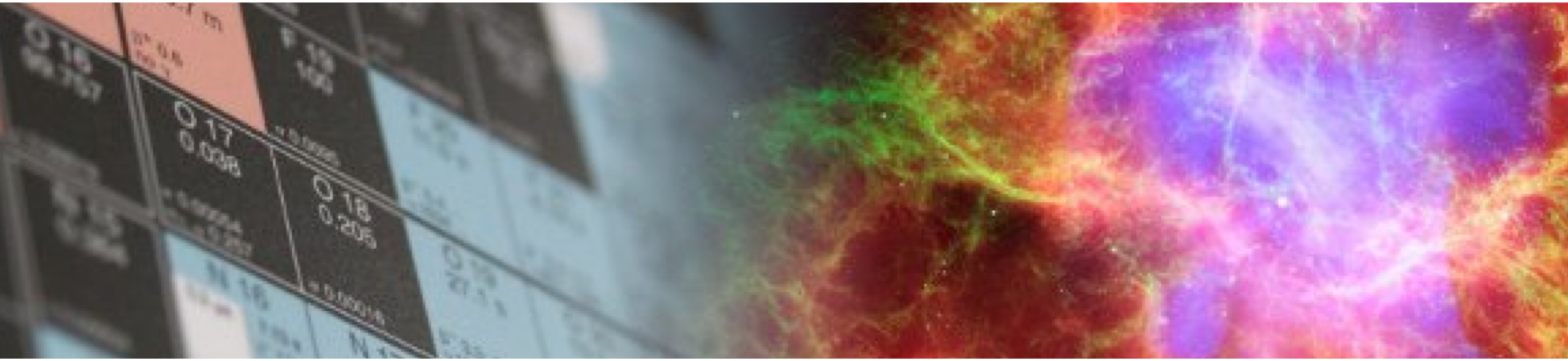
Uncertainty estimates for neutron-rich nuclei and neutron stars

Achim Schwenk

TECHNISCHE UNIVERSITÄT DARMSTADT



Uncertainty Quantification at the Extremes (ISNET-6), Oct. 10, 2018

DFG SFB 1245 erc Bundesministerium für Bildung und Forschung HELMHOLTZ ASSOCIATION

Main points

Many-body calculations of medium-mass nuclei have smaller uncertainties compared to uncertainties in nuclear forces

How should we propagate these uncertainties in calculations and possibly include fits to saturation?

General equation of state band for neutron stars based on nuclear physics and observations

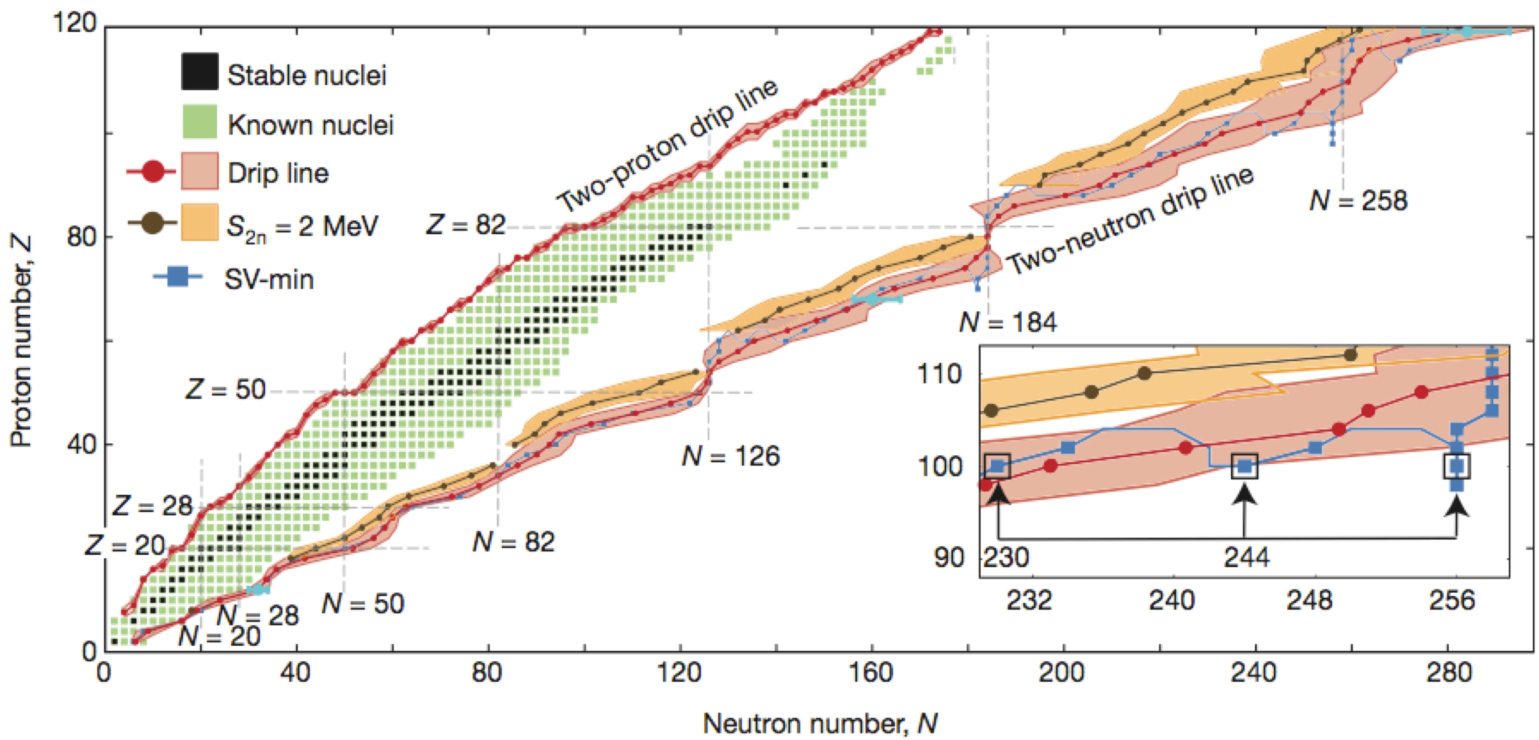
What are sensitivities to different parametrization? Sensitivities when inferring neutron star properties?

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 quantum chromodynamics?

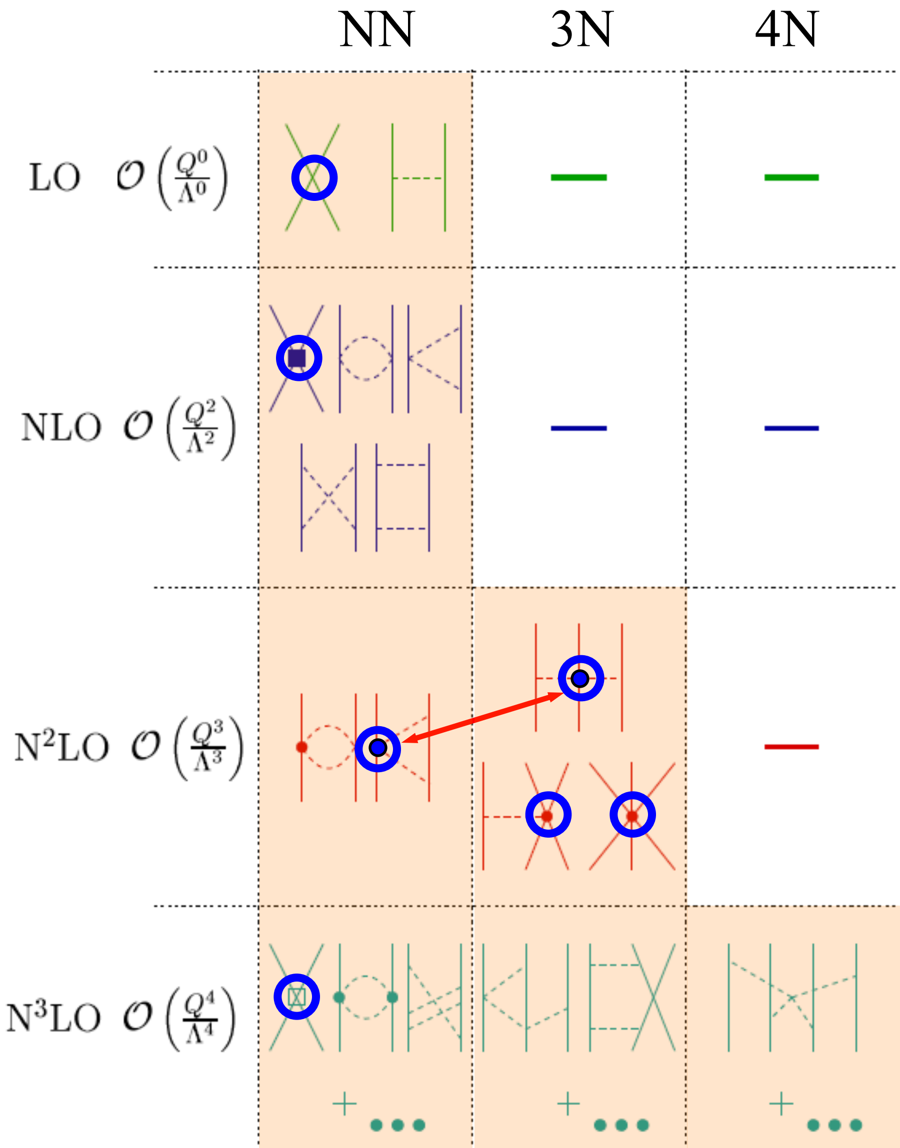
Lattice QCD and **effective field theories of the strong interaction**

for few nucleons — for all nuclei

Chiral effective field theory for nuclear forces

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

$\sim m_\Delta - m_N \ldots m_\rho$



include long-range pion physics

short-range couplings, fit to experiment once

consistent NN-3N-4N interactions

new developments in power counting, **uncertainty quantification, optimization** ISNET-6 et al., ...

consistent electroweak interactions and matching to lattice QCD

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

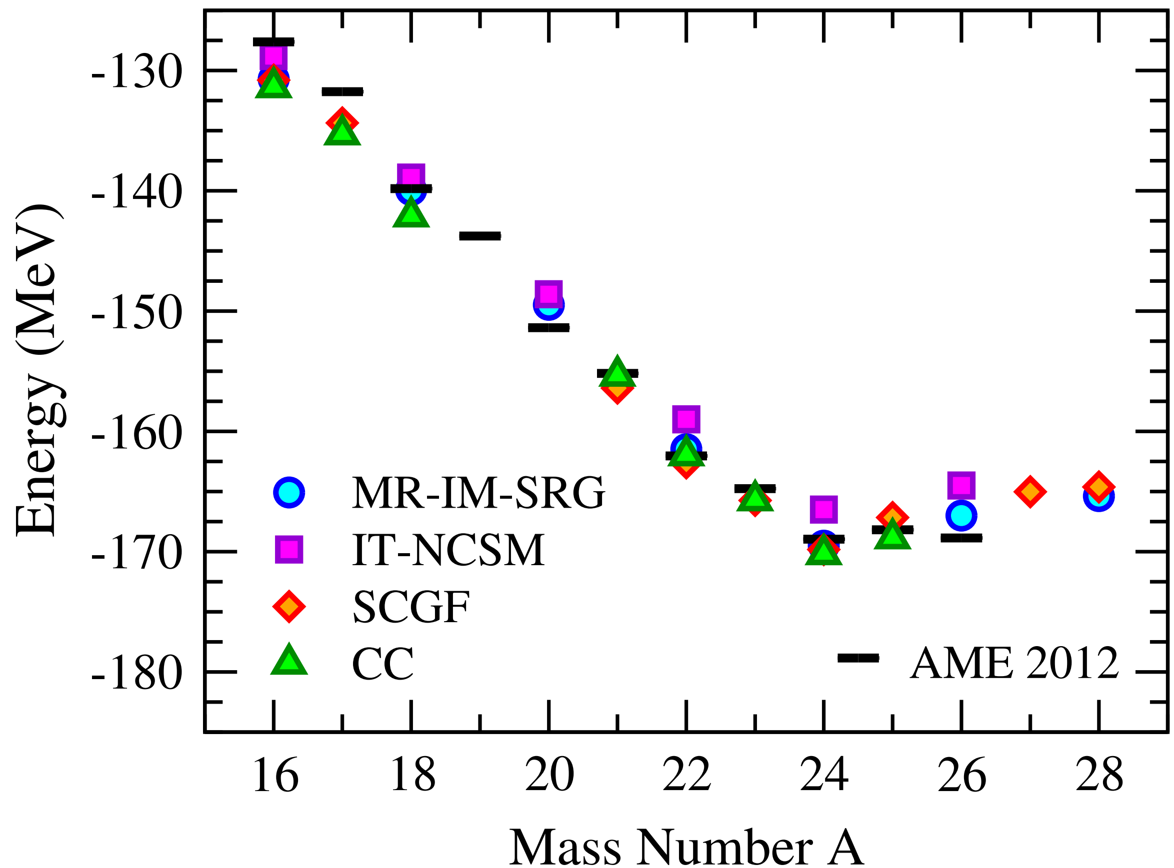
Ab initio calculations of neutron-rich oxygen isotopes

based on same NN+3N interactions with different many-body methods

CC 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)

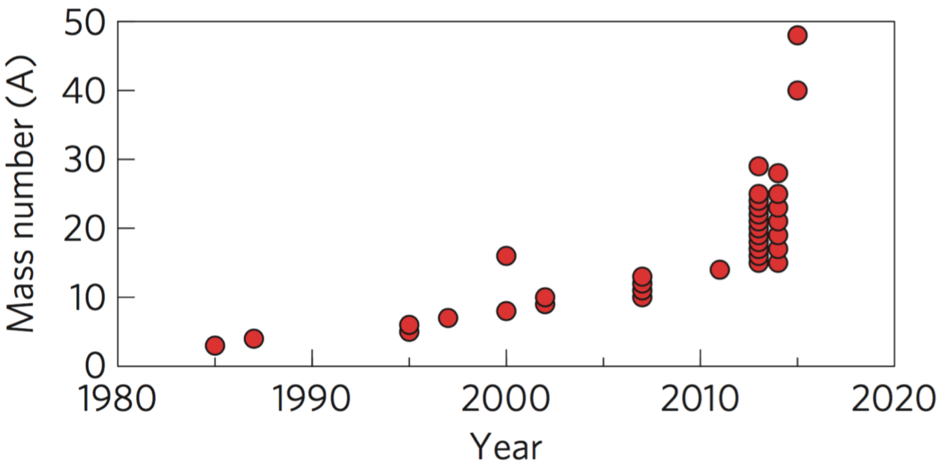
Self-Consistent
Green's Functions
Cipollone et al., PRL (2013)



Many-body calculations of medium-mass nuclei have smaller uncertainty compared to uncertainties in nuclear forces

Progress in ab initio calculations of nuclei

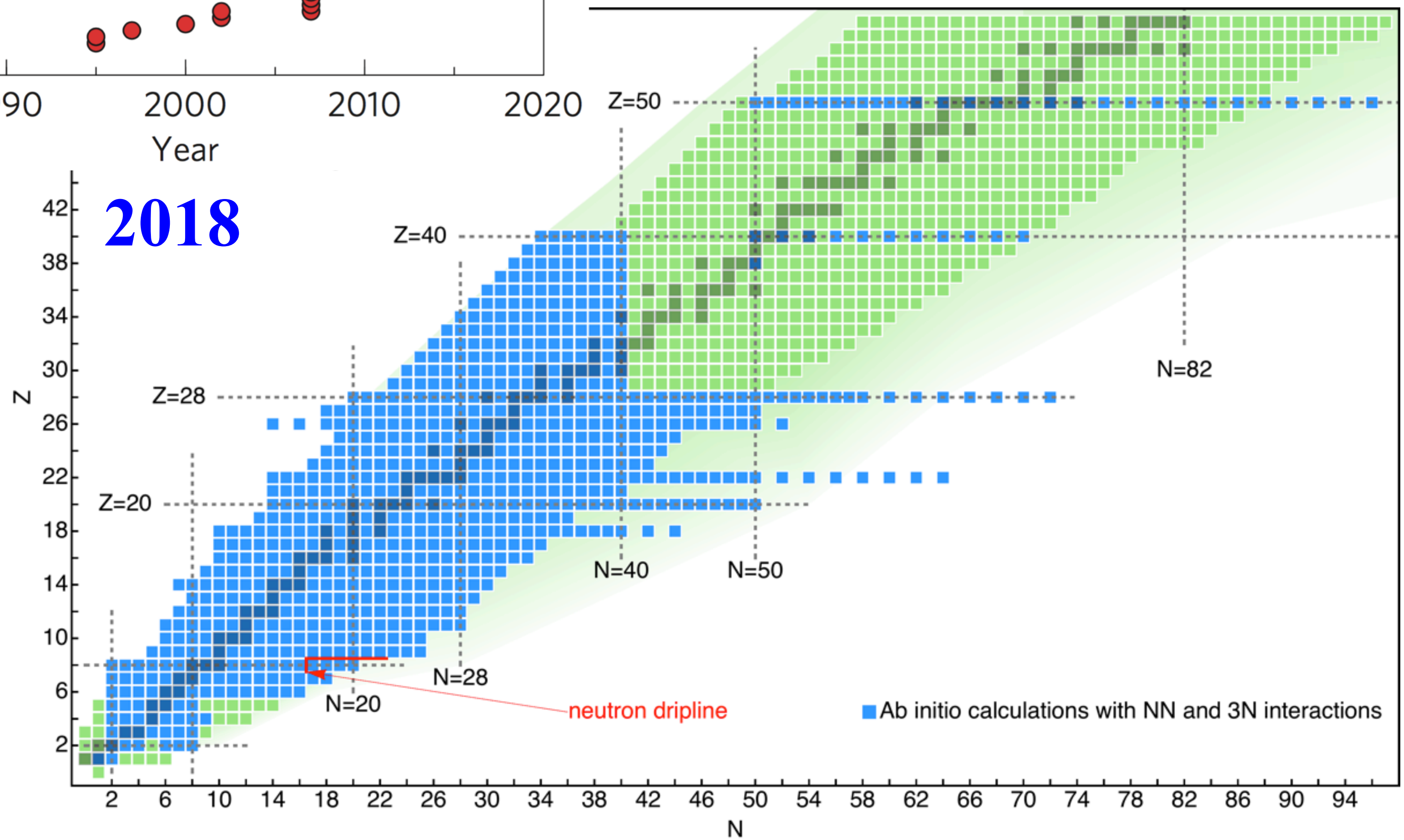
dramatic progress in last 5 years to access nuclei up to A ~ 50



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

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

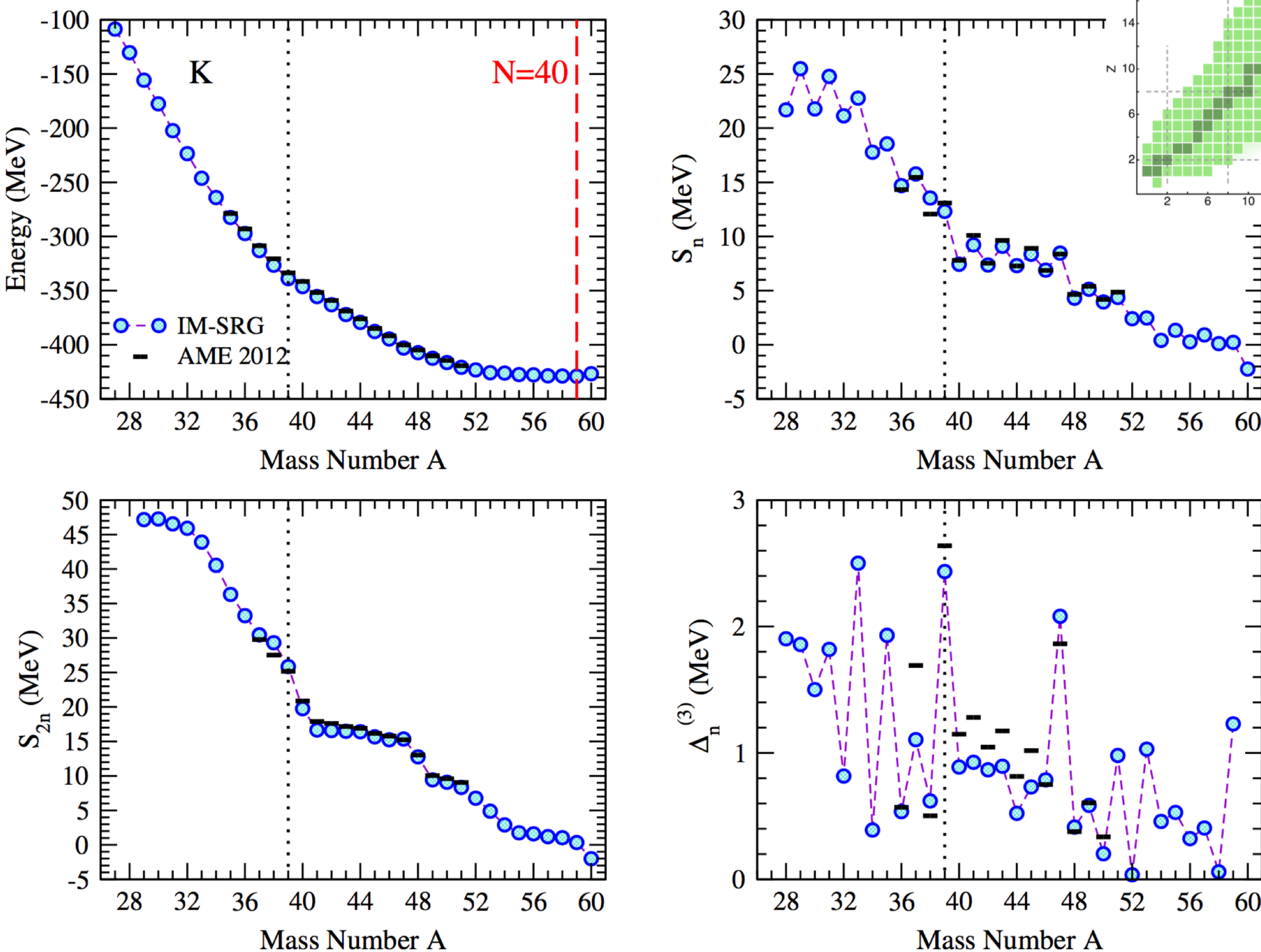
2018

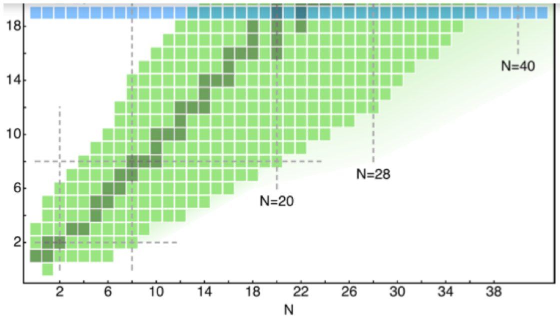


Great progress from medium to heavy nuclei

In-medium similarity renormalization group (IM-SRG) for open shell

Tsukiyama, Bogner, AS, **Hergert, Holt, Stroberg, Simonis, Hebeler,…**





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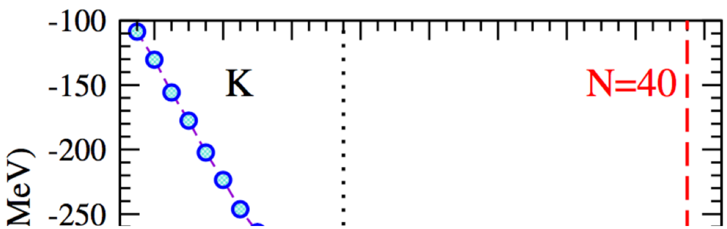

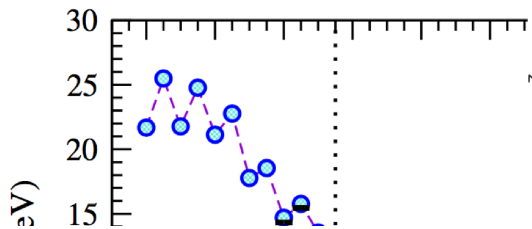

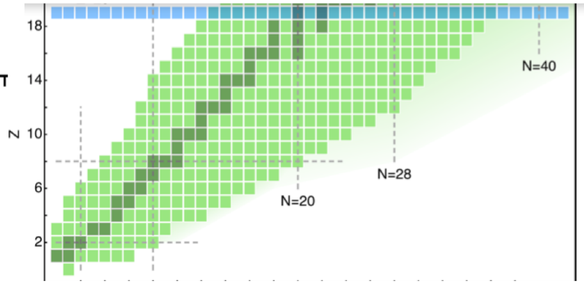

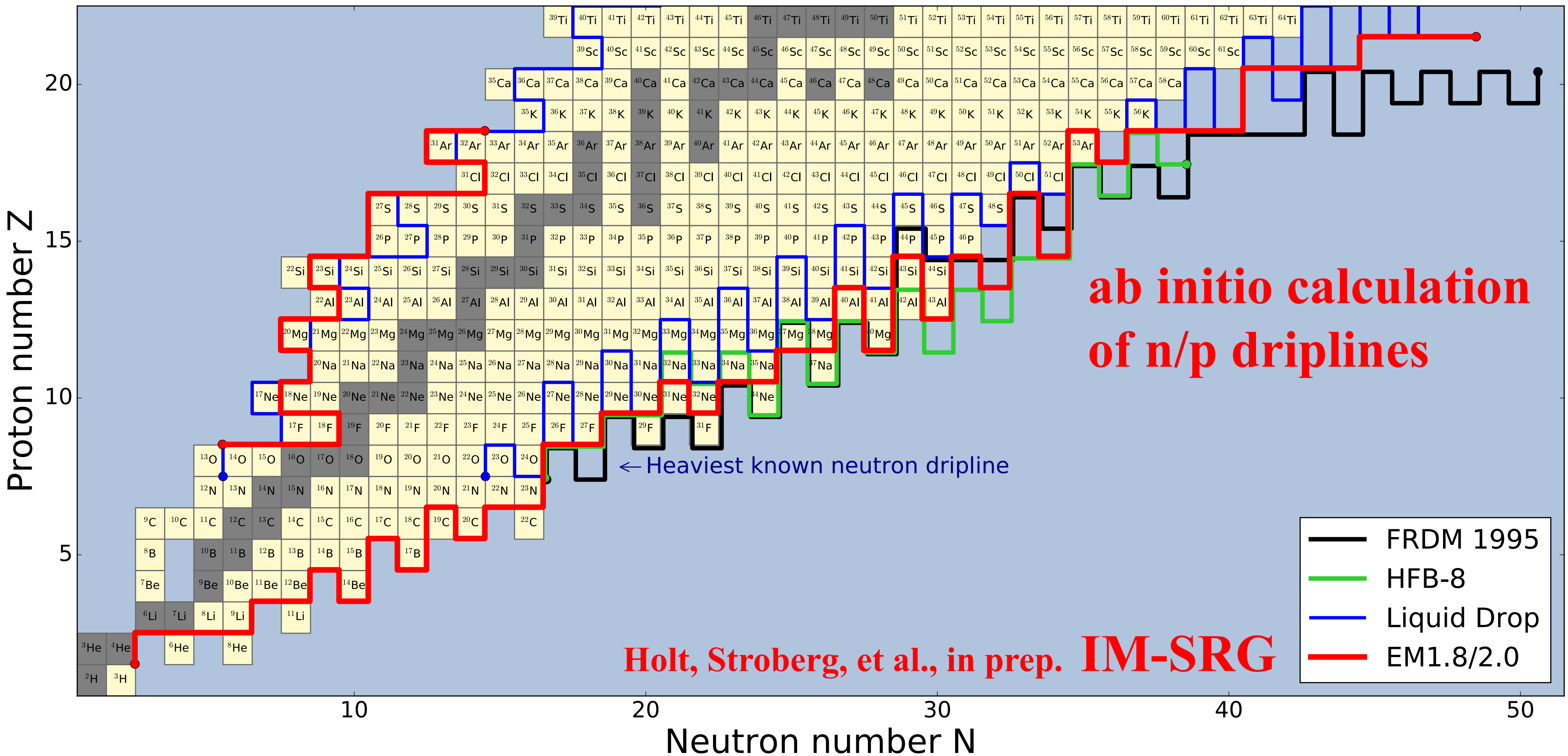

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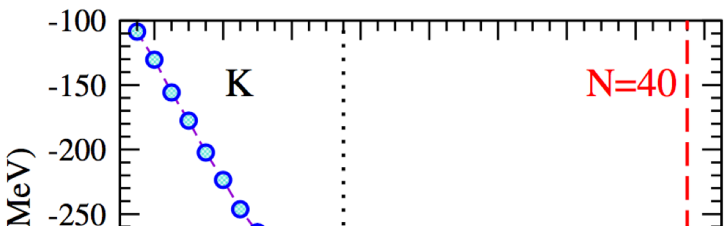

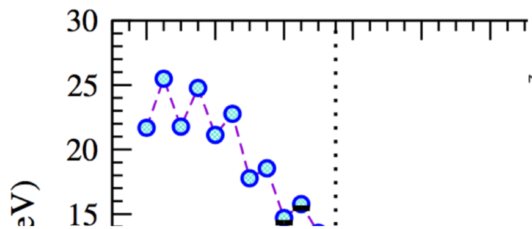

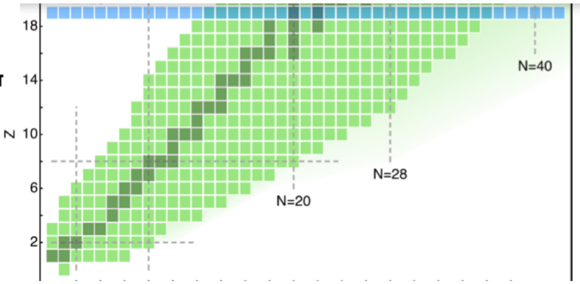

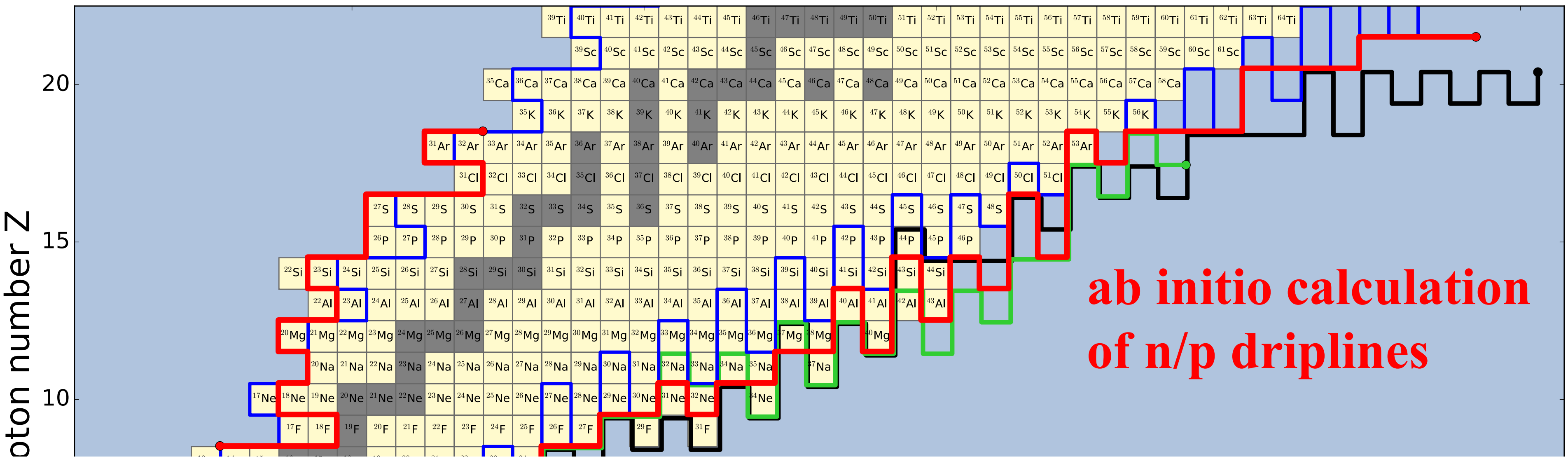

Important for medium-mass nuclei:

Consider nuclear forces with good (nuclear matter) saturation properties

N^2LO_{sat} fit to selected nuclei up to A=24 Ekström et al. (2015)

"Magnificent Seven": NN evolved + 3N fit to ^{3}H, ^{4}He Hebeler et al. (2011)

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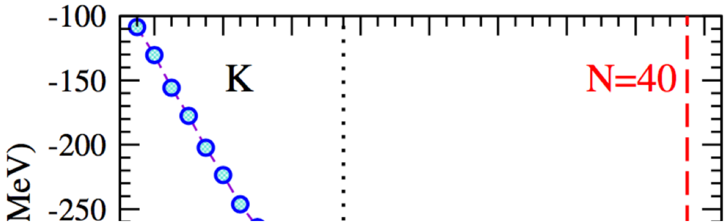

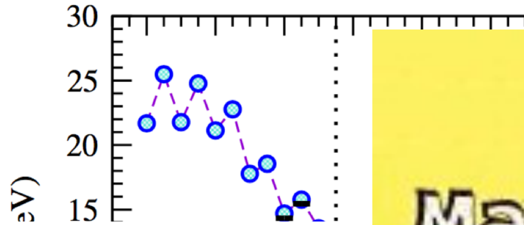

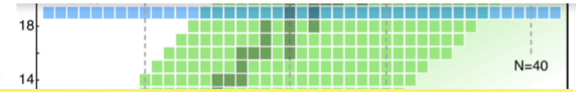

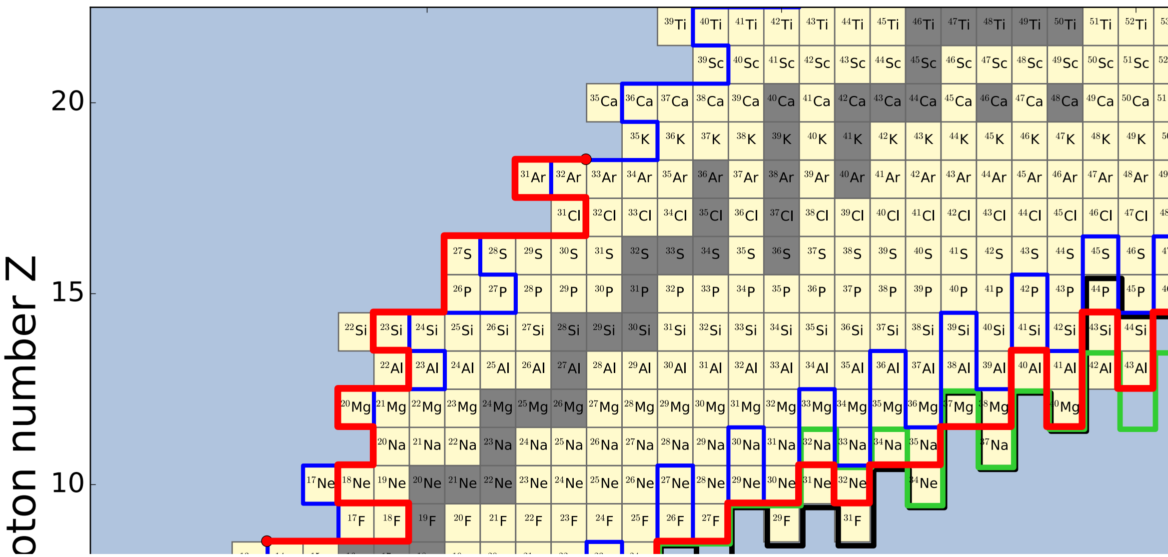

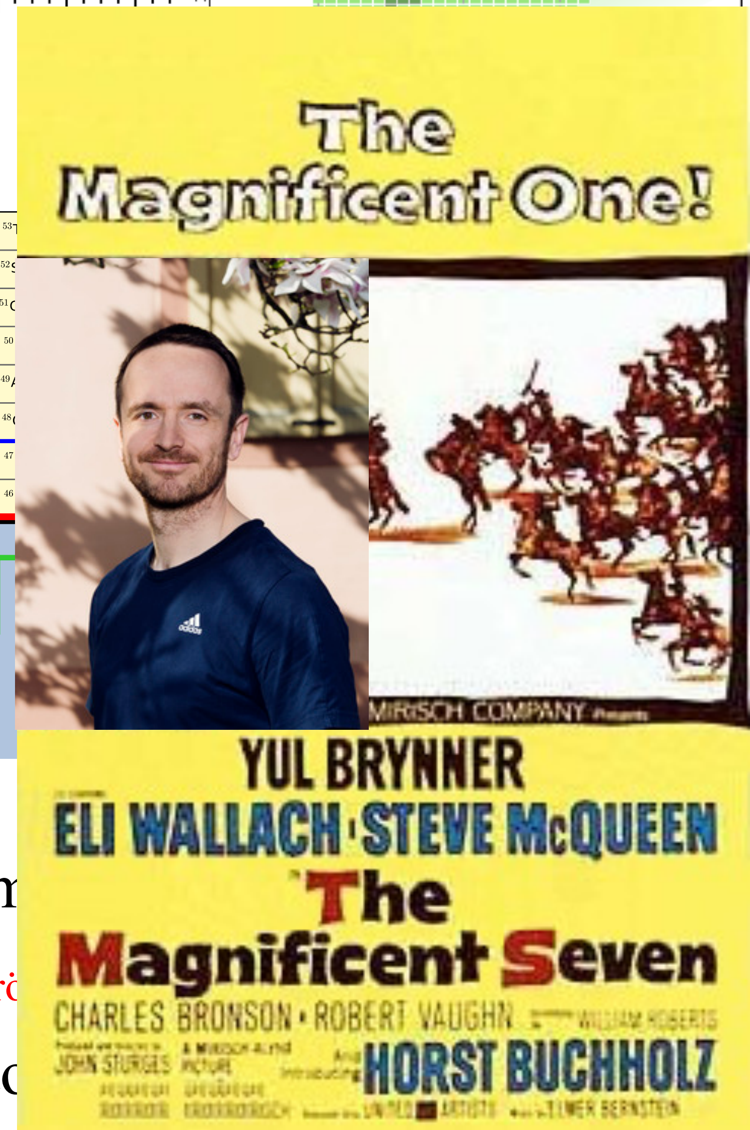

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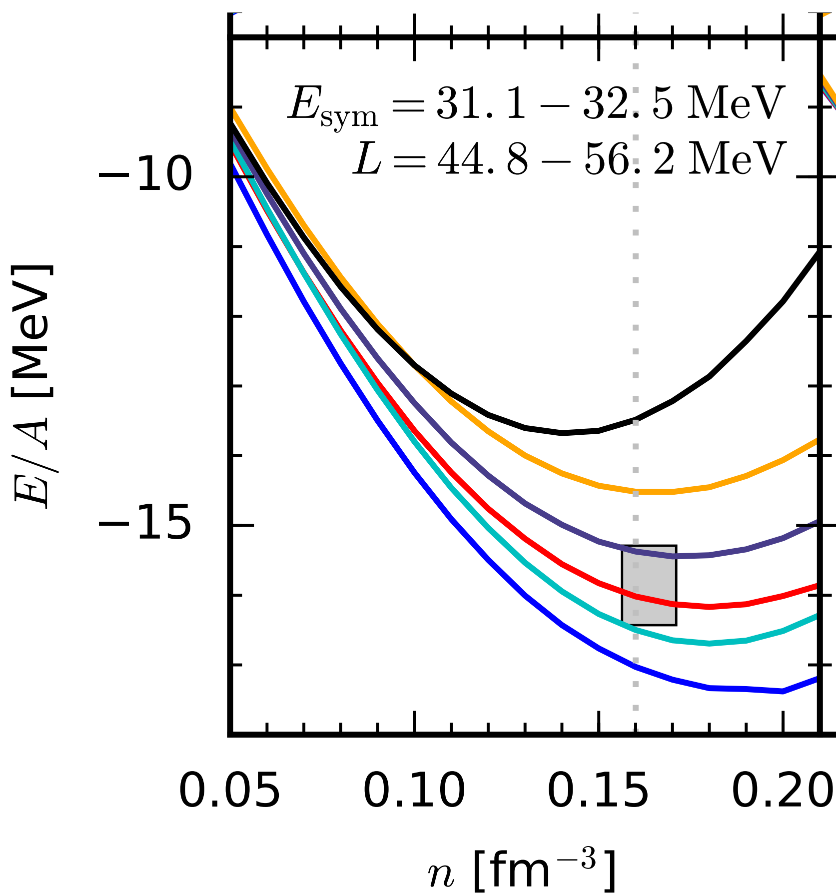
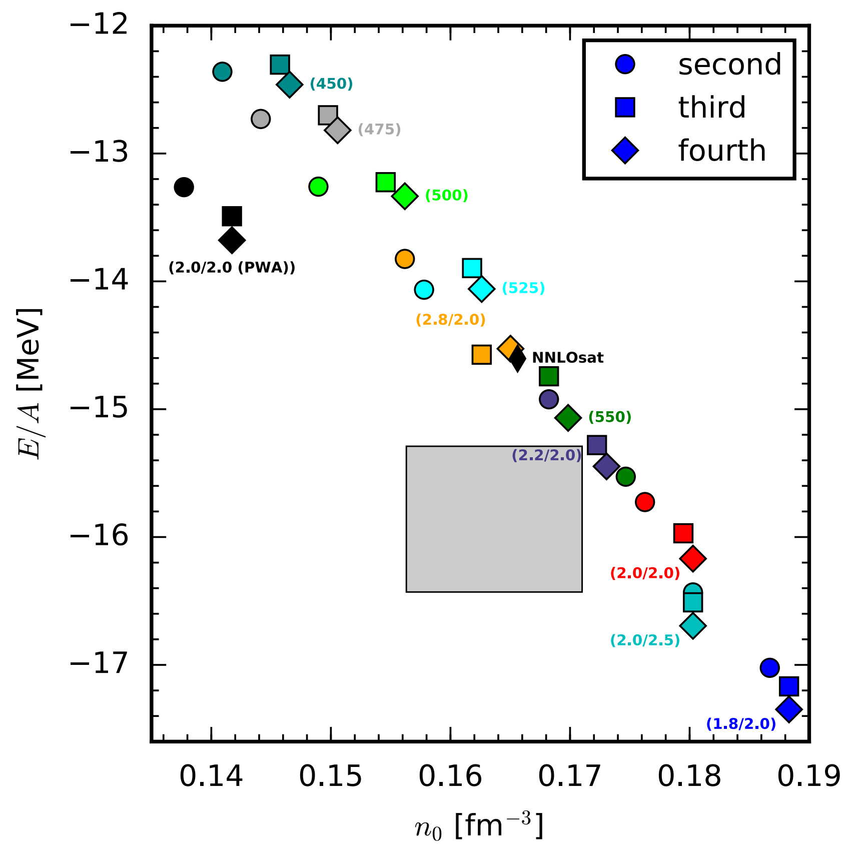
Nuclear forces and nuclear matter

Monte-Carlo calculation of all energy diagrams up to 4th order in MBPT

Drischler, Hebeler, AS, arXiv:1710.08220, automated 5th and 6th order calculation, Drischler et al. in prep.

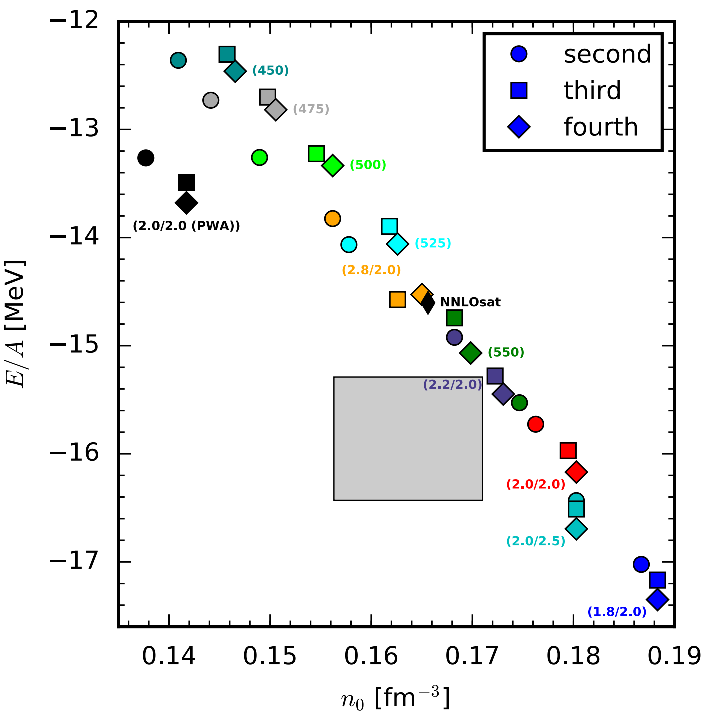
chiral order	Λ/c_D	second order NN-only	second order NN+3N	second order 3N res.	third order NN+3N	fourth order NN-only	fourth order NN+3N[a]
N^3LO/N^2LO	$\lambda/\Lambda = 1.8/2.0\ \text{fm}^{-1}$	-2.30	-2.24	-0.40	-0.10	-0.20	-0.07

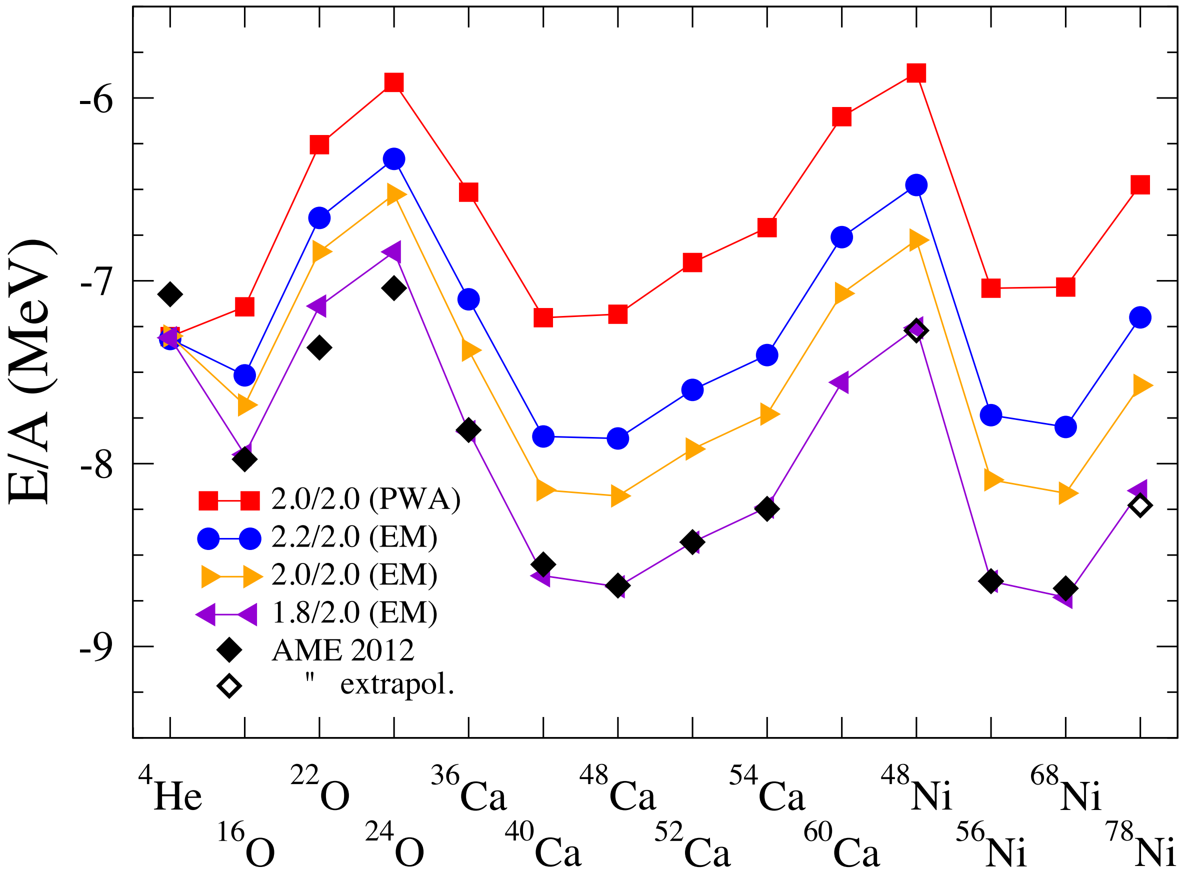




Importance of saturation for nuclear forces
Simonis, Stroberg et al. (2017)

IM-SRG calculations of closed shell nuclei follow nuclear matter saturation trends





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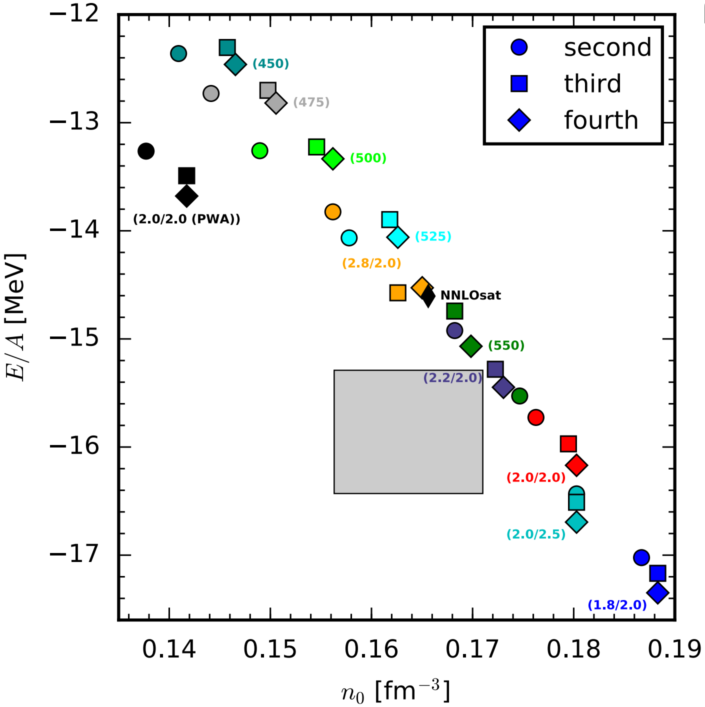
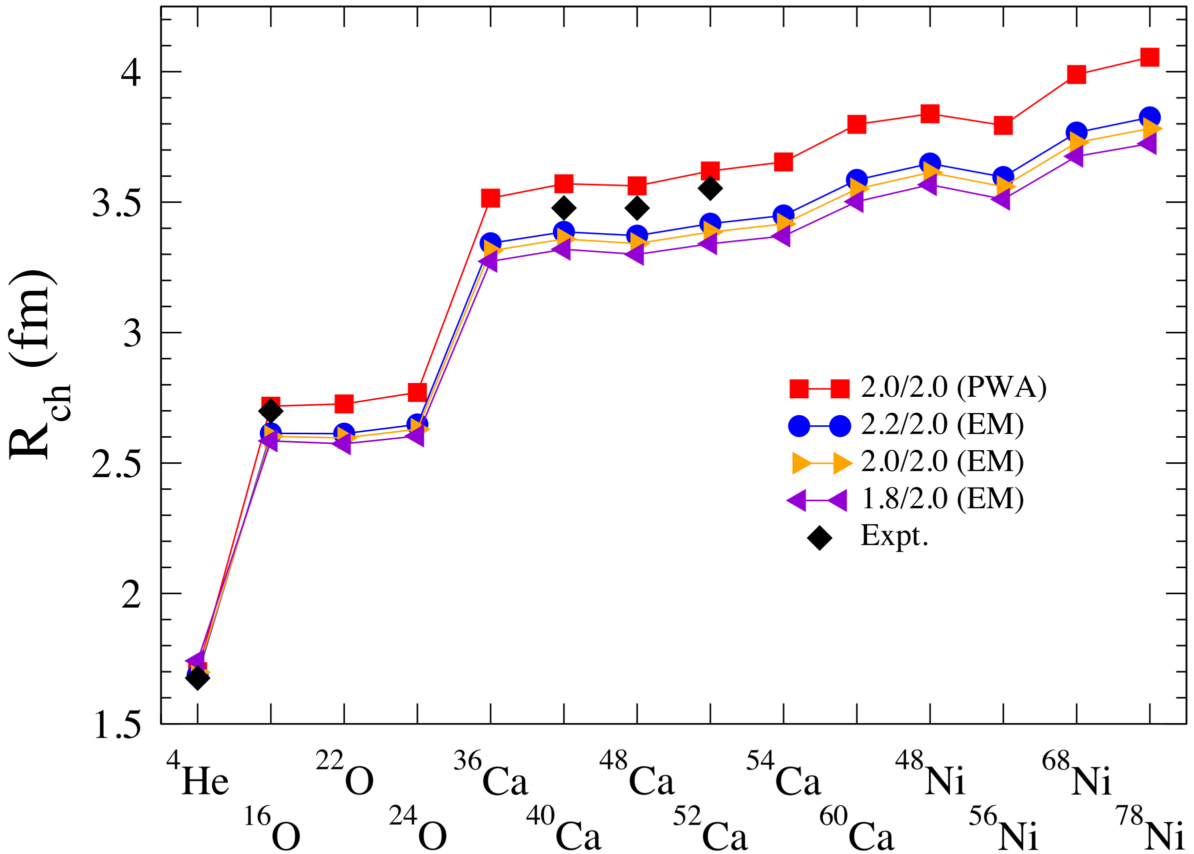




Nuclear forces and nuclear matter

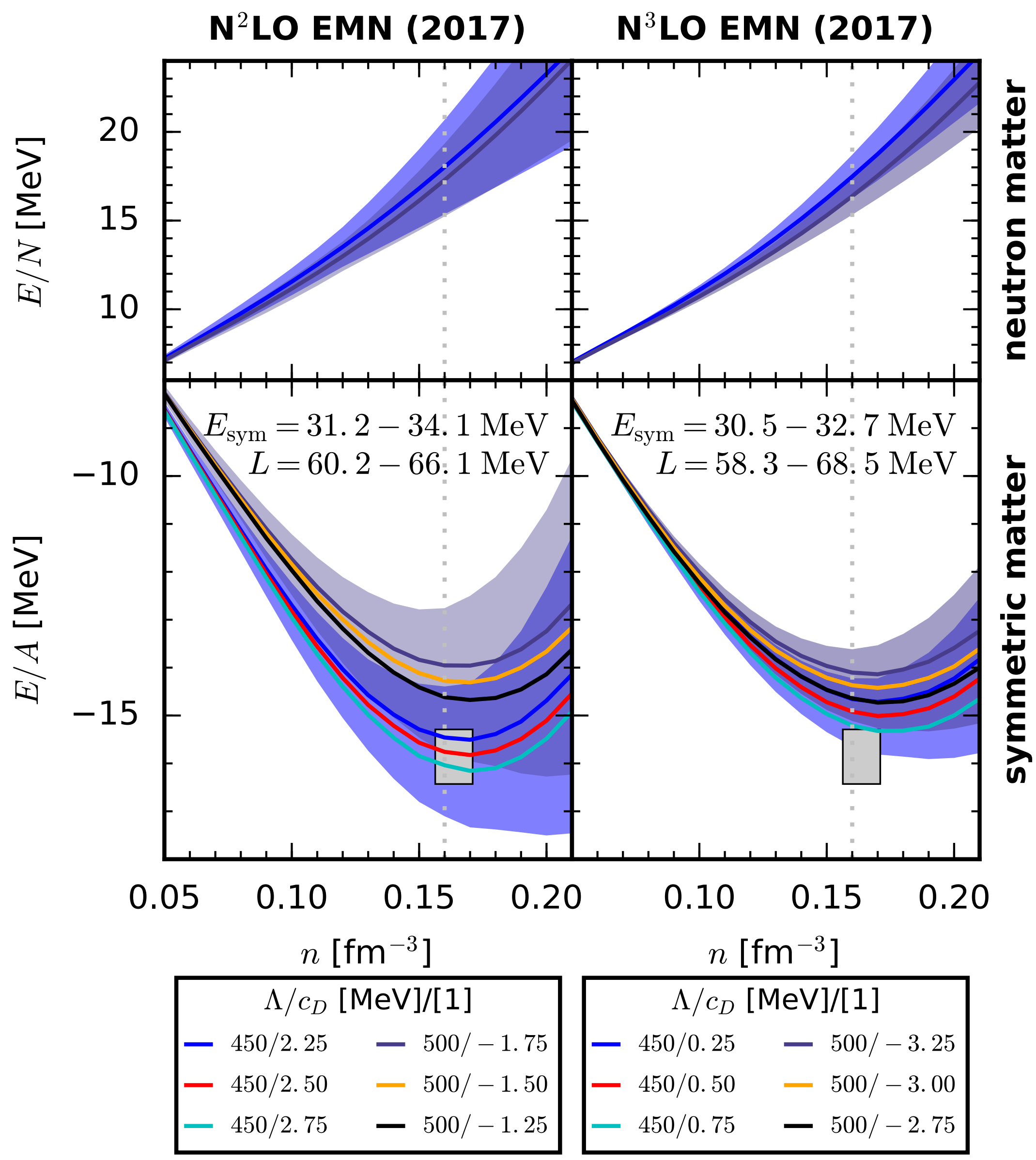
Monte-Carlo calculation of all energy diagrams
up to 4th order in MBPT

Drischler, Hebeler, AS, arXiv:1710.08220

including NN, 3N, 4N
3N fit to saturation region

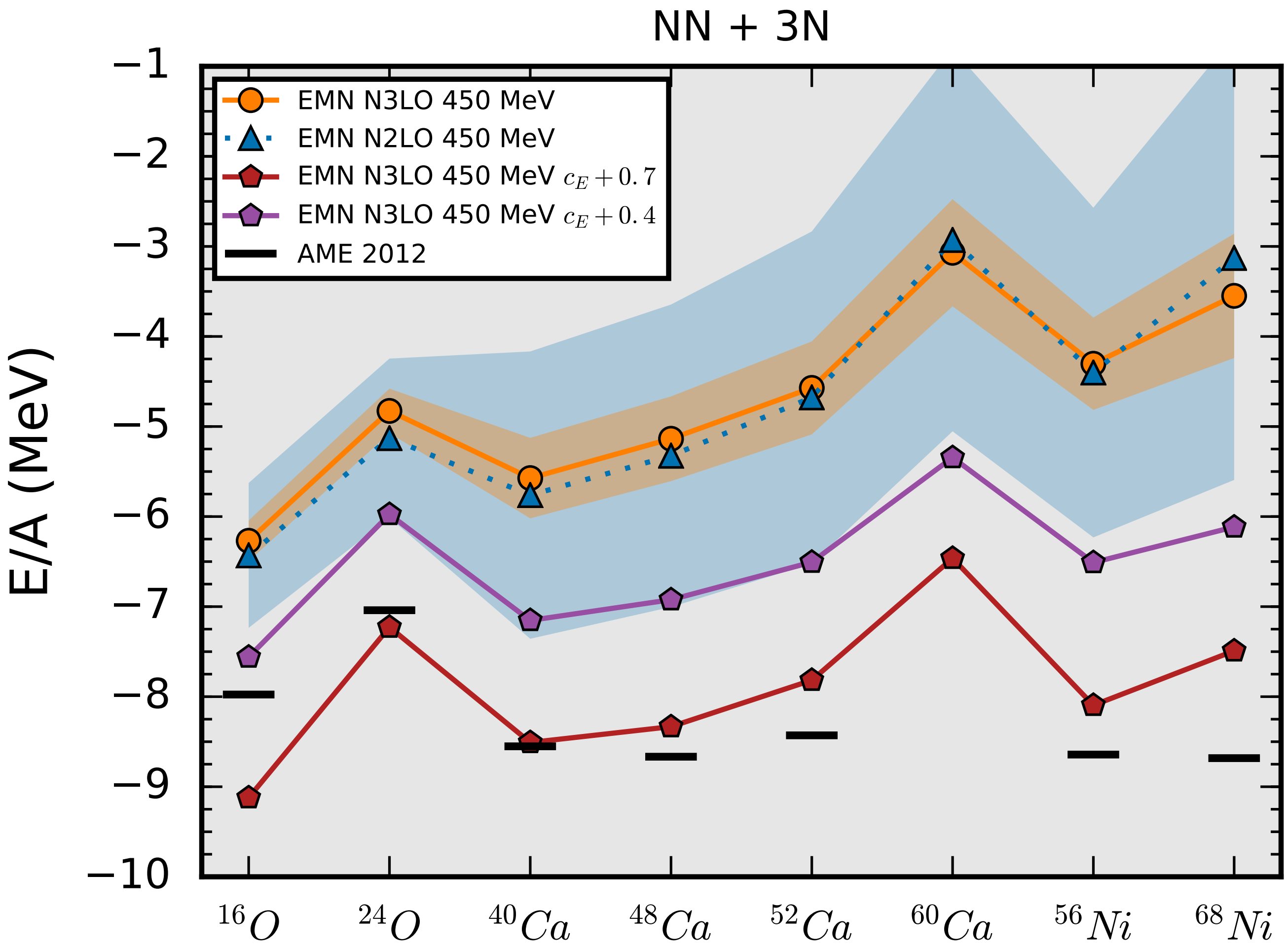
systematic improvement
from N^2LO to N^3LO

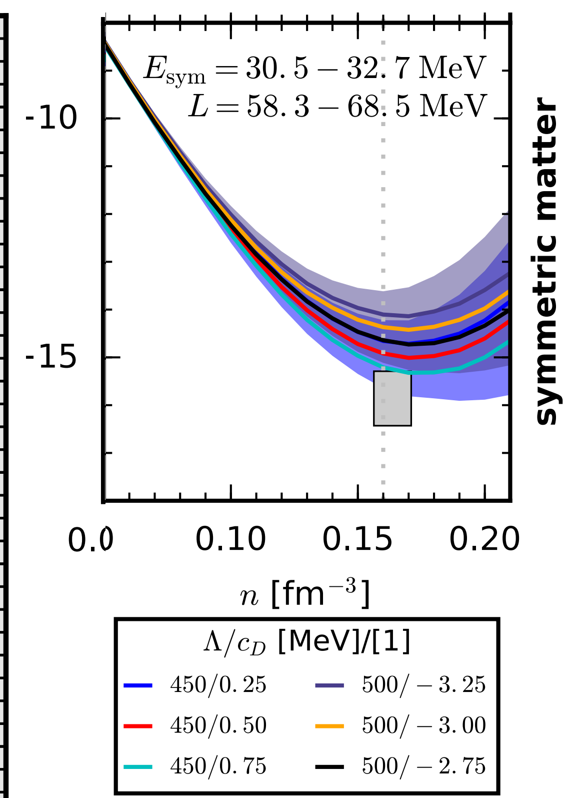
first full N^3LO Hamiltonians
for use in nuclear structure
and EOS calculations



First (preliminary) N^{3}LO results for nuclei **Hoppe**, Simonis et al.

with EFT uncertainties, follows nuclear matter saturation behavior





testing sensitivity to 3N couplings, but more studies needed!

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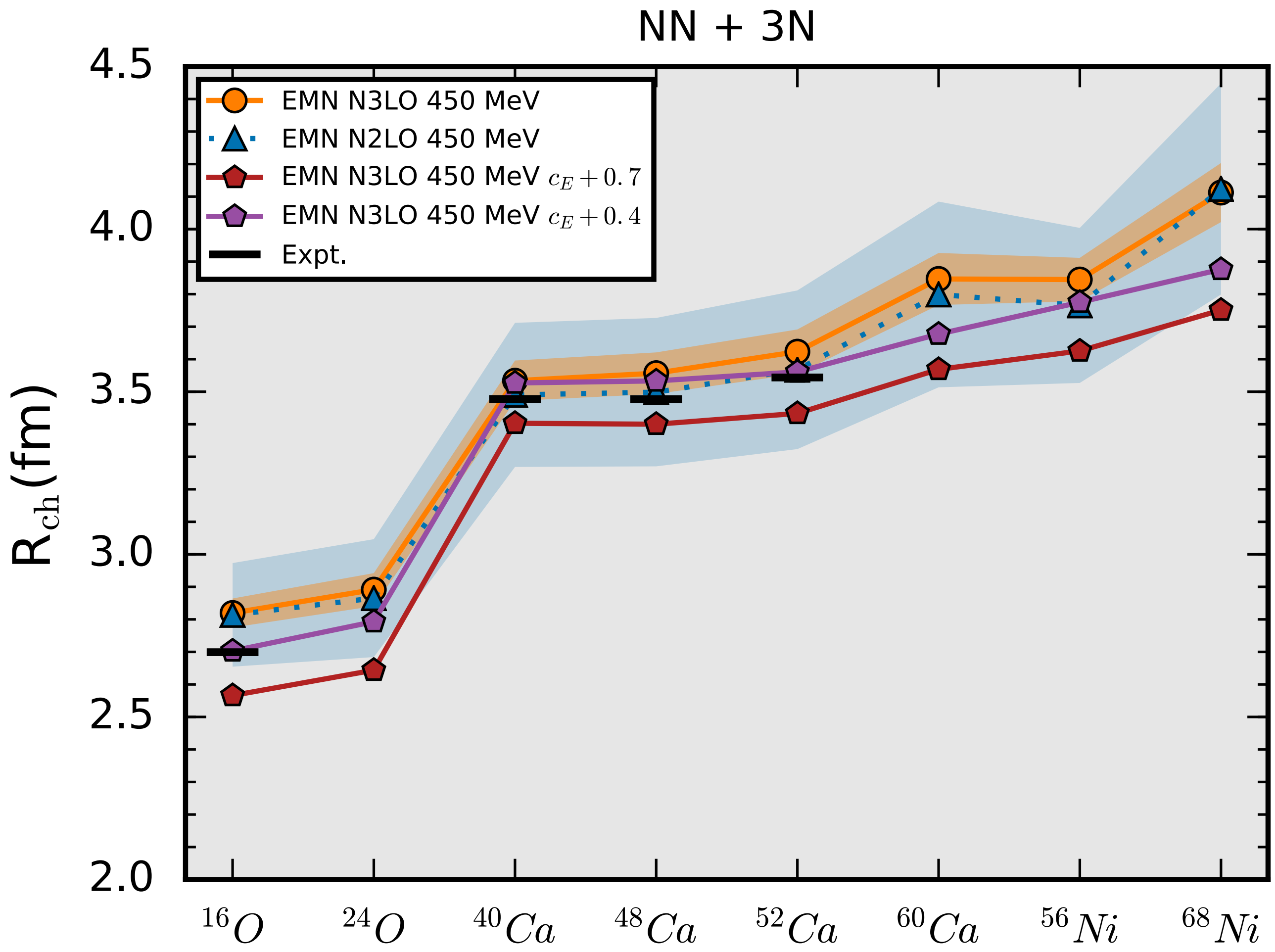
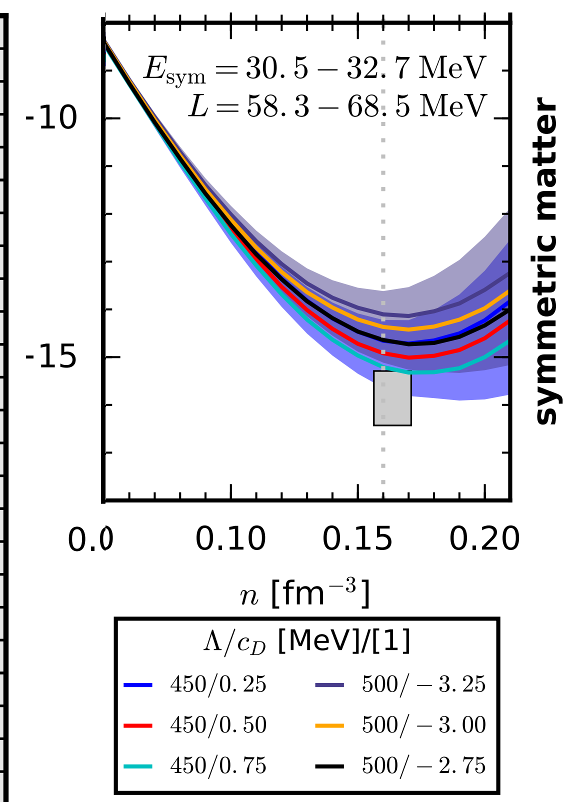




testing sensitivity to 3N couplings, but more studies needed!

Main points

How should we propagate these uncertainties in calculations and possibly include fits to saturation?

Are EFT uncertainty estimates sufficient?
Full statistical modeling at N^3LO will be challenging.

Can one define a representative class of Hamiltonians?
(To probe uncertainties beyond statistical fits, from regulators,…)

How do we best include information from nuclear matter (or other anchor points)?

Is there a way to factor in success of a particular Hamiltonian?

Main points

Many-body calculations of medium-mass nuclei have smaller uncertainties compared to uncertainties in nuclear forces

How should we propagate these uncertainties in calculations and possibly include fits to saturation?

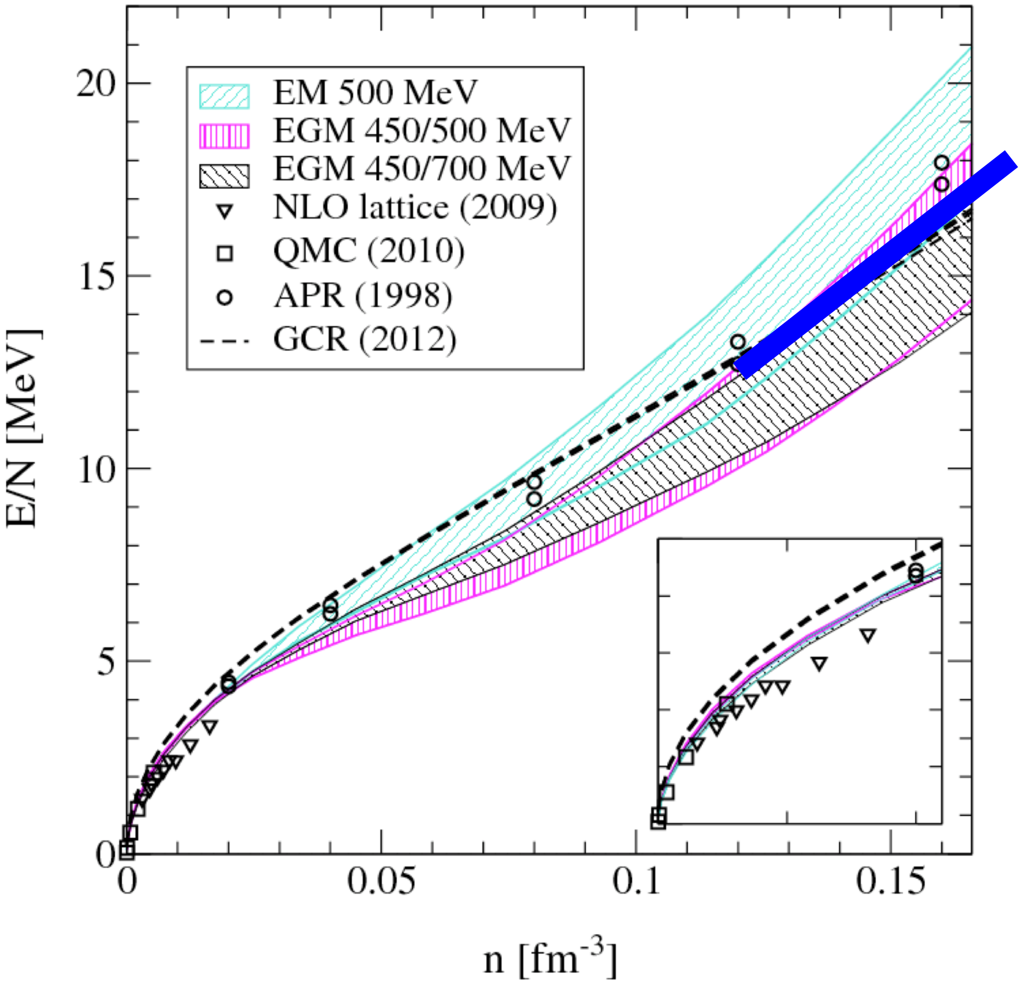
General equation of state band for neutron stars based on nuclear physics and observations

What are sensitivities to different parametrization?
Sensitivities when inferring neutron star properties?

Complete N^3LO calculation of neutron matter

first complete N^3LO result Tews et al., PRL (2013)

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



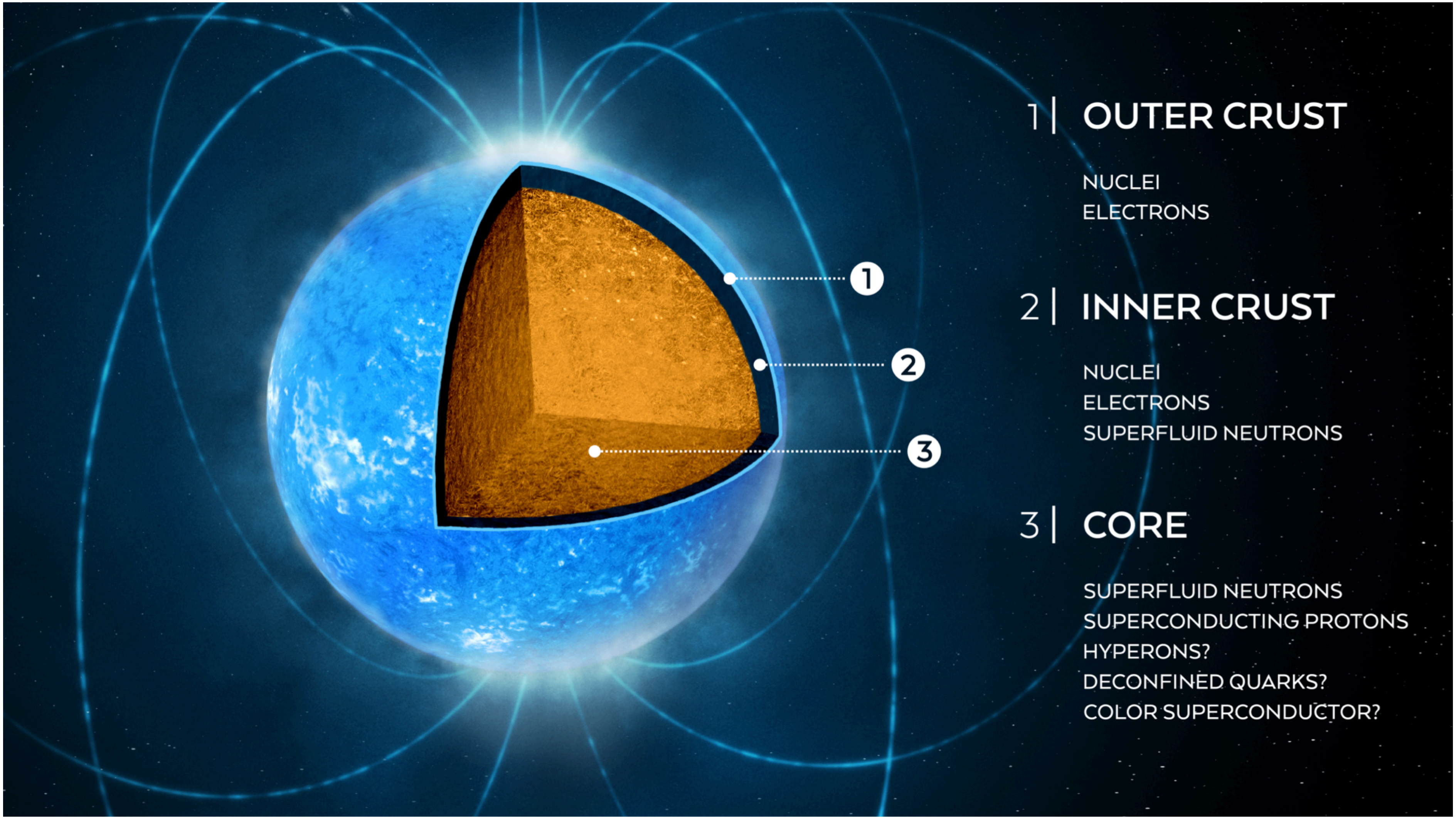
slope determines pressure of neutron matter

good agreement with Quantum Monte Carlo (GFMC, AFDMC)

Carlson, Gandolfi, Gezerlis, Lynn, Lonardoni, Pederiva, Tews,…

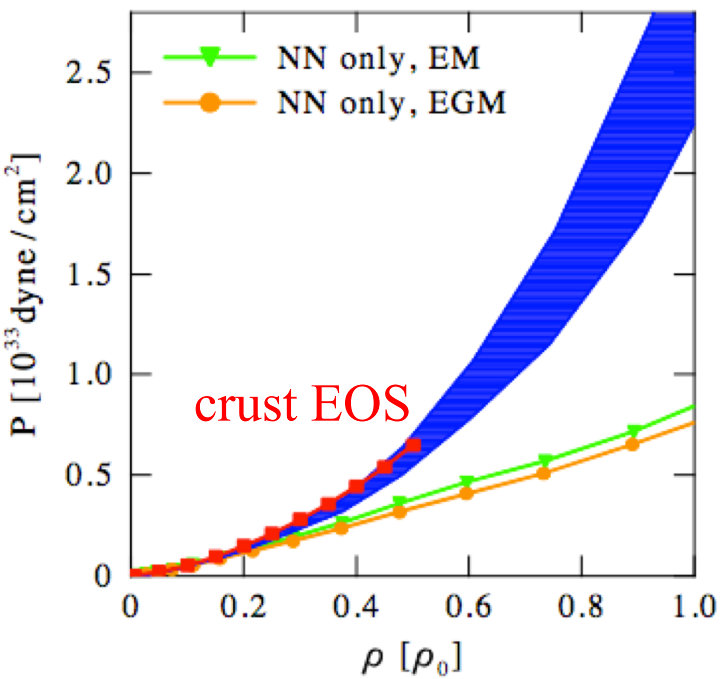
Neutron matter and neutron stars

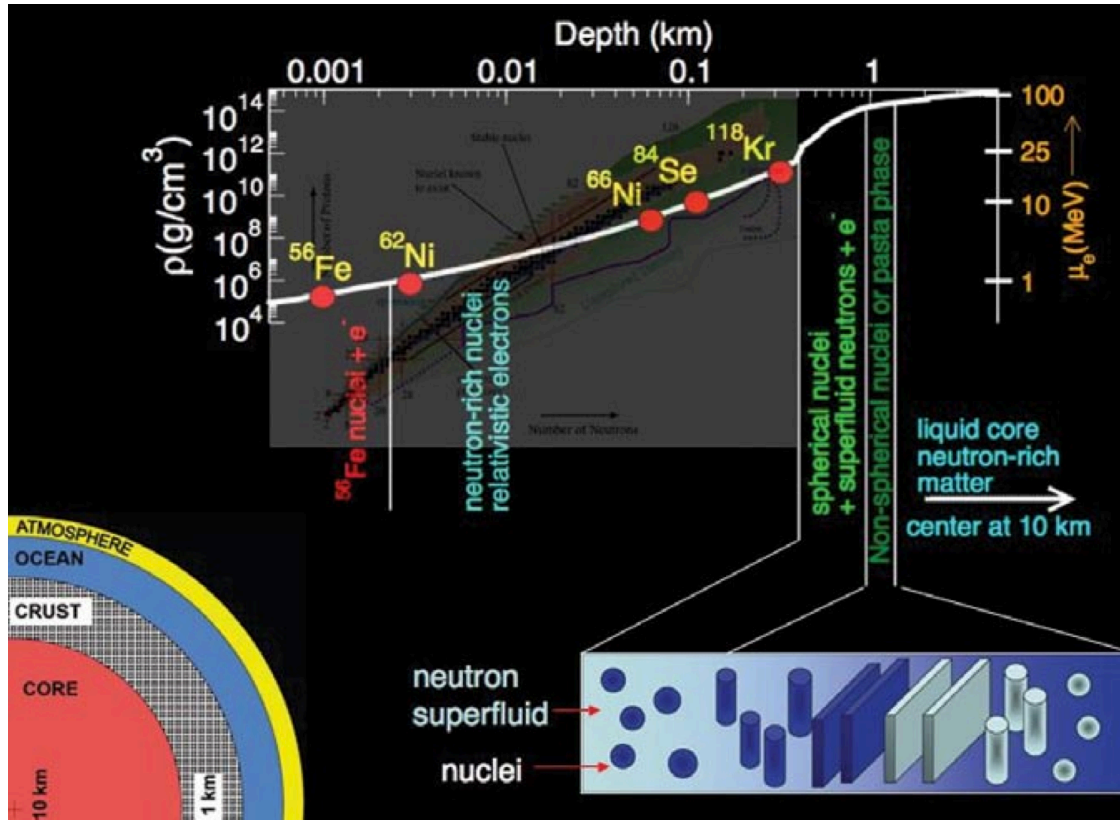
Watts et al., RMP (2016)



Impact on neutron stars Hebeler et al., 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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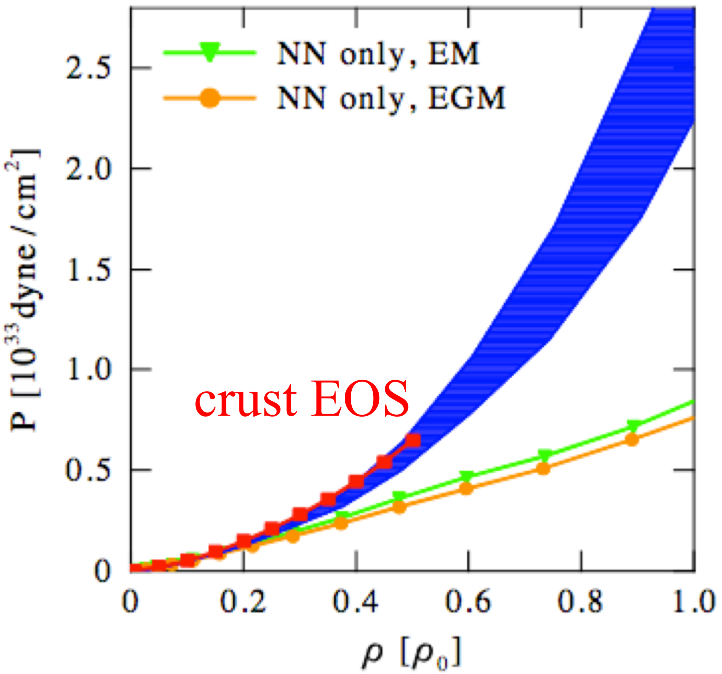
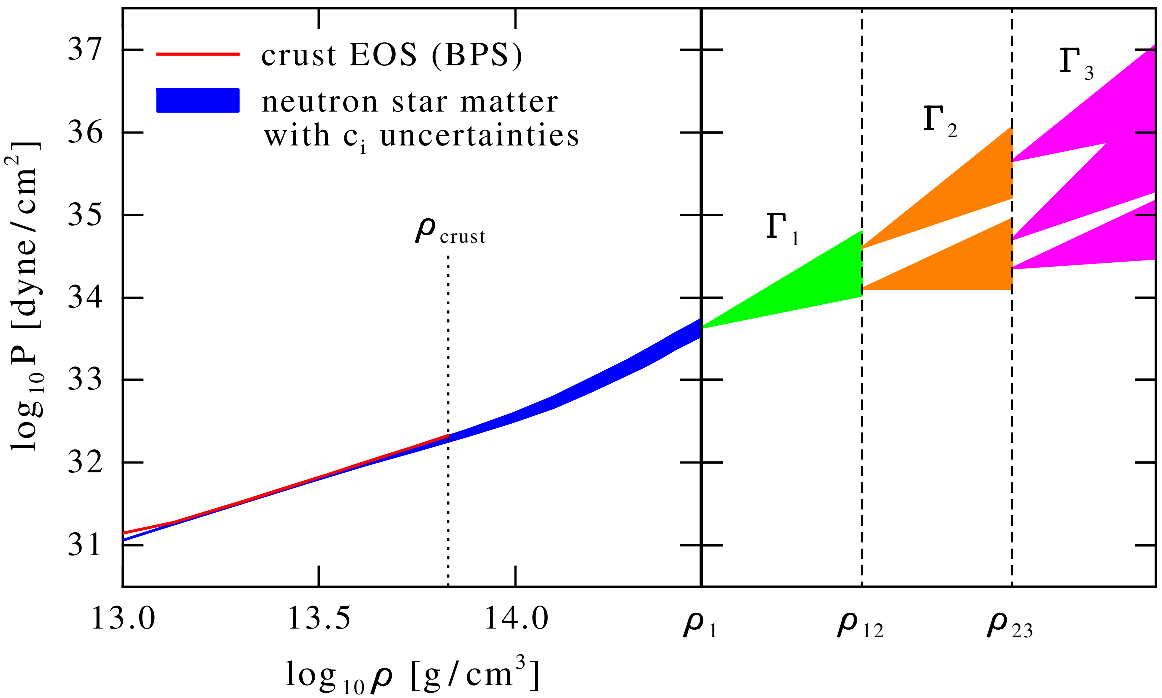


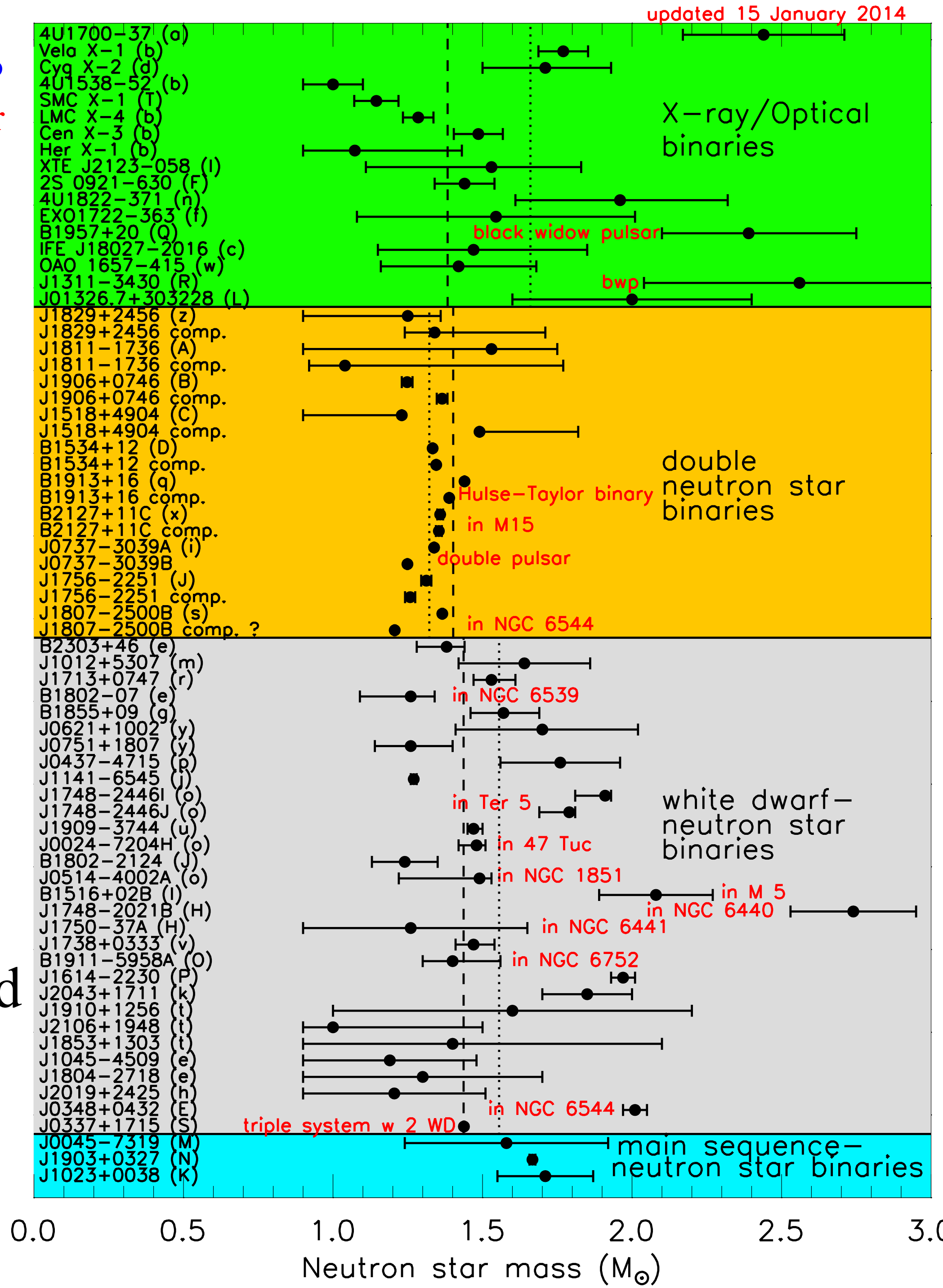


pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

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

Chart of neutron star masses

from Jim Lattimer



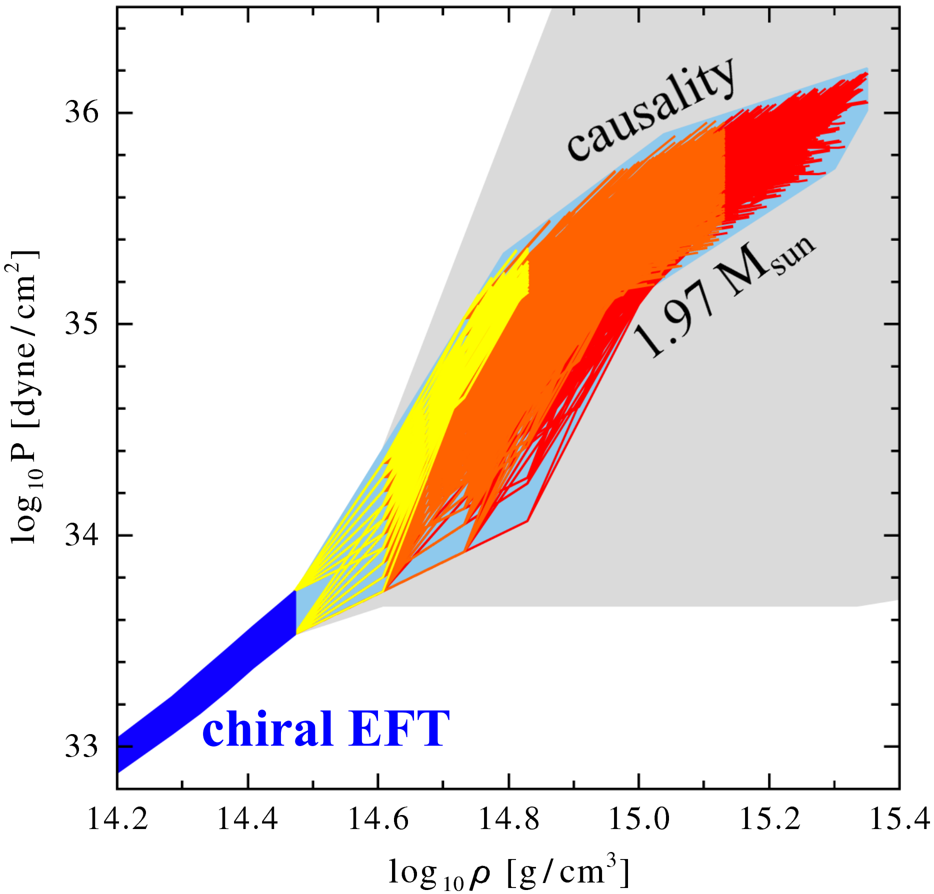
two 2 M_{sun} neutron stars observed

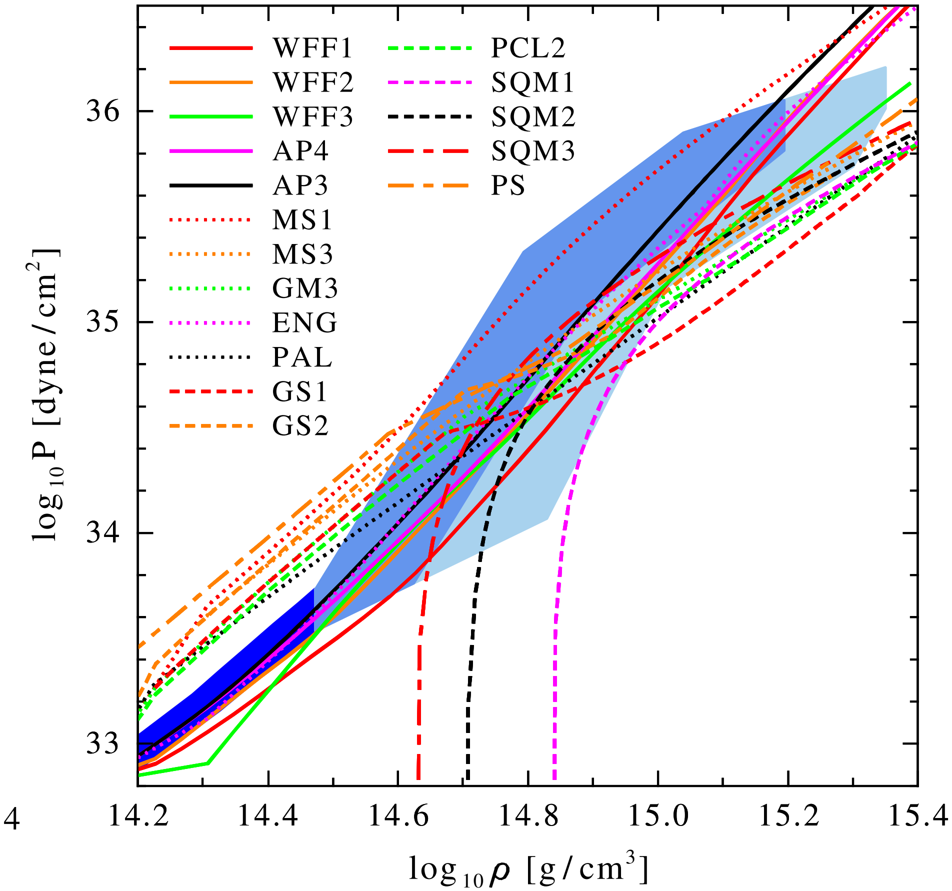
Demorest et al, Nature (2010),

Antoniadis et al., Science (2013)

Impact on neutron stars Hebeler et al., PRL (2010), ApJ (2013)

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

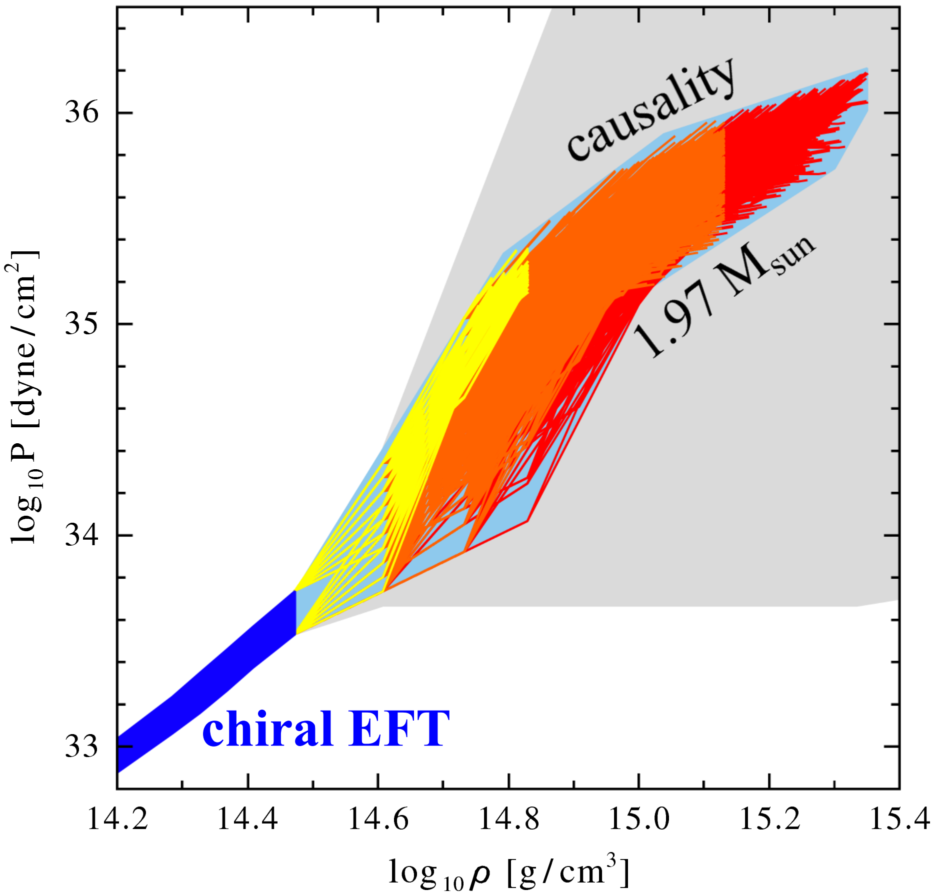


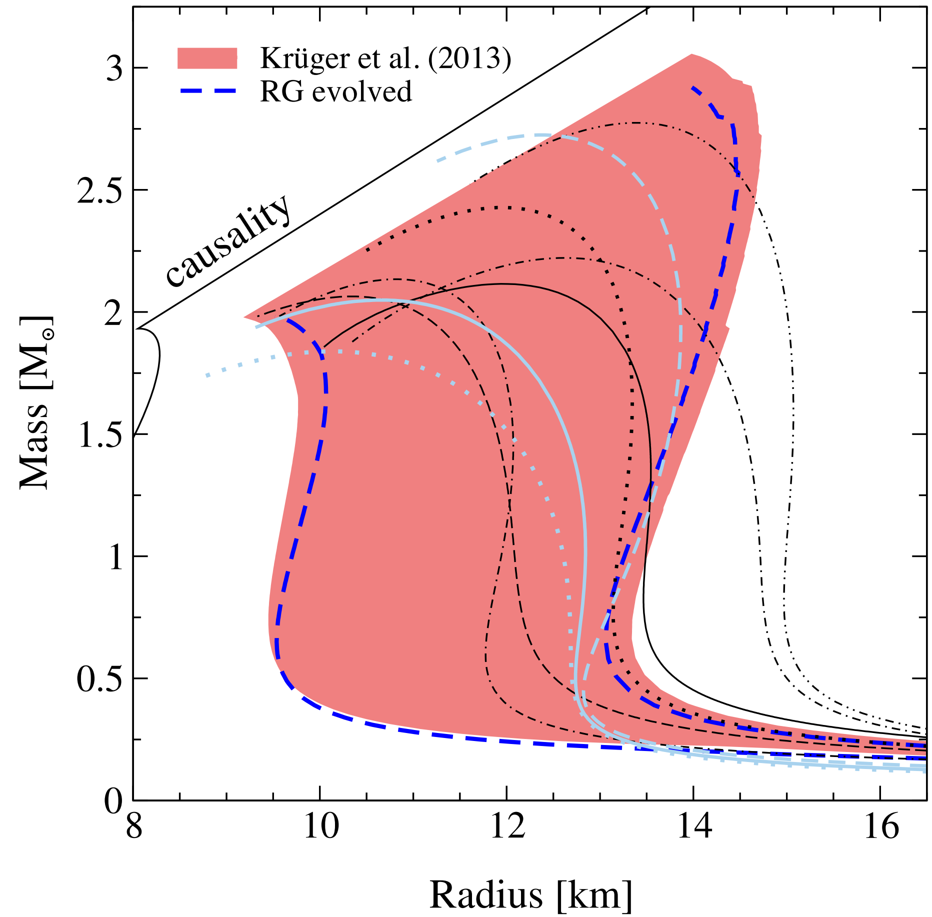


low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

Impact on neutron stars Hebeler et al., 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}

1.8-4.4 ρ_0 modest central densities

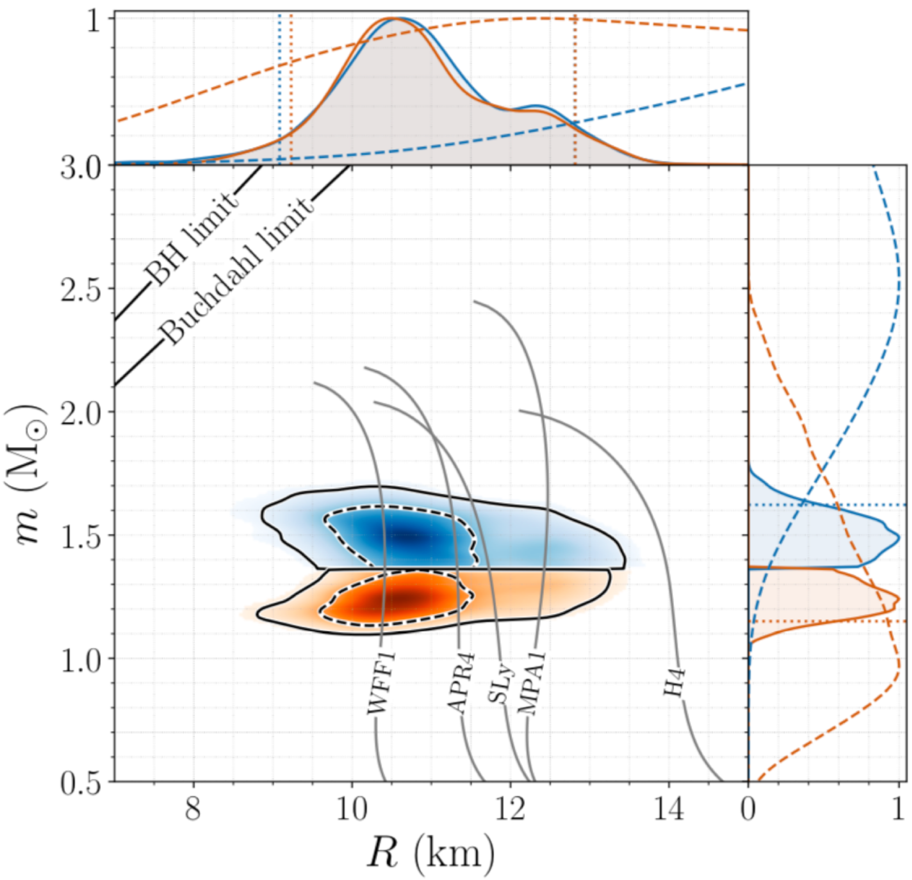
speed of sound needs to exceed ~0.65c to get 2 M_{sun} stars Greif et al.

Neutron star radius from GW170817

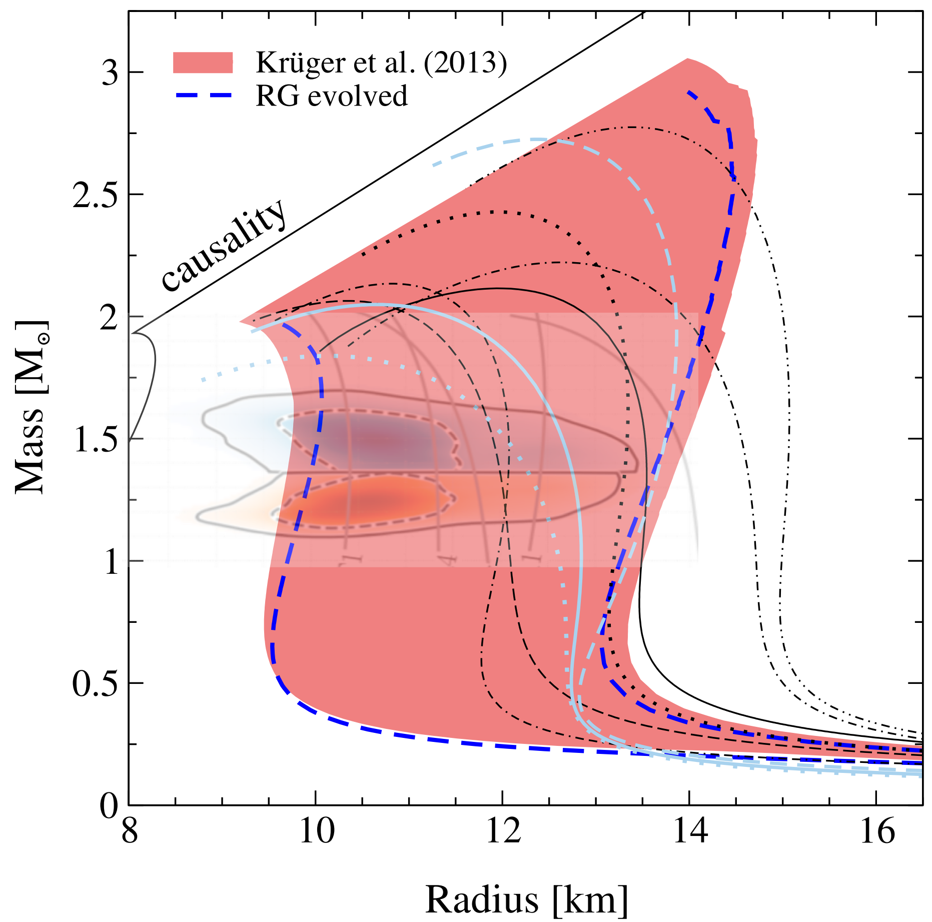
chiral EFT + general EOS extrapolation: 9.7-13.9 km for M=1.4 M_{sun}

GW170817: Measurements of neutron star radii and equation of state

The LIGO Scientific Collaboration and The Virgo Collaboration
(compiled 30 May 2018)



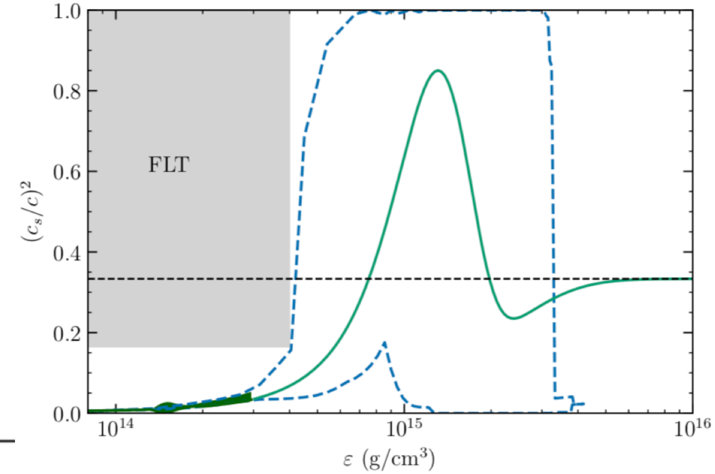
excellent agreement with GW170817 from LIGO/Virgo

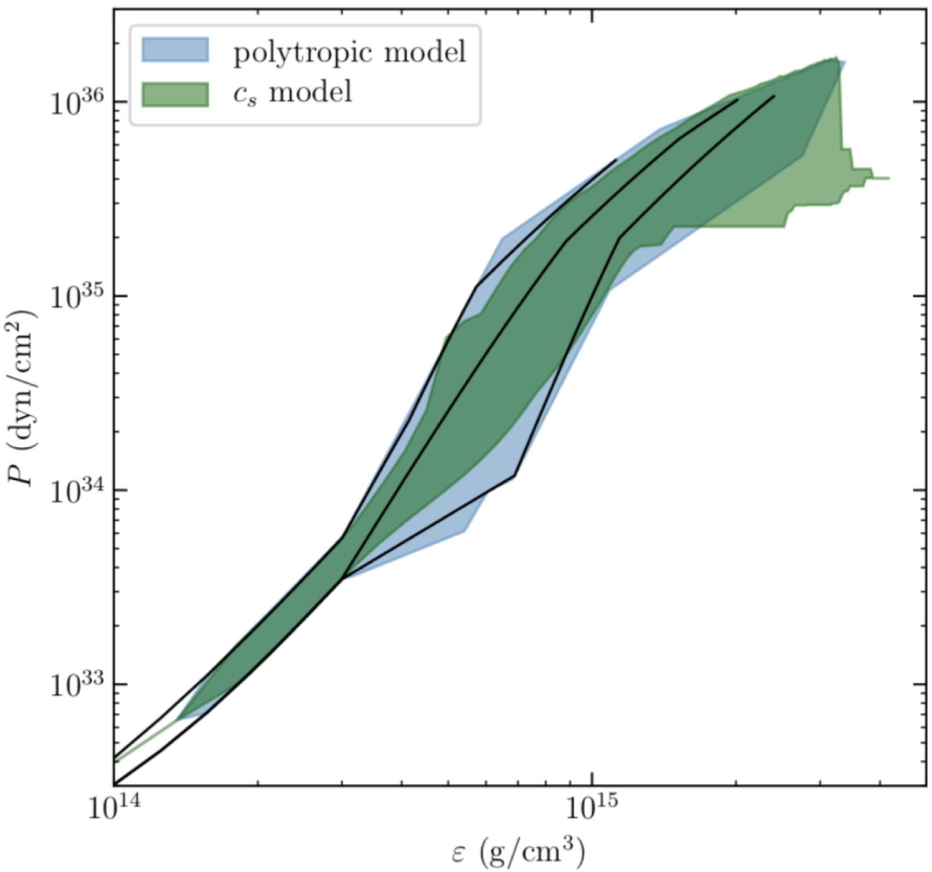


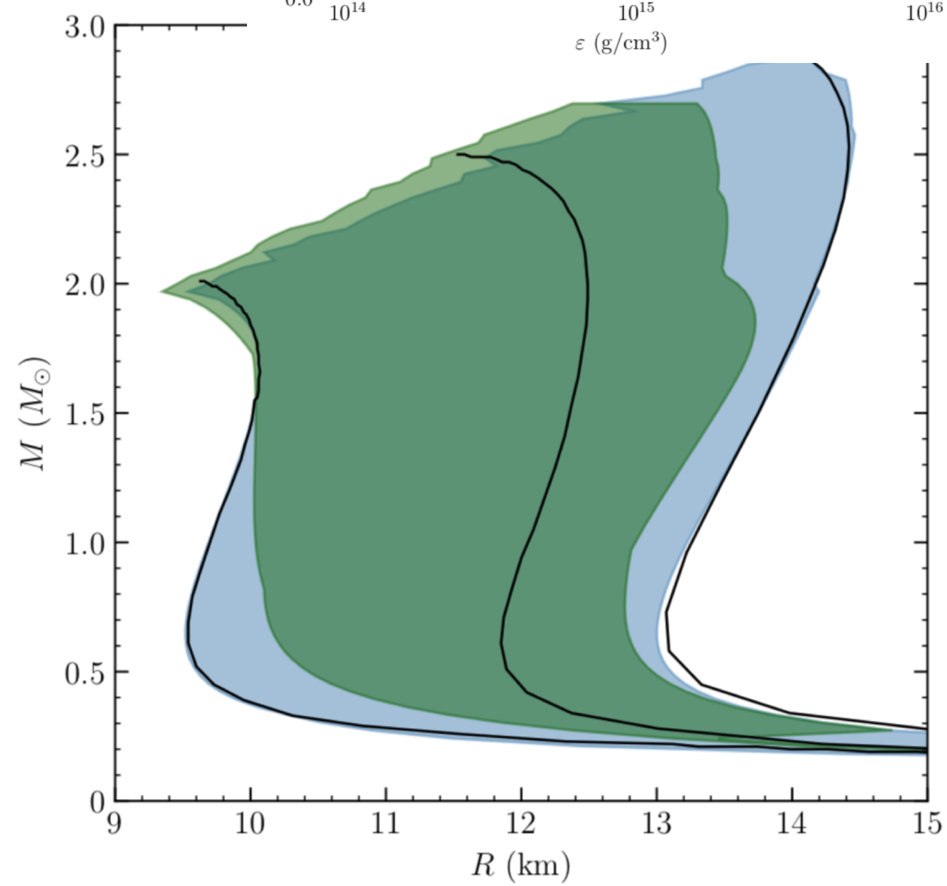
Sensitivities to different parametrizations

Greif, Raaijmakers, Hebeler, AS, Watts

explore polytropic and
speed of sound extensions to high densities



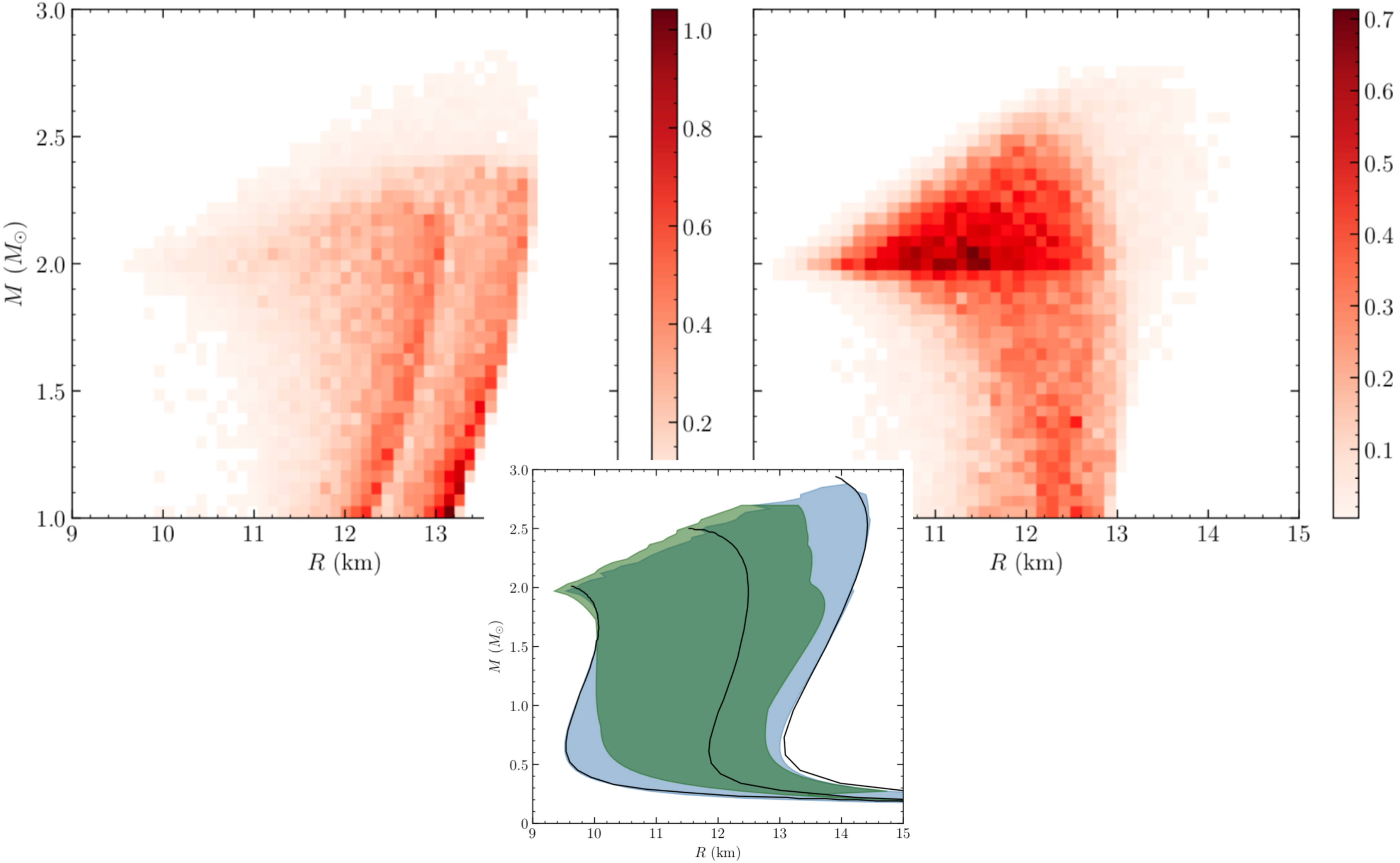




Sensitivities to different parametrizations: Prior distributions

Greif, Raaijmakers, Hebeler, AS, Watts

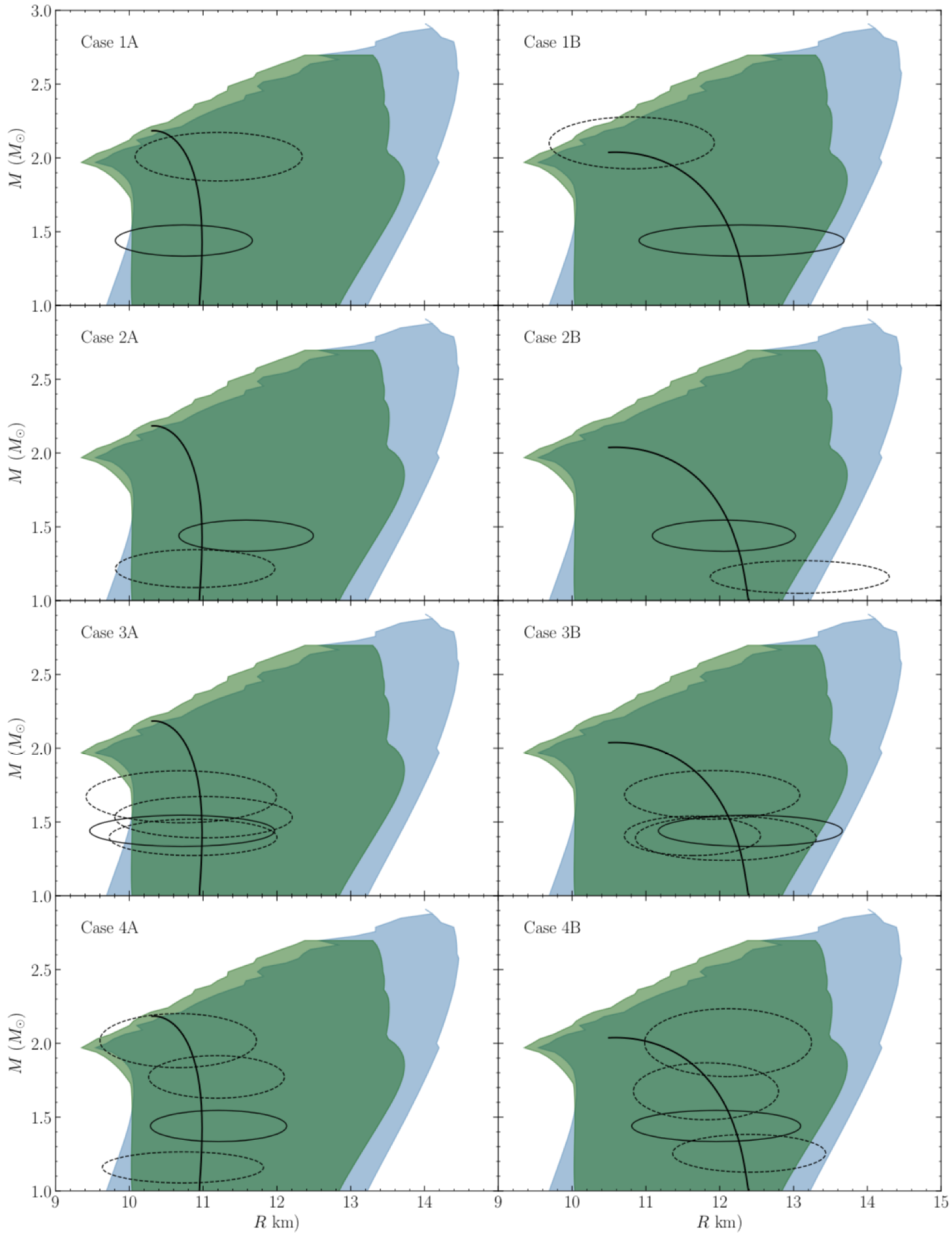
polytropes | **speed of sound**



Impact on inferring neutron star properties

Greif, Raaijmakers, Hebeler, AS, Watts

consider different scenarios from observations (1A-4B)



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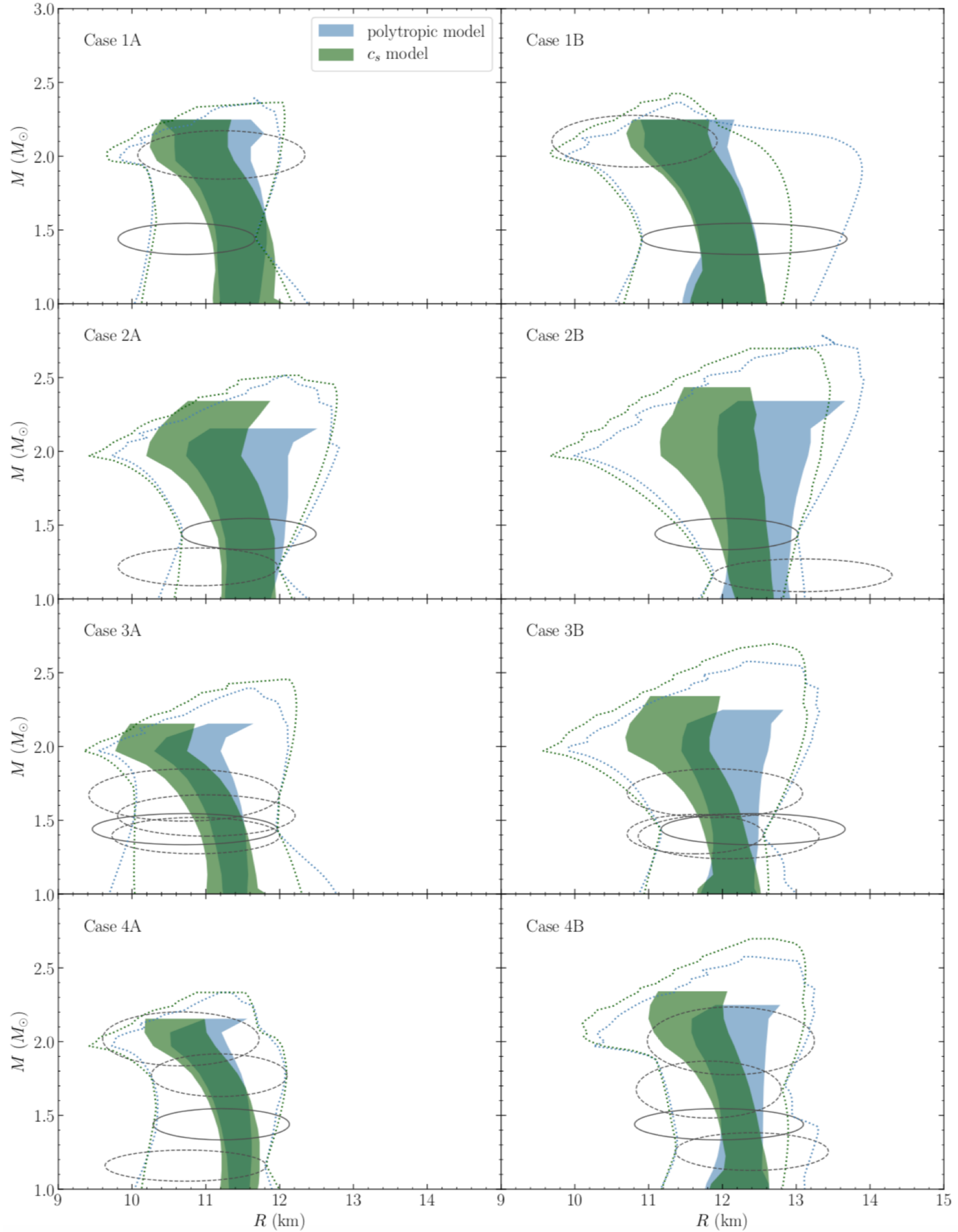
give remarkably narrow ranges ~11-12km, based on Bayesian inference from Riley, Raaijmakers, Watts, MNRAS (2018)



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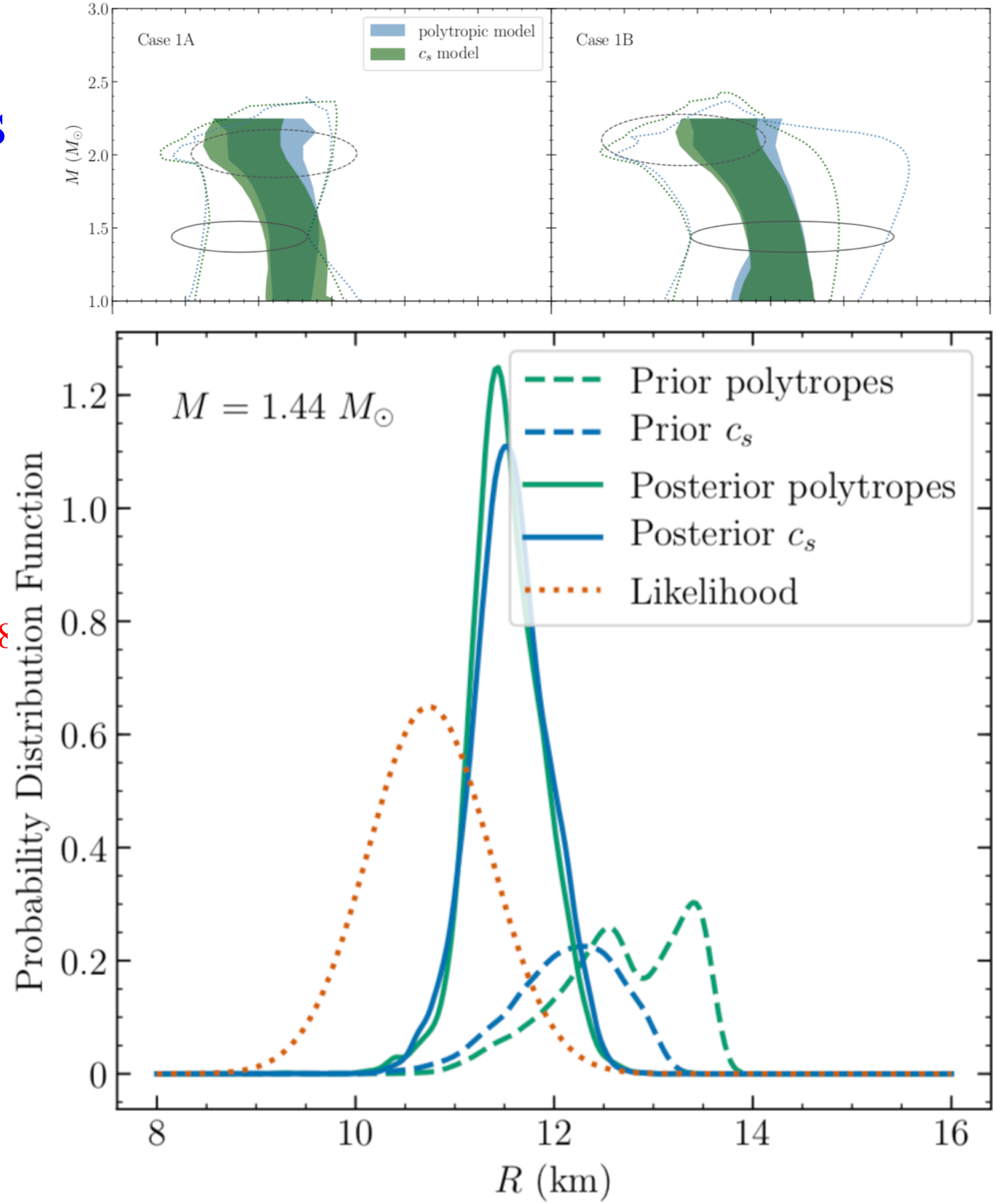
sensitivities to prior information/assumptions



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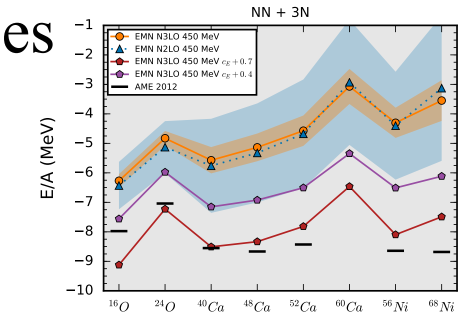
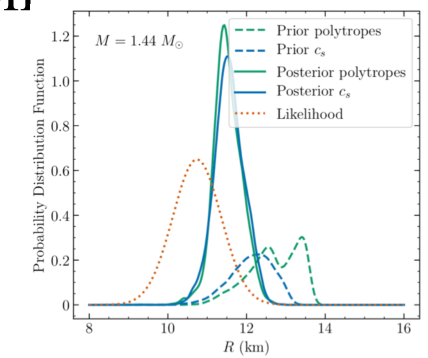


How should we propagate these uncertainties in calculations and possibly include fits to saturation?

General equation of state band for neutron stars based on nuclear physics and observations



What are sensitivities to different parametrization? Sensitivities when inferring neutron star properties?

Thanks to: **C. Drischler, S. Greif,** K. Hebeler, H. Hergert, J.D. Holt, **J. Hoppe,** J. Lattimer, C. Pethick, **G. Raaijmakers, R. Stroberg, J. Simonis, I. Tews,** A. Watts