Nuclear forces and their impact on matter at neutron-rich extremes

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TECHNISCHE
UNIVERSITÄT
DARMSTADT

EMMI

GSI colloquium
July 14, 2015

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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

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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]

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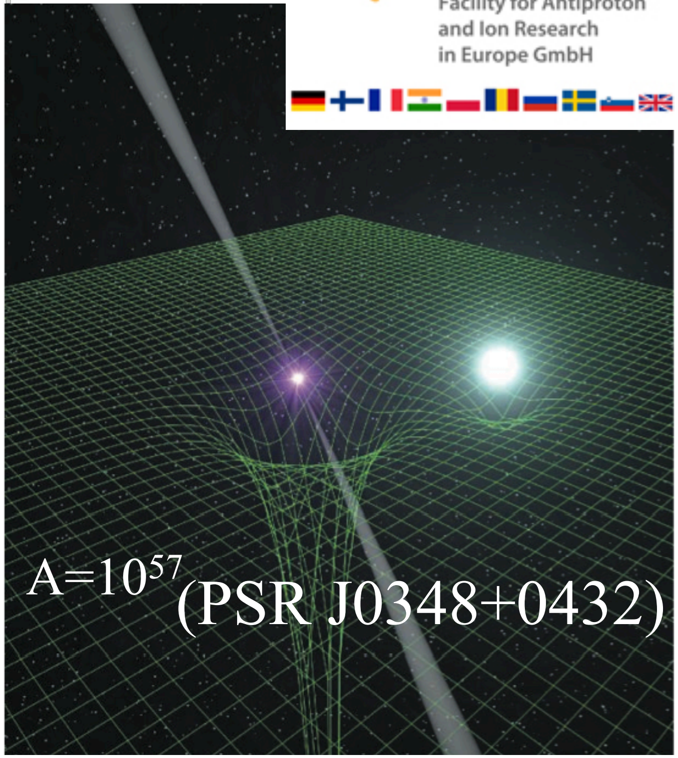
Nuclear forces and neutron stars

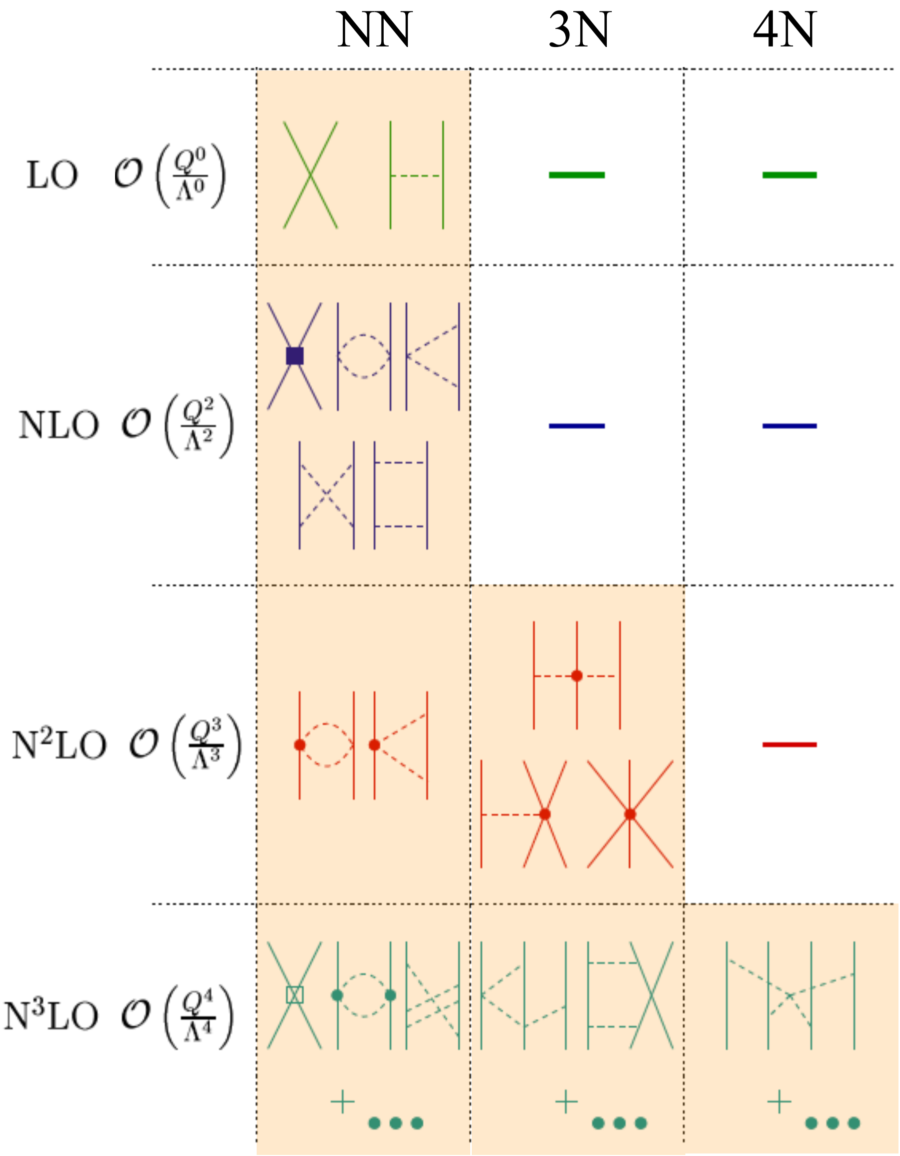
with C. Drischler, K. Hebeler, T. Krüger, J.M. Lattimer,
C.J. Pethick, **V. Somá, I. Tews**



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



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

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

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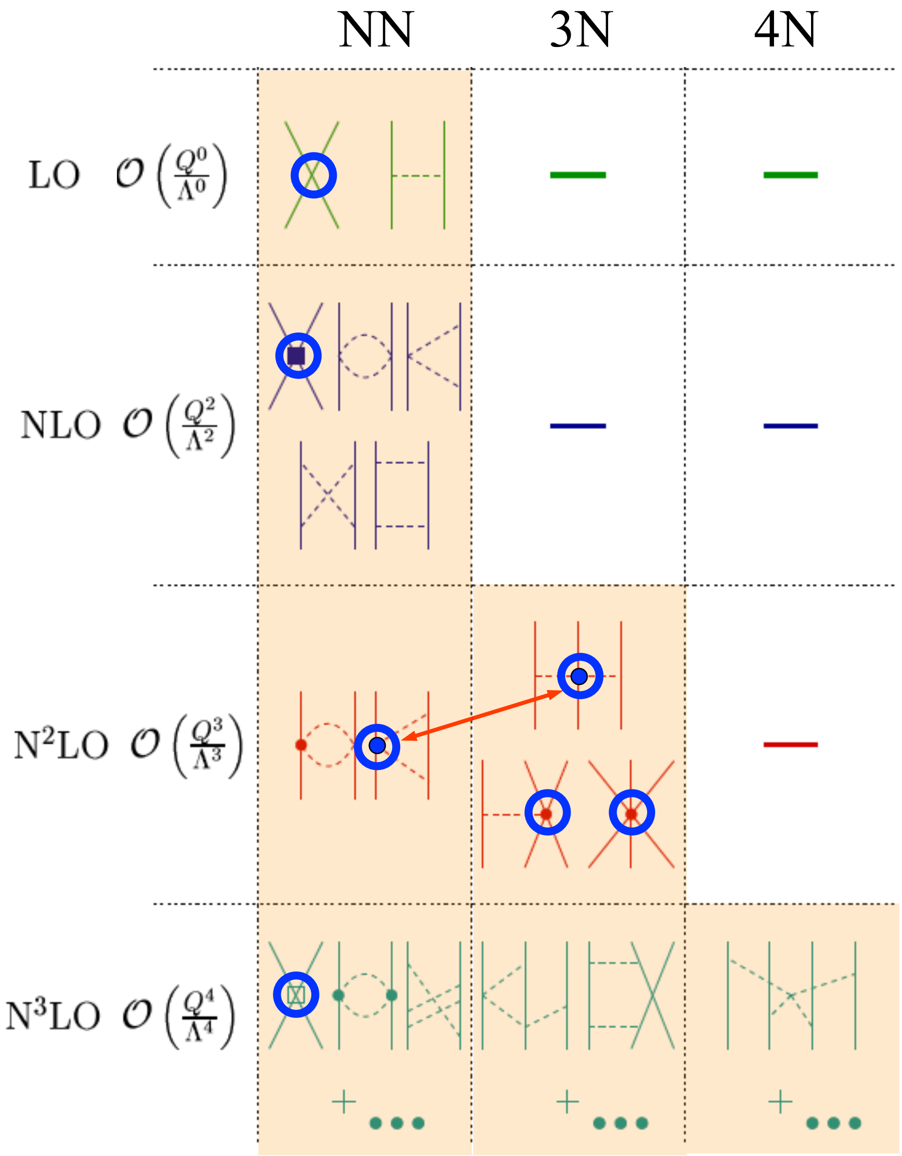


include long-range pion physics

few short-range couplings,
fit to experiment once

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

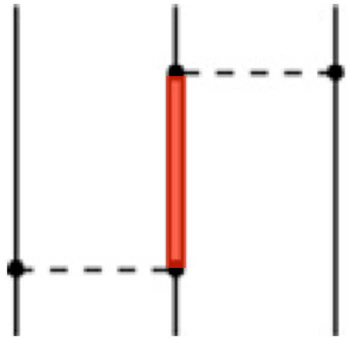
consistent **electroweak interactions** and **matching to lattice QCD**

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

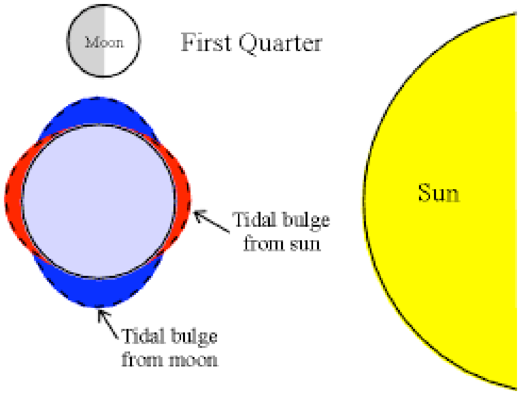
Why are there 3N forces?

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

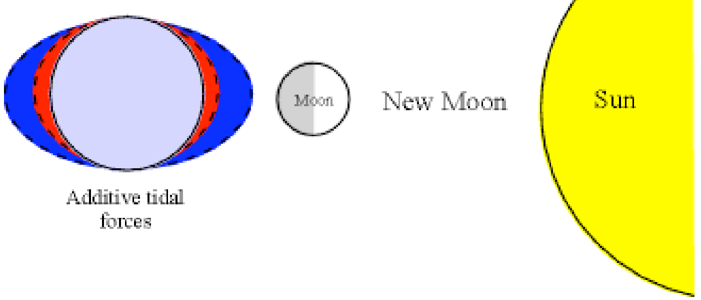
dominant contribution from Δ(1232 MeV)



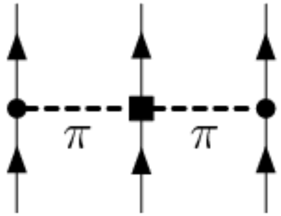
+ many shorter-range parts



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



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**

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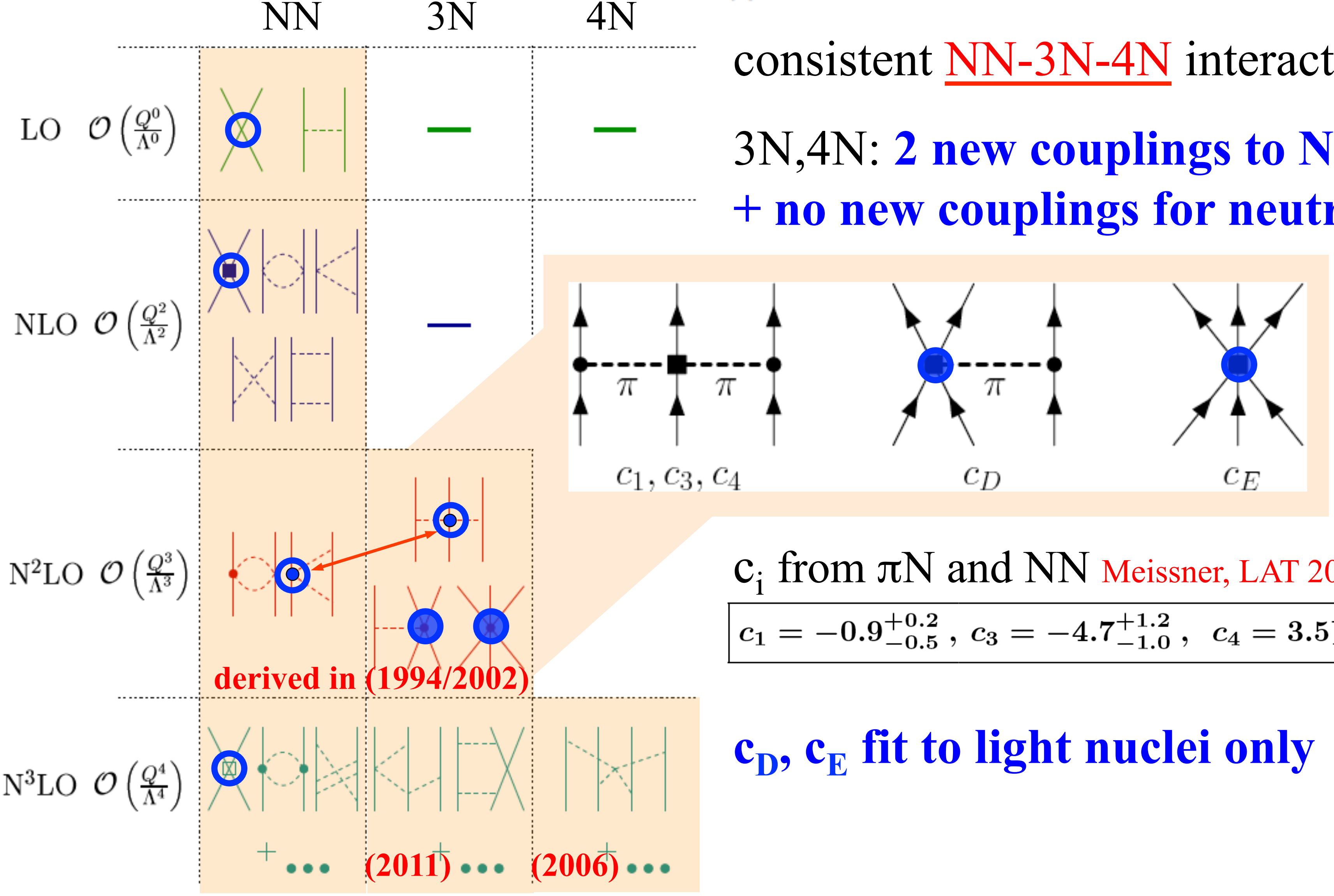


consistent NN-3N-4N interactions

3N,4N: **2 new couplings to N^{3}LO**

+ 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,…

Nuclei bound by strong interactions

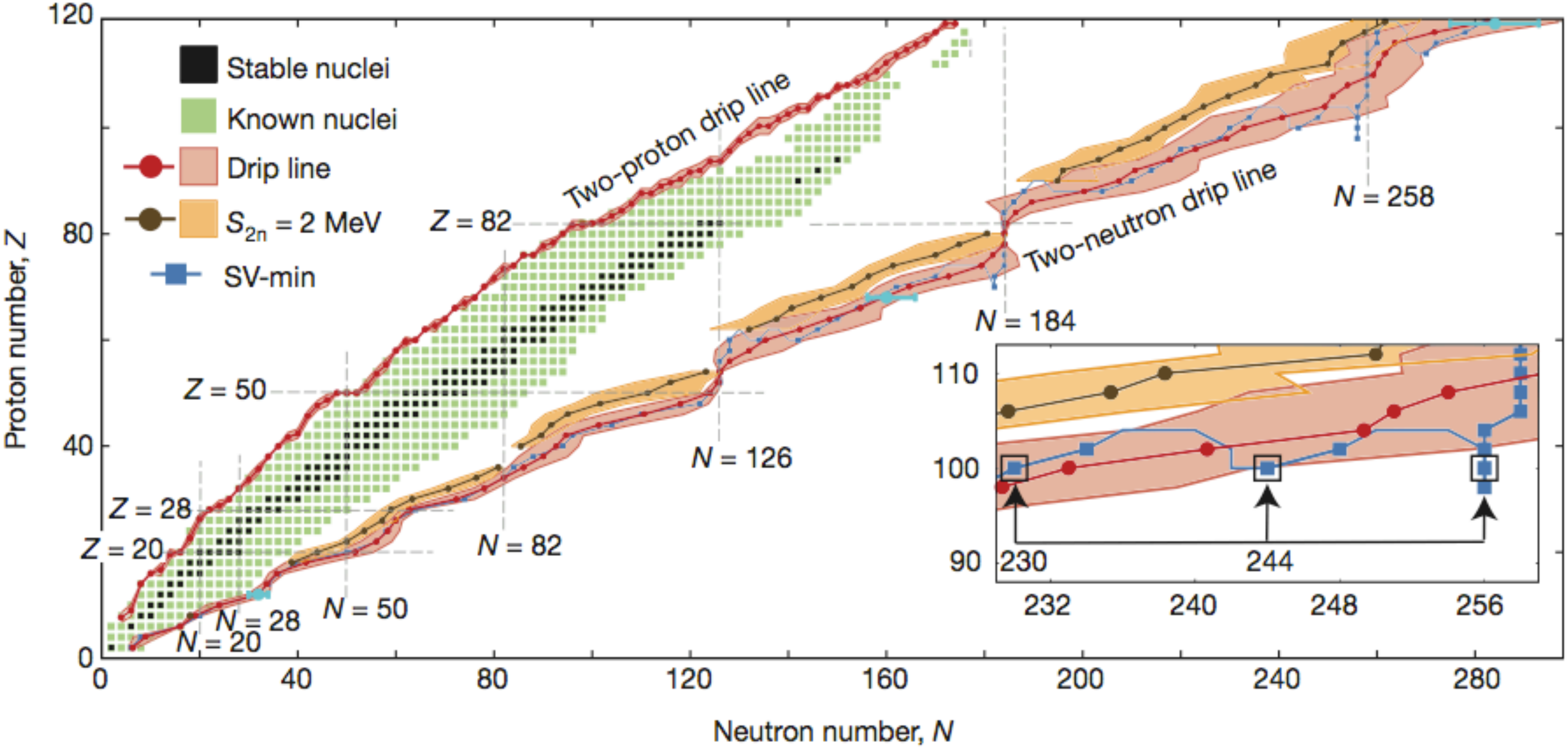
doi:10.1038/nature11188

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



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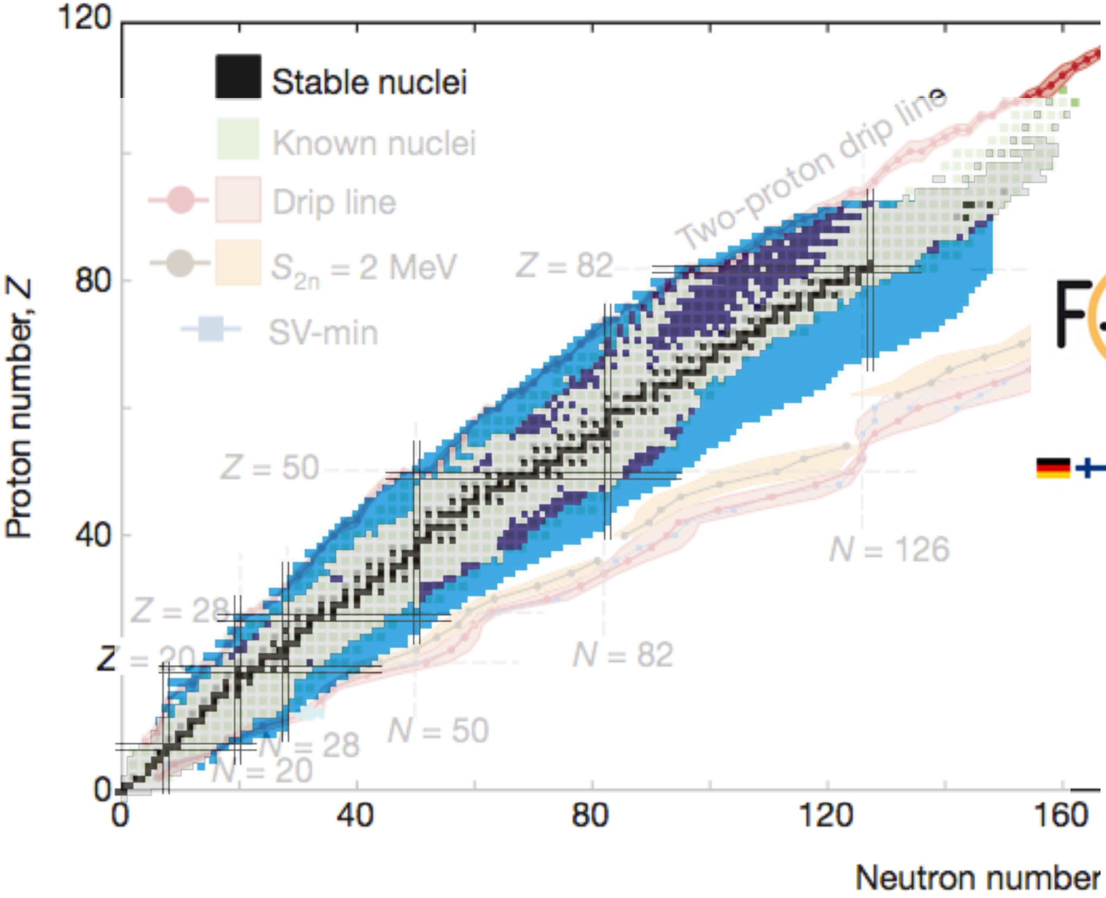

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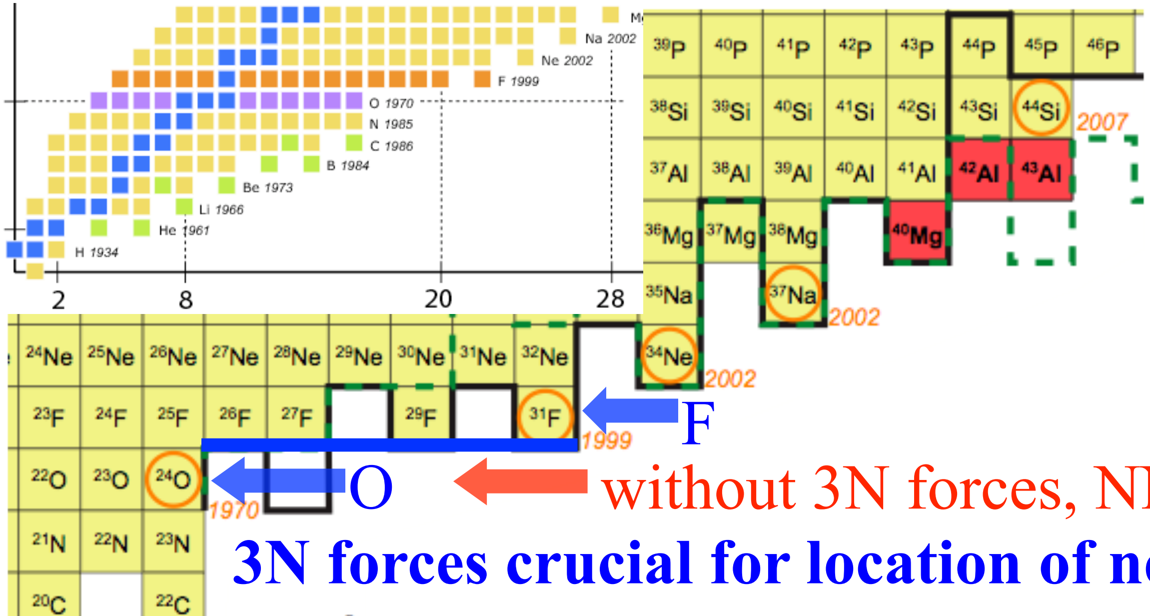
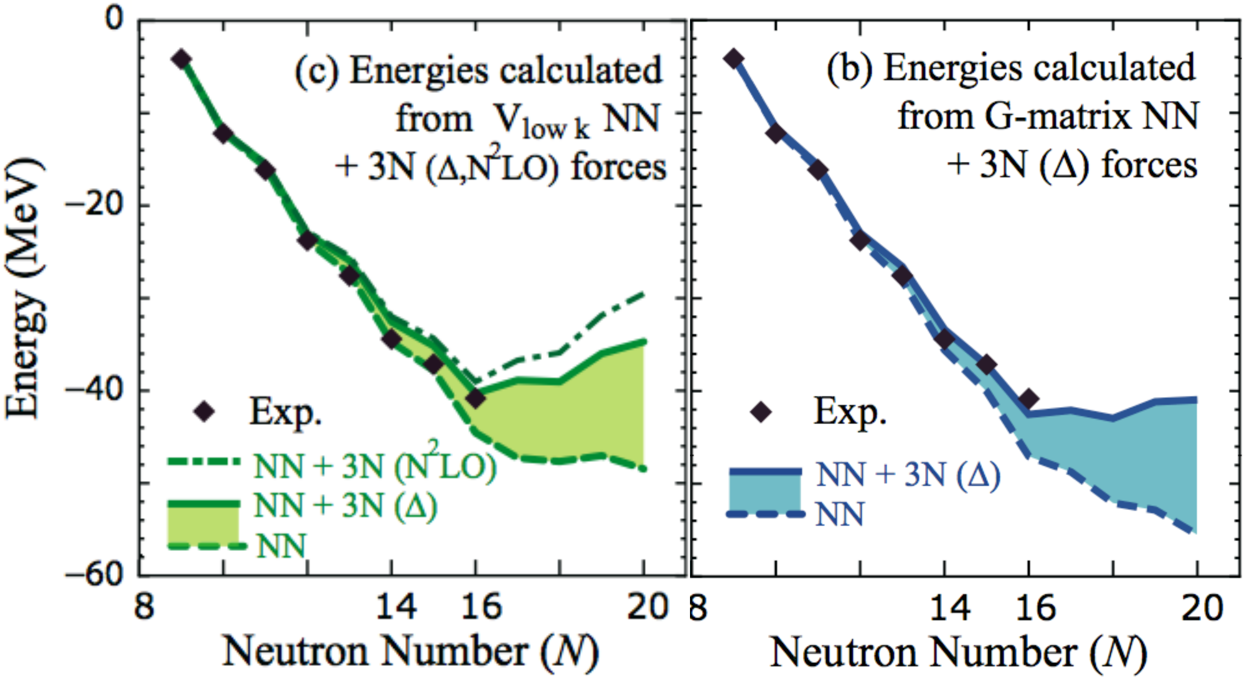
The oxygen anomaly

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



without 3N forces, NN interactions too attractive

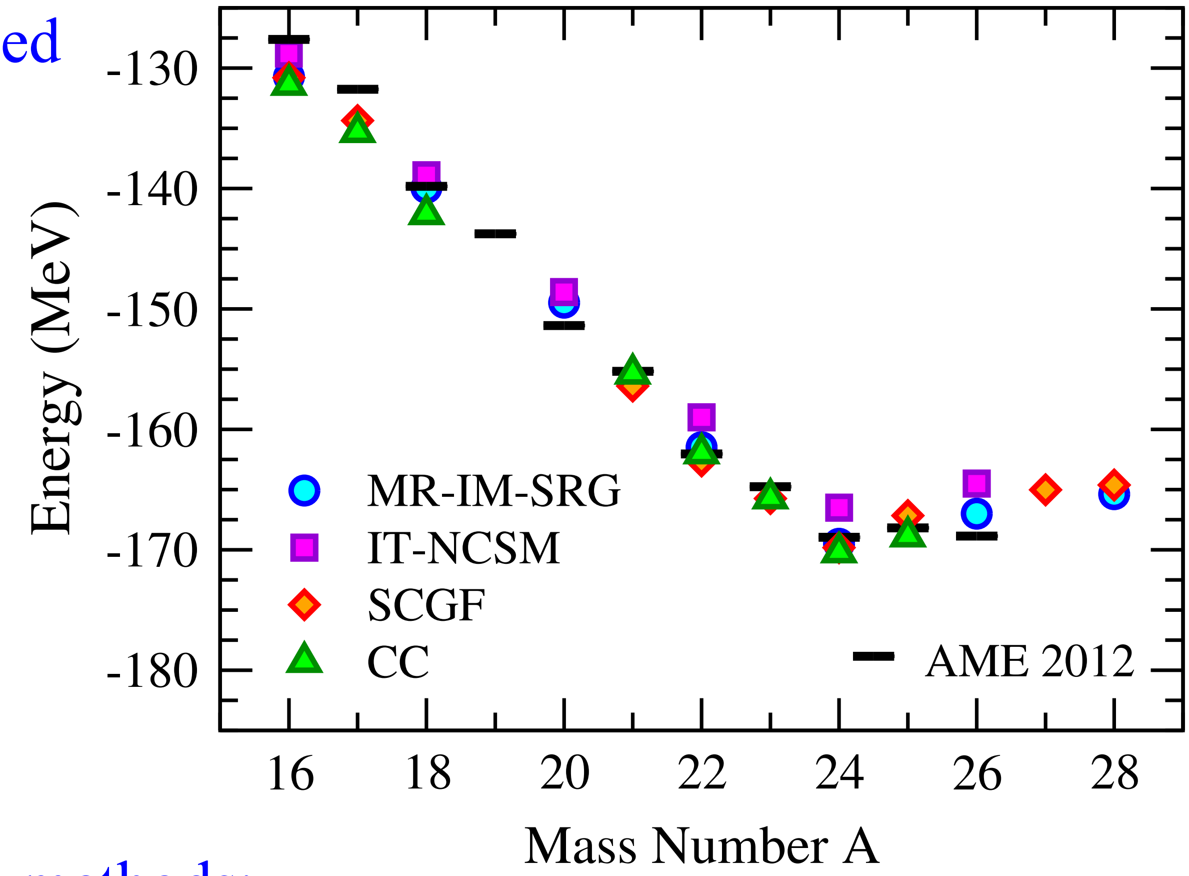
3N forces crucial for location of neutron dripline



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)

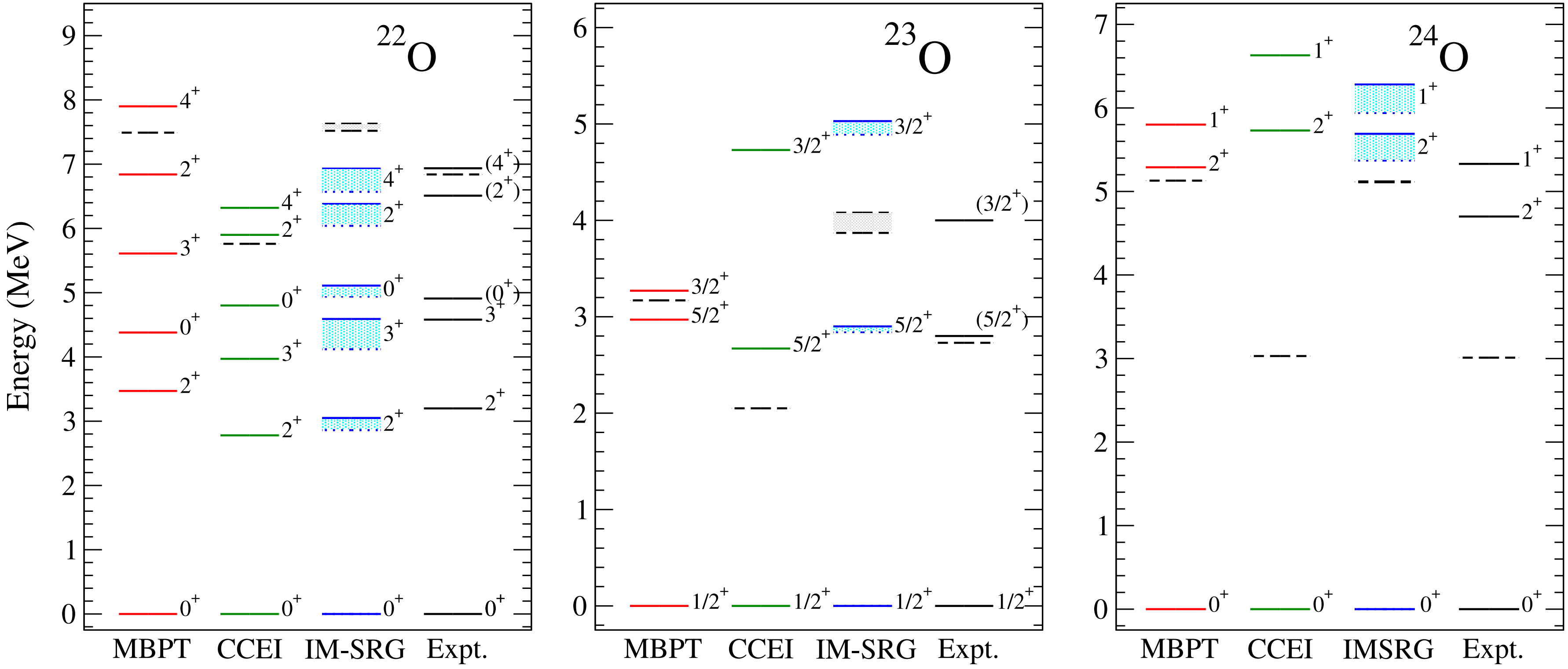
Self-Consistent Green’s Function methods Cipollone et al., PRL (2013)

Ab initio calculations going open shell

In-Medium SRG to derive valence-shell interactions

Tsukiyama, Bogner, AS, PRL (2011), PRC (2012); Bogner et al., PRL (2014)

Coupled Cluster for effective interactions (CCEI) Jansen et al., PRL (2014)



Experiments at GANIL, GSI, NSCL, RIBF: ^{22}O and ^{24}O doubly magic

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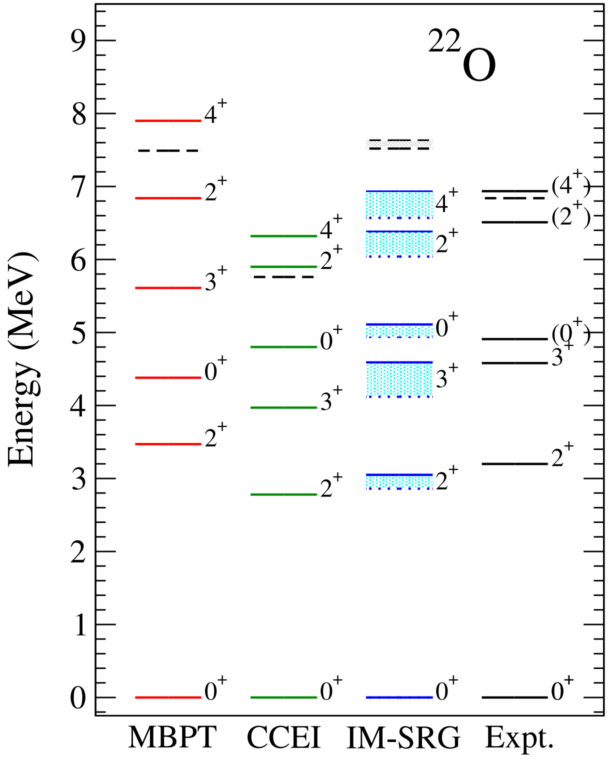
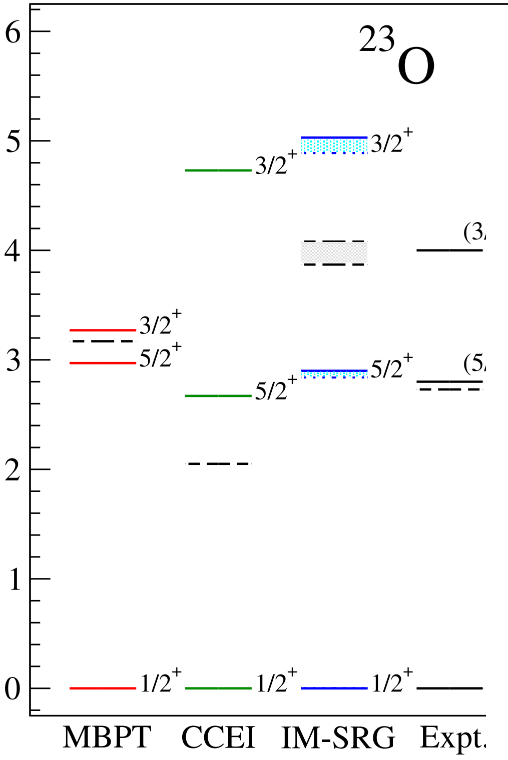
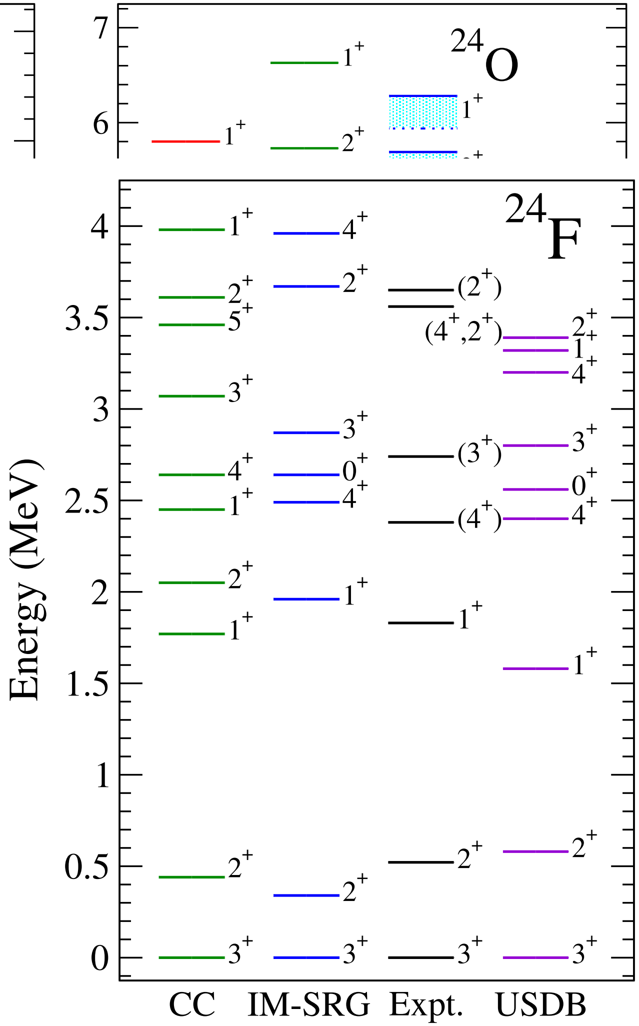




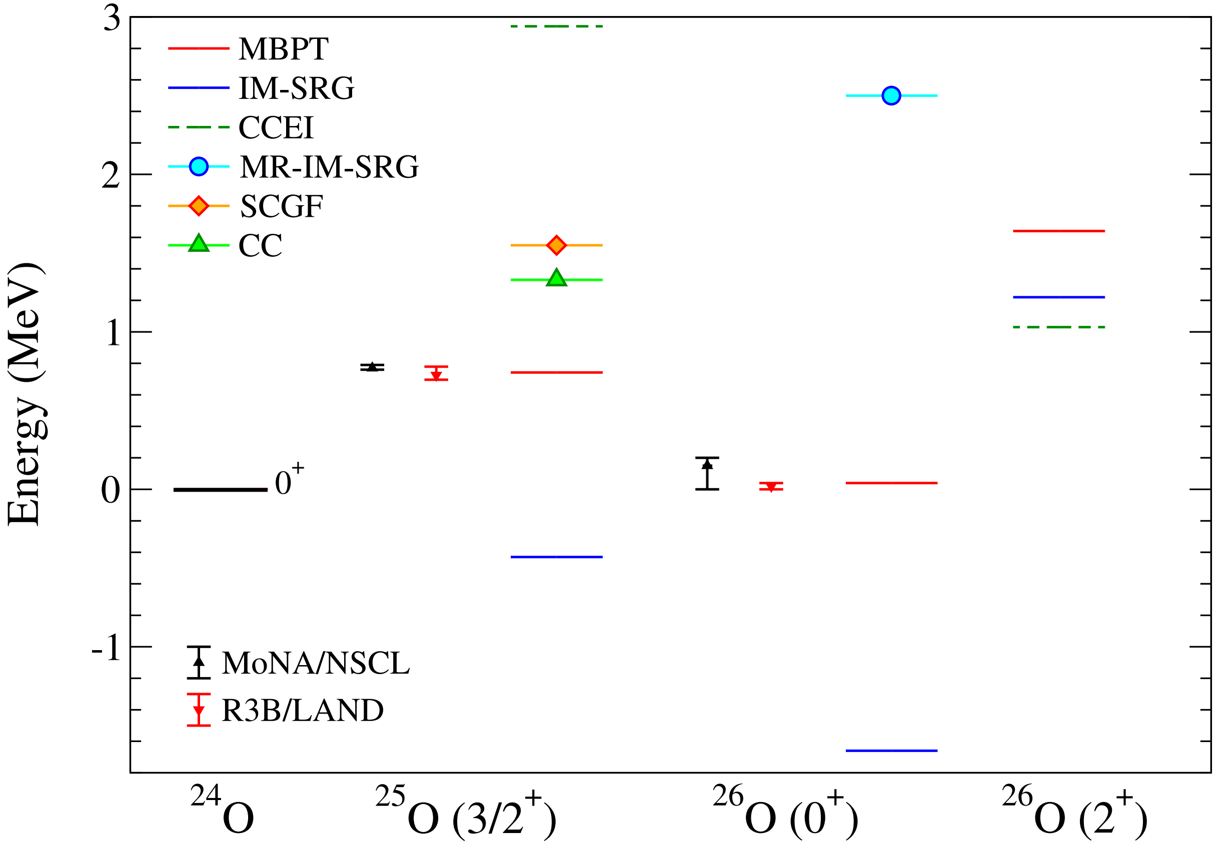


Experiments at GANIL, GSI, NSCL, RIBF

Spectrum of ^{24}F Cáceres et al., 1501.01166

Beyond the neutron dripline in oxygen

Pioneering experiments with MoNA/NSCL, R3B-LAND and at RIBF



calculations with NN+3N forces, continuum needs to be included

MBPT includes residual 3N forces, more important with N Simonis et al (2013)

challenging and large sensitivity to method and NN+3N forces

Frontier of ab initio calculations at A~50

doi:10.1038/nature12226

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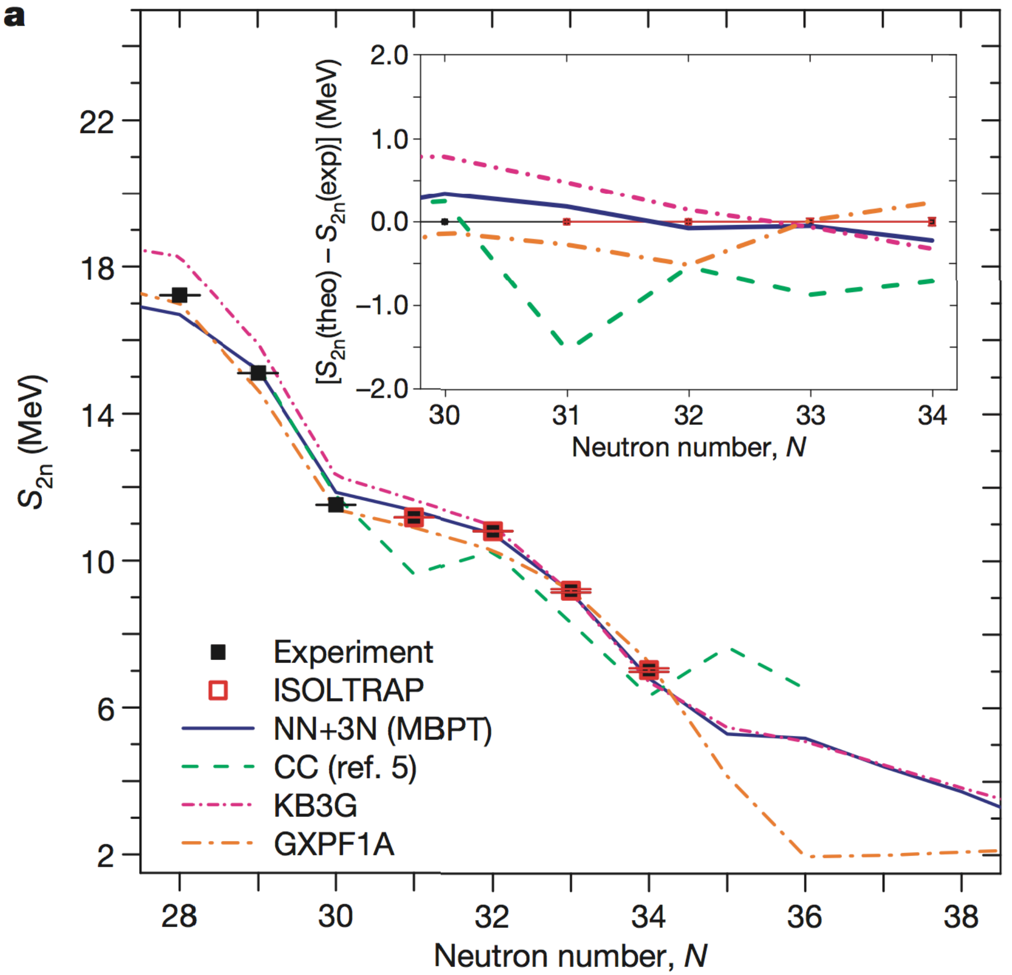
^{51,52}Ca masses at TITAN

Gallant et al., PRL (2012)

^{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



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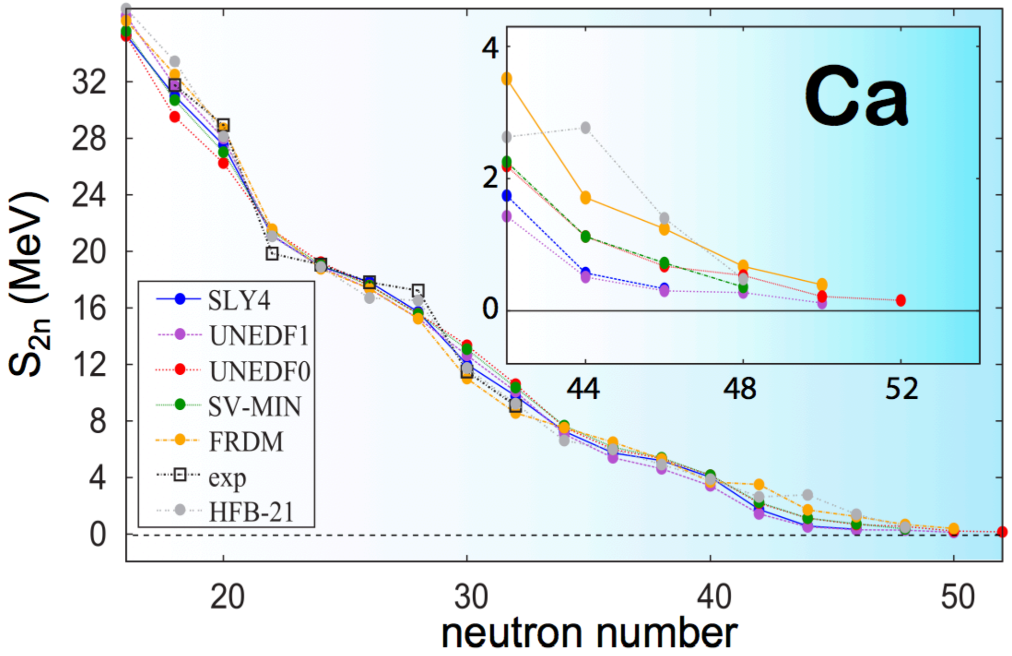

interesting continuum effects for very neutron-rich Ca

see Forssen et al., Physica Scripta (2013)

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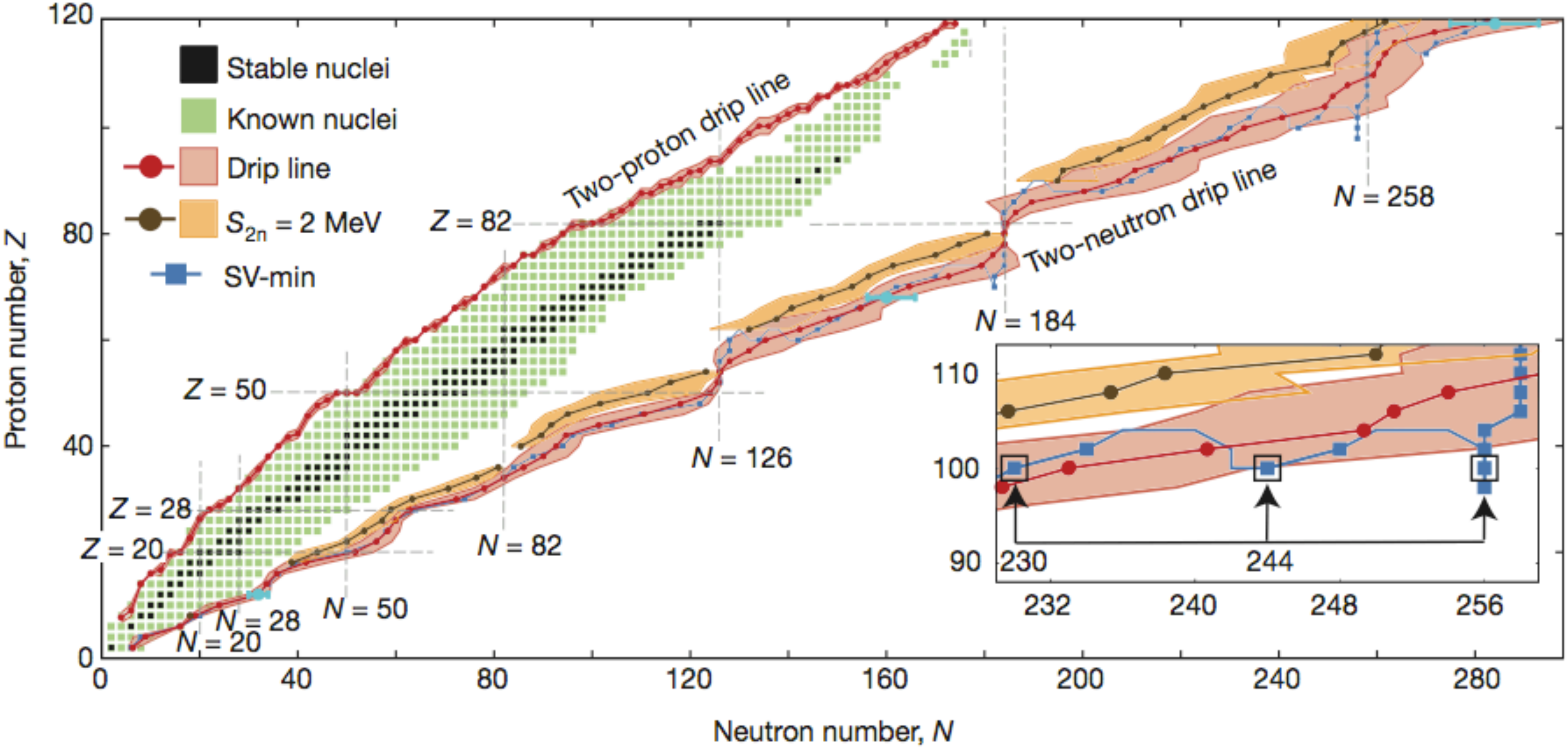
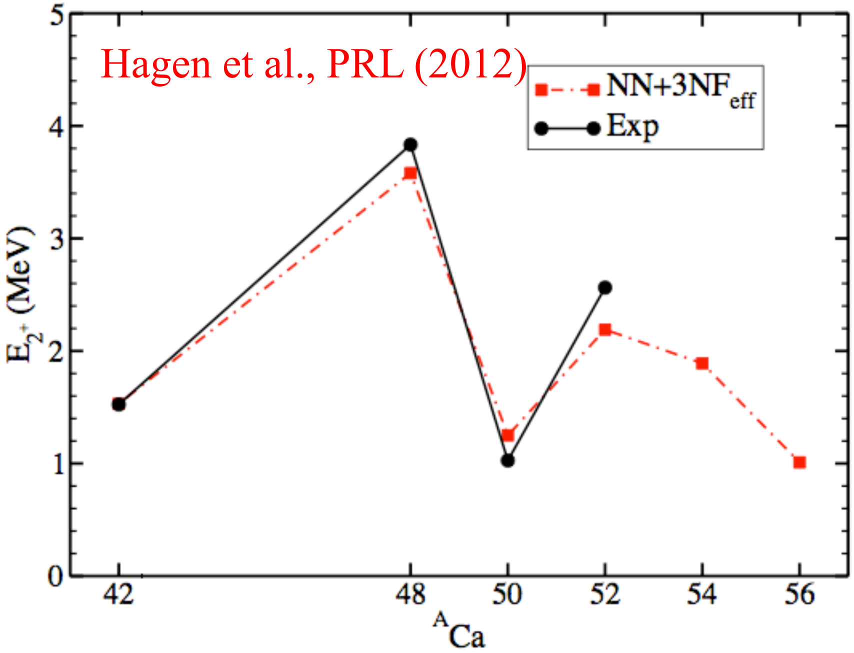
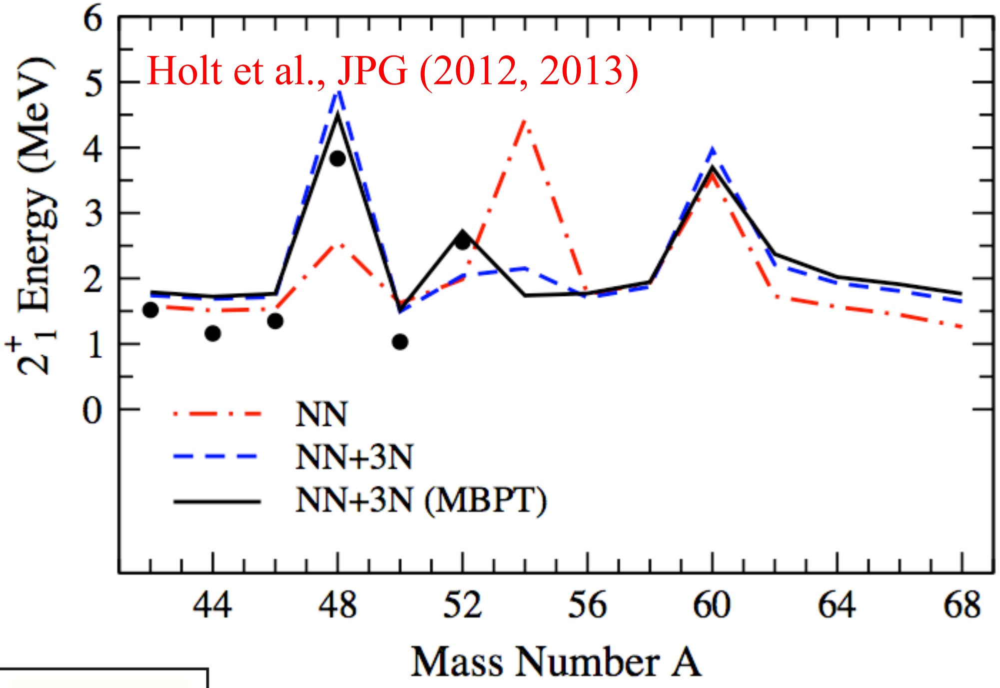
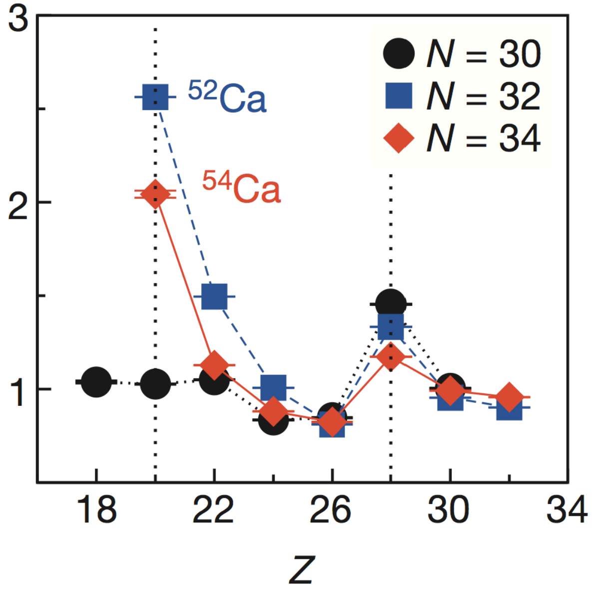


3N forces and magic numbers


Hagen et al., PRL (2012)


Holt et al., JPG (2012, 2013)



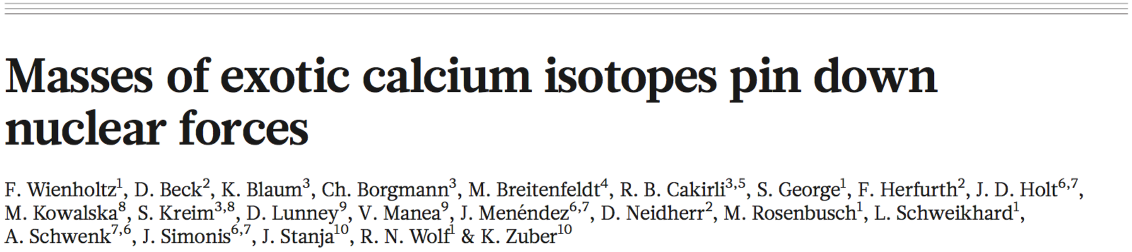
2^+ energy measured at RIBF suggests magic number N=34

Steppenbeck et al., Nature (2013)

Main message

3N forces and neutron-rich nuclei

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



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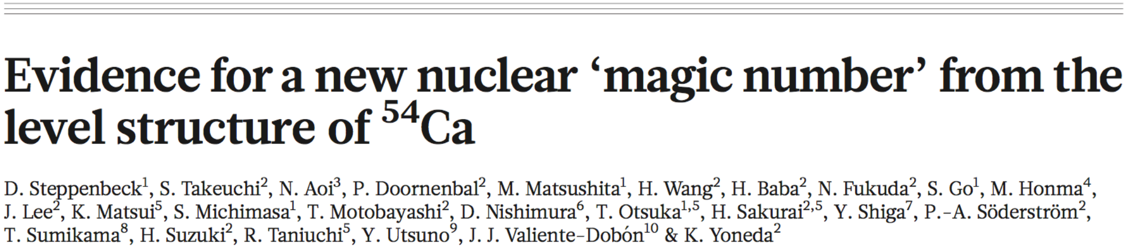

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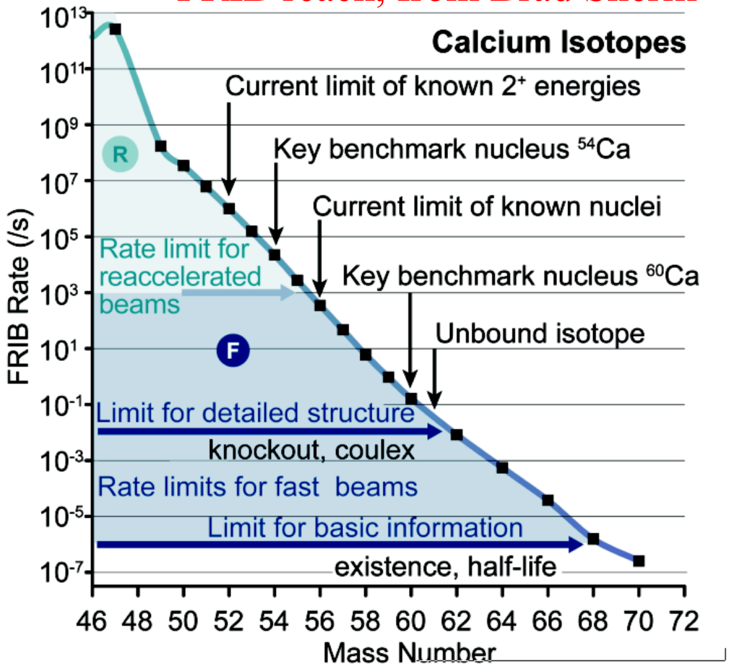
FRIB reach, from Brad Sherill



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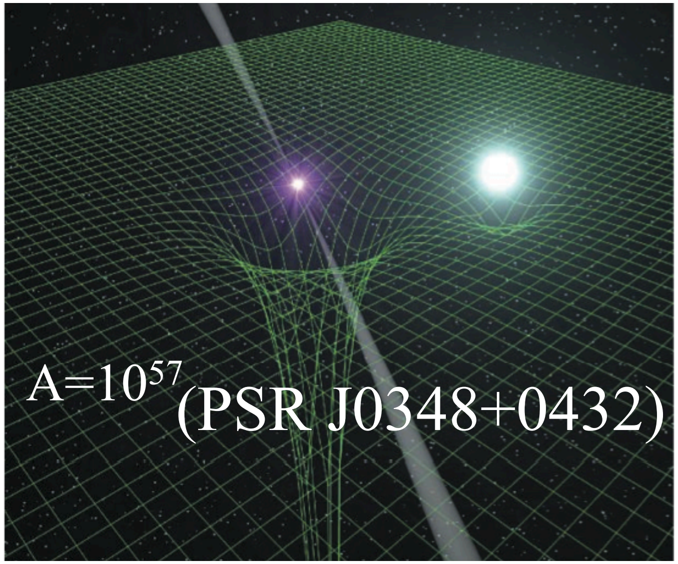

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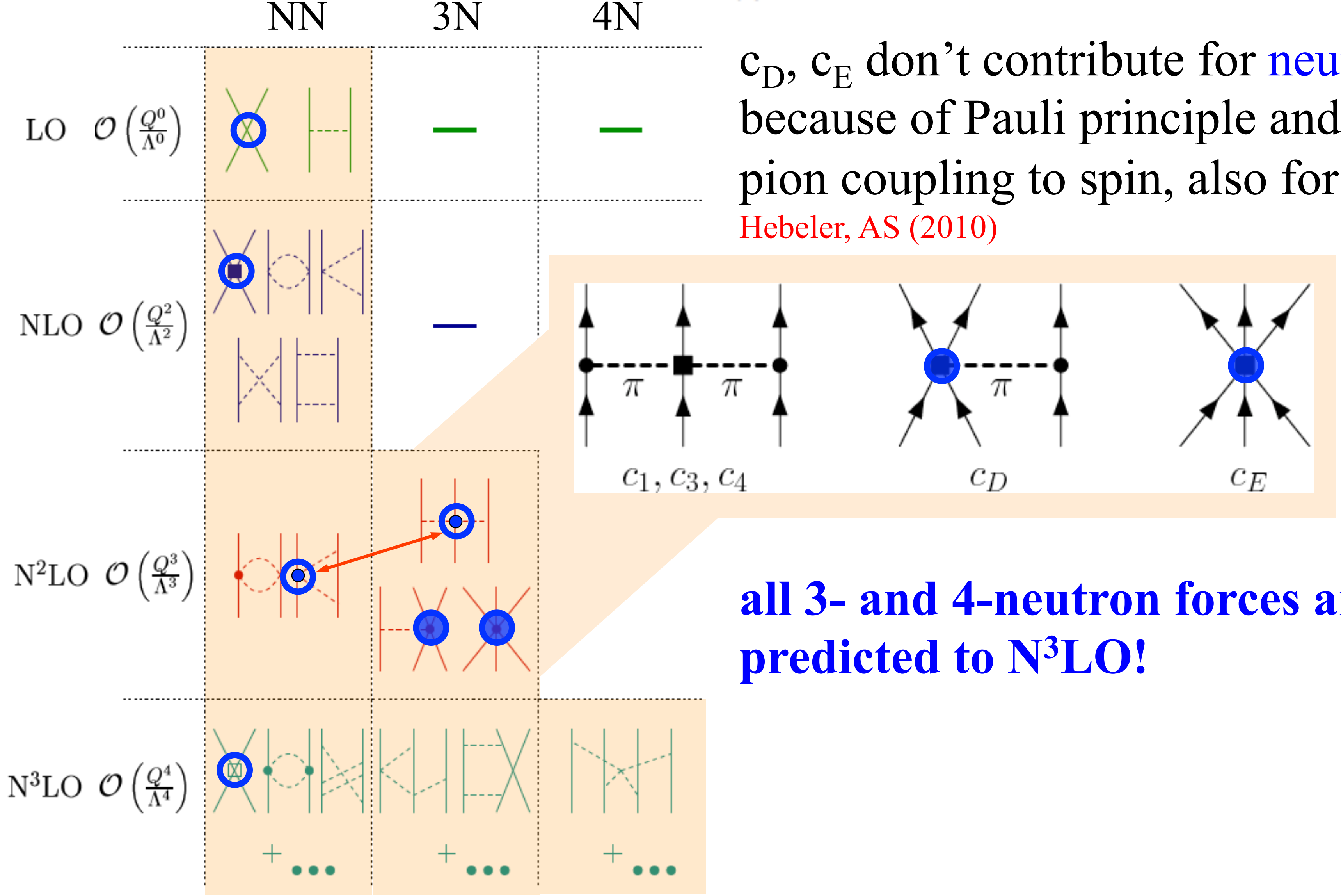

c_D, c_E don't contribute for neutrons because of Pauli principle and pion coupling to spin, also for c_4

Hebeler, AS (2010)

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

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

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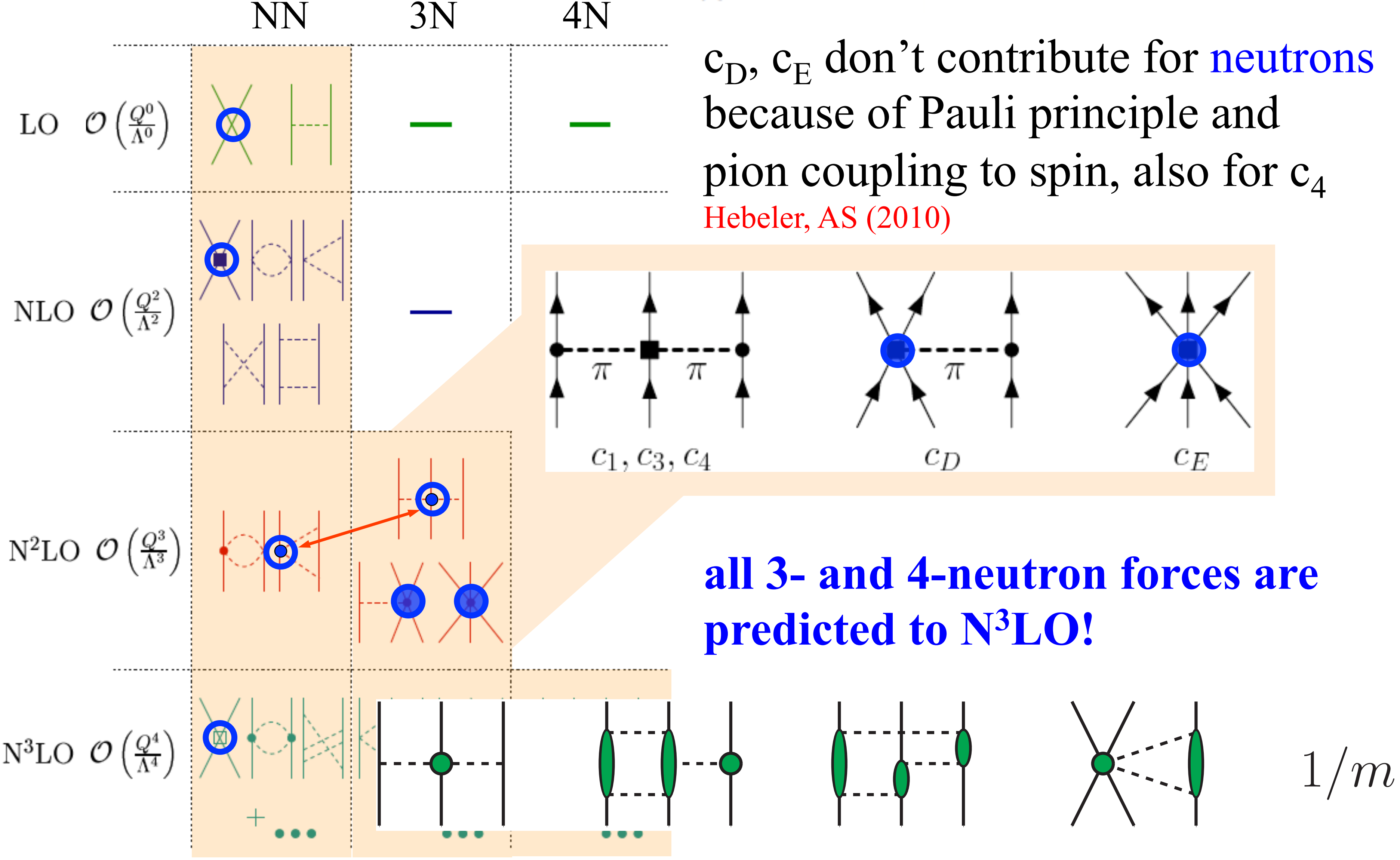

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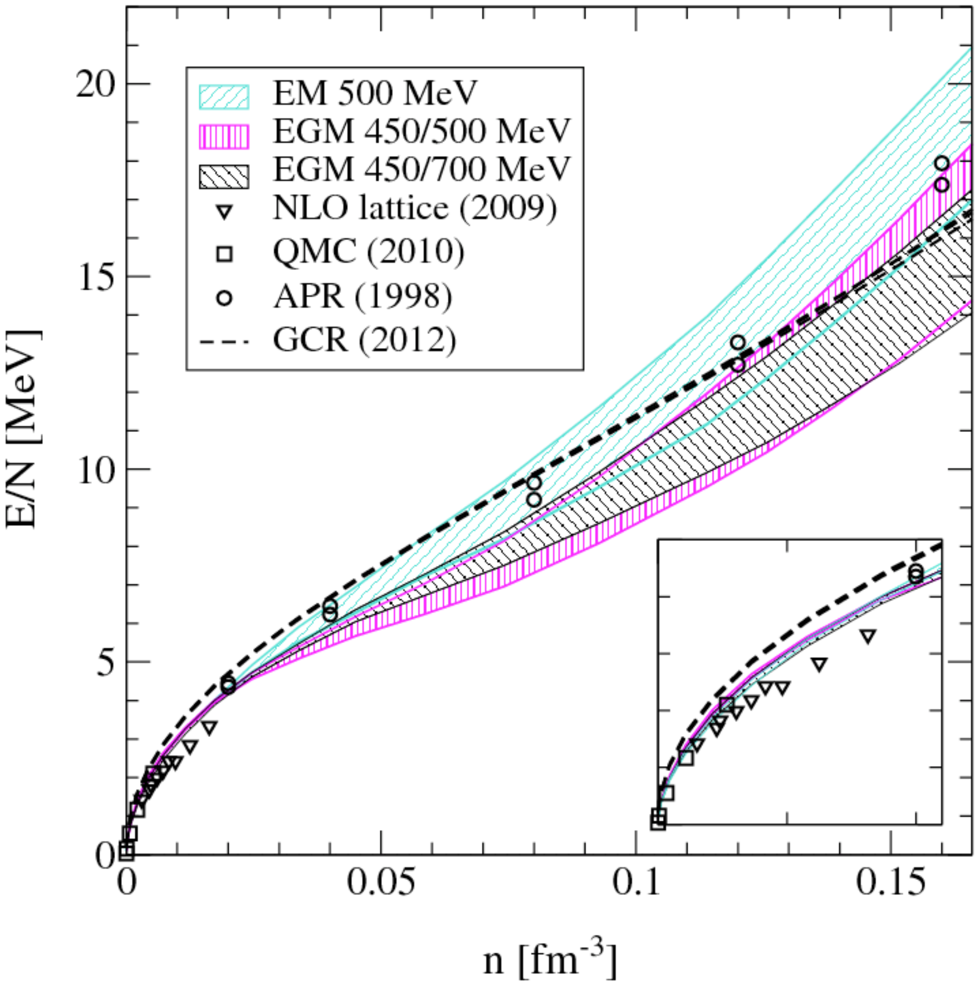
Complete N^{3}LO calculation of neutron matter

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

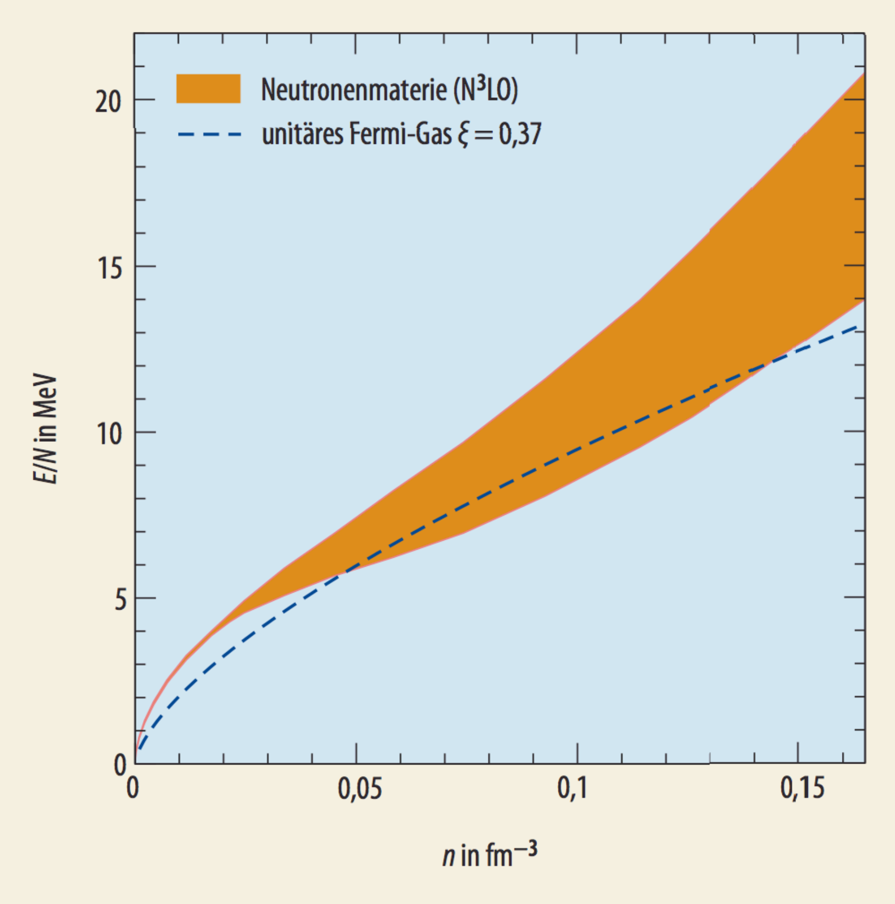
Large scattering lengths: universal thermodynamics

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=0.372(5)

Carlson et al. (2012)

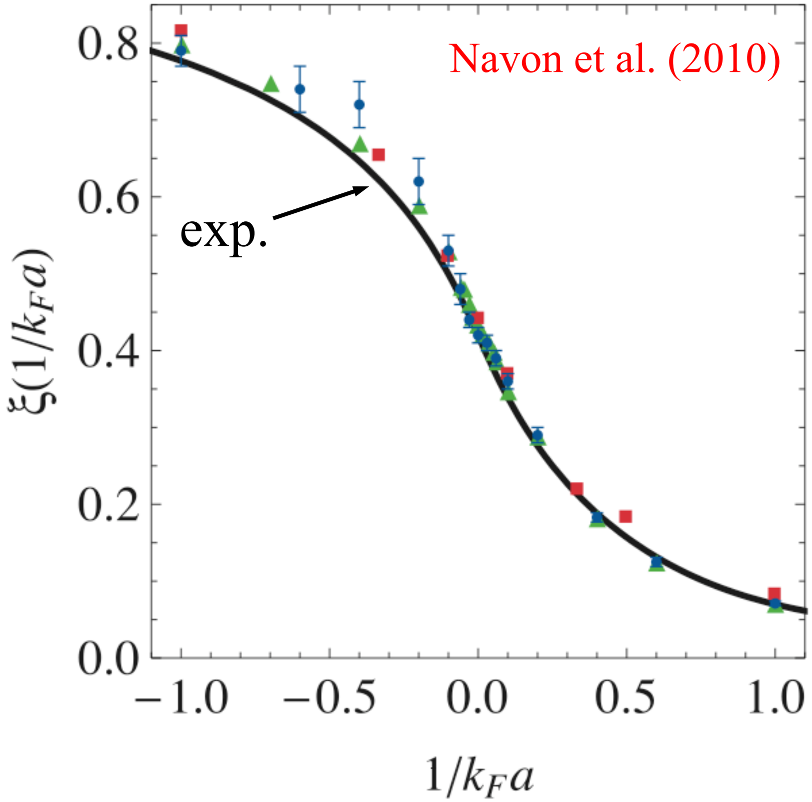


most precise results with ^{6}Li

ξ=0.370(5)(8)

Ku et al. (2012), Zürn et al. (2013)

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


Navon et al. (2010)

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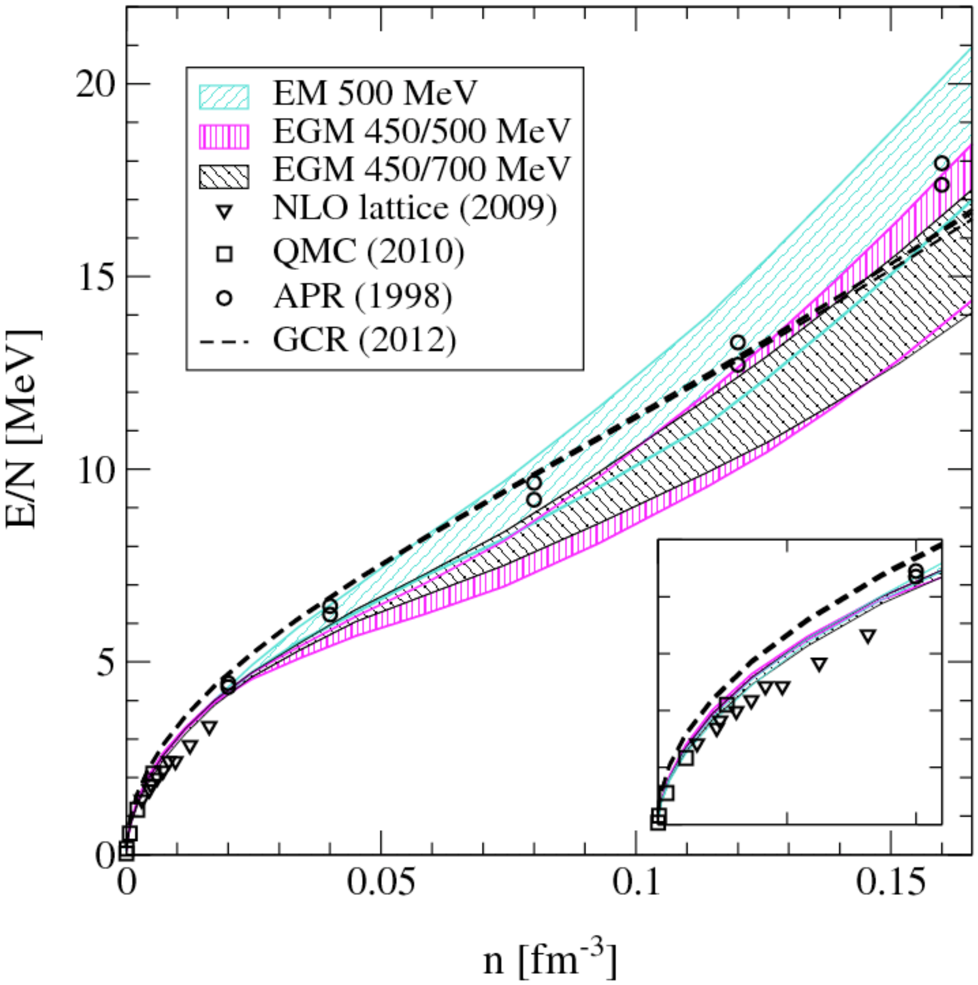
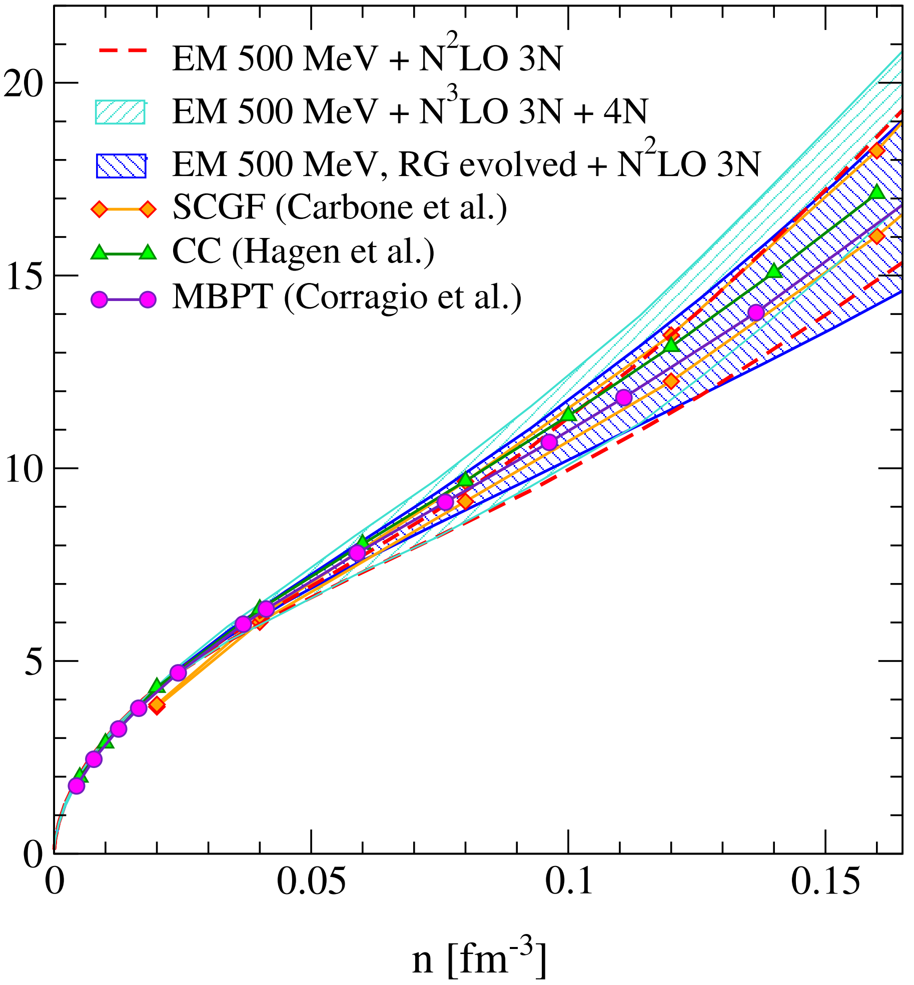


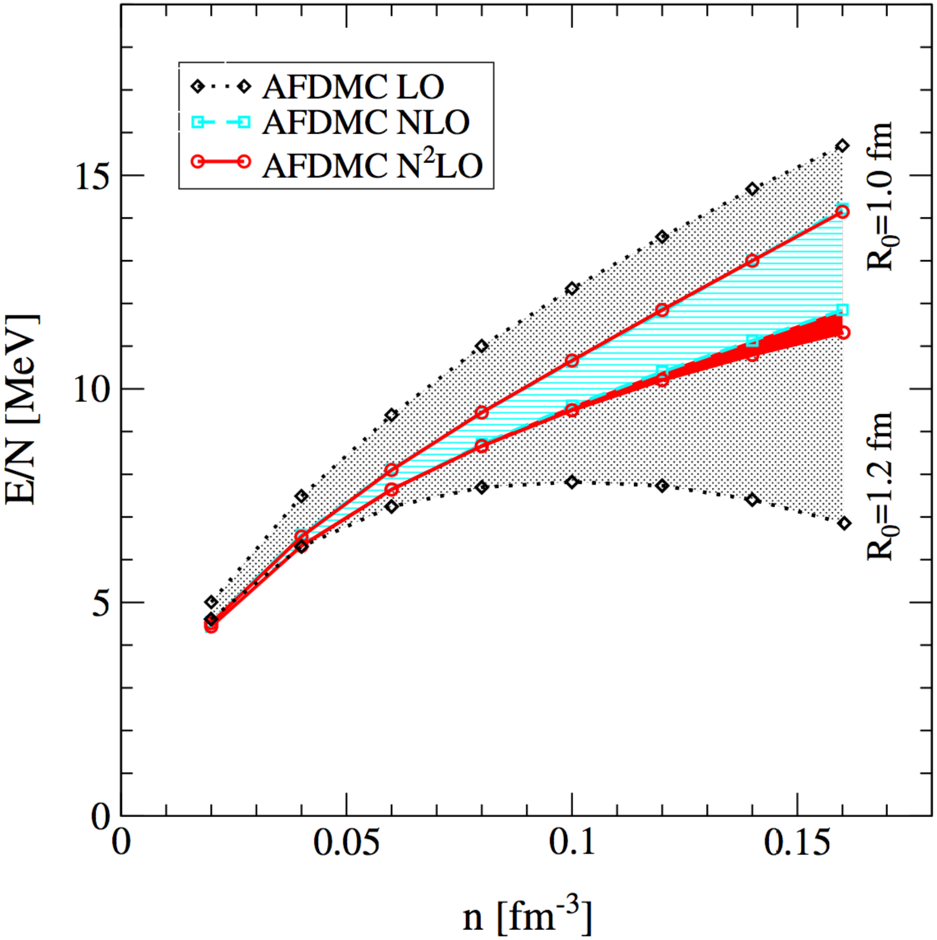


excellent agreement with other methods!

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



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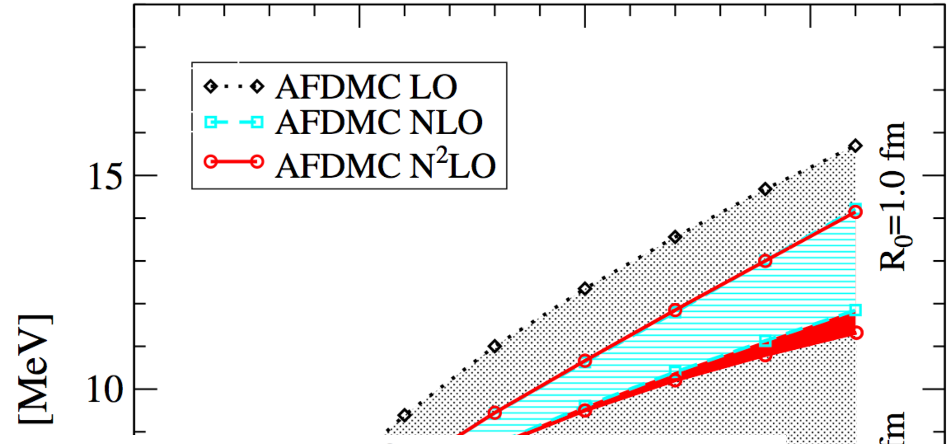
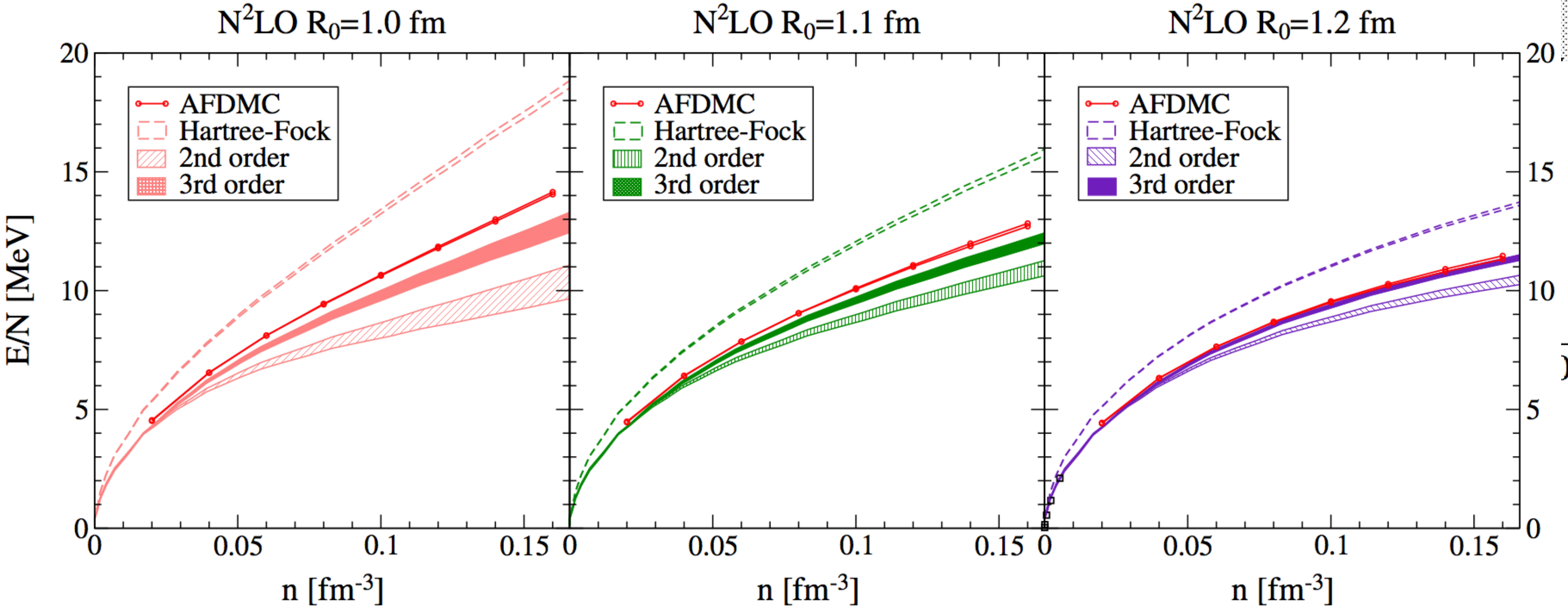
excellent agreement with
perturbative calculations
for low cutoffs (~400 MeV)





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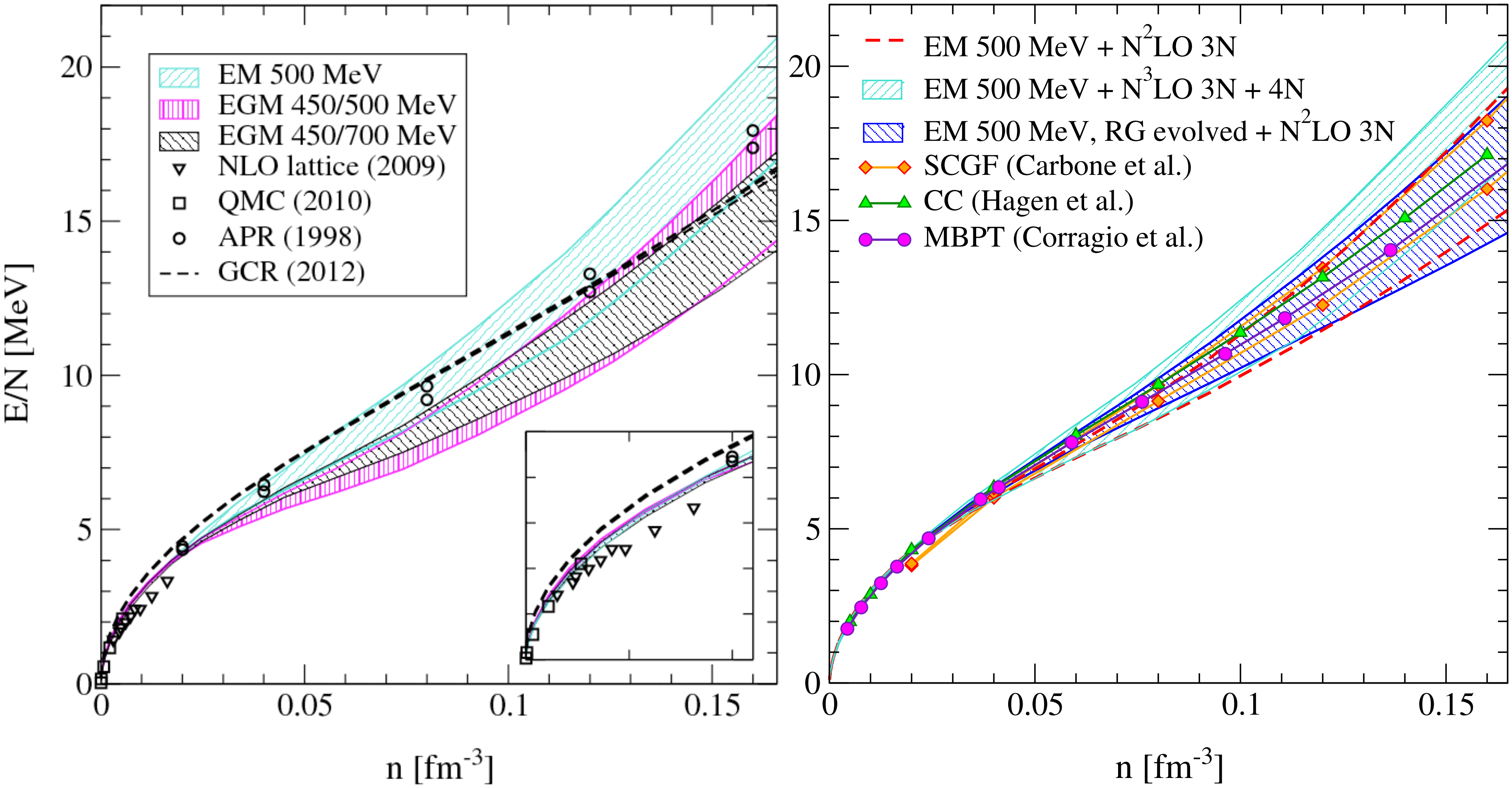
first complete N^{3}LO result Tews, Krüger, Hebeler, AS, PRL (2013)

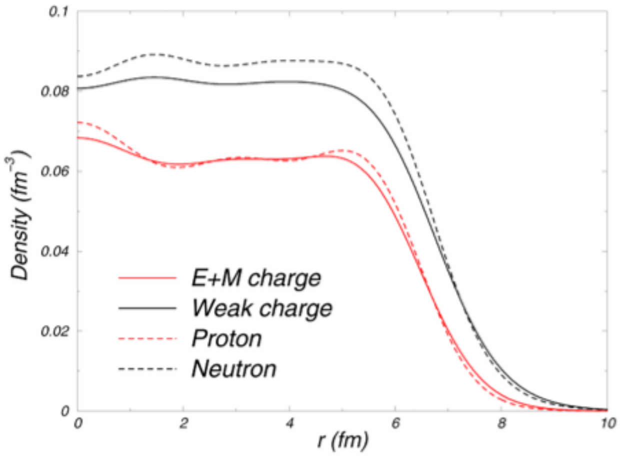
includes uncertainties from NN, 3N (dominates), 4N



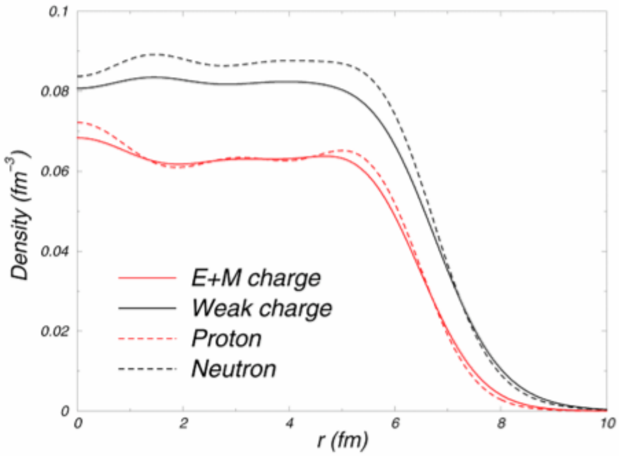
excellent agreement with other methods!

Neutron skin of ^{208}Pb

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

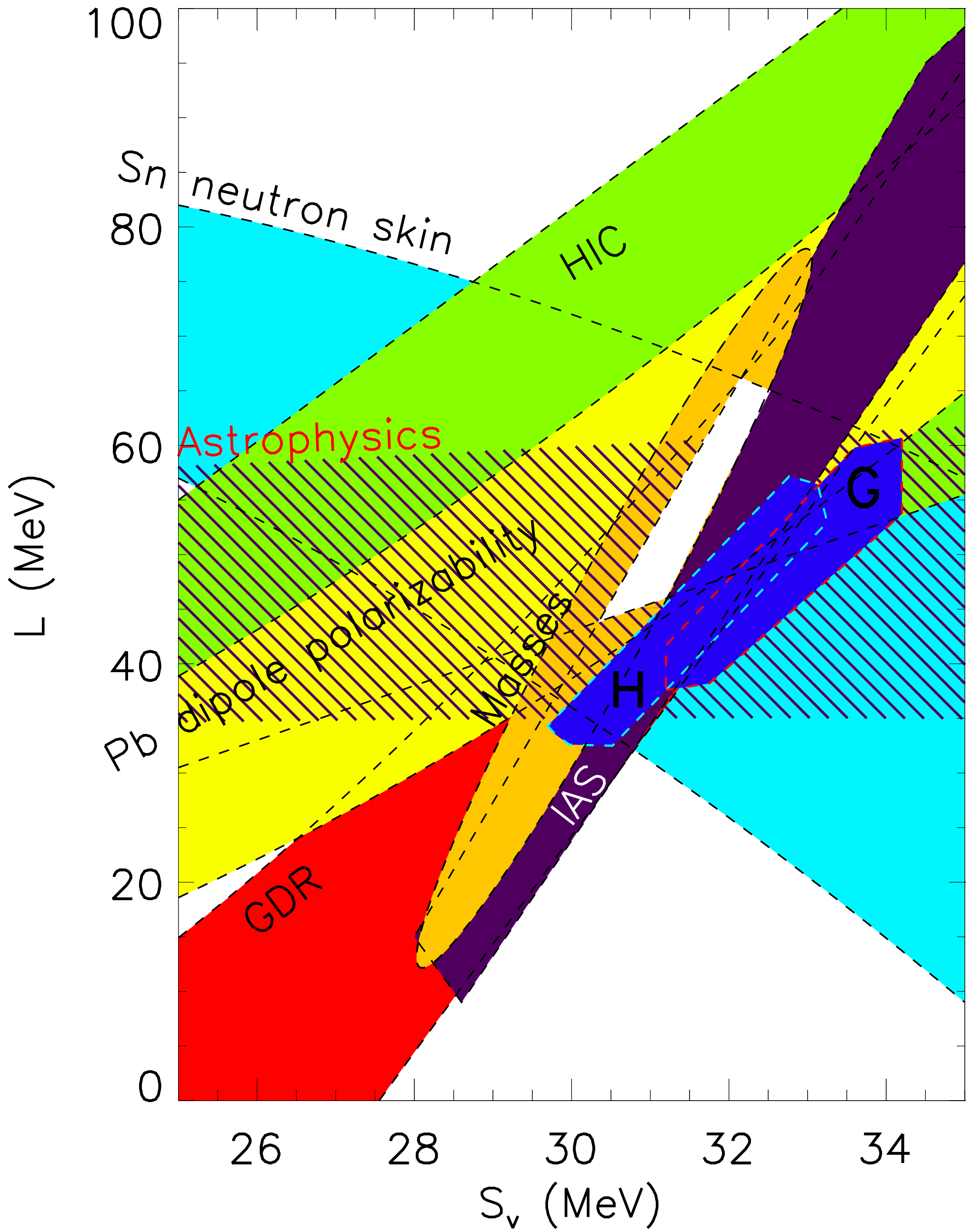
Symmetry energy and pressure of neutron matter

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

comparison to experimental and observational constraints
Lattimer, Lim, ApJ (2012), EPJA (2014)

neutron matter constraints
H: Hebeler et al. (2010)
G: Gandolfi et al. (2011)
provide tight constraints!

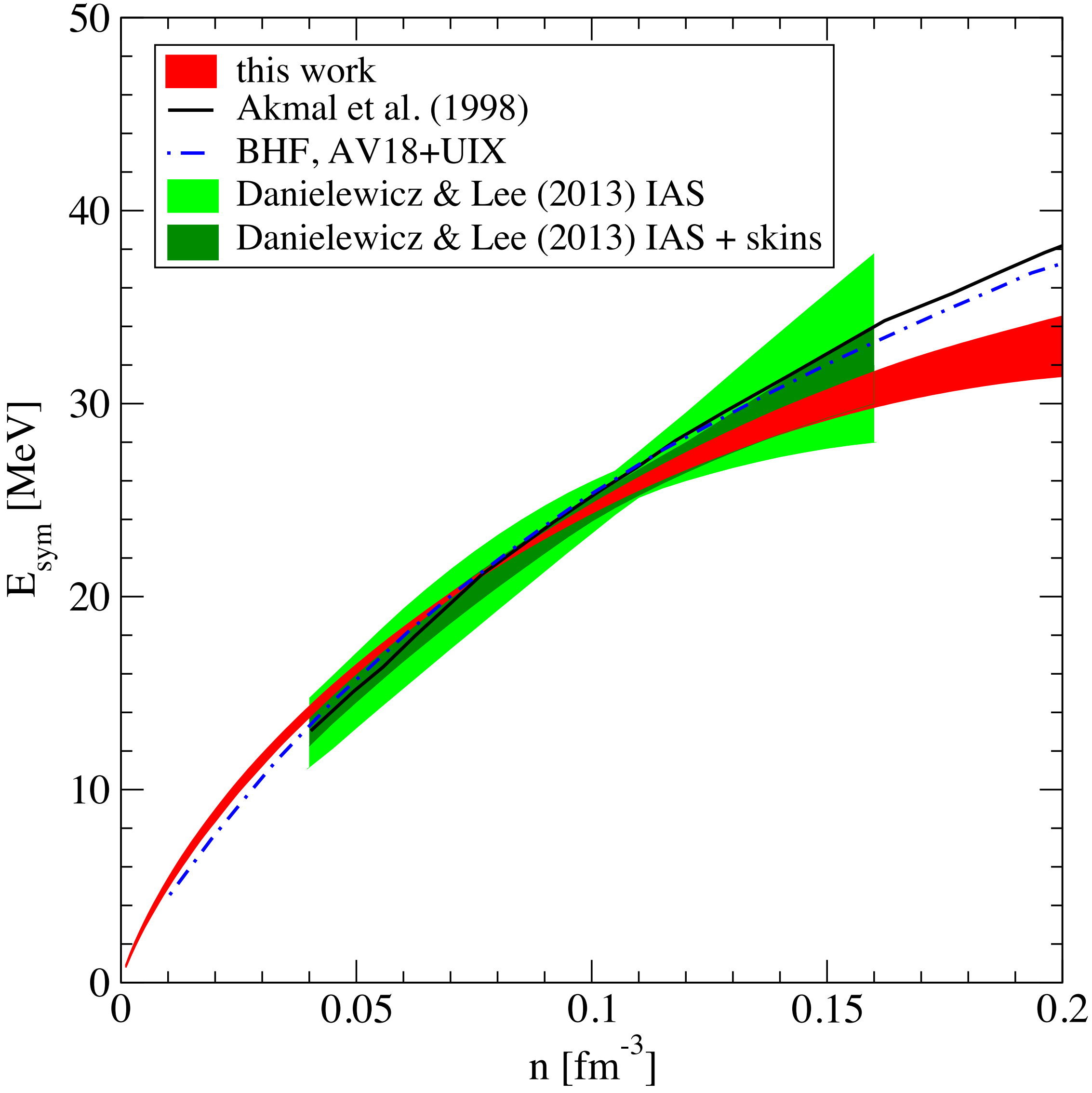
combined with Skyrme EDFs predicts neutron skin
^{208}Pb: 0.182(10) fm
Brown, AS (2014)



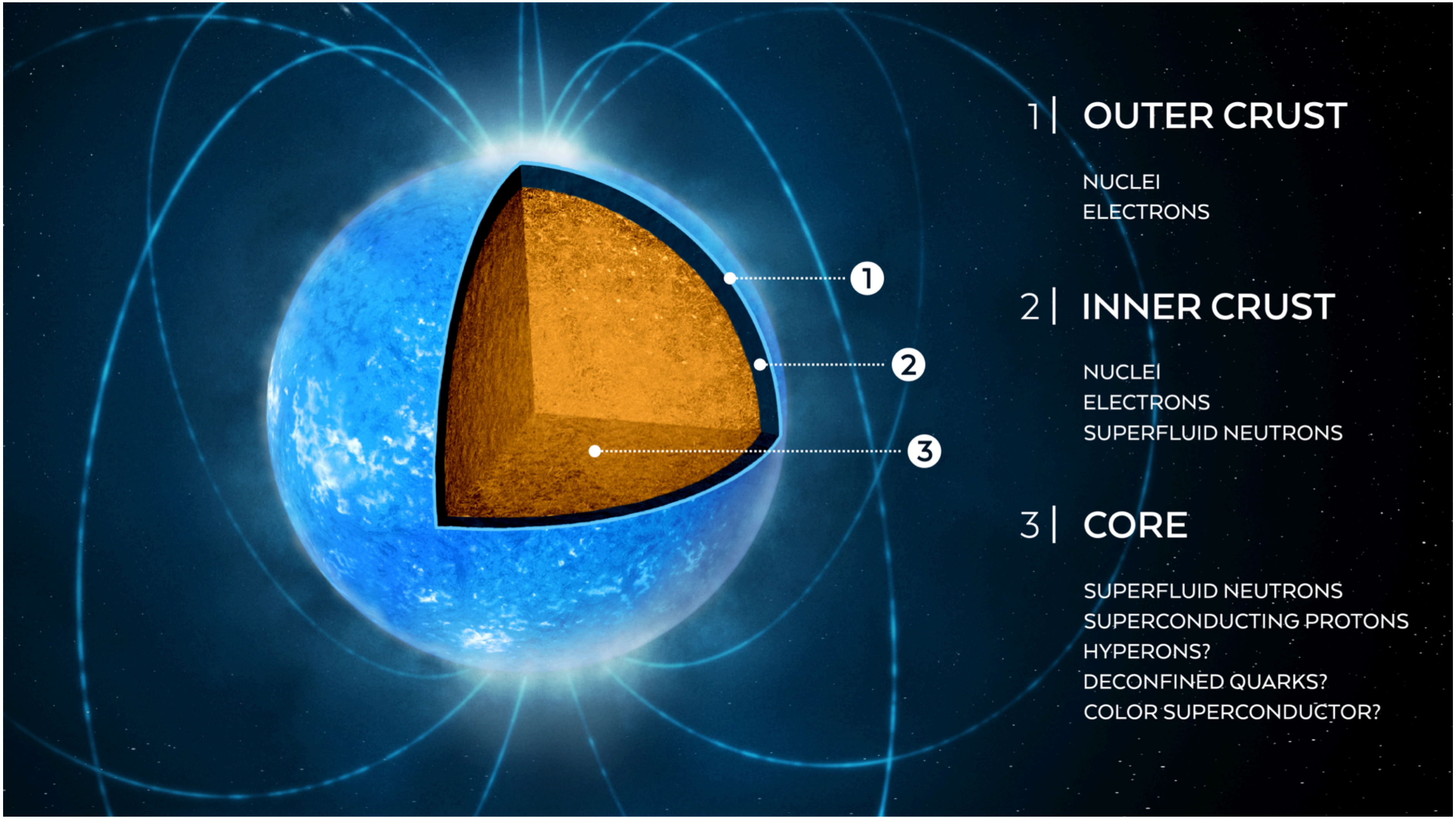
Calculations of asymmetric matter Drischler, Soma, AS, PRD (2014)

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

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



Neutron matter and neutron stars



Neutron matter and neutron stars

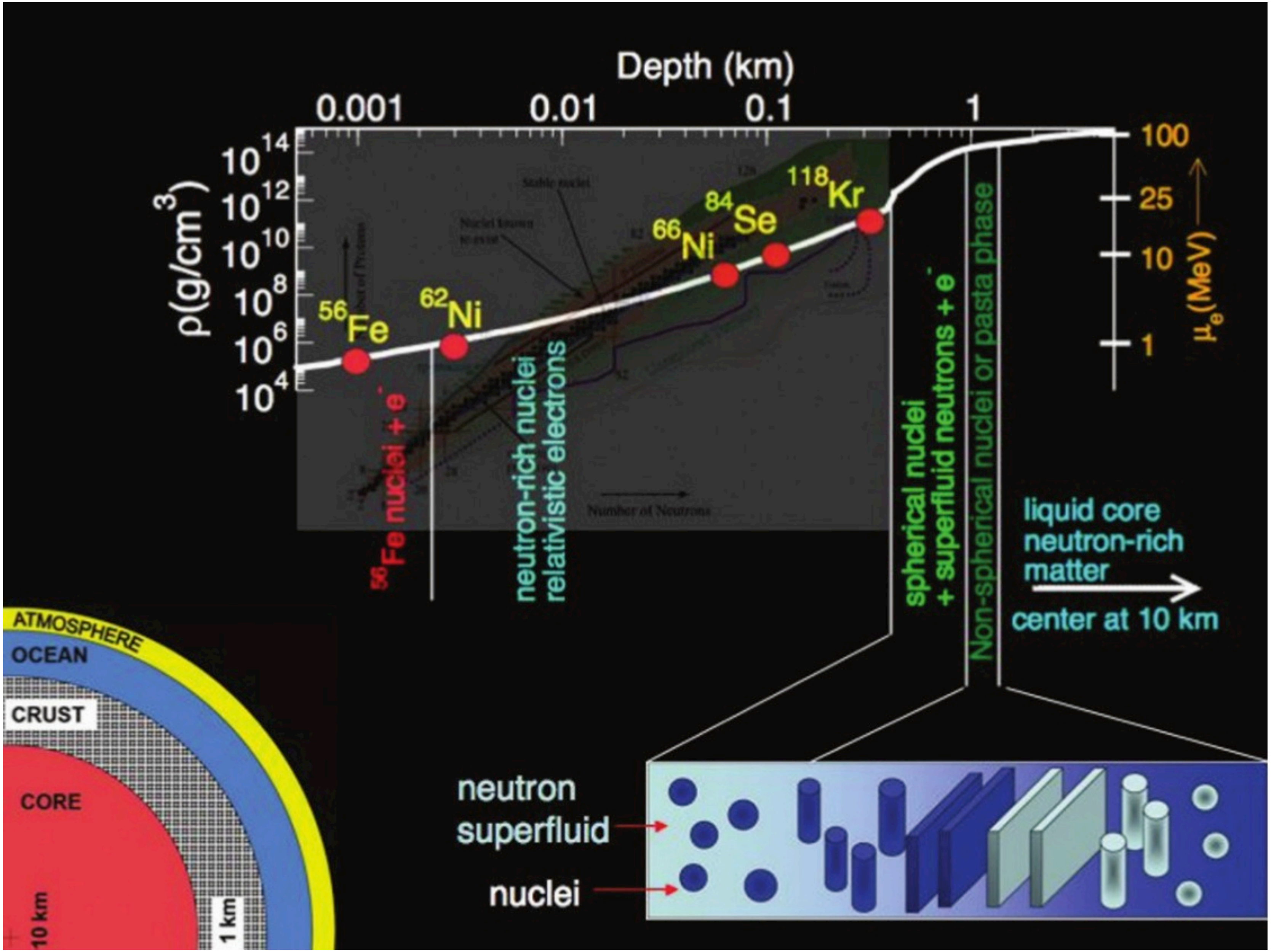
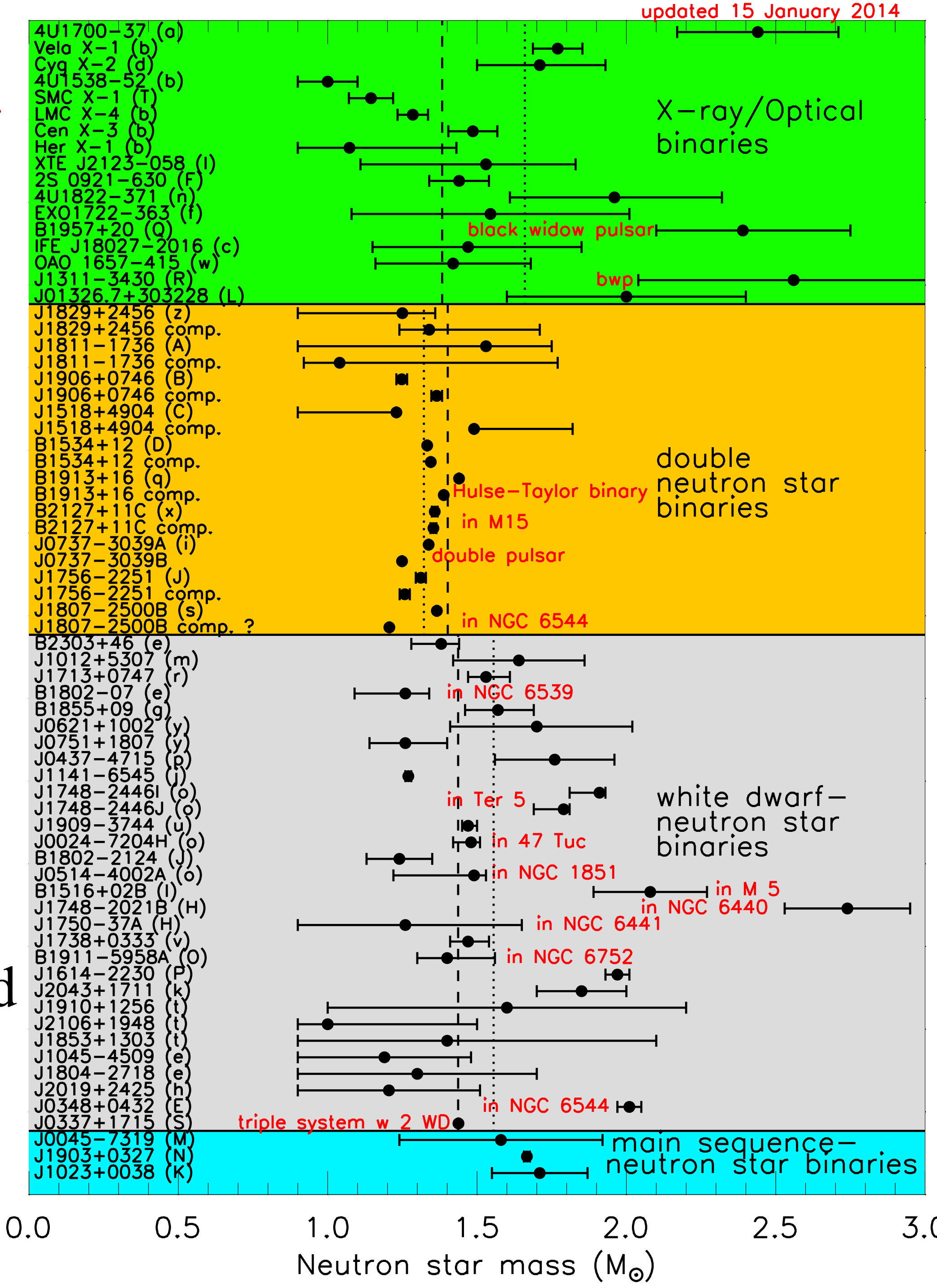


Chart of neutron star masses

from Jim Lattimer

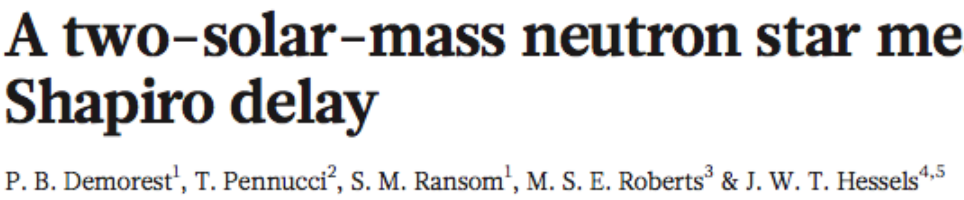


two 2 M_{sun} neutron stars observed

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

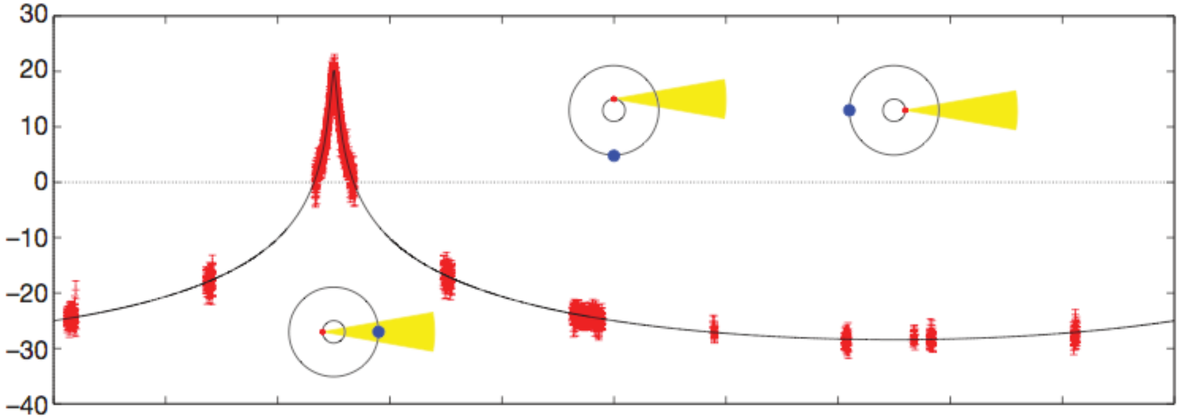
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

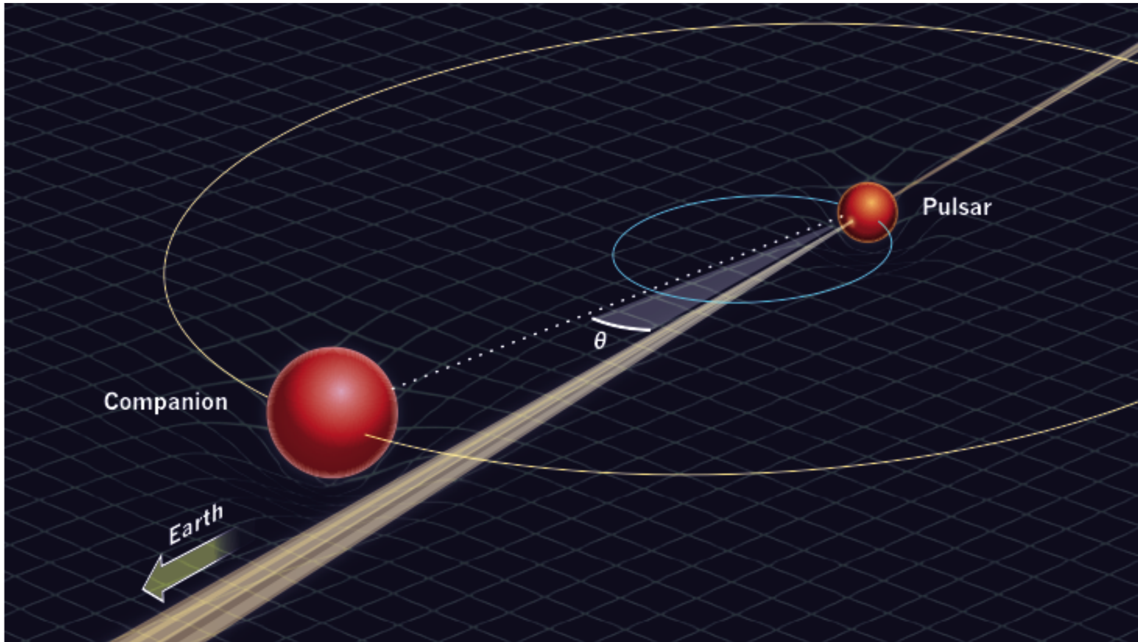
Nature (2010)

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

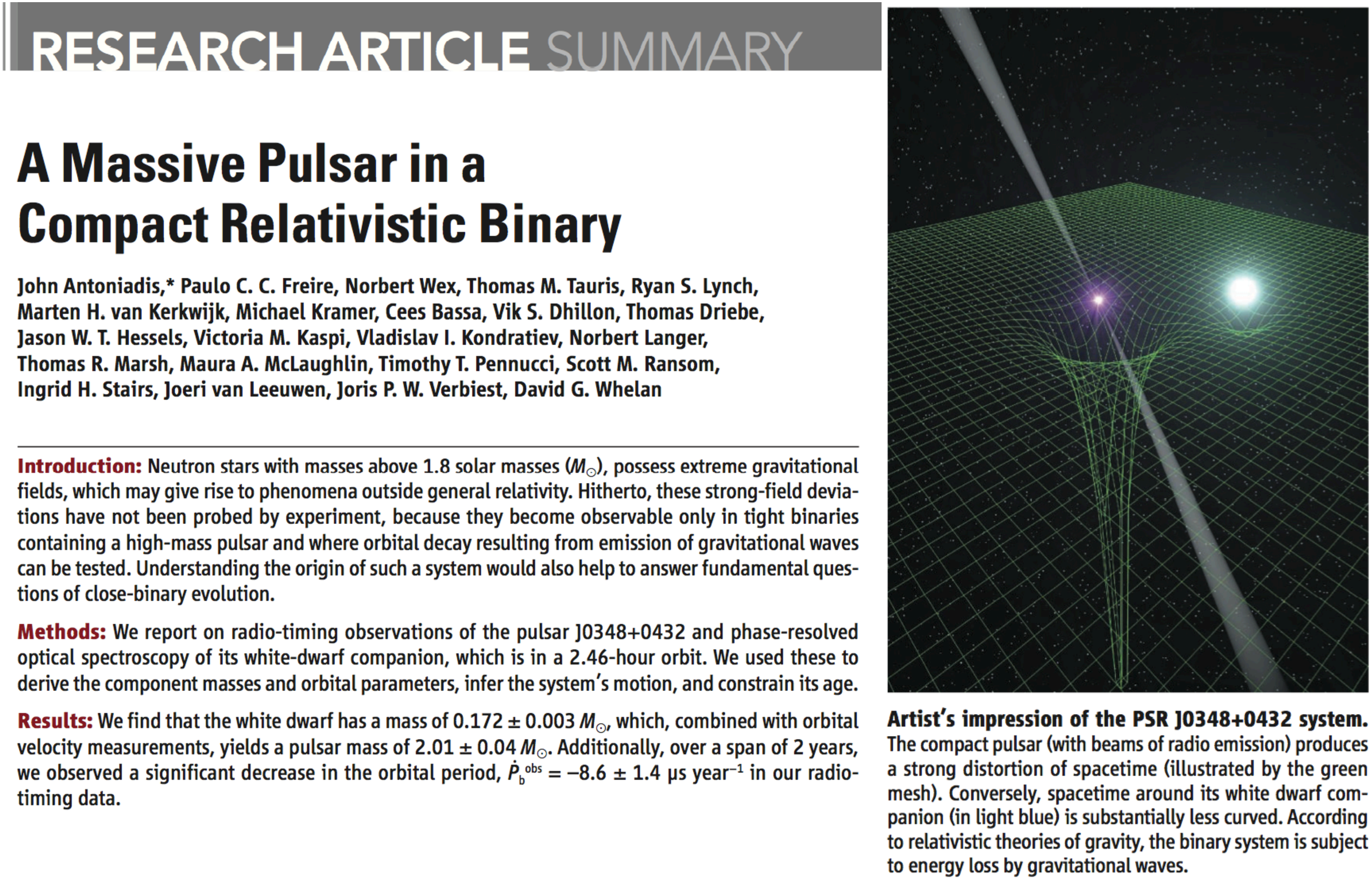
J1614-2230
most edge-on binary pulsar known (89.17°)
+ massive white dwarf companion (0.5 M_{sun})

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.

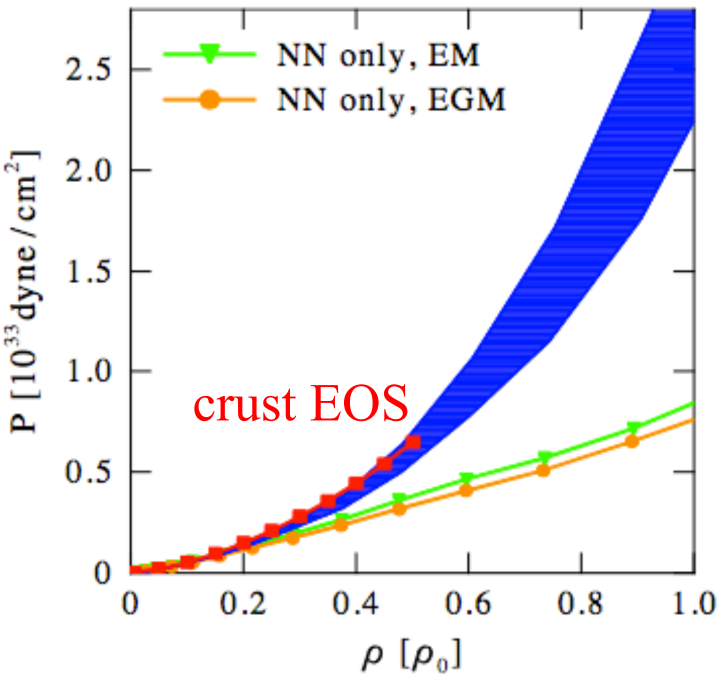
Methods: We report on radio-timing observations of the pulsar J0348+0432 and phase-resolved optical spectroscopy of its white-dwarf companion, which is in a 2.46-hour orbit. We used these to derive the component masses and orbital parameters, infer the system's motion, and constrain its age.

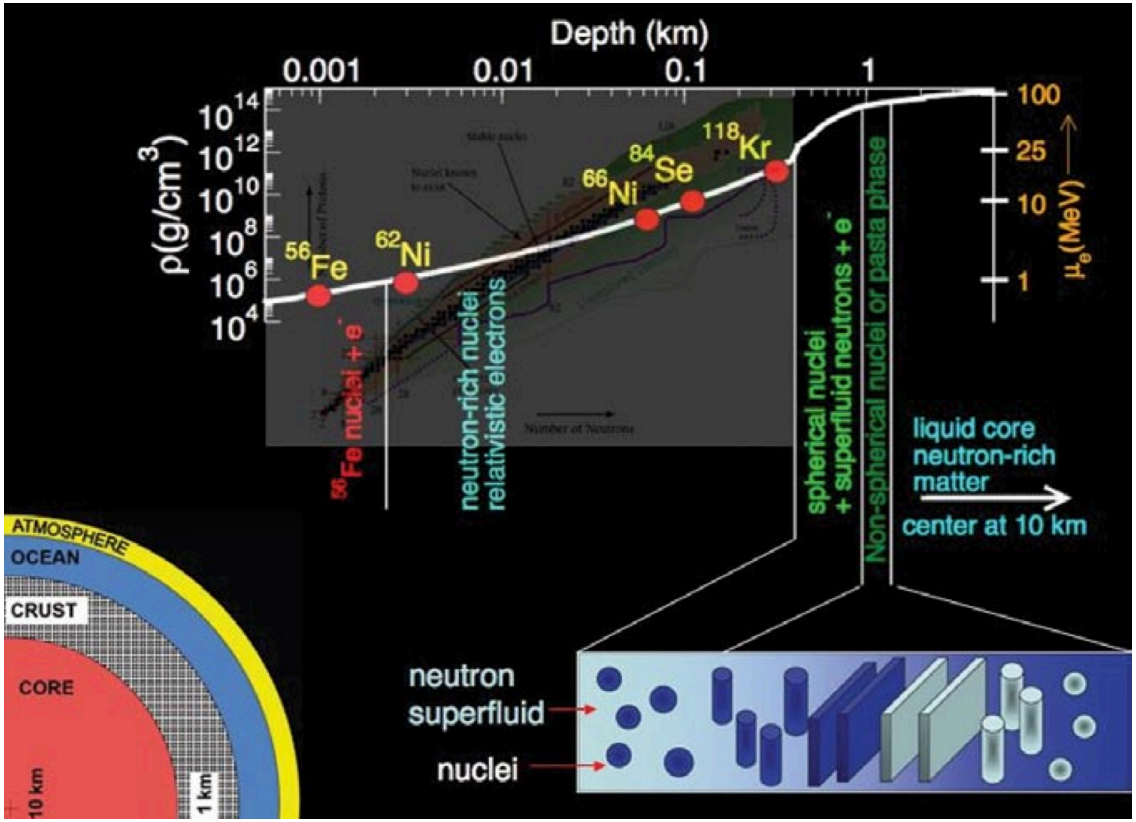
Results: We find that the white dwarf has a mass of $0.172 \pm 0.003\ M_\odot$, which, combined with orbital velocity measurements, yields a pulsar mass of $2.01 \pm 0.04\ M_\odot$. Additionally, over a span of 2 years, we observed a significant decrease in the orbital period, $\dot{P}_b^{\mathrm{obs}}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

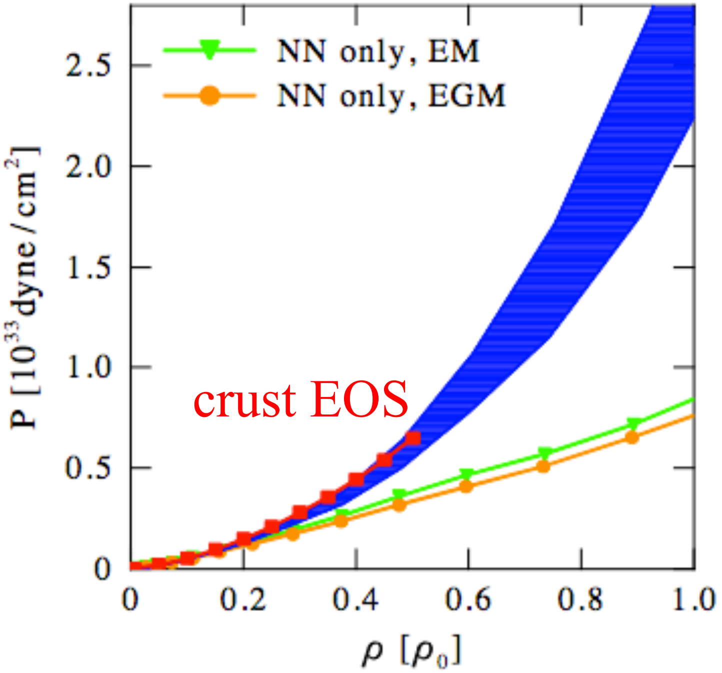


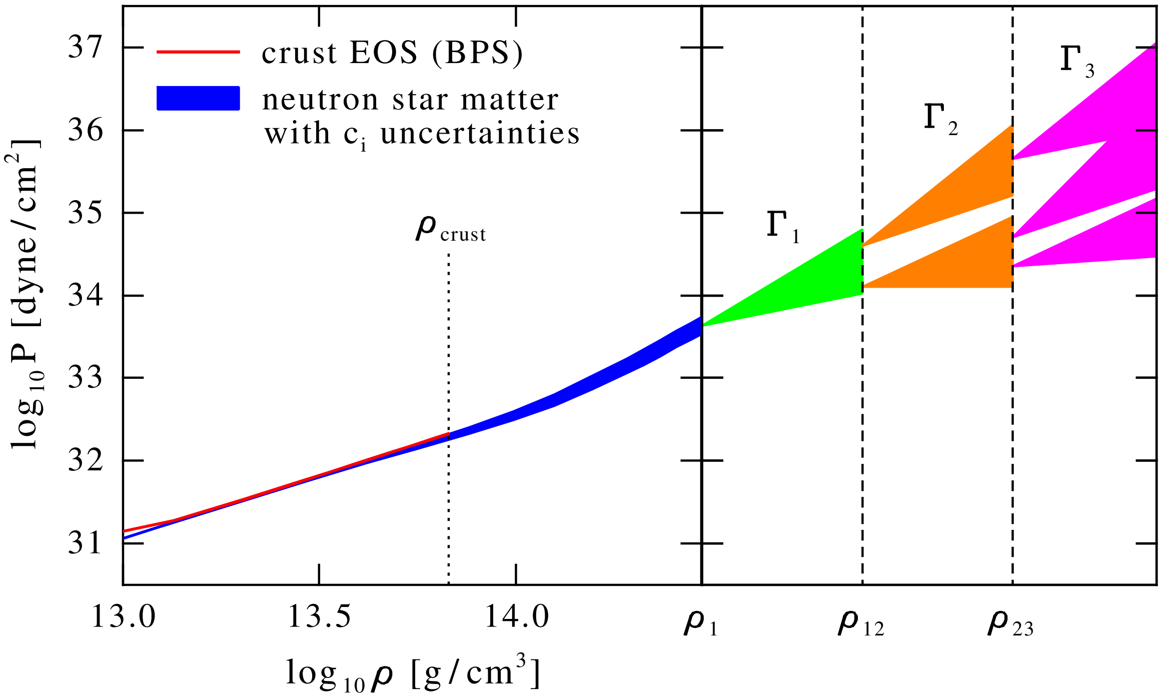


pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

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

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





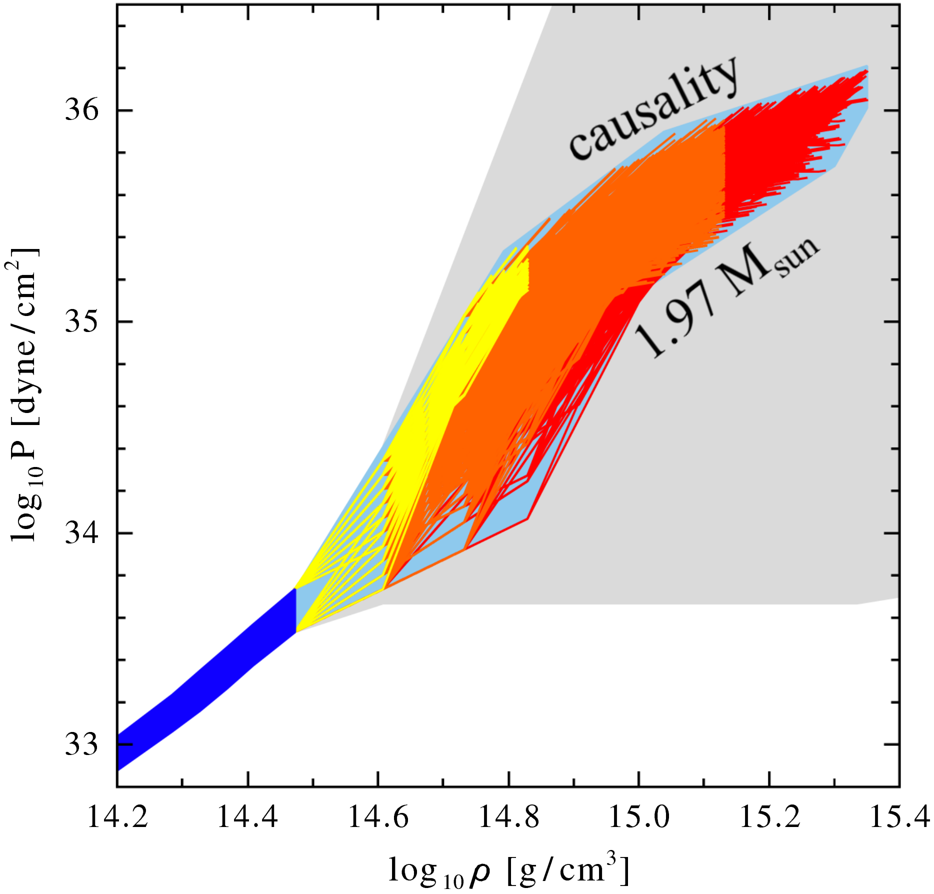
pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

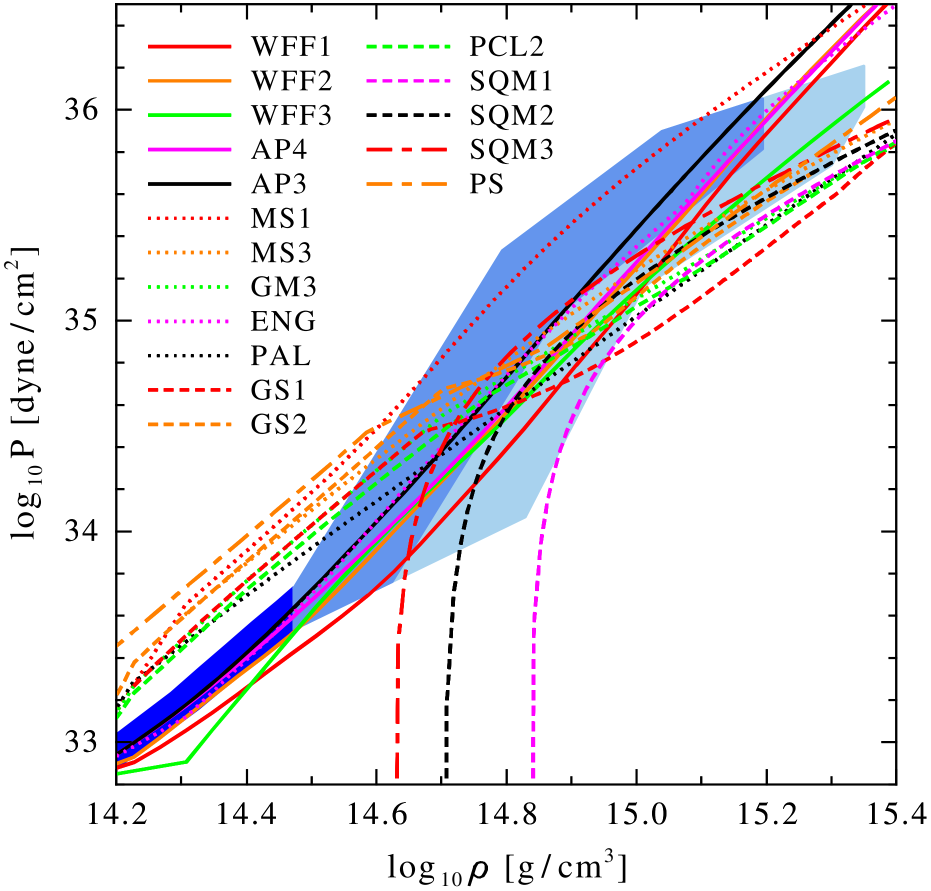
extend uncertainty band to higher densities using piecewise polytropes allow for soft regions

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



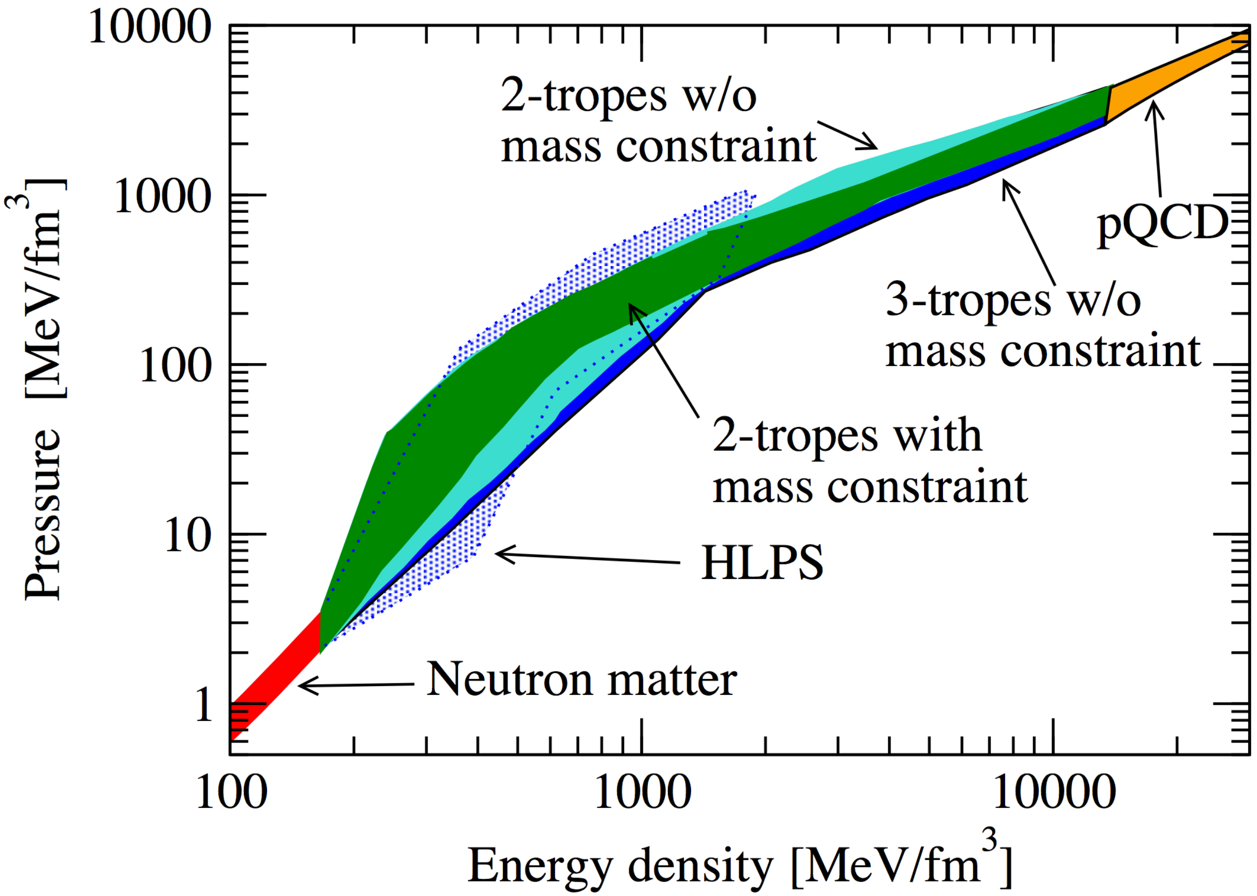


low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

Connecting the equation of state to pQCD calculations

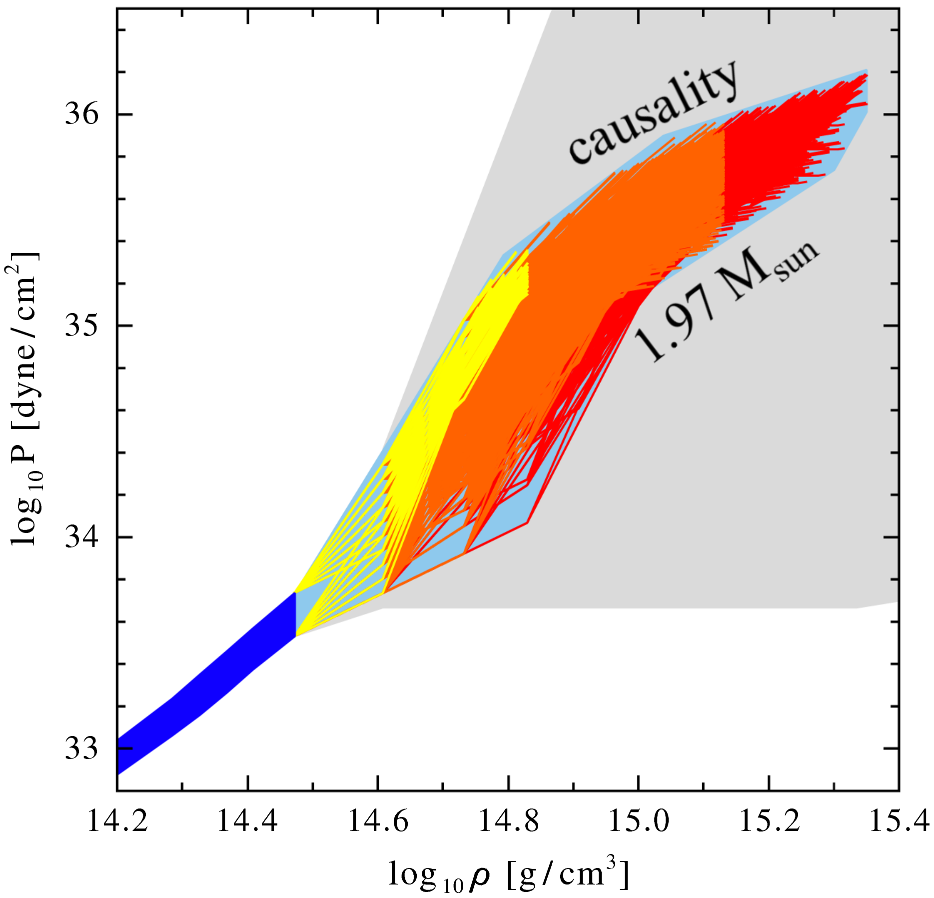
recent O(α_s^2) calculation of quark matter in perturbative QCD provides constraint at very high densities

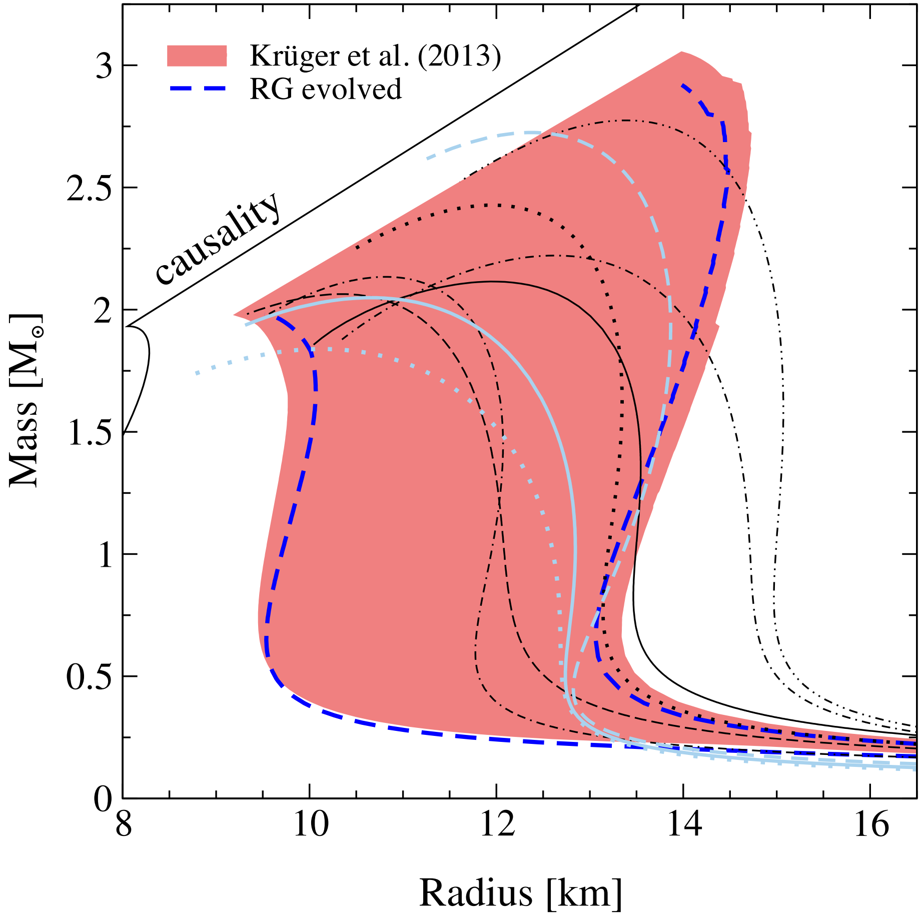
interpolating between **neutron matter calculations** and **pQCD** gives consistent EOS band Kurkela, Fraga, Schaffner-Bielich, Vuorinen, ApJ (2014).



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





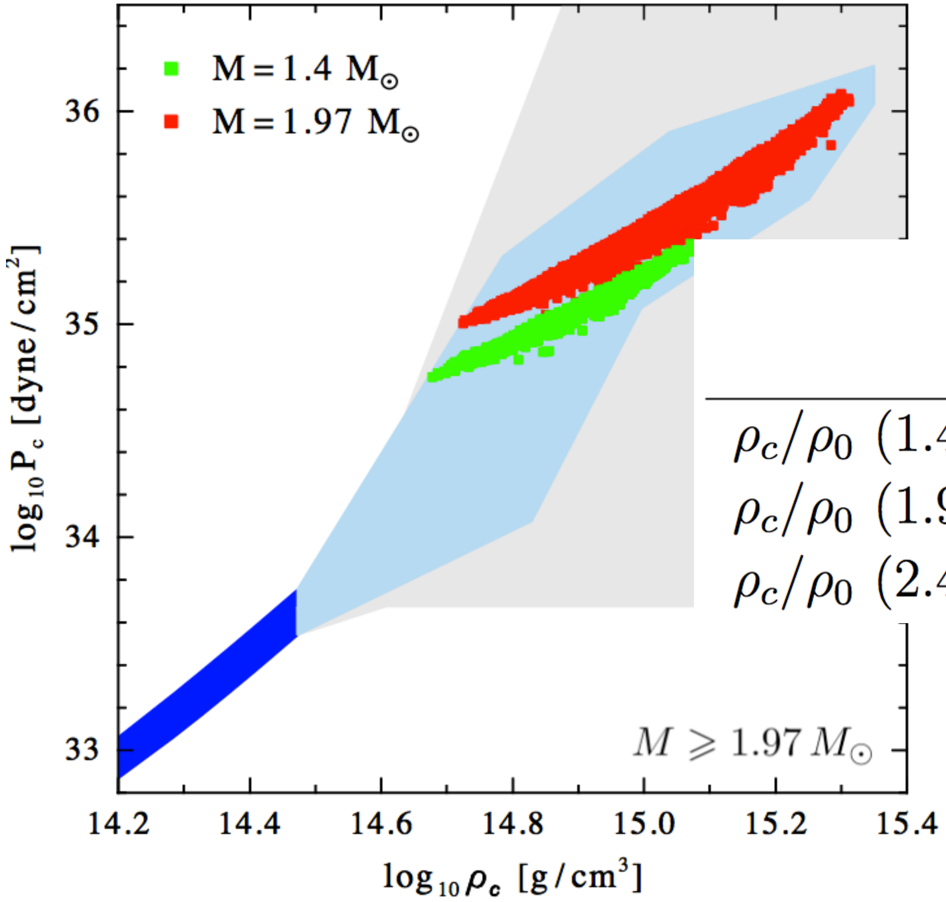
low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

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

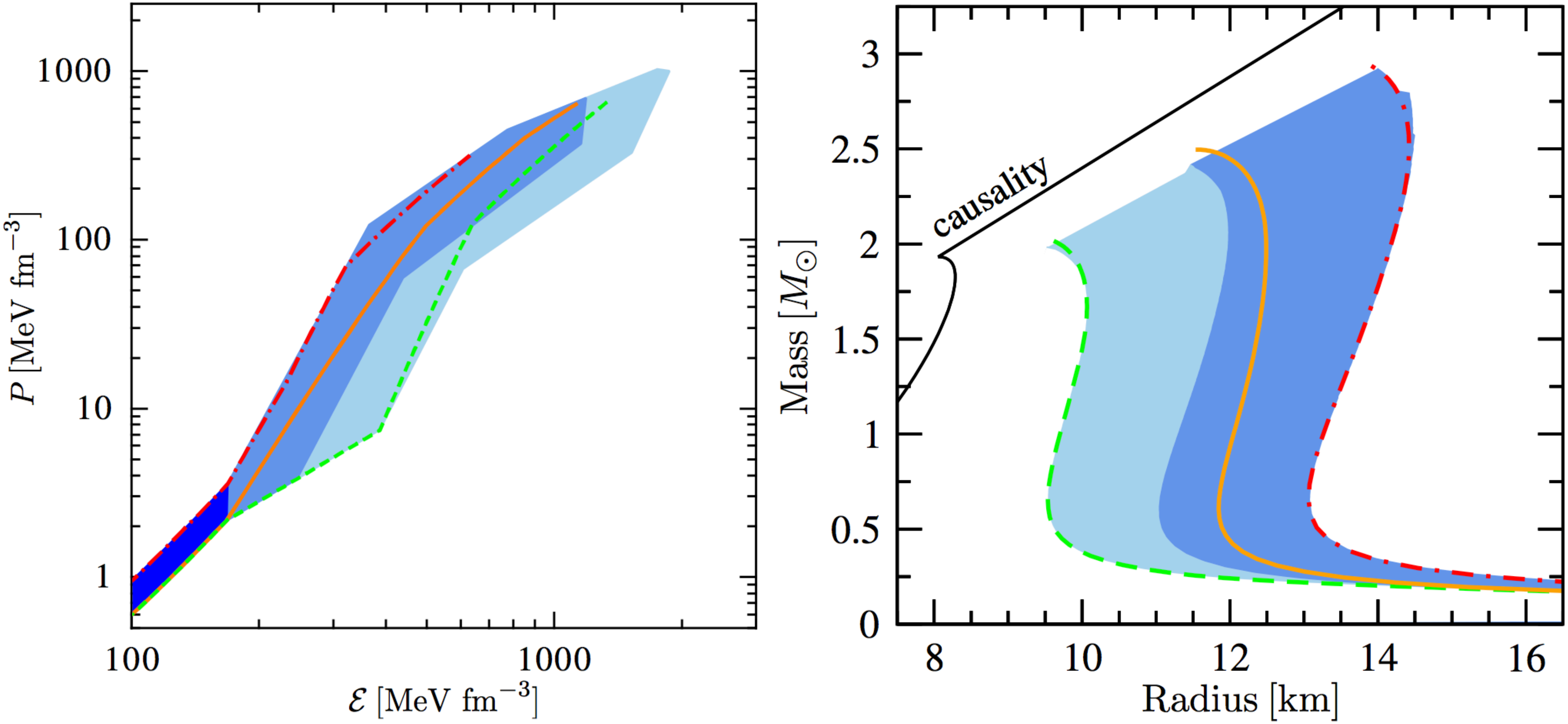
central densities
for 1.4 M_{sun} star: 1.8-4.4 ρ_0

not very high momenta!

Representative equations of state

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

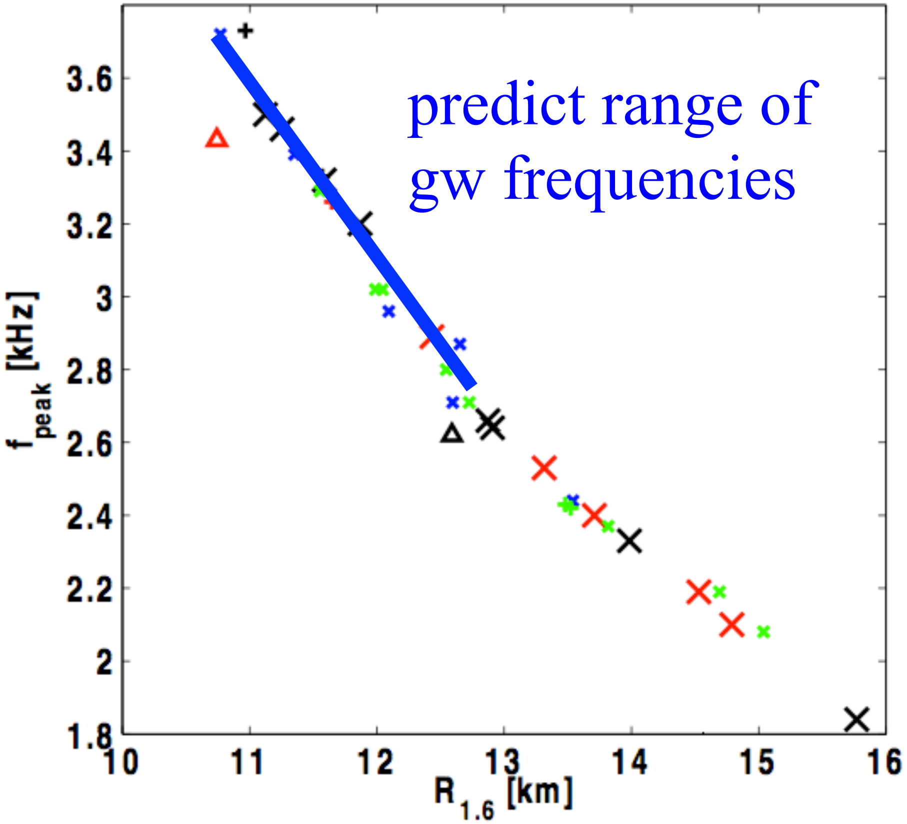
constructed 3 representative EOS for users: soft, intermediate, stiff



Neutron-star mergers and gravitational waves

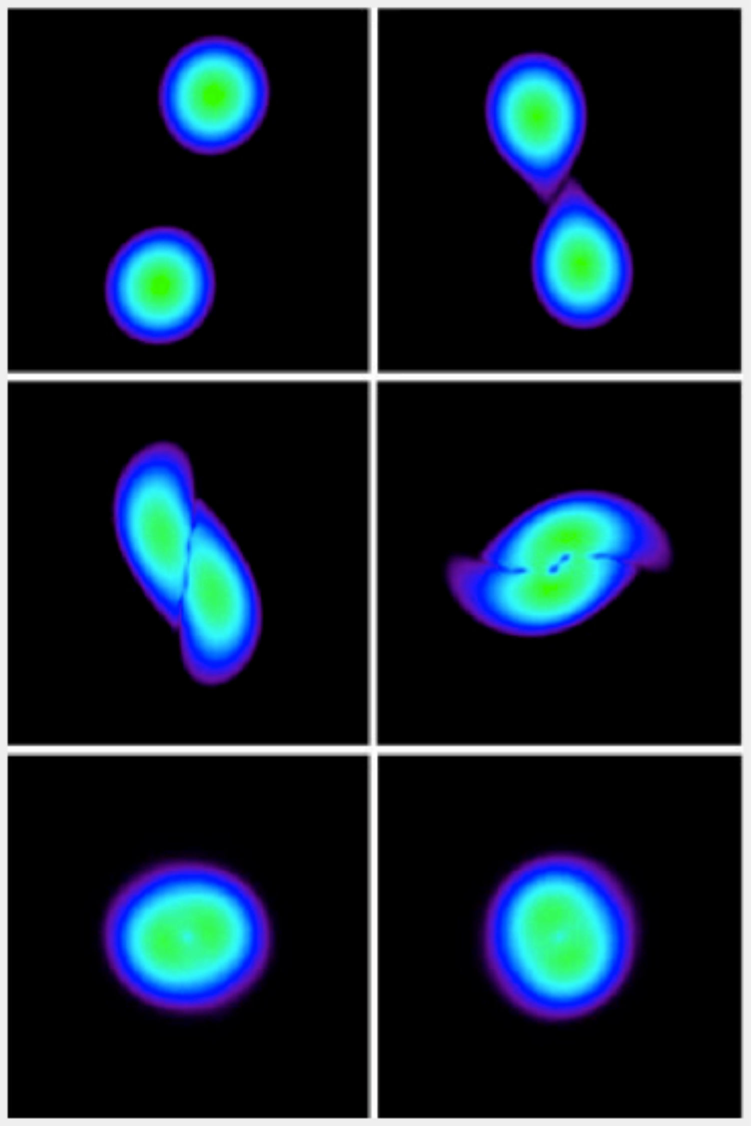
explore sensitivity to neutron-rich matter in neutron-star merger predictions for gravitational-wave signal, including NP uncertainties

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



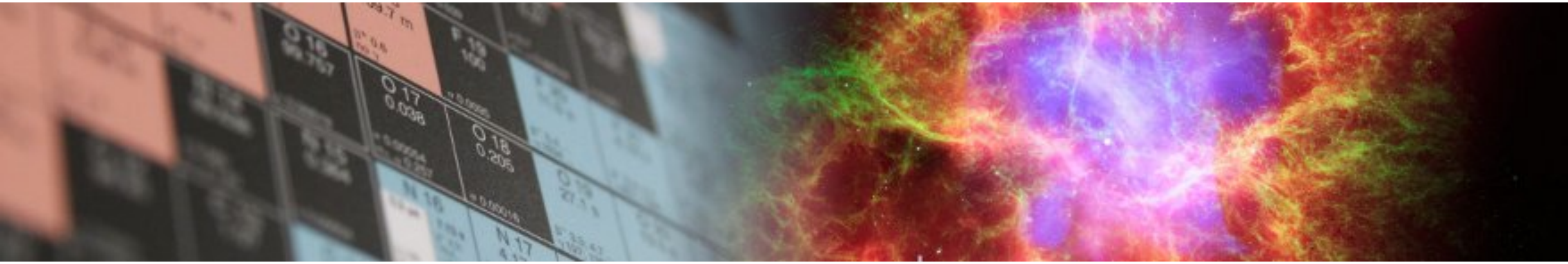
predict range of gw frequencies

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.



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

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

on neutron-rich matter and neutron stars

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

future: consistent electroweak interactions from chiral EFT
lattice QCD to connect chiral EFT to QCD