Dense matter from nuclear forces

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TECHNISCHE
UNIVERSITÄT
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EMMI

INT Program "The Phases of Dense Matter"
Aug. 8, 2016

DFG

SFB 1245

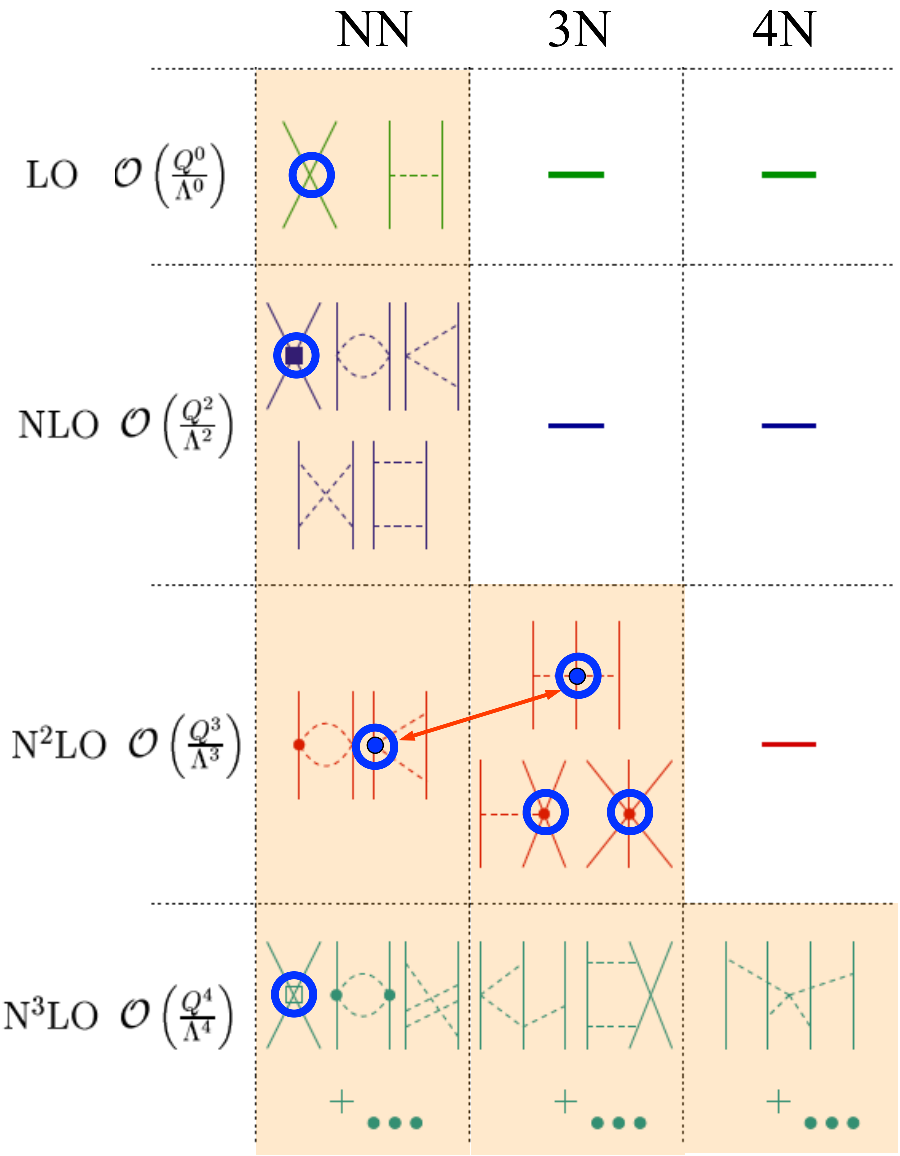
erc

Bundesministerium
für Bildung
und Forschung

HELMHOLTZ
ASSOCIATION

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**

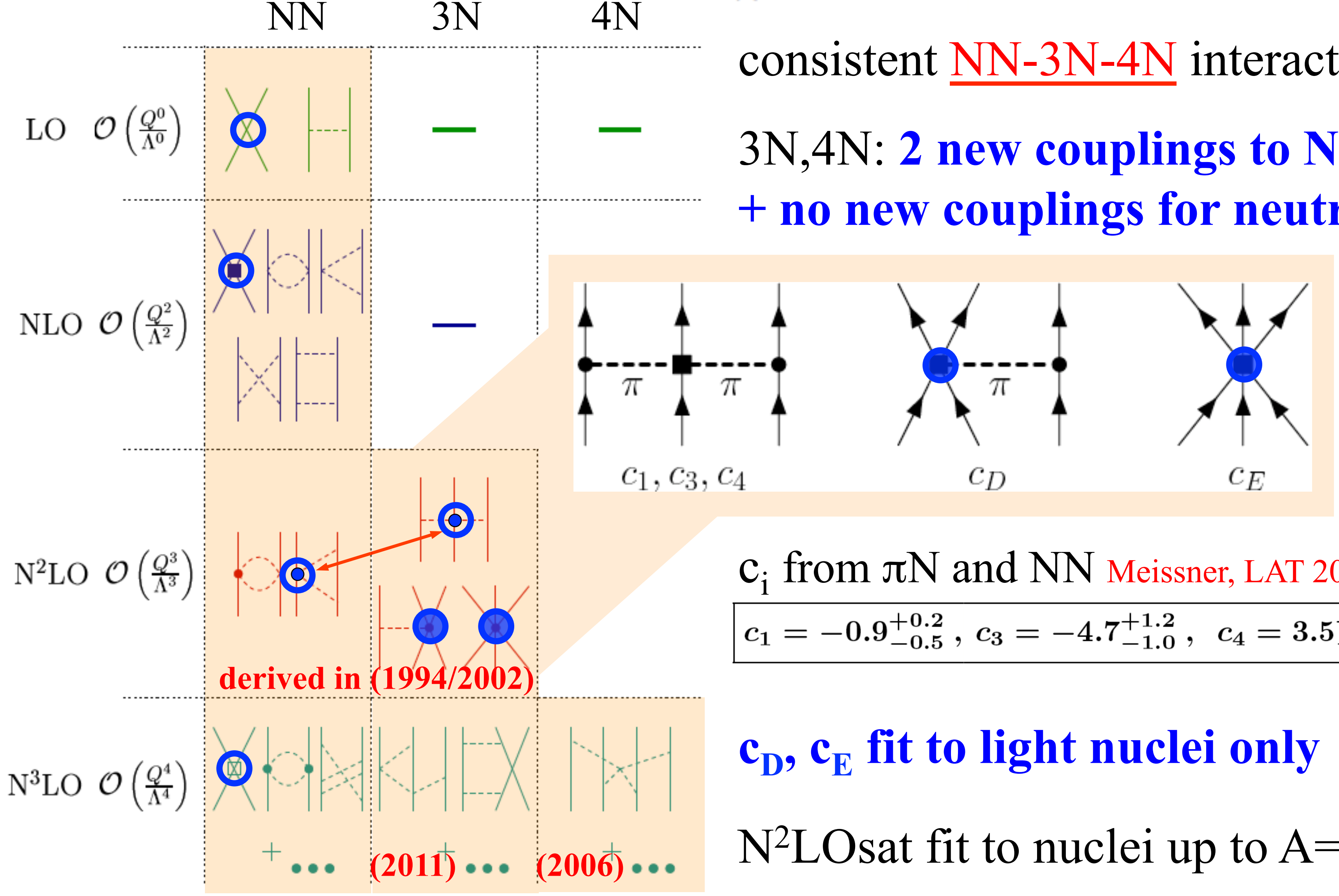
consistent **electroweak interactions**
and **matching to lattice QCD**

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 $\frac{1}{\lambda} = Q \ll \Lambda_\mathrm{b}$ 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

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

c$_D$, c$_E$ fit to light nuclei only

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

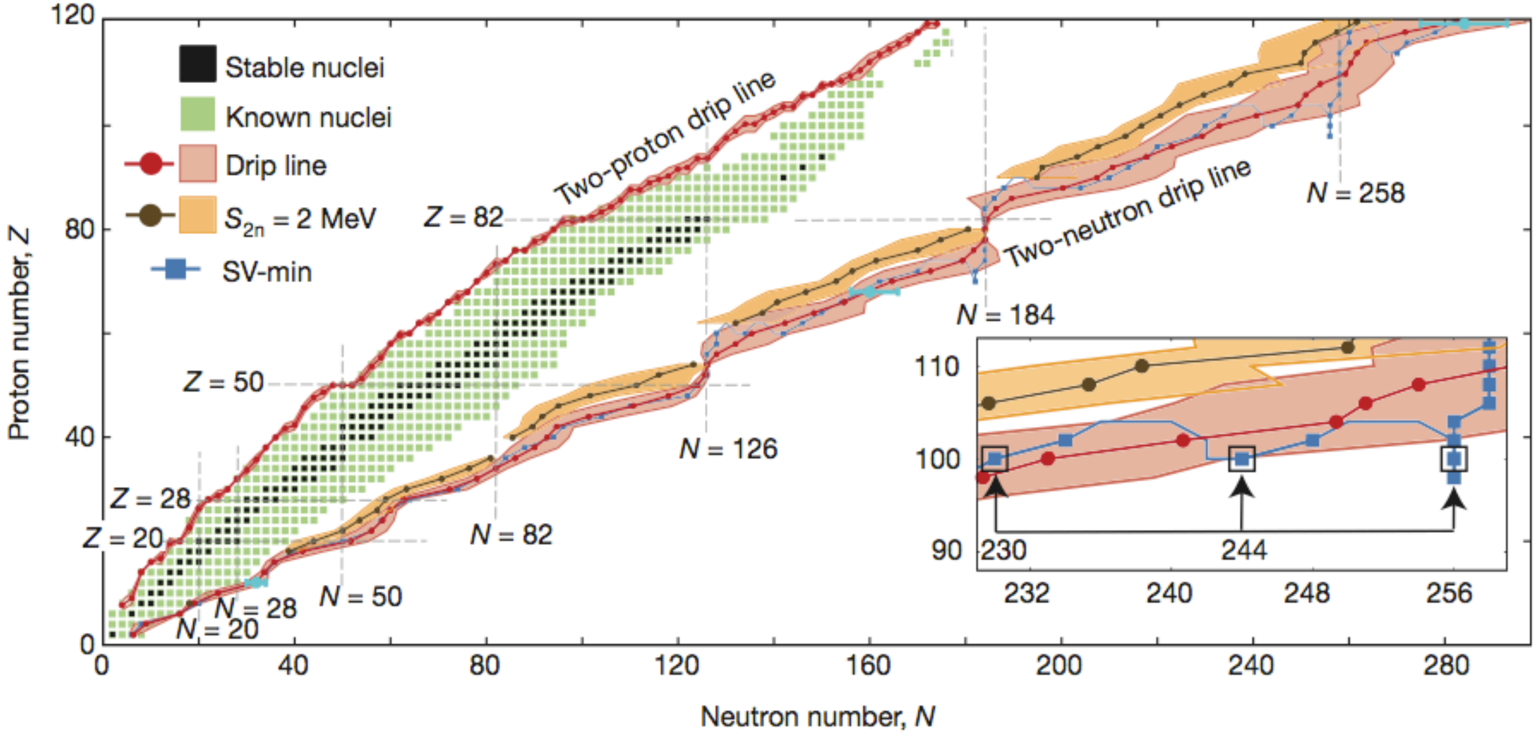
Weinberg, van Kolck, Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Machleidt, Meissner,…

Nuclei bound by strong interactions

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]‡



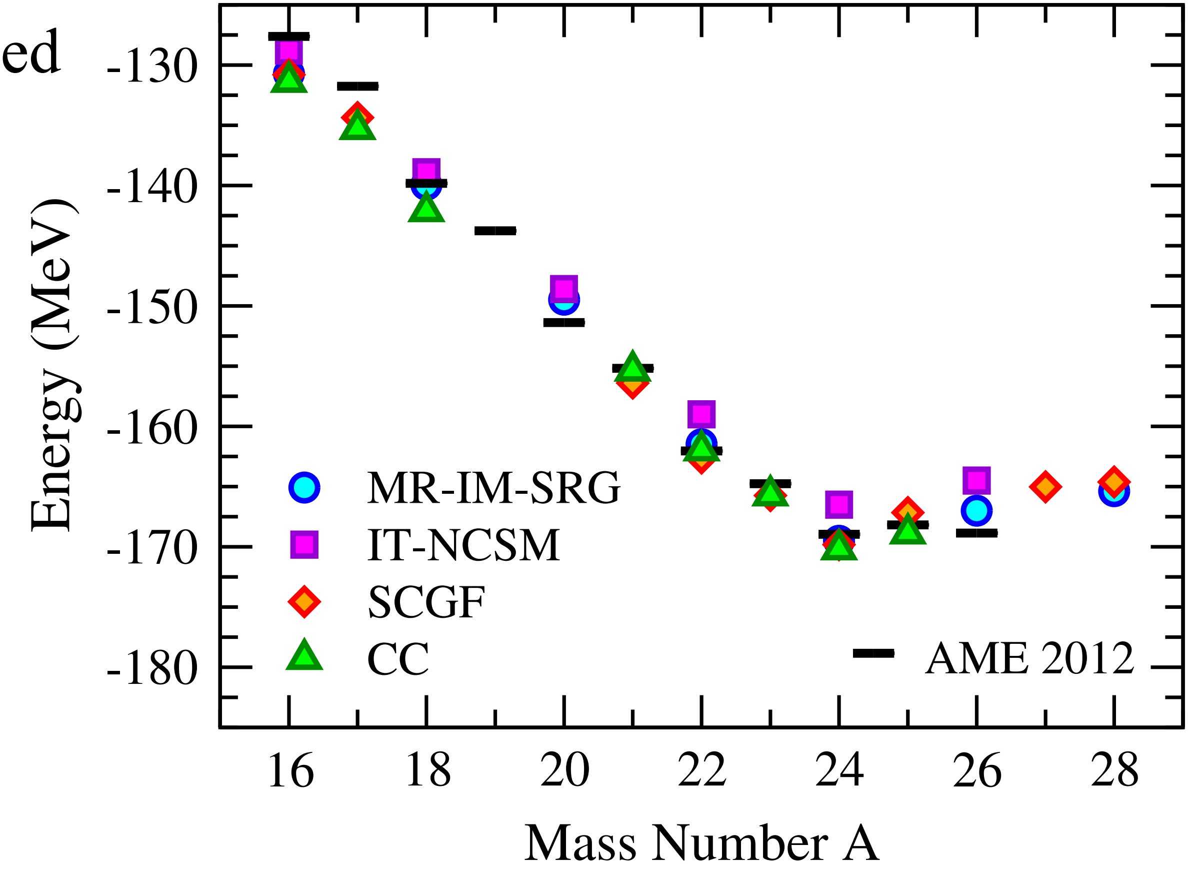
How does the nuclear chart emerge from chiral EFT?

Future: Connect chiral EFT to Lattice QCD

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)

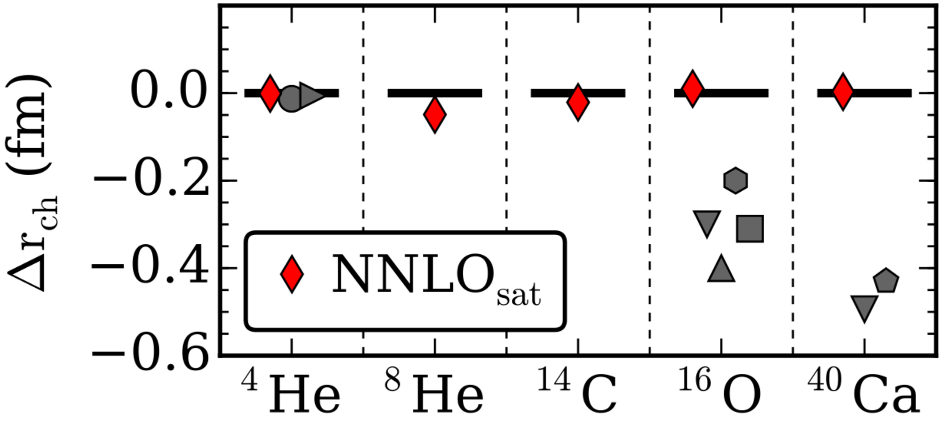
Self-Consistent Green’s Function methods Cipollone et al., PRL (2013)

Resolution of radius problems

good saturation properties essential for radii

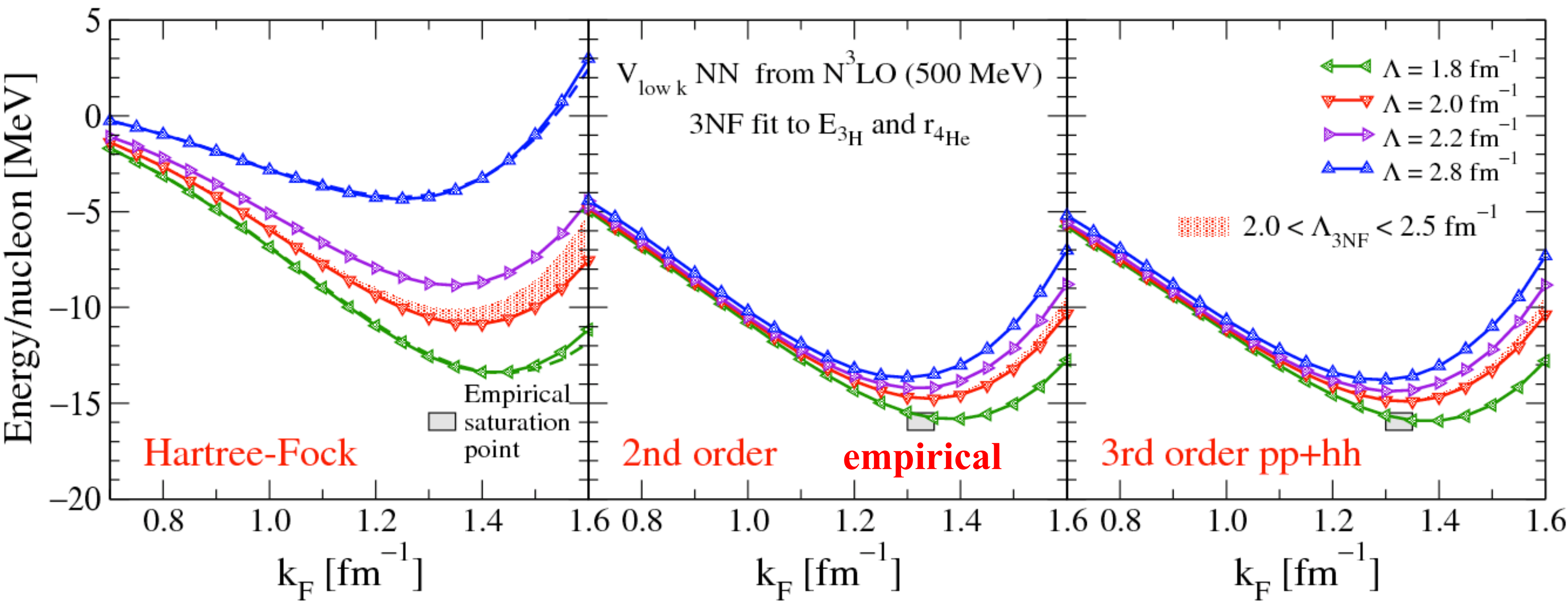
N^2LOsat potential fit to nuclei up to A=24

Ekström et al., PRC (2015)



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)



empirical

Resolution of radius problems

good saturation properties essential for radii

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

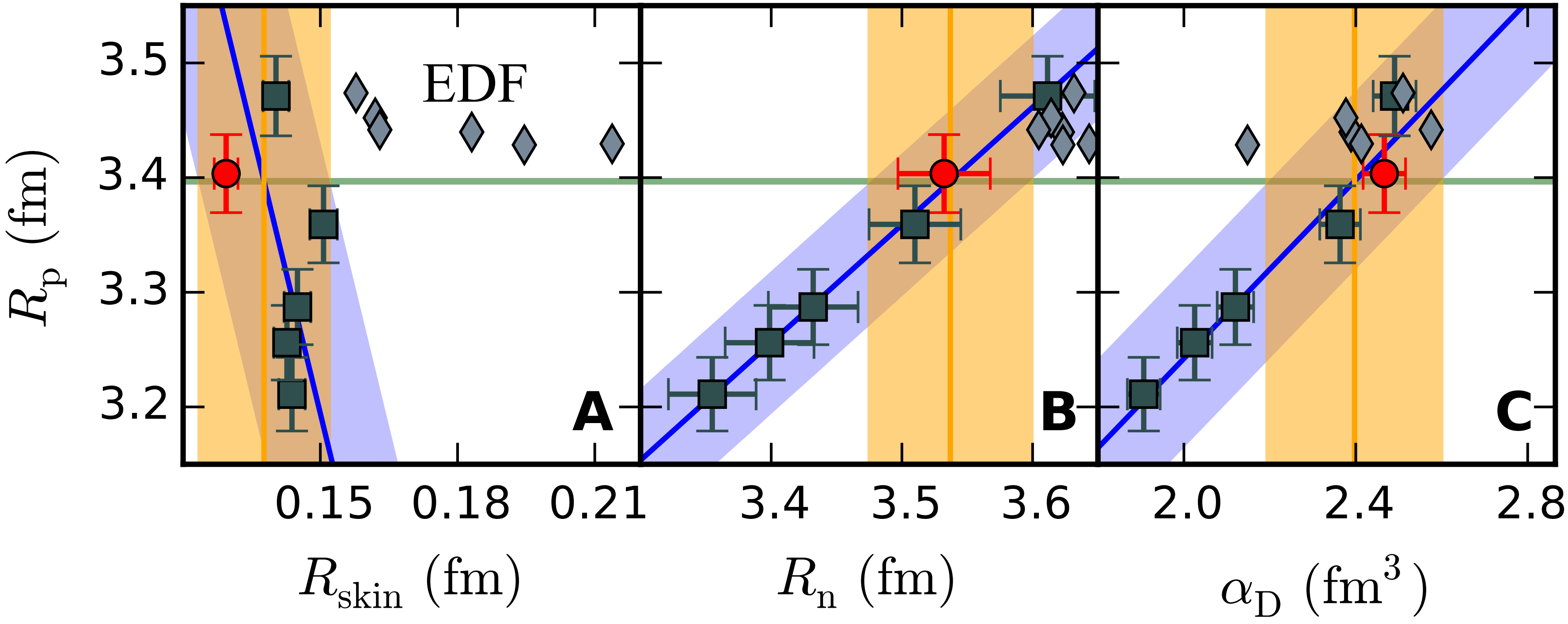
Ekström et al., PRC (2015)

NN+3N interactions that predict nuclear matter saturation

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

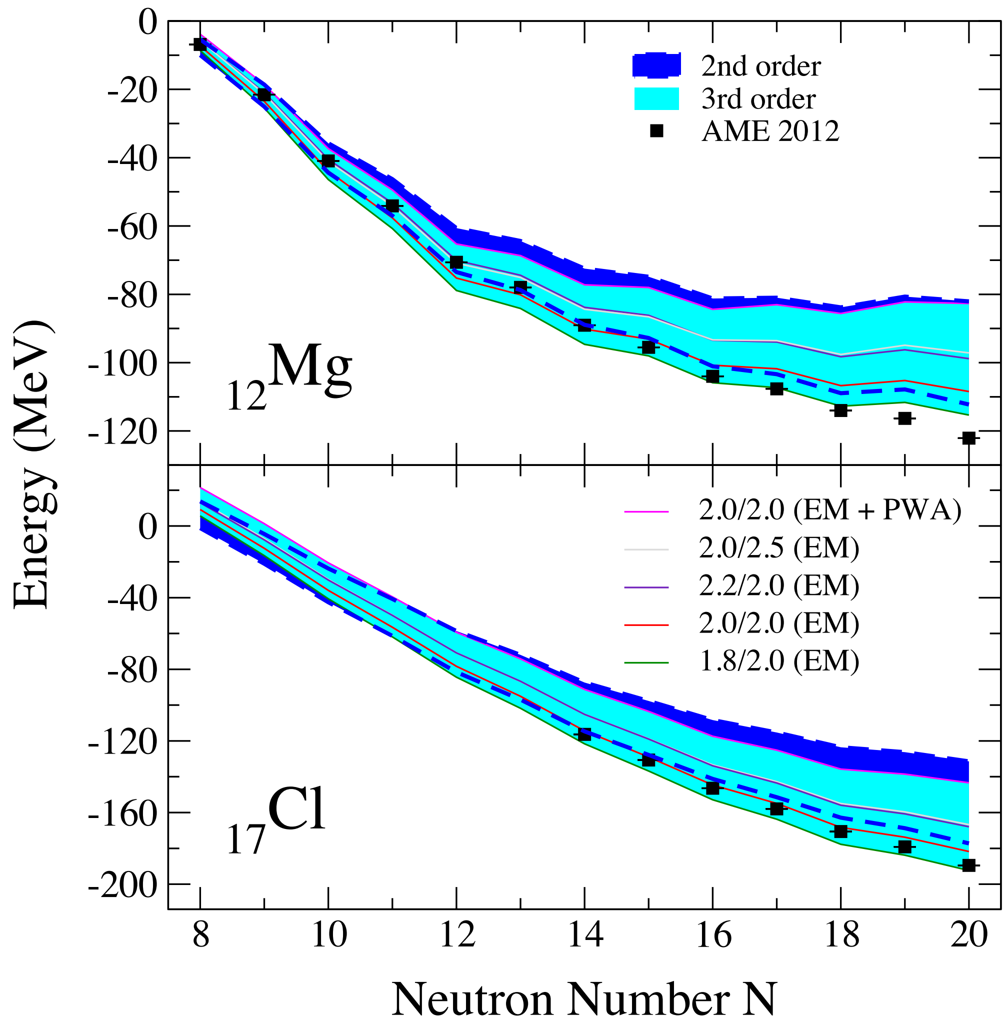
lead to radii consistent with experiment for ^{48}Ca Hagen et al., Nature Phys. (2015)

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

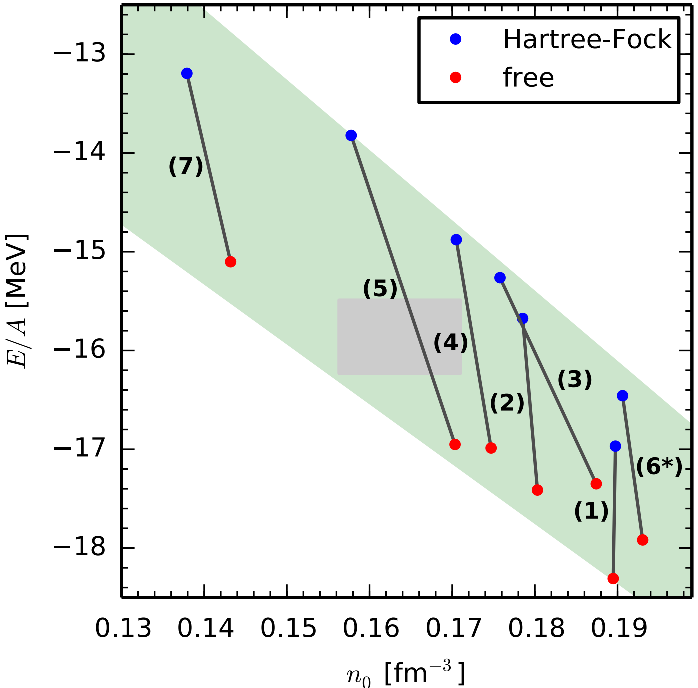


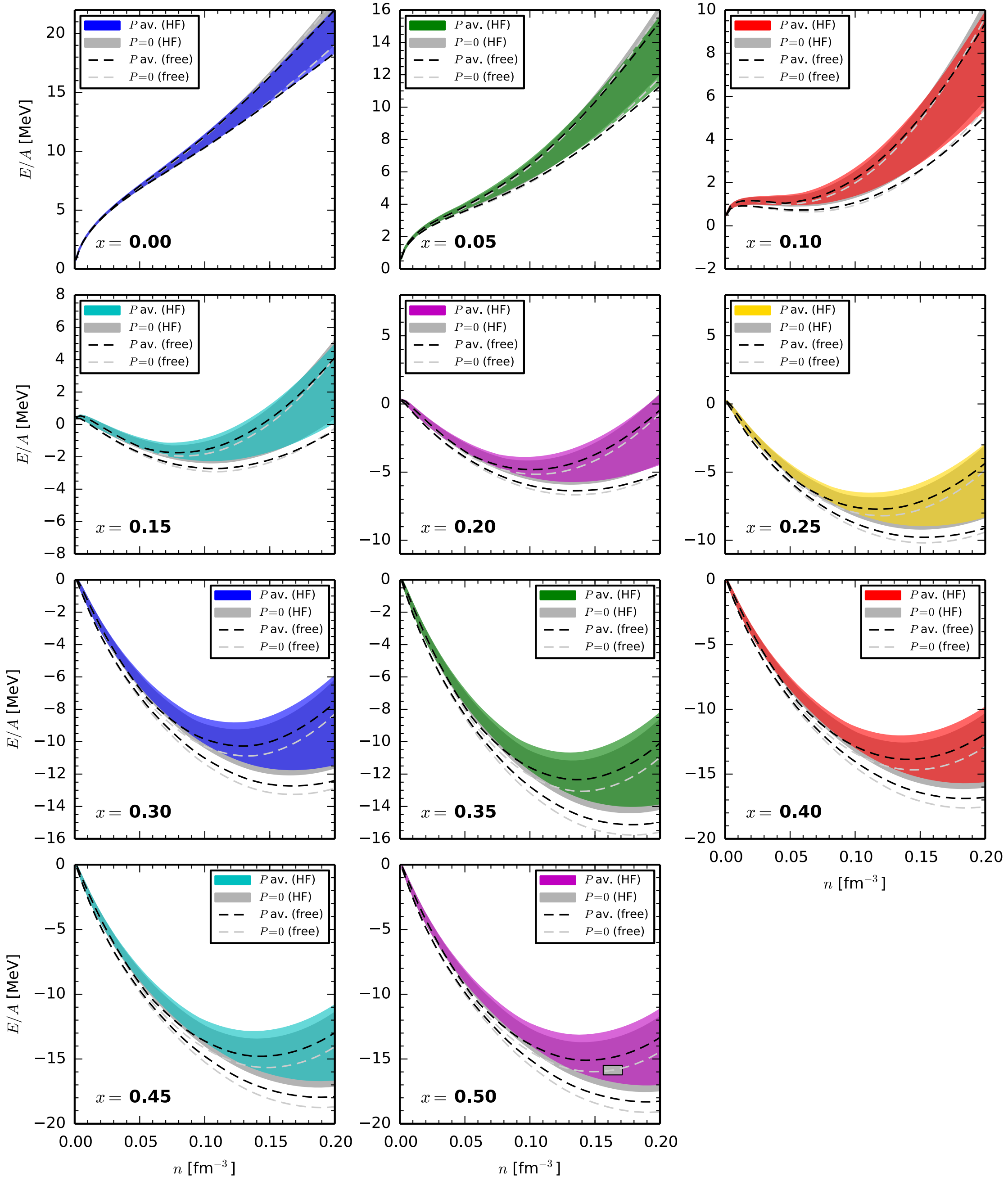
Theoretical uncertainties dominated by uncertainties in nuclear forces!

Nuclear forces and nuclear matter

asymmetric matter
with improved treatment
of 3N forces

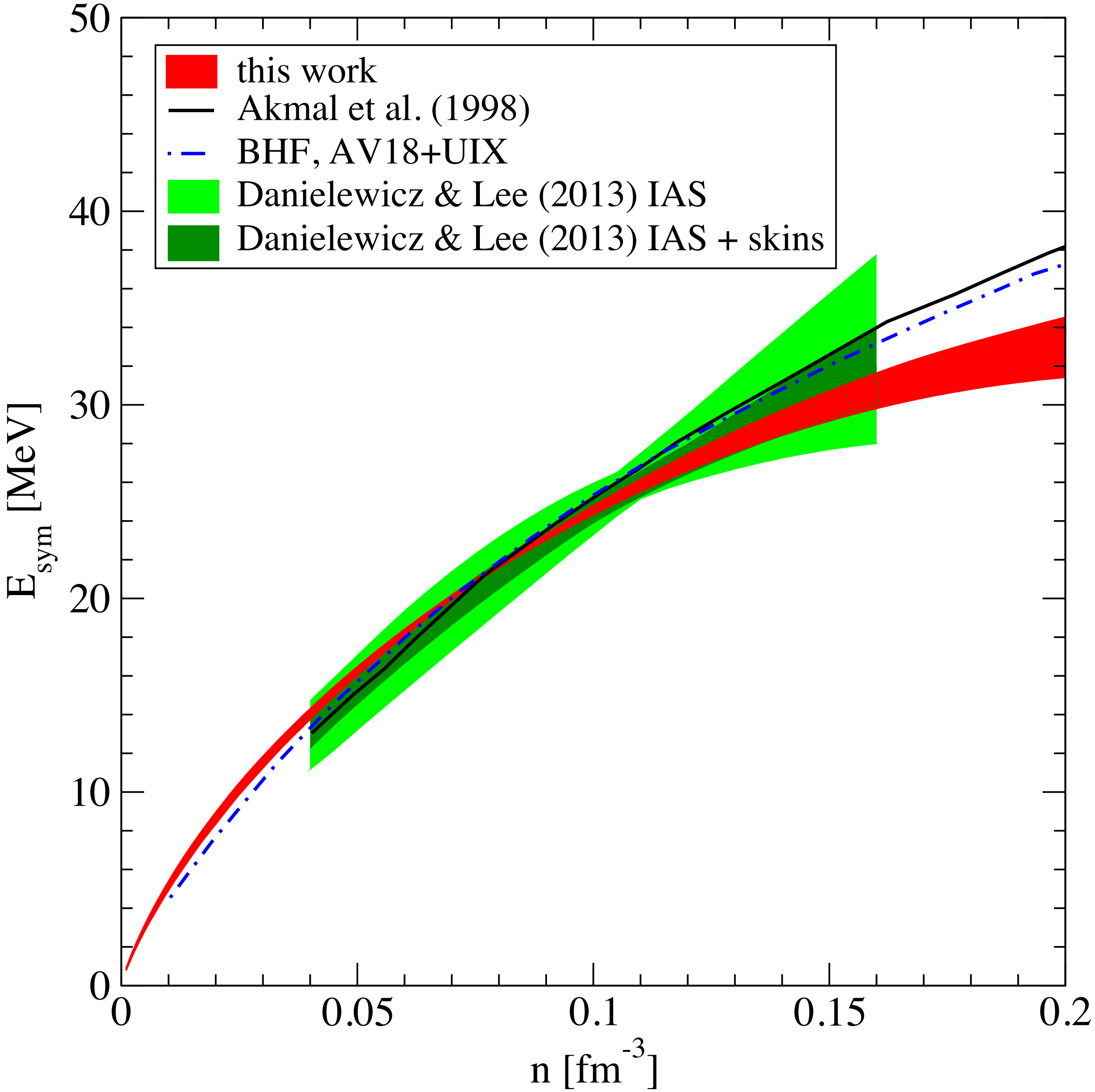
Drischler, Hebeler, AS, PRC (2016)
see also Holt, Kaiser, Weise, Wellenhofer



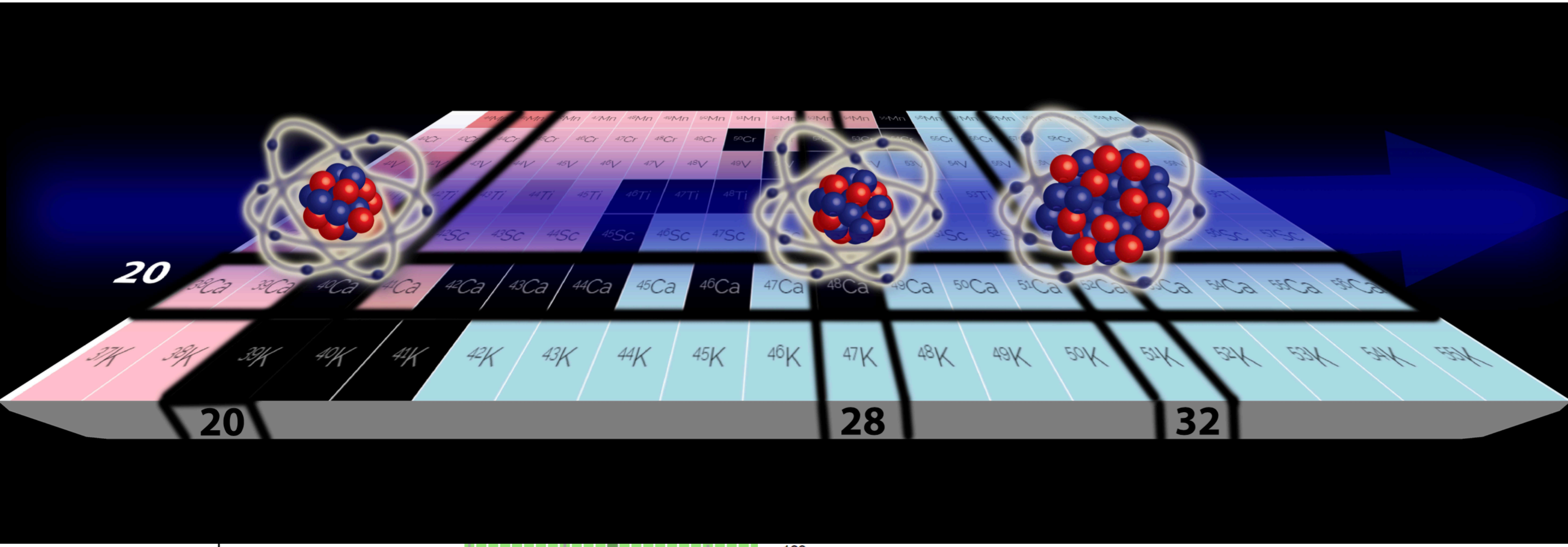


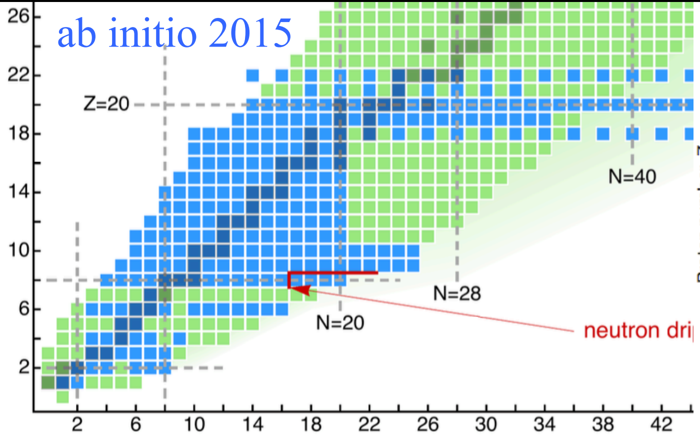
Calculations of asymmetric matter Drischler, Soma, AS, PRC (2014)

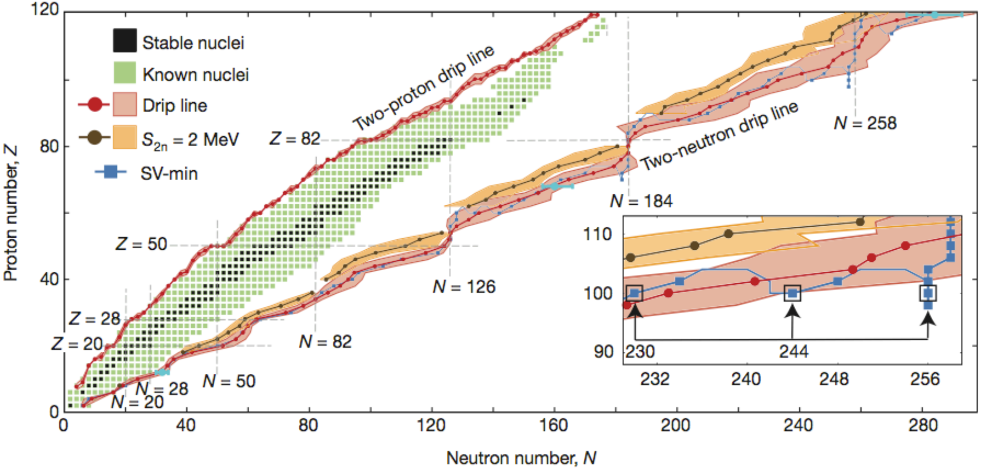
E_{sym} comparison with extraction from isobaric analogue states (IAS)
3N forces fit to ^{3}H, ^{4}He properties only



Neutron-rich calcium isotopes







Frontier of ab initio calculations at A~50

doi:10.1038/nature12226

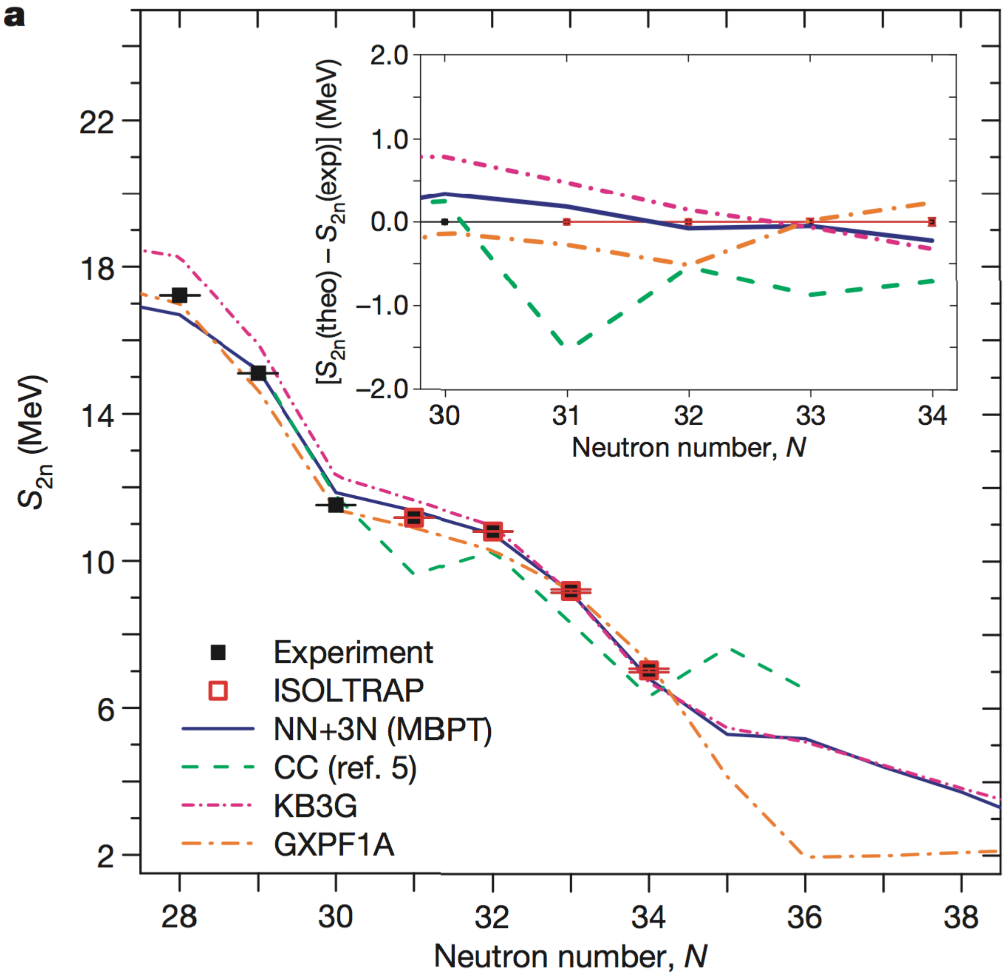
Masses of exotic calcium isotopes pin down nuclear forces

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

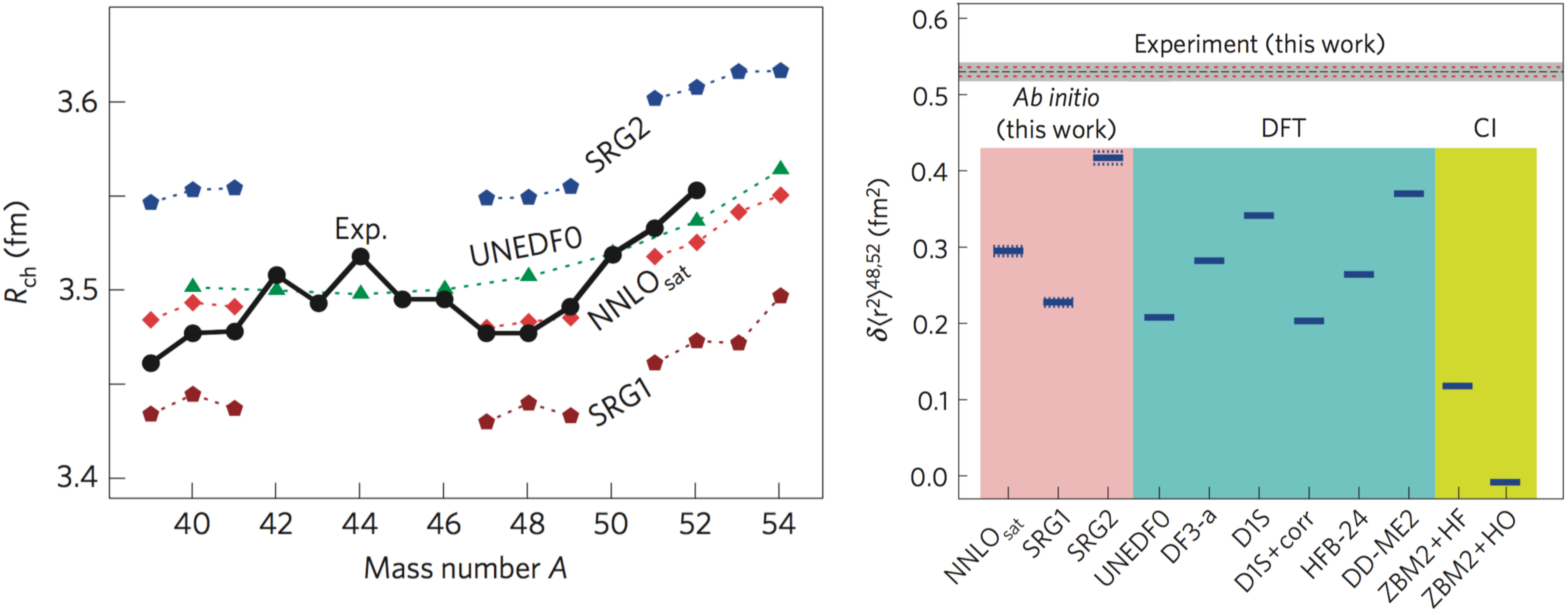
suggests N=32 shell closure



nature physics
ARTICLES
PUBLISHED ONLINE: 8 FEBRUARY 2016 | DOI: 10.1038/NPHYS3645

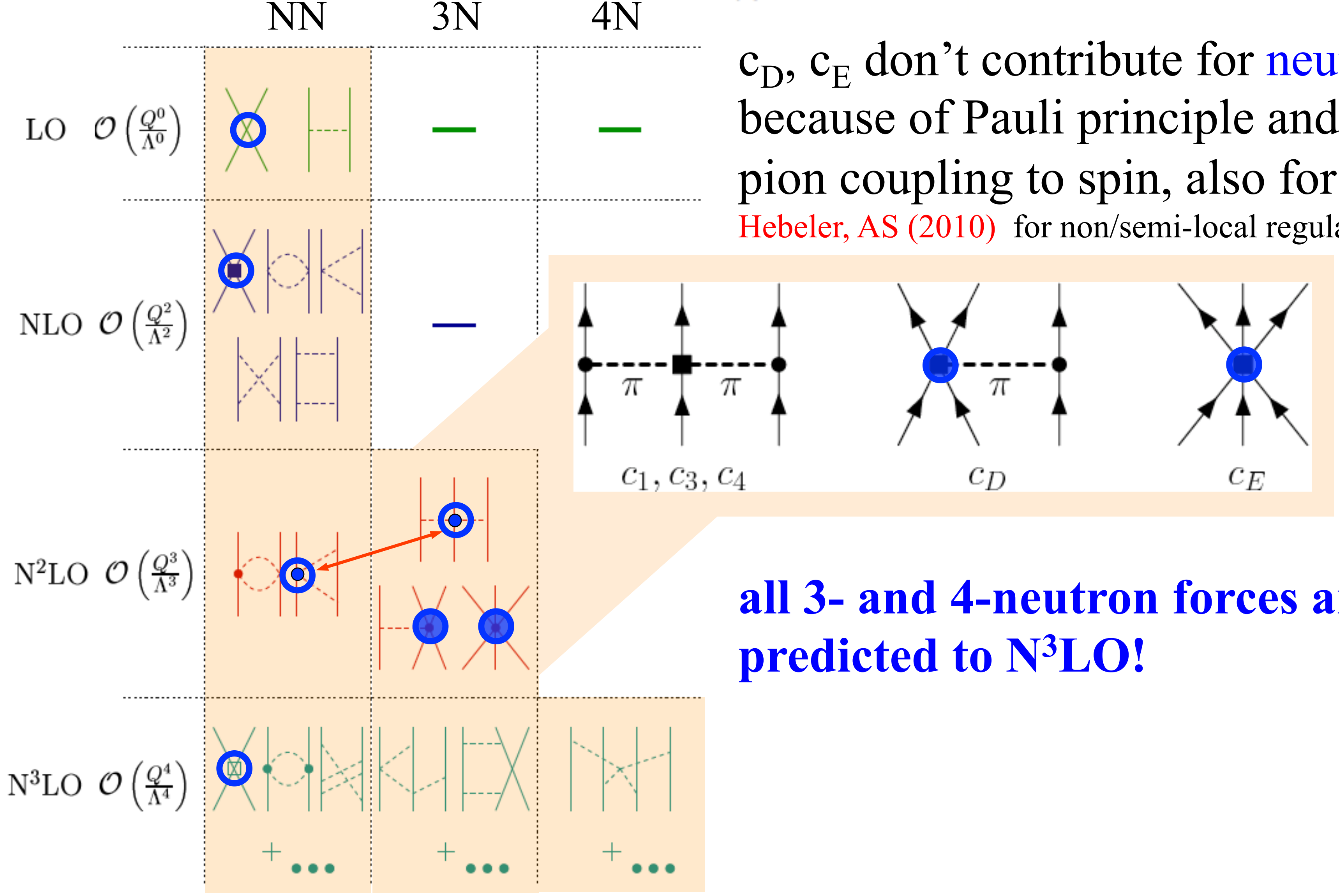
Unexpectedly large charge radii of neutron-rich calcium isotopes

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) for non/semi-local regulators

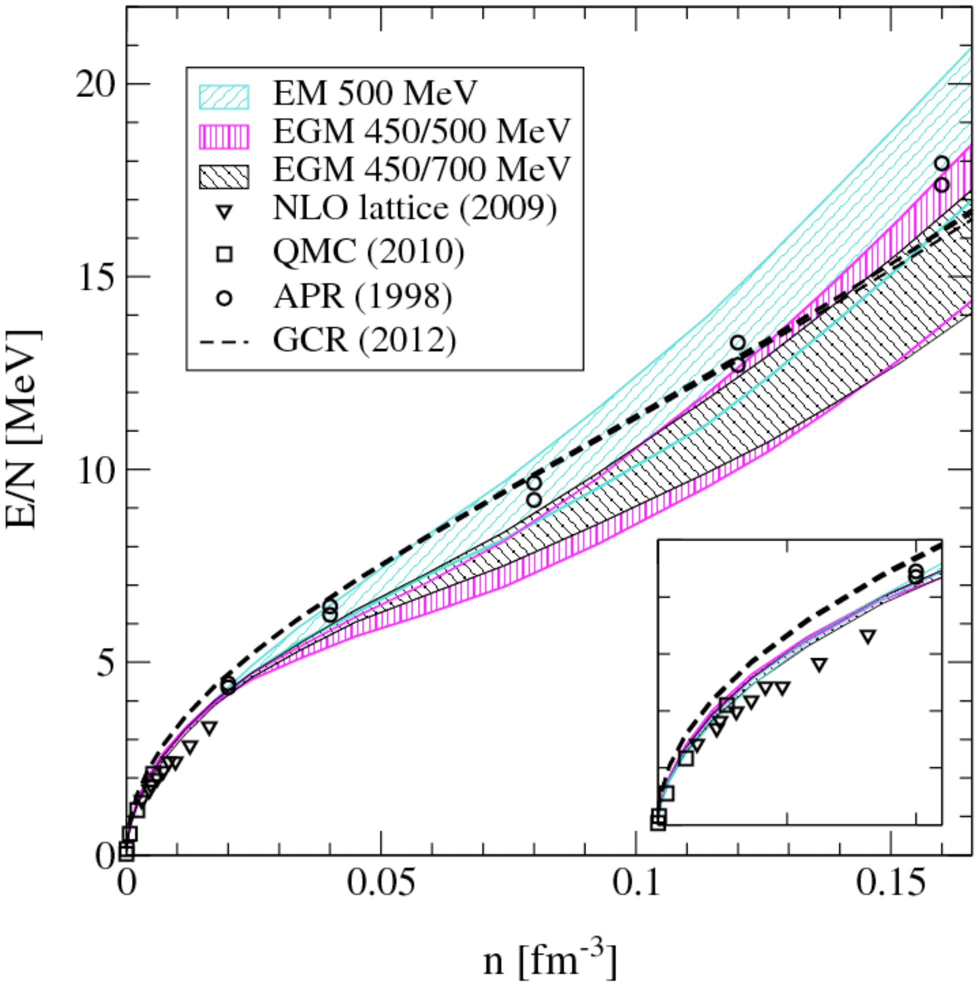
all 3- and 4-neutron forces are predicted to N^{3}LO!

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

Complete N^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

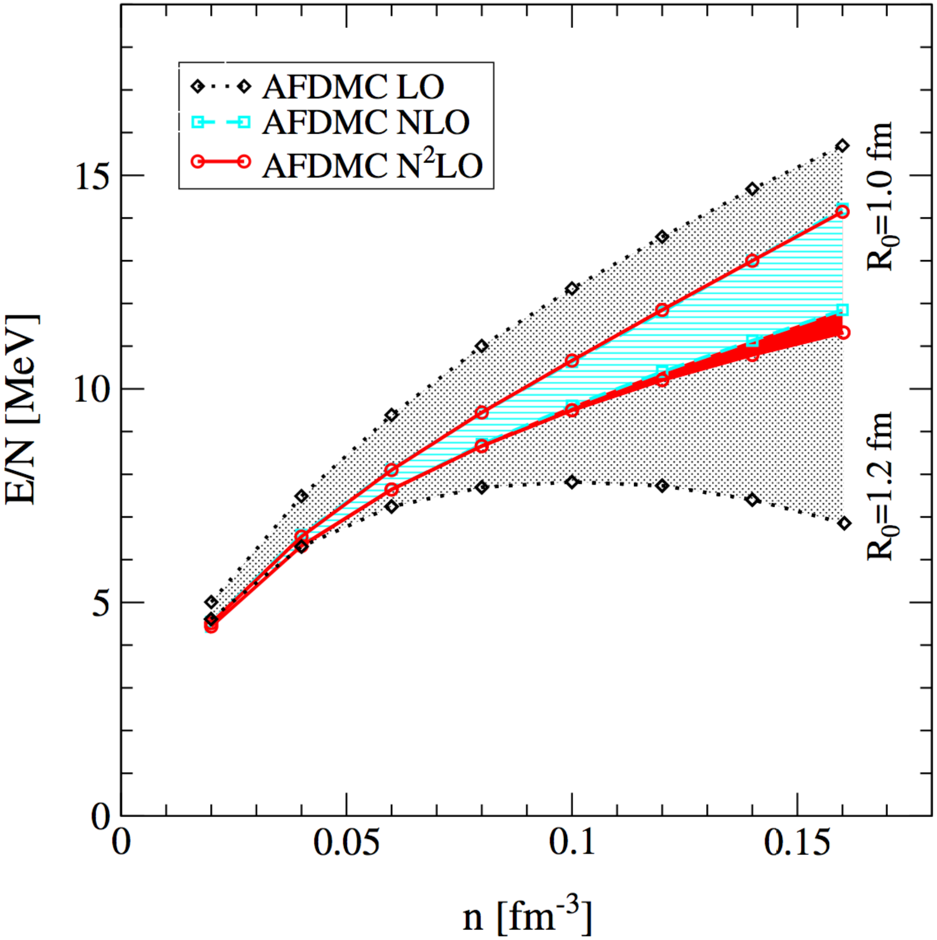
new QMC benchmarks with local chiral potentials

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

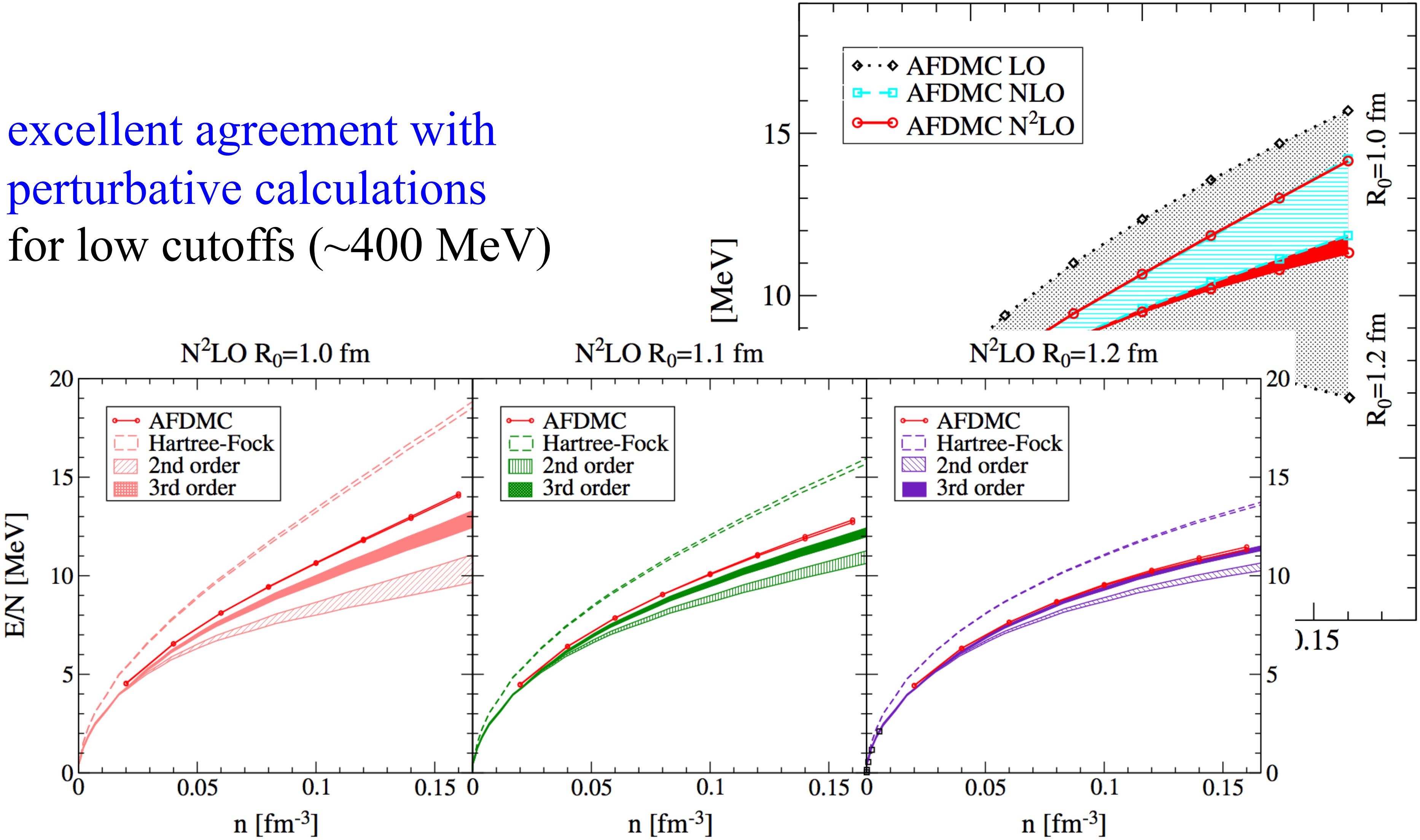


Quantum Monte Carlo for neutron matter

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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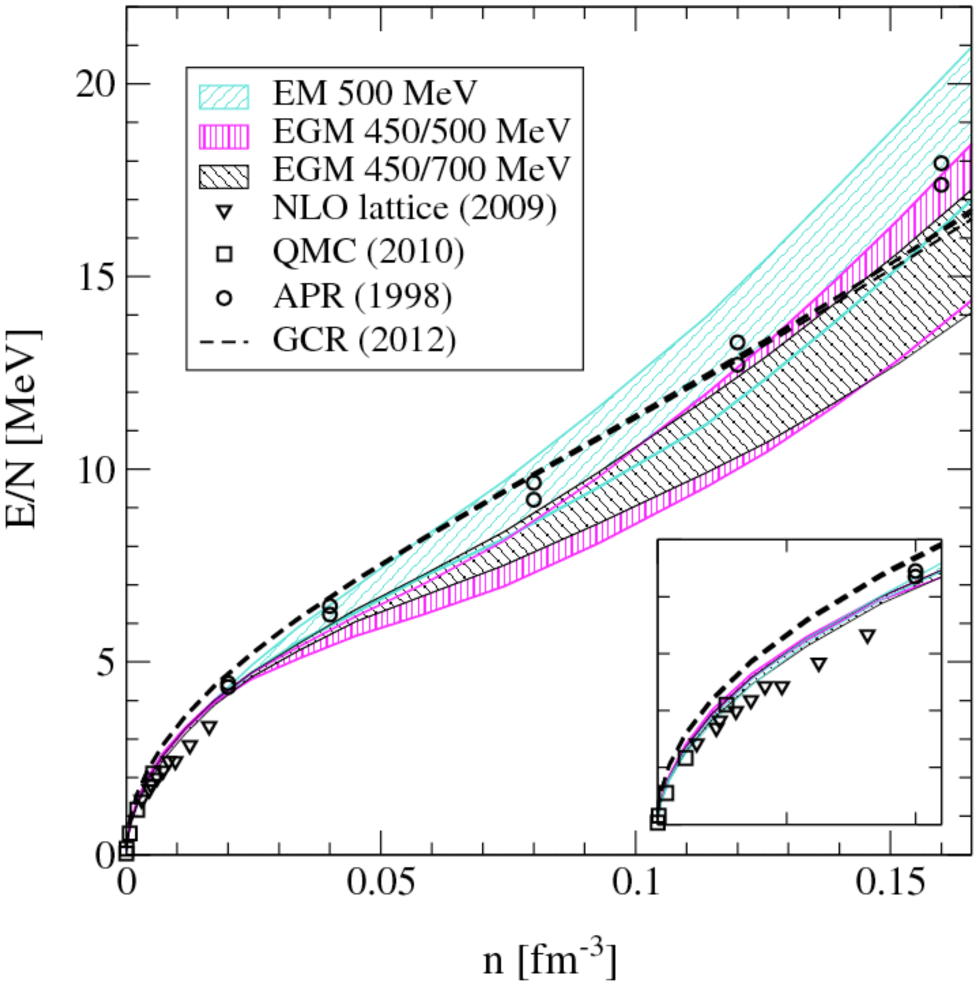

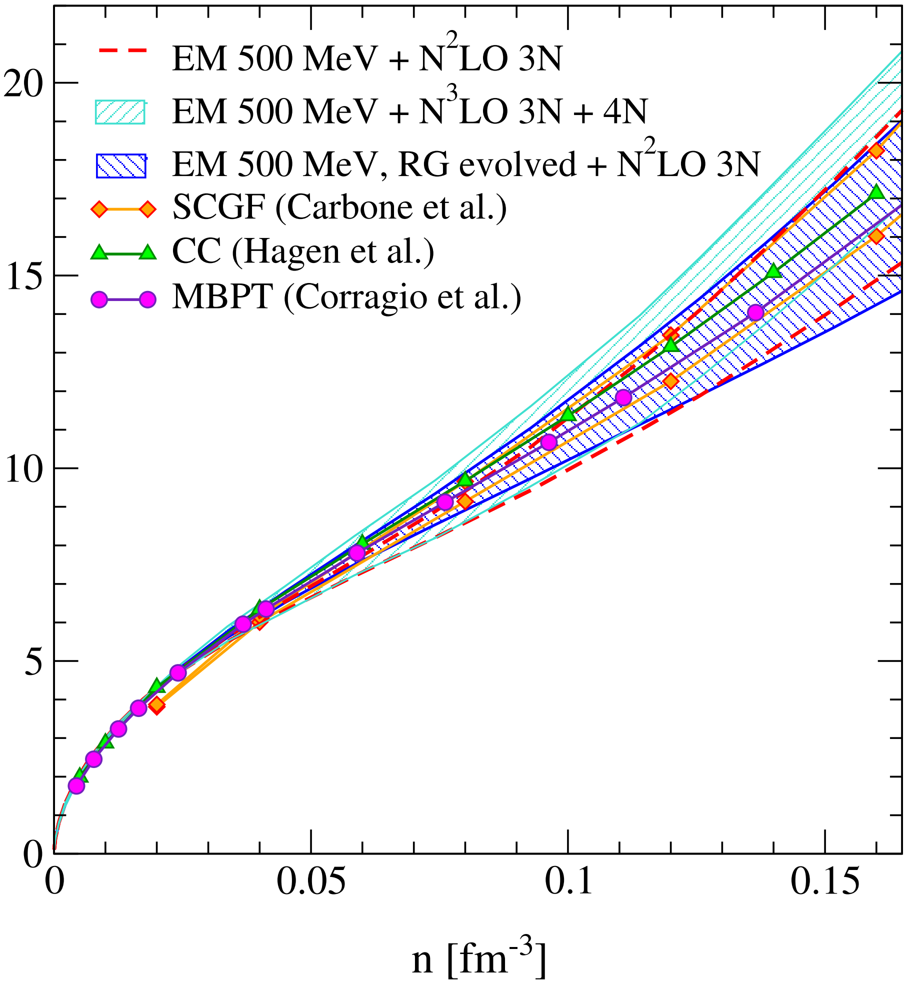

excellent agreement with other methods!

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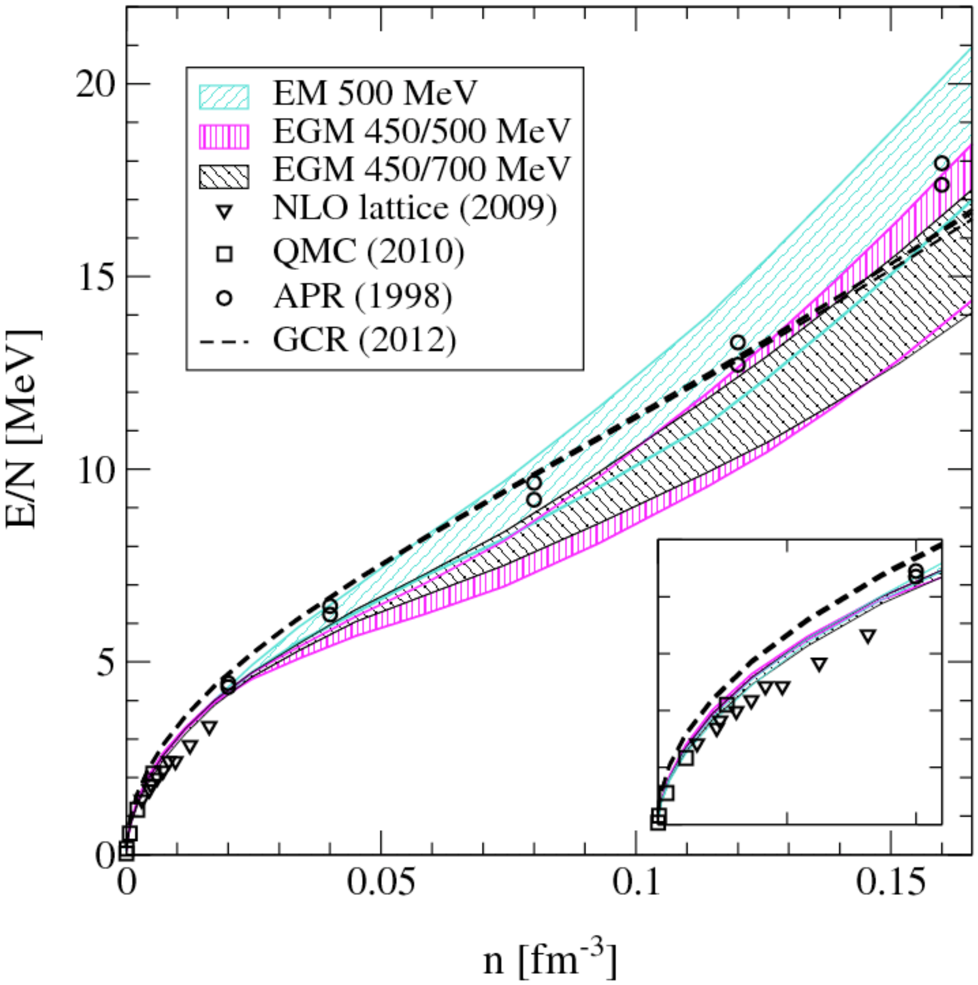
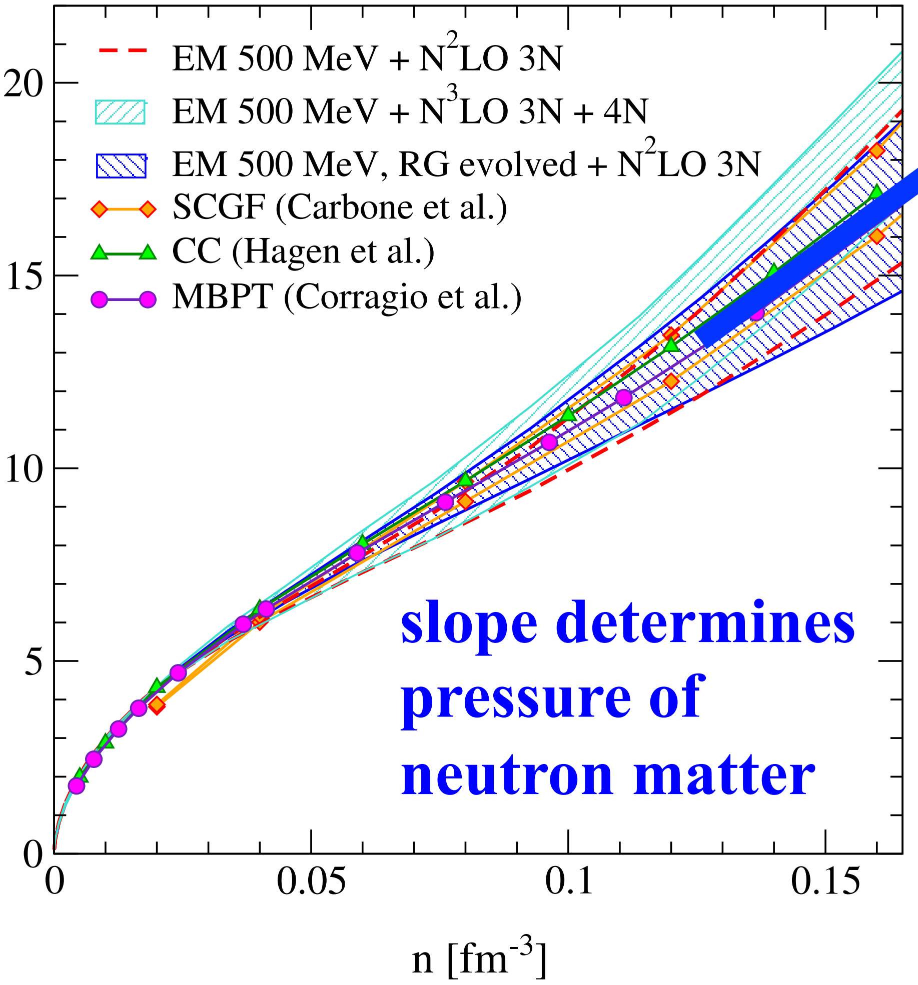




slope determines pressure of neutron matter

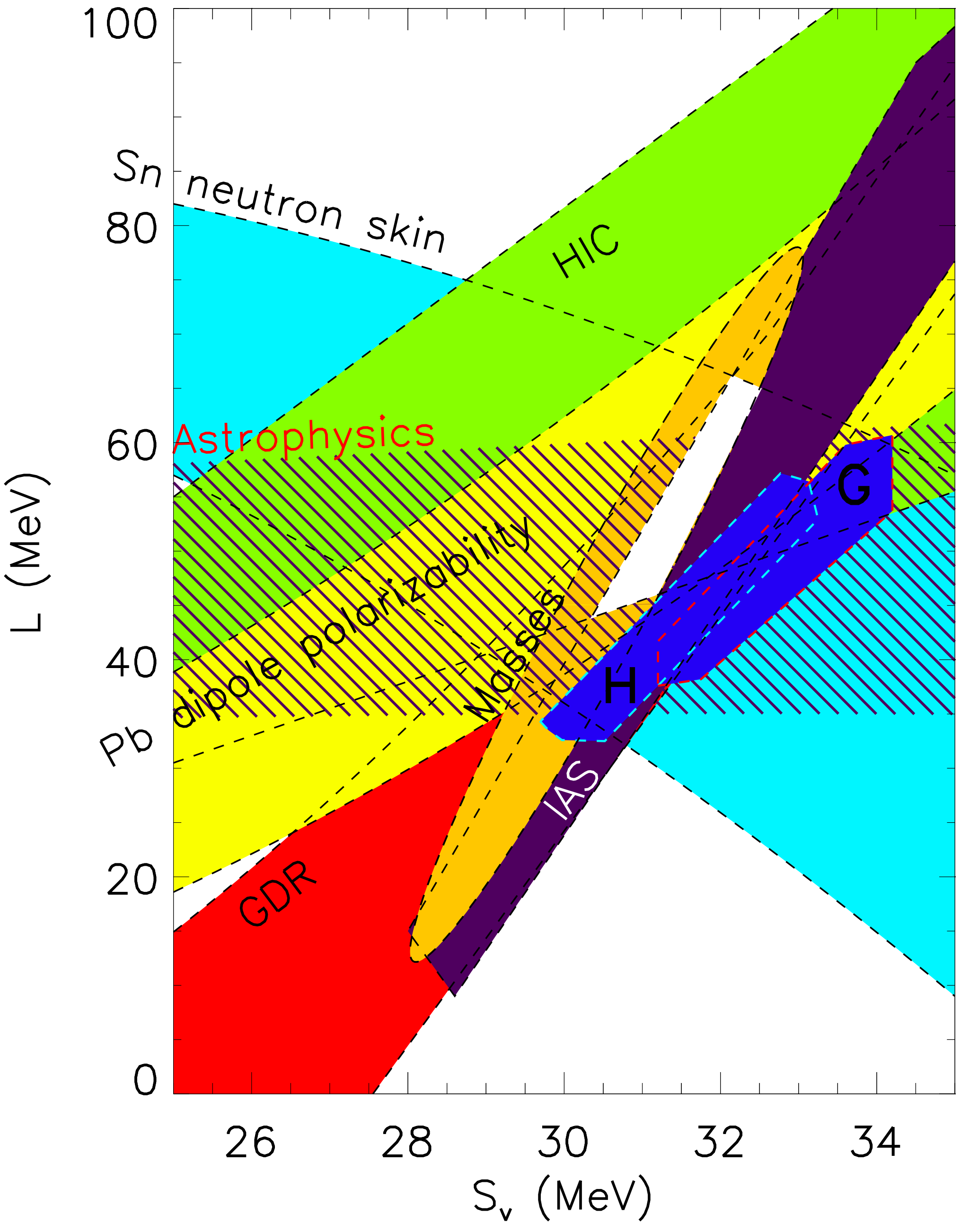
excellent agreement with other methods!

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)

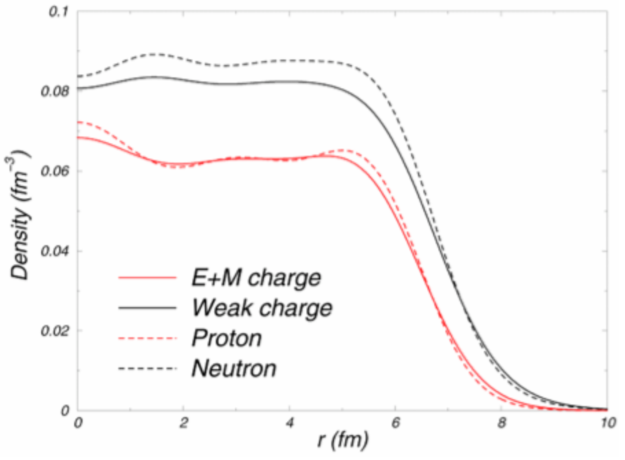
neutron matter constraints
H: Hebeler et al. (2010)
G: Gandolfi et al. (2011)
provide tight constraints!

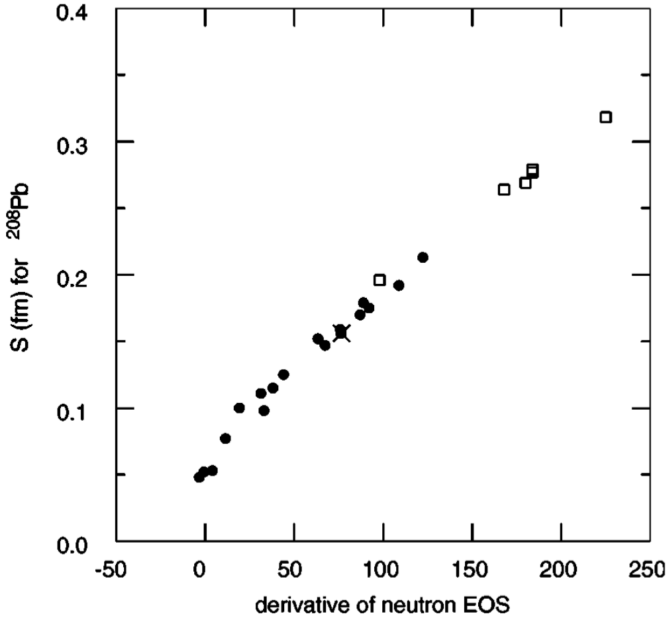


Neutron skin of ^{208}Pb

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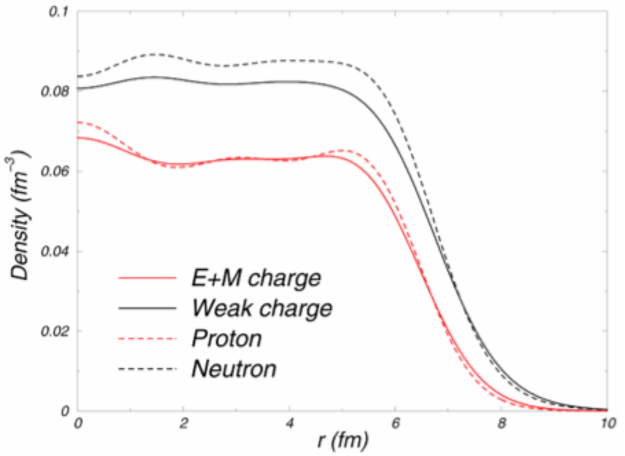
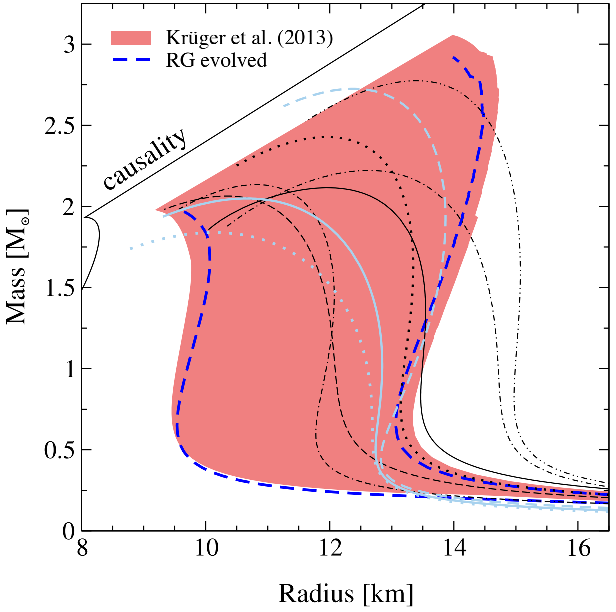
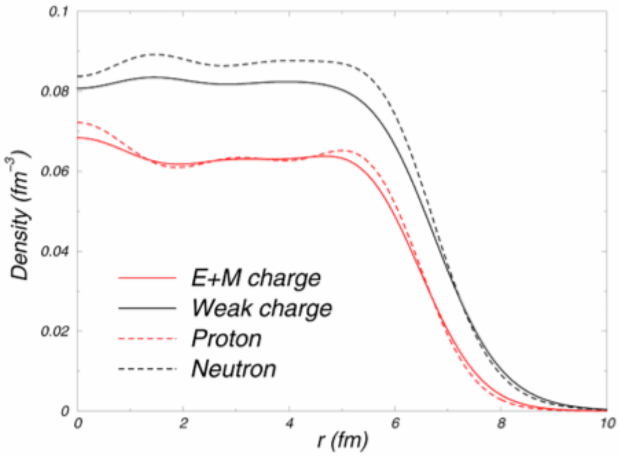
Hebeler, Lattimer, Pethick, AS, PRL (2010)



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



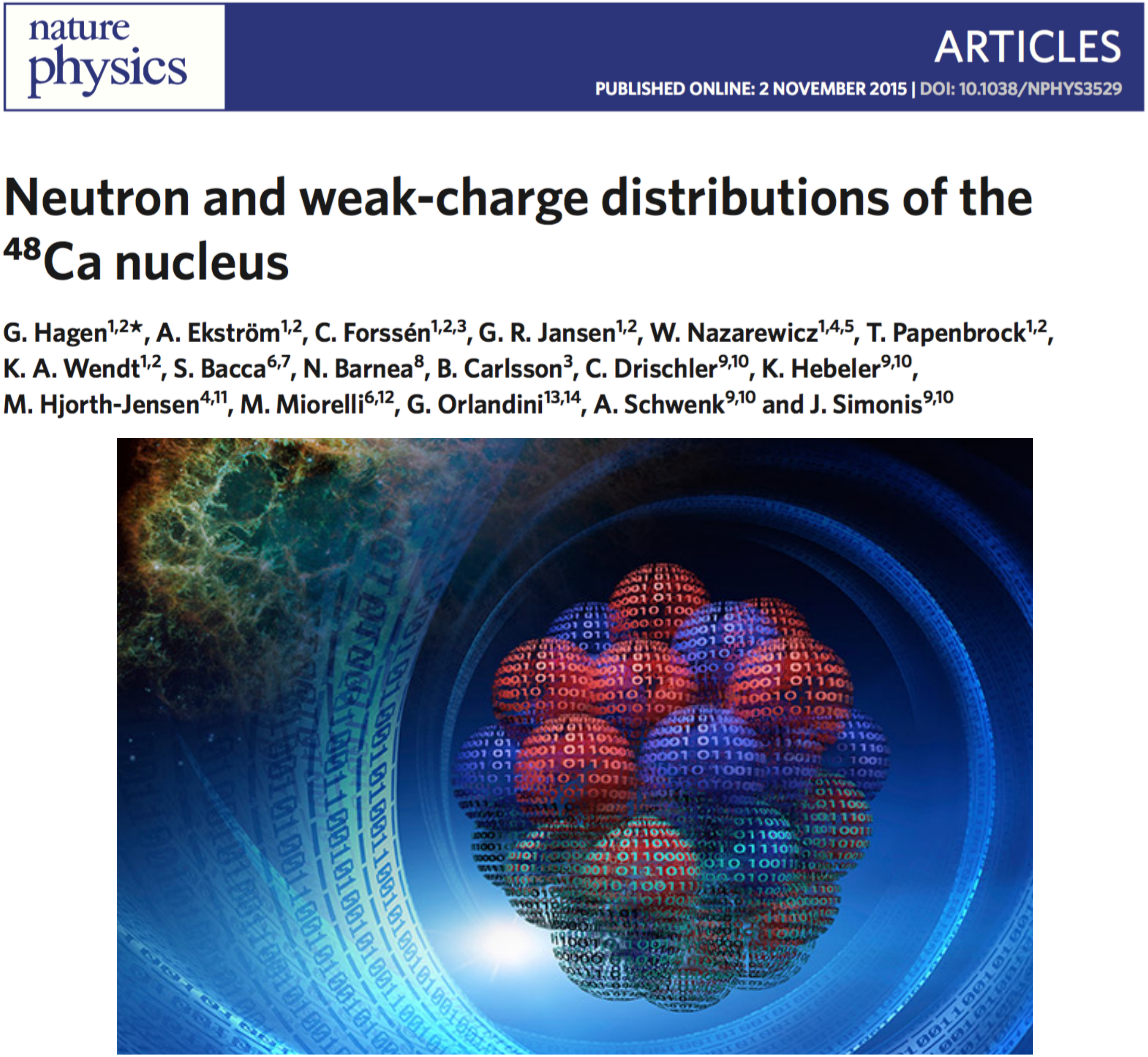
probes neutron matter energy/pressure,
neutron matter band predicts
neutron skin of ^{208}Pb: 0.17±0.03 fm (±18%)
Hebeler, Lattimer, Pethick, AS, PRL (2010)

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



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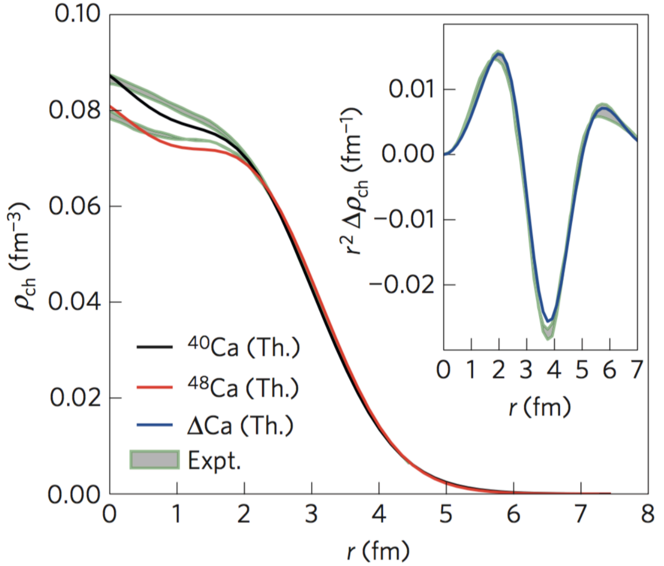
Neutron and weak-charge distributions of the ^{48}Ca nucleus

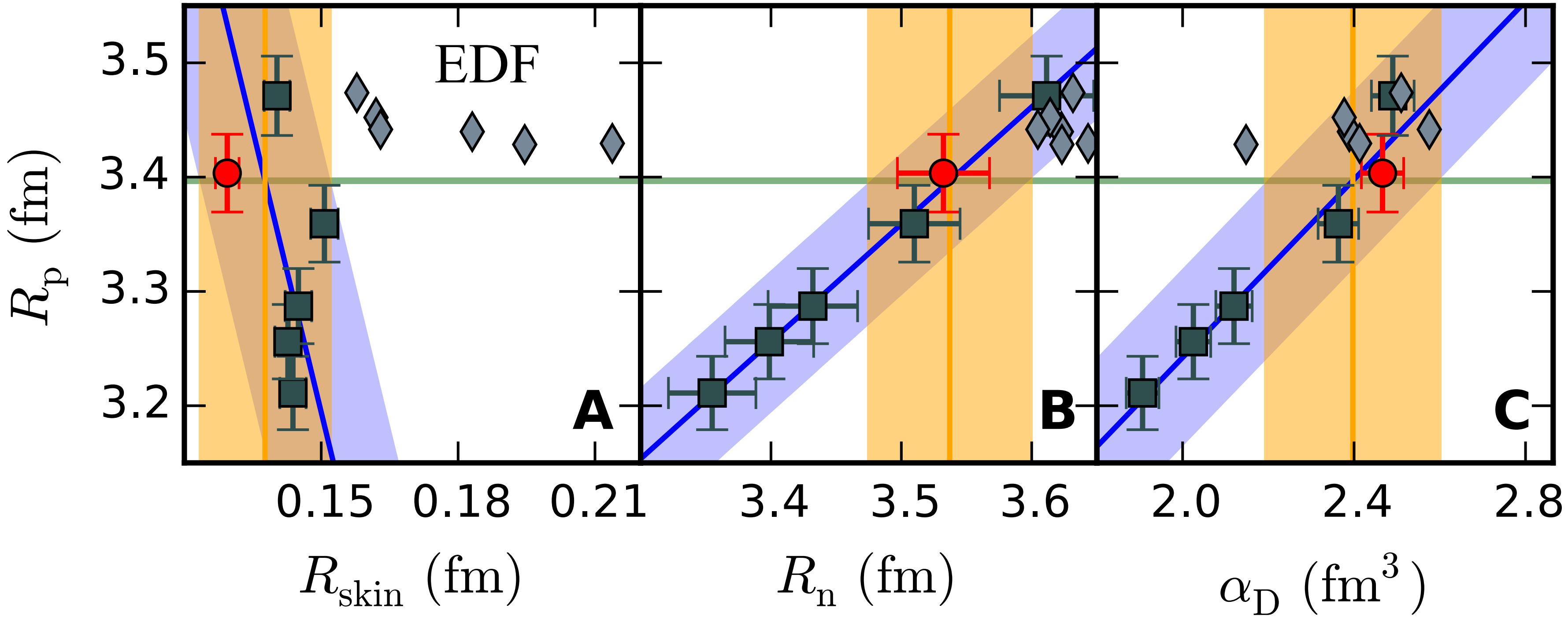
G. Hagen[1,2*], A. Ekström[1,2], C. Forssén[1,2,3], G. R. Jansen[1,2], W. Nazarewicz[1,4,5], T. Papenbrock[1,2], K. A. Wendt[1,2], S. Bacca[6,7], N. Barnea[8], B. Carlsson[3], C. Drischler[9,10], K. Hebeler[9,10], M. Hjorth-Jensen[4,11], M. Miorelli[6,12], G. Orlandini[13,14], A. Schwenk[9,10] and J.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

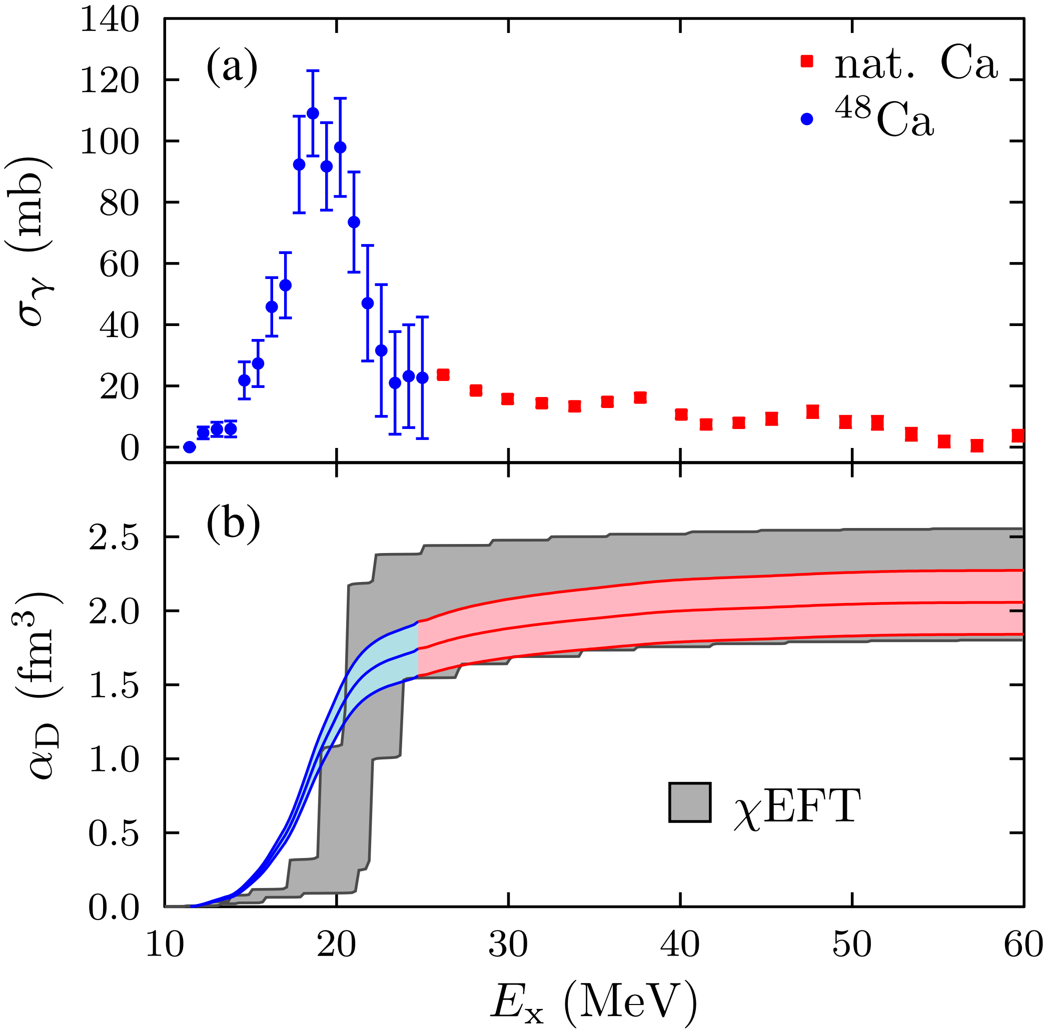


Dipole polarizability of ^{48}Ca

from photo-absorption cross section, measured at Osaka up to 25 MeV

Birkhan, von Neumann-Cosel, Richter, Tamii et al.

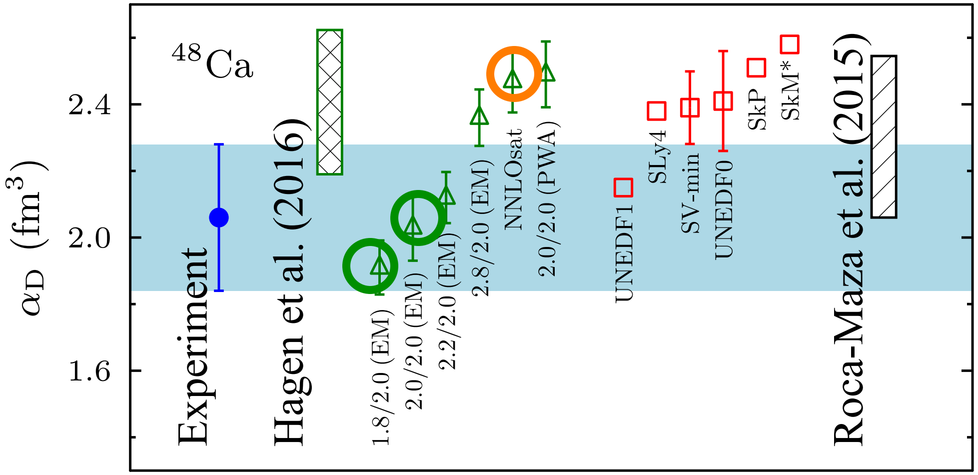
very similar to ^{40}Ca except for shift of giant dipole resonance



good agreement with chiral EFT predictions

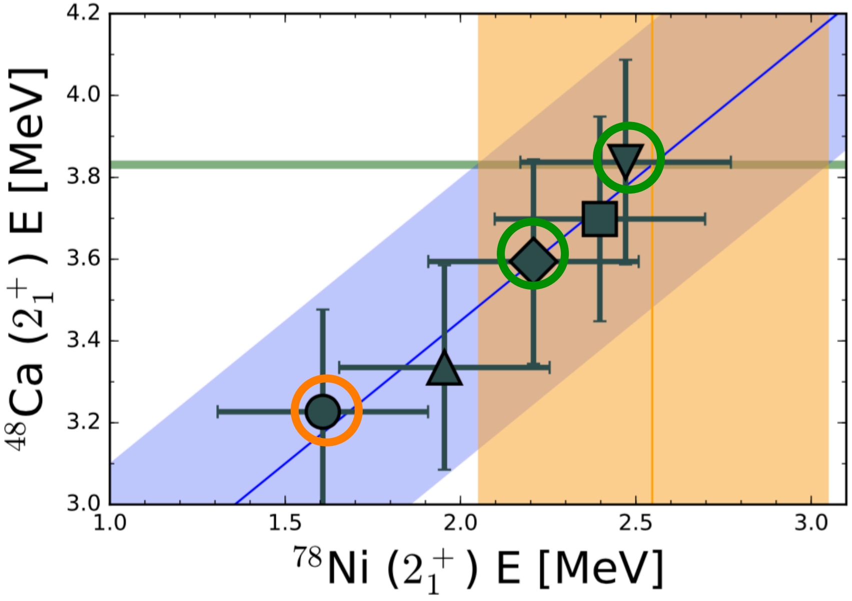
Miorelli, Bacca, Hagen et al.

Dipole polarizability of ^{48}Ca



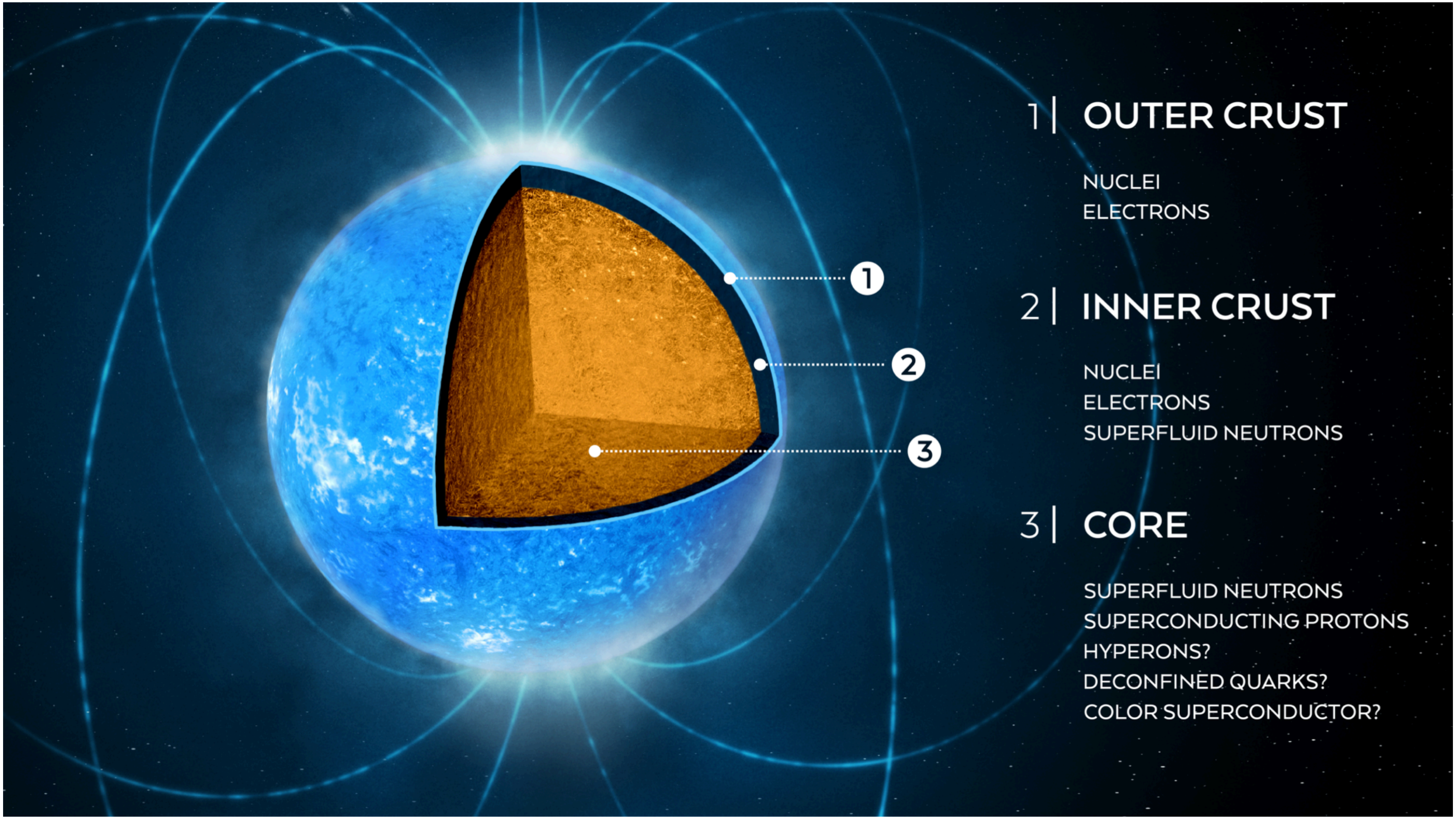
theory comparison gives
R_{skin} = 0.14-0.20 fm

sensitive to
neutron matter properties
and strong shell closure



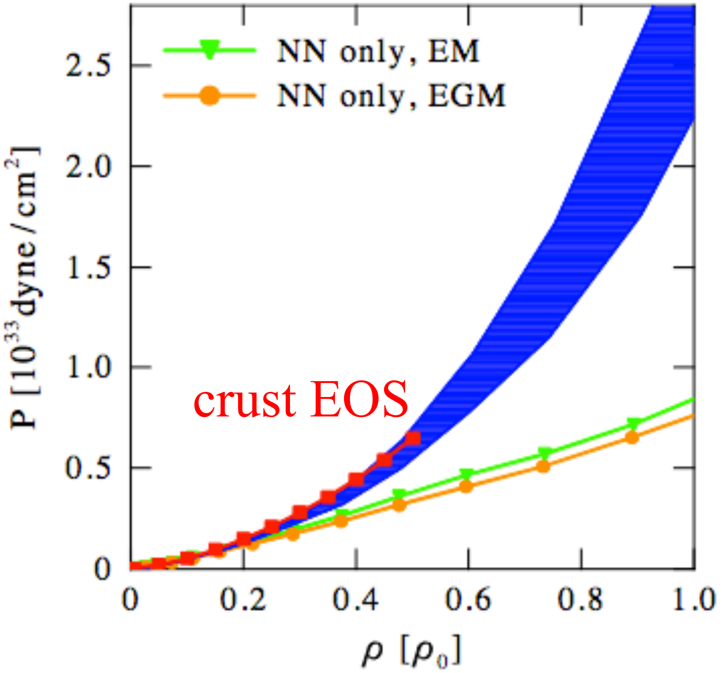
Hagen et al., 1605.01477

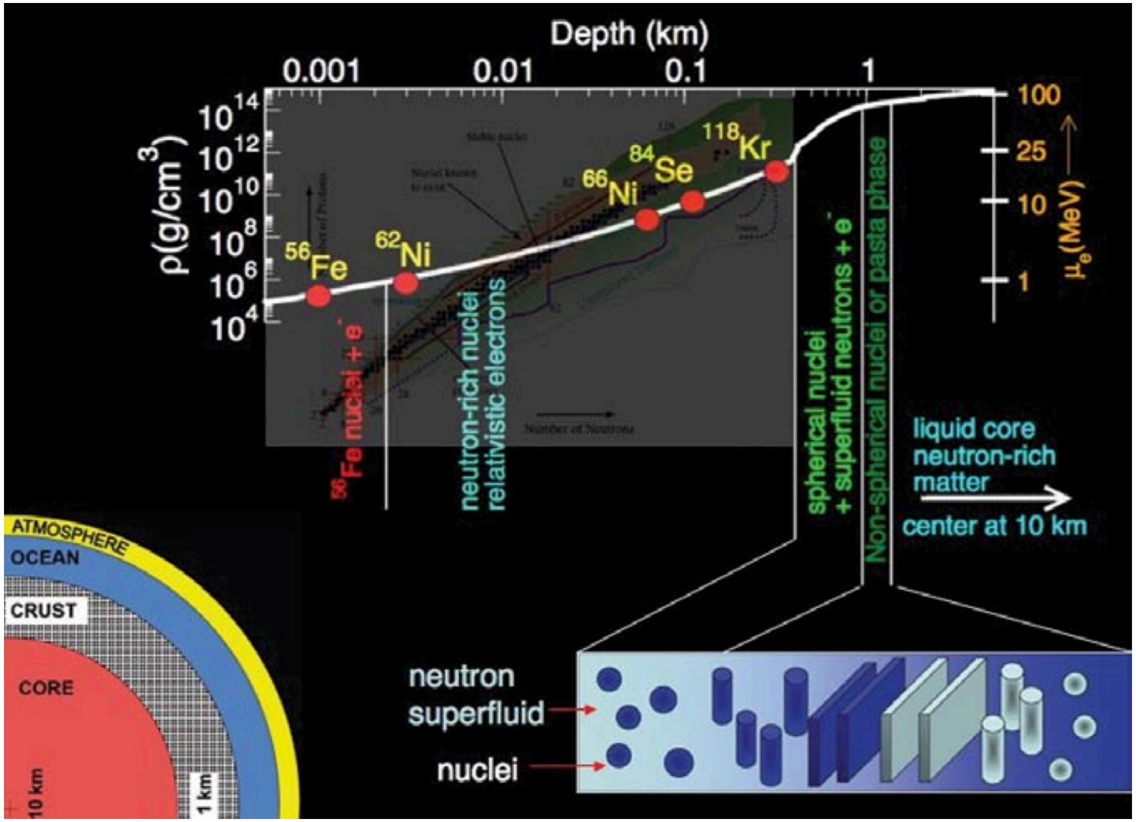
Neutron matter and neutron stars



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

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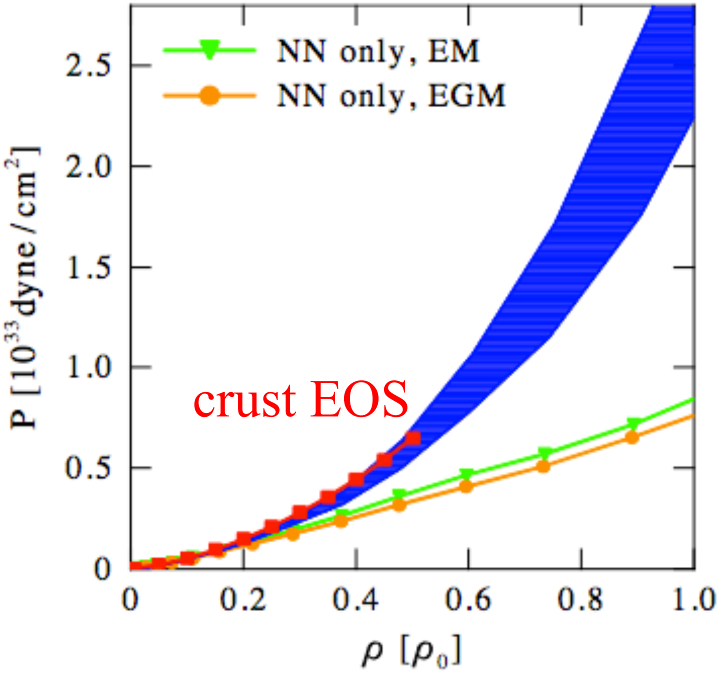
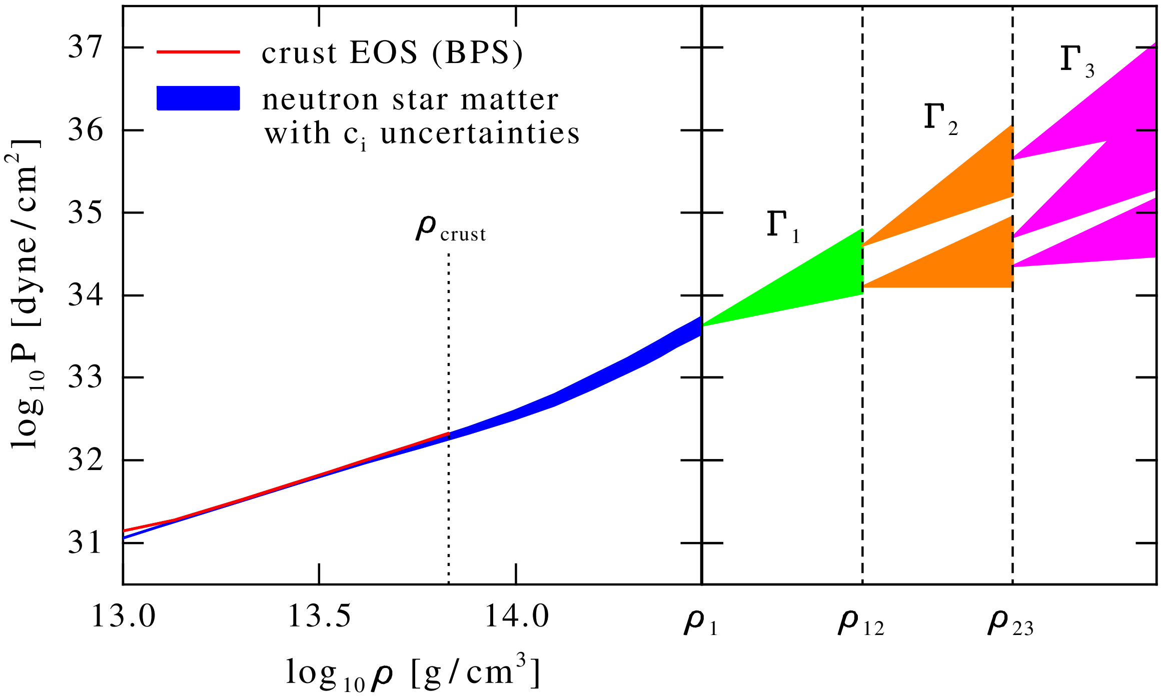


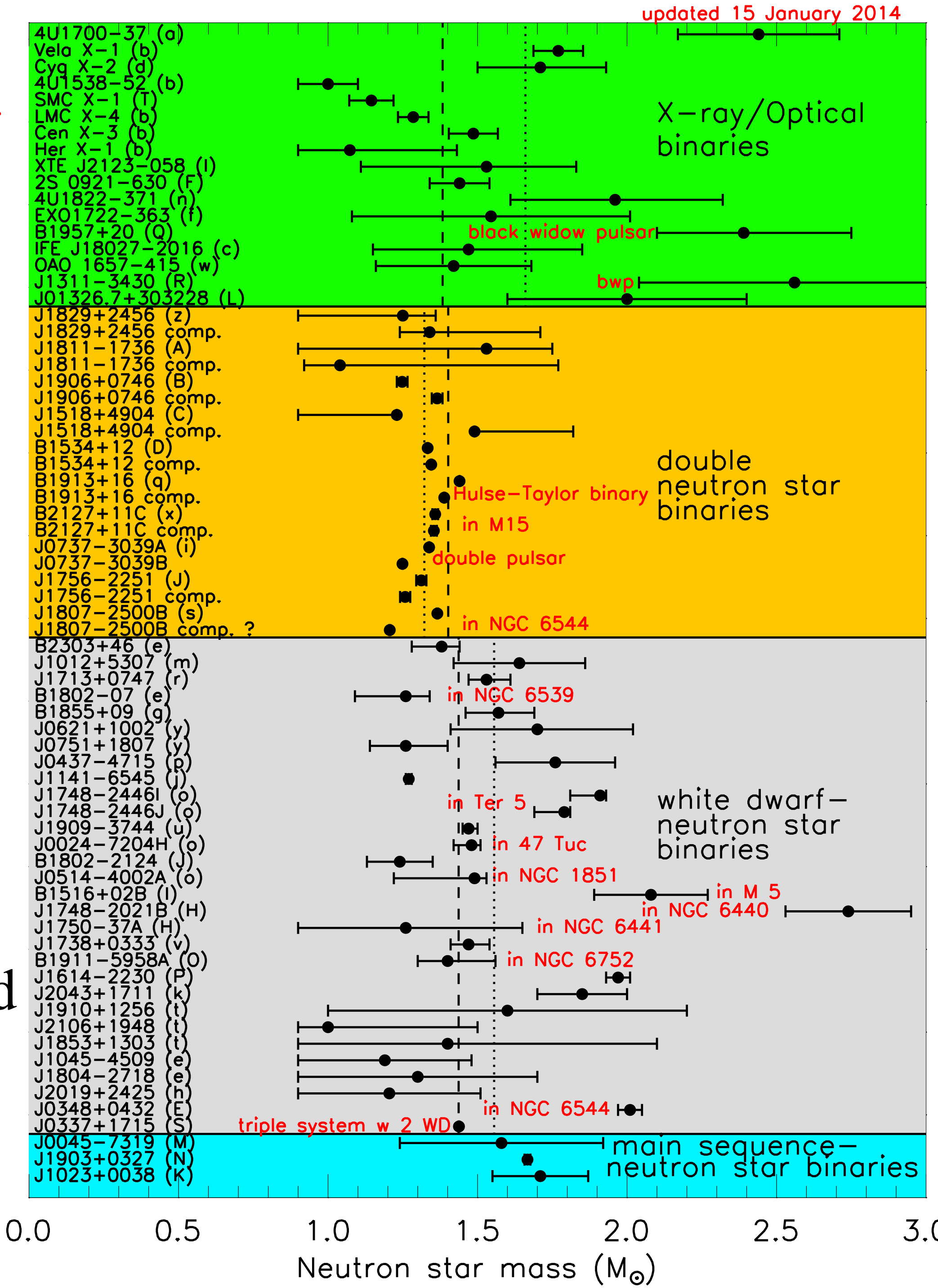


pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

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

Chart of neutron star masses

from Jim Lattimer



two 2 M_{sun} neutron stars observed

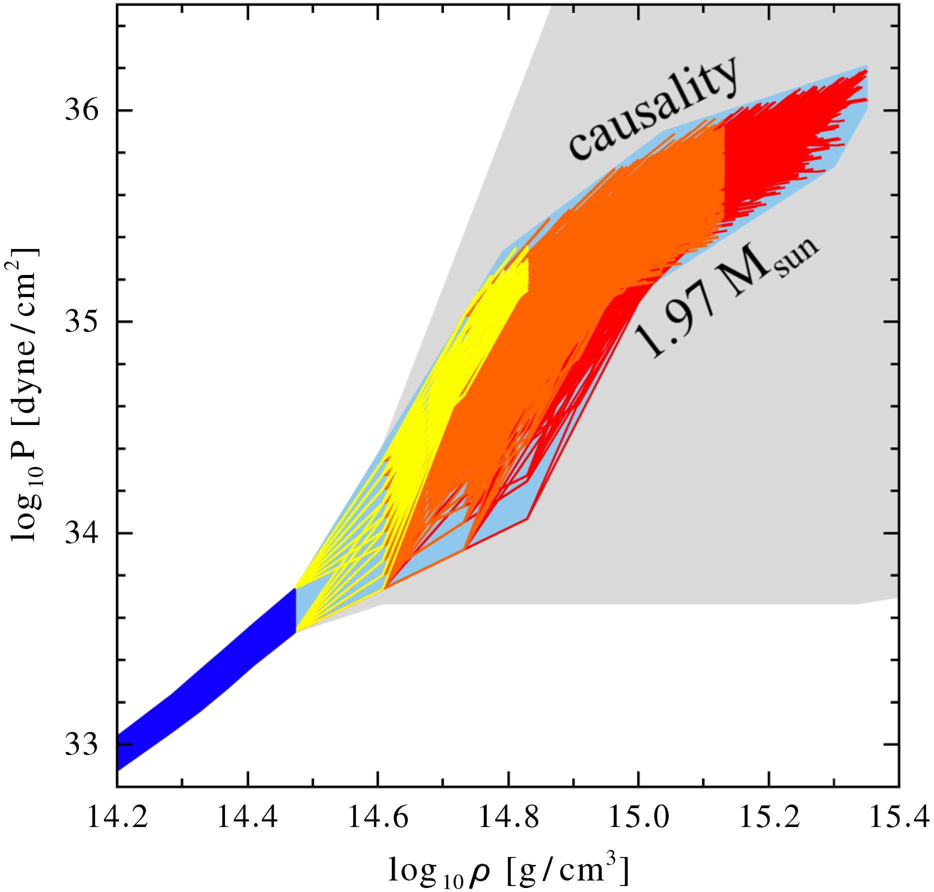
Demorest et al, Nature (2010),

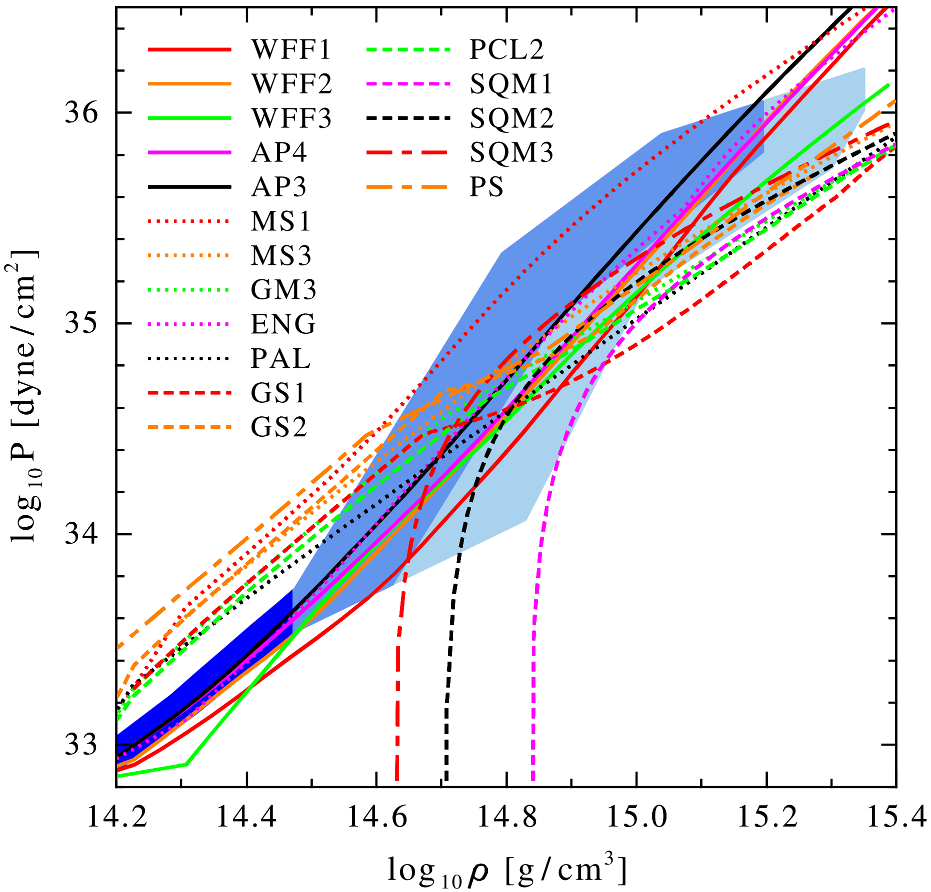
Antoniadis et al., Science (2013)

Impact on neutron stars

Hebeler, Lattimer, Pethick, AS, PRL (2010), ApJ (2013)

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

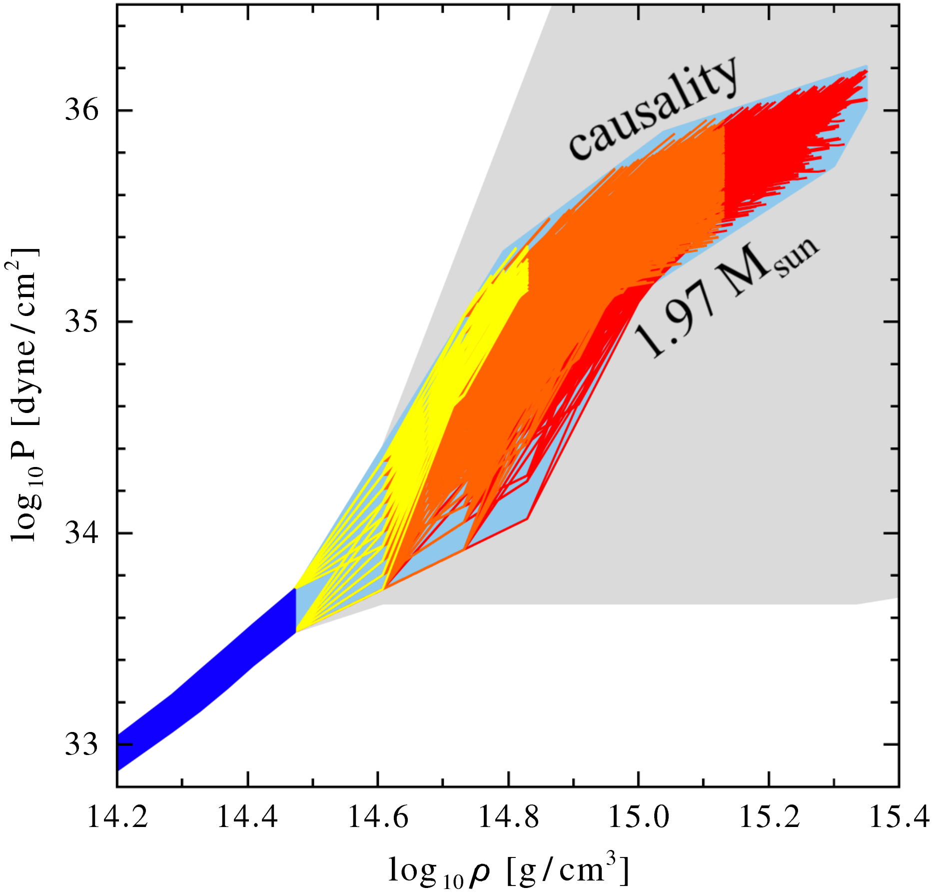


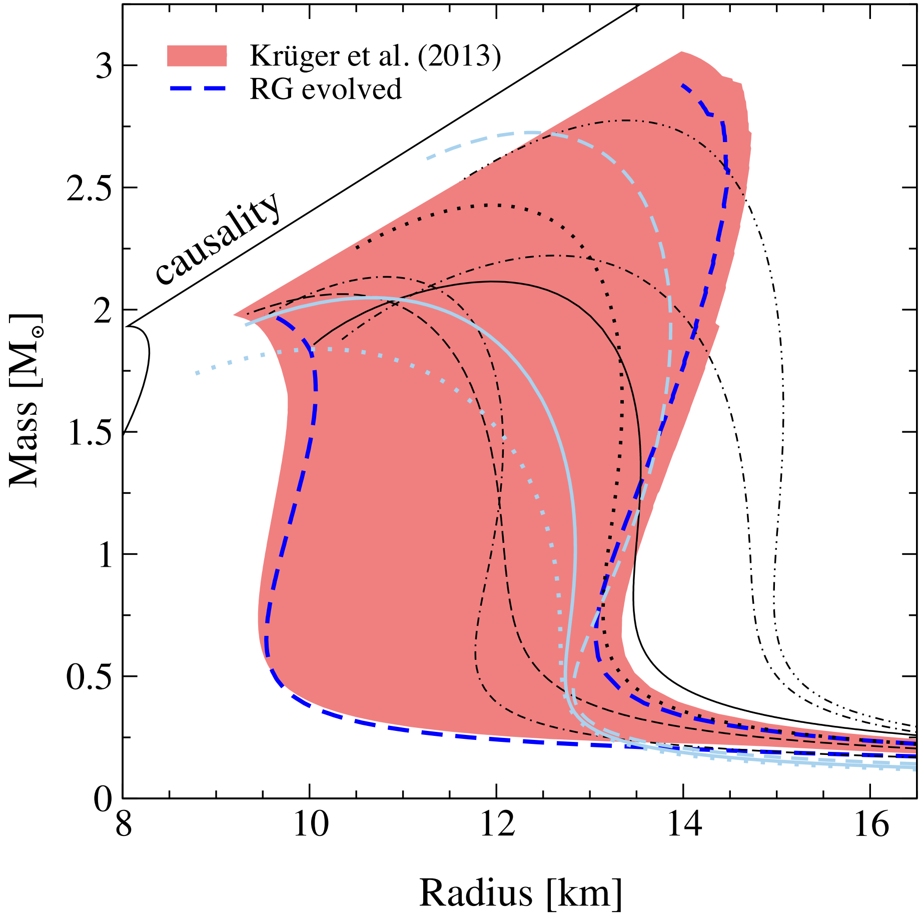


low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

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



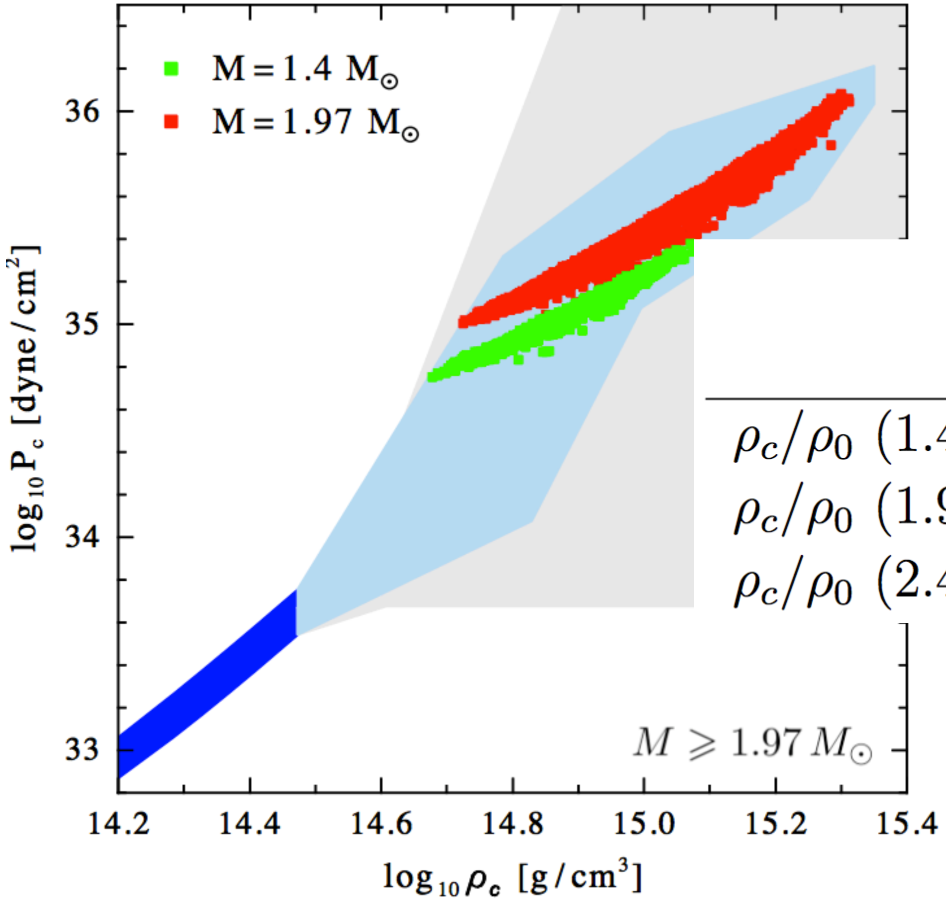


low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

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



	$\widehat{M} = 1.97\, M_\odot$ 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

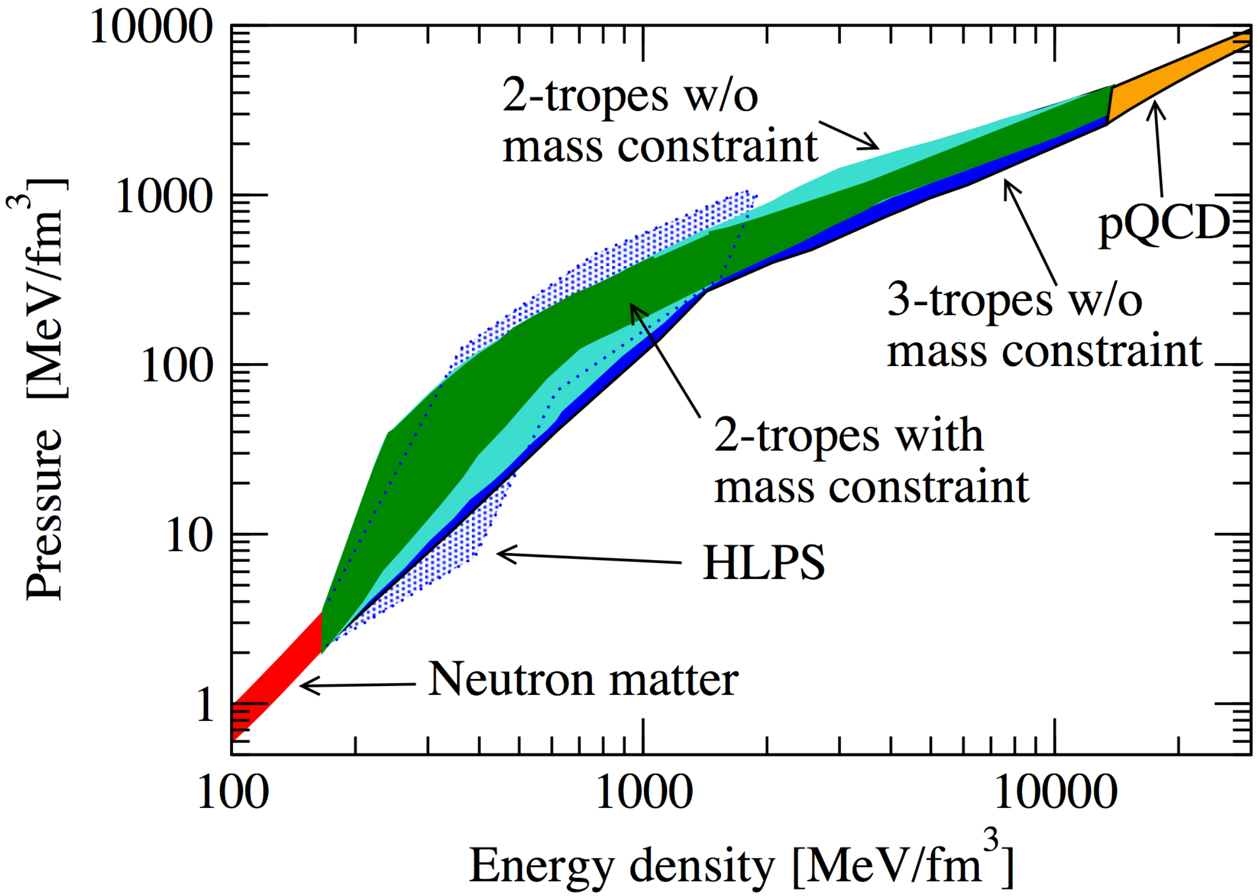
central densities
for 1.4 M_{sun} star: 1.8-4.4 ρ_0

not very high momenta!

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

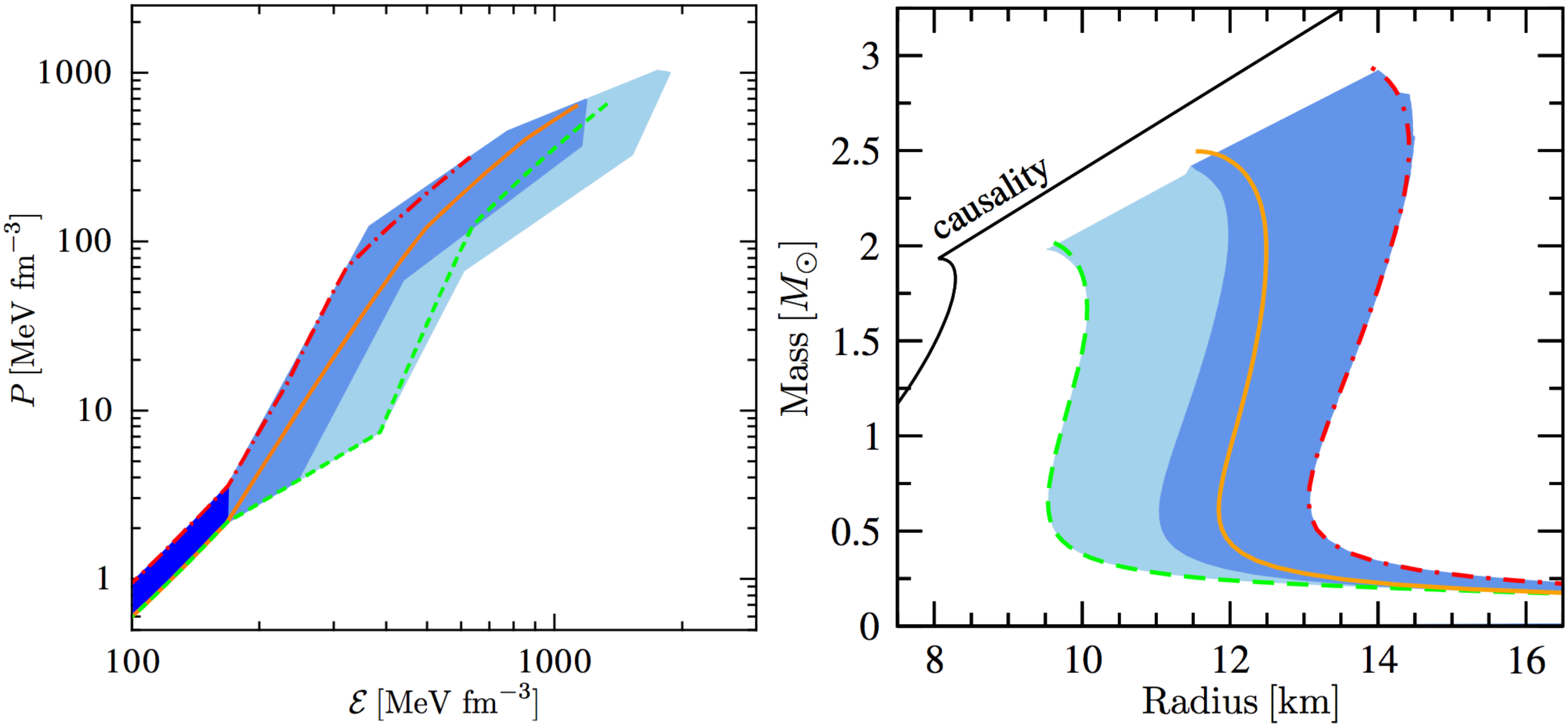
interpolating between **neutron matter calculations** and **pQCD** gives consistent EOS band Kurkela et al., ApJ (2014)



Representative equations of state

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

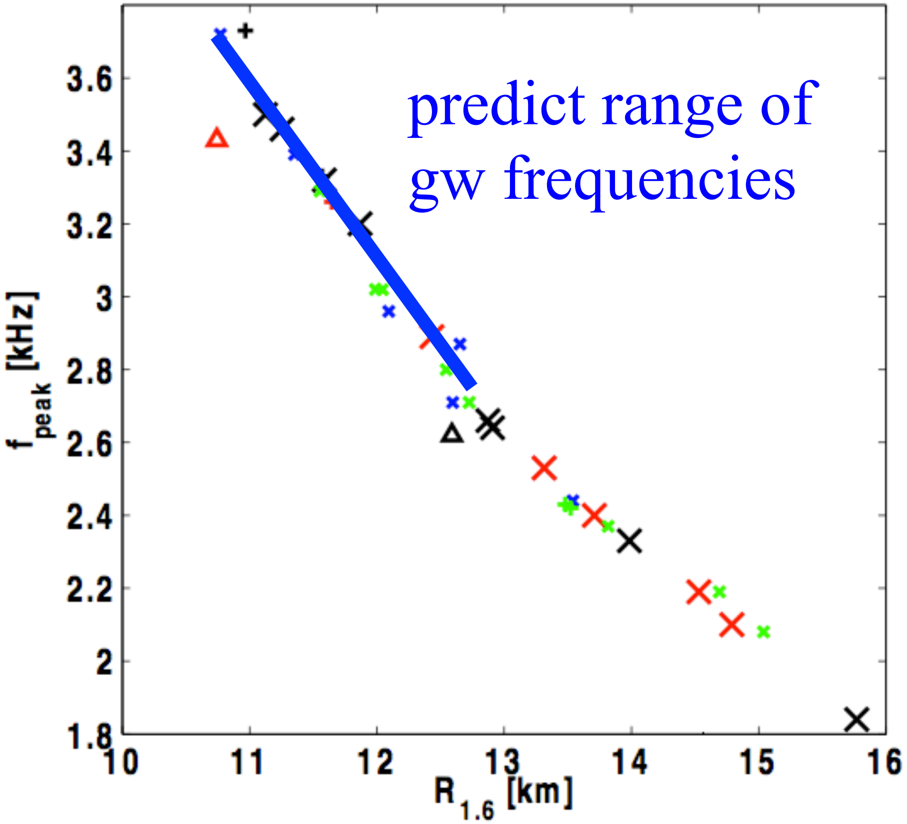
constructed 3 representative EOS for users: soft, intermediate, stiff



Neutron-star mergers and gravitational waves

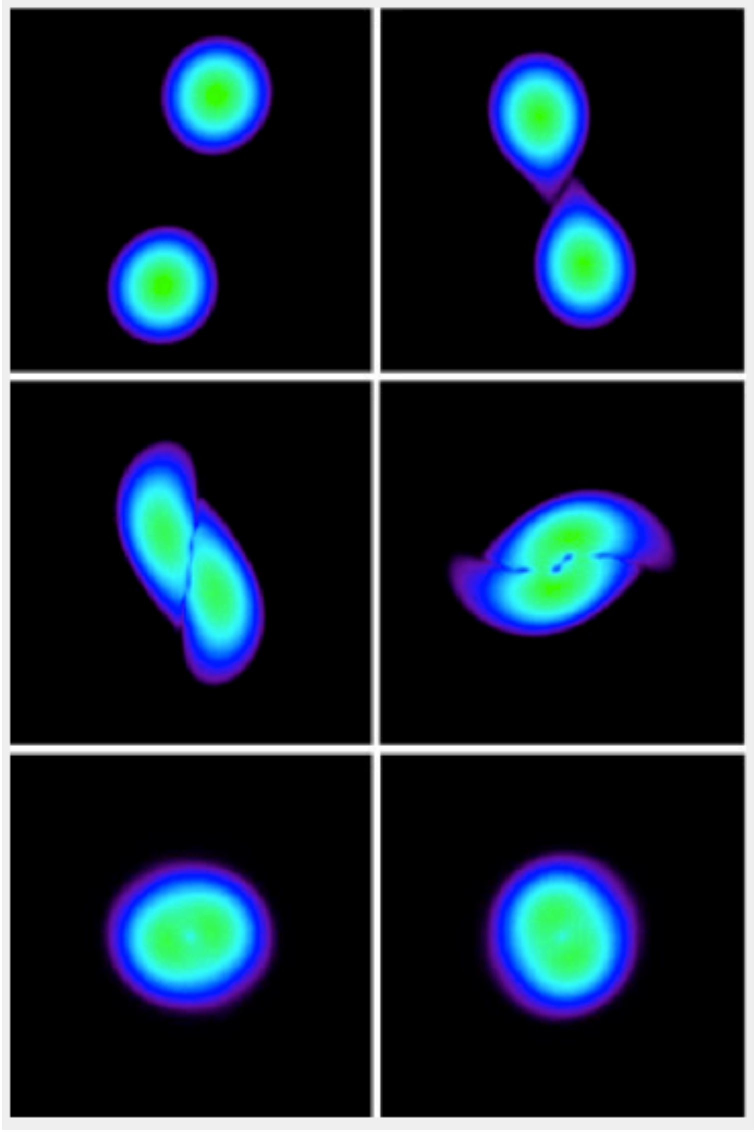
explore sensitivity to neutron-rich matter in neutron-star merger predictions for gravitational-wave signal, including NP uncertainties

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



predict range of gw frequencies

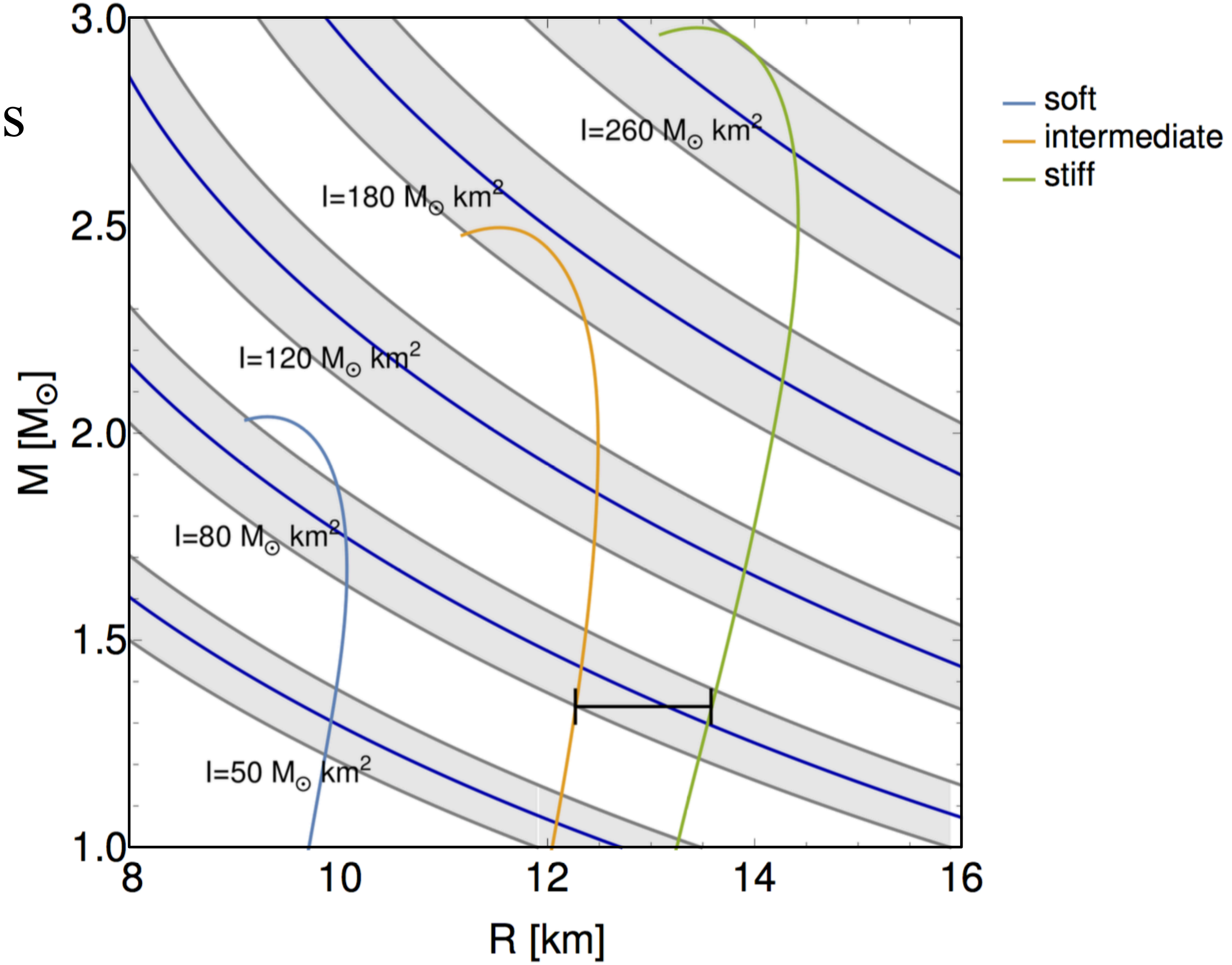
FIG. 10: Peak frequency of the postmerger GW emission versus the radius of a nonrotating NS with 1.6 $M_\odot$ for different EoSs. Symbols have the same meaning as in Fig. 8.



Radius constraints from moment of inertia Svenja Greif et al., in prep.

candidate neutron star:
PSR J0737-3039 M=1.35 M_{sun}

10% measurement of moment of inertia reduces radius range by 1/2



Summary

Chiral EFT interactions provide powerful constraints for dense matter:
especially for neutron-rich matter up to around saturation density

Combined with heaviest neutron star observations
limits radius to 9.7-13.9 km for $M=1.4\ M_{sun}$

Can be further constrained with heavier neutron stars,
extending EOS to higher densities, moment of inertia

Neutron-rich calcium isotopes present test-bench for nuclear forces:
Energies, shell structure, charge radii
first constraints on neutron skin from ^{48}Ca dipole polarizability

Thanks: S. Bacca, **C. Drischler**, S. Gandolfi, A. Gezerlis, **S. Greif**, G. Hagen, **K. Hebeler,** J.D. Holt, **T. Krüger,** J. Lattimer, **J. Lynn,** W. Nazarewicz, **M. Miorelli,** T. Papenbrock, C. Pethick, **I. Tews, K. Wendt**