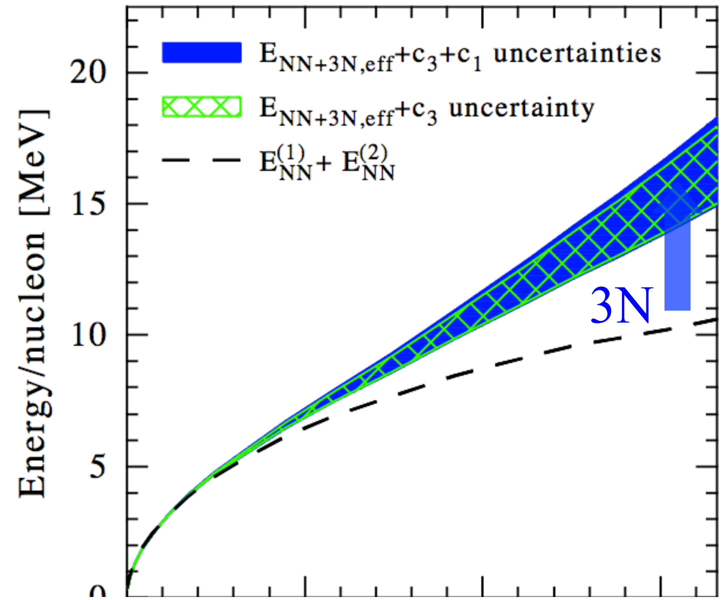
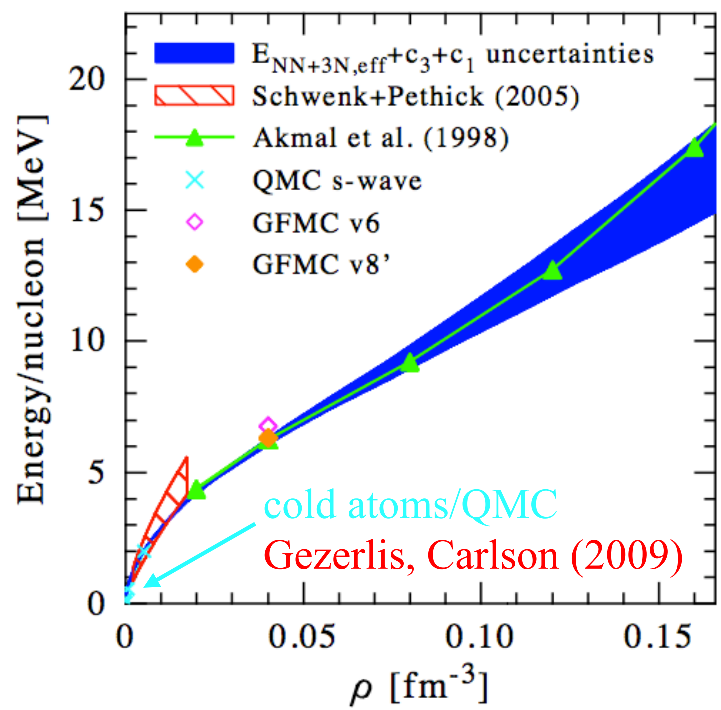


other microscopic calculations within band
(but without uncertainties)



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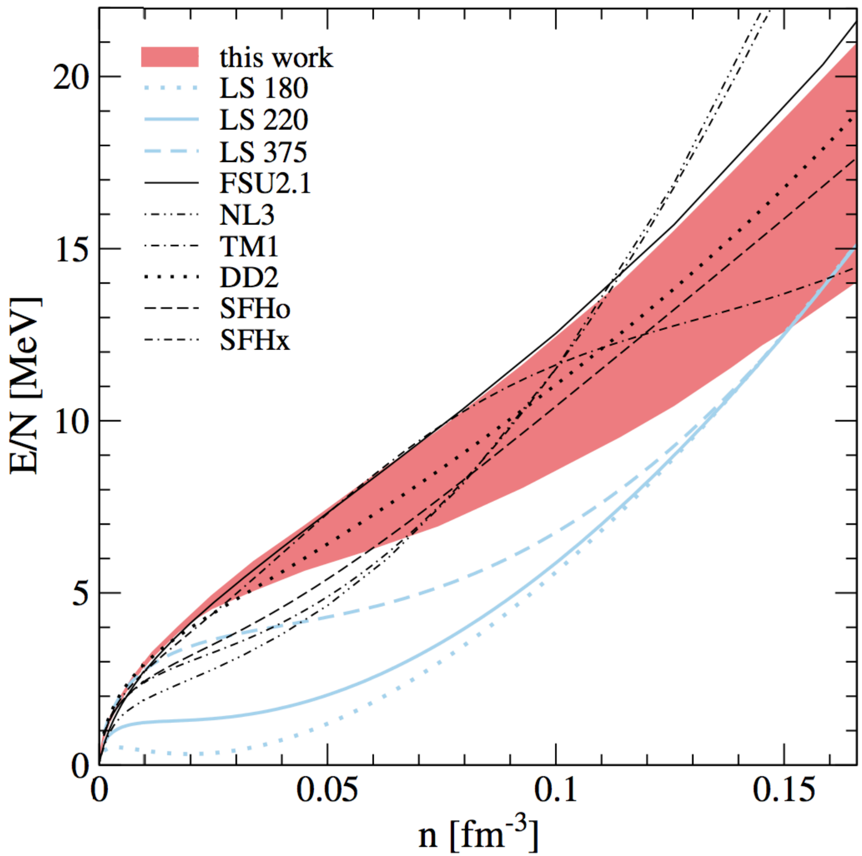
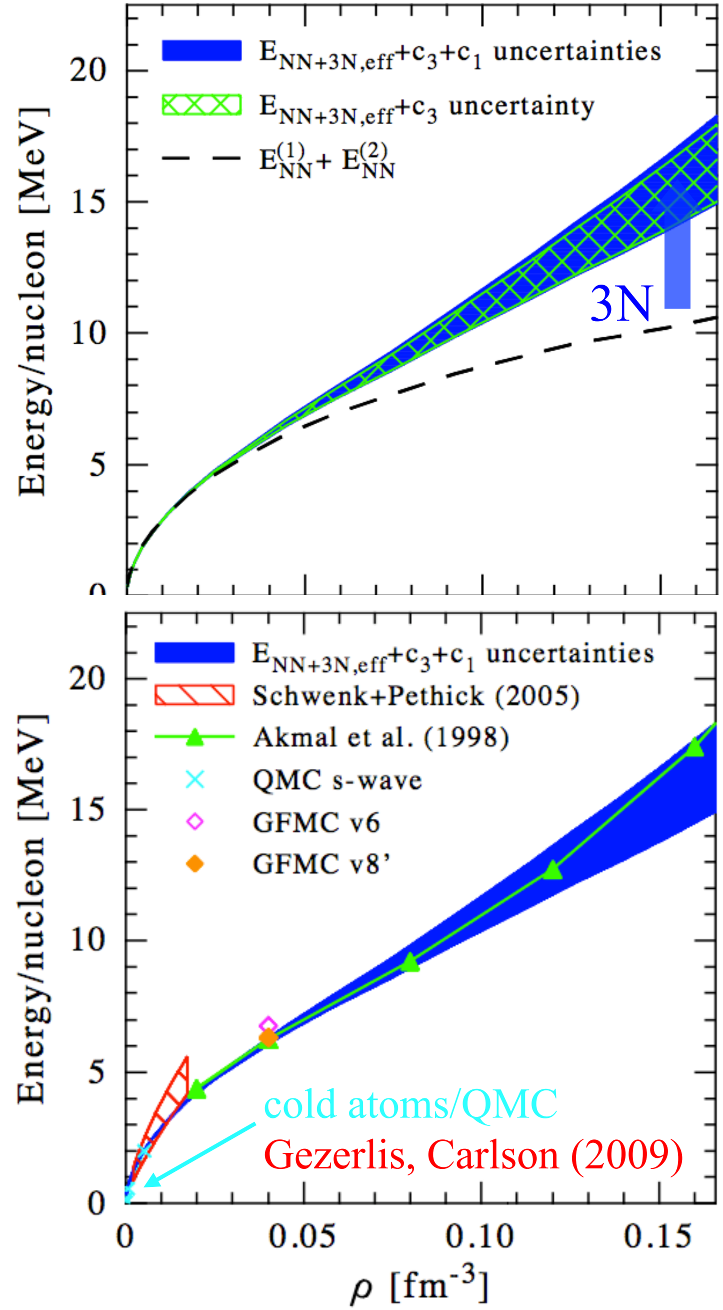
Hebeler, AS (2010)

Problem: many equations of state
not consistent with neutron matter results





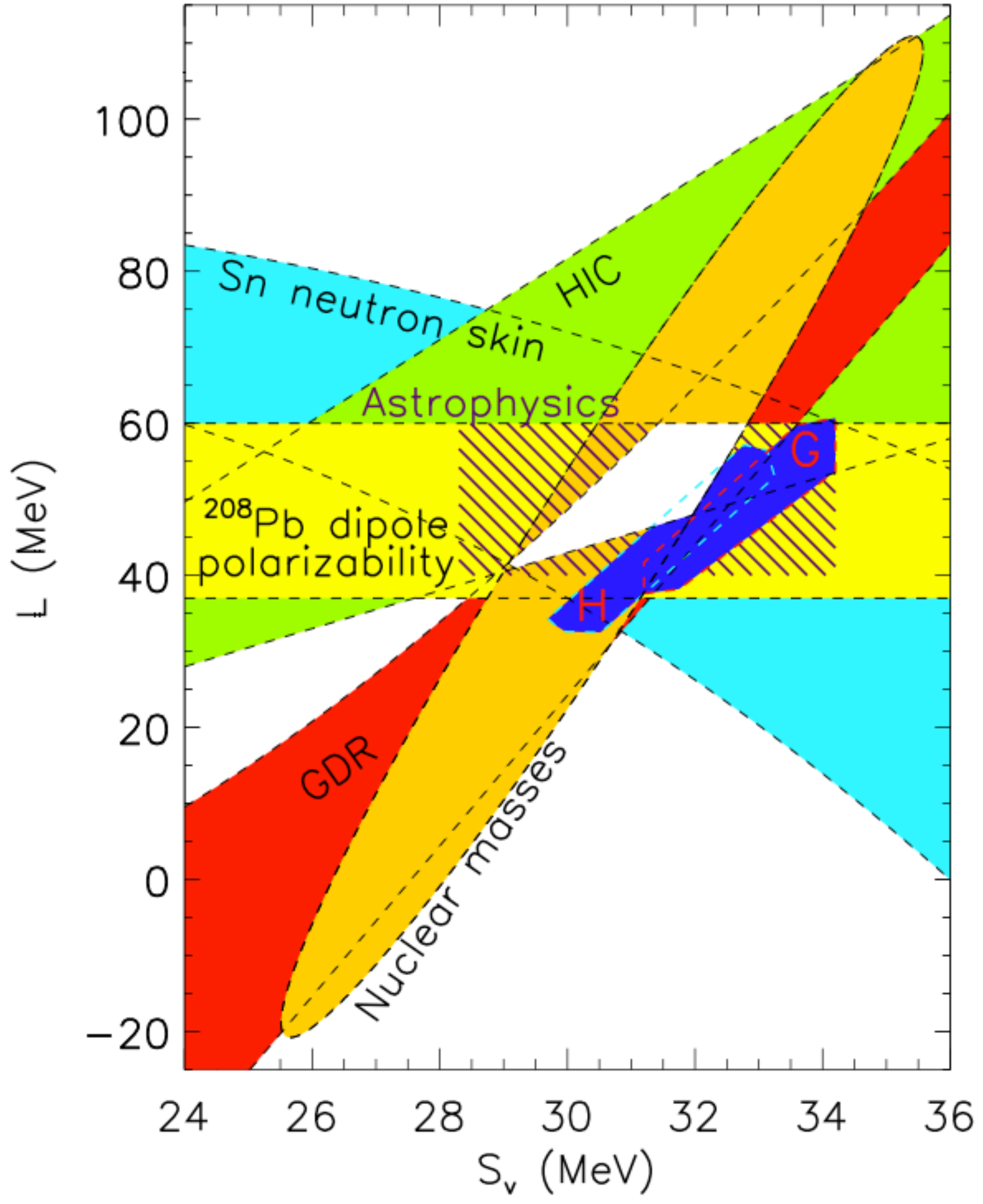
Symmetry energy and pressure of neutron matter

neutron matter band predicts symmetry energy S_v and its density dependence L

comparison to experimental and observational constraints
Lattimer, Lim (2012)

neutron matter constraints
H: Hebeler et al. (2010) and in prep.

G: Gandolfi et al. (2011)
predicts correlation but not range of S_v and L



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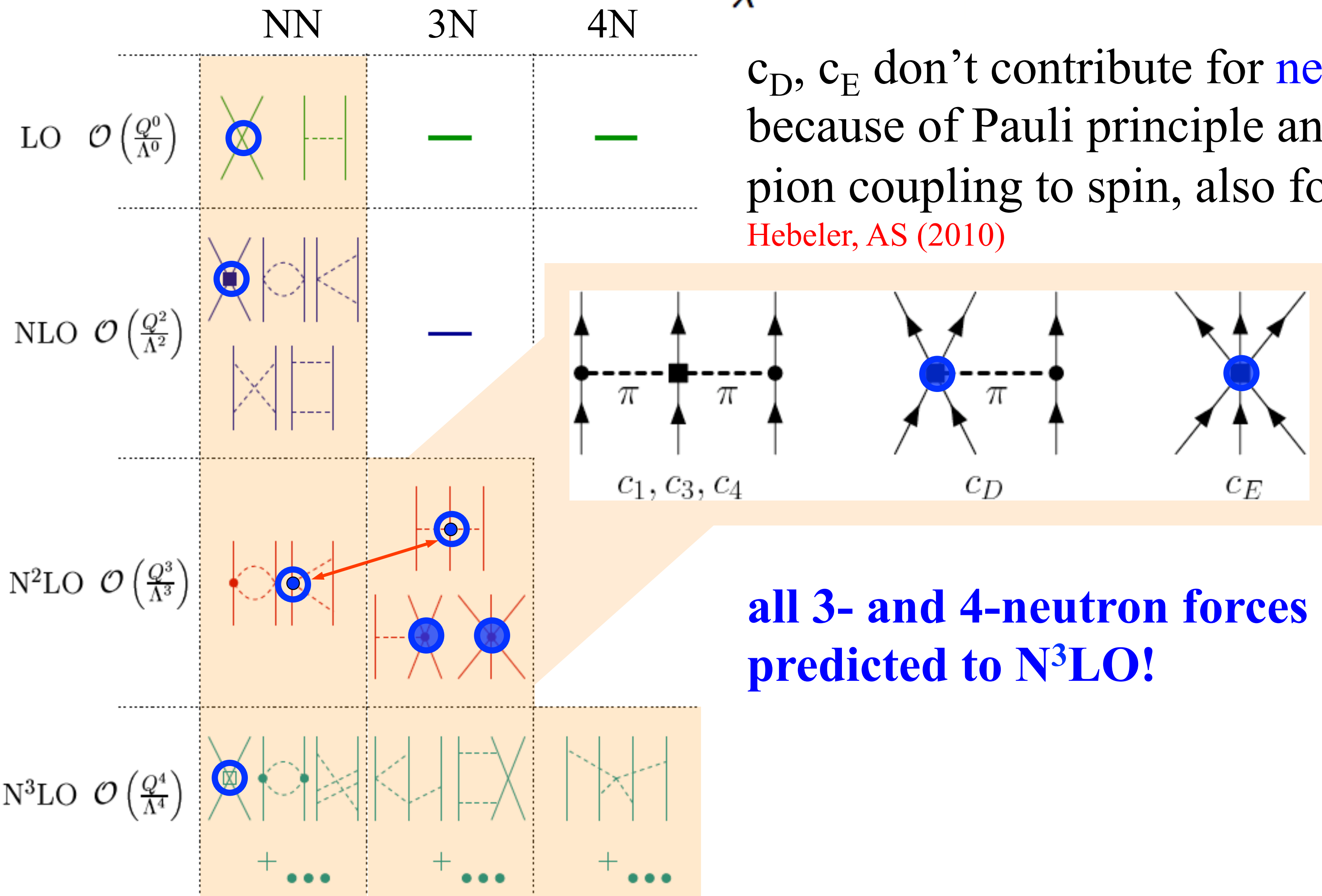

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Hebeler, AS (2010)

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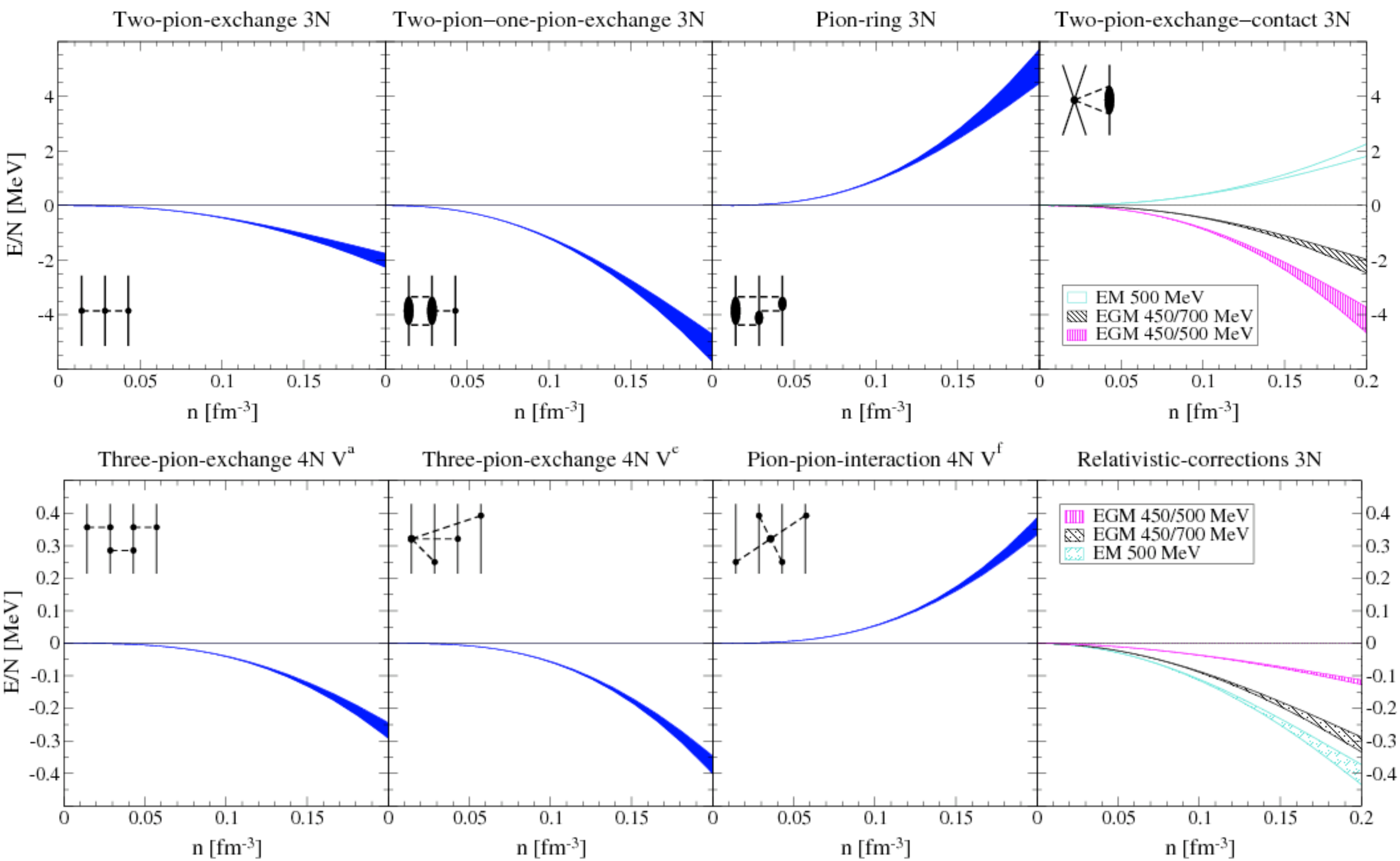
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

Complete N^3LO calculation of neutron matter

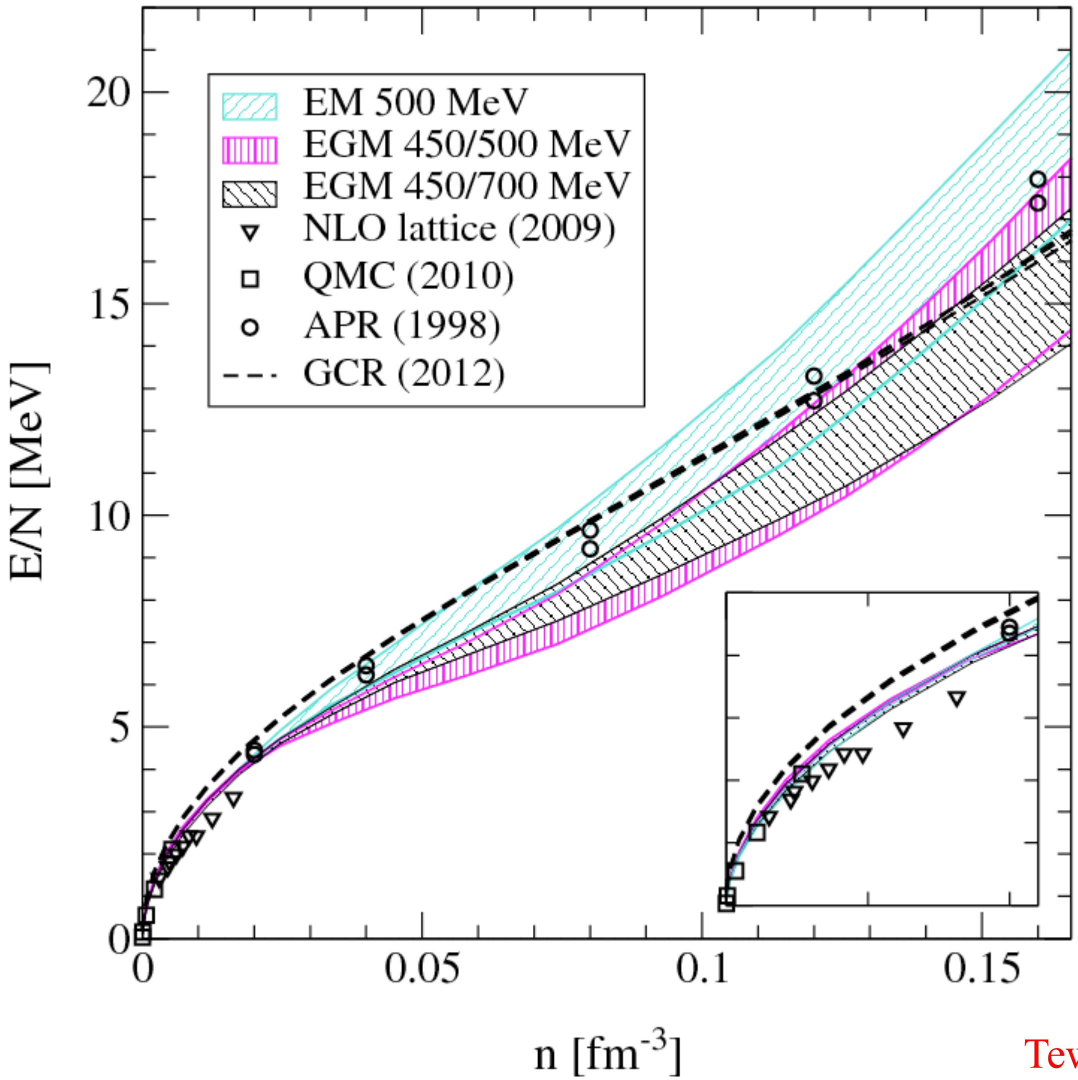


Tews, Krüger, Hebeler, AS (2013).

Complete N^3LO calculation of neutron matter

first complete N^3LO result

includes uncertainties from bare NN, 3N, 4N



Tews, Krüger, Hebeler, AS (2013).

Discovery of the heaviest neutron star

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

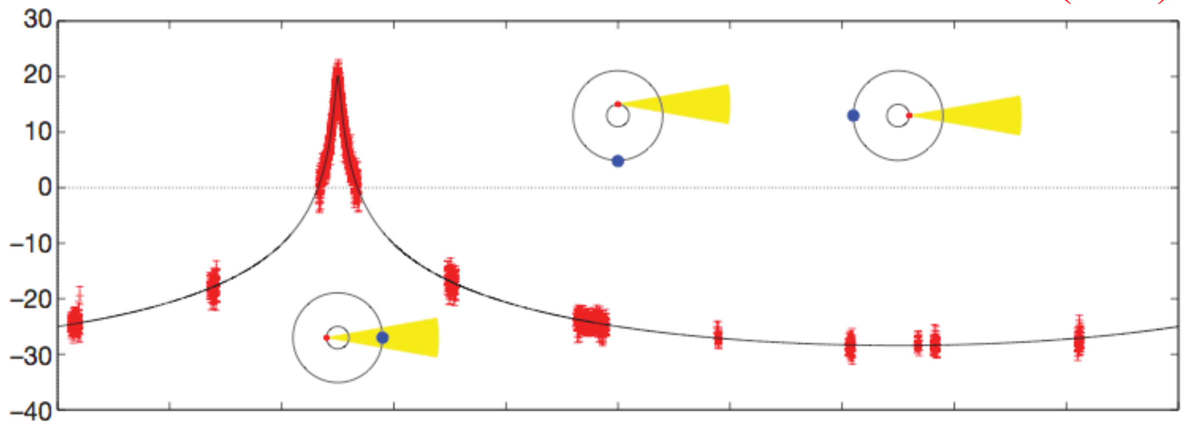
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

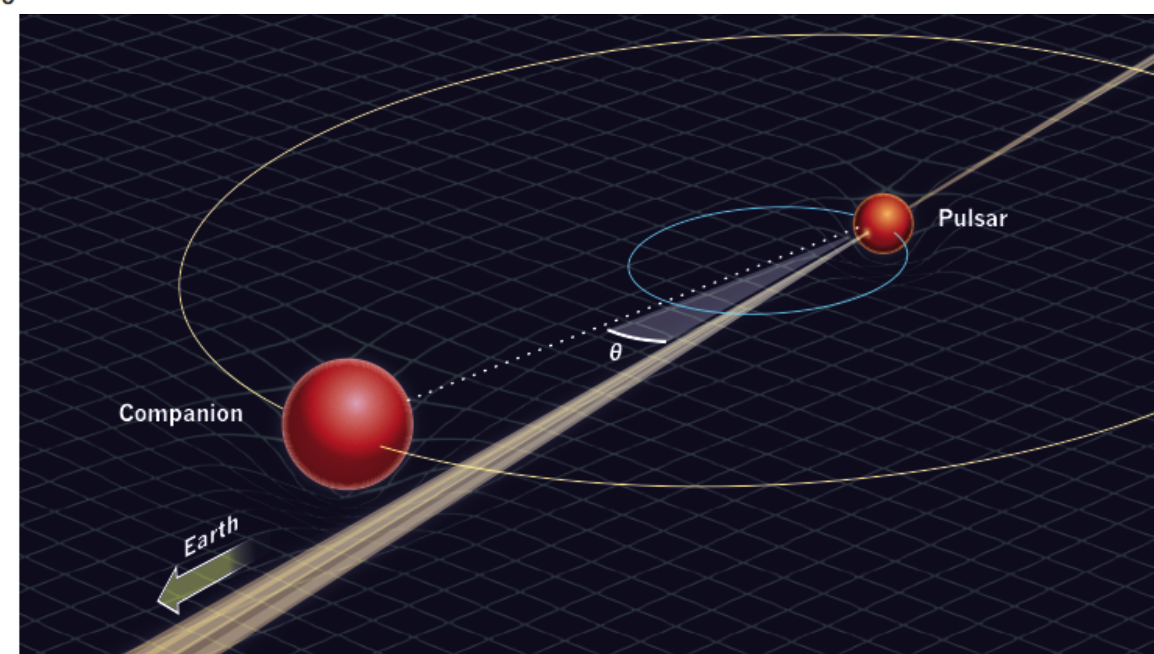
Nature (2010)

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})

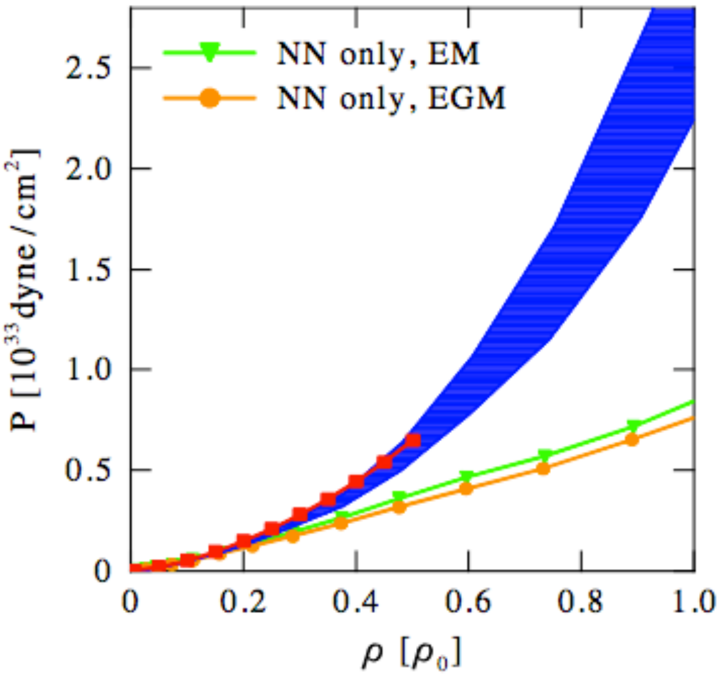
heaviest neutron star with 1.97±0.04 M_{sun}





Impact on neutron stars Hebeler et al. (2010) and in prep.

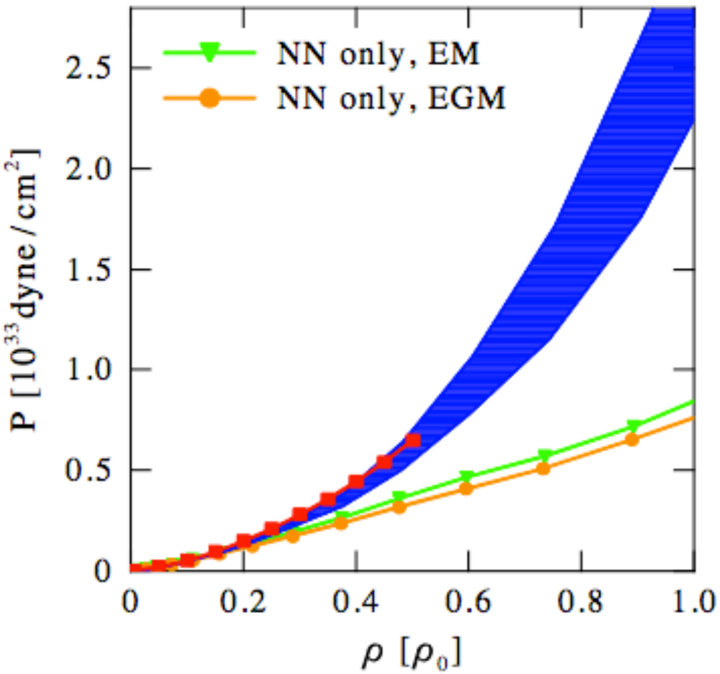
Equation of state/pressure for neutron-star matter (includes small $Y_{e,p}$)

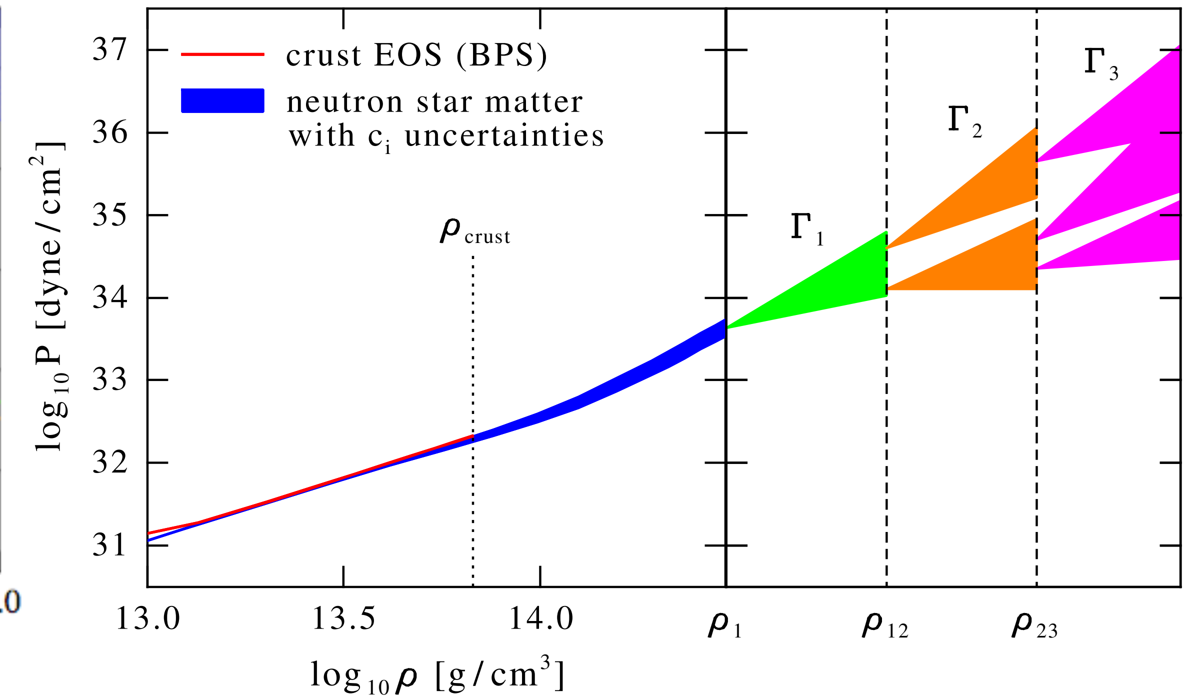


pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

Impact on neutron stars Hebeler et al. (2010) and in prep.

Equation of state/pressure for neutron-star matter (includes small $Y_{e,p}$)



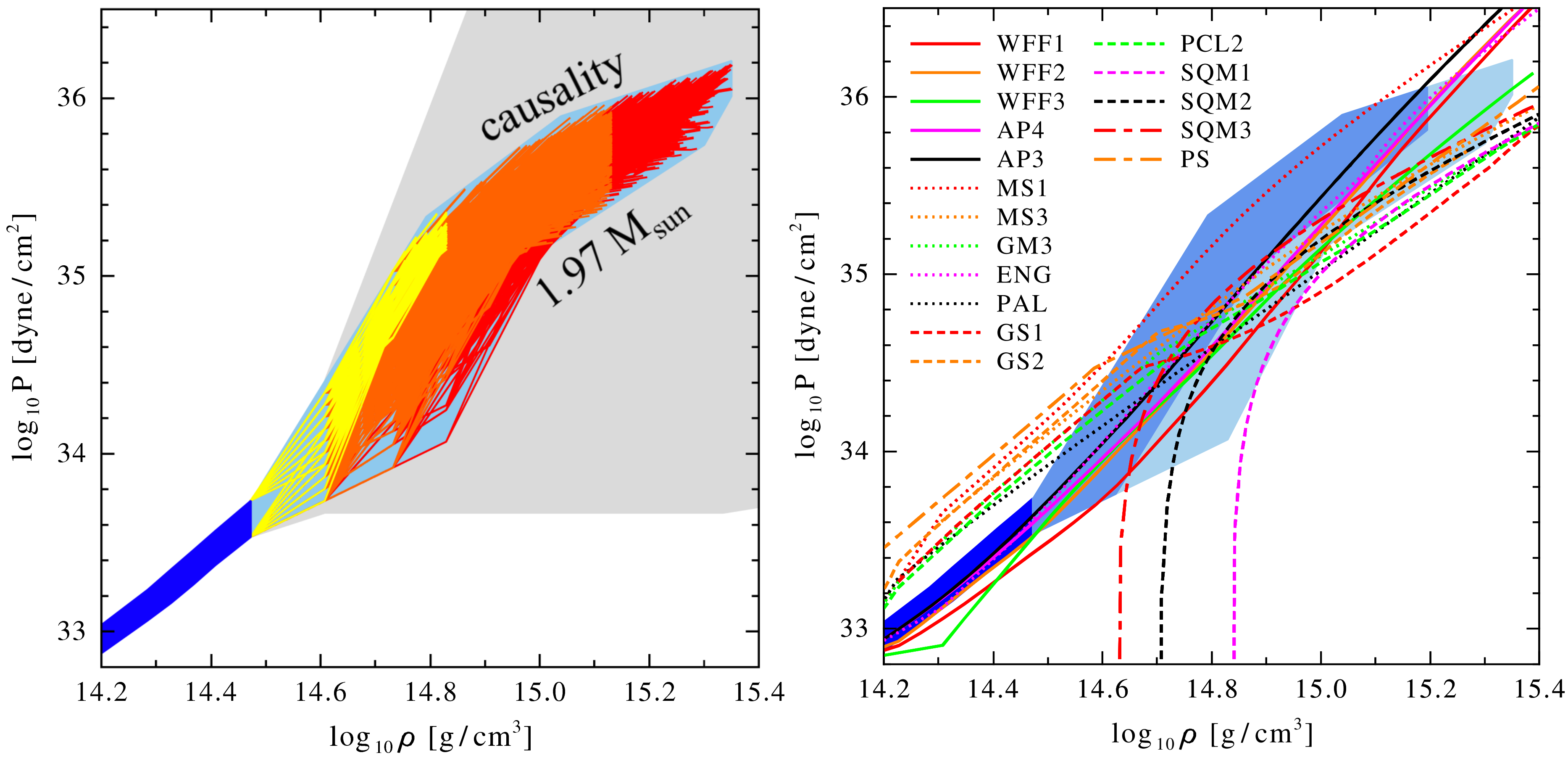


pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

extend uncertainty band to higher densities using piecewise polytropes allow for soft regions

Pressure of neutron star matter

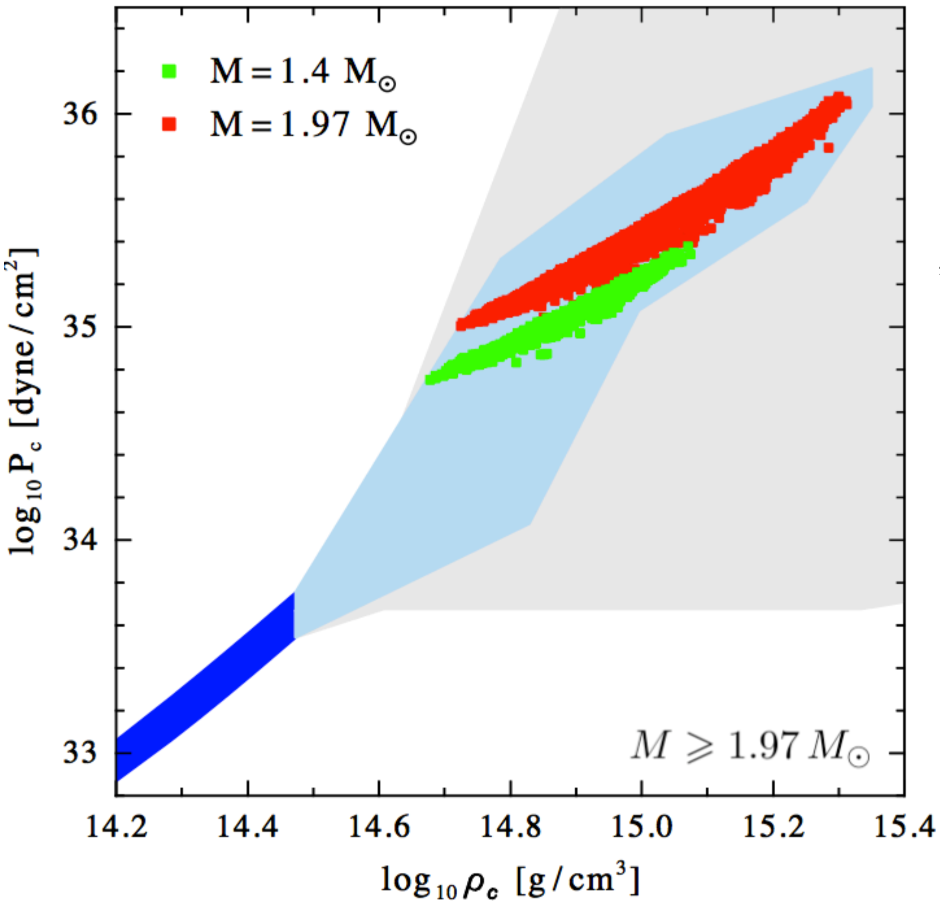
constrain polytropes by causality and require to support 1.97 M_{sun} star

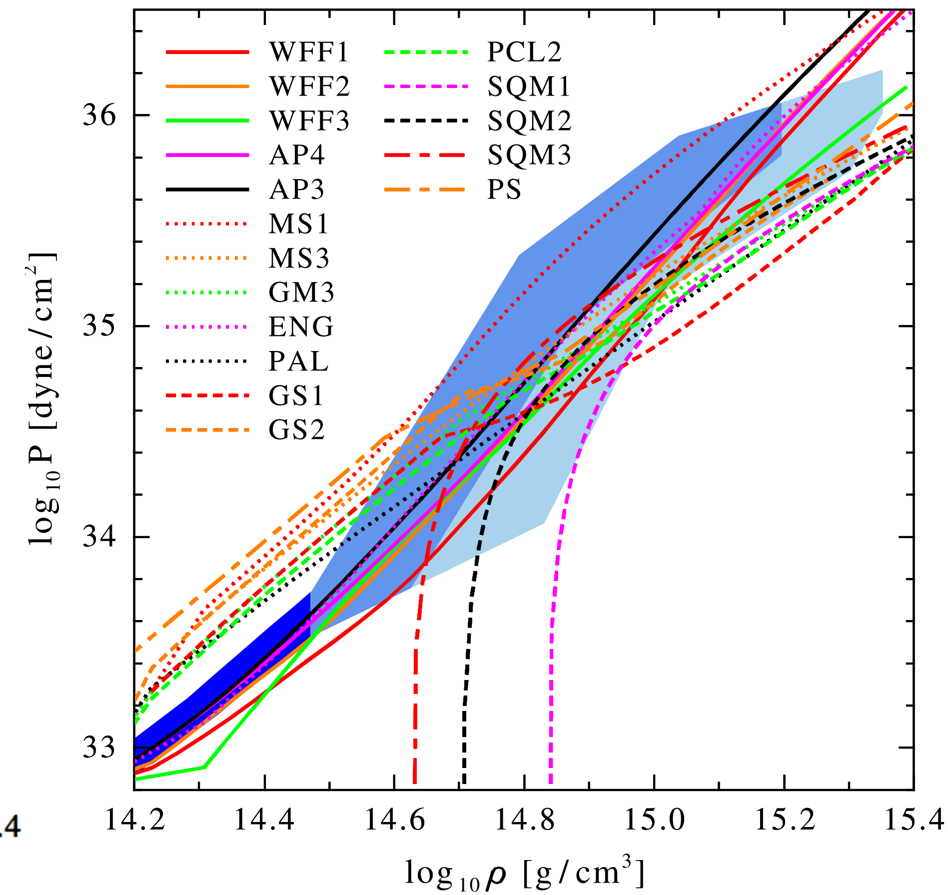


low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

Pressure of neutron star matter

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



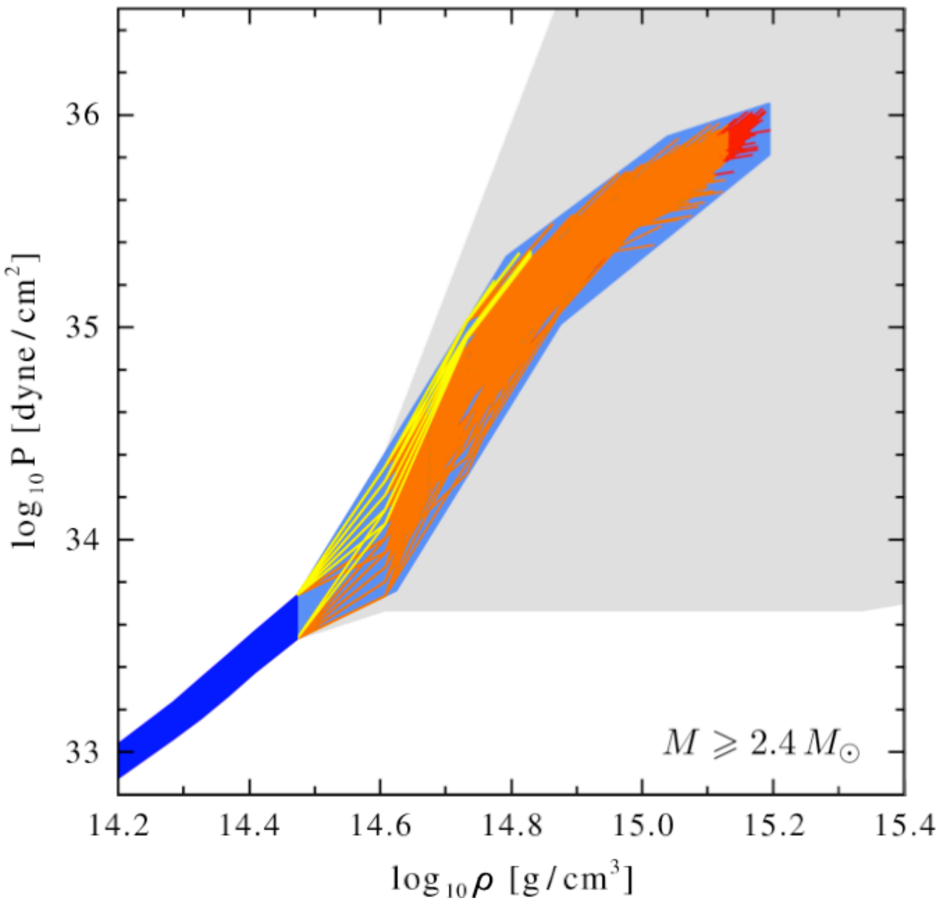


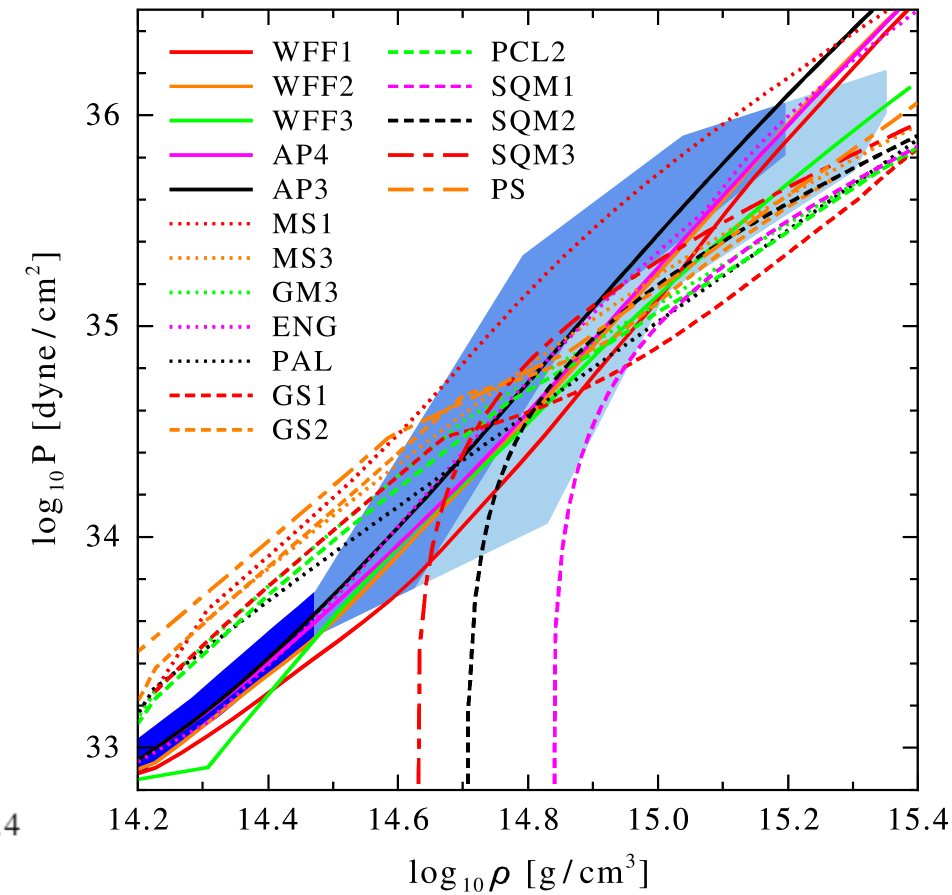
low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

central densities for 1.4 M_{sun} star: 1.7-4.4 ρ_0

Pressure of neutron star matter

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



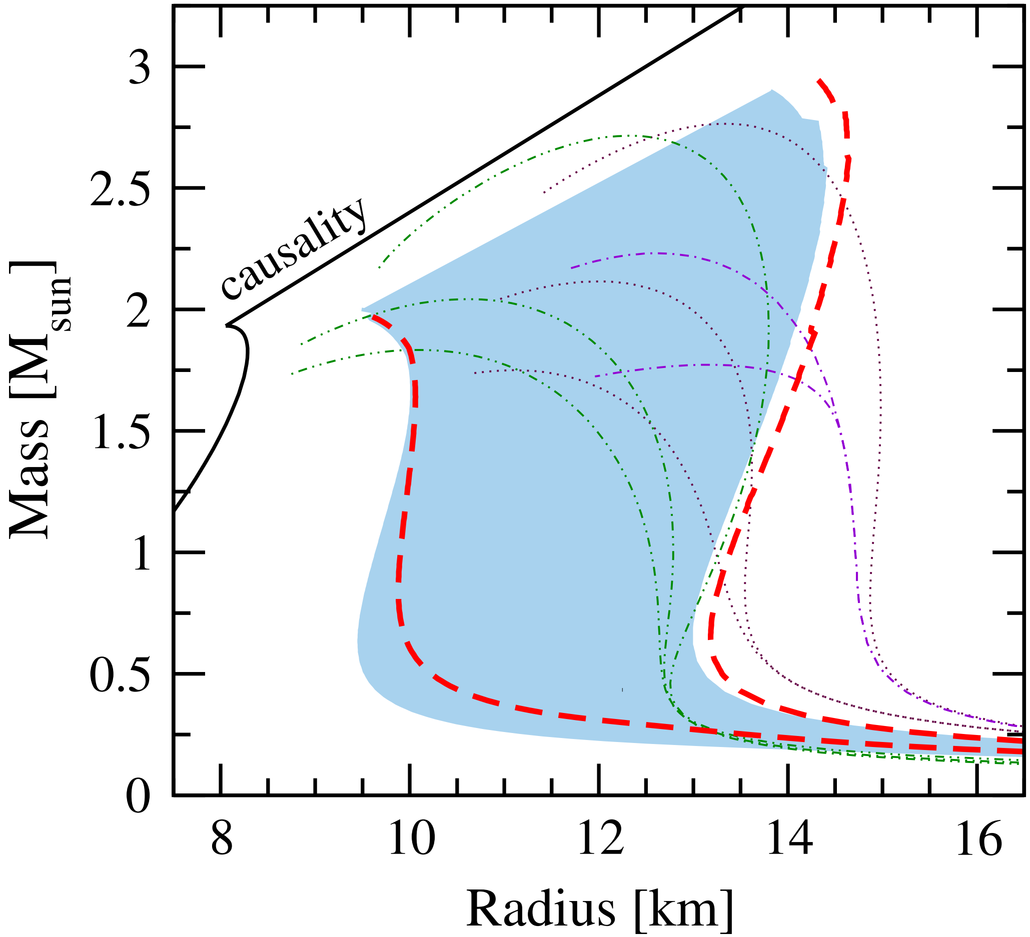


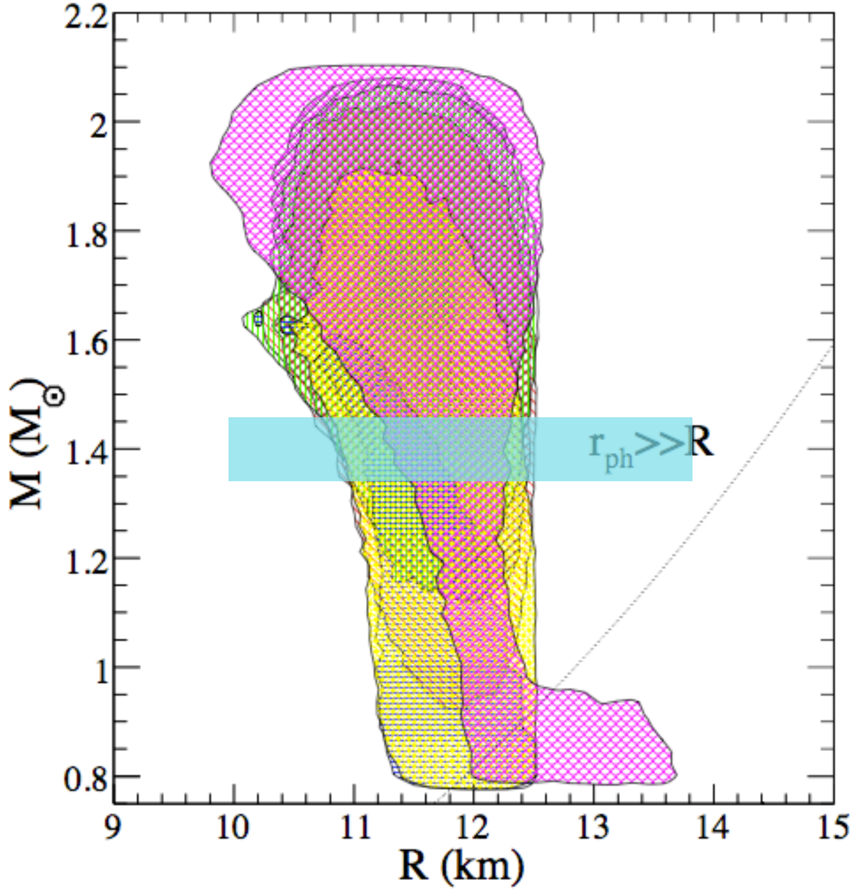
low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

darker blue band for 2.4 M_{sun} star

Neutron star radius constraints

uncertainty from many-body forces and general extrapolation





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

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

provides important constraints for EOS for core-collapse supernovae

Neutron-star merger and gravitational waves

explore sensitivity to neutron-rich matter in neutron-star merger and gw signal

Bauswein, Janka (2012) and A. Bauswein et al., arXiv:1204.1888.

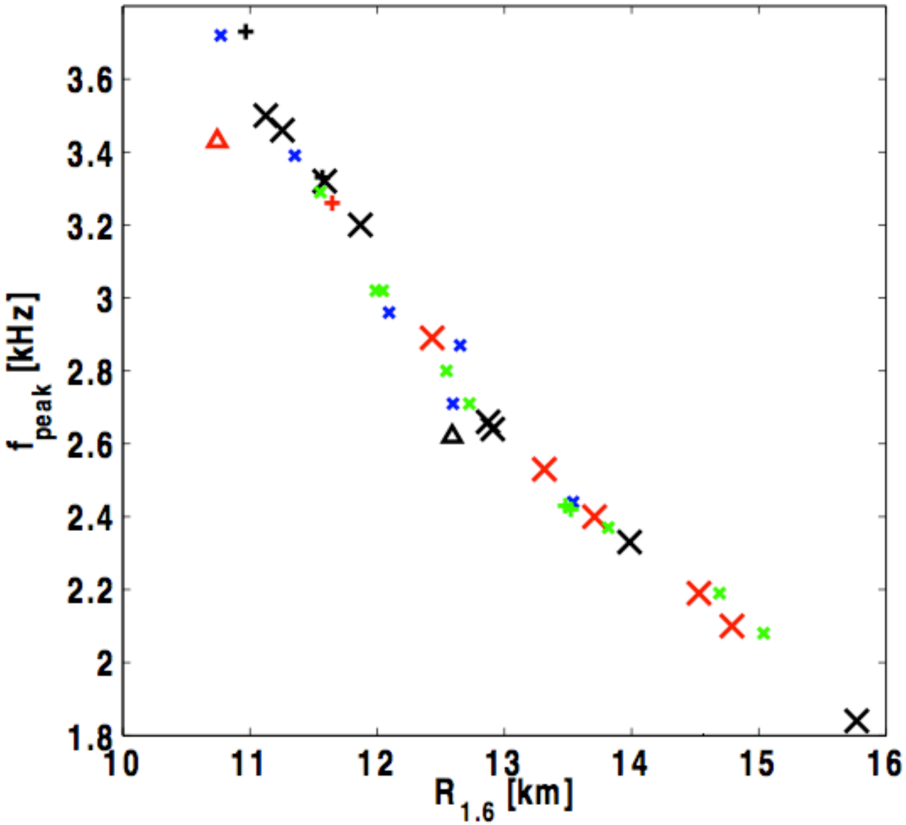


FIG. 10: Peak frequency of the postmerger GW emission versus the radius of a nonrotating NS with 1.6 $M_{\odot}$ for different EoSs. Symbols have the same meaning as in Fig. 8.

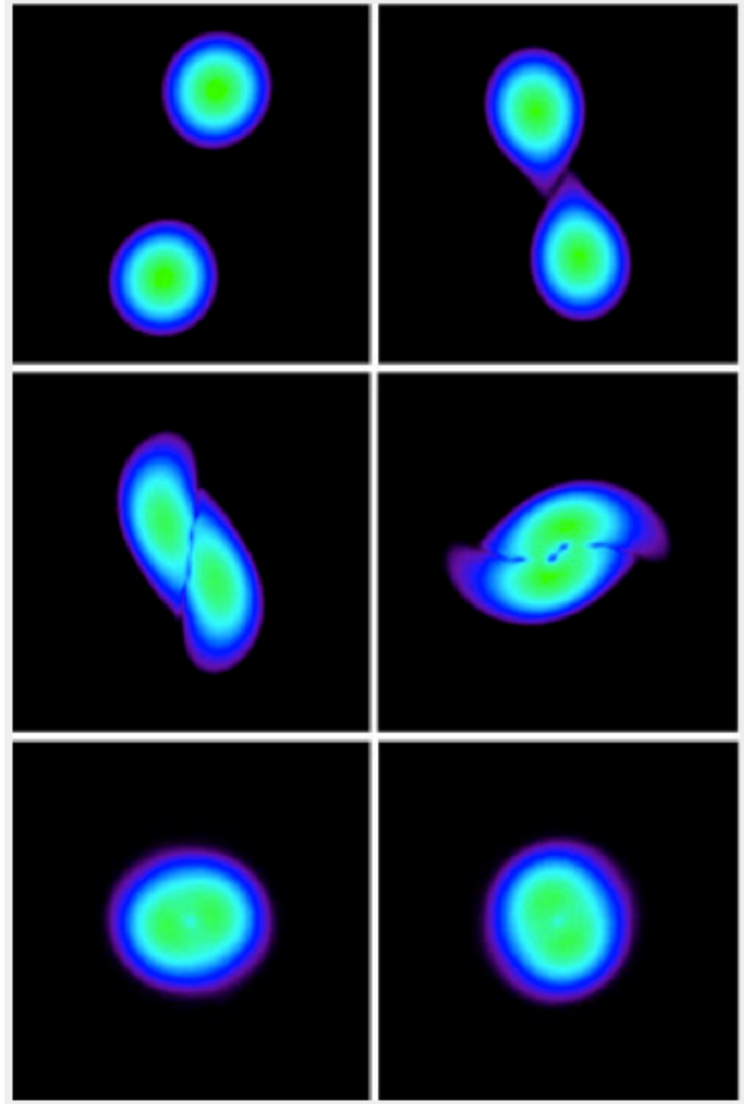
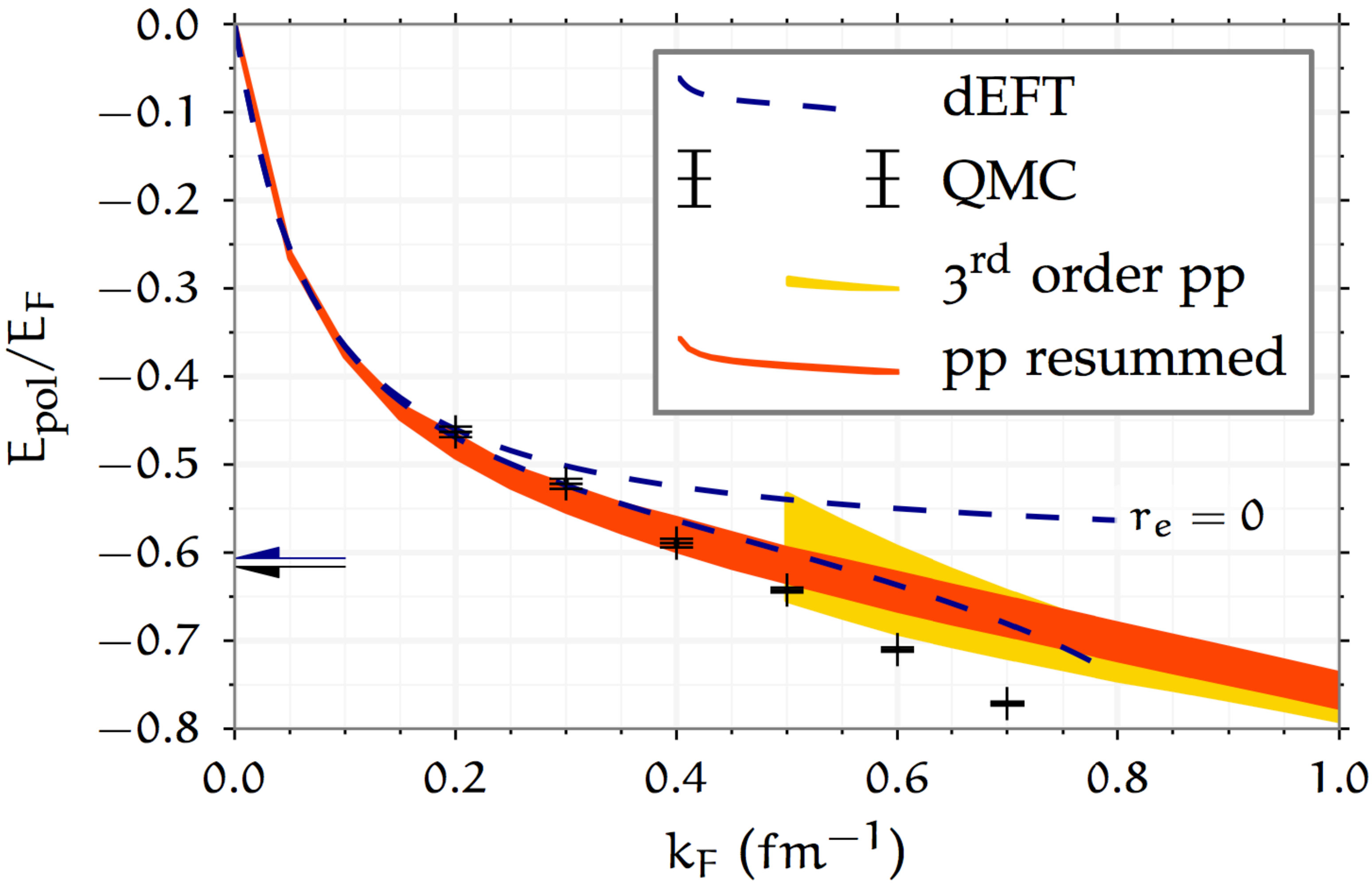


Fig. 1: Various snapshots of the collision of two neutron stars initially revolving around each other. The sequence simulated by the computer covers only 0.03 seconds. The two stars orbit each other counterclockwise (top left) and quickly come closer (top right). Finally they collide (centre left), merge (centre right), and form a dense, superheavy neutron star (bottom). Strong vibrations of the collision remnant are noticeable as deformations in east-west direction and in north-south direction (bottom panels). (Simulation: Andreas Bauswein and H.-Thomas Janka/MPA)

Neutron polaron

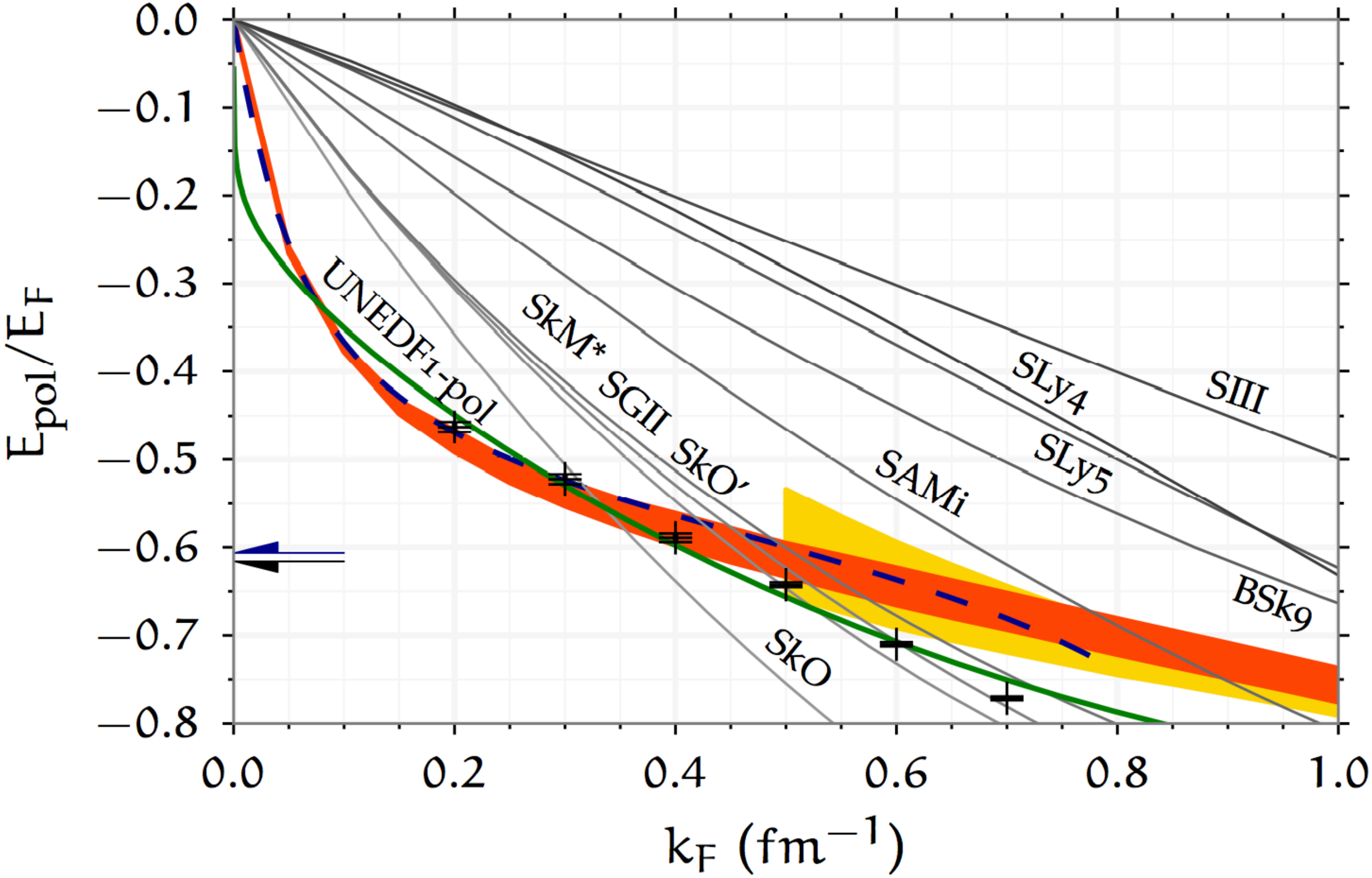
calculated with QMC and effective field theory methods,
polaron energy increases due to effective range



Forbes, Gezerlis, Hebeler, Lesinski, AS, in prep.

Neutron polaron and density functionals

Neutron polaron provides constraints for nuclear density functional, most state-of-the-art functionals underpredict polaron energy



Forbes, Gezerlis, Hebeler, Lesinski, AS, in prep.

Summary

Chiral effective field theory interactions provide strong constraints for neutron-rich nuclei/matter, 3N forces are a frontier

key to explain why ^{24}O is the heaviest oxygen isotope
key for neutron-rich nuclei: Ca isotopes and magic numbers

3N forces are dominant uncertainty of neutron (star) matter below nuclear densities, constrains neutron-star radii and equation of state

neutron polaron constrains nuclear density functional

cold atoms provide anchor points at low densities