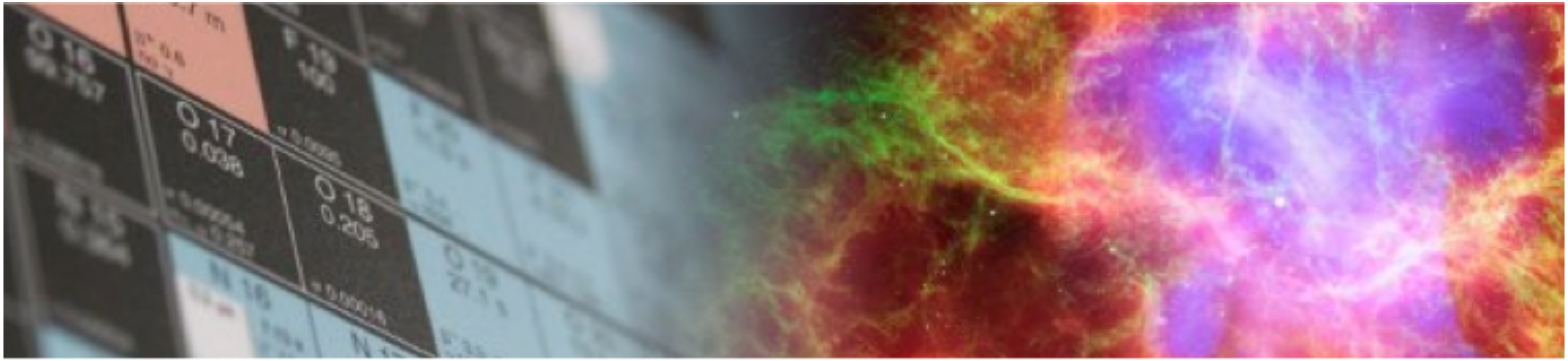
Equation of state and neutron star properties constrained by chiral effective field theory and observations

Achim Schwenk

TECHNISCHE UNIVERSITÄT DARMSTADT



The physics of neutron star mergers at GSI/FAIR, June 14, 2018

DFG

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Bundesministerium für Bildung und Forschung

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Main points

EOS is **well constrained by ab initio calculations** for

Neutron-rich conditions and low/moderate temperatures

especially interesting for neutron stars, cooling and mergers

General EOS band based on nuclear physics and observations

neutron star radius 9.7-13.9 km for $M=1.4\ M_{sun}$

How to constrain this further?
astro: GW170817, **future moment of inertia measurements**,…
theory: reliable EOS calculations to higher densities?
exp: extreme n-rich nuclei, extractions from heavy-ion collisions?

Nuclei bound by strong interactions

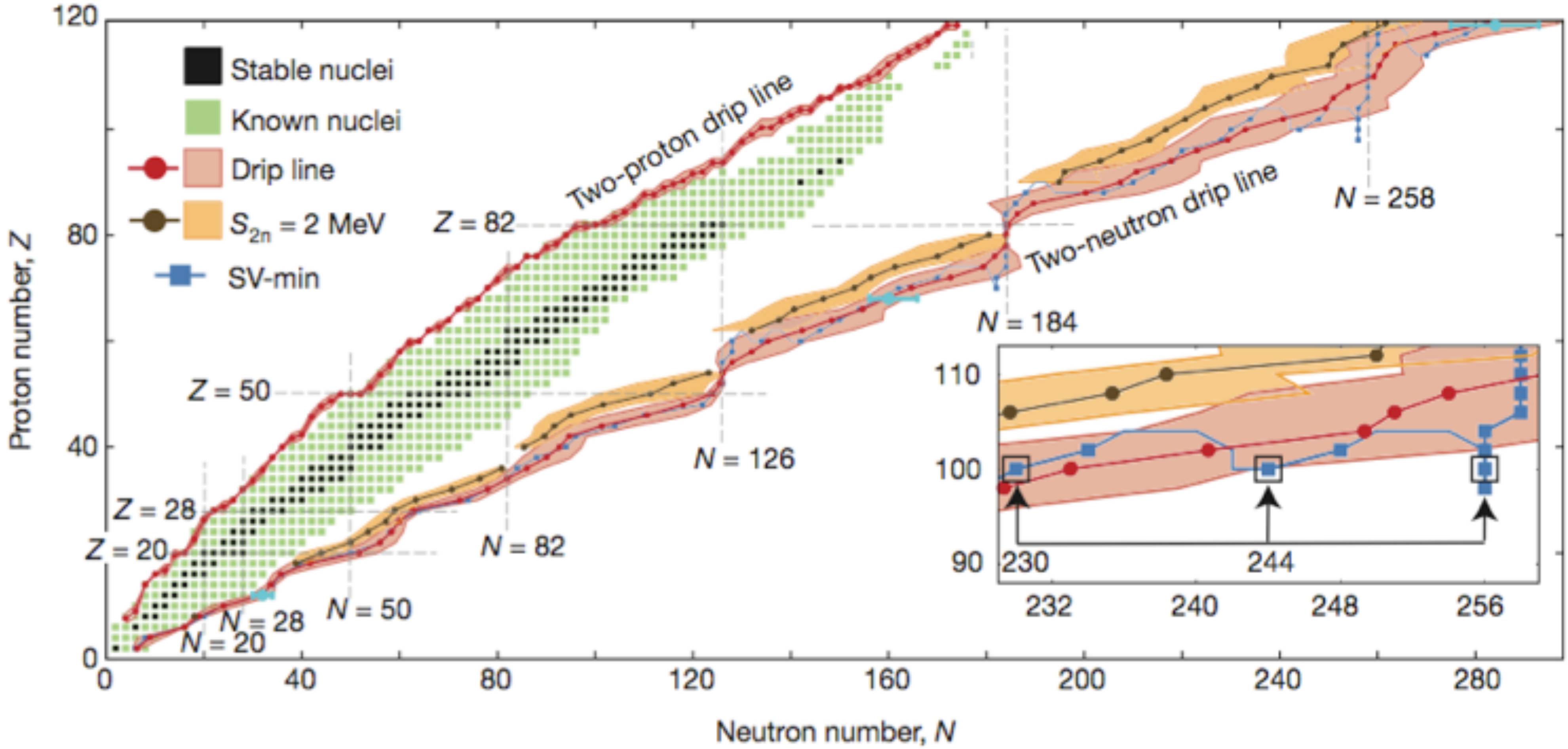
doi:10.1038/nature11188

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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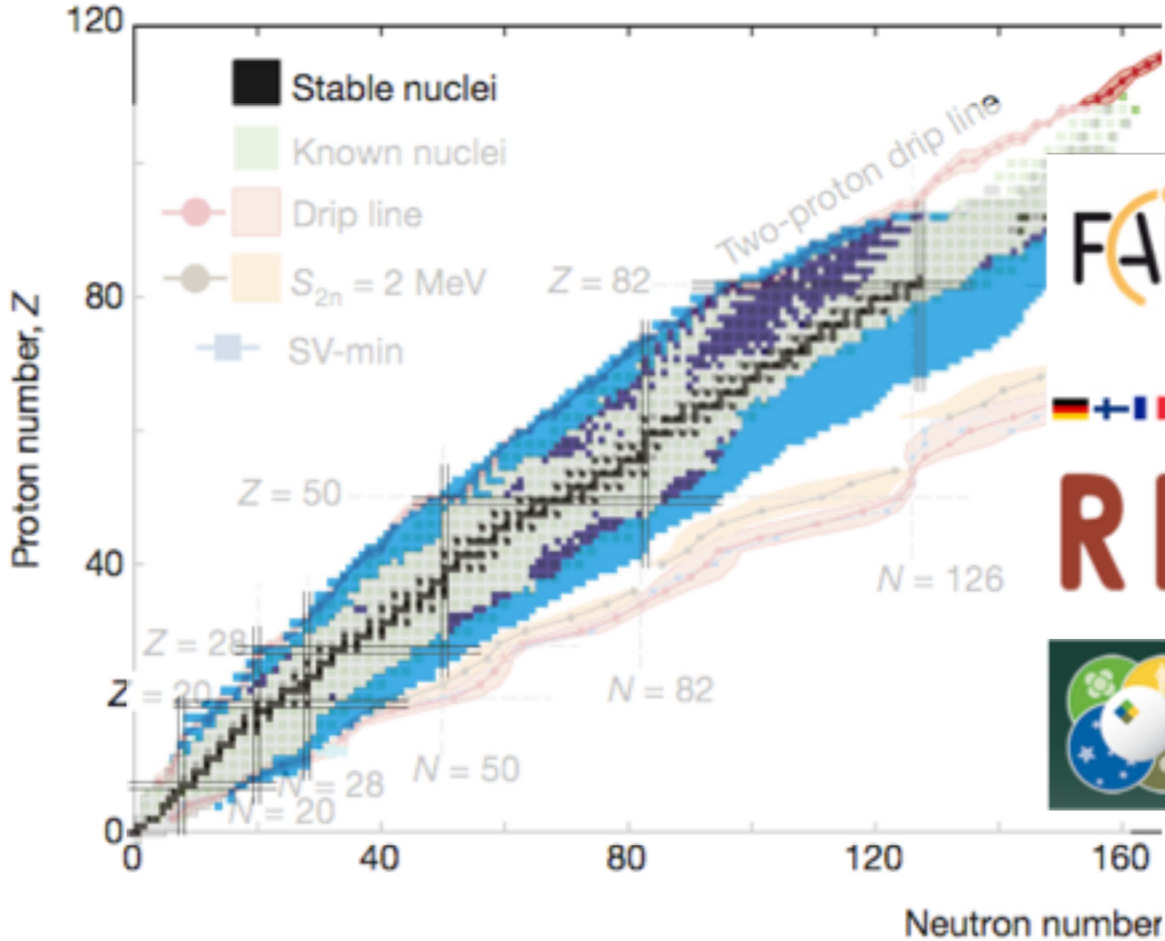


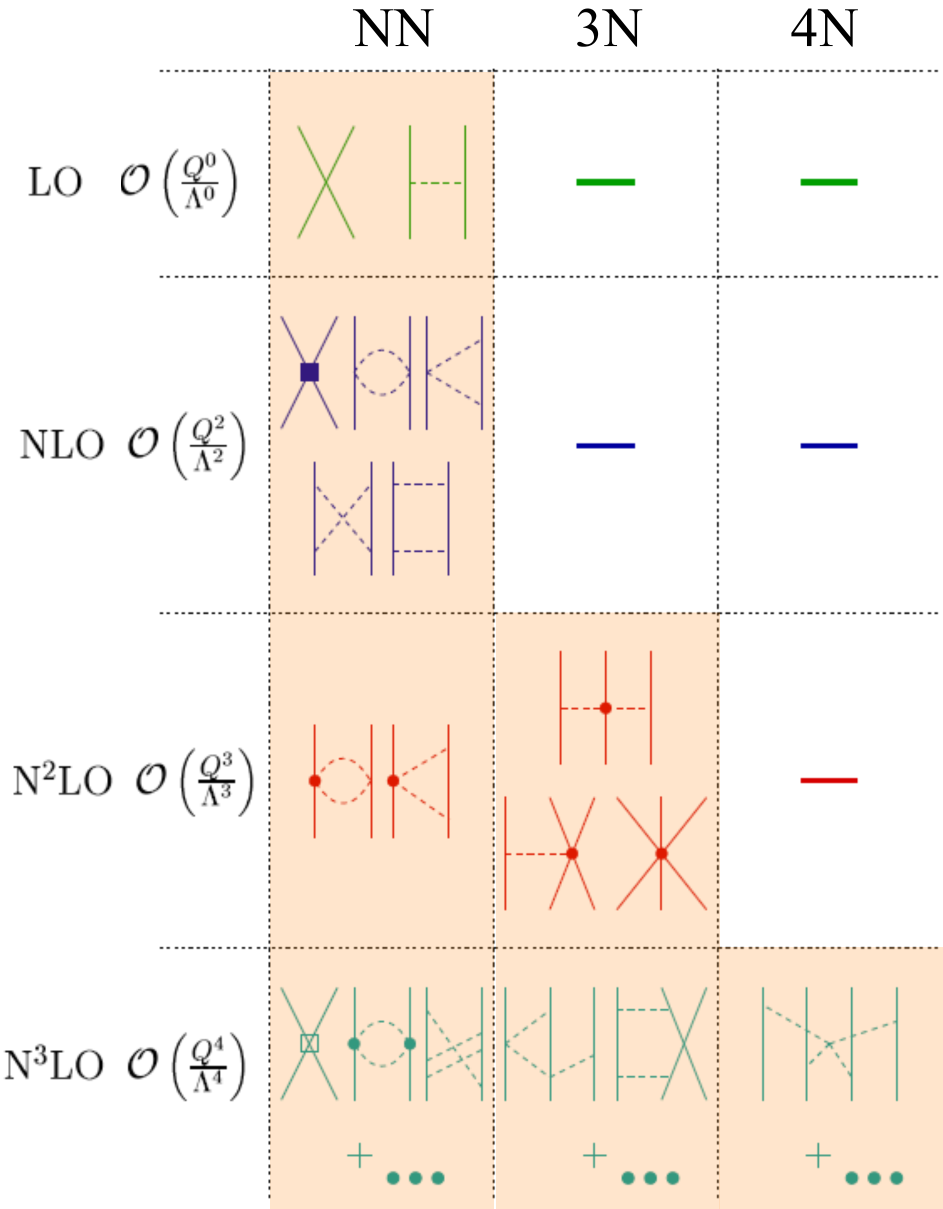
FAIR
Facility for Antiproton and Ion Research in Europe GmbH

RIBF
RIKEN NISHINA CENTER
RIKEN Nishina Center for Accelerator-Based Science

Facility for Rare Isotope Beams
at Michigan State University

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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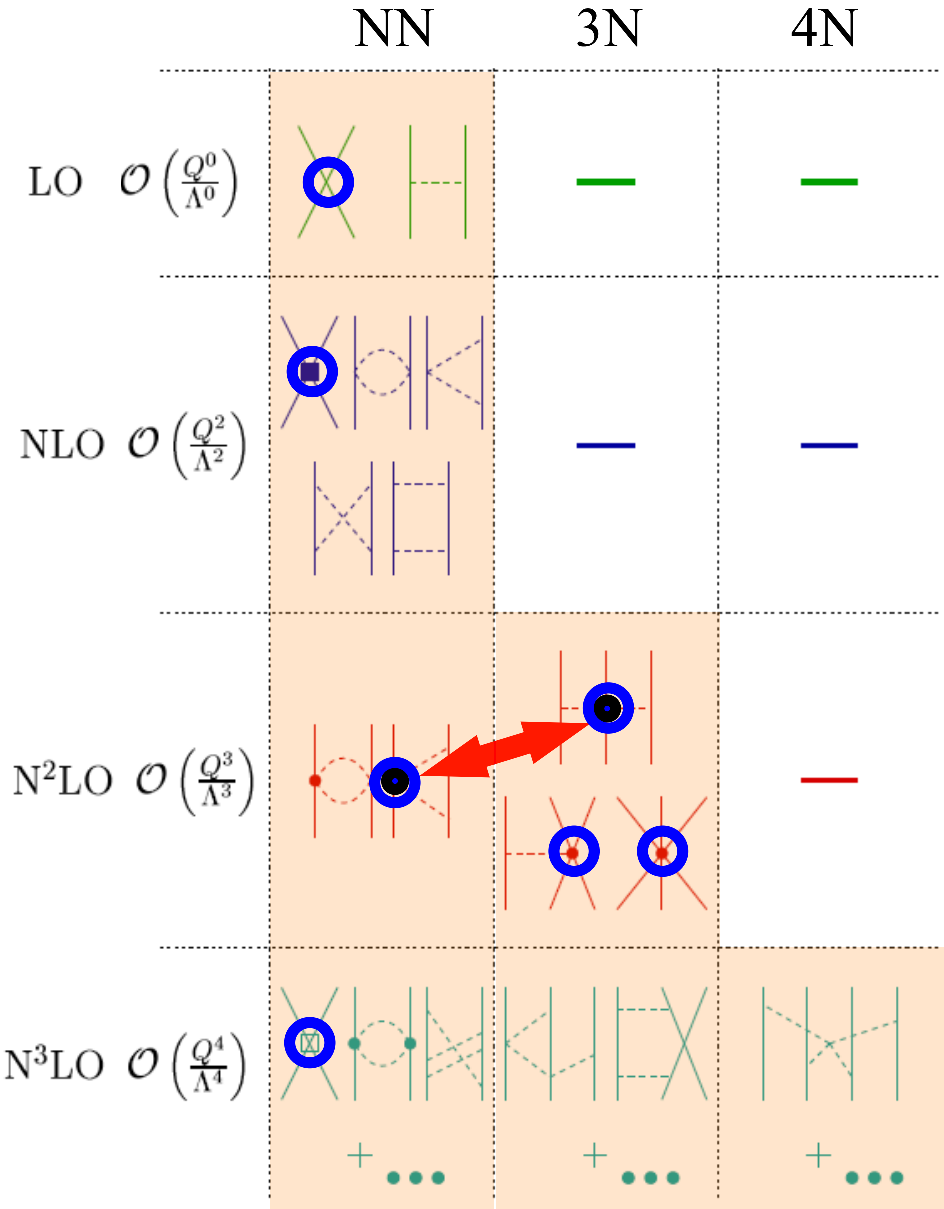


include long-range pion physics

few short-range couplings, fit to experiment once

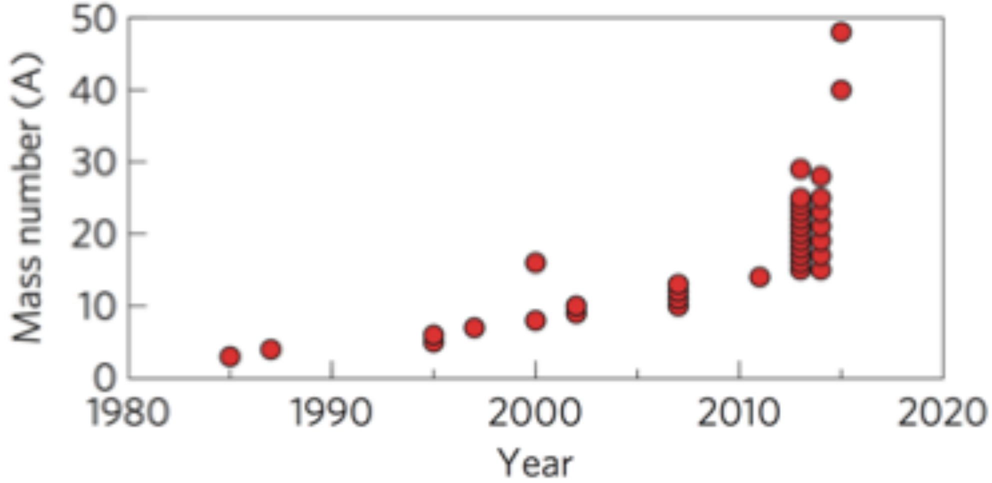
systematic: can work to desired accuracy and obtain **error estimates**

powerful approach for **many-body interactions**

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

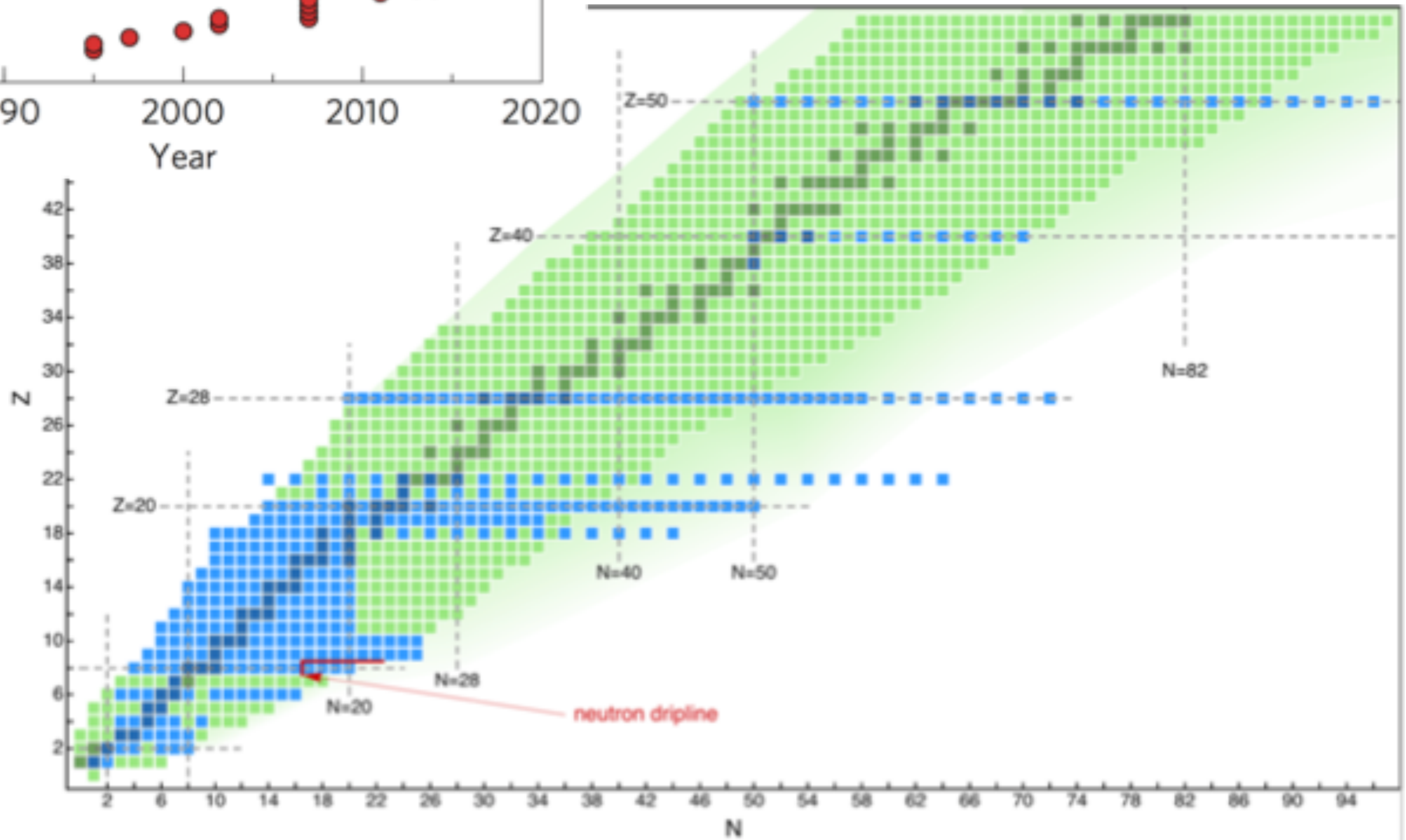
Progress in ab initio calculations of nuclei

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)



Ab initio calculations of neutron-rich oxygen isotopes

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

CC theory/CCEI

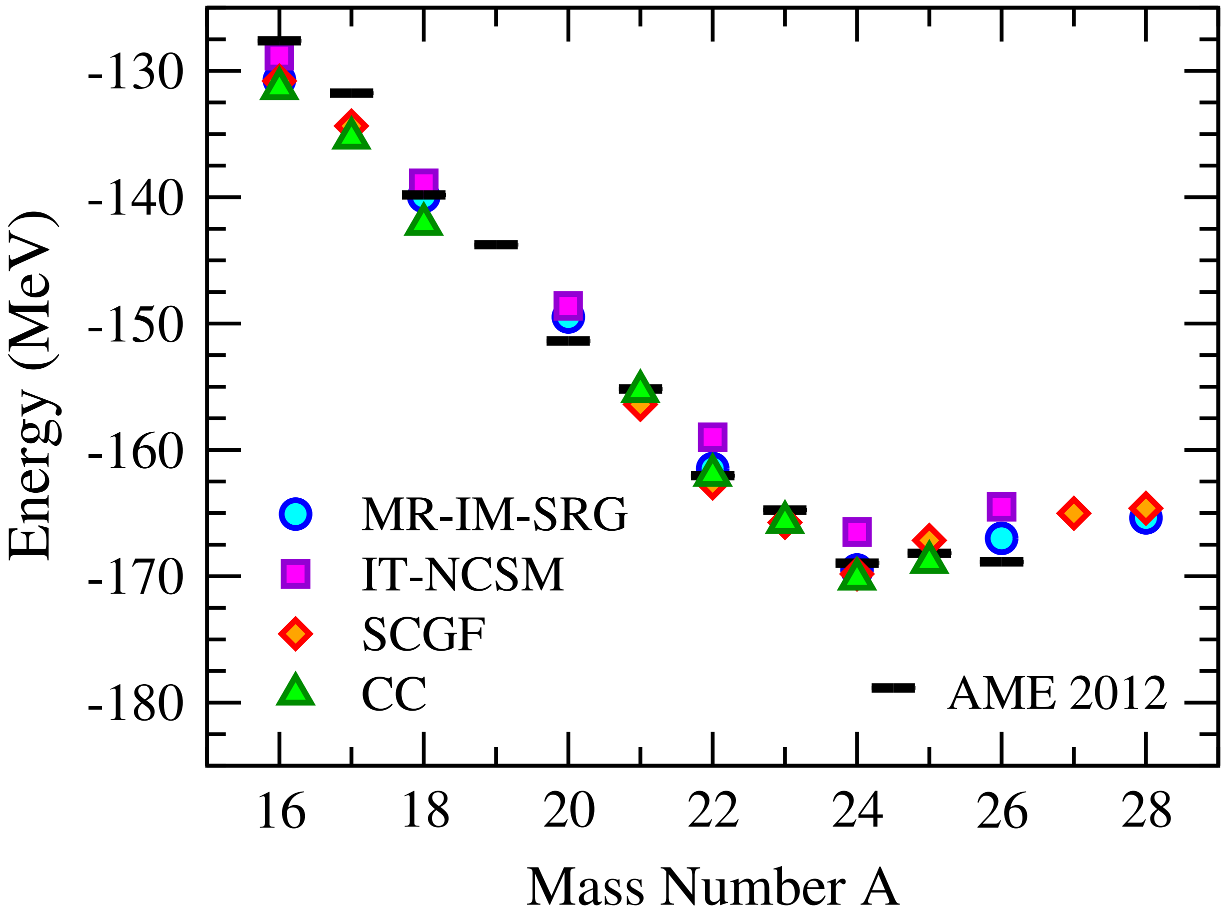
Hagen et al., PRL (2012),
Jansen et al., PRL (2014)

Multi-Reference In-Medium SRG and IT-NCSM

Hergert et al., PRL (2013)

Self-Consistent Green's Functions

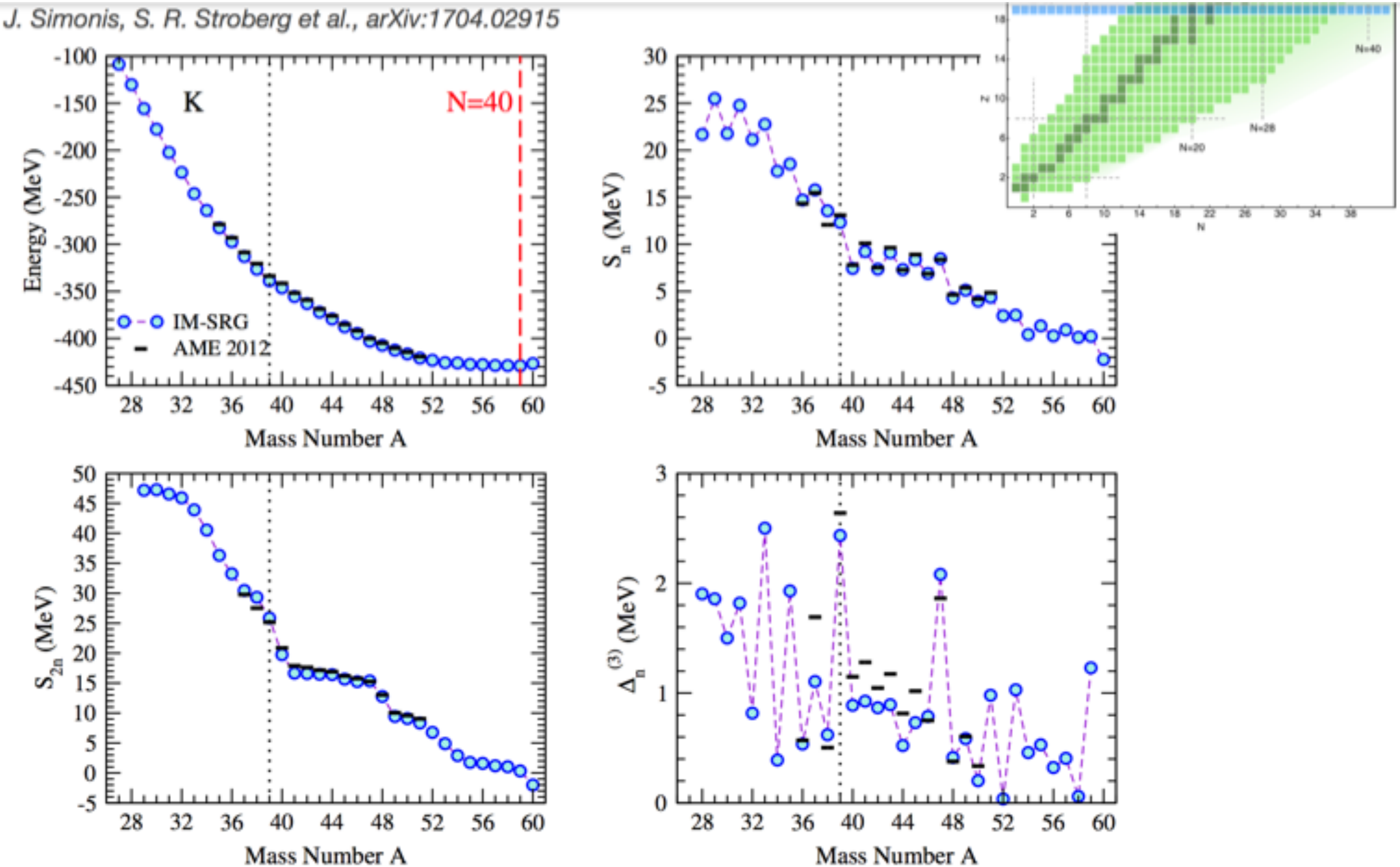
Cipollone et al., PRL (2013)



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

Great progress from medium to heavy nuclei

J. Simonis, S. R. Stroberg et al., arXiv:1704.02915



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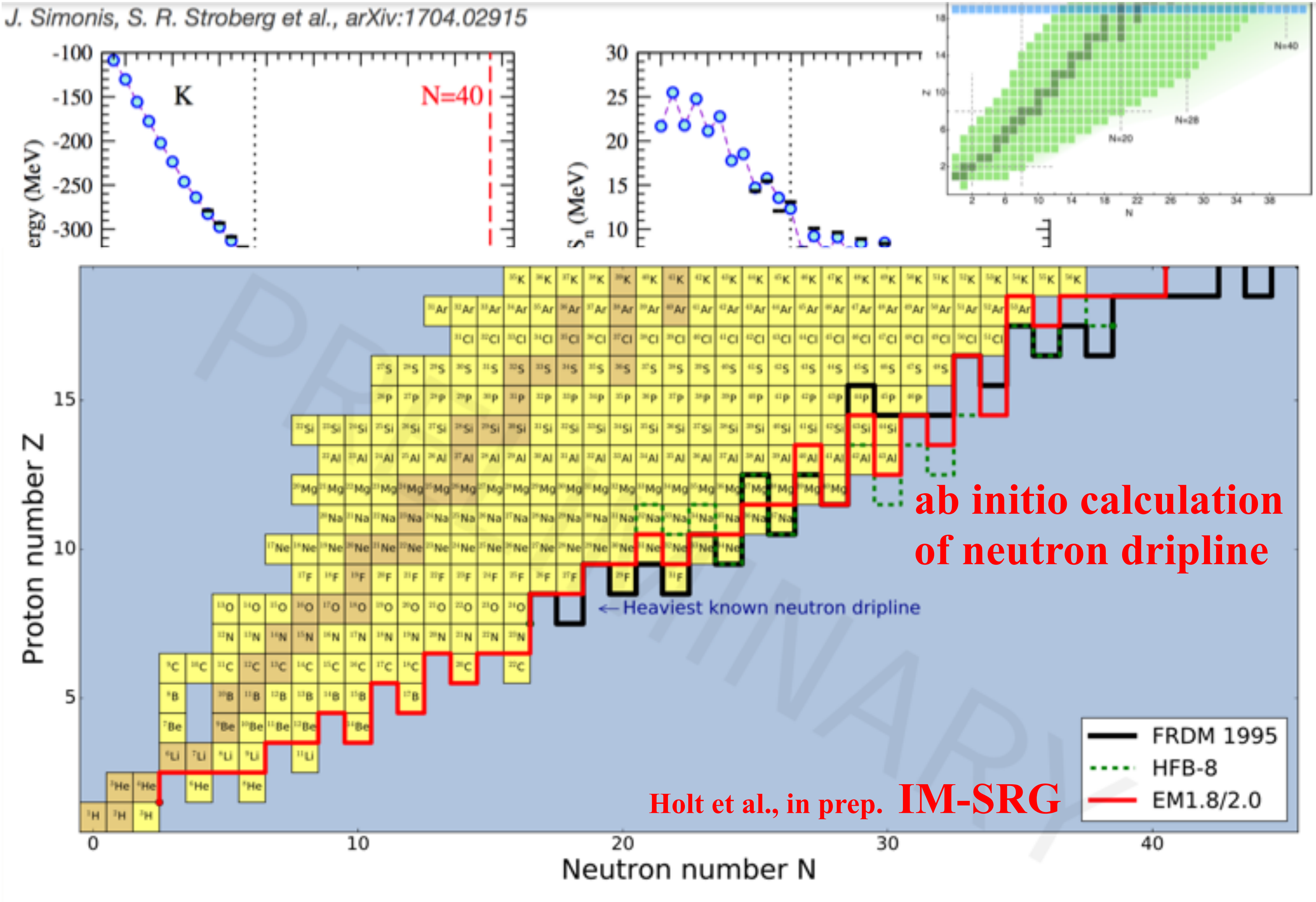

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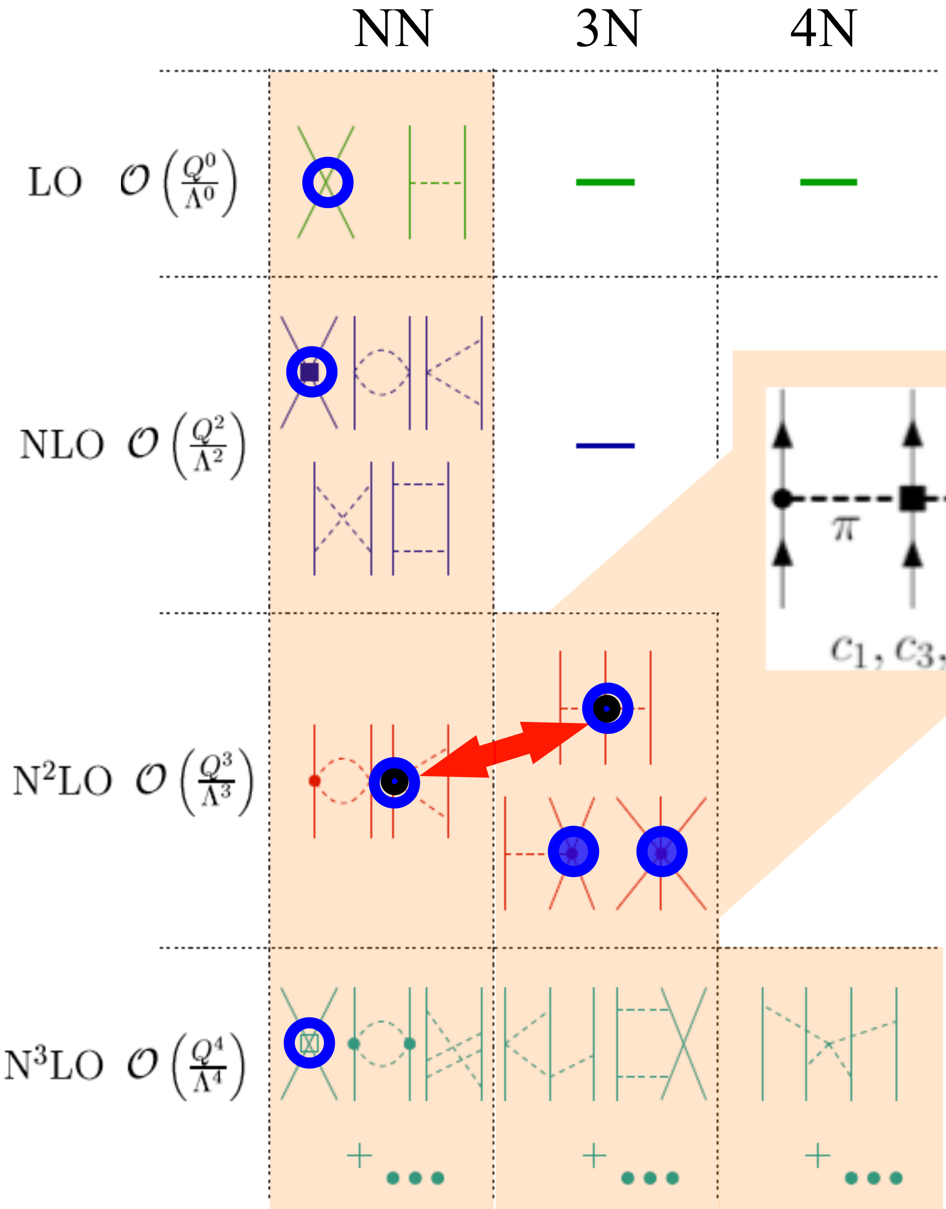
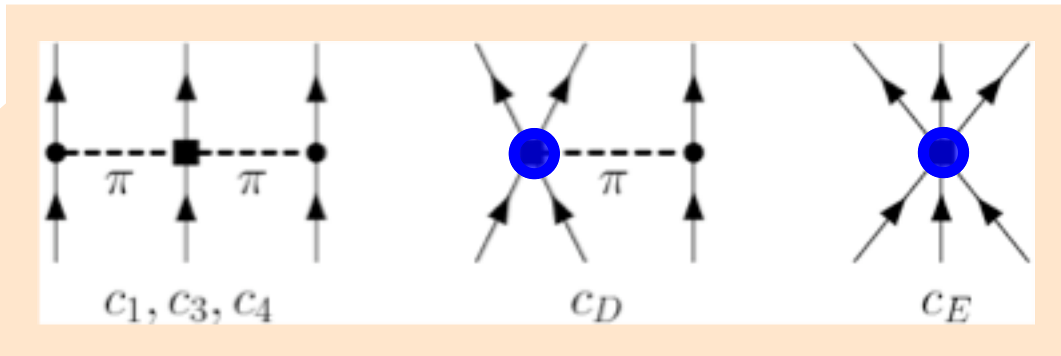


c_D, c_E don't contribute for neutrons because of Pauli principle and pion coupling to spin, also for c_4

Hebeler, AS (2010)



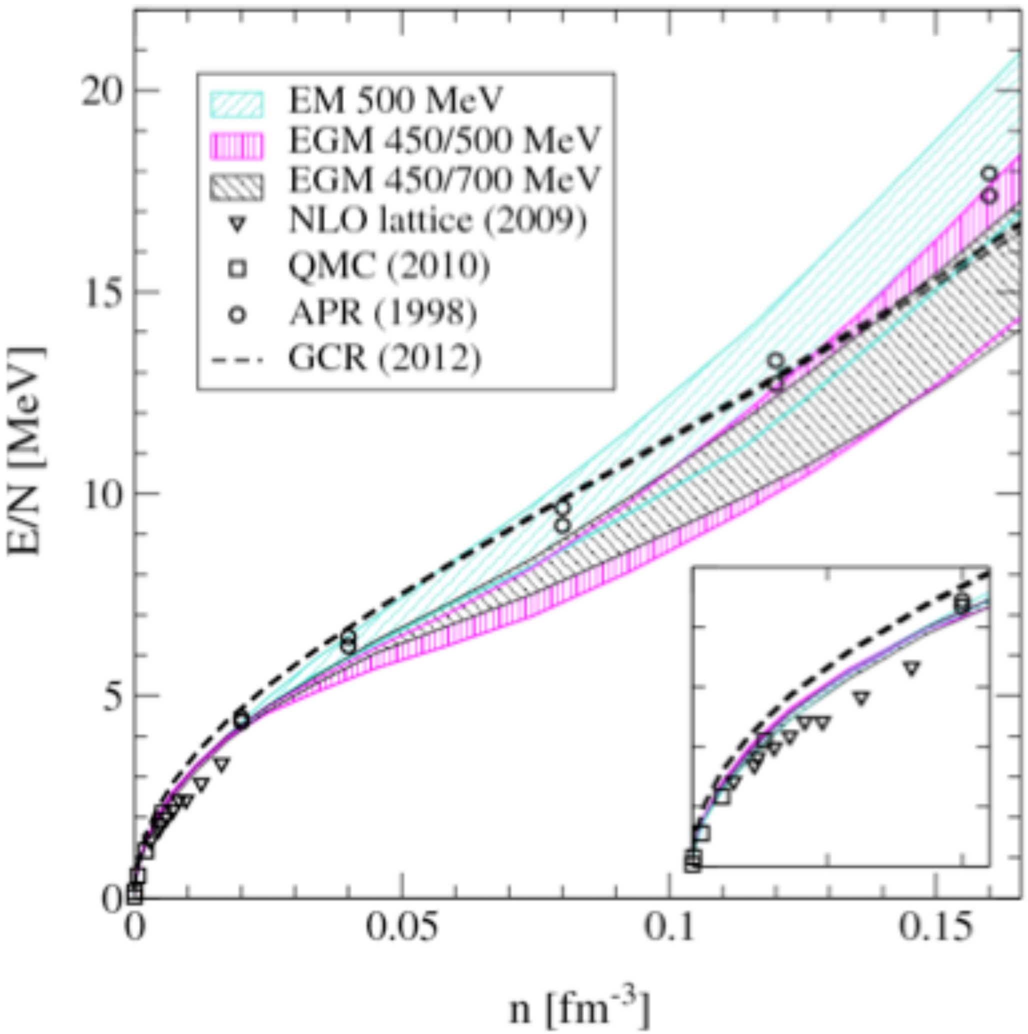
all 3- and 4-neutron forces are predicted to N^{3}LO!

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

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, Tews, Lynn et al.

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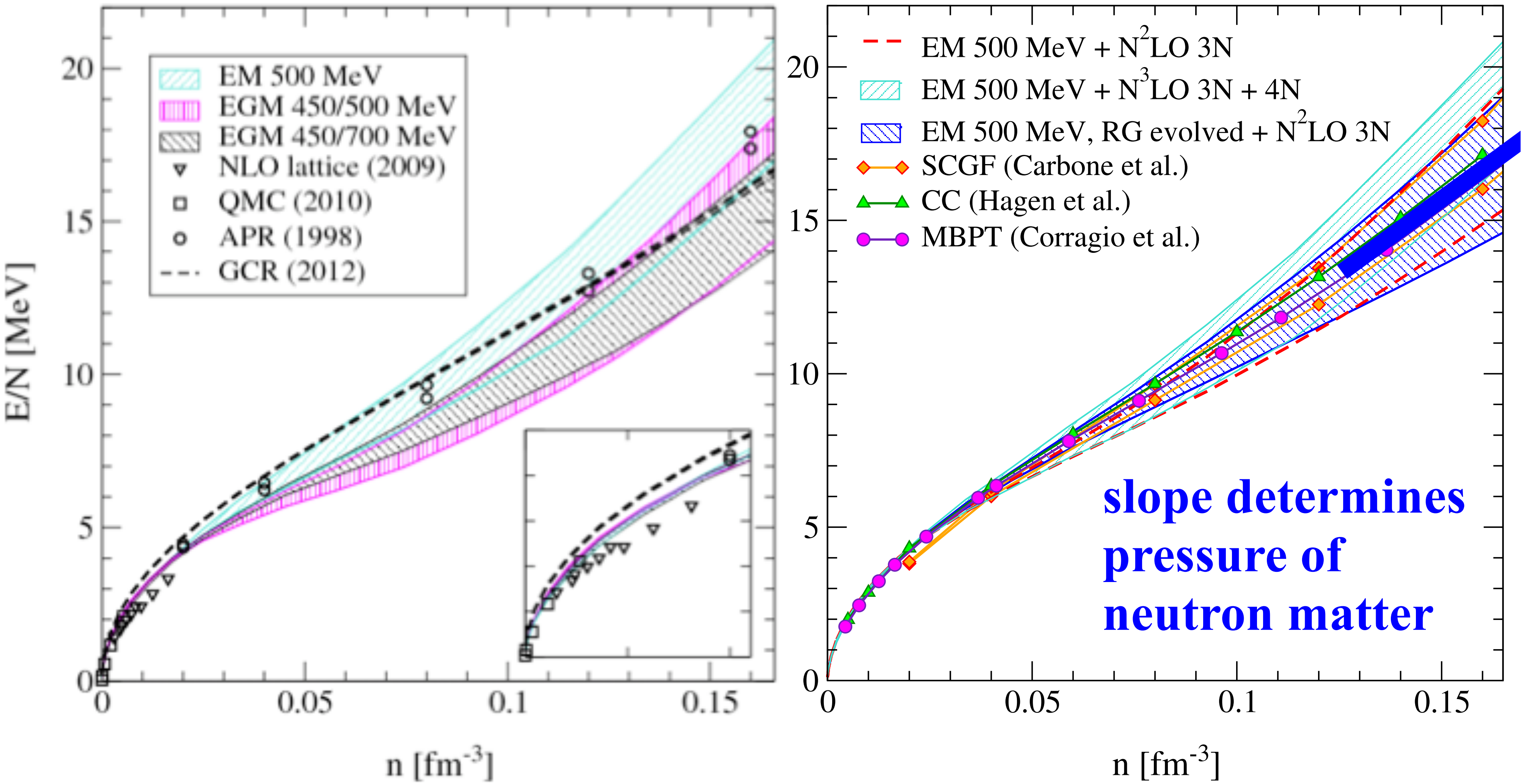
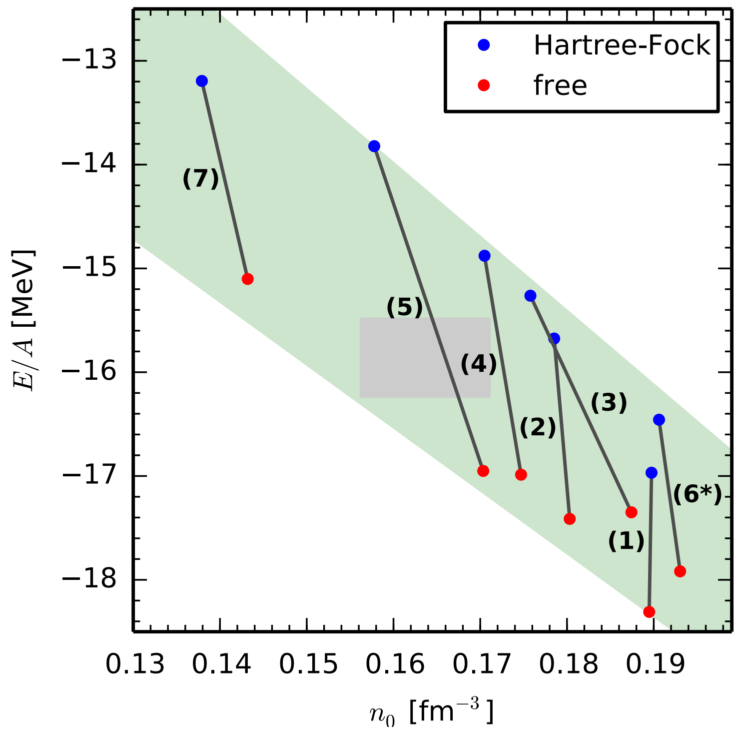


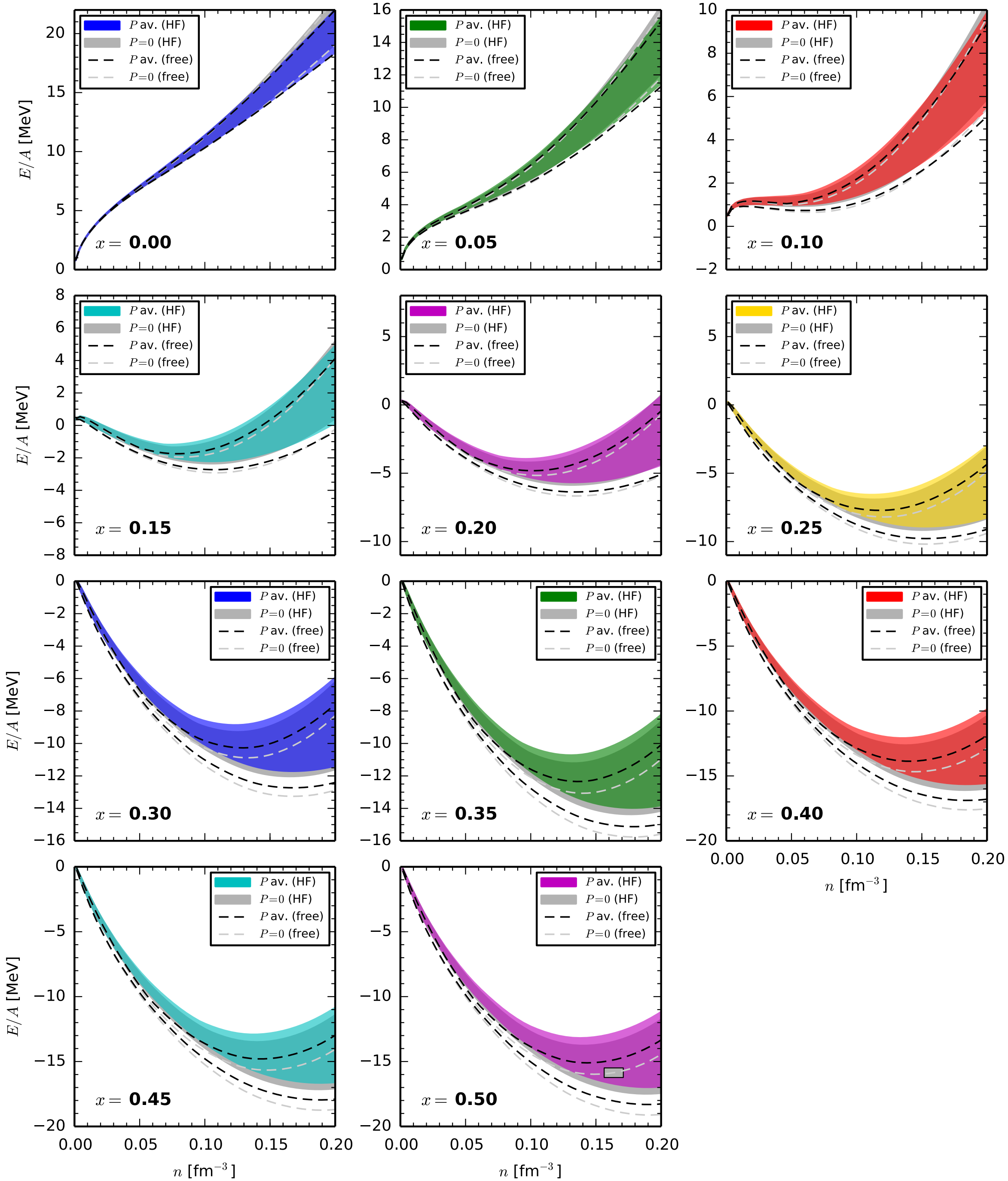
excellent agreement with other methods see also Drischler, Carbone et al., PRC (2016)

Nuclear forces and nuclear matter

asymmetric matter
with improved treatment
of 3N forces

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





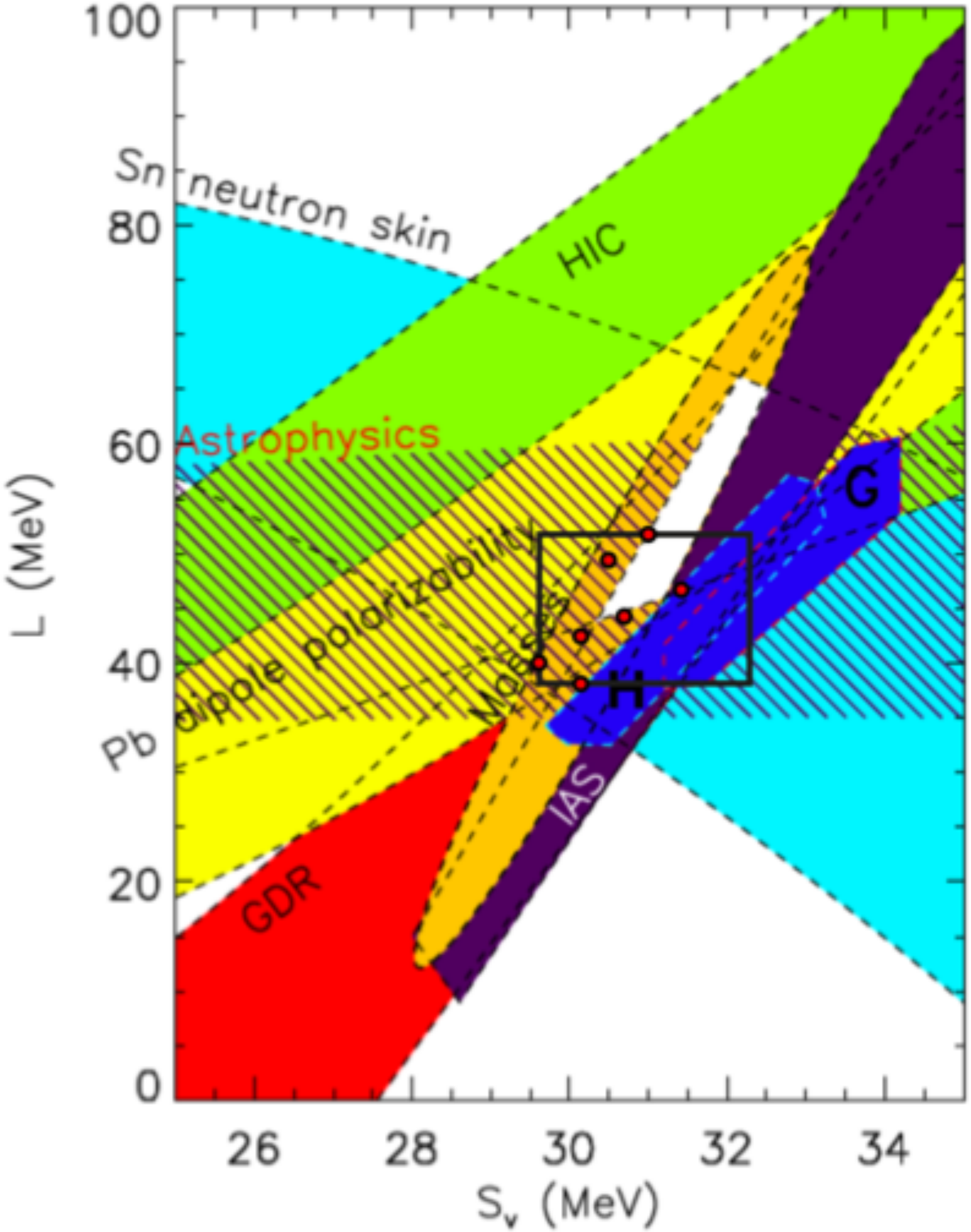
Symmetry energy and pressure of neutron matter

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!

from asymmetric matter
calculations Drischler

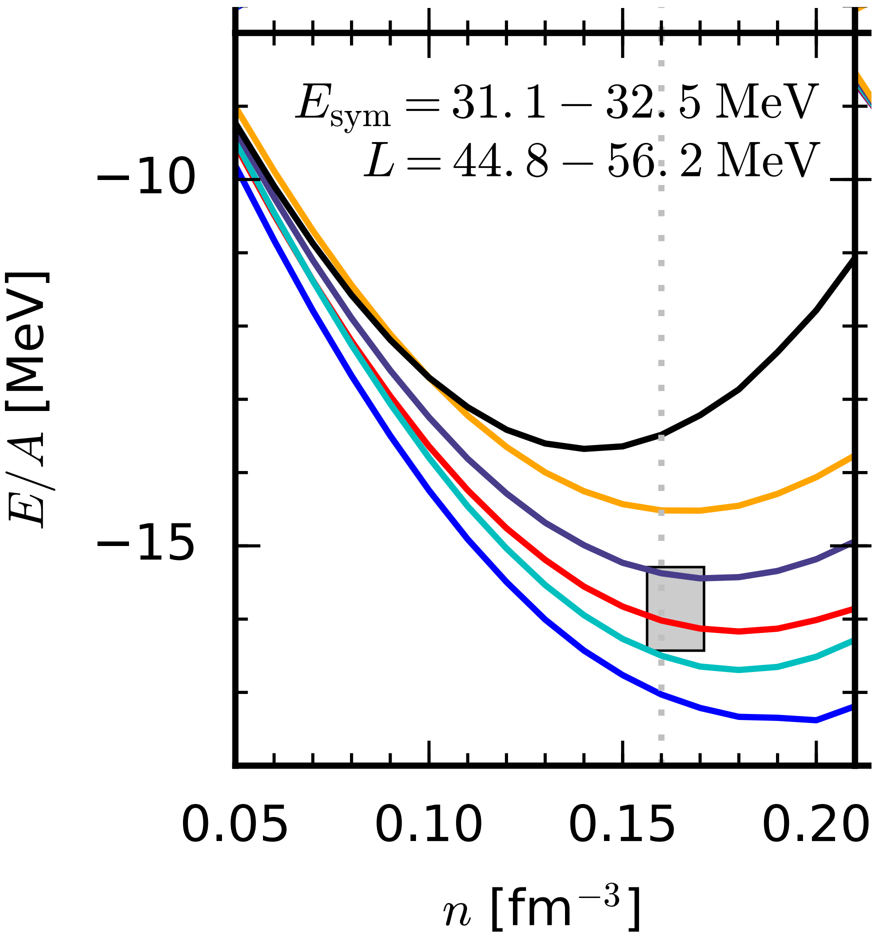


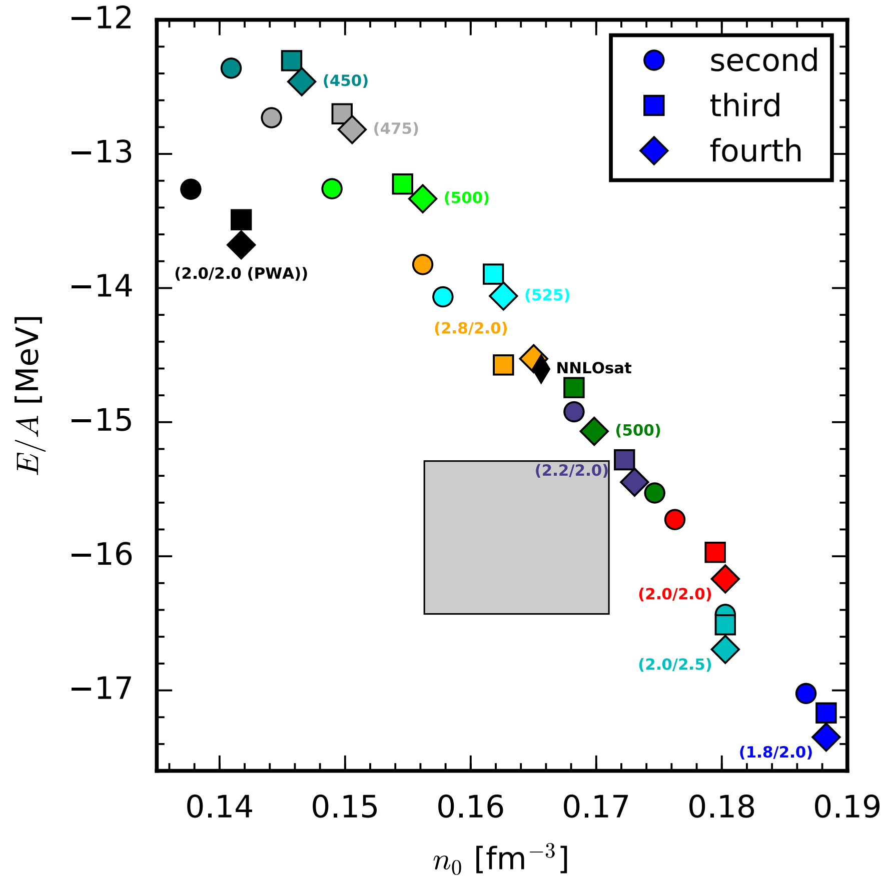
Nuclear forces and nuclear matter

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	$\lambda/\Lambda = 1.8/2.0\ \mathrm{fm}^{-1}$	−2.30	−2.24	−0.40	−0.10	−0.20	−0.07





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Monte-Carlo calculation of all energy diagrams
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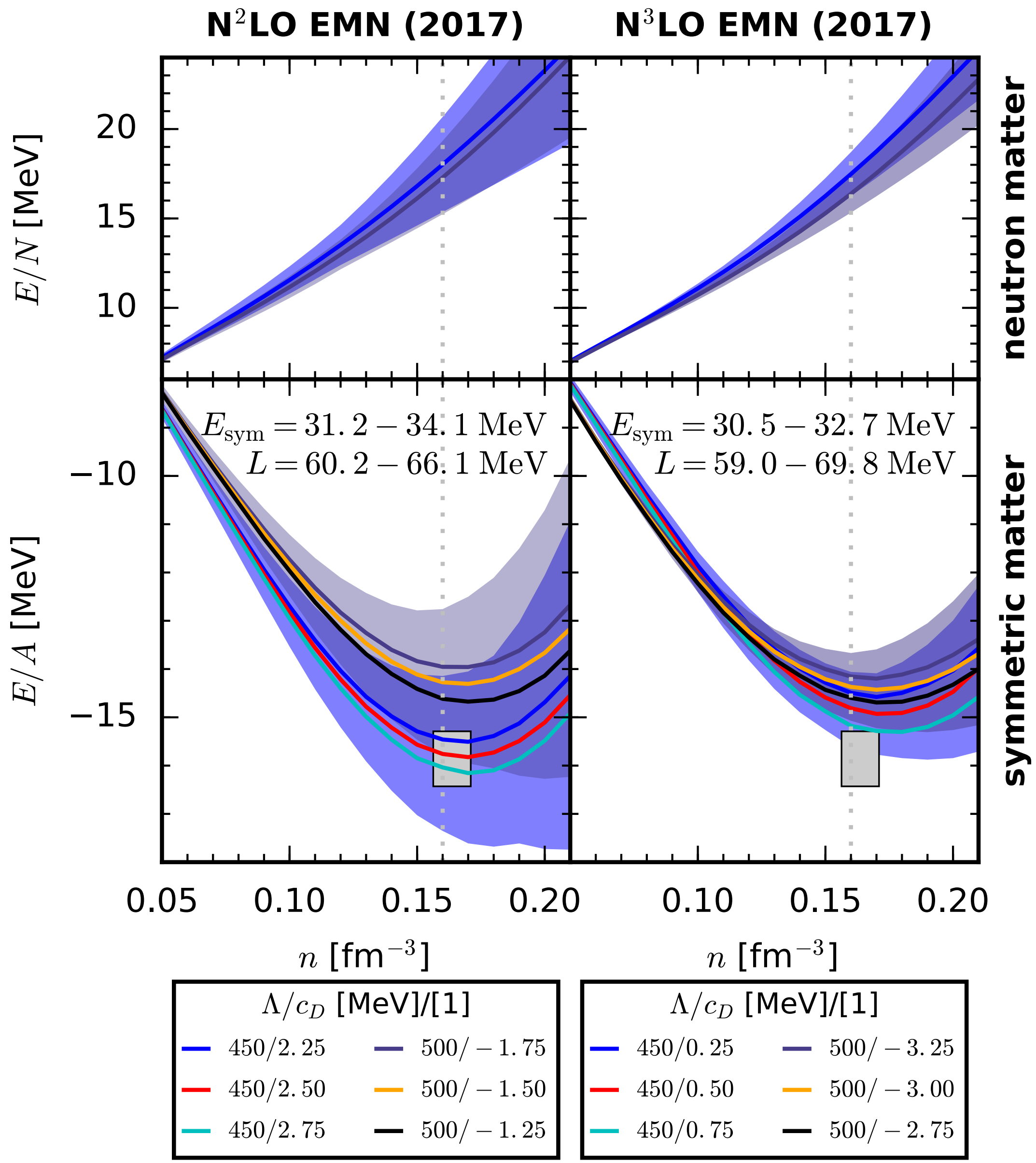
Drischler, Hebeler, AS, arXiv:1710.08220

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

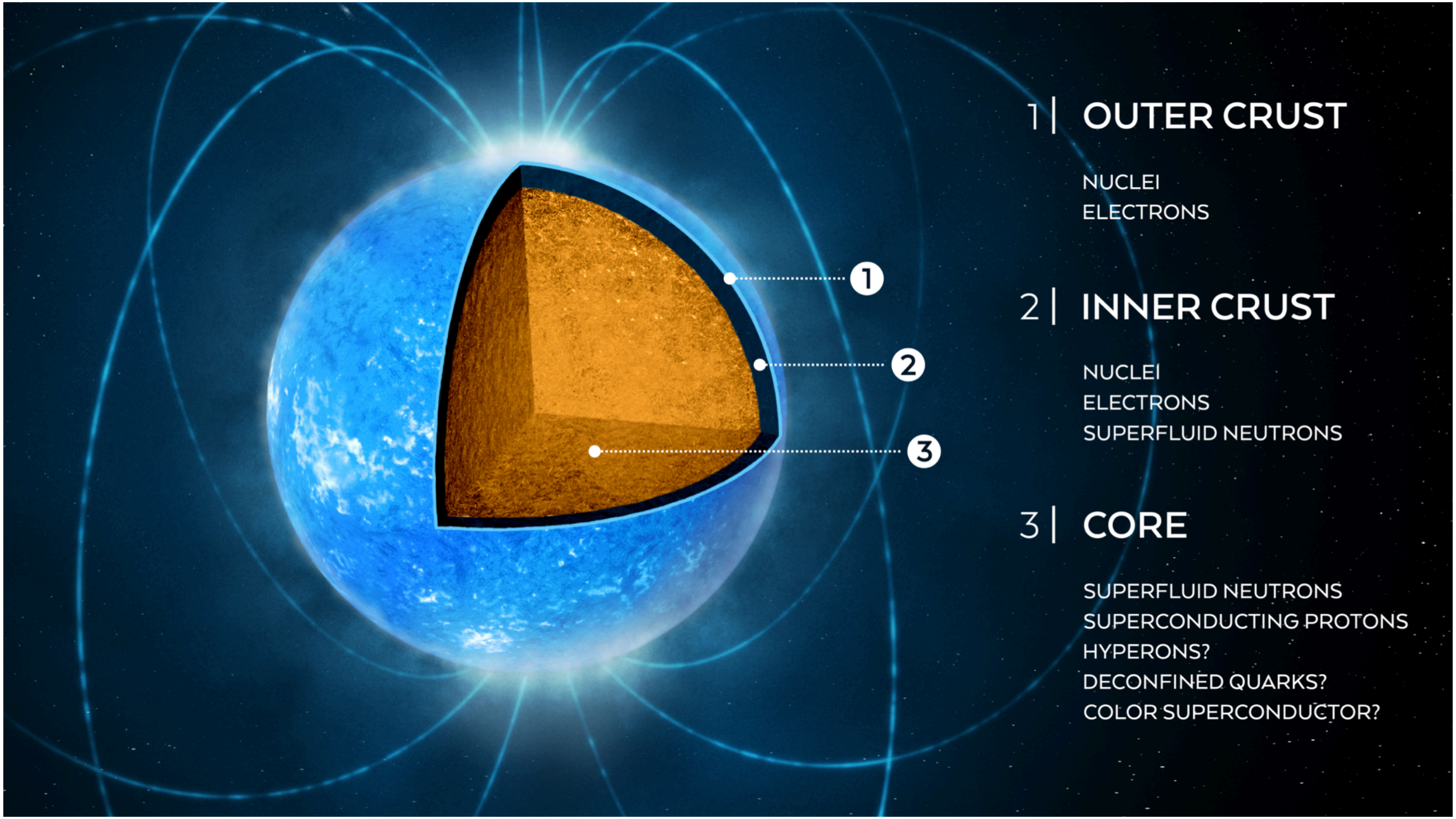
systematic improvement
from N^2LO to N^3LO

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



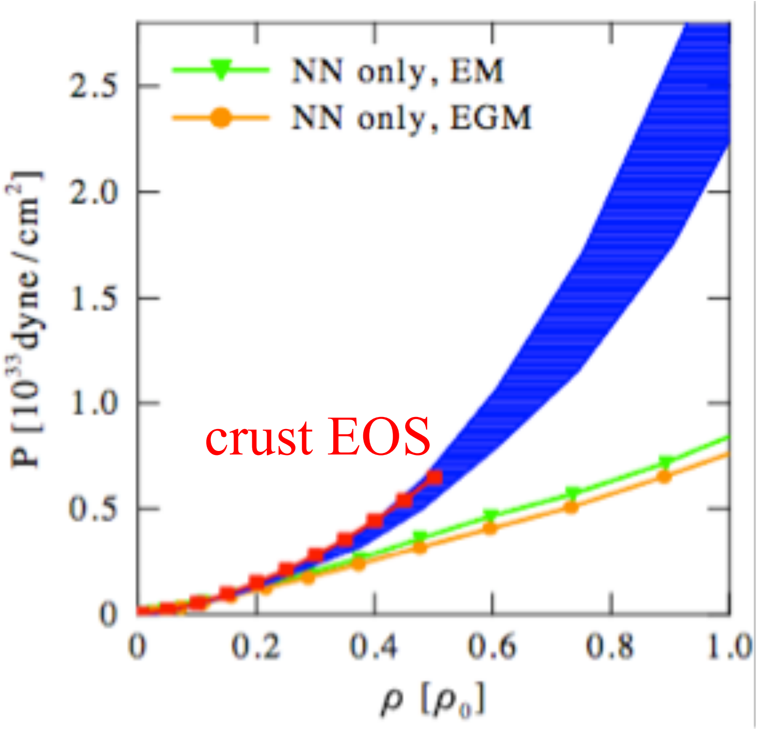
Neutron matter and neutron stars

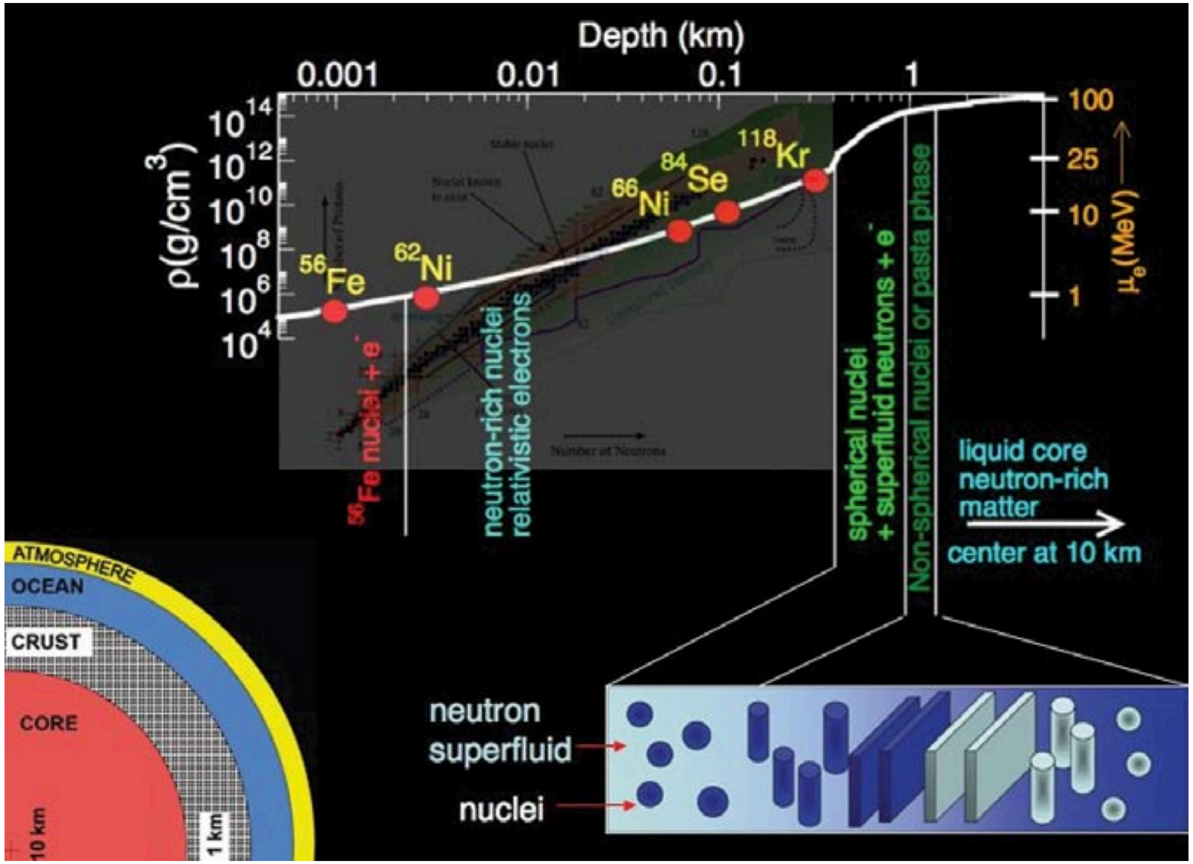
Watts et al., RMP (2016)



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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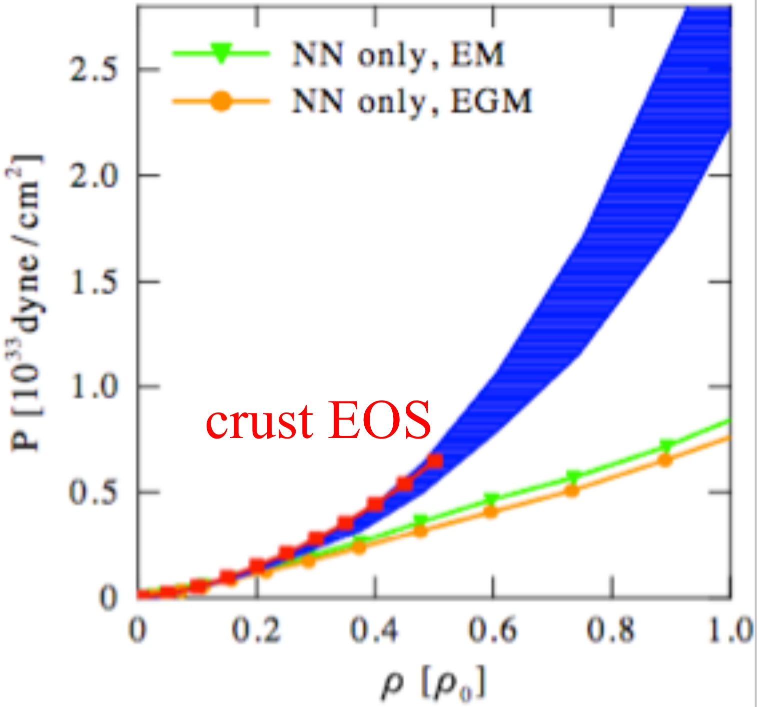
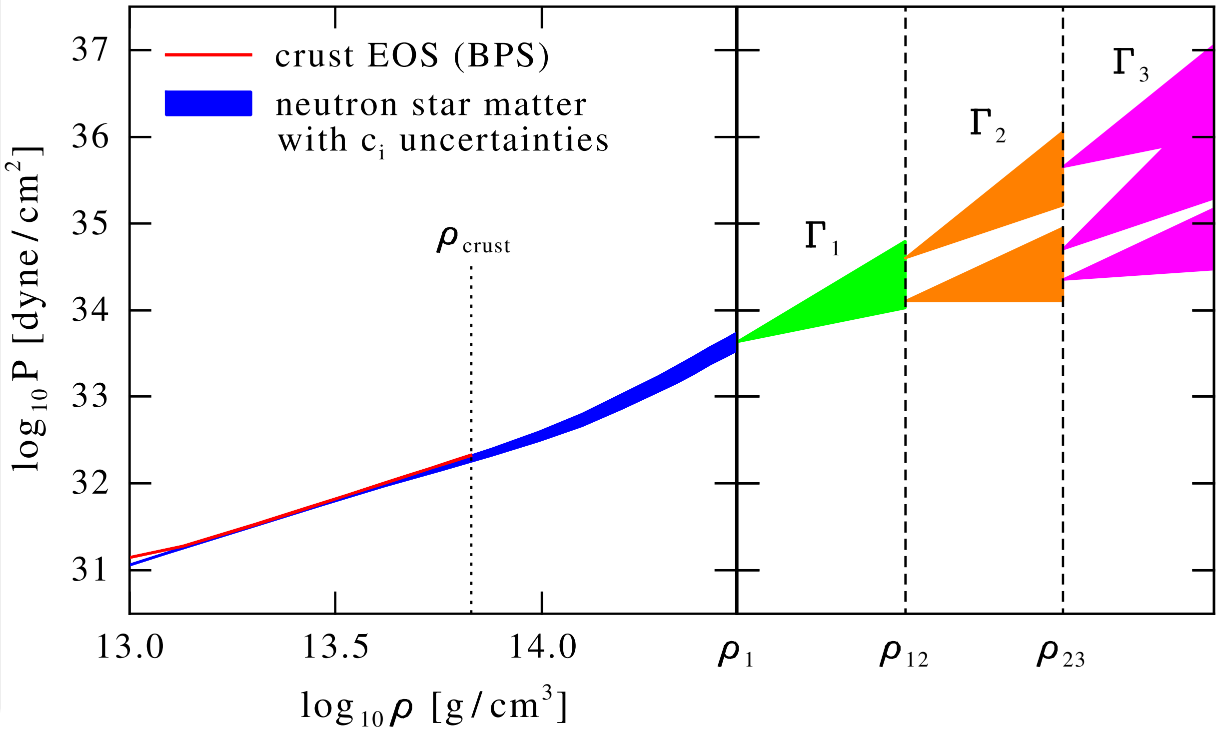


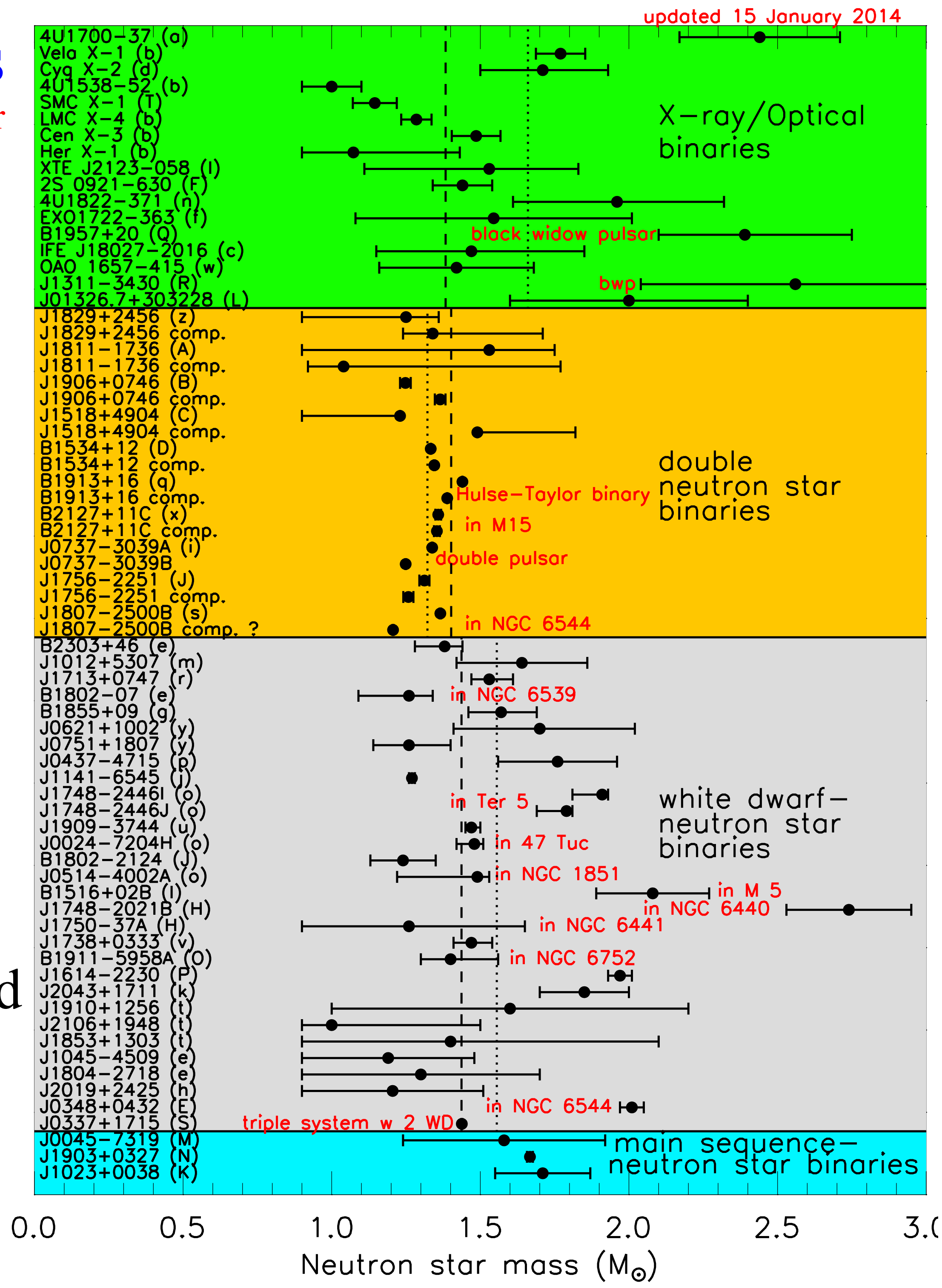


pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

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

Chart of neutron star masses

from Jim Lattimer



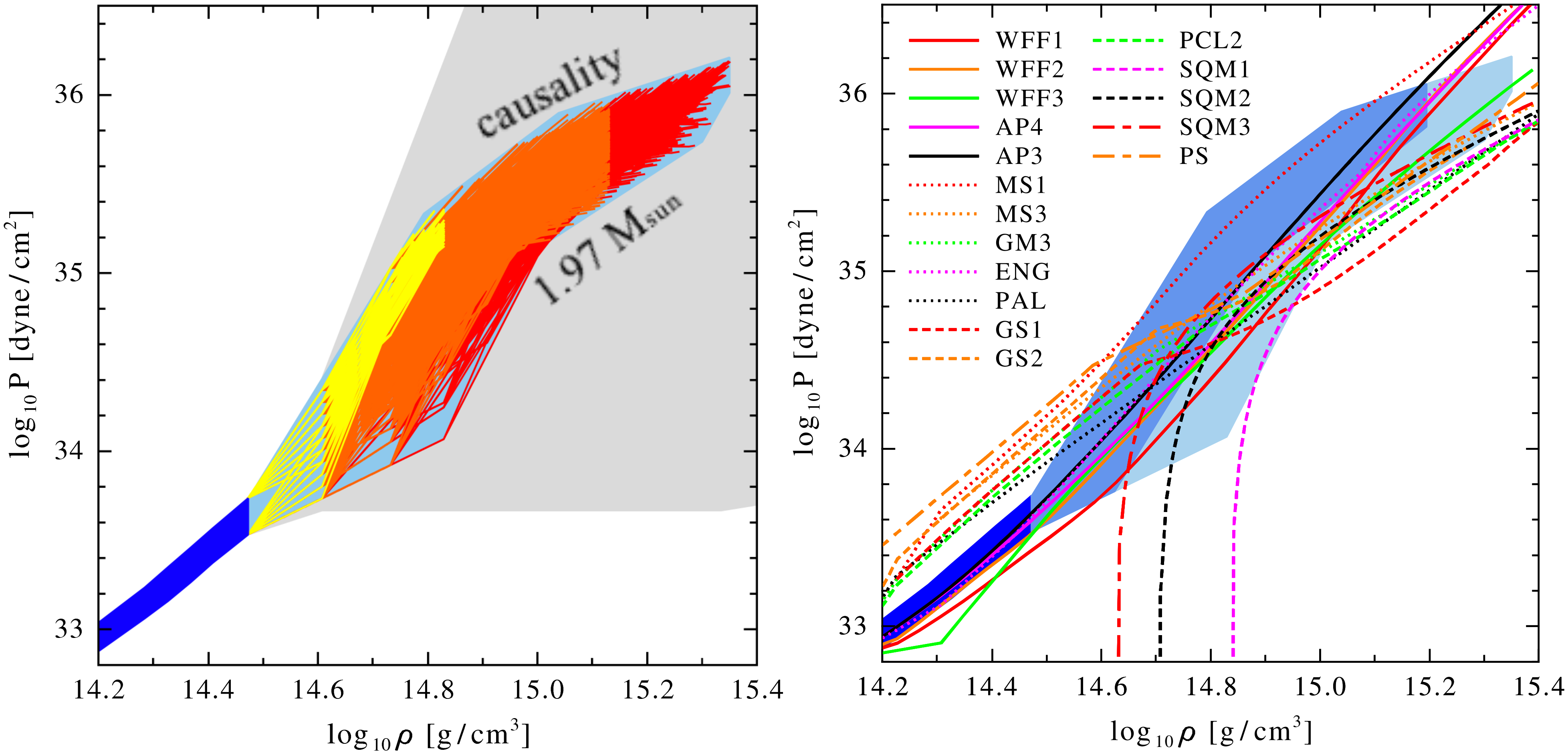
two 2 M_{sun} neutron stars observed

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)

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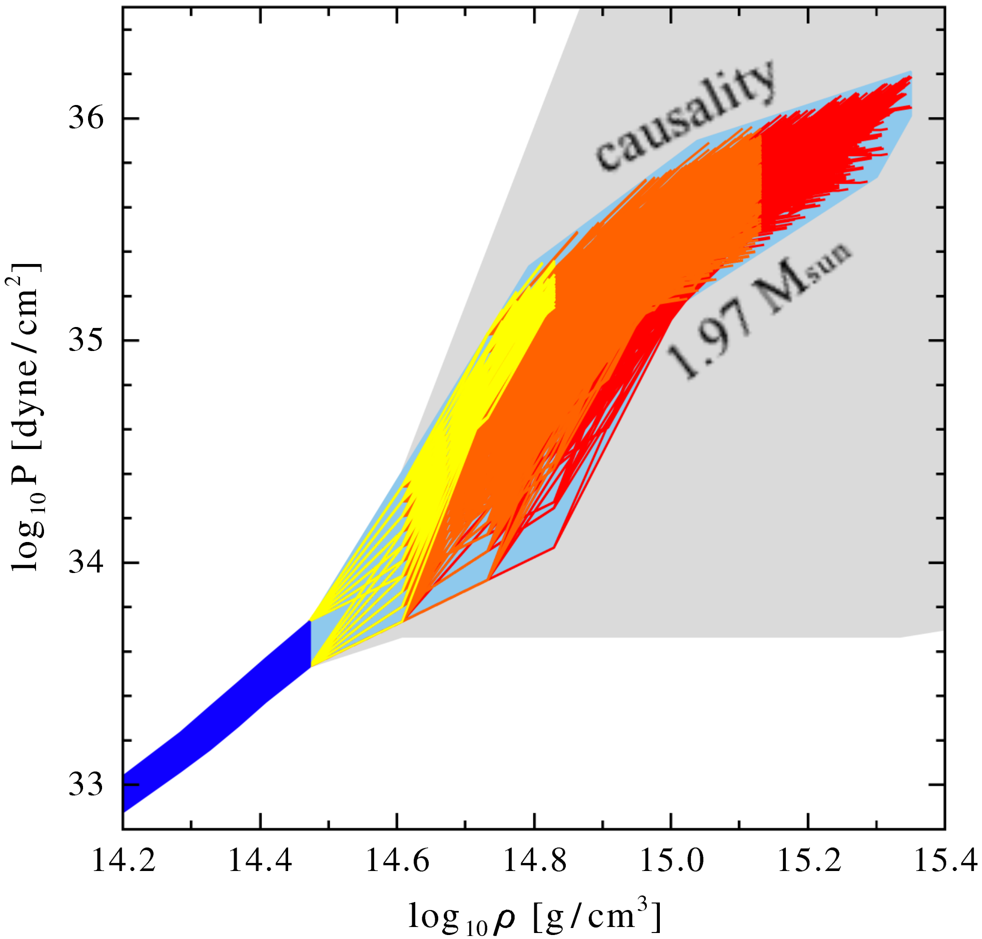
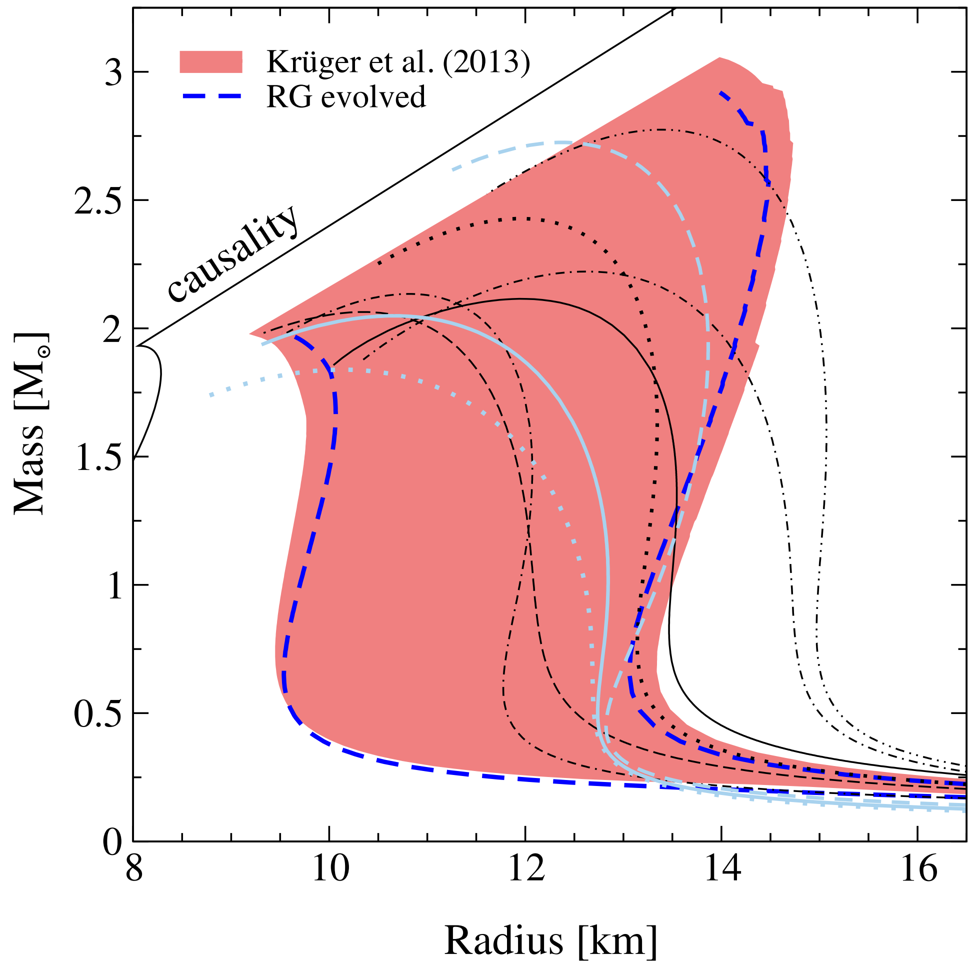


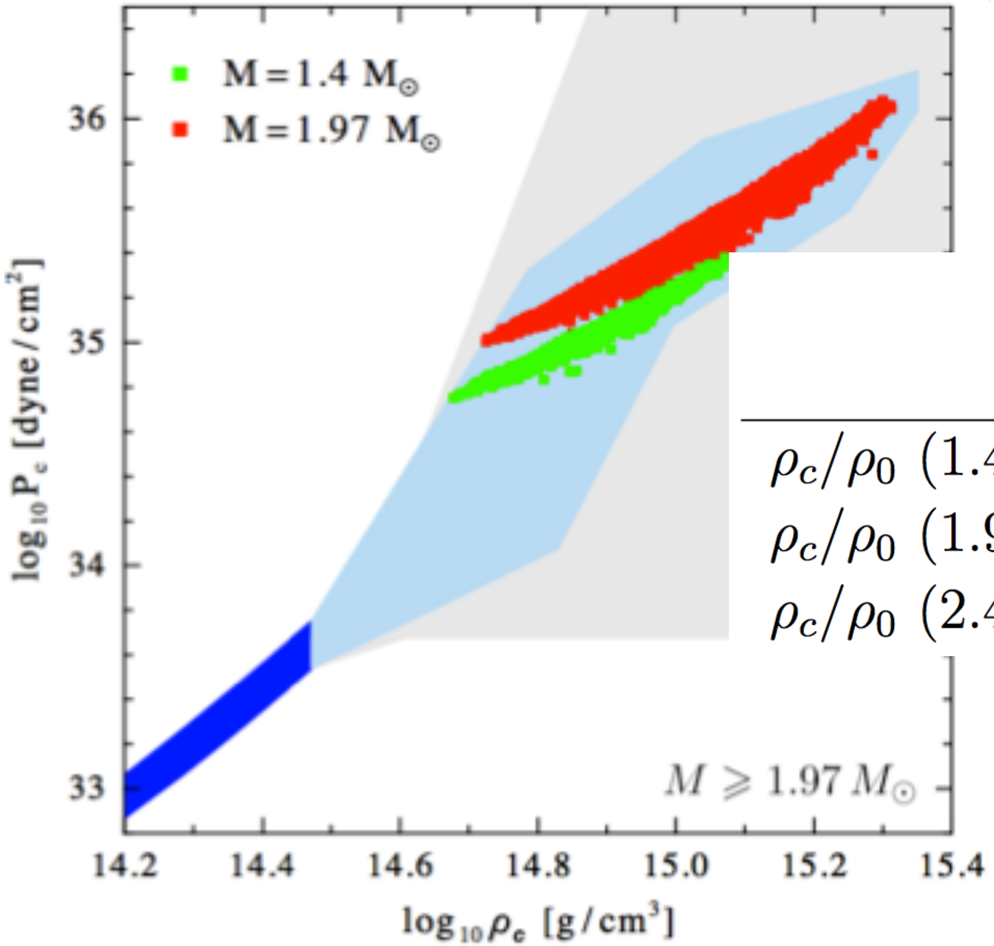


low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

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



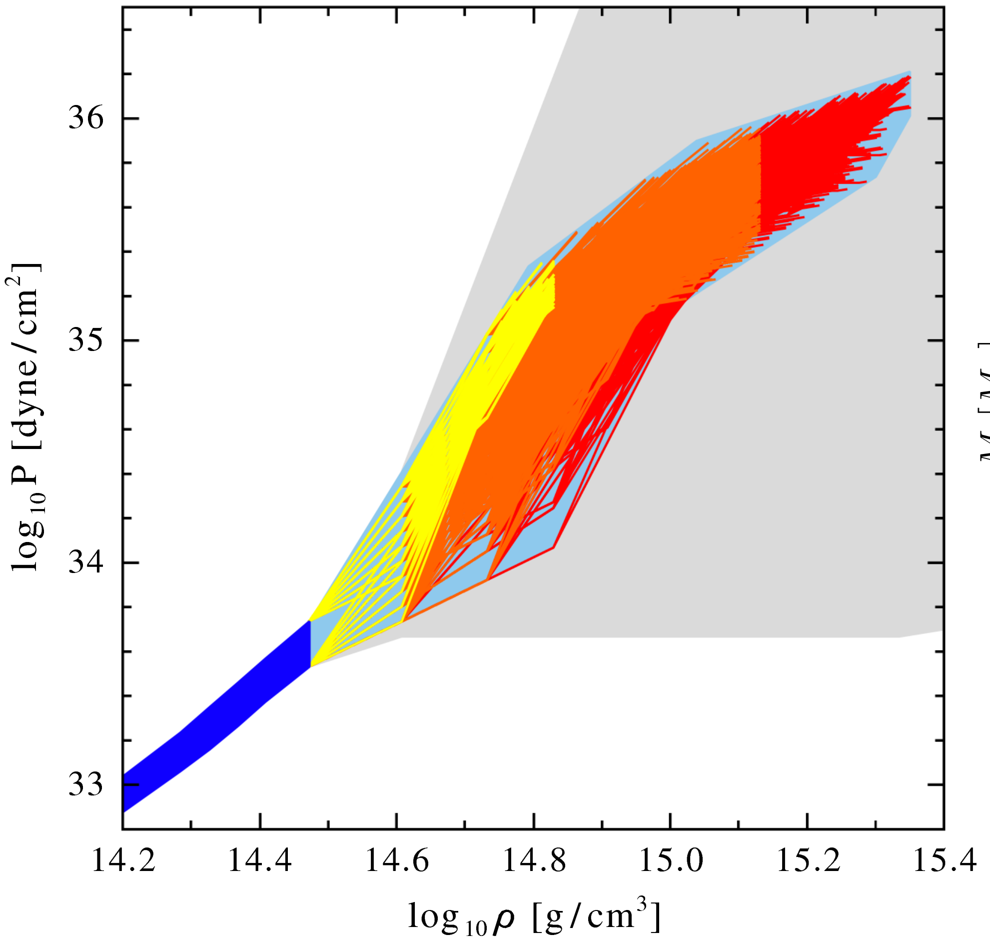
	$\widehat{M} = 1.97\,M_\odot$ min	$\widehat{M} = 1.97\,M_\odot$ max	$\widehat{M} = 2.4\,M_\odot$ min	$\widehat{M} = 2.4\,M_\odot$ max
ρ_c/ρ_0 $(1.4\,M_\odot)$	1.8	4.4	1.8	2.7
ρ_c/ρ_0 $(1.97\,M_\odot)$	2.0	7.6	2.0	3.4
ρ_c/ρ_0 $(2.4\,M_\odot)$			2.2	5.4

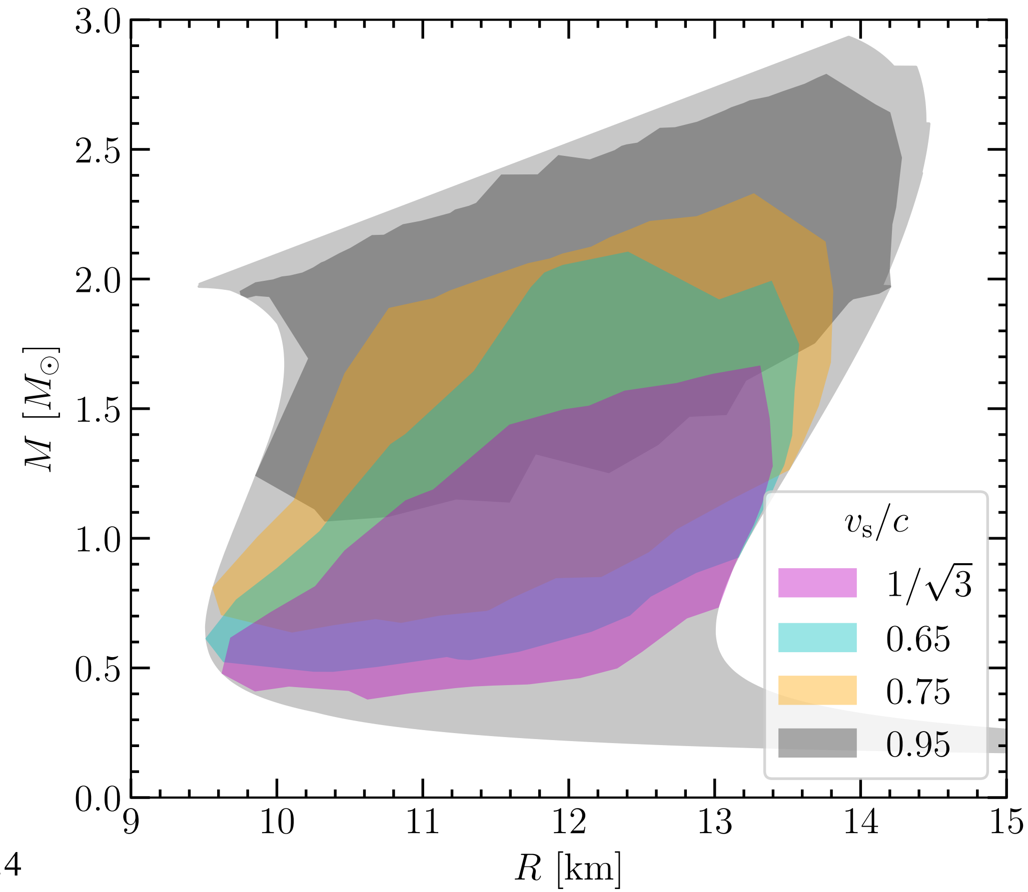
central densities
for 1.4 M_{sun} star: 1.8-4.4 ρ_0

Fermi momenta < 550 MeV
(not very high!)

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





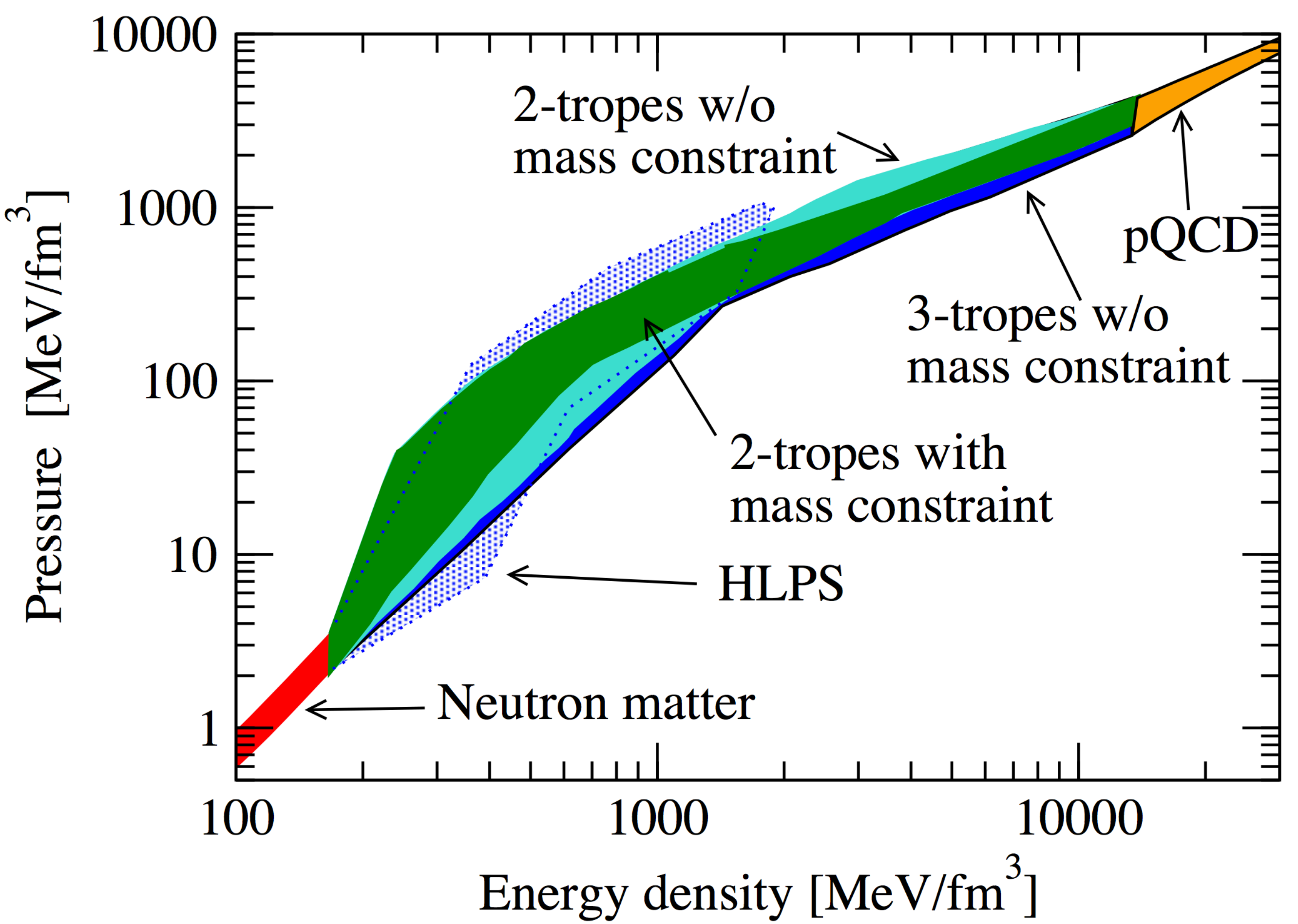
speed of sound needs to exceed ~0.65c to get 2 M_{sun} stars

Greif et al., in prep.

Connecting the equation of state to pQCD calculations

$O(\alpha_s^2)$ calculation of quark matter in perturbative QCD provides constraint at ultra high densities (above 50 saturation density)

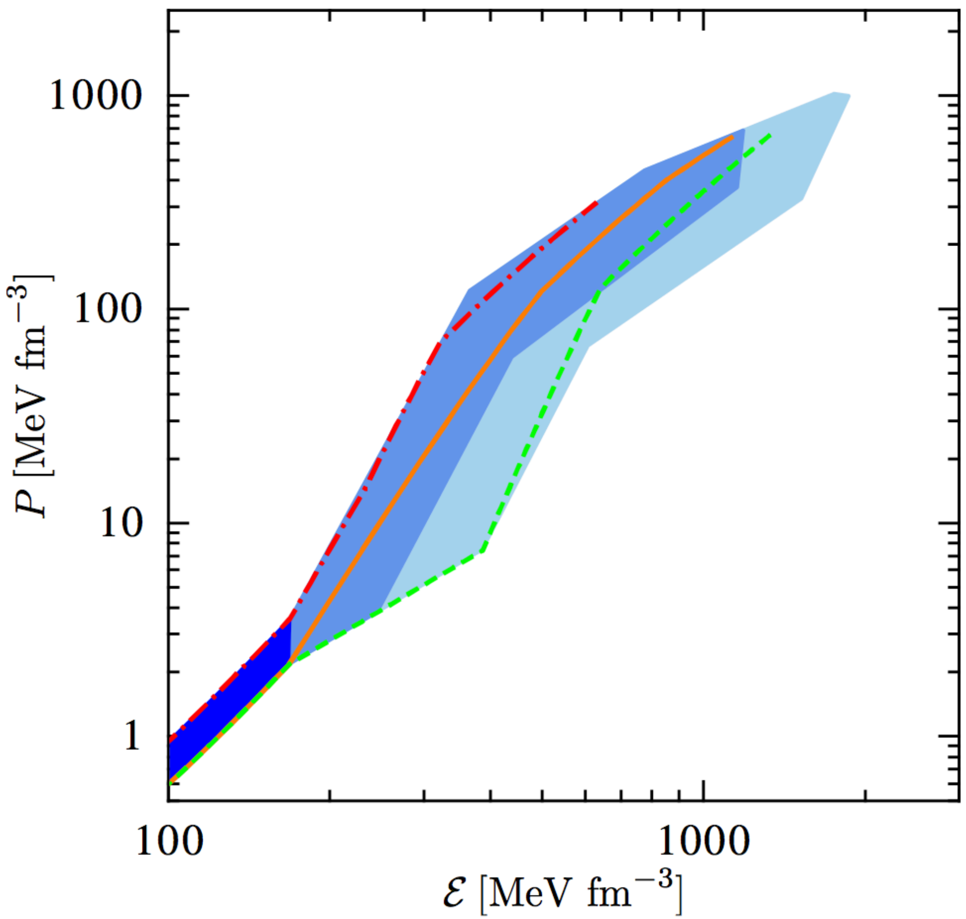
interpolating between **neutron matter calculations** and **pQCD** gives consistent EOS band Kurkela et al., ApJ (2014)

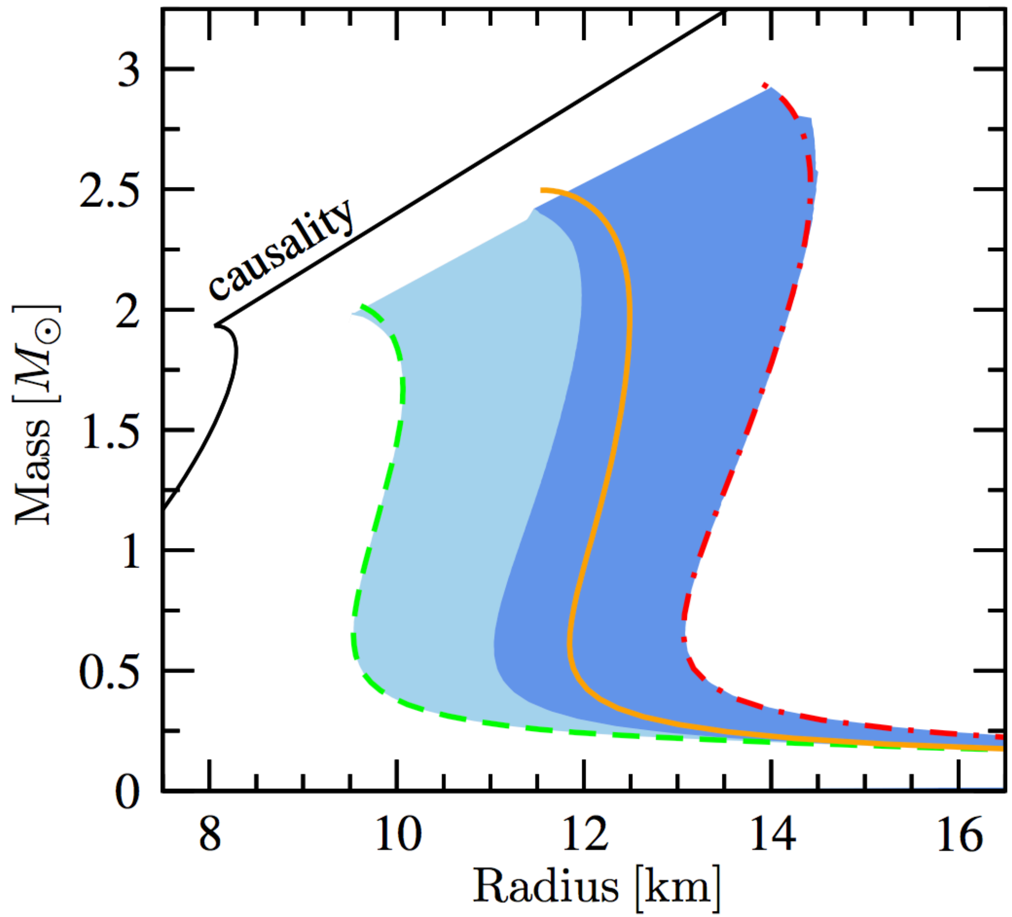


Representative equations of state

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)

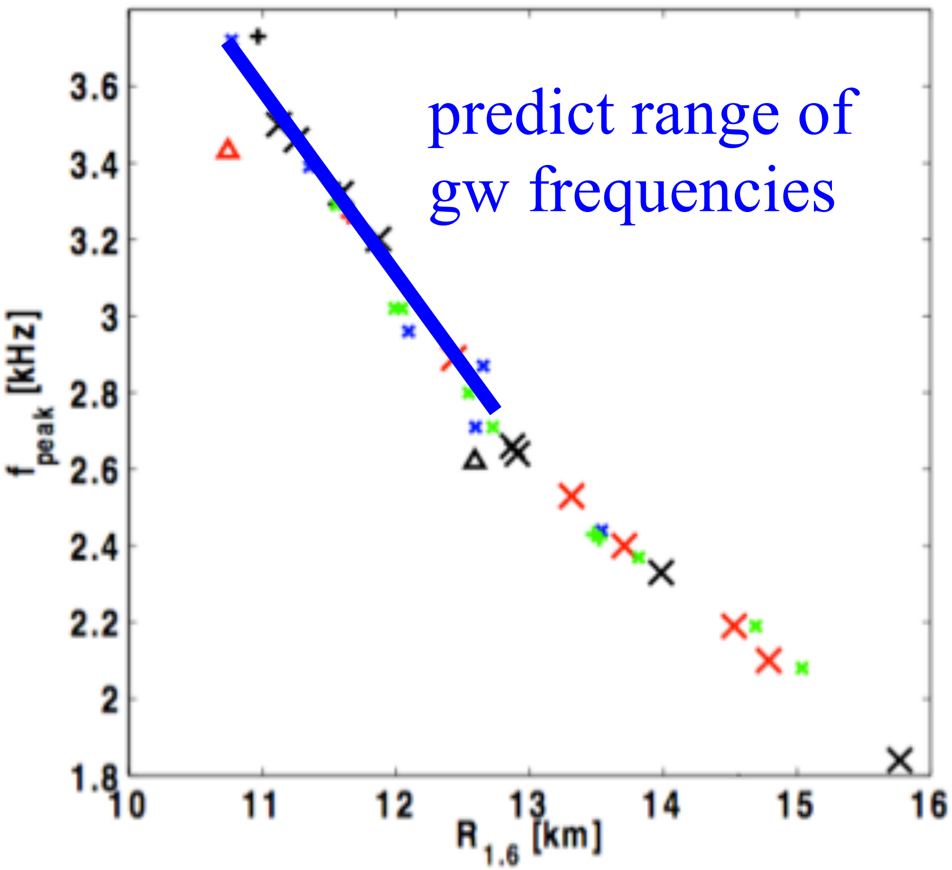
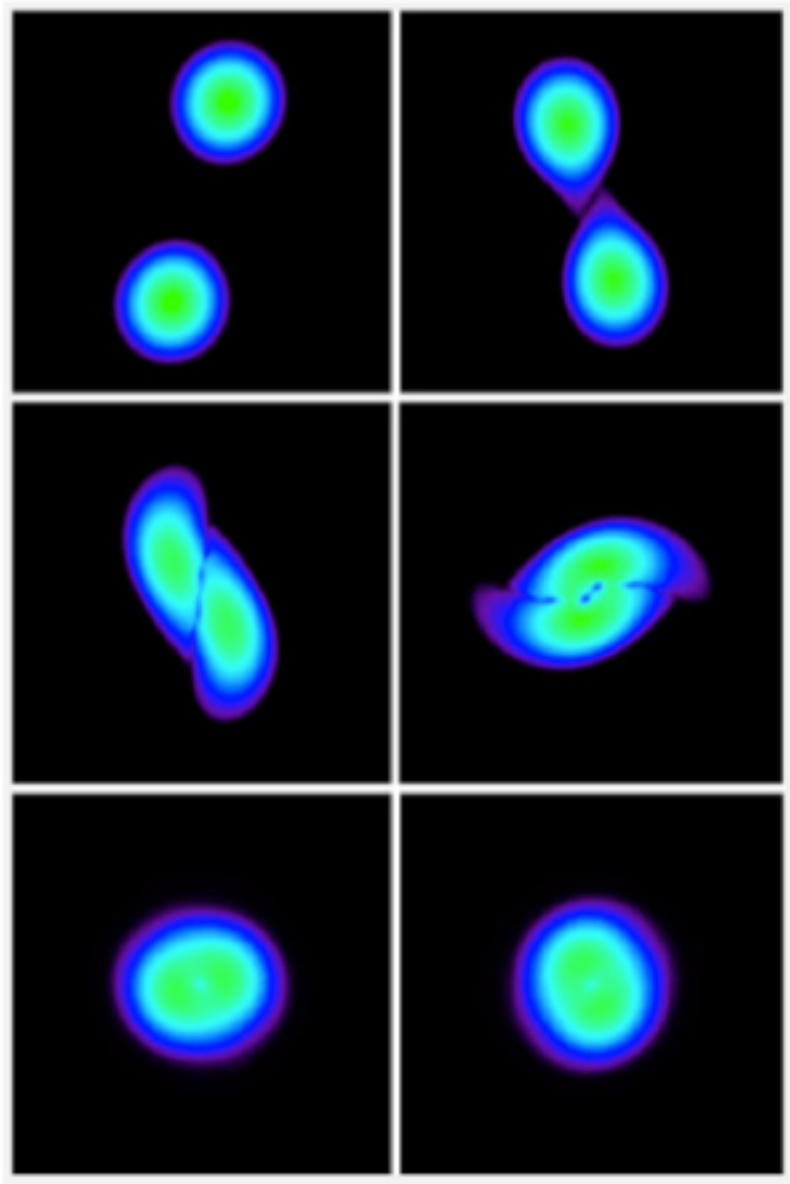
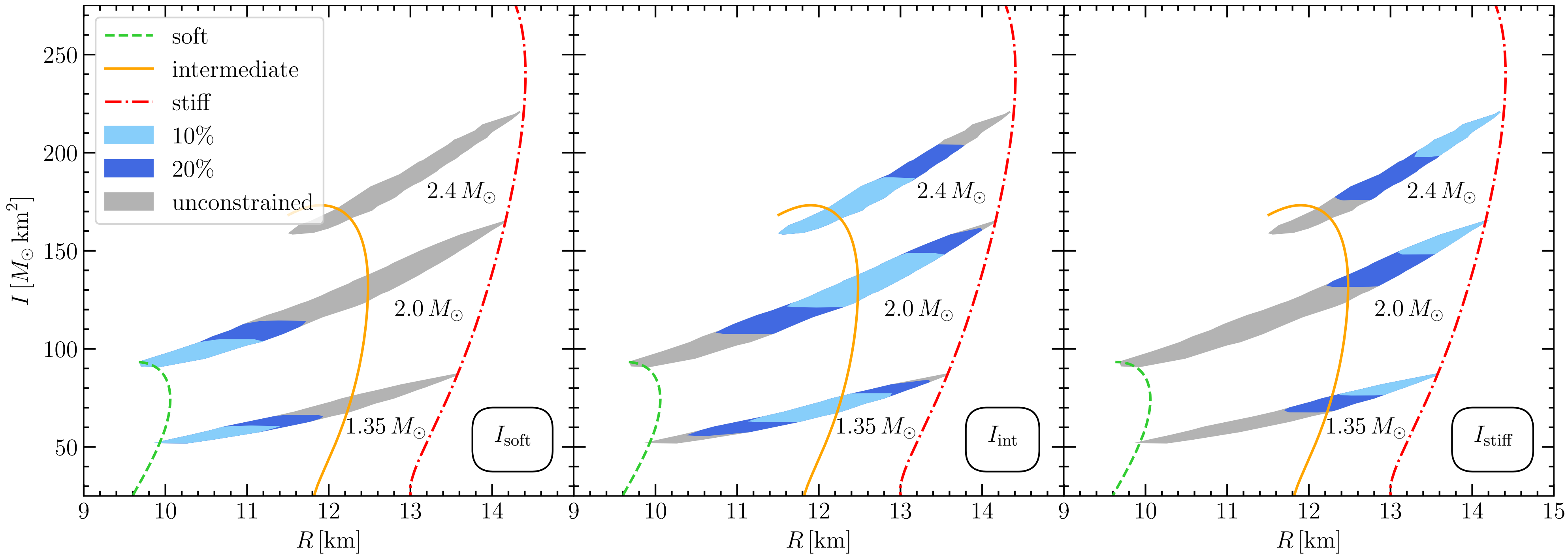


FIG. 10: Peak frequency of the postmerger GW emission versus the radius of a nonrotating NS with 1.6 $M_\odot$ for different EoSs. Symbols have the same meaning as in Fig. 8.



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

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



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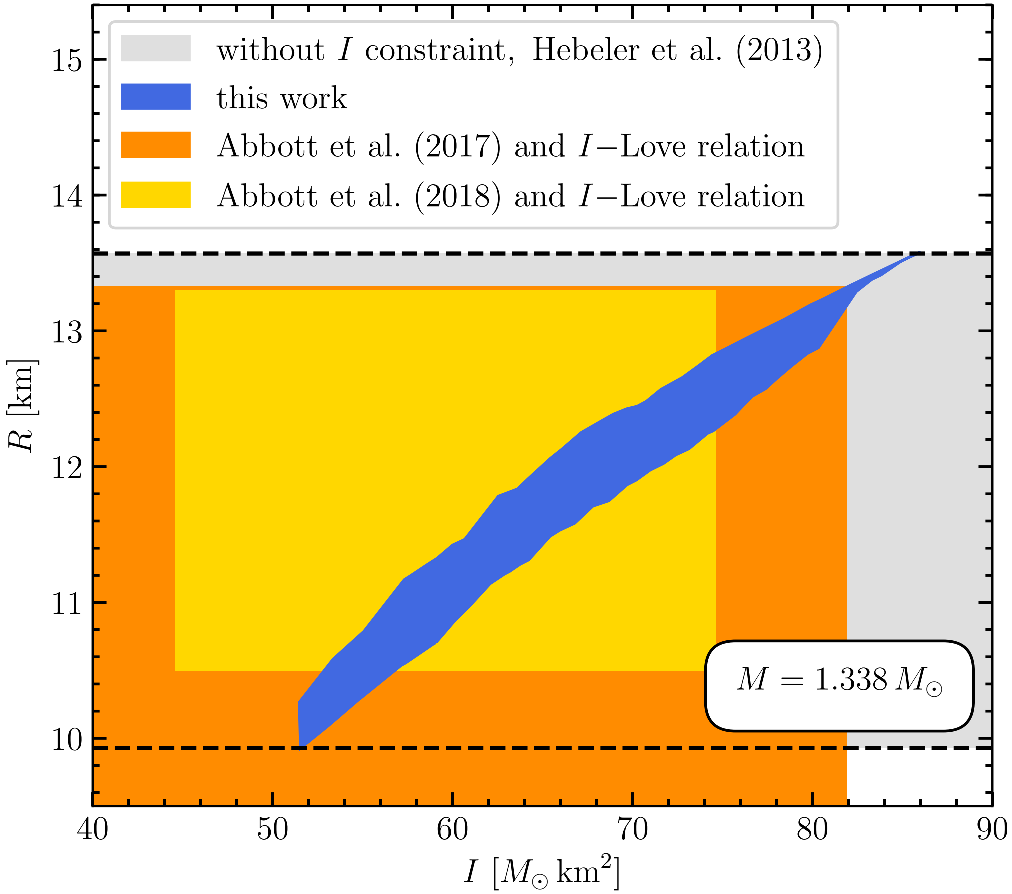
candidate neutron star: PSR J0737-3039



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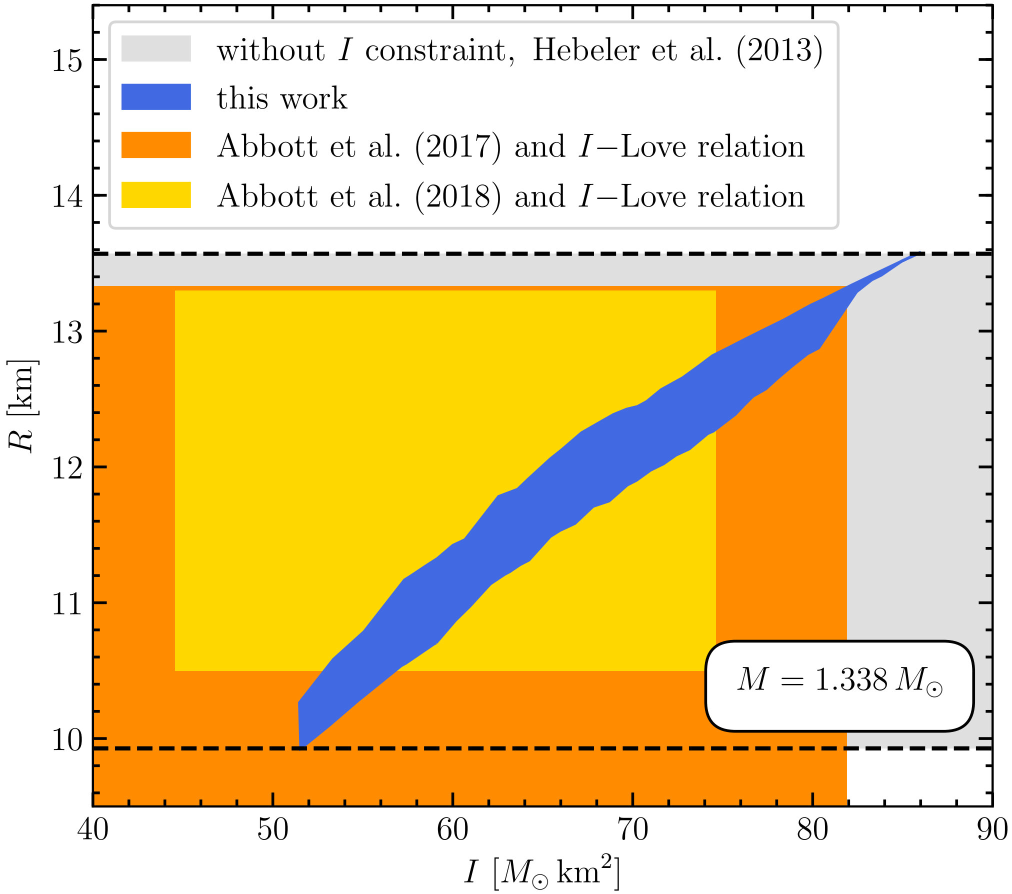

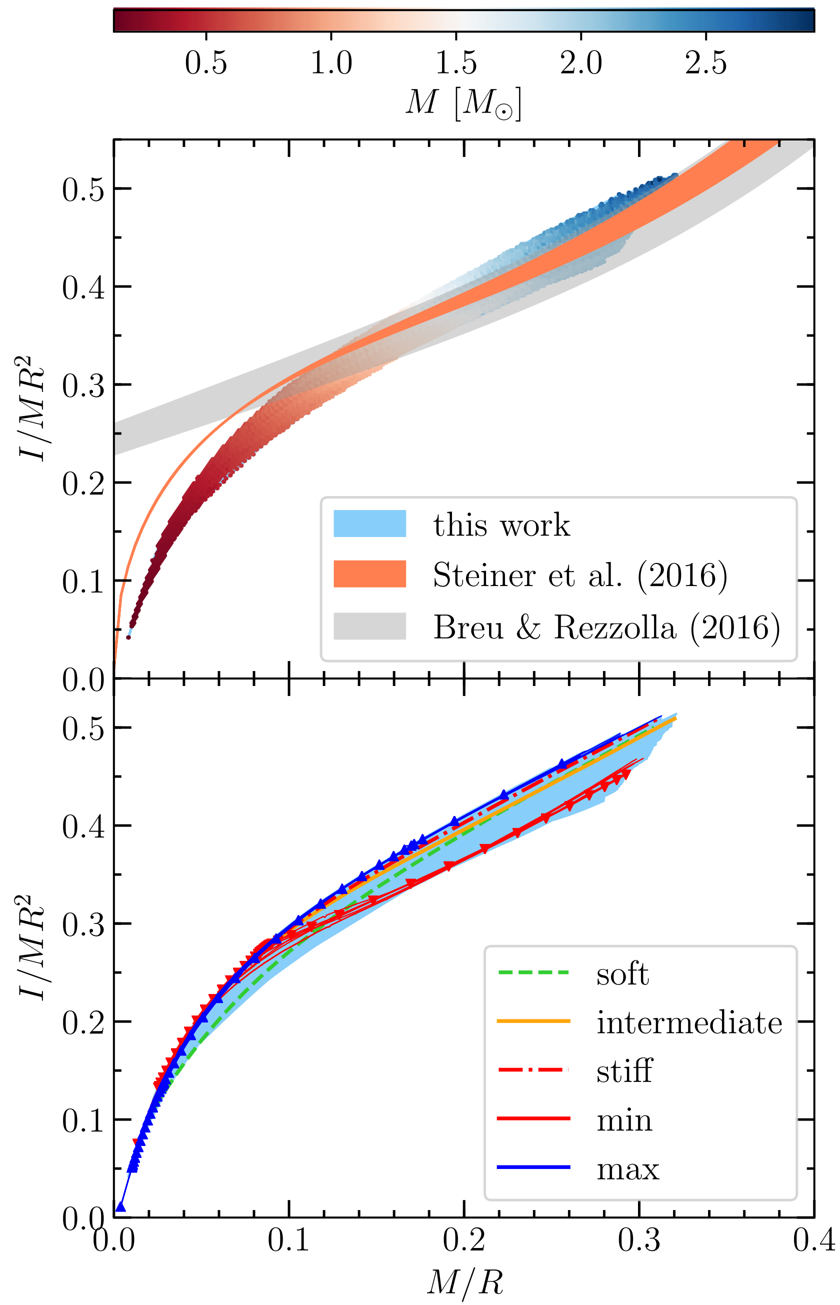

"universal" relations are broader with general EOS band

Radius constraints from moment of inertia

Greif et al., in prep.

10% measurement of moment of inertia rec

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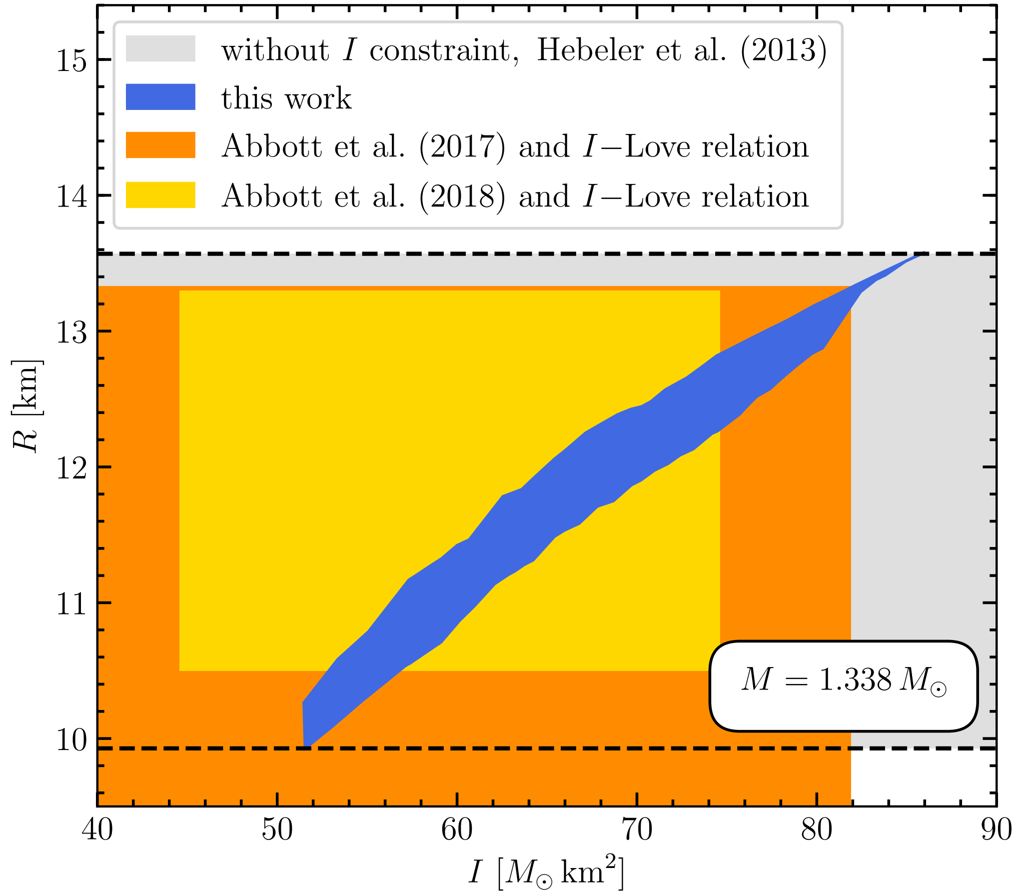
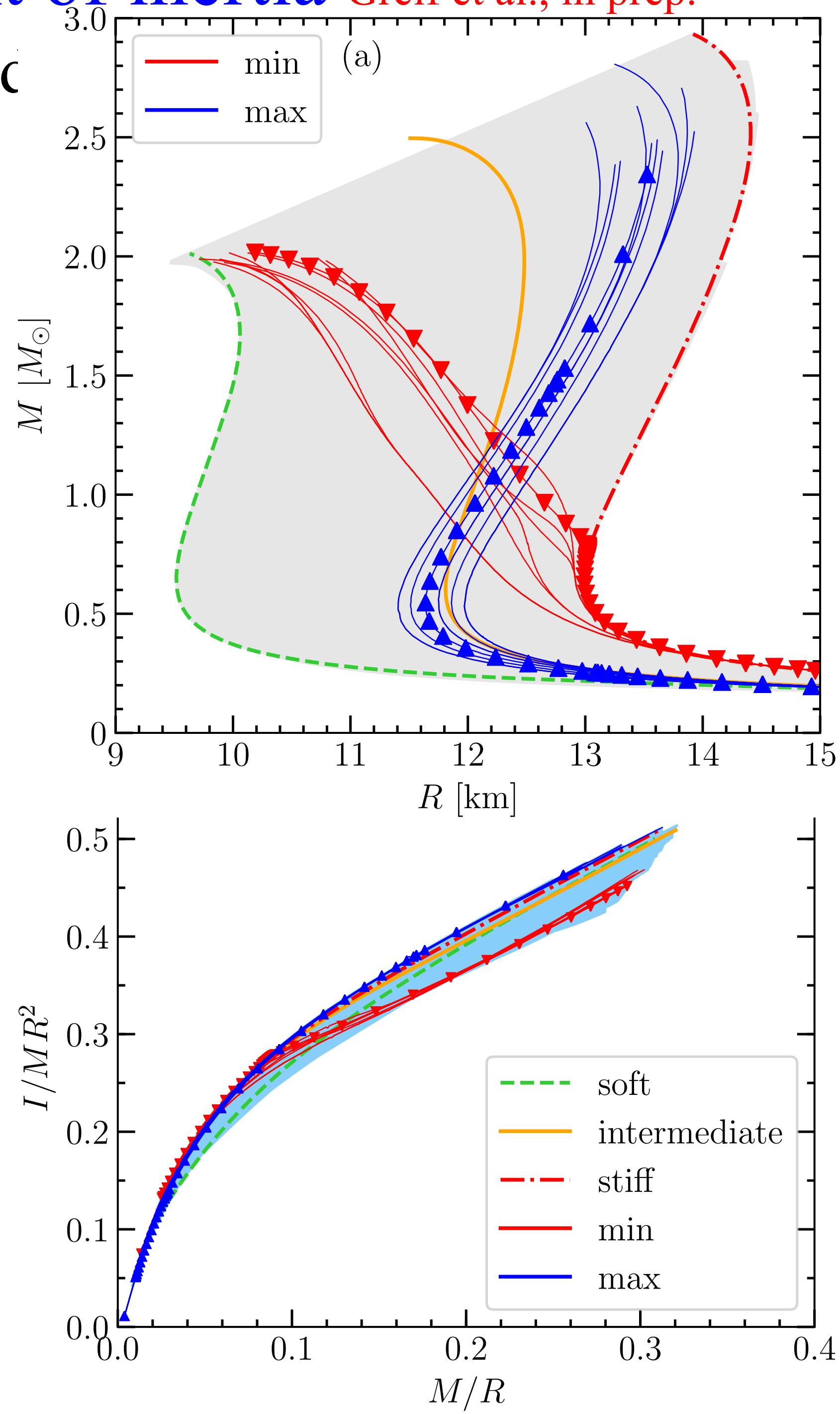


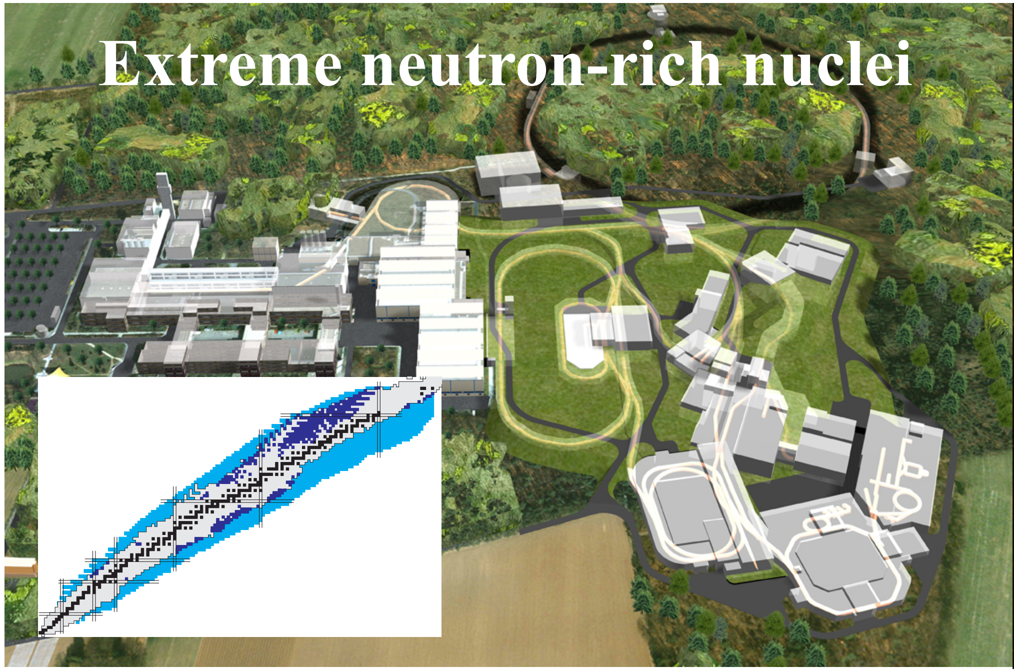


"universal" relations are broader with general EOS band

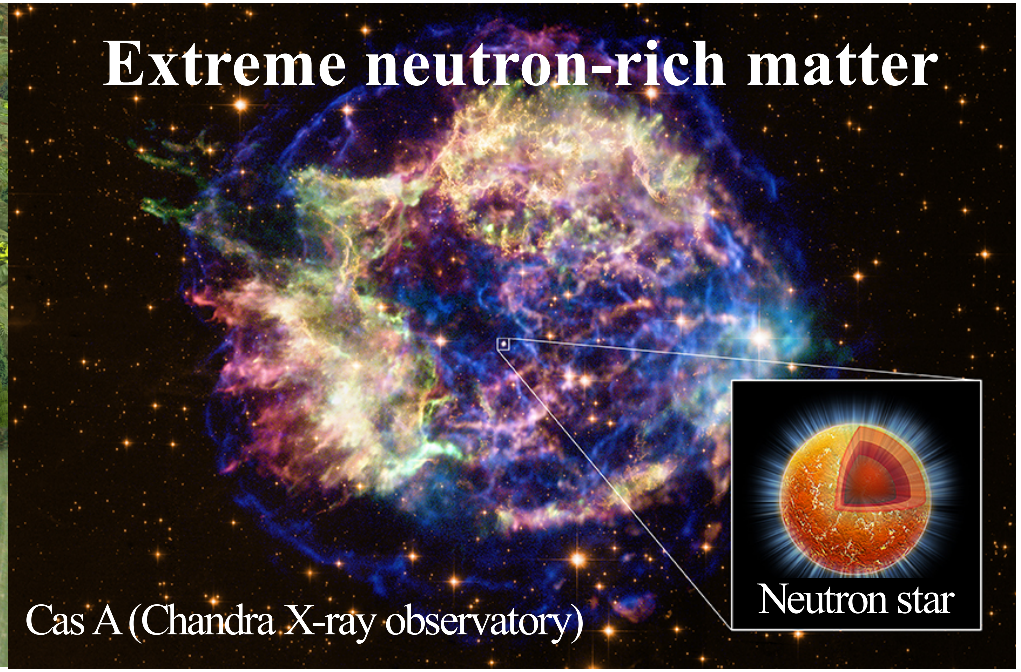
Exciting era in nuclear physics

Effective field theory of the strong interaction

New experimental frontier



New observations in astrophysics



Thanks to: **A. Carbone, C. Drischler, S. Greif,** K. Hebeler, J.D. Holt, **J.E. Lynn,** T. Krüger, J. Lattimer, C. Pethick, **R. Stroberg, J. Simonis, I. Tews**

Main points

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Neutron-rich conditions and low/moderate temperatures

especially interesting for neutron stars, cooling and mergers

General EOS band based on nuclear physics and observations

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theory: reliable EOS calculations to higher densities?
exp: extreme n-rich nuclei, extractions from heavy-ion collisions?