# Neutron matter: From cold atoms to astrophysics

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TECHNISCHE
UNIVERSITÄT
DARMSTADT

EMMI

EMMI Workshop “Quark Gluon Plasma meets Cold Atoms III”
Hirschegg, Aug. 27, 2012

DFG

HELMHOLTZ ASSOCIATION

Minerva Stiftung

Bundesministerium
für Bildung
und Forschung

# Main points

Advances in nuclear forces and nuclear matter theory

Impact on neutron stars:

provides strong constraints for the equation of state

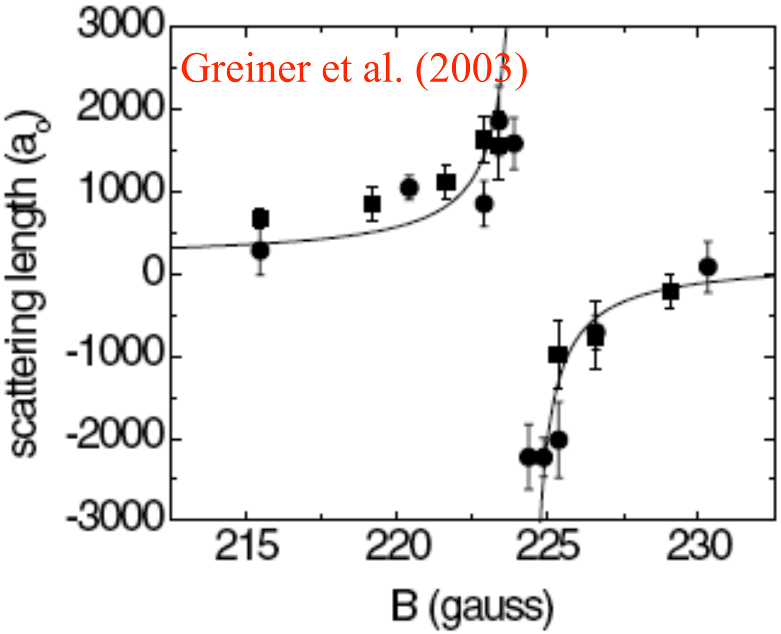
neutron star radius 9.9-13.8 km for $M=1.4\ M_{sun}$ (±15%)

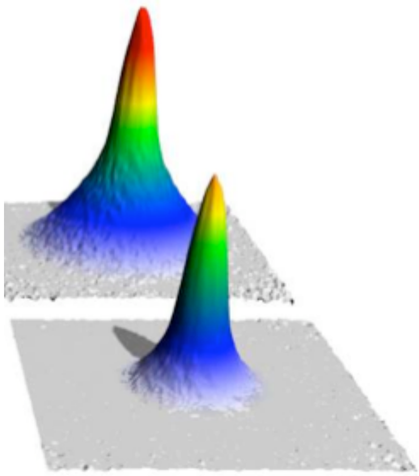
K. Hebeler, J.M. Lattimer, C.J. Pethick, AS, PRL **105**, 161102 (2010) and in prep.
I. Tews, T. Krüger, K. Hebeler, AS, arXiv:1206.0025.

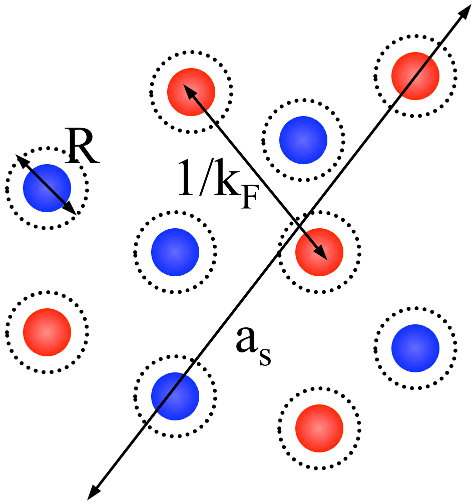
Impact on neutrino-matter interactions

S. Bacca, K. Hally, C.J. Pethick, AS, PRC **80**, 032802(R) (2009) and
S. Bacca, K. Hally, M. Liebendörfer, A. Perego, C.J. Pethick, AS, ApJ (2012).

# Large scattering lengths: Universal properties at low densities







$$a_{\rm nn} \; = \; -18.5 \pm 0.3 \, \text{fm}$$

strong interactions via Feshbach resonances

large for neutrons

dilute Fermi system with large scattering length has universal properties

$$0 \leftarrow 1/a_s \quad \ll \quad k_{\rm F} \quad \ll \quad 1/r_e \, , 1/R \, , \ldots \rightarrow \; \infty$$

strongly-interacting

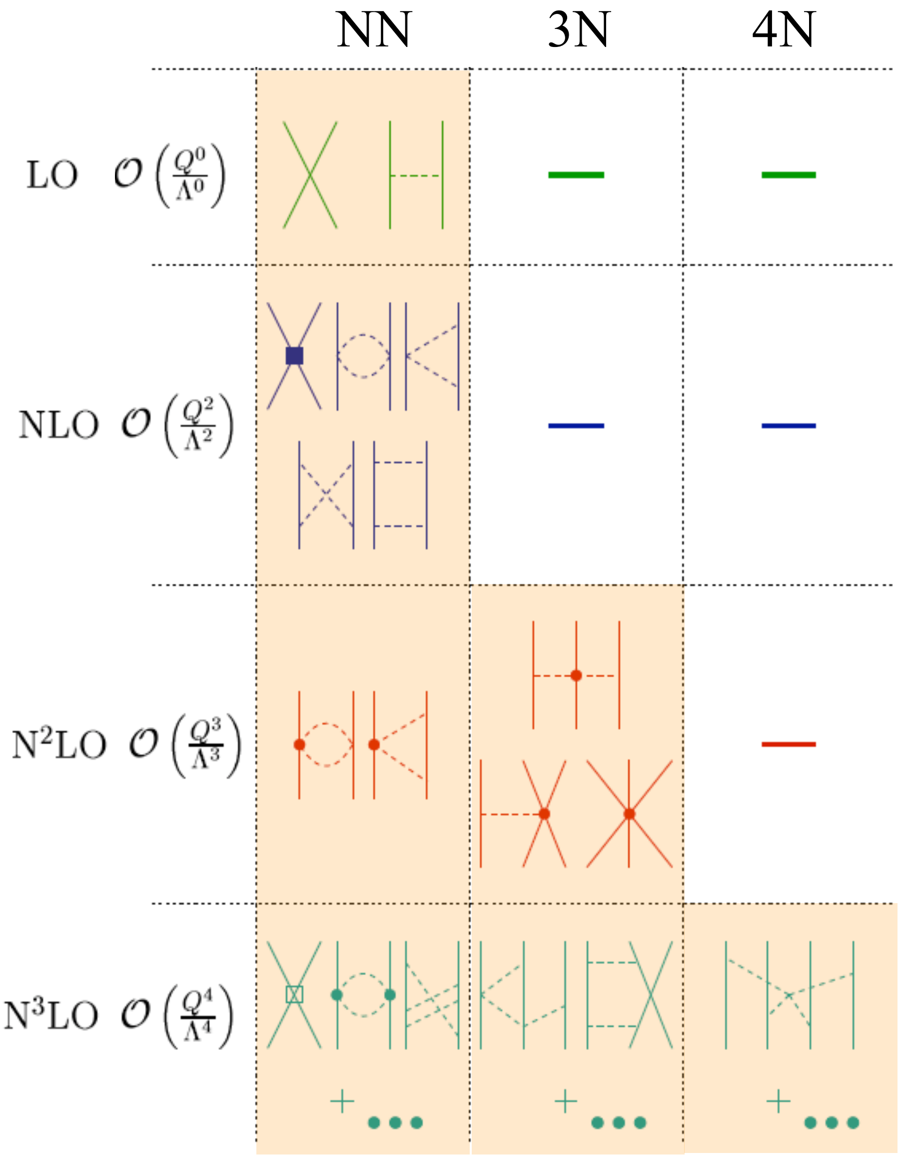
dilute

only Fermi momentum or density sets scale

physics is independent of interaction/system details:
from dilute neutron matter to resonant $^6$Li or $^{40}$K atoms in traps

# 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

(compare to multipole expansion
for a charge distribution)

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

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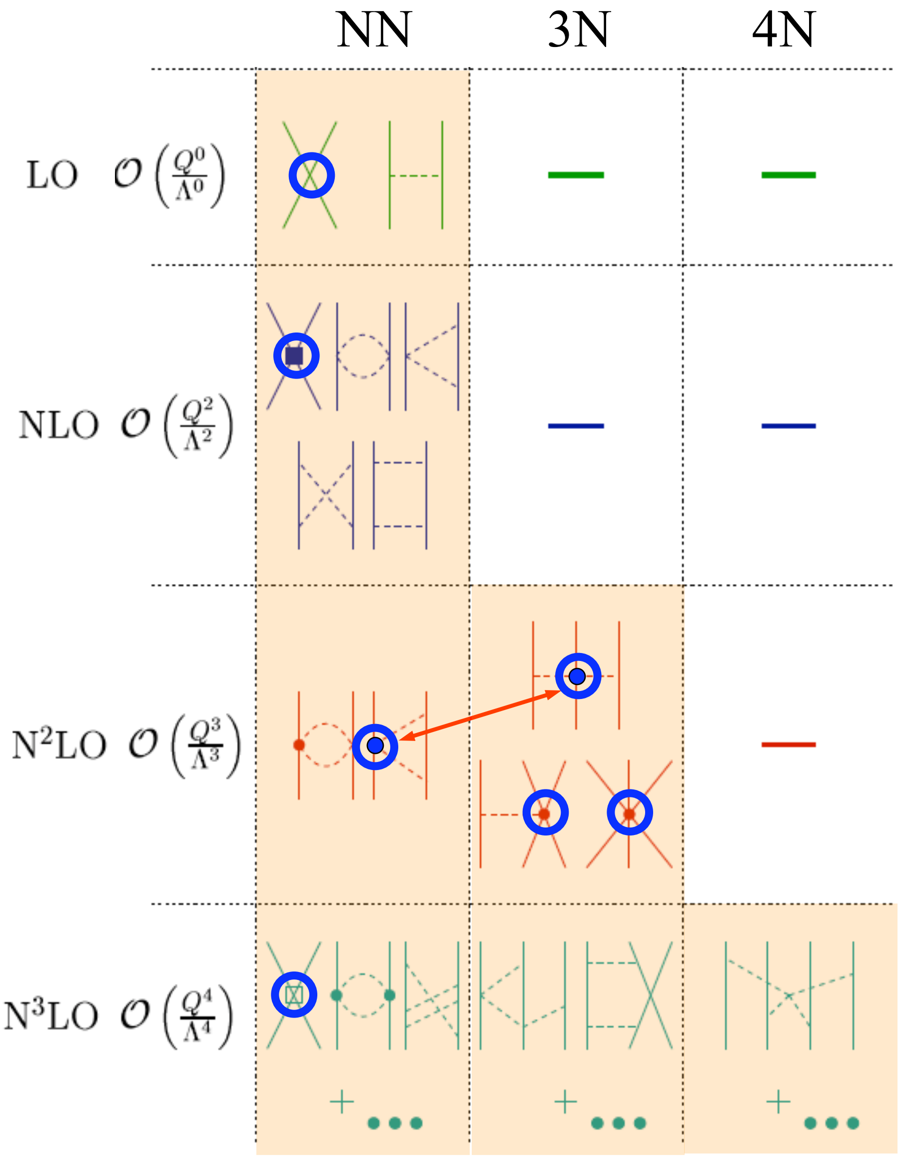

include long-range pion physics

few short-range couplings,
fit to experiment once

systematic: can work to desired accuracy and obtain error estimates

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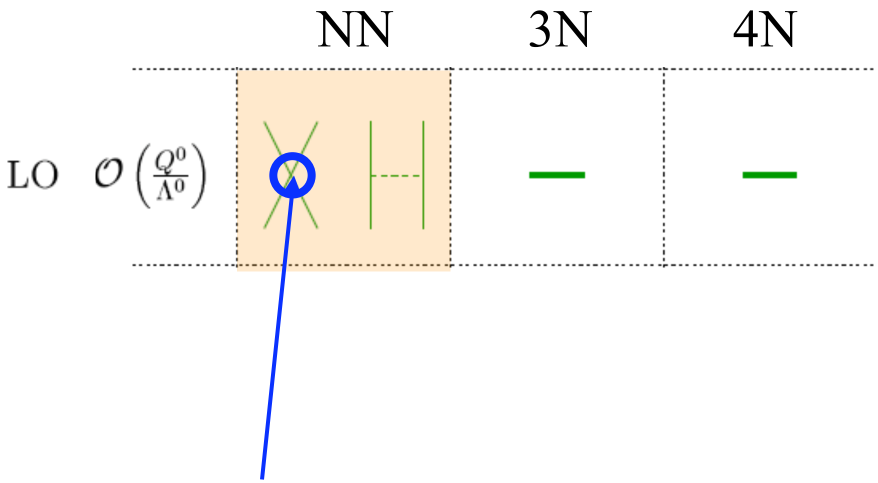
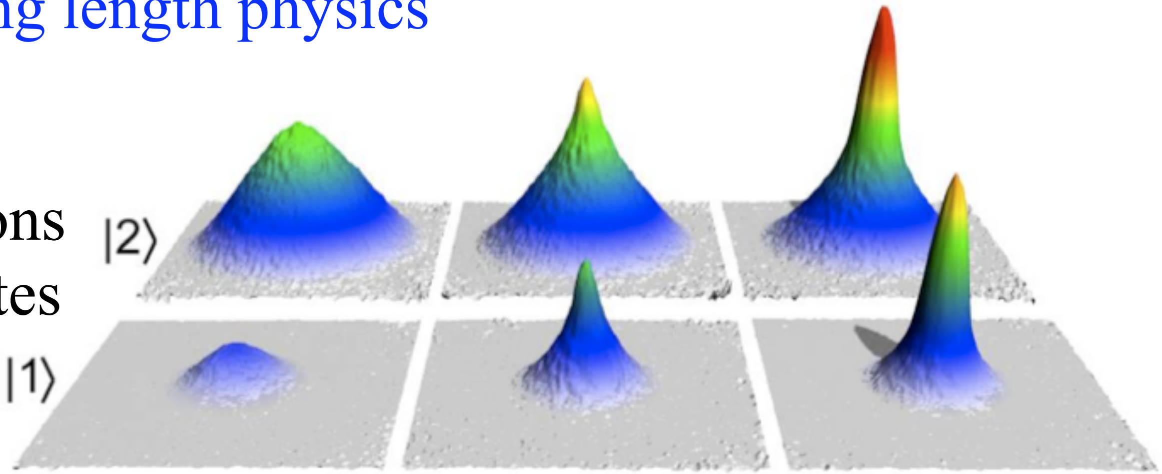


large scattering length physics

$^6$Li fermions
2 spin states



from M. Zwierlein

neutrons with same density, temperature and spin polarization
have the same properties!

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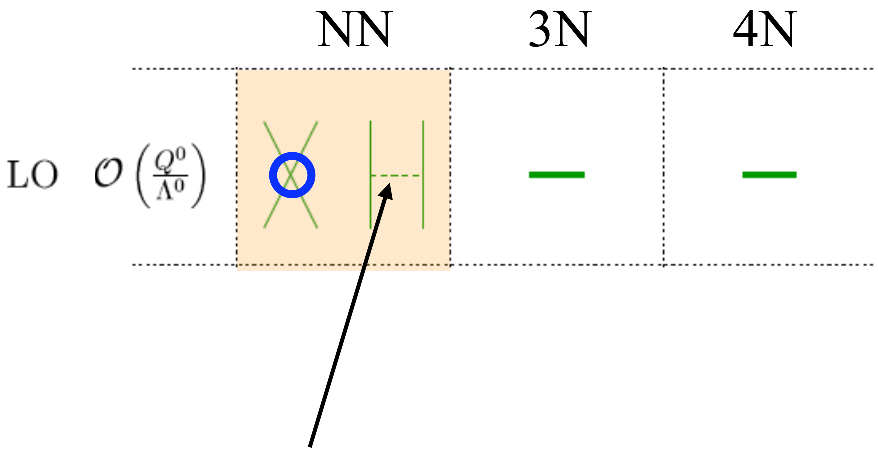
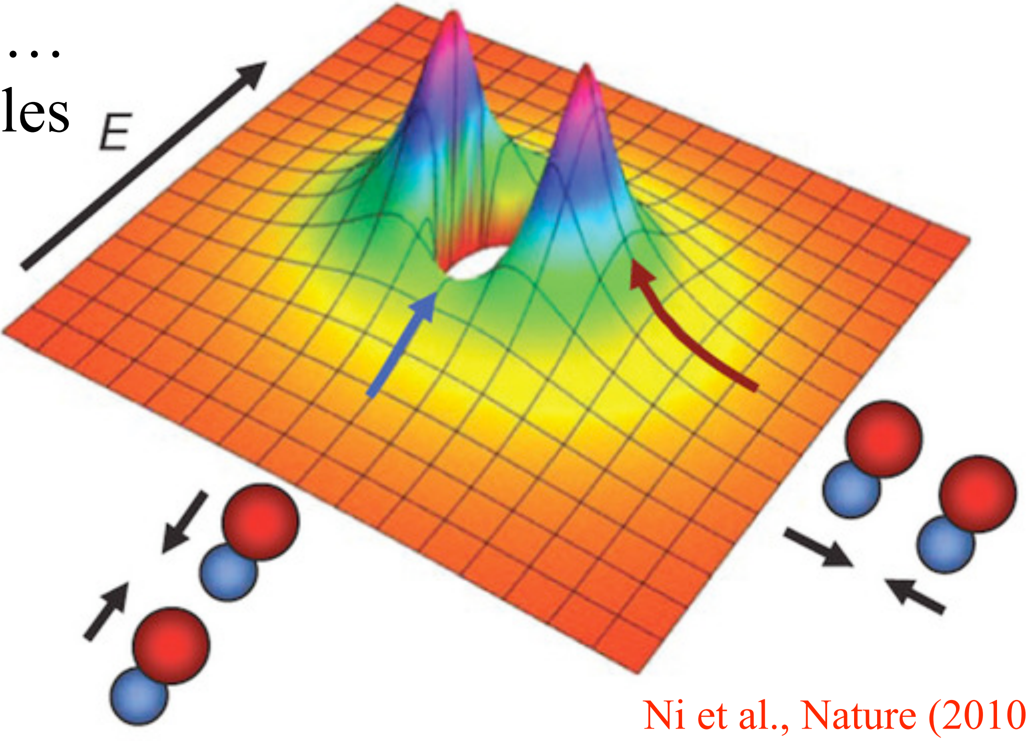


pion tensor/dipole interactions + …
→ compare to cold polar molecules



Ni et al., Nature (2010)

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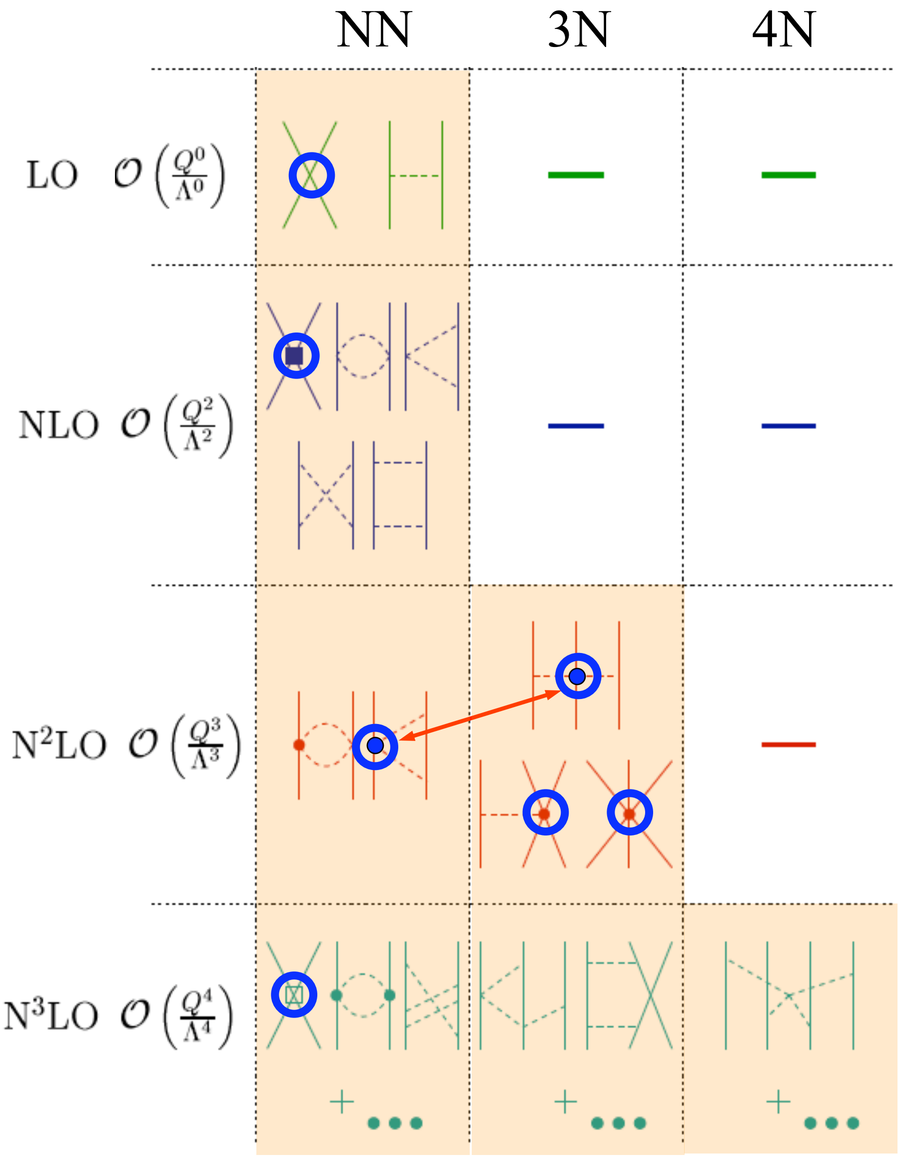

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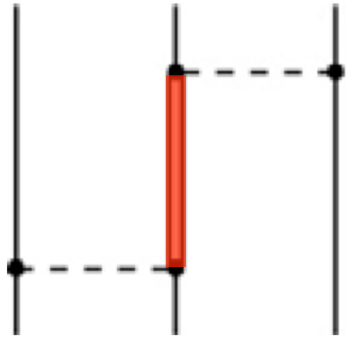
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

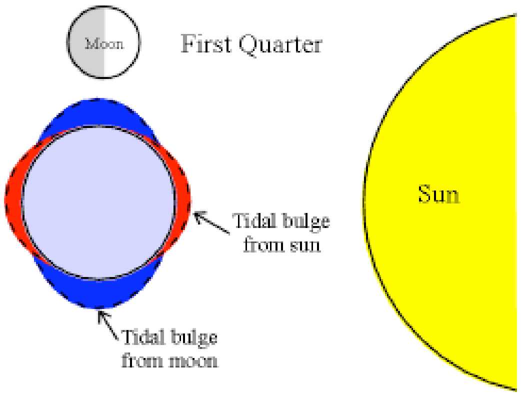
# Why are there three-nucleon (3N) forces?

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

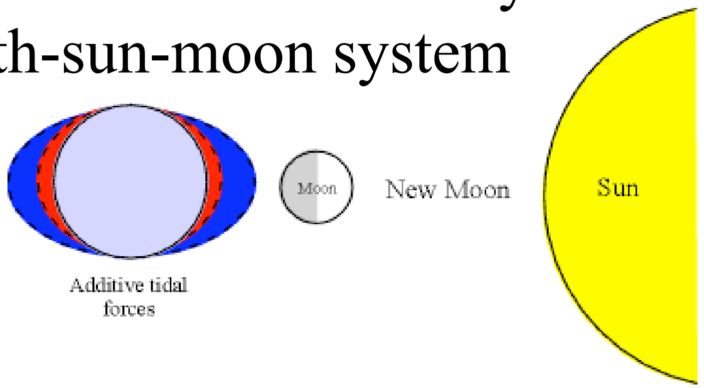
dominant contribution from Δ(1232 MeV)

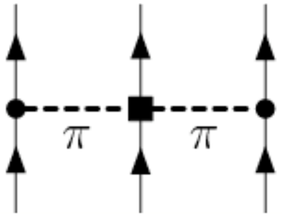


+ many shorter-range parts



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



in chiral EFT (Delta-less):  + shorter-range parts

EFT provides a systematic and powerful approach to organize 3N forces

# Chiral Effective Field Theory and many-body forces

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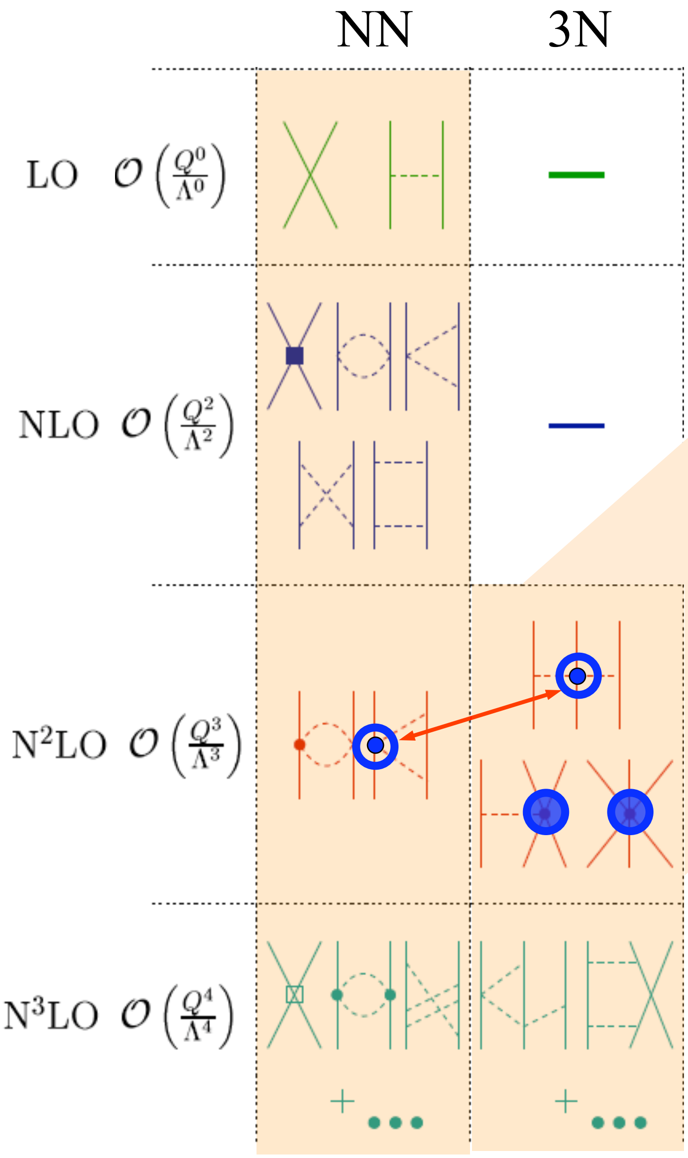
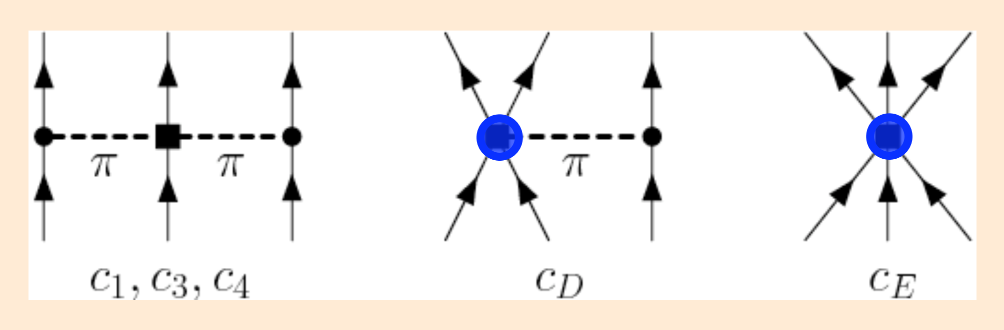


consistent NN-3N interactions

3N,4N: only 2 new couplings to N$^3$LO



long-range 3N: $c_i$ from πN and NN

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

3- and 4-neutron forces are predicted to N$^3$LO ($c_{D,E}$ don't contribute)

Hebeler, AS (2010)

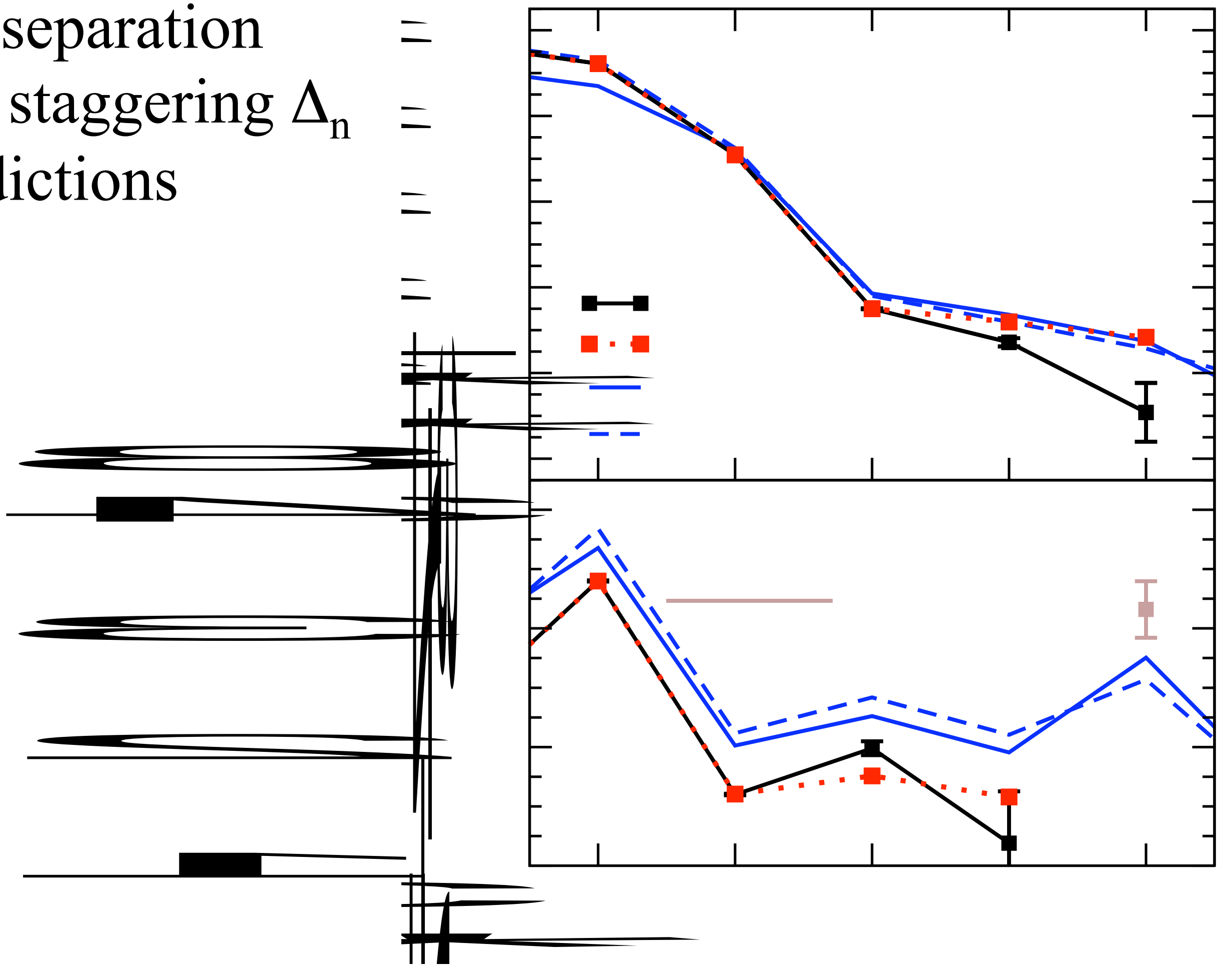
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

# new $^{51,52}$Ca TITAN measurements

$^{52}$Ca is 1.75 MeV more bound compared to atomic mass evaluation

Gallant et al. (2012)

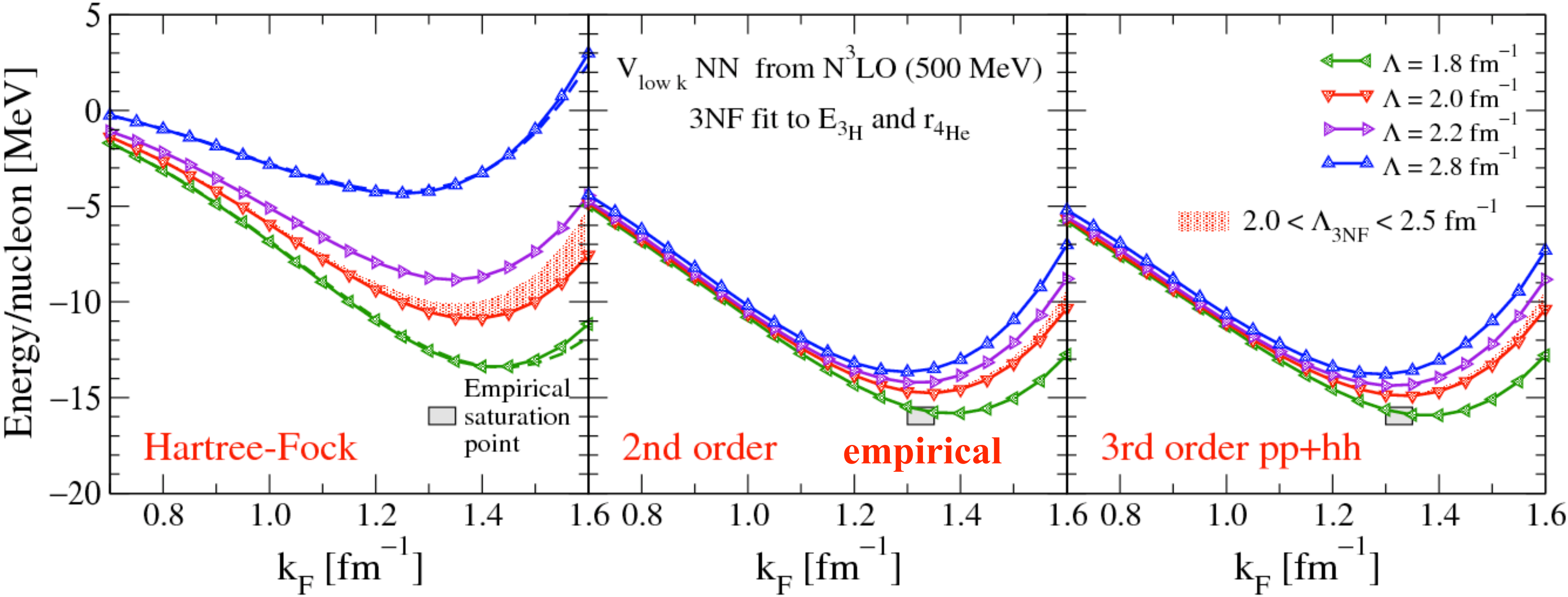
behavior of two-neutron separation energy $S_{2n}$ and odd-even staggering $\Delta_n$ agrees with NN+3N predictions



# Impact of 3N forces on nuclear matter

chiral 3N forces fit to light nuclei
predict nuclear matter saturation
with theoretical uncertainties

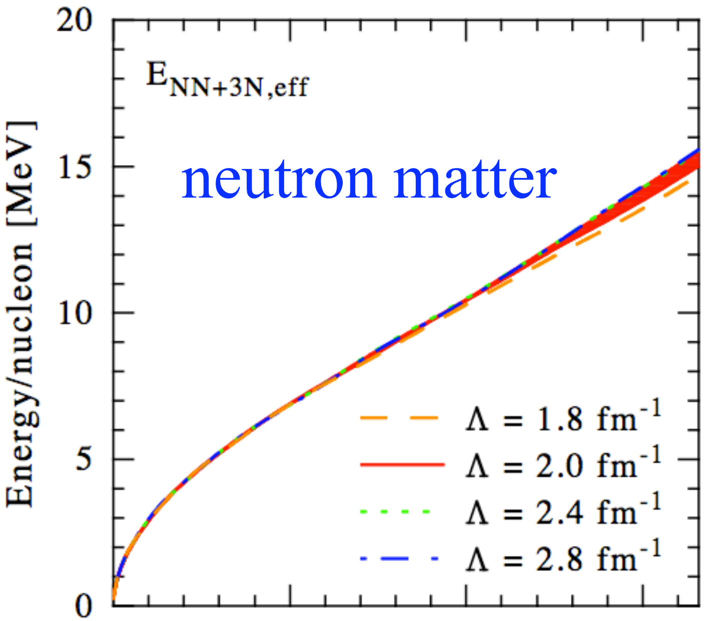
Hebeler et al. (2011), Bogner et al. (2005)

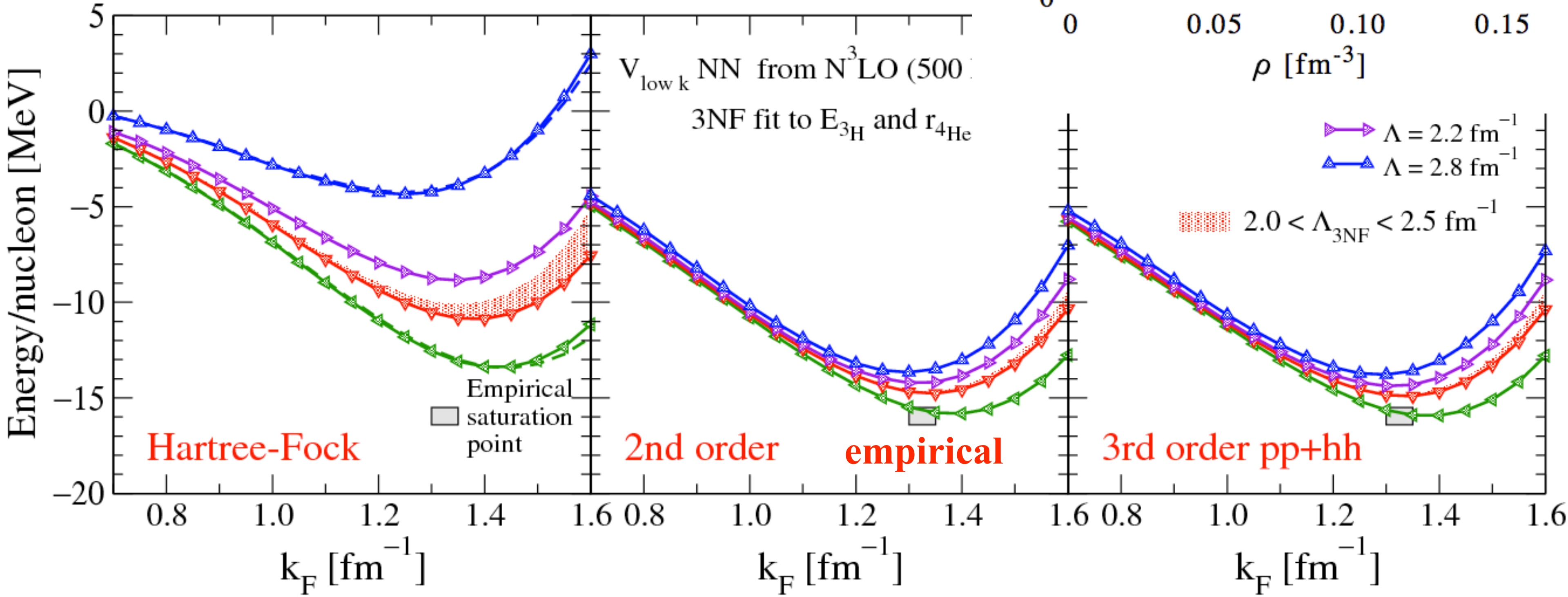


# Impact of 3N forces on neutron matter

neutron matter is simpler system,
only long-range parts of 3N forces
contribute ($c_1$ and $c_3$)

Hebeler, AS (2010)





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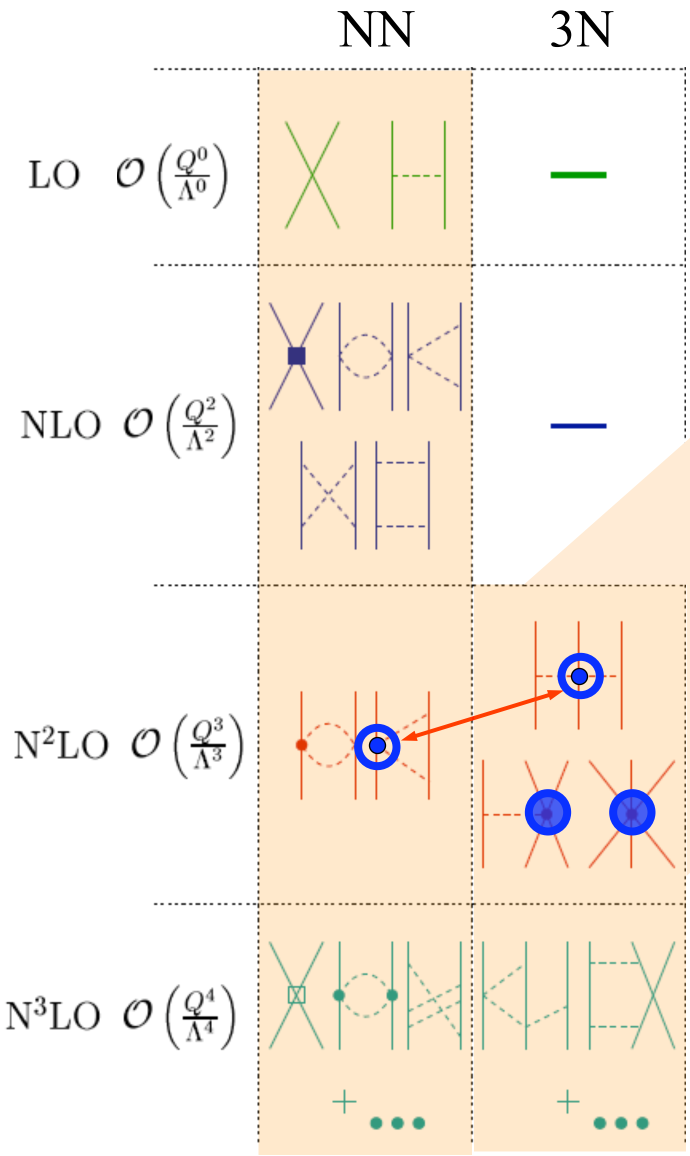

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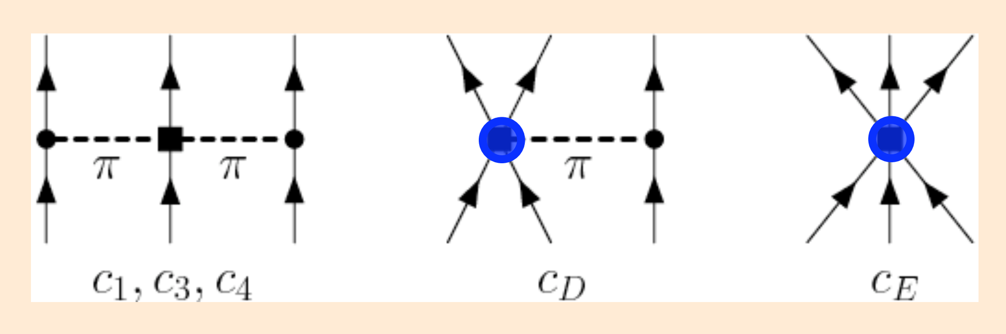

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Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

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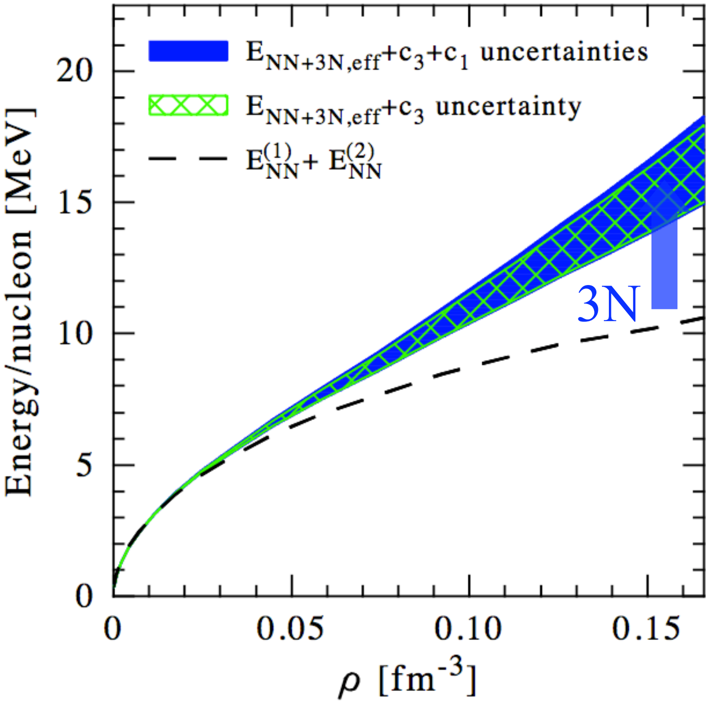
neutron matter uncertainties
dominated by 3N forces ($c_3$ coupling)

Hebeler, AS (2010)



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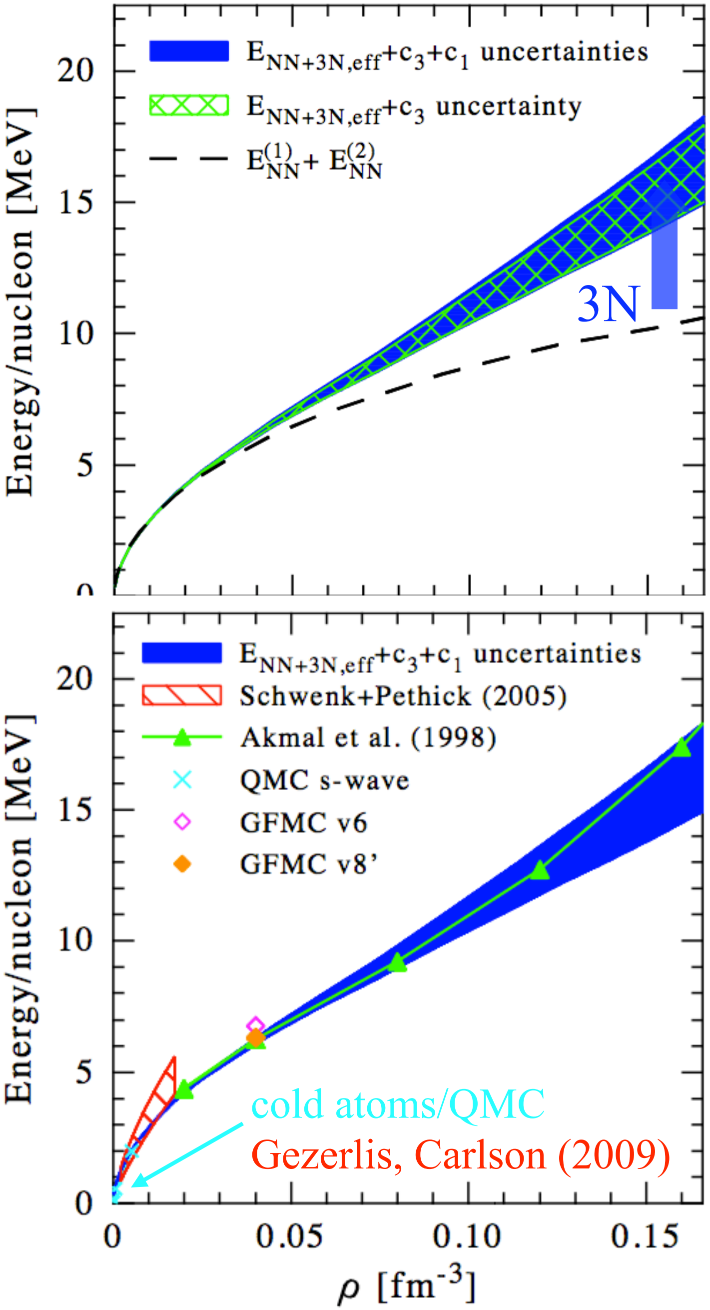
Hebeler, AS (2010)

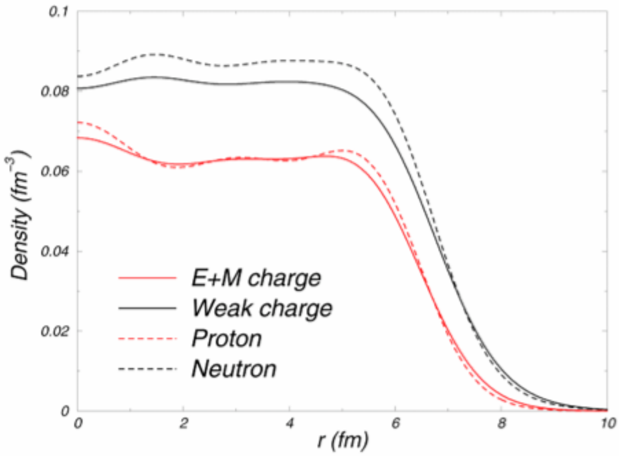
other microscopic calculations within band
(but without uncertainties)



# Neutron skin of $^{208}$Pb

probes neutron matter energy/pressure,
neutron matter band predicts
neutron skin of $^{208}$Pb: 0.17±0.03 fm

Hebeler et al. (2010)



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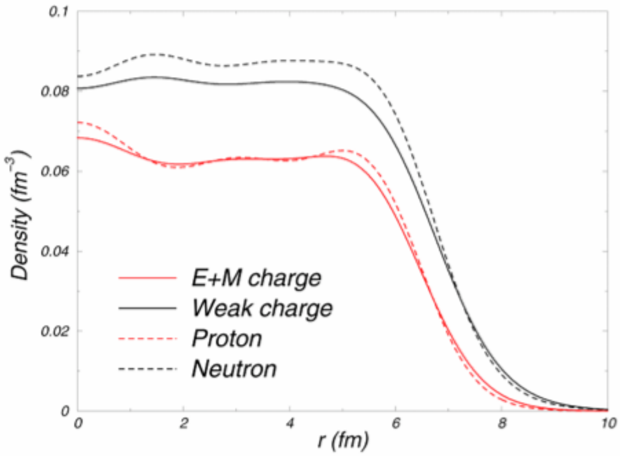

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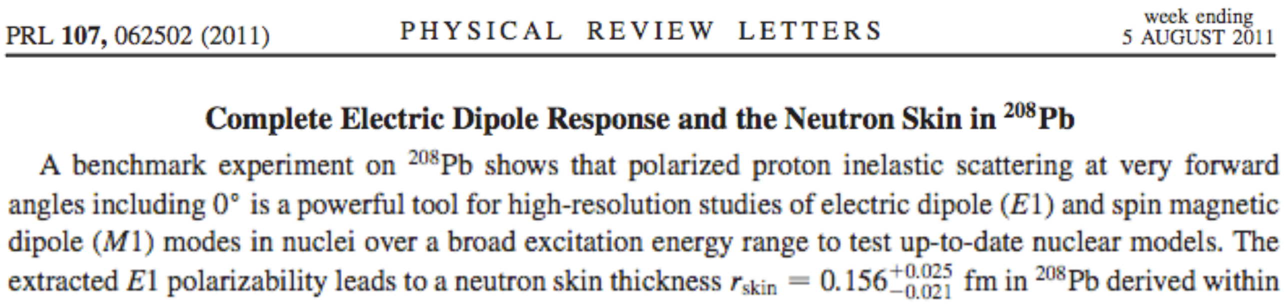
in excellent agreement with extraction from complete E1 response
0.156+0.025-0.021 fm

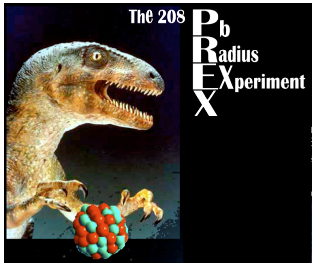


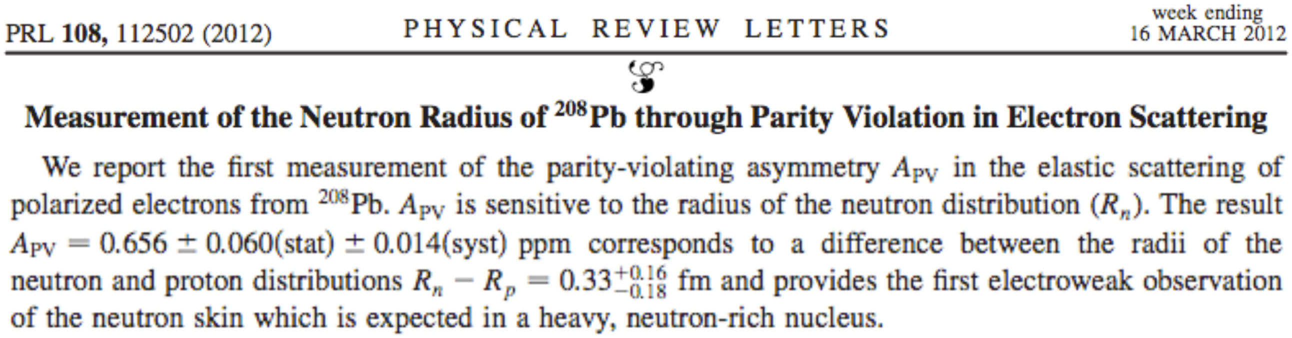
PRL **107,** 062502 (2011) PHYSICAL REVIEW LETTERS week ending 5 AUGUST 2011

**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 $r_{\mathrm{skin}} = 0.156^{+0.025}_{-0.021}$ 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 $A_{\mathrm{PV}}$ in the elastic scattering of polarized electrons from $^{208}$Pb. $A_{\mathrm{PV}}$ is sensitive to the radius of the neutron distribution ($R_n$). The result $A_{\mathrm{PV}} = 0.656 \pm 0.060(\mathrm{stat}) \pm 0.014(\mathrm{syst})$ 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 pressure of neutron matter

neutron matter band predicts
symmetry energy $S_v$ and
its density dependence L

comparison to experimental
and observational constraints
Lattimer, Lim (2012)

neutron matter constraints
H: Hebeler et al. (2010) and in prep.

G: Gandolfi et al. (2011)
predicts correlation
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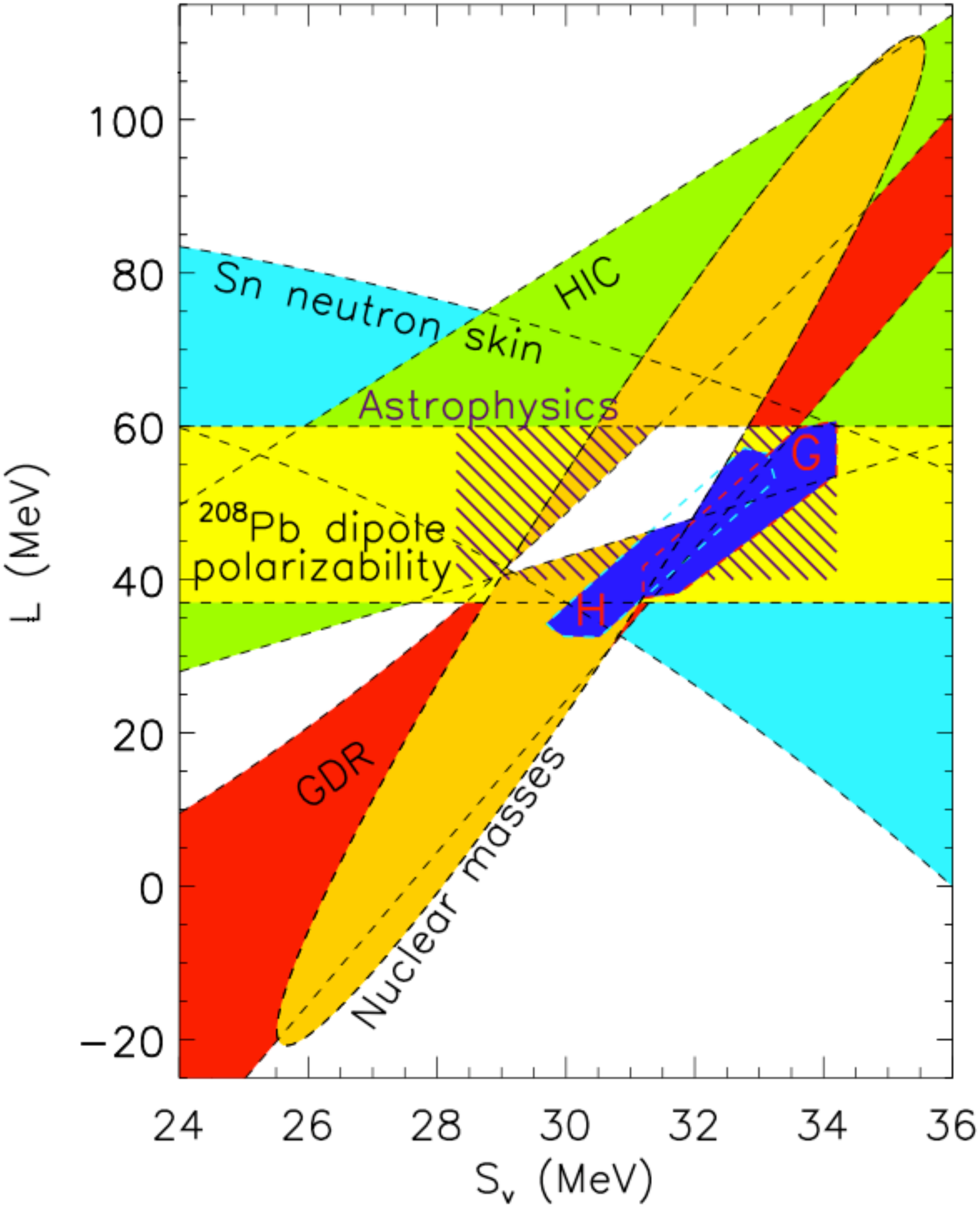

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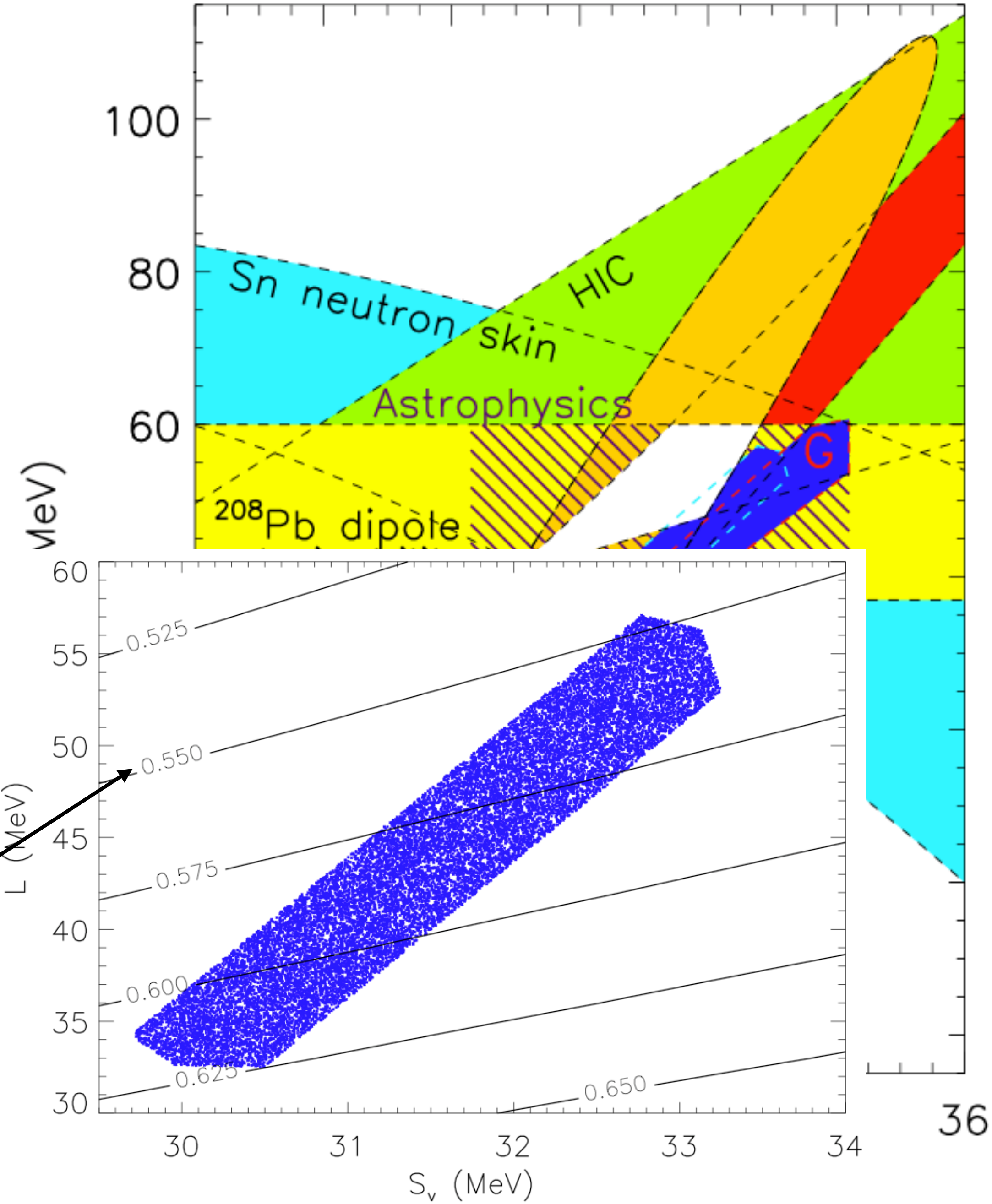
lower limit on crust-core
transition density



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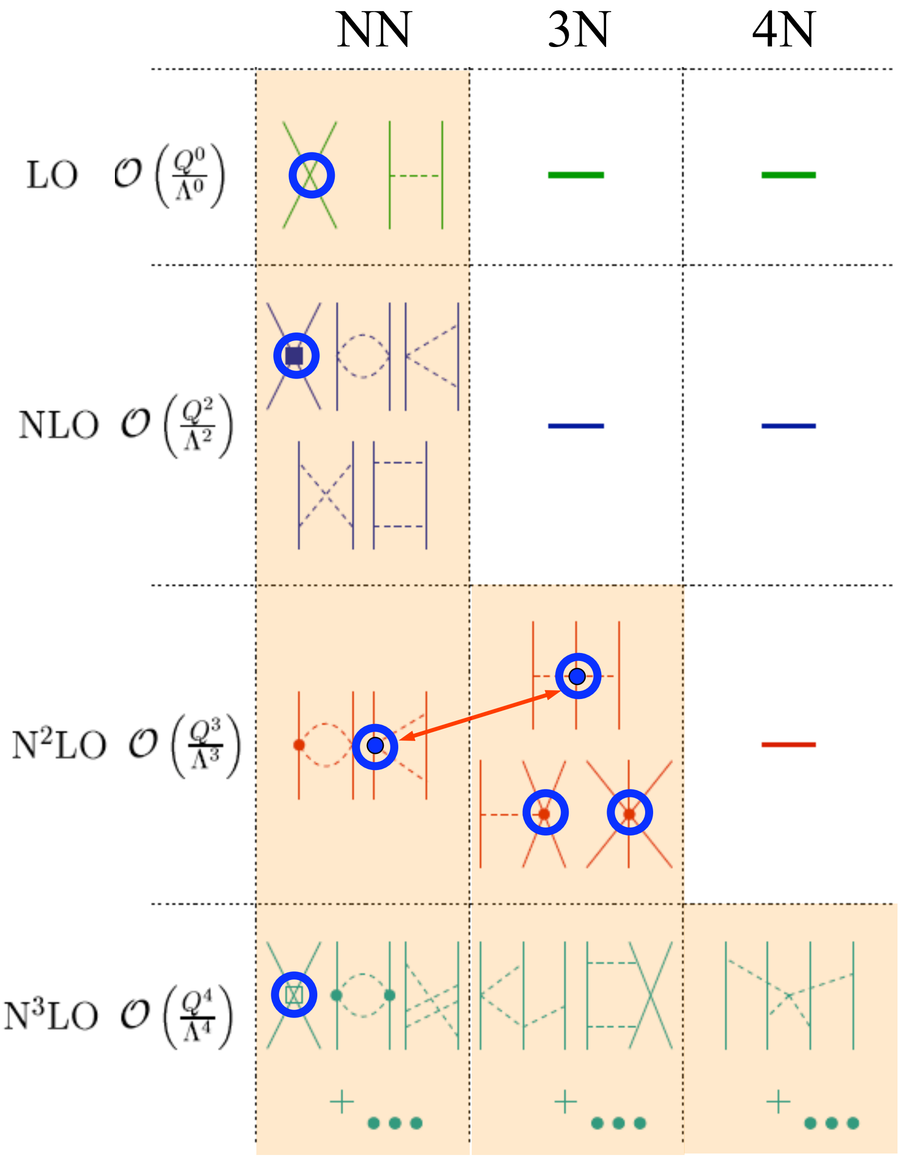

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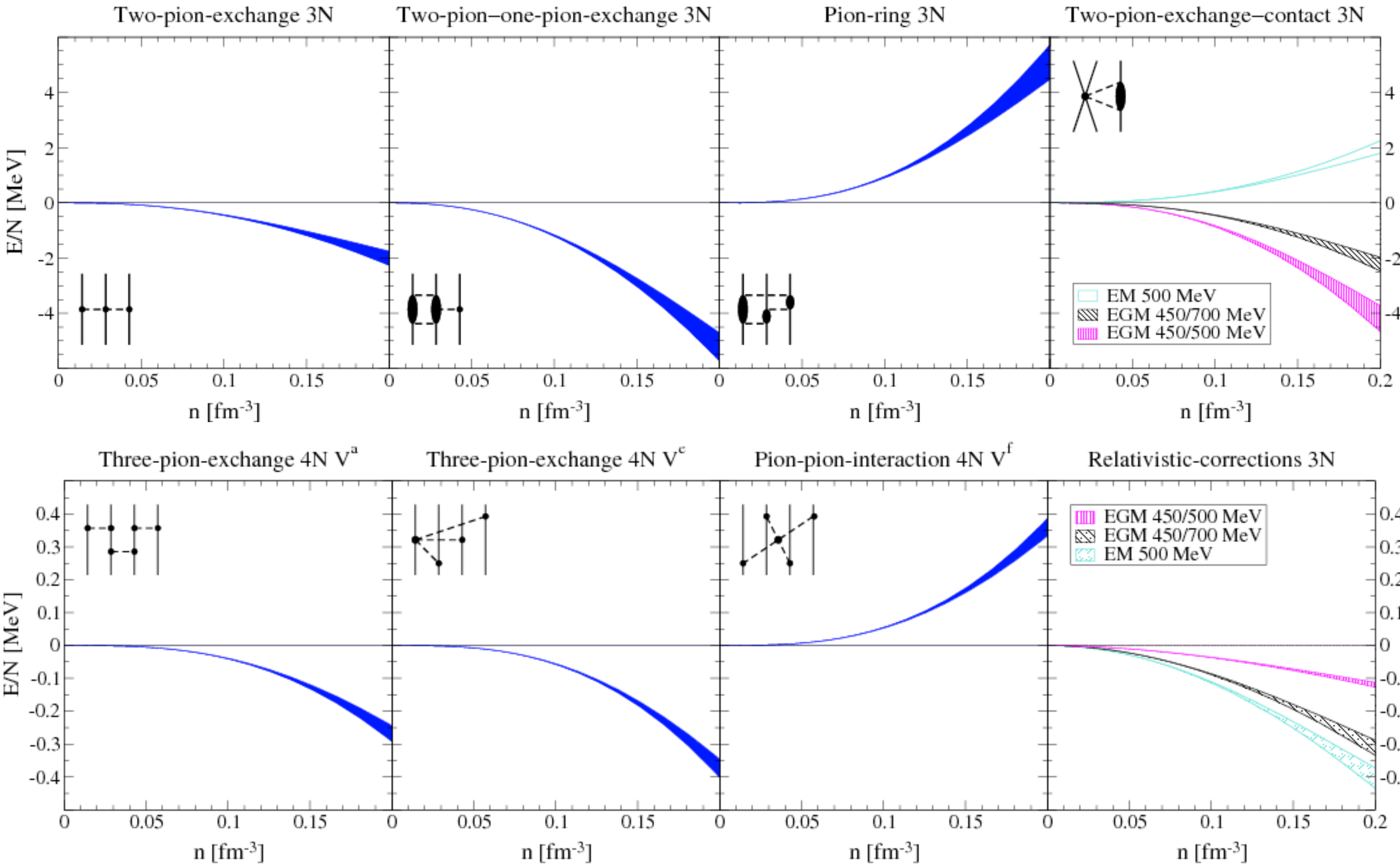
# Complete N$^3$LO calculation of neutron matter



Krüger, Tews, Hebeler, AS, arXiv:1206.0025.

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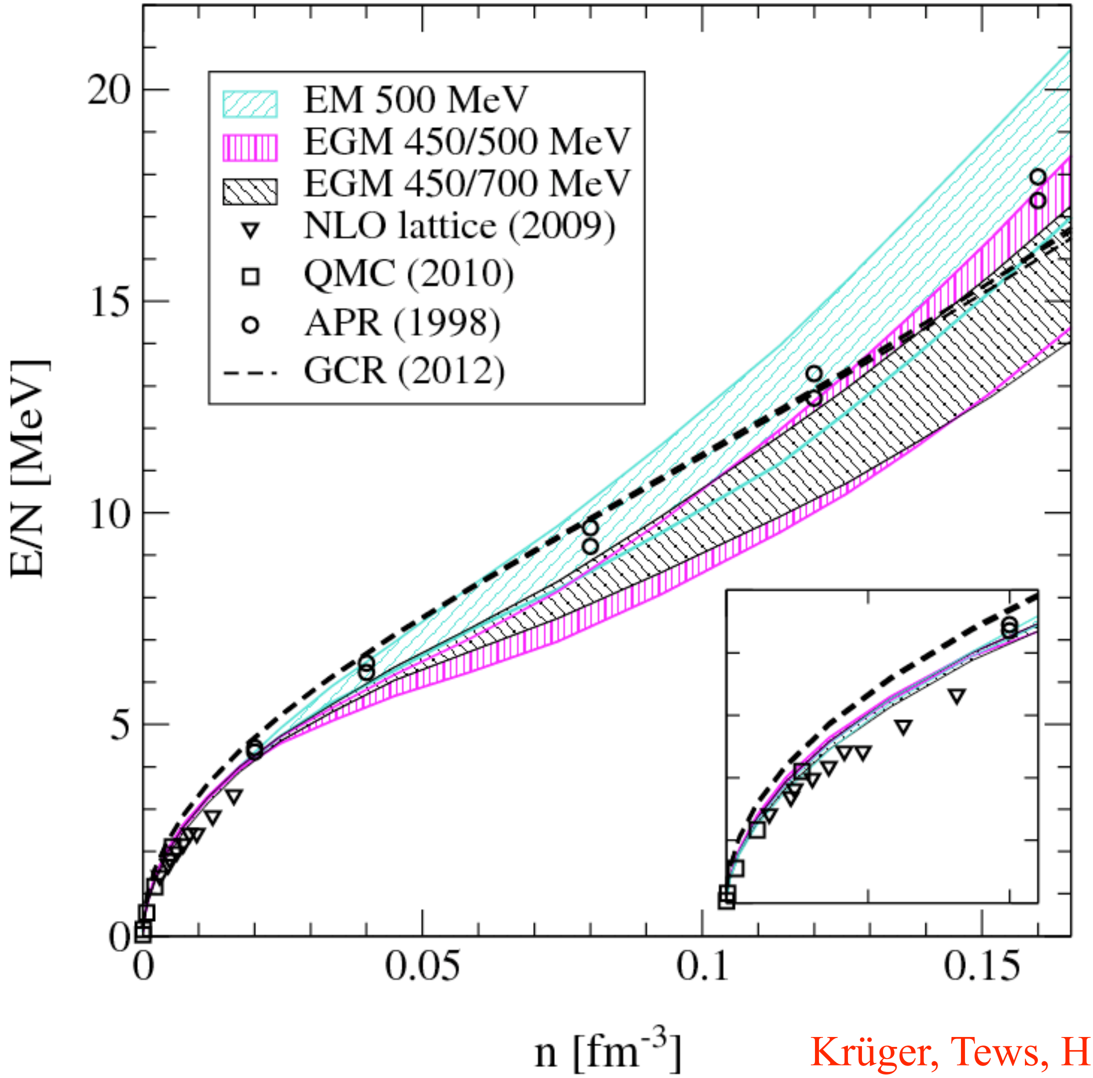
first complete N$^3$LO result

no RG evolution necessary, includes uncertainties from bare NN, 3N, 4N



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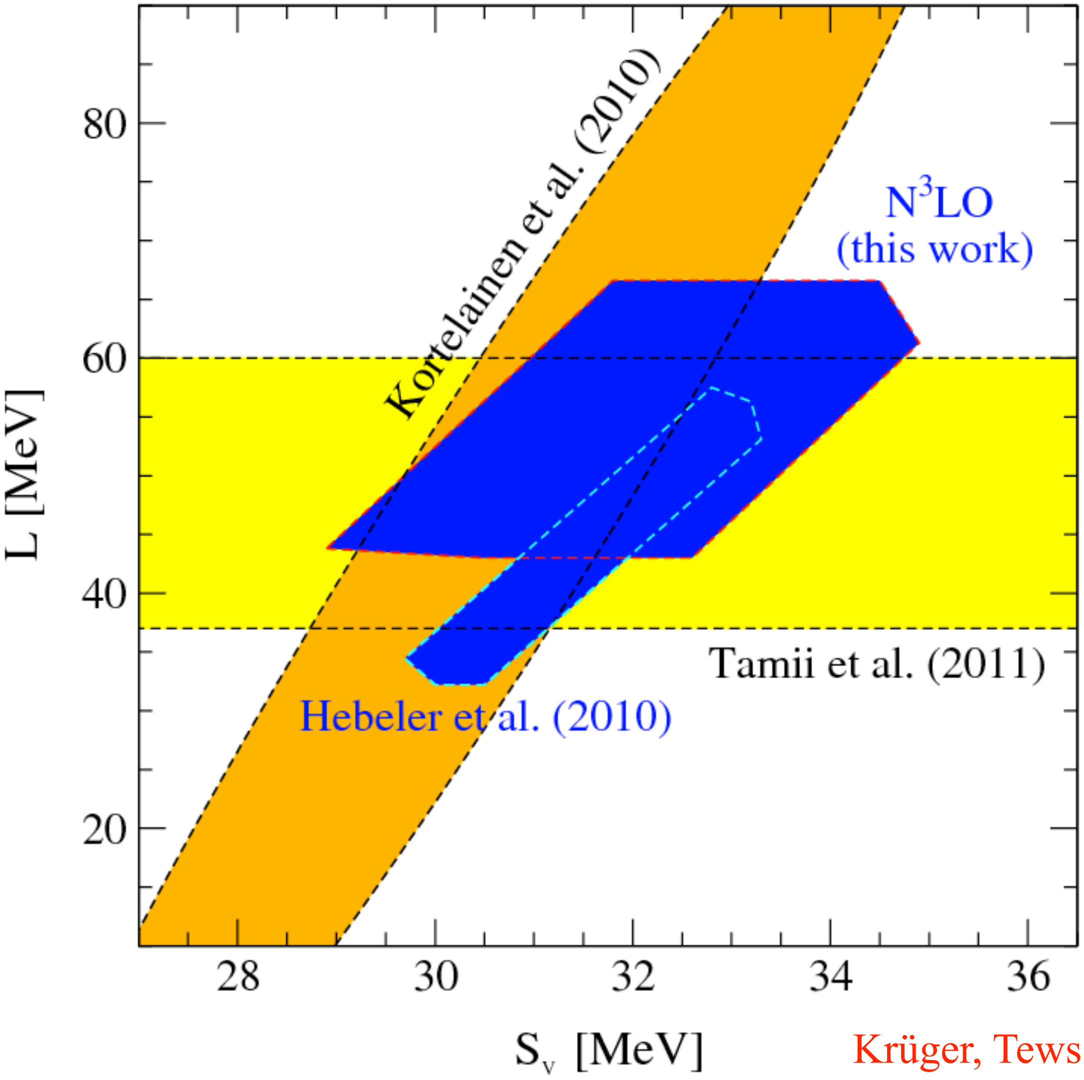


N$^3$LO correlation broader because more density dependences

Krüger, Tews, Hebeler, AS, arXiv:1206.0025.

# Discovery of the heaviest neutron star

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

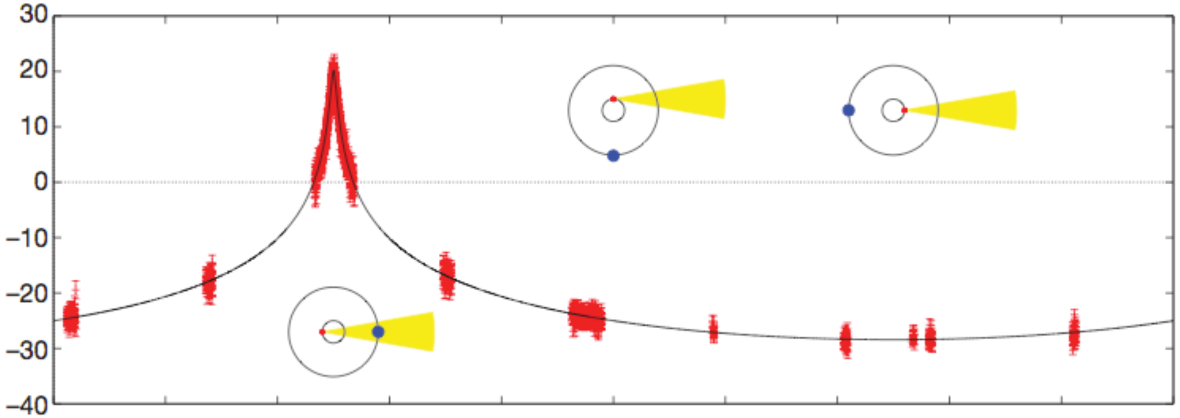
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

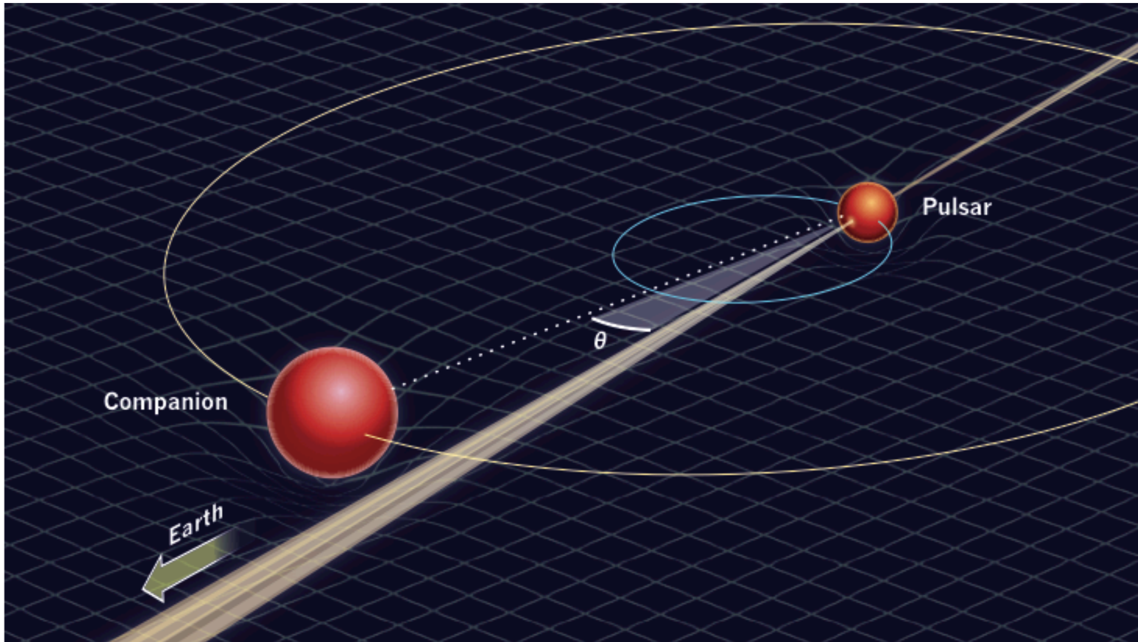
Nature (2010)

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 $M_{sun}$)

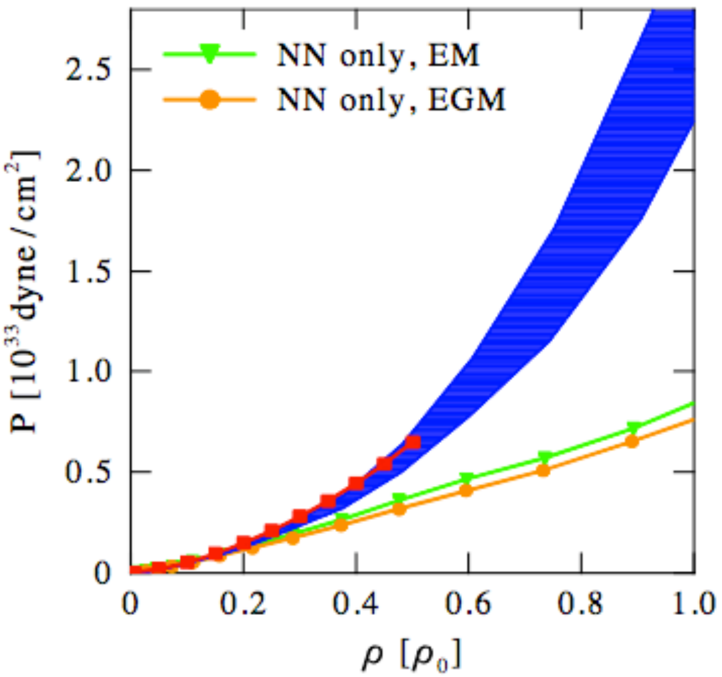
heaviest neutron star with 1.97±0.04 $M_{sun}$





# Impact on neutron stars Hebeler et al. (2010) and in prep.

Equation of state/pressure for neutron-star matter (includes small $Y_{e,p}$)



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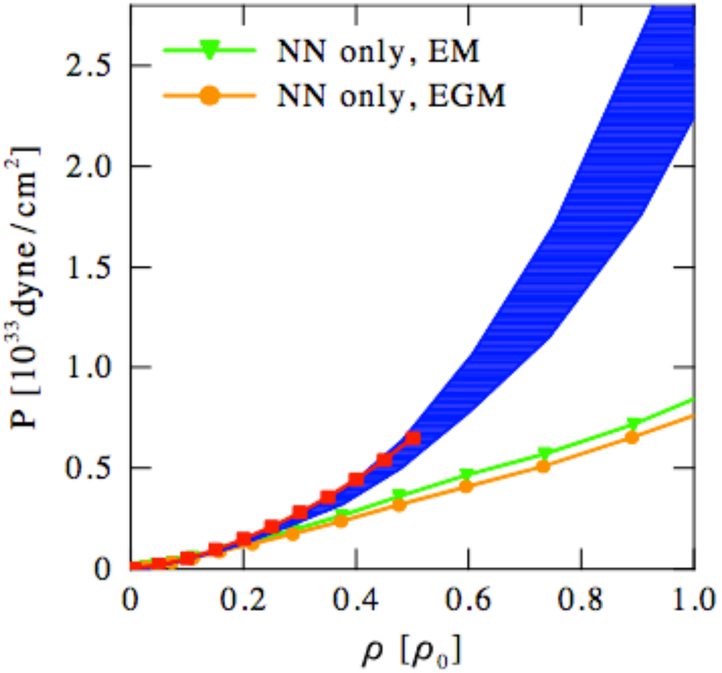

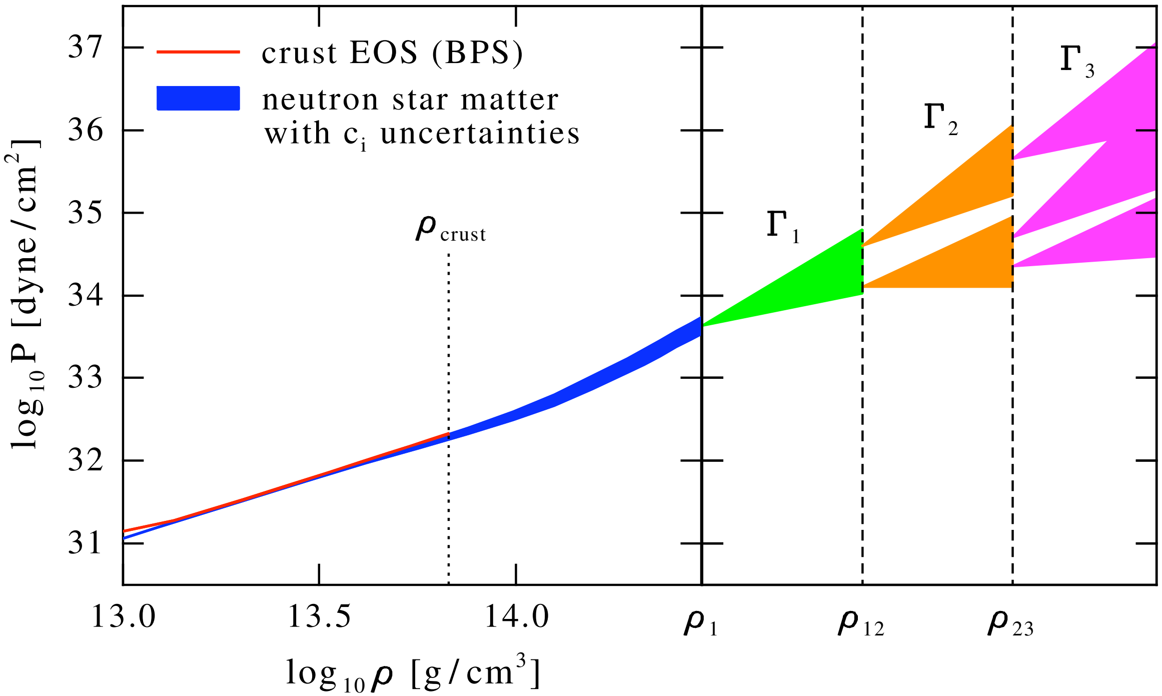

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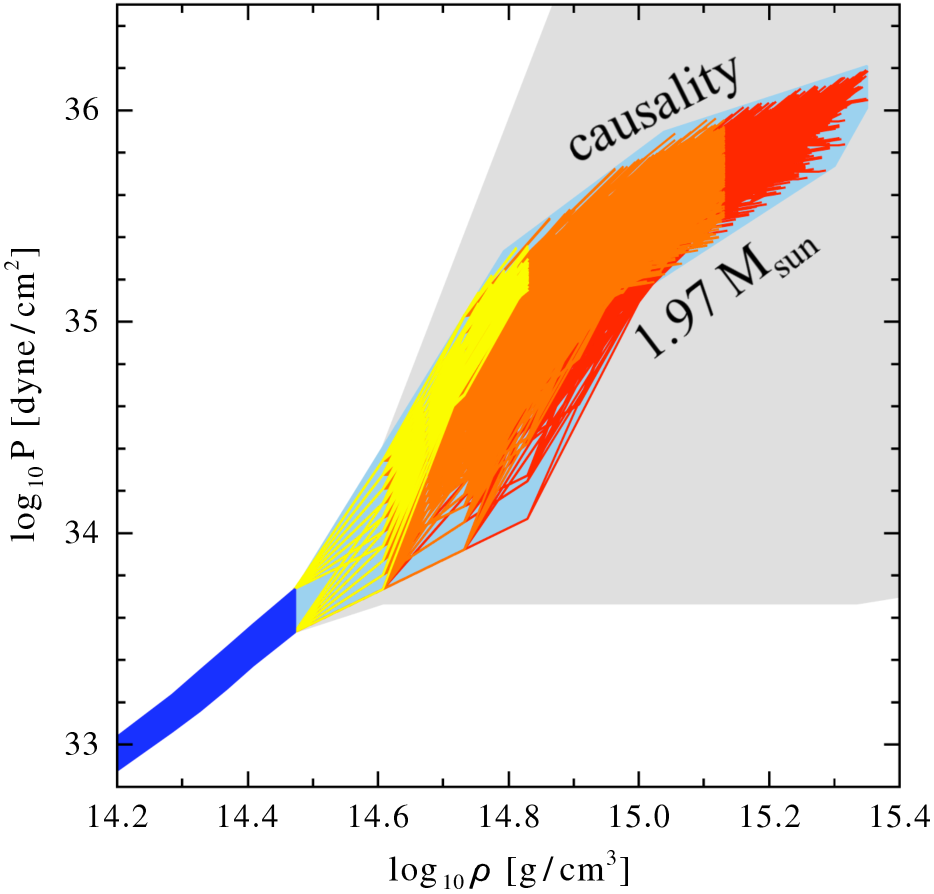
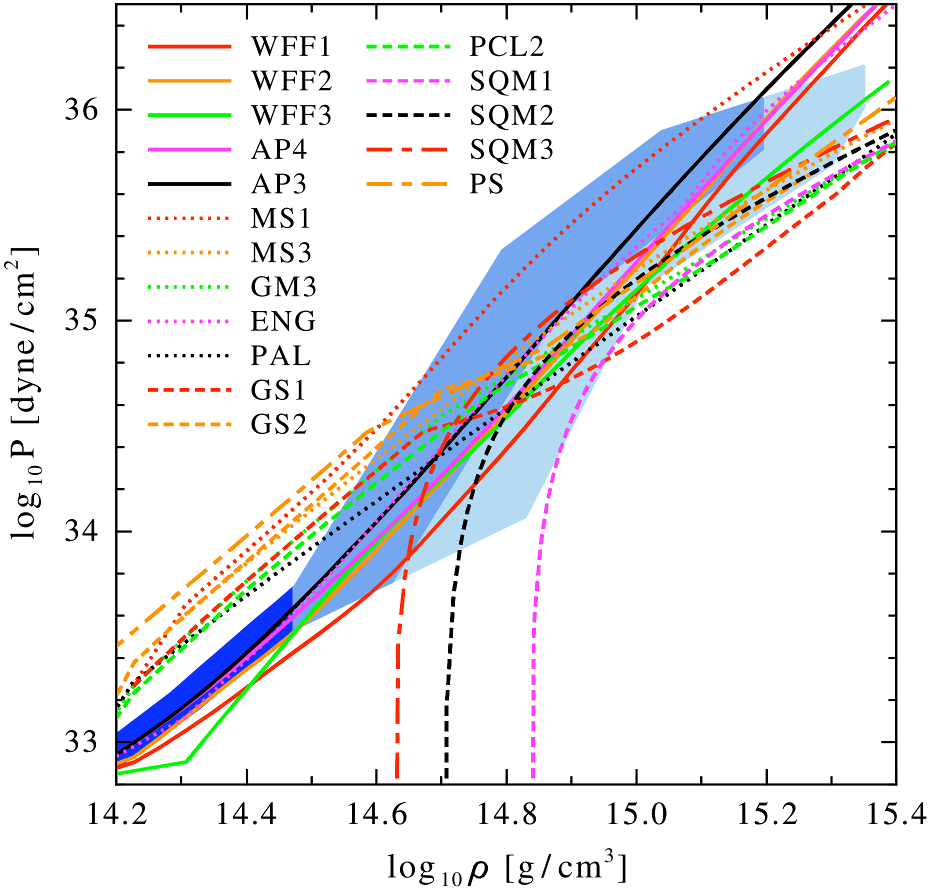
extend uncertainty band to higher densities using piecewise polytropes allow for soft regions

# Pressure of neutron star matter

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





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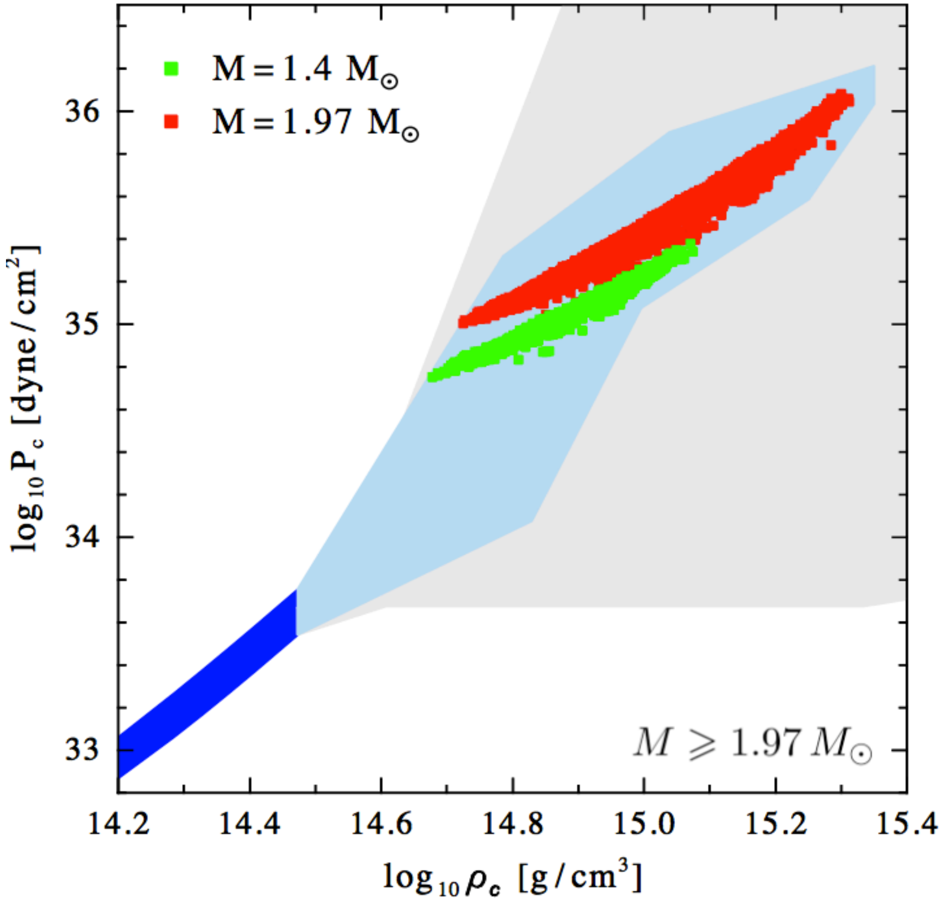

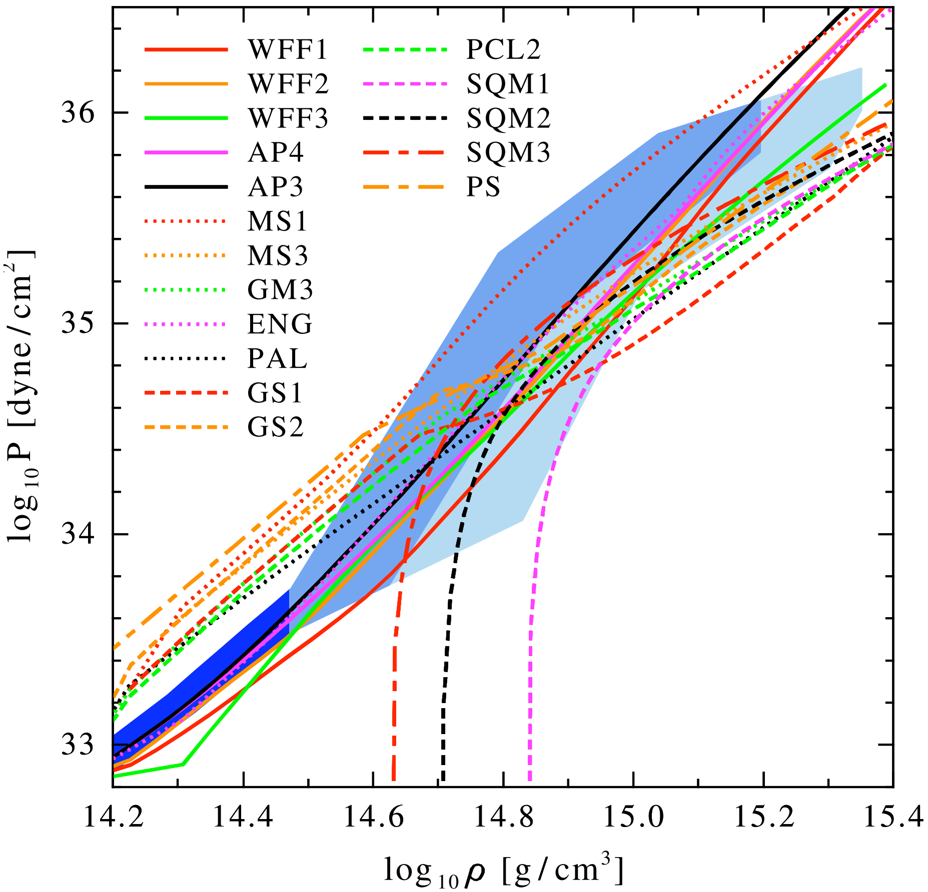

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**central densities for 1.4 $M_{sun}$ star: 1.7-4.4 $\rho_0$**

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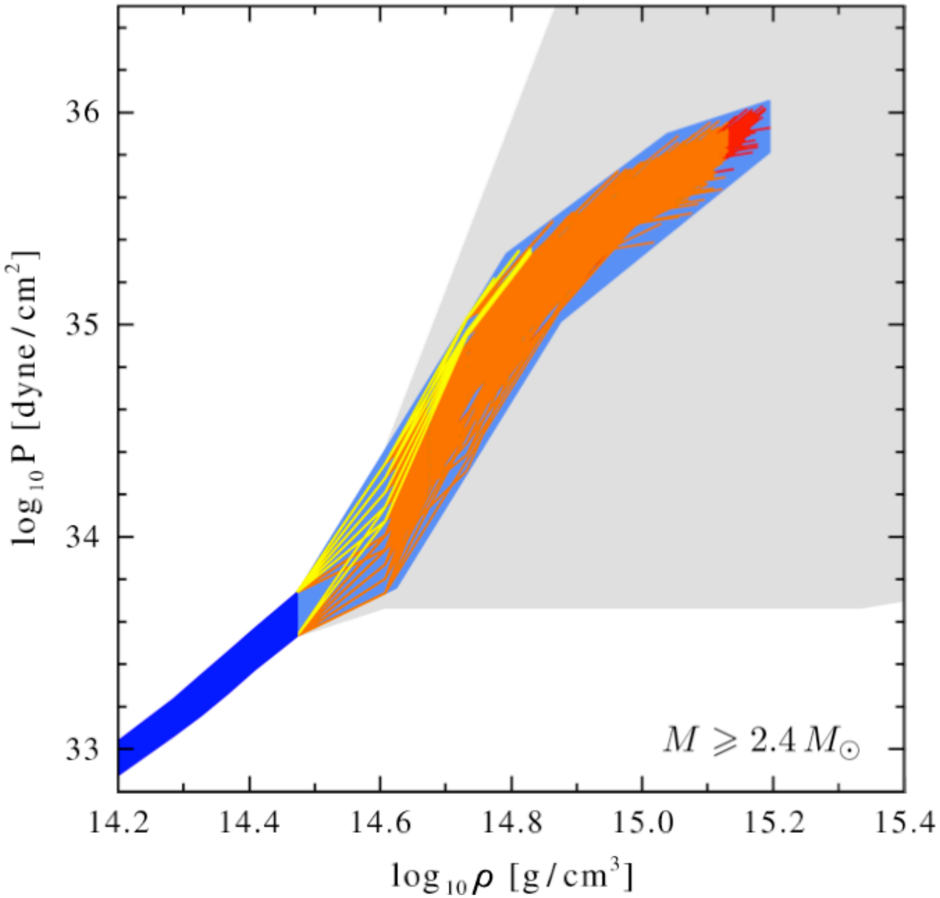
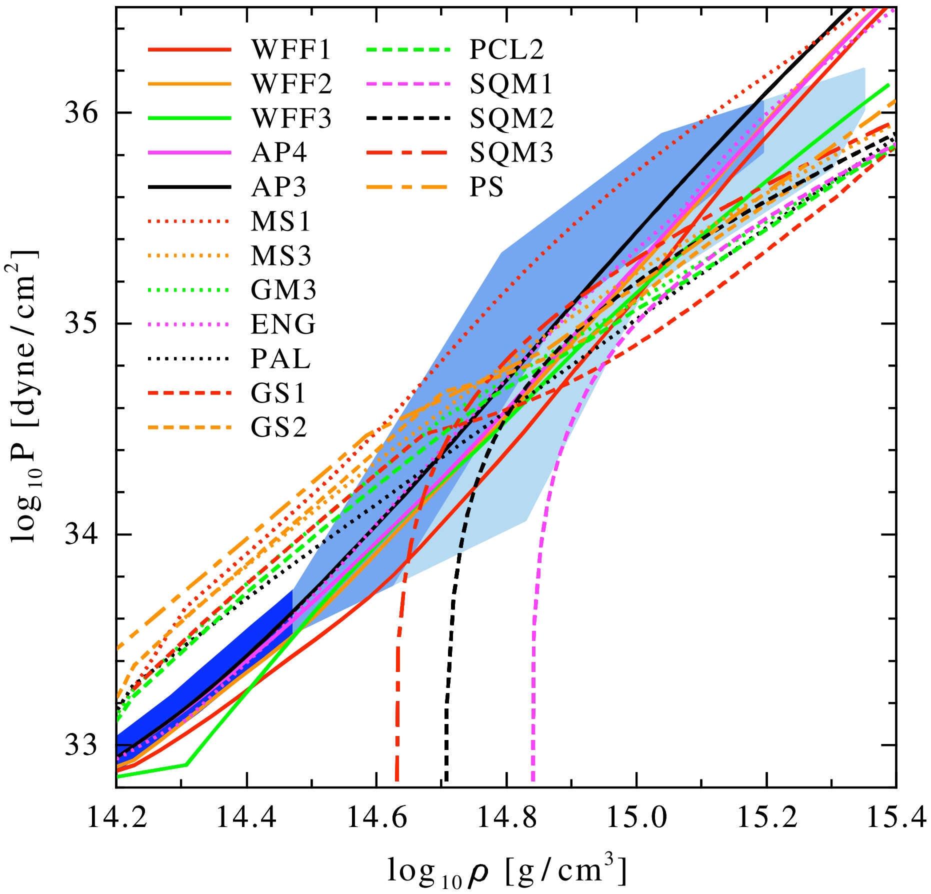
constrain polytropes by causality and require to support 1.97 $M_{sun}$ star



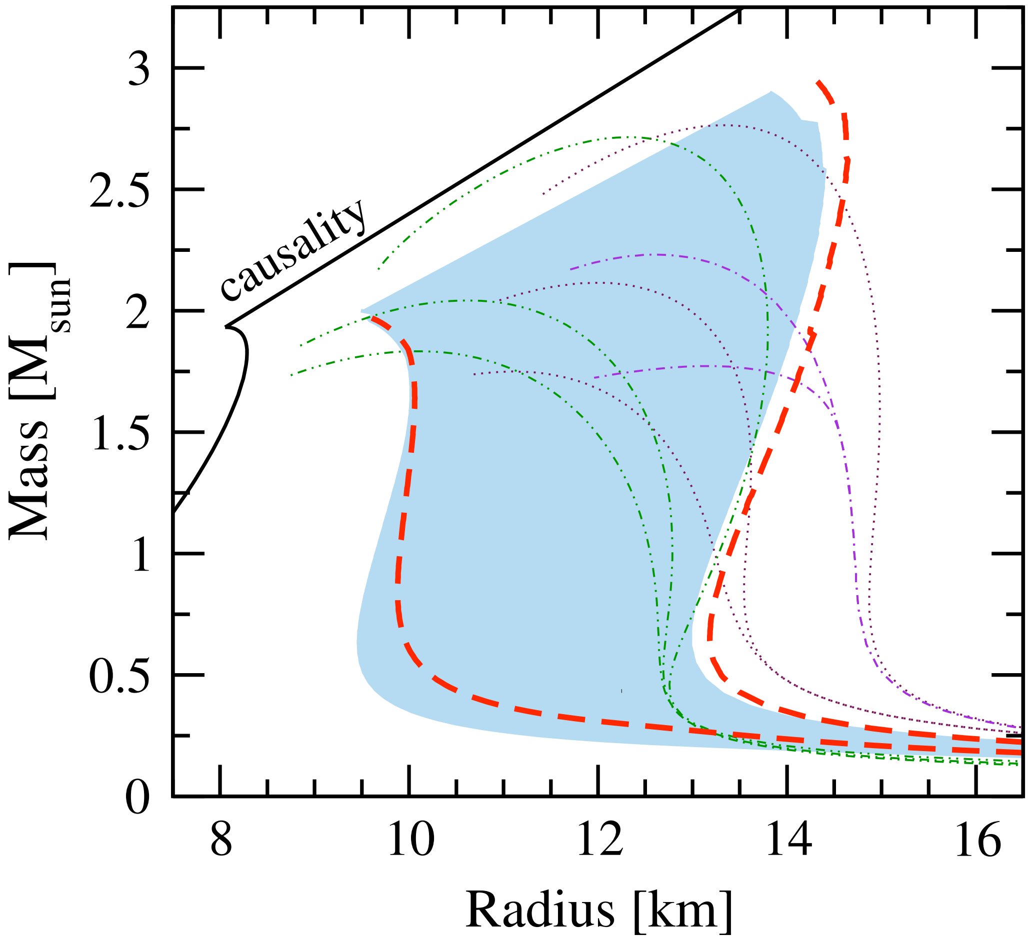


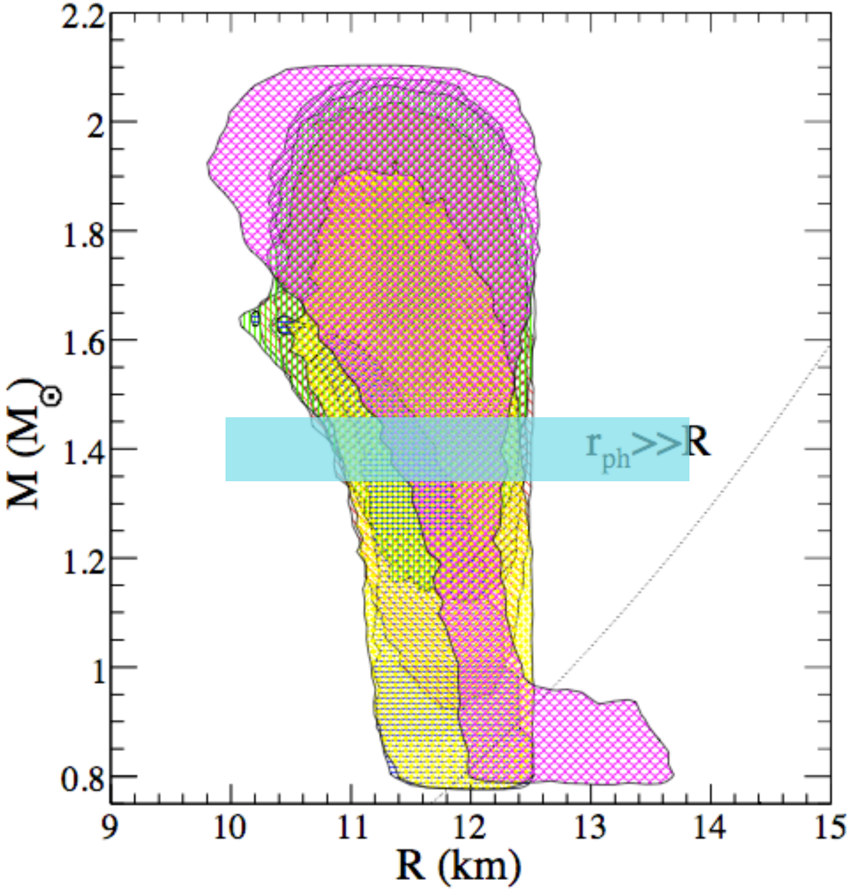
low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

darker blue band for 2.4 $M_{sun}$ star

# Neutron star radius constraints

uncertainty from many-body forces and general extrapolation





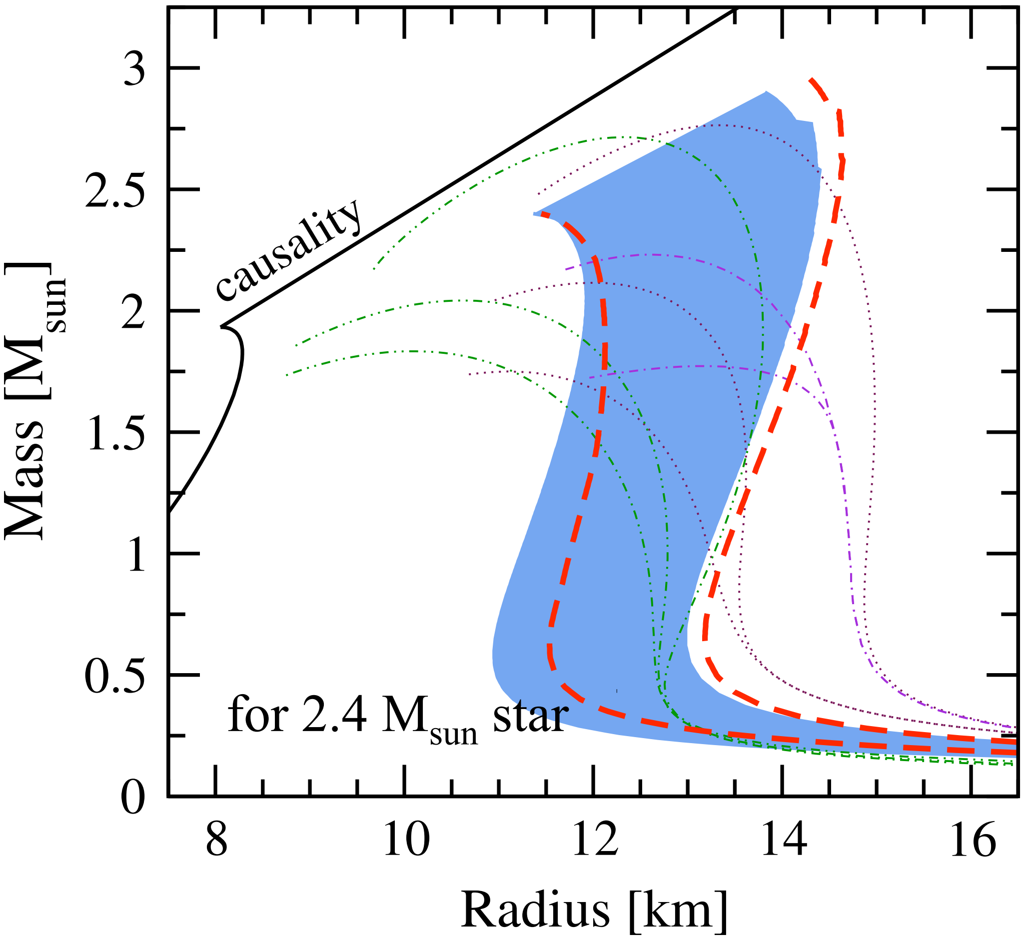
constrains neutron star radius: 9.9-13.8 km for M=1.4 $M_{sun}$ (±15% !)

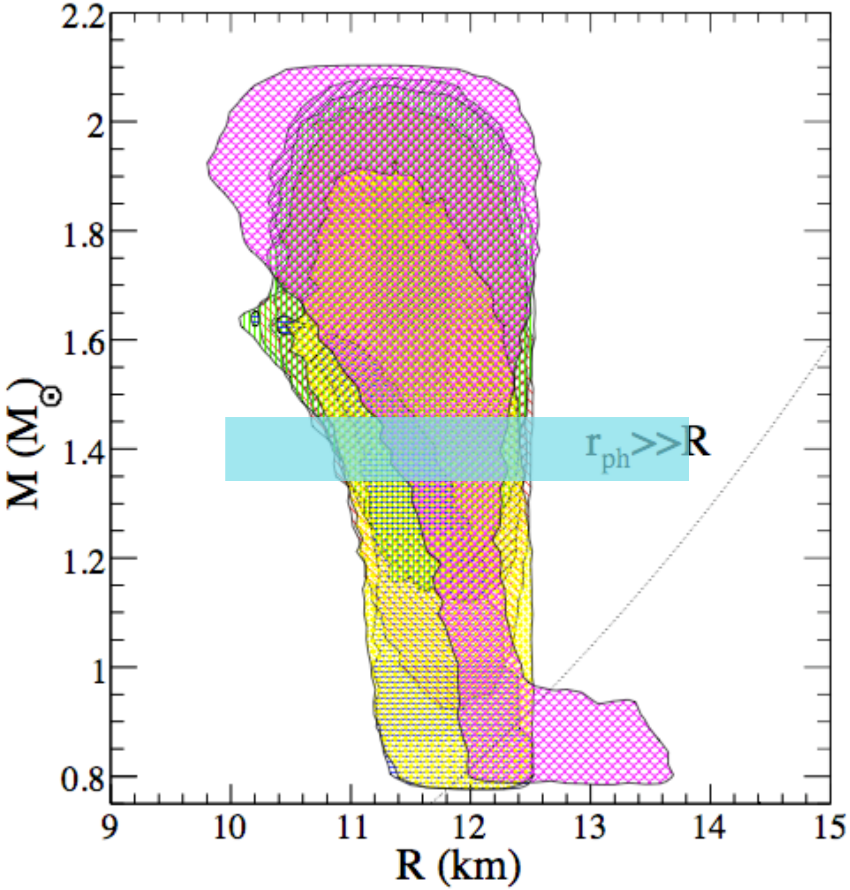
consistent with extraction from X-ray burst sources Steiner et al. (2010)

provides important constraints for EOS for core-collapse supernovae

# Neutron star 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% !)

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# Neutron-star merger and gravitational waves

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

Bauswein, Janka (2012) and A. Bauswein et al., arXiv:1204.1888.

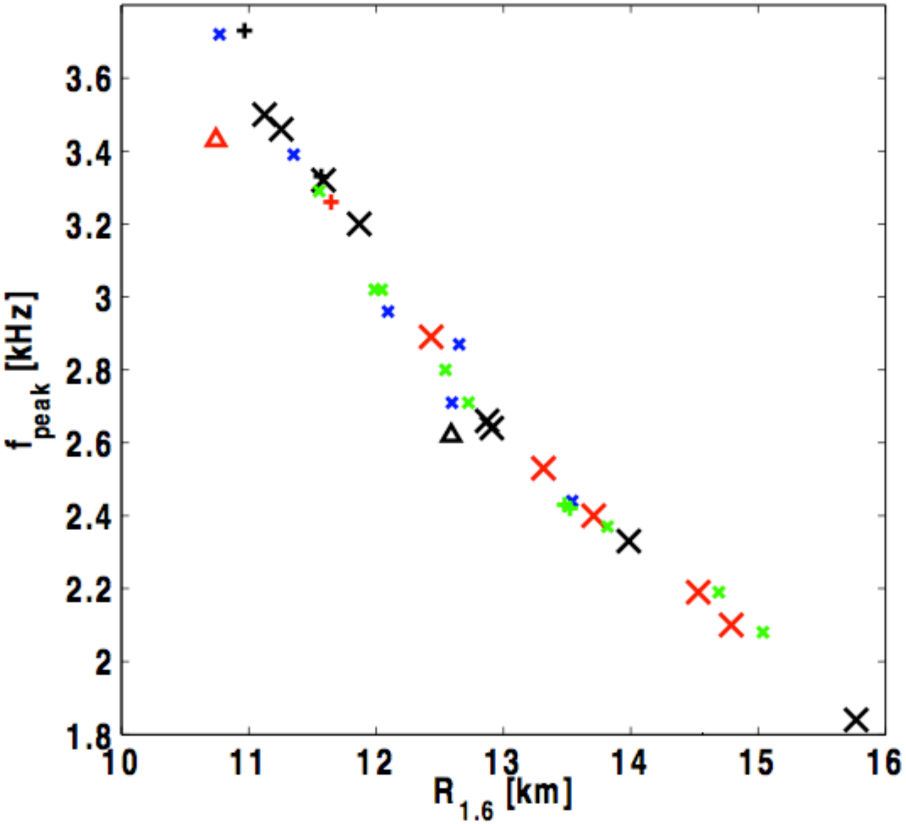


FIG. 10: Peak frequency of the postmerger GW emission versus the radius of a nonrotating NS with 1.6 $M_\odot$ for different EoSs. Symbols have the same meaning as in Fig. 8.

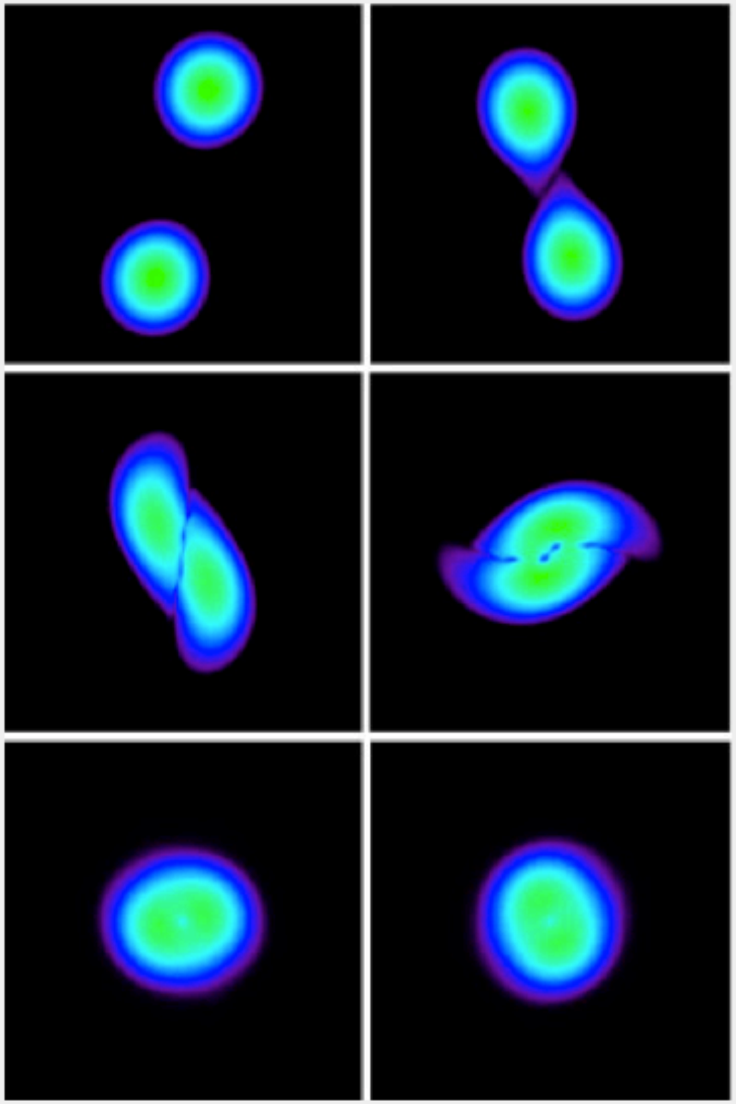
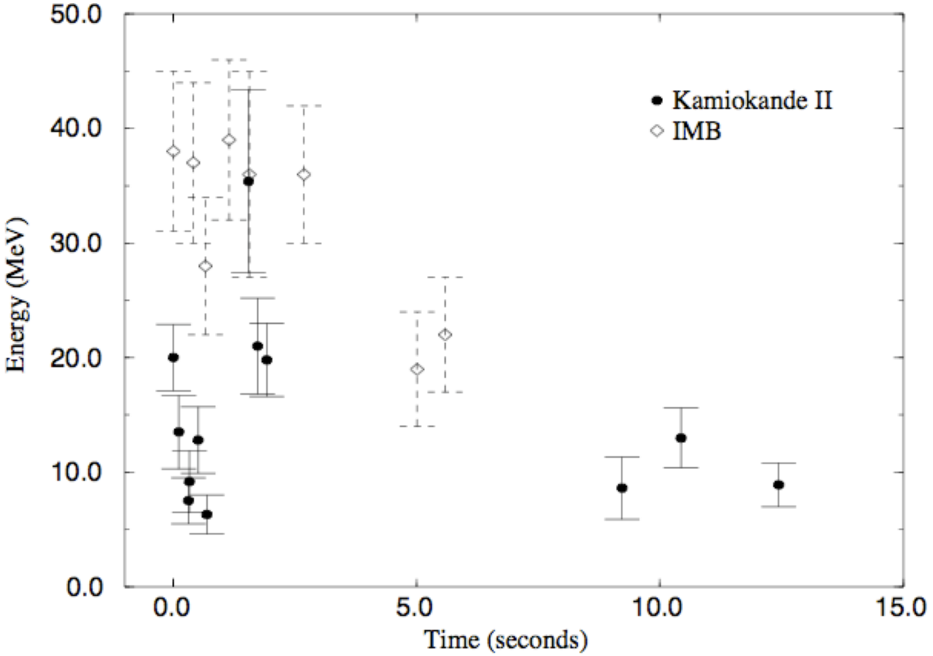


**Fig. 1:** Various snapshots of the collision of two neutron stars initially revolving around each other. The sequence simulated by the computer covers only 0.03 seconds. The two stars orbit each other counterclockwise (top left) and quickly come closer (top right). Finally they collide (centre left), 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)

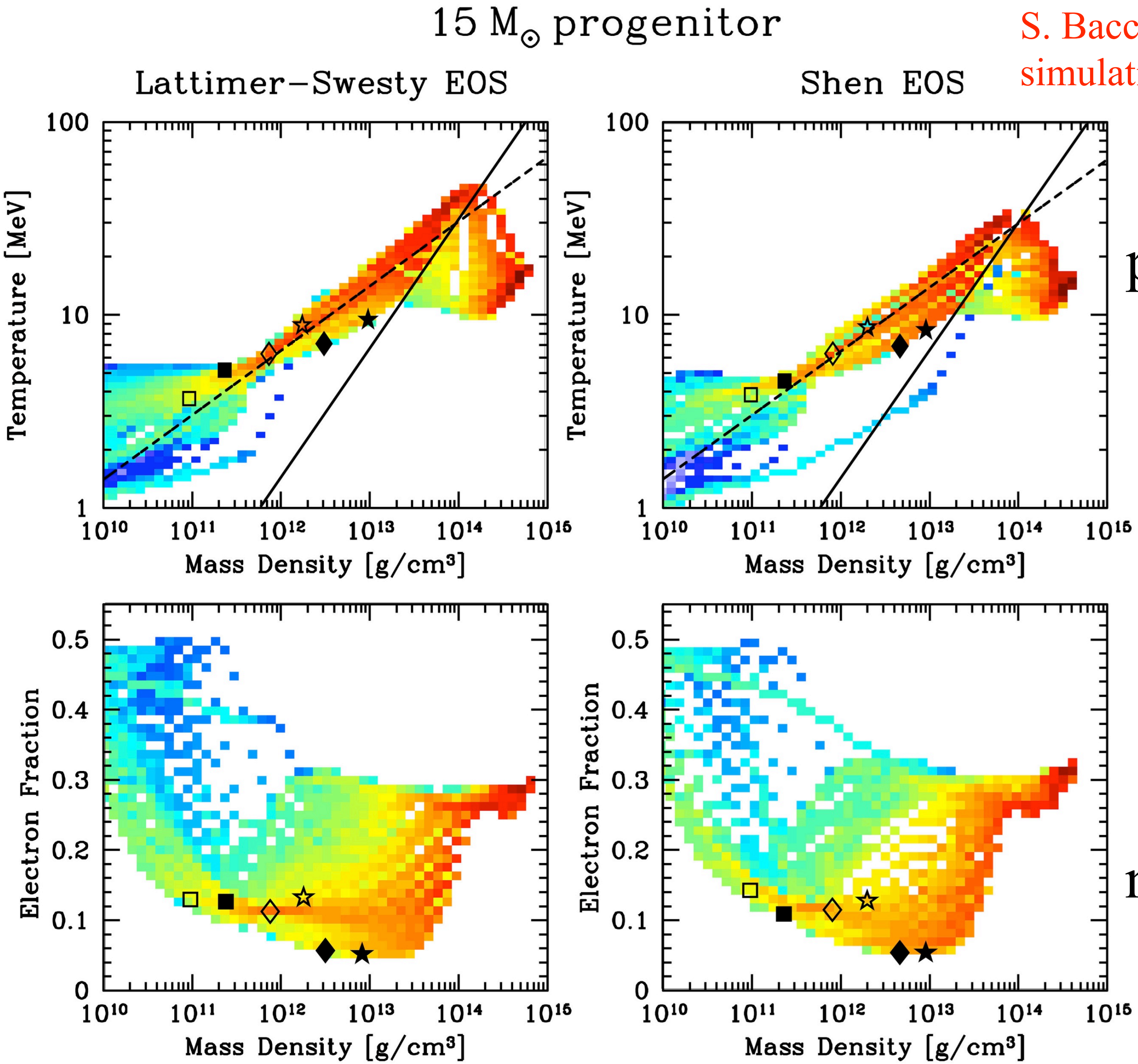
# Neutrinos under extreme conditions



anti-electron neutrinos from SN1987a

# Relevant conditions in core-collapse supernovae

S. Bacca et al. (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

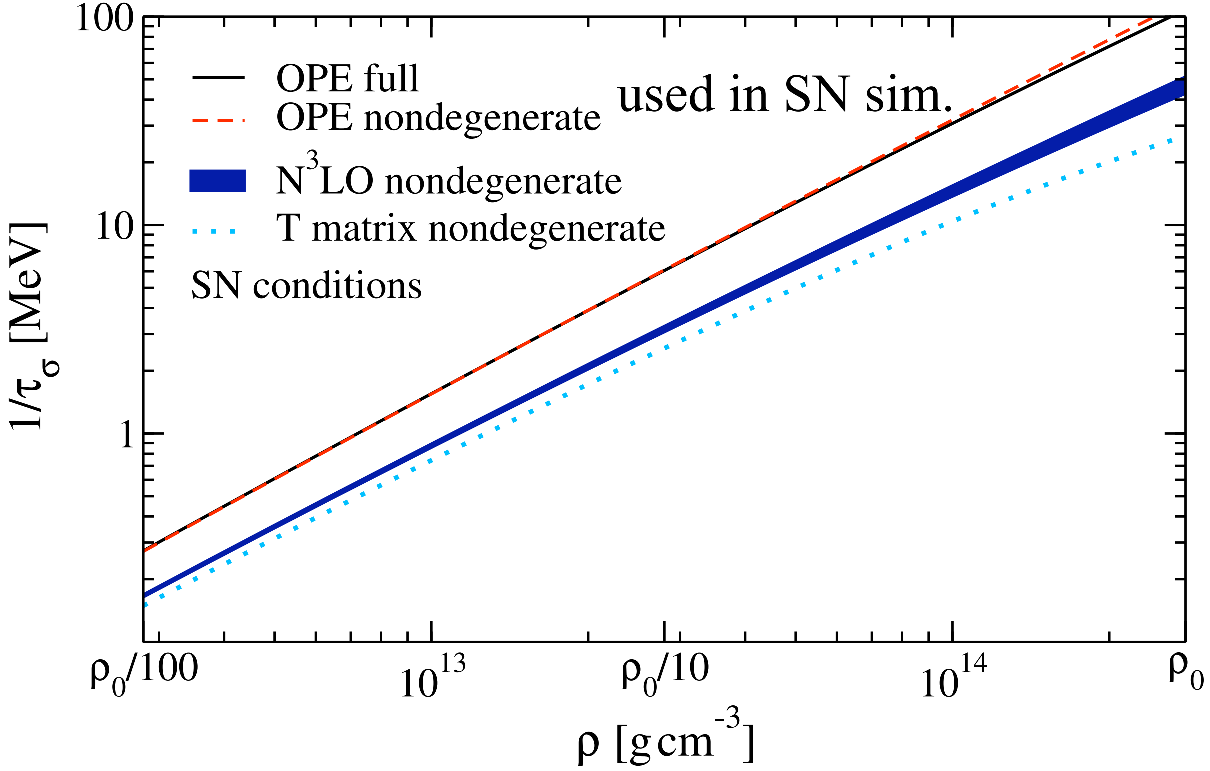
processes involving two nucleons play a special role Friman,… Suzuki, Raffelt,…

$NN \leftrightarrow NN\nu\bar{\nu}$ 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
Bacca et al. (2009,2012)

shorter-range interactions reduce rates for neutrons



towards chiral EFT rates in supernova simulations

# Energy transfer in neutrino scattering from nucleons

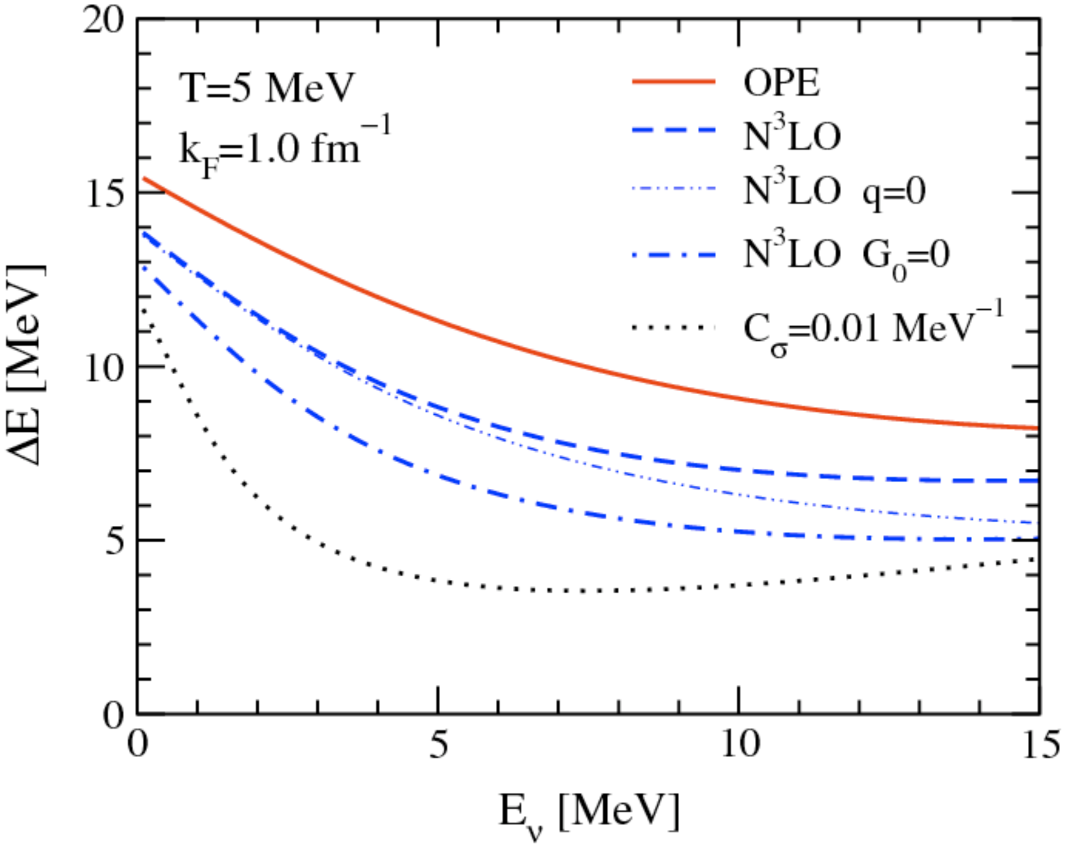
mean-square neutrino energy transfer in $\nu nn \leftrightarrow \nu nn$

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

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

energy transfer significant,
dominates over recoil effects

not included in simulations



# Main points and summary

Chiral EFT interactions provide strong constraints for EOS,
3N forces are a frontier for neutron-rich nuclei/matter

exciting intersections with cold atoms at low densities

dominant uncertainty of neutron (star) matter below nuclear densities
also key to explain neutron-rich nuclei

neutron star radius 9.9-13.8 km for $M=1.4\ M_{\text{sun}}$ (±15%)

towards chiral EFT rates in supernova simulations,
can constrain structure factors with cold atoms at low densities