Nuclear forces and neutron skins

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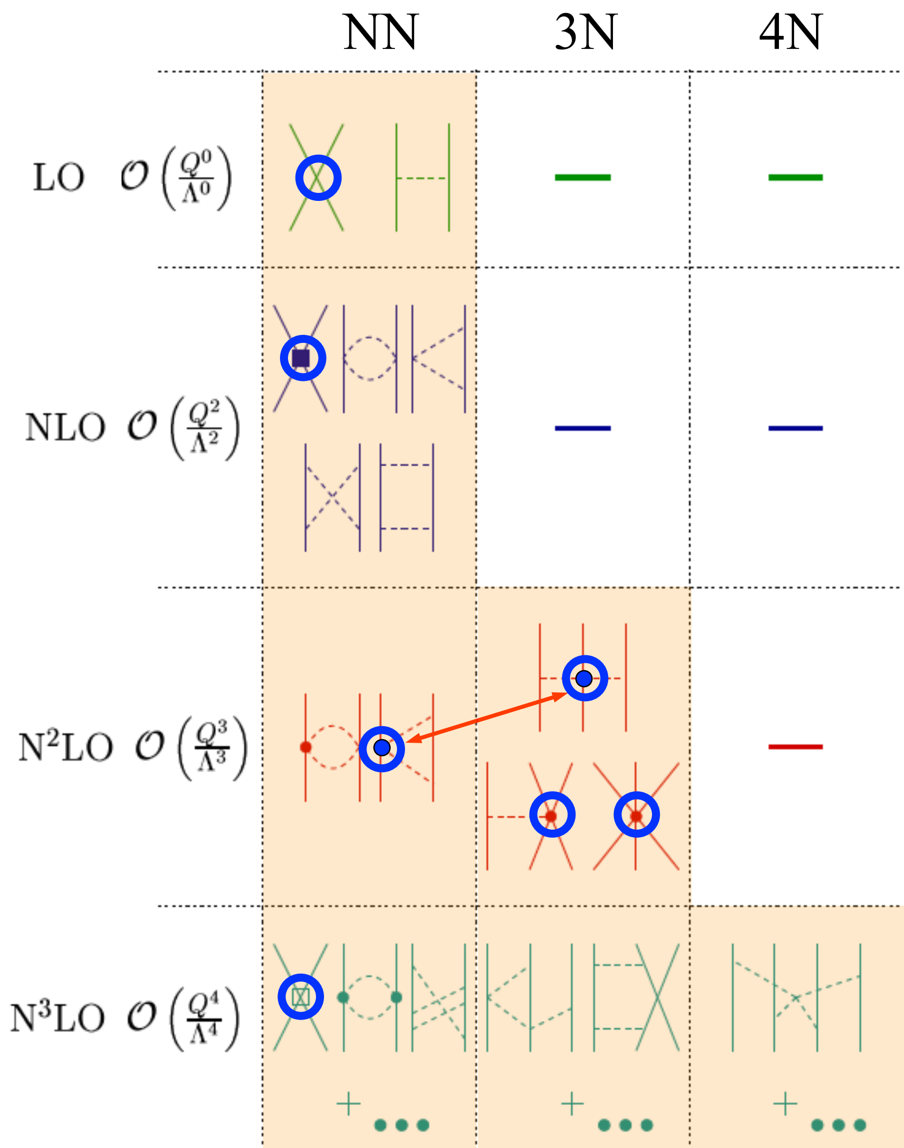
TECHNISCHE UNIVERSITÄT DARMSTADT

MITP Workshop "Neutron Skins in Nuclei"

May 23, 2016

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

short-range couplings, fit to experiment once

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

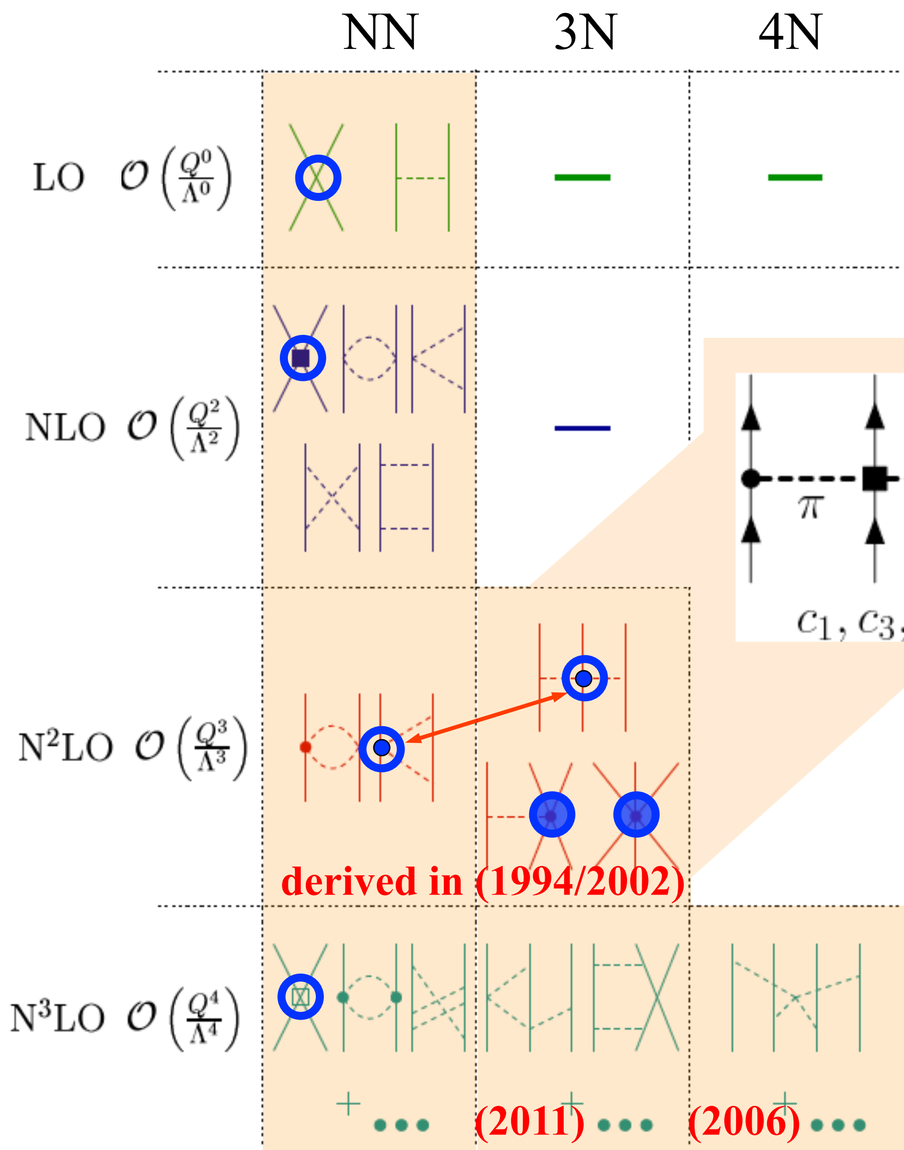
consistent **electroweak interactions** and **matching to lattice QCD**

new developments in power counting, uncertainty quantification, optimization Ektröm, Forssen, Furnstahl,...

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

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

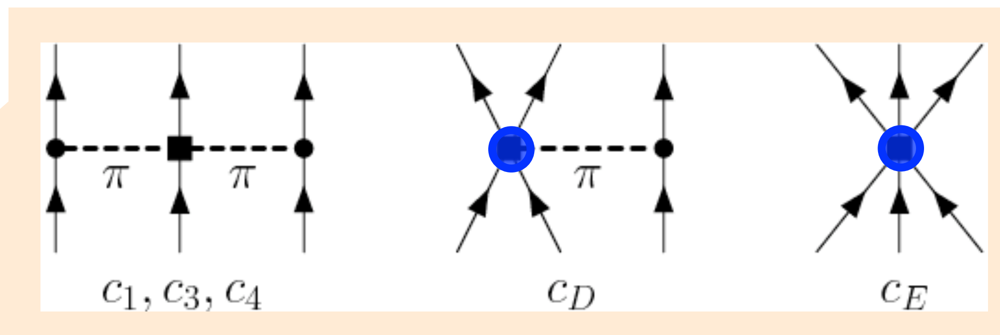
Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale ~500 MeV



consistent NN-3N-4N interactions

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

+ no new couplings for neutrons



c_i from πN and NN Meissner, LAT 2005

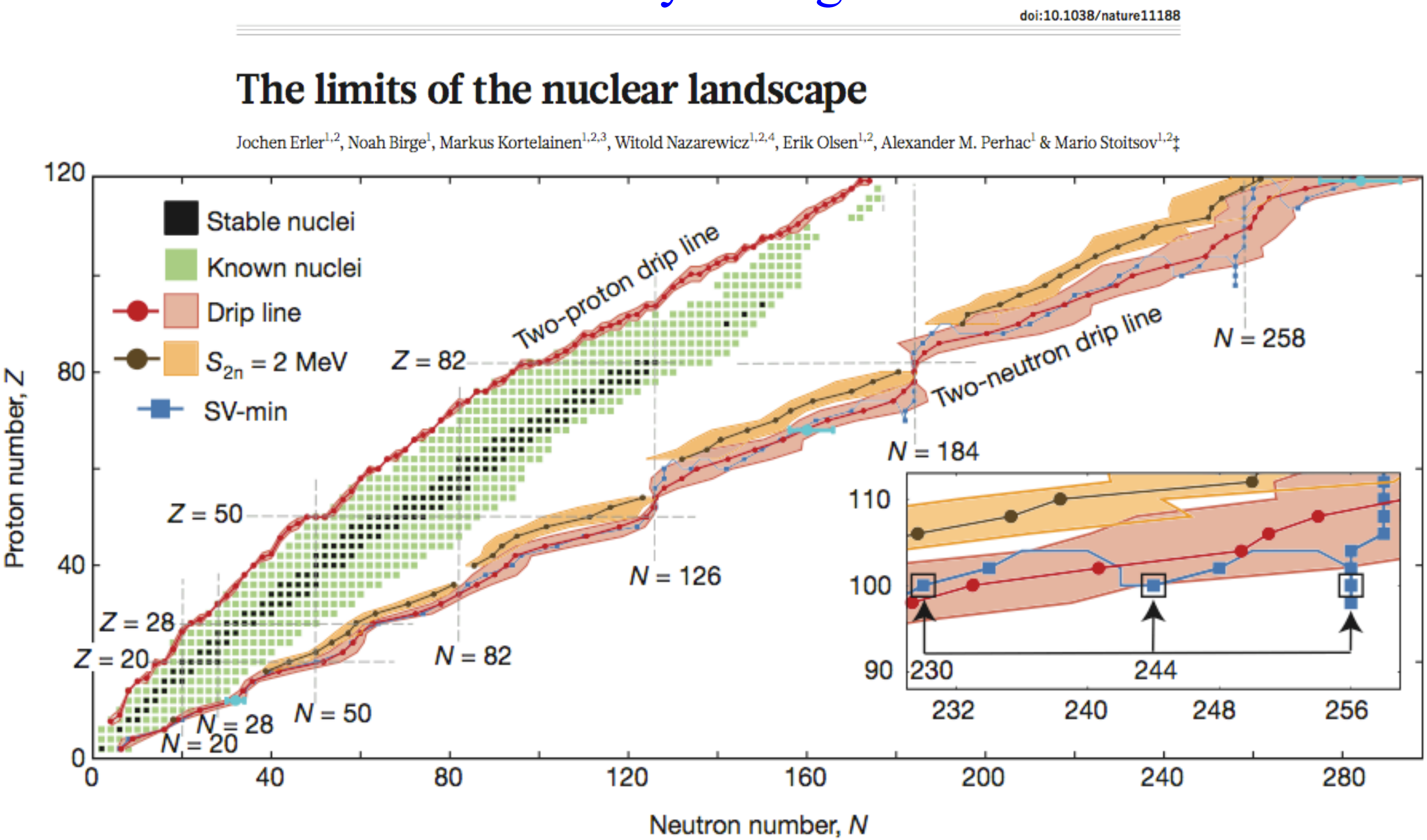
$$c_1 = -0.9^{+0.2}_{-0.5}\,,\quad c_3 = -4.7^{+1.2}_{-1.0}\,,\quad c_4 = 3.5^{+0.5}_{-0.2}$$

c_D, c_E fit to light nuclei only

N^{2}LOsat fit to nuclei up to A=24

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

Nuclei bound by strong interactions

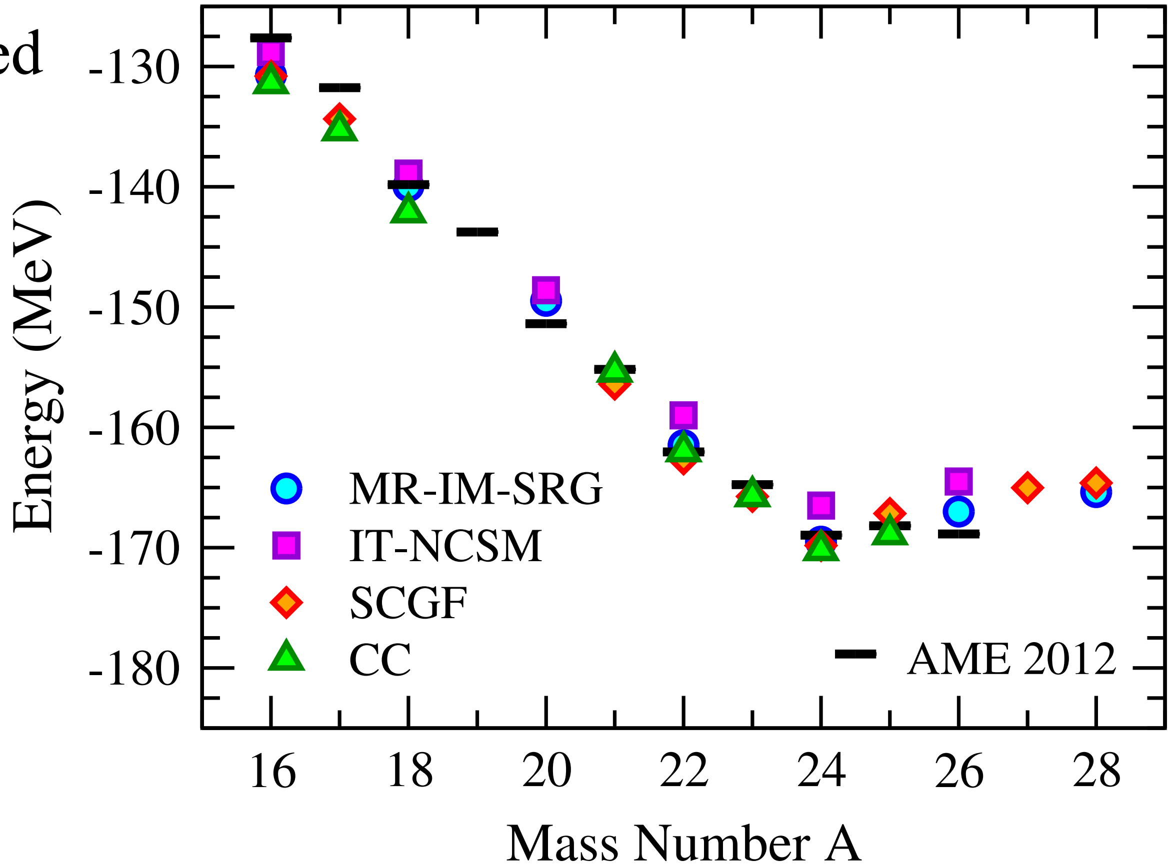


How does the nuclear chart emerge from chiral EFT?

Ab initio calculations of neutron-rich oxygen isotopes

impact of **3N forces key for neutron dripline** Otsuka et al., PRL (2010)

based on same SRG-evolved NN+3N interactions



using different many-body methods:

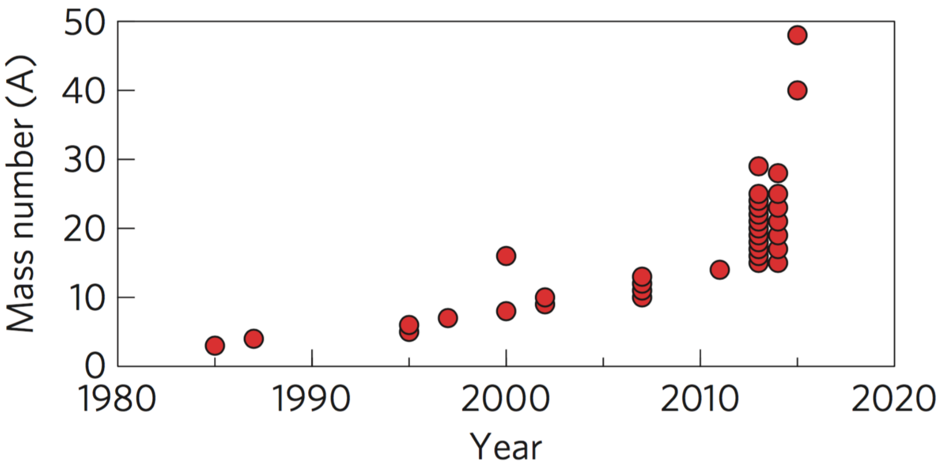
Coupled Cluster theory/CCEI Hagen et al., PRL (2012), Jansen et al., PRL (2014)

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

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

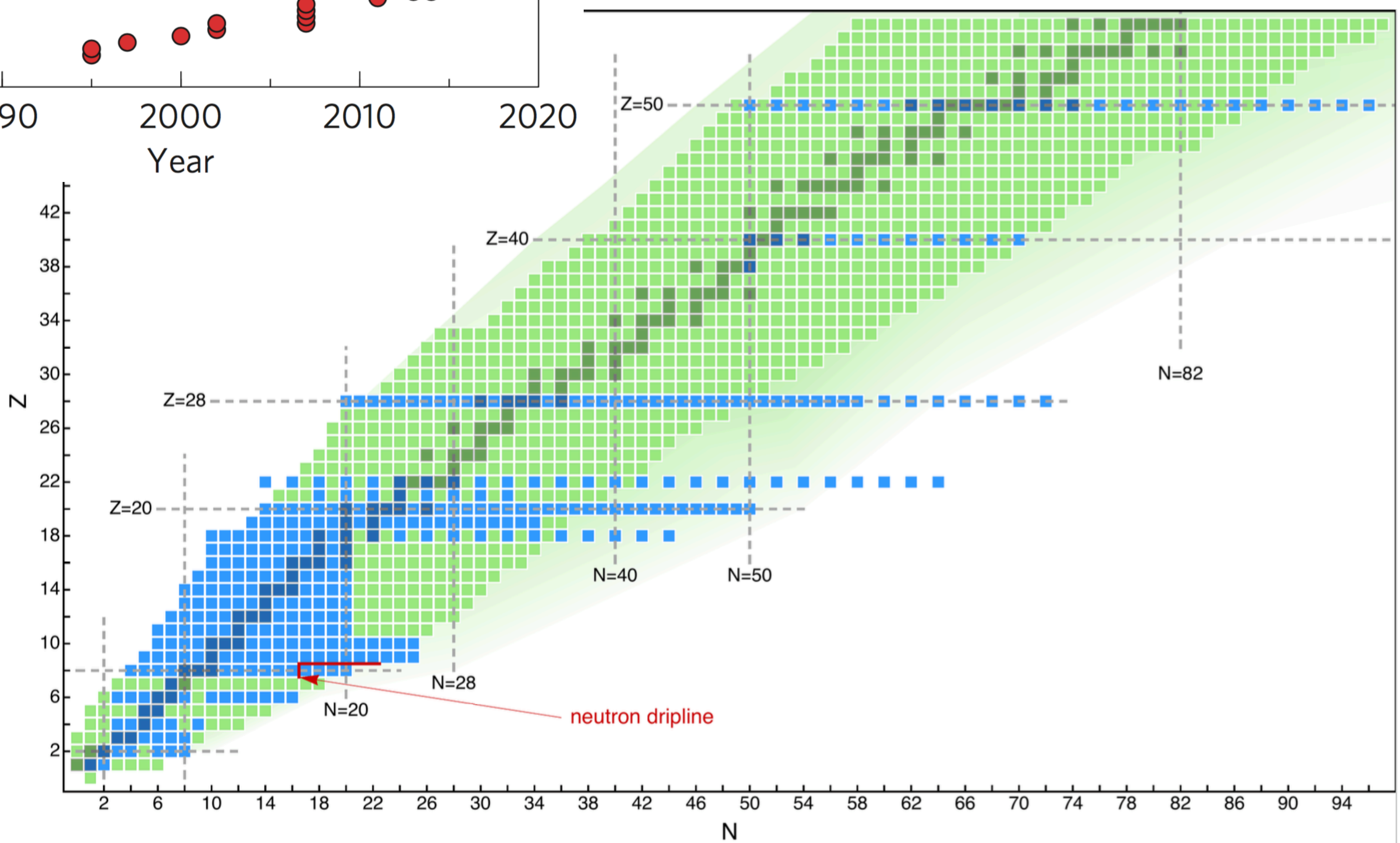
Progress in ab initio calculations of nuclei

dramatic progress in last 5 years to access nuclei up to A ~ 50



from Hagen et al., Nature Phys. (2016)

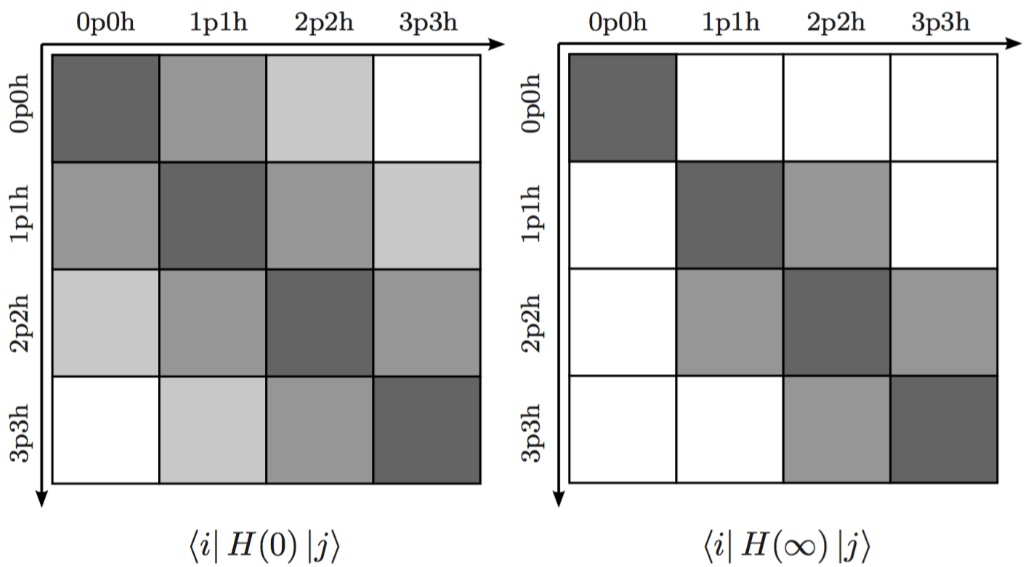
from Hergert et al., Phys. Rep. (2016)

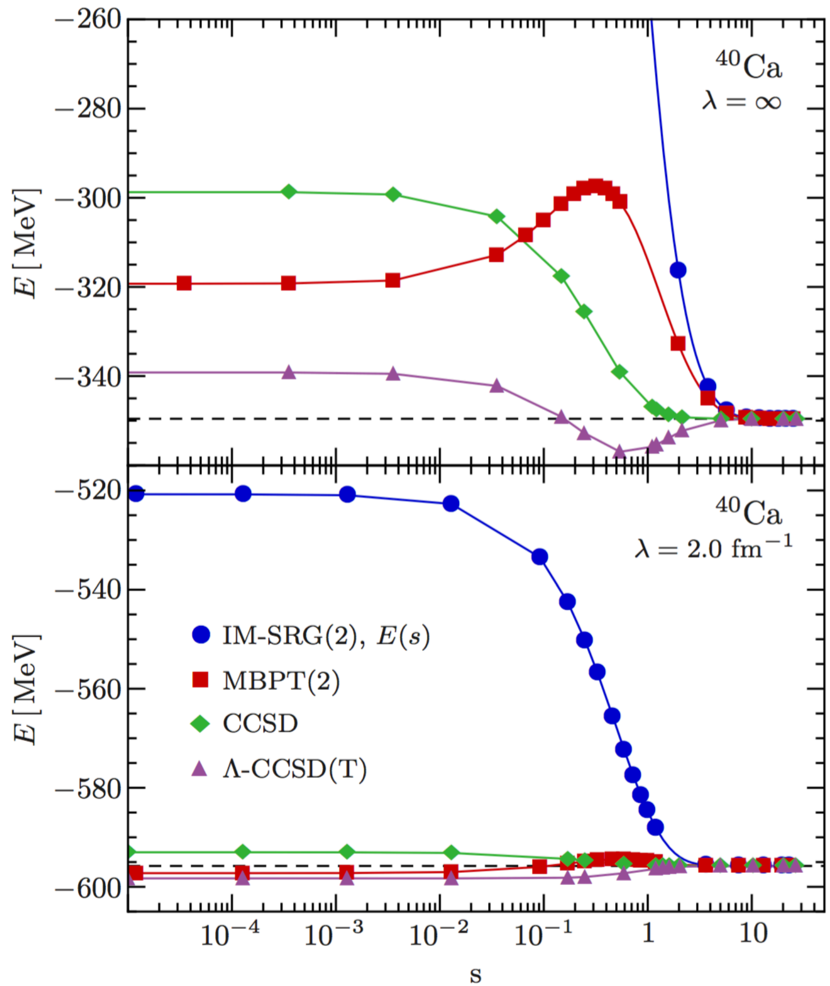


In-medium similarity renormalization group

flow equations to decouple higher-lying particle-hole states

Tsukiyama, Bogner, AS, PRL (2011), Hergert et al., Phys. Rep. (2016)



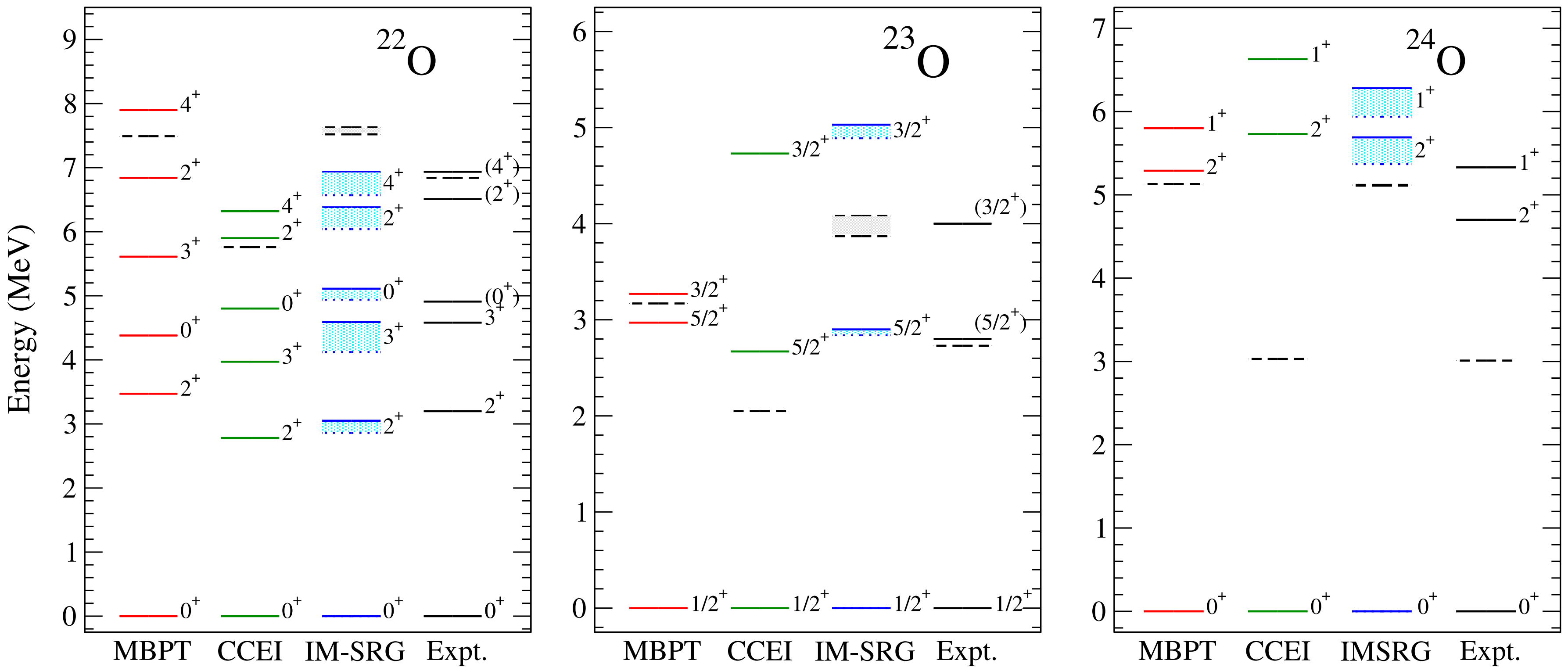


Ab initio calculations going open shell

In-Medium SRG to derive nonperturbative shell-model interactions

Tsukiyama, Bogner, AS, 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

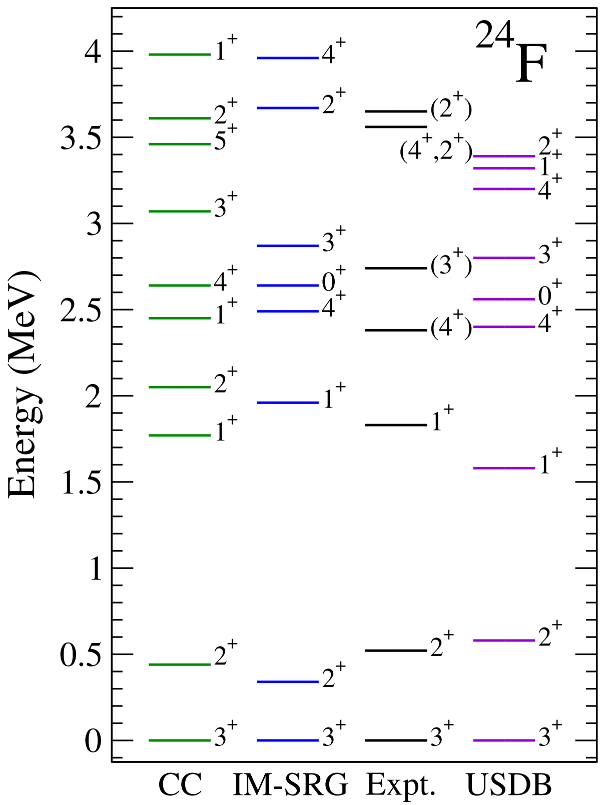
Ab initio calculations going open shell

In-Medium SRG to derive nonperturbative shell-model interactions

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

Spectrum of ^{24}F Cáceres et al., PRC (2015)

vs. new GANIL experiment



Ab initio calculations going open shell

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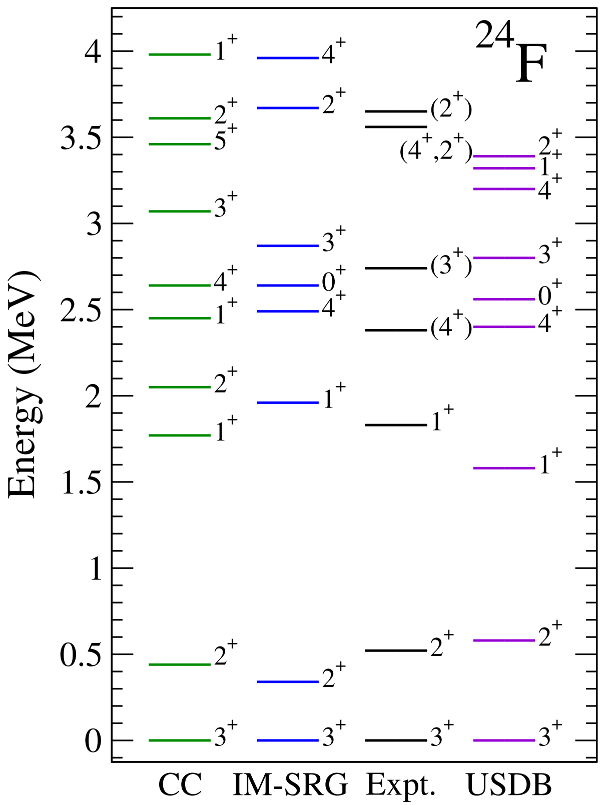
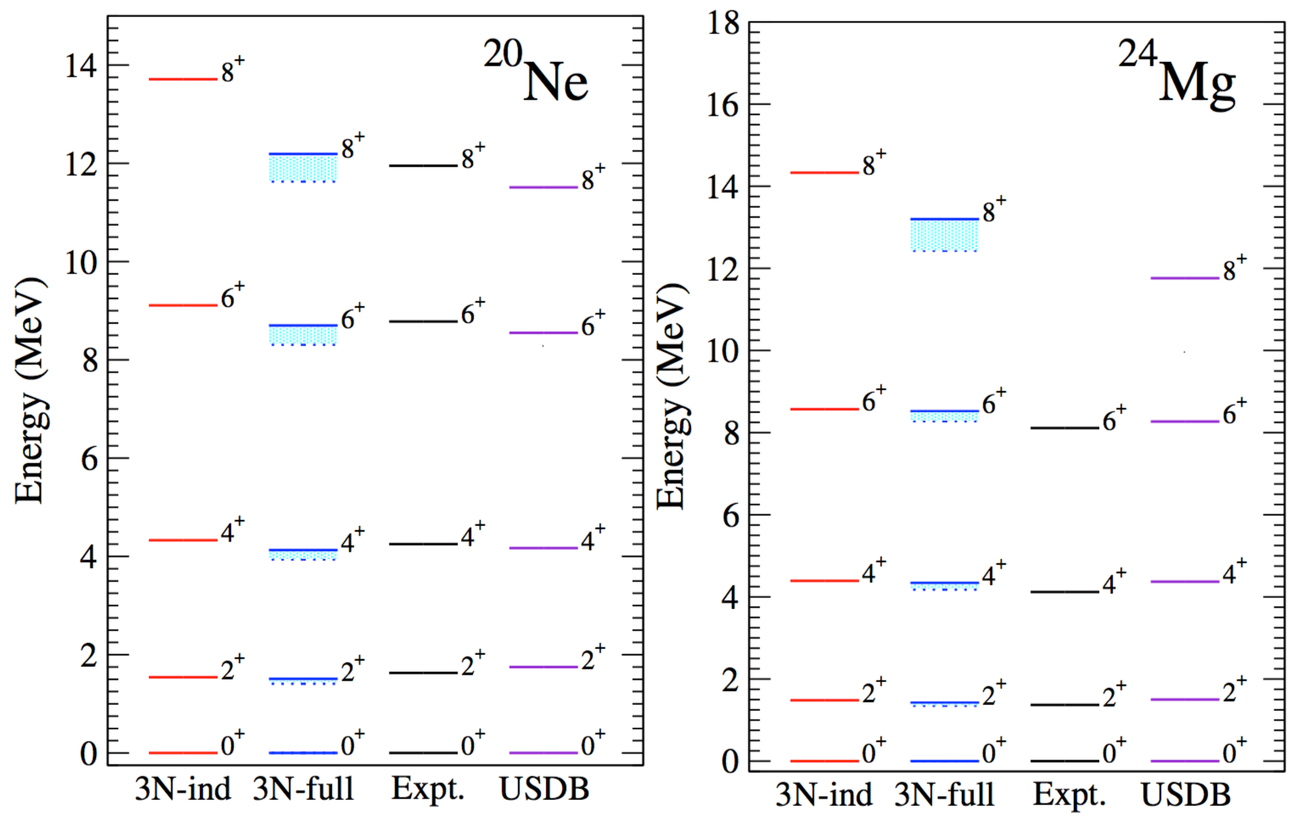


Deformed nuclei Stroberg et al., PRC (2016)
CCEI Jansen et al., PRC (2016)

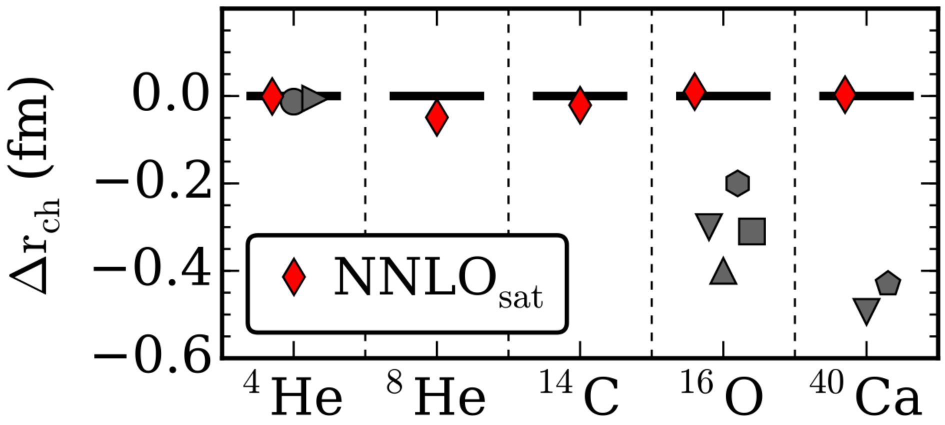


Resolution of radius problems

good saturation properties essential for radii

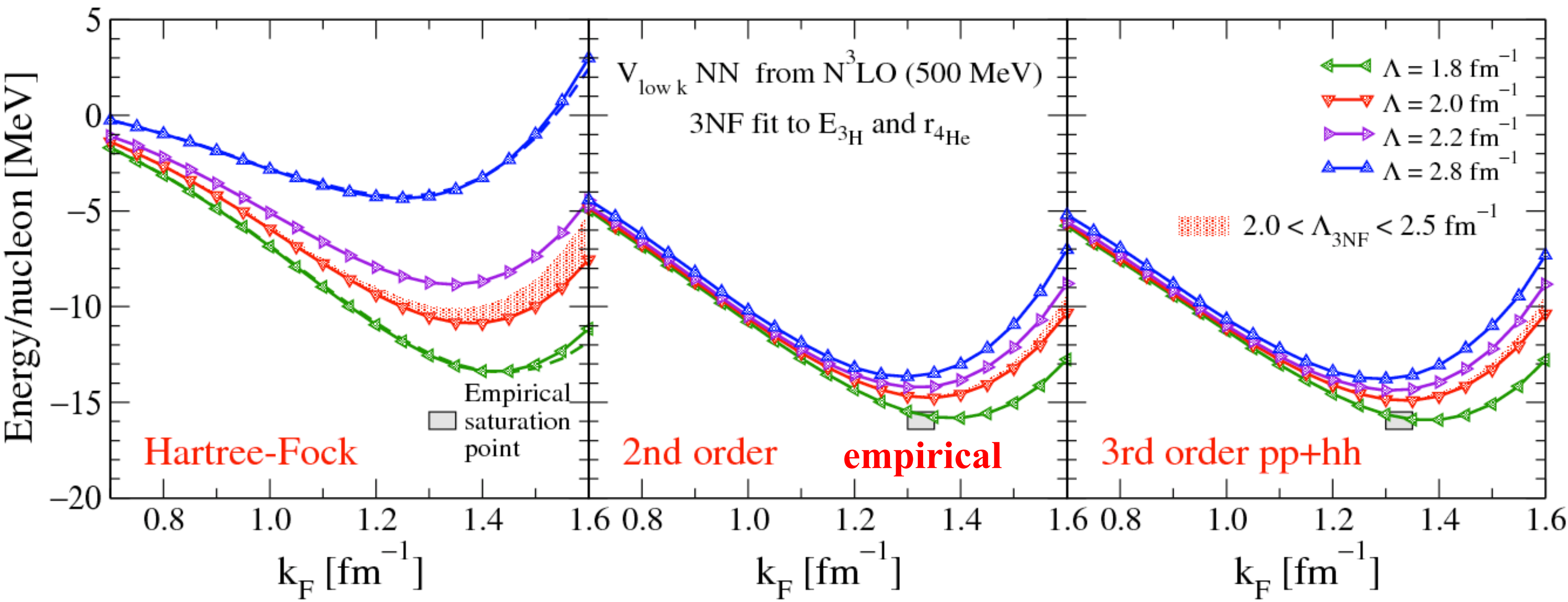
N^{2}LOsat potential fit to nuclei up to A=24

Ekström et al., PRC (2015)



Nuclear forces and nuclear matter

chiral 3N forces fit to light nuclei predict nuclear matter saturation with theoretical uncertainties Hebeler et al., PRC (2011), Bogner et al., NPA (2005)



Resolution of radius problems

good saturation properties essential for radii

N^2LOsat potential fit to nuclei up to A=24

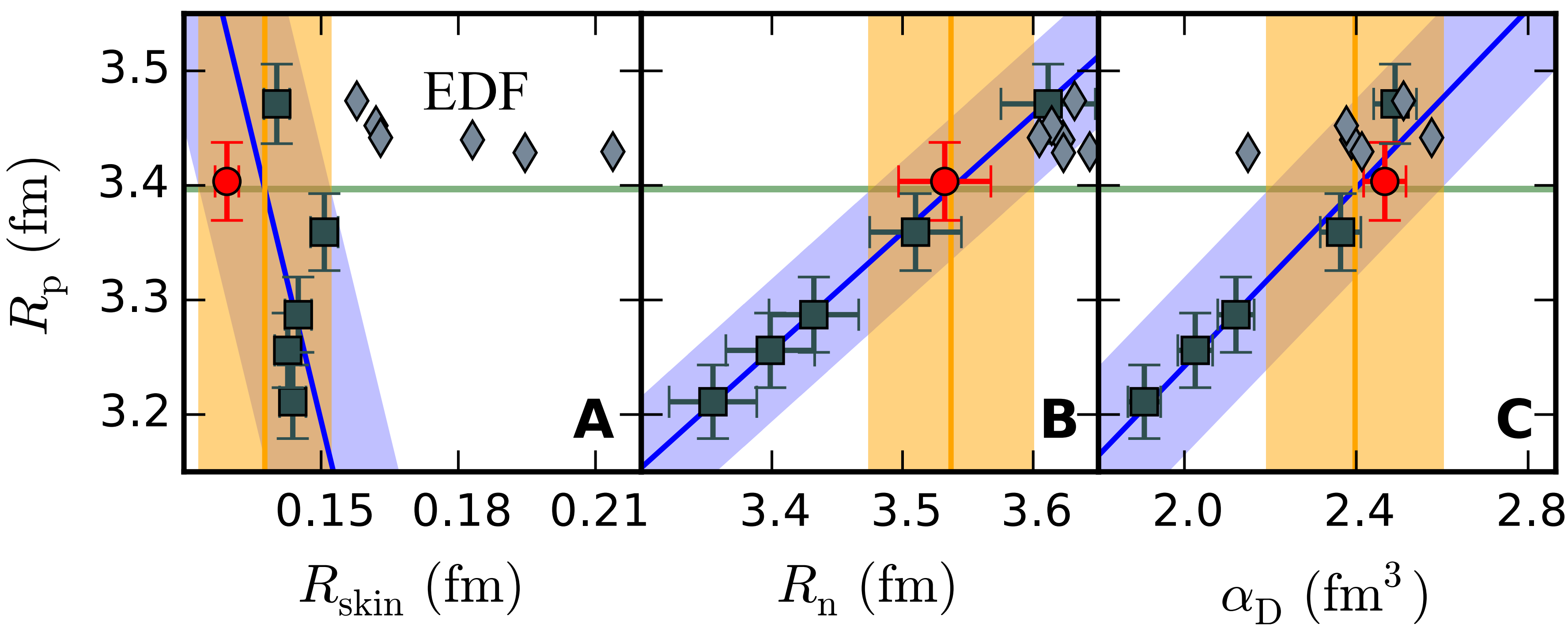
Ekström et al., PRC (2015)

NN+3N interactions that predict nuclear matter saturation

Hebeler et al., PRC (2011) only fit to light nuclei, but nonlocal 3N regulators

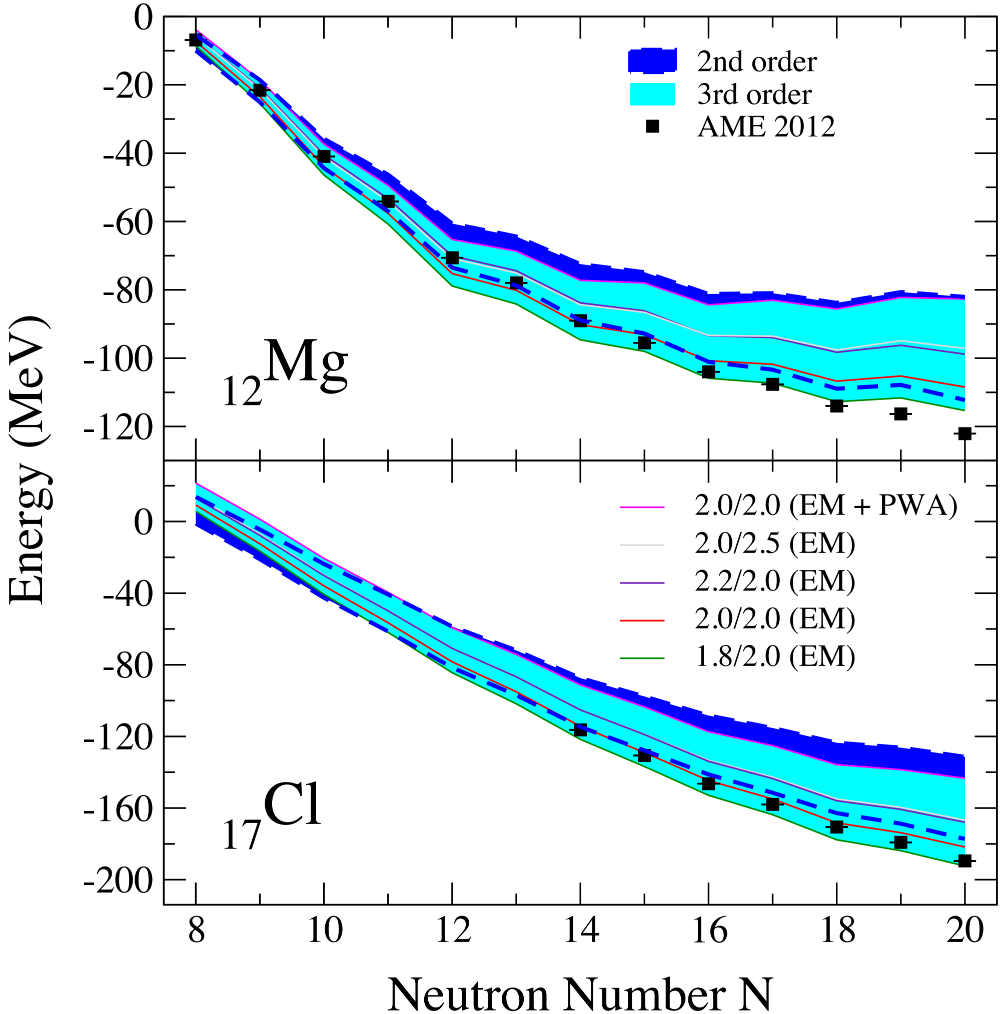
lead to radii consistent with experiment for ^{48}Ca Hagen et al., Nature Phys. (2015)

predict small neutron skin, dipole polarizability, and weak formfactor



Towards theoretical uncertainties Simonis et al., PRC (2016)

based on NN+3N interactions (sd shell)
that predict nuclear matter saturation within uncertainties



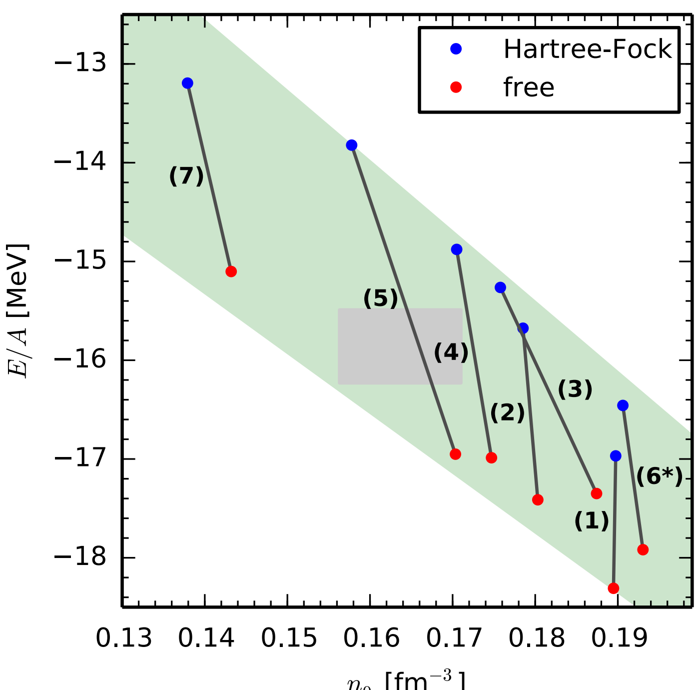
Theoretical uncertainties dominated by uncertainties in nuclear forces!

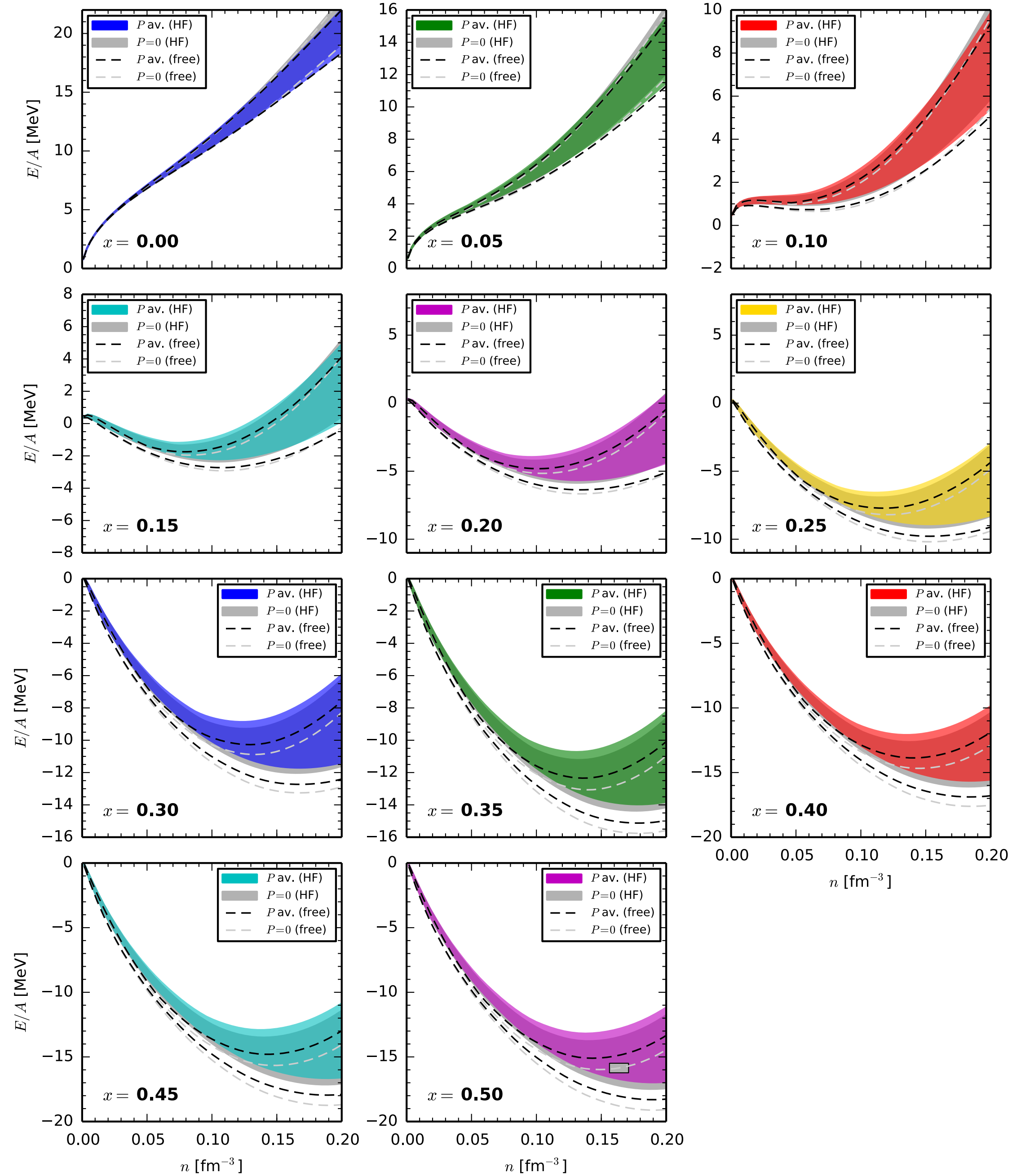
Nuclear forces and nuclear matter

first results for asymmetric matter with improved treatment of 3N forces

Drischler, Hebeler, AS, PRC (2016)

see also Holt, Kaiser, Weise, Wellenhofer

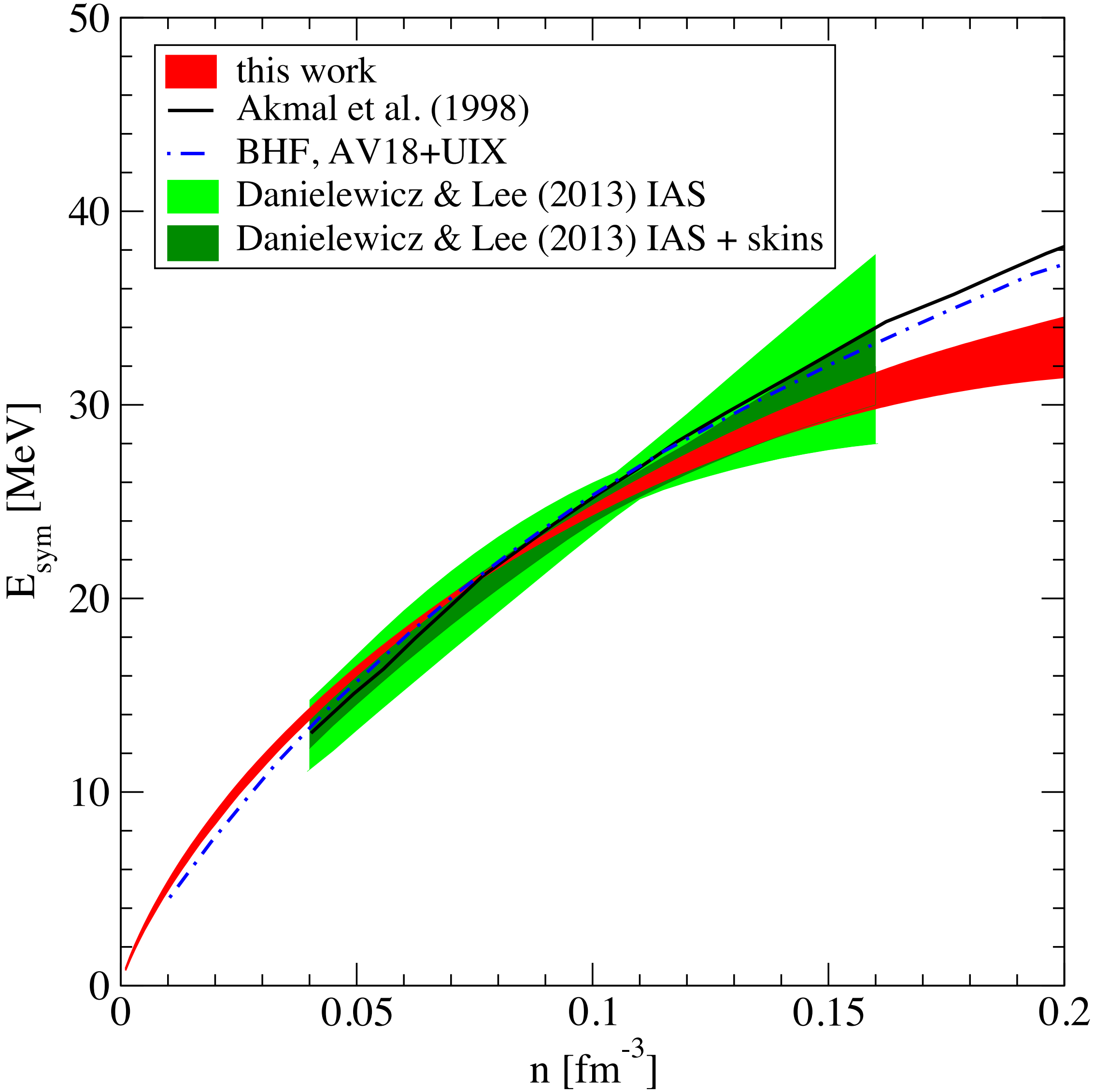




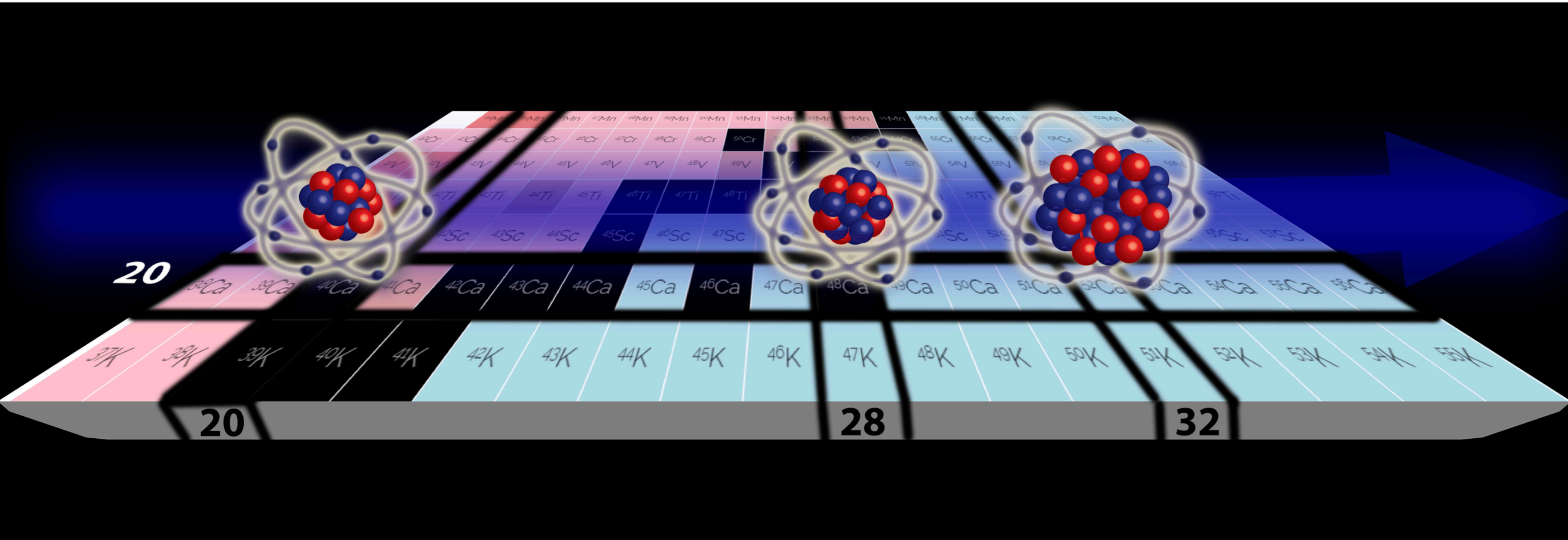
Calculations of asymmetric matter Drischler, Soma, AS, PRc (2014)

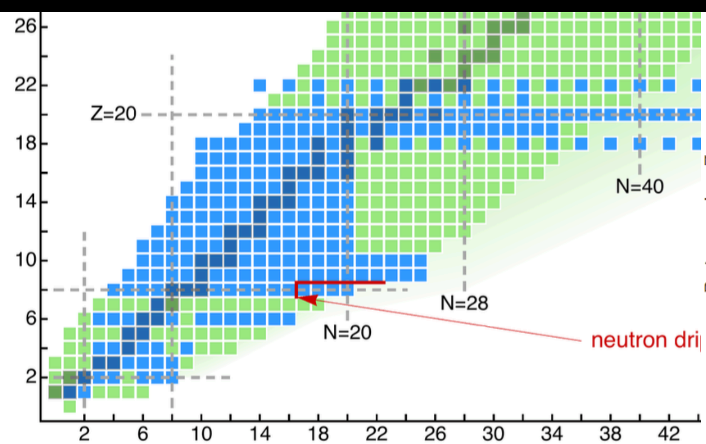
E_{sym} comparison with extraction from isobaric analogue states (IAS)

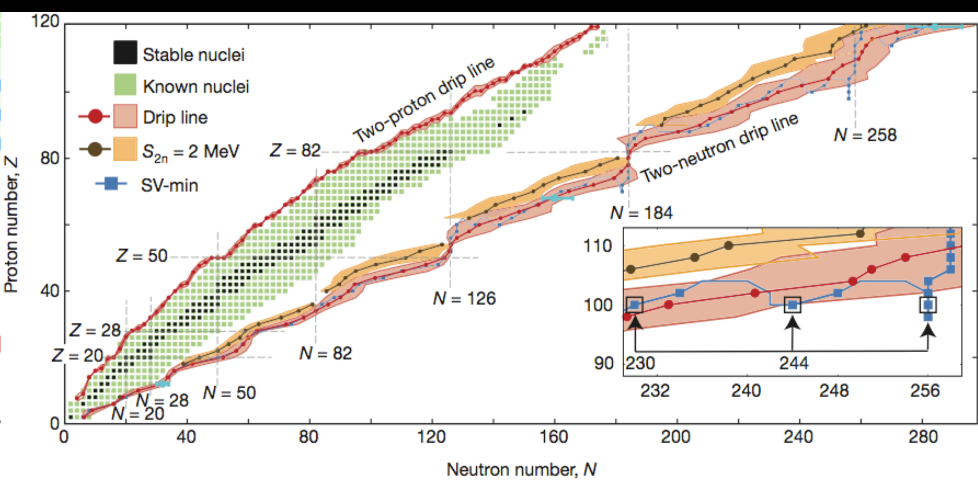
3N forces fit to ^{3}H, ^{4}He properties only



Neutron-rich calcium isotopes







Frontier of ab initio calculations at A~50

doi:10.1038/nature12226

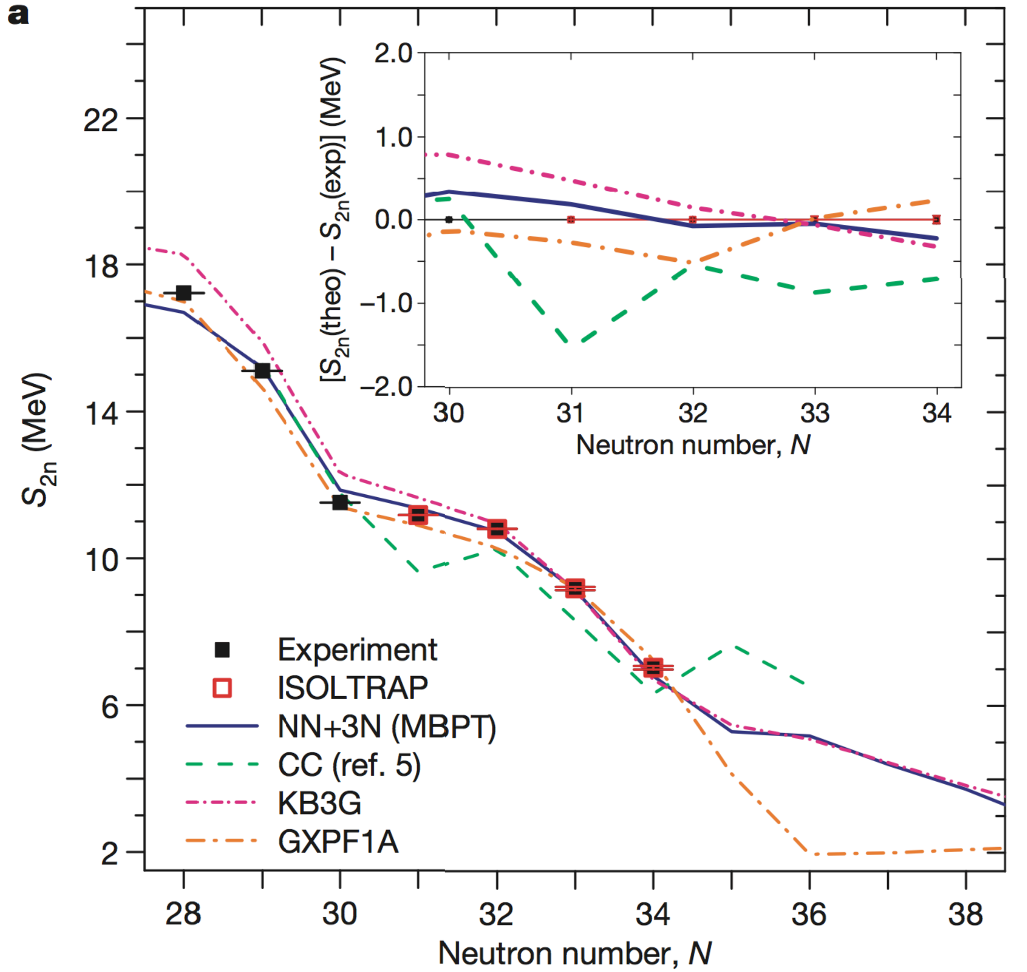
Masses of exotic calcium isotopes pin down nuclear forces

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/CERN using new MR-TOF mass spectrometer

excellent agreement with theoretical NN+3N prediction

suggests N=32 shell closure



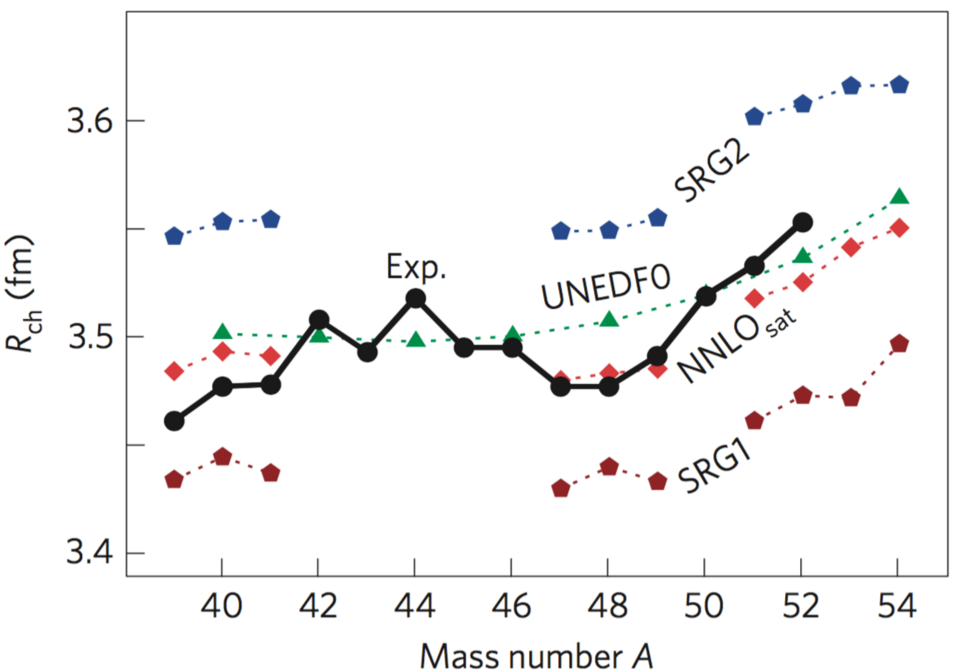
nature physics

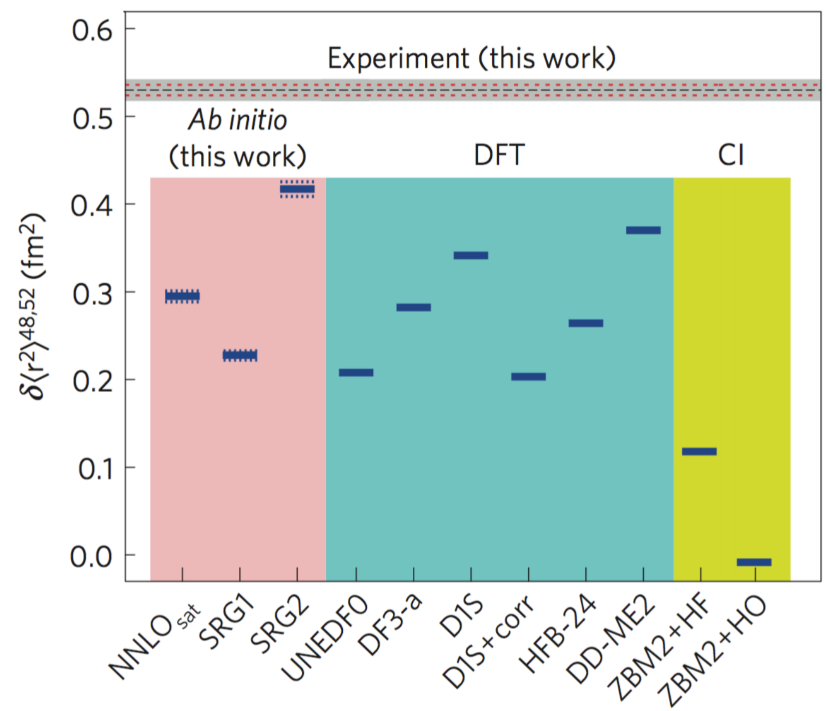
ARTICLES

PUBLISHED ONLINE: 8 FEBRUARY 2016 | DOI: 10.1038/NPHYS3645

Unexpectedly large charge radii of neutron-rich calcium isotopes

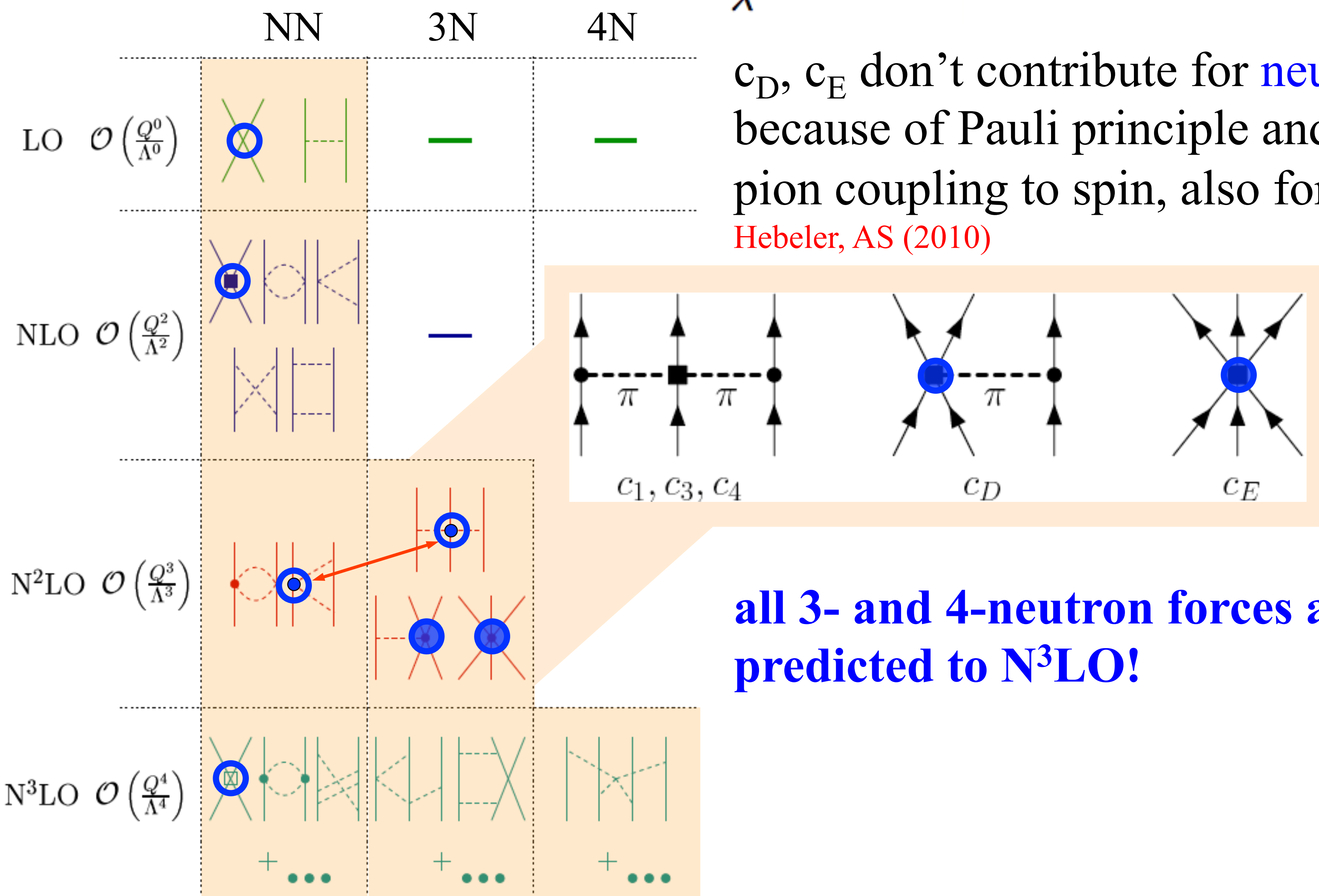
R. F. Garcia Ruiz[1★], M. L. Bissell[1,2], K. Blaum[3], A. Ekström[4,5], N. Frömmgen[6], G. Hagen[4], M. Hammen[6], K. Hebeler[7,8], J. D. Holt[9], G. R. Jansen[4,5], M. Kowalska[10], K. Kreim[3], W. Nazarewicz[4,11,12], R. Neugart[3,6], G. Neyens[1], W. Nörtershäuser[6,7], T. Papenbrock[4,5], J. Papuga[1], A. Schwenk[3,7,8], J. Simonis[7,8], K. A. Wendt[4,5] and D. T. Yordanov[3,13]





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)

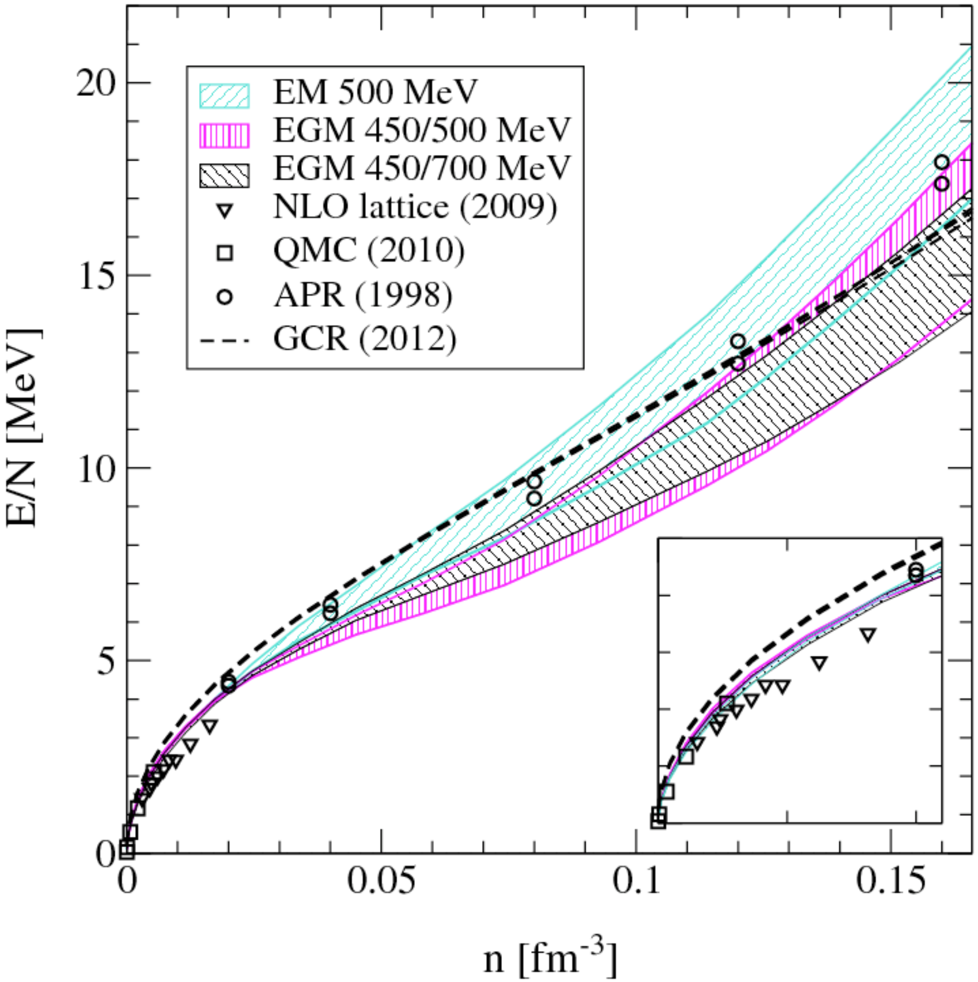
all 3- and 4-neutron forces are predicted to N^{3}LO!

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

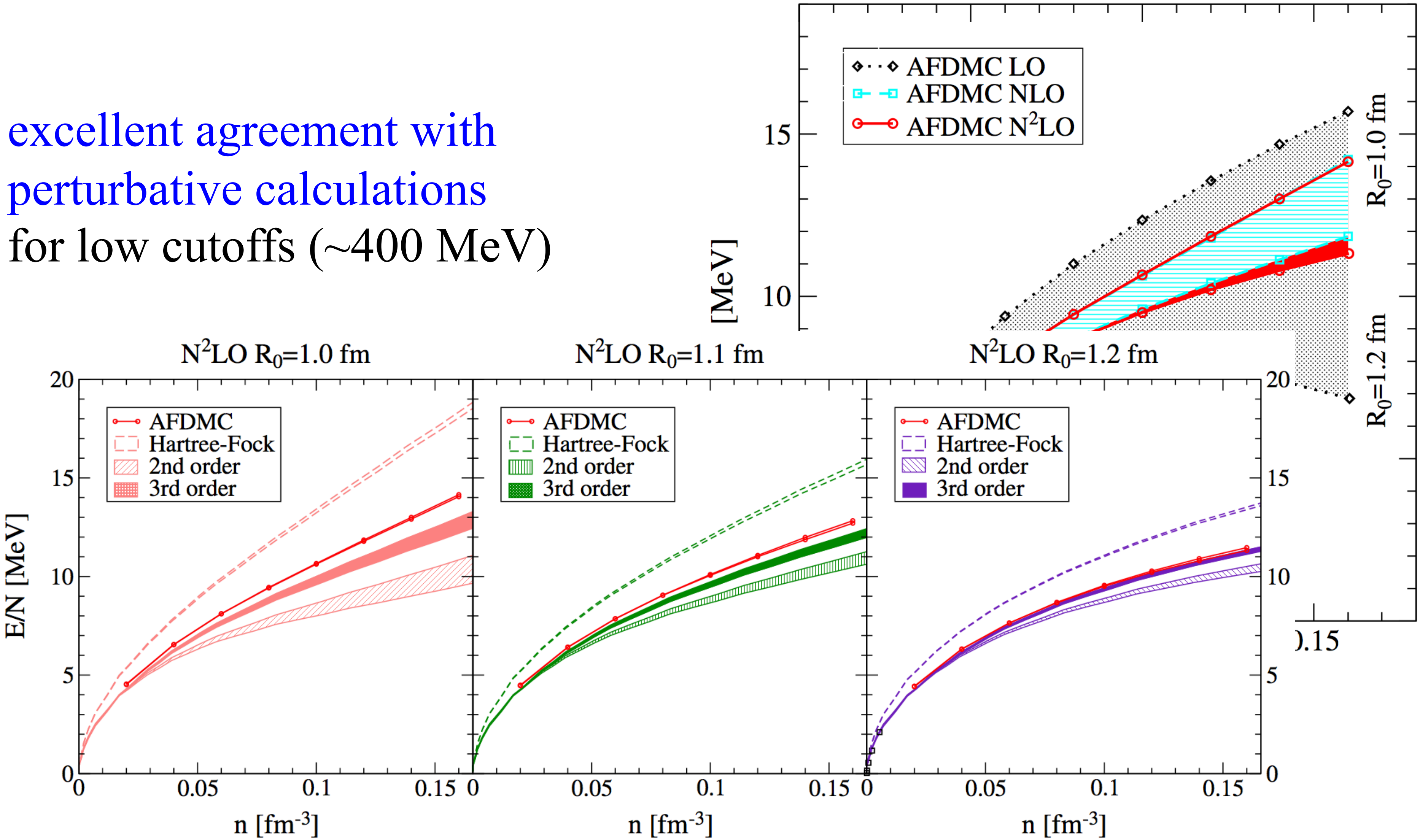
new QMC benchmarks with local chiral potentials
Gezerlis, Lynn, Tews et al.

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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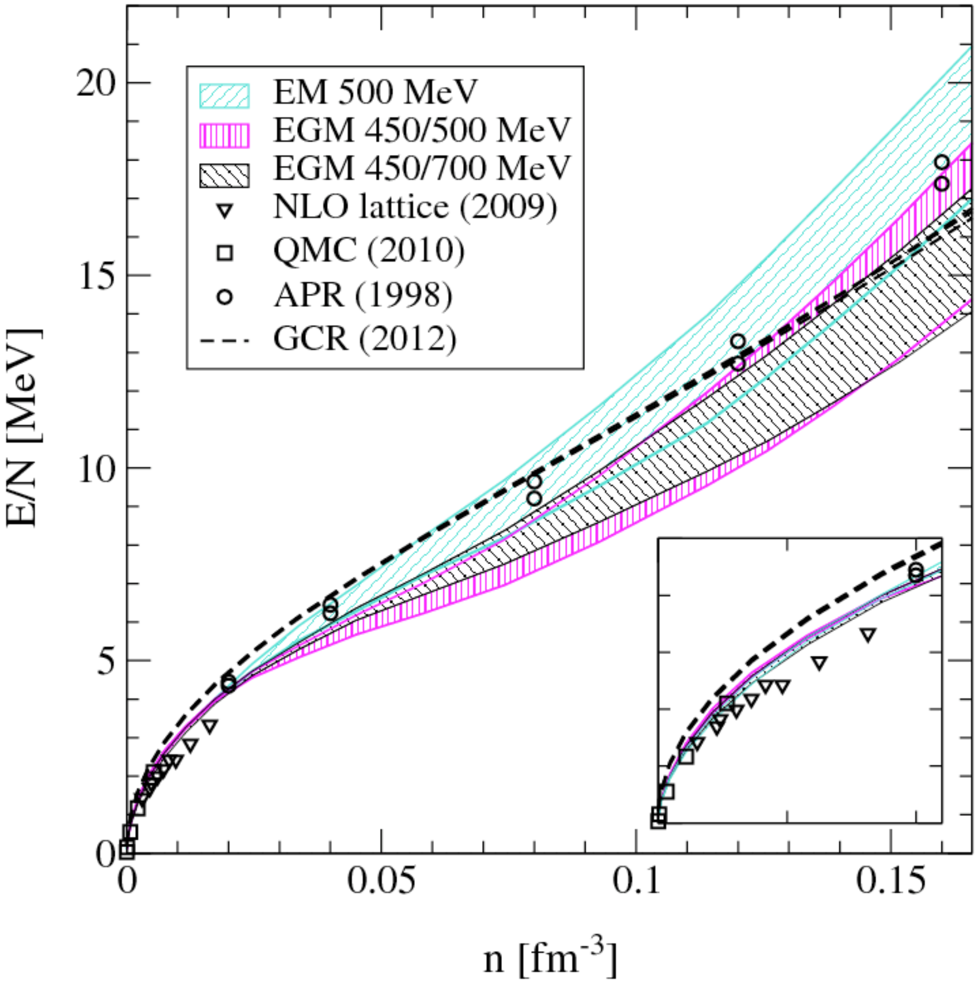

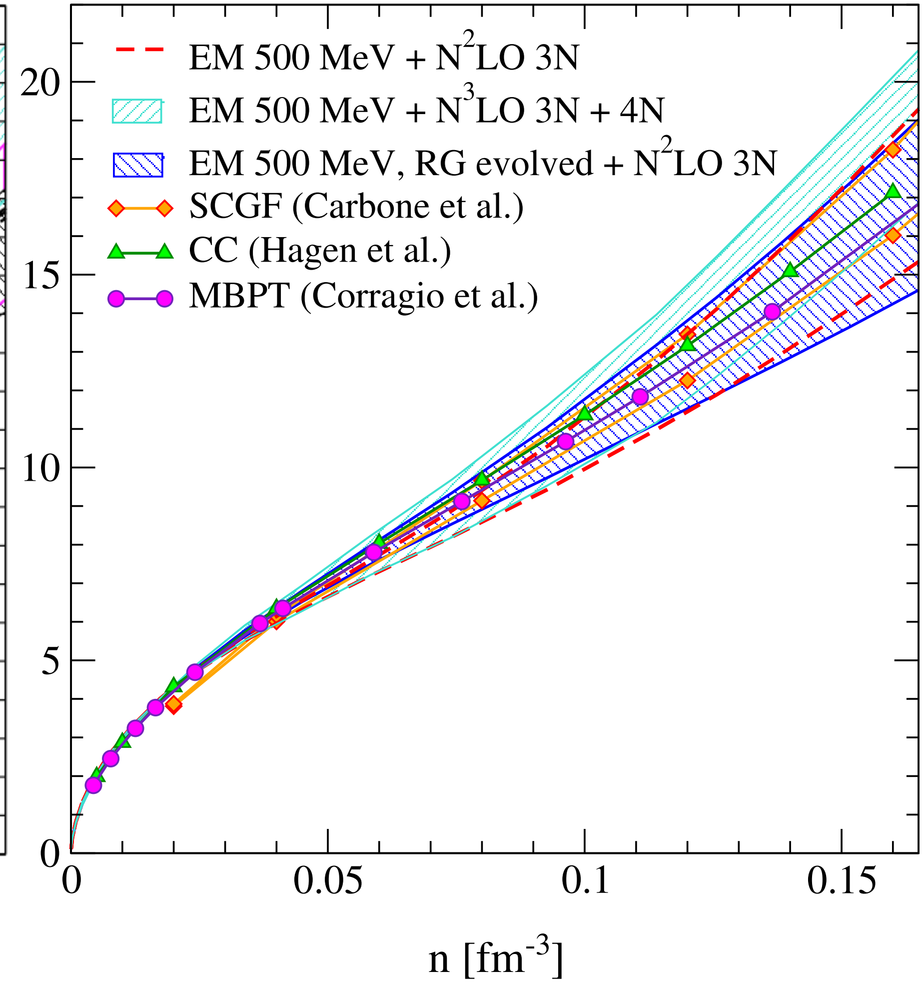

excellent agreement with other methods!

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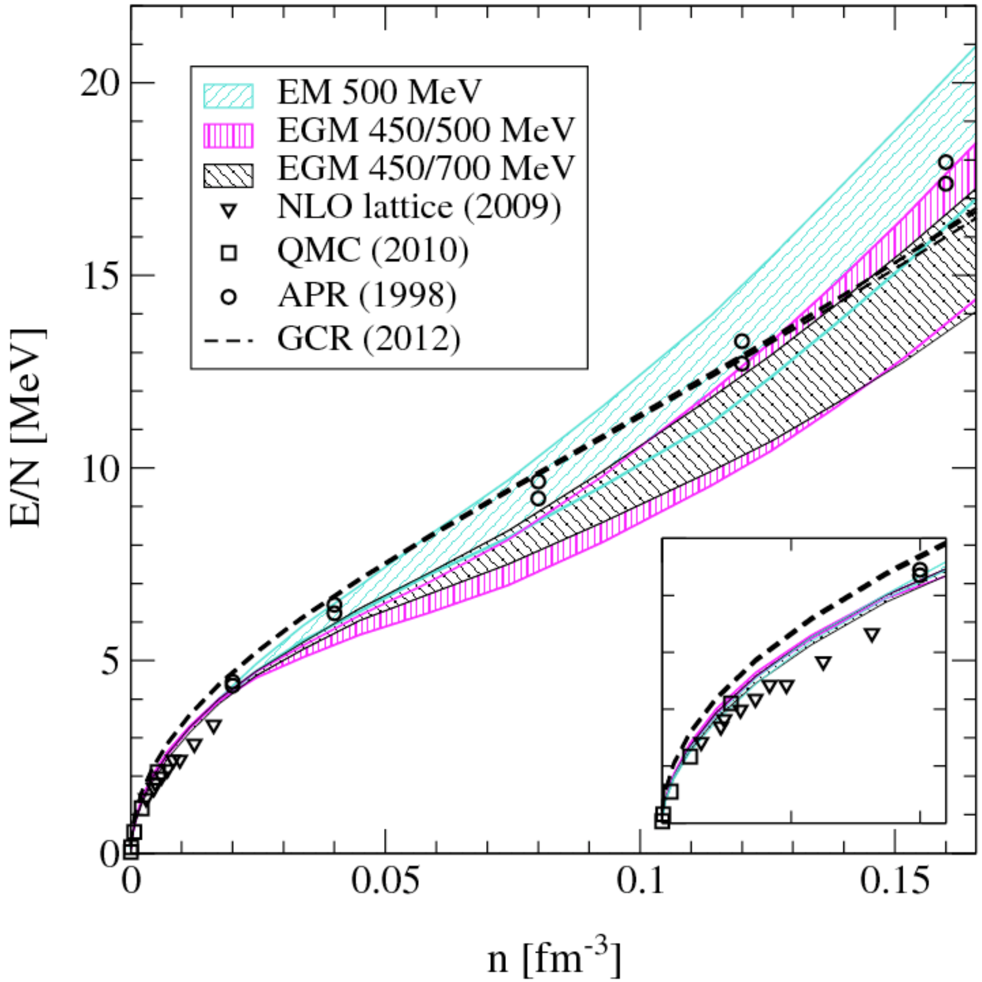
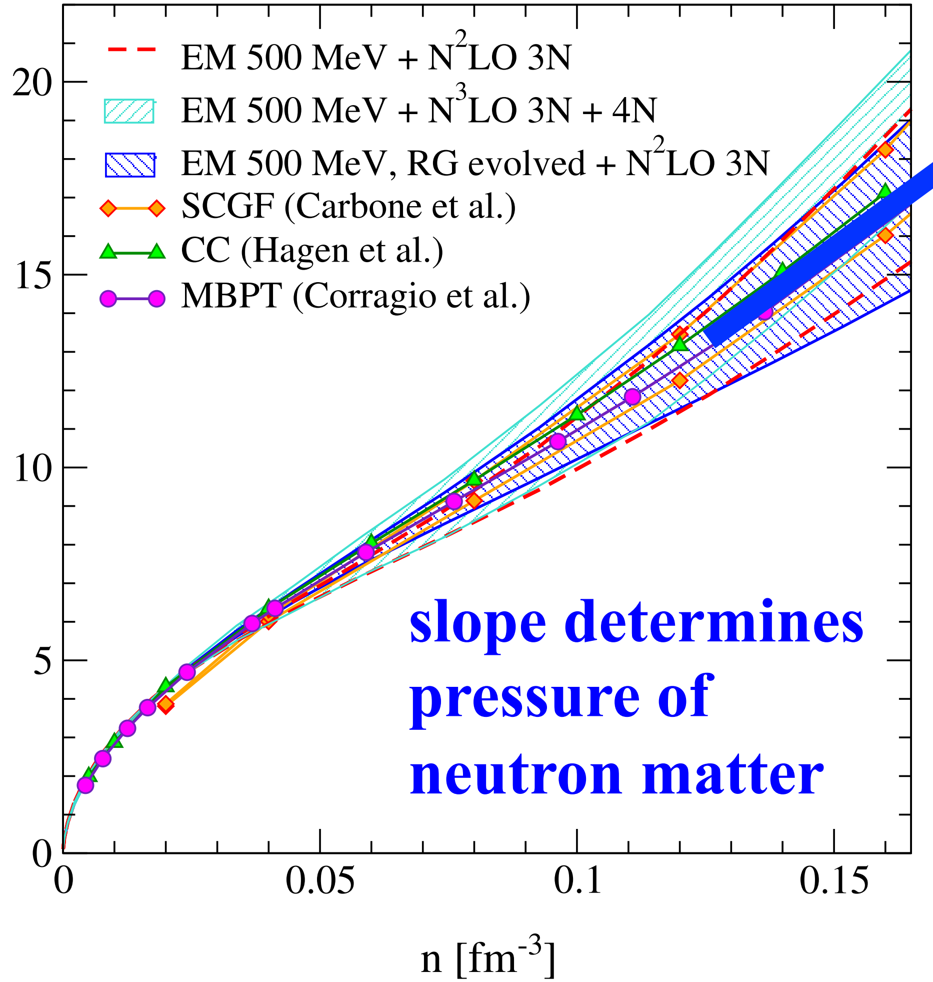




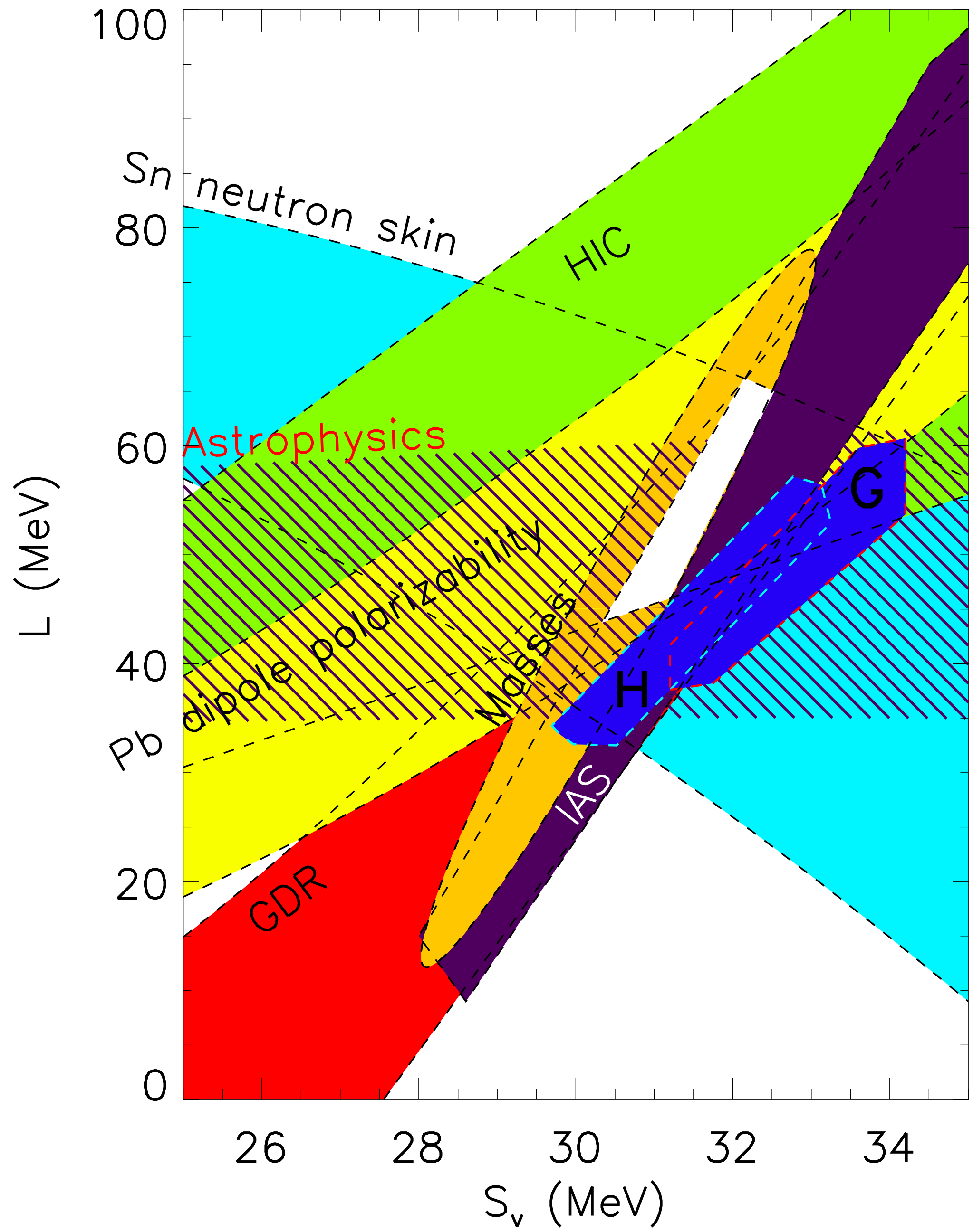
excellent agreement with other methods!

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)

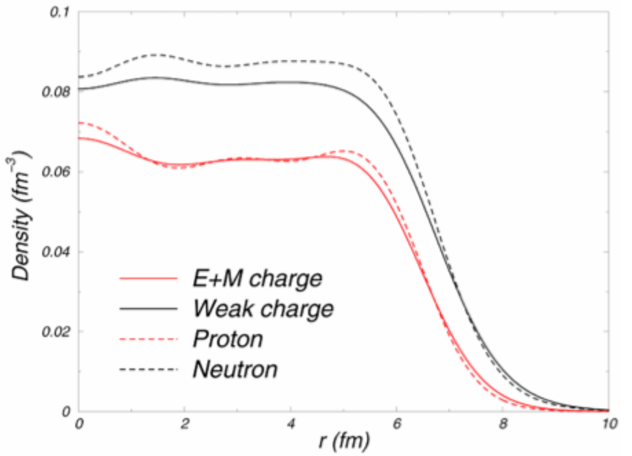
neutron matter constraints
H: Hebeler et al. (2010)
G: Gandolfi et al. (2011)
provide tight constraints!

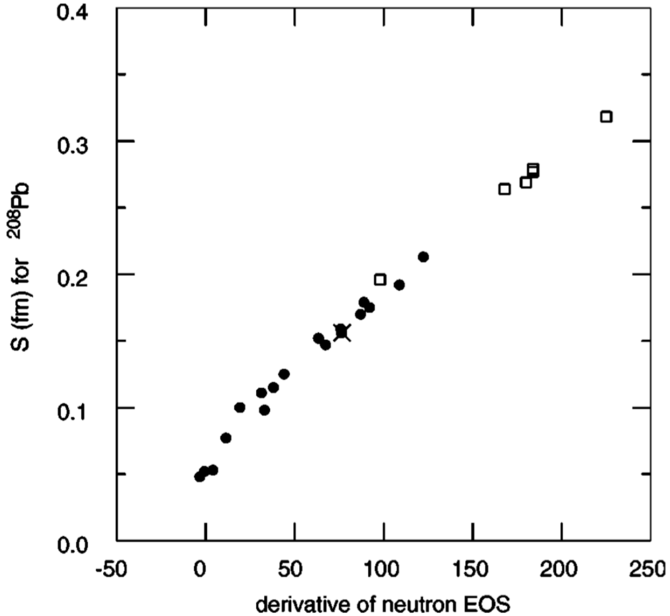


Neutron skin of ^{208}Pb

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

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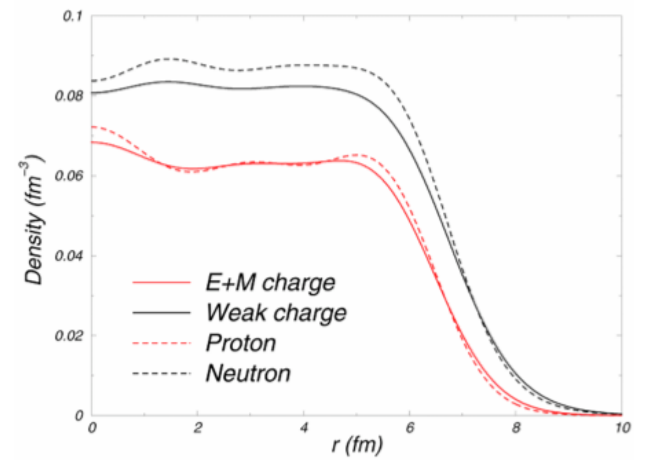
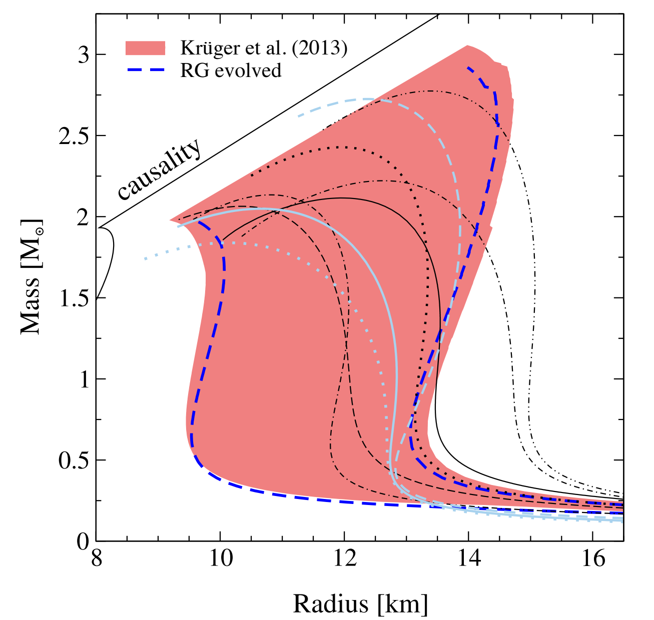
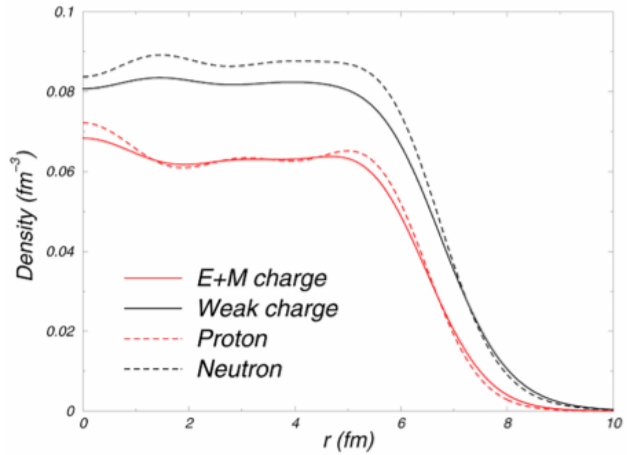


same interactions lead to neutron star
radius: 9.7-13.9 km for M=1.4 M_{sun} (±18%)
Hebeler, Lattimer, Pethick, AS, PRL (2010), ApJ (2013)



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 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 skin of ^{48}Ca

nature physics

ARTICLES

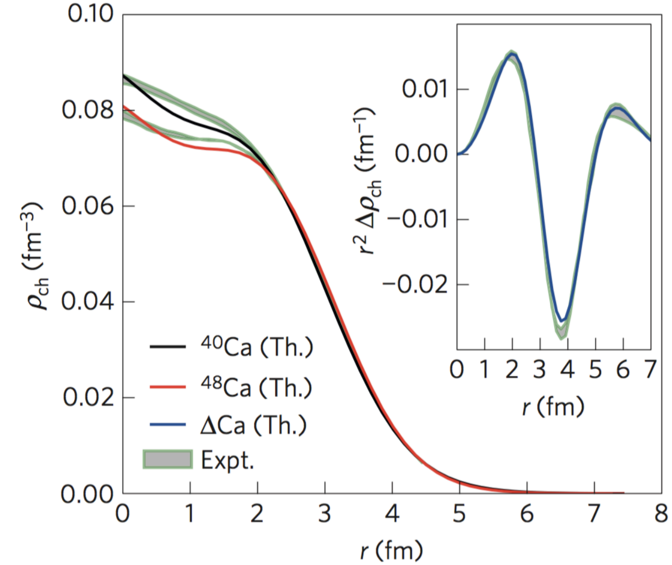
PUBLISHED ONLINE: 2 NOVEMBER 2015 | DOI: 10.1038/NPHYS3529

Neutron and weak-charge distributions of the ^{48}Ca nucleus

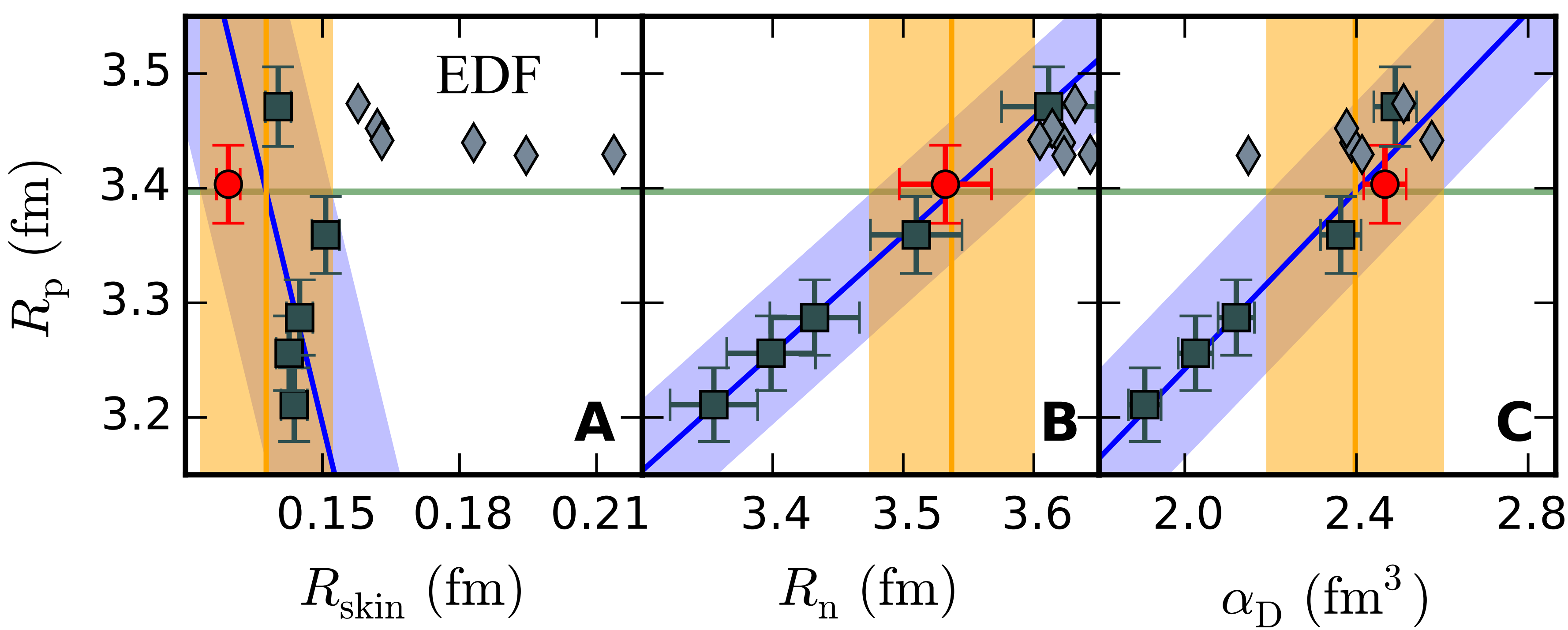
G. Hagen[1,2*], A. Ekström[1,2], C. Forssén[1,2,3], G. R. Jansen[1,2], W. Nazarewicz[1,4,5], T. Papenbrock[1,2], K. A. Wendt[1,2], S. Bacca[6,7], N. Barnea[8], B. Carlsson[3], C. Drischler[9,10], K. Hebeler[9,10], M. Hjorth-Jensen[4,11], M. Miorelli[6,12], G. Orlandini[13,14], A. Schwenk[9,10] and J. Simonis[9,10]

Neutron and weak-charge distributions of ^{48}Ca

ab initio calculations lead to charge distributions consistent with experiment

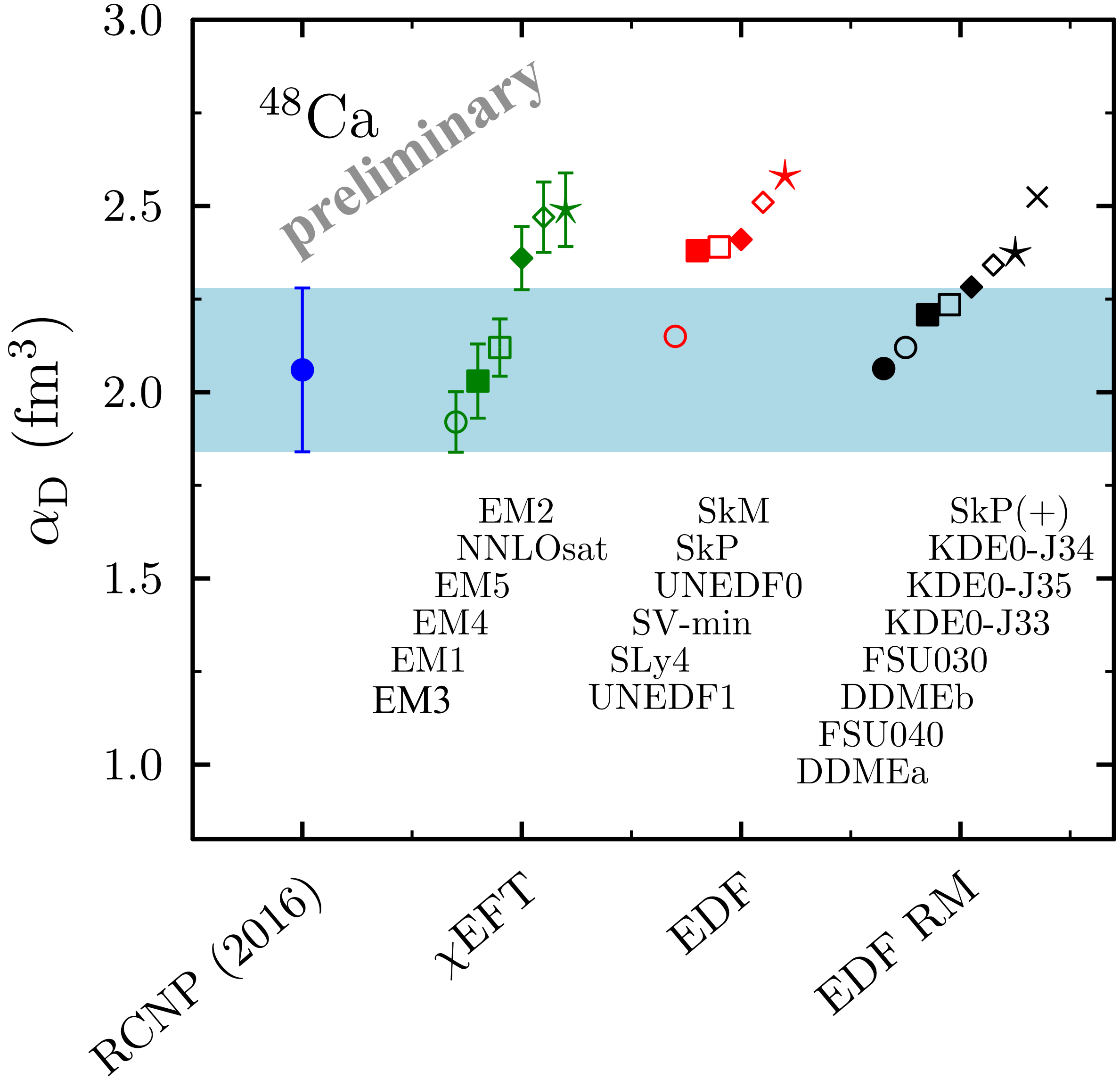


predict small neutron skin, dipole polarizability, and weak formfactor



Dipole polarizability of ^{48}Ca

see Peter vNC's talk (Darmstadt-Osaka collaboration)



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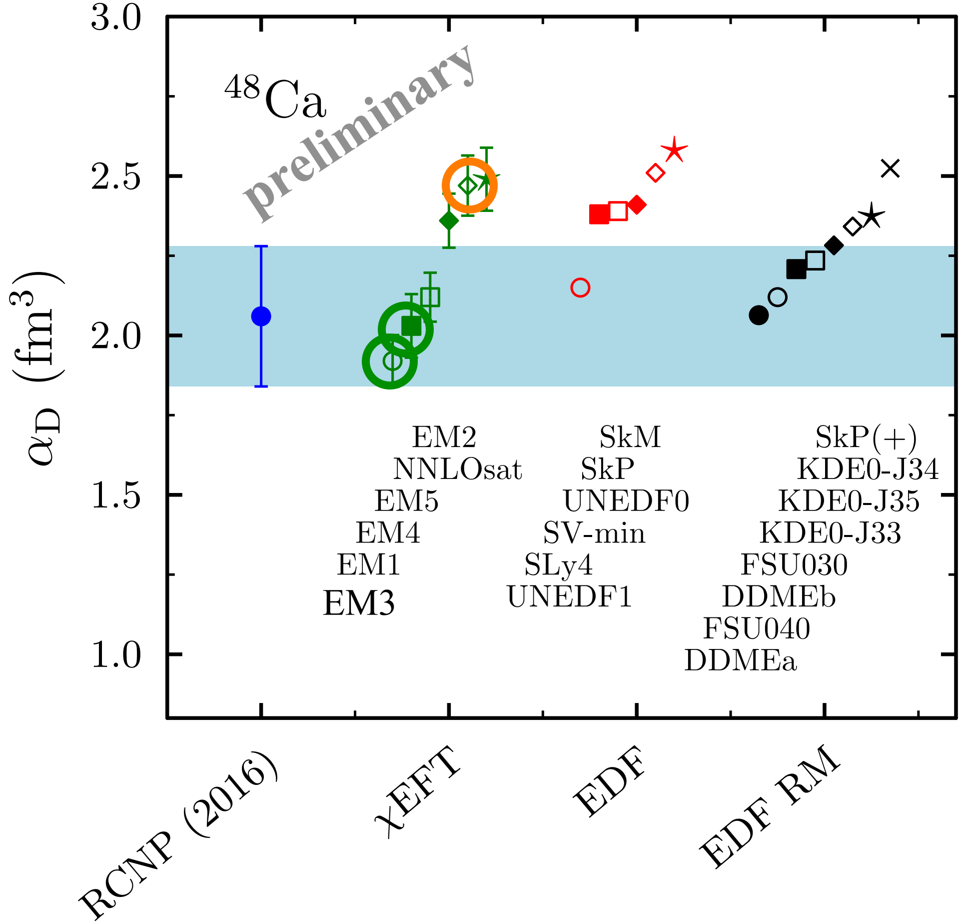
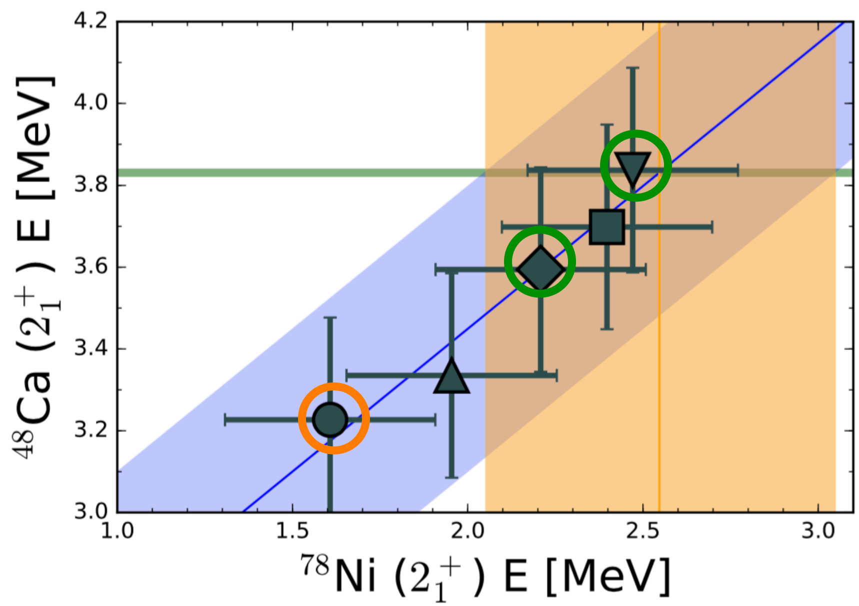
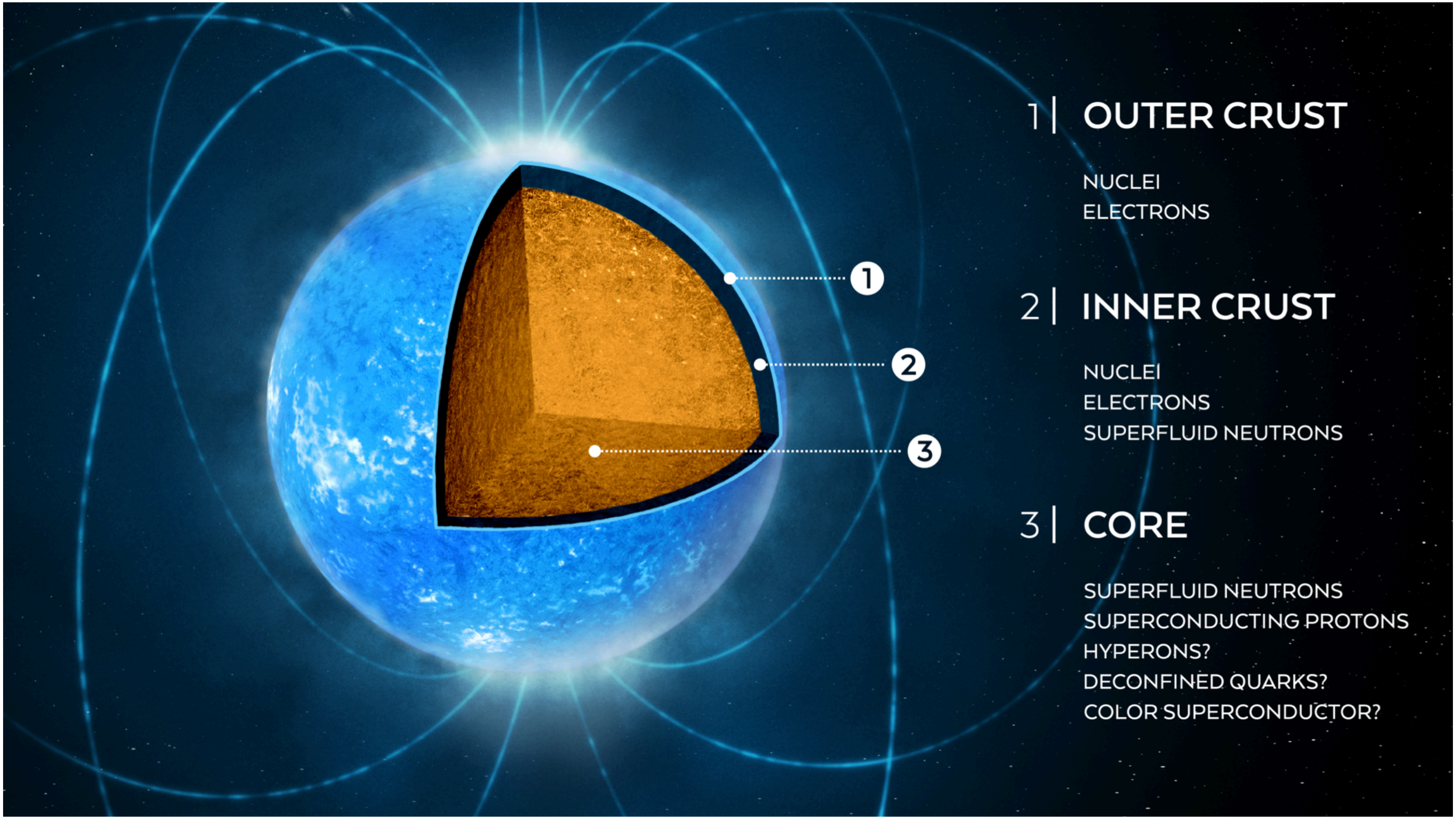


sensitive to
neutron matter properties
and strong shell closure



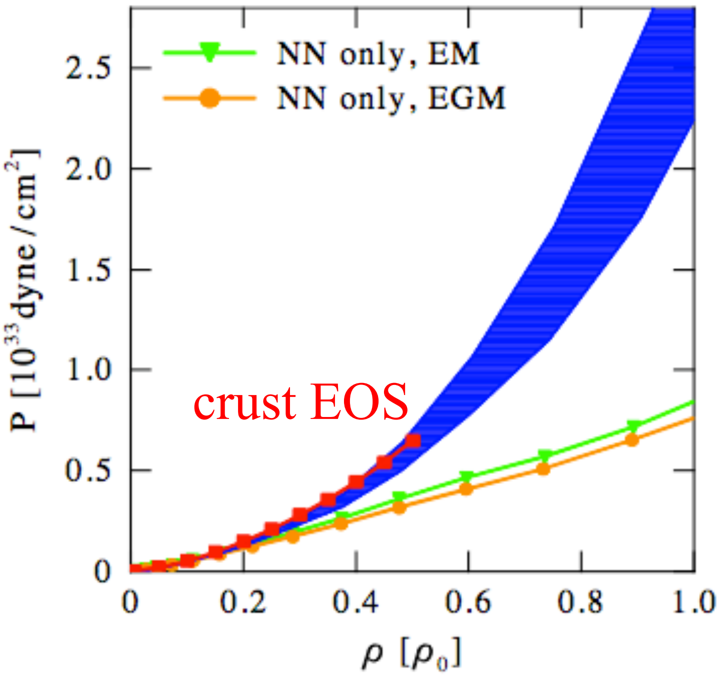
Hagen et al., 1605.01477

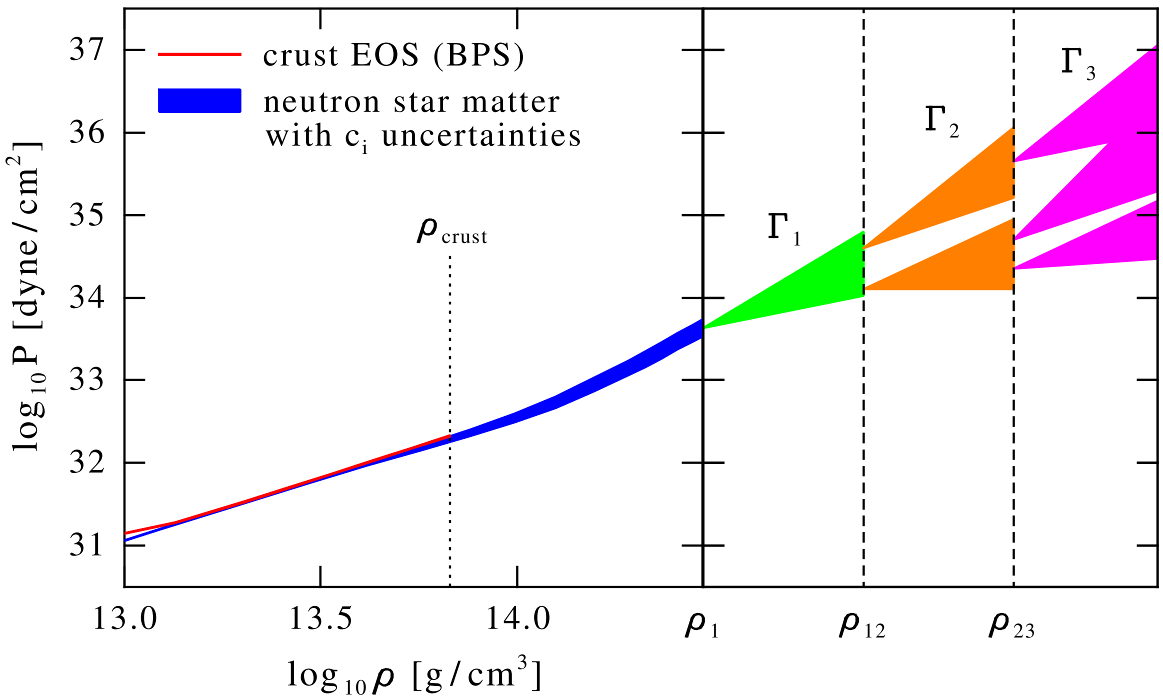
Neutron matter and neutron stars



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

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



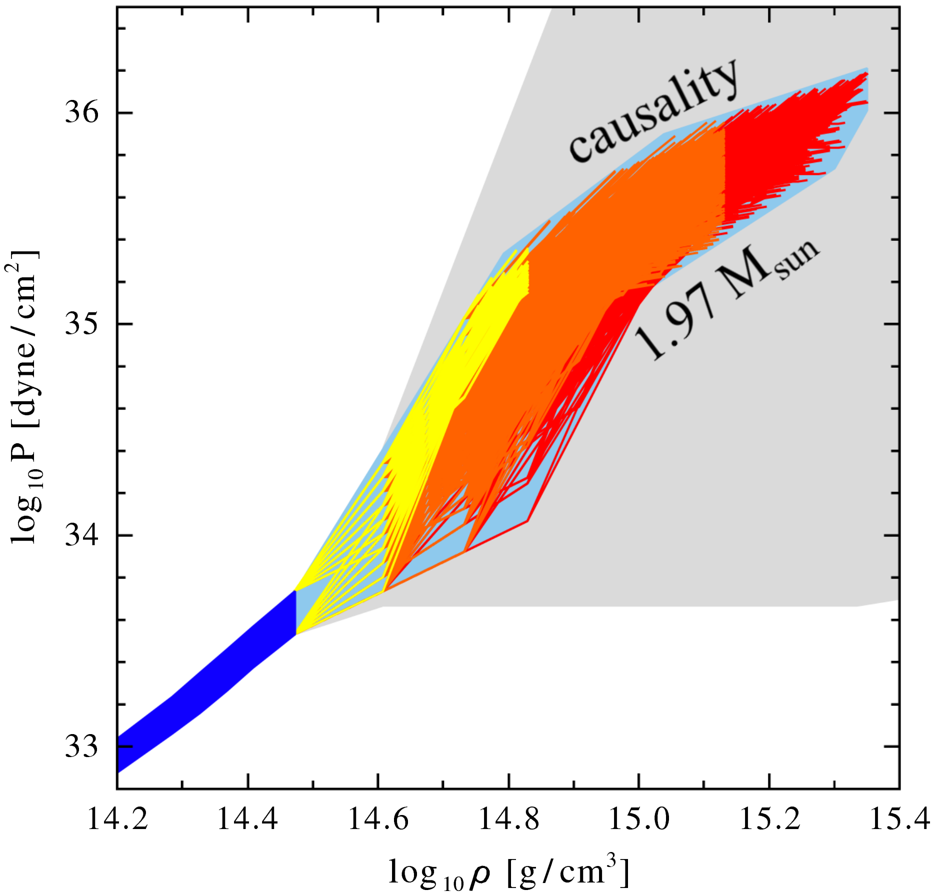


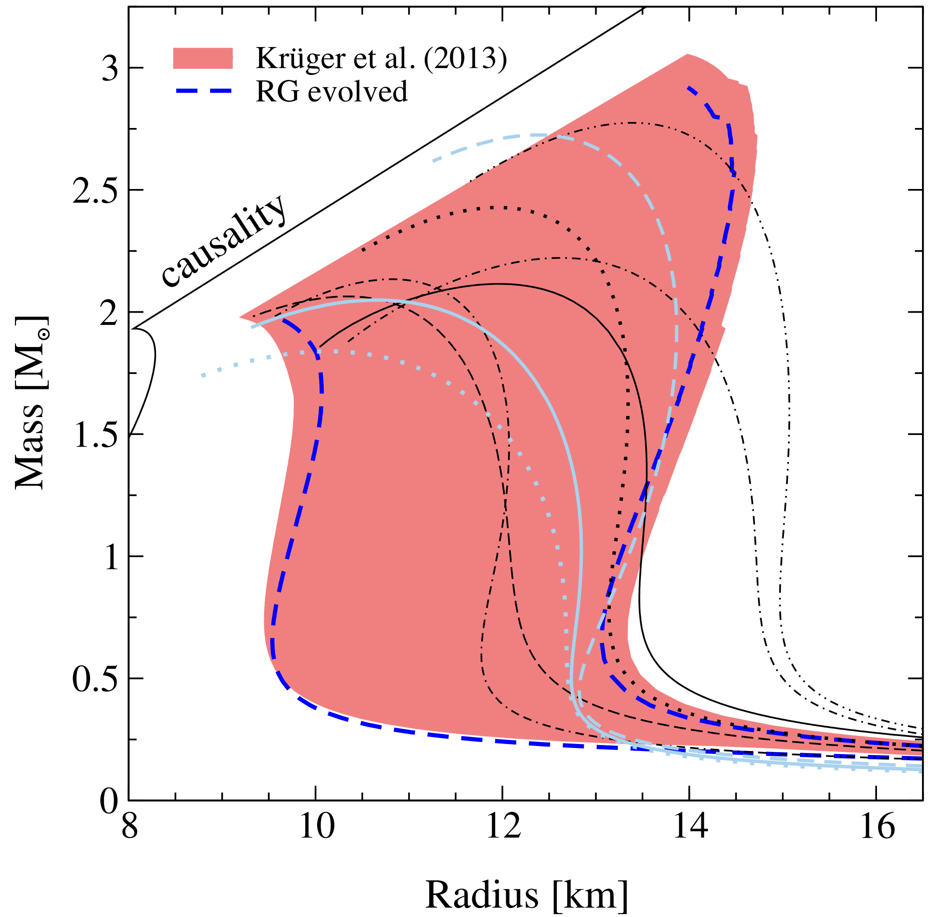
pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

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





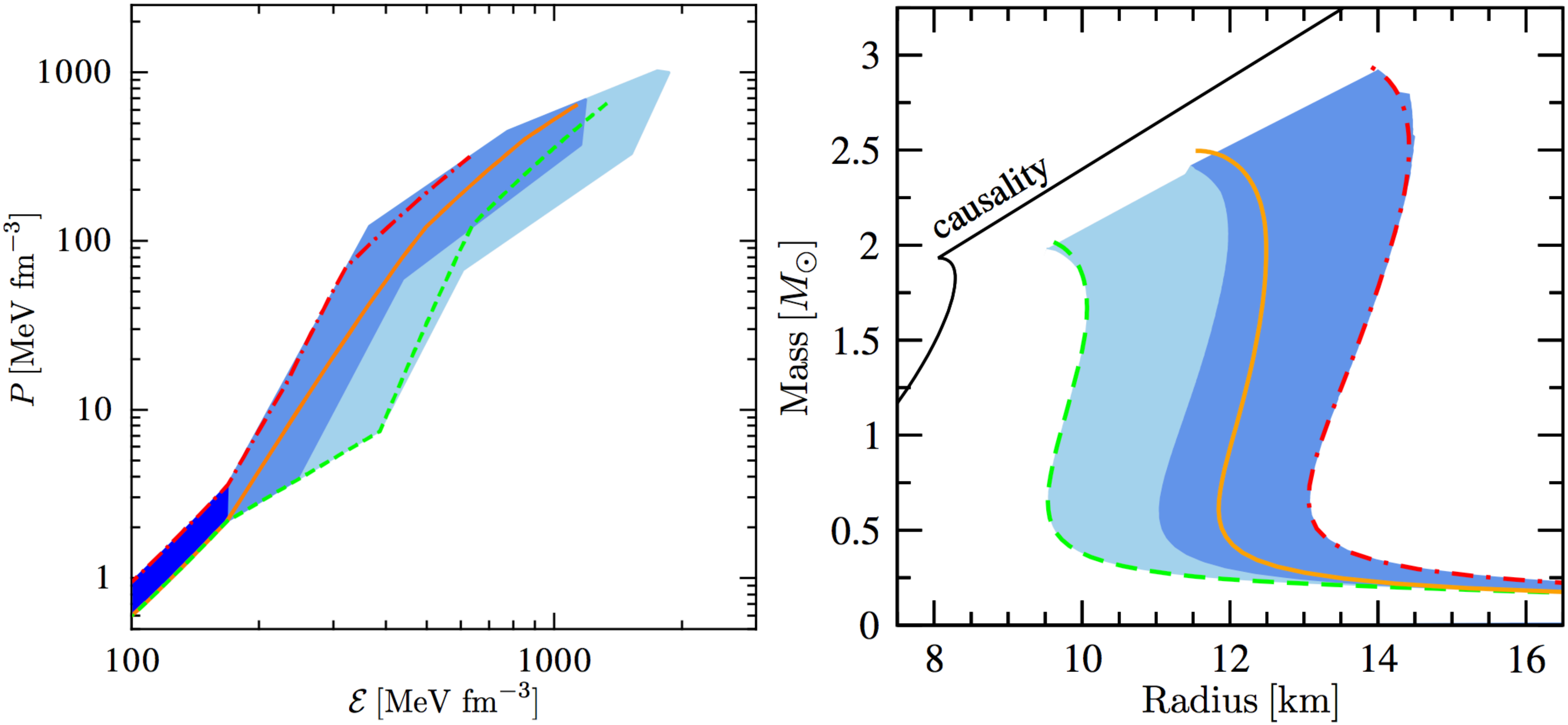
low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

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

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)

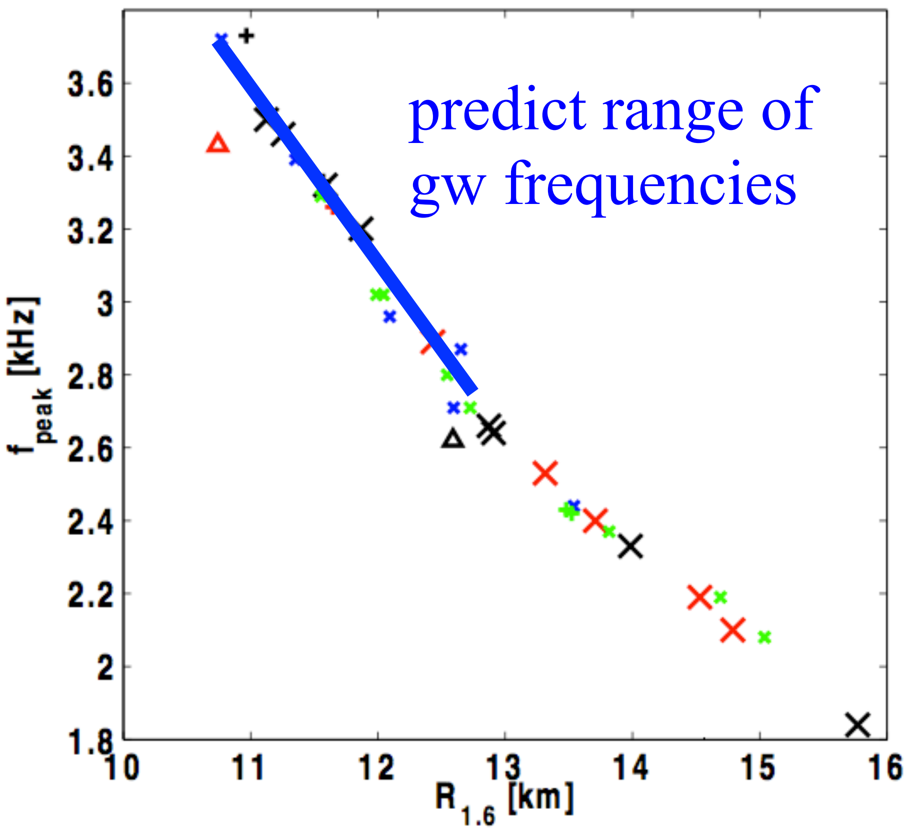
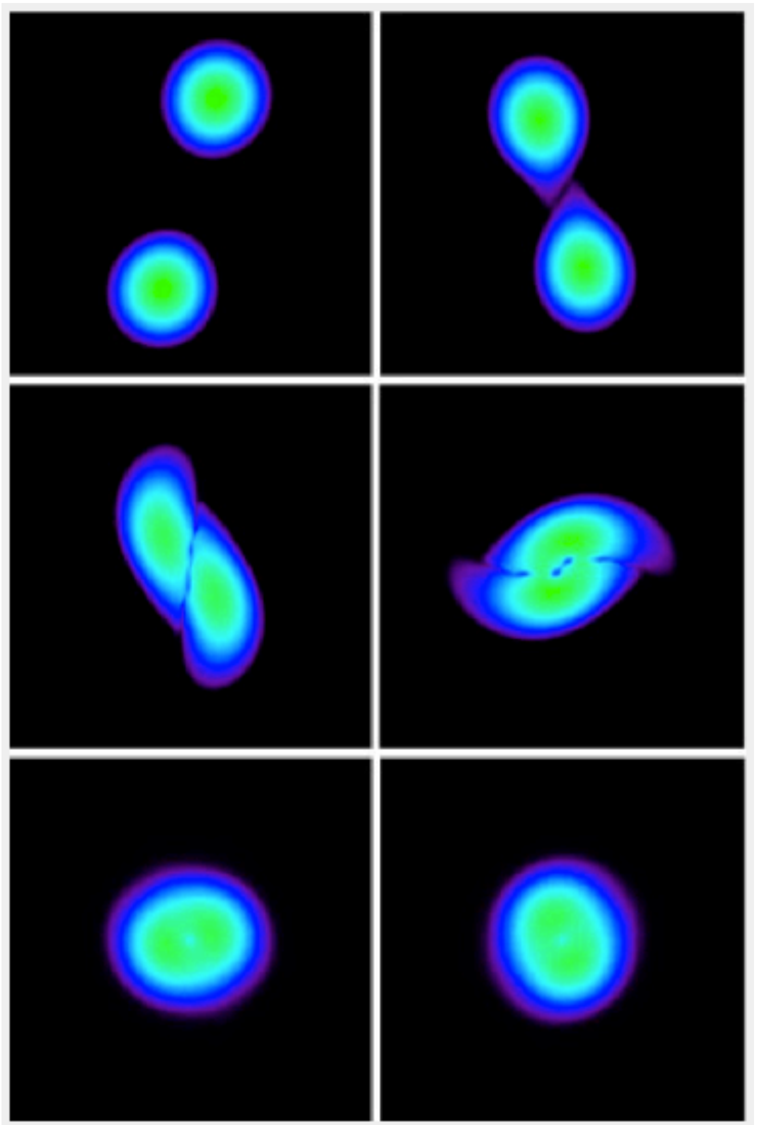
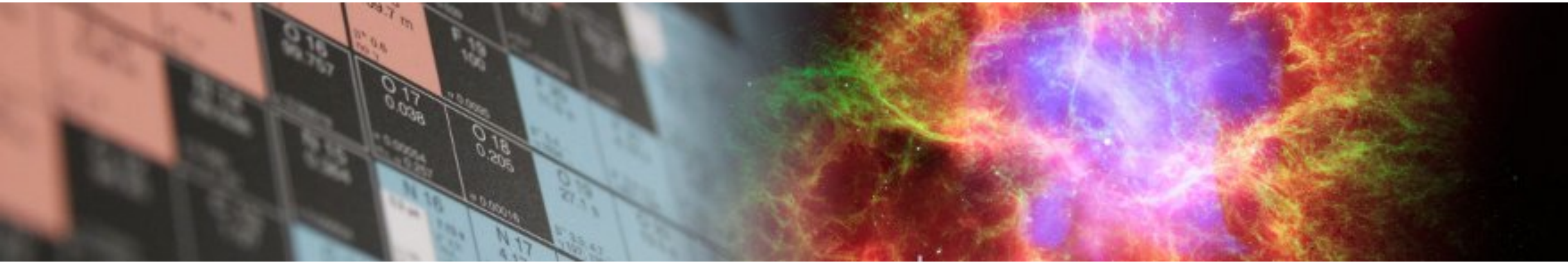


FIG. 10: Peak frequency of the postmerger GW emission versus the radius of a nonrotating NS with 1.6 $M_\odot$ for different EoSs. Symbols have the same meaning as in Fig. 8.



Summary

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



Nuclear forces and powerful many-body calculations are an exciting frontier for nuclear physics and astrophysics

impact on neutron-rich nuclei and neutron stars

^{48}Ca: meeting point for theory from ab initio to DFT
and for experiment from electromagnetic, weak, hadronic probes

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