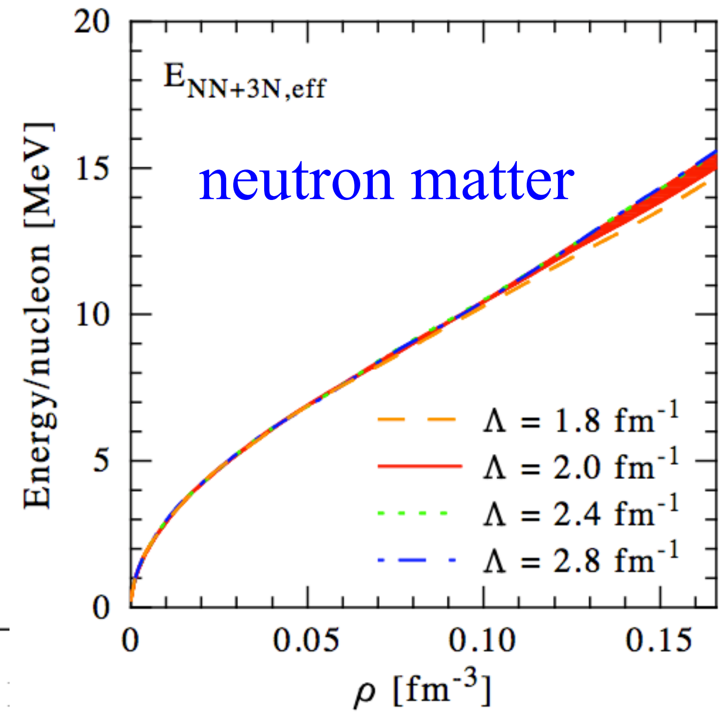
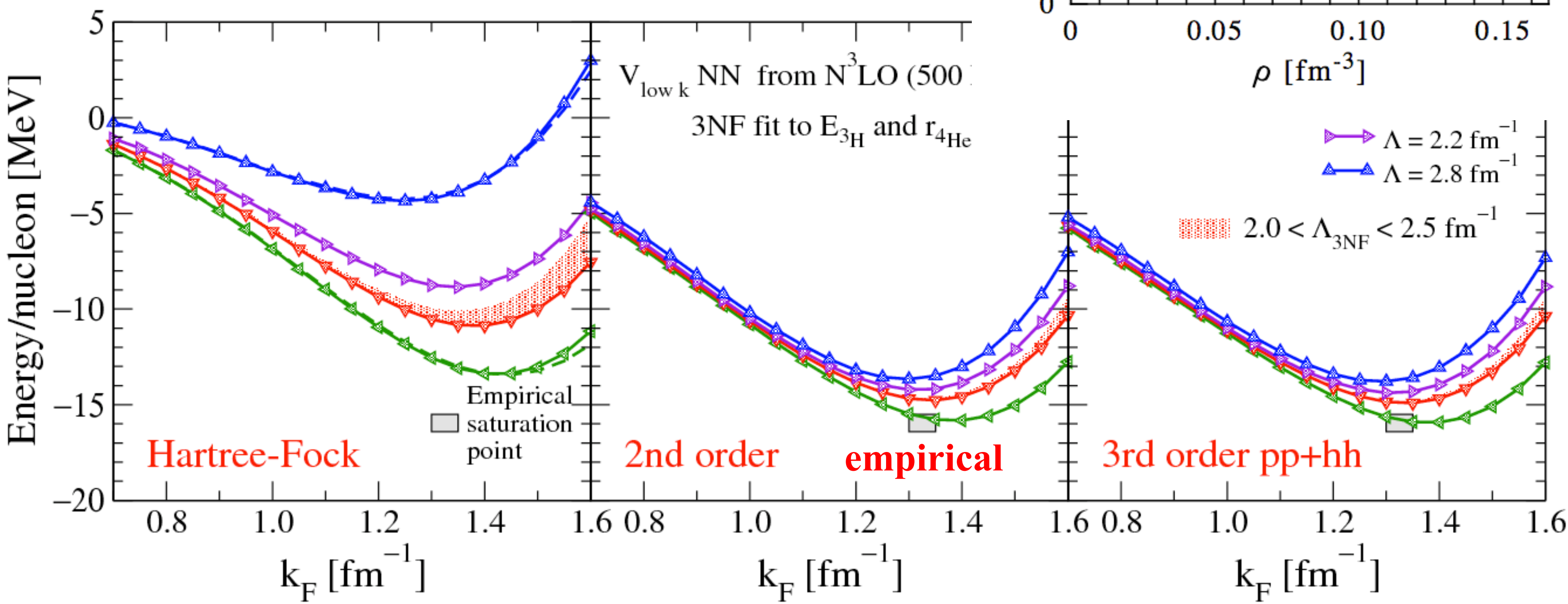
Impact of 3N forces on neutron matter

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

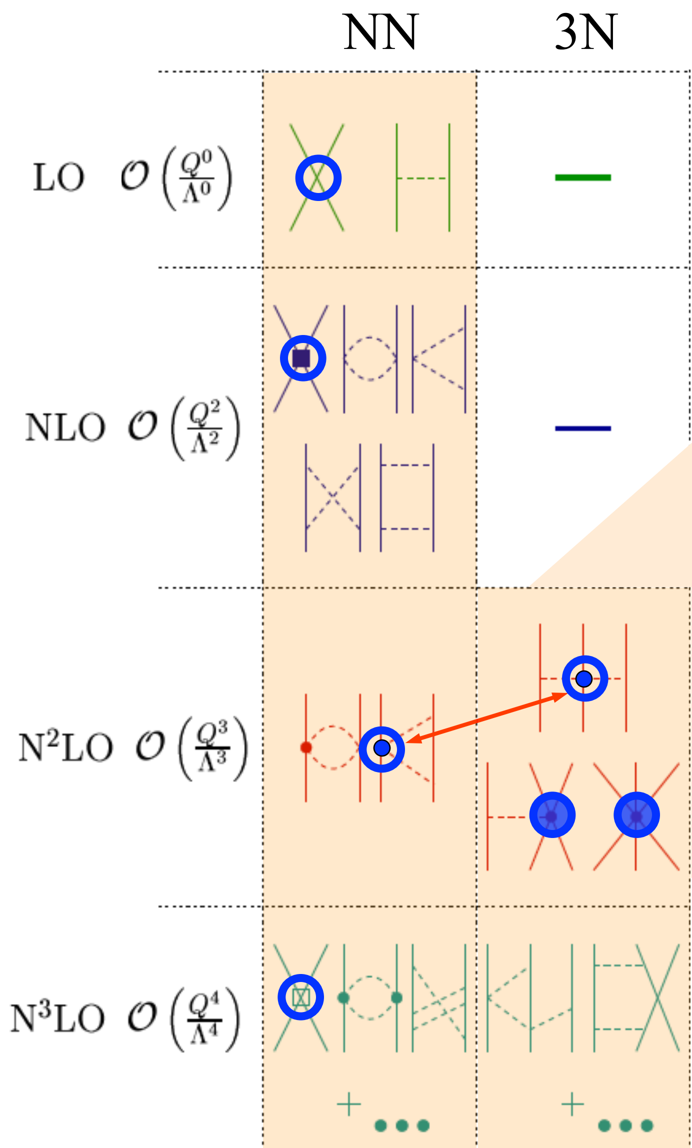
Hebeler, AS (2010)





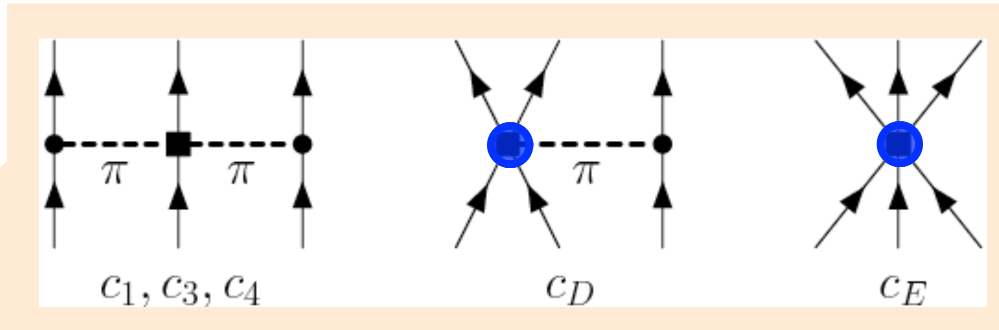
Chiral effective field theory and **many-body forces**

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^{3}LO



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

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

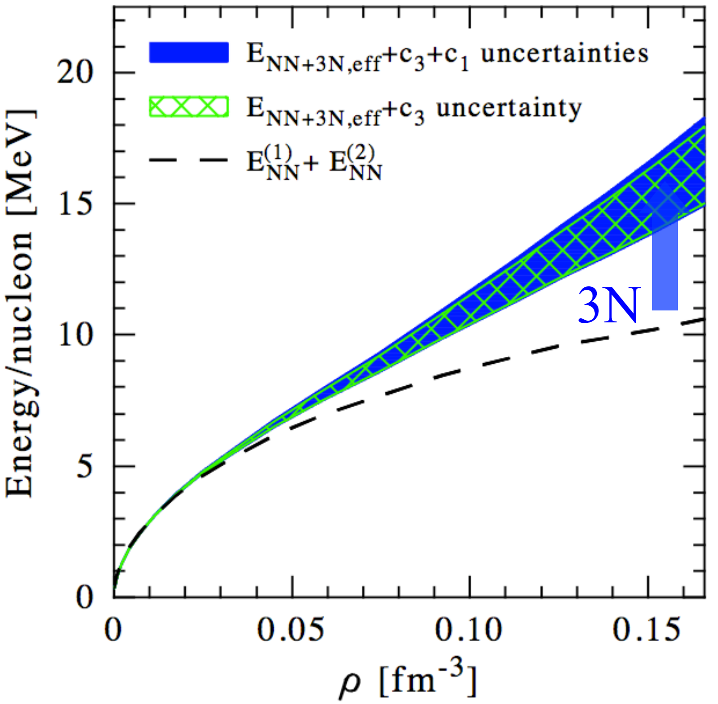
single-Δ: c_1=0, c_3=-c_4/2=-3 GeV^{-1}

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

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

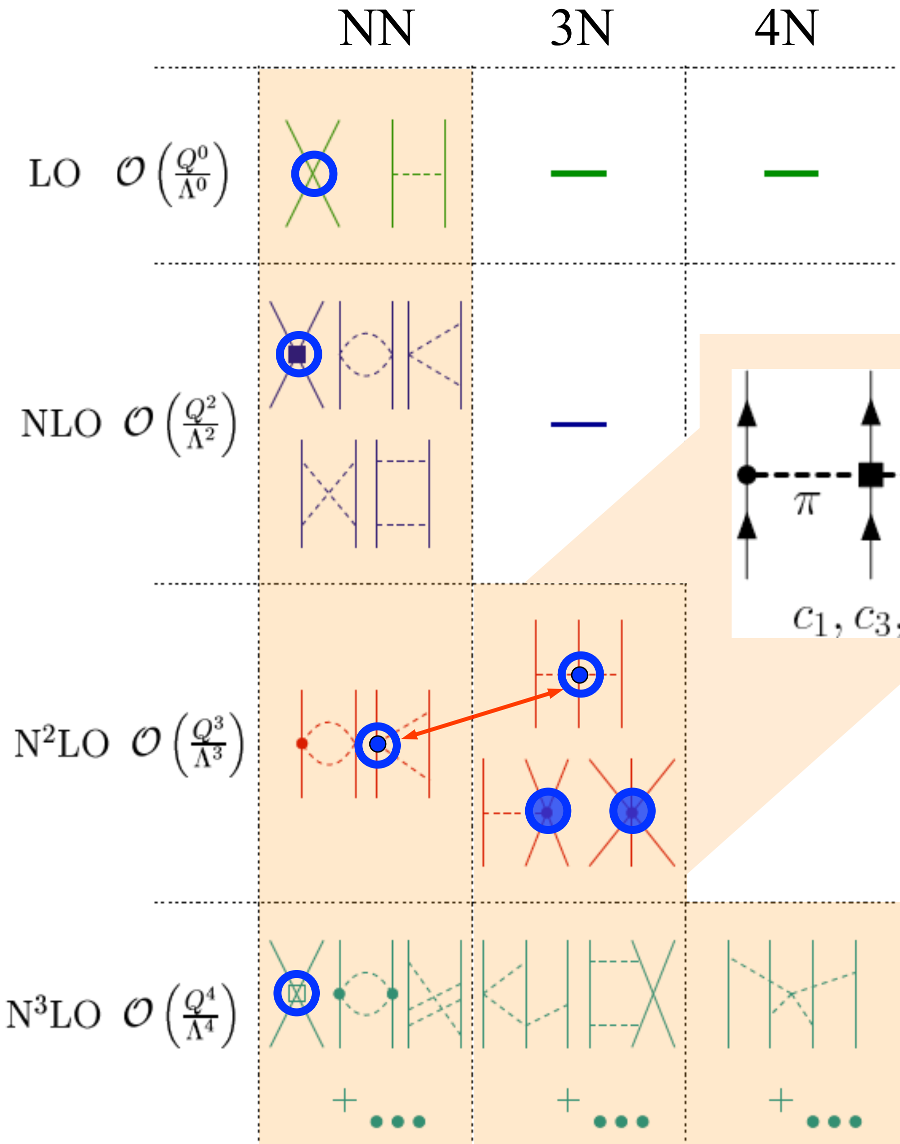
Impact of 3N forces on neutron matter

neutron matter uncertainties
dominated by 3N forces (c_3 coupling)
Hebeler, AS (2010)



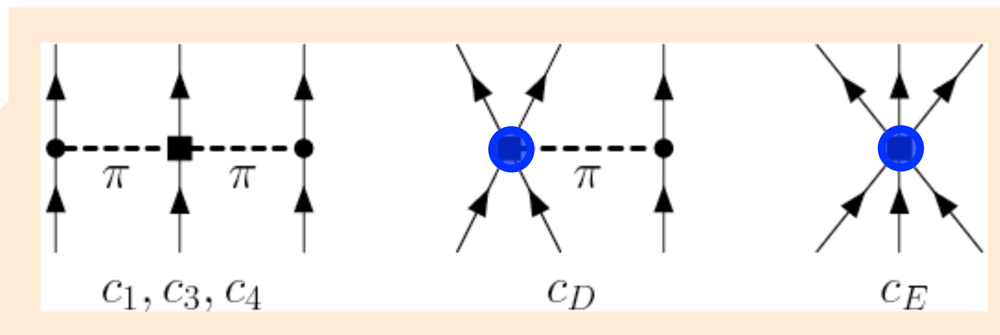
Chiral effective field theory for nuclear forces

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



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!

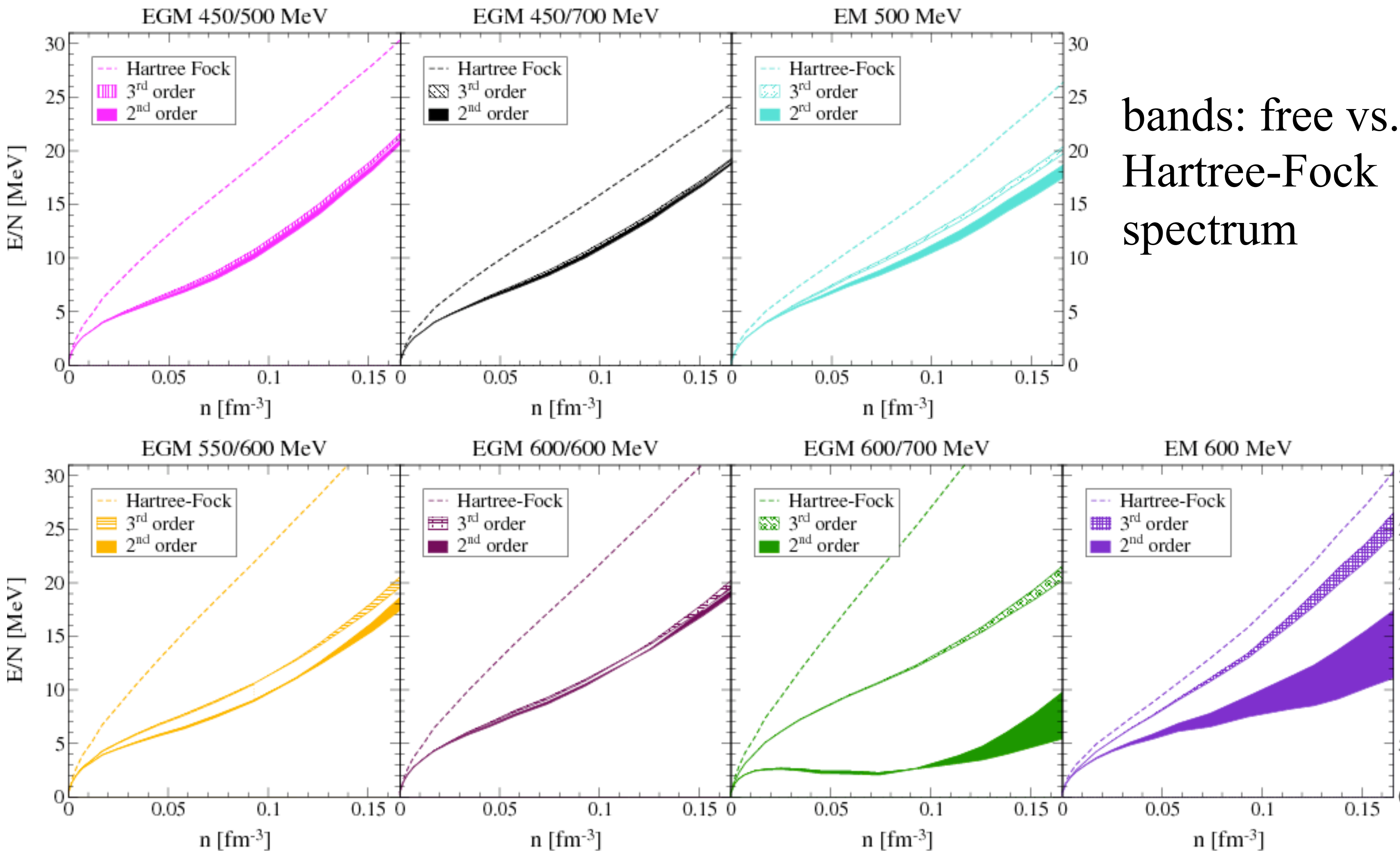
study 3N and 4N in neutron matter

Tews, Krüger, Hebeler, AS (2013)

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

Neutron matter from chiral EFT interactions

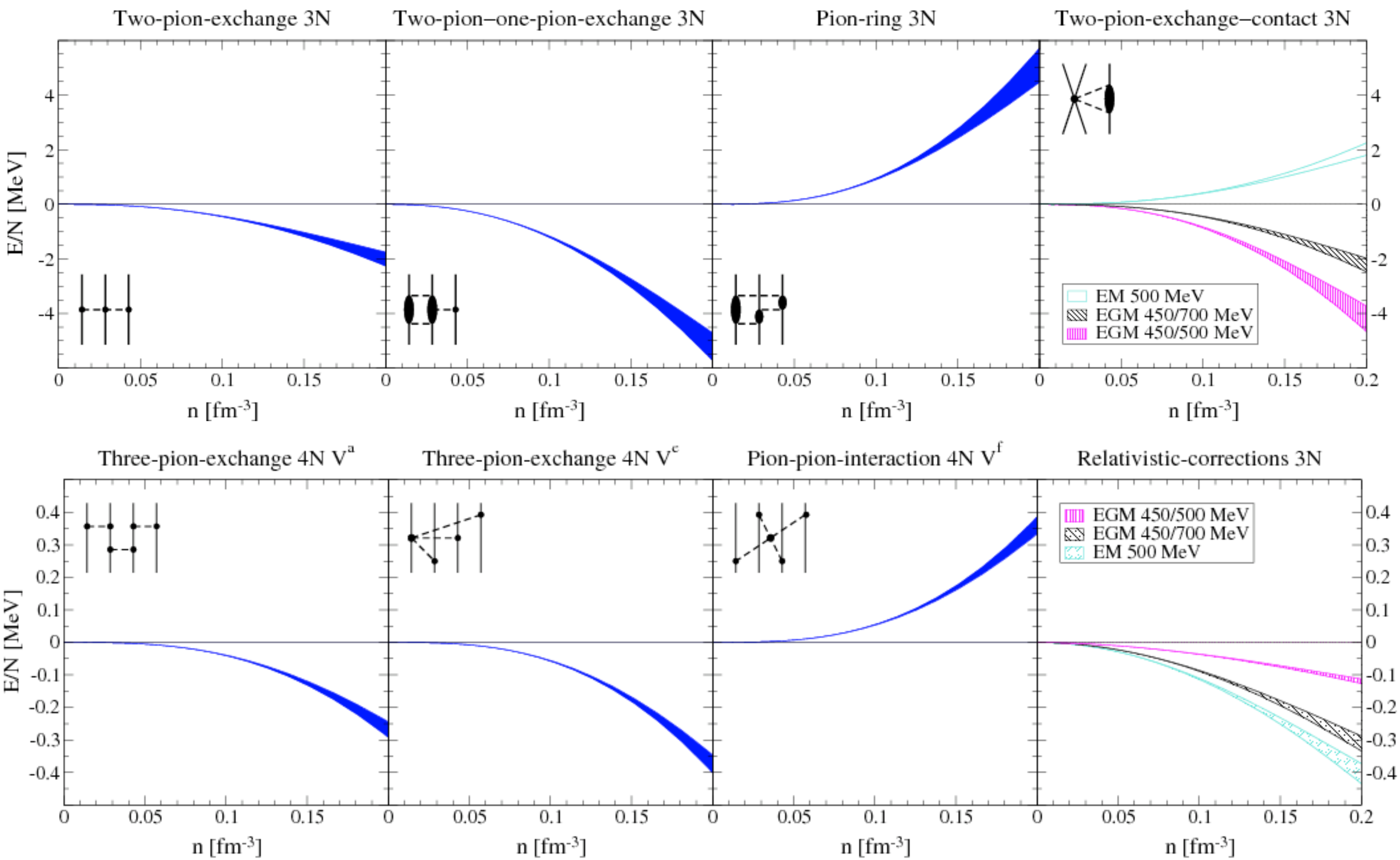
direct calculations without RG/SRG evolution, 3N to N^2LO only



bands: free vs. Hartree-Fock spectrum

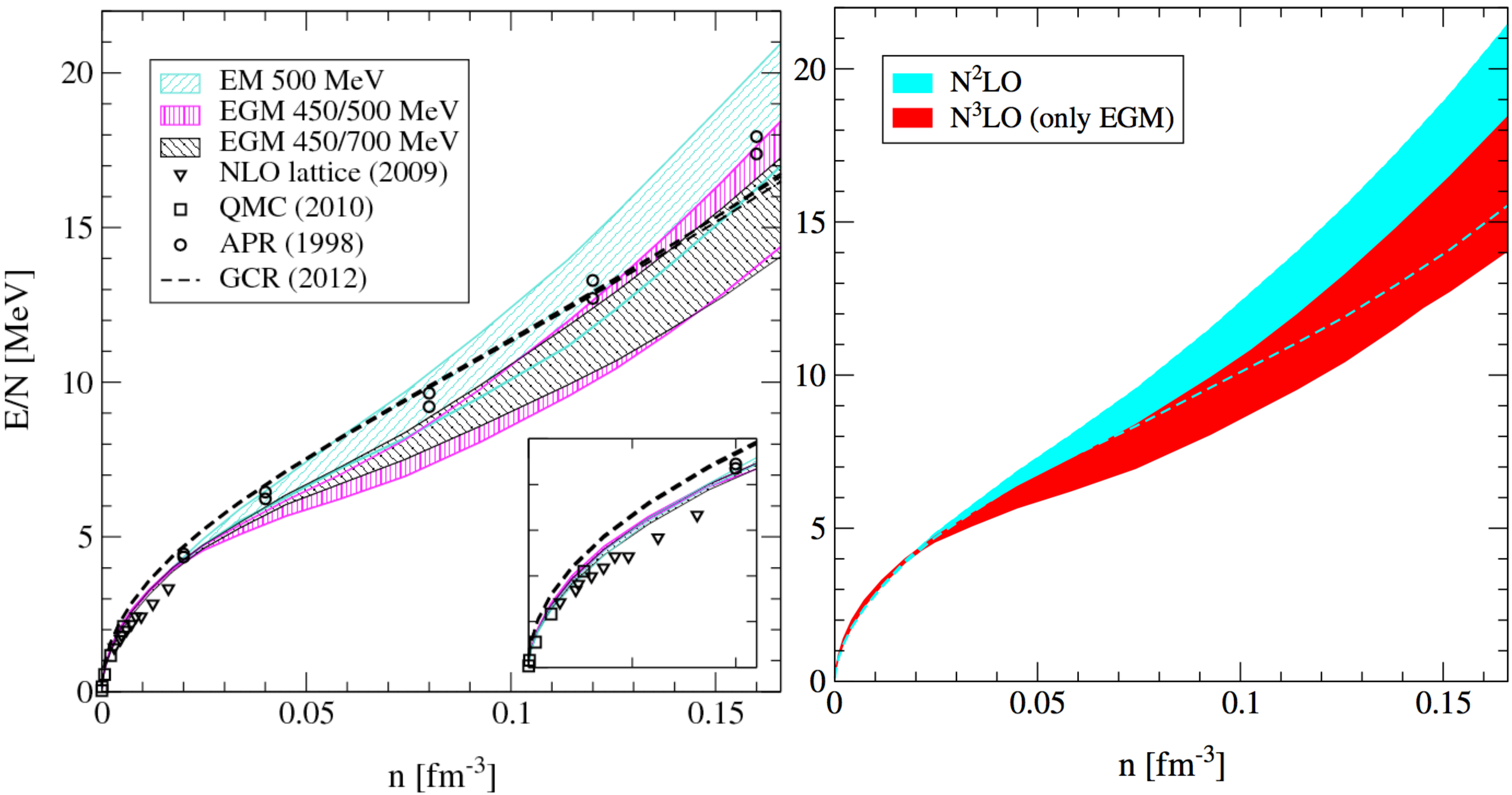
N^{3}LO 3N and 4N interactions in neutron matter

evaluated at Hartree-Fock level



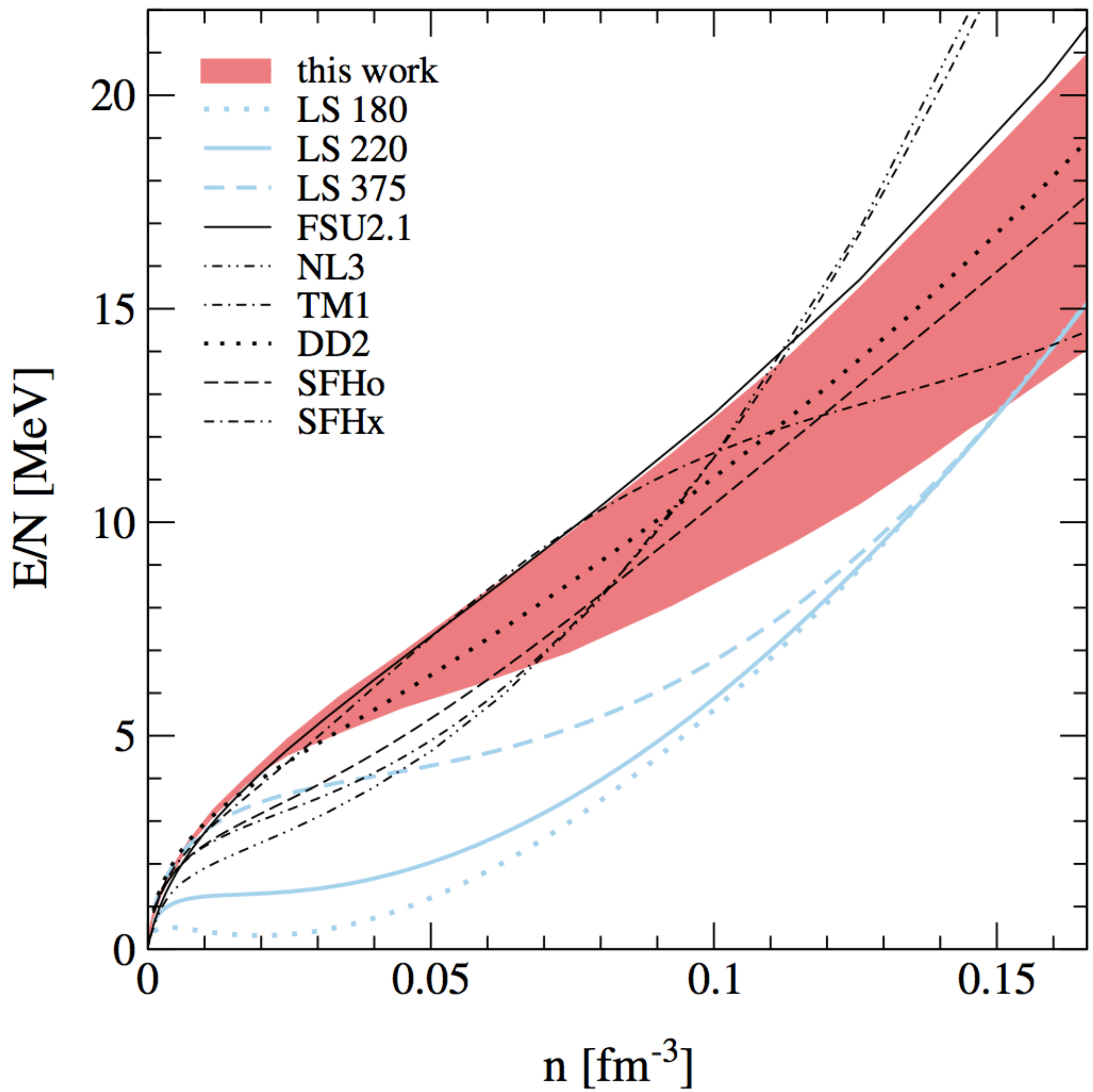
Complete N^3LO calculation of neutron matter

first complete N^3LO result, Hartree-Fock +2nd order +3rd order (pp+hh)
includes uncertainties from NN, 3N (dominates), 4N



Comparisons to equations of state in astrophysics

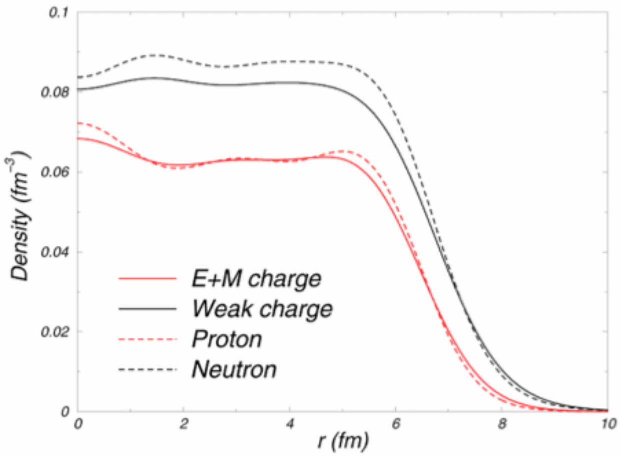
many equations of state used in supernova simulations not consistent with neutron matter results



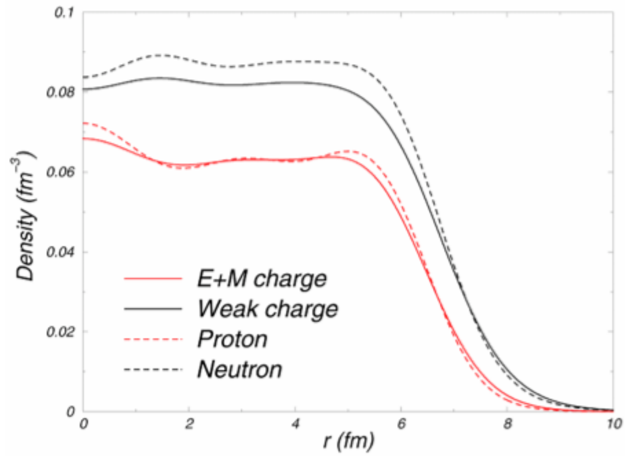
Neutron skin of ^{208}Pb

probes neutron matter energy/pressure,
neutron matter band predicts
neutron skin of ^{208}Pb: 0.17±0.03 fm (±18% !)

Hebeler et al. (2010)



Neutron skin of ^{208}Pb



probes neutron matter energy/pressure,
neutron matter band predicts
neutron skin of ^{208}Pb: 0.17±0.03 fm (±18% !)
Hebeler et al. (2010)

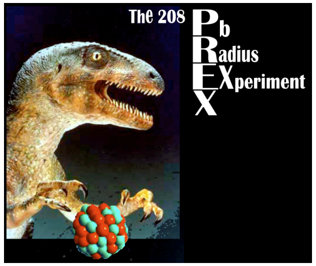
in excellent agreement with extraction from complete E1 response
0.156+0.025-0.021 fm

PRL **107,** 062502 (2011) PHYSICAL REVIEW LETTERS week ending 5 AUGUST 2011

Complete Electric Dipole Response and the Neutron Skin in ^{208}Pb

A benchmark experiment on ^{208}Pb shows that polarized proton inelastic scattering at very forward angles including 0° is a powerful tool for high-resolution studies of electric dipole ($E1$) and spin magnetic dipole ($M1$) modes in nuclei over a broad excitation energy range to test up-to-date nuclear models. The extracted $E1$ polarizability leads to a neutron skin thickness $r_{\rm skin} = 0.156^{+0.025}_{-0.021}$ fm in ^{208}Pb derived within

PREX: neutron skin from parity-violating electron-scattering at JLAB
electron exchanges Z-boson, couples preferentially to neutrons
goal II: ±0.06 fm



PRL **108,** 112502 (2012) PHYSICAL REVIEW LETTERS week ending 16 MARCH 2012

Measurement of the Neutron Radius of ^{208}Pb through Parity Violation in Electron Scattering

We report the first measurement of the parity-violating asymmetry $A_{\rm PV}$ in the elastic scattering of polarized electrons from ^{208}Pb. $A_{\rm PV}$ is sensitive to the radius of the neutron distribution (R_n). The result $A_{\rm PV} = 0.656 \pm 0.060({\rm stat}) \pm 0.014({\rm syst})$ ppm corresponds to a difference between the radii of the neutron and proton distributions $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm and provides the first electroweak observation of the neutron skin which is expected in a heavy, neutron-rich nucleus.

Symmetry energy and pressure of neutron matter

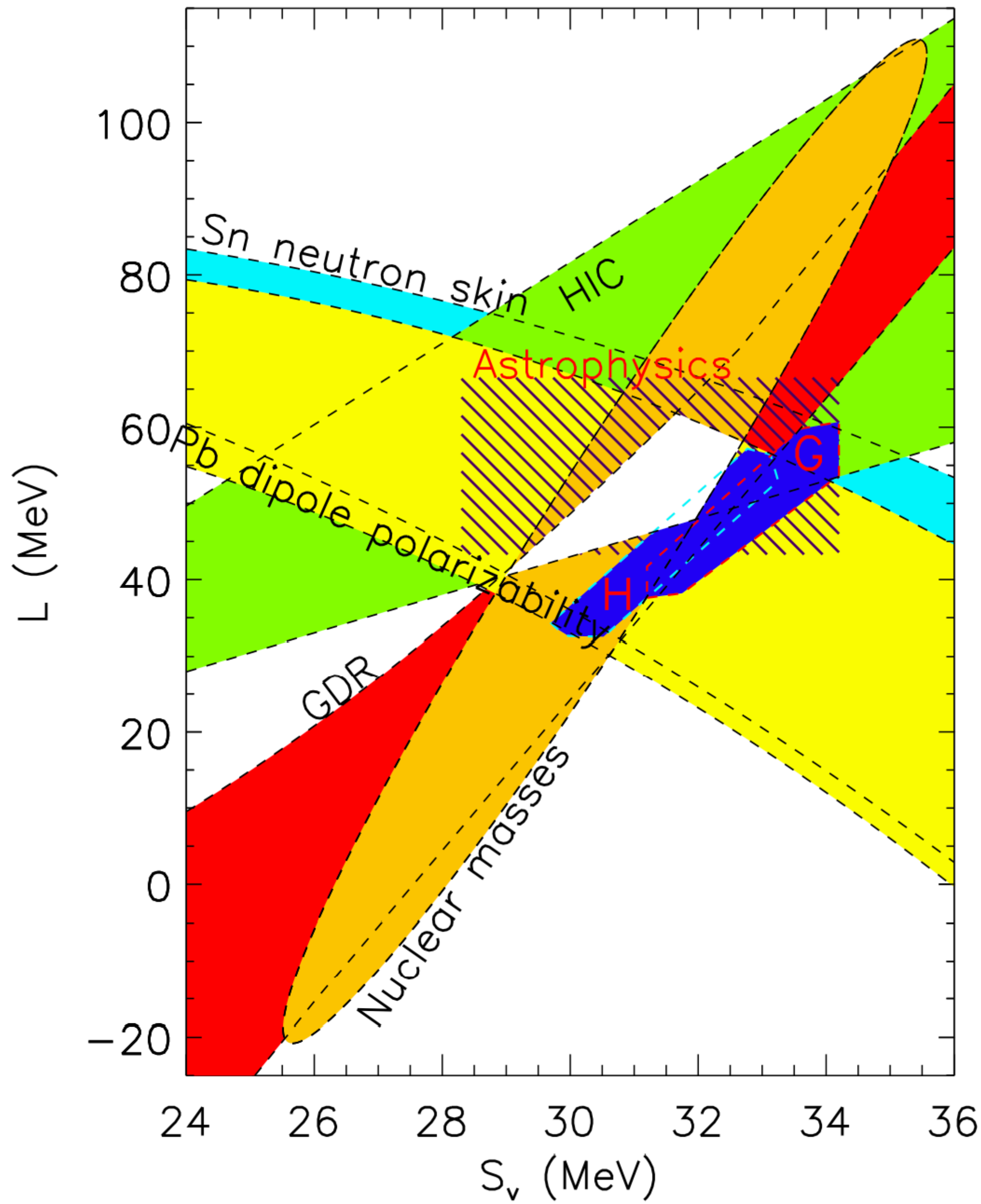
neutron matter band predicts symmetry energy S_v and its density derivative L

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

neutron matter constraints
H: Hebeler et al. (2010, 2013)

G: Gandolfi et al. (2011)

microscopic calculations provide tight constraints!



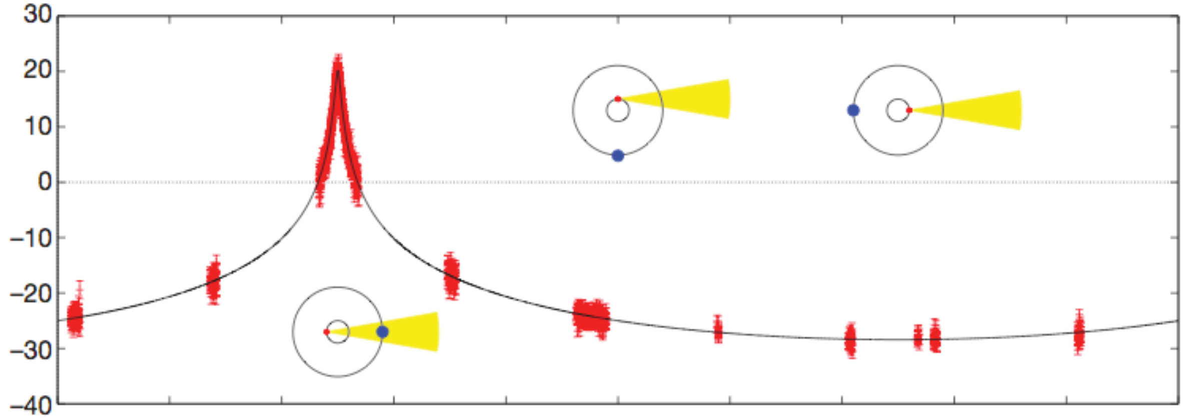
Discovery of the heaviest neutron star

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

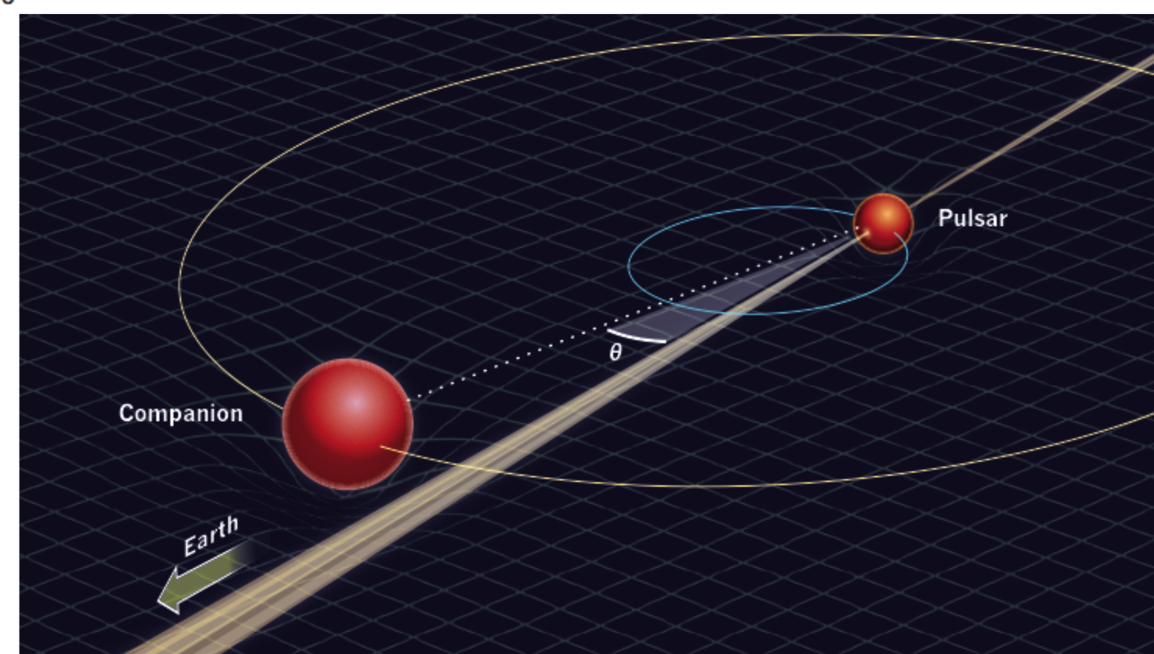
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

Nature (2010)

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

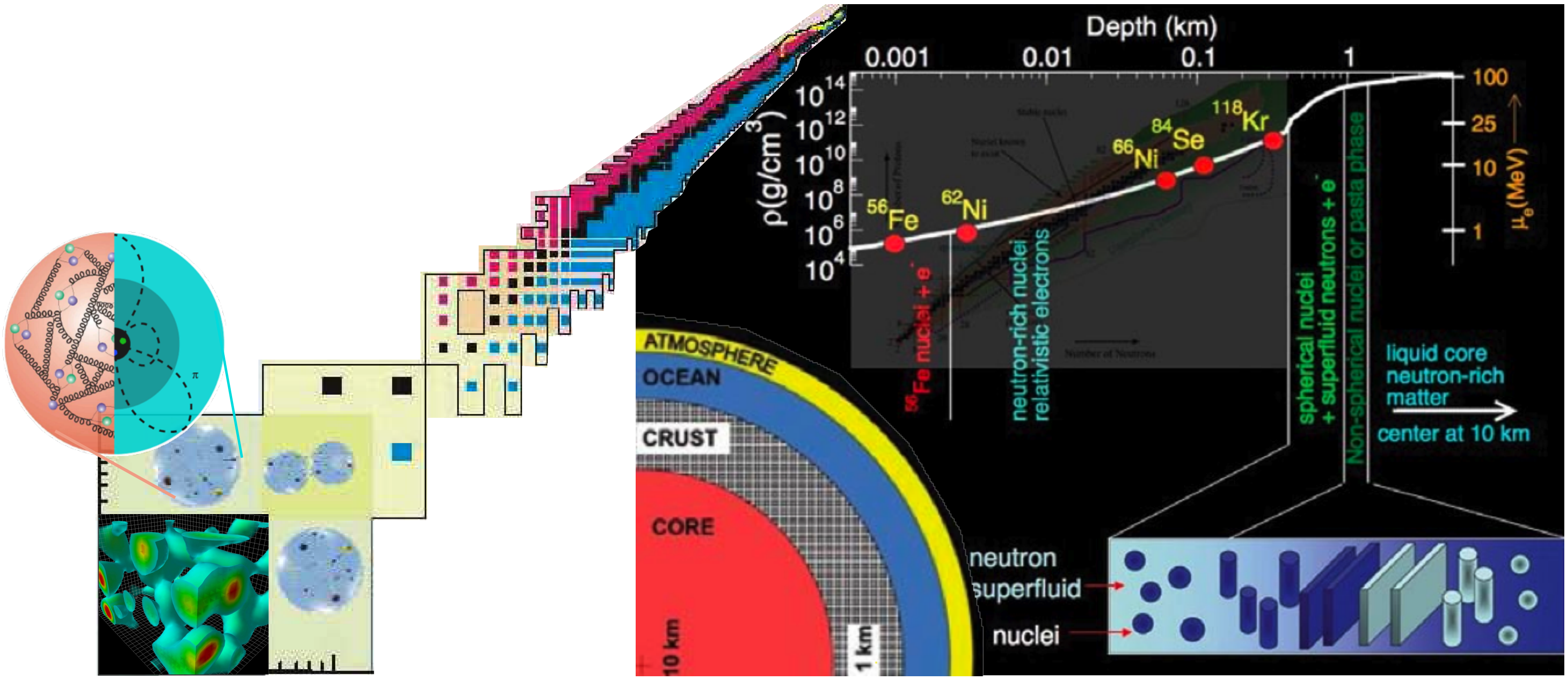


J1614-2230
most edge-on binary pulsar known (89.17°)
+ massive white dwarf companion (0.5 M_{sun})



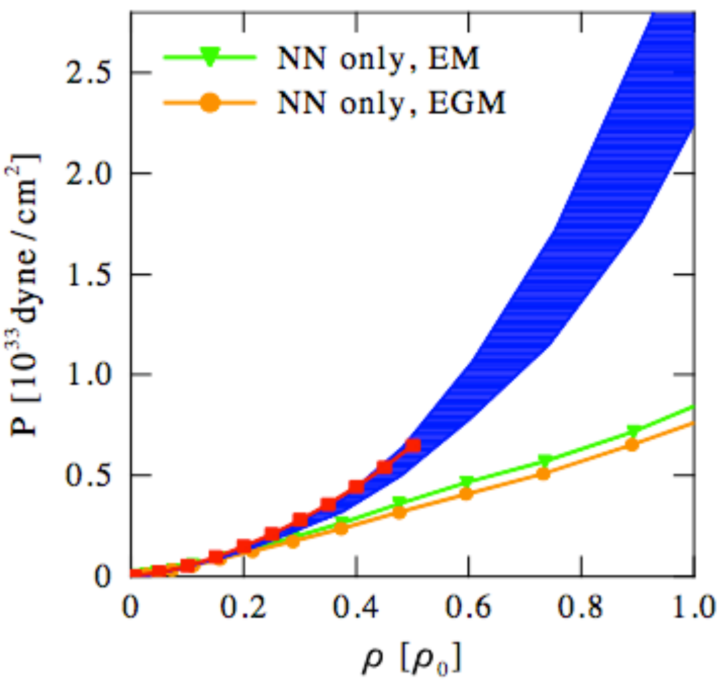
heaviest neutron star with 1.97±0.04 M_{sun}

Neutron matter and neutron stars



Impact on neutron stars Hebeler et al. (2010, 2013)

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

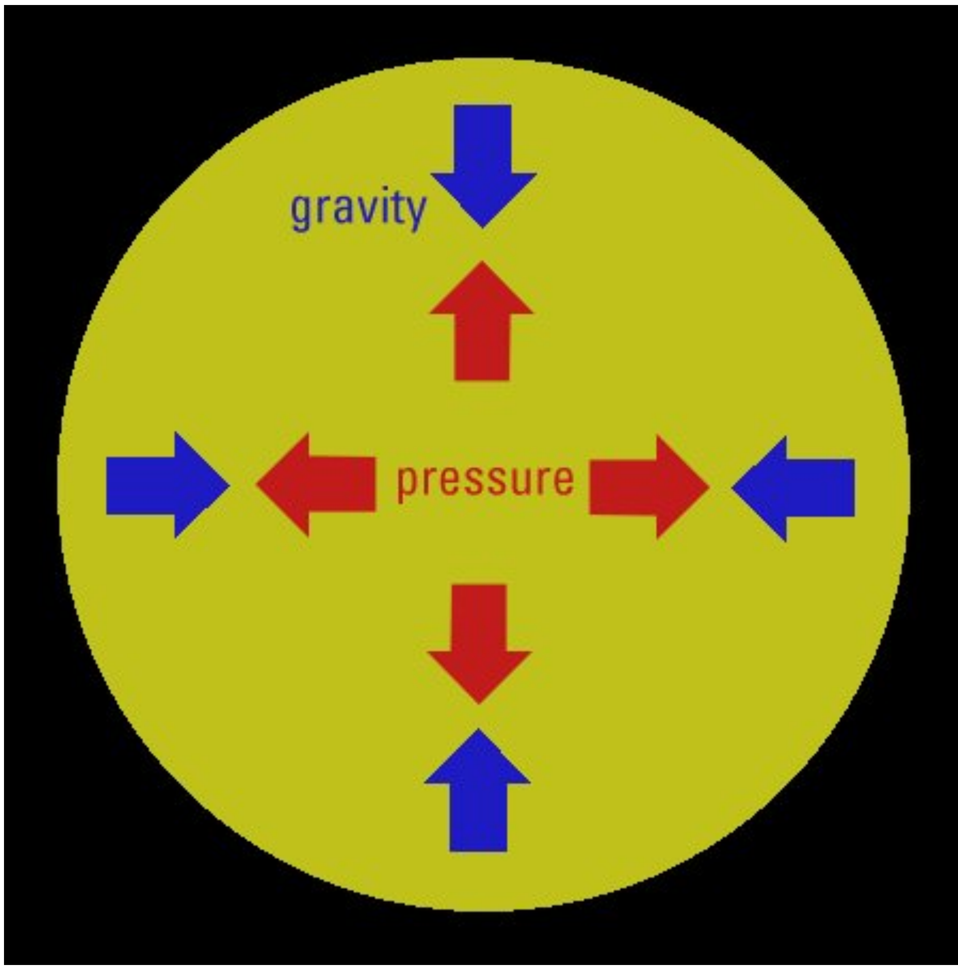


pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

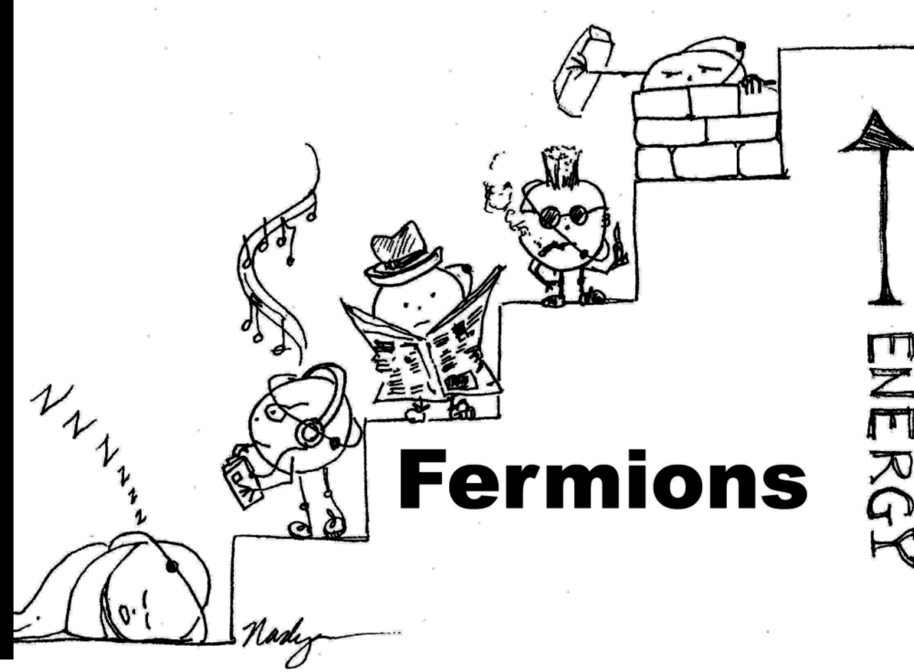
Why are (neutron) stars stable?

equilibrium between pressure of matter and gravity

leads to Tolman-Oppenheimer-Volkov equations for neutron stars:
solve for enclosed M(r), total M and R, only input: equation of state

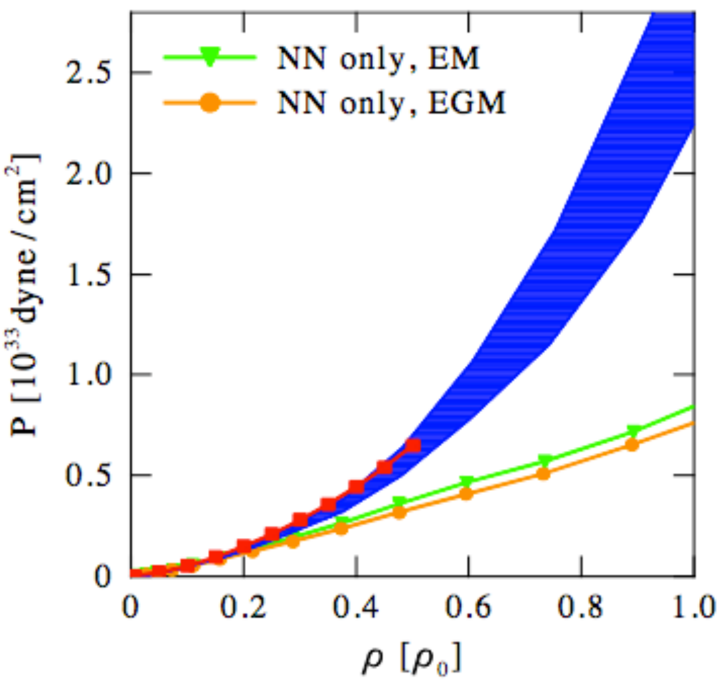


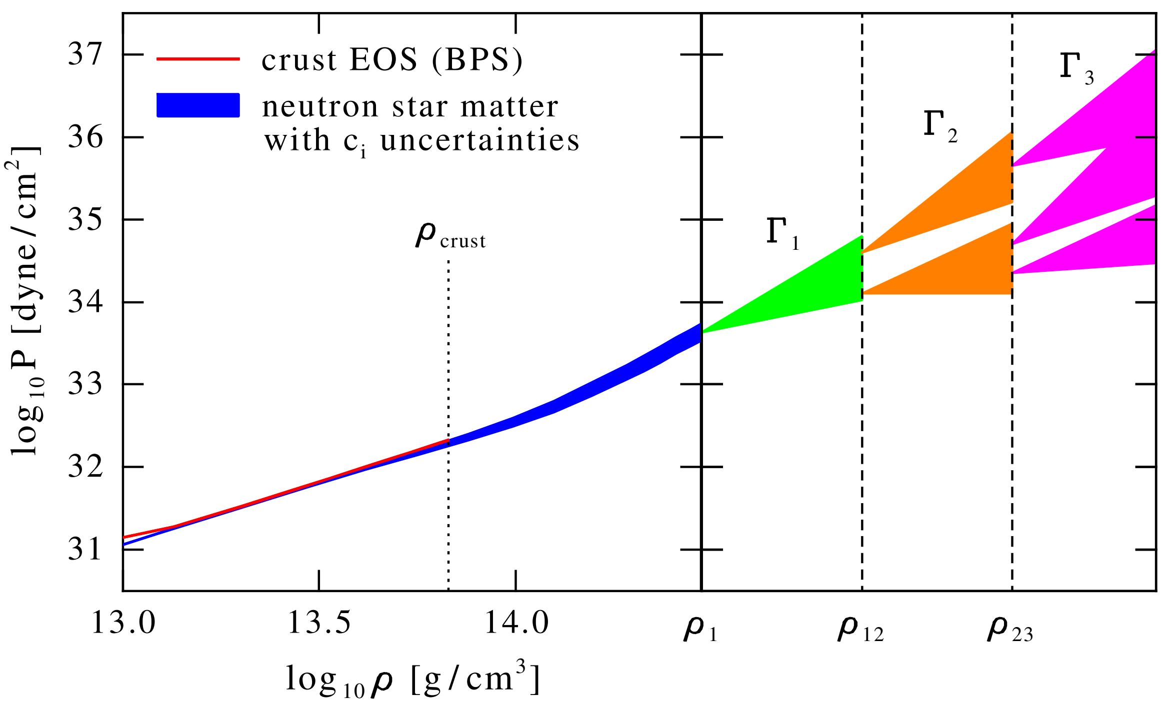
pressure for neutrons:
Fermi pressure plus
NN, 3N,… interactions



Impact on neutron stars Hebeler et al. (2010, 2013)

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



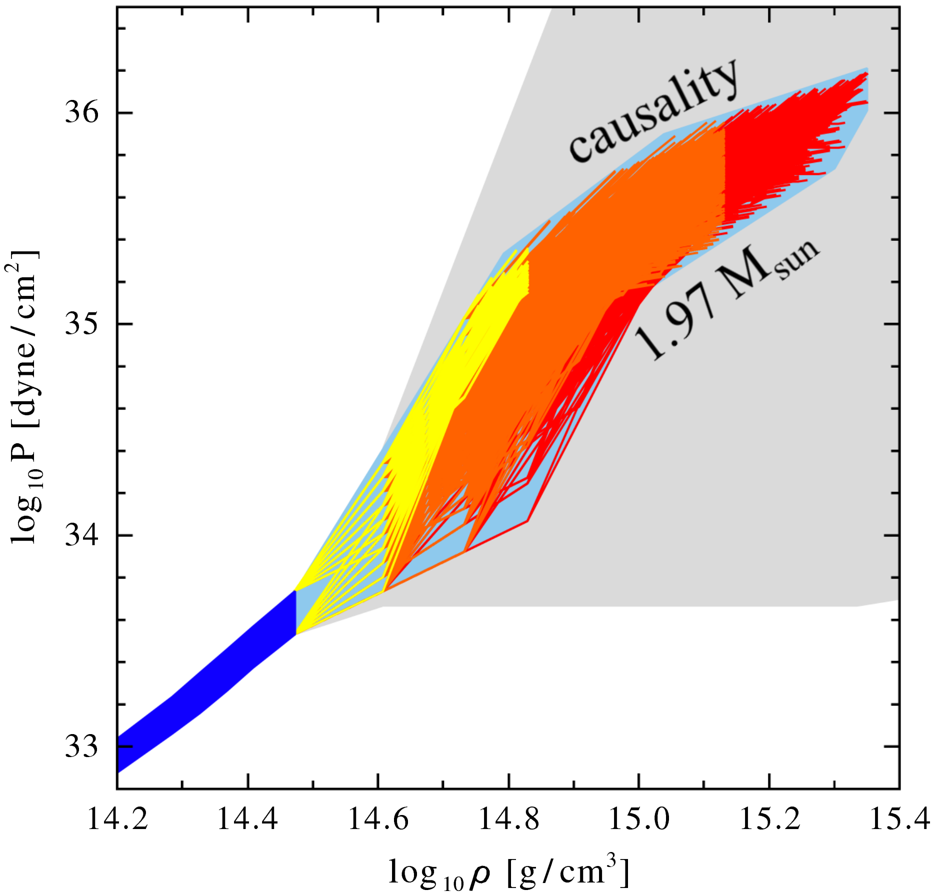


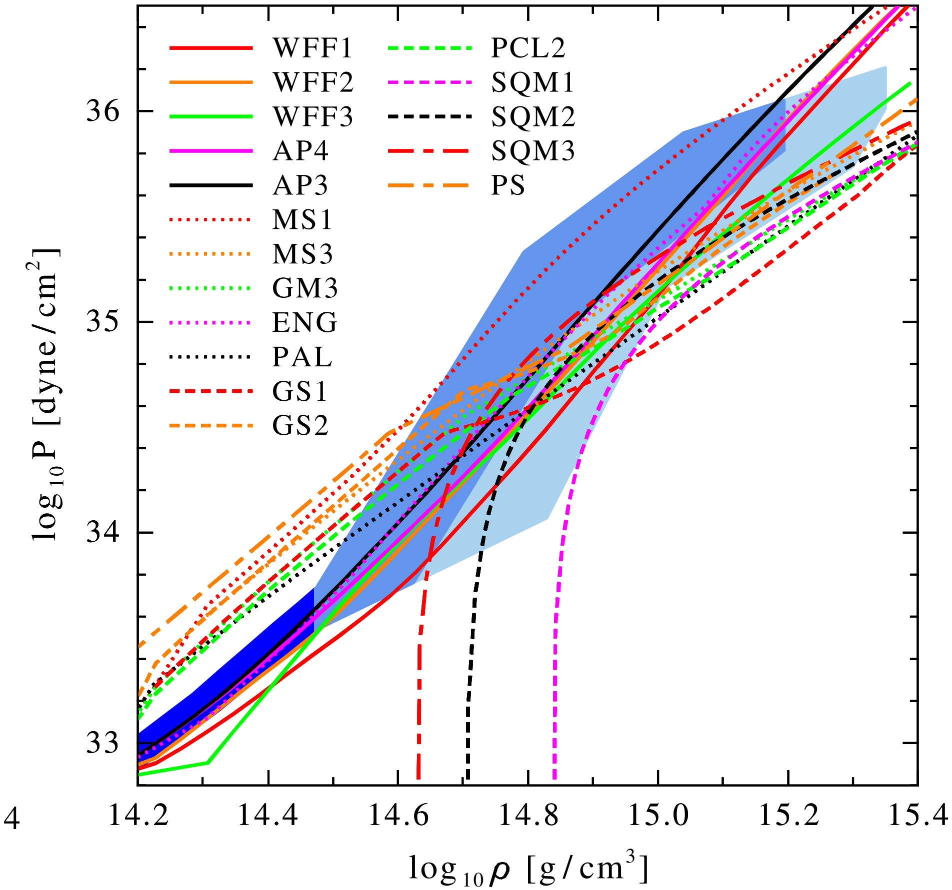
pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

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

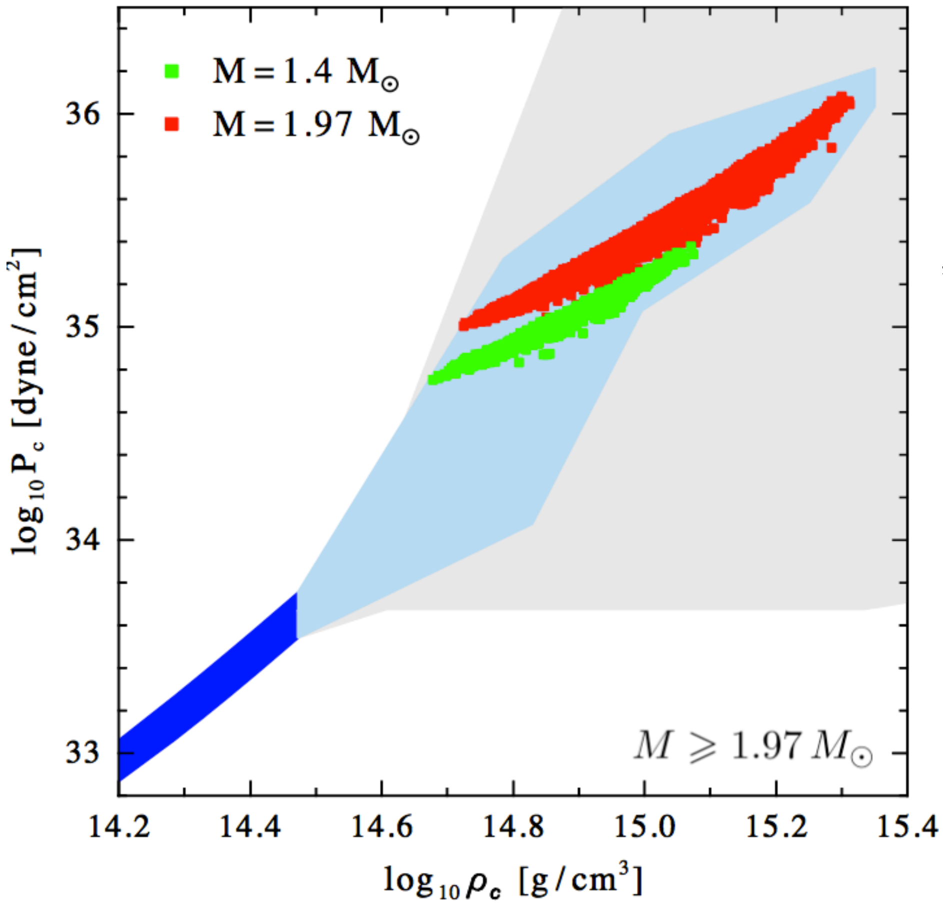


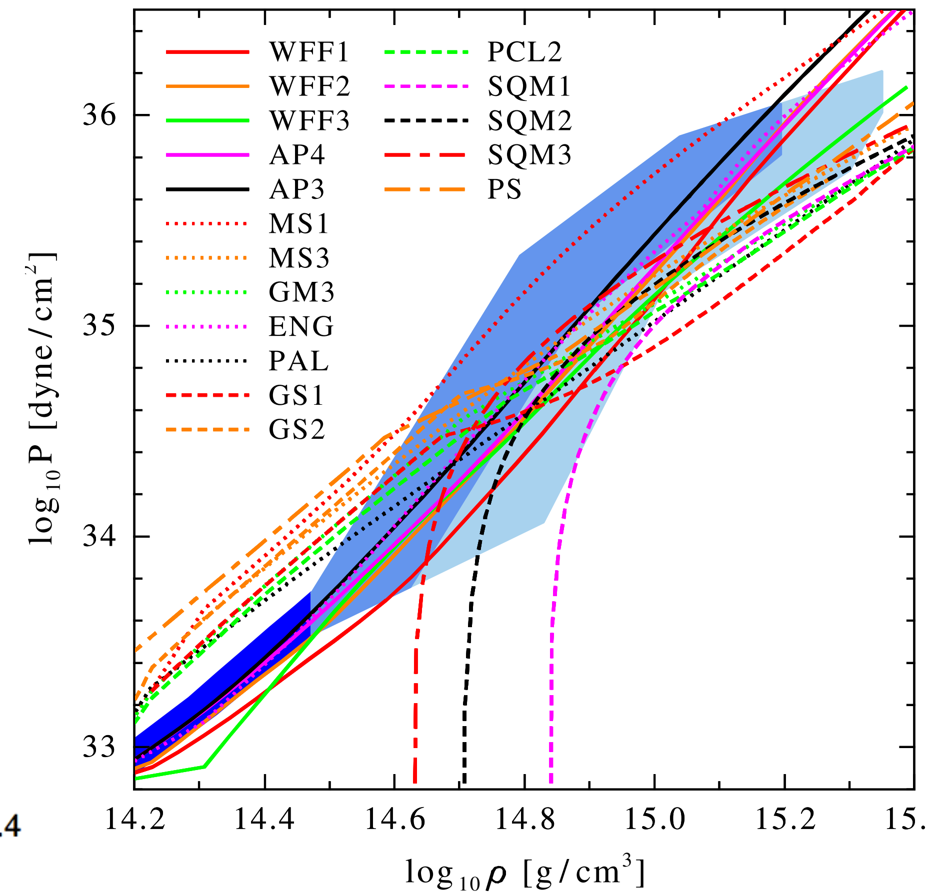


low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

Pressure of neutron star matter

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



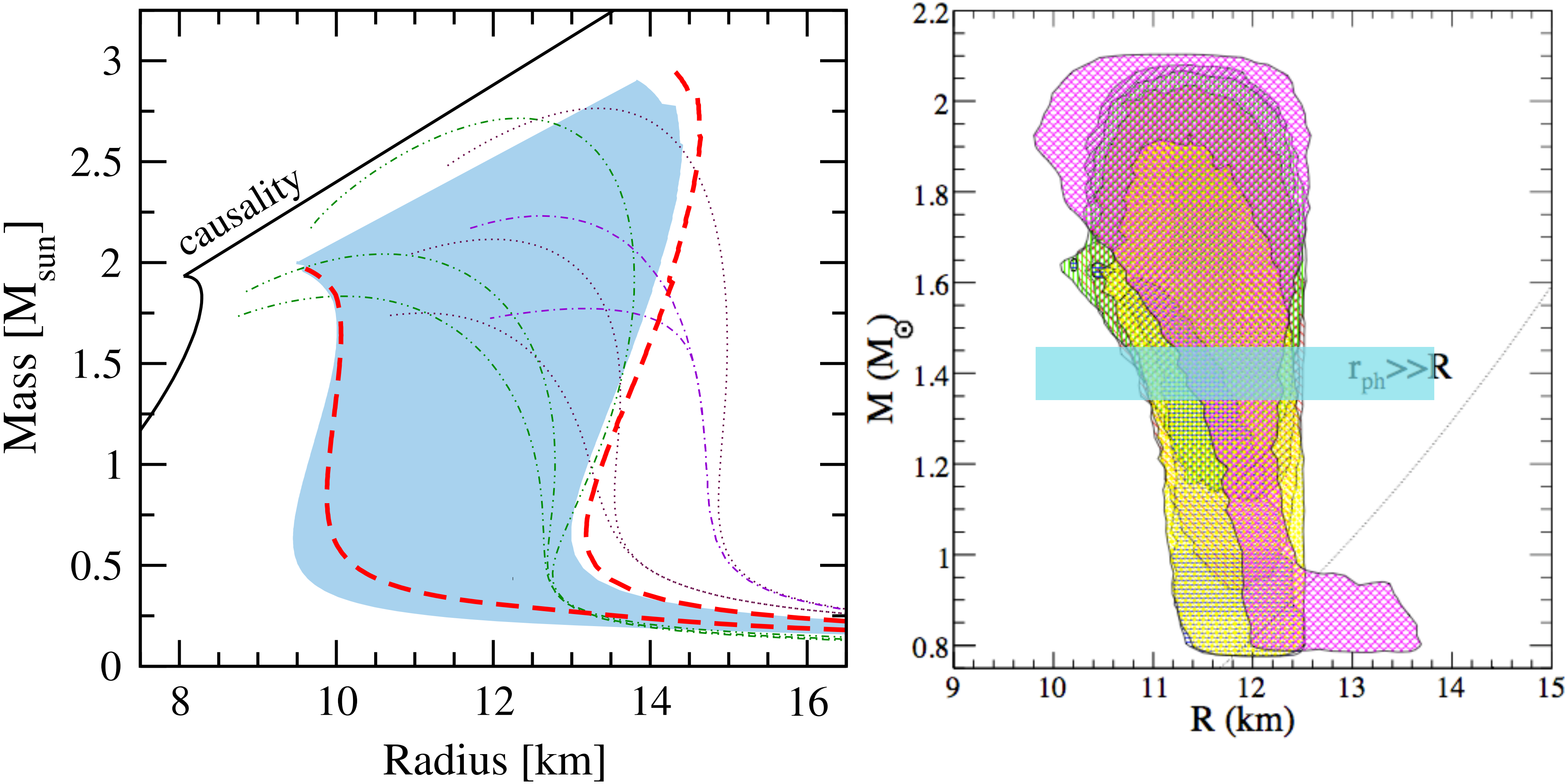


low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

central densities for 1.4 M_{sun} star: 1.8-4.4 ρ_0

Neutron star radius constraints

uncertainty from many-body forces and general extrapolation



constrains neutron star radius: 9.7-13.9 km for M=1.4 M_{sun} (±18% !)

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

Neutron-star mergers and gravitational waves

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

Bauswein, Janka (2012), Bauswein, Janka, Hebeler, AS (2012).

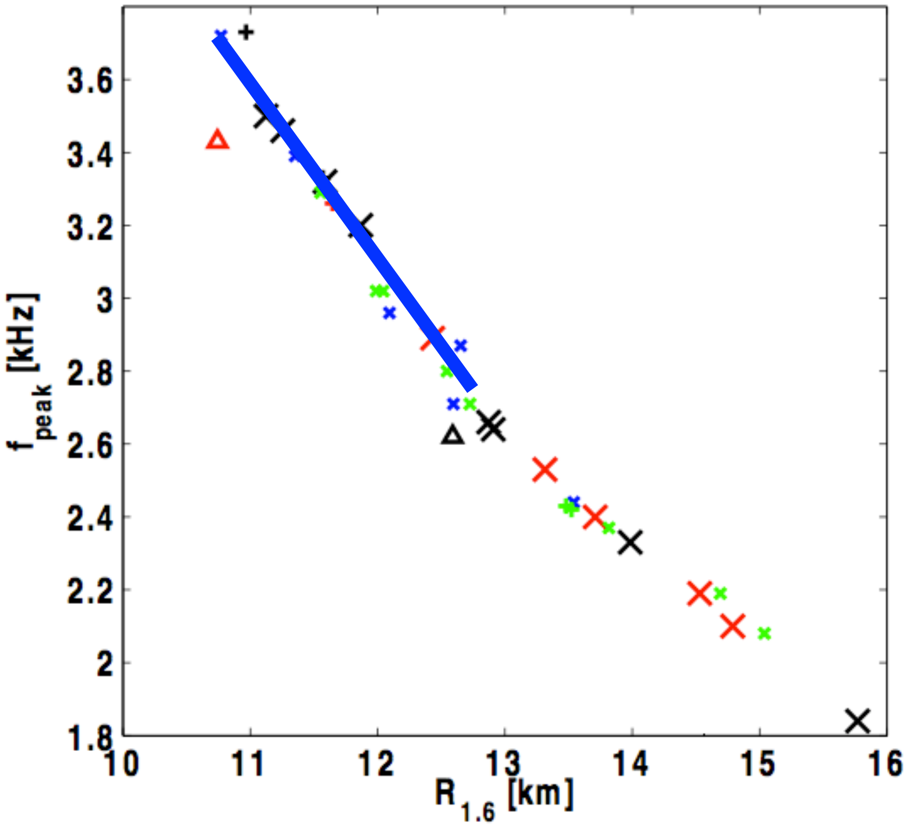


FIG. 10: Peak frequency of the postmerger GW emission versus the radius of a nonrotating NS with 1.6 $M_\odot$ for different EoSs. Symbols have the same meaning as in Fig. 8.

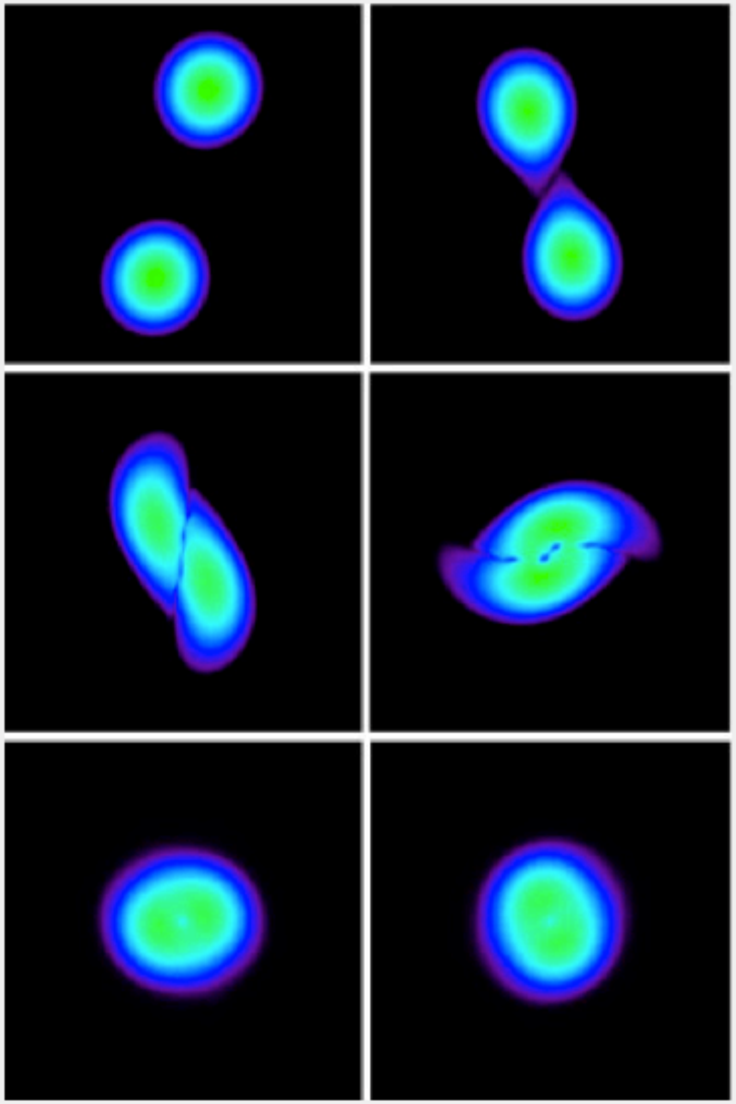


Fig. 1: Various snapshots of the collision of two neutron stars initially revolving around each other. The sequence simulated by the computer covers only 0.03 seconds. The two stars orbit each other counterclockwise (top left) and quickly come closer (top right). Finally they collide (centre left), merge (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)

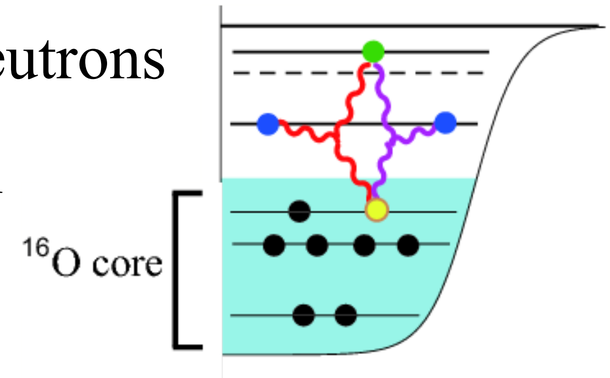
Oxygen isotopes - impact of 3N forces

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

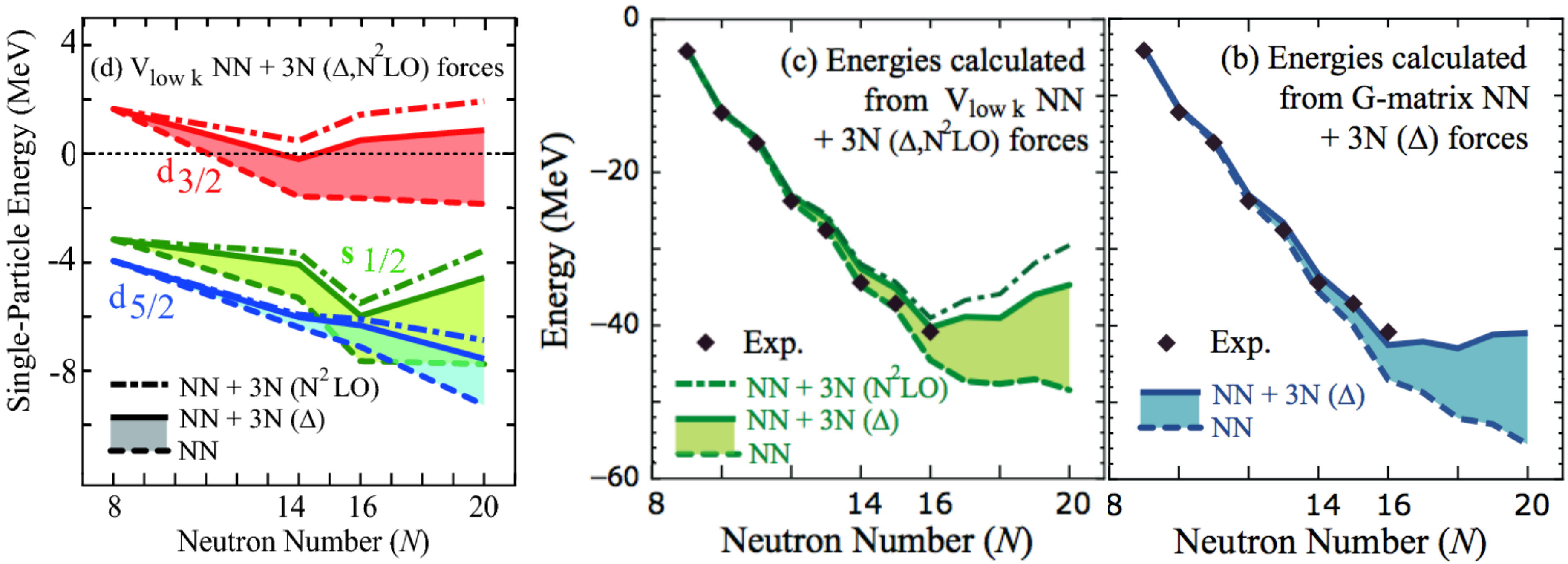
leads to repulsive interactions between valence neutrons

contributions from residual three valence-nucleon interactions suppressed by $E_{ex}/E_F \sim N_{valence}/N_{core}$

Friman, AS (2011)



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



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

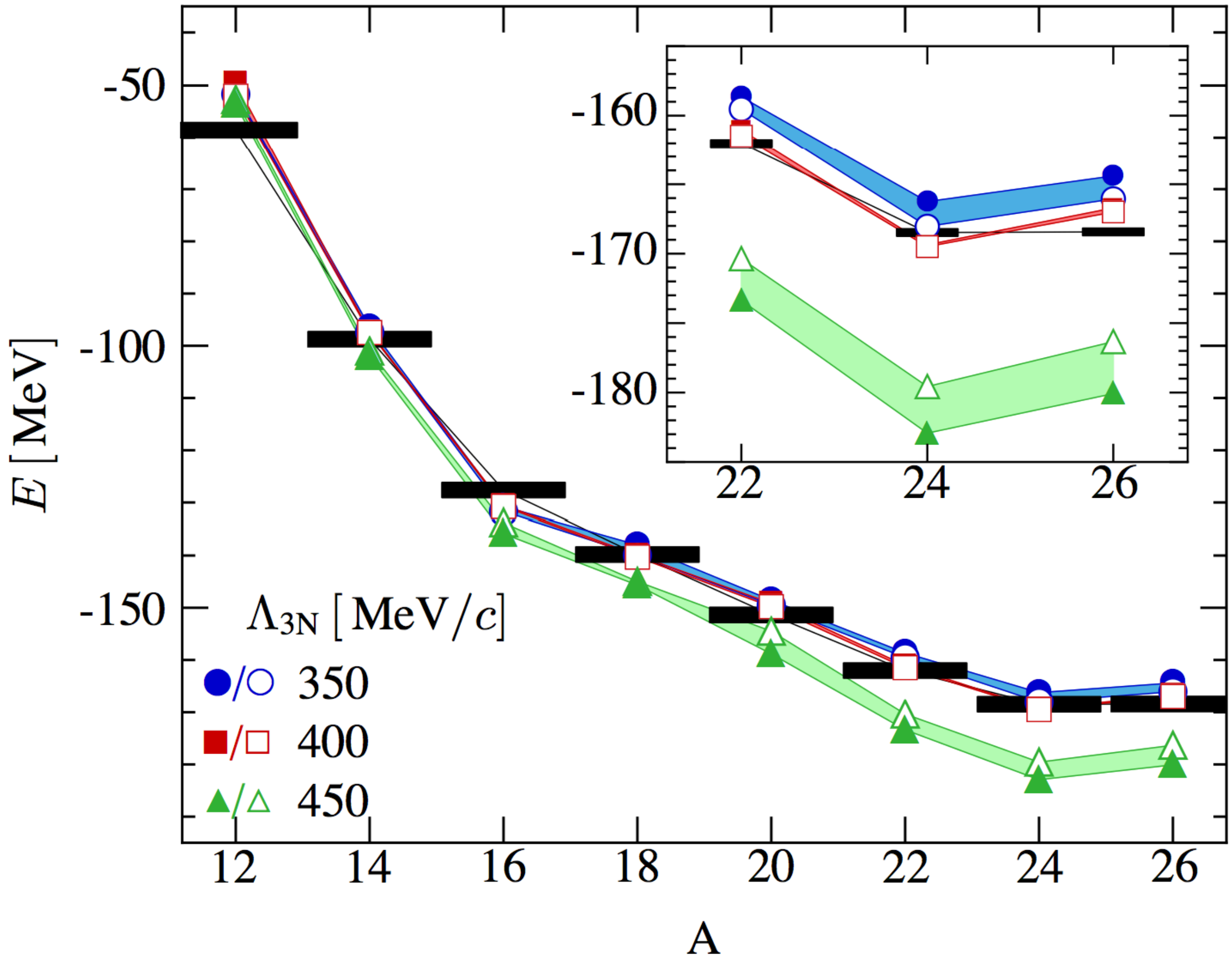
New ab-initio methods extend reach

impact of 3N forces confirmed in large-space calculations:

Coupled Cluster theory with phenomenological 3N forces Hagen et al. (2012)

In-Medium Similarity RG based on chiral NN+3N Hergert et al. (2013)

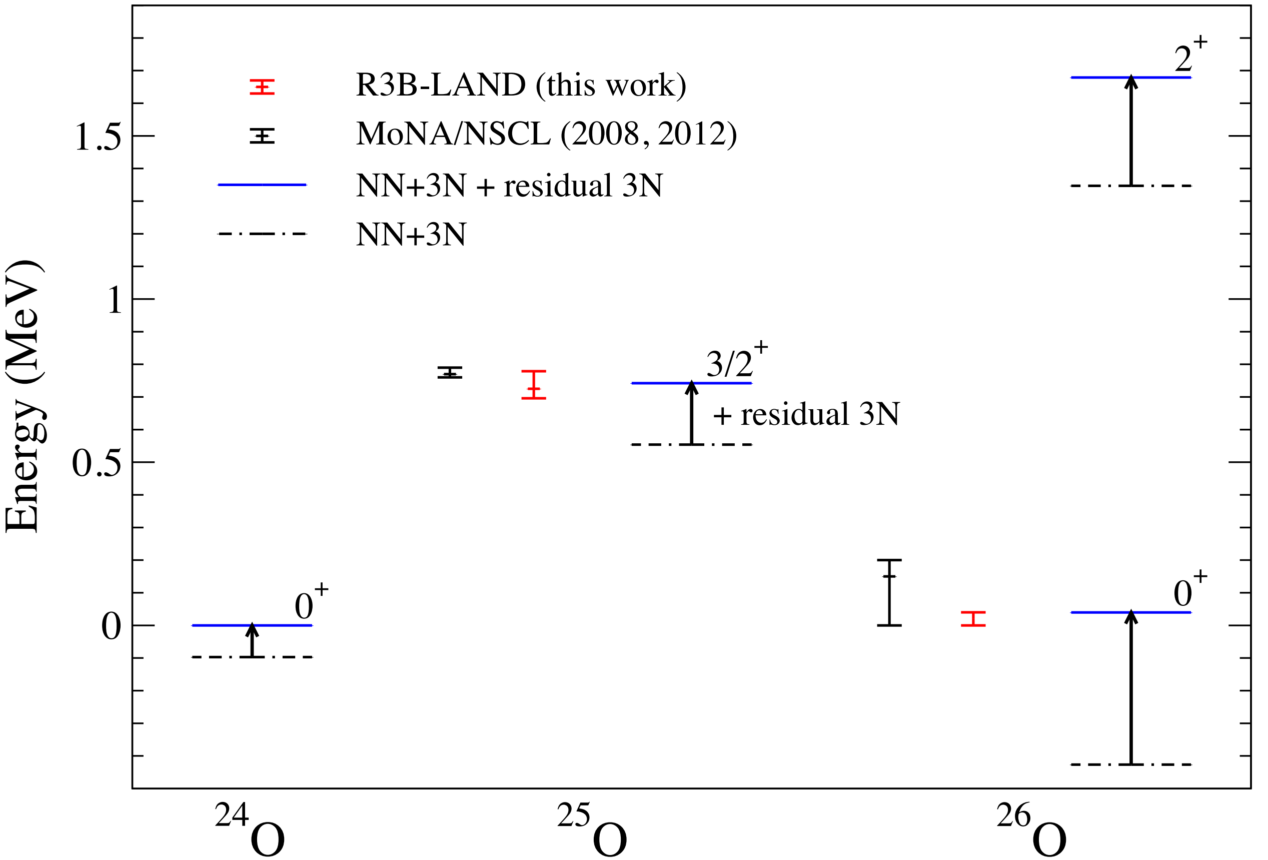
Green's function methods based on chiral NN+3N Cipollone et al. (2013)

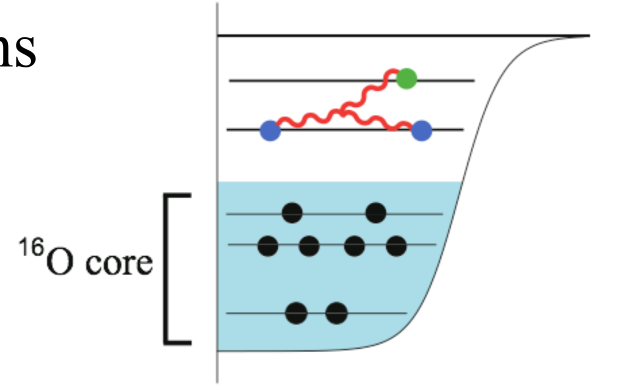


Residual 3N forces and extreme neutron-rich nuclei

amplified in the shell model with valence nucleons

R3B collaboration, Simonis, Holt, Menendez, AS, arXiv:1209.0156.





residual 3N small compared to normal-ordered contributions

increases with N, important for neutron-rich $^{25,26}O$
studied at MoNA/NSCL and R3B-LAND

PRL 110, 192502 (2013) PHYSICAL REVIEW LETTERS week ending 10 MAY 2013

Optimized Chiral Nucleon-Nucleon Interaction at Next-to-Next-to-Leading Order

A. Ekström,[1,2] G. Baardsen,[1] C. Forssén,[3] G. Hagen,[4,5] M. Hjorth-Jensen,[1,2,6] G. R. Jansen,[4,5] R. Machleidt,[7] W. Nazarewicz,[5,4,8] T. Papenbrock,[5,4] J. Sarich,[9] and S. M. Wild[9]
[1]*Department of Physics and Center of Mathematics for Applications, University of Oslo, N-0316 Oslo, Norway*
[2]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
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[6]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[7]*Department of Physics, University of Idaho, Moscow, Idaho 83844, USA*
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[9]*Mathematics and Computer Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
(Received 19 March 2013; published 7 May 2013)

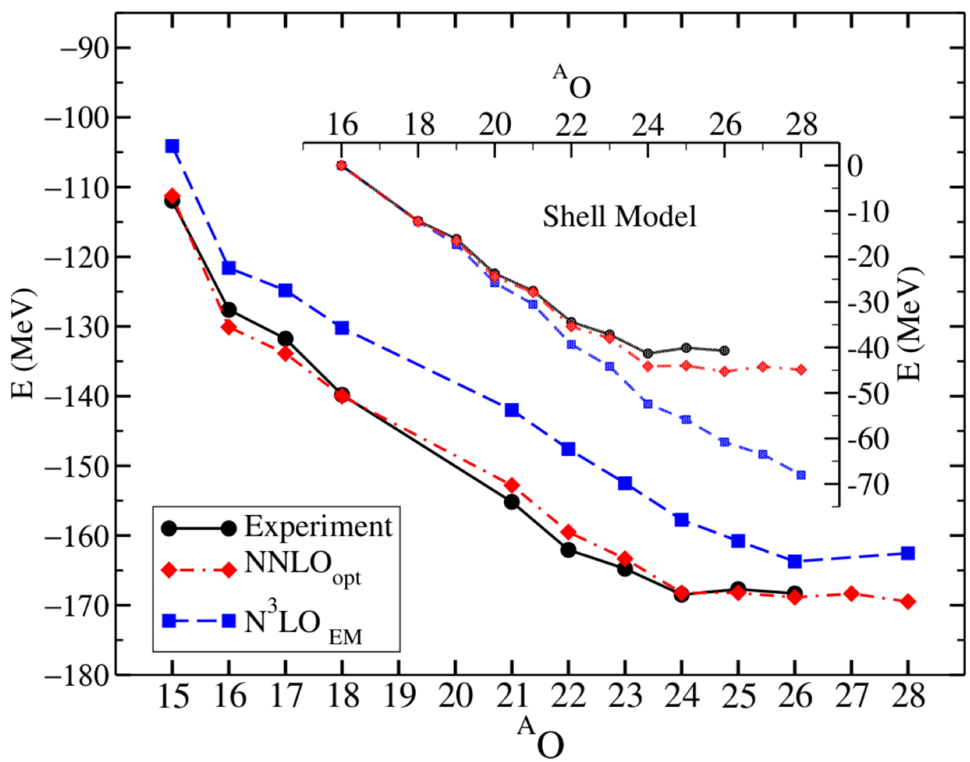
We optimize the nucleon-nucleon interaction from chiral effective field theory at next-to-next-to-leading order (NNLO). The resulting new chiral force $\mathrm{NNLO_{opt}}$ yields $\chi^2 \approx 1$ per degree of freedom for laboratory energies below approximately 125 MeV. In the $A = 3$, 4 nucleon systems, the contributions of three-nucleon forces are smaller than for previous parametrizations of chiral interactions. We use $\mathrm{NNLO_{opt}}$ to study properties of key nuclei and neutron matter, and we demonstrate that many aspects of nuclear structure can be understood in terms of this nucleon-nucleon interaction, without explicitly invoking three-nucleon forces.

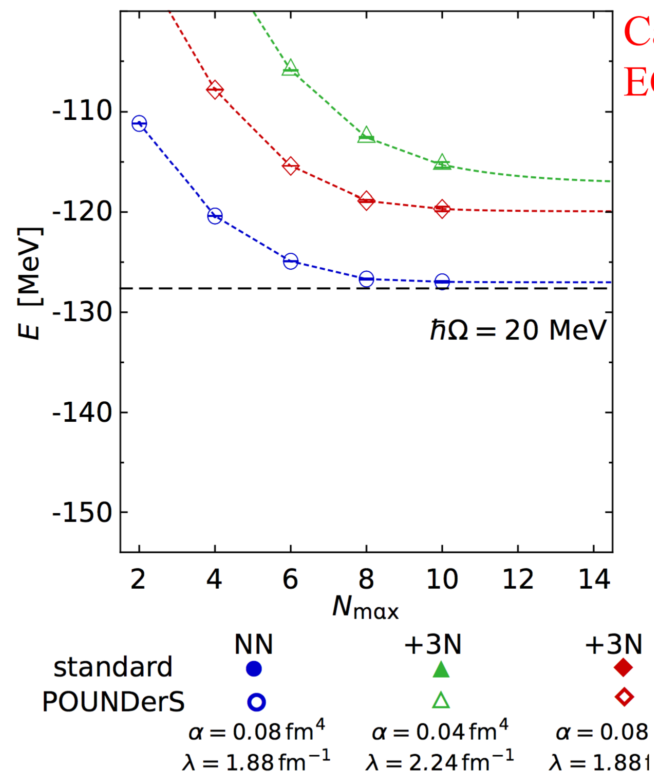
Does one need 3N forces?

calculations with "optimized" N^2LO NN potential:
maybe 3N forces are small

explicit calculations disagree

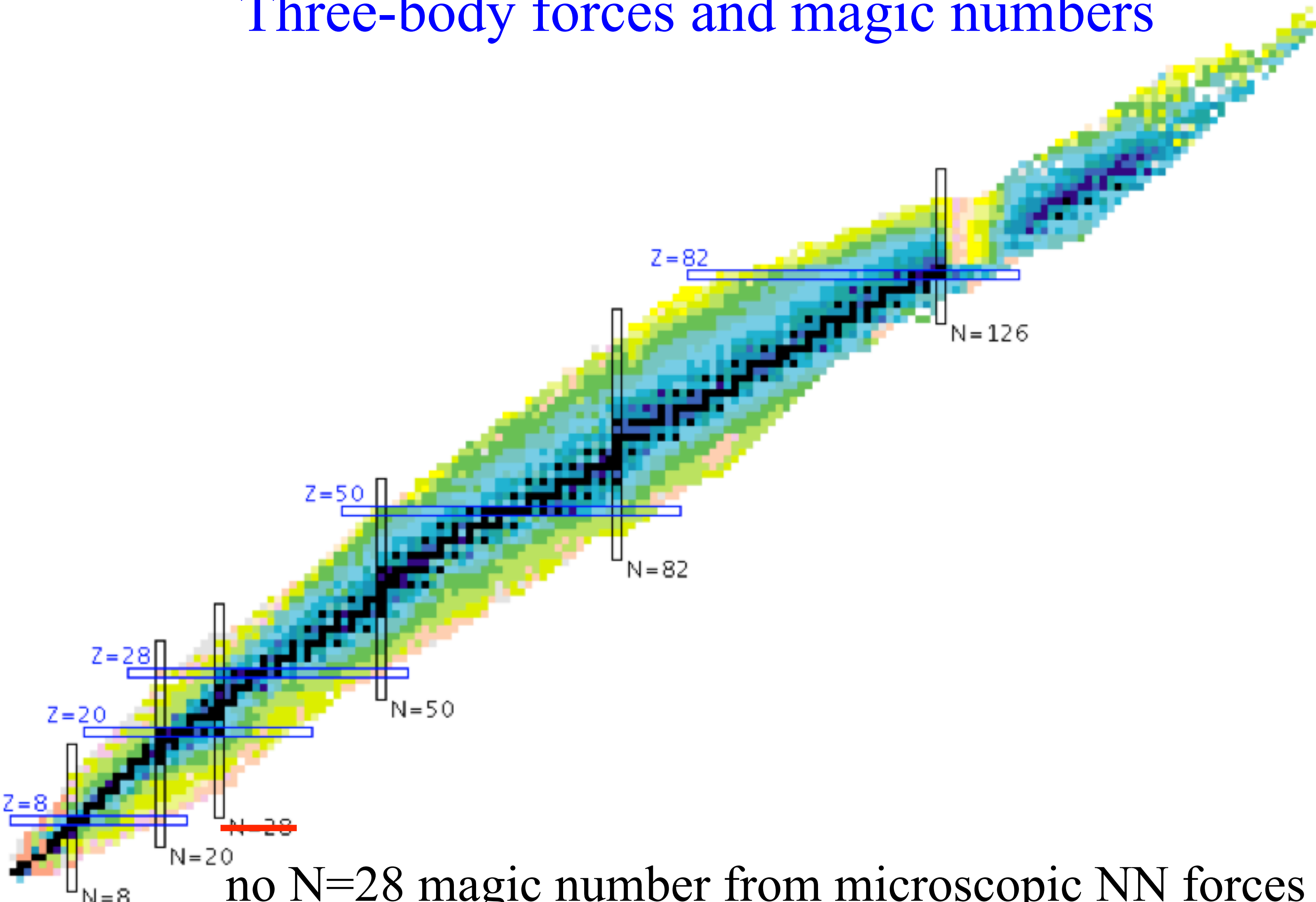
^{16}O: ~10 MeV 3N repulsion,
Ca overbound without 3N,…





Calci et al.
ECT* workshop

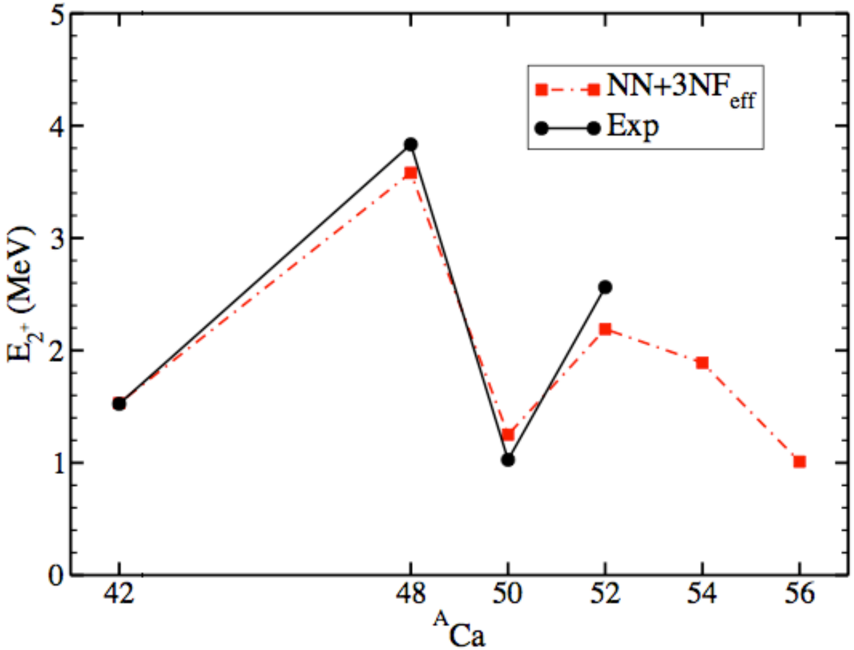
Three-body forces and magic numbers

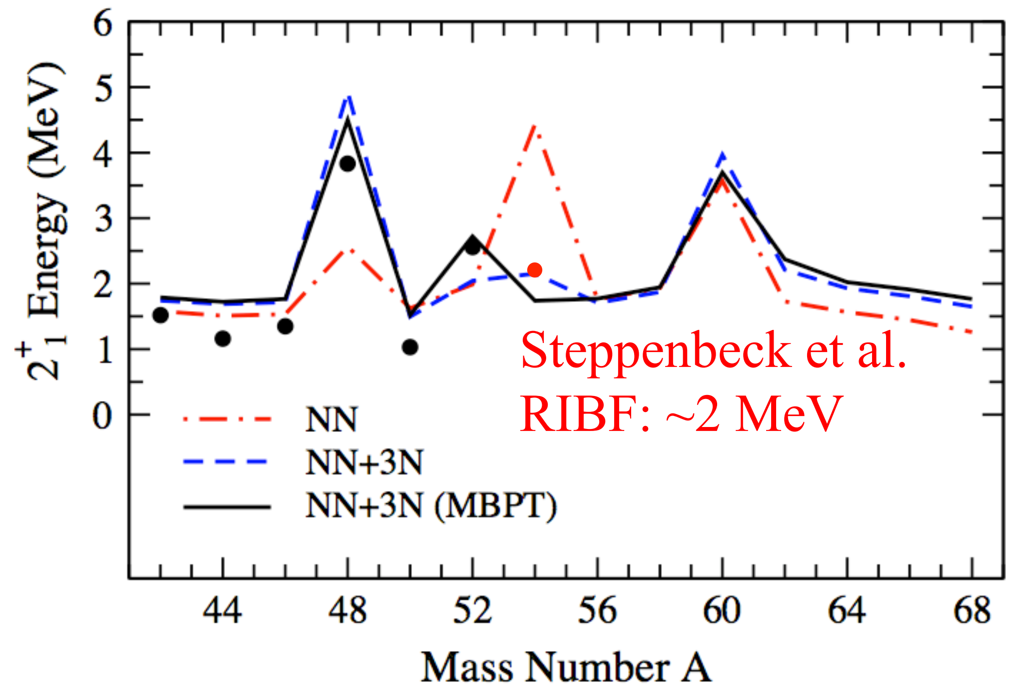


no N=28 magic number from microscopic NN forces

Zuker, Poves,…

Three-body forces and magic numbers



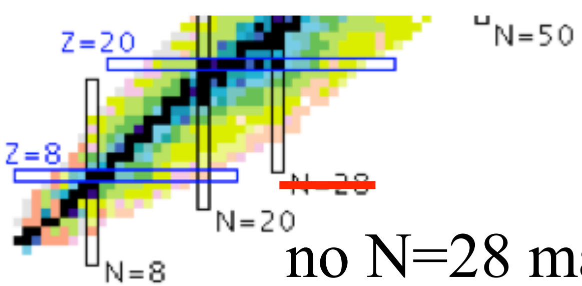


Hagen et al. (2012)

Holt et al. (2012, 2013)

without 3N forces to 3rd order,

2^+ is higher in ^{54}Ca



no N=28 magic number from microscopic NN forces

Zuker, Poves,…

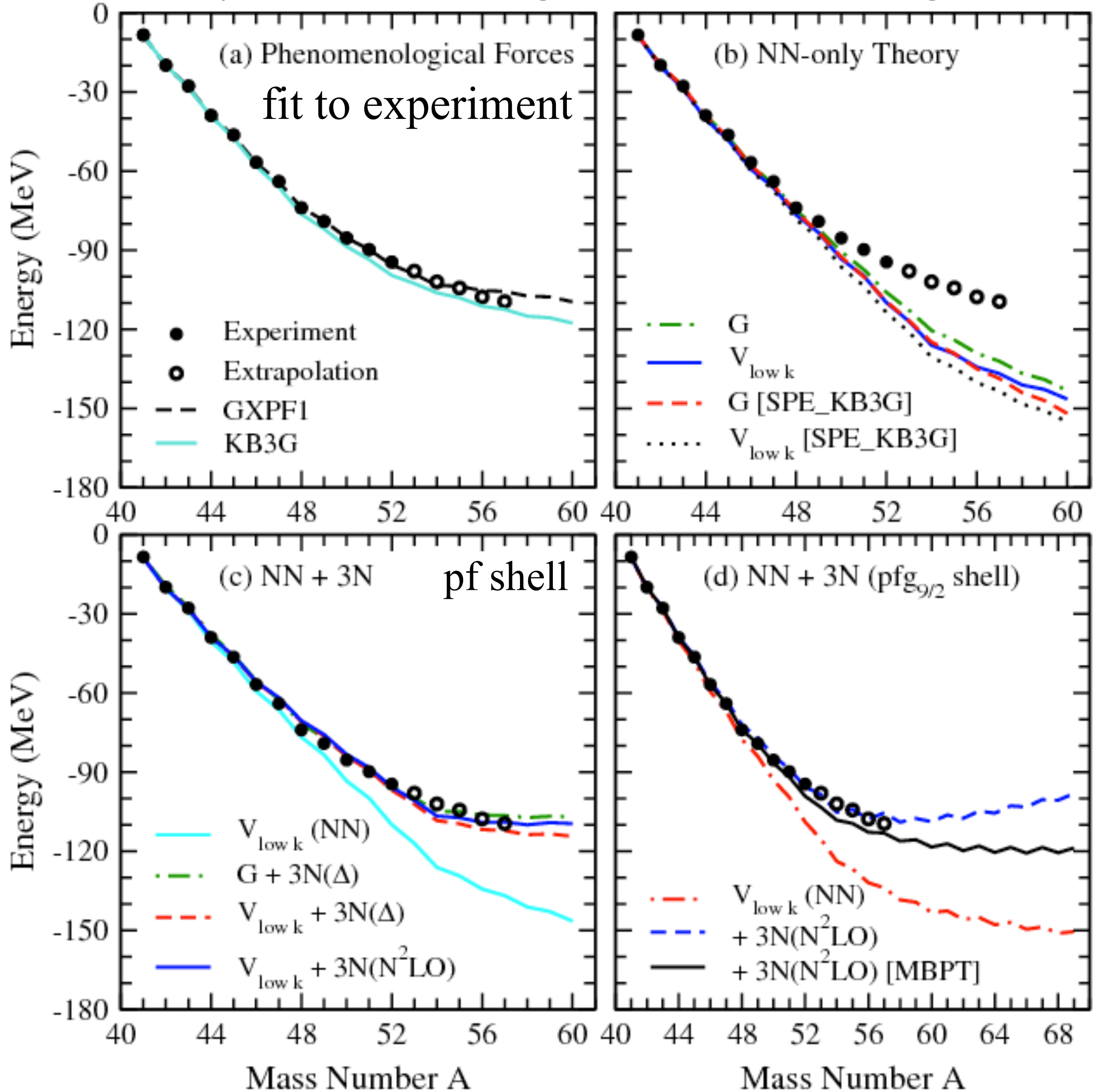
Evolution to neutron-rich calcium isotopes

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

Holt, Otsuka, AS, Suzuki (2012)

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

gs energy flat with N,
continuum important
for dripline location

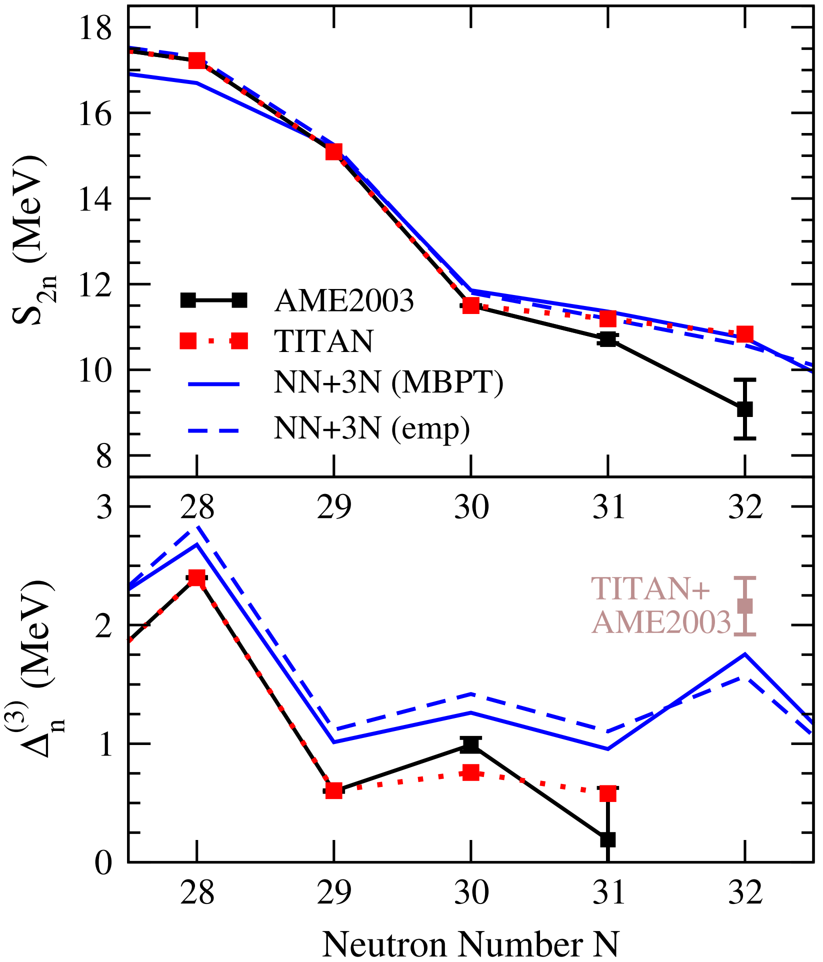


new ^{51,52}Ca TITAN measurements

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

Gallant et al. (2012)

behavior of 2n separation energy S_{2n} agrees with NN+3N predictions



doi:10.1038/nature12226

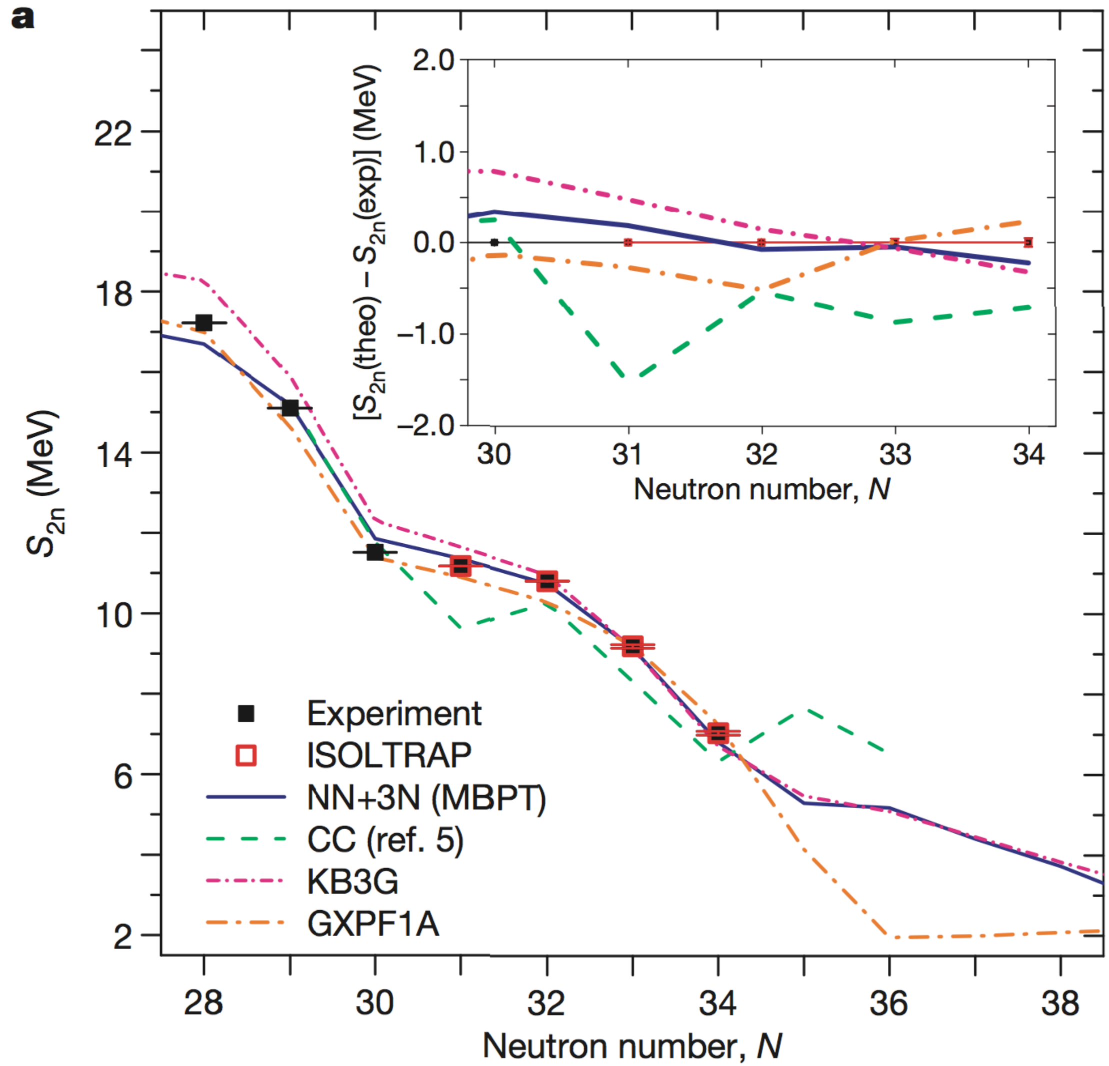
Masses of exotic calcium isotopes pin down nuclear forces

F. Wienholtz[1], D. Beck[2], K. Blaum[3], Ch. Borgmann[3], M. Breitenfeldt[4], R. B. Cakirli[3,5], S. George[1], F. Herfurth[2], J. D. Holt[6,7], M. Kowalska[8], S. Kreim[3,8], D. Lunney[9], V. Manea[9], J. Menéndez[6,7], D. Neidherr[2], M. Rosenbusch[1], L. Schweikhard[1], A. Schwenk[7,6], J. Simonis[6,7], J. Stanja[10], R. N. Wolf[1] & K. Zuber[10]

^{53,54}Ca masses measured at ISOLTRAP using new MR-TOF mass spectrometer

establish prominent N=32 shell closure in calcium

excellent agreement with theoretical predictions



doi:10.1038/nature12226

Masses of exotic calcium isotopes pin down nuclear forces

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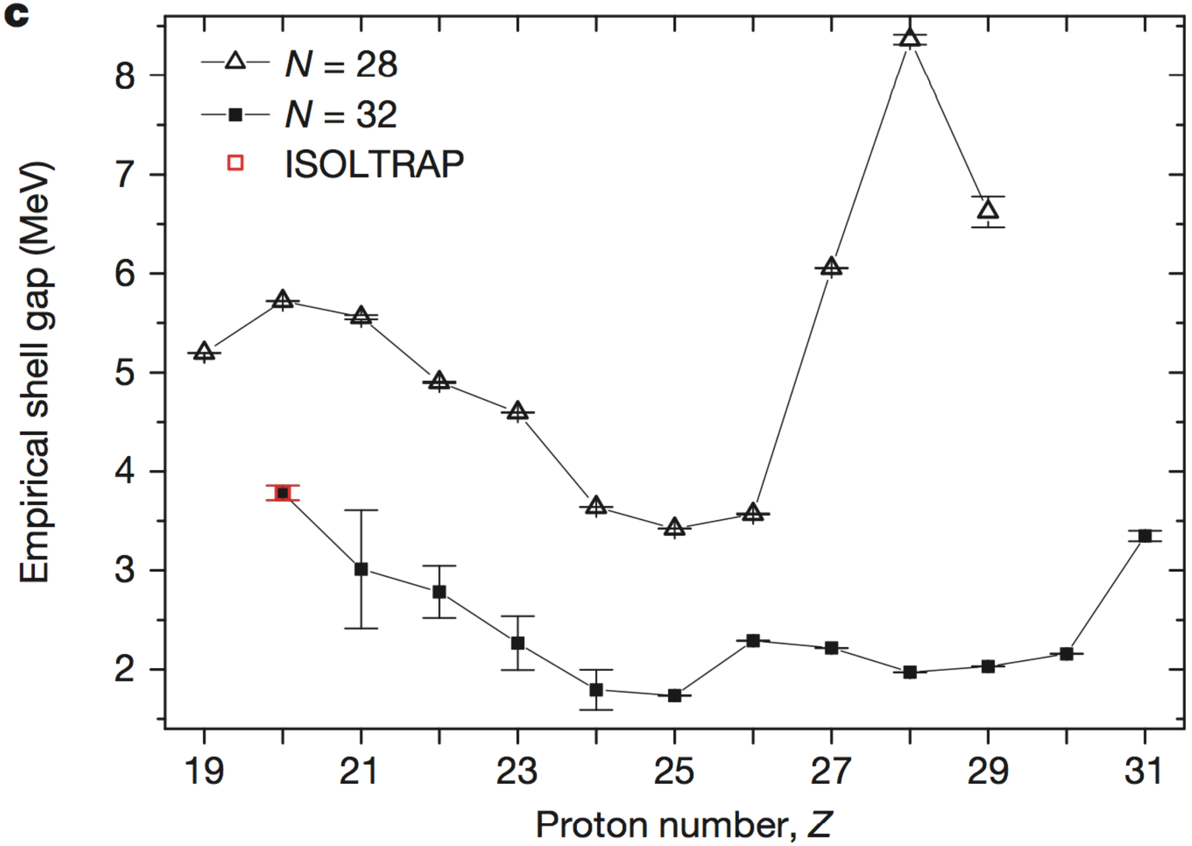
shell gap of 4 MeV

evolution to Z=20
similar for N=28 and 32

c



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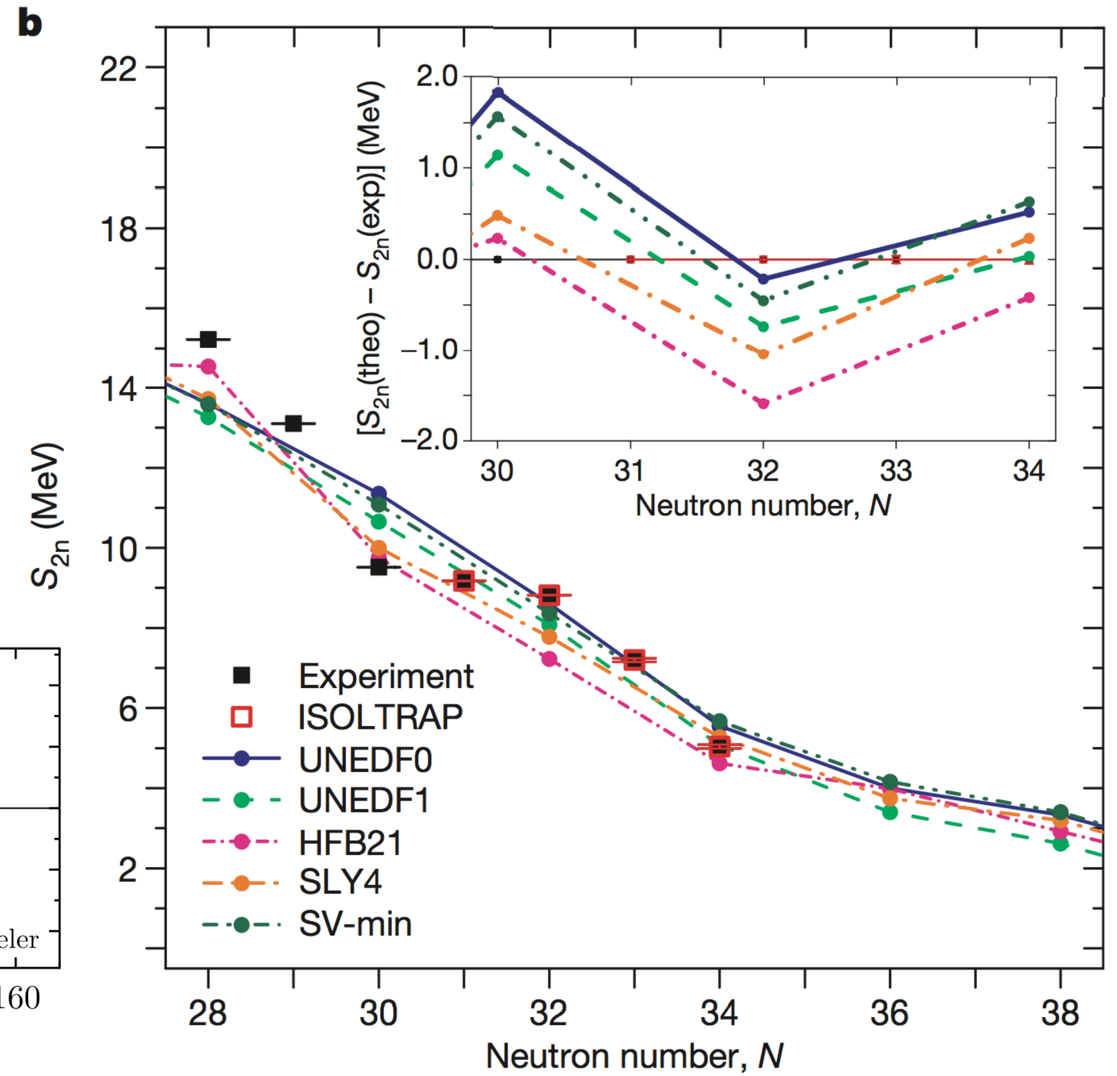
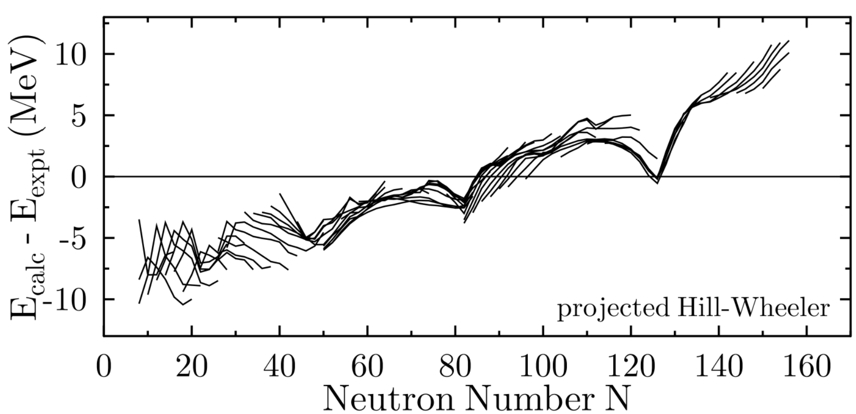
overall good agreement with density functional predictions

but DF's do not reproduce shell closures

cf. N=50, 82, 126 "arches"

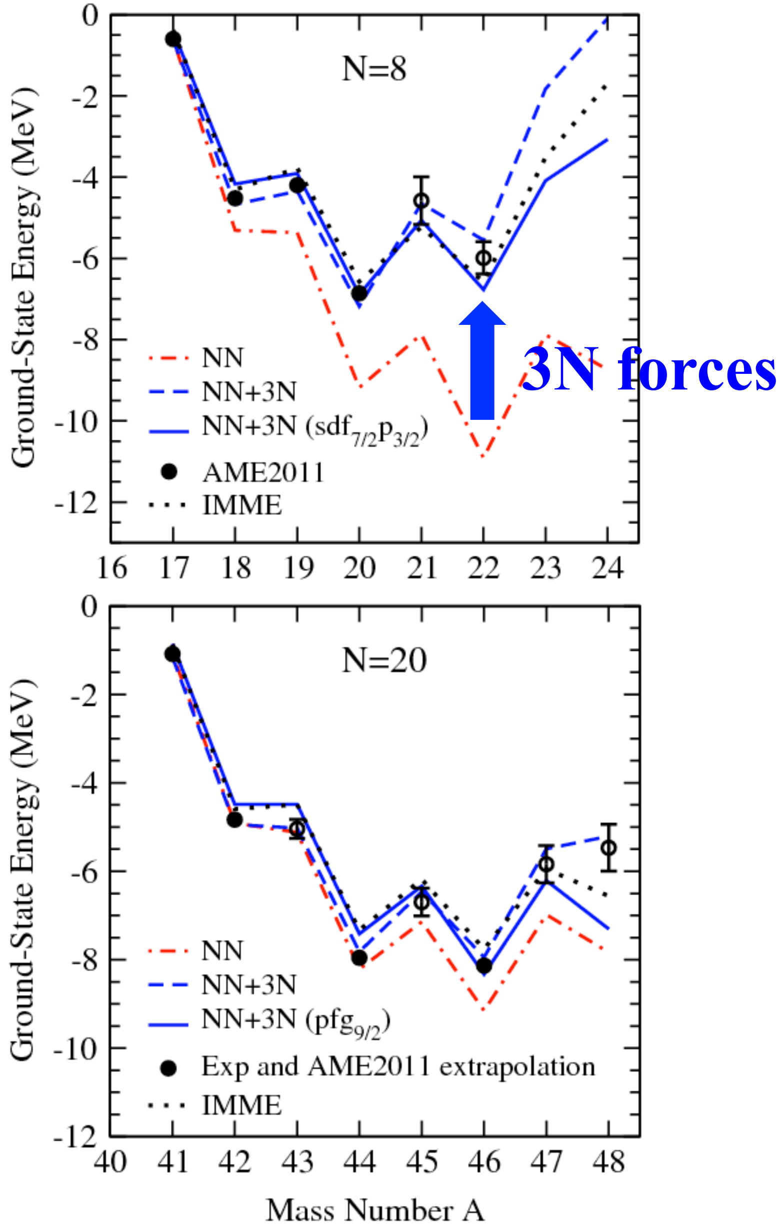
Bender et al. (2005)

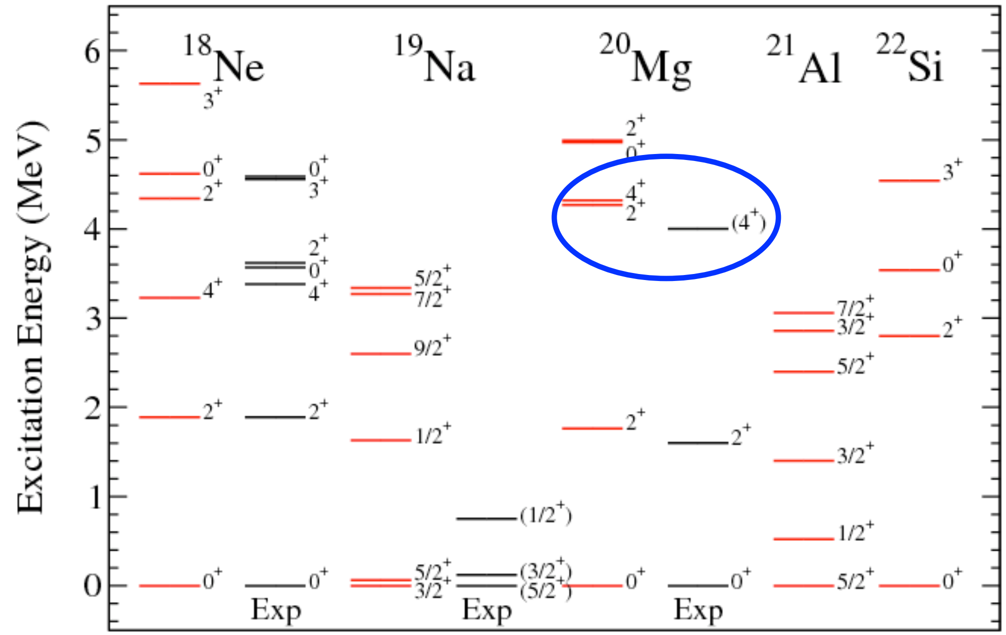




3N forces and proton-rich nuclei Holt, Menendez, AS (2013)

first results with 3N forces for ground and excited states of N=8, 20

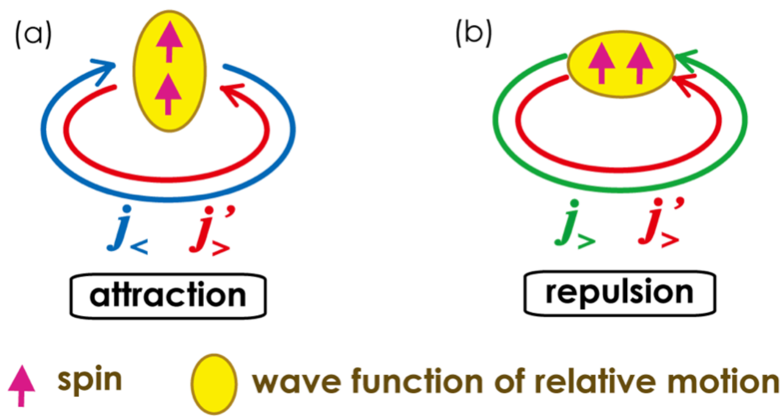




prediction for ^{20}Mg agrees with new state observed at GSI Mukha, private comm.

Tensor forces and exotic nuclei Otsuka et al.

attractive tensor force decreases spin-orbit splitting of protons with N



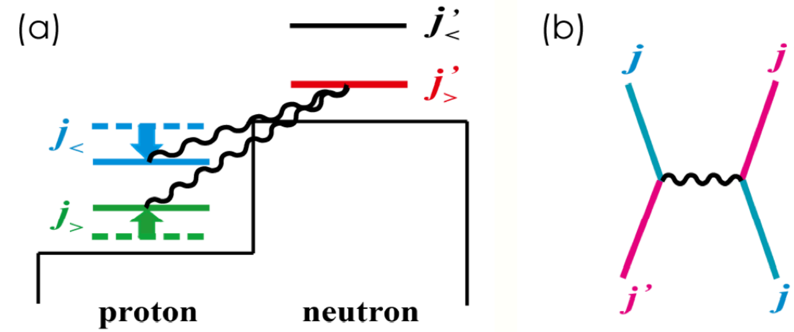
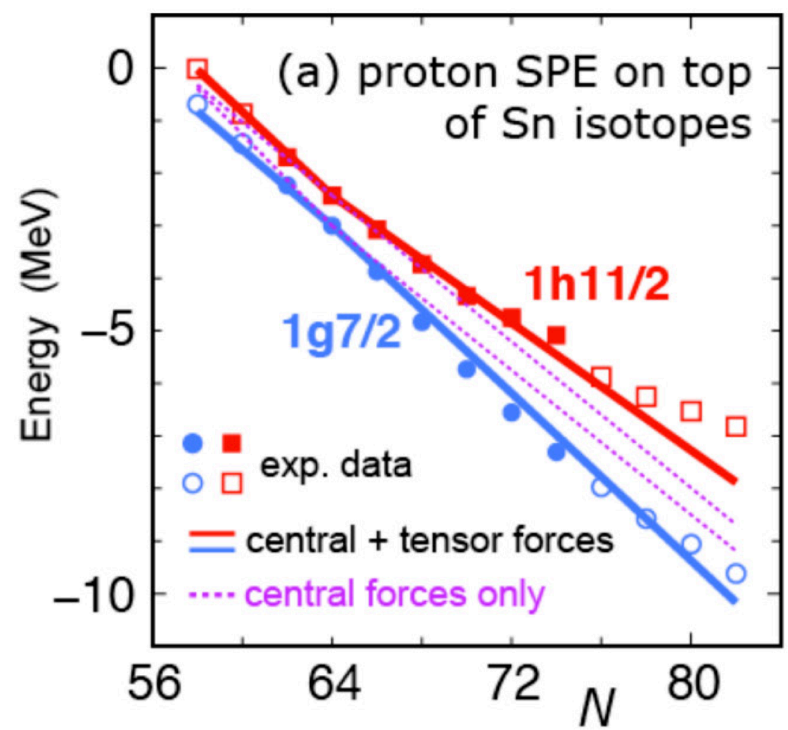


Figure 2. *(a) Change of spin-orbit splitting by the tensor force. (b) Diagram causing the change in (a). Wavy line stands for the tensor force. Modified from Ref. [6].*

larger relative momentum decreases horizontal overlap: attractive



figures from Otsuka, AS, Nuclear Physics News (2012)