First calculations with N^{3}LO 3N and 4N interactions

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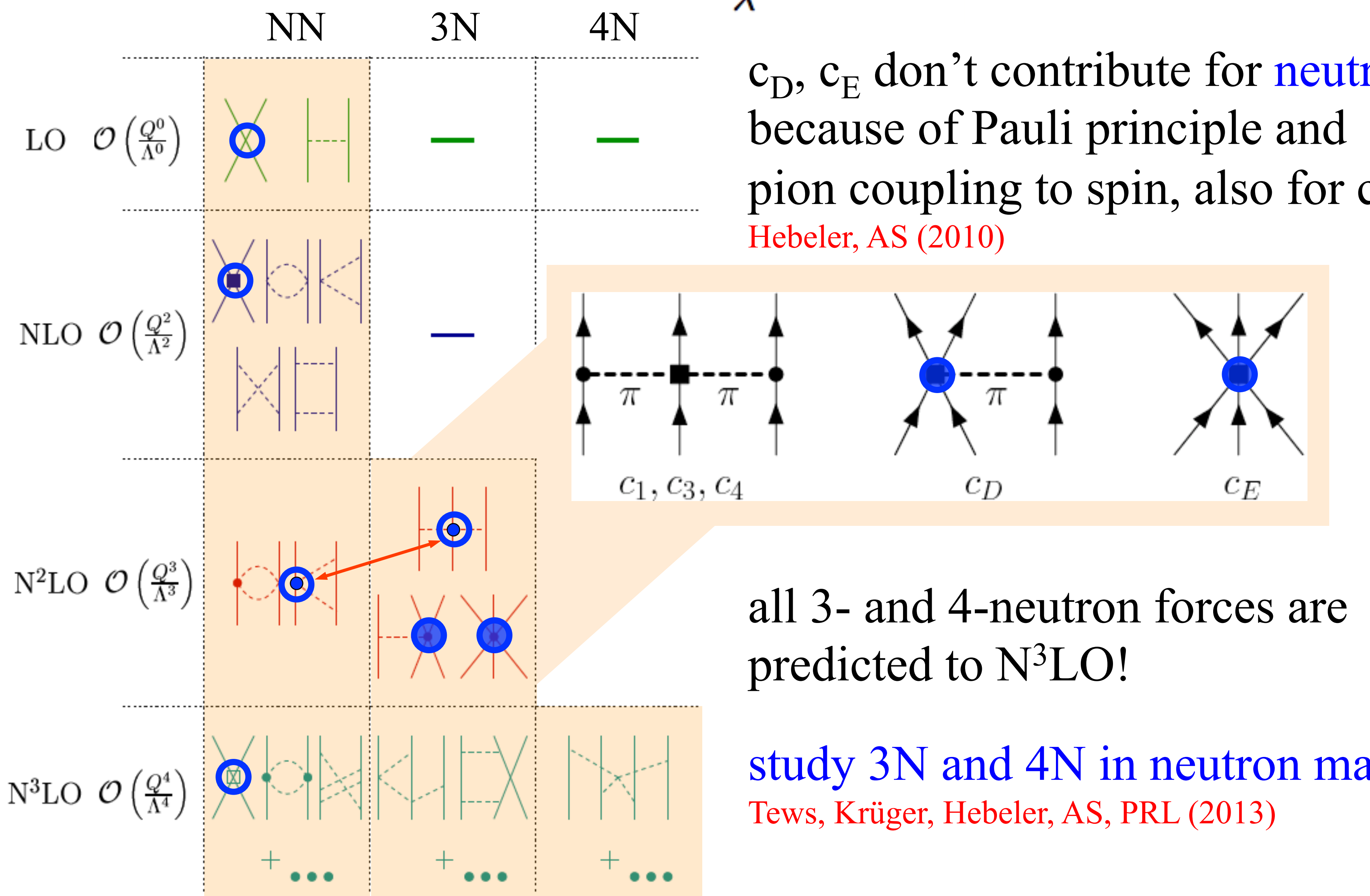
with Kai Hebeler, Thomas Krüger and Ingo Tews

TRIUMF ab-initio workshop

Feb. 21, 2013

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!

study 3N and 4N in neutron matter

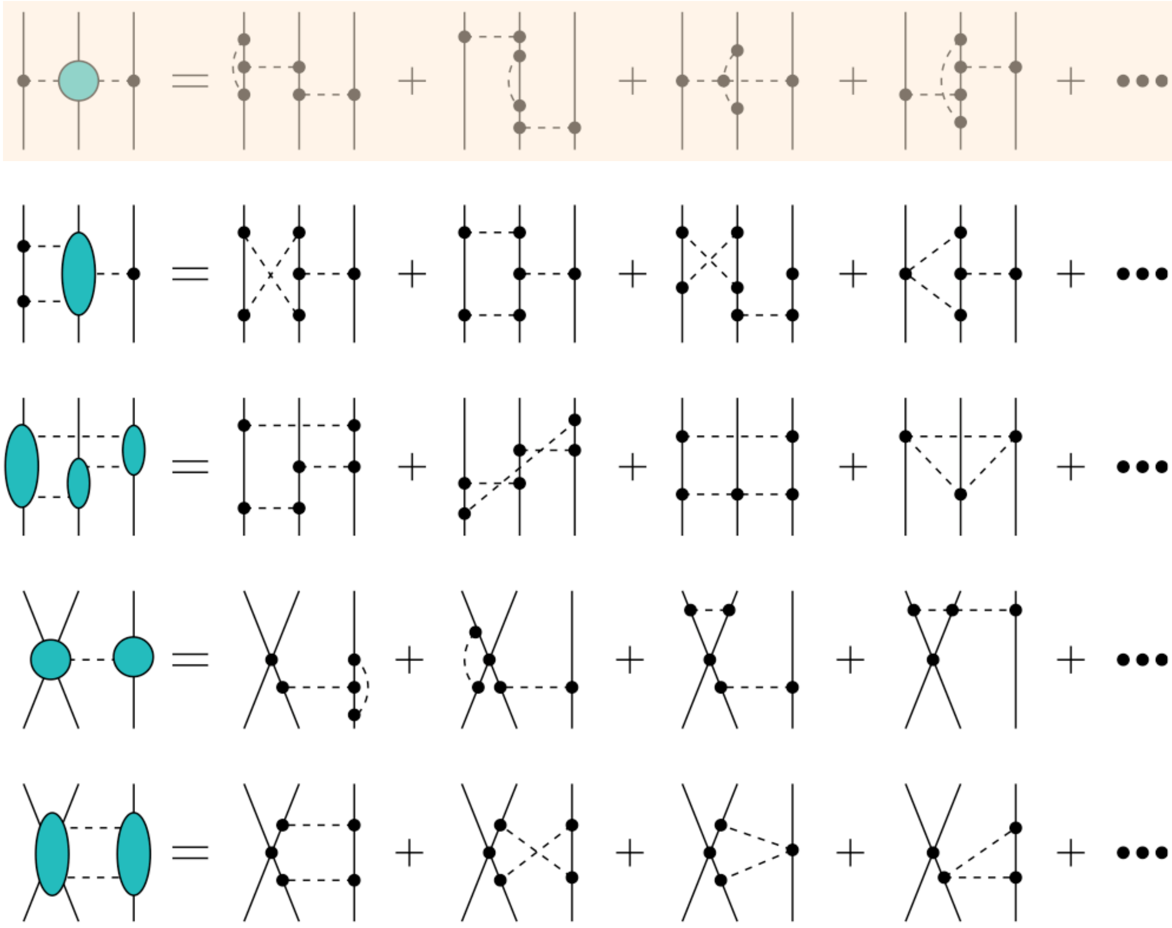
Tews, Krüger, Hebeler, AS, PRL (2013)

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

Subleading chiral 3N forces

parameter-free N^3LO Bernard et al. (2007,2011), Ishikawa, Robilotta (2007)

one-loop contributions:
2π-exchange, 2π-1π-exchange, rings, contact-1π-, contact-2π-exchange



decrease c_i strengths
$\delta c_3 = -\delta c_4 = 1\ \mathrm{GeV}^{-1}$
comparable to
N^2LO uncertainty

1/m corrections: spin-orbit parts, interesting for A_y puzzle

Range of c_i couplings

Uncertainty range

	c_1	c_3	c_4	
Fettes *et al.* (1998) (Fit 1)	-1.2	-5.9	3.5	πN
Büttiker and Meißner (2000)	-0.8	-4.7	3.4	πN
Meißner (2007)	-0.9	-4.7	3.5	πN
Rentmeester *et al.* (2003)	-0.8	-4.8	4.0	NN
Entem and Machleidt (2002)	-0.8	-3.4	3.4	NN
Entem and Machleidt (2003)	-0.8	-3.2	5.4	NN
Epelbaum *et al.* (2005)	-0.8	-3.4	3.4	NN
Bernard *et al.* (1997)	-0.9	-5.3	3.7	res

High-order analysis Krebs et al. (KGE) (2012)

	c_1 [GeV^{-1}]	c_3 [GeV^{-1}]
N^{2}LO/N^{3}LO EGM NN [31, 32]	-0.81	-3.40
N^{3}LO EM NN [33, 34]	-0.81	-3.20
N^{2}LO KGE [39]	$-(0.26-0.58)$	$-(2.80-3.14)$
'N^{2}LO' KGE (recom.) [39]	$-(0.37-0.73)$	$-(2.71-3.38)$
N^{3}LO KGE [39]	$-(0.75-1.13)$	$-(4.77-5.51)$
N^{2}LO this work	$-(0.37-0.81)$	$-(2.71-3.40)$
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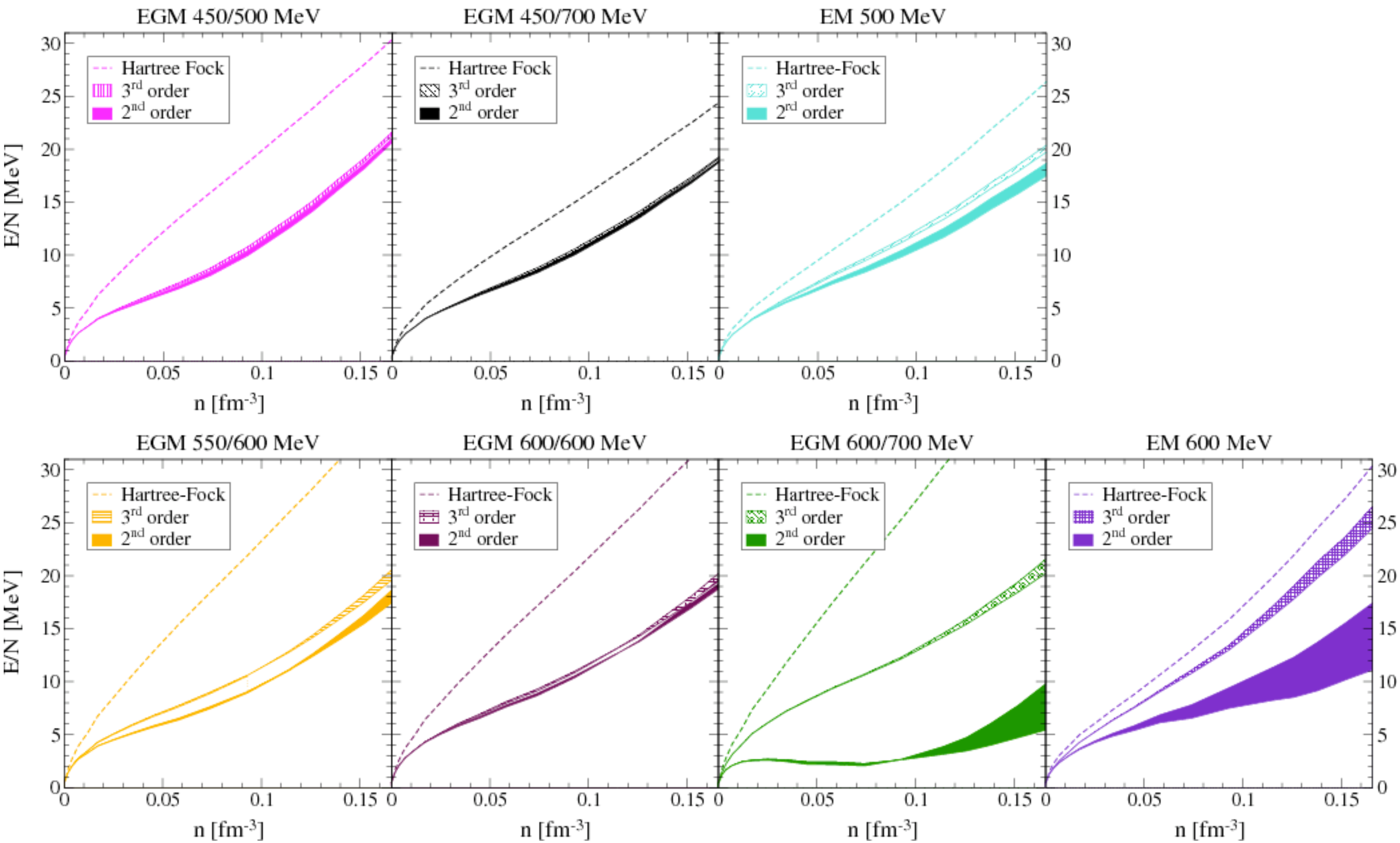
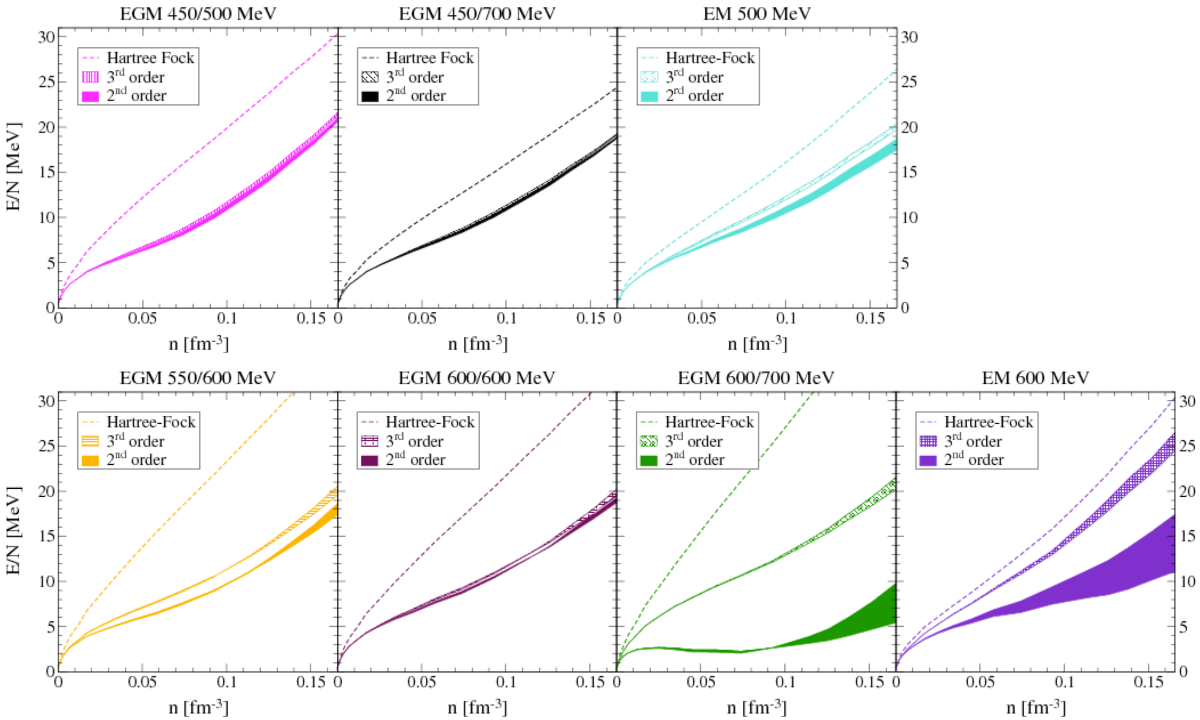
Neutron matter from chiral EFT interactions

direct calculations without RG/SRG evolution



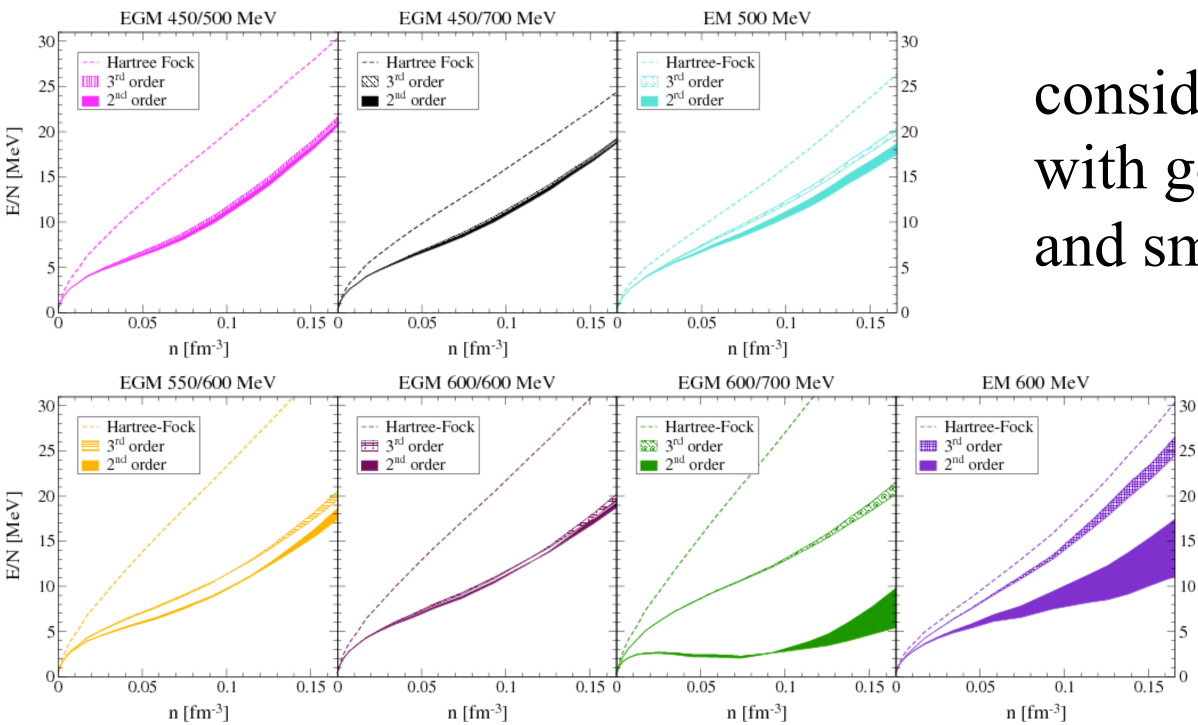
Measure of convergence and comments on C_T

N^3LO NN potential	$\lvert\Delta E^{(2/3)}_{\text{NN-only}}\rvert$	$\lvert\Delta E^{(2/3)}_{\text{NN/3N}}\rvert$
EGM 450/500 MeV	0.8 MeV	0.6 MeV
EGM 450/700 MeV	0.4 MeV	0.4 MeV
EM 500 MeV	1.1 MeV	1.7 MeV
EGM 550/600 MeV	1.0 MeV	3.1 MeV
EGM 600/600 MeV	0.2 MeV	1.5 MeV
EGM 600/700 MeV	11.4 MeV	16.1 MeV
EM 600 MeV	7.7 MeV	9.1 MeV



Measure of convergence and comments on C_T

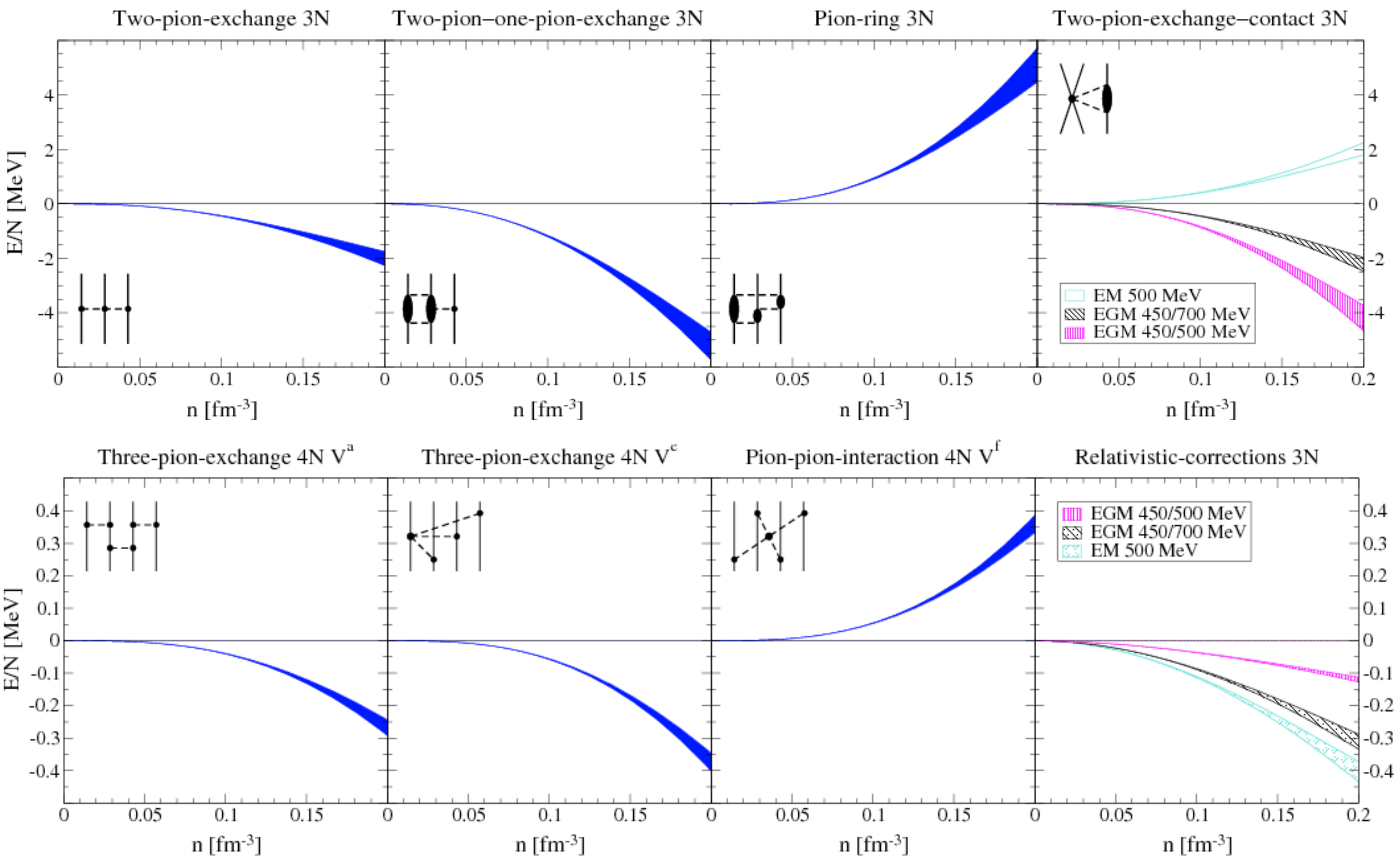
N^3LO NN potential	$\lvert \Delta E^{(2/3)}_{\text{NN-only}} \rvert$	$\lvert \Delta E^{(2/3)}_{\text{NN/3N}} \rvert$	C_S [fm^2]	C_T [fm^2]
EGM 450/500 MeV	0.8 MeV	0.6 MeV	−4.19	−0.45
EGM 450/700 MeV	0.4 MeV	0.4 MeV	−4.71	−0.24
EM 500 MeV	1.1 MeV	1.7 MeV	−3.90	0.22
EGM 550/600 MeV	1.0 MeV	3.1 MeV	−1.24	0.36
EGM 600/600 MeV	0.2 MeV	1.5 MeV	3.45	2.07
EGM 600/700 MeV	11.4 MeV	16.1 MeV	1.31	1.00
EM 600 MeV	7.7 MeV	9.1 MeV	−3.88	0.28



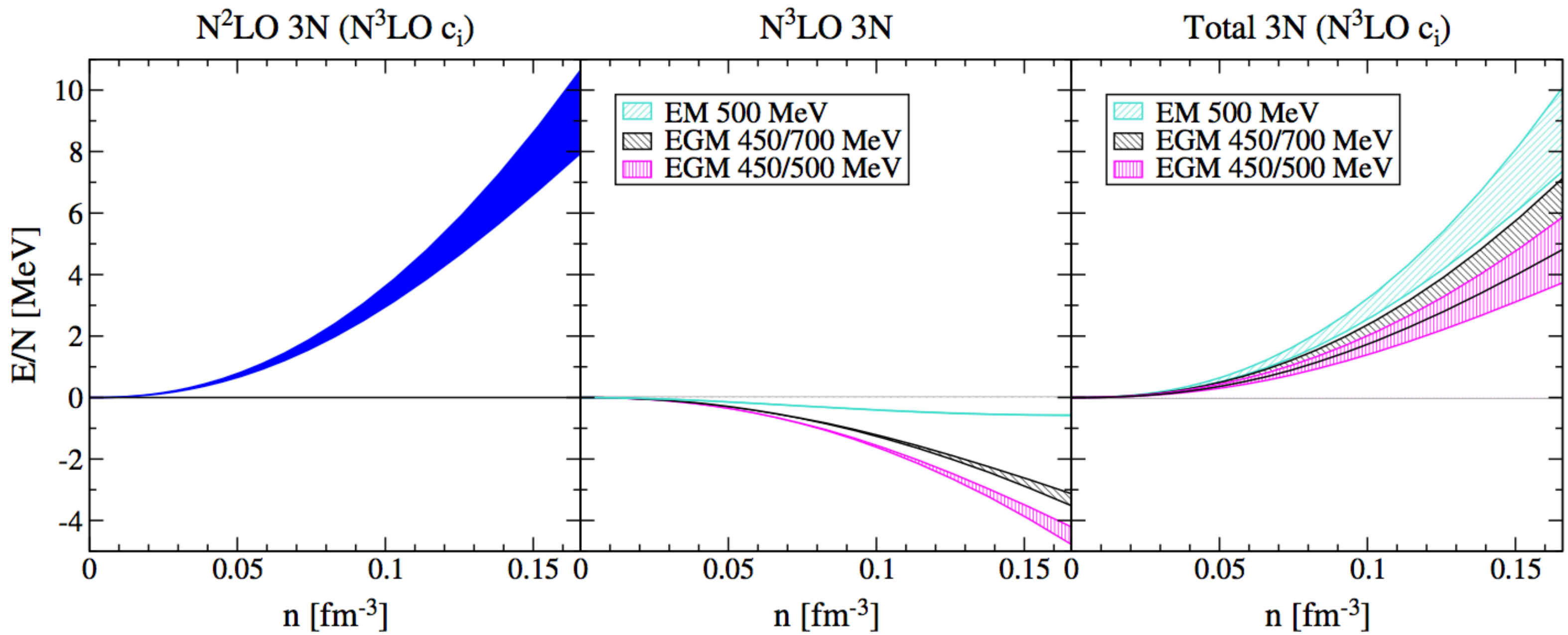
consider all NN interactions with good convergence pattern and small C_T

N^{3}LO 3N and 4N interactions in neutron matter

evaluated at Hartree-Fock level



N^2LO vs. N^3LO 3N



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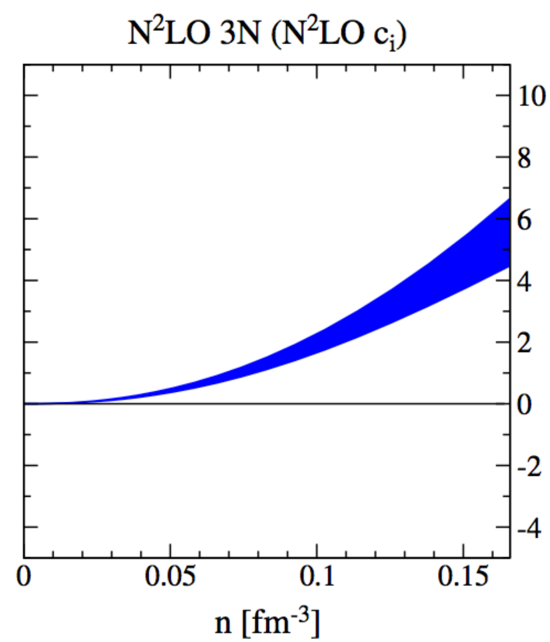
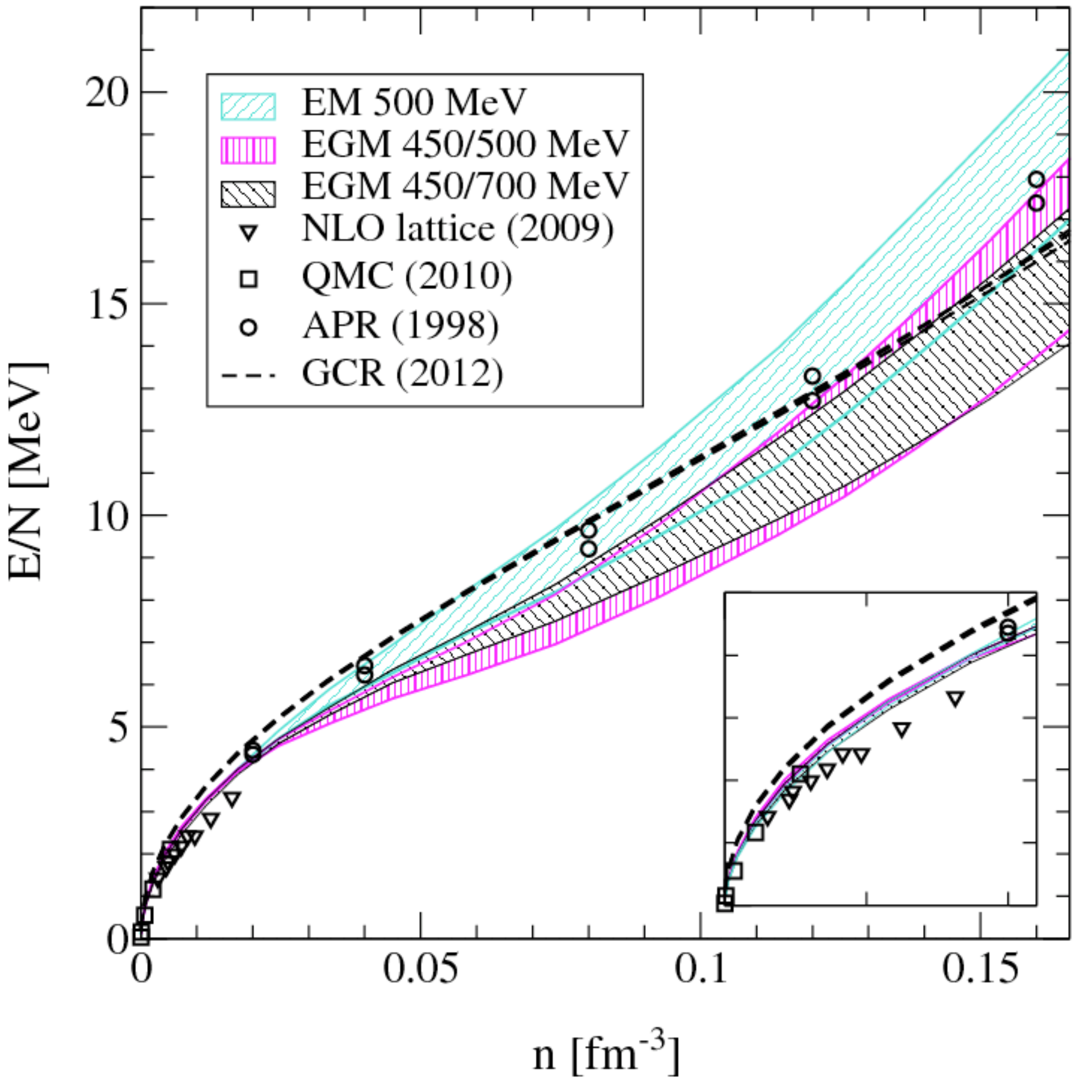


Complete N^3LO calculation of neutron matter

first complete N^3LO result
includes uncertainties from bare NN, 3N, 4N



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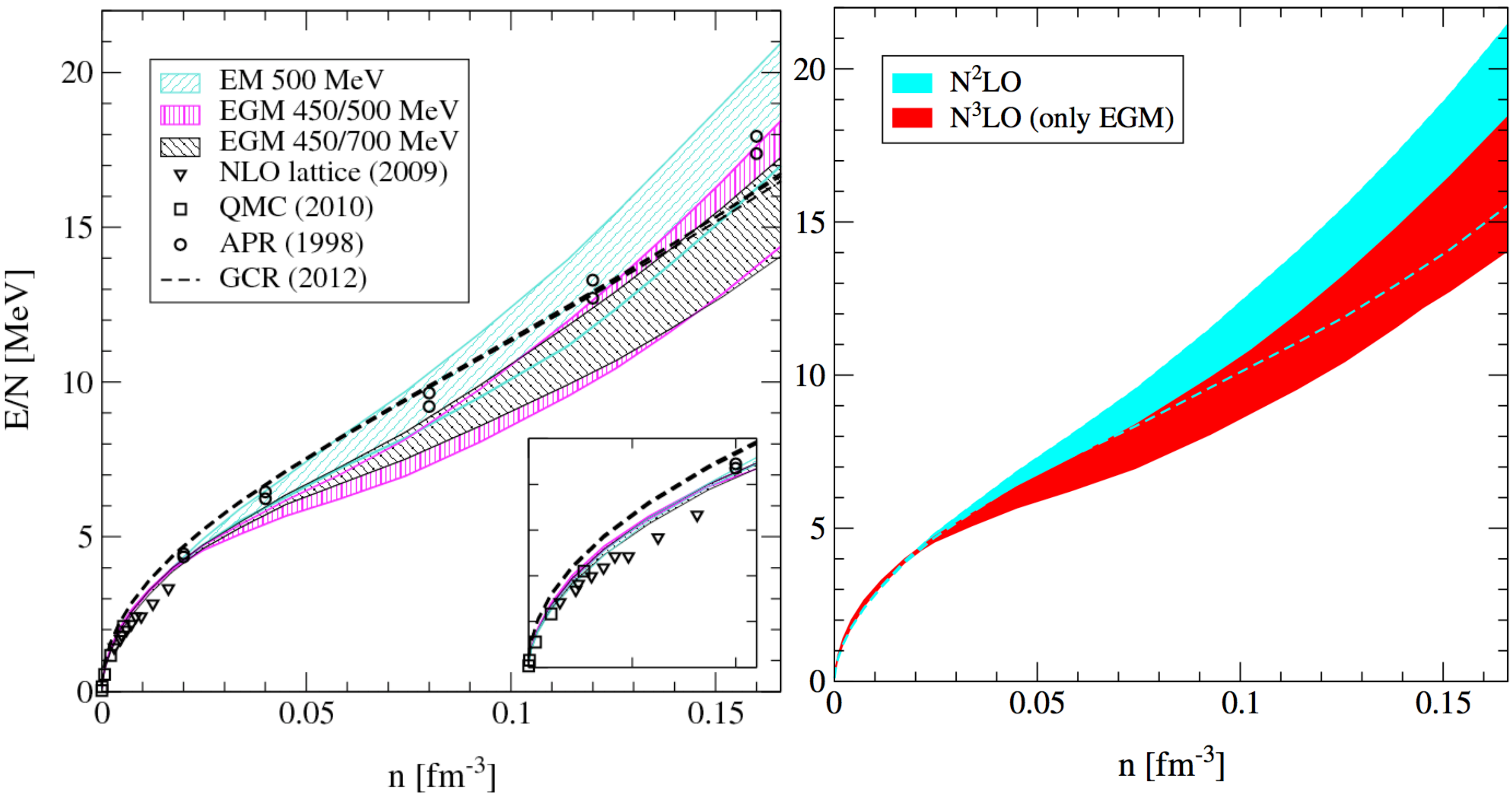
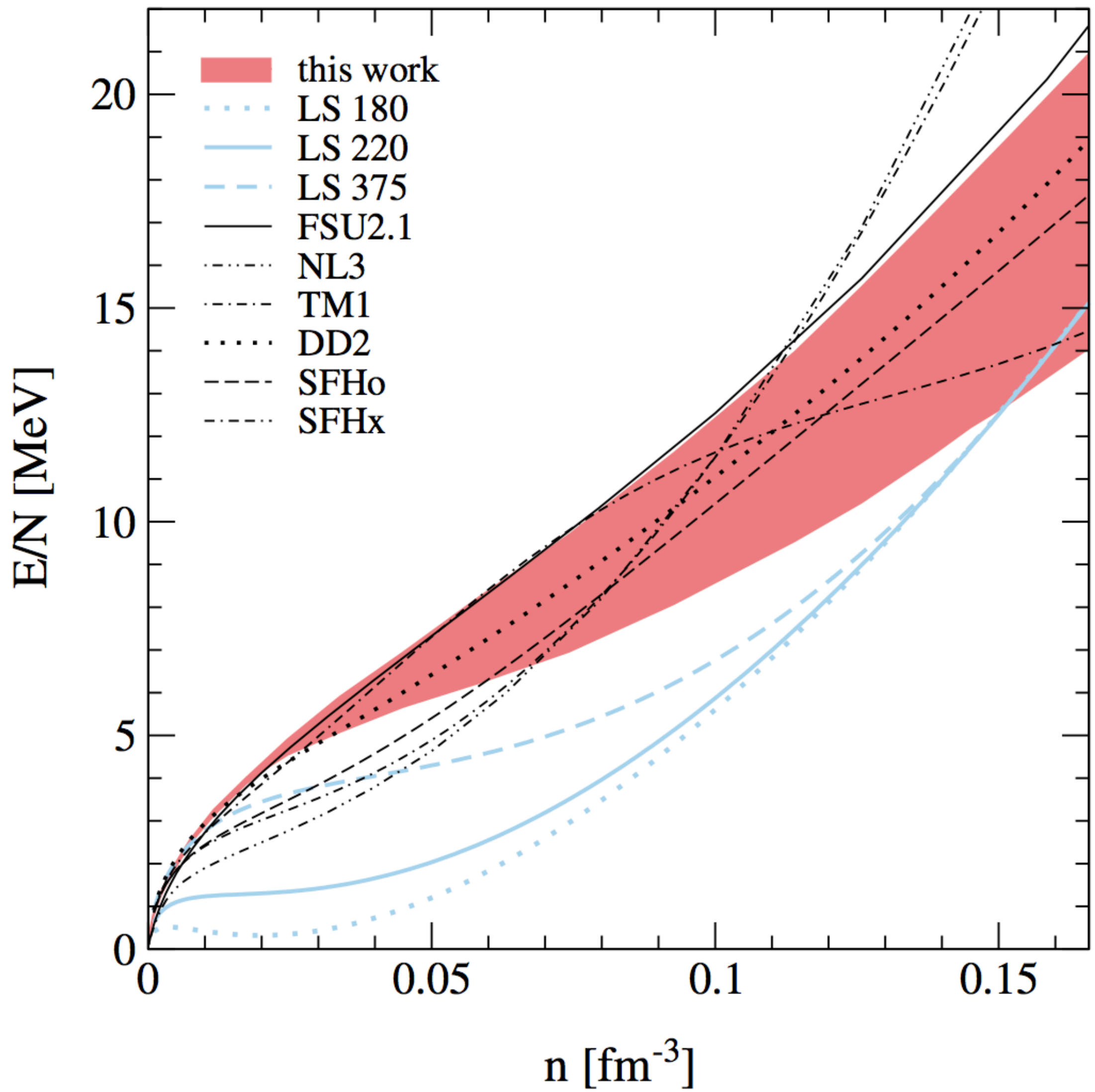


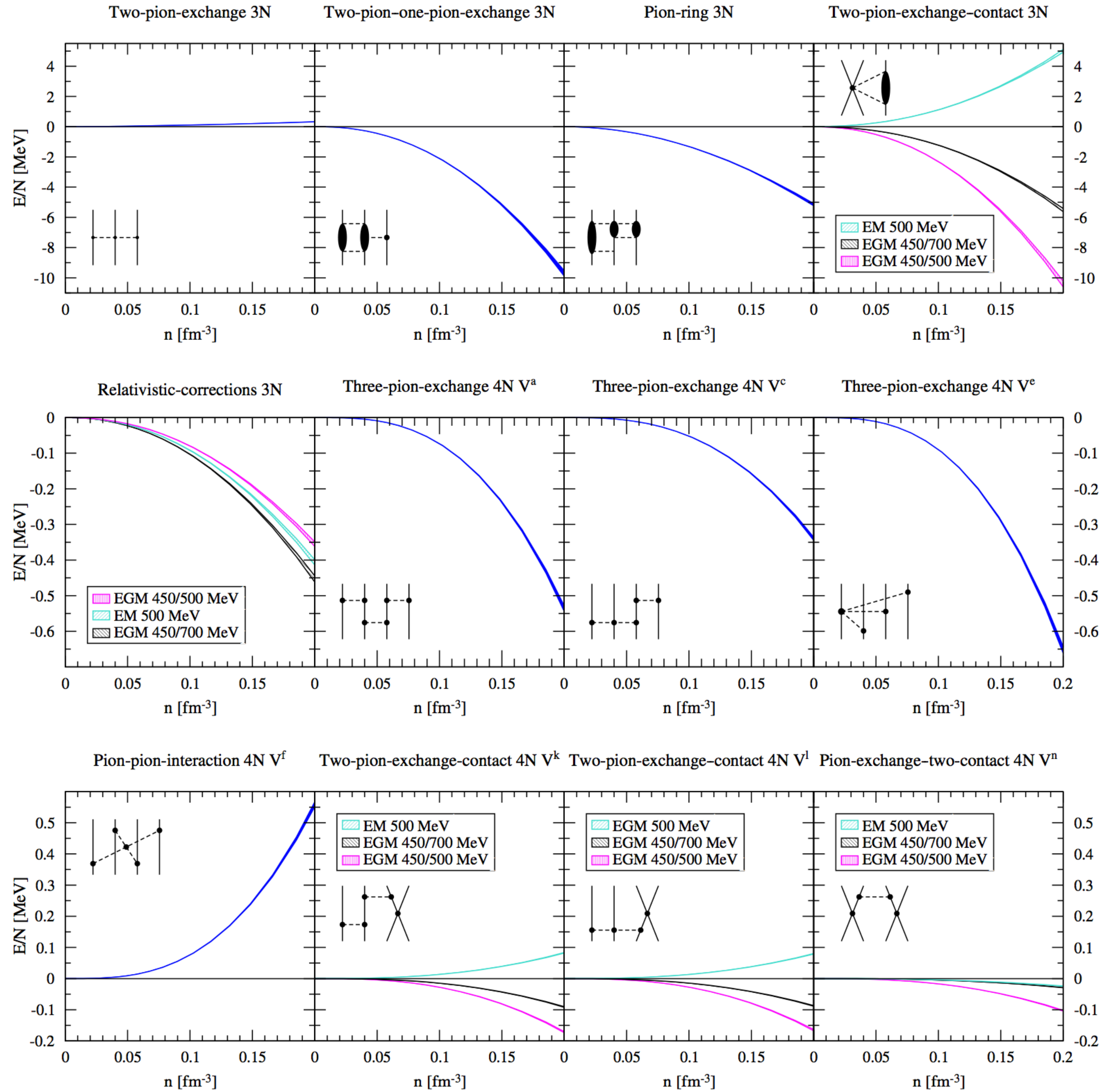
Comparisons to equations of state in astrophysics

many equations of state not consistent with neutron matter results



N^{3}LO 3N and 4N interactions in **nuclear matter**

dominant parts
where Δ's can enter



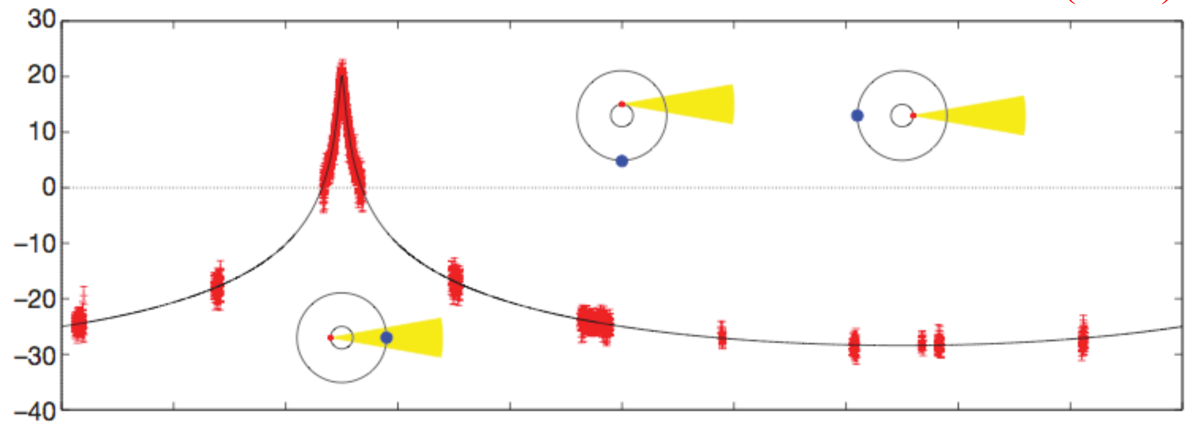
Discovery of the heaviest neutron star

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

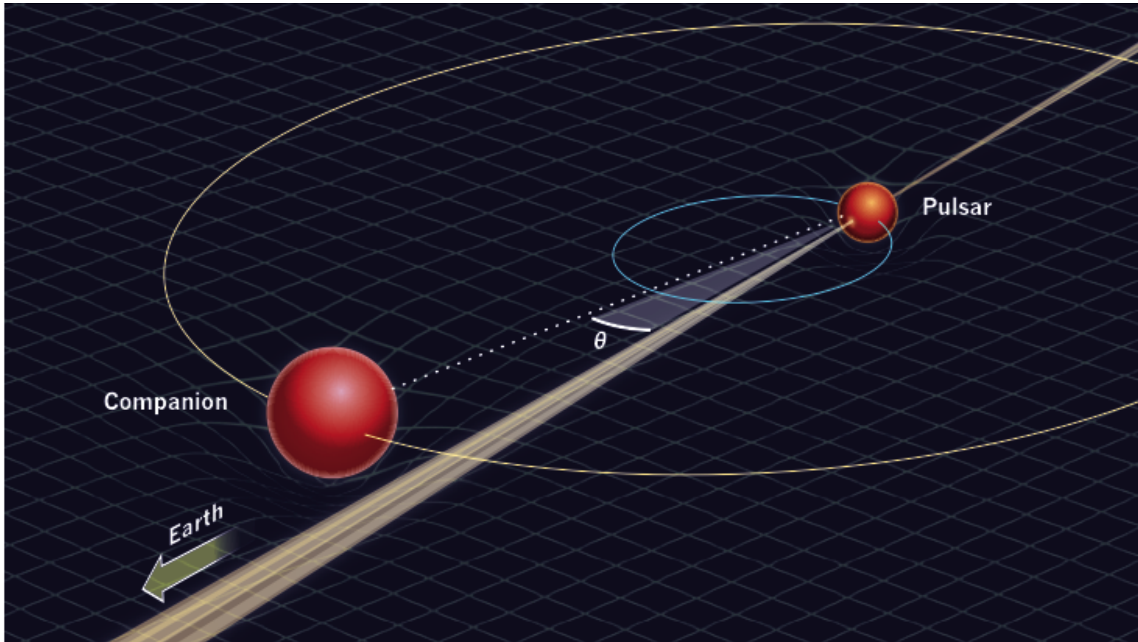
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

Nature (2010)

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



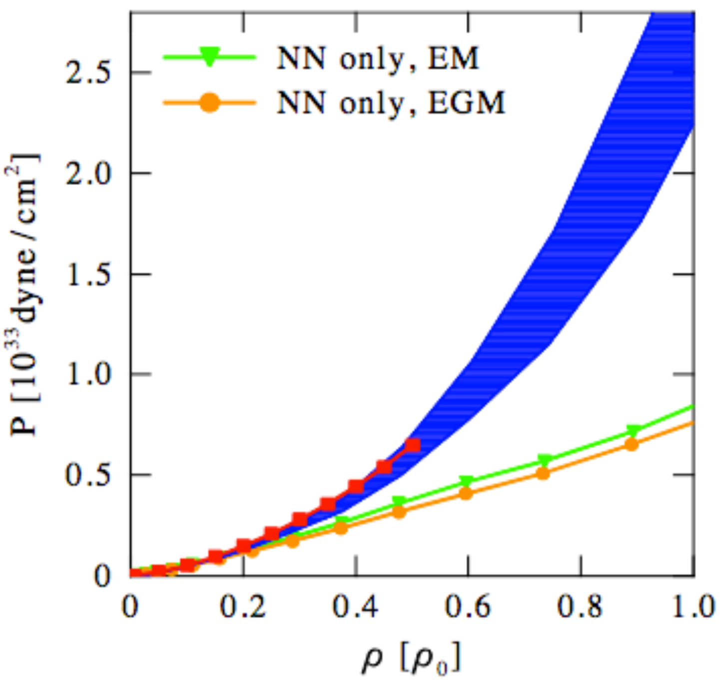
J1614-2230
most edge-on binary pulsar known (89.17°)
+ massive white dwarf companion (0.5 M_{sun})



heaviest neutron star with $1.97 \pm 0.04\ M_{sun}$

Impact on neutron stars Hebeler, Lattimer, Pethick, AS (2010) and in prep.

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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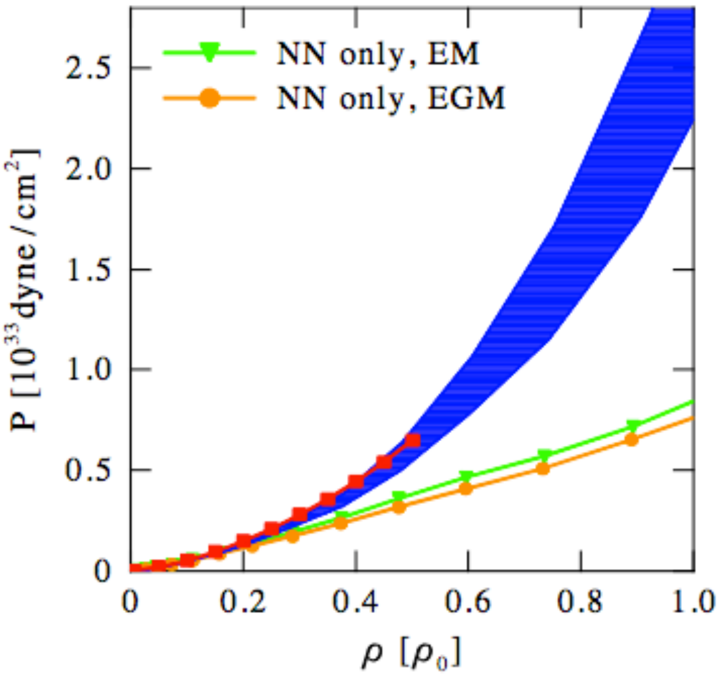
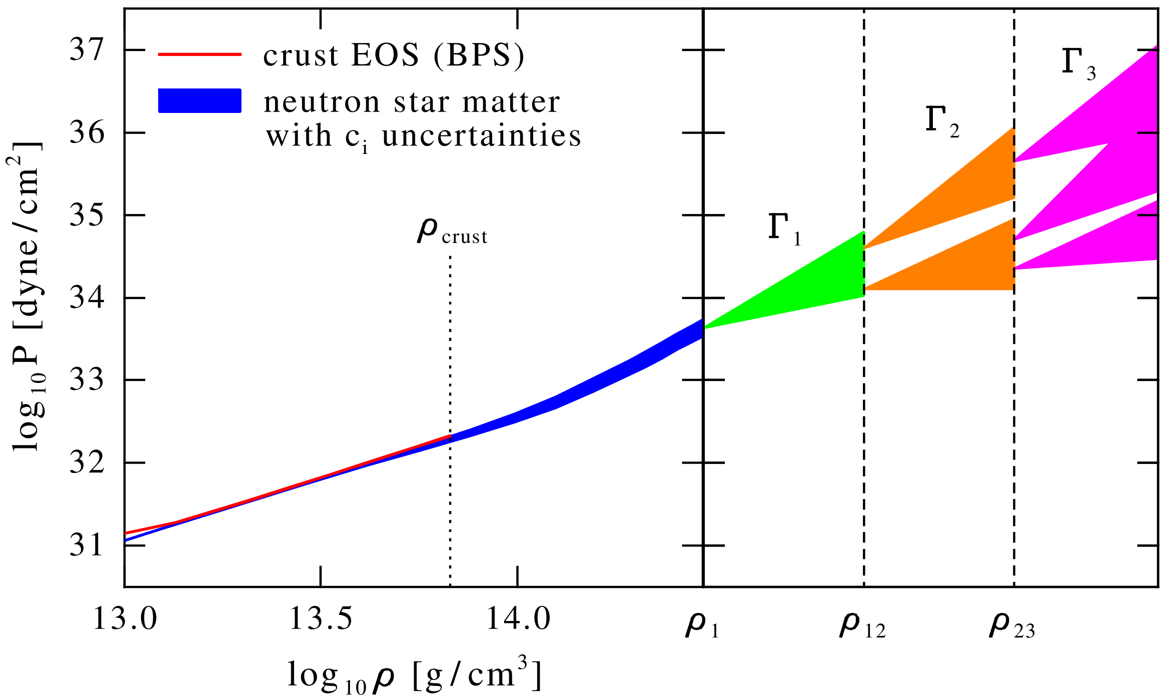


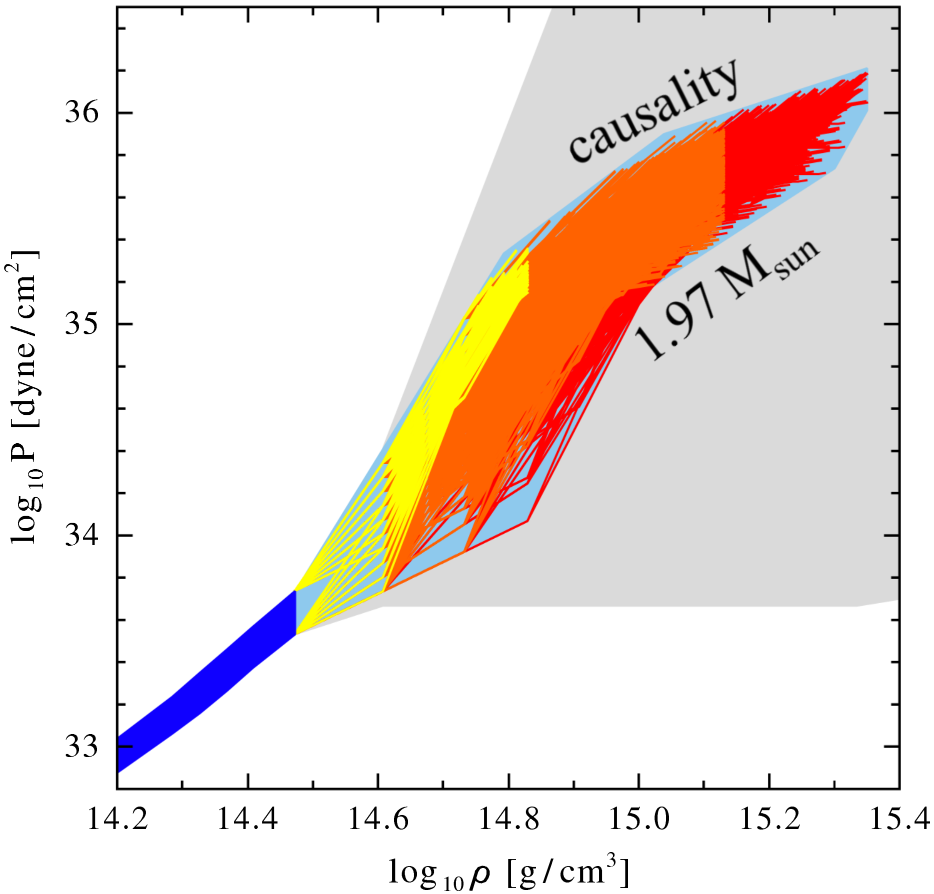


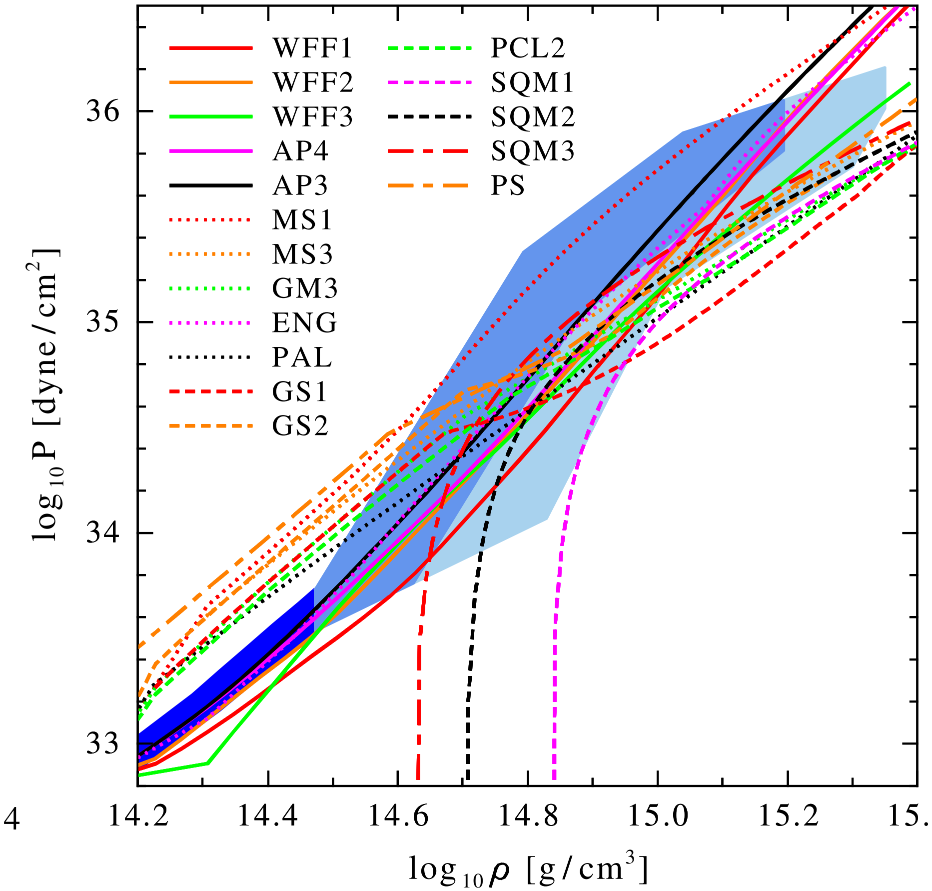
pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

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

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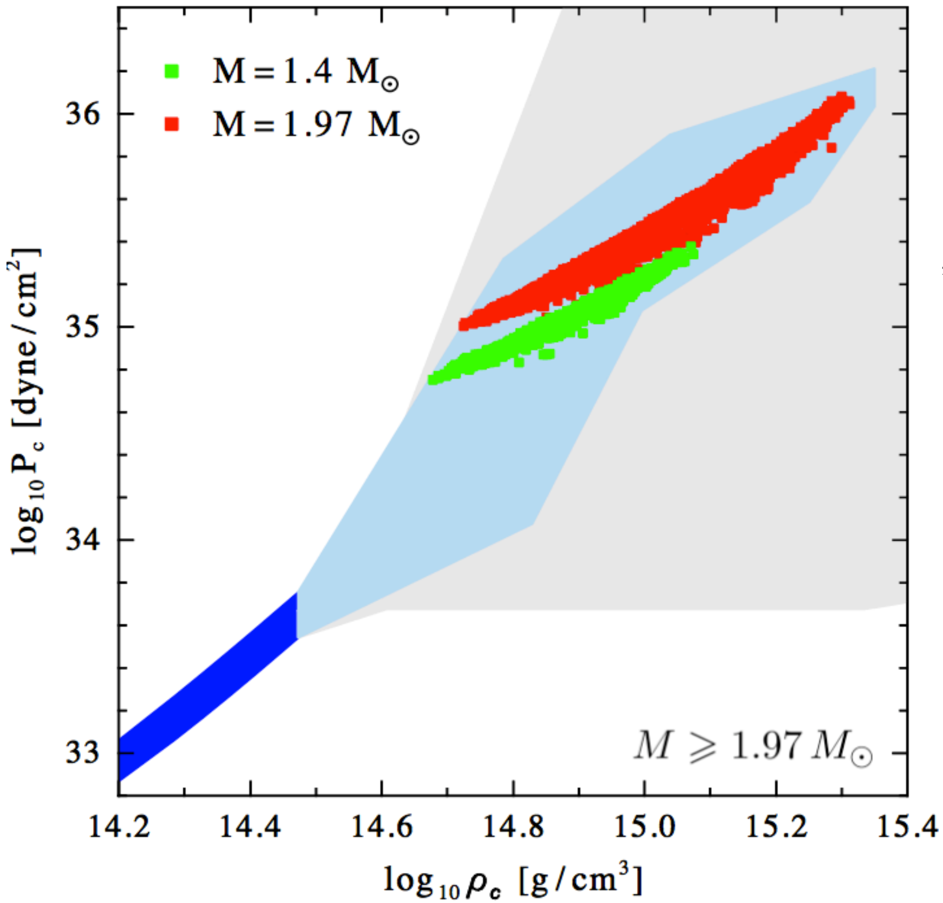
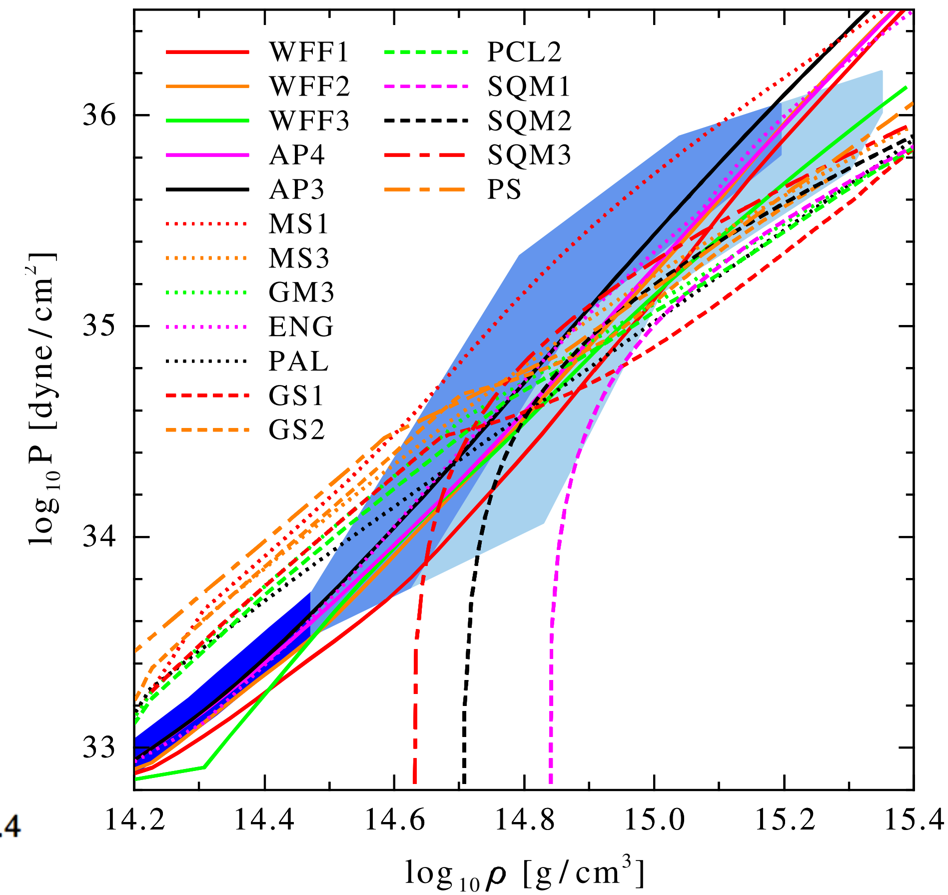
constrain polytropes by causality and require to support 1.97 M_{sun} star





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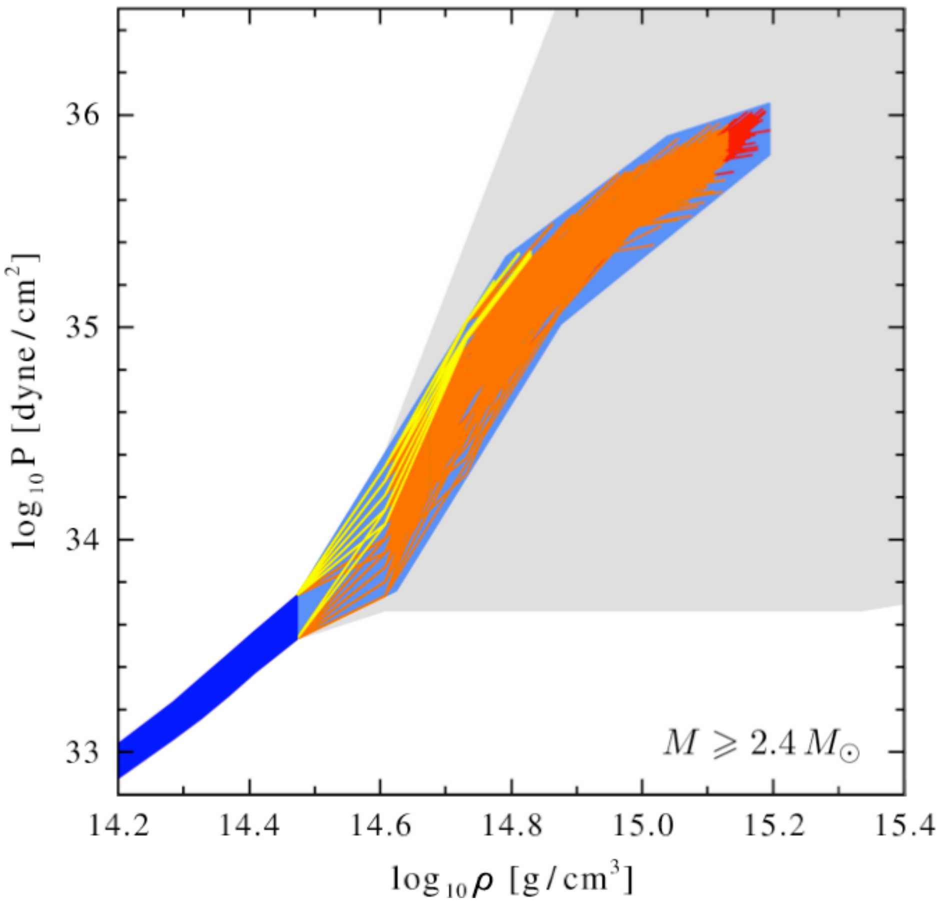
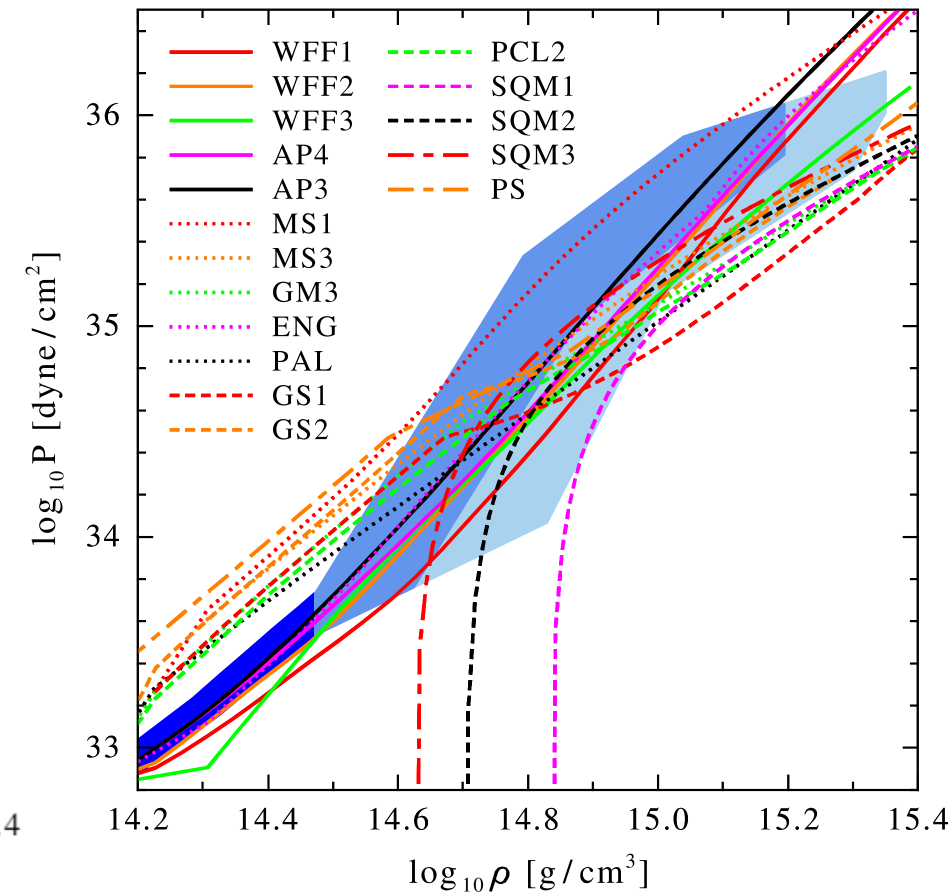
central densities for 1.4 M_{sun} star: 1.7-4.4 ρ_0

Pressure of neutron star matter

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



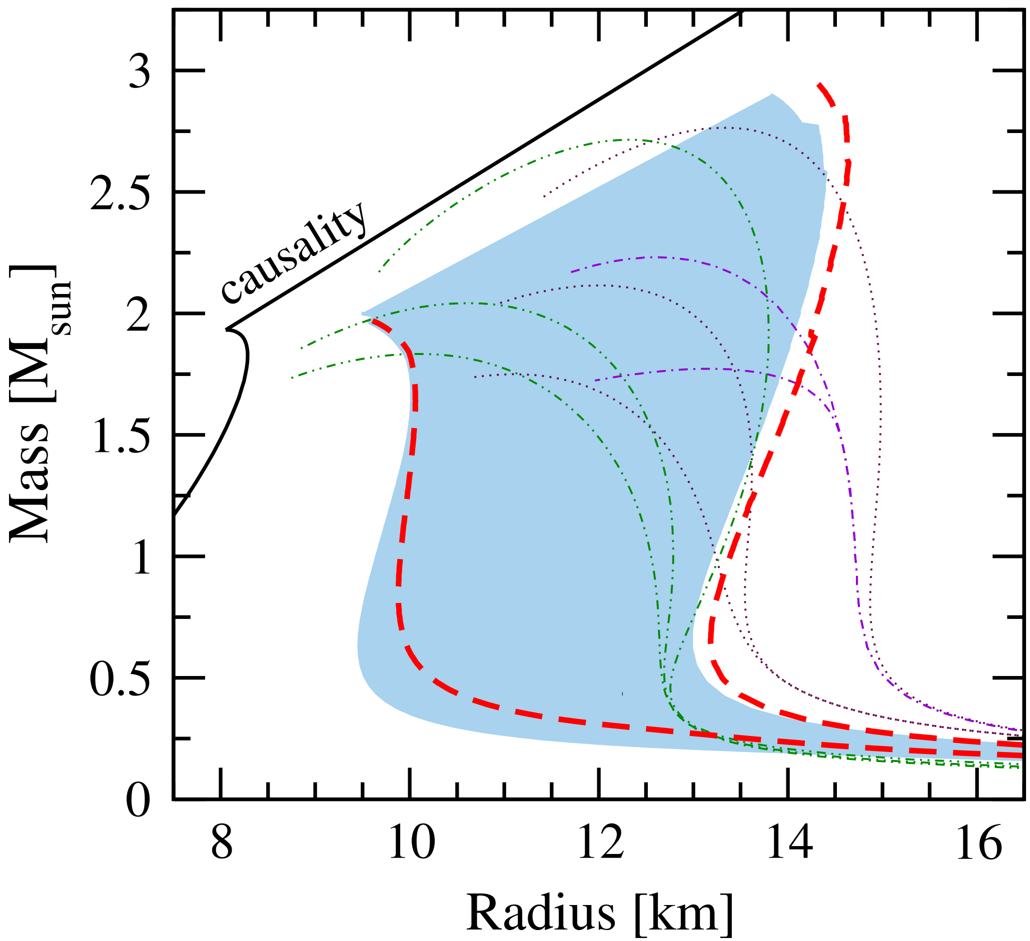


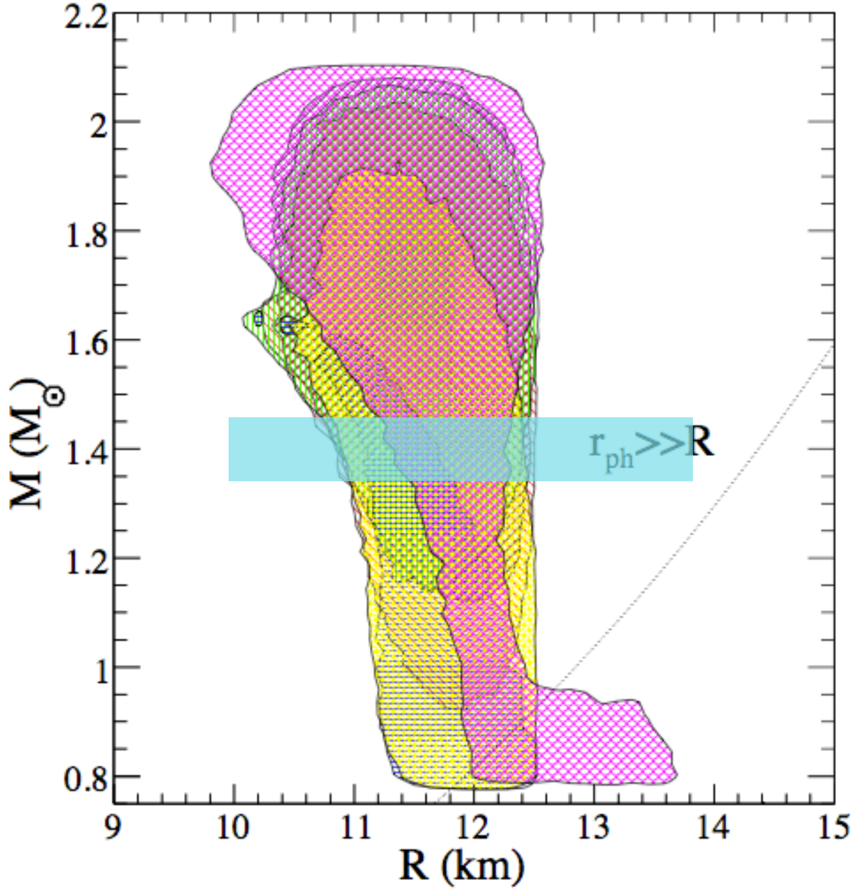
low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

darker blue band for 2.4 M_{sun} star

Neutron star radius constraints

uncertainty from many-body forces and general extrapolation





constrains neutron star radius: 9.9-13.8 km for M=1.4 M_{sun} (±15% !)

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

provides important constraints for EOS for core-collapse supernovae

Neutron-star mergers and gravitational waves

explore sensitivity to neutron-rich matter in neutron-star merger and gw signal

Bauswein, Janka (2012), Bauswein, Janka, Hebeler, AS (2012).

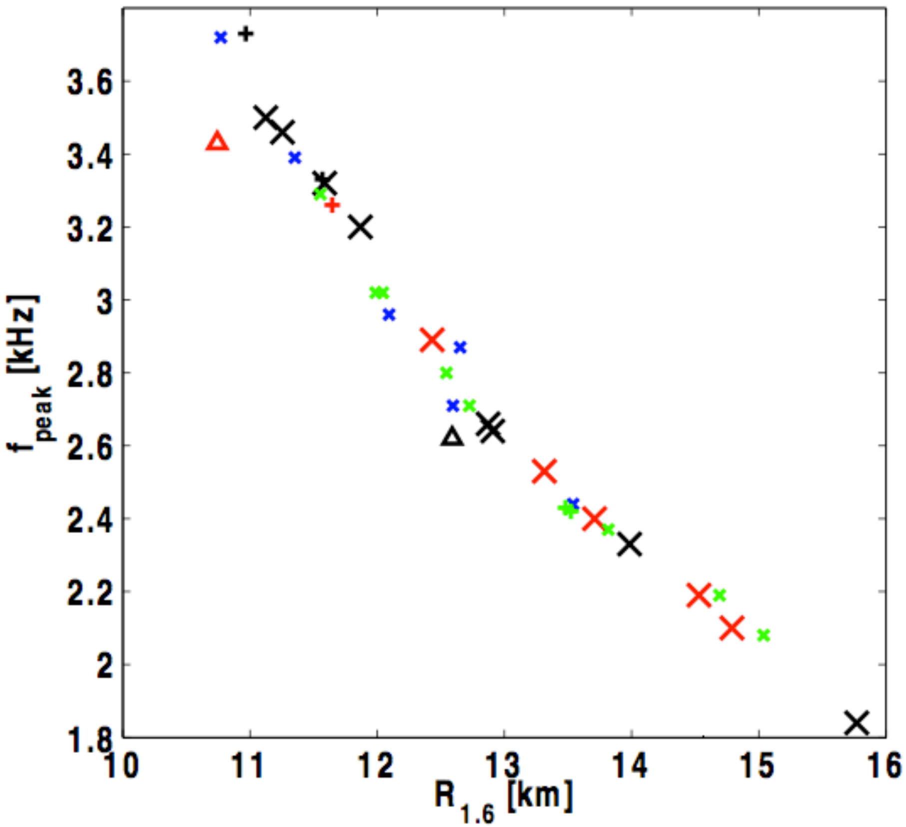


FIG. 10: Peak frequency of the postmerger GW emission versus the radius of a nonrotating NS with 1.6 $M_\odot$ for different EoSs. Symbols have the same meaning as in Fig. 8.

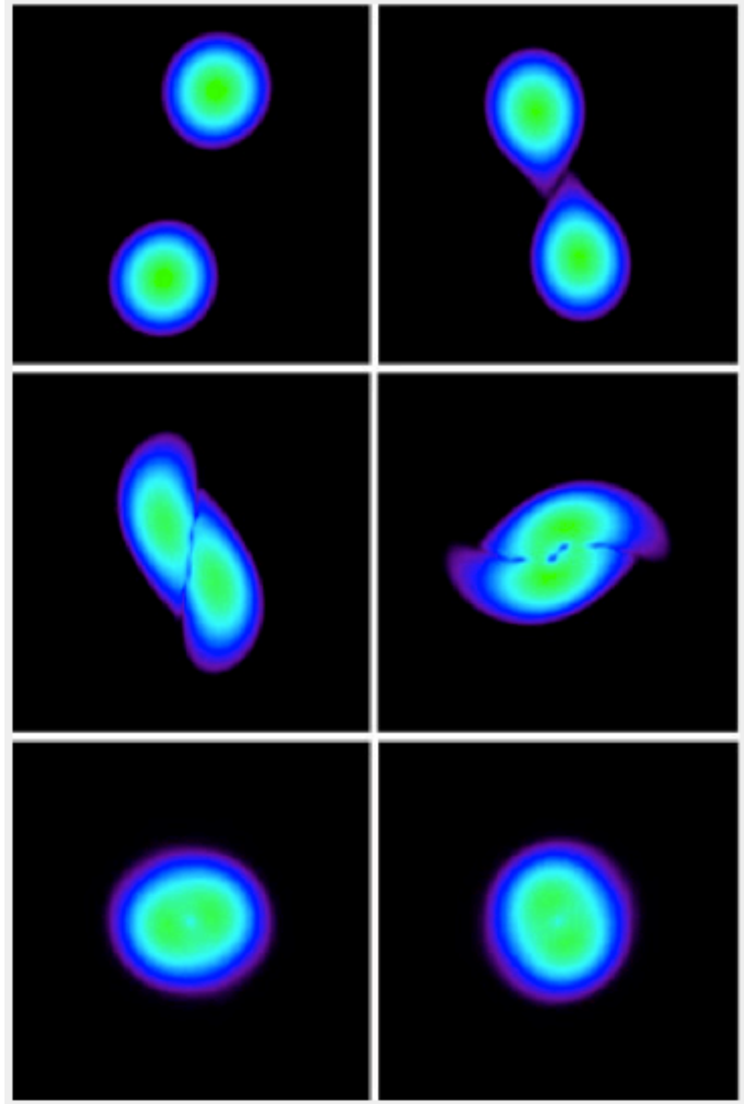


Fig. 1: Various snapshots of the collision of two neutron stars initially revolving around each other. The sequence simulated by the computer covers only 0.03 seconds. The two stars orbit each other counterclockwise (top left) and quickly come closer (top right). Finally they collide (centre left), merge (centre right), and form a dense, superheavy neutron star (bottom). Strong vibrations of the collision remnant are noticeable as deformations in east-west direction and in north-south direction (bottom panels). (Simulation: Andreas Bauswein and H.-Thomas Janka/MPA)

Summary

first calculation with N^3LO 3N and 4N interactions

dominant parts where Δ's can enter

3N forces are dominant uncertainty of neutron (star) matter below nuclear densities

constrains neutron-star radii and equation of state

3N force provide forefront connection between neutron-rich nuclei and neutron-rich matter