Equation of state and neutrino interactions from nuclear forces

Achim Schwenk

TECHNISCHE
UNIVERSITÄT
DARMSTADT

EMMI

INT r-process workshop

Seattle, July 31, 2014

DFG

erc

HELMHOLTZ
ASSOCIATION

Minerva Stiftung

ARCHES
Award for Research Cooperation and
High Excellence in Science

Bundesministerium
für Bildung
und Forschung

Main points

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

Neutron-rich conditions and nondegenerate conditions

especially interesting for mergers!

General EOS band based on nuclear physics and observations

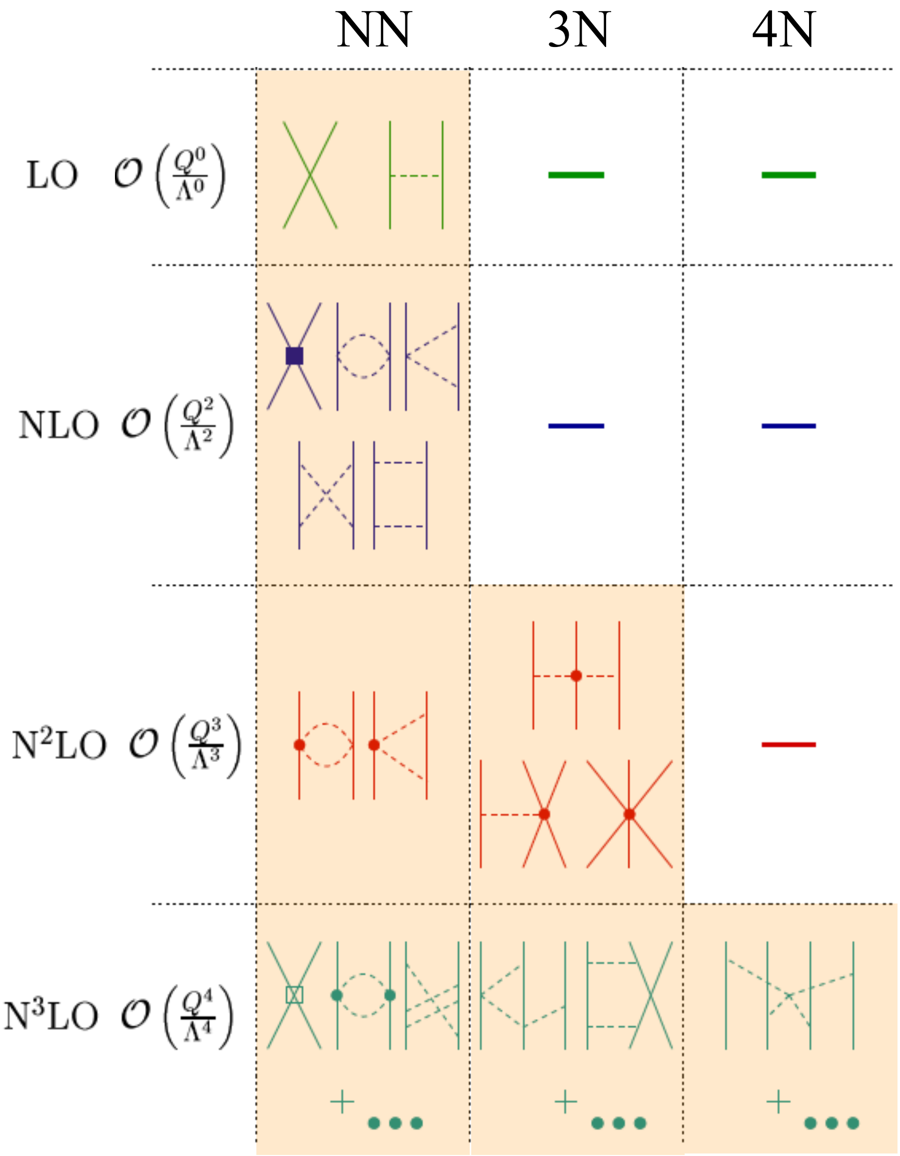
neutron star radius 9.7-13.9 km for $M=1.4\ M_{sun}$ (±15%)

Chiral EFT important for consistent neutrino-matter interactions

Enhancement of neutrino bremsstrahlung at low densities

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,…

Chiral effective field theory for nuclear forces

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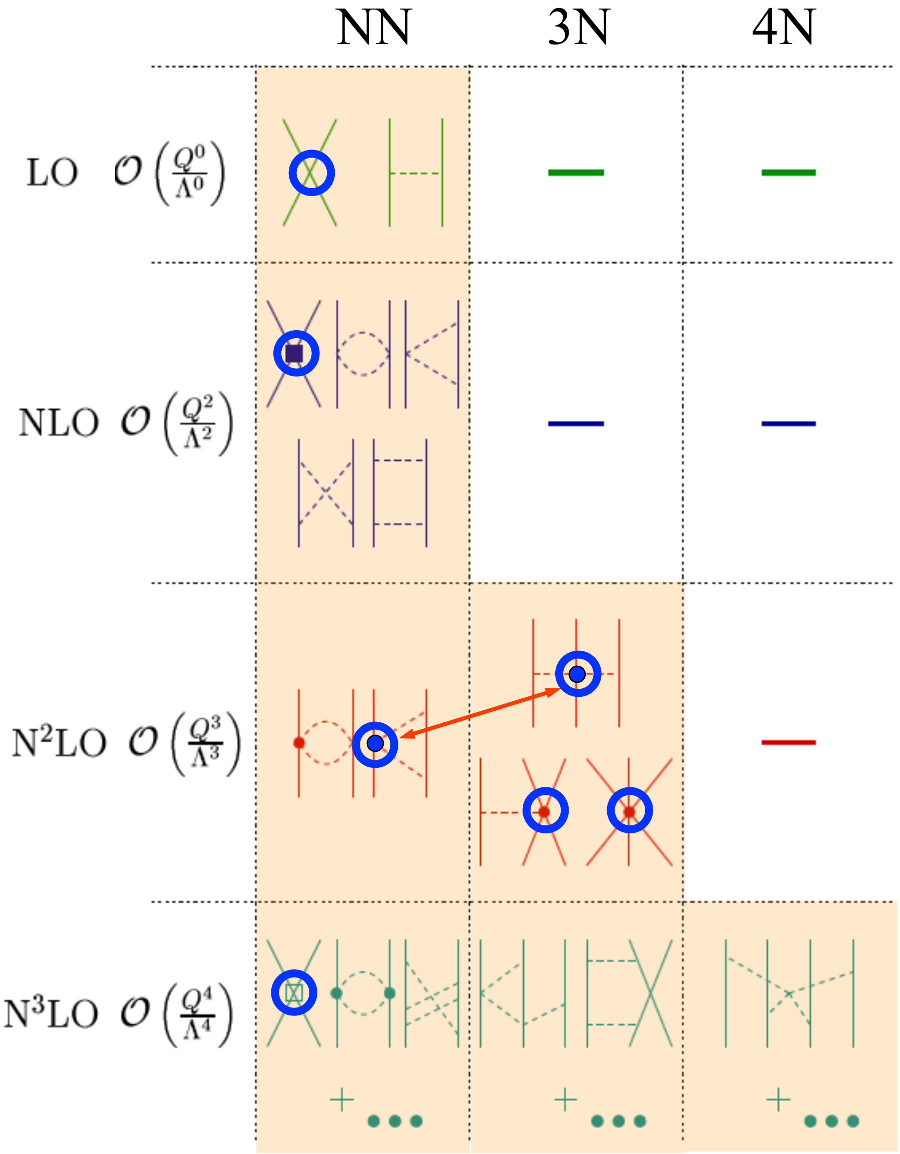


include long-range pion physics

few short-range couplings,
fit to experiment once

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

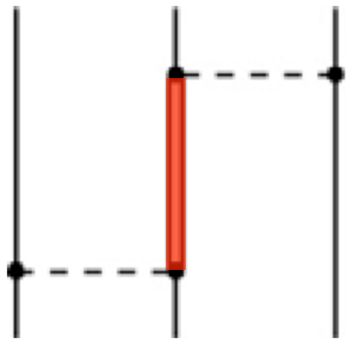
consistent **electroweak interactions** and **matching to lattice QCD**

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

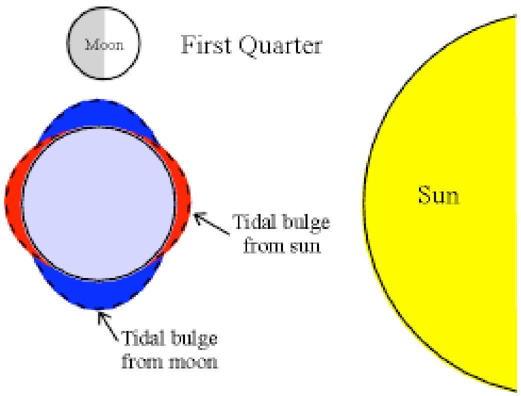
Why are there 3N forces?

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

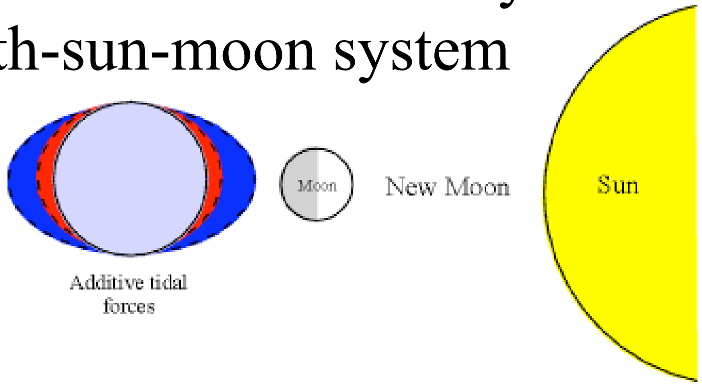
dominant contribution from Δ(1232 MeV)



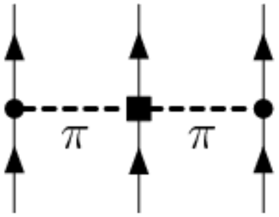
+ many shorter-range parts



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



chiral effective field theory (EFT)
Delta-less (Δ is treated as heavy):

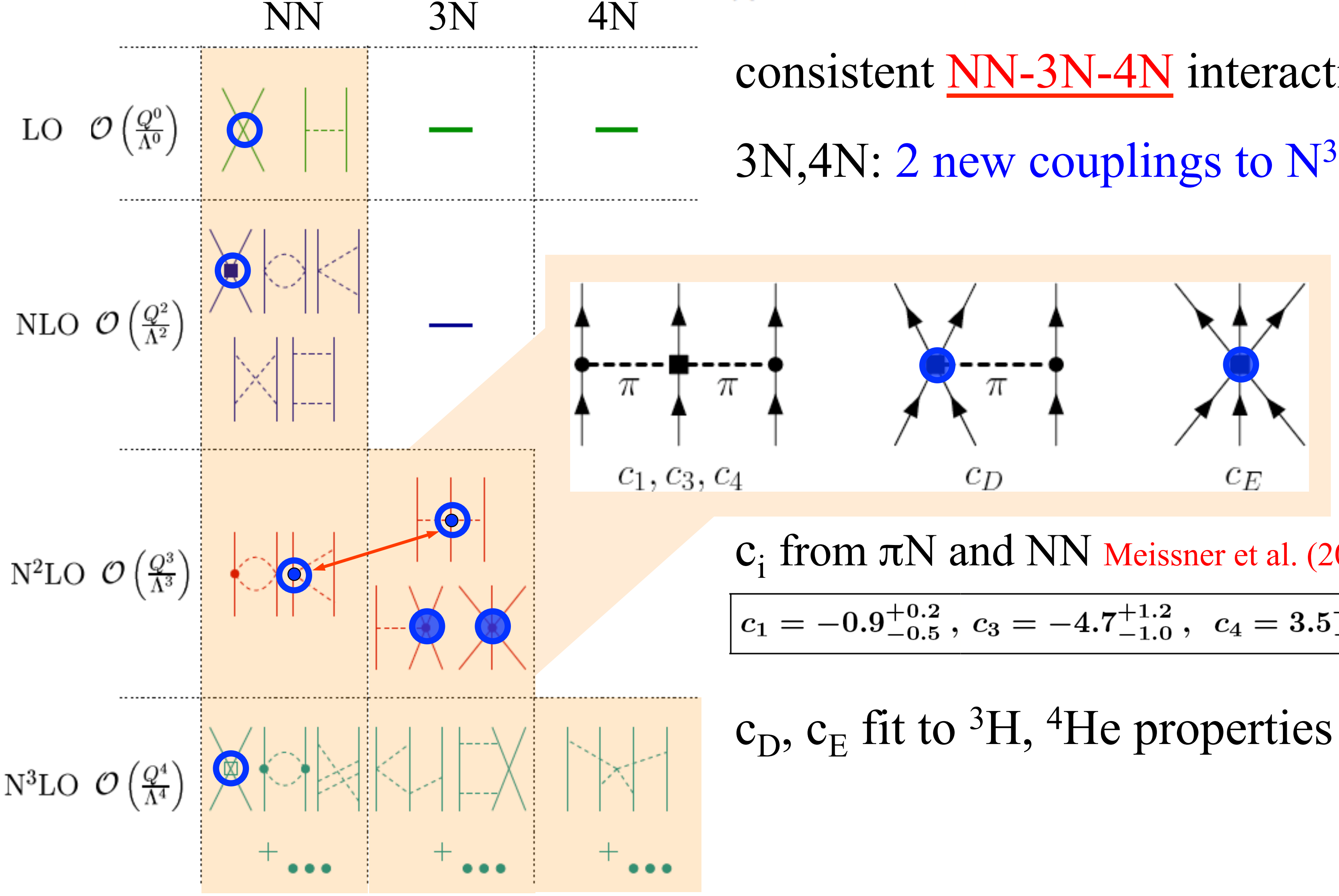


+ shorter-range parts

EFT provides a systematic and powerful approach for 3N forces

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

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

c_i from πN and NN Meissner et al. (2007)

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

c_D, c_E fit to ^{3}H, ^{4}He properties only

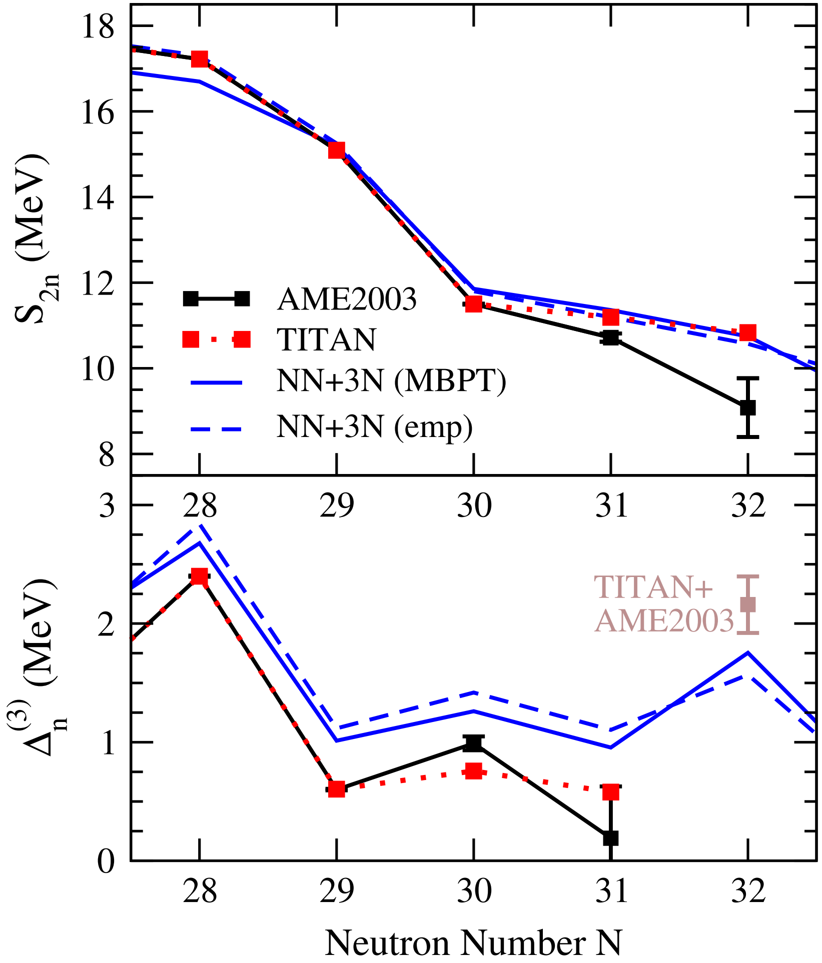
Weinberg, van Kolck, Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Machleidt, Meissner,…

new ^{51,52}Ca TITAN measurements

^{52}Ca is 1.74 MeV more bound compared to atomic mass evaluation

Gallant et al. (2012)

behavior of 2n separation energy S_{2n} agrees with NN+3N predictions



Frontier of ab-initio calculations at A~50

doi:10.1038/nature12226

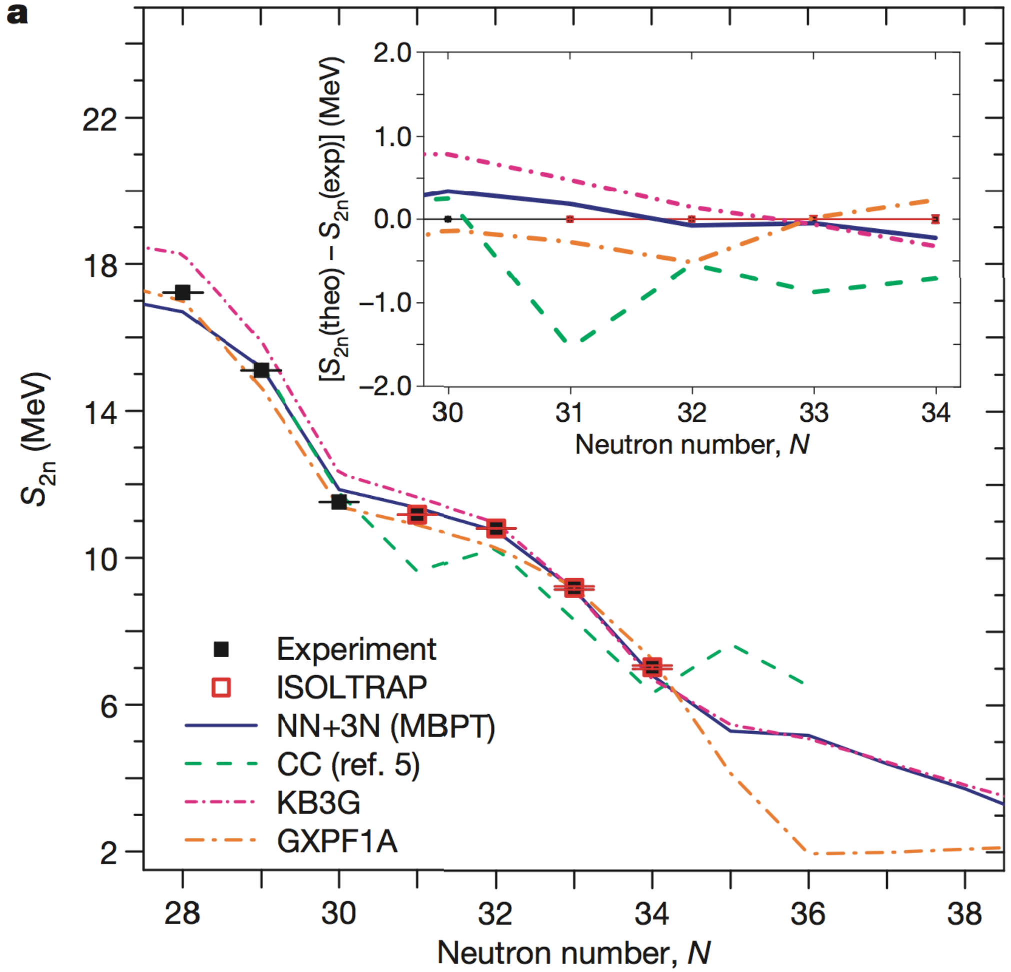
Masses of exotic calcium isotopes pin down nuclear forces

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]

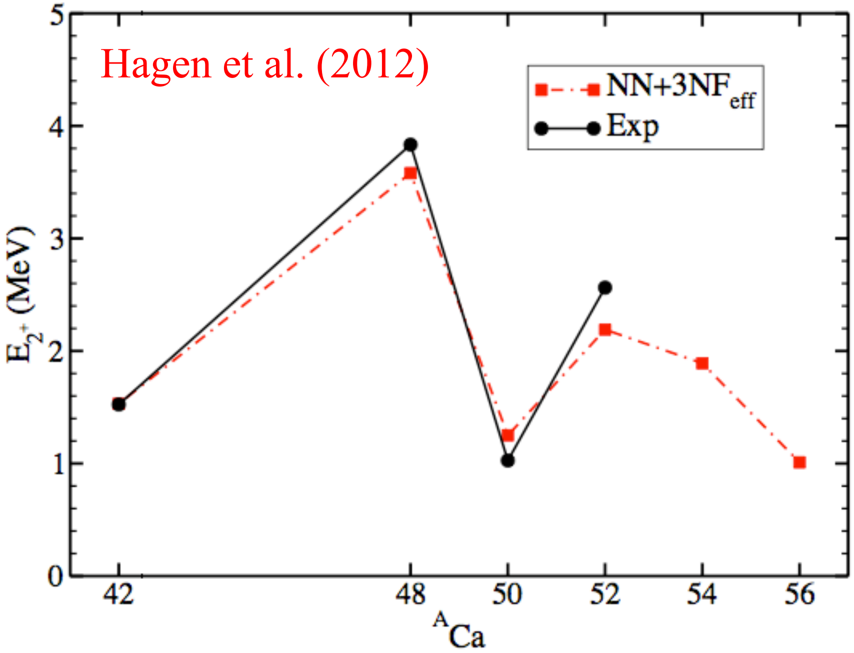
^{53,54}Ca masses measured at ISOLTRAP using new MR-TOF mass spectrometer

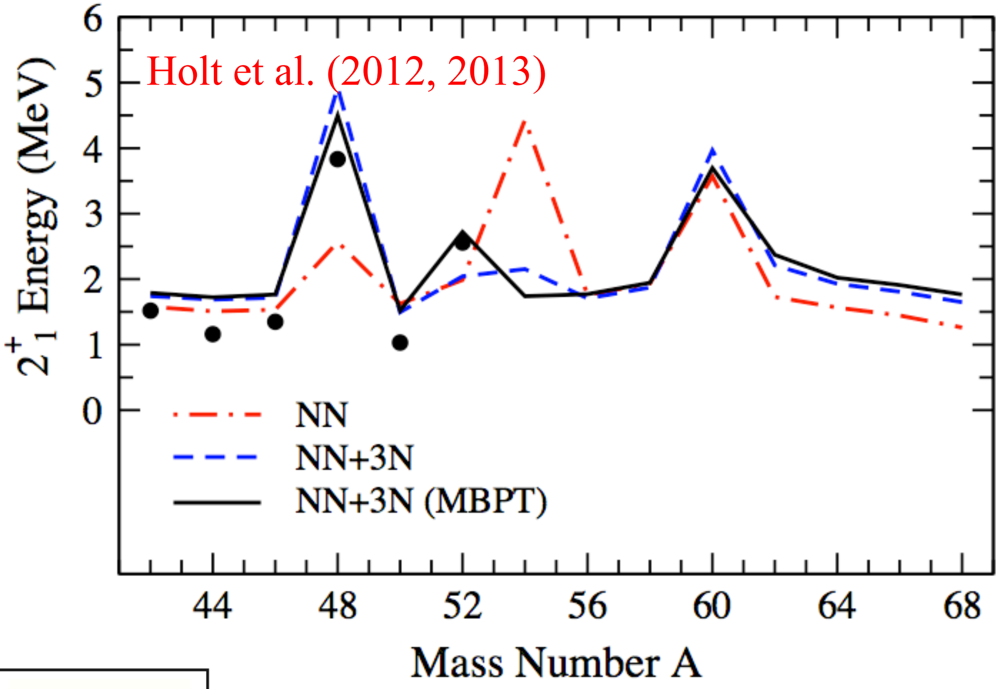
establish prominent N=32 shell closure in calcium

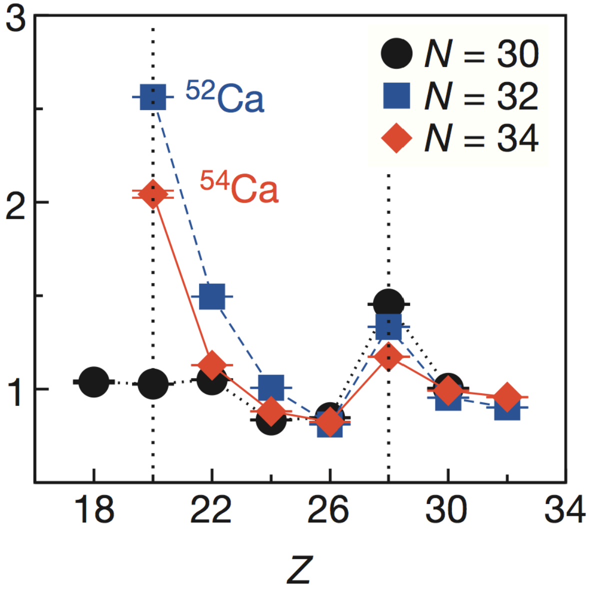
excellent agreement with theoretical NN+3N prediction



Three-body forces and magic numbers


Hagen et al. (2012)

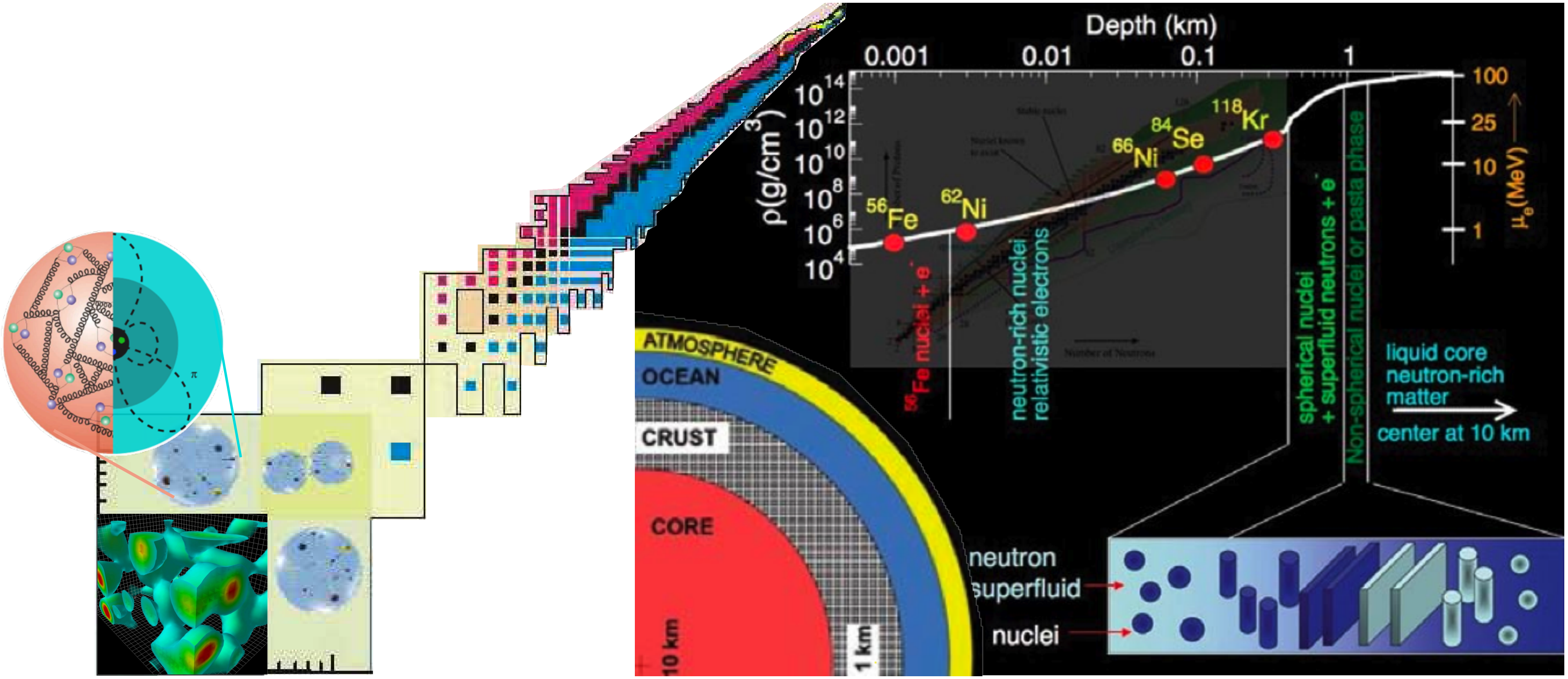

Holt et al. (2012, 2013)



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

Steppenbeck et al. (2013)

Neutron matter and neutron stars



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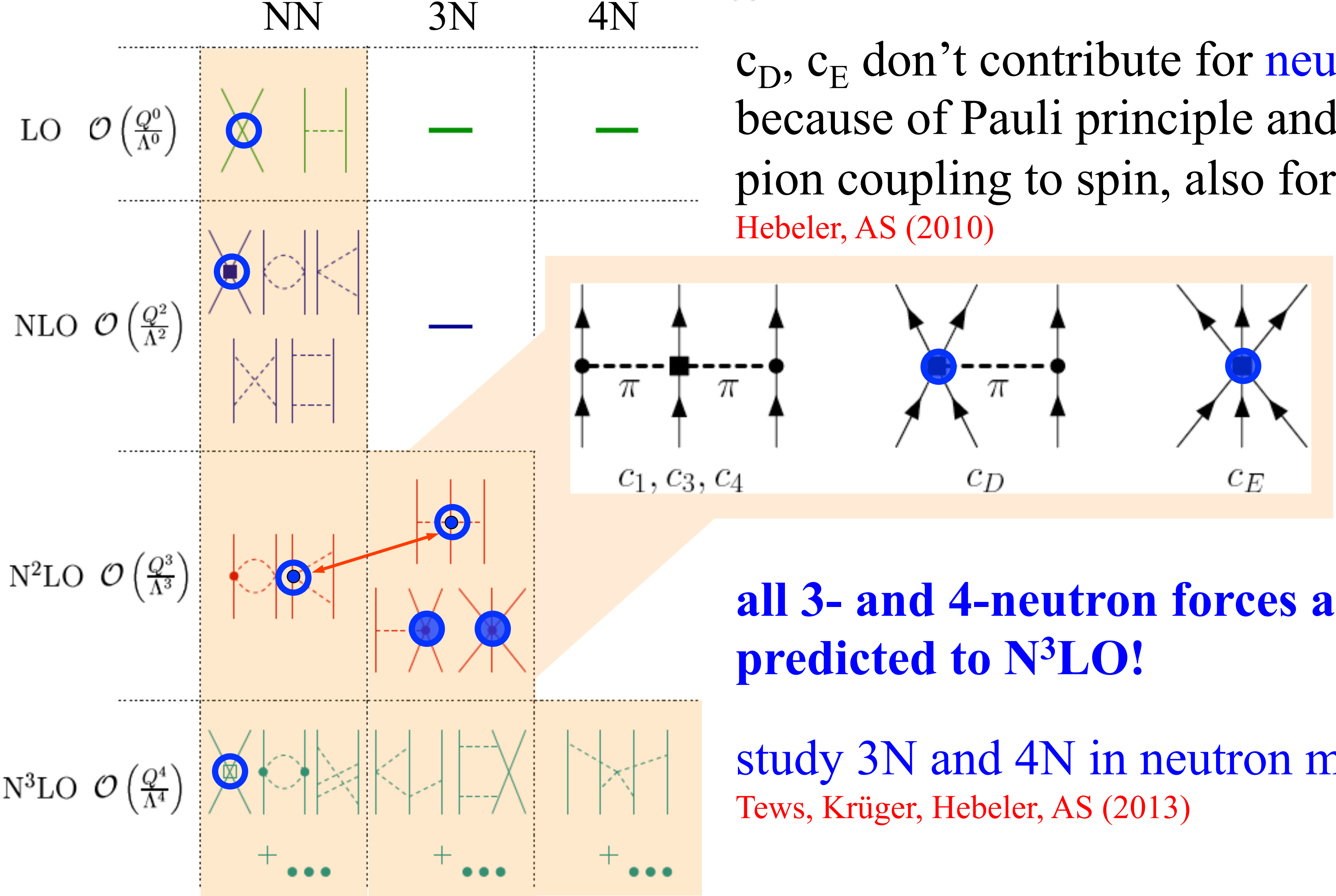


c_D, c_E don't contribute for neutrons because of Pauli principle and pion coupling to spin, also for c_4

Hebeler, AS (2010)

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

study 3N and 4N in neutron matter

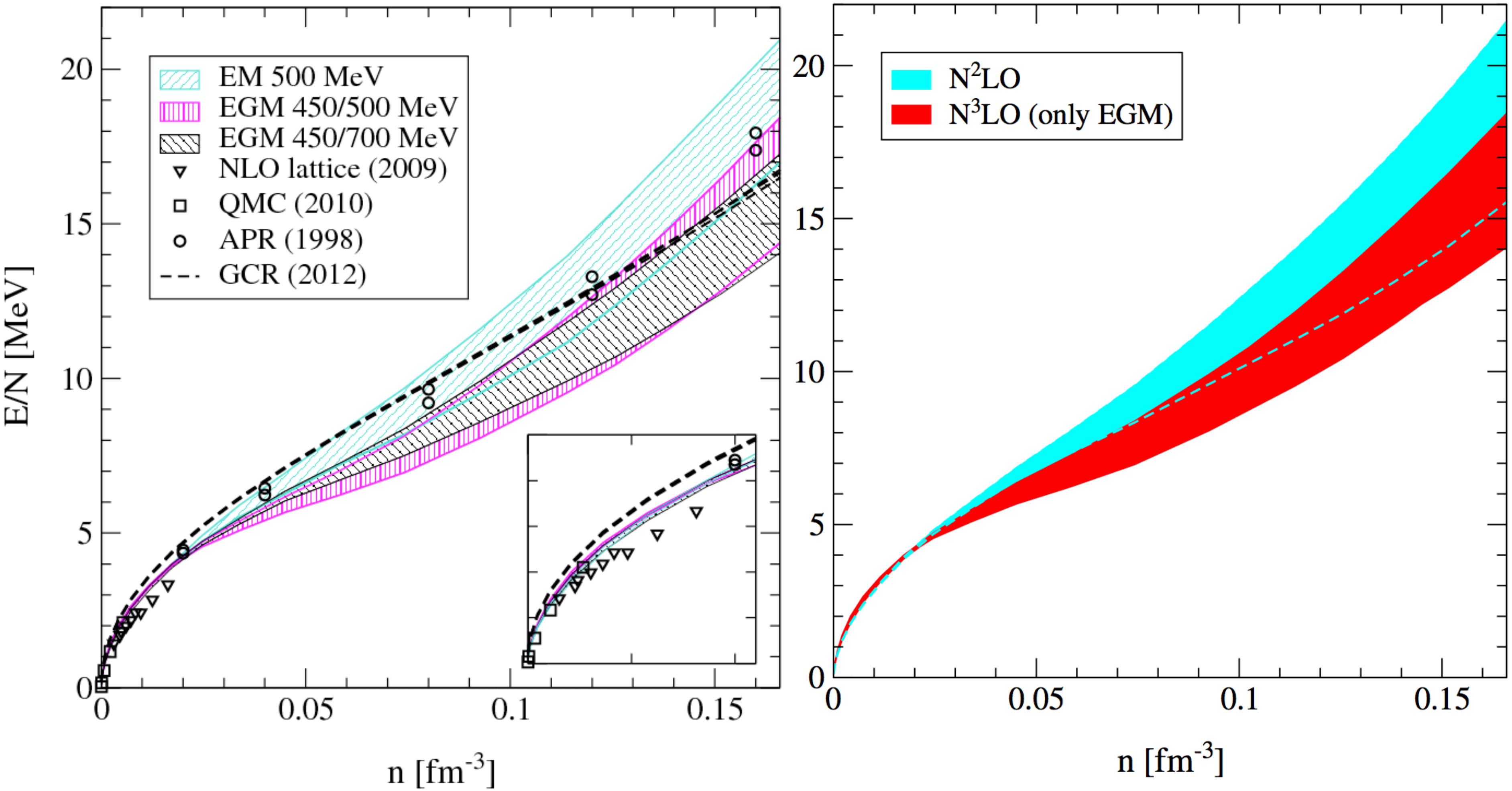
Tews, Krüger, Hebeler, AS (2013)

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

Complete N^3LO calculation of neutron matter

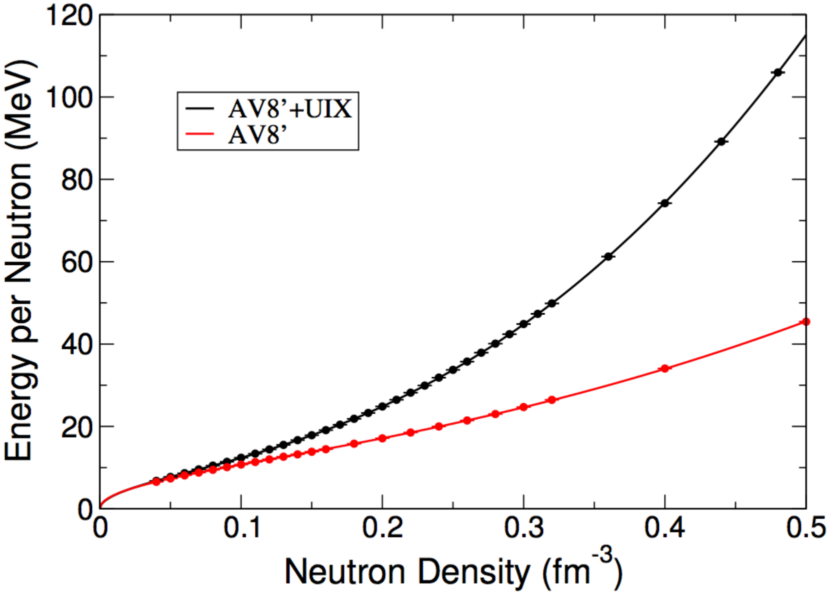
first complete N^3LO result **Tews, Krüger**, Hebeler, AS (2013)

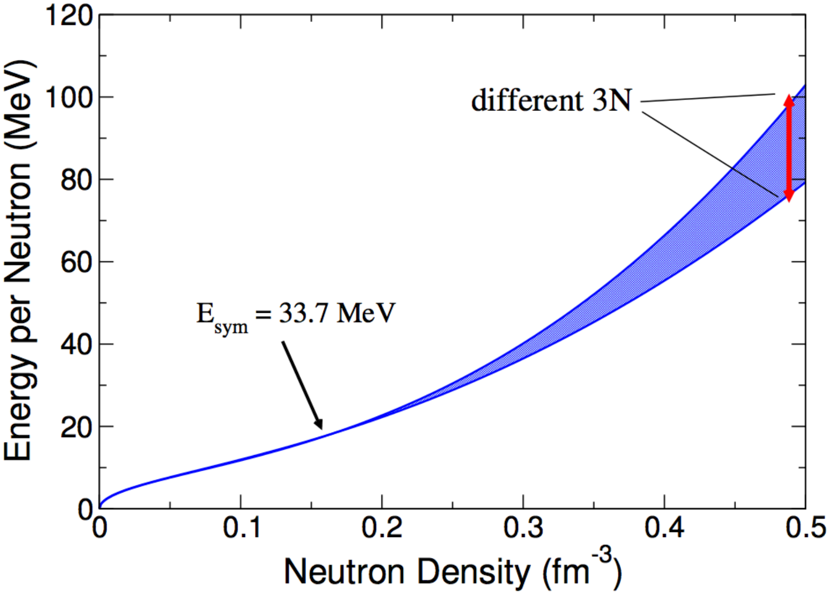
includes uncertainties from NN, 3N (dominates), 4N



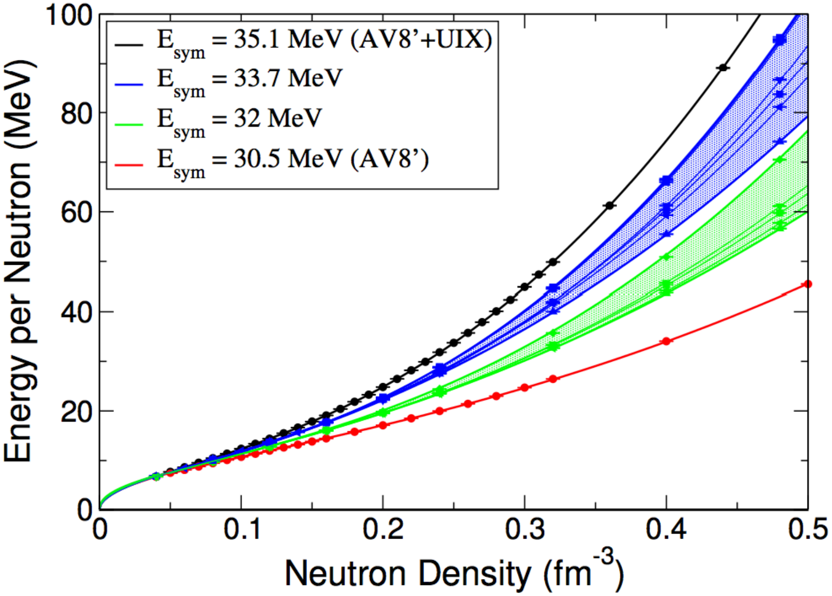
Other ab initio calculations

AFDMC based on AV8’ NN + UIX 3N potentials Gandolfi, Carlson, Reddy (2012)



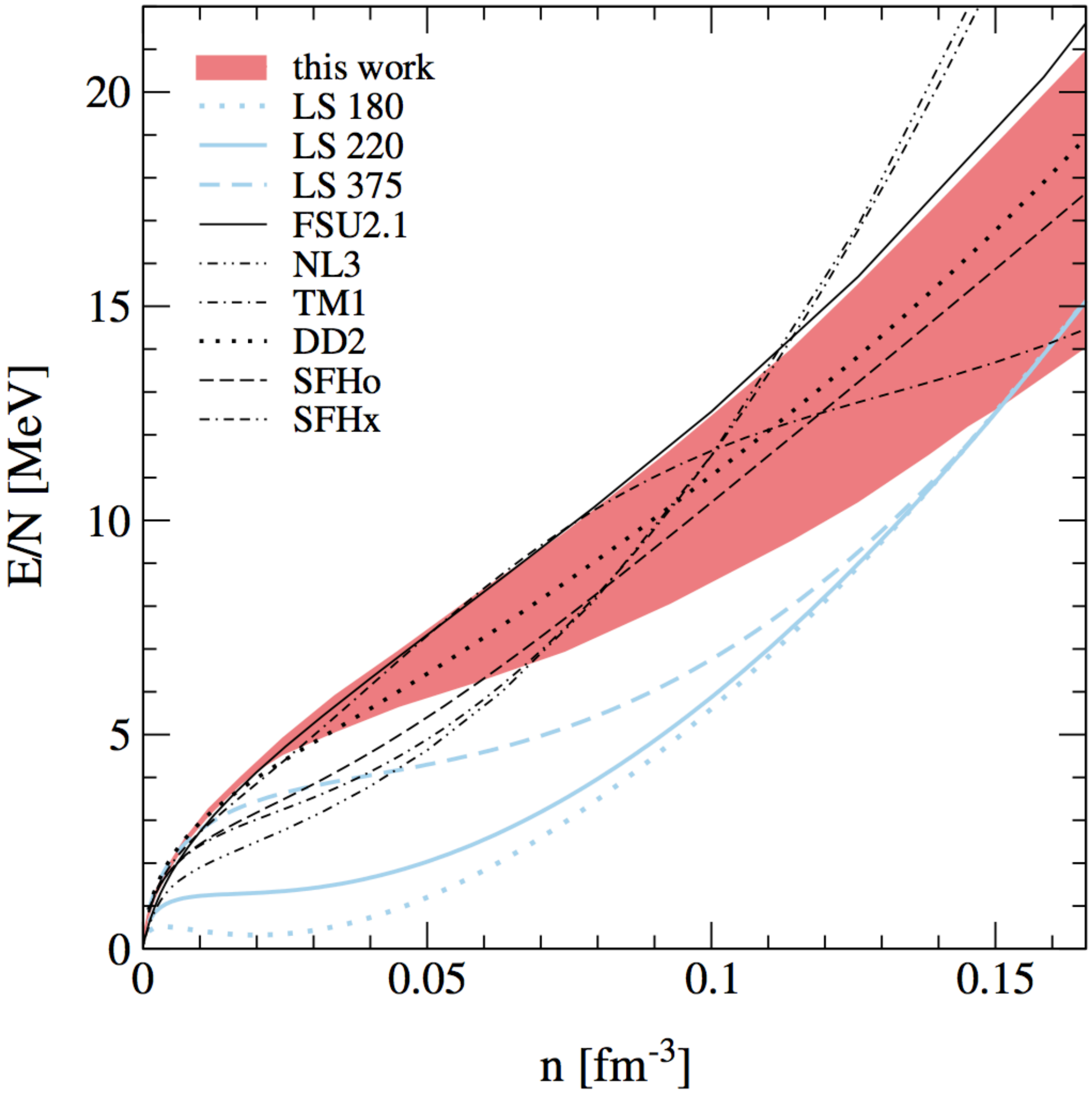


constructed different 3N forces
with symmetry energy range
between NN only and NN+3N



Comparisons to equations of state in astrophysics

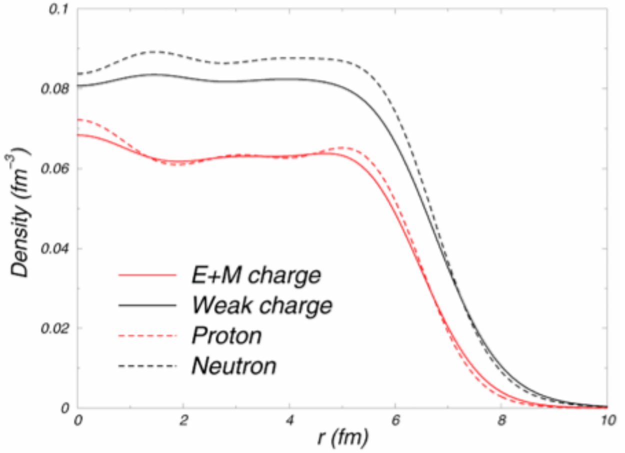
many equations of state used in supernova simulations not consistent with neutron matter results



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)



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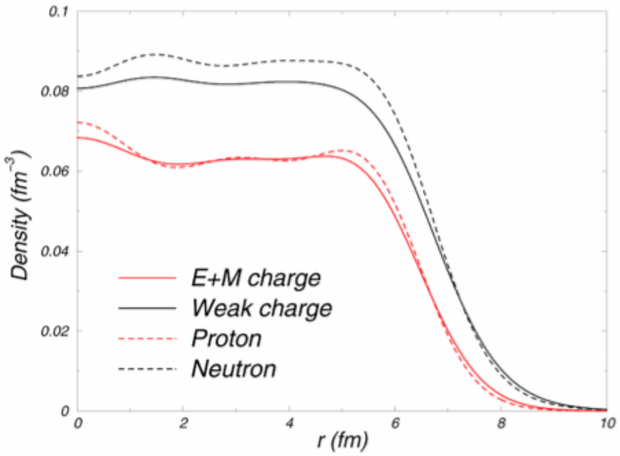
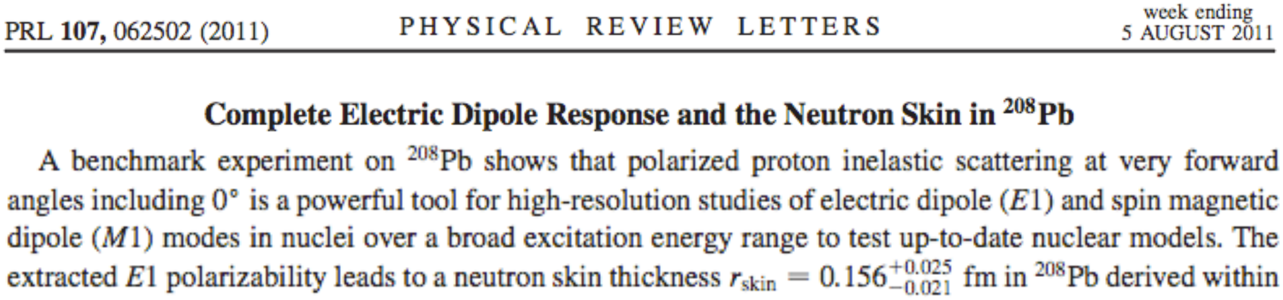


in excellent agreement with extraction from complete E1 response
0.156+0.025-0.021 fm

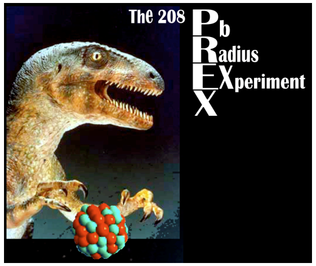


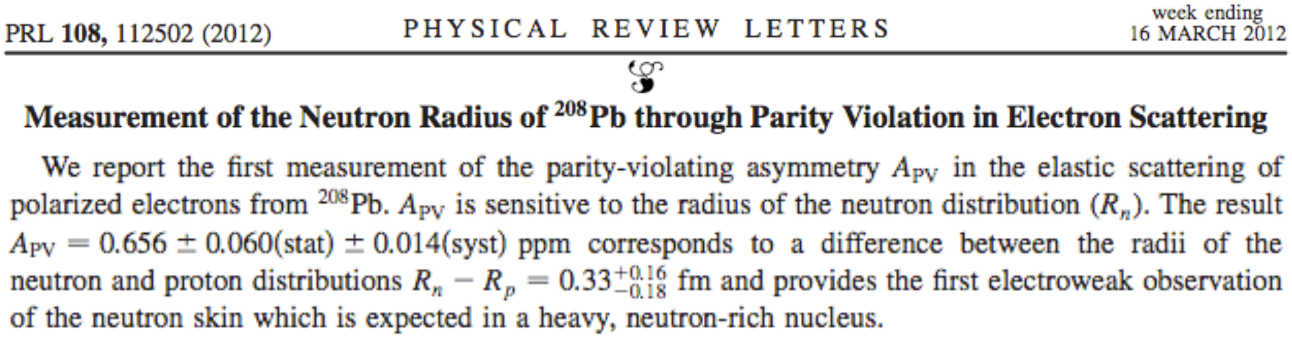
PRL **107,** 062502 (2011) PHYSICAL REVIEW LETTERS week ending 5 AUGUST 2011

Complete Electric Dipole Response and the Neutron Skin in ^{208}Pb

A benchmark experiment on ^{208}Pb shows that polarized proton inelastic scattering at very forward angles including 0° is a powerful tool for high-resolution studies of electric dipole ($E1$) and spin magnetic dipole ($M1$) modes in nuclei over a broad excitation energy range to test up-to-date nuclear models. The extracted $E1$ polarizability leads to a neutron skin thickness $r_{\text{skin}} = 0.156^{+0.025}_{-0.021}$ fm in ^{208}Pb derived within

PREX: neutron skin from parity-violating electron-scattering at JLAB
electron exchanges Z-boson, couples preferentially to neutrons
goal II: ±0.06 fm





PRL **108,** 112502 (2012) PHYSICAL REVIEW LETTERS week ending 16 MARCH 2012

Measurement of the Neutron Radius of ^{208}Pb through Parity Violation in Electron Scattering

We report the first measurement of the parity-violating asymmetry A_{PV} in the elastic scattering of polarized electrons from ^{208}Pb. A_{PV} is sensitive to the radius of the neutron distribution (R_n). The result $A_{\text{PV}} = 0.656 \pm 0.060(\text{stat}) \pm 0.014(\text{syst})$ ppm corresponds to a difference between the radii of the neutron and proton distributions $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm and provides the first electroweak observation of the neutron skin which is expected in a heavy, neutron-rich nucleus.

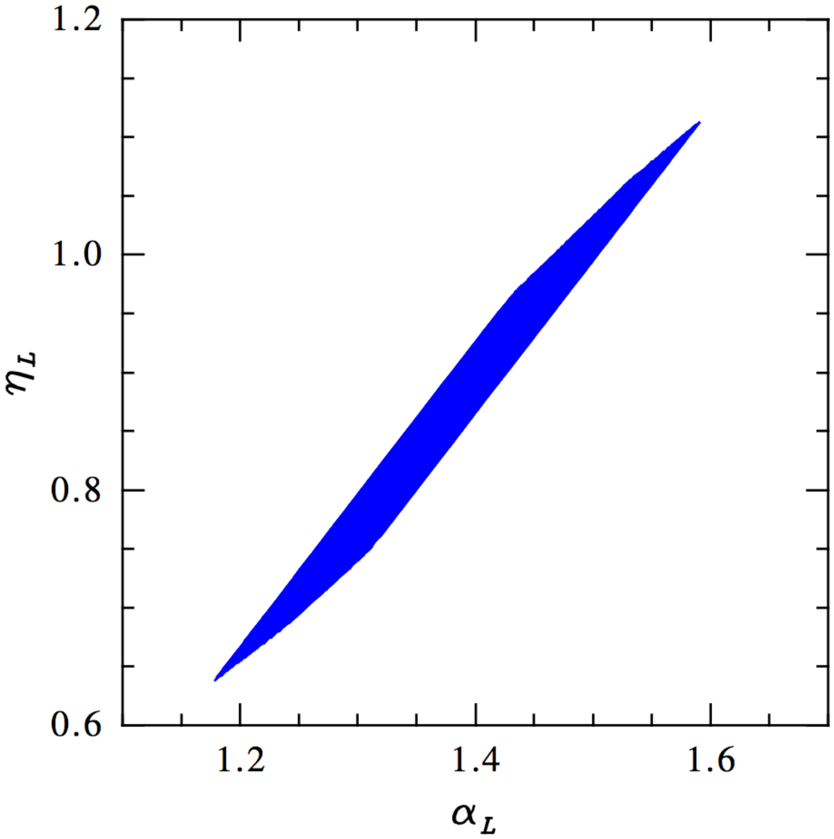
Symmetry energy and density derivative L

extract using empirical parametrization Hebeler, Lattimer, Pethick, AS (2013)

$$\frac{E(\overline{n},x)}{A} = T_0 \left[\frac{3}{5}\left(x^{\frac{5}{3}} + (1-x)^{\frac{5}{3}}\right)(2\overline{n})^{\frac{2}{3}} - \left((2\alpha - 4\alpha_L)\, x\, (1-x) + \alpha_L\right)\overline{n} + \left((2\eta - 4\eta_L)\, x\, (1-x) + \eta_L\right)\overline{n}^{\gamma} \right]$$

expansion in Fermi momentum (γ=4/3),
kinetic energy + quadratic asymmetry

α, η fit to empirical saturation point
α_L, η_L fit to neutron matter calculations



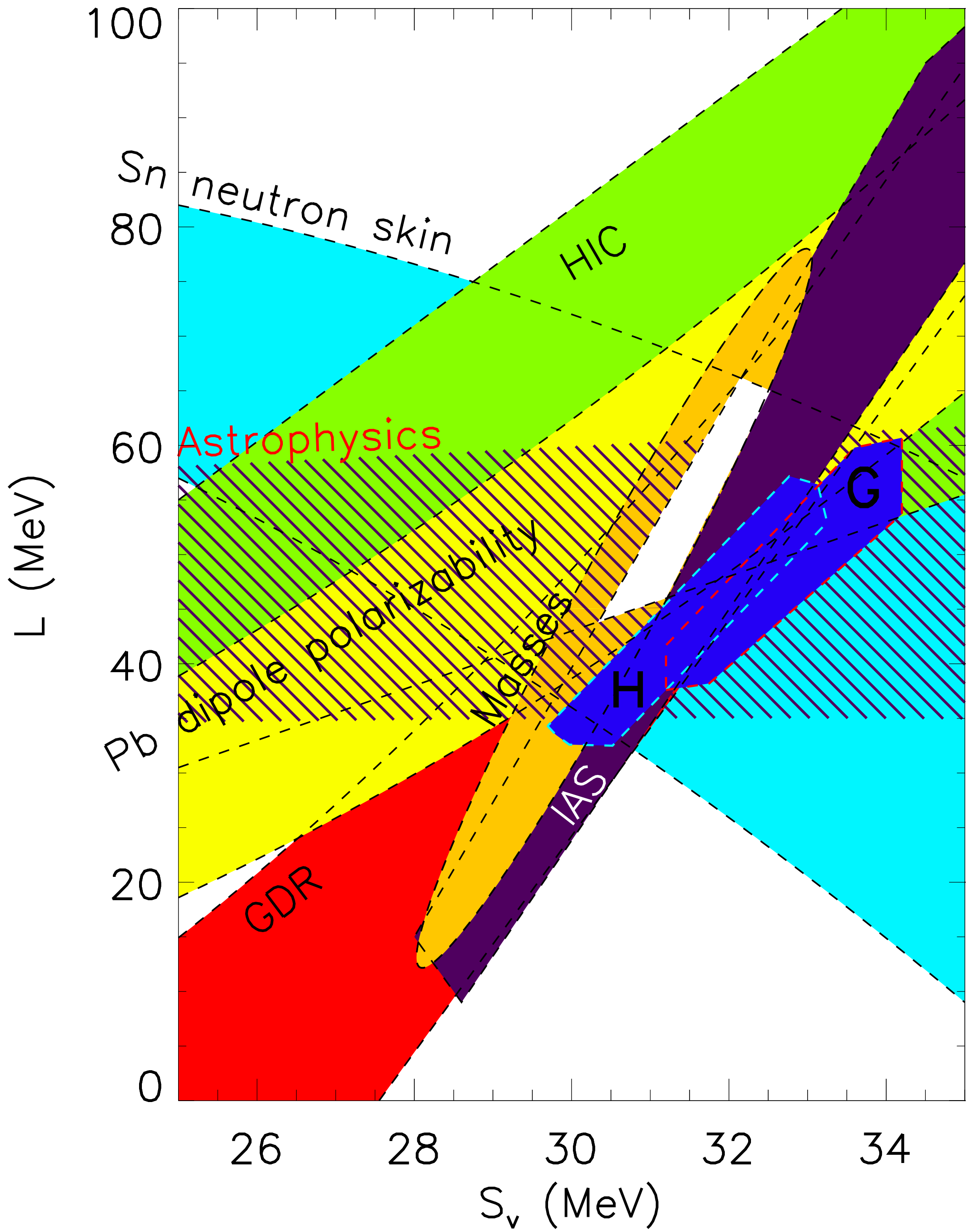
Symmetry energy and pressure of neutron matter

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!

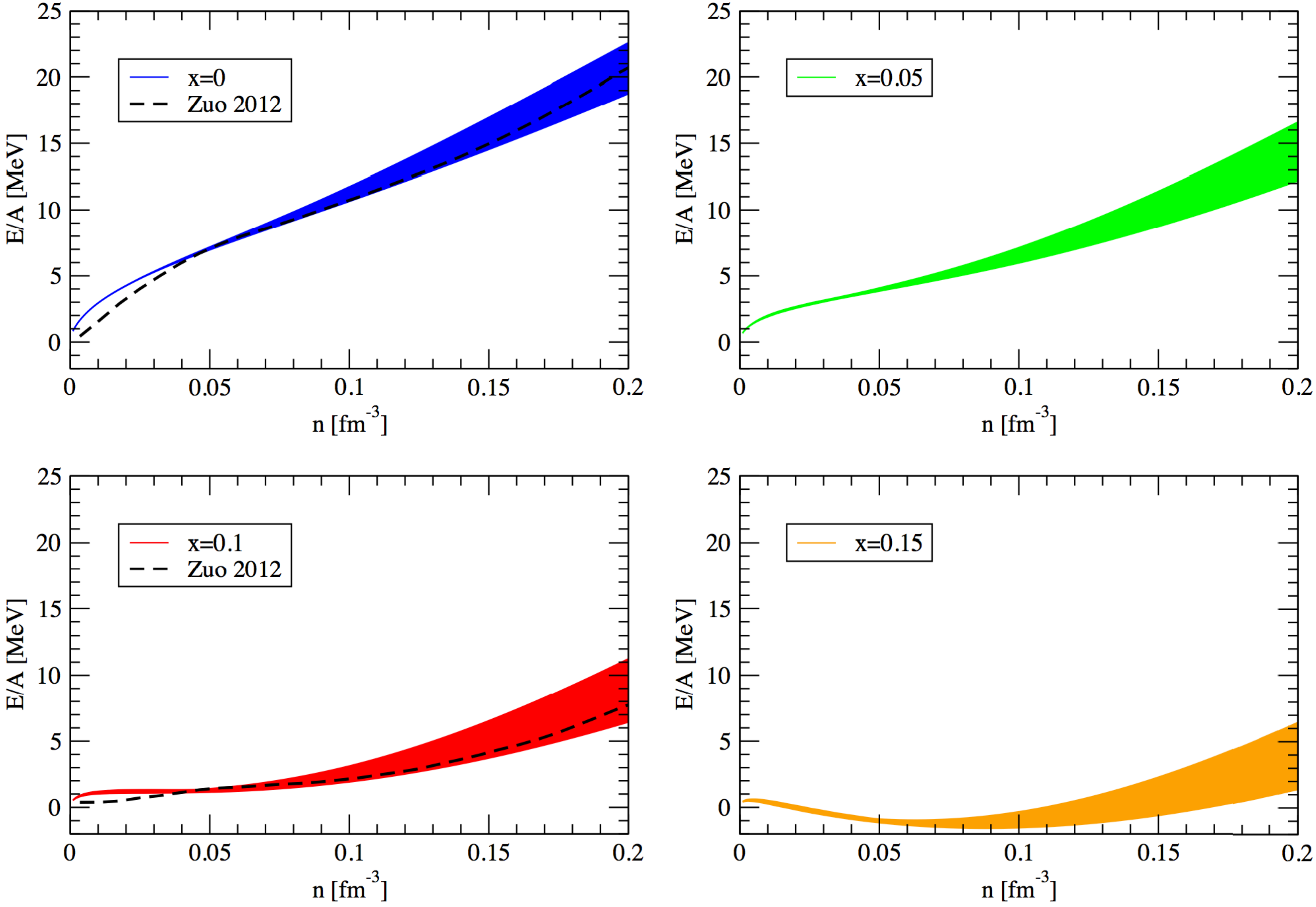
combined with Skyrme EDFs
predicts neutron skin
^{208}Pb: 0.182(10) fm
^{48}Ca: 0.173(5) fm
Brown, AS, PRC (2014)



Ab initio calculations of asymmetric matter

based on N^{3}LO NN + N^{2}LO 3N interactions **Drischler, Soma**, AS, PRC (2014)

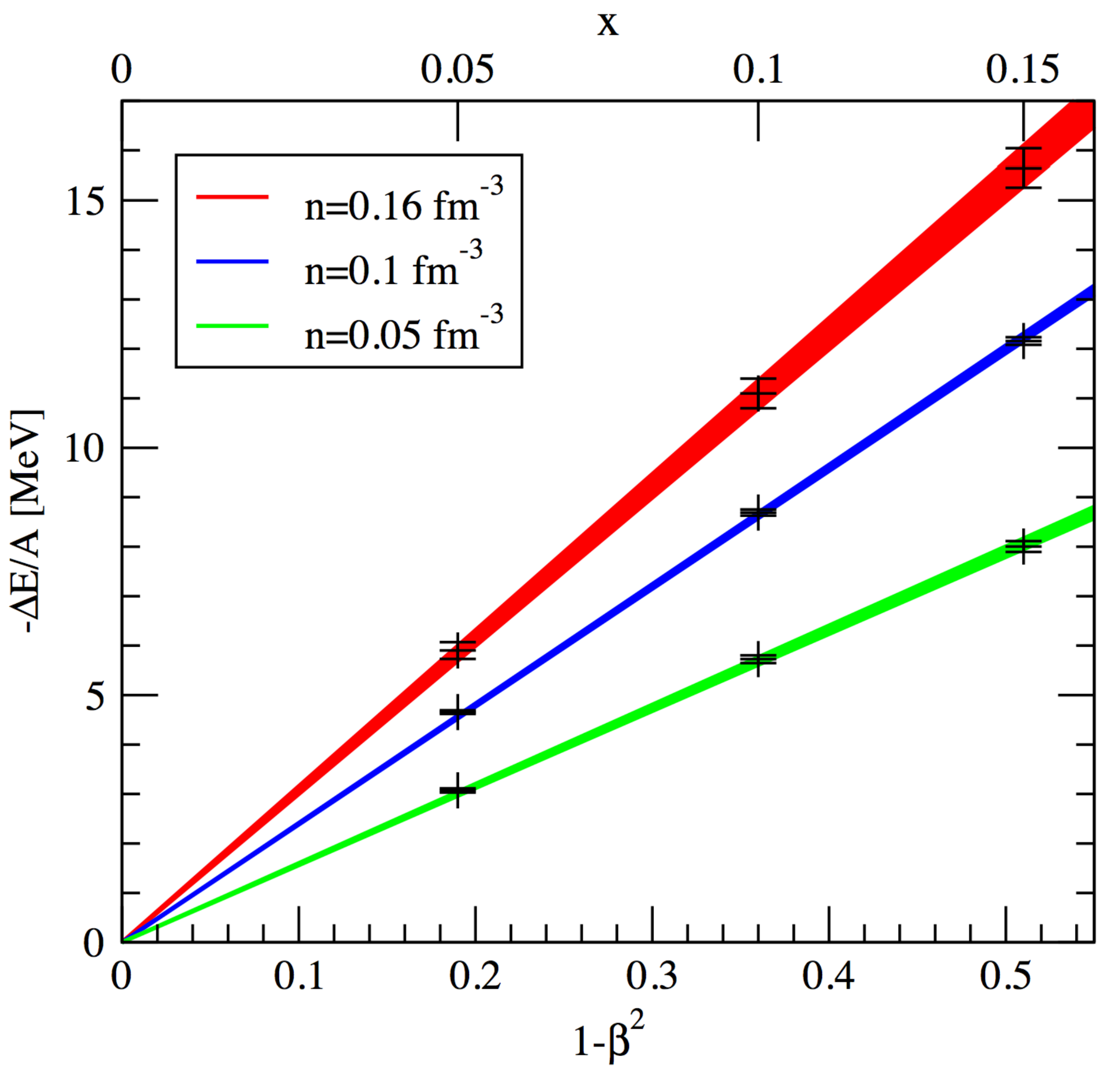
uncertainty band dominated by 3N



Ab-initio calculations of asymmetric matter

compares well with quadratic expansion even for n-rich conditions

$$\frac{E(n,\beta)}{A} = \frac{E(n,\beta=0)}{A} + E_{\rm sym}(n)\,\beta^2 + \mathcal{O}(\beta^4)$$

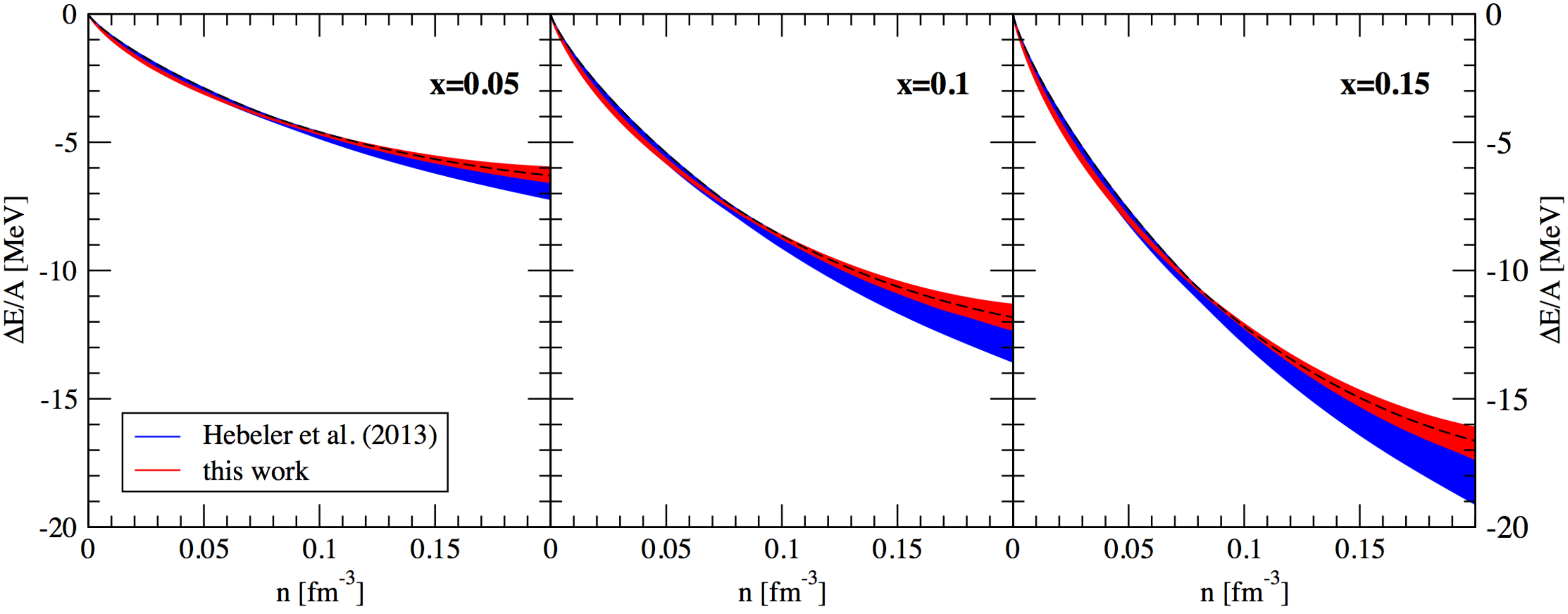


Ab-initio calculations of asymmetric matter

benchmark empirical parametrization: ΔE = diff. to neutron matter

good agreement with ab-initio calculations, very useful for astrophysics

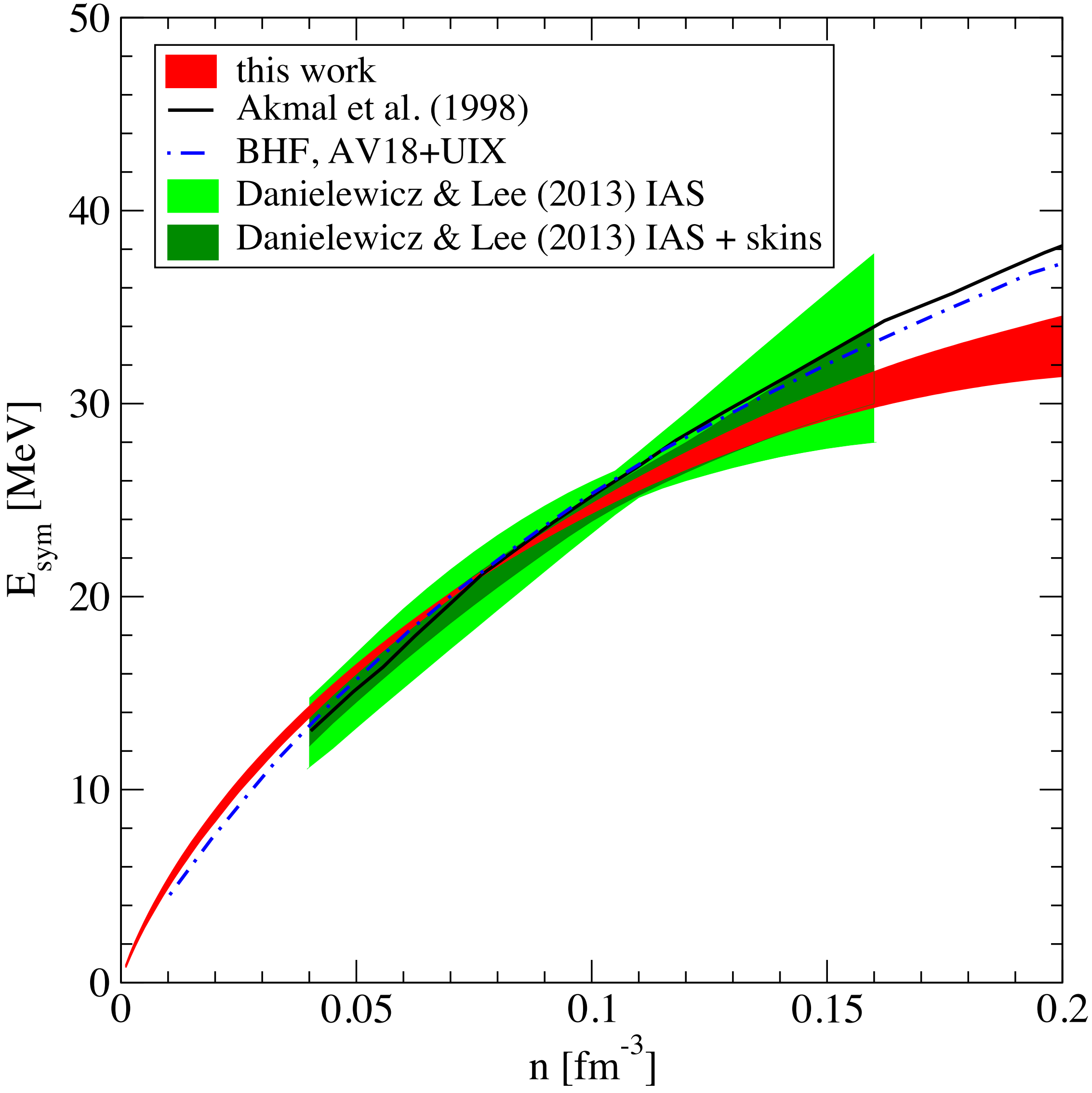
$$\begin{aligned}\frac{E(\overline{n},x)}{A} = T_0 \Bigg[& \frac{3}{5}\left(x^{\frac{5}{3}} + (1-x)^{\frac{5}{3}}\right)(2\overline{n})^{\frac{2}{3}} \\ & - \left((2\alpha - 4\alpha_L)\; x\;(1-x) + \alpha_L\right)\overline{n} \\ & + \left((2\eta - 4\eta_L)\; x\;(1-x) + \eta_L\right)\overline{n}^{\gamma}\Bigg]\end{aligned}$$



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

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

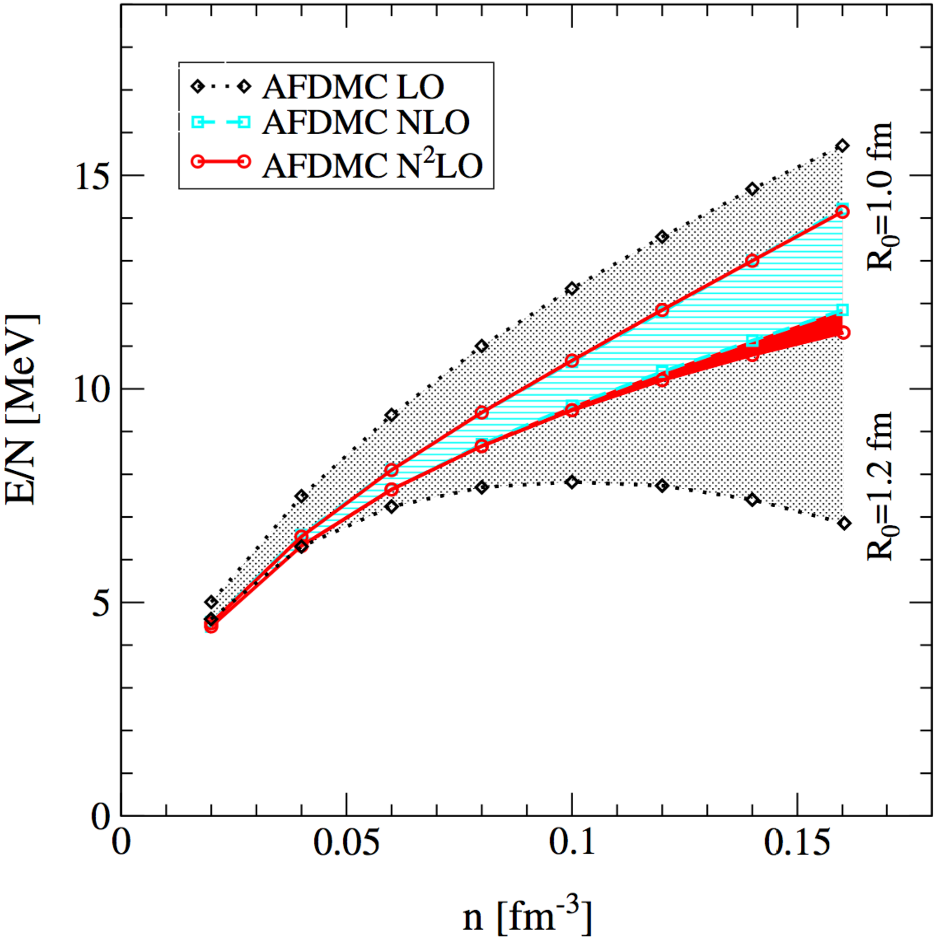
3N forces fit to ^{3}H, ^{4}He properties only



Quantum Monte Carlo for neutron matter

Gezerlis, Tews, et al., PRL (2013)
and arXiv:1406.0454

based on new local chiral EFT potentials,
order-by-order convergence up to saturation density



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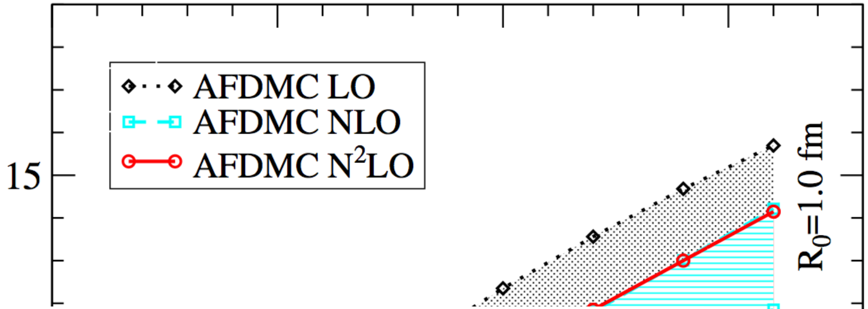

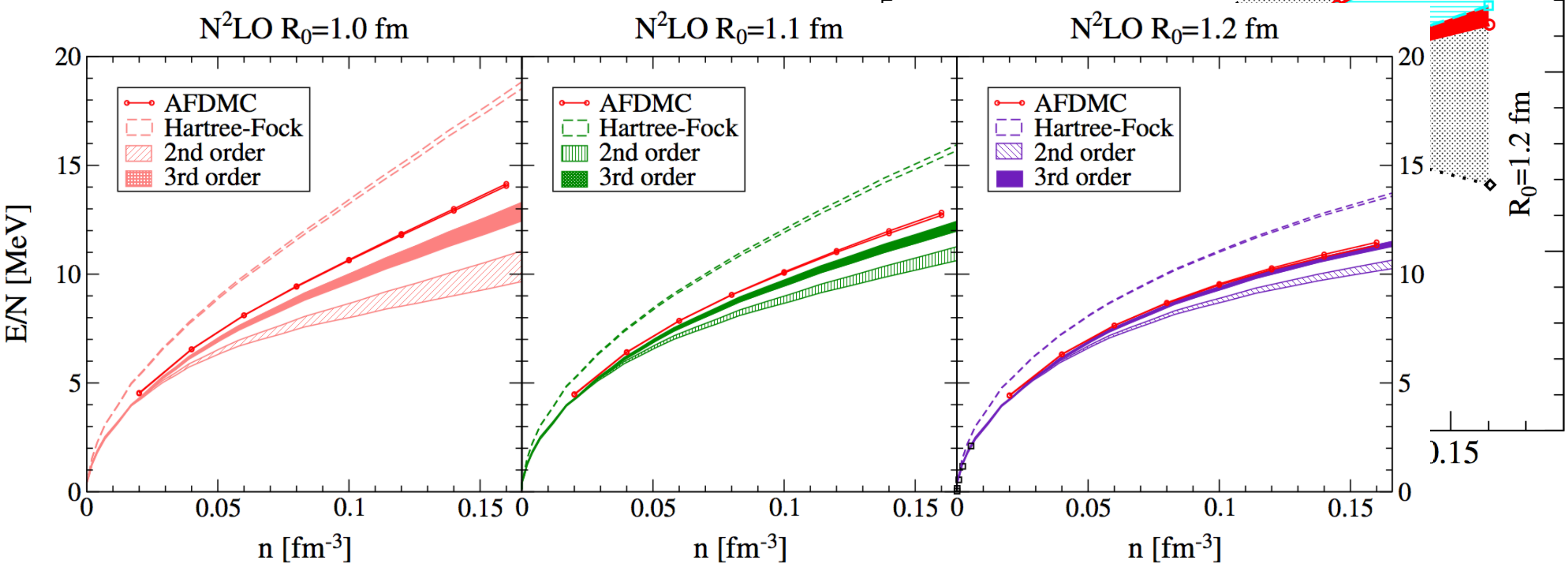

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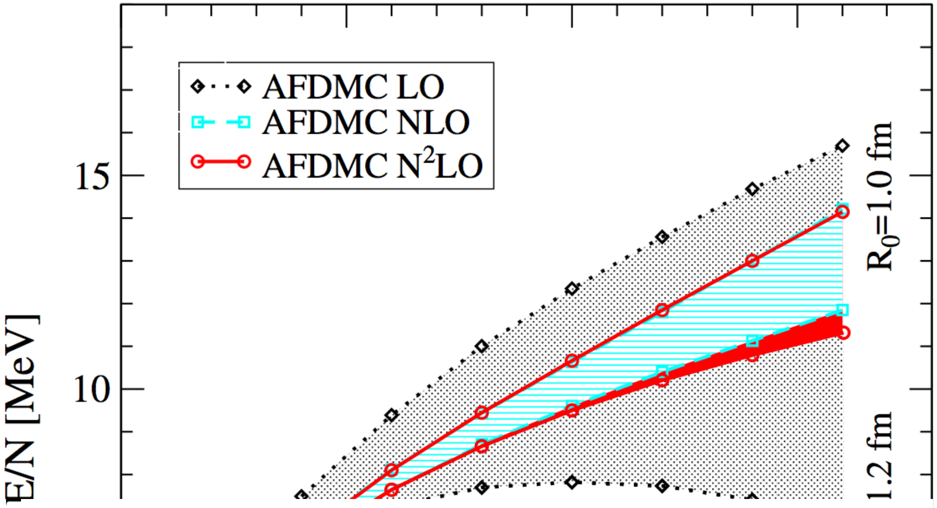
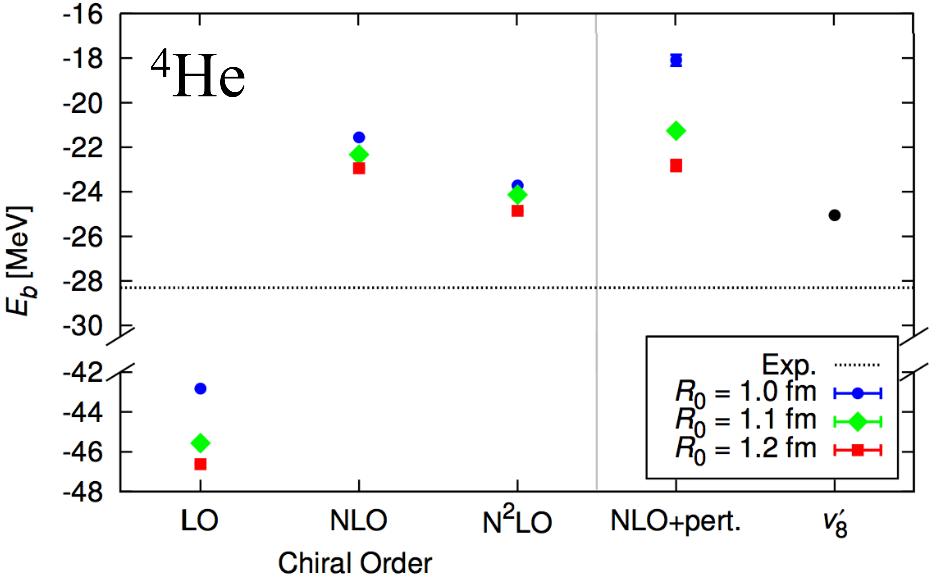
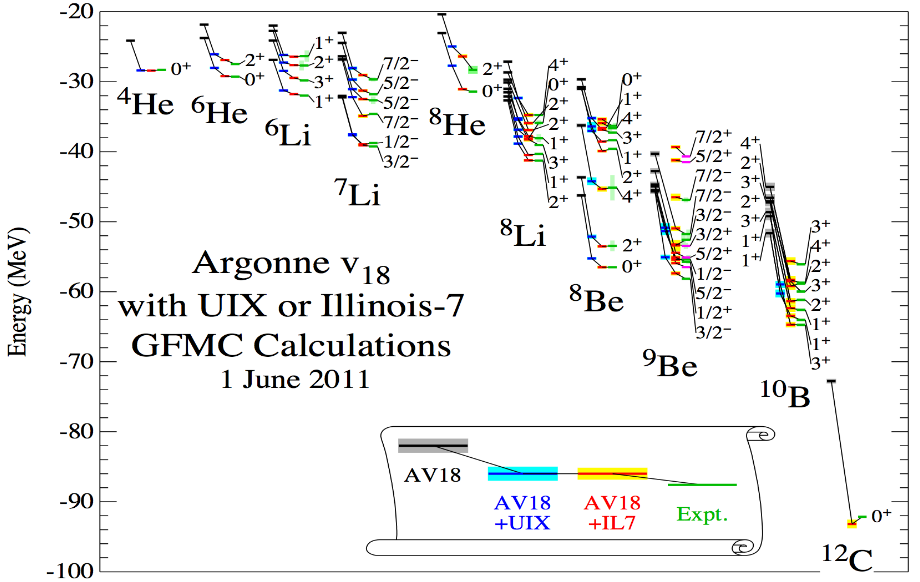


excellent agreement with perturbative calculations
for low cutoffs (~400 MeV)

light nuclei based on GFMC

Lynn et al., arXiv:1406.2718

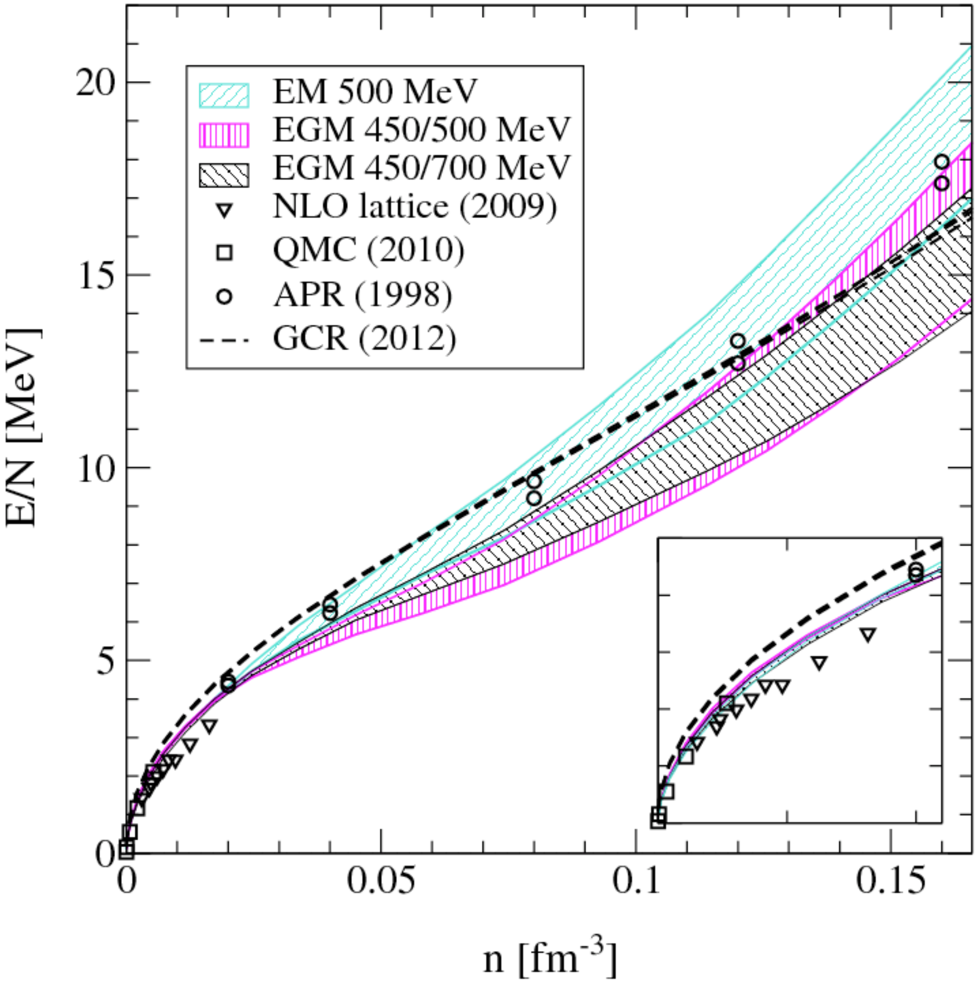


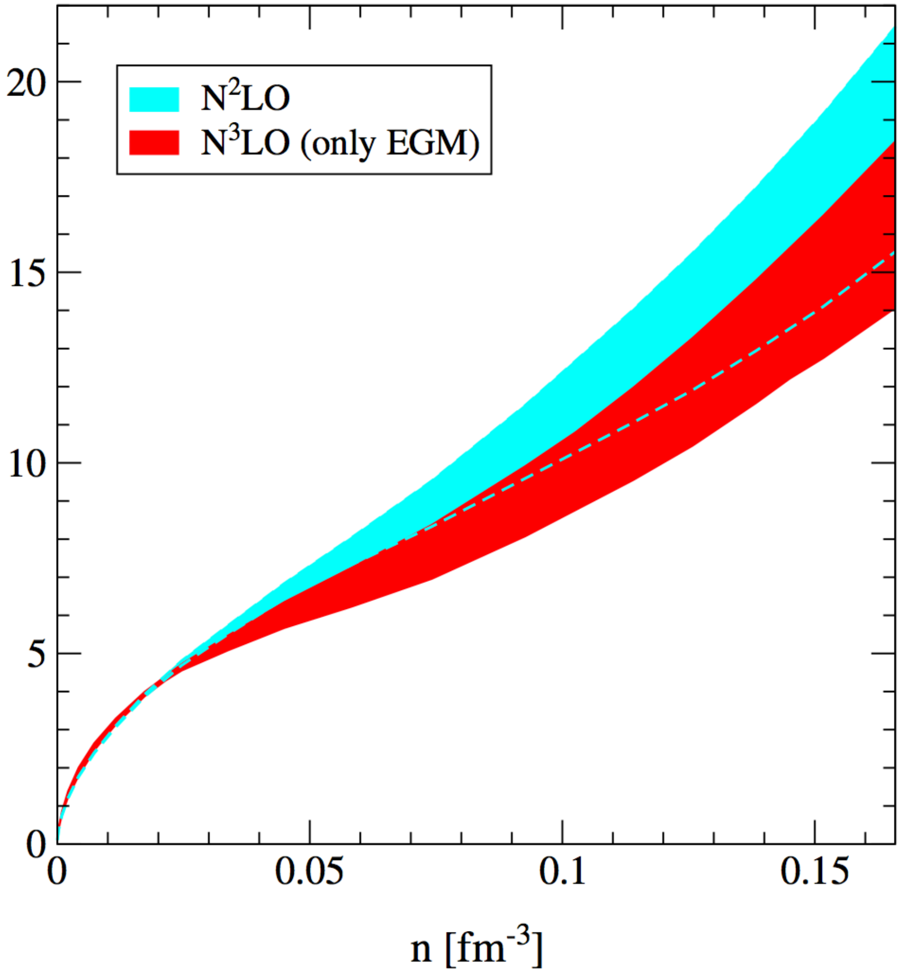


Complete N^{3}LO calculation of neutron matter

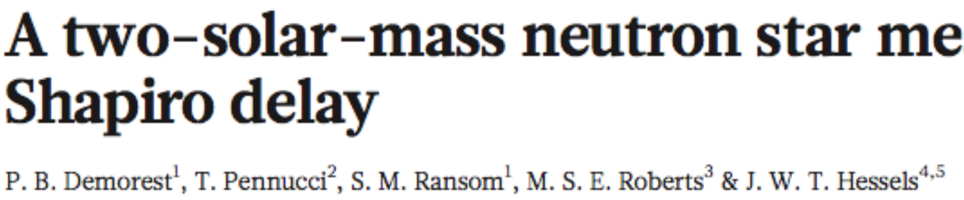
first complete N^{3}LO result Tews, Krüger, Hebeler, AS (2013)

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





Discovery of the heaviest neutron star



A two-solar-mass neutron star measured using Shapiro delay

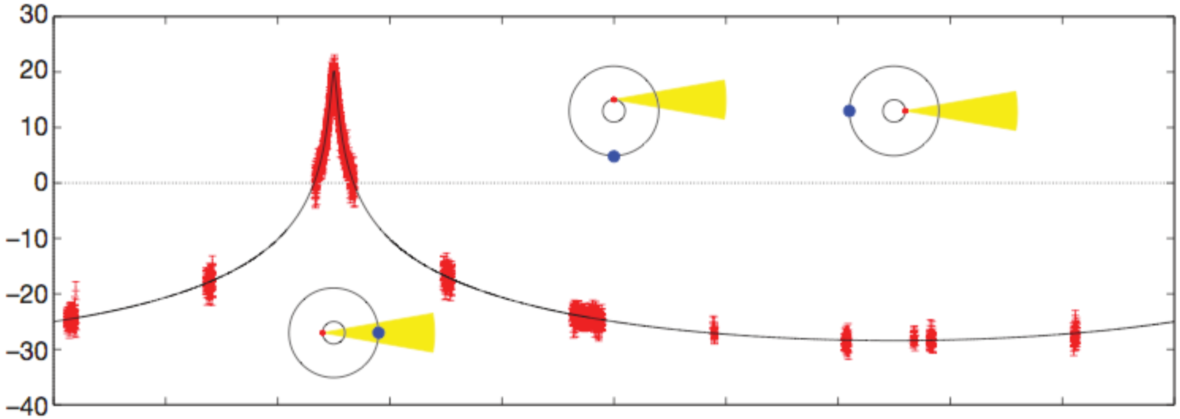
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

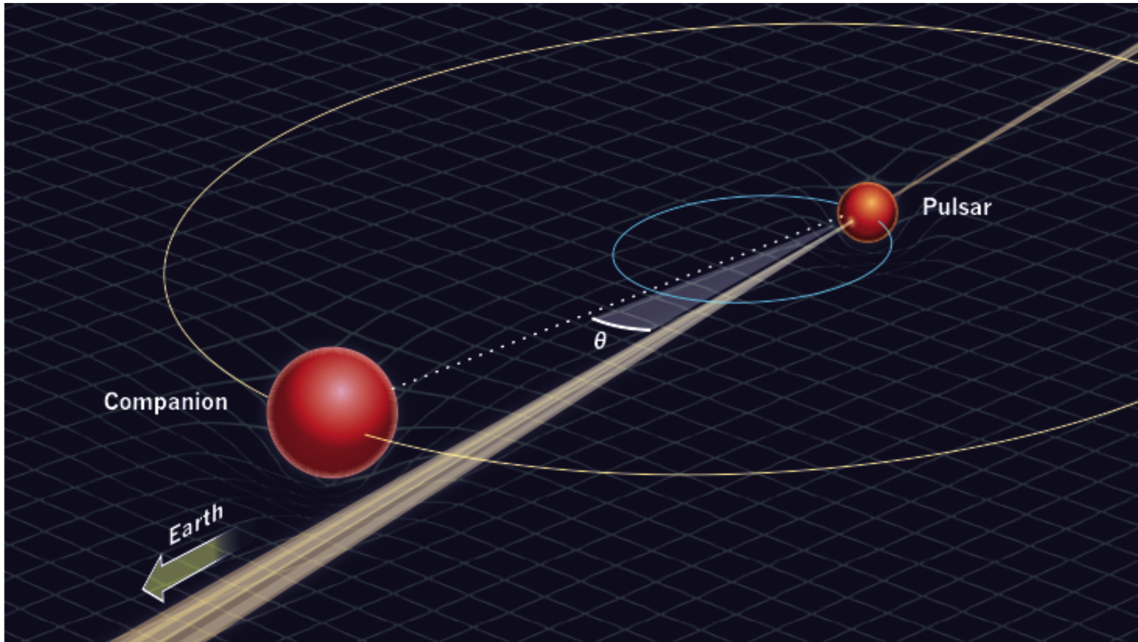
Nature (2010)

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

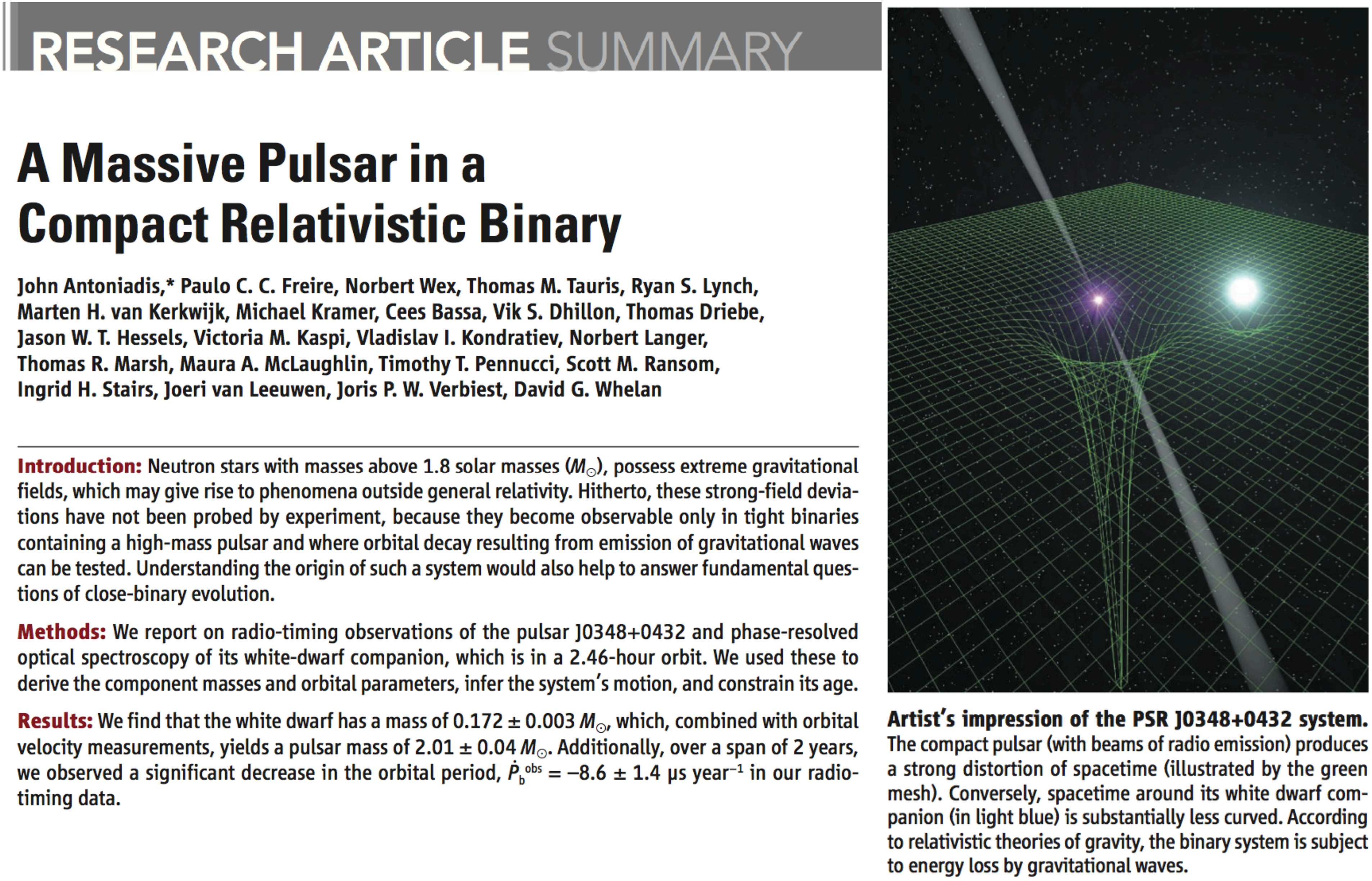
J1614-2230
most edge-on binary pulsar known (89.17°)
+ massive white dwarf companion (0.5 M_{sun})

heaviest neutron star with 1.97±0.04 M_{sun}





Discovery of the heaviest neutron star Science (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.

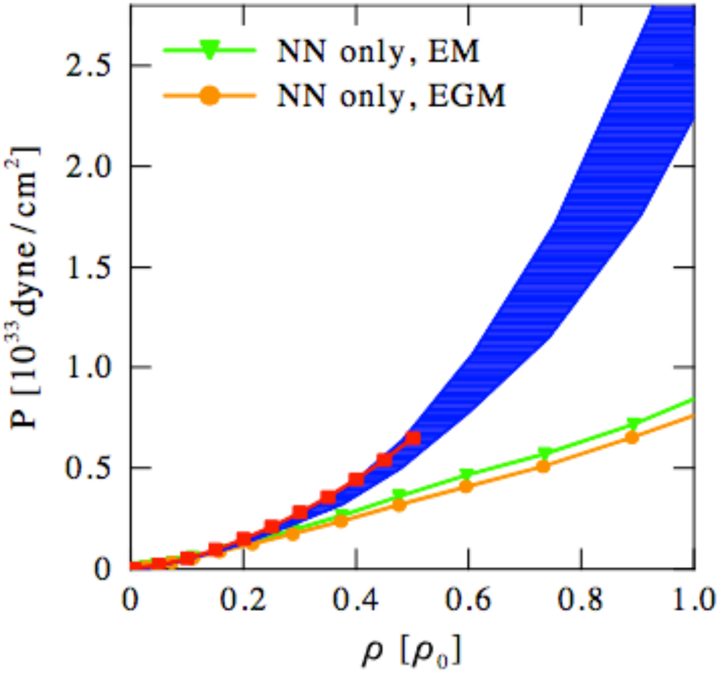
Methods: We report on radio-timing observations of the pulsar J0348+0432 and phase-resolved optical spectroscopy of its white-dwarf companion, which is in a 2.46-hour orbit. We used these to derive the component masses and orbital parameters, infer the system's motion, and constrain its age.

Results: We find that the white dwarf has a mass of 0.172 ± 0.003 $M_\odot$, which, combined with orbital velocity measurements, yields a pulsar mass of 2.01 ± 0.04 $M_\odot$. Additionally, over a span of 2 years, we observed a significant decrease in the orbital period, $\dot{P}_b^{obs} = -8.6 \pm 1.4$ μs 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 (2010, 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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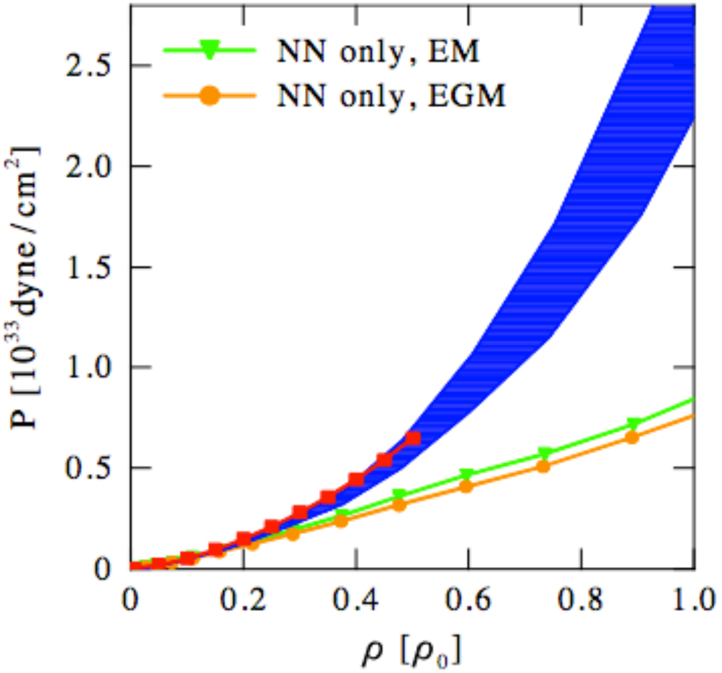
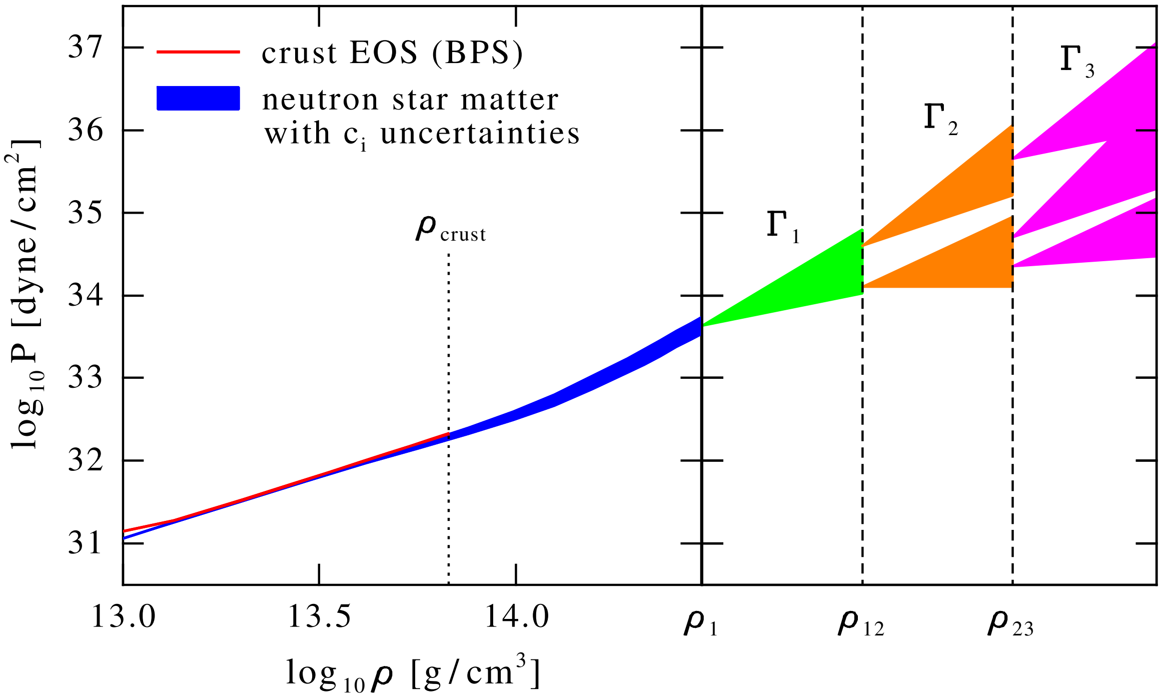


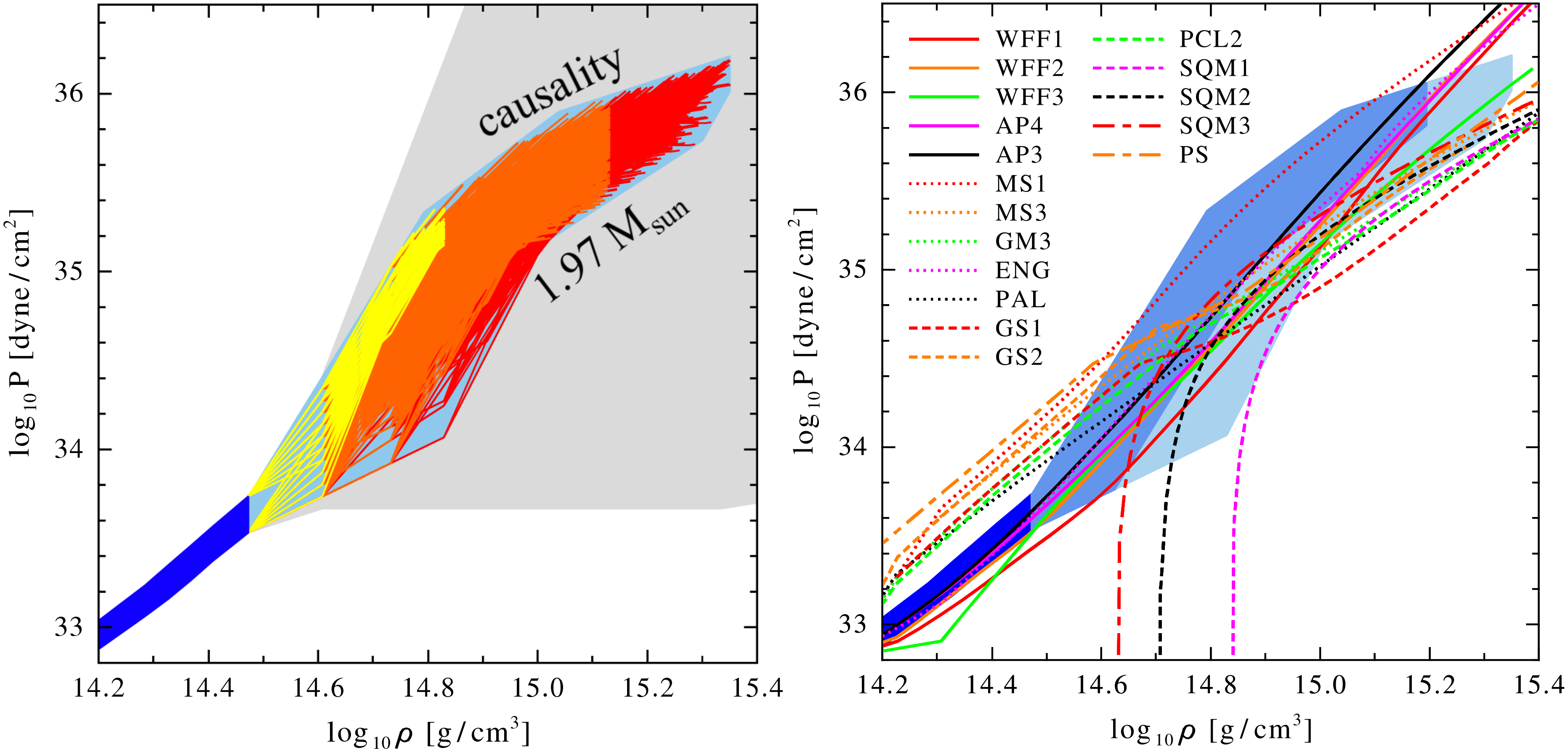


pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

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

Pressure of neutron star matter

constrain polytropes by causality and require to support 1.97 M_{sun} star



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

Pressure of neutron star matter

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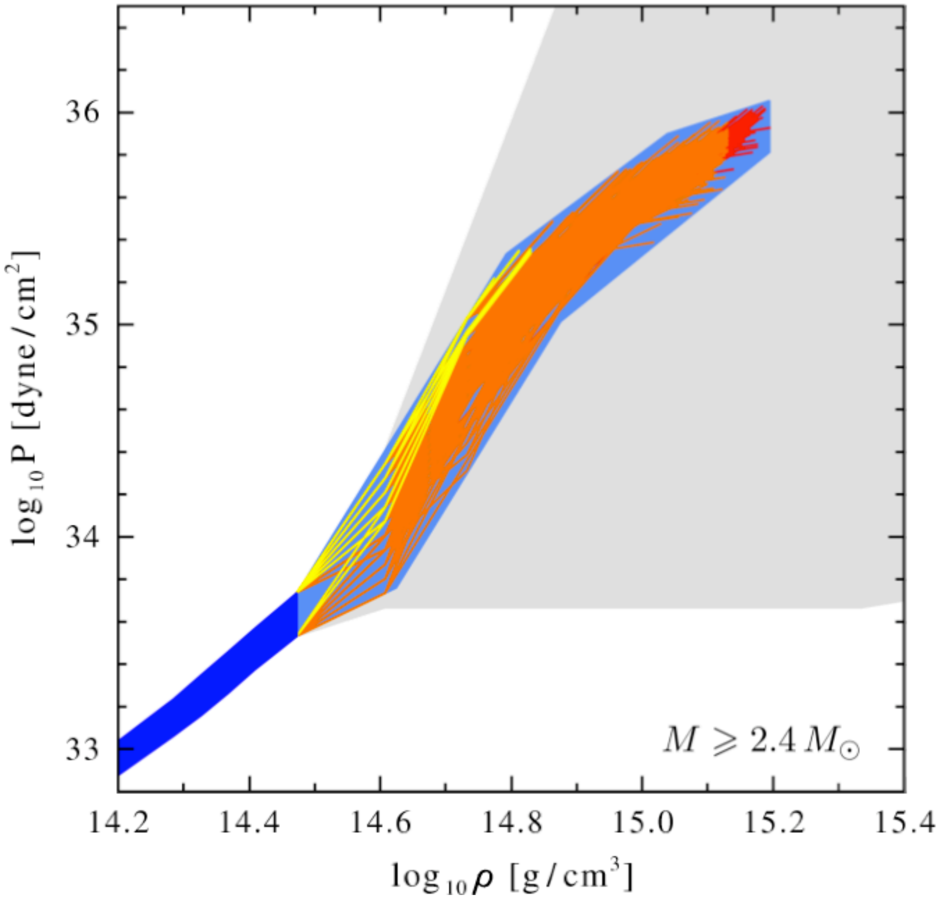
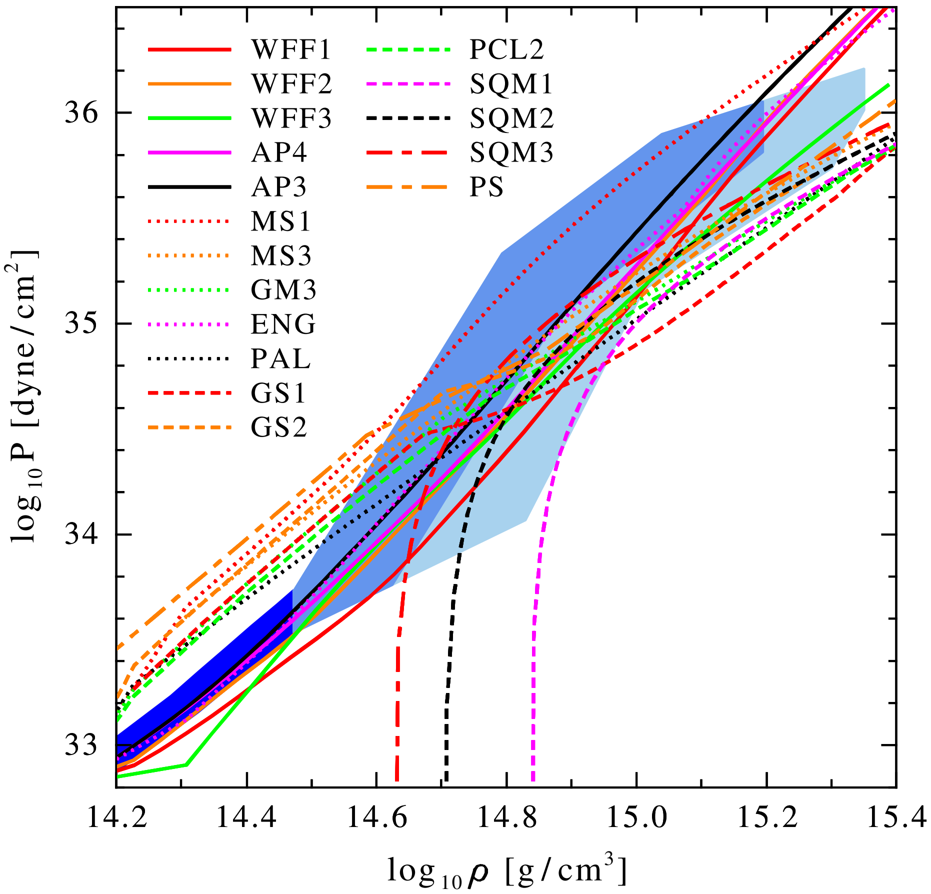


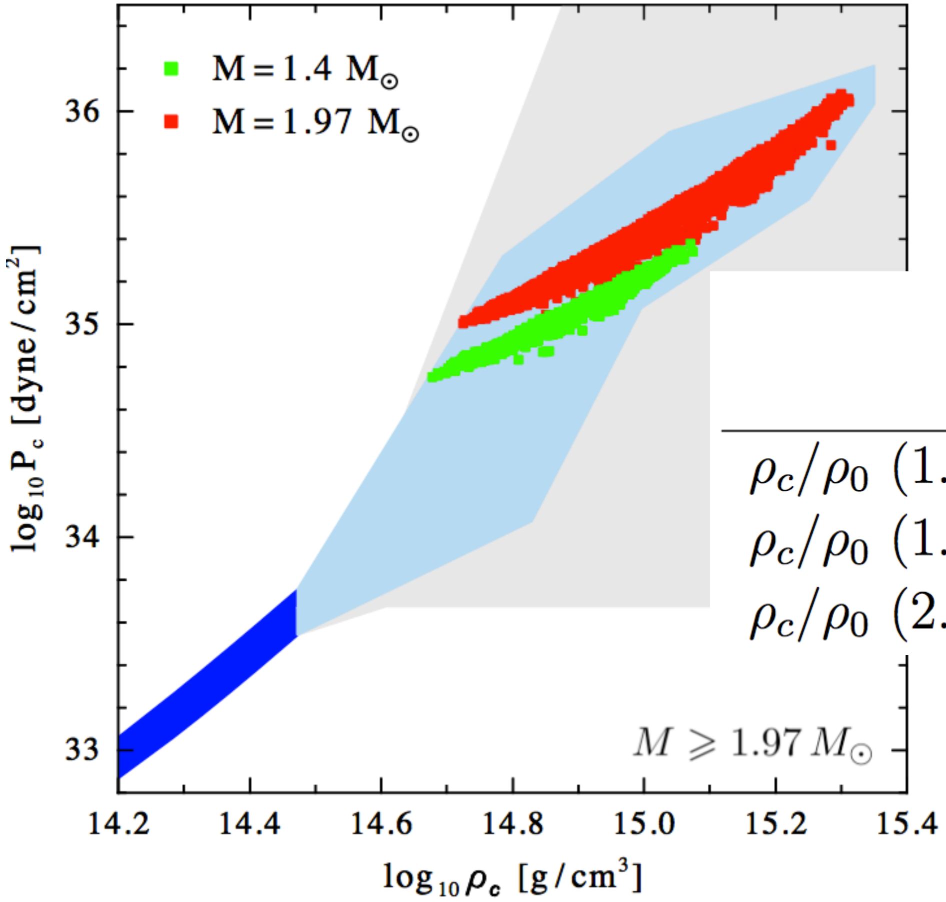


low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

darker blue band for 2.4 M_{sun} star

Pressure of neutron star matter

constrain polytropes by causality and require to support 1.97 M_{sun} star



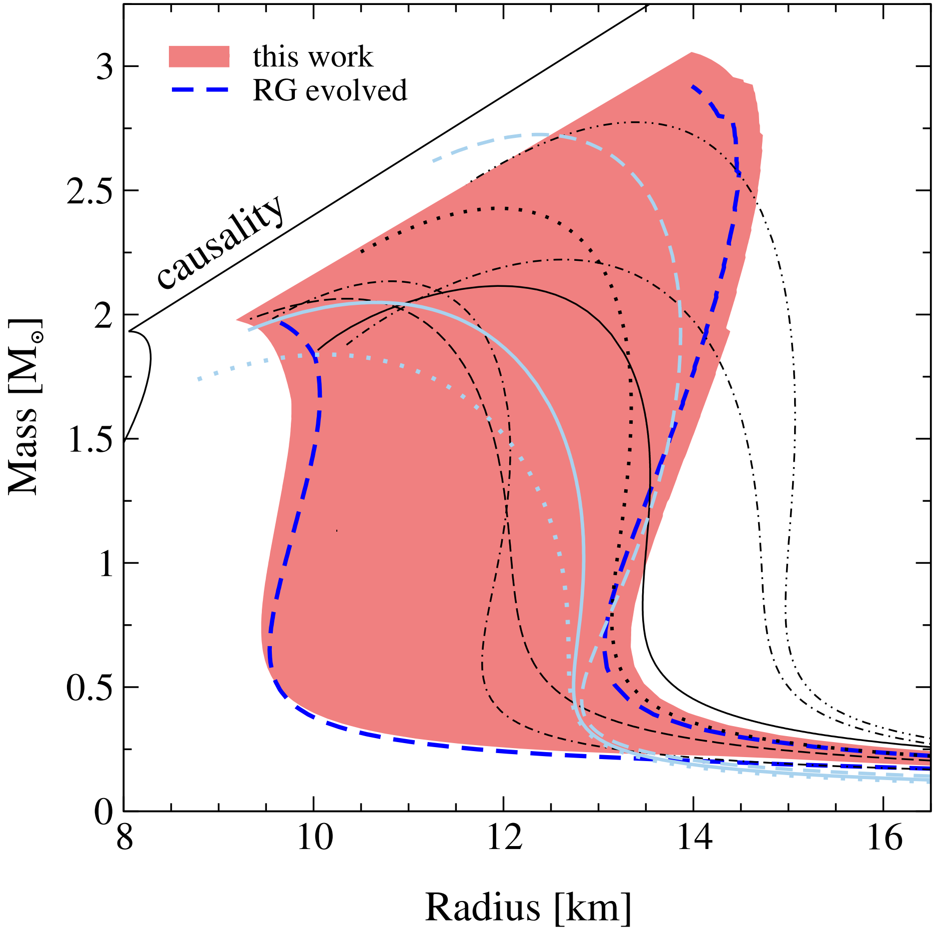
	$\widehat{M} = 1.97\, M_\odot$		$\widehat{M} = 2.4\, M_\odot$	
	min	max	min	max
ρ_c/ρ_0 $(1.4\, M_\odot)$	1.8	4.4	1.8	2.7
ρ_c/ρ_0 $(1.97\, M_\odot)$	2.0	7.6	2.0	3.4
ρ_c/ρ_0 $(2.4\, M_\odot)$			2.2	5.4

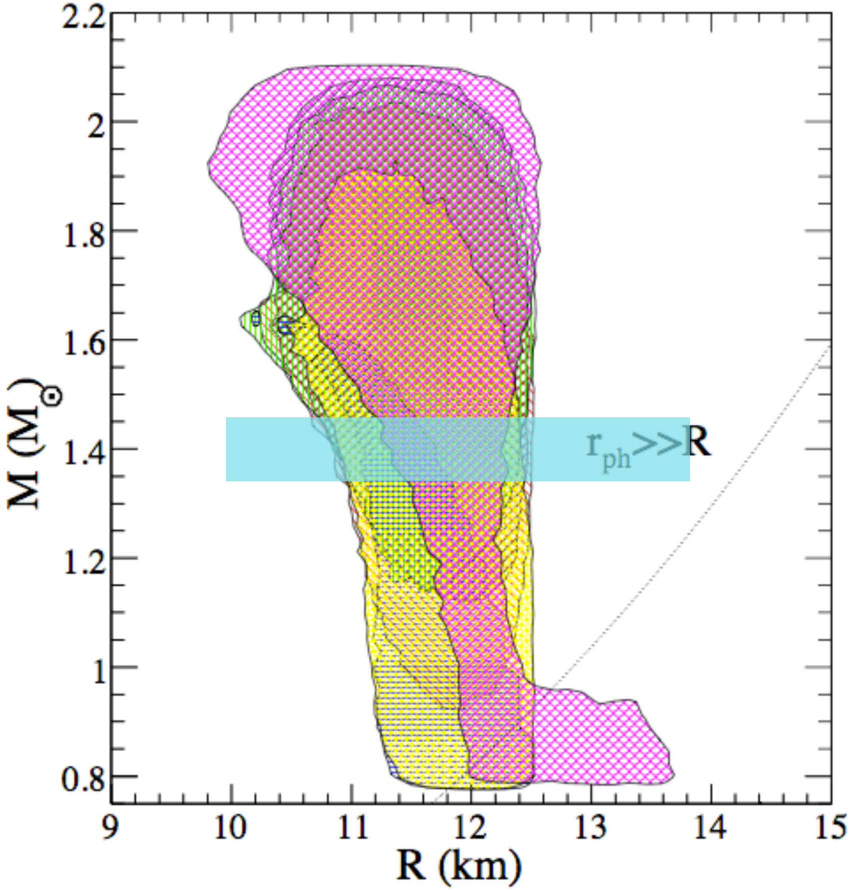
low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

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

Neutron star radius constraints

uncertainty from many-body forces and general extrapolation





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

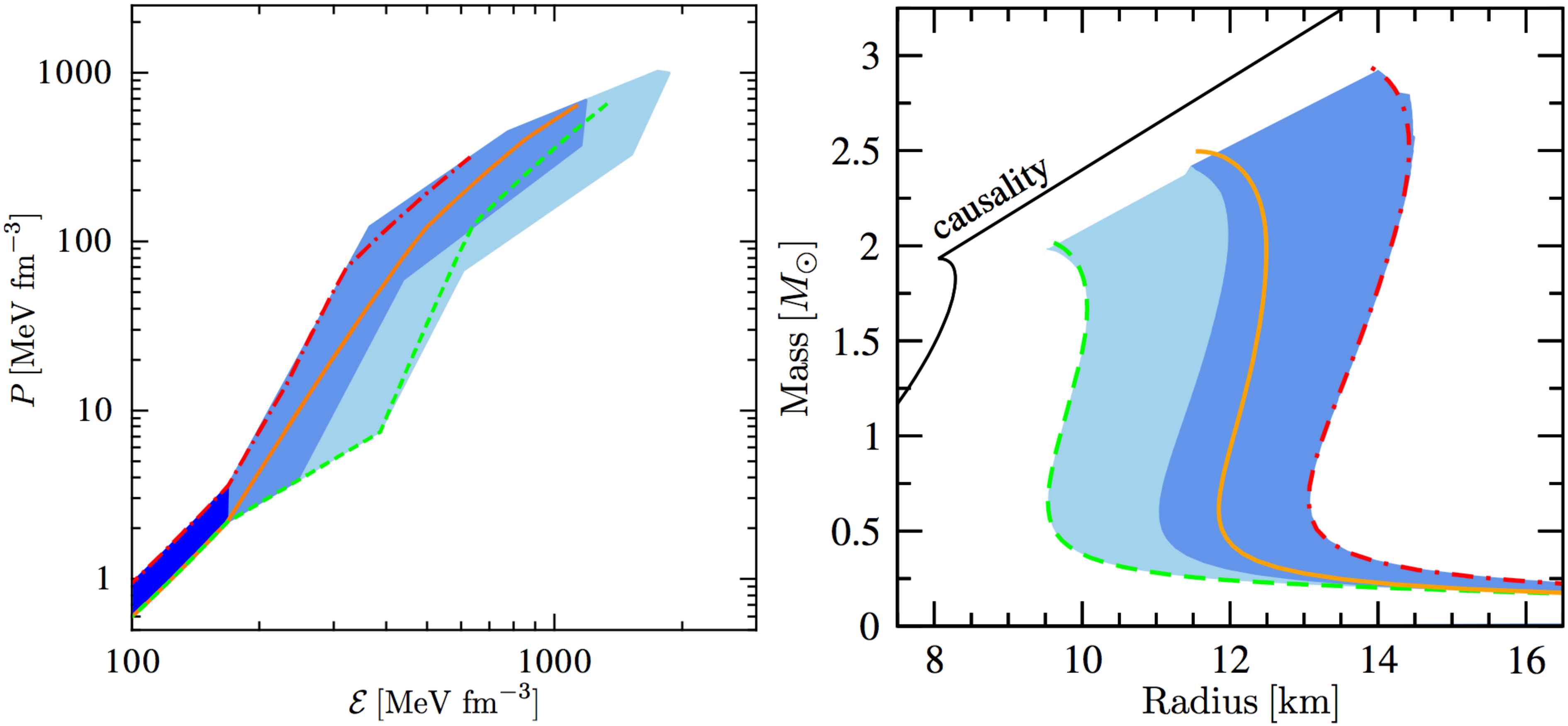
consistent with extraction from X-ray burst sources Steiner et al. (2010)

provides important constraints for EOS for core-collapse supernovae

Representative equations of state

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

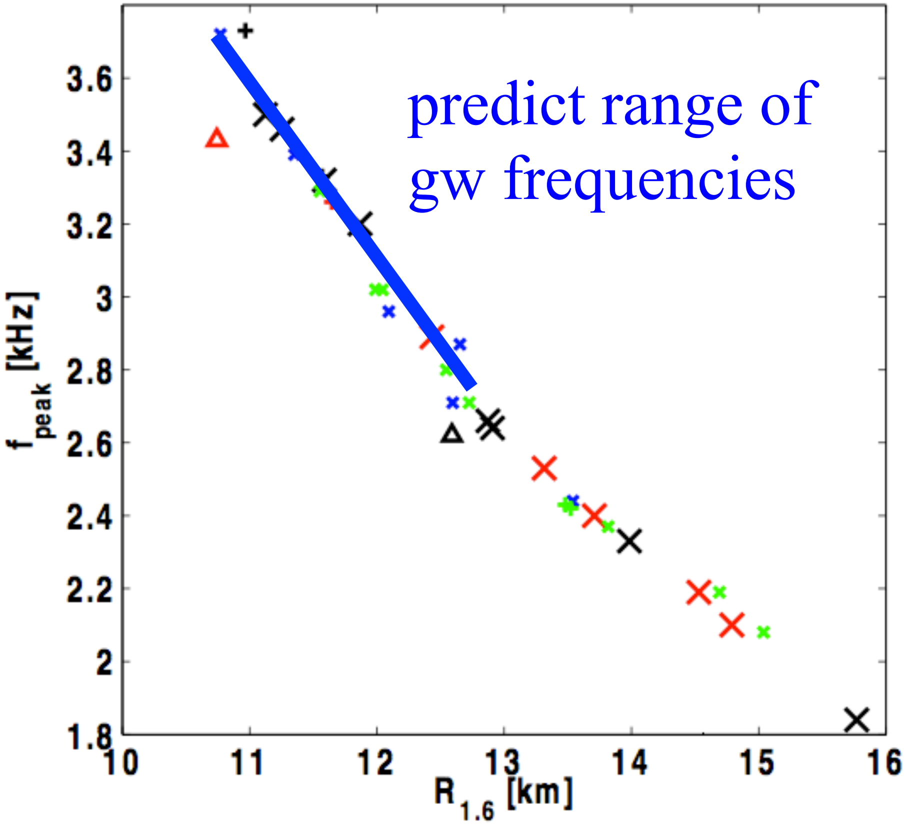
constructed 3 representative EOS for users: soft, intermediate, stiff



Neutron-star mergers and gravitational waves

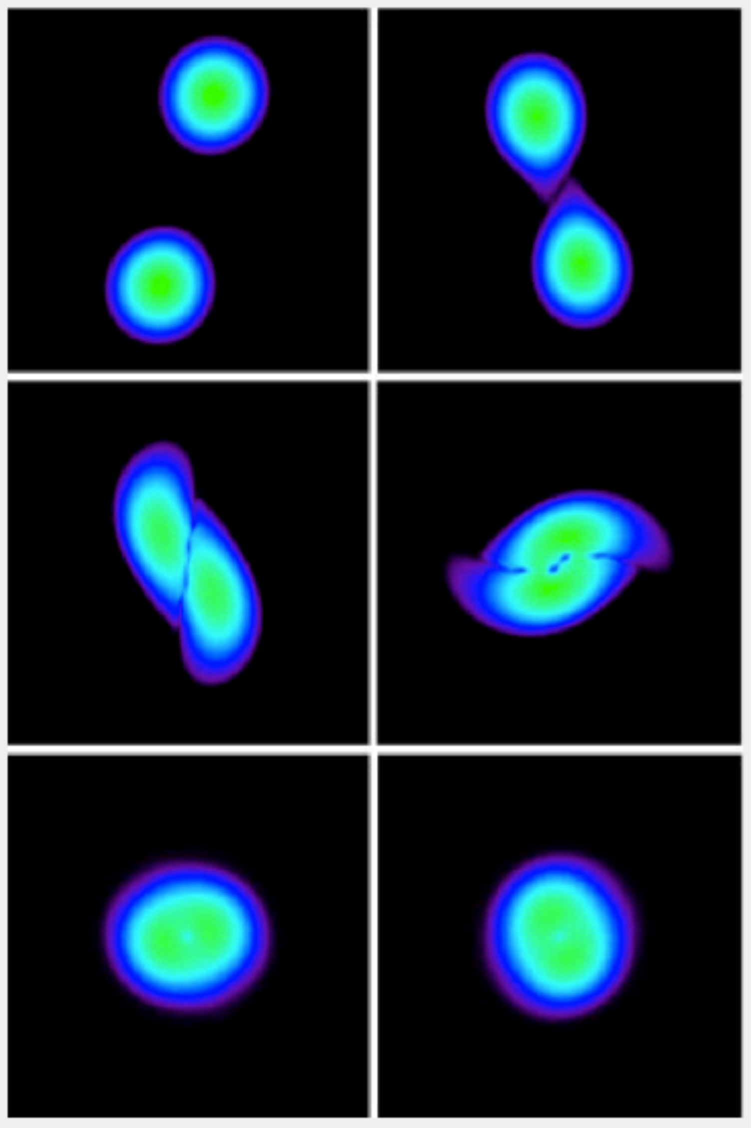
explore sensitivity to neutron-rich matter in neutron-star merger predictions for gravitational-wave signal, including NP uncertainties

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



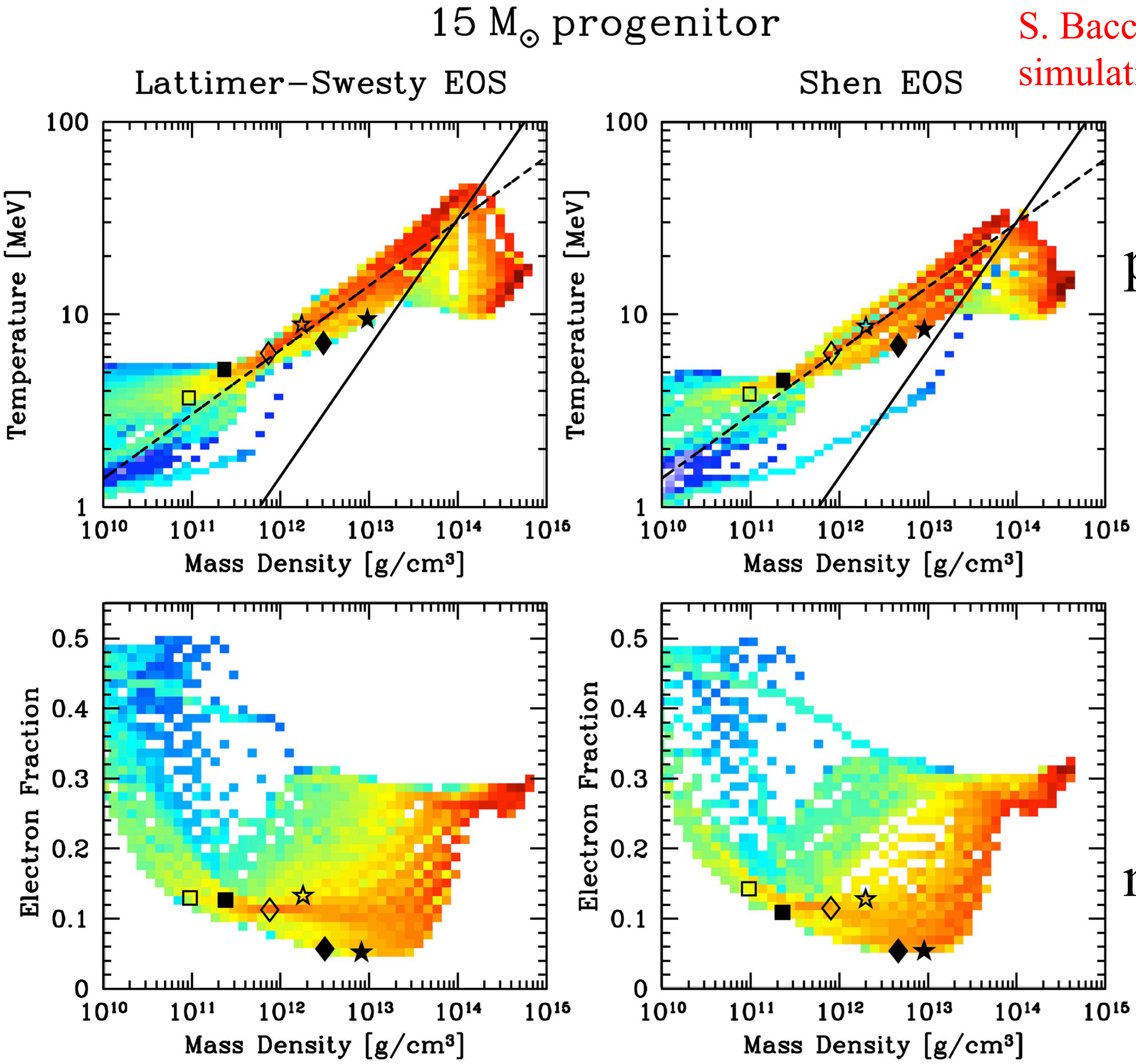
predict range of gw frequencies

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.



Relevant conditions in core-collapse supernovae

S. Bacca et al., ApJ (2012)
simulations by M. Liebendörfer et al.



partially degenerate

neutron-rich

crucial densities below nuclear matter density ~10^{13}-10^{14} g/cm^3
(high densities: neutrinos trap; low densities: few interactions)

Neutrino rates from chiral effective field theory

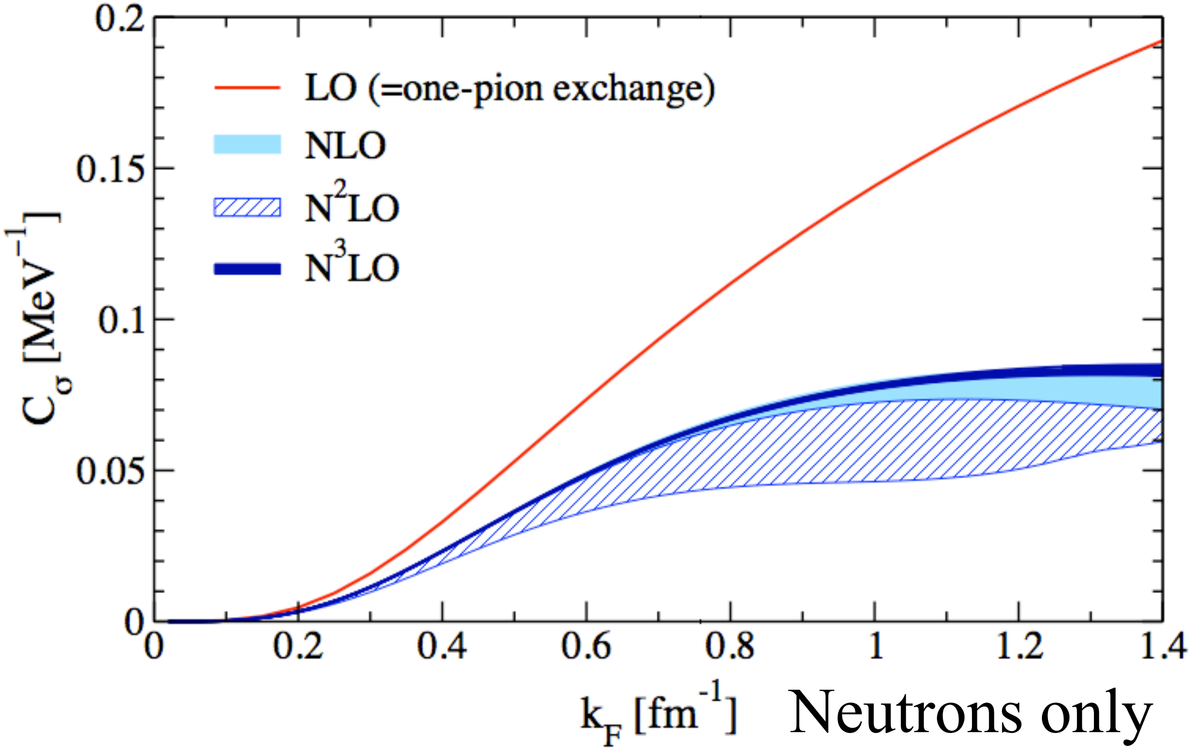
processes involving two nucleons play a special role Friman,… Suzuki, Raffelt,…

$NN \leftrightarrow NN\nu\bar{\nu}$ key for muon and tau neutrino production in supernovae (and neutron stars crust and core cooling)

determined by spin relaxation time = rate of change of nucleon spin through collisions

first neutrino rates based on chiral EFT, degenerate conditions
Bacca et al. (2009)

shorter-range interactions reduce rates for neutrons



Neutrons only

Relevant conditions in core-collapse supernovae

S. Bacca et al., ApJ (2012)
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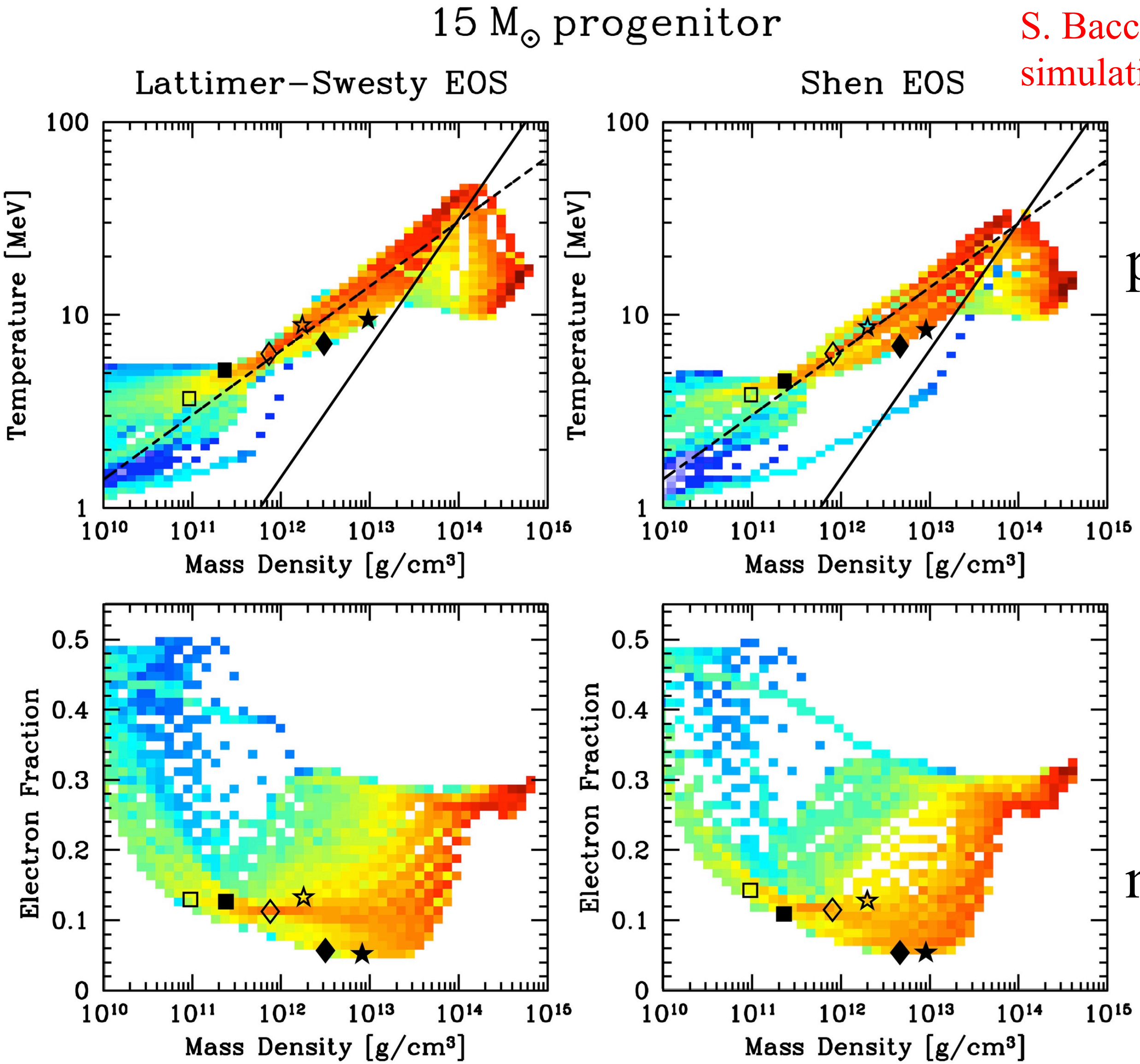

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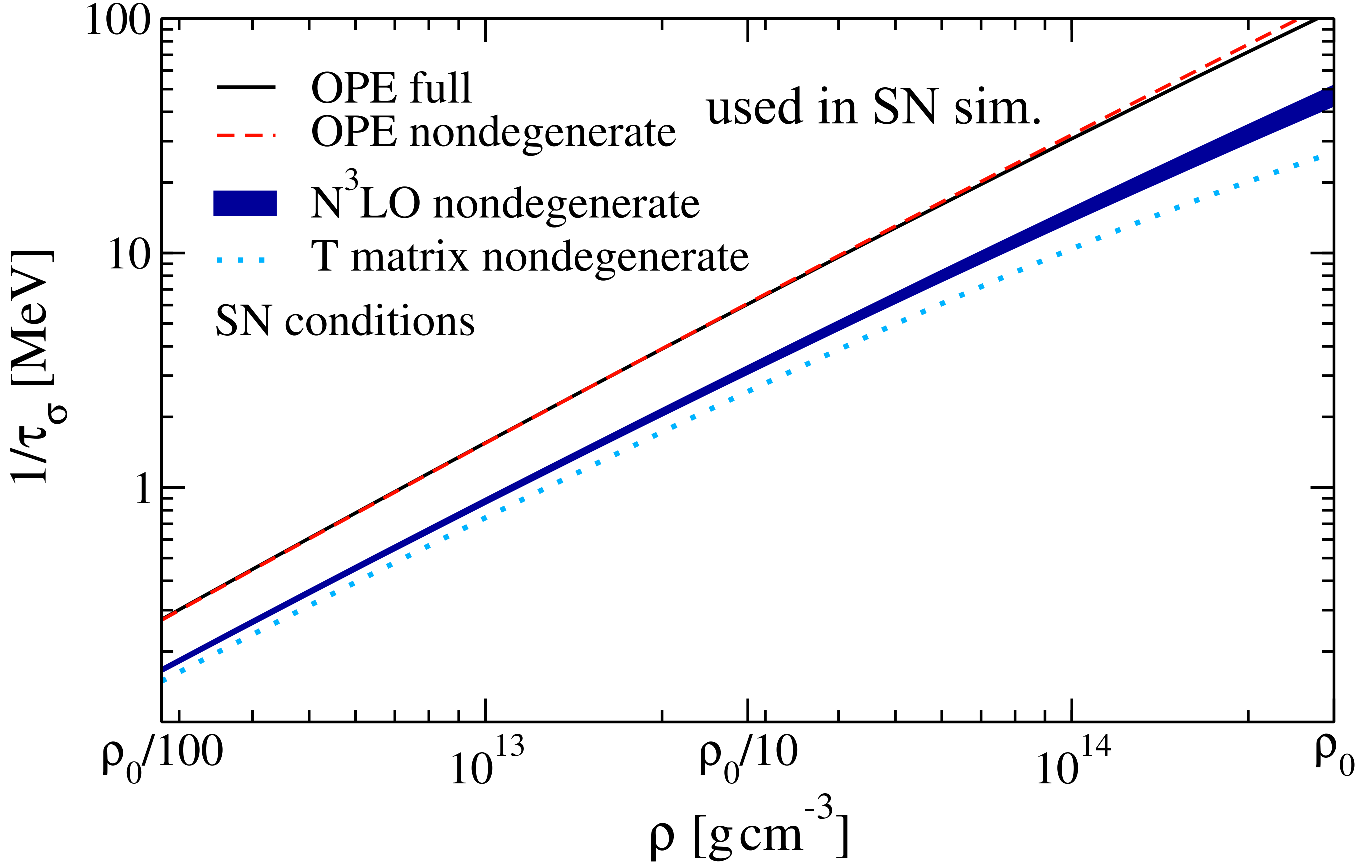
Neutrino rates from chiral EFT S. Bacca et al., ApJ (2012)

neutrons only, arbitrary degeneracy



similar reduction along SN conditions

Energy transfer in neutrino scattering from nucleons

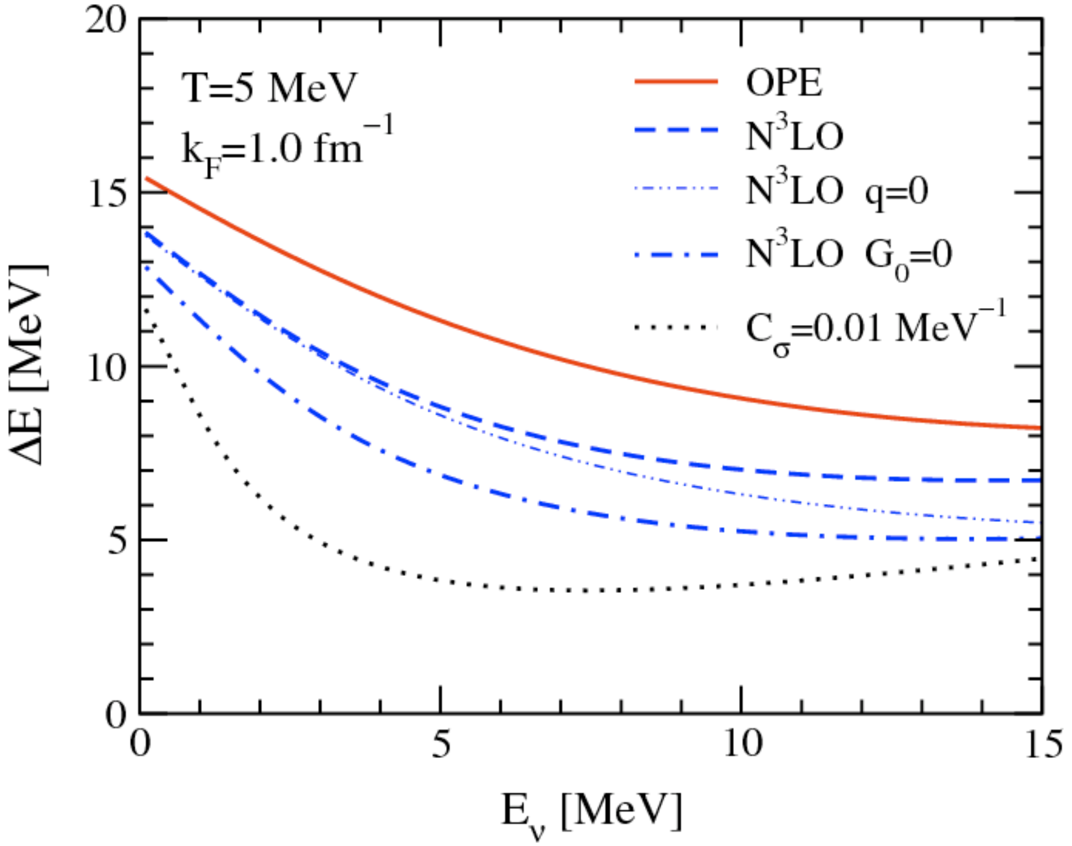
mean-square neutrino energy transfer in $\nu n n \leftrightarrow \nu n n$

$$(\Delta E)^2 = \frac{\int d\mathbf{p}'_\nu \, (E_\nu - E'_\nu)^2 \, \Gamma(E_\nu - E'_\nu, p_\nu - p'_\nu)}{\int d\mathbf{p}'_\nu \, \Gamma(E_\nu - E'_\nu, p_\nu - p'_\nu)}$$

leads to heating,
NN analogue of inelastic
excitations of nuclei
(but post-collapse)

energy transfer significant,
dominates over recoil effects

not included in simulations

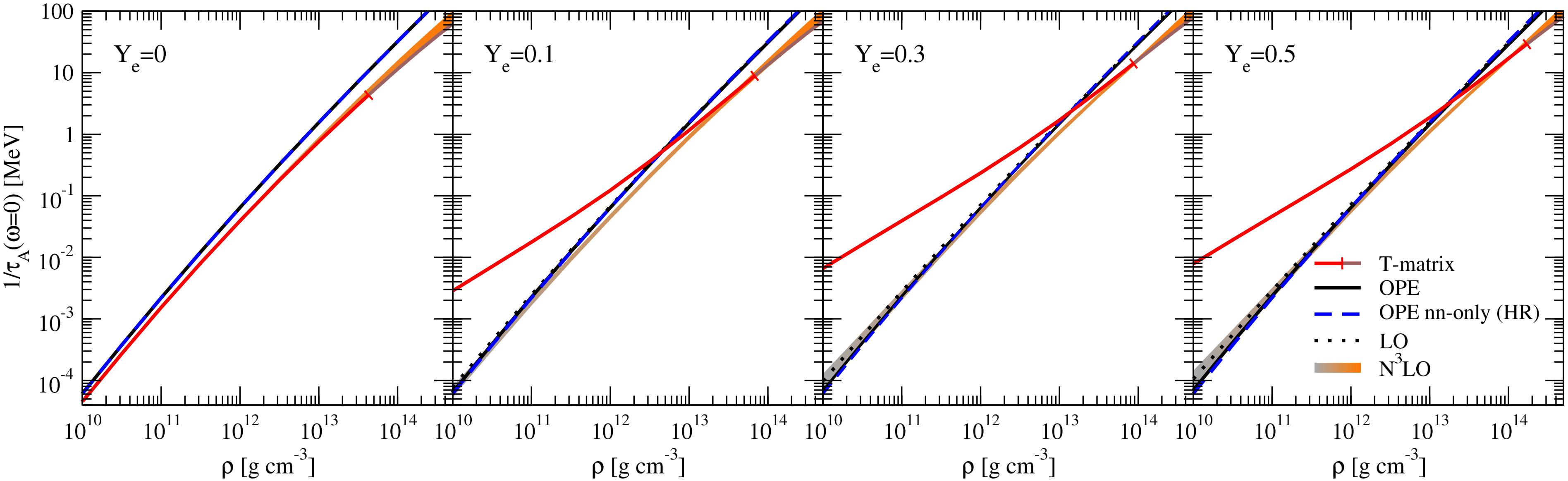


Neutrino bremsstrahlung in mixtures of neutron and protons

in mixtures also S-wave interactions enter: large scattering lengths!

lead to enhancement of bremsstrahlung at low densities for nonzero Y_e

Bartl, Pethick, AS, arXiv:1403.4114



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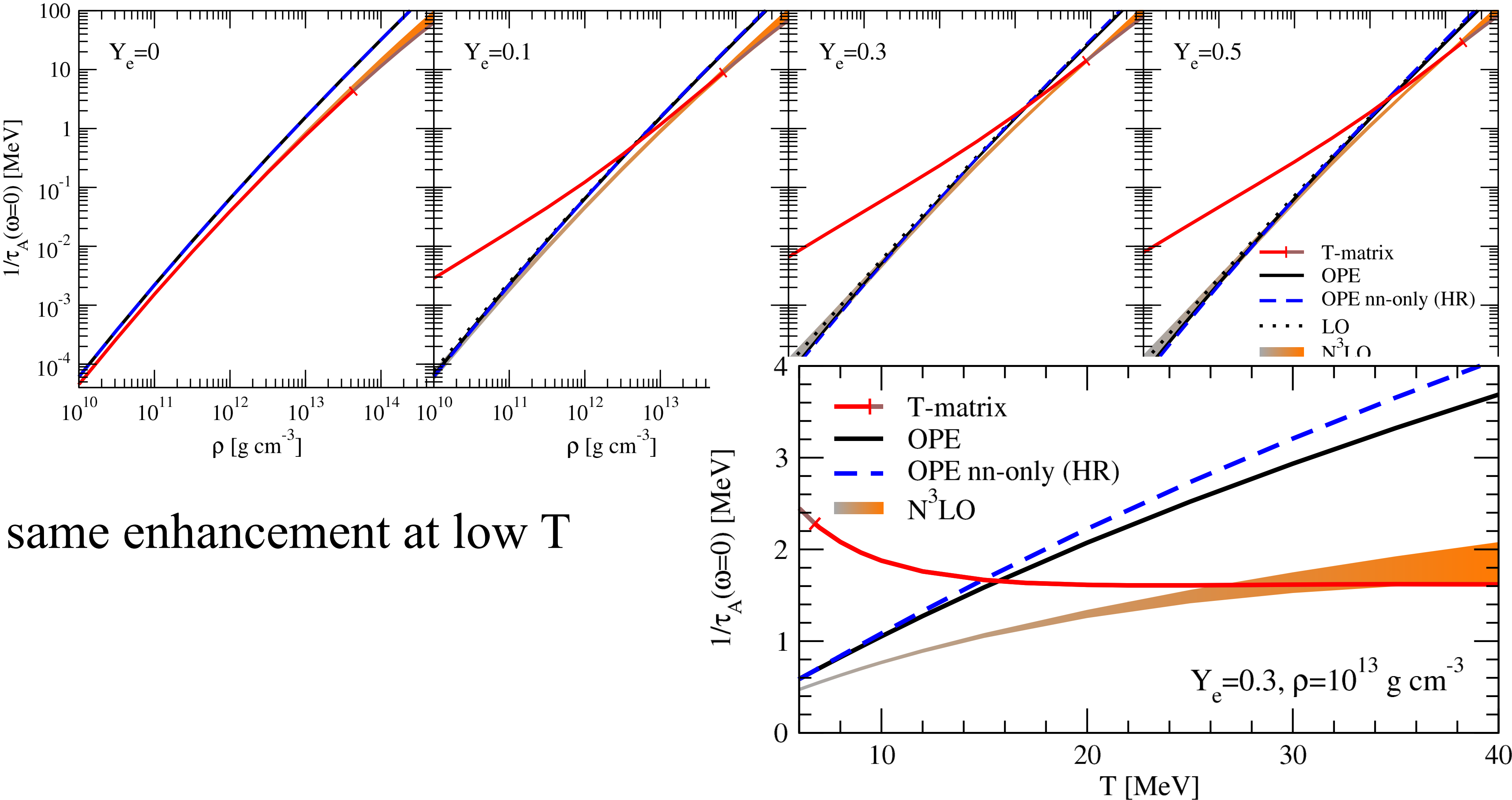

same enhancement at low T

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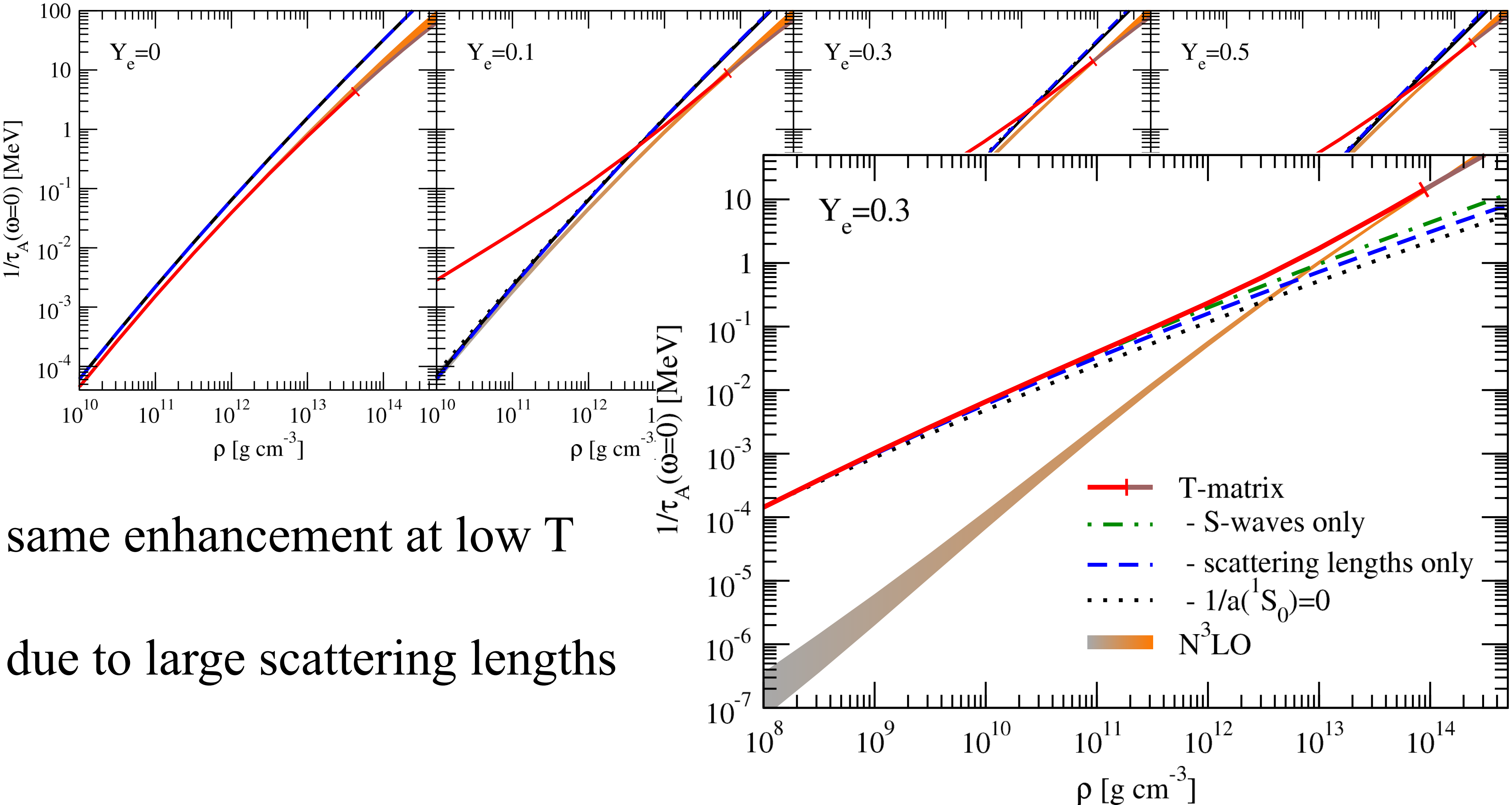

same enhancement at low T

due to large scattering lengths

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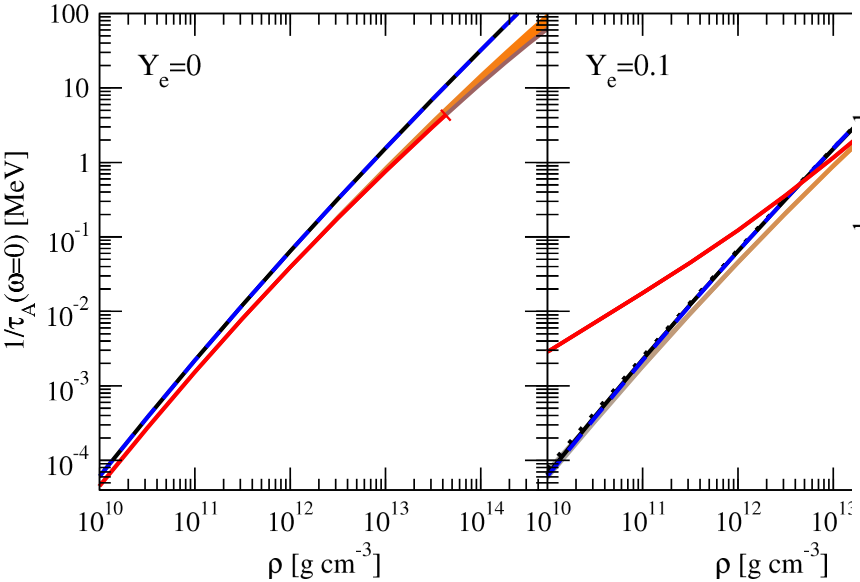

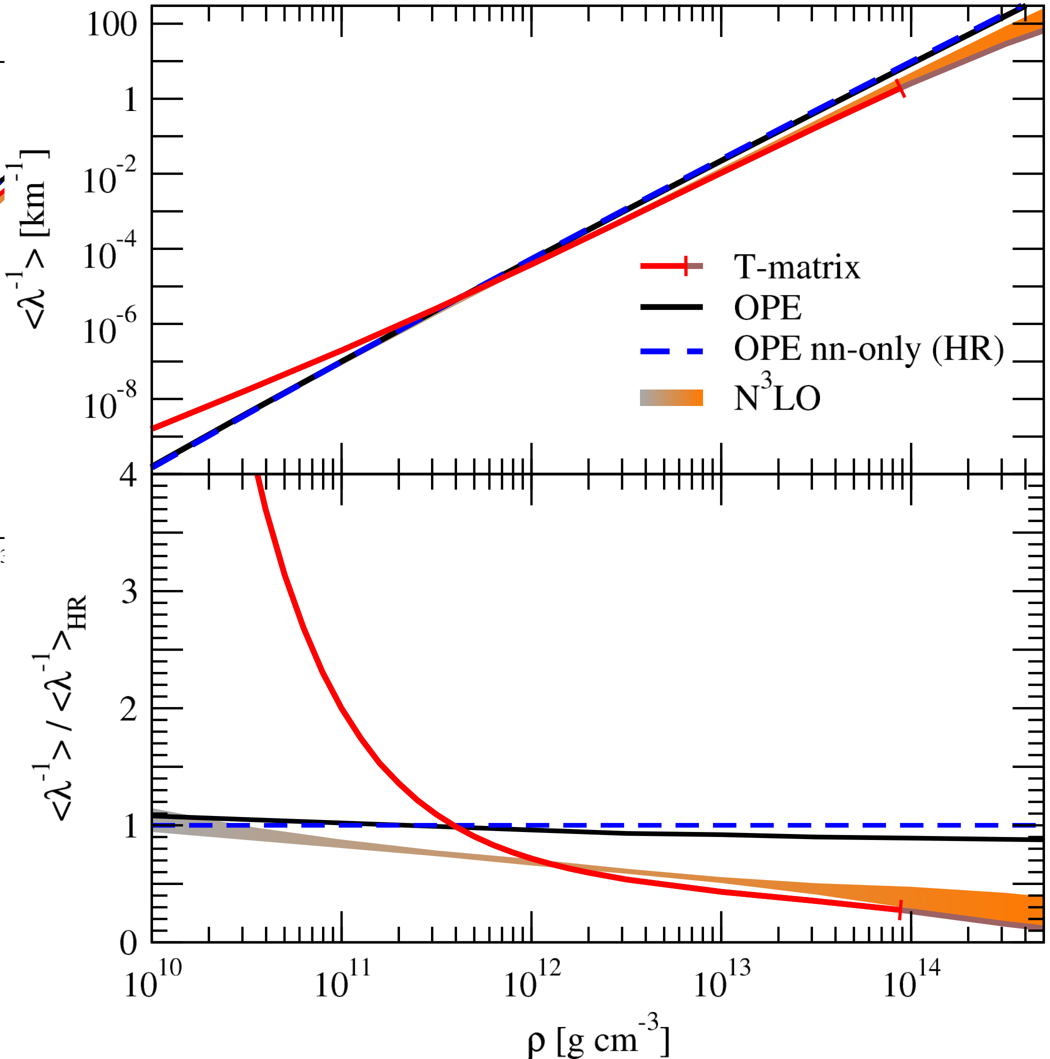

same enhancement at low T

smaller enhancement of inverse mf paths

Main points

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

Neutron-rich conditions and nondegenerate conditions

especially interesting for mergers!

General EOS band based on nuclear physics and observations

neutron star radius 9.7-13.9 km for $M=1.4\ M_{\mathrm{sun}}$ (±15%)

Chiral EFT important for consistent neutrino-matter interactions

Enhancement of neutrino bremsstrahlung at low densities

Main work with: A. Bartl, K. Hebeler, J. Lattimer, C. Pethick