Equation of state and neutrino-matter interactions from chiral effective field theory

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EMMI

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HELMHOLTZ ASSOCIATION

Main points

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

Neutron-rich conditions and nondegenerate conditions

especially interesting for proto-neutron star cooling and mergers

General EOS band based on nuclear physics and observations

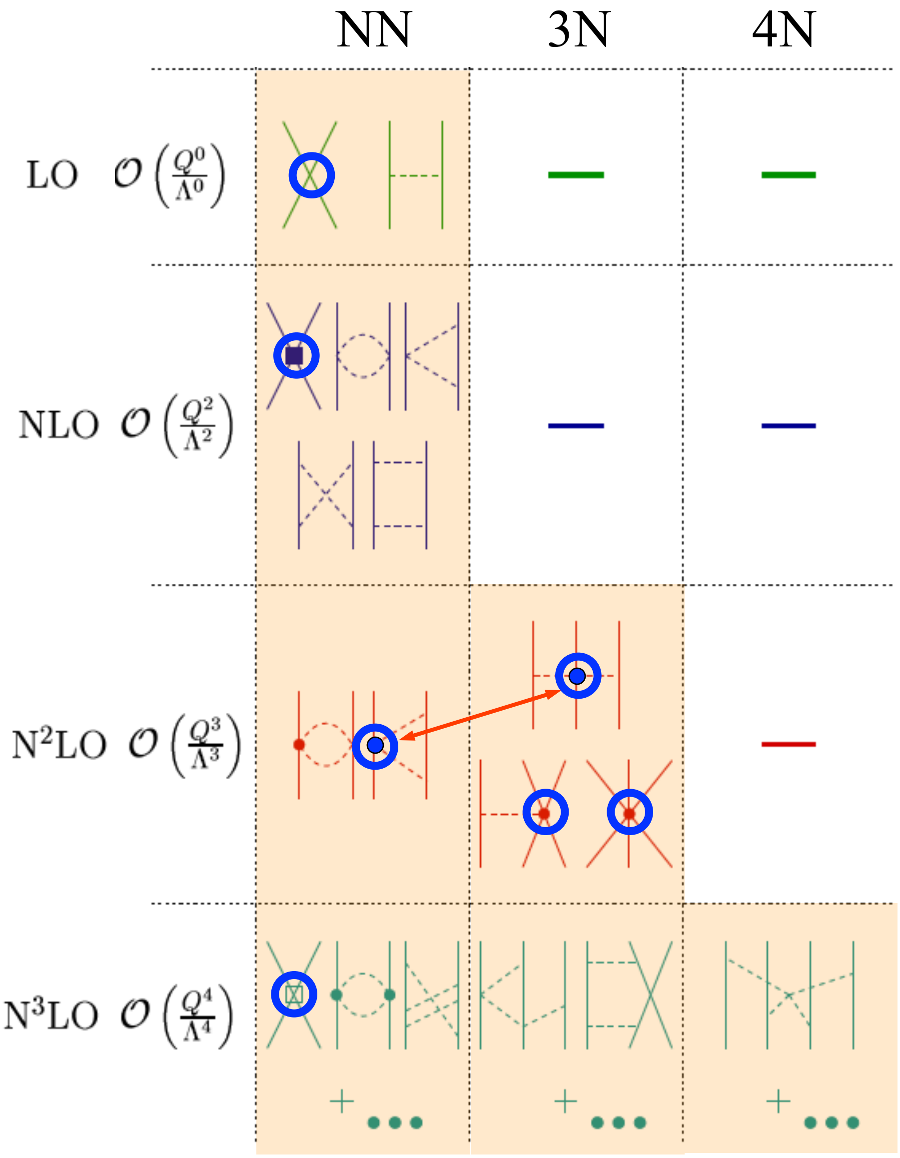
neutron star radius 9.7-13.9 km for $M=1.4\ M_{\text{sun}}$ (±18%)

Chiral EFT important for consistent neutrino-matter interactions

Enhancement of neutrino bremsstrahlung at low densities, important for inelastic scattering

Chiral effective field theory for nuclear forces

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



include long-range
pion physics

short-range couplings,
fit to experiment once

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

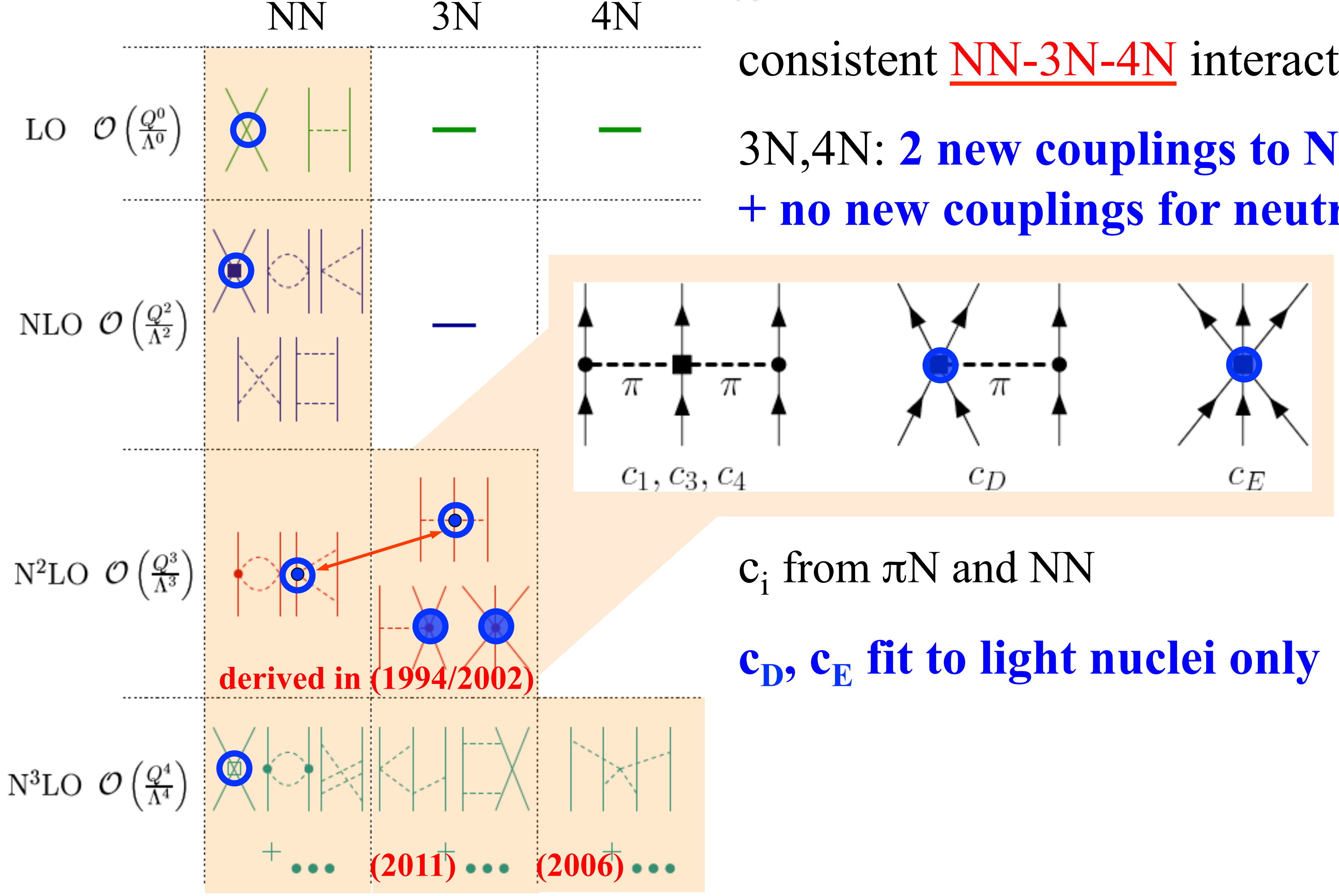
consistent **electroweak interactions**
and **matching to lattice QCD**

new developments in power counting,
uncertainty quantification,
optimization Ektröm, Forssen, Furnstahl,...

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

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**

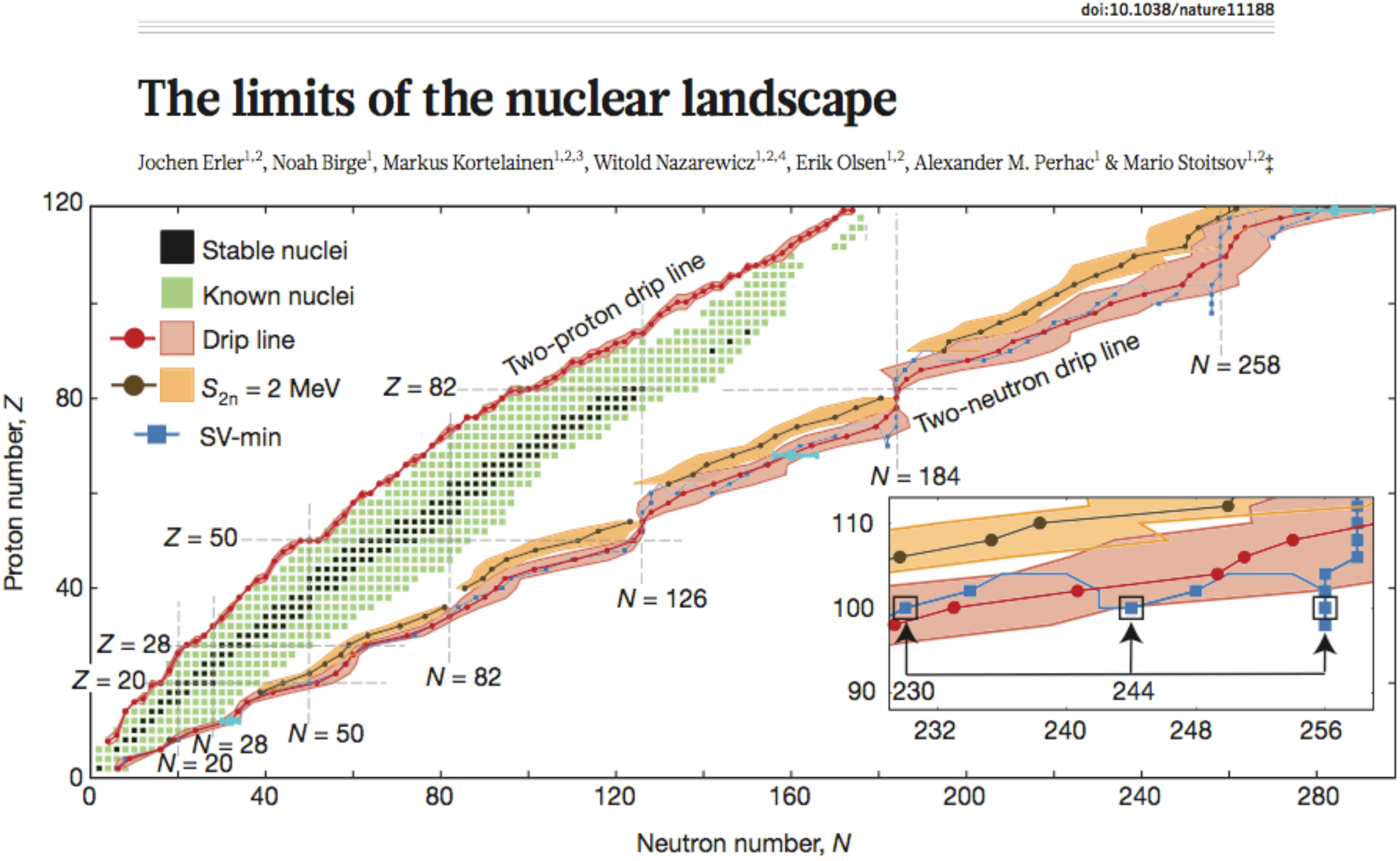
+ no new couplings for neutrons

c_i from πN and NN

c_D, c_E fit to light nuclei only

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

Nuclei bound by strong interactions



doi:10.1038/nature11188

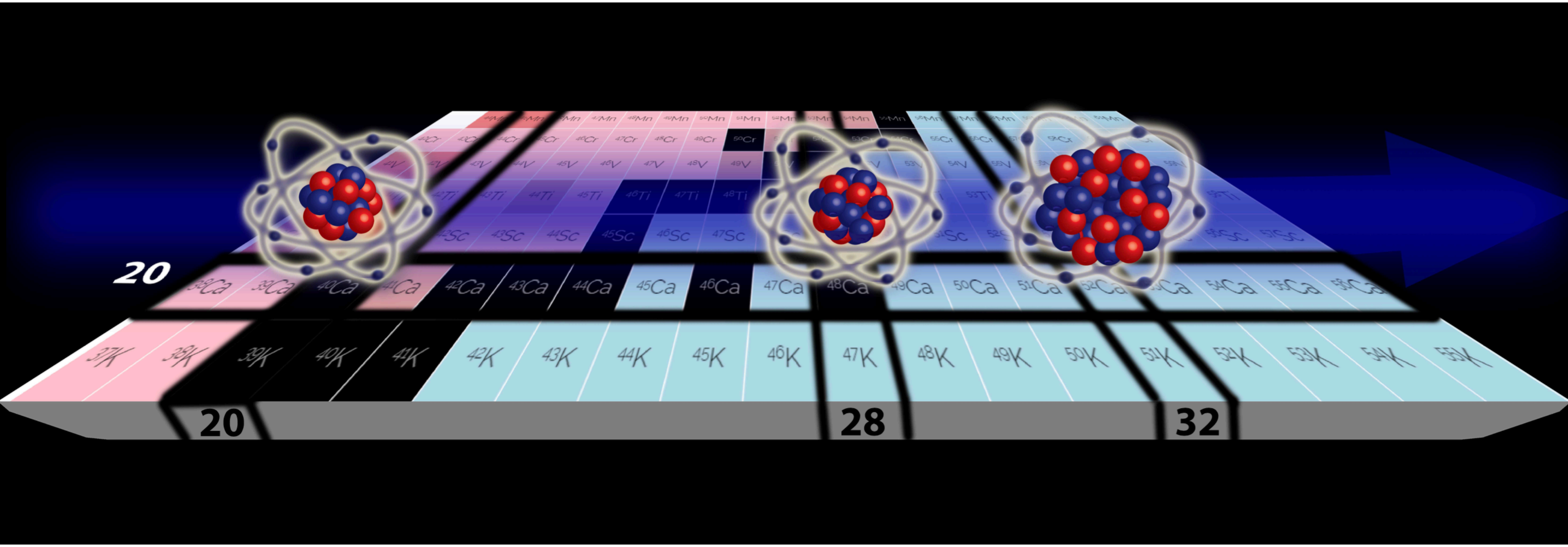
The limits of the nuclear landscape

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 chiral EFT?

Future: Connect chiral EFT to Lattice QCD

Neutron-rich calcium isotopes



Frontier of ab initio calculations at A~50

doi:10.1038/nature12226

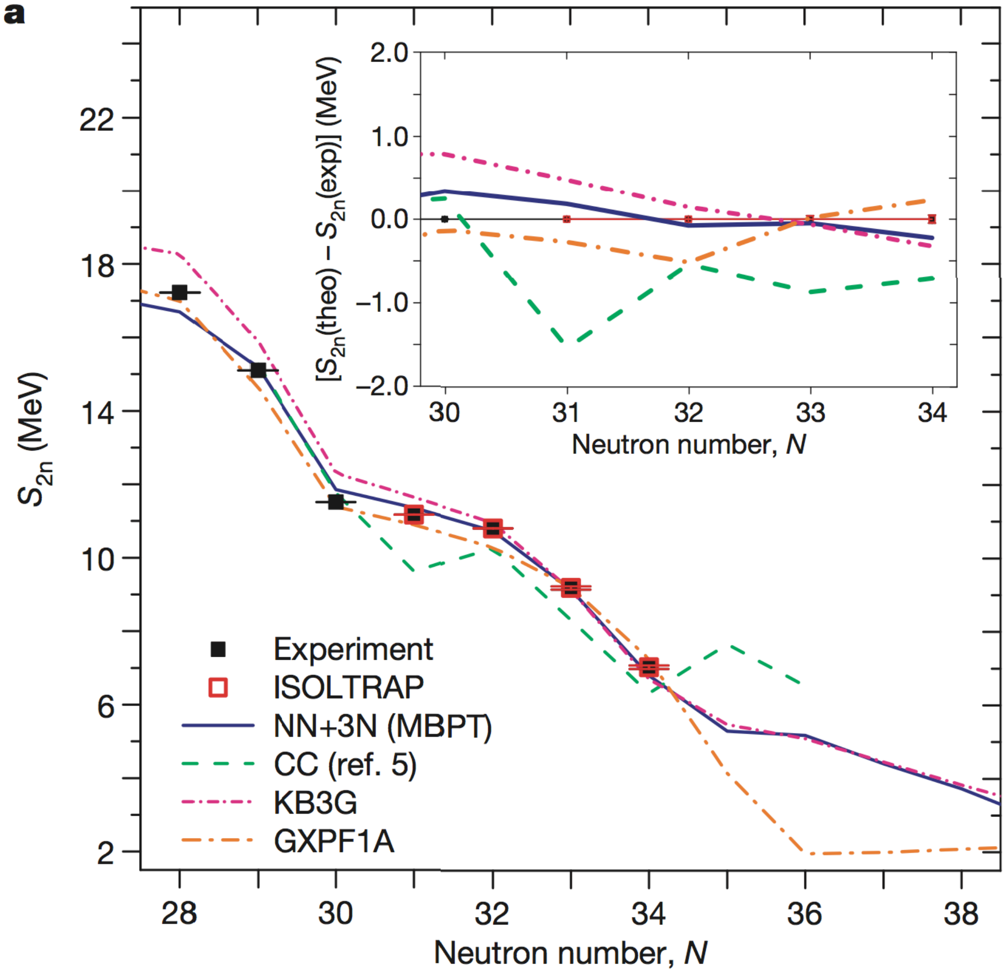
Masses of exotic calcium isotopes pin down nuclear forces

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/CERN using new MR-TOF mass spectrometer

excellent agreement with theoretical NN+3N prediction

suggests N=32 shell closure



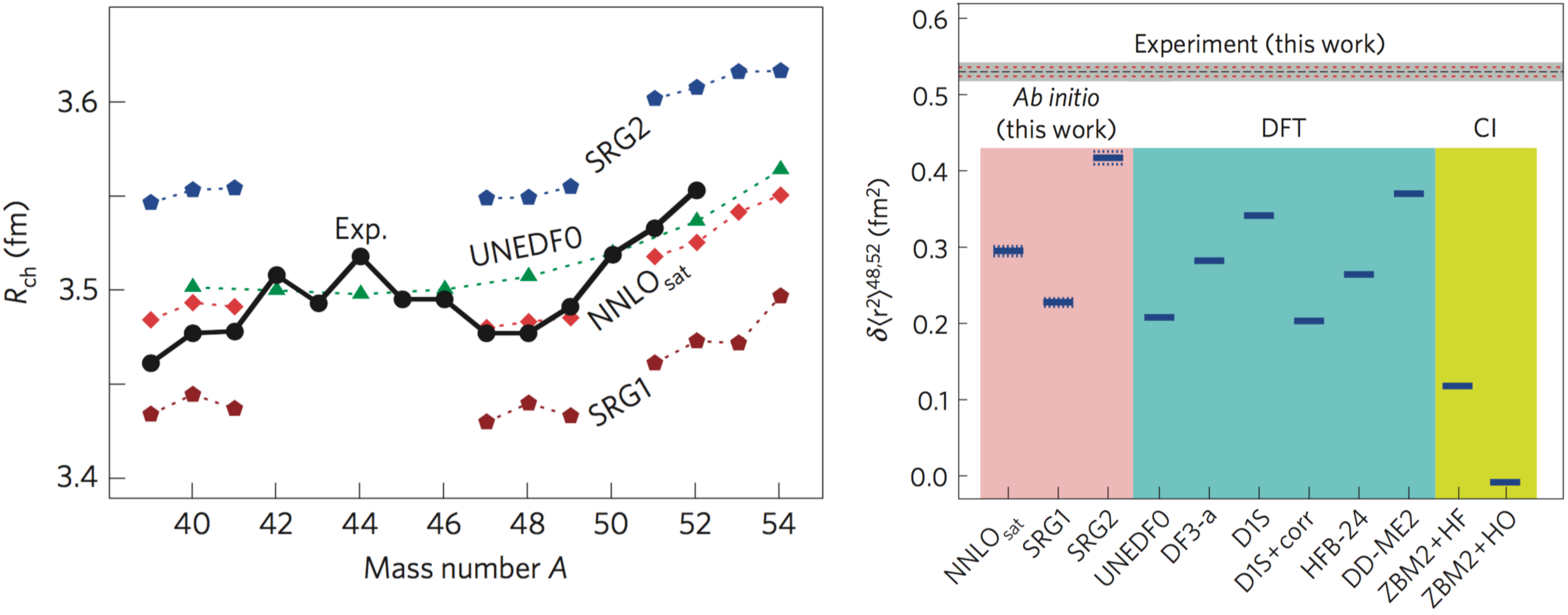
nature physics

ARTICLES

PUBLISHED ONLINE: 8 FEBRUARY 2016 | DOI: 10.1038/NPHYS3645

Unexpectedly large charge radii of neutron-rich calcium isotopes

R. F. Garcia Ruiz[1]*, M. L. Bissell[1,2], K. Blaum[3], A. Ekström[4,5], N. Frömmgen[6], G. Hagen[4], M. Hammen[6], K. Hebeler[7,8], J. D. Holt[9], G. R. Jansen[4,5], M. Kowalska[10], K. Kreim[3], W. Nazarewicz[4,11,12], R. Neugart[3,6], G. Neyens[1], W. Nörtershäuser[6,7], T. Papenbrock[4,5], J. Papuga[1], A. Schwenk[3,7,8], J. Simonis[7,8], K. A. Wendt[4,5] and D. T. Yordanov[3,13]



Neutron skin of ^{48}Ca

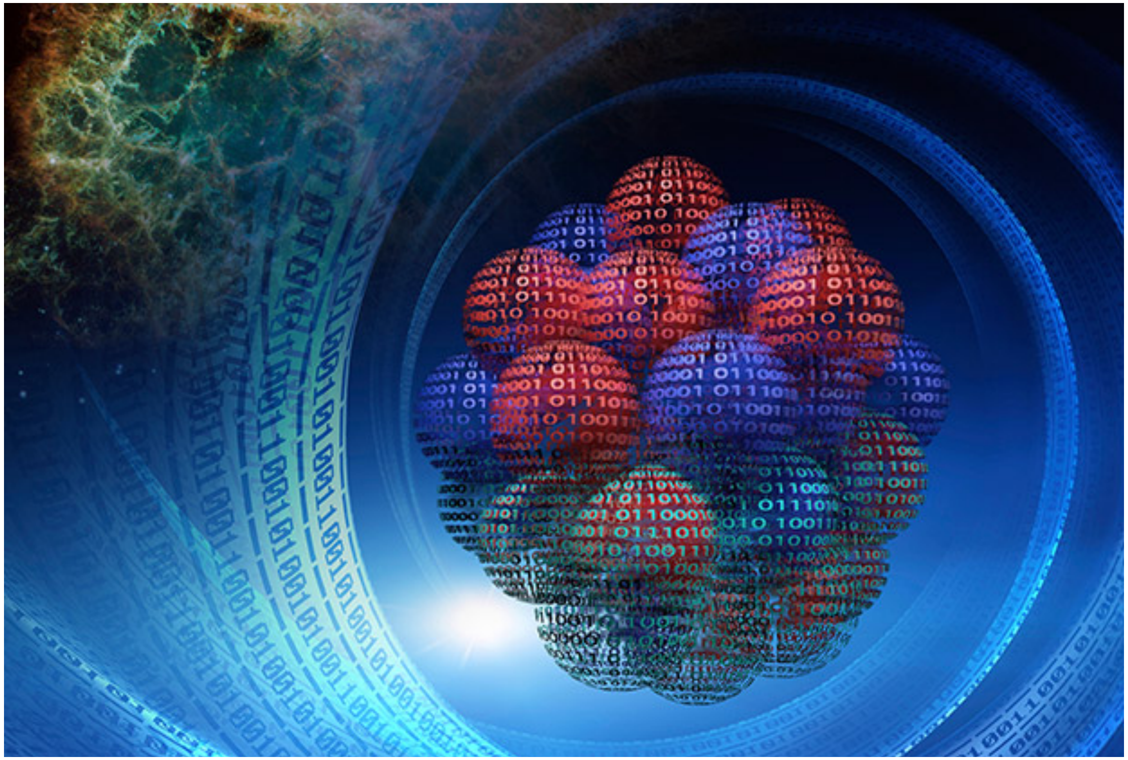
nature physics

ARTICLES

PUBLISHED ONLINE: 2 NOVEMBER 2015 | DOI: 10.1038/NPHYS3529

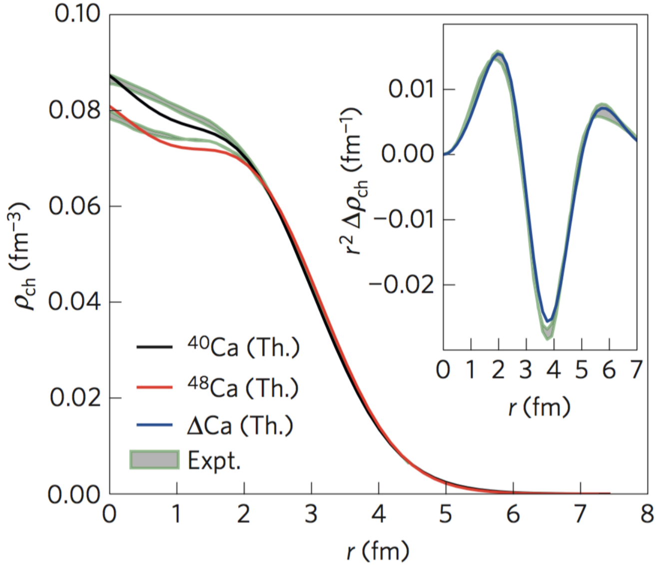
Neutron and weak-charge distributions of the ^{48}Ca nucleus

G. Hagen[1,2]*, A. Ekström[1,2], C. Forssén[1,2,3], G. R. Jansen[1,2], W. Nazarewicz[1,4,5], T. Papenbrock[1,2], K. A. Wendt[1,2], S. Bacca[6,7], N. Barnea[8], B. Carlsson[3], C. Drischler[9,10], K. Hebeler[9,10], M. Hjorth-Jensen[4,11], M. Miorelli[6,12], G. Orlandini[13,14], A. Schwenk[9,10] and J. Simonis[9,10]

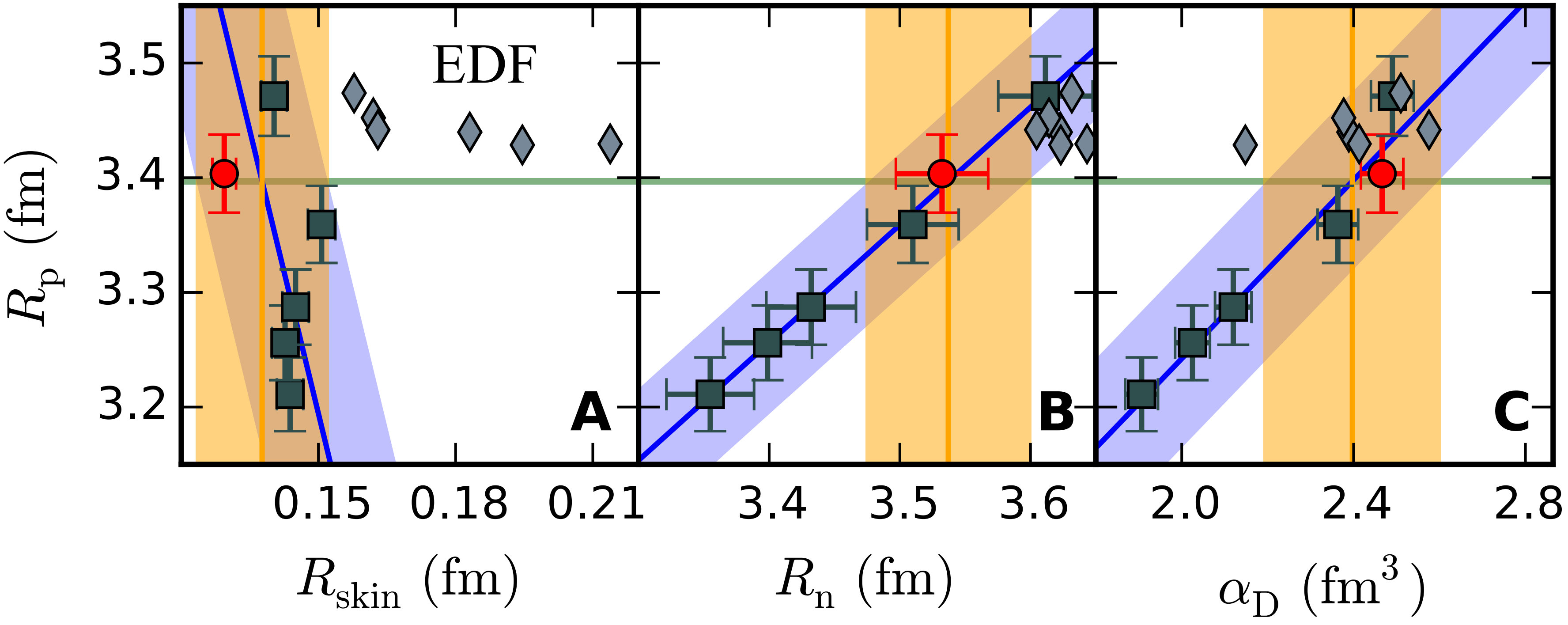


Neutron and weak-charge distributions of ^{48}Ca

ab initio calculations lead to charge distributions consistent with experiment



predict small neutron skin, dipole polarizability, and weak formfactor

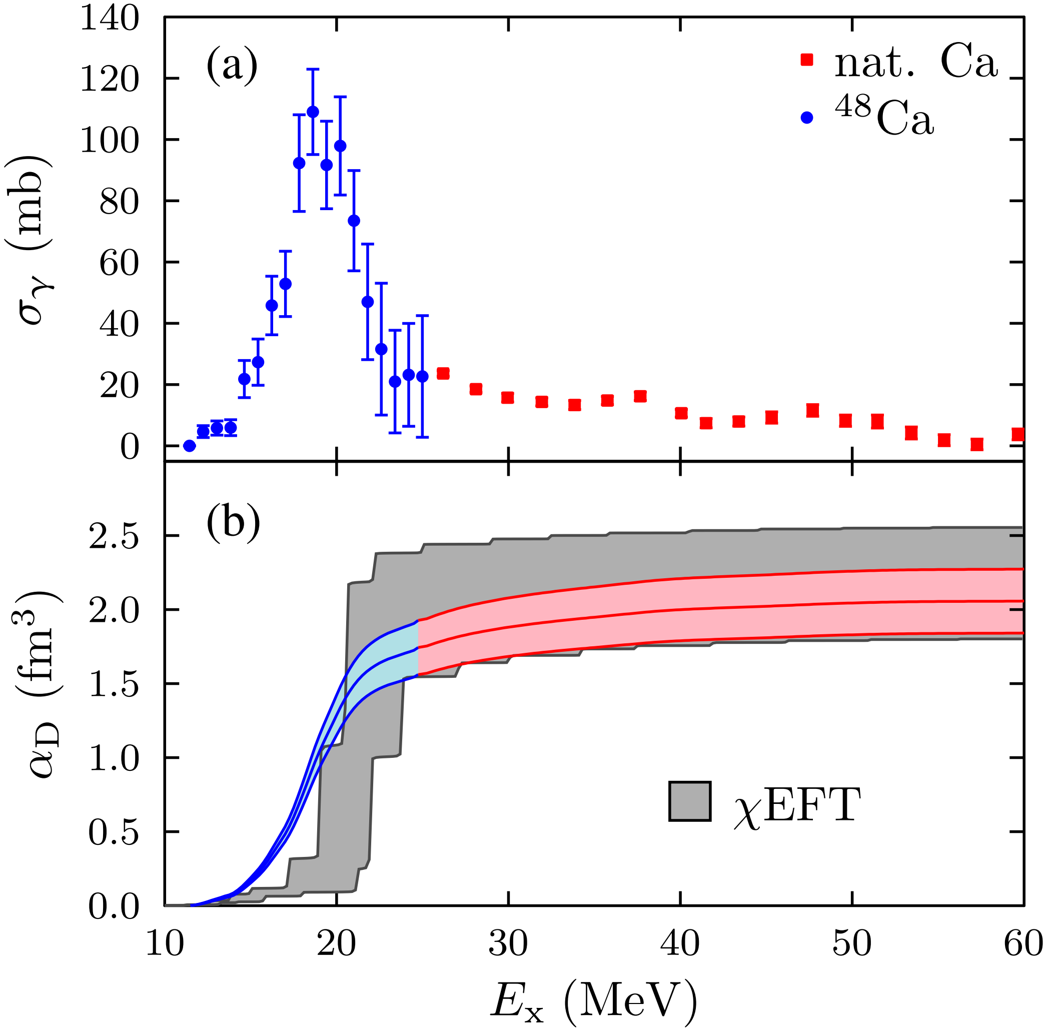


Dipole polarizability of ^{48}Ca

from photo-absorption cross section, measured at Osaka up to 25 MeV

Birkhan, von Neumann-Cosel, Richter, Tamii et al.

very similar to ^{40}Ca except for shift of giant dipole resonance

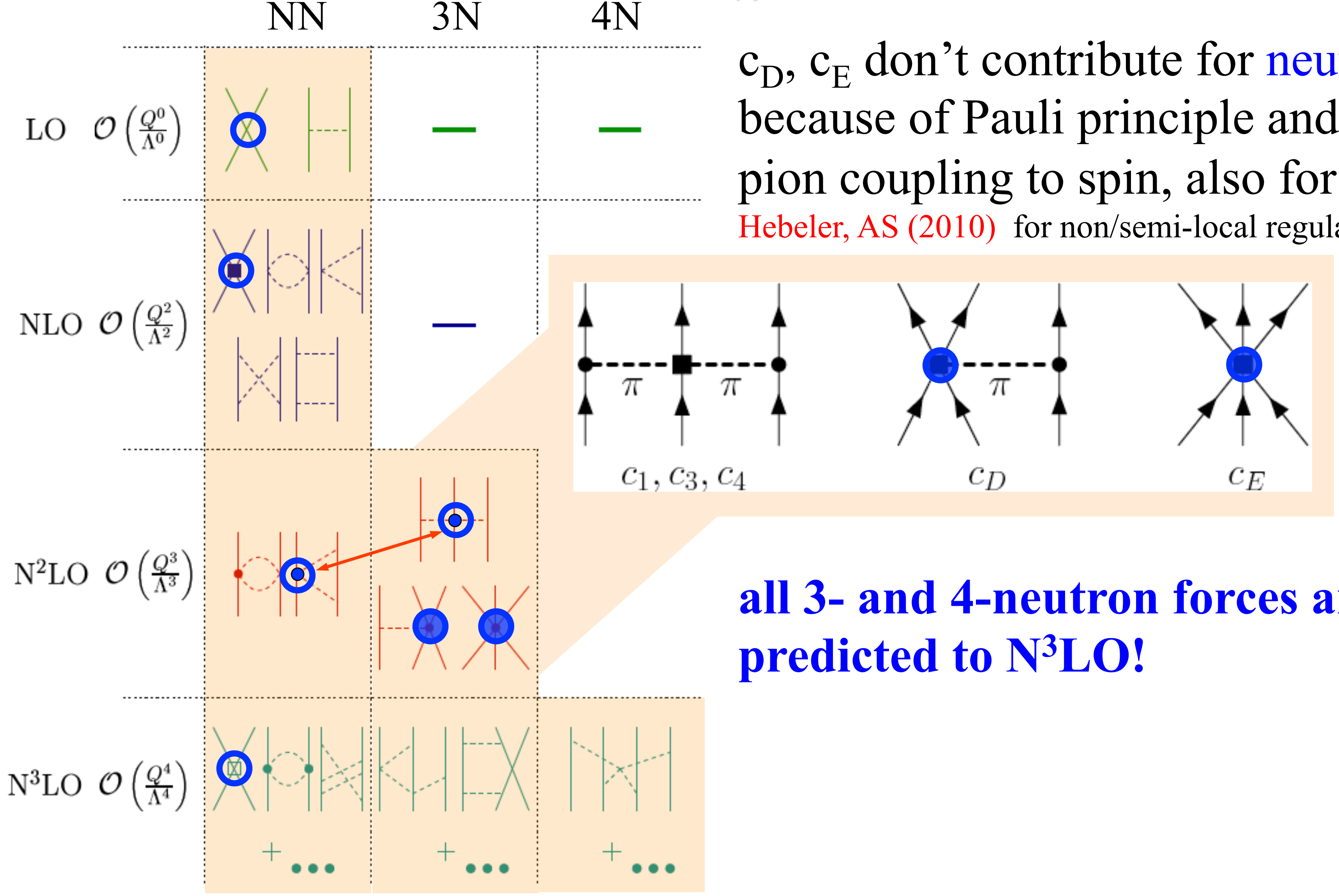


good agreement with chiral EFT predictions

Miorelli, Bacca, Hagen et al.

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) for non/semi-local regulators

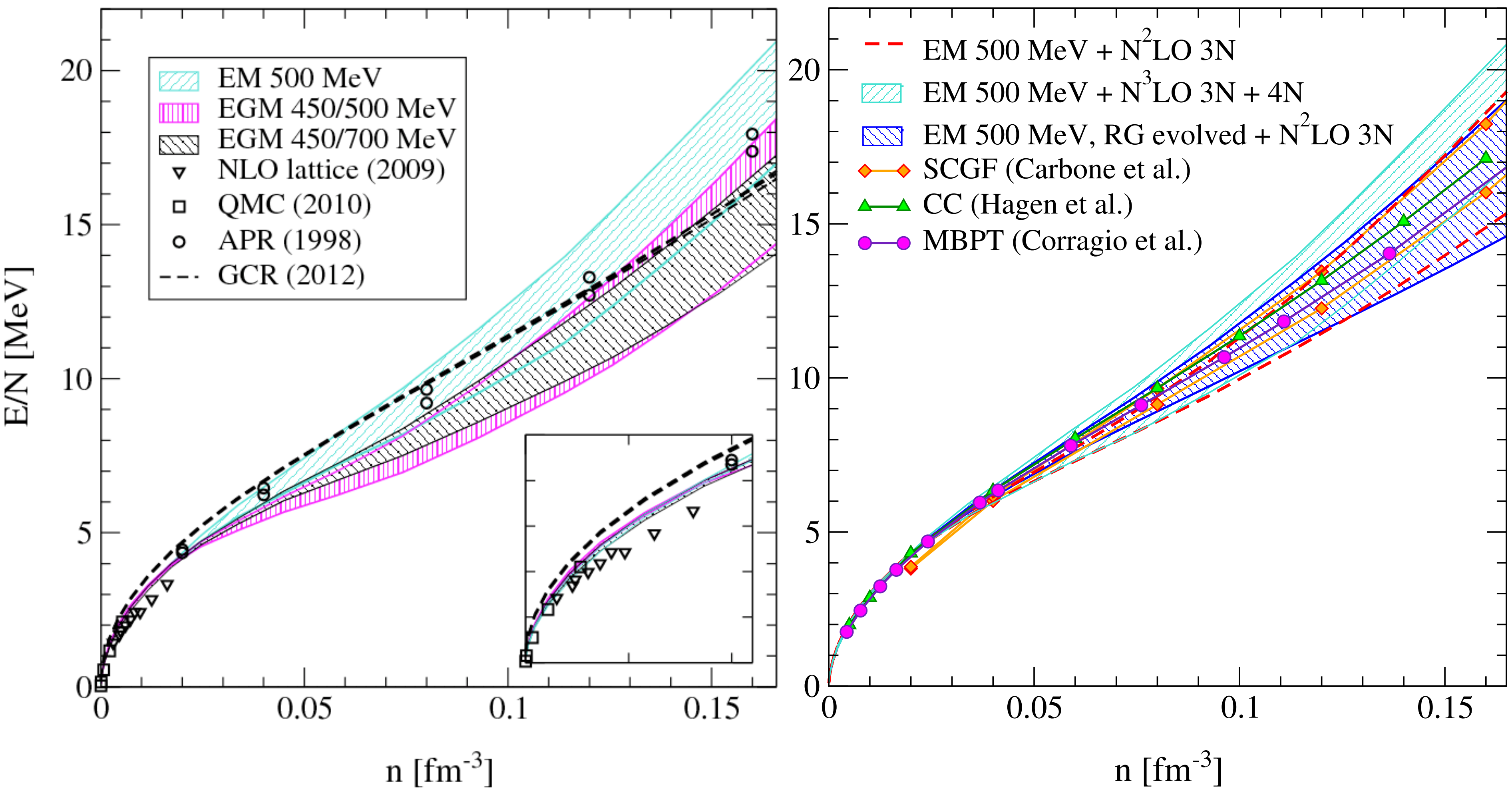
all 3- and 4-neutron forces are predicted to N³LO!

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

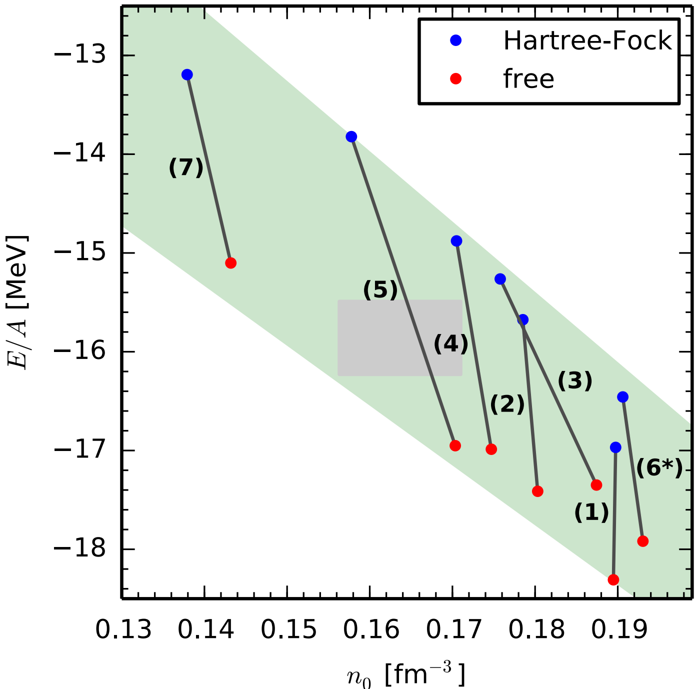


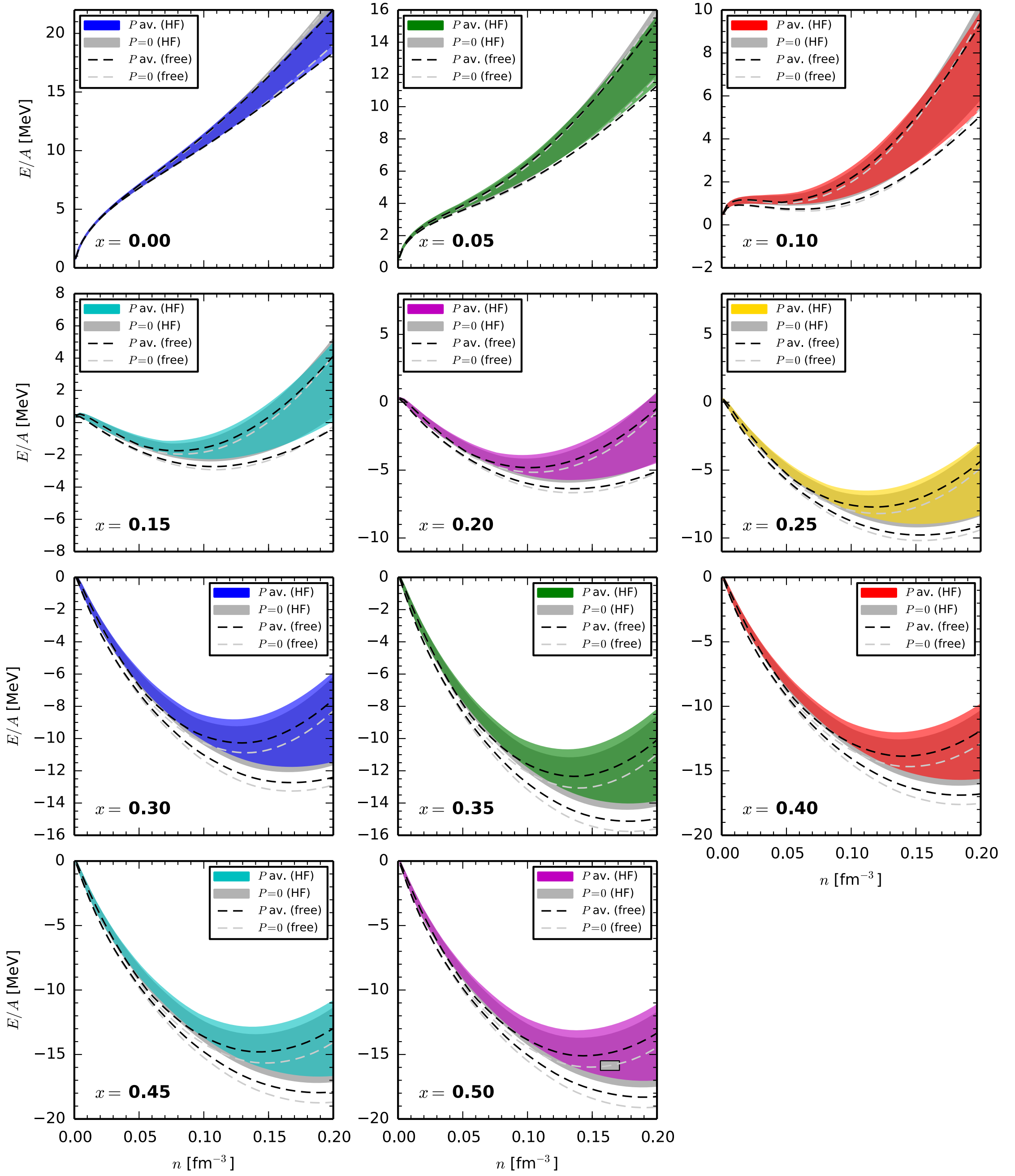
excellent agreement with other methods!

Nuclear forces and nuclear matter

asymmetric matter
with improved treatment
of 3N forces

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



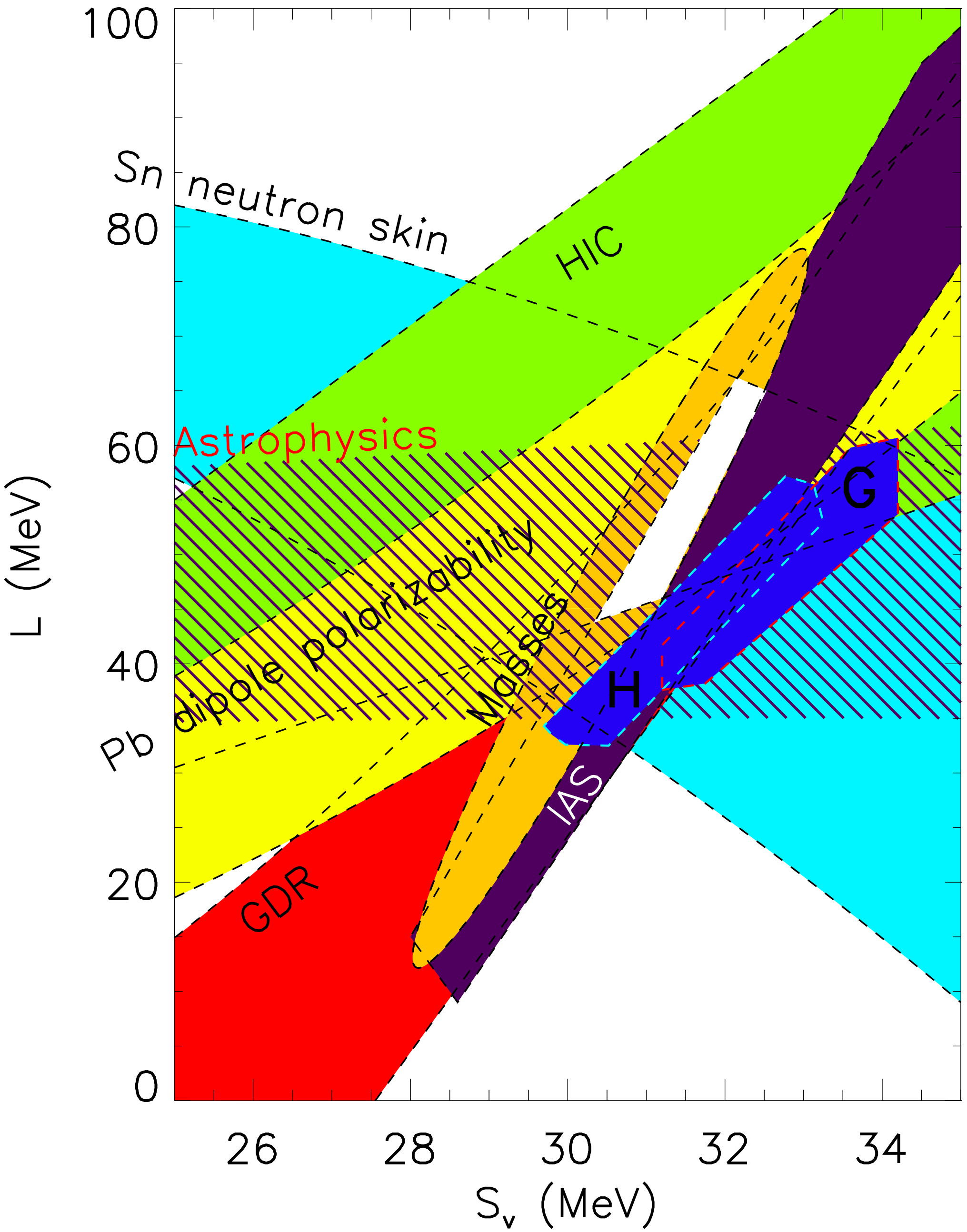


Symmetry energy and pressure of neutron matter

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!



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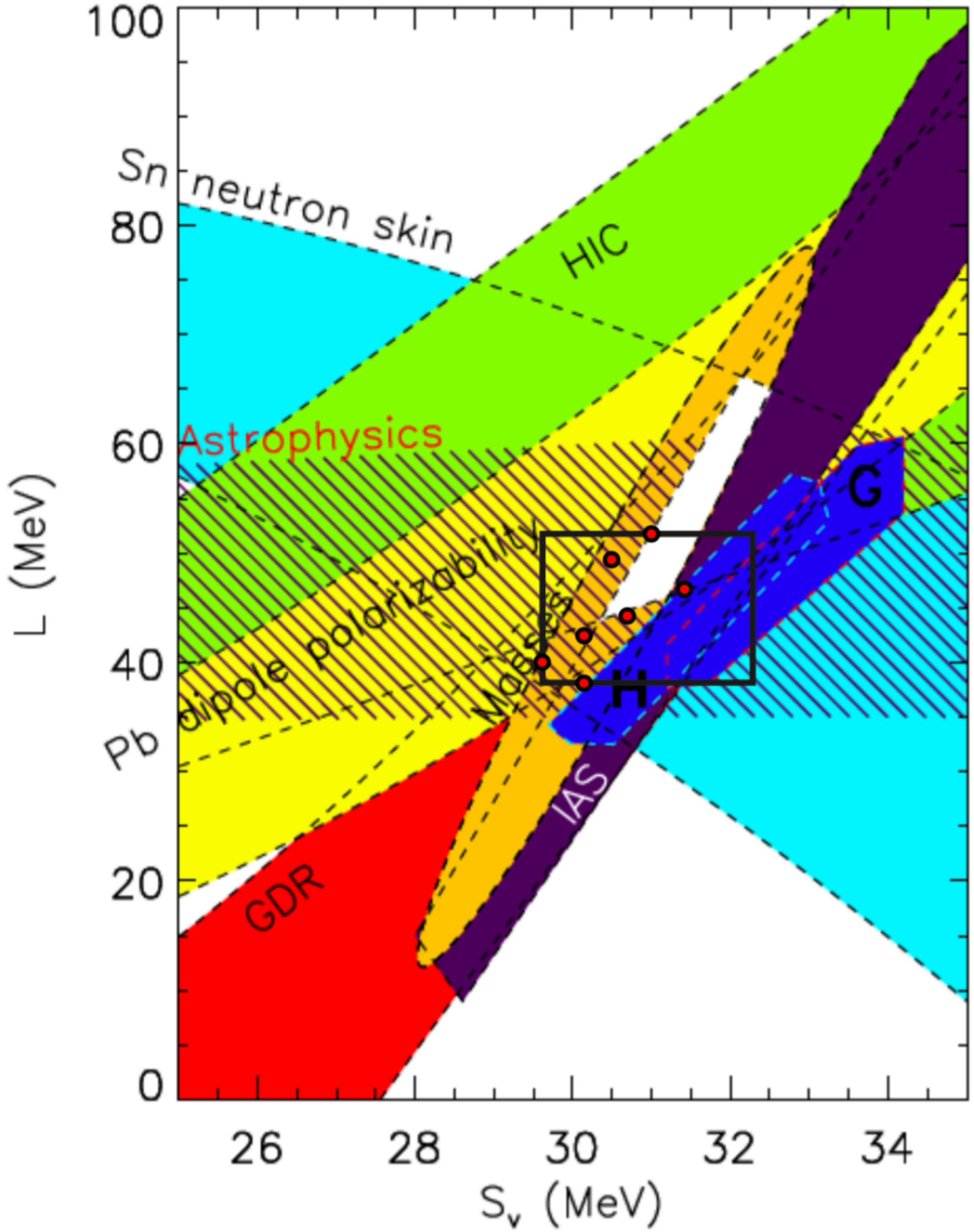
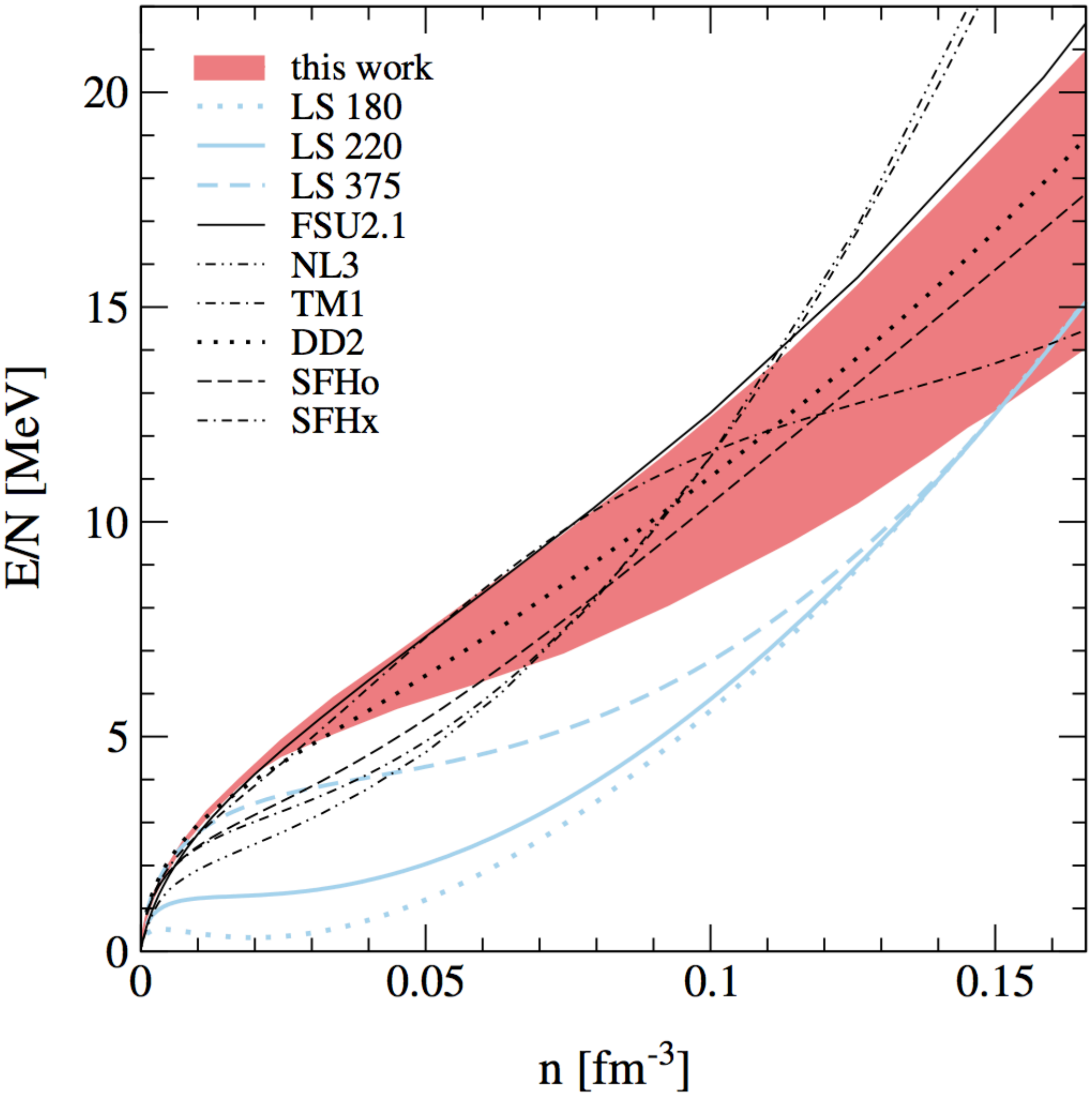
from asymmetric matter calculations Drischler



Comparisons to equations of state in astrophysics

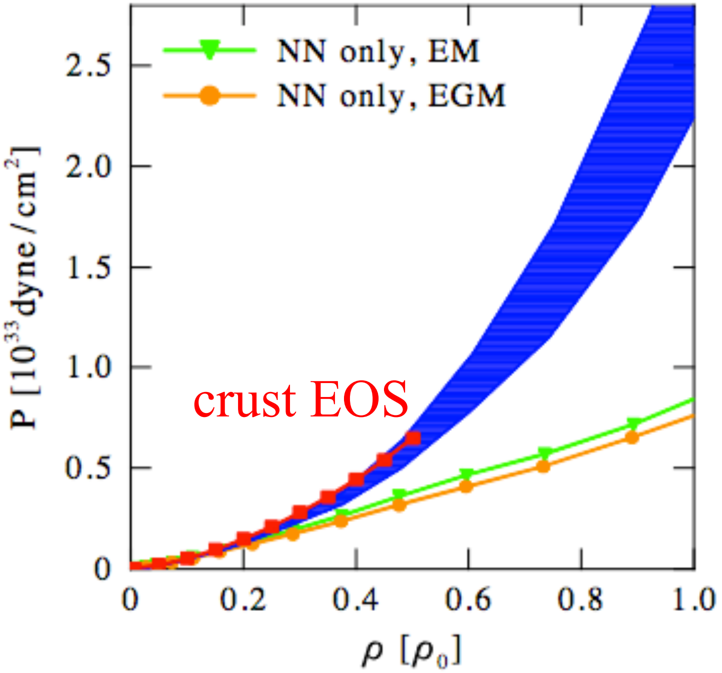
many equations of state used in supernova simulations not consistent with neutron matter results

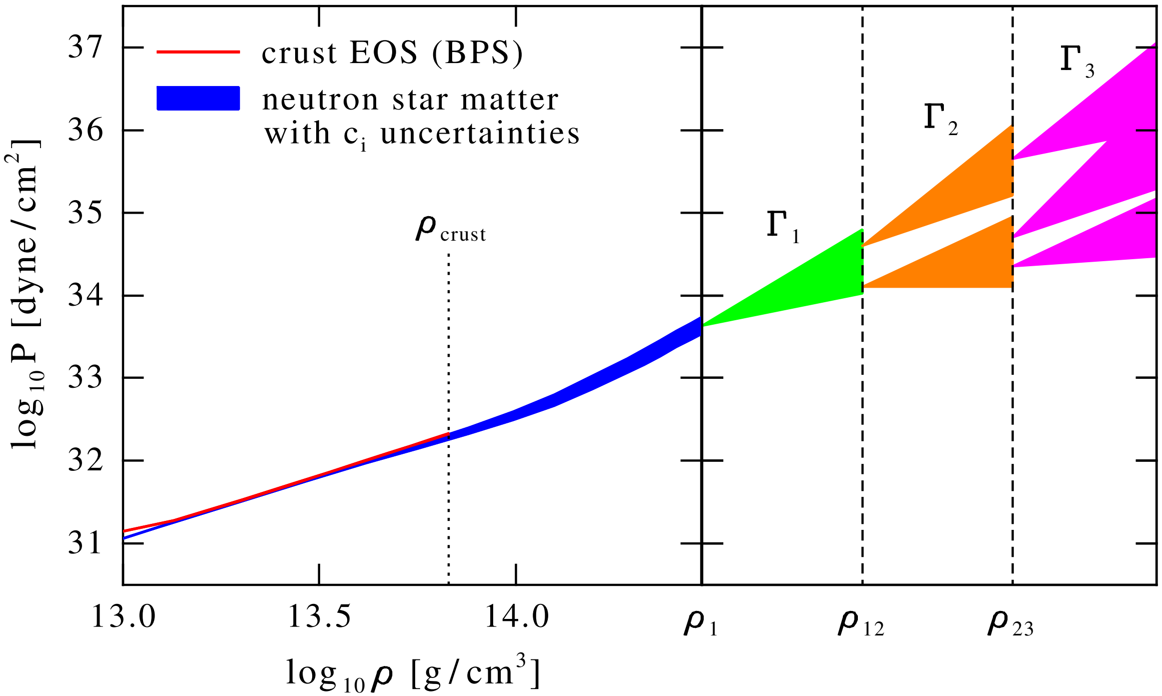


Impact on neutron stars

Hebeler, Lattimer, Pethick, AS, PRL (2010), ApJ (2013)

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





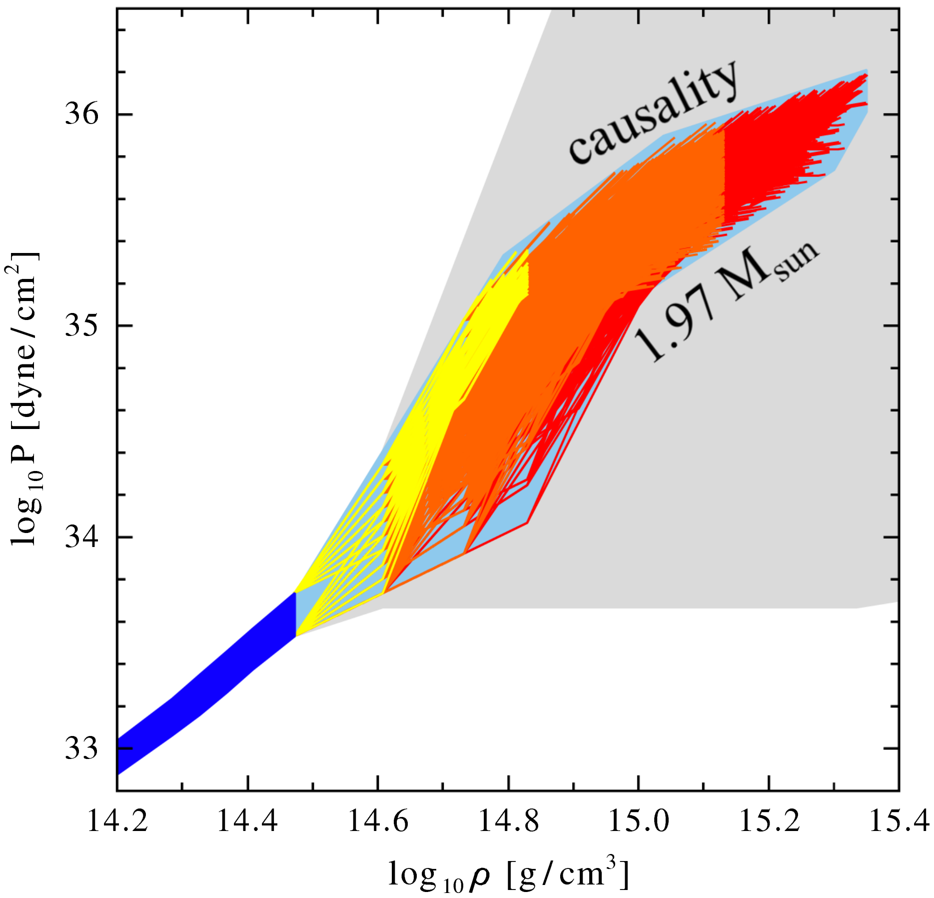
pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

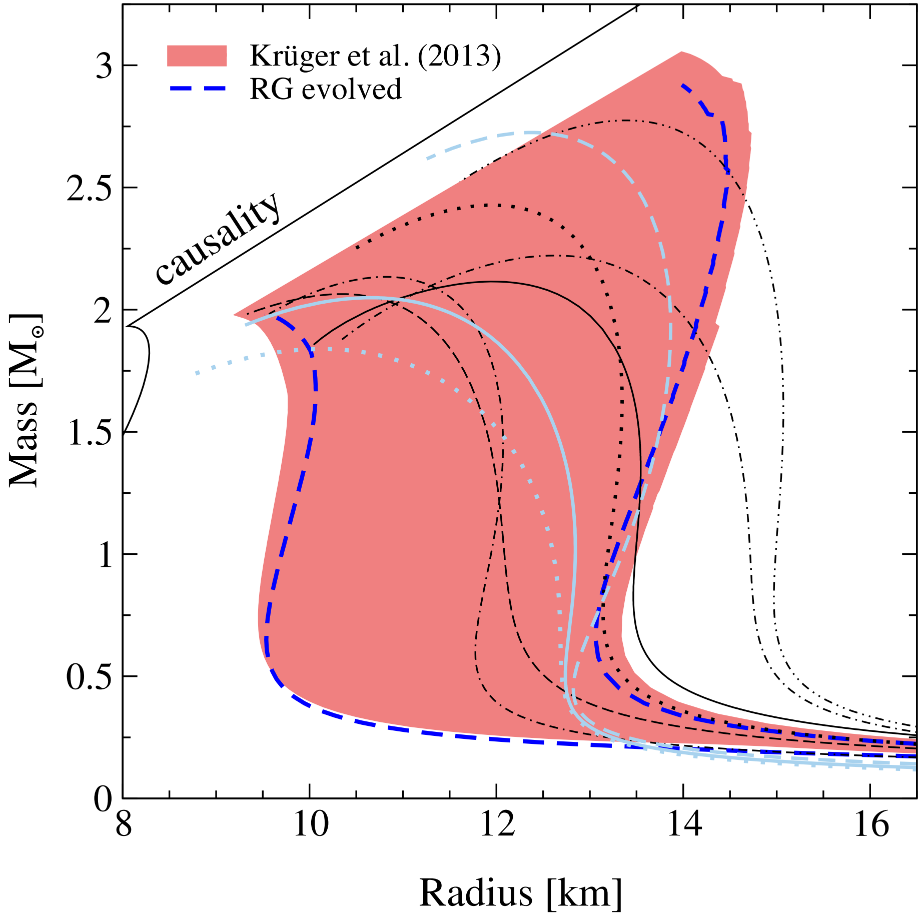
extend uncertainty band to higher densities using piecewise polytropes allow for soft regions

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





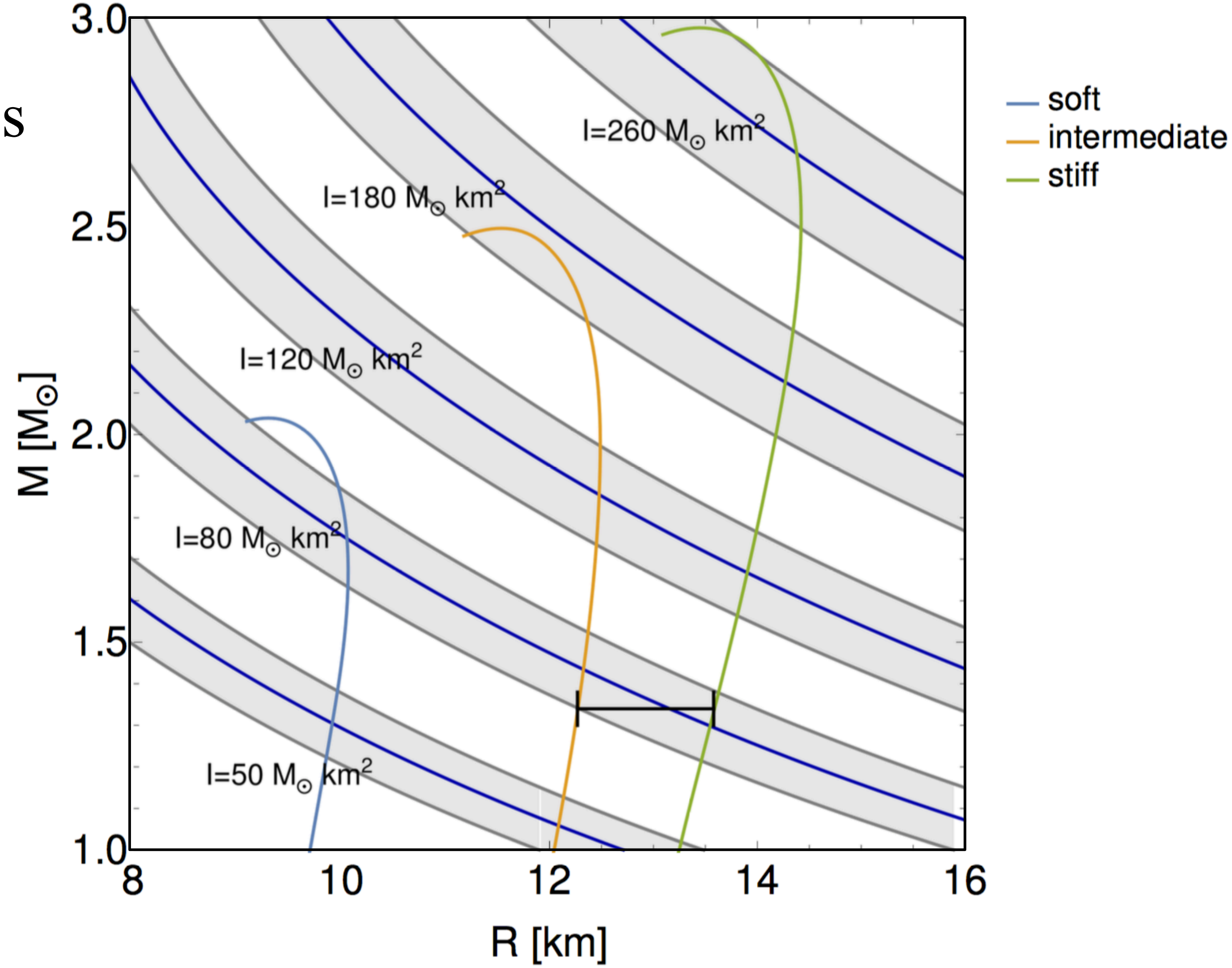
low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

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

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

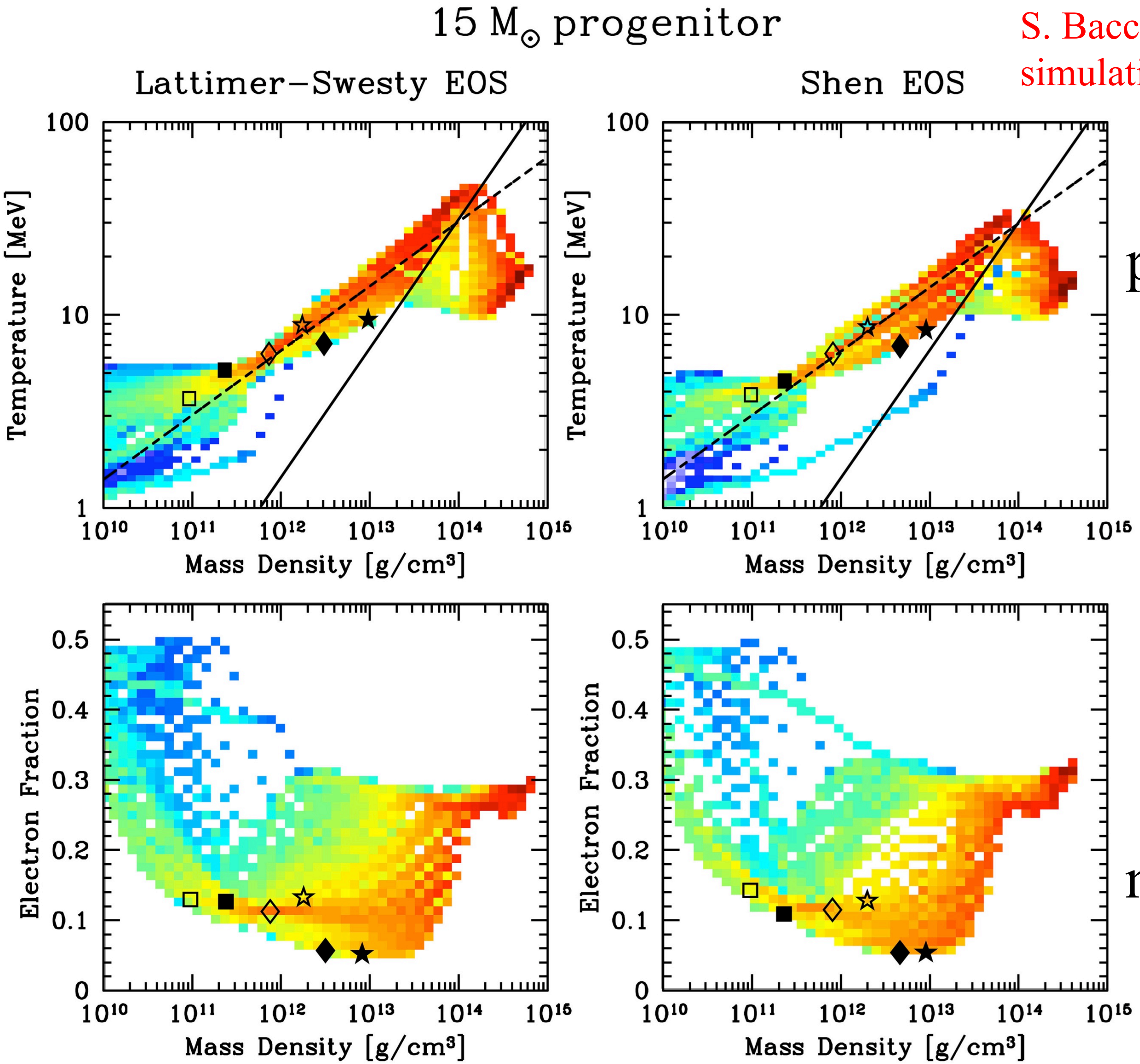
candidate neutron star:
PSR J0737-3039 $M=1.35\ M_{sun}$

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



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 $\sim 10^{13}$-10^{14} g/cm^3
(high densities: neutrinos trap; low densities: few interactions)

Neutrino rates from chiral effective field theory

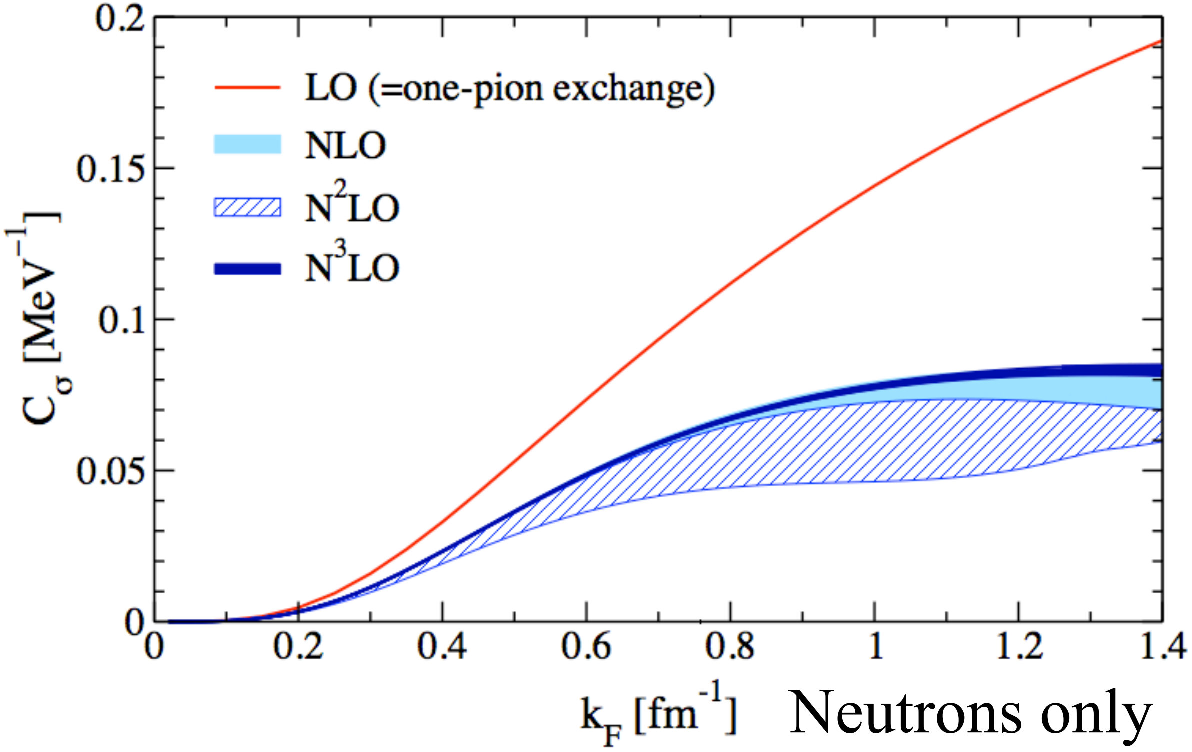
processes involving two nucleons play a special role Friman,… Suzuki, **Raffelt**,…

$NN \leftrightarrow NN\nu\overline{\nu}$ 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

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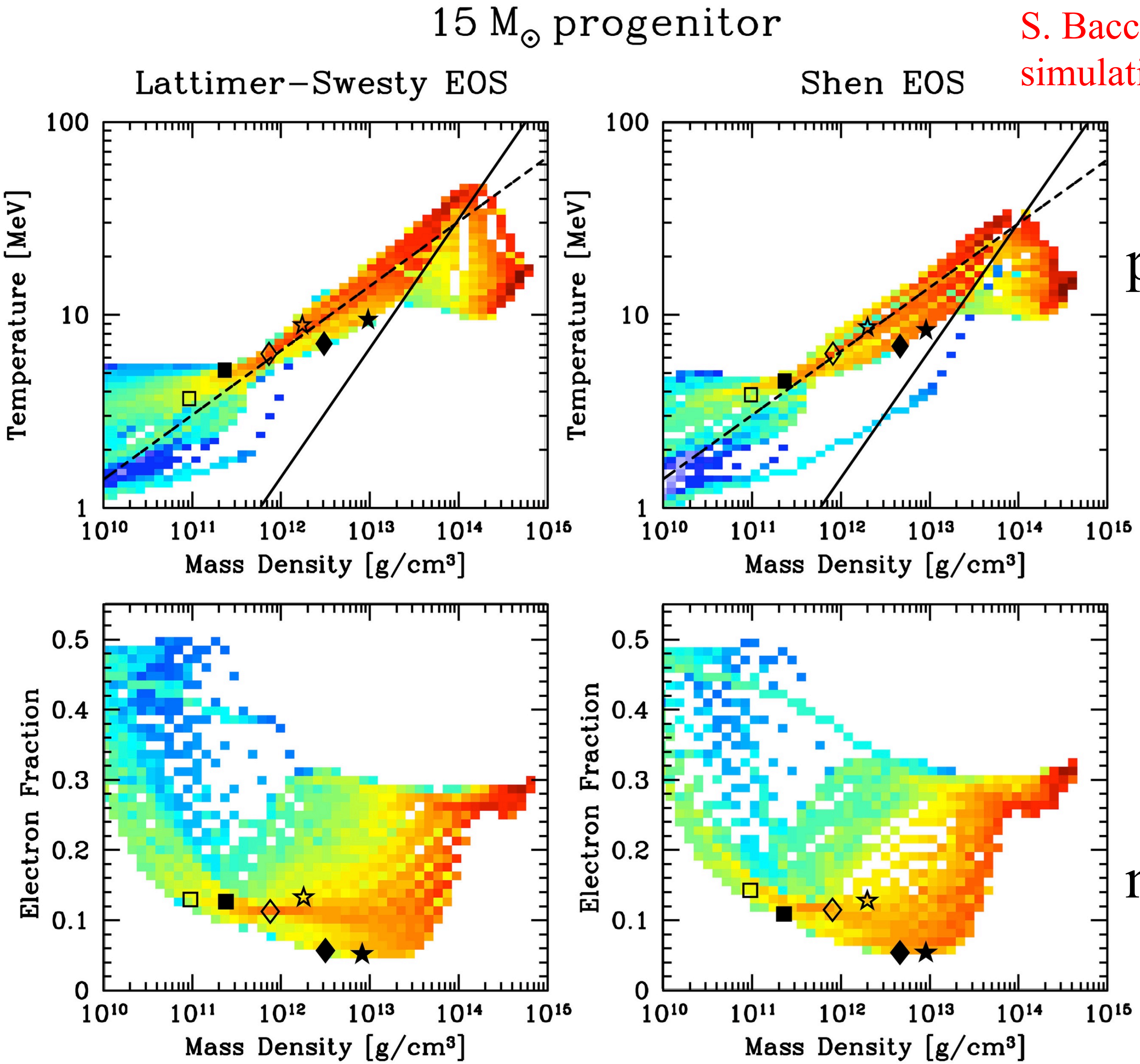

partially degenerate

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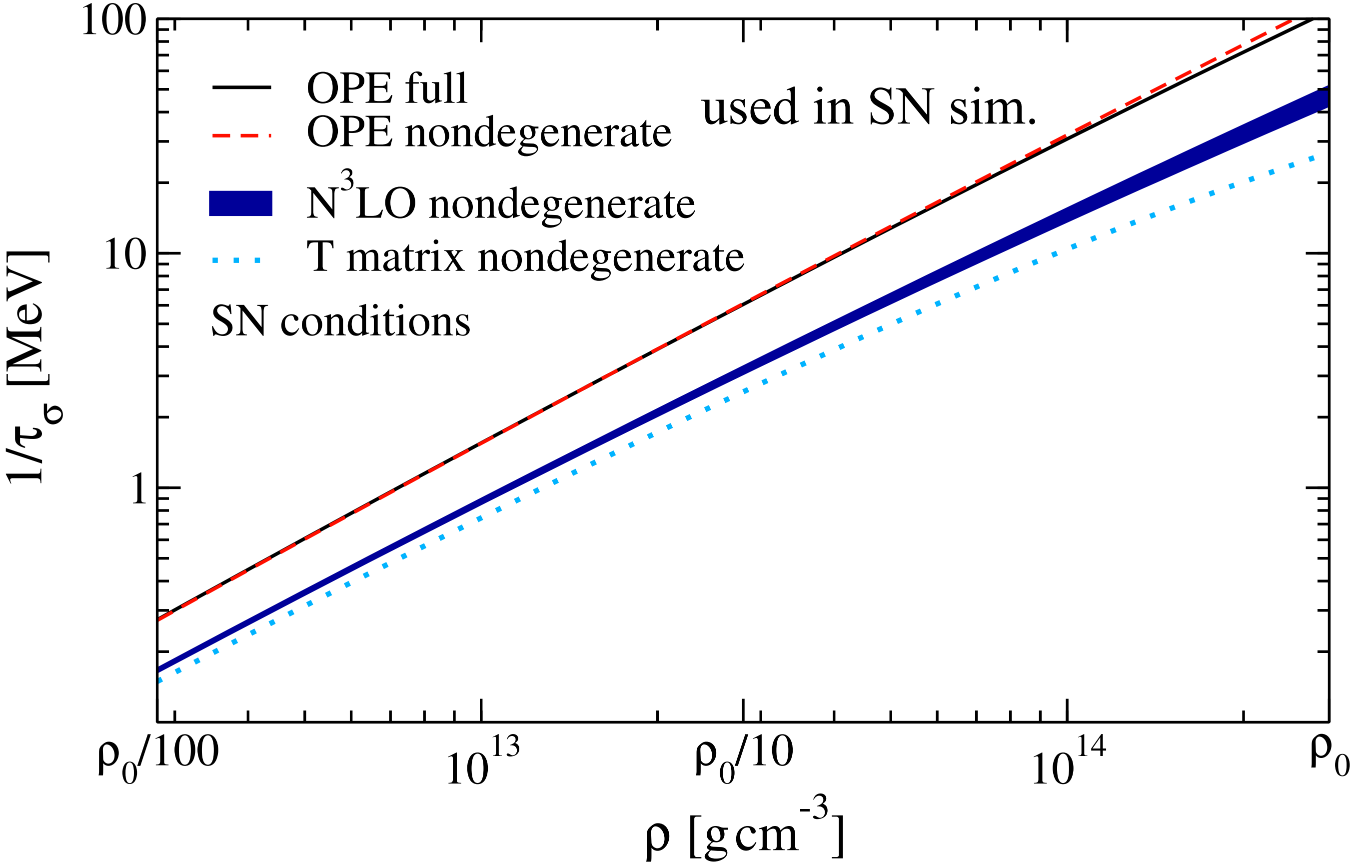
crucial densities below nuclear matter density ~10^{13}-10^{14} g/cm^3
(high densities: neutrinos trap; low densities: few interactions)

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

neutrons only, arbitrary degeneracy



used in SN sim.

similar reduction along SN conditions

Energy transfer in neutrino scattering from nucleons Bartl et al., in prep.

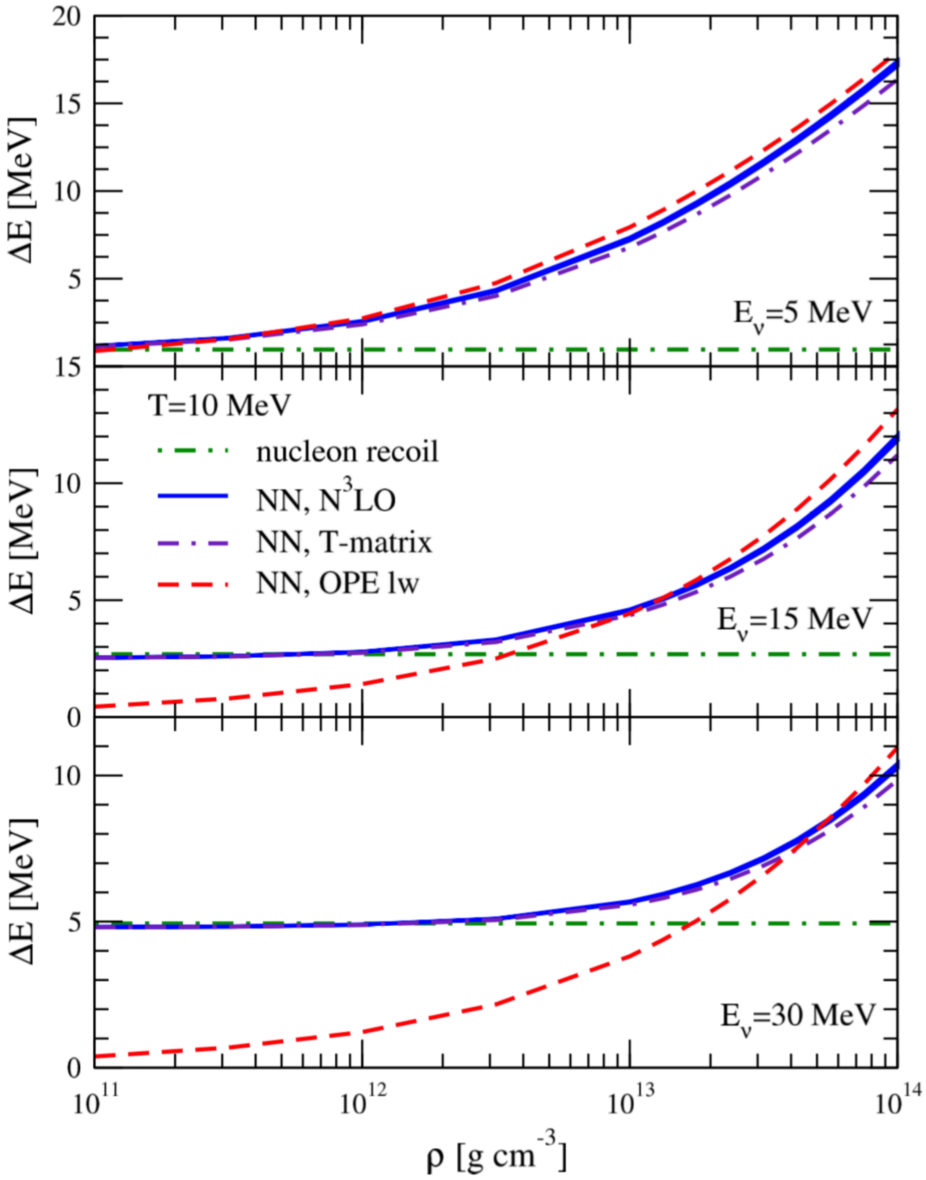
mean-square neutrino energy transfer in $\nu n n \leftrightarrow \nu n n$

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

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

energy transfer significant,
can dominate over recoil

not included in simulations

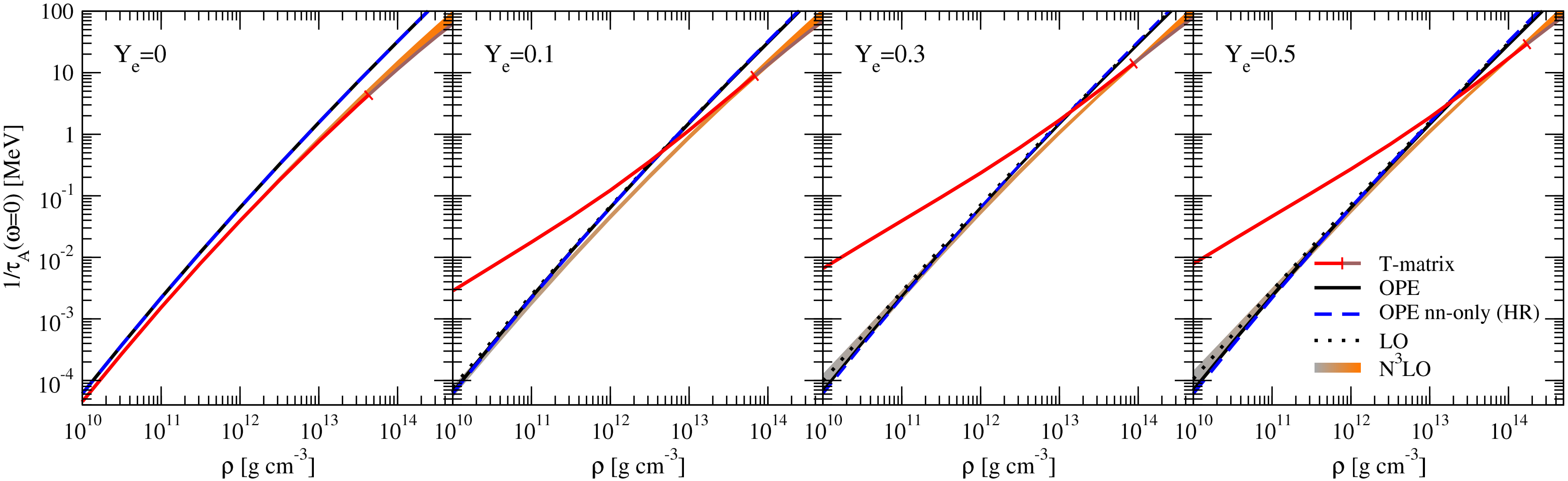


Neutrino bremsstrahlung in mixtures of neutron and protons

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, PRL (2015)



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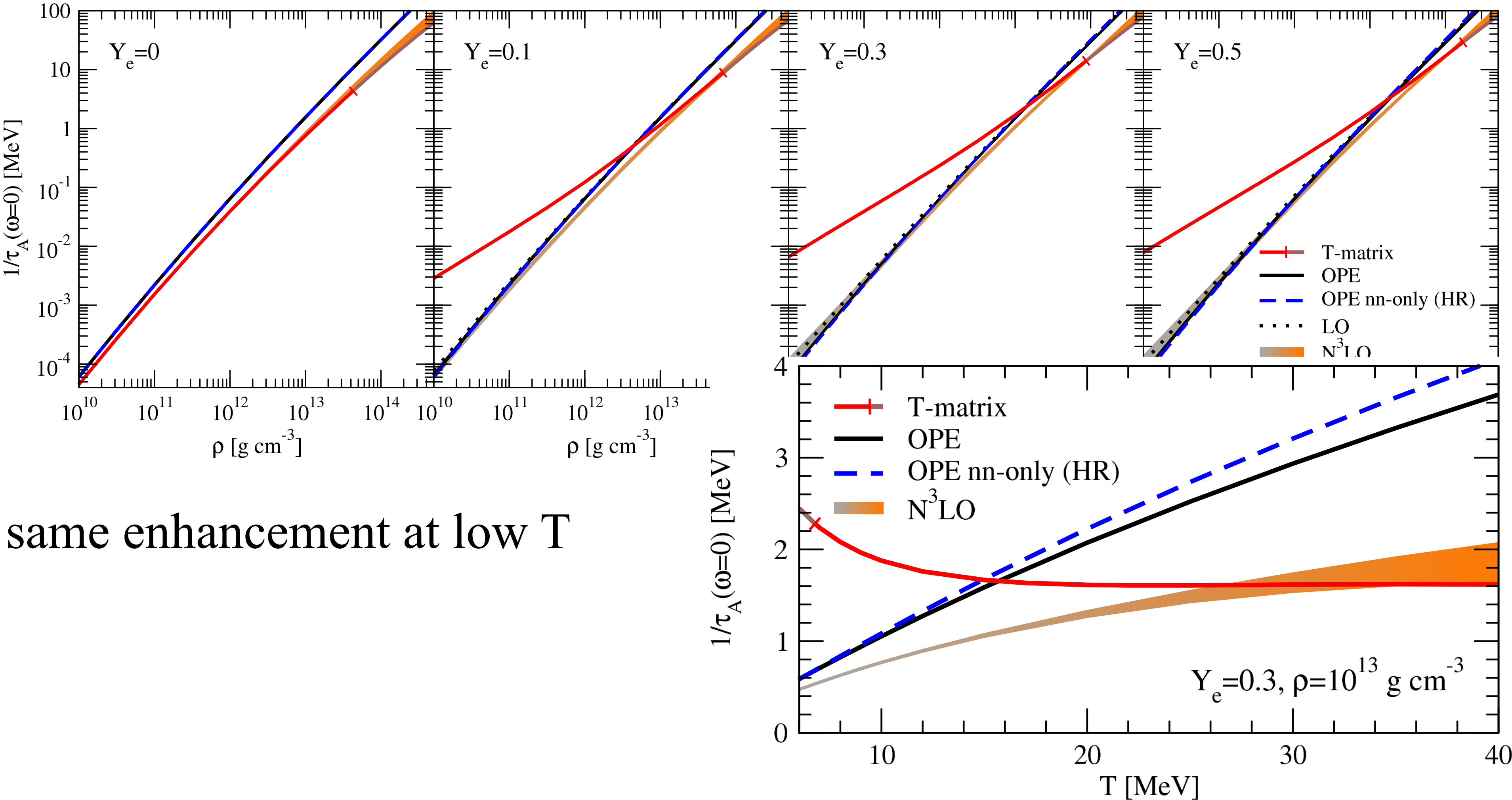

same enhancement at low T

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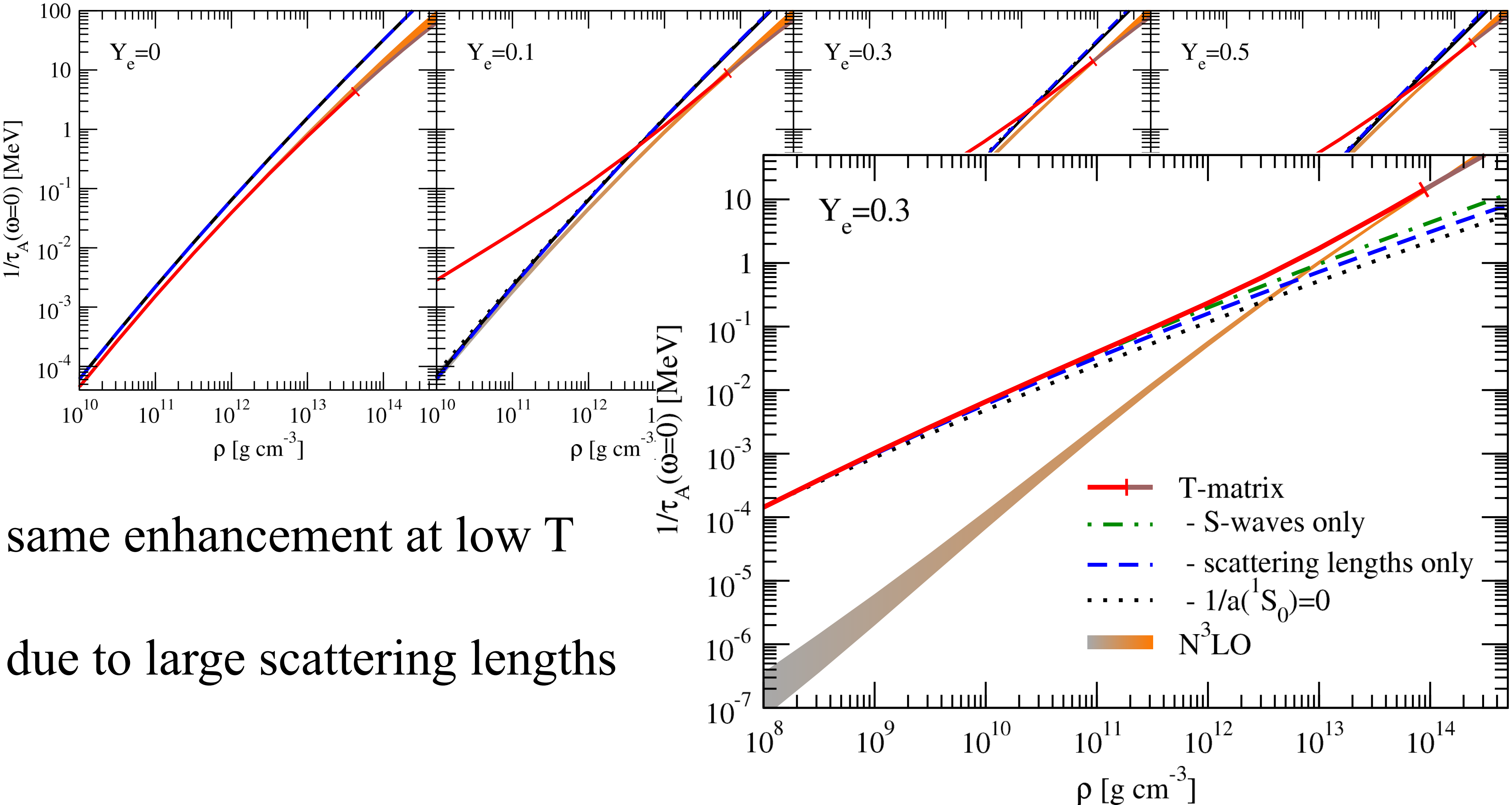

same enhancement at low T

due to large scattering lengths

Neutrino bremsstrahlung in mixtures of neutron and protons

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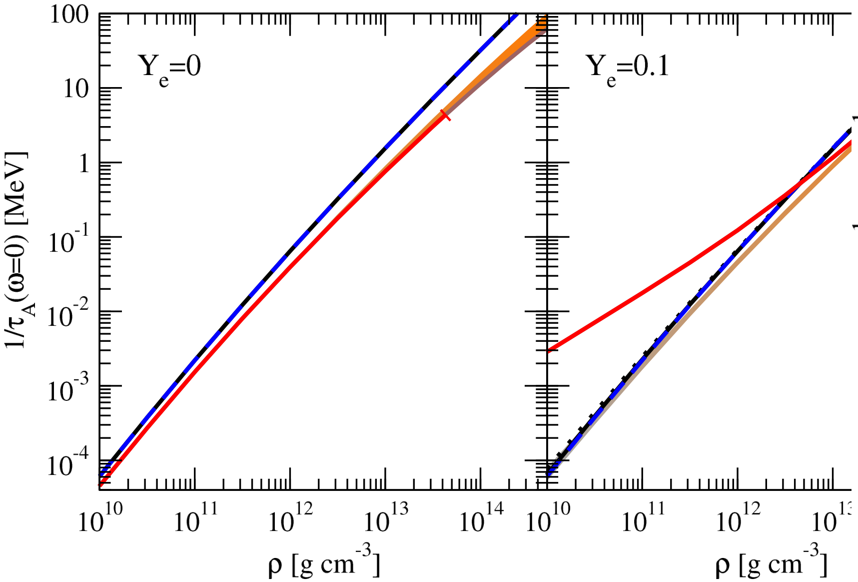

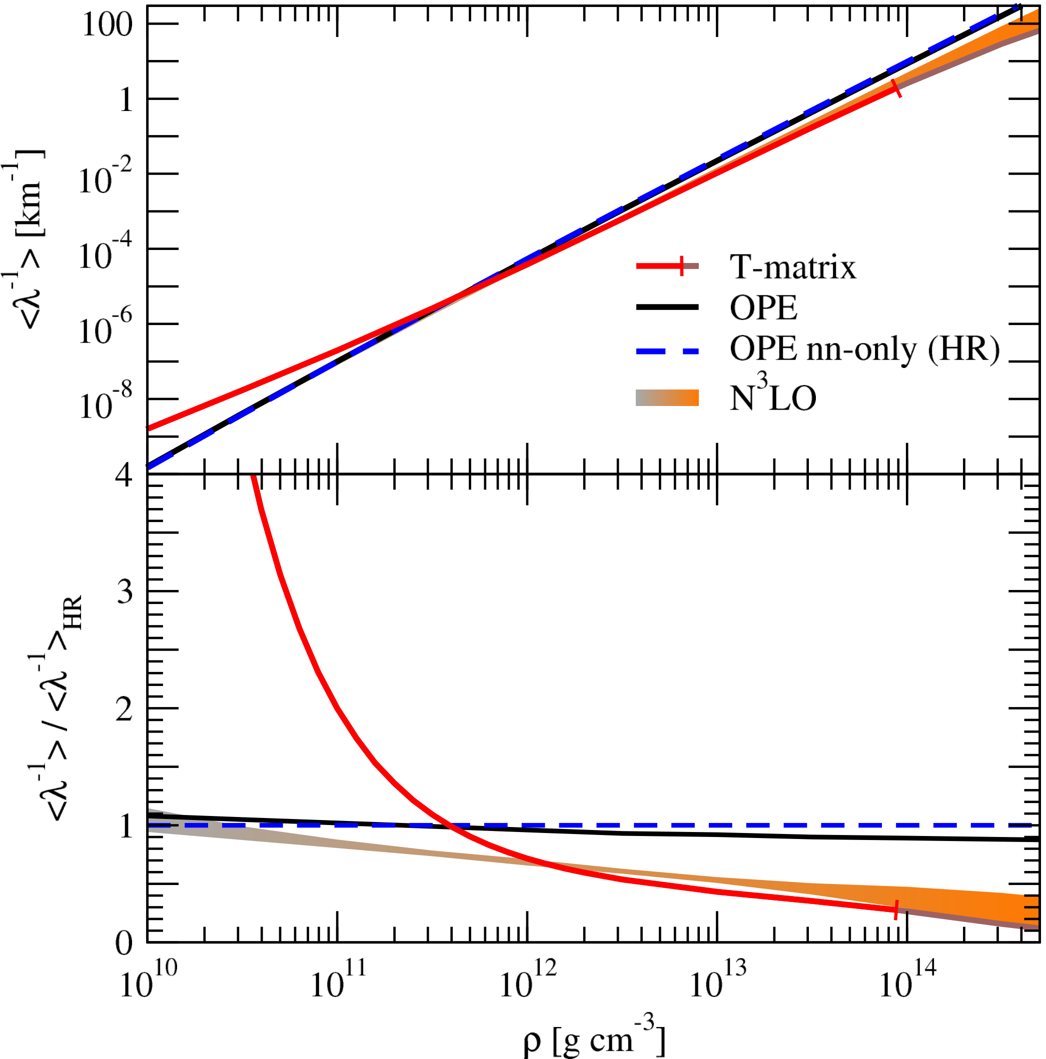

same enhancement at low T

smaller enhancement of inverse mf paths

Main points

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General EOS band based on nuclear physics and observations
neutron star radius 9.7-13.9 km for $M=1.4\ M_{sun}$ (±18%)

Chiral EFT important for consistent neutrino-matter interactions

Enhancement of neutrino bremsstrahlung at low densities
see talk by **Robert Bollig** on impact in simulations
important to explore inelastic scattering

Main results thanks to: **A. Bartl, C. Drischler, S. Greif,**
K. Hebeler, T. Krüger, J. Lattimer, C. Pethick, **I. Tews**