Cold atoms and neutrons

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EMMI

Cold atoms meet quantum field theory

Bad Honnef, July 8, 2015

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Award for Research Cooperation and High Excellence in Science

Bundesministerium für Bildung und Forschung

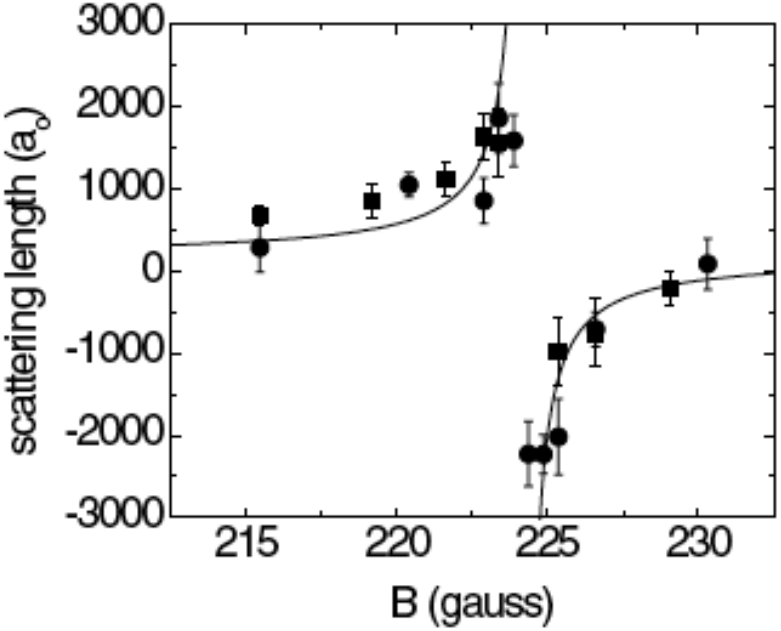
Outline

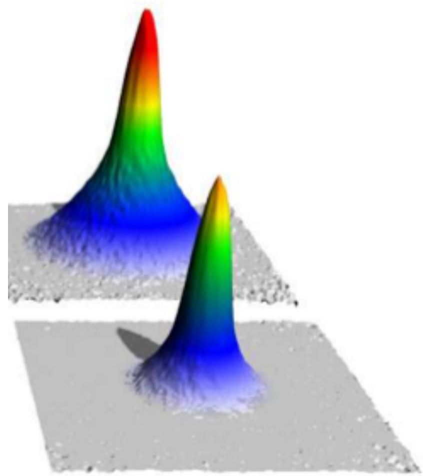
Strong interactions for neutrons and cold atoms

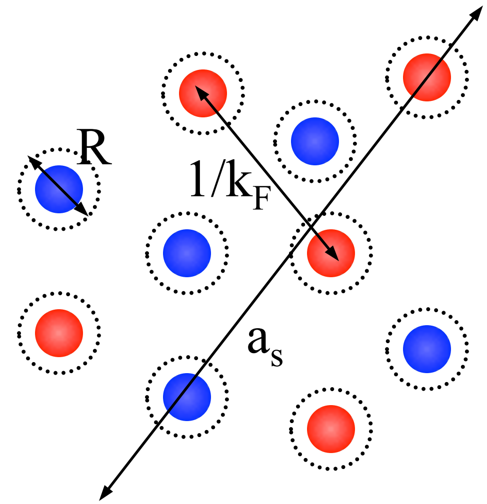
Neutron matter from low to high densities

Impact on neutron stars

Large scattering lengths: universal properties at low densities



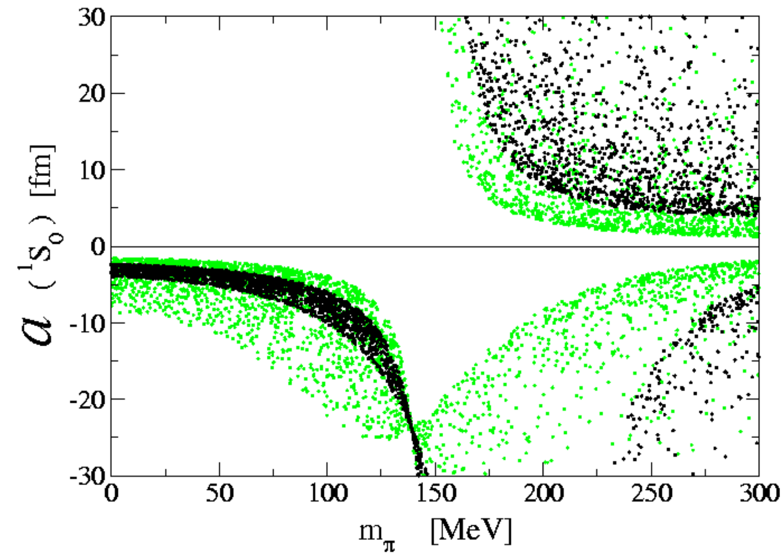




$$a_{\rm nn} \;=\; -18.5 \pm 0.3\,\mathrm{fm}$$

strong interactions via Feshbach resonances

large for neutrons



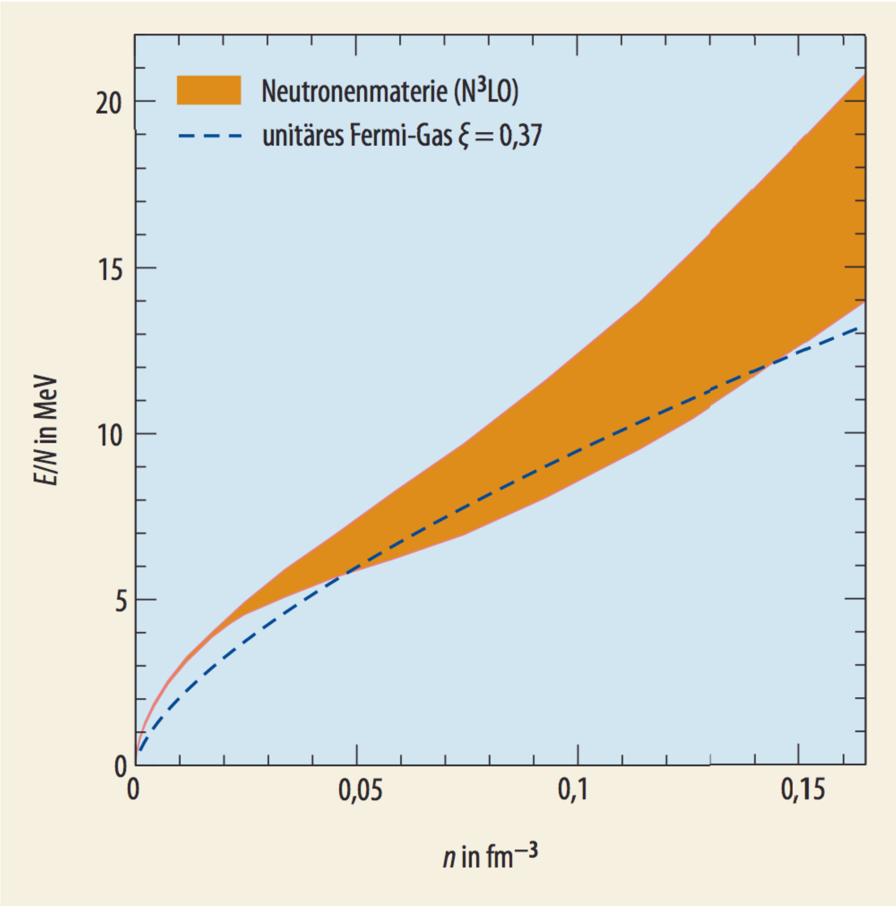
Large scattering lengths: universal thermodynamics

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

with universal Bertsch parameter ξ

Quantum Monte Carlo: ξ=0.372(5)

Carlson et al. (2012)

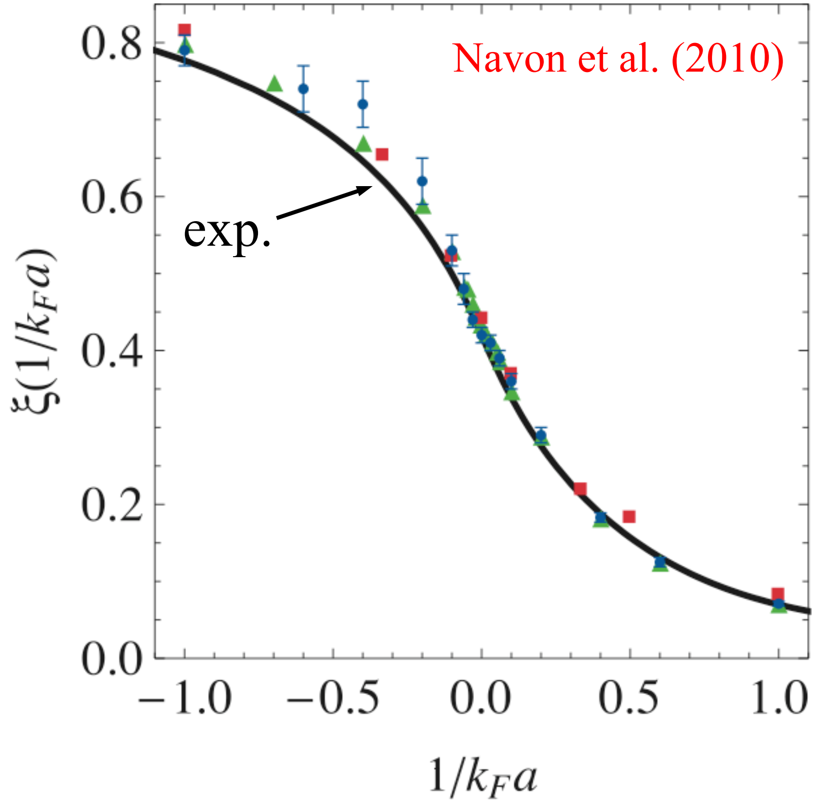


most precise results with ^{6}Li

ξ=0.370(5)(8)

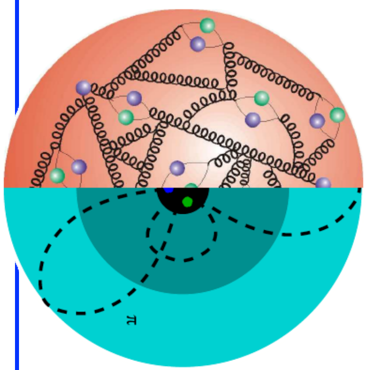
Ku et al. (2012), Zürn et al. (2013)

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

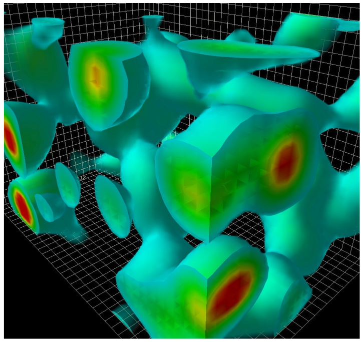


Scale dependence of nuclear forces

with high-energy probes:
quarks+gluons



at low energies:
complex QCD vacuum



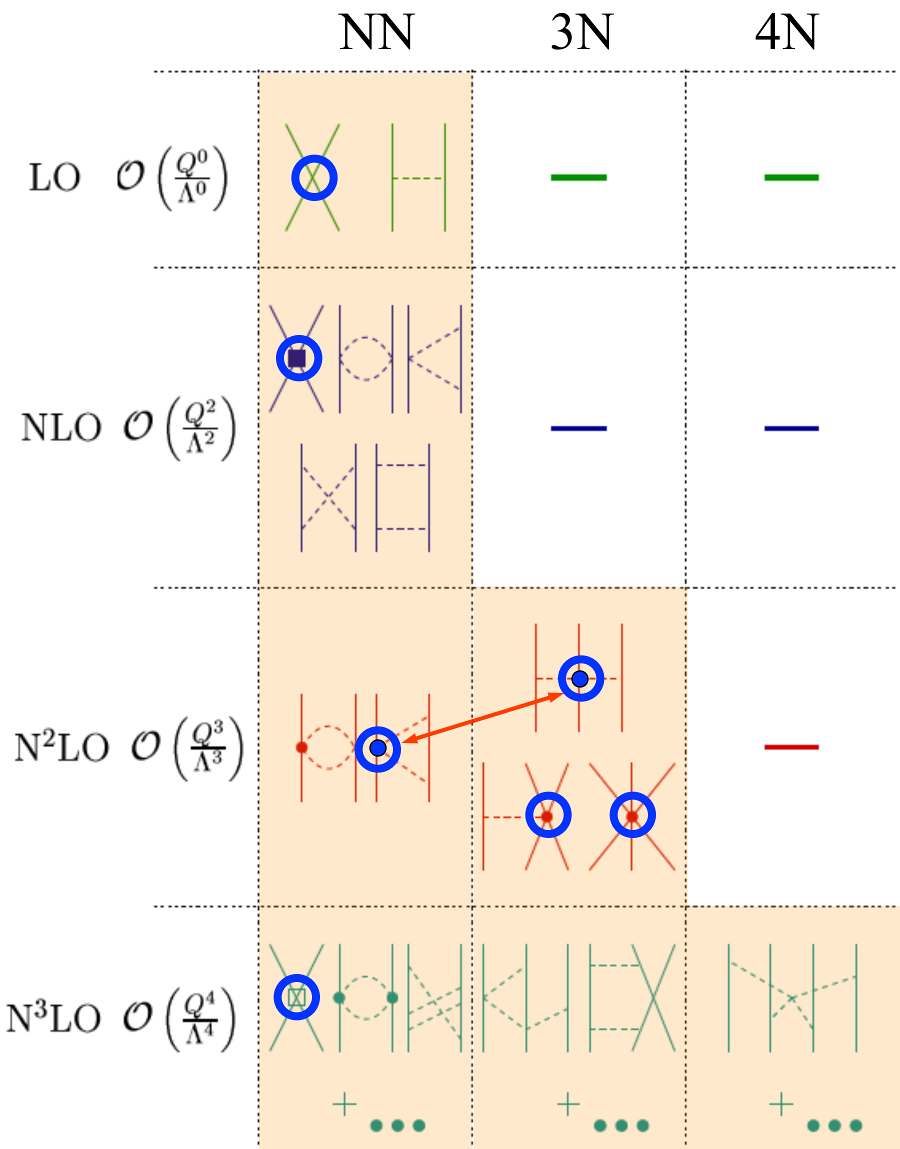
lowest energy excitations:
pions, nearly massless, m_π=140 MeV
'phonons' of QCD vacuum

Λ_{chiral}
momenta $Q \sim m_\pi$

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

Chiral effective field theory for nuclear forces

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



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

include long-range pion physics

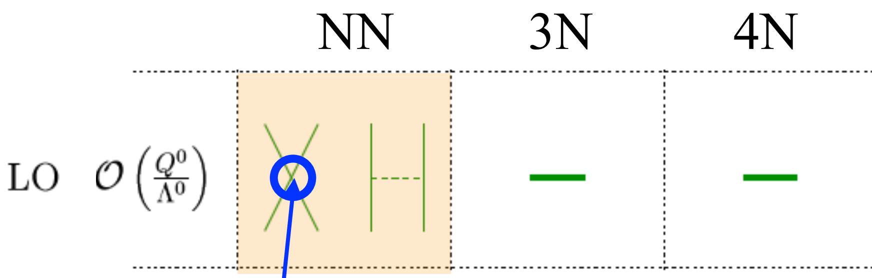
few short-range couplings, fit to experiment once

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

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

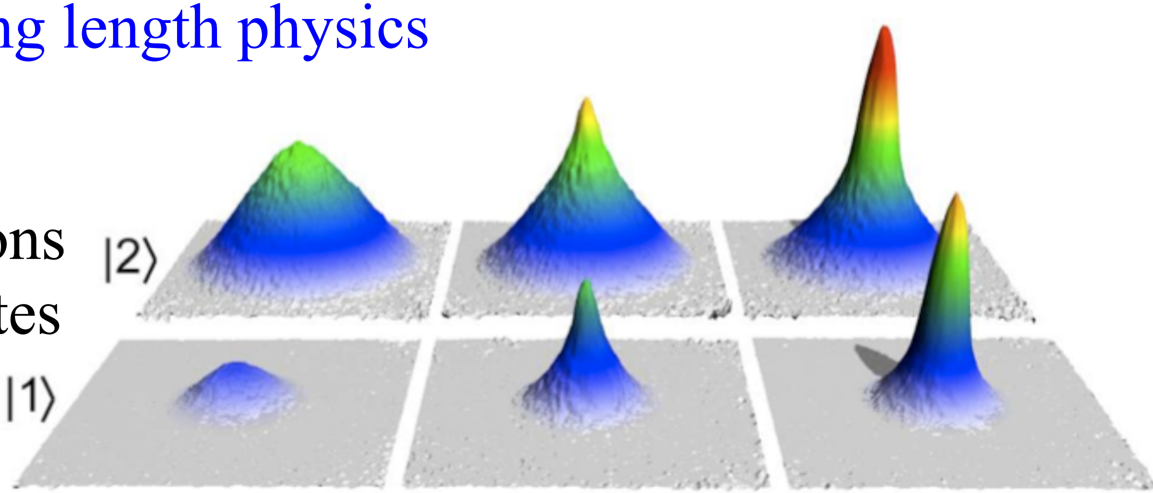
Chiral effective field theory for nuclear forces

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



large scattering length physics

^{6}Li fermions
2 spin states

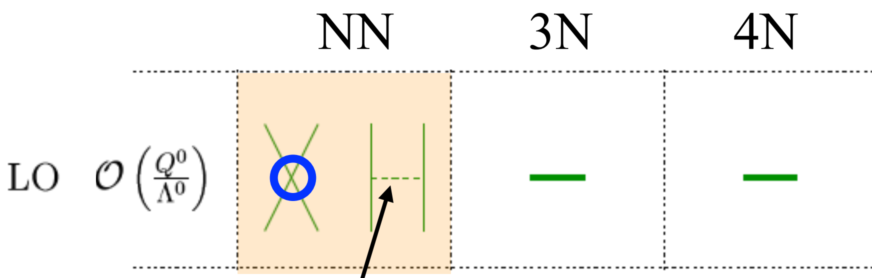


from M. Zwierlein

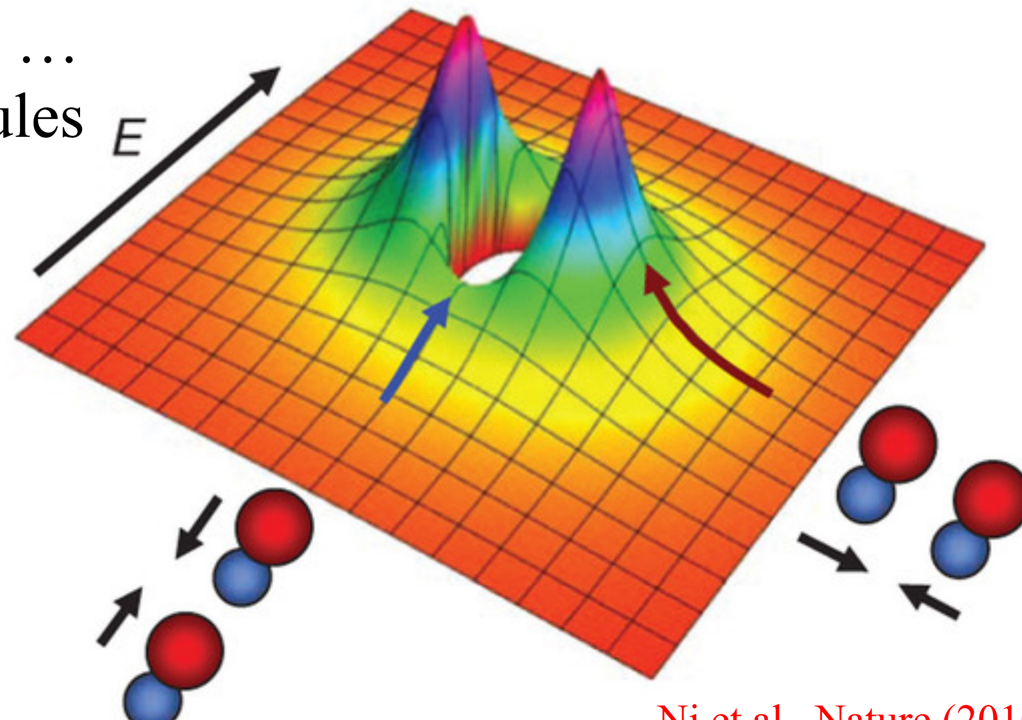
neutrons with same density, temperature and spin polarization
have the same properties!

Chiral effective field theory for nuclear forces

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



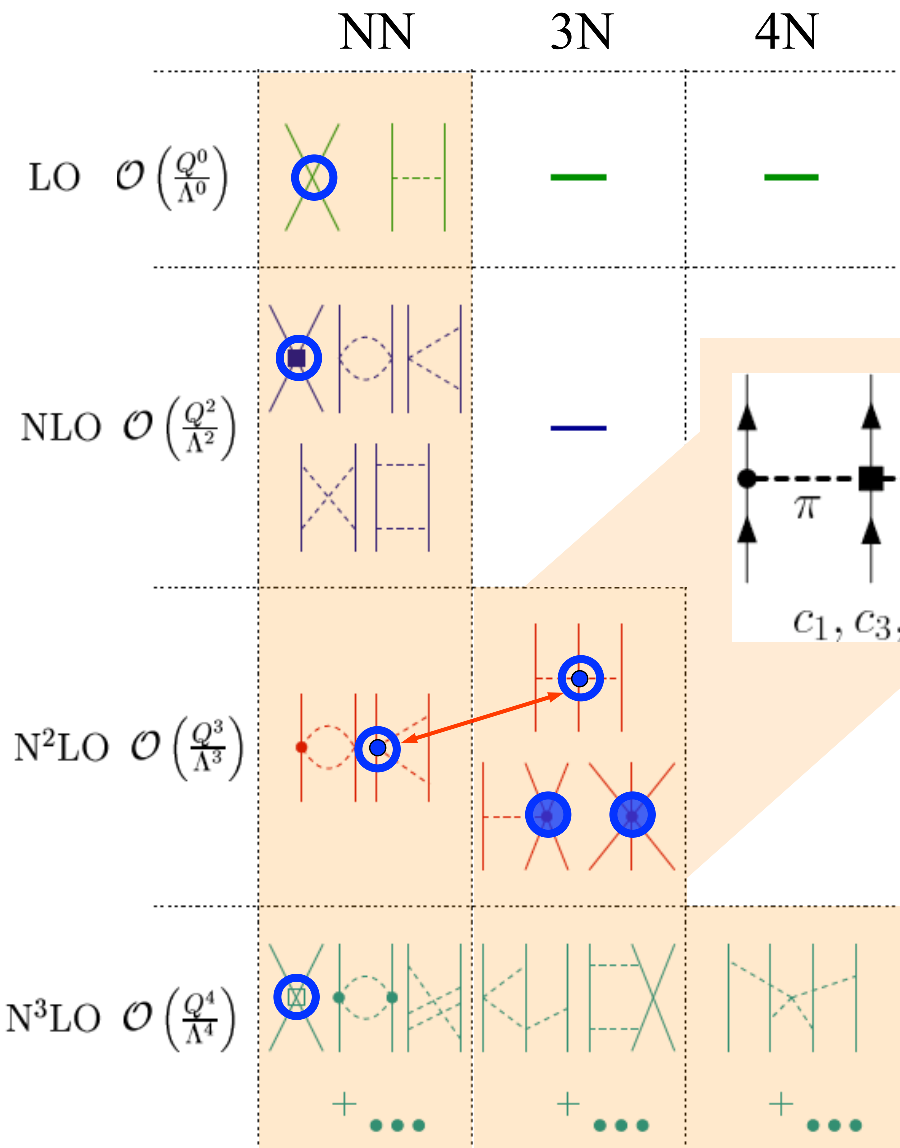
pion tensor/dipole interactions + …
→ compare to cold polar molecules



Ni et al., Nature (2010)

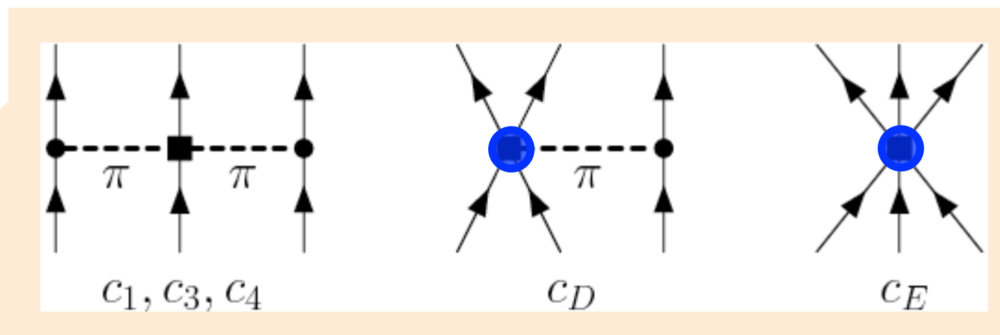
Chiral effective field theory for nuclear forces

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



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)



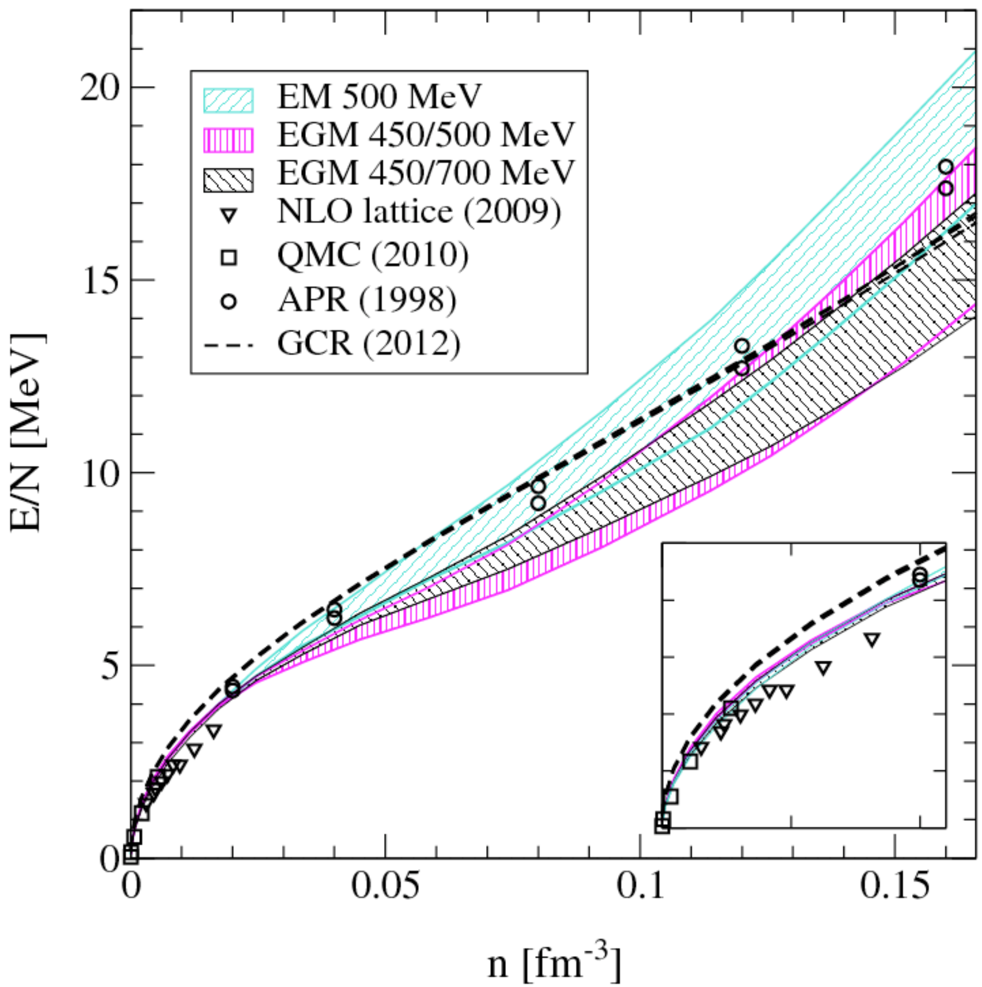
all 3- and 4-neutron forces are predicted to N^{3}LO!

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

Complete N^{3}LO calculation of neutron matter

first complete N^{3}LO result **Tews, Krüger**, Hebeler, AS, PRL (2013)

includes uncertainties from NN, 3N (dominates), 4N



good agreement with Quantum Monte Carlo calculations at low densities

Complete N^3LO calculation of neutron matter

first complete N^3LO result **Tews, Krüger**, Hebeler, AS, PRL (2013)

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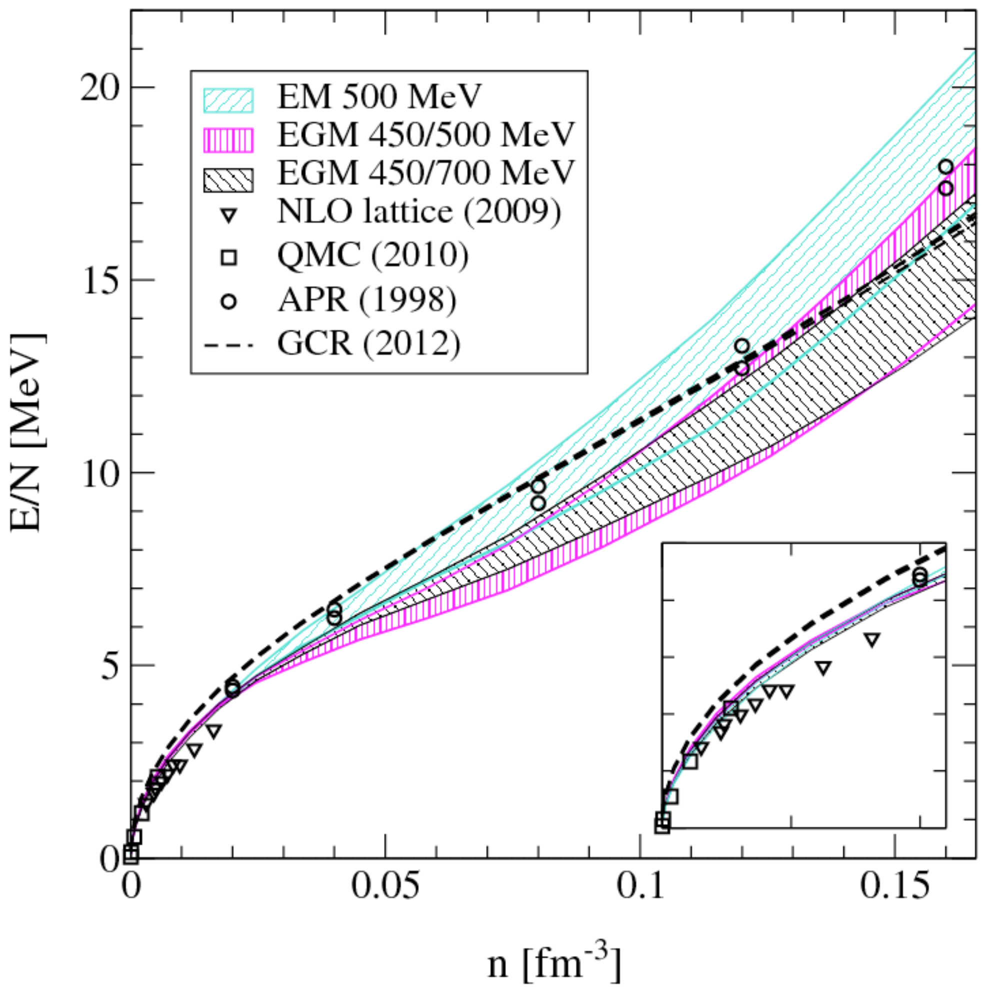
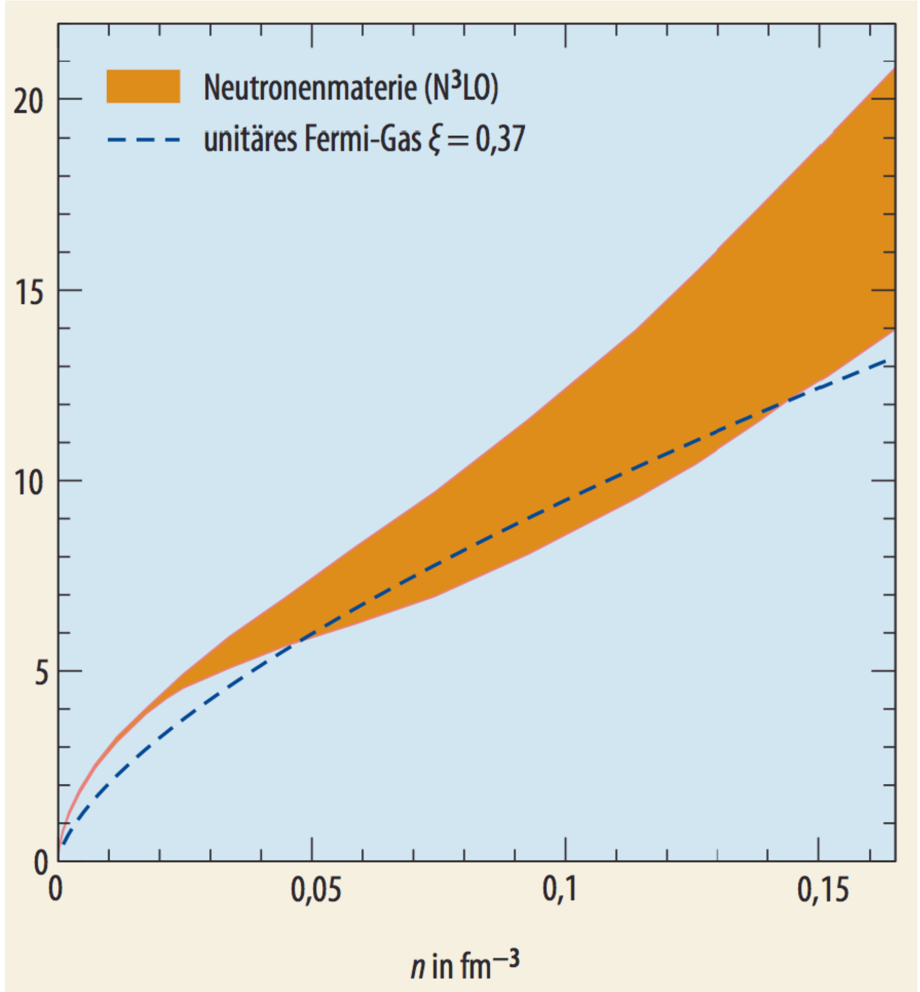
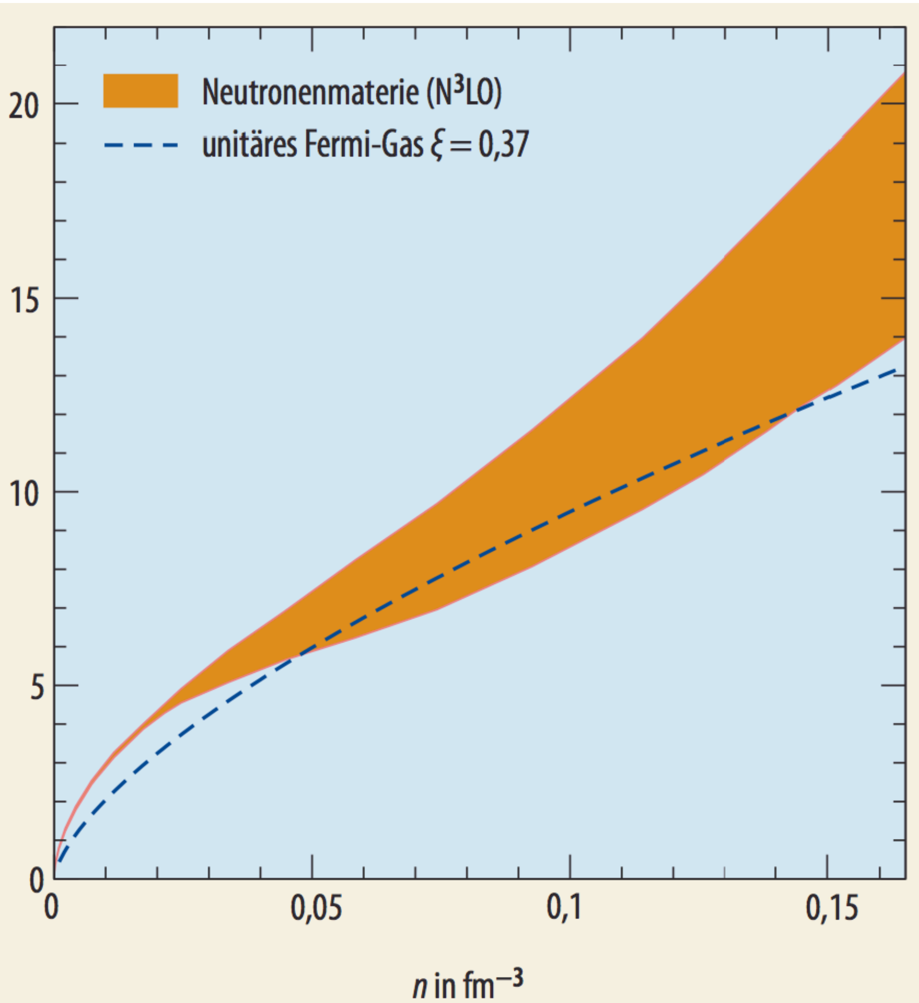
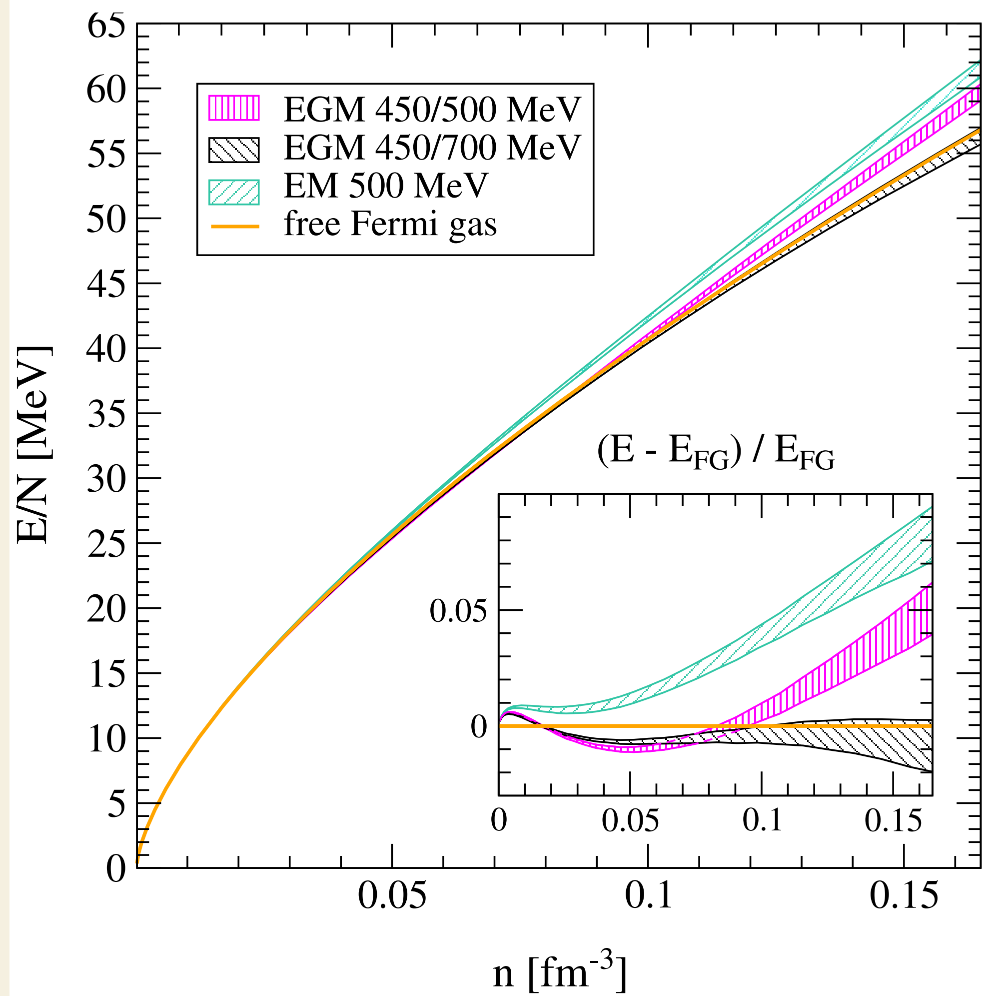




Complete N^{3}LO calculation of neutron matter

spin polarized neutron matter close to free Fermi gas **Krüger,** Hebeler, AS (2014)

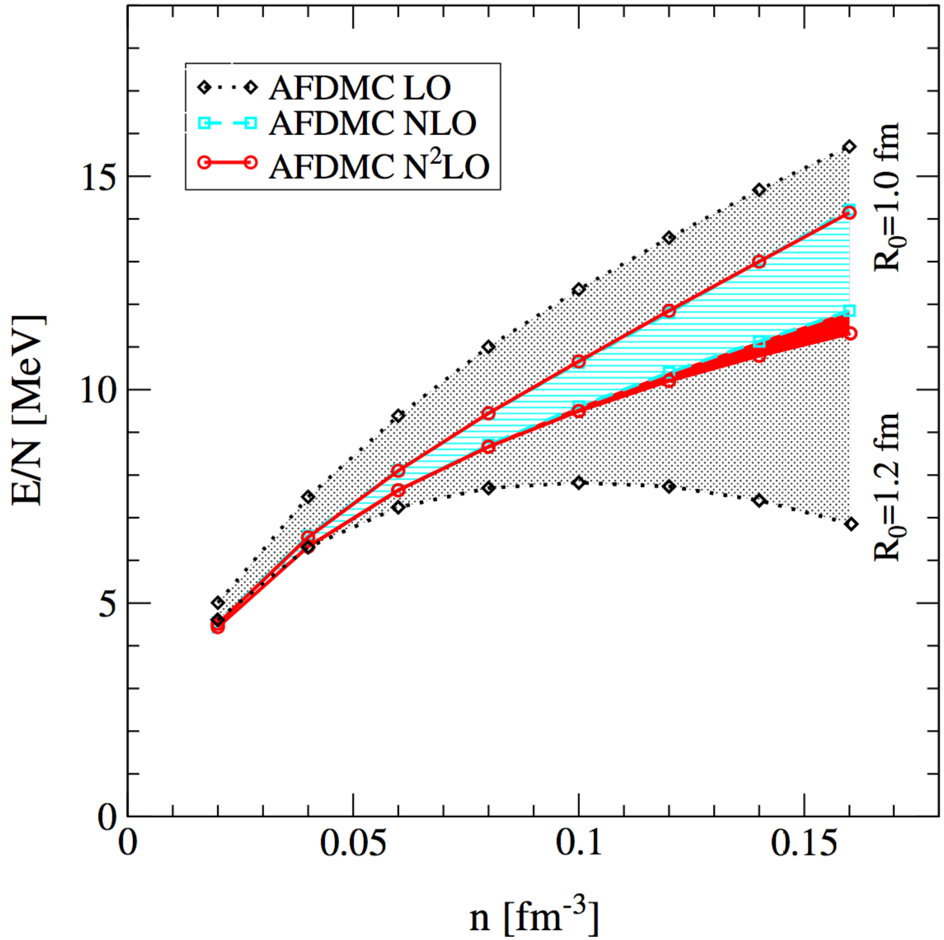




Quantum Monte Carlo for neutron matter

Gezerlis, Tews, et al., PRL (2013) and PRC (2014)

based on new local chiral EFT potentials,
order-by-order convergence up to saturation density

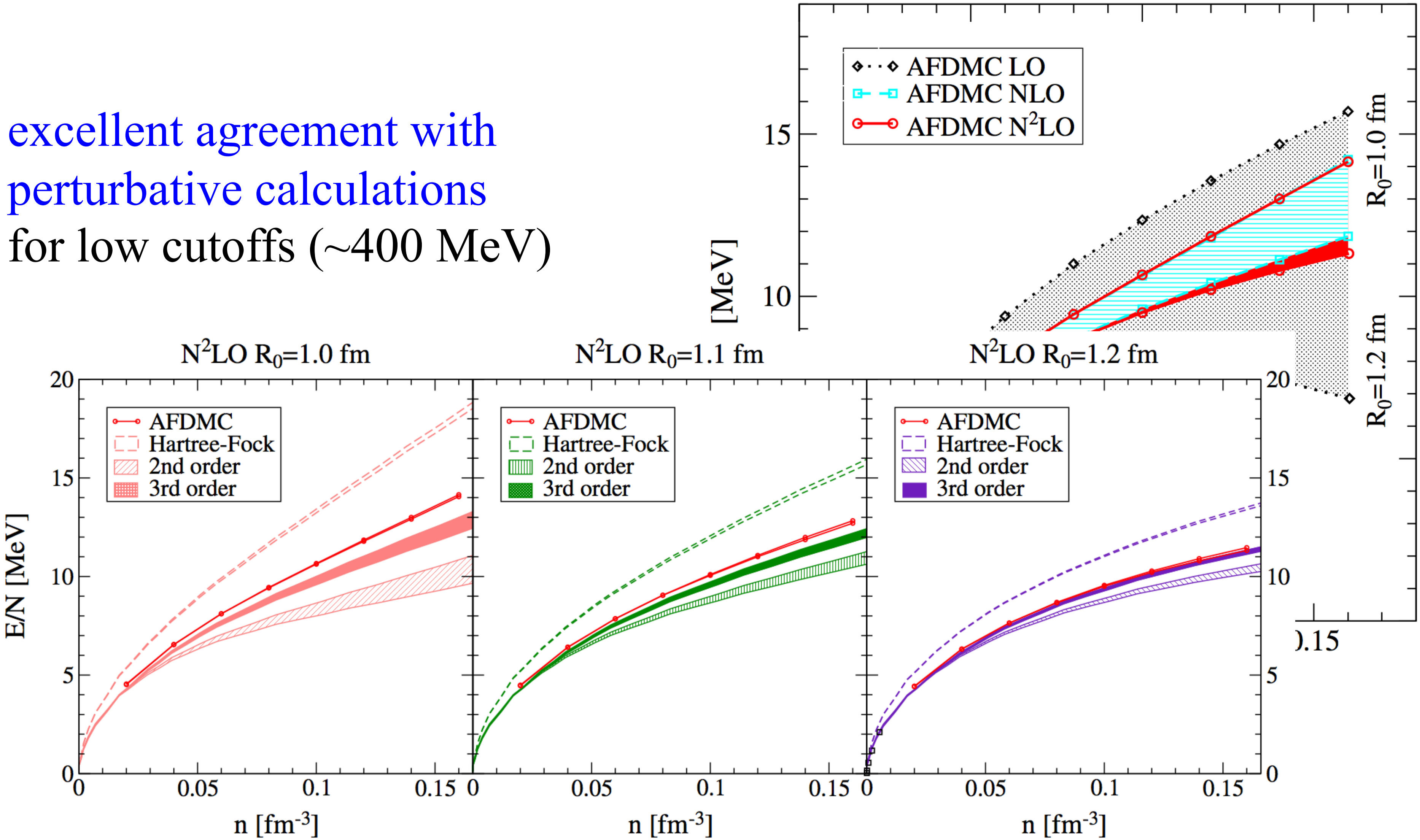


Quantum Monte Carlo for neutron matter

Gezerlis, Tews, et al., PRL (2013) and PRC (2014)

based on new local chiral EFT potentials,
order-by-order convergence up to saturation density

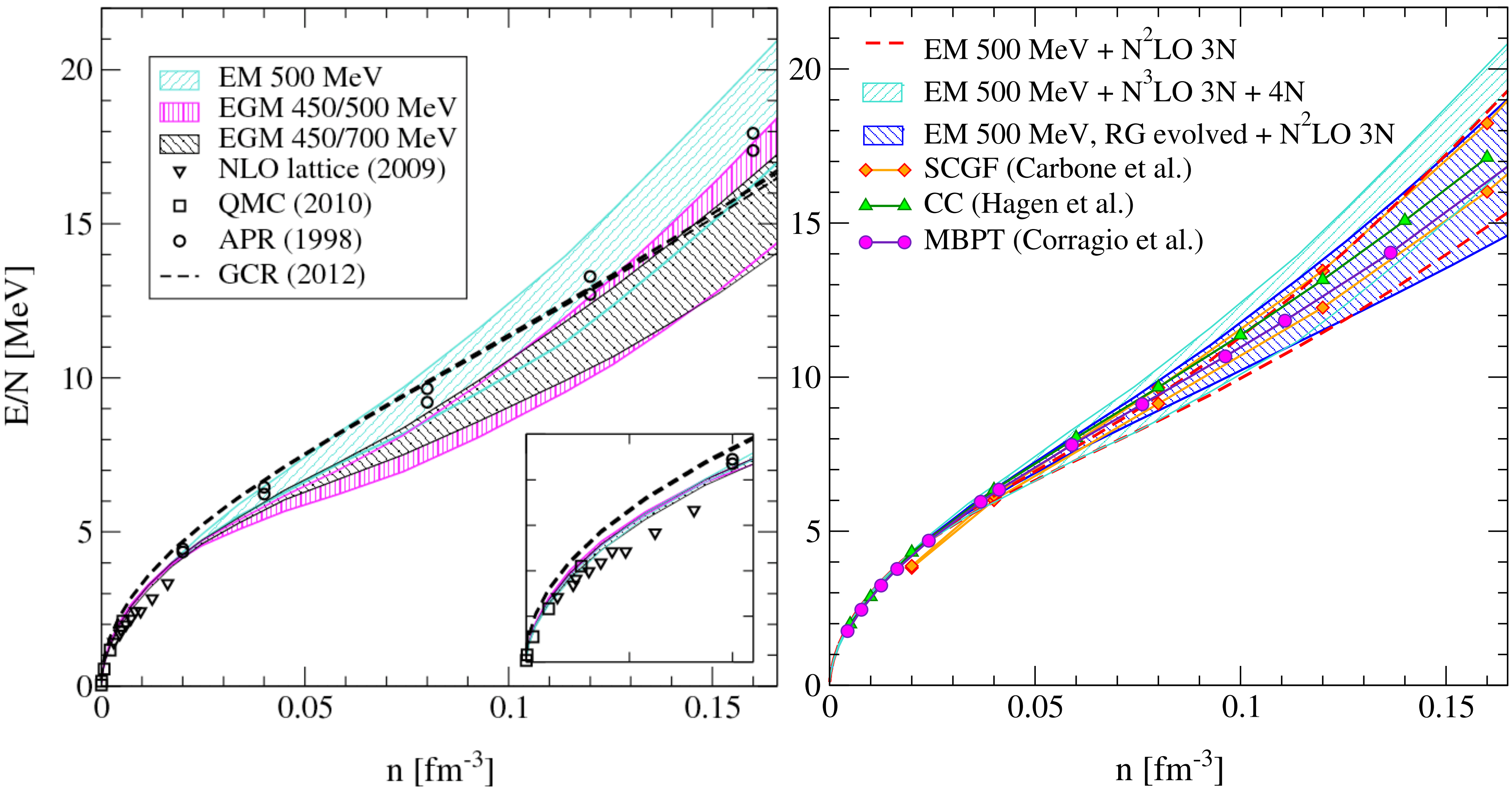
excellent agreement with perturbative calculations
for low cutoffs (~400 MeV)



Complete N^{3}LO calculation of neutron matter

first complete N^{3}LO result **Tews, Krüger**, Hebeler, AS, PRL (2013)

includes uncertainties from NN, 3N (dominates), 4N

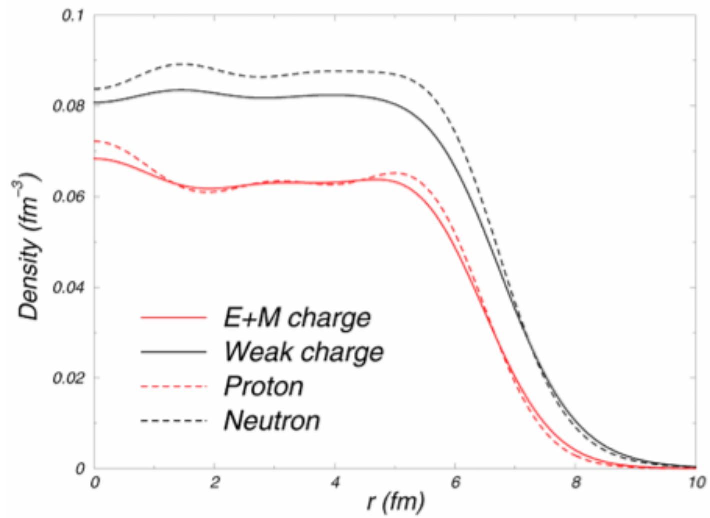


excellent agreement with other methods!

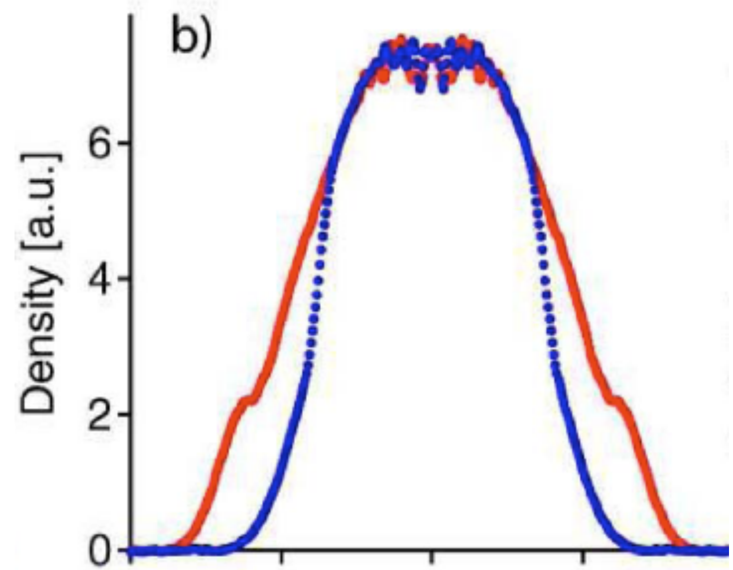
Neutron skin of ^{208}Pb

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

Hebeler, Lattimer, Pethick, AS, PRL (2010)

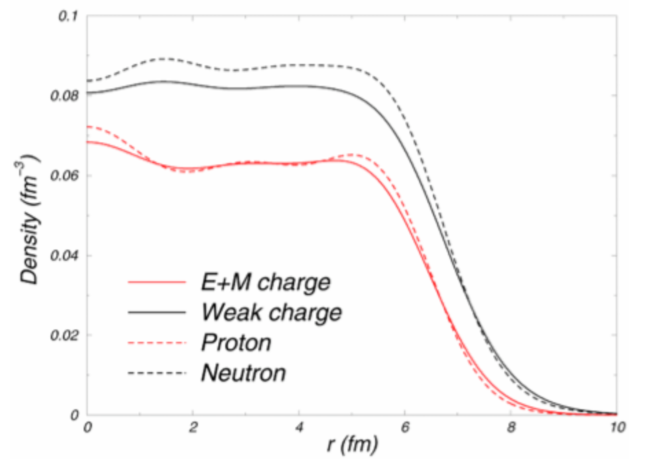


similar to to excess fermion wings for
asymmetric Fermi gases



Shin et al. (2006)

Neutron skin of ^{208}Pb



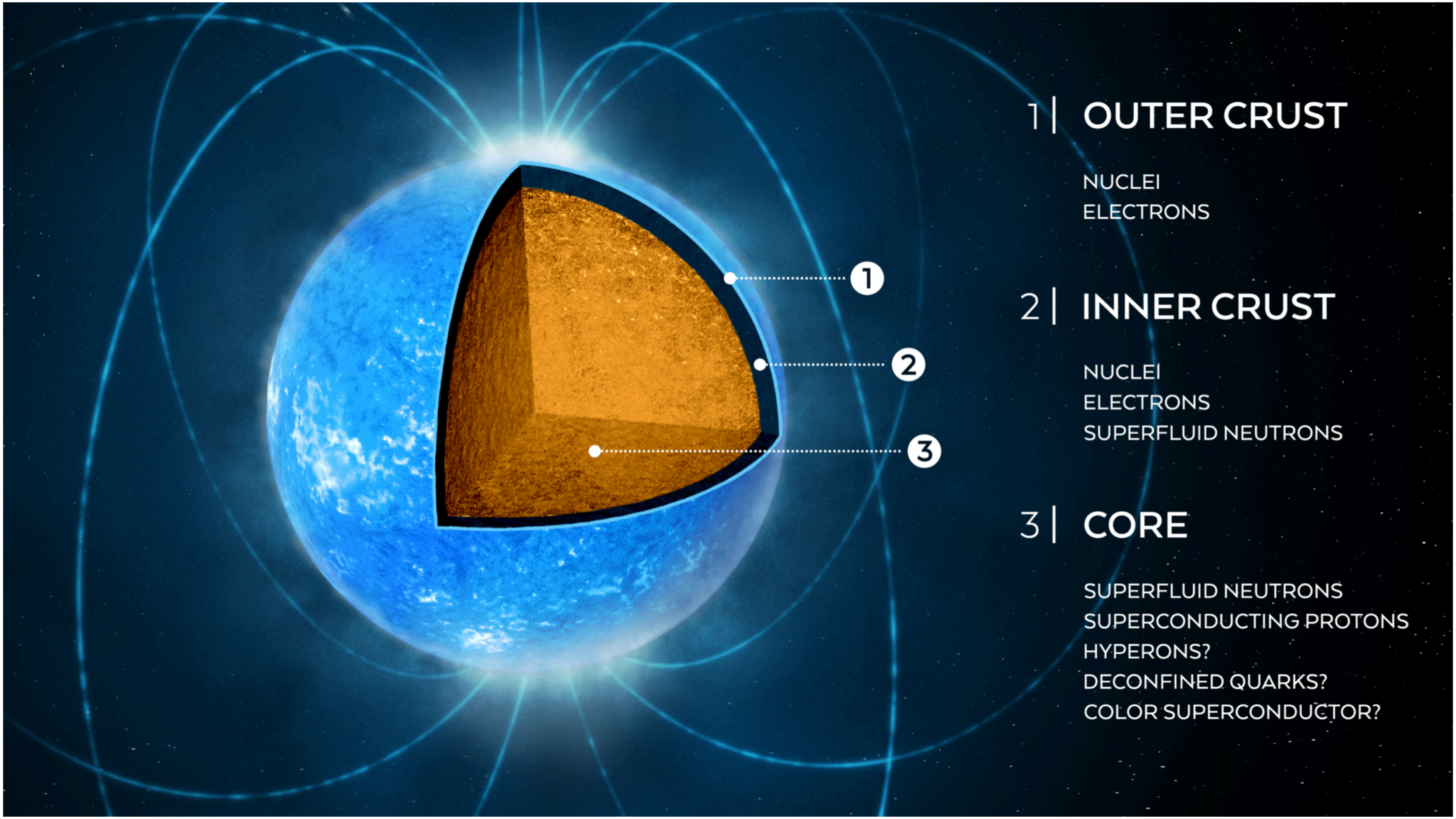
probes neutron matter energy/pressure,
neutron matter band predicts
neutron skin of ^{208}Pb: 0.17±0.03 fm
Hebeler, Lattimer, Pethick, AS, PRL (2010)

in excellent agreement with extraction from dipole polarizability
0.156+0.025-0.021 fm Tamii et al., PRL (2011)

PREX: neutron skin from parity-violating electron-scattering at JLAB
goal II: ±0.06 fm Abrahamyan et al., PRL (2012)

MAMI: coherent pion photoproduction
0.15+0.04-0.06 fm Tabert et al., PRL (2014)

Neutron matter and neutron stars



Neutron matter and neutron stars

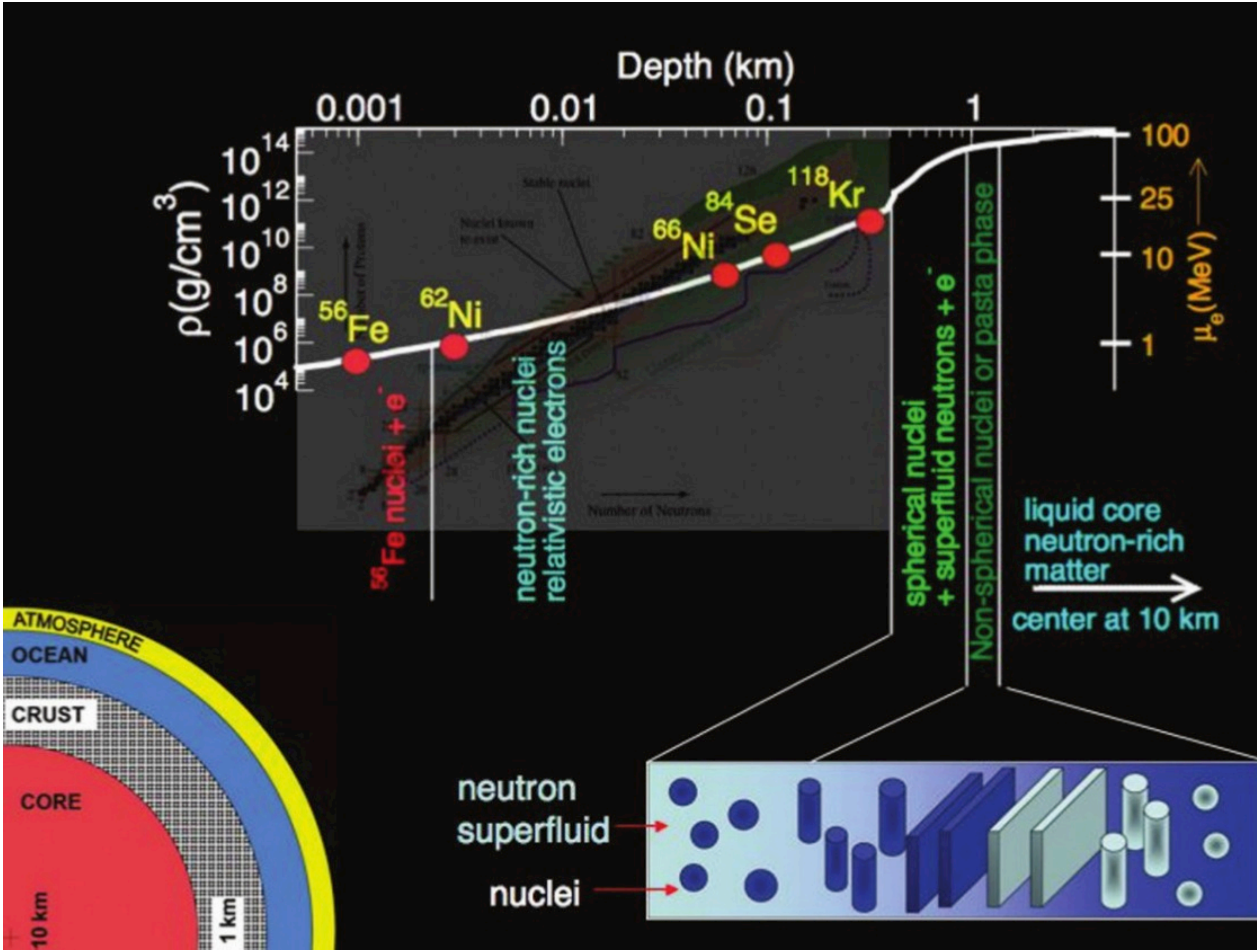
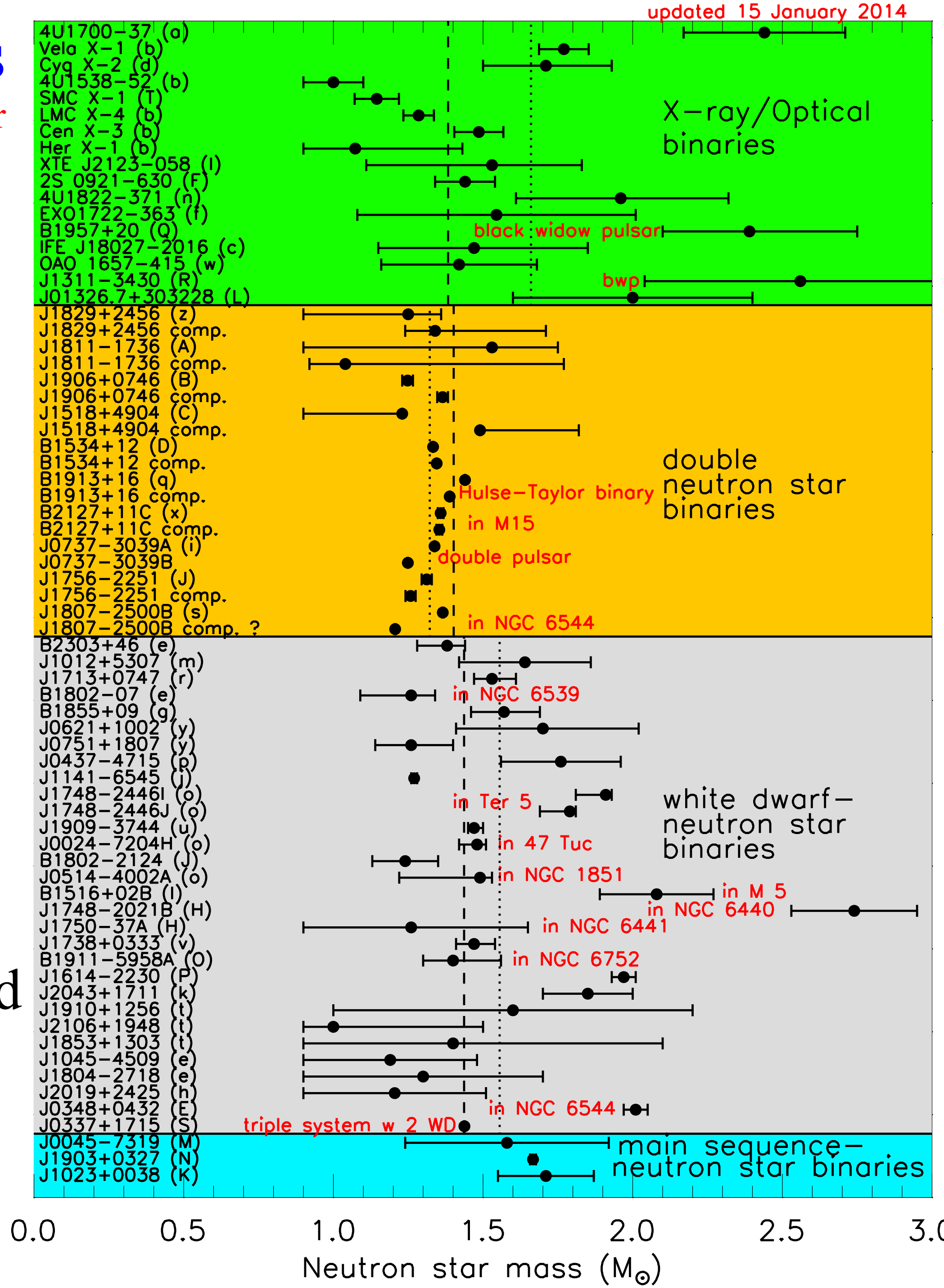


Chart of neutron star masses

from Jim Lattimer



two 2 M_{sun} neutron stars observed

Demorest et al, Nature (2010),

Antoniadis et al., Science (2013)

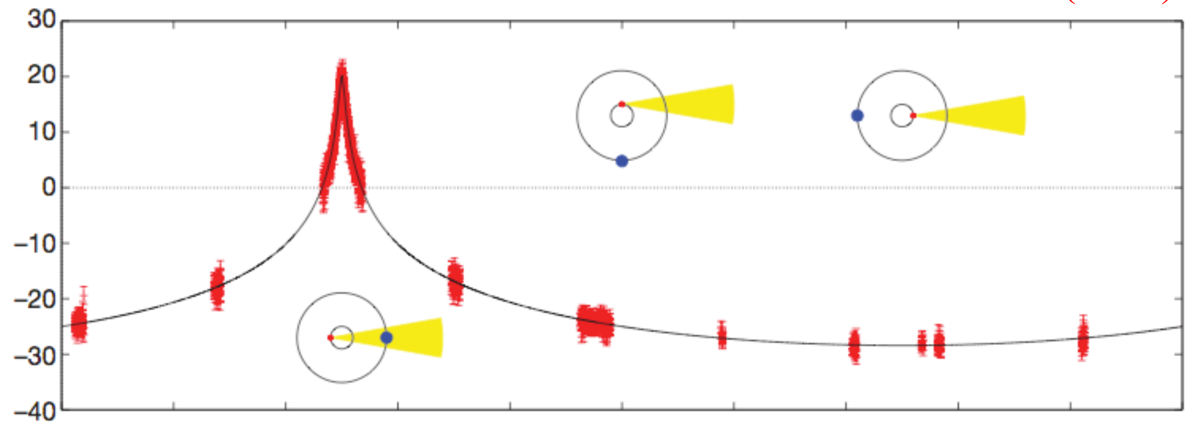
Discovery of the heaviest neutron star

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

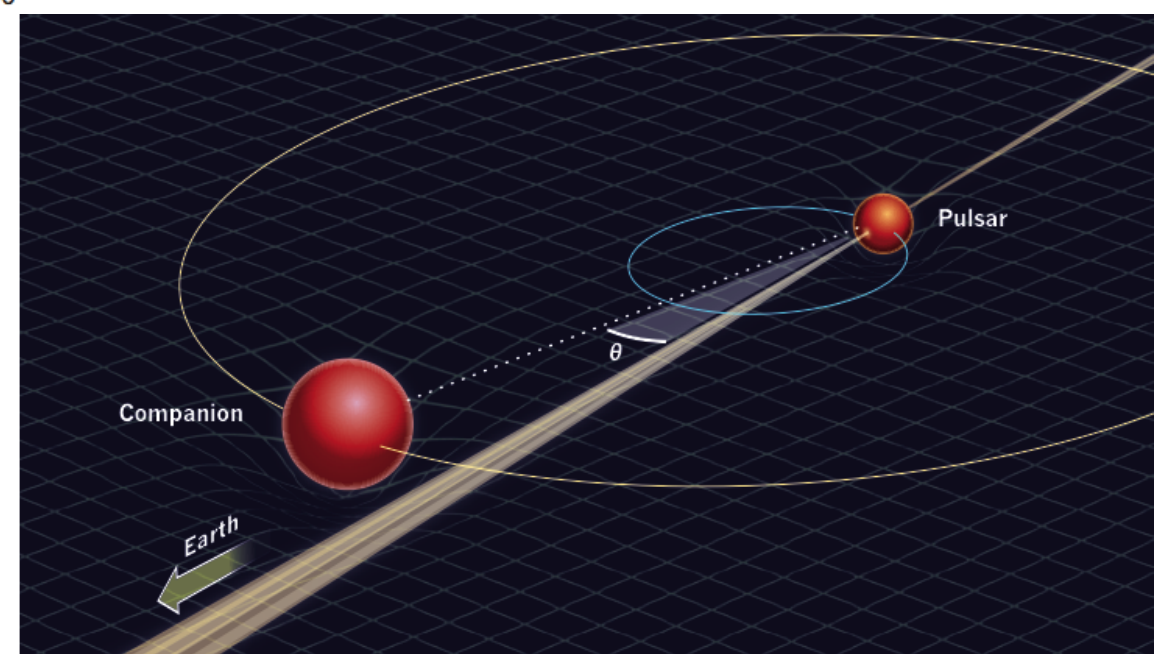
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

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}

Discovery of the heaviest neutron star (2013)

RESEARCH ARTICLE SUMMARY

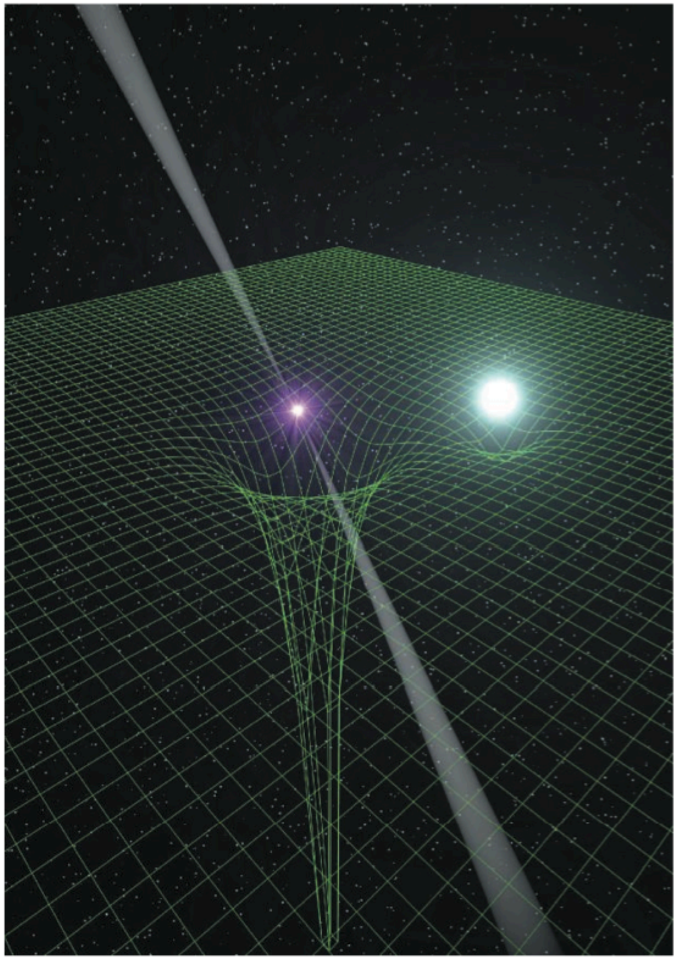
A Massive Pulsar in a Compact Relativistic Binary

John Antoniadis,* Paulo C. C. Freire, Norbert Wex, Thomas M. Tauris, Ryan S. Lynch, Marten H. van Kerkwijk, Michael Kramer, Cees Bassa, Vik S. Dhillon, Thomas Driebe, Jason W. T. Hessels, Victoria M. Kaspi, Vladislav I. Kondratiev, Norbert Langer, Thomas R. Marsh, Maura A. McLaughlin, Timothy T. Pennucci, Scott M. Ransom, Ingrid H. Stairs, Joeri van Leeuwen, Joris P. W. Verbiest, David G. Whelan

Introduction: Neutron stars with masses above 1.8 solar masses ($M_{\odot}$), possess extreme gravitational fields, which may give rise to phenomena outside general relativity. Hitherto, these strong-field deviations have not been probed by experiment, because they become observable only in tight binaries containing a high-mass pulsar and where orbital decay resulting from emission of gravitational waves can be tested. Understanding the origin of such a system would also help to answer fundamental questions of close-binary evolution.

Methods: We report on radio-timing observations of the pulsar J0348+0432 and phase-resolved optical spectroscopy of its white-dwarf companion, which is in a 2.46-hour orbit. We used these to derive the component masses and orbital parameters, infer the system's motion, and constrain its age.

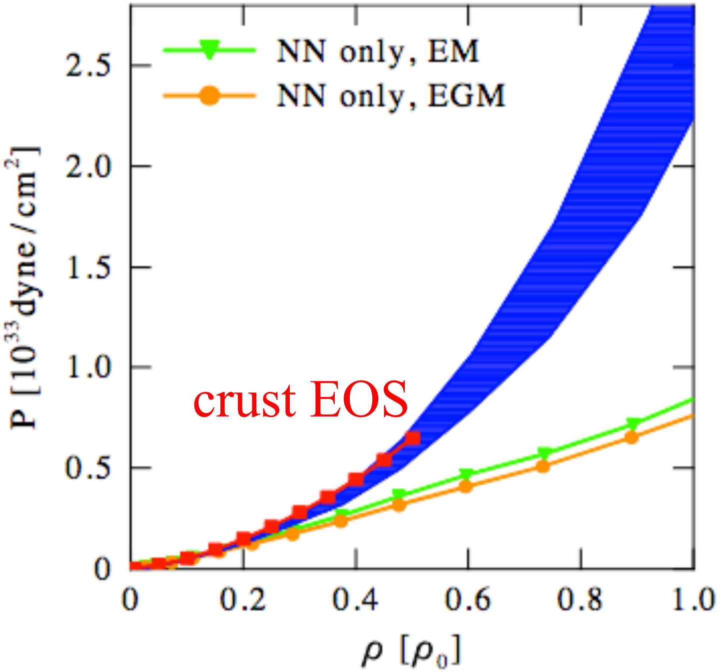
Results: We find that the white dwarf has a mass of $0.172 \pm 0.003\ M_{\odot}$, which, combined with orbital velocity measurements, yields a pulsar mass of $2.01 \pm 0.04\ M_{\odot}$. Additionally, over a span of 2 years, we observed a significant decrease in the orbital period, $\dot{P}_b^{obs} = -8.6 \pm 1.4\ \mu s\ year^{-1}$ in our radio-timing data.

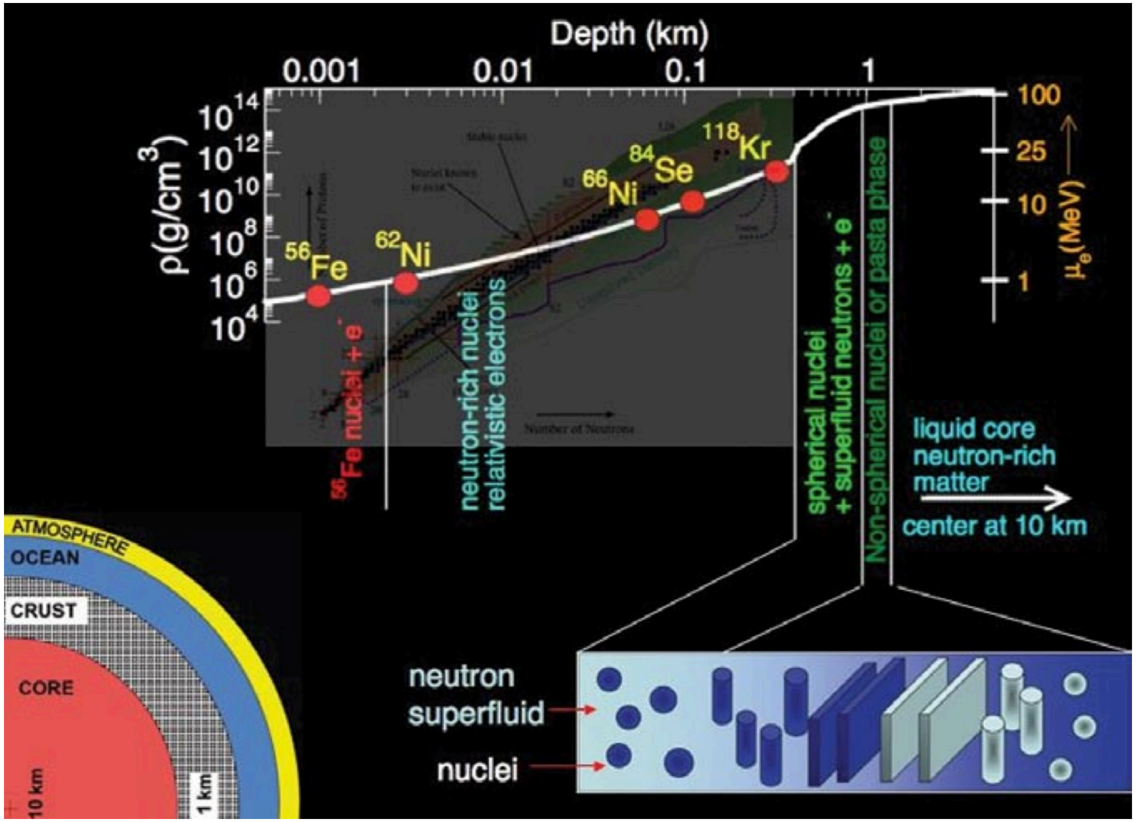


Artist's impression of the PSR J0348+0432 system. The compact pulsar (with beams of radio emission) produces a strong distortion of spacetime (illustrated by the green mesh). Conversely, spacetime around its white dwarf companion (in light blue) is substantially less curved. According to relativistic theories of gravity, the binary system is subject to energy loss by gravitational waves.

Impact on neutron stars Hebeler, Lattimer, Pethick, AS, PRL (2010), ApJ (2013)

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

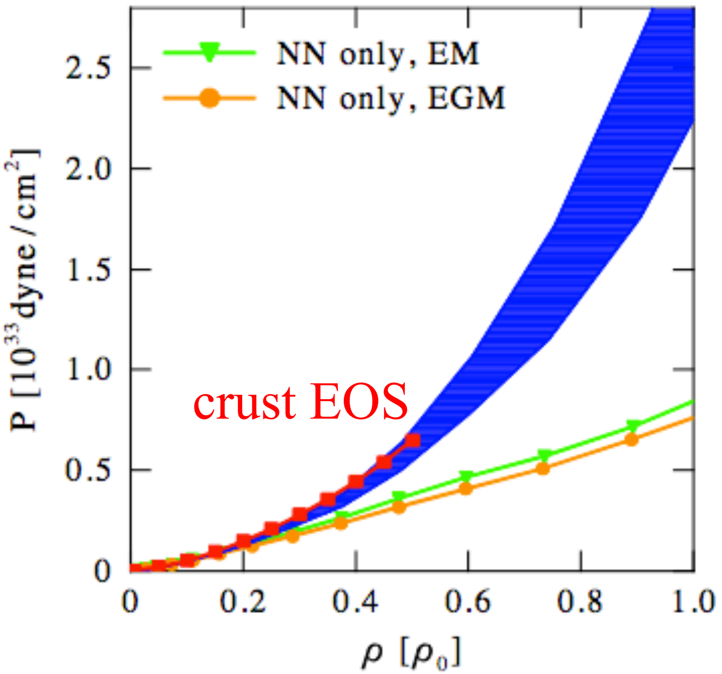


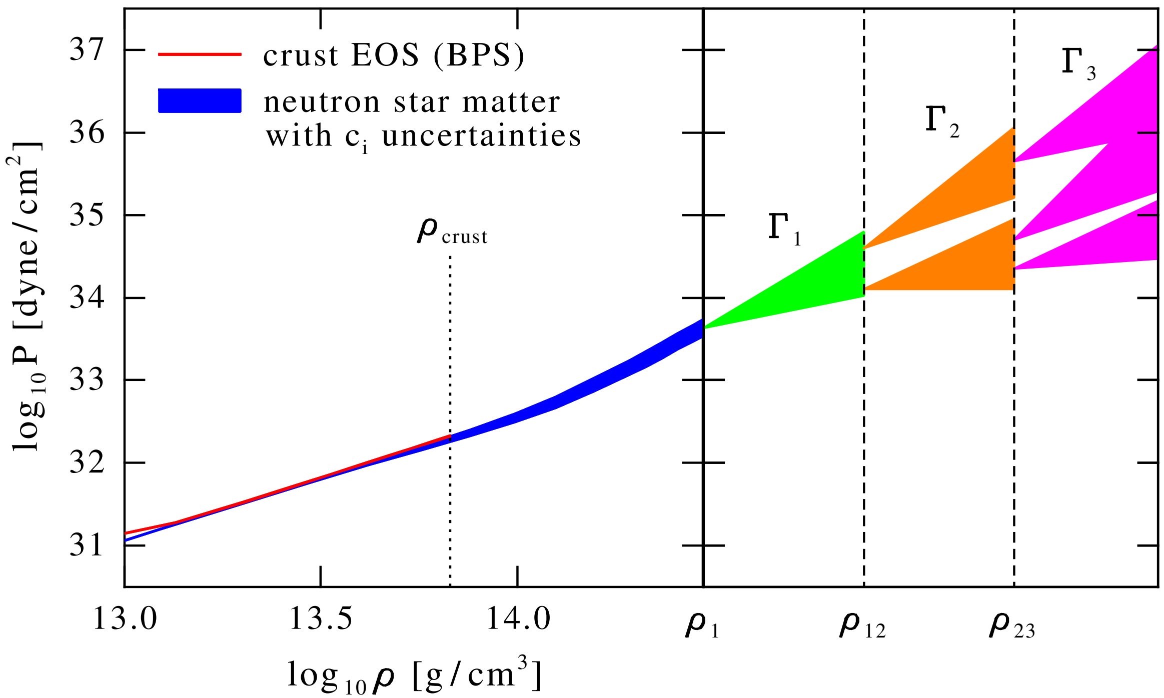


pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

Impact on neutron stars Hebeler, Lattimer, Pethick, AS, PRL (2010), ApJ (2013)

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

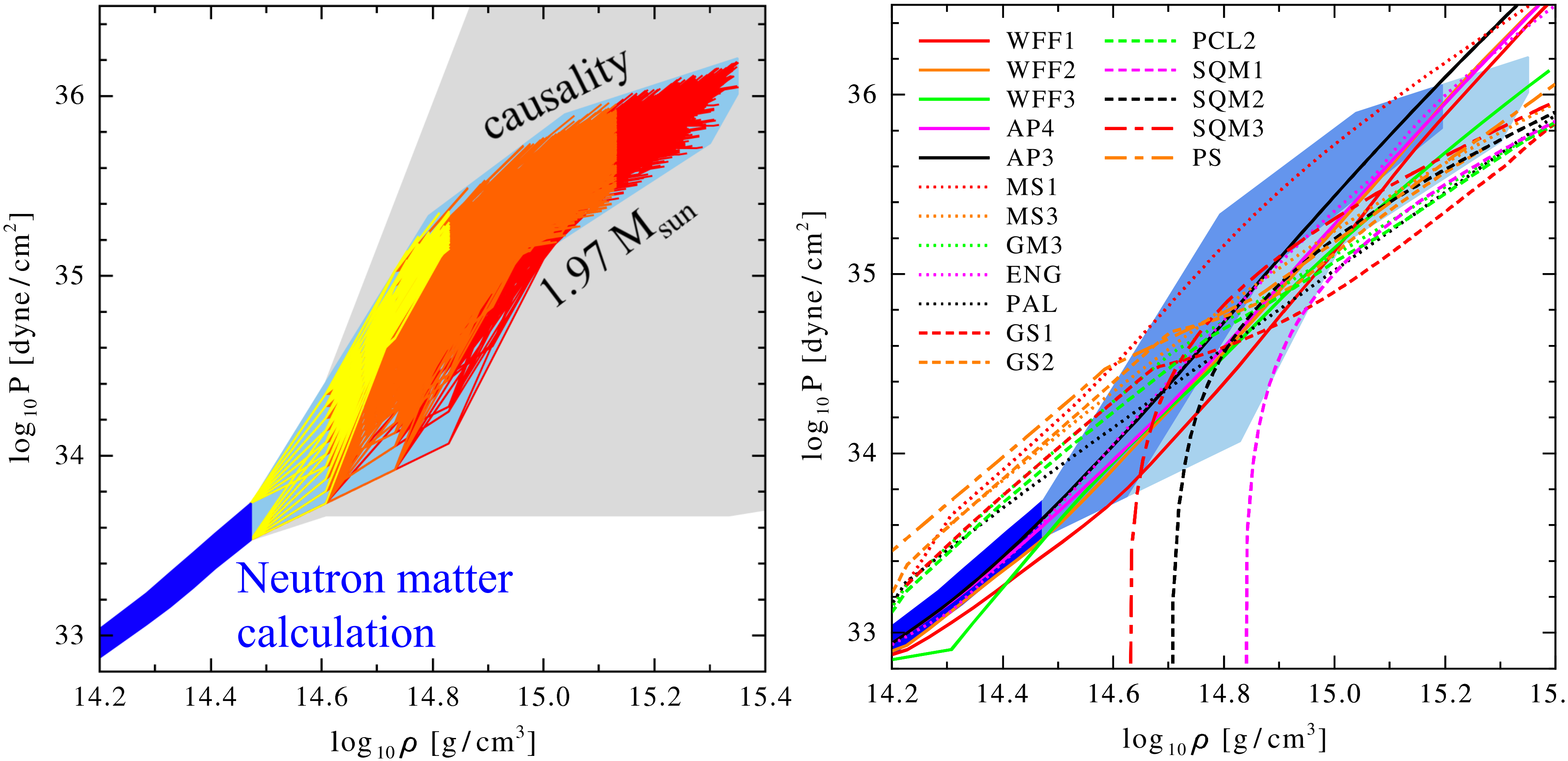




extend uncertainty band to higher densities using piecewise polytropes
allow for soft regions

Impact on neutron stars Hebeler, Lattimer, Pethick, AS, PRL (2010), ApJ (2013)

constrain high-density EOS by causality, require to support 2 M_{sun} star

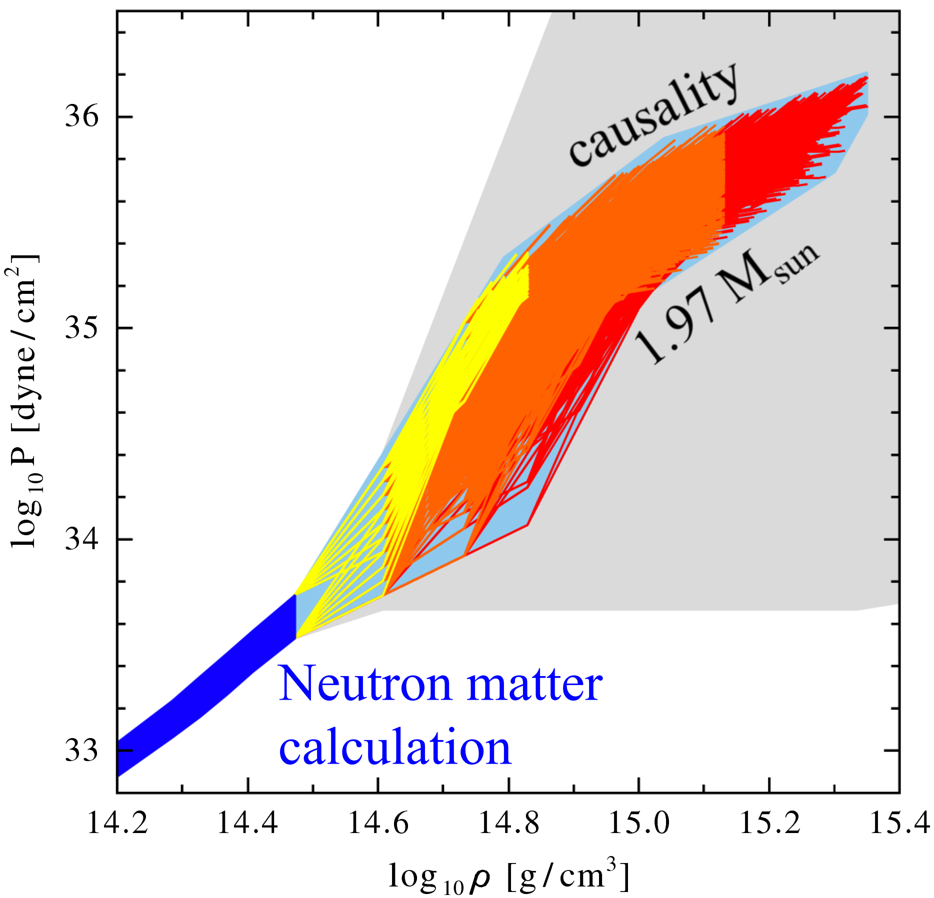


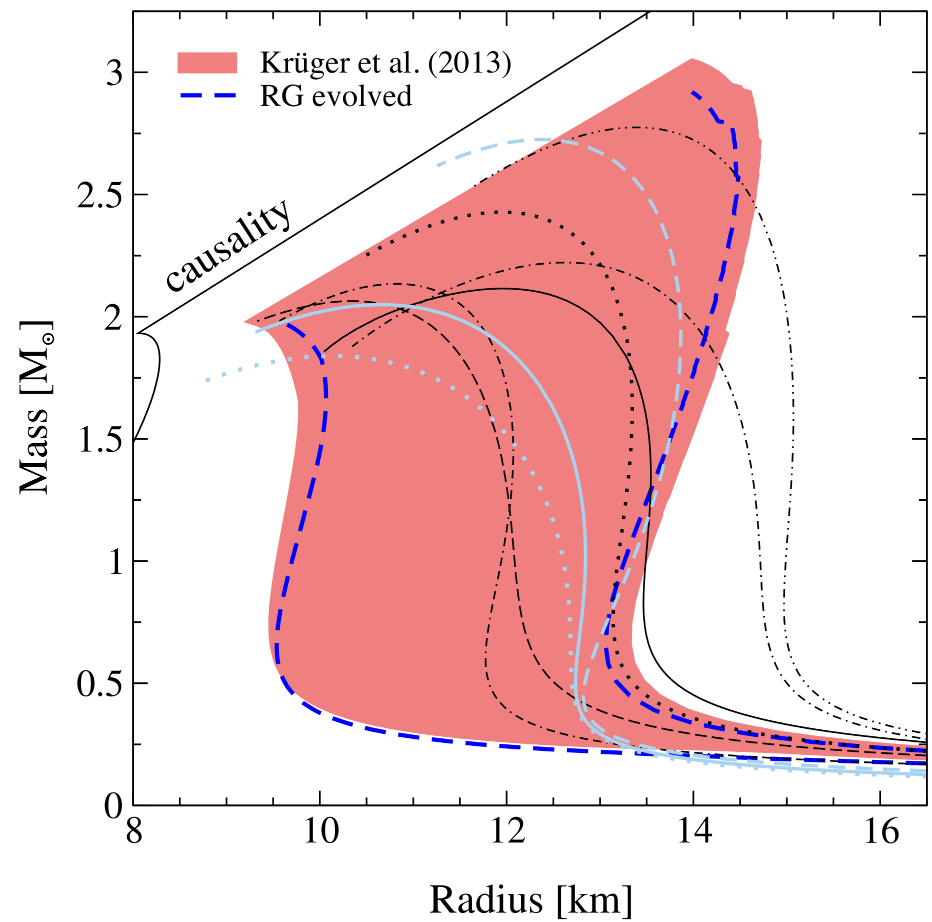
low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

high pressures at low densities are also ruled out by cold atoms

Impact on neutron stars Hebeler, Lattimer, Pethick, AS, PRL (2010), ApJ (2013)

constrain high-density EOS by causality, require to support 2 M_{sun} star





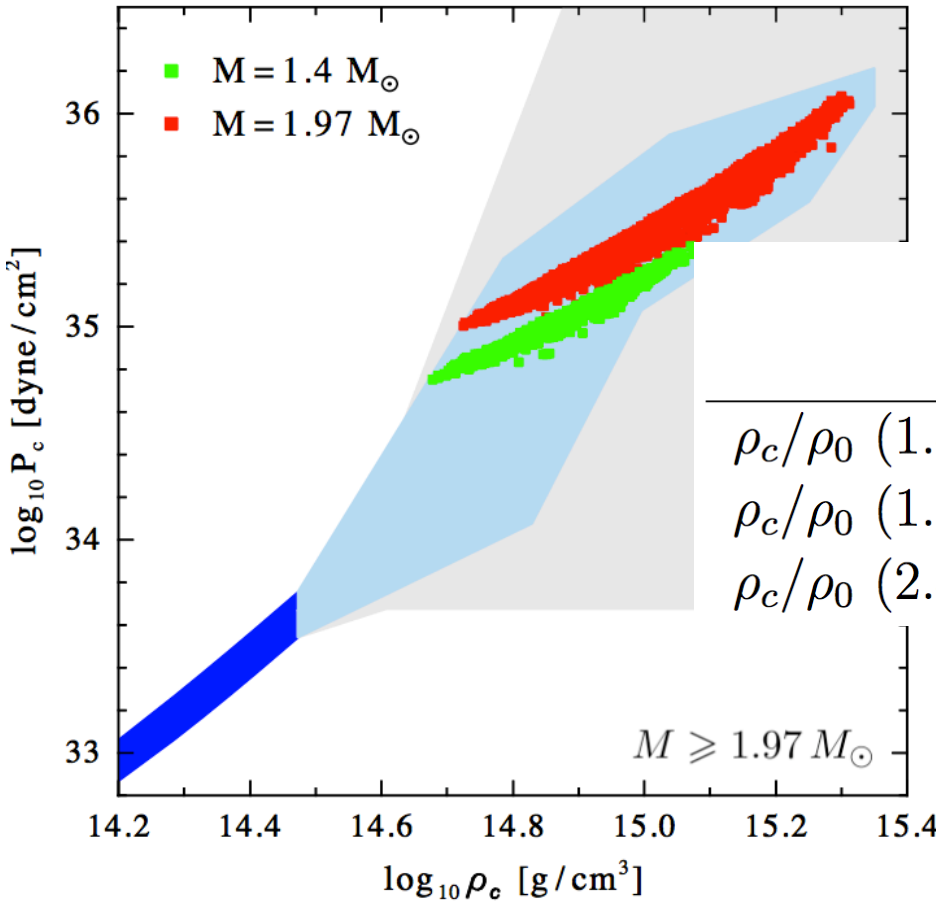
predicts neutron star radius: 9.7-13.9 km for M=1.4 M_{sun}

empirical scaling $R(1{,}4\,M_\odot) \simeq (9{,}5 \pm 0{,}5)\,\mathrm{km}\ \ [P(n_0)]^{1/4} \sim \xi^{1/4}$ cf. atom cloud

ξ=0.37 gives 9.7-10.9 km

Impact on neutron stars Hebeler, Lattimer, Pethick, AS, PRL (2010), ApJ (2013)

constrain high-density EOS by causality, require to support 2 M_{sun} star



	$\widehat{M} = 1.97\, M_\odot$ min	$\widehat{M} = 1.97\, M_\odot$ max	$\widehat{M} = 2.4\, M_\odot$ min	$\widehat{M} = 2.4\, M_\odot$ max
$\rho_c/\rho_0\ (1.4\, M_\odot)$	1.8	4.4	1.8	2.7
$\rho_c/\rho_0\ (1.97\, M_\odot)$	2.0	7.6	2.0	3.4
$\rho_c/\rho_0\ (2.4\, M_\odot)$			2.2	5.4

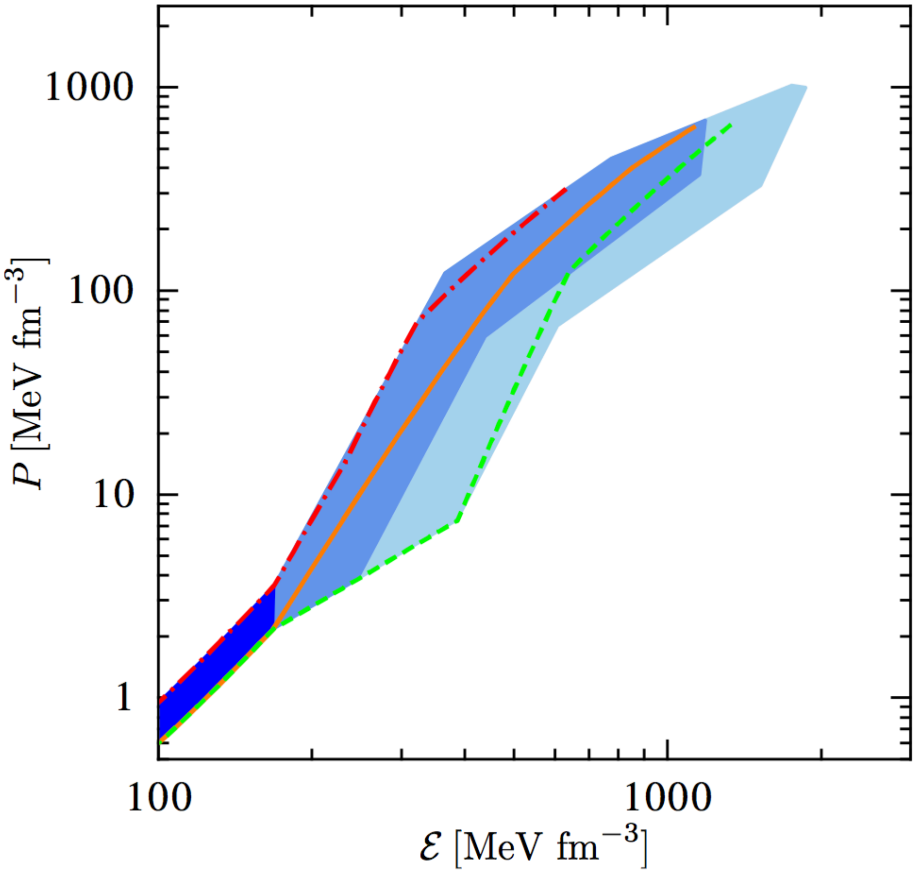
central densities
for 1.4 M_{sun} star: 1.8-4.4 ρ_0

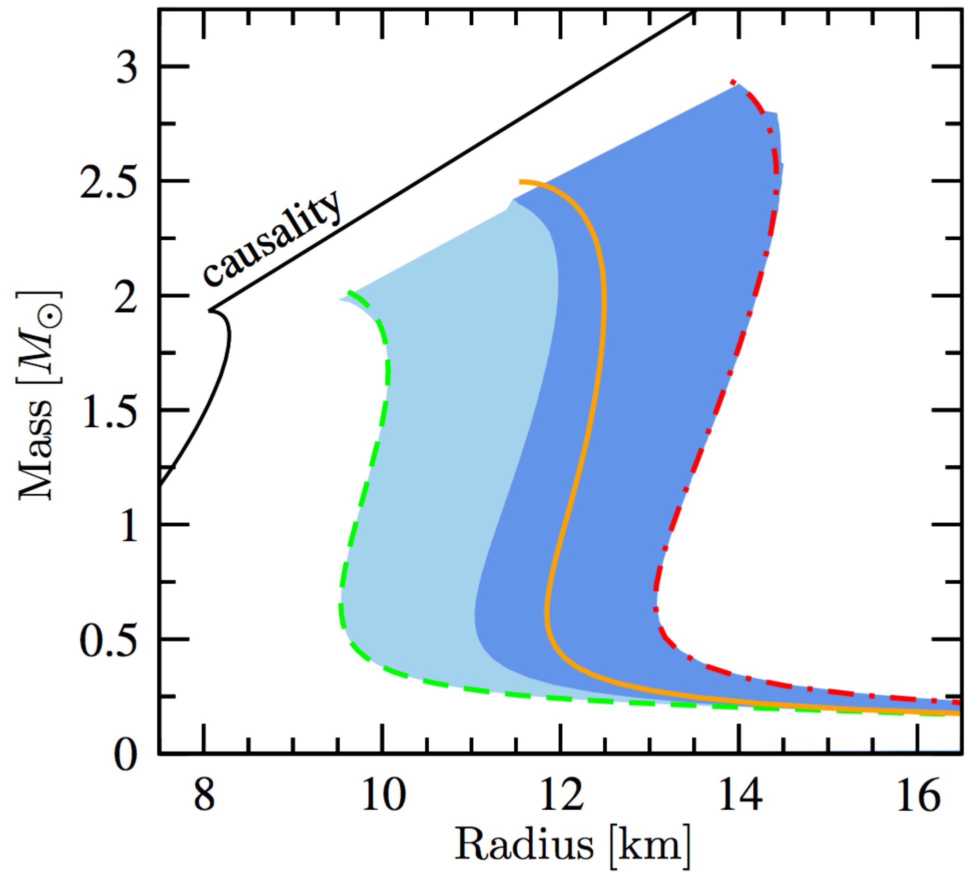
not very high momenta!

Representative equations of state

all EOS for cold matter in beta equilibrium should go through our band

constructed 3 representative EOS for users: soft, intermediate, stiff





Neutron-star mergers and gravitational waves

explore sensitivity to neutron-rich matter in neutron-star merger predictions for gravitational-wave signal, including NP uncertainties

Bauswein, Janka, PRL (2012)
Bauswein, Janka, Hebeler, AS, PRD (2012)

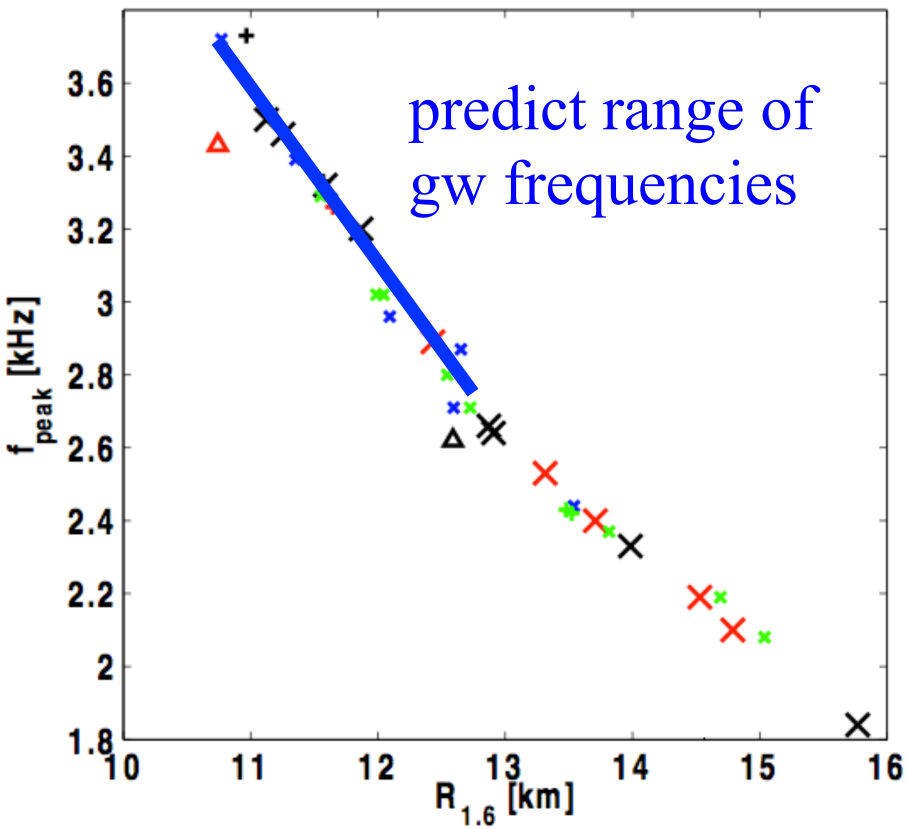
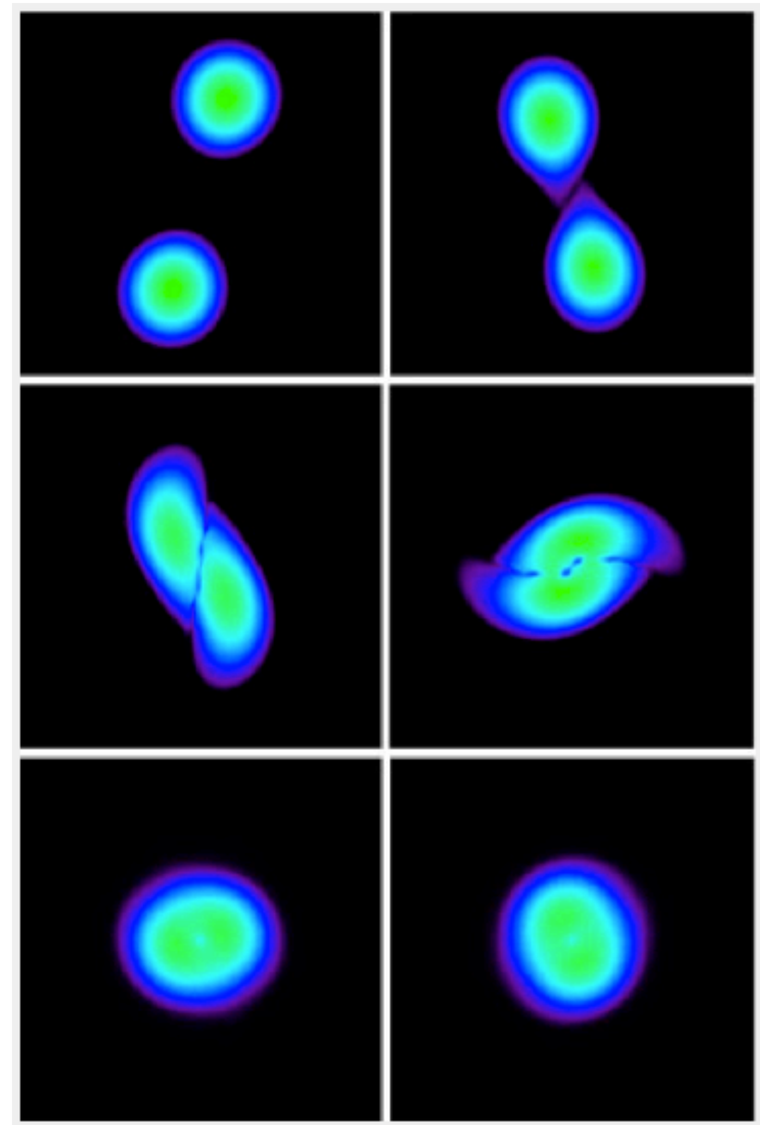
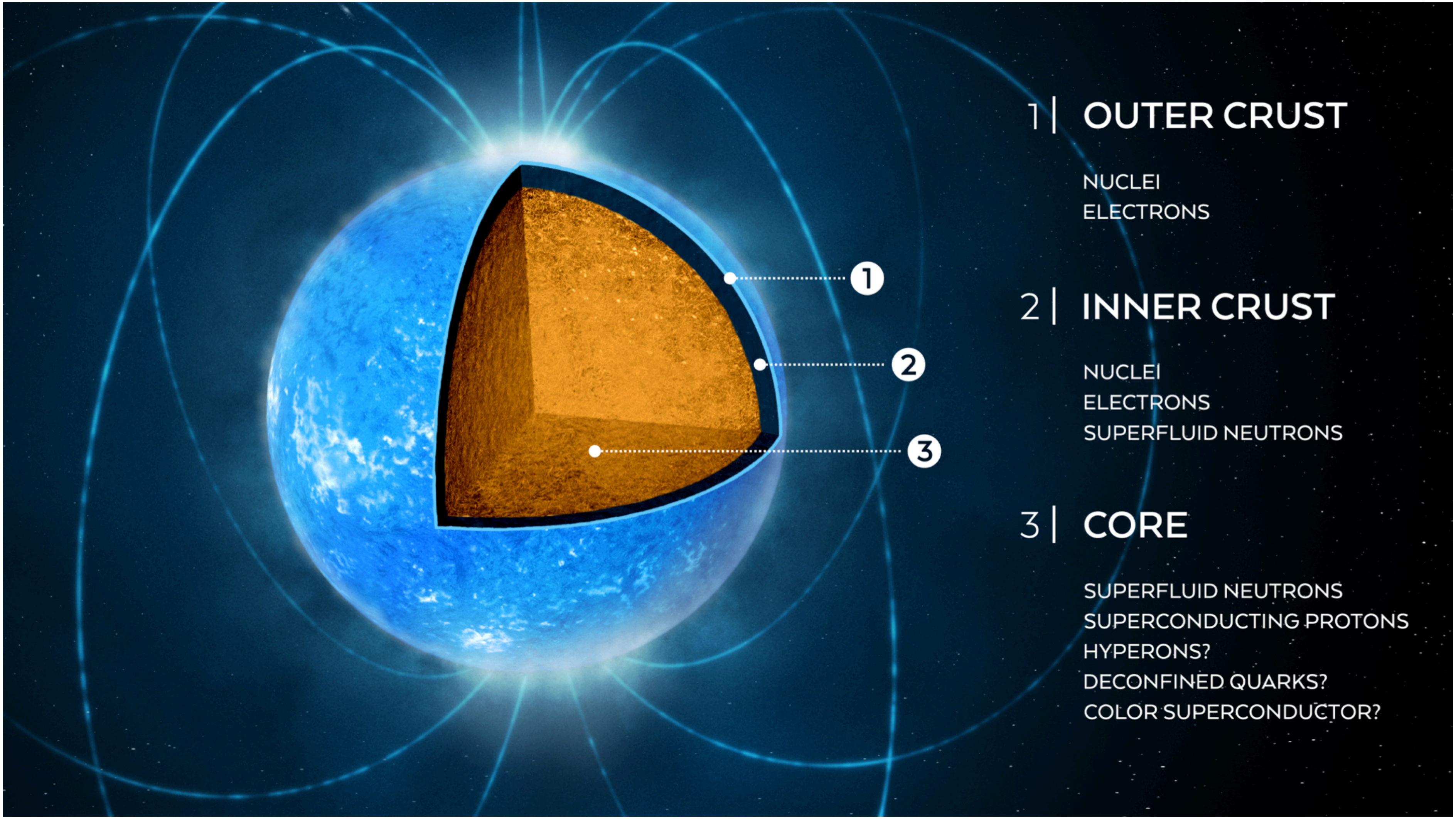


FIG. 10: Peak frequency of the postmerger GW emission versus the radius of a nonrotating NS with 1.6 $M_\odot$ for different EoSs. Symbols have the same meaning as in Fig. 8.



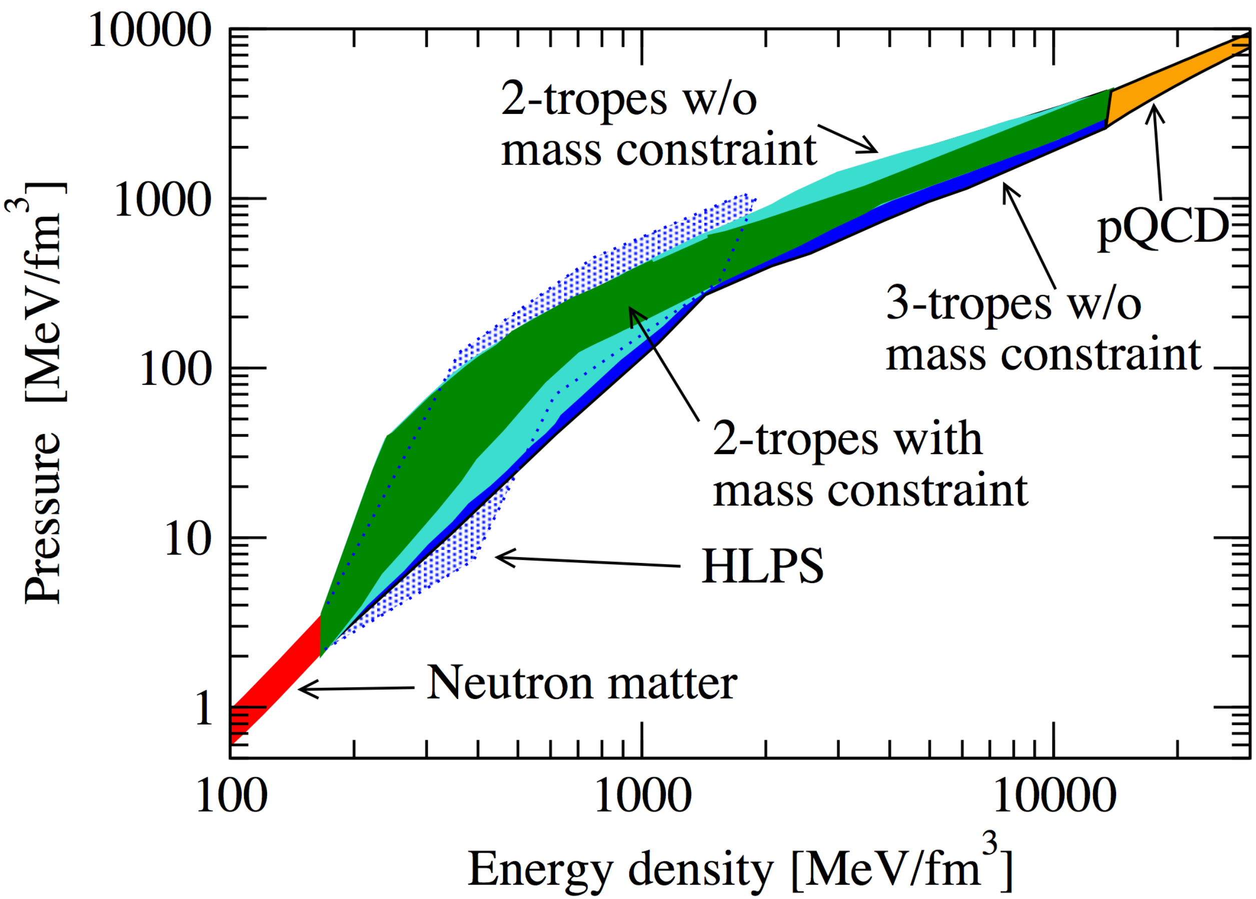
Interesting developments at higher densities



Connecting the equation of state to pQCD calculations

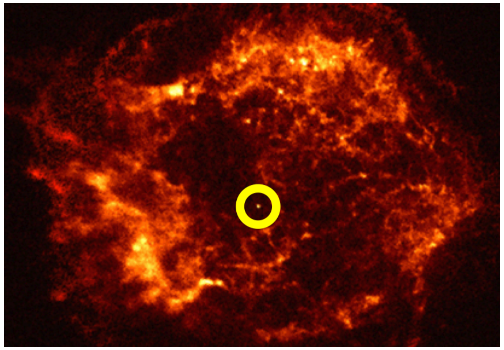
recent $O(\alpha_s^2)$ calculation of quark matter in perturbative QCD provides constraint at very high densities

interpolating between **neutron matter calculations** and **pQCD** gives consistent EOS band Kurkela, Fraga, Schaffner-Bielich, Vuorinen, ApJ (2014).



Potential observation of the cooling of Cas A

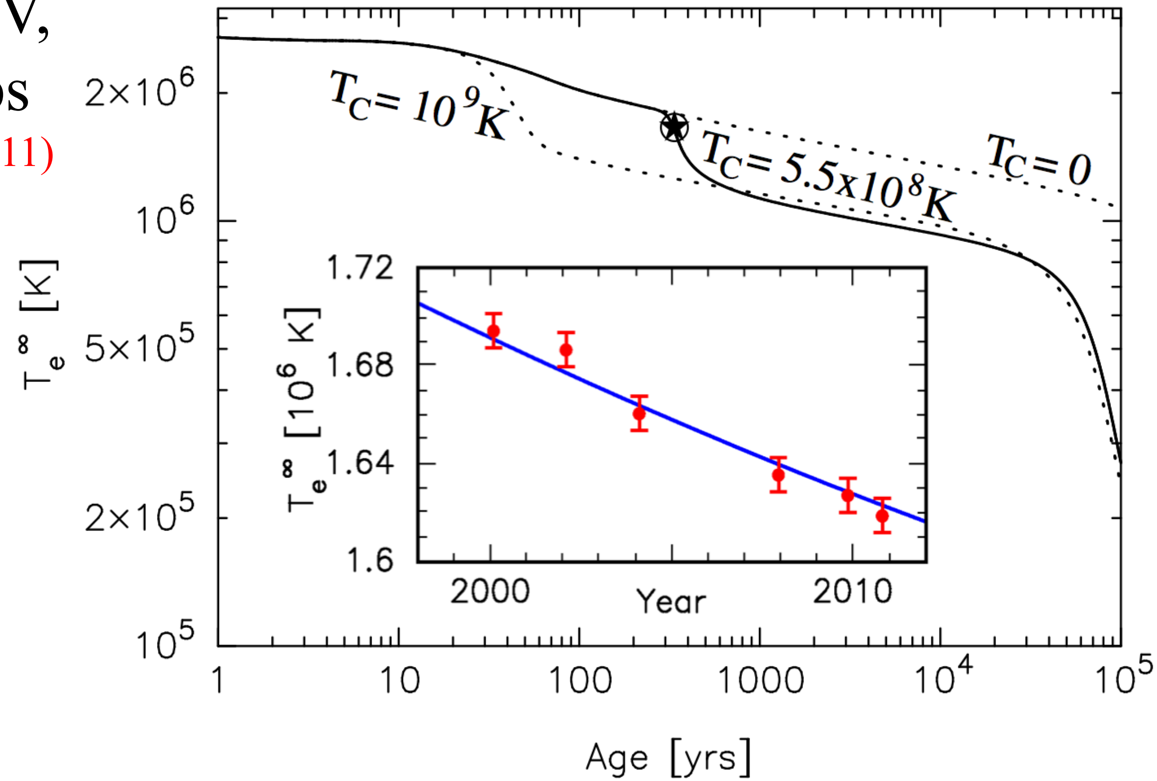
cooling of neutron stars is sensitive to P-wave pairing of neutrons in the core of neutron stars, as star cools across T_c, enhanced neutrino emission leads to rapid cooling, until well below T_c



Chandra observations show change of Cas A (but need to understand instrument better)

points to small T_c of ~50 keV, much smaller than BCS gaps

Page, Prakash, Lattimer, Steiner, PRL (2011)



Nuclei bound by strong interactions

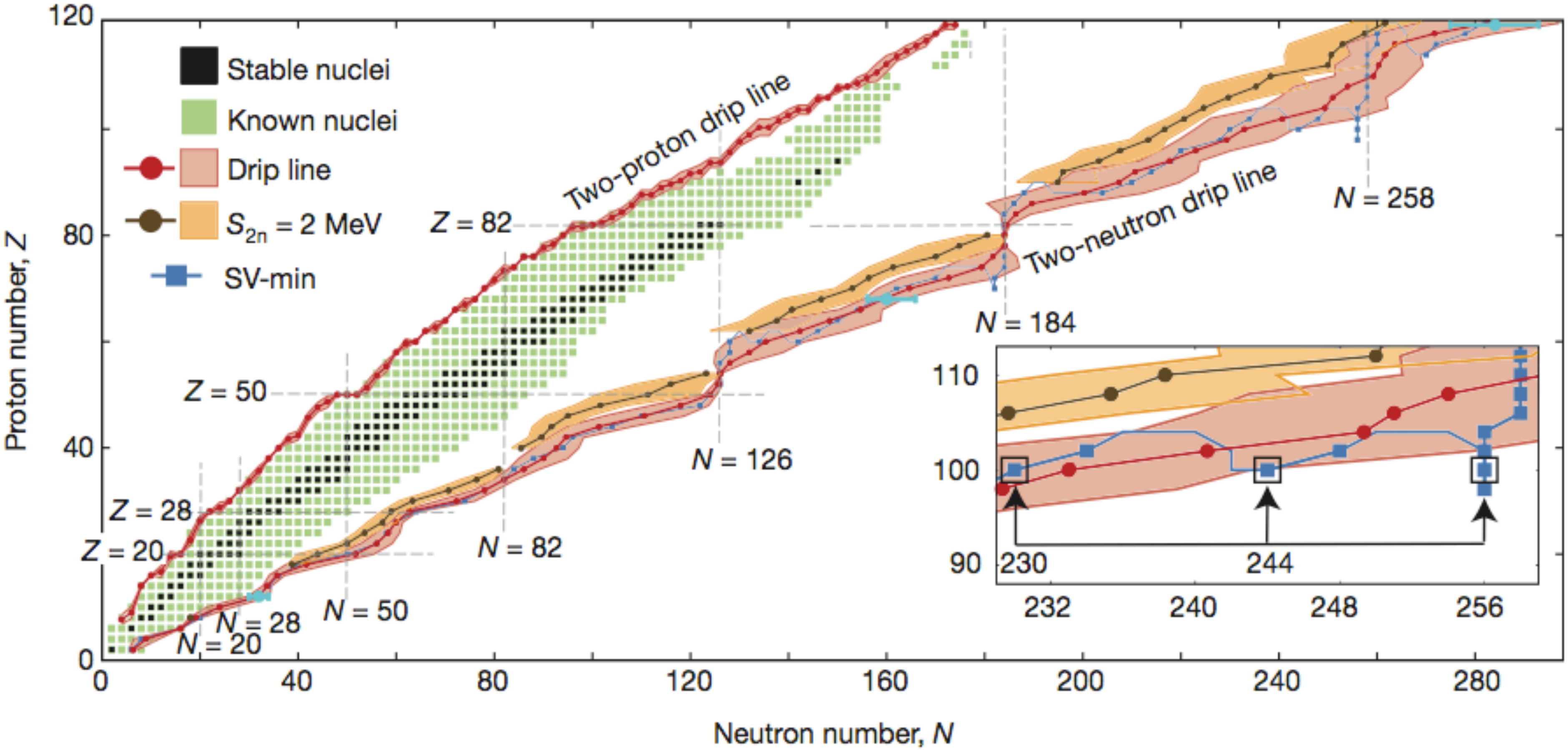
doi:10.1038/nature11188

The limits of the nuclear landscape

Jochen Erler[1,2], Noah Birge[1], Markus Kortelainen[1,2,3], Witold Nazarewicz[1,2,4], Erik Olsen[1,2], Alexander M. Perhac[1] & Mario Stoitsov[1,2]‡

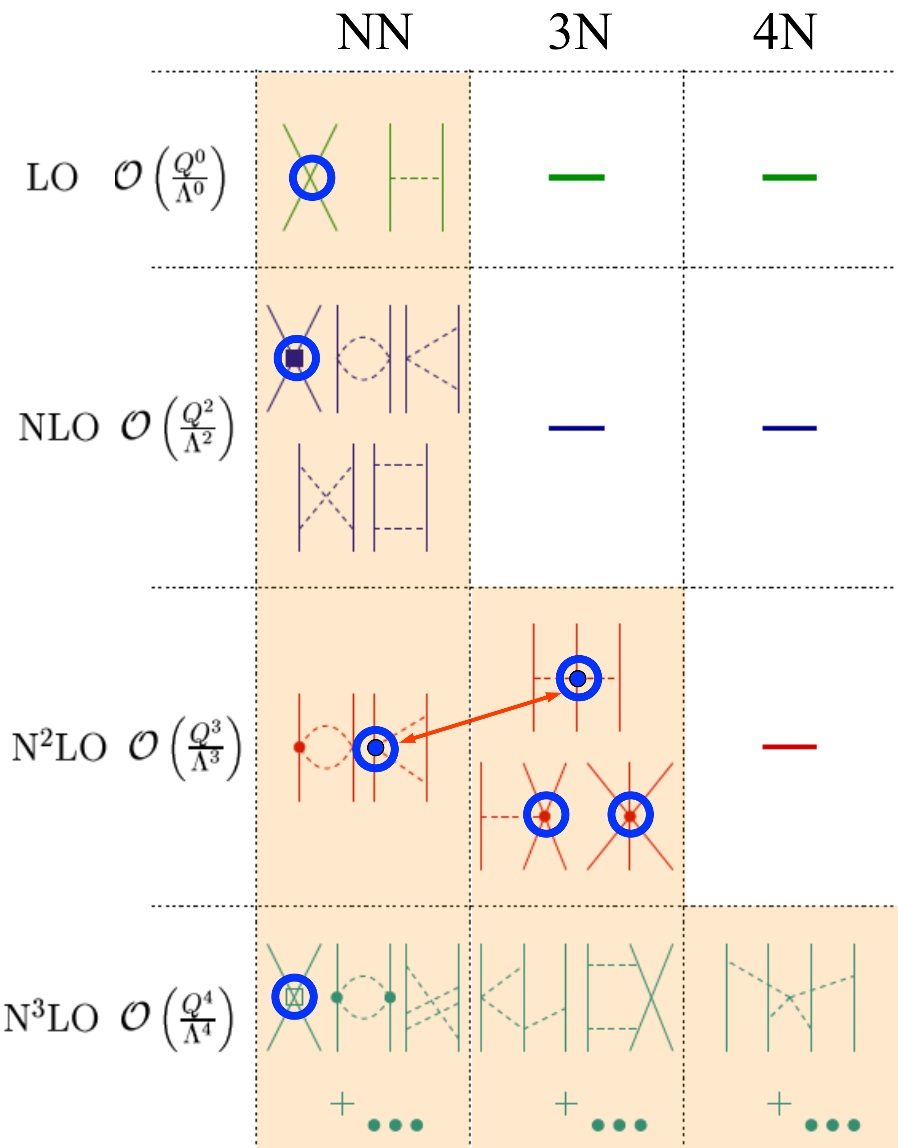
~ 3000 nuclei discovered (288 stable), 118 elements

~ 4000 nuclei unknown, extreme neutron-rich



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 $(Q/\Lambda_b)^n$

include long-range pion physics

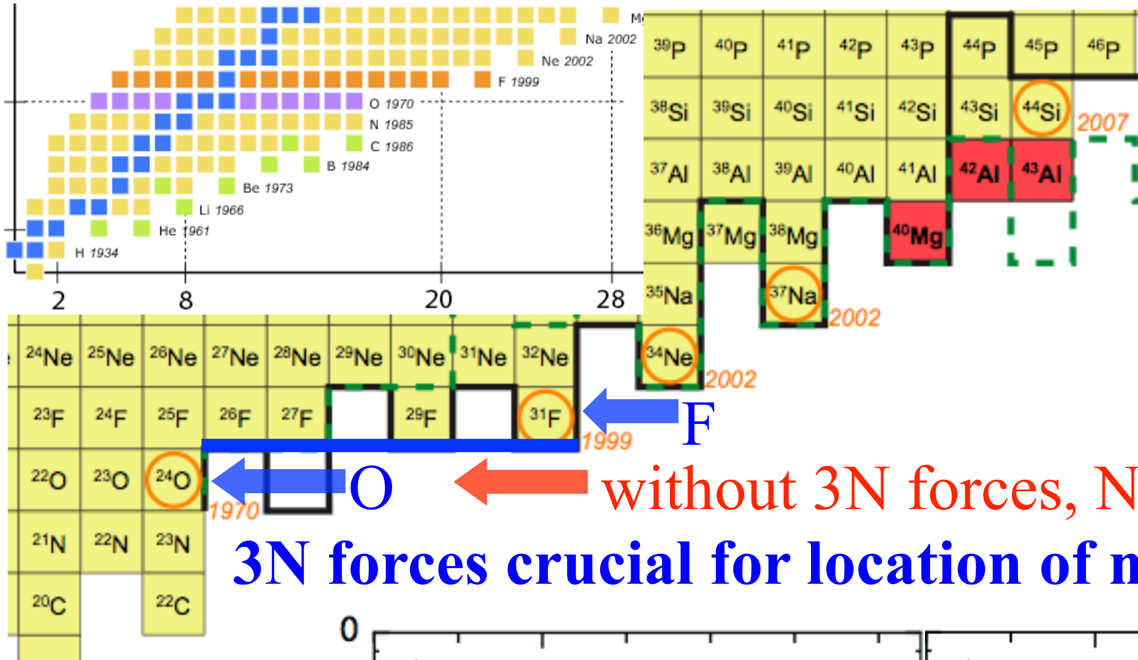
few short-range couplings, fit to experiment once

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

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

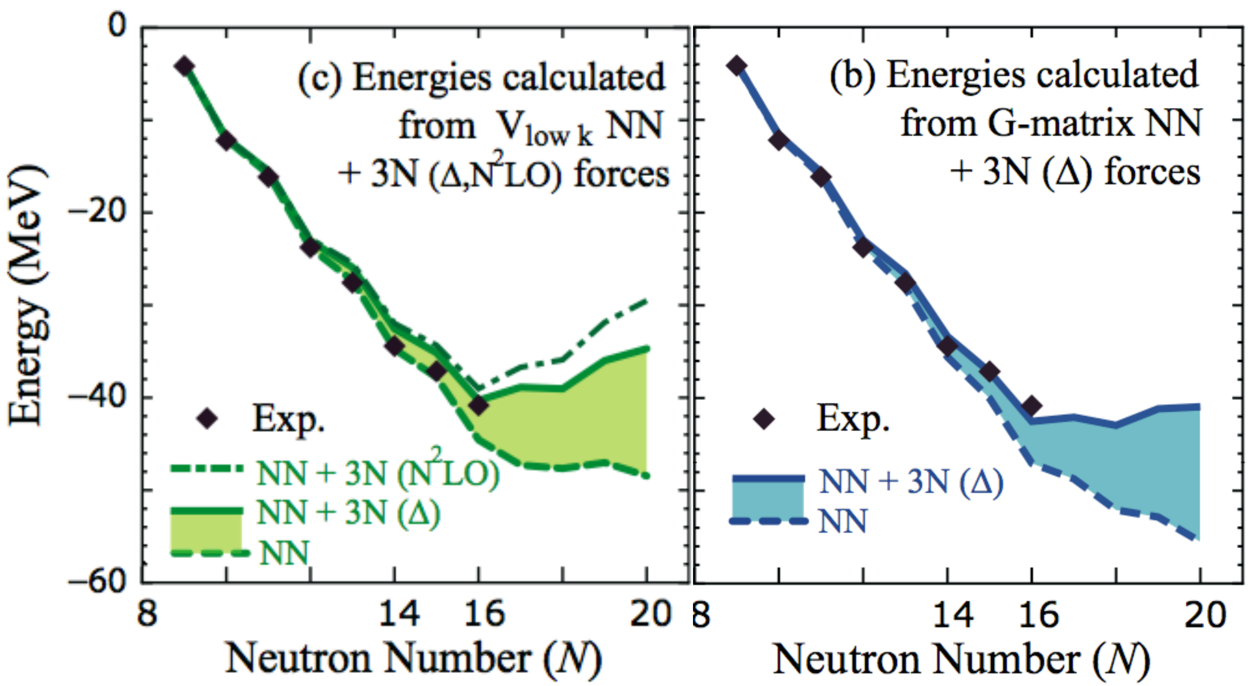
The oxygen anomaly

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



without 3N forces, NN interactions too attractive

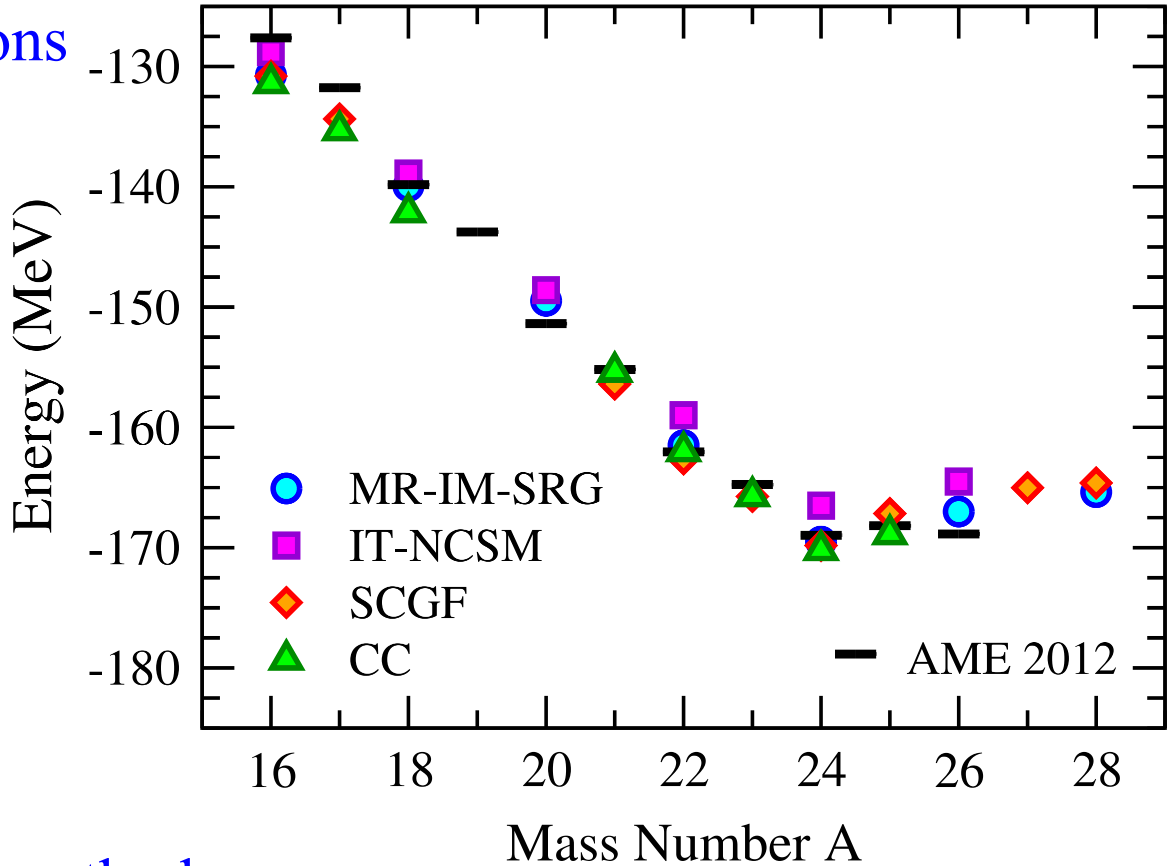
3N forces crucial for location of neutron dripline



Ab initio calculations of the oxygen anomaly

impact of 3N forces confirmed in large-space calculations

based on NN+3N interactions



using different many-body methods:

Coupled Cluster theory/CCEI Hagen et al., PRL (2012), Jansen et al., PRL (2014)

Multi-Reference In-Medium SRG and IT-NCSM Hergert et al., PRL (2013)

Self-Consistent Green's Function methods Cipollone et al., PRL (2013)

Frontier of ab initio calculations at A~50

doi:10.1038/nature12226

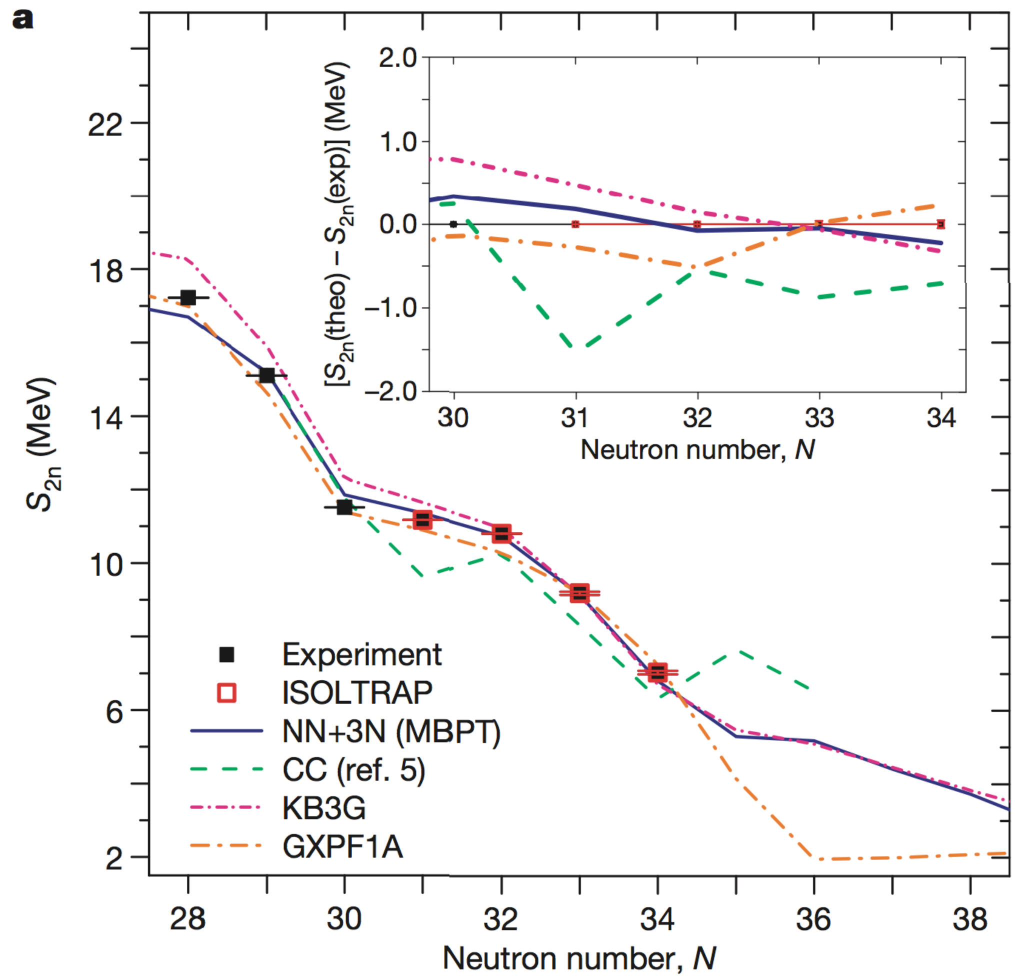
Masses of exotic calcium isotopes pin down nuclear forces

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

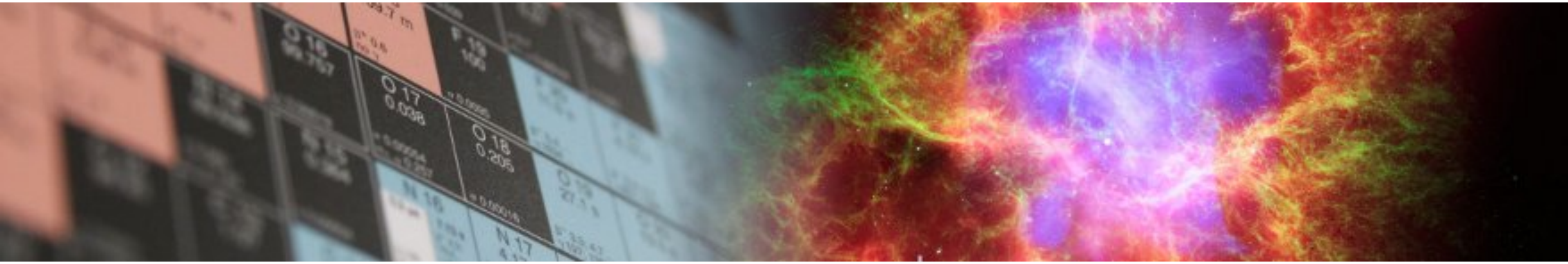
establish prominent N=32 shell closure in calcium

excellent agreement with theoretical NN+3N prediction



Summary

EFT opens up unified description of matter from lab to cosmos



Nuclear forces: an exciting frontier for nuclear physics and astrophysics

Cold atoms provide anchor point for neutrons at low densities

Nuclear forces and their impact on neutron-rich matter and neutron stars
K. Hebeler, T. Krüger, J.M. Lattimer, C.J. Pethick, **I. Tews**

3N forces also key for neutron-rich nuclei
S.K. Bogner, **H. Hergert, J.D. Holt, J. Menéndez**, T. Otsuka, **J. Simonis**, T. Suzuki