Nuclear forces and their impact on neutron-rich matter

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EMMI

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Main message

Nuclear forces and neutron-rich nuclei

with S.K. Bogner, **H. Hergert, J.D. Holt, J. Menéndez**, T. Otsuka, **J. Simonis**, T. Suzuki

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]

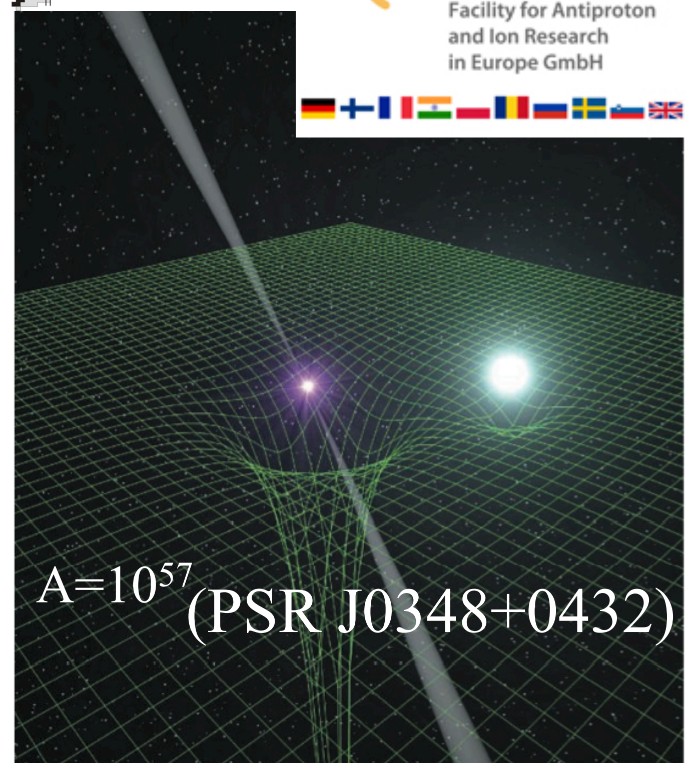
Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

FAIR
Facility for Antiproton and Ion Research in Europe GmbH

Nuclear forces and neutron stars

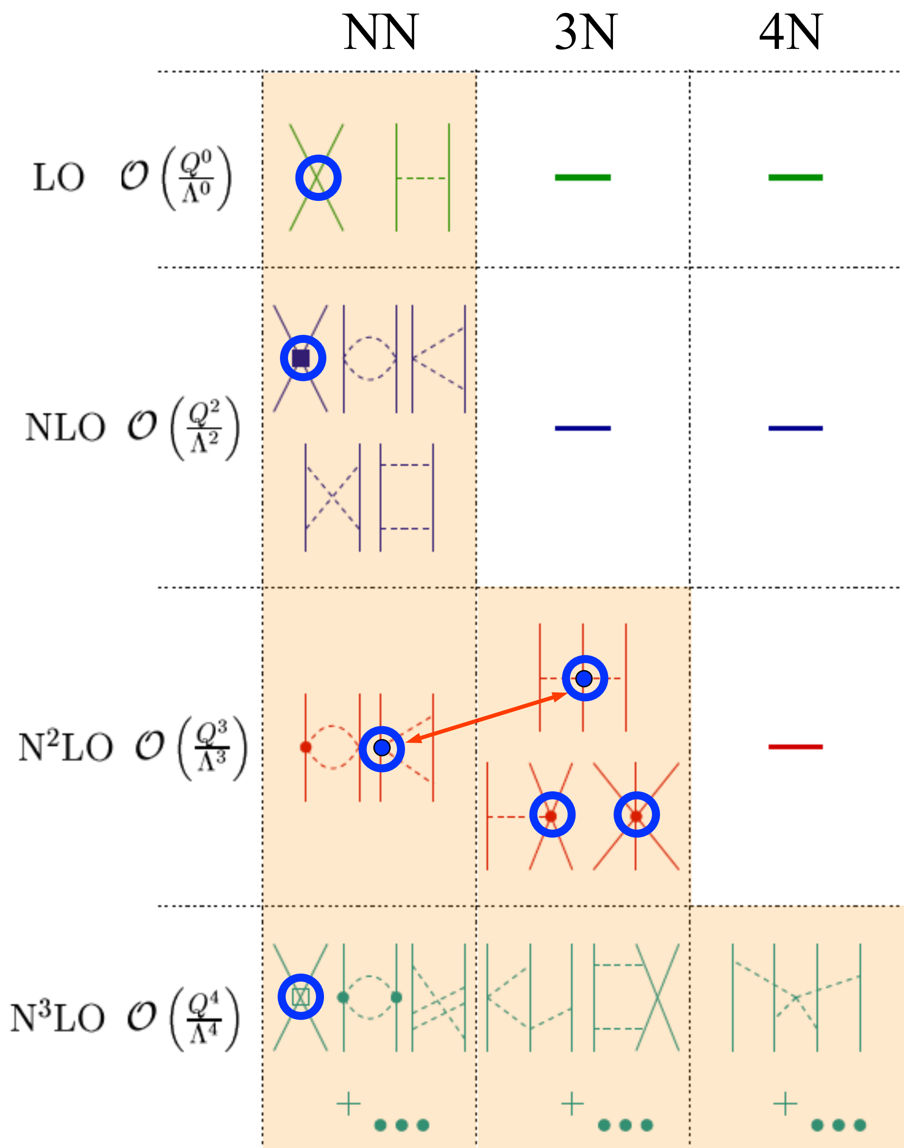
with C. Drischler, K. Hebeler, T. Krüger, J.M. Lattimer, C.J. Pethick, **V. Somá, I. Tews**



based on same strong interactions!

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

few short-range couplings,
fit to experiment once

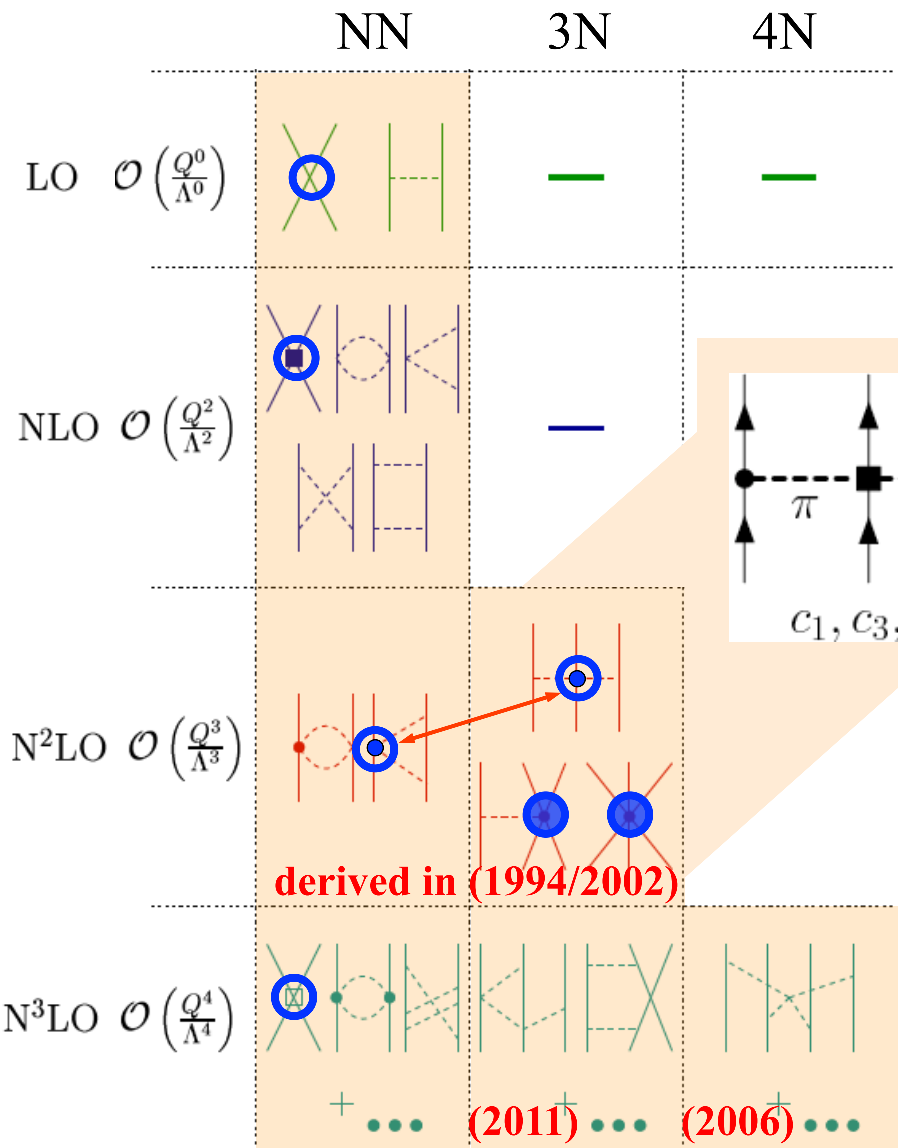
systematic: can work to desired accuracy and obtain **error estimates**

consistent **electroweak interactions** and **matching to lattice QCD**

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

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

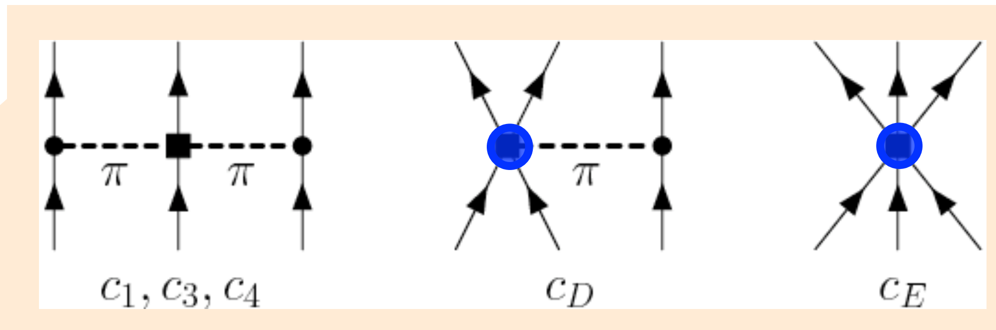
Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale ~500 MeV



consistent NN-3N-4N interactions

3N,4N: **2 new couplings to N³LO**

+ no new couplings for neutrons



c_i from πN and NN Meissner, LAT 2005

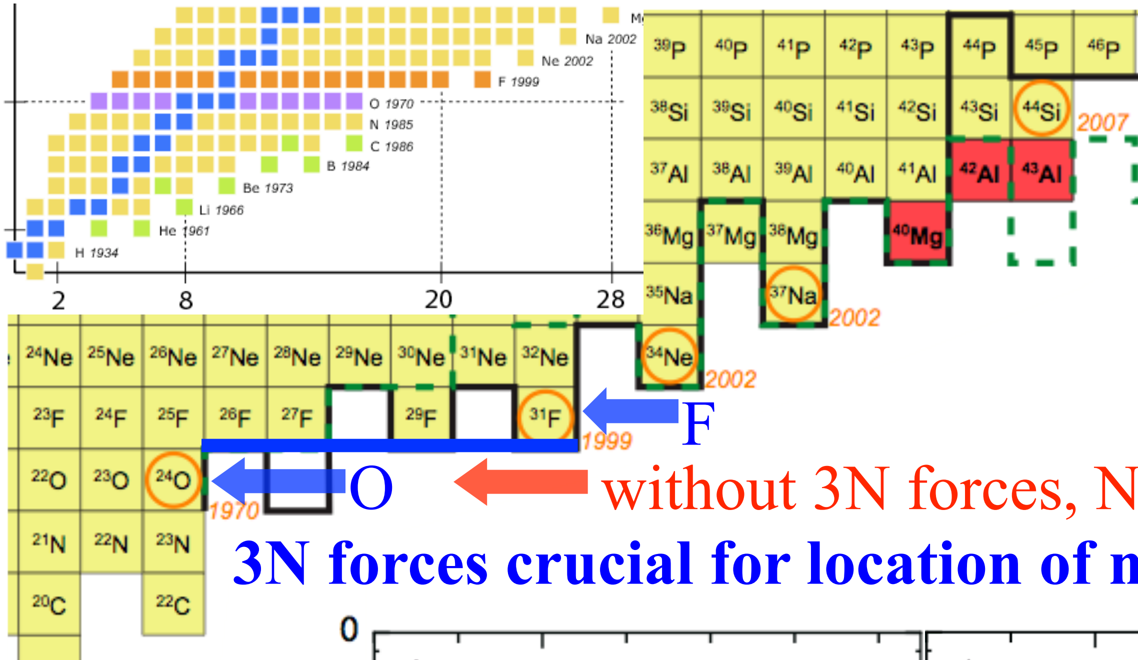
$$c_1 = -0.9^{+0.2}_{-0.5}\ ,\ c_3 = -4.7^{+1.2}_{-1.0}\ ,\ c_4 = 3.5^{+0.5}_{-0.2}$$

c_D, c_E fit to light nuclei only

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

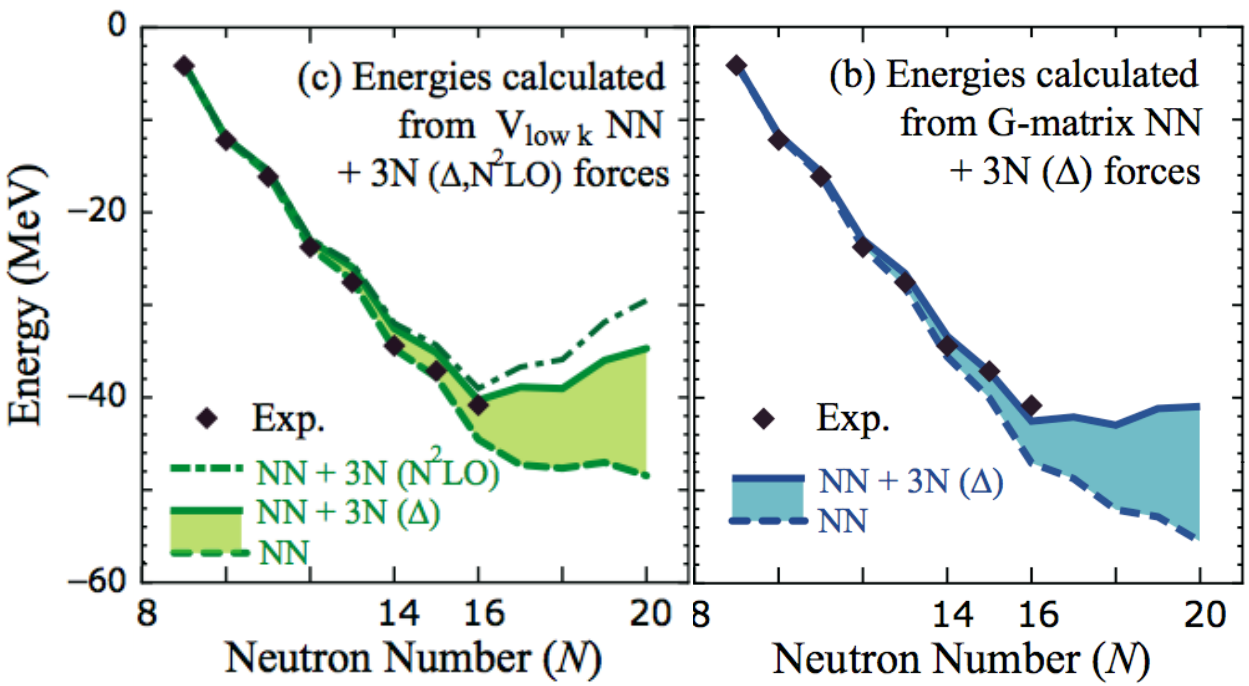
The oxygen anomaly

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



without 3N forces, NN interactions too attractive

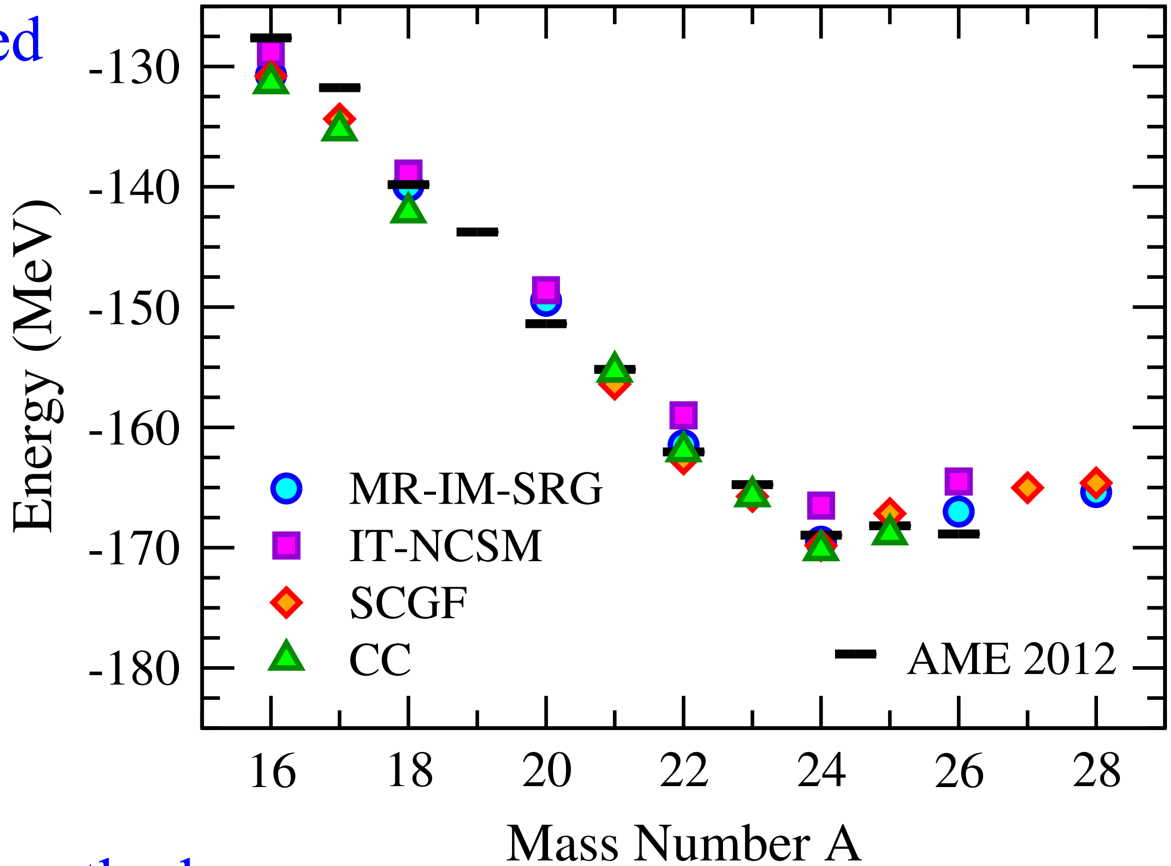
3N forces crucial for location of neutron dripline



Ab initio calculations of the oxygen anomaly

impact of 3N forces confirmed in large-space calculations

based on same SRG-evolved 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

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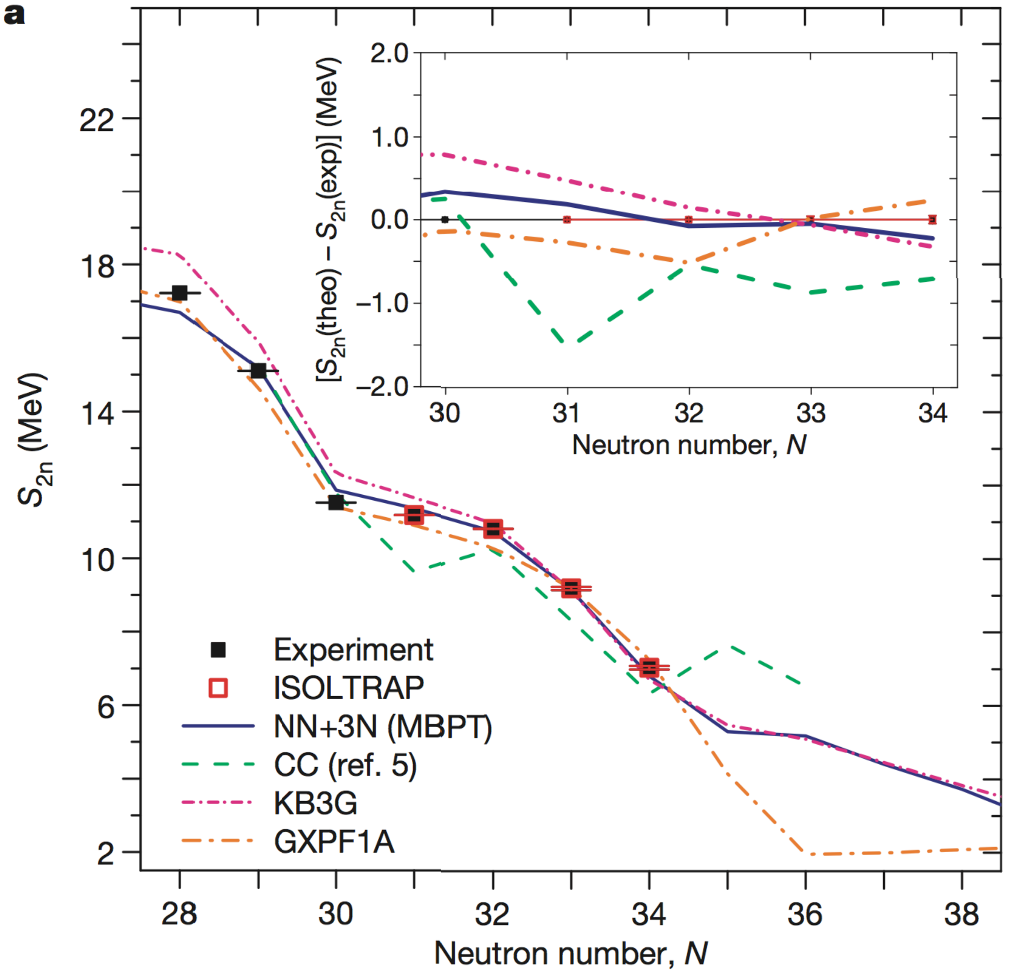
^{53,54}Ca masses measured at ISOLTRAP using new MR-TOF mass spectrometer

establish prominent N=32 shell closure in calcium

excellent agreement with theoretical NN+3N prediction

a



Chiral effective field theory for nuclear forces

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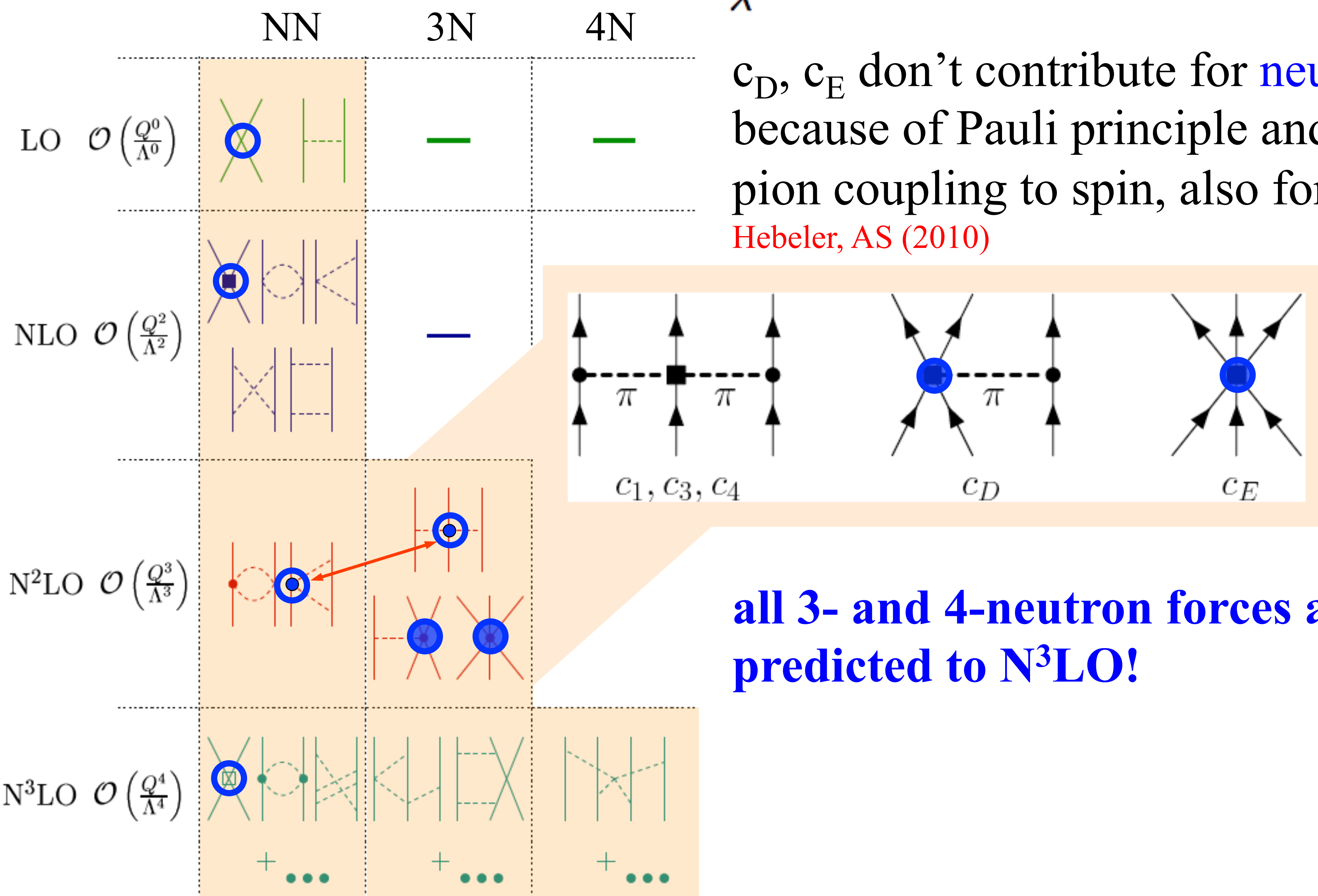


c_D, c_E don't contribute for neutrons because of Pauli principle and pion coupling to spin, also for c_4

Hebeler, AS (2010)

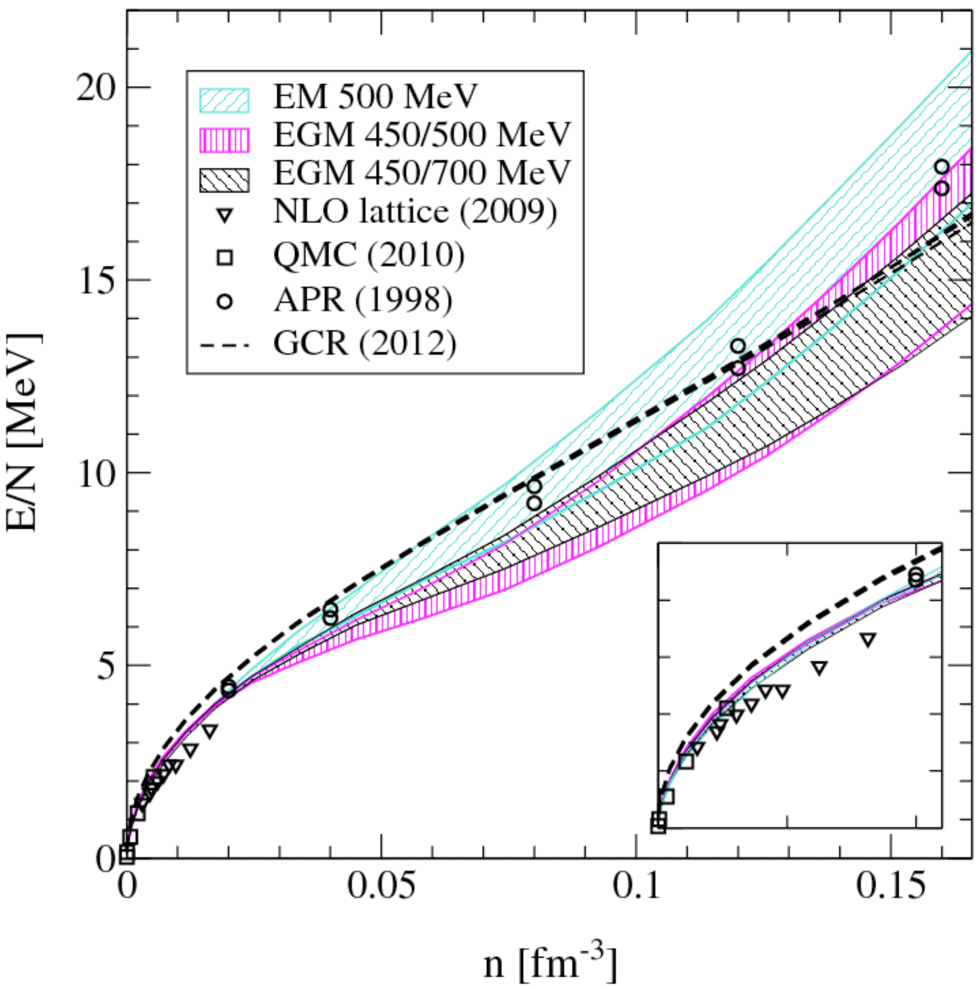
all 3- and 4-neutron forces are predicted to N³LO!

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

Complete N^3LO calculation of neutron matter

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

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

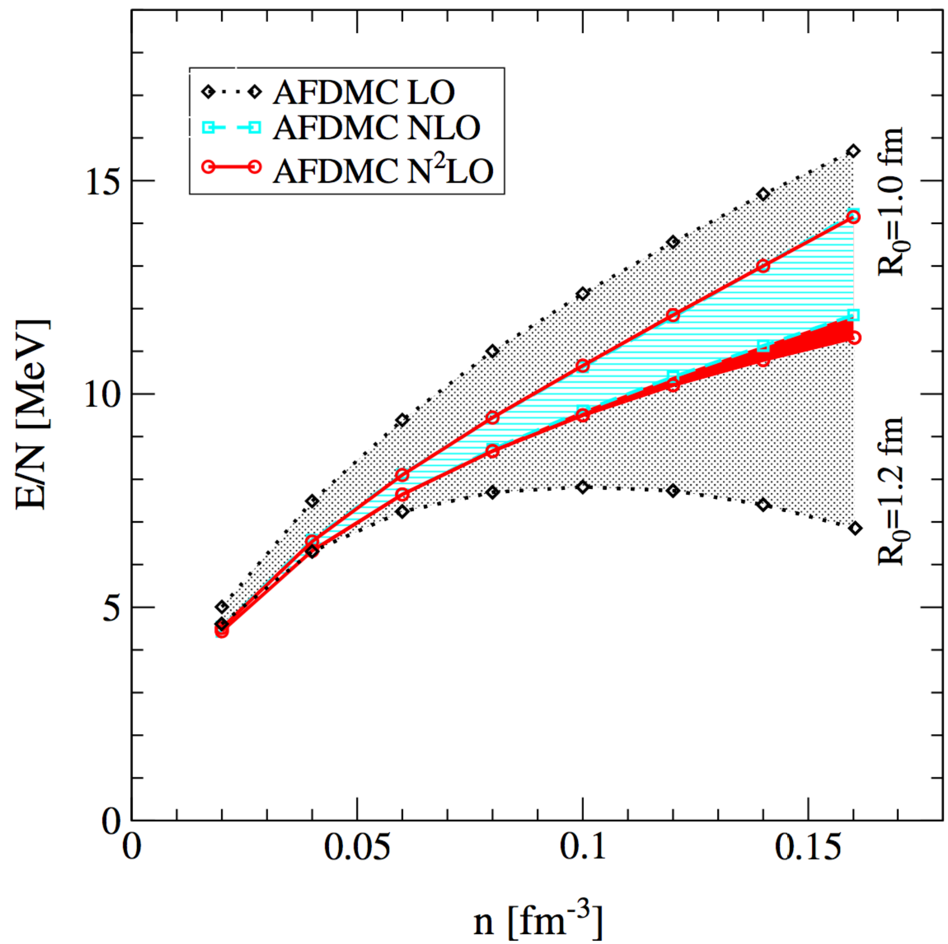


good agreement with Quantum Monte Carlo calculations at low densities

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

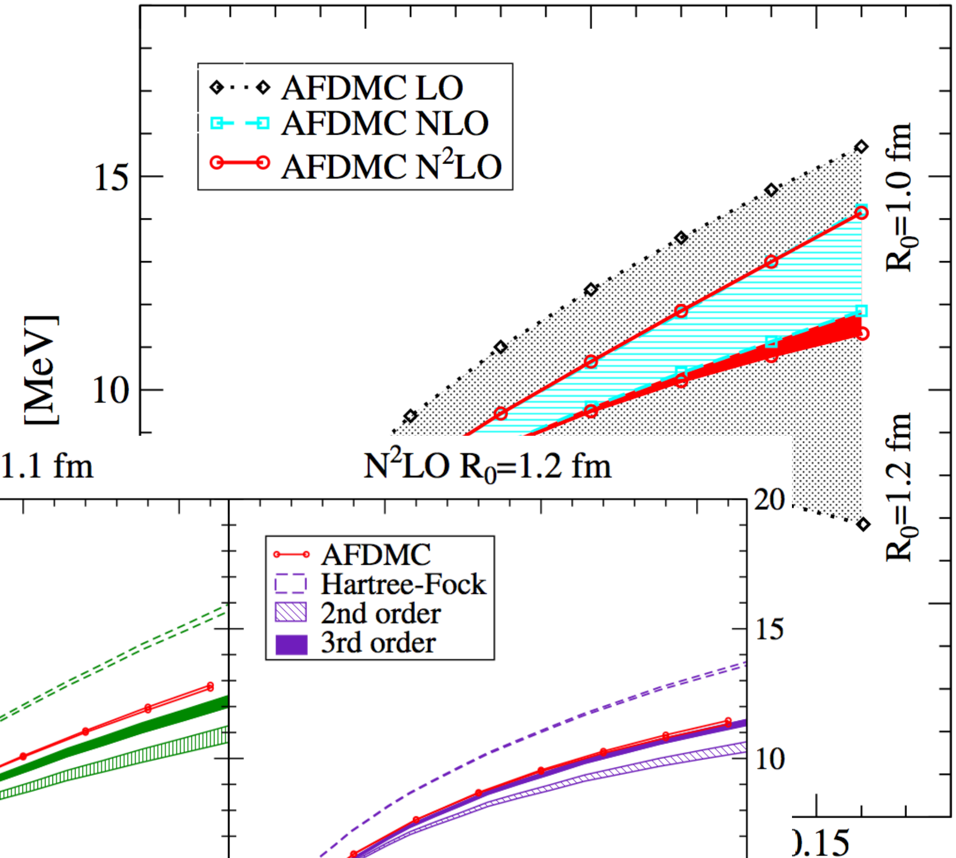


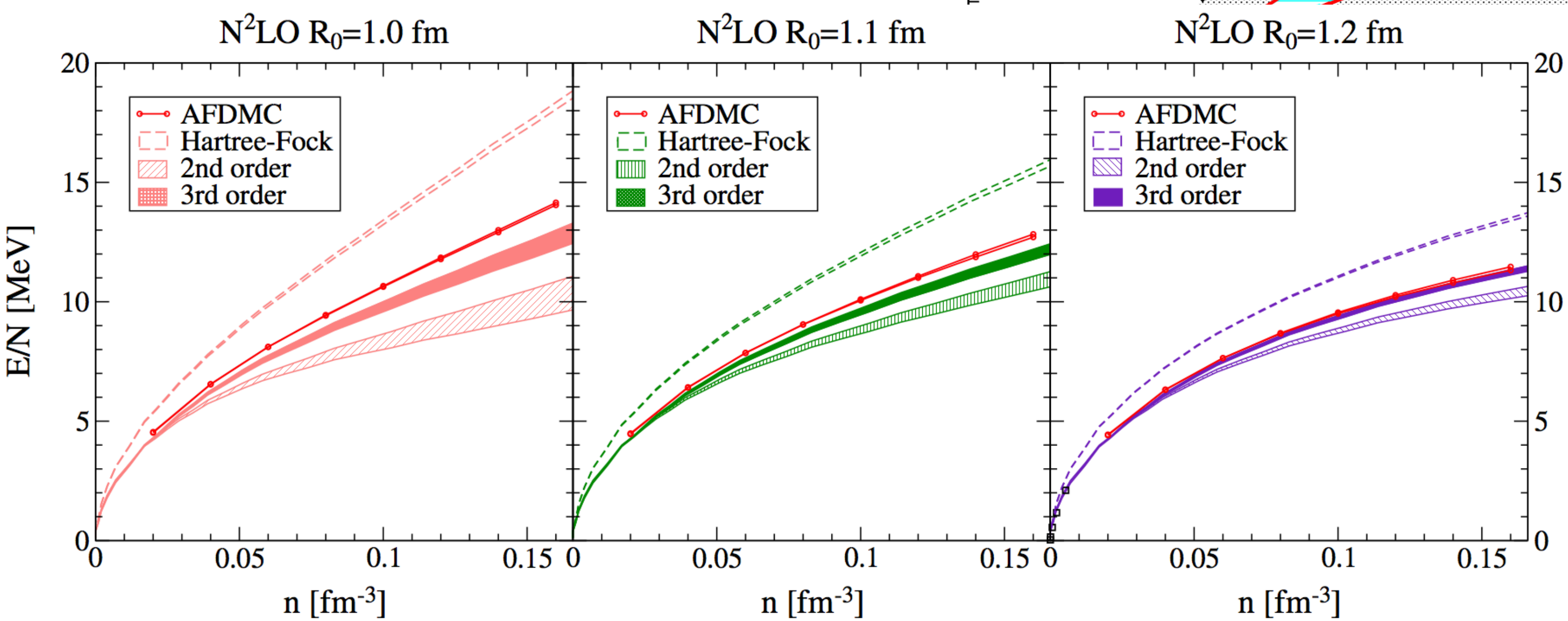
Quantum Monte Carlo for neutron matter

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)





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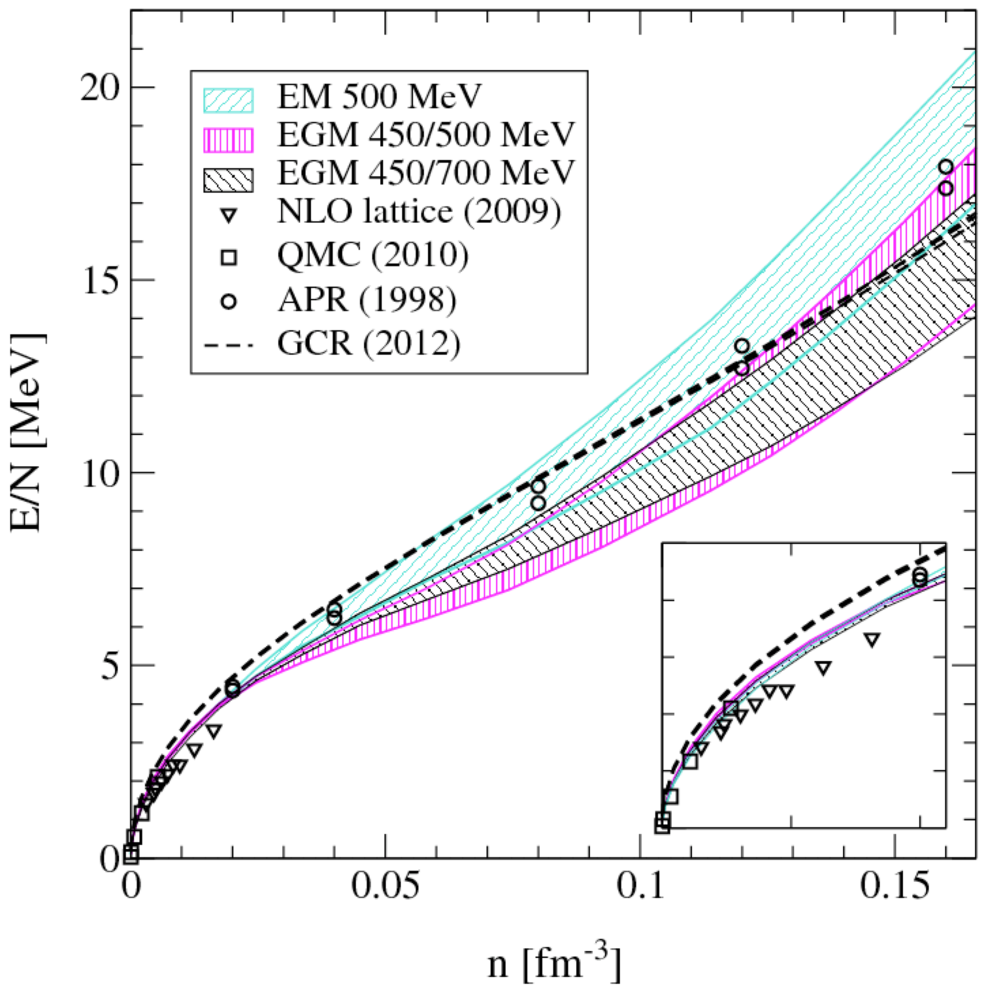
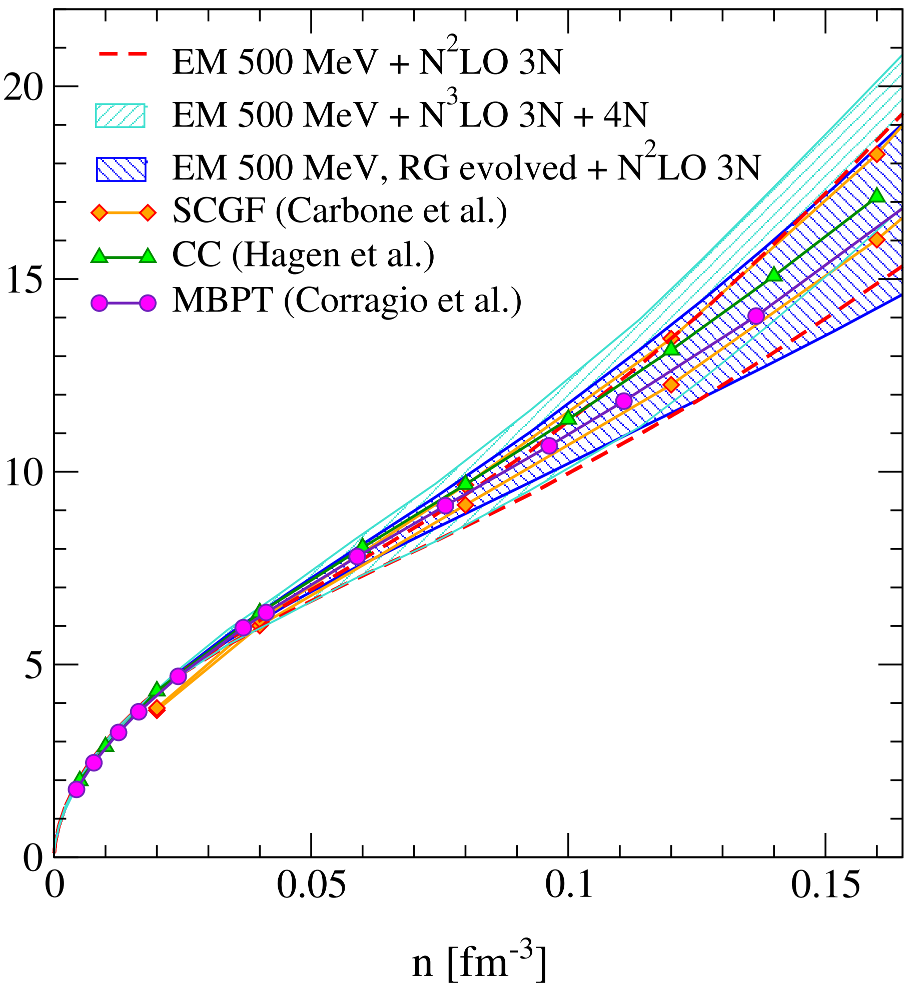


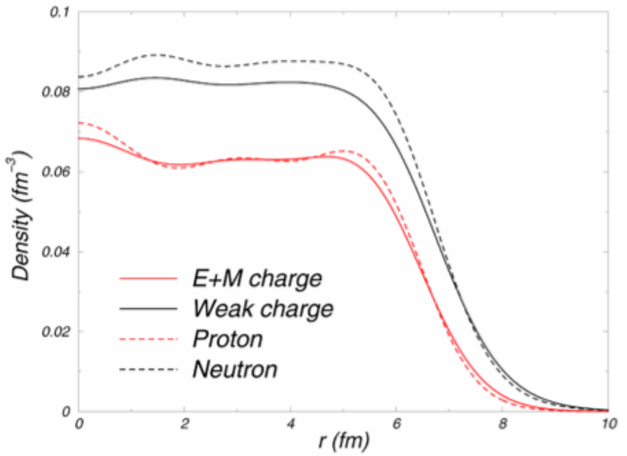


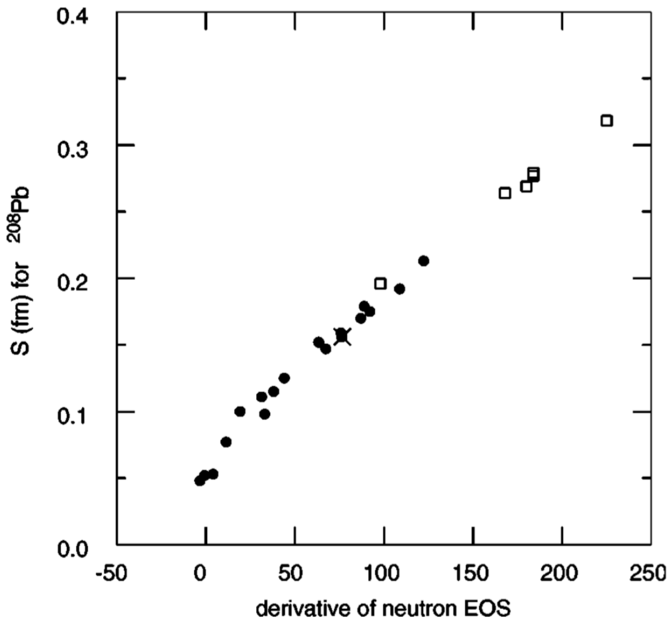
excellent agreement with other methods!

Neutron skin of ^{208}Pb

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

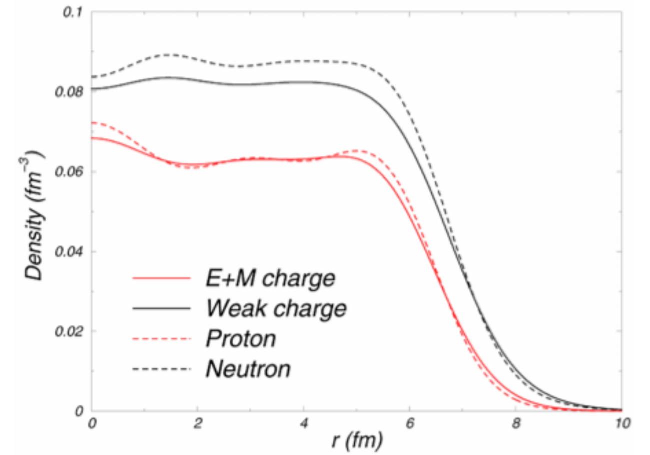
Hebeler, Lattimer, Pethick, AS, PRL (2010)





Brown (2000), Typel, Brown (2001)

Neutron skin of ^{208}Pb



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

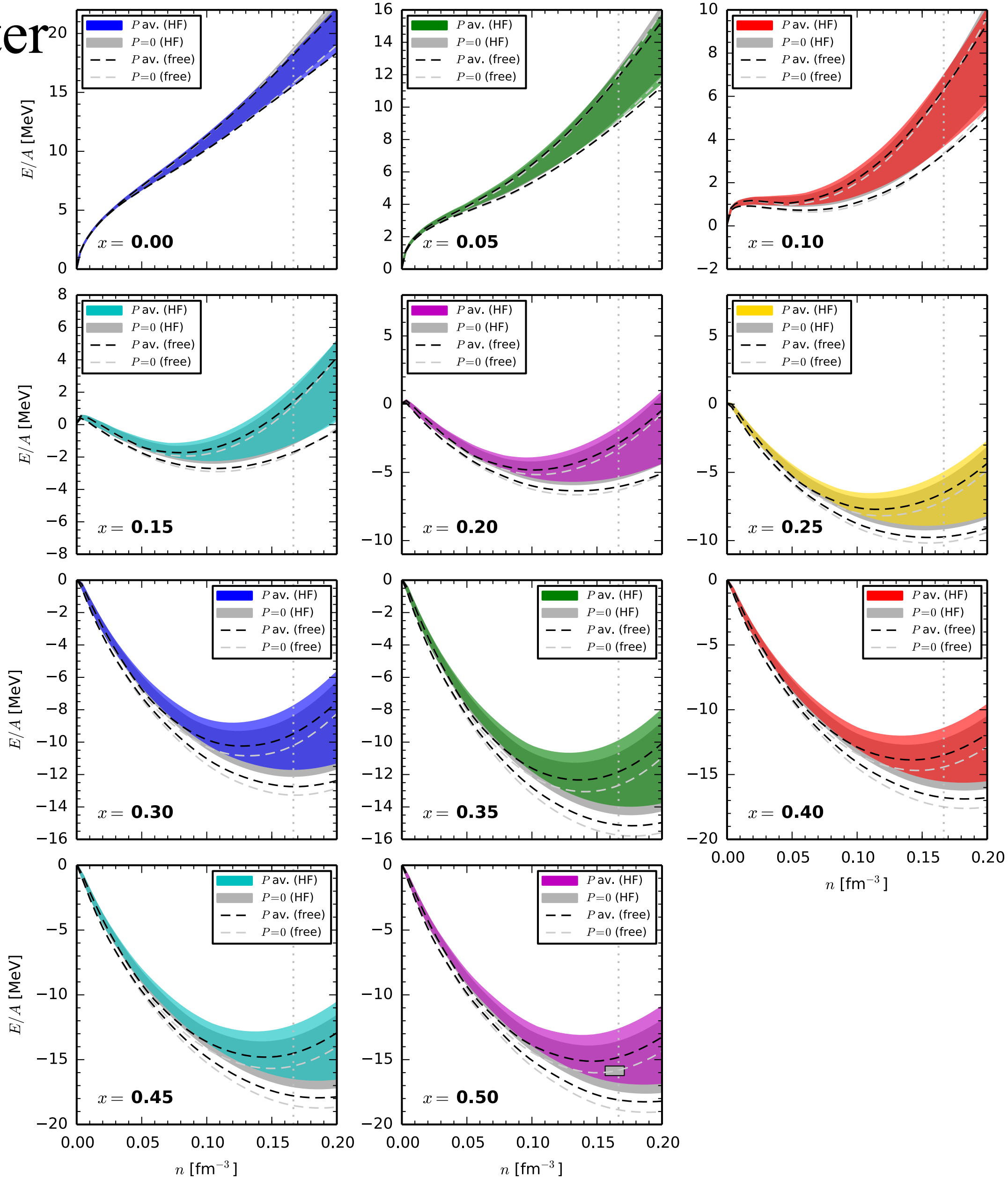
PREX: neutron skin from parity-violating electron-scattering at JLAB
goal II: ±0.06 fm Abrahamyan et al., PRL (2012)

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

Nuclear forces and nuclear matter

first results for asymmetric matter
with arbitrary proton fraction

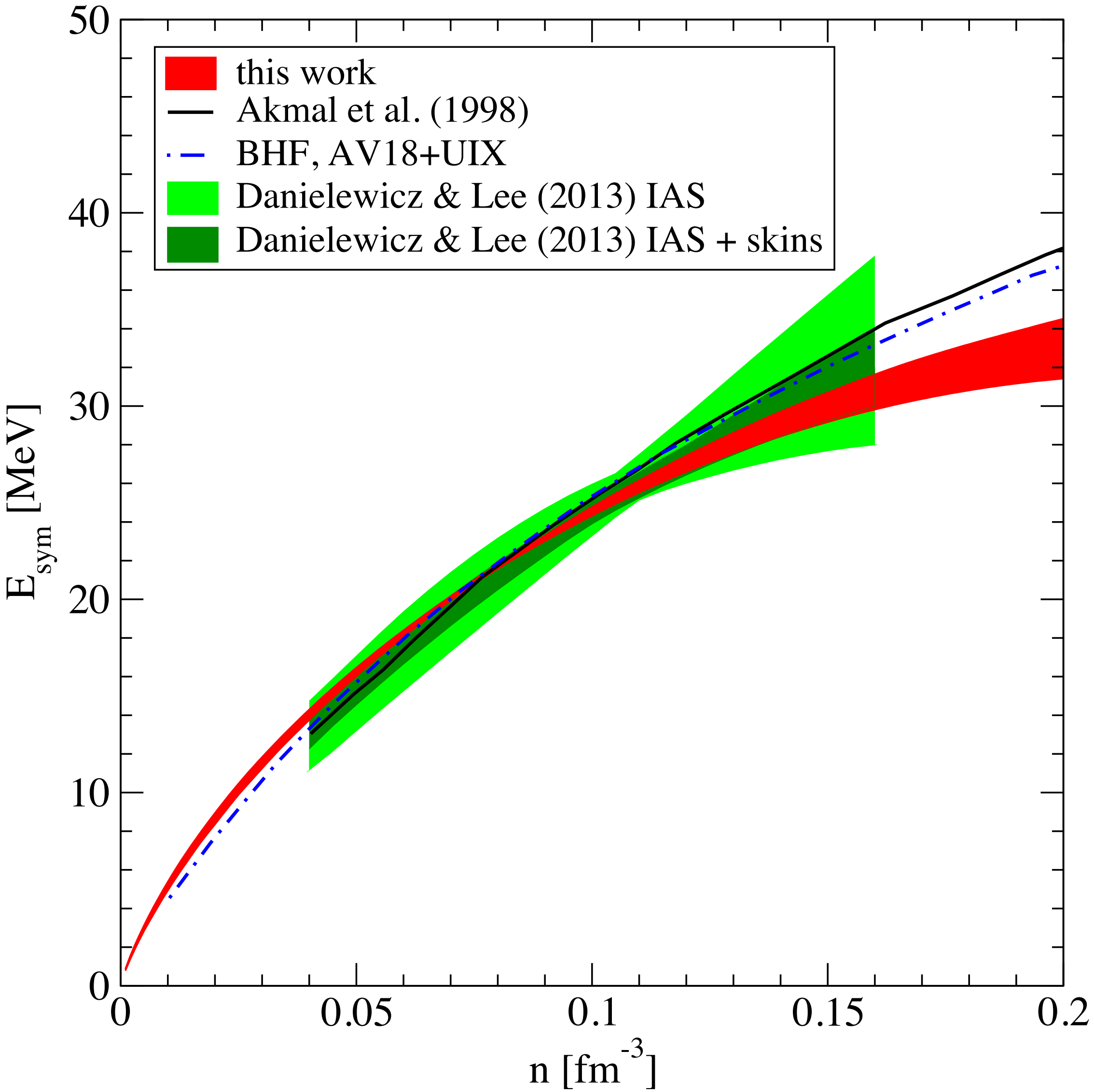
Drischler, Hebeler, AS, in prep.



Calculations of asymmetric matter Drischler, Soma, AS, PRD (2014)

E_{sym} comparison with extraction from isobaric analogue states (IAS)

3N forces fit to ^3H, ^4He properties only



Neutron matter and neutron stars

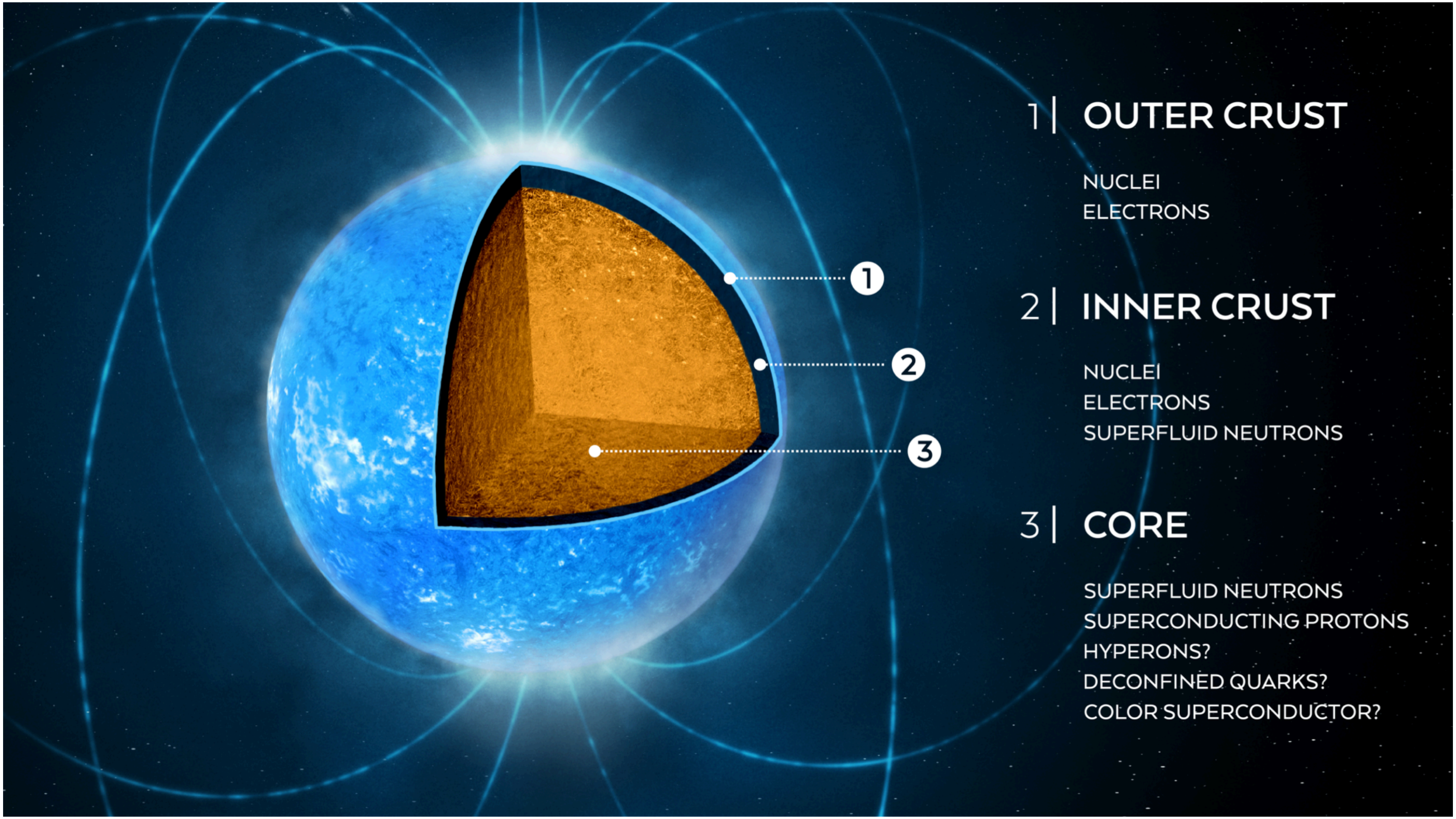
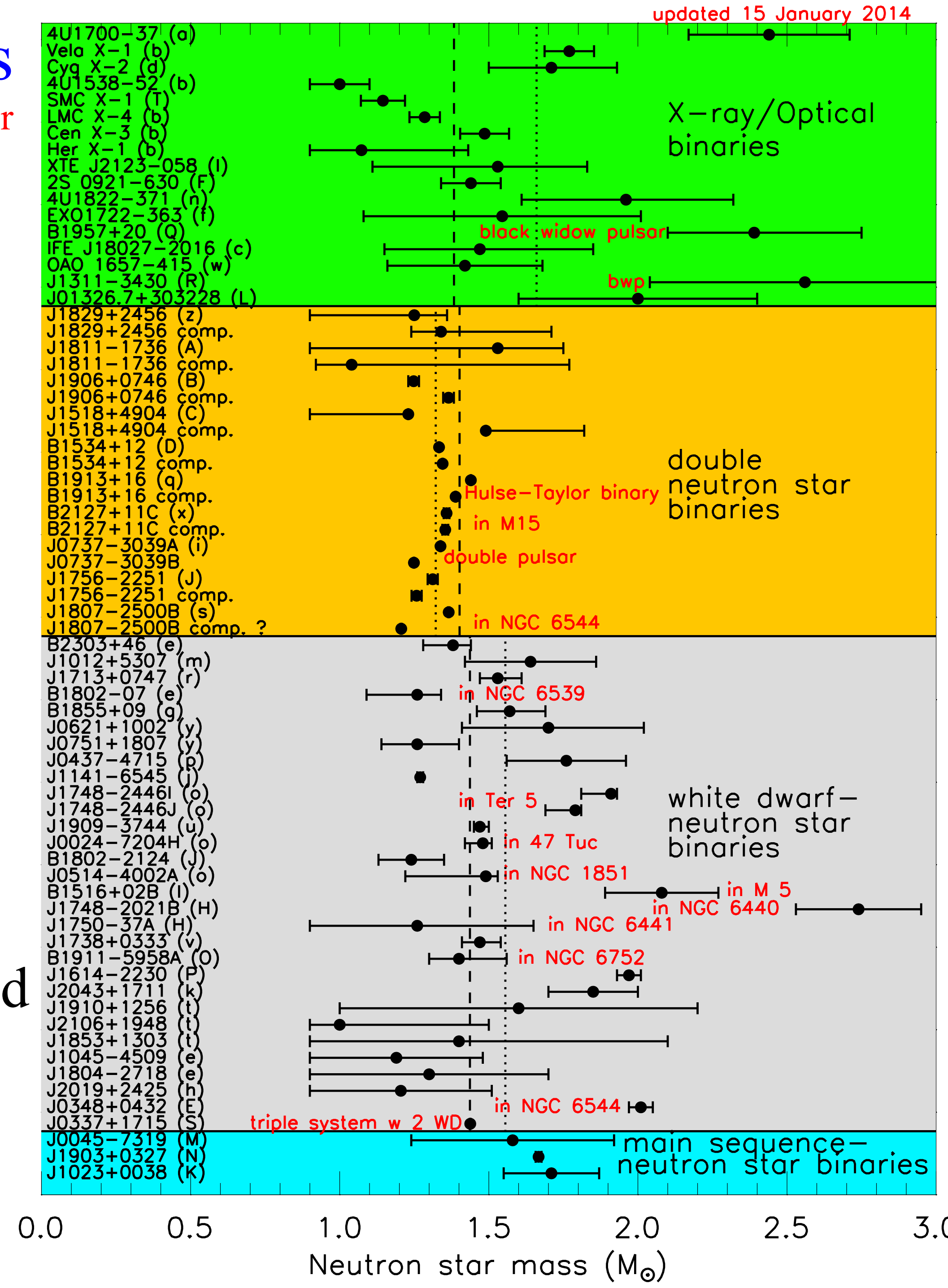


Chart of neutron star masses

from Jim Lattimer



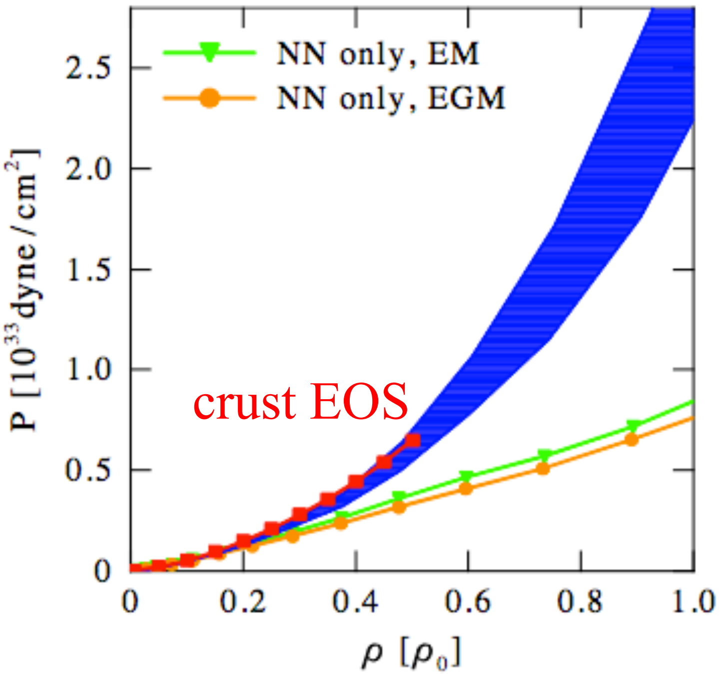
two 2 M_{sun} neutron stars observed

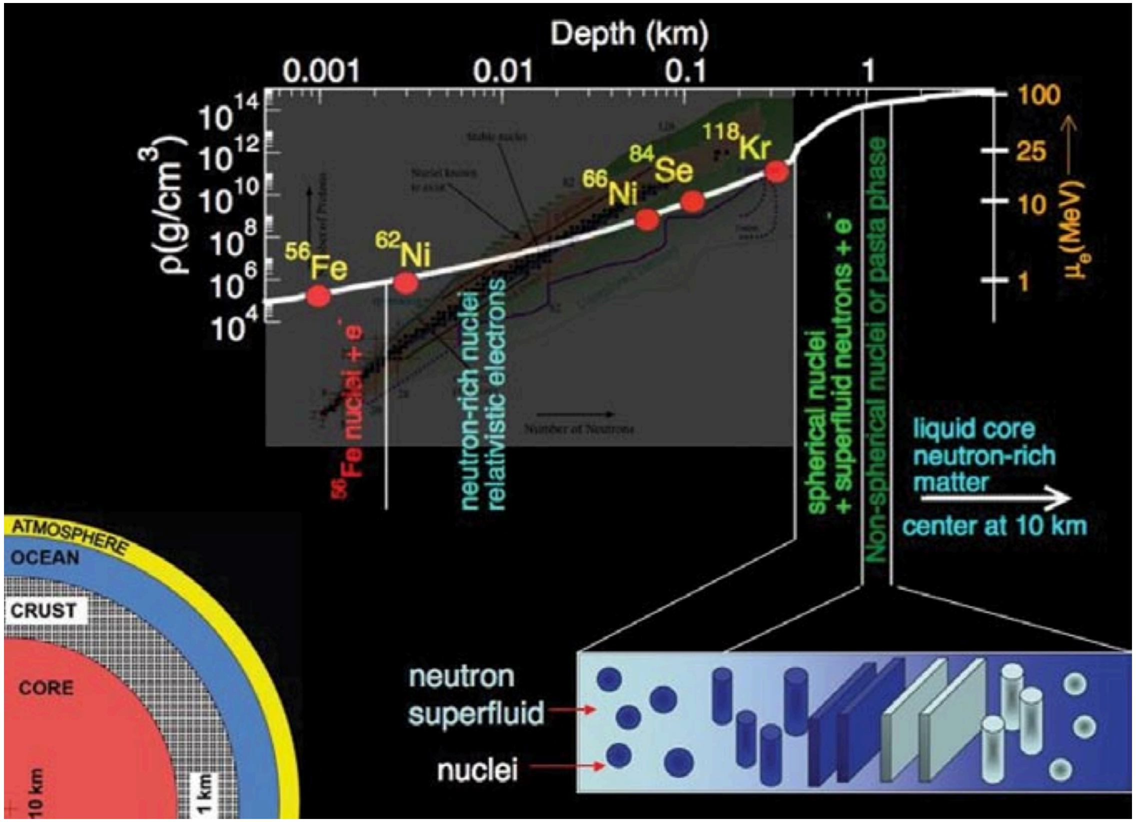
Demorest et al, Nature (2010),

Antoniadis et al., Science (2013)

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)

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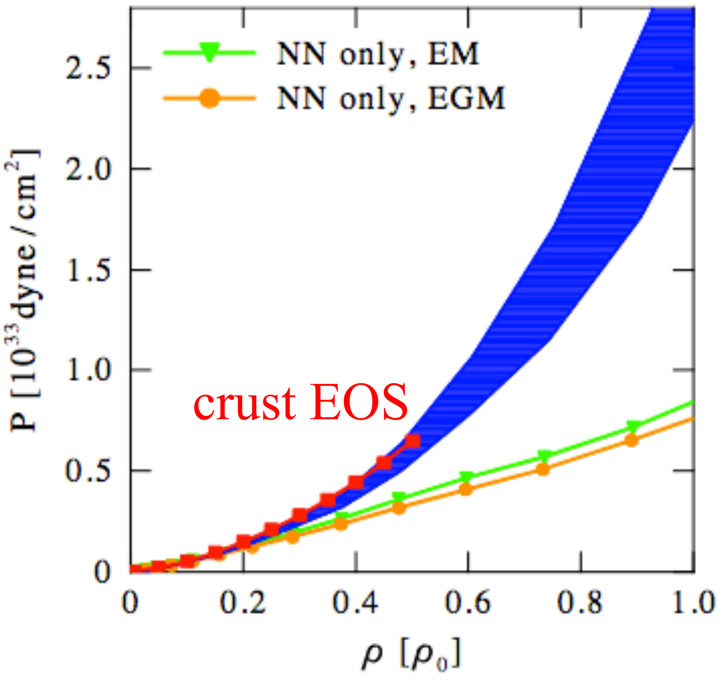
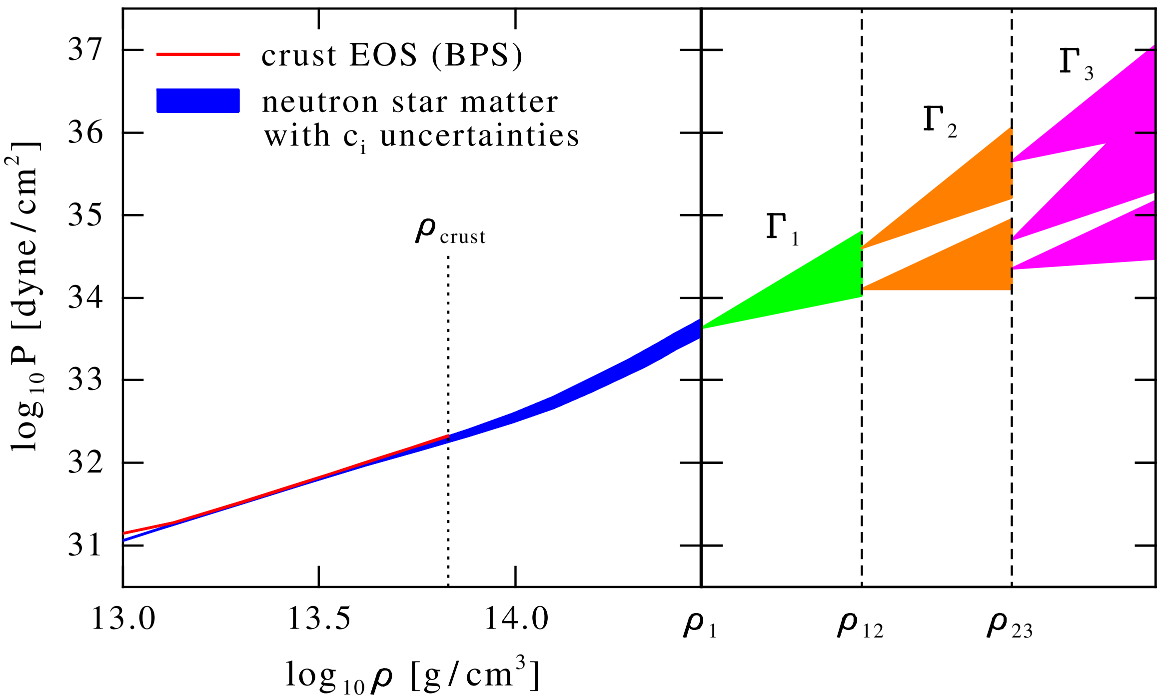


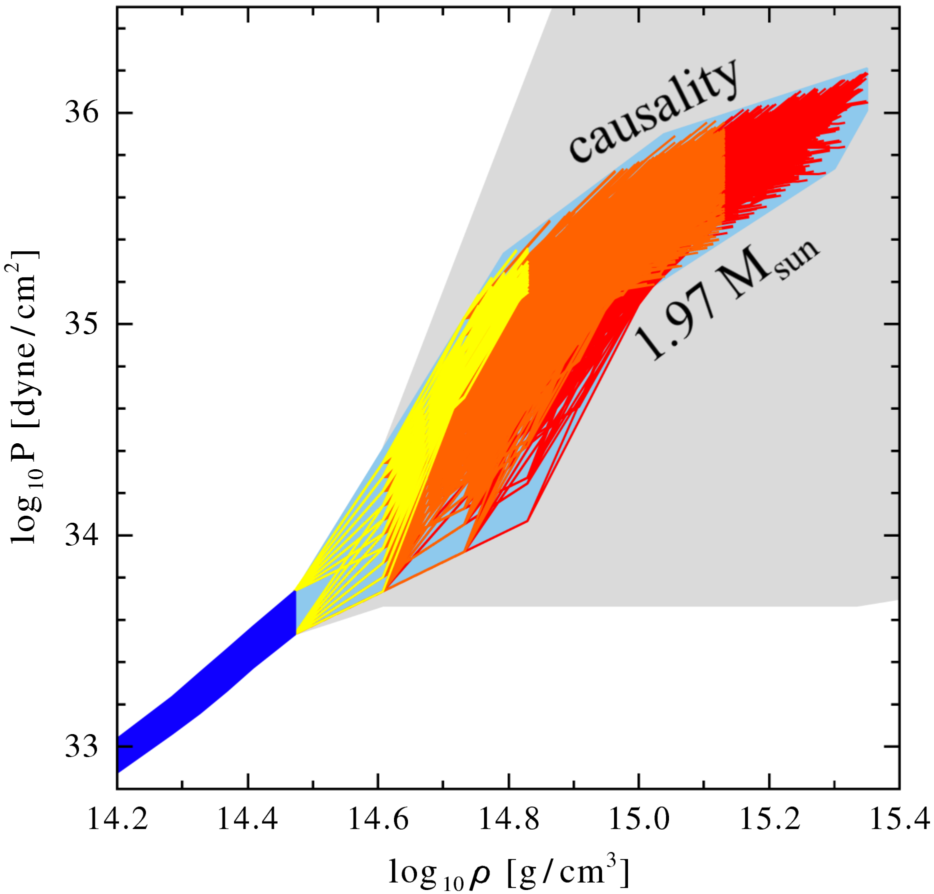


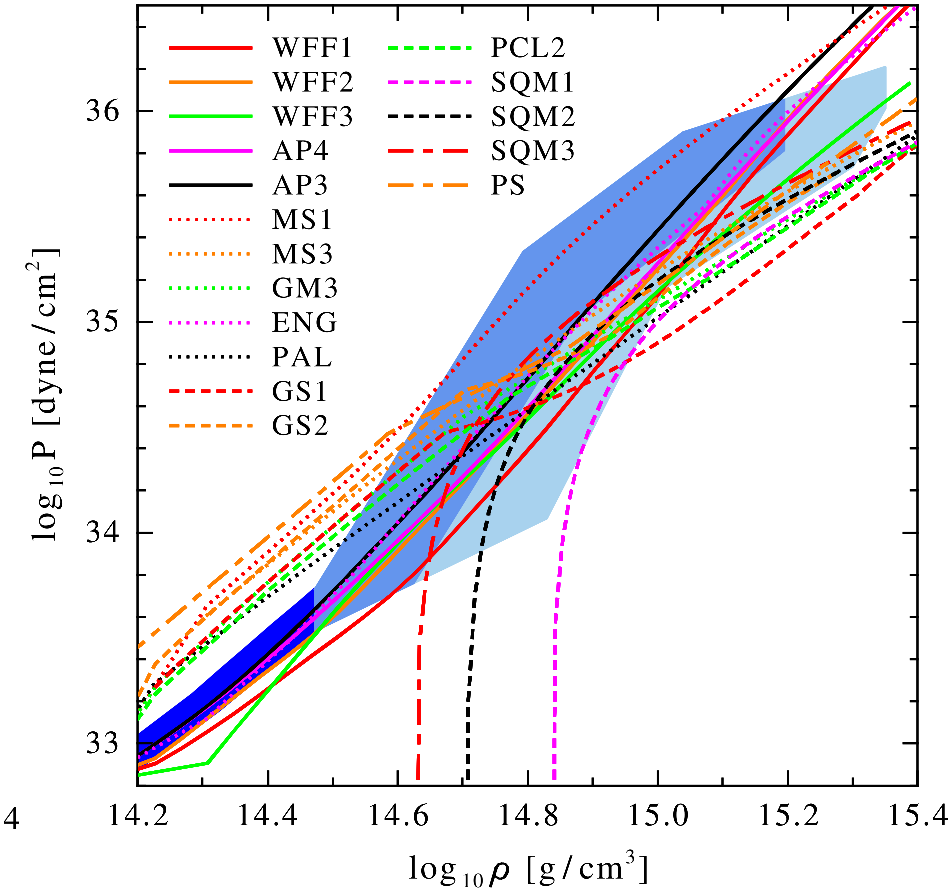
pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

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

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

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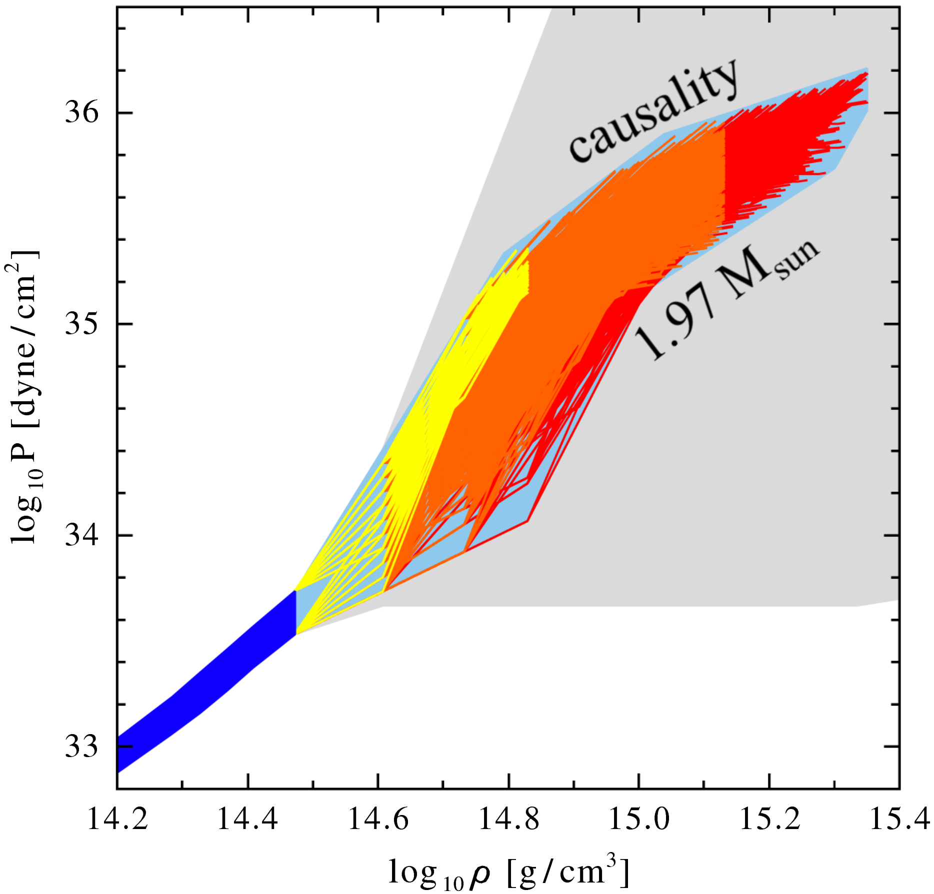
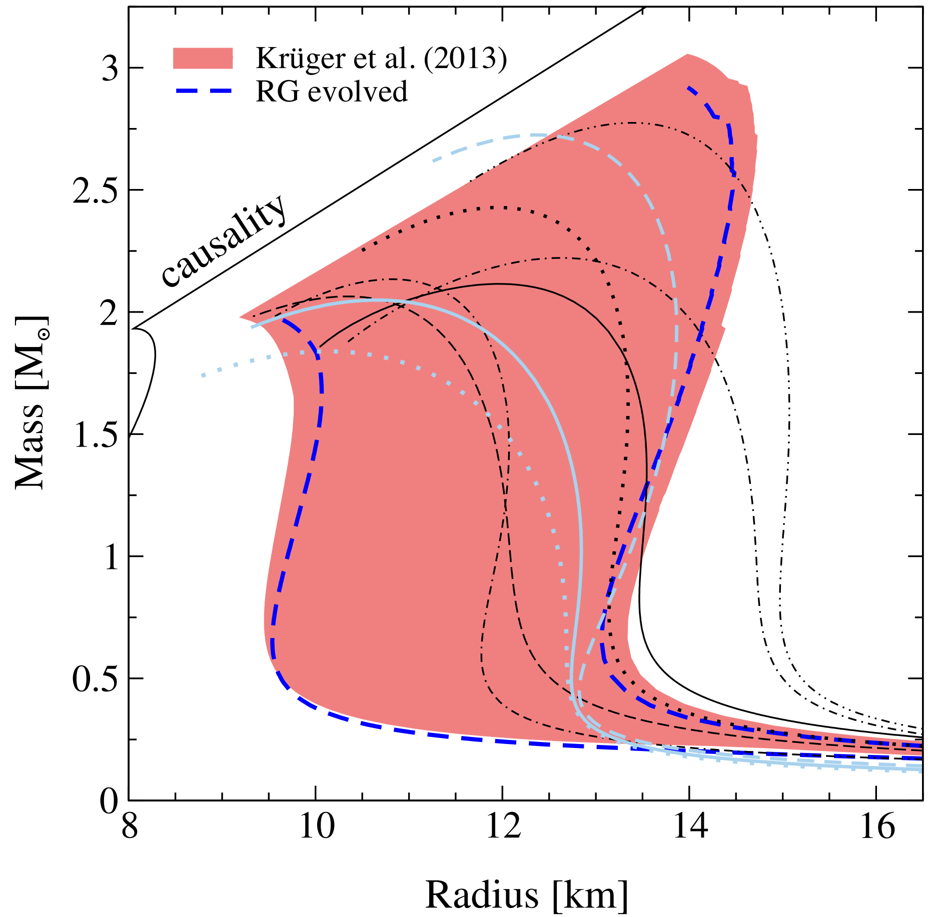




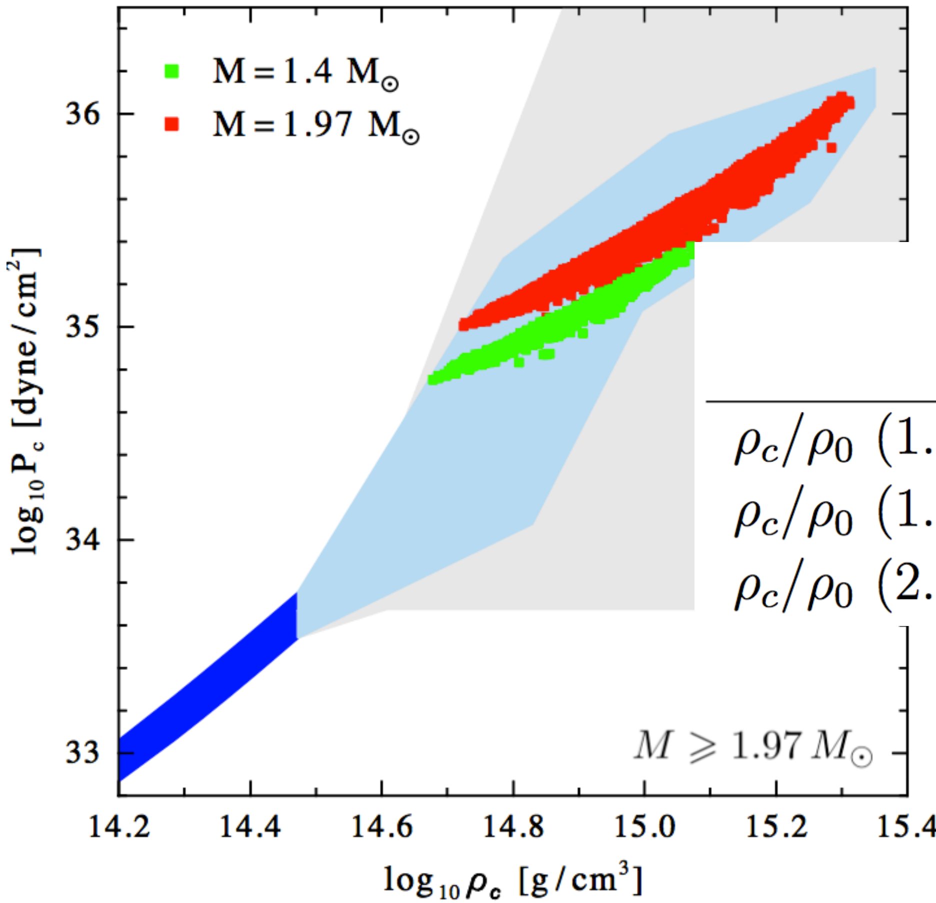
low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

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

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



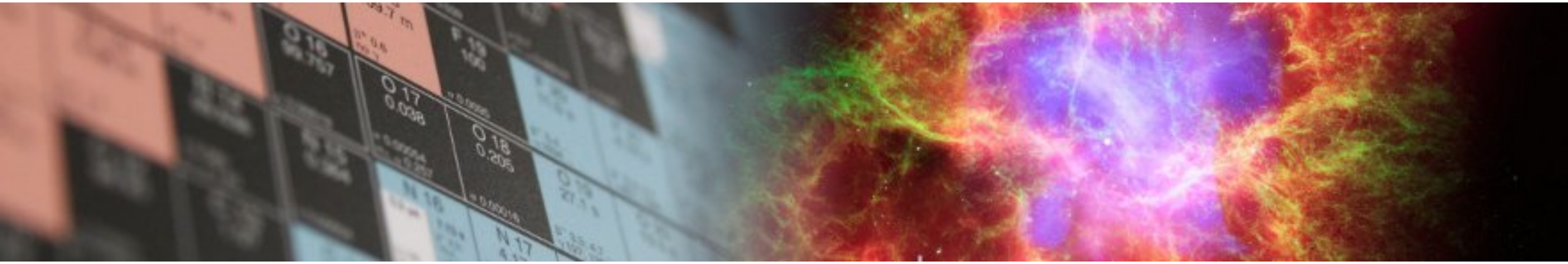
	$\widehat{M} = 1.97\, M_\odot$		$\widehat{M} = 2.4\, M_\odot$	
	min	max	min	max
ρ_c/ρ_0 $(1.4\, M_\odot)$	1.8	4.4	1.8	2.7
ρ_c/ρ_0 $(1.97\, M_\odot)$	2.0	7.6	2.0	3.4
ρ_c/ρ_0 $(2.4\, M_\odot)$			2.2	5.4

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

not very high momenta!

Summary

Chiral EFT opens up unified description of matter from lab to cosmos



3N force are an exciting frontier for nuclear physics and astrophysics

Nuclear forces and their impact on neutron-rich nuclei

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on neutron-rich matter and neutron stars

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Correlations are included