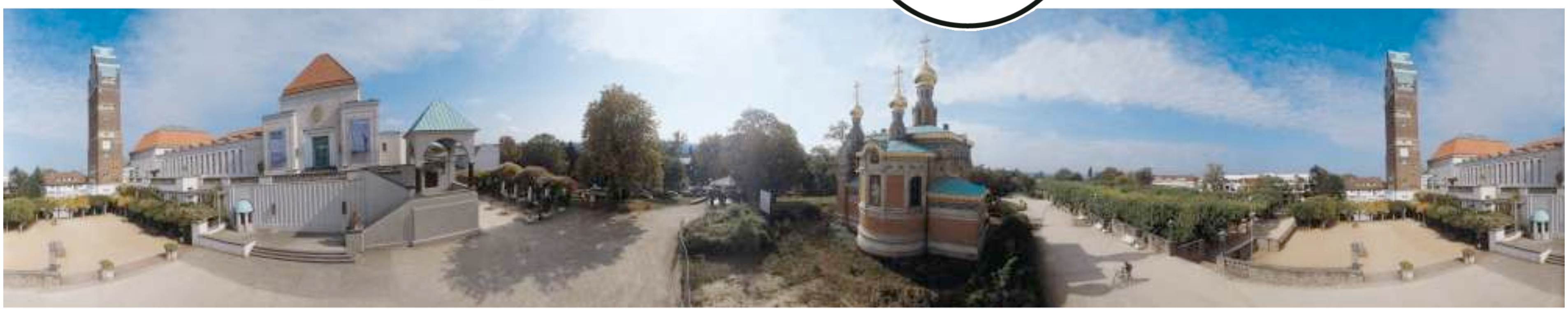
Neutron-rich matter and neutrino-matter interactions based on chiral effective field theory

Achim Schwenk



Astrophysical Transients: Multi-Messenger Probes of Nuclear Physics

INT, July 29, 2011

Outline

Chiral effective field theory for nuclear forces

Three-nucleon forces and neutron (neutron-star) matter

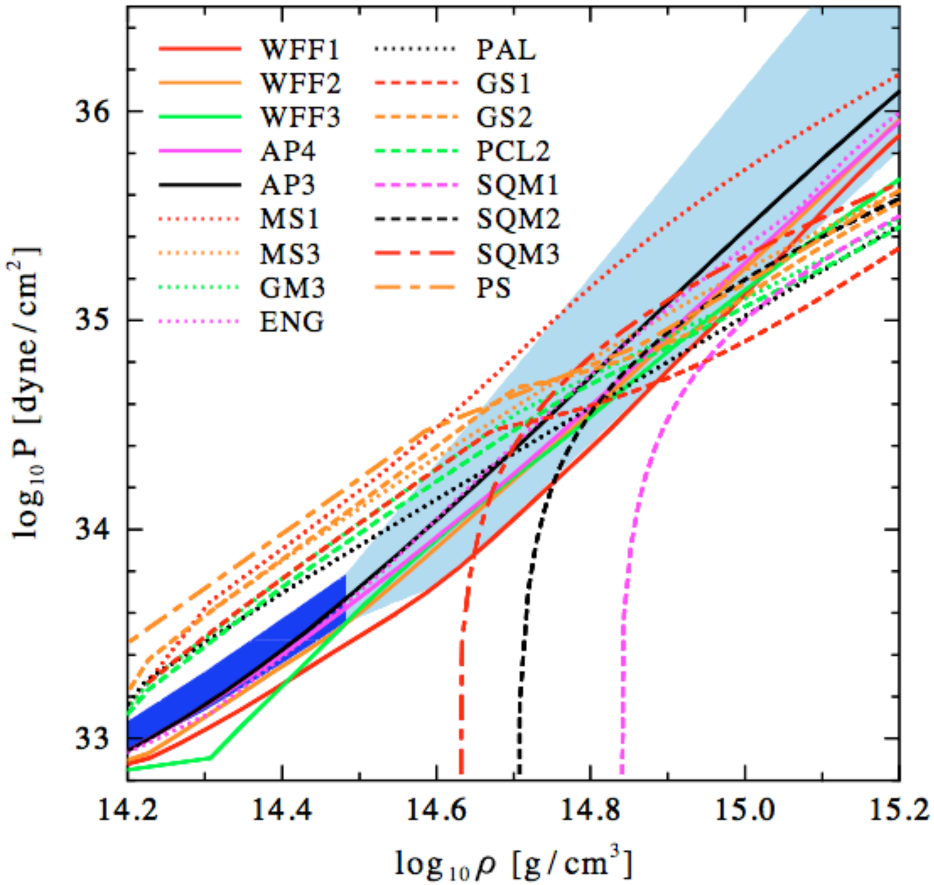
Impact on neutron stars

Three-nucleon forces and neutron-rich nuclei

Opportunities for neutrino-matter interactions

Pressure of neutron star matter

based on chiral effective field theory interactions at nuclear densities
and general extrapolation that supports 1.97 M_{sun} star

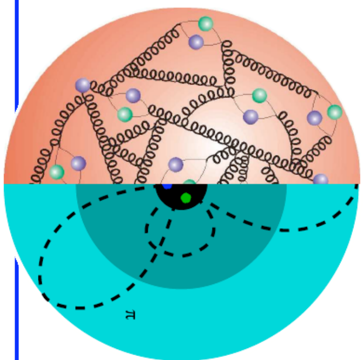


Hebeler, Lattimer, Pethick, AS, PRL (2010) + update for 1.97 M_{sun} star

provides strong constraints, ruling out many model equations of state

impact of three-nucleon forces on neutron-rich matter and nuclei

Λ / Resolution dependence of nuclear forces



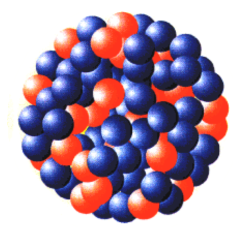
Effective theory for NN, 3N, many-N interactions and electroweak operators: resolution scale/Λ-dependent

$$H(\Lambda) = T + V_{\mathrm{NN}}(\Lambda) + V_{3\mathrm{N}}(\Lambda) + V_{4\mathrm{N}}(\Lambda) + \ldots$$

Λ_{chiral}

momenta $Q \sim \lambda^{-1} \sim m_\pi$=140 MeV: chiral effective field theory

neutrons and protons interacting via pion exchanges and shorter-range contact interactions



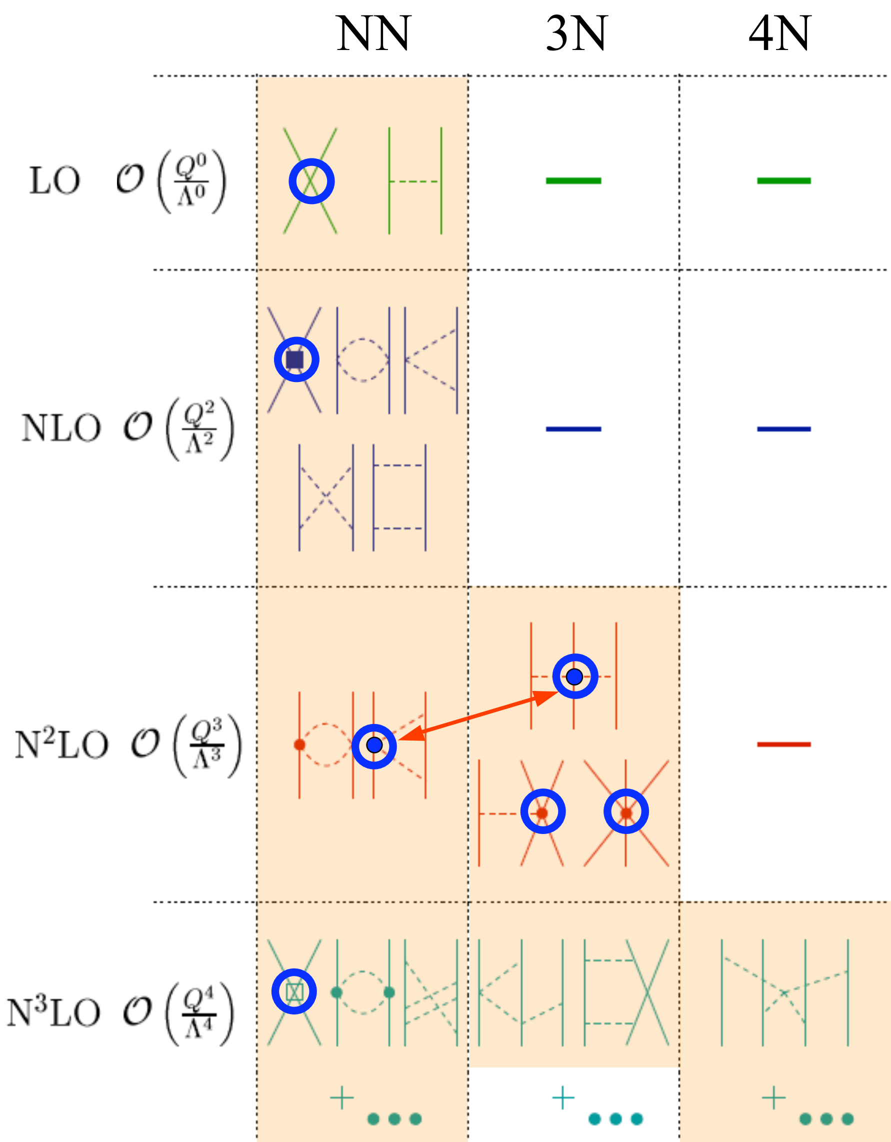
typical momenta in nuclei $\sim m_\pi$

$\Lambda_{pionless}$

$Q \ll m_\pi$

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 $(Q/\Lambda_b)^n$

include long-range pion physics

details at short distance not resolved

capture in few short-range couplings, fit to experiment once, Λ-dependent

systematic: can work to desired accuracy and obtain error estimates from truncation order and Λ variation

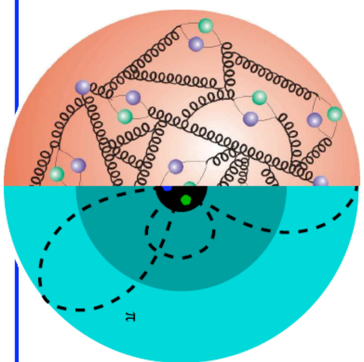
open problems: renormalization and power counting

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

Nuclear forces and the Renormalization Group (RG)

RG evolution to lower resolution/cutoffs Bogner, Kuo, AS, Furnstahl,…

$$H(\Lambda) = T + V_{\rm NN}(\Lambda) + V_{\rm 3N}(\Lambda) + V_{\rm 4N}(\Lambda) + \ldots$$



$\Lambda_{\rm chiral}$

Λ ↓

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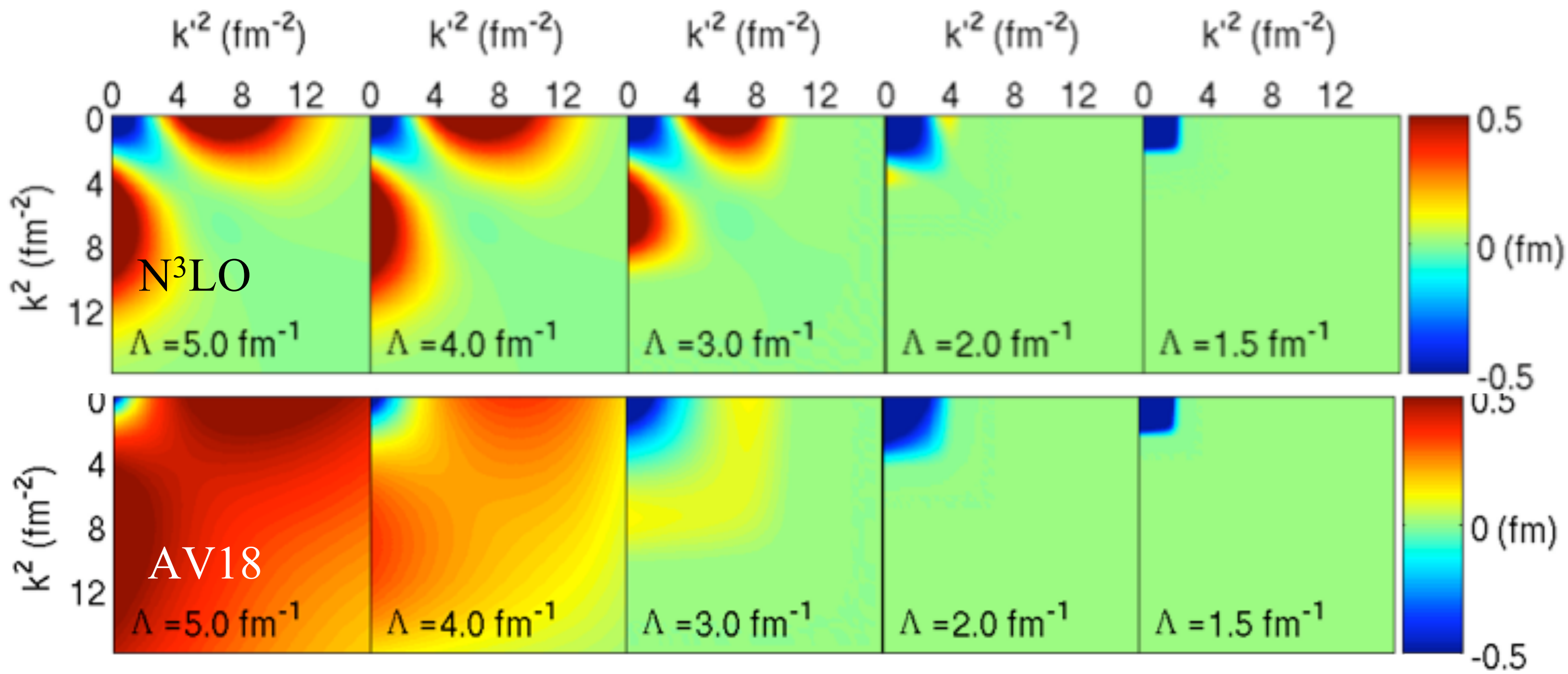

low-momentum interactions $V_{{\rm low}\,k}(\Lambda)$

RG decouples low-momentum physics from high momenta

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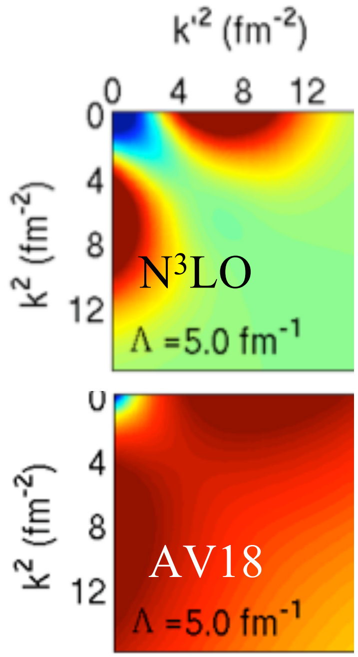

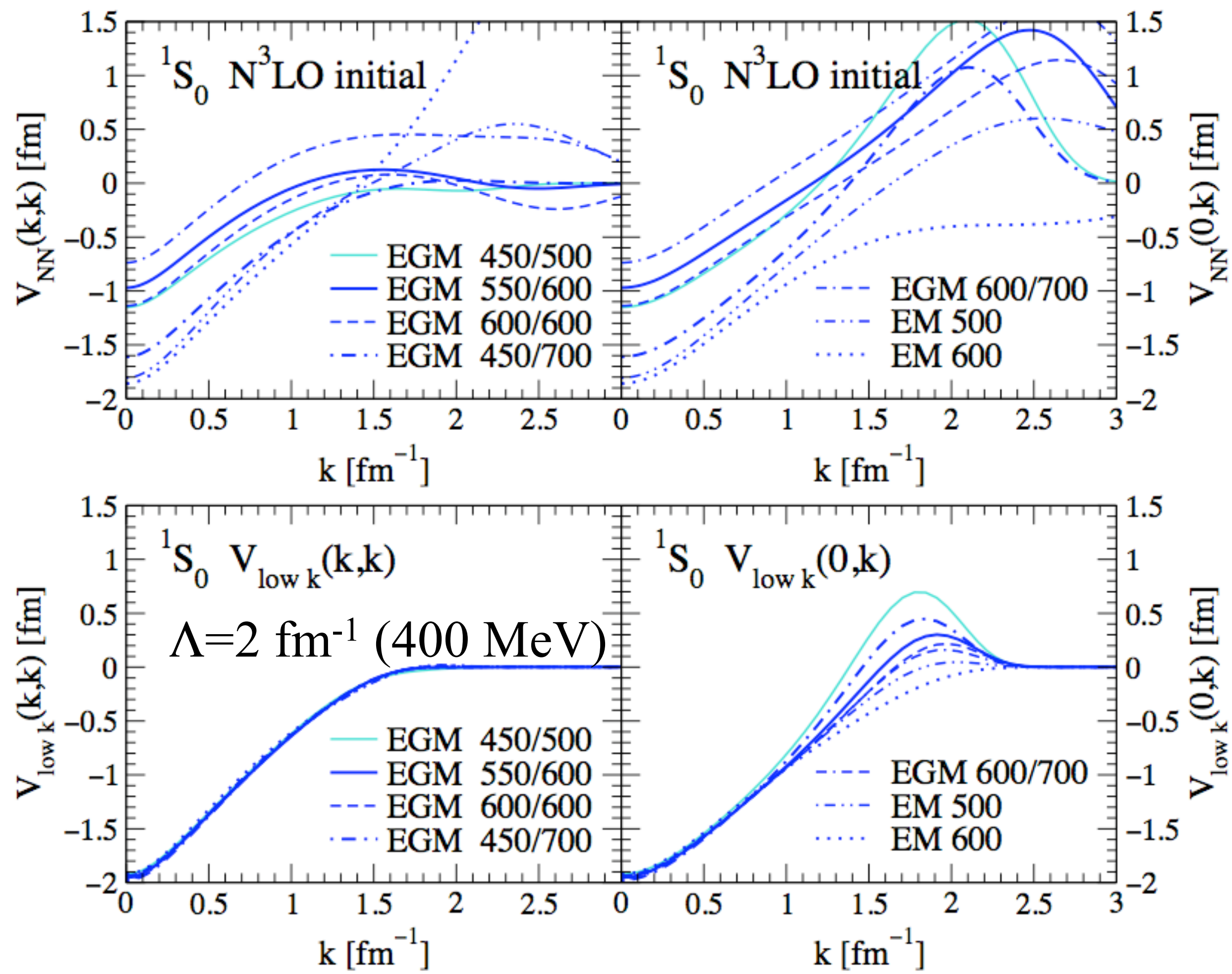

low-momentum i

RG decouples lov

low-momentum universality from different chiral N³LO potentials

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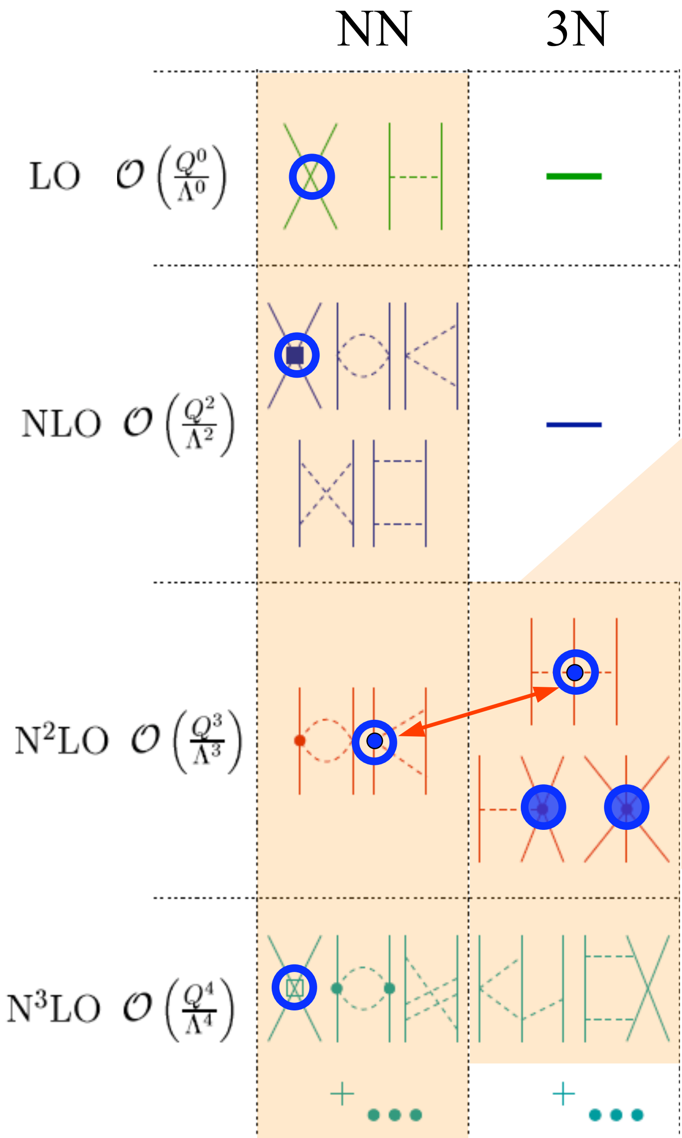
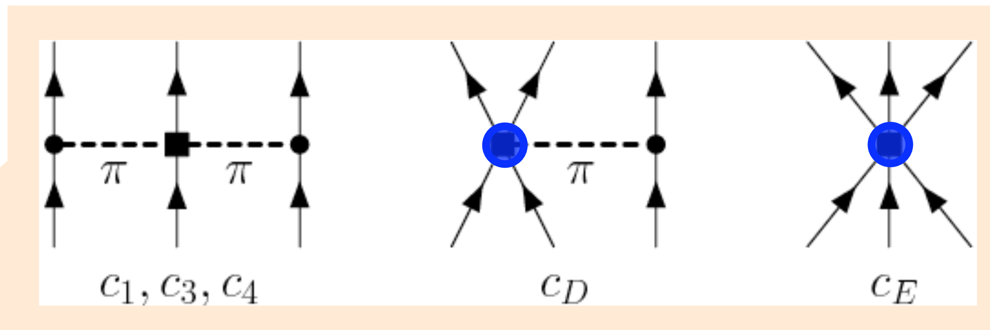


consistent NN-3N interactions

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



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

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

single-Δ: $c_1=0$, $c_3=-c_4/2=-3$ GeV^{-1}

c_D, c_E fit to ^3H binding energy and ^4He radius (or ^3H beta decay half-life)

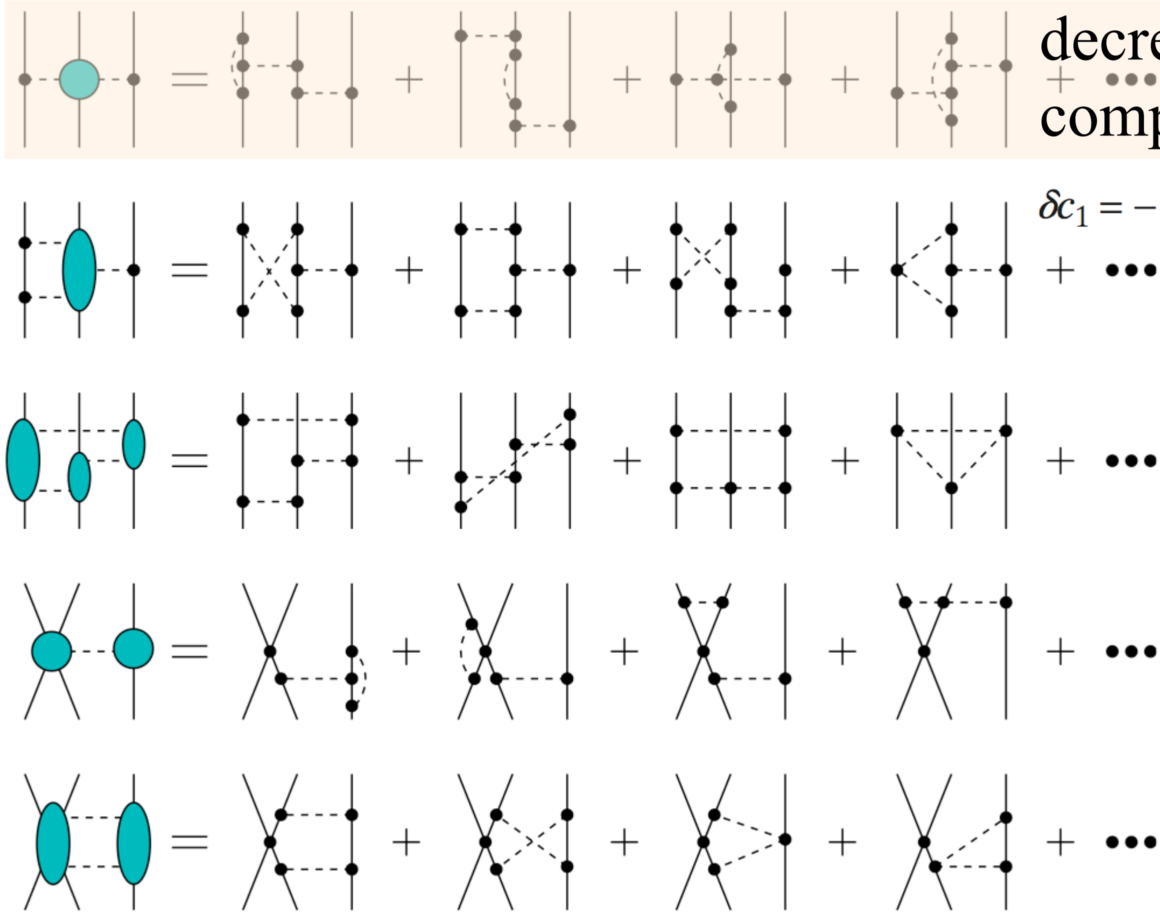
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Meissner,…

Subleading chiral 3N forces

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

one-loop contributions:

2π-exchange, 2π-1π-exchange, rings, contact-1π-, contact-2π-exchange



decrease c_i strengths

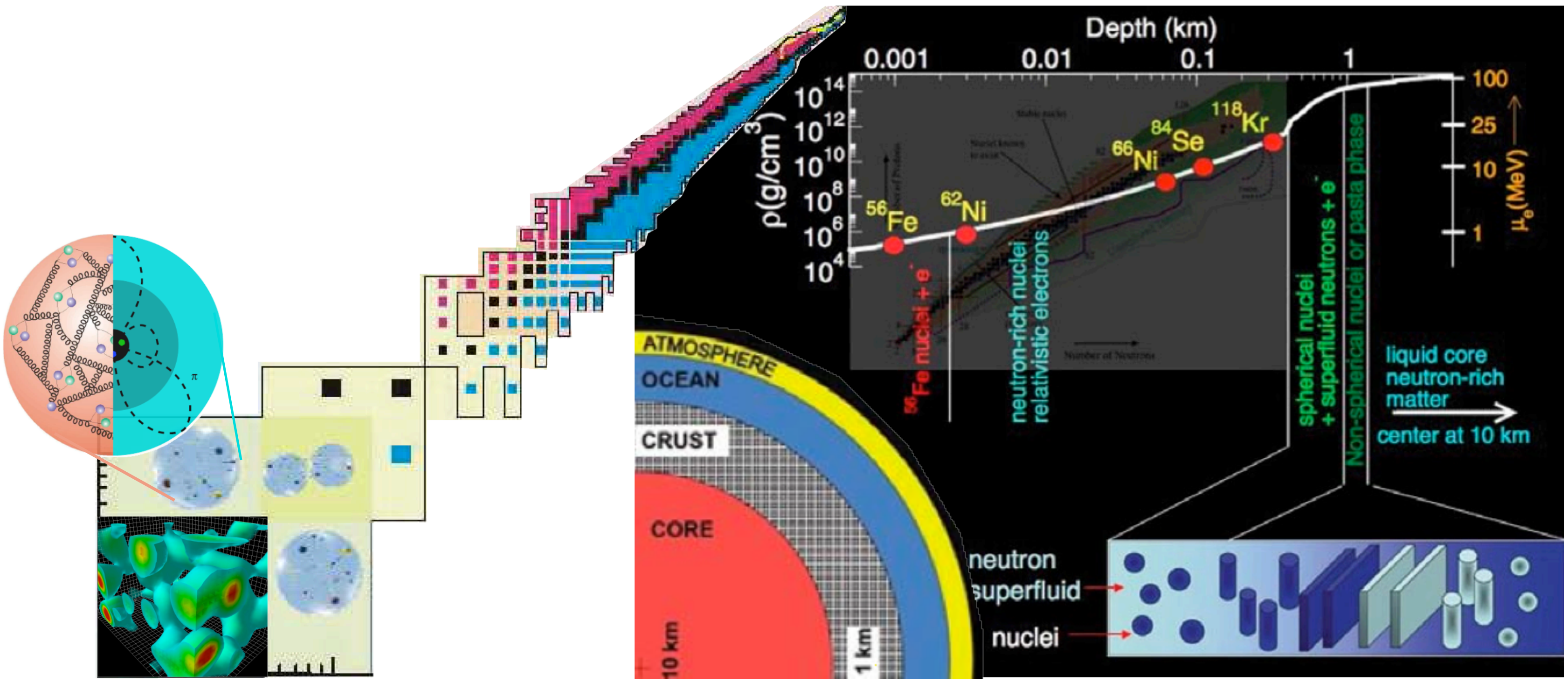
comparable to N^2LO uncertainty

$\delta c_1 = -g_A^2 M_\pi / 64\pi F_\pi^2$, $\delta c_3 = -\delta c_4 = g_A^4 M_\pi / 16\pi F_\pi^2$

$\delta c_3 = -\delta c_4 = 1\ \mathrm{GeV}^{-1}$

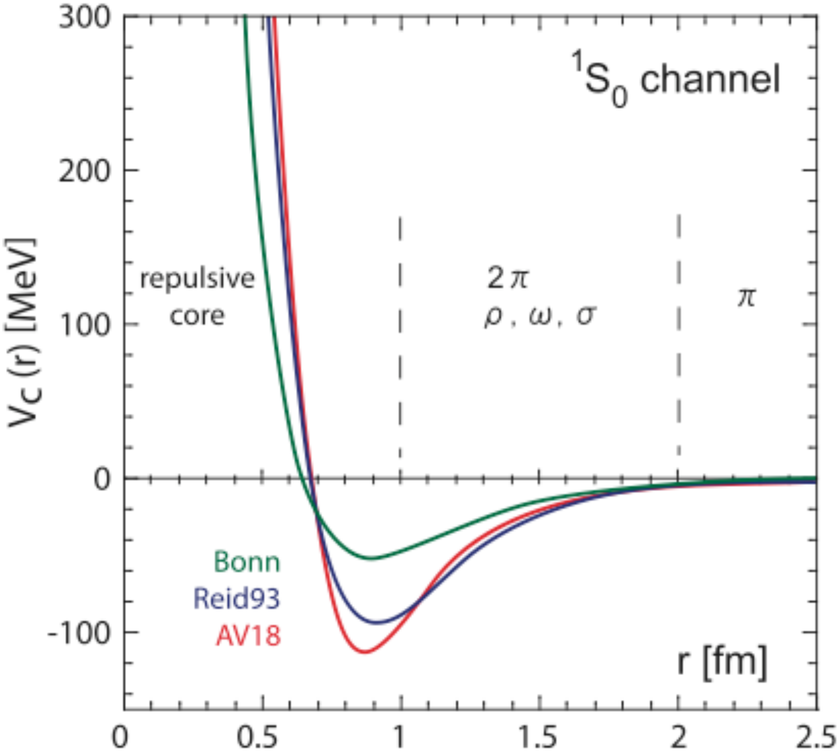
1/m corrections: spin-orbit parts, interesting for A_y puzzle

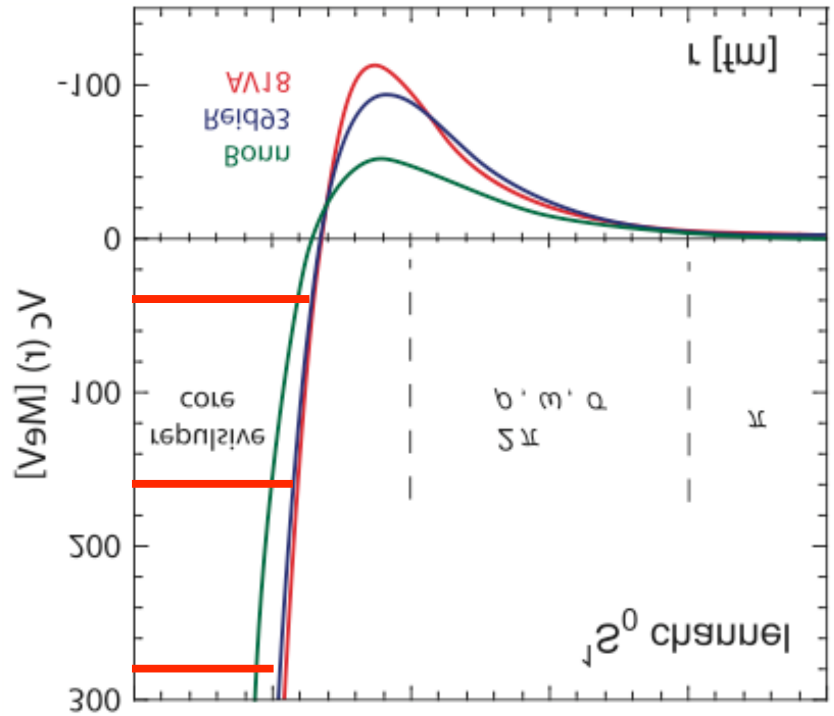
Extreme neutron-rich matter in stars



Convergence with low-momentum interactions

large cutoffs lead to flipped-potential bound states, even for small $-\lambda V$
requires nonperturbative expansion, leads to slow convergence for nuclei





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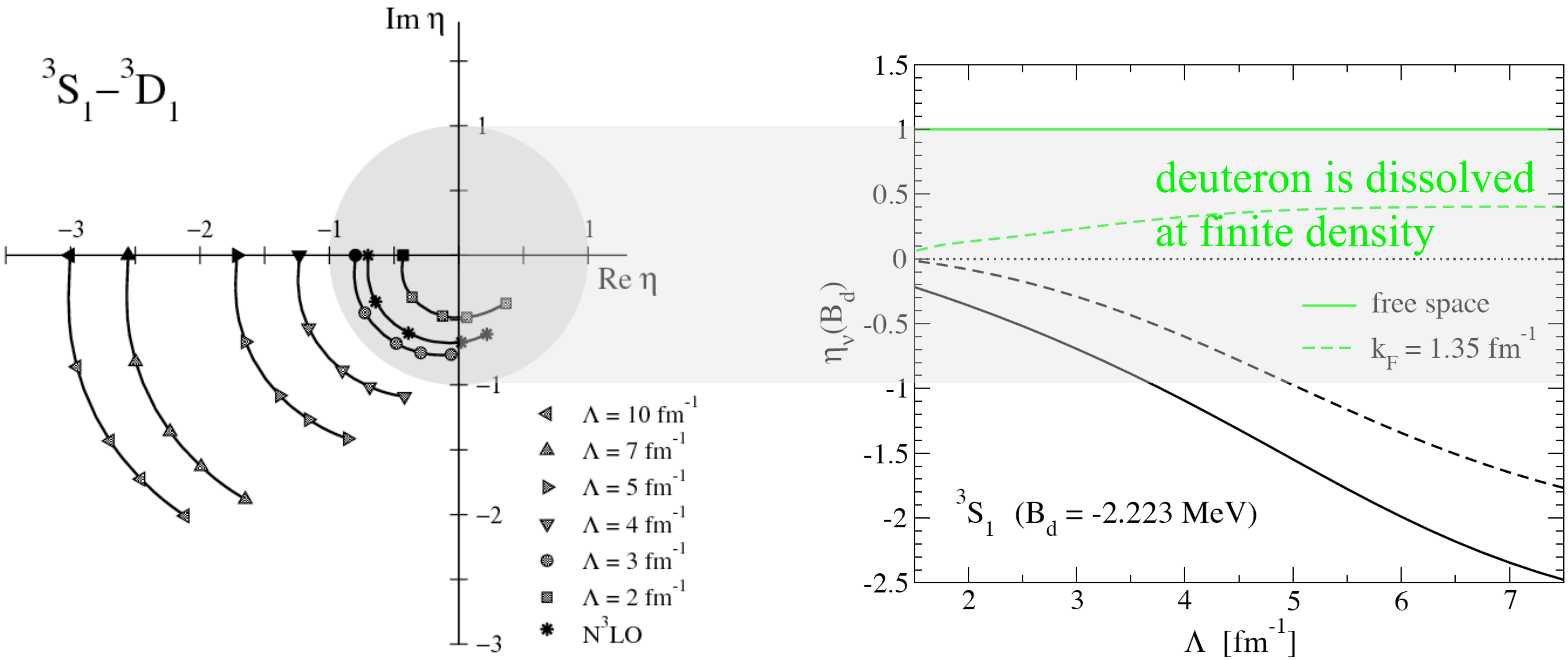


Weinberg eigenvalues: two-body scattering becomes perturbative after RG evolution, except in channels with bound states

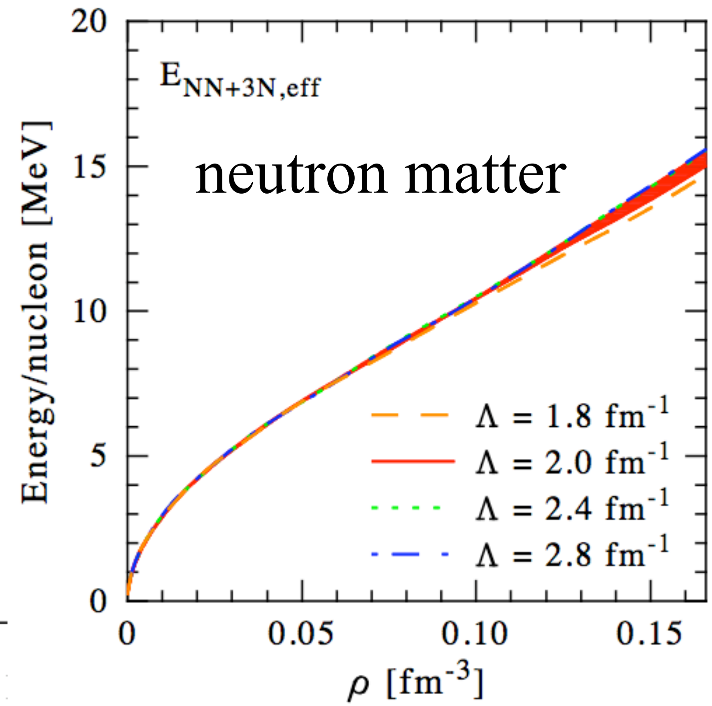
RG leads to improved convergence for nuclei and nuclear matter

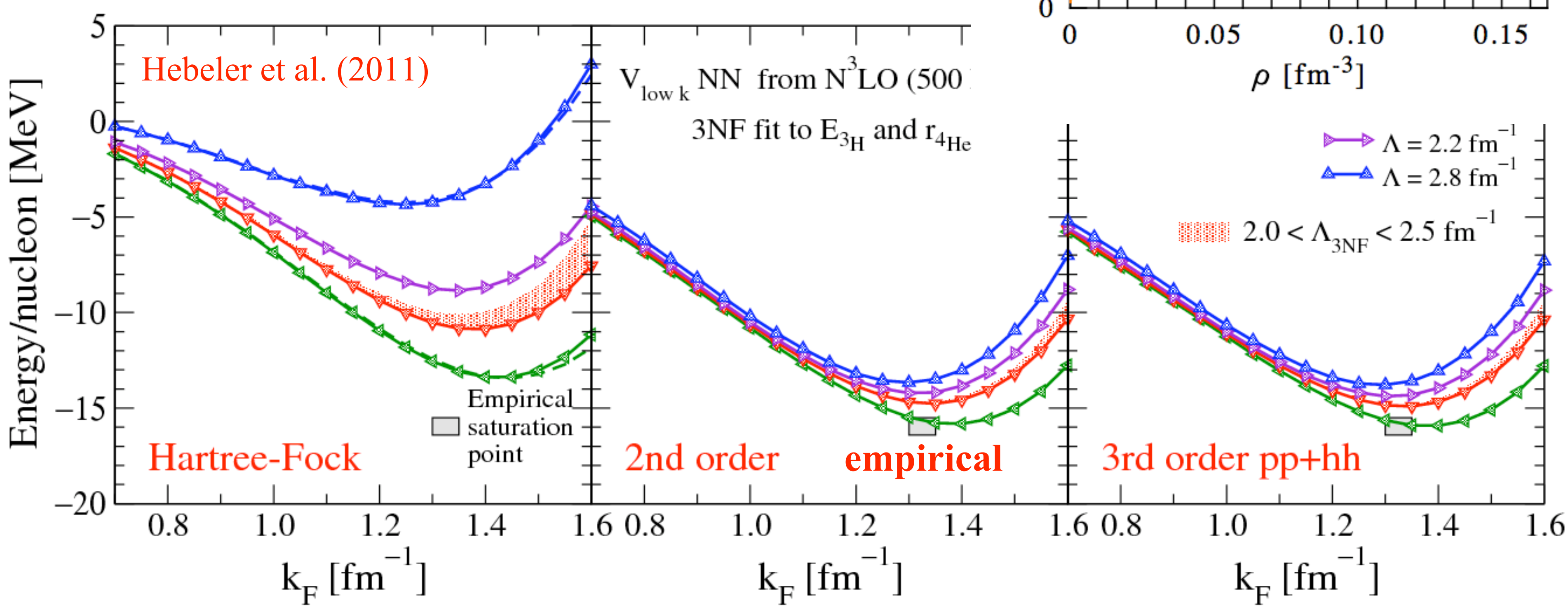
Impact of 3N forces on neutron matter

Hebeler, AS (2010); Tolos, Friman, AS (2007)

only long-range parts of 3N forces contribute to neutron matter (c_1 and c_3)

neutron matter: no new parameters in many-body forces to N^3LO!





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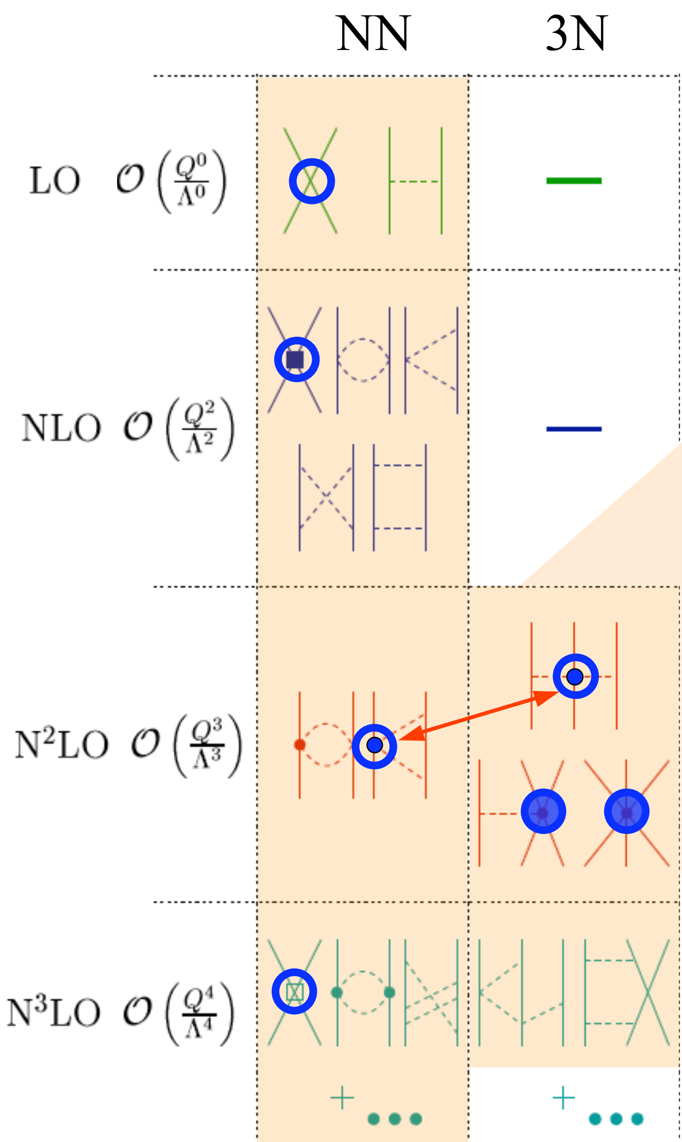

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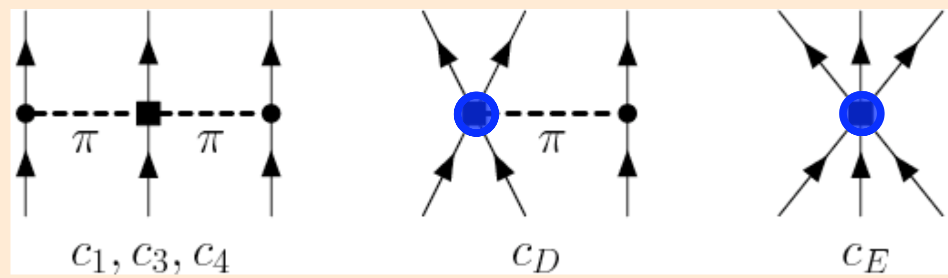

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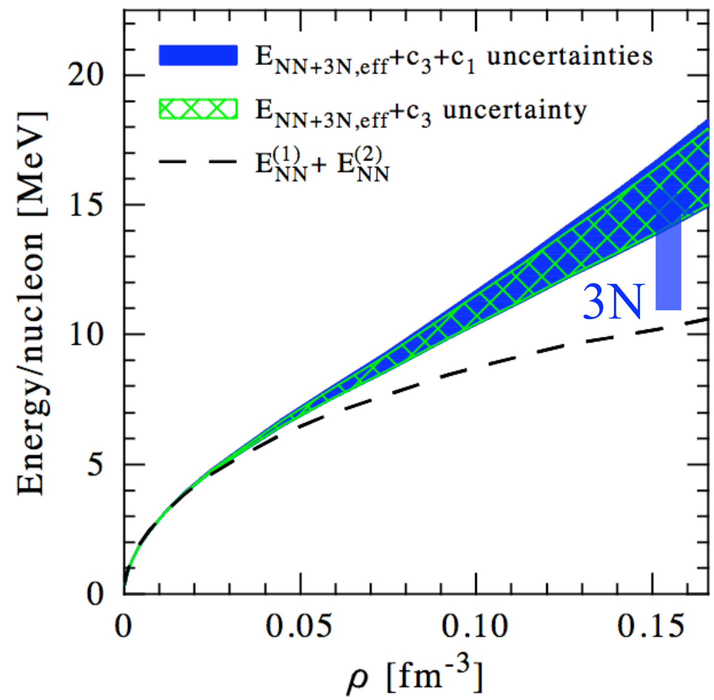
uncertainties dominated by c_3 coupling



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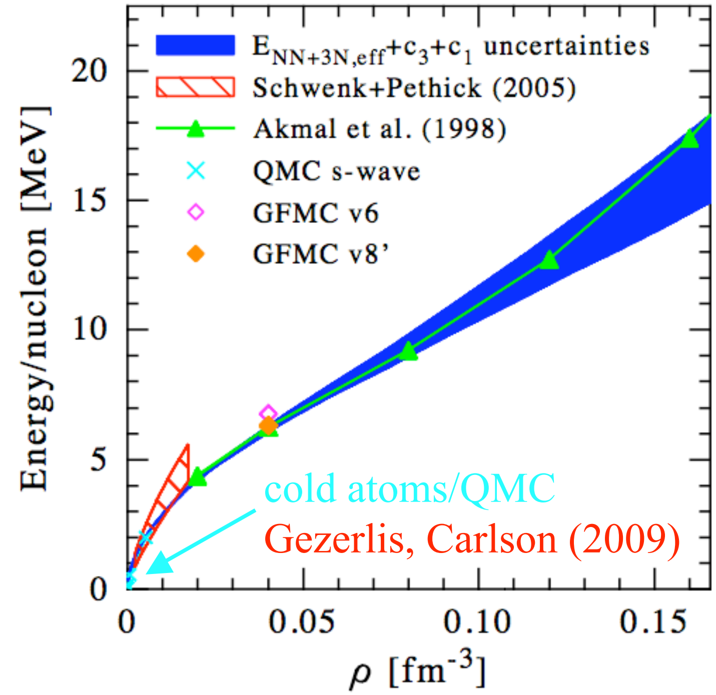
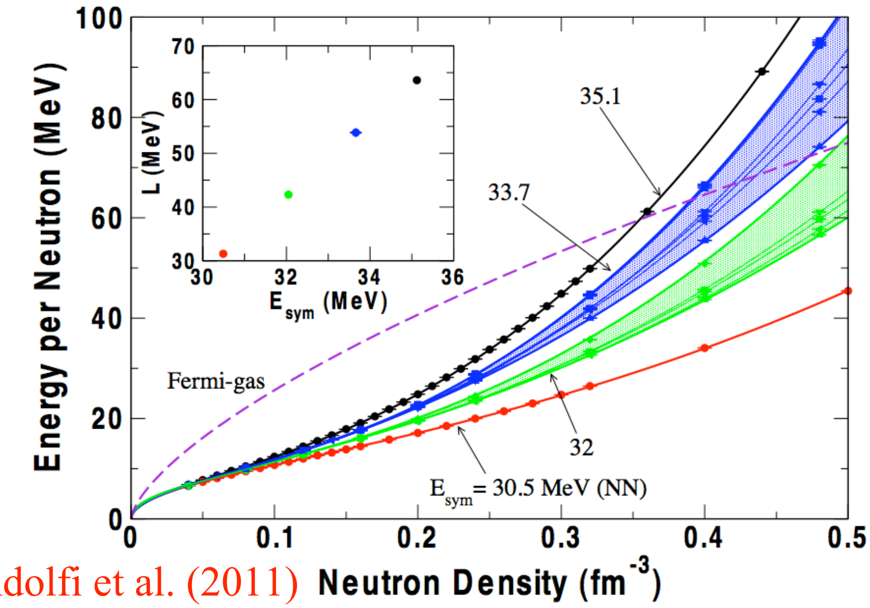
microscopic calculations within band



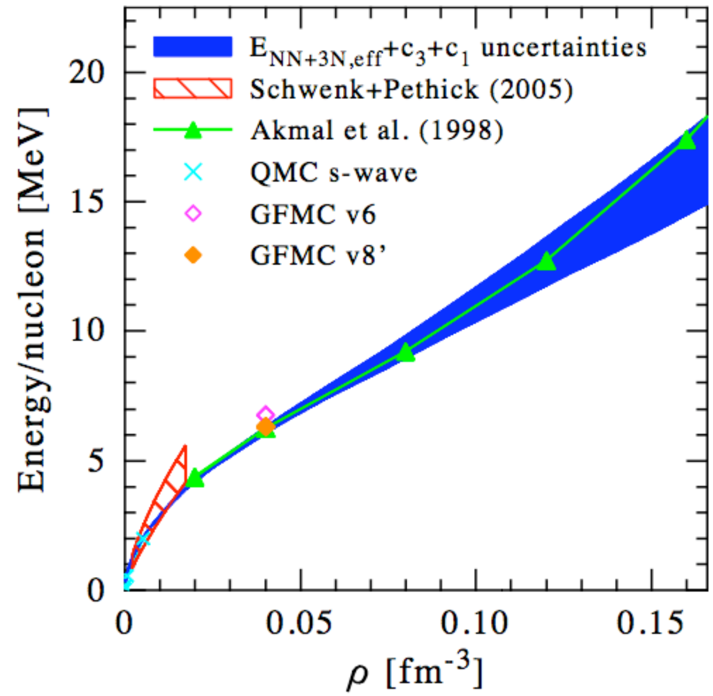


Gandolfi et al. (2011)

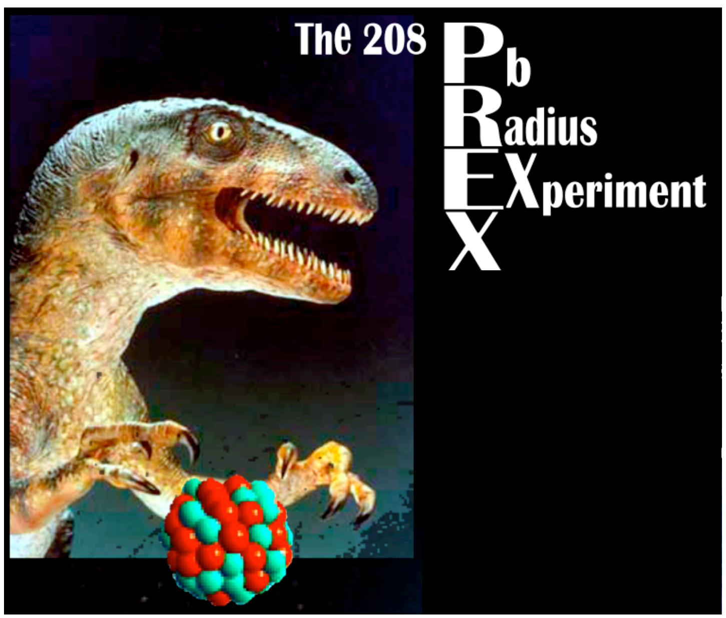
Symmetry energy and neutron skin Hebeler et al. (2010)

neutron matter band predicts range for symmetry energy 30.1-34.4 MeV

c_1 [GeV^{-1}]	c_3 [GeV^{-1}]	$\bar{S}_2$ [MeV]
−0.7	−2.2	30.1
−1.4	−4.8	34.4
NN-only EM		26.5
NN-only EGM		25.6



and neutron skin of ^{208}Pb to 0.17±0.03 fm



compare to ±0.05 fm future PREX goal
first result: 0.34+0.15-0.17 fm

from complete E1 response
0.156+0.025-0.021 fm Tamii et al., PRL in press.

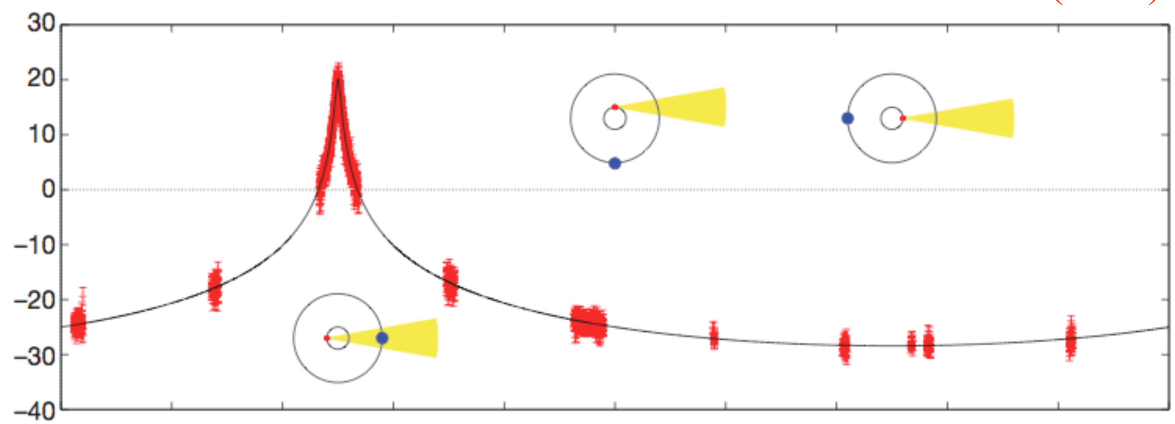
Discovery of the heaviest neutron star

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

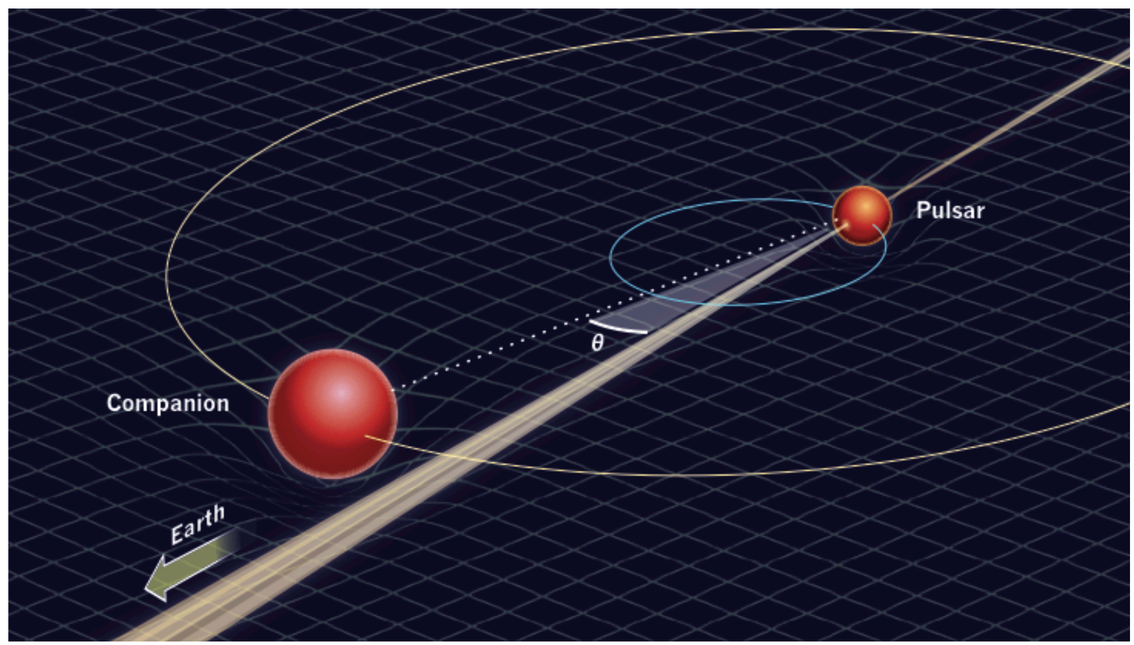
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

Nature (2010)

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

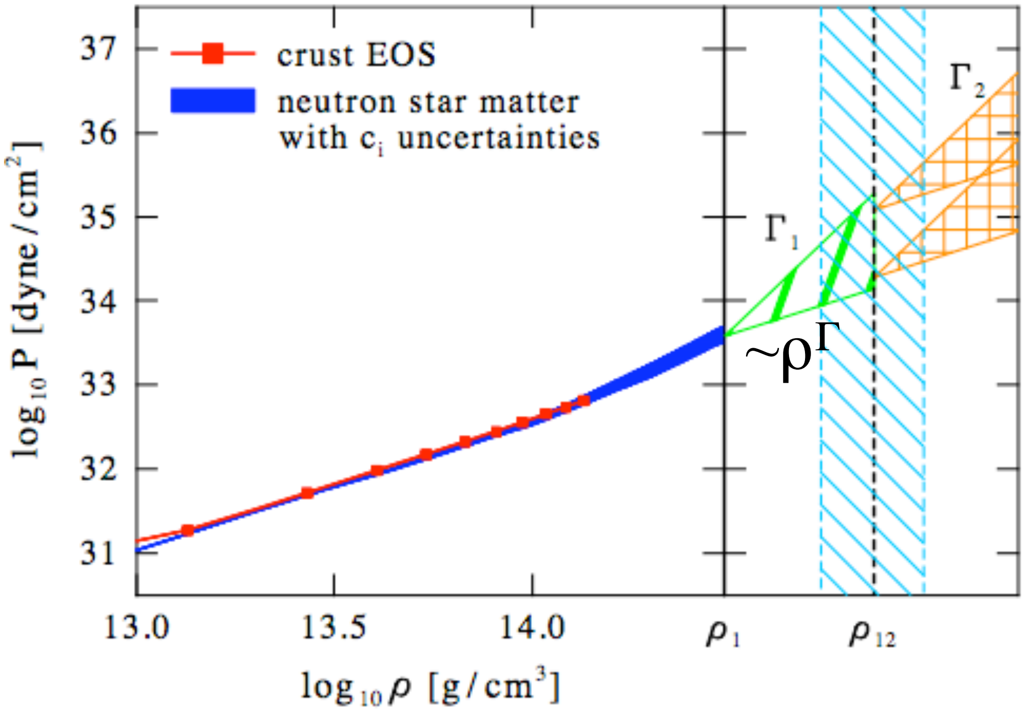


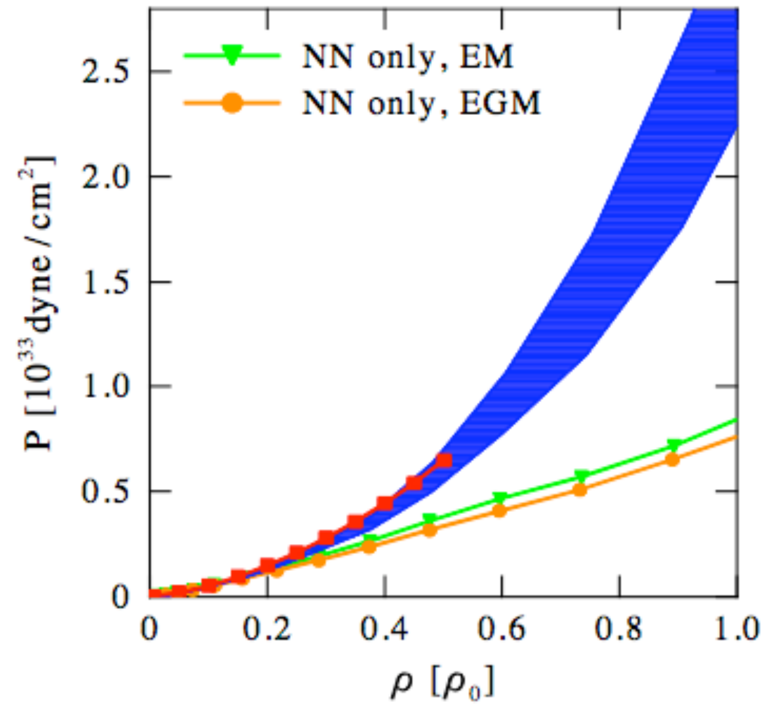
J1614-2230
most edge-on binary pulsar known (89.17°)
+ massive white dwarf companion (0.5 M_{sun})



heaviest neutron star with 1.97±0.04 M_{sun}

Impact of 3N forces on neutron stars Hebeler et al. (2010)





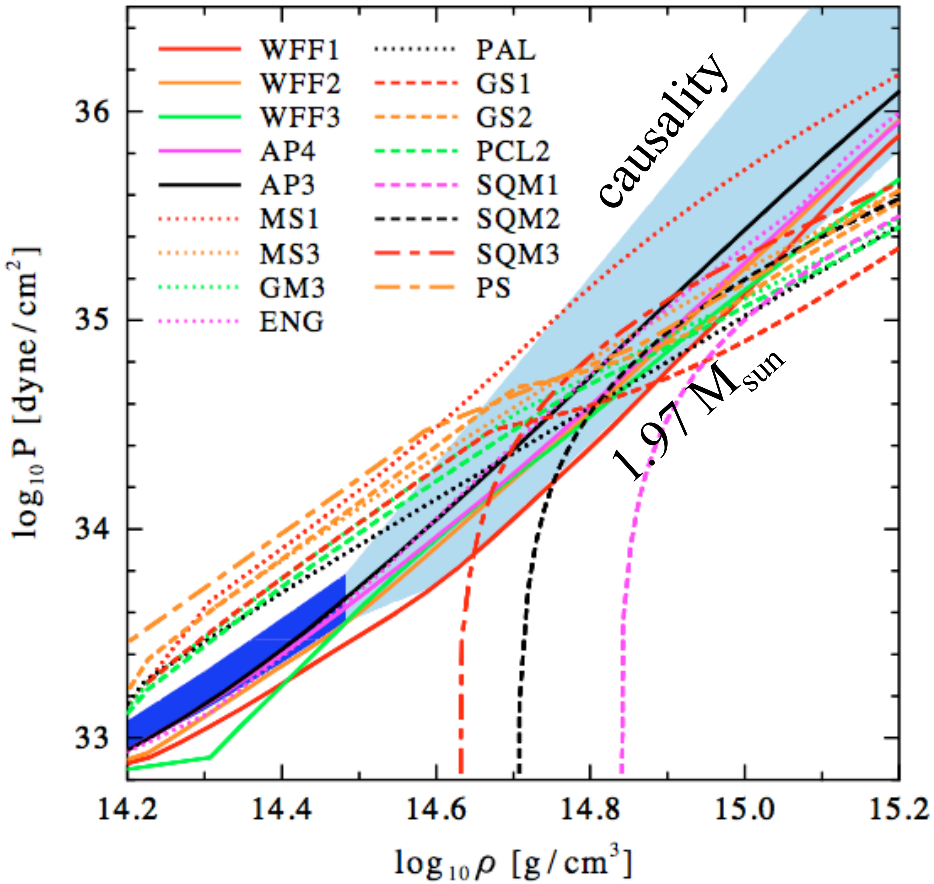
pressure below nuclear densities agrees with standard crust EOS only after 3N forces are included

extend uncertainty band to higher densities using piecewise polytropes

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

Pressure of neutron star matter Hebeler et al. (2010)

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

Neutron star radius constraints Hebeler et al. (2010)

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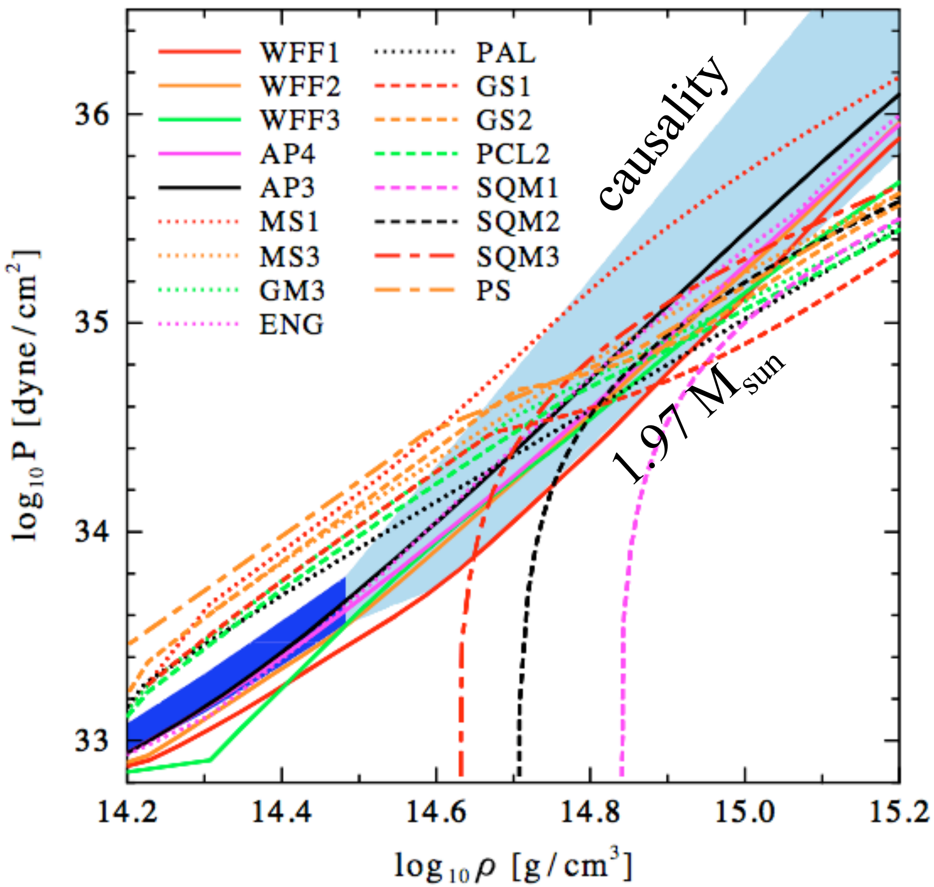

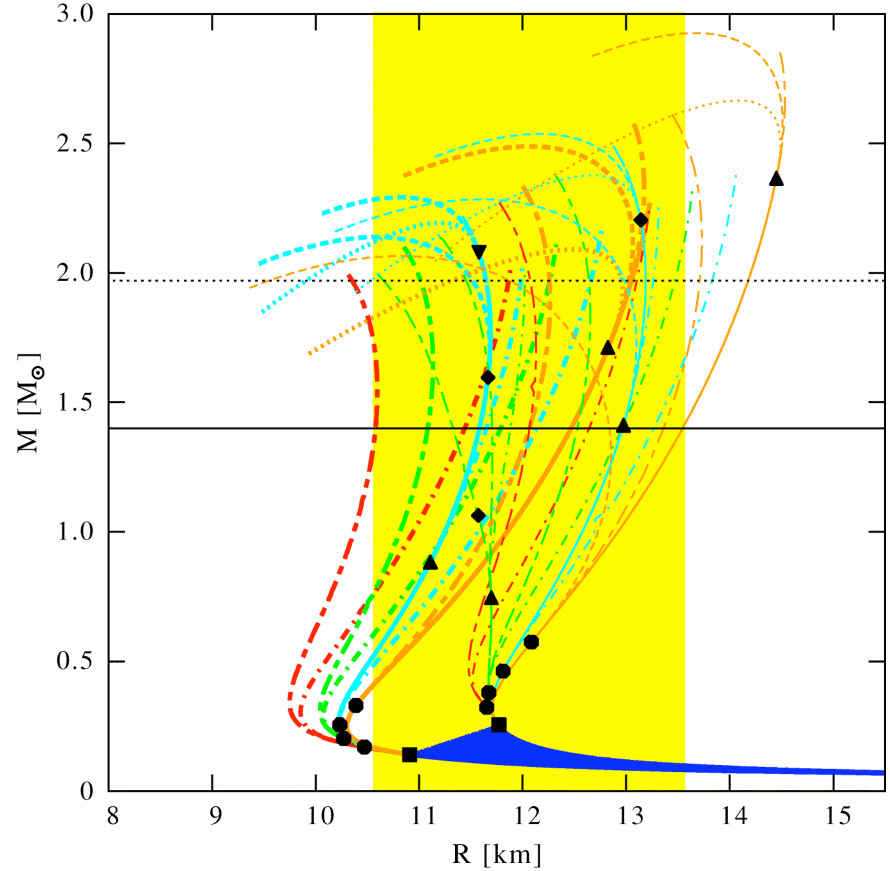

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constrains neutron star radius: 10.9-13.9 km for M=1.4 M_{sun} (±12% !)

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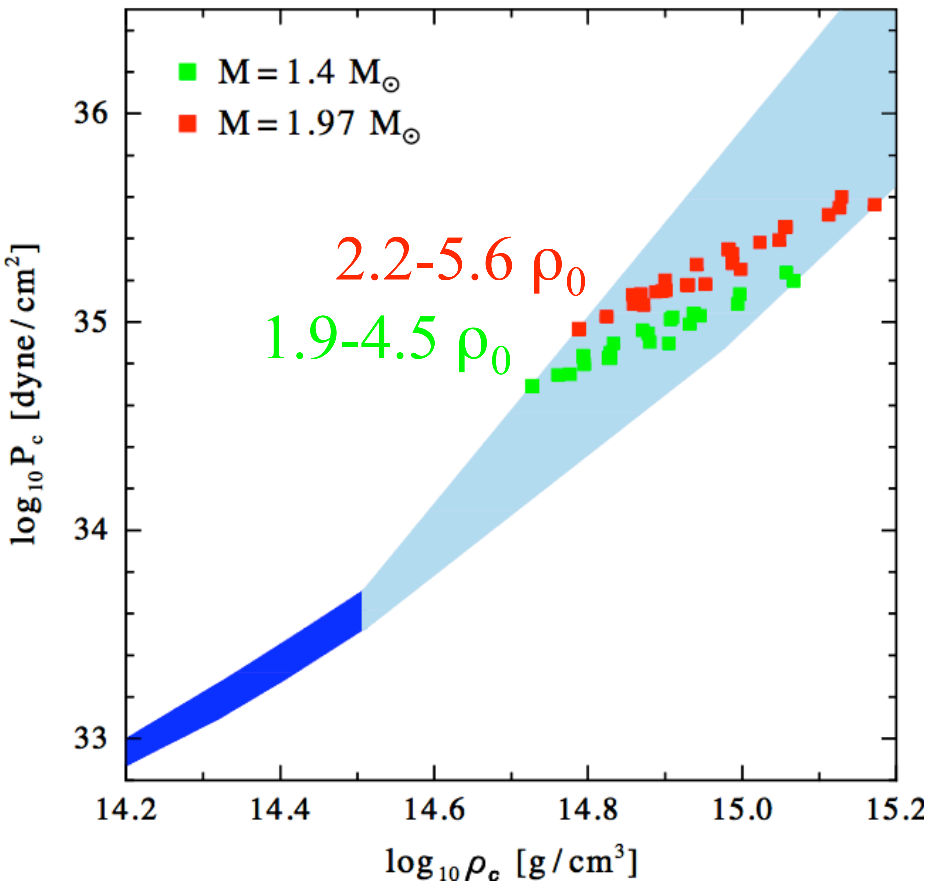

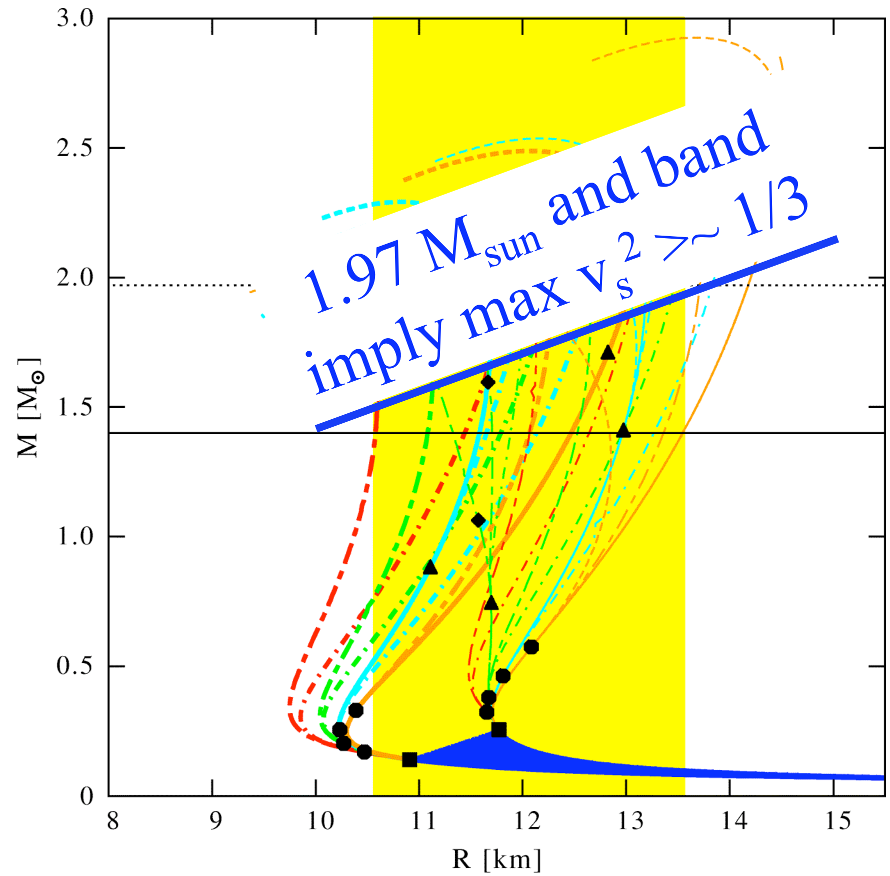

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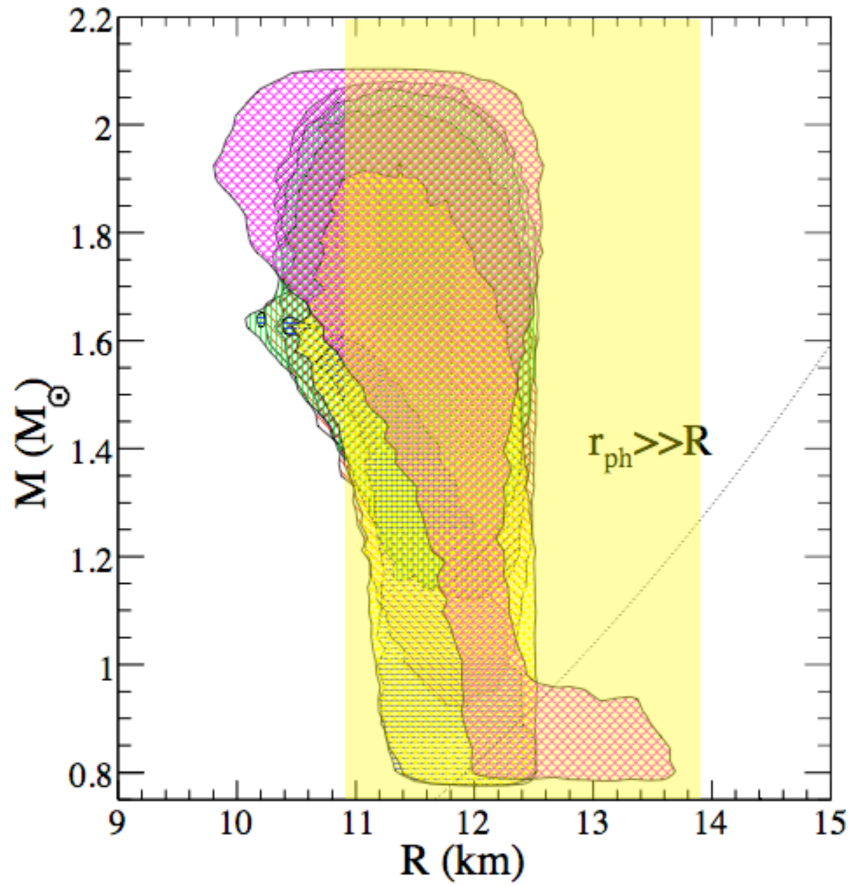
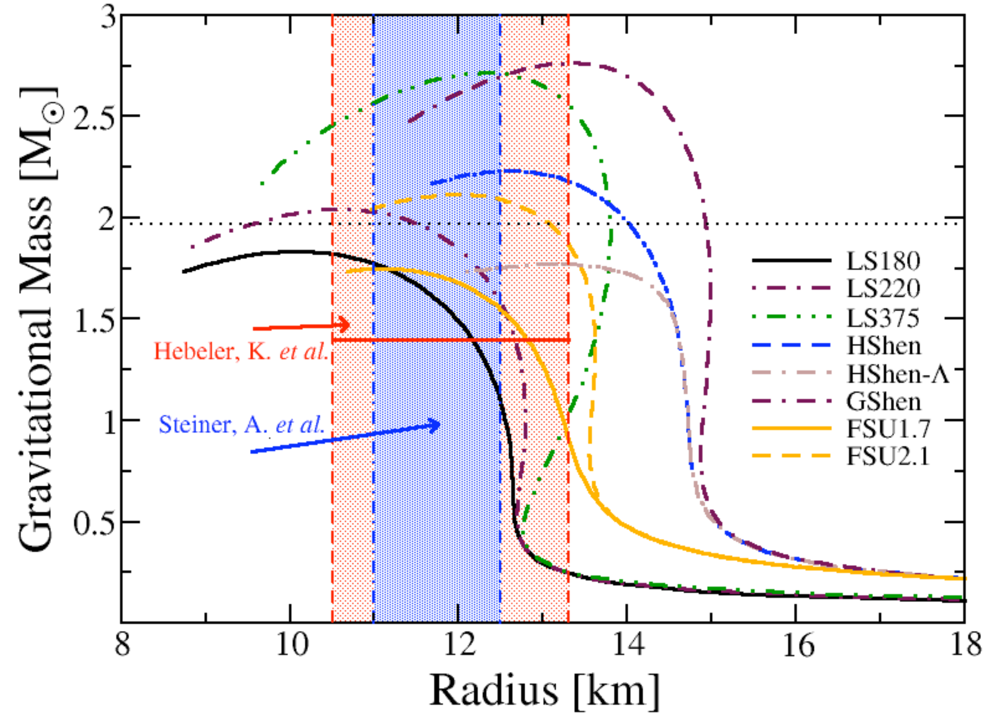
Comparison to astrophysics

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





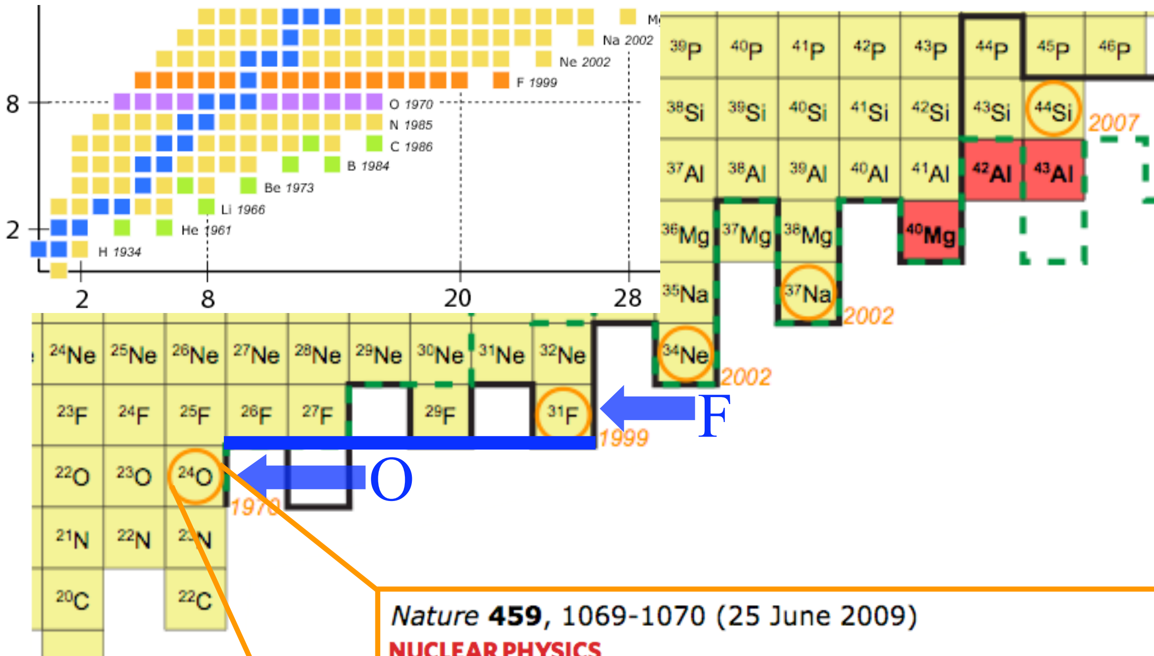
from Evan O'Connor

constrains neutron star radius: 10.9-13.9 km for M=1.4 M_{sun} (±12% !)

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

provides important constraints for EOS for core-collapse supernovae

3N forces and neutron-rich nuclei: The oxygen anomaly



Nature **459**, 1069-1070 (25 June 2009)

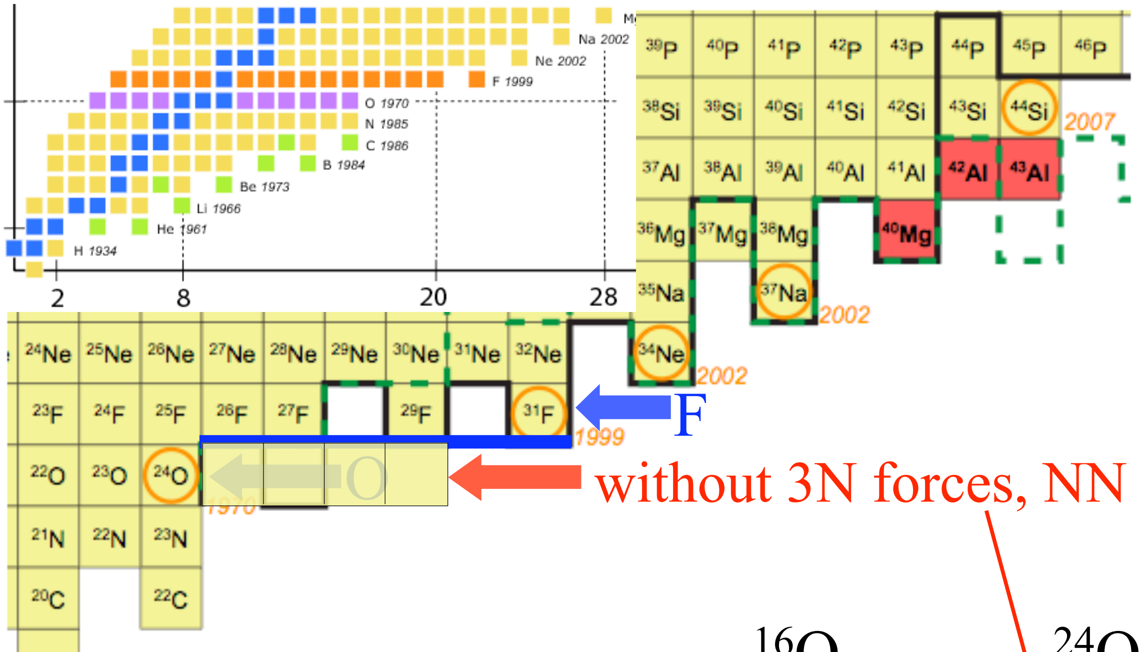
NUCLEAR PHYSICS

Unexpected doubly magic nucleus

Robert V. F. Janssens

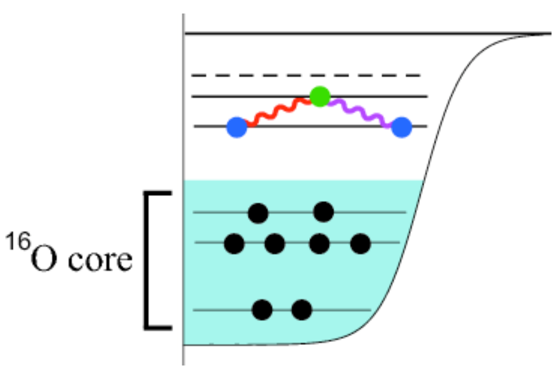
Nuclei with a 'magic' number of both protons and neutrons, dubbed doubly magic, are particularly stable. The oxygen isotope ^{24}O has been found to be one such nucleus — yet it lies just at the limit of stability.

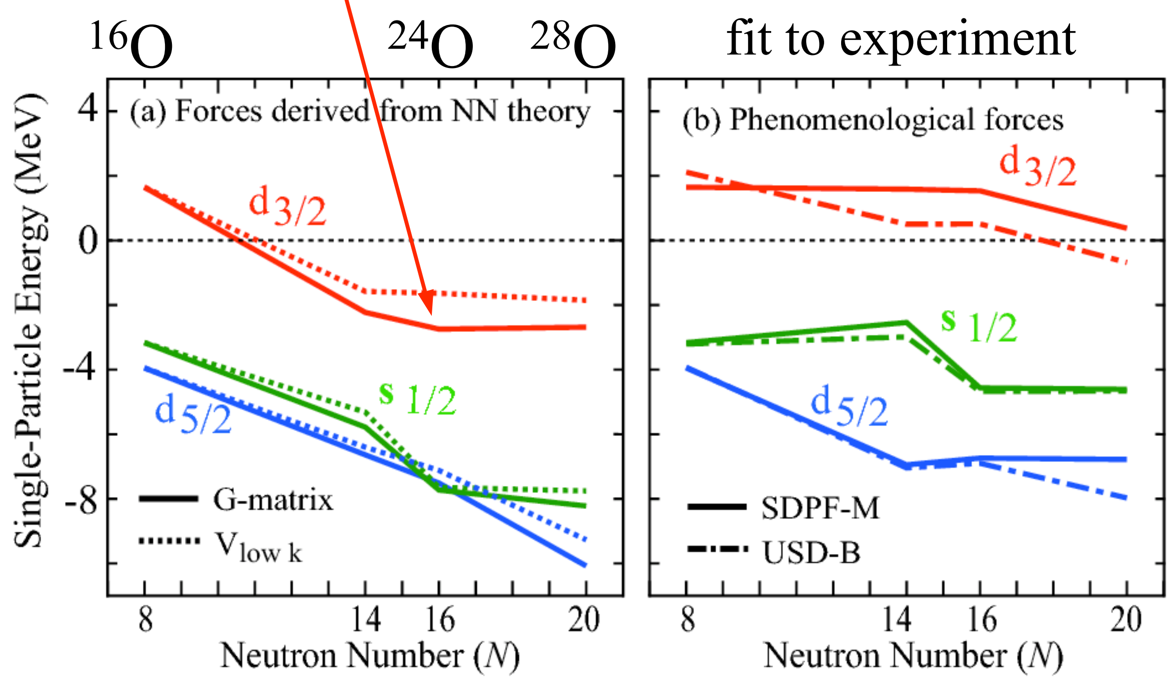
The oxygen anomaly - not reproduced without 3N forces



without 3N forces, NN interactions too attractive

many-body theory based on two-nucleon forces:
drip-line incorrect at ^{28}O





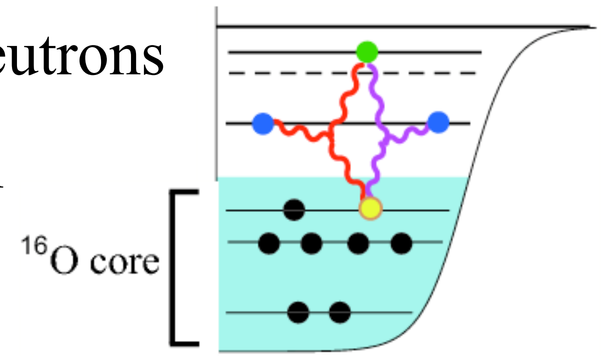
The oxygen anomaly - impact of 3N forces

include "normal-ordered" 2-body part of 3N forces (enhanced by core A)

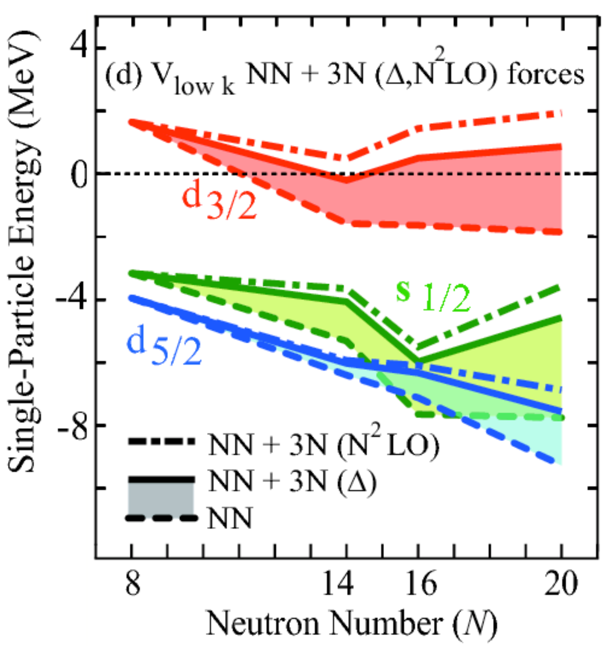
leads to repulsive interactions between valence neutrons

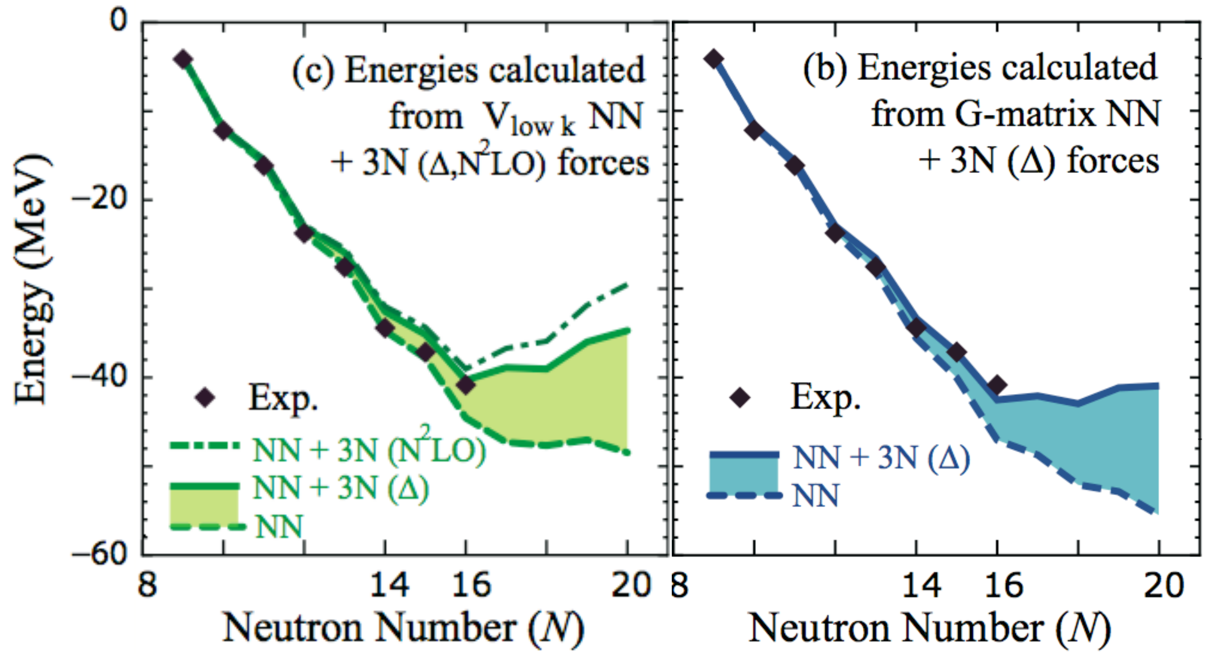
contributions from residual three valence-nucleon interactions suppressed by $E_{ex}/E_F \sim N_{valence}/N_{core}$

Friman, AS, arXiv:1101.4858.



$d_{3/2}$ orbital remains unbound from ^{16}O to ^{28}O





microscopic explanation of the oxygen anomaly Otsuka et al., PRL (2010)

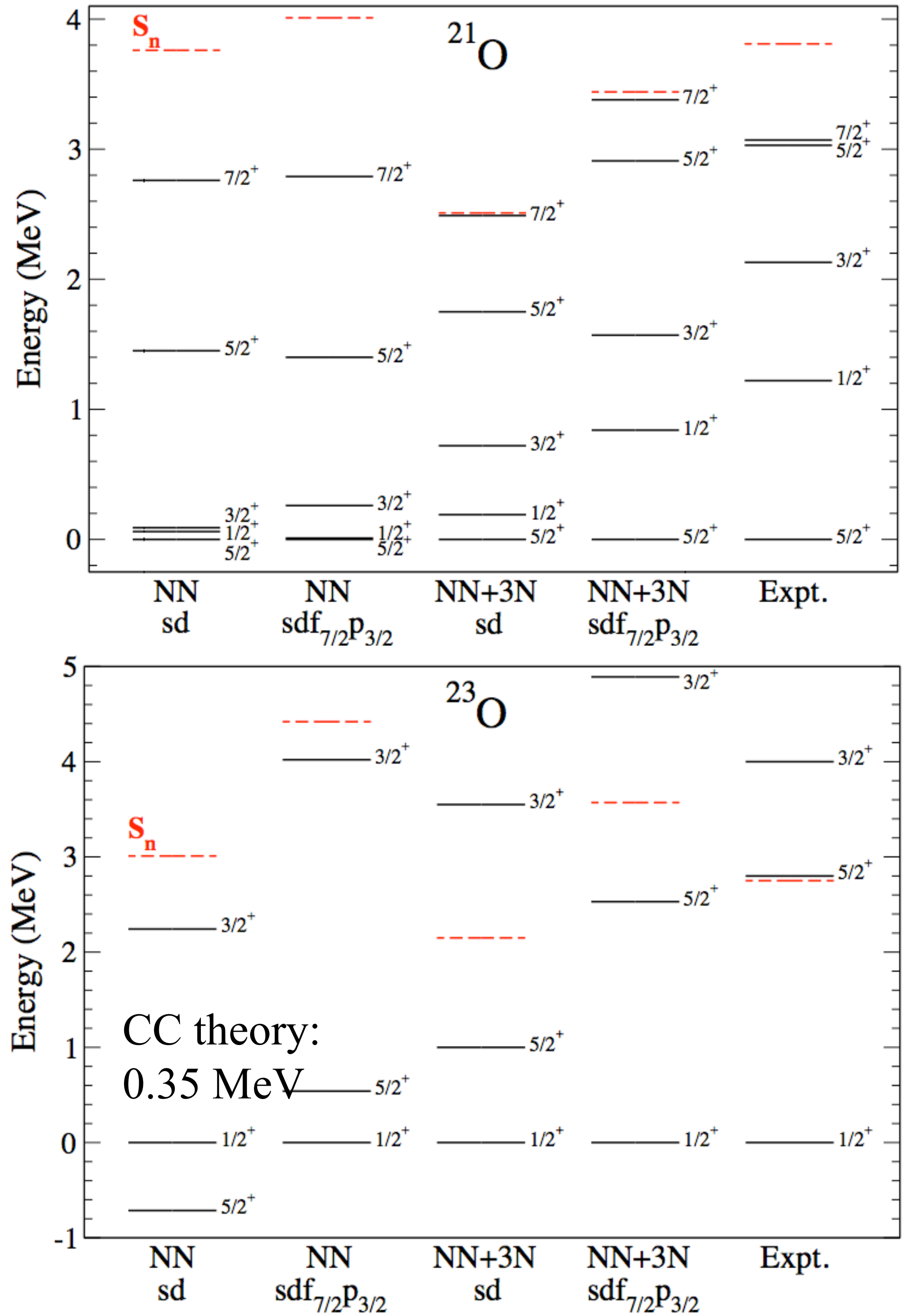
Oxygen spectra

focused on bound excited states

Holt et al., in prep.

NN only too compressed

3N contributions and extended valence space are key to reproduce excited states



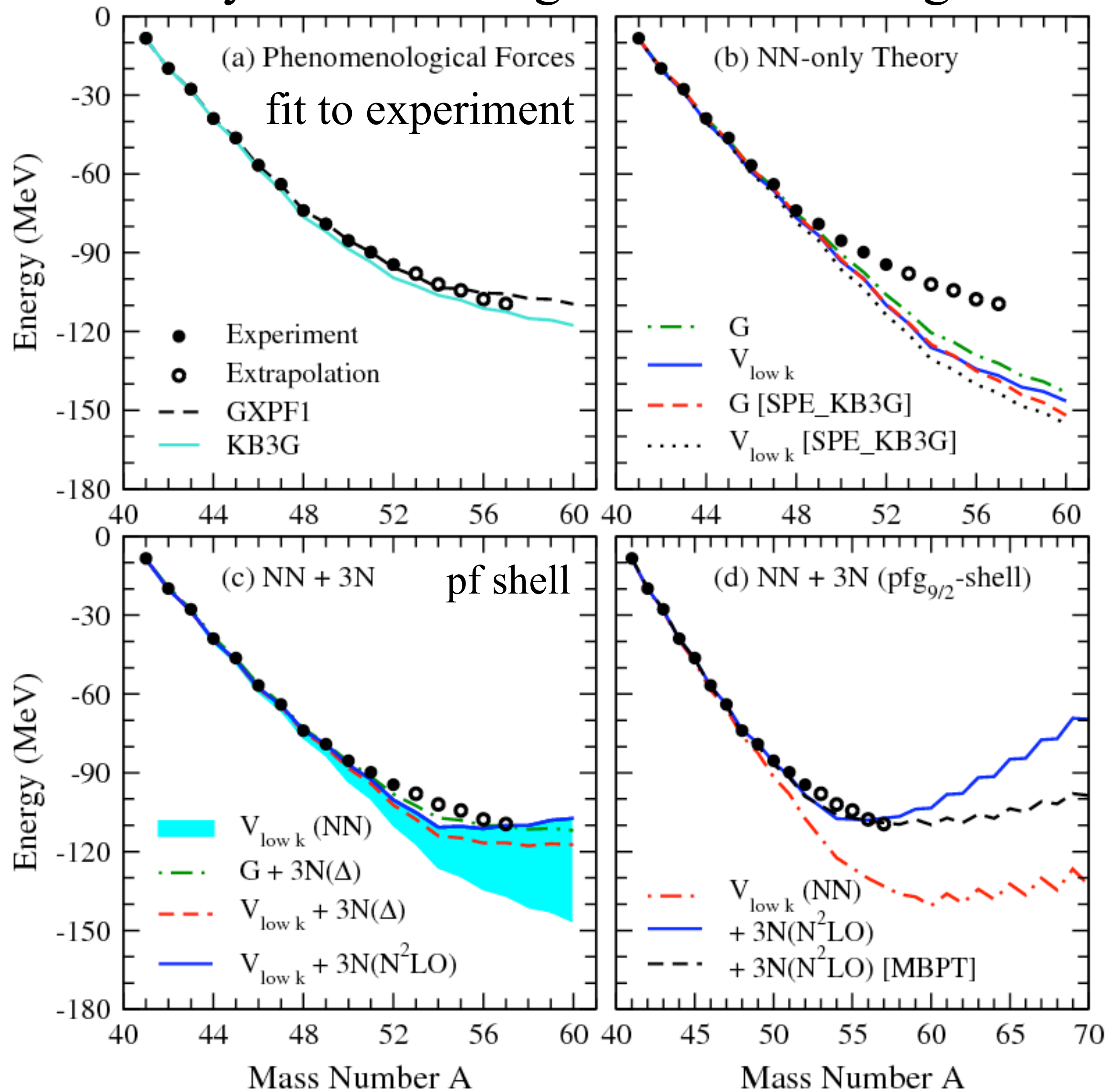
Evolution to neutron-rich calcium isotopes

repulsive 3N contributions also key for calcium ground-state energies

Holt et al., arXiv:1009:5984

mass measured to ^{52}Ca
shown to exist to ^{58}Ca

3N forces connect
heaviest O and Ca
and neutron stars



Neutrino rates at subnuclear densities - Motivation

Neutrino rates important for neutron star crust and core cooling, supernova explosions, neutrino spectra,…

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

neutrino-pair bremsstrahlung and absorption $NN \leftrightarrow NN\nu\overline{\nu}$

standard cooling of low-mass neutron stars

key for production of muon and tau neutrinos in supernovae

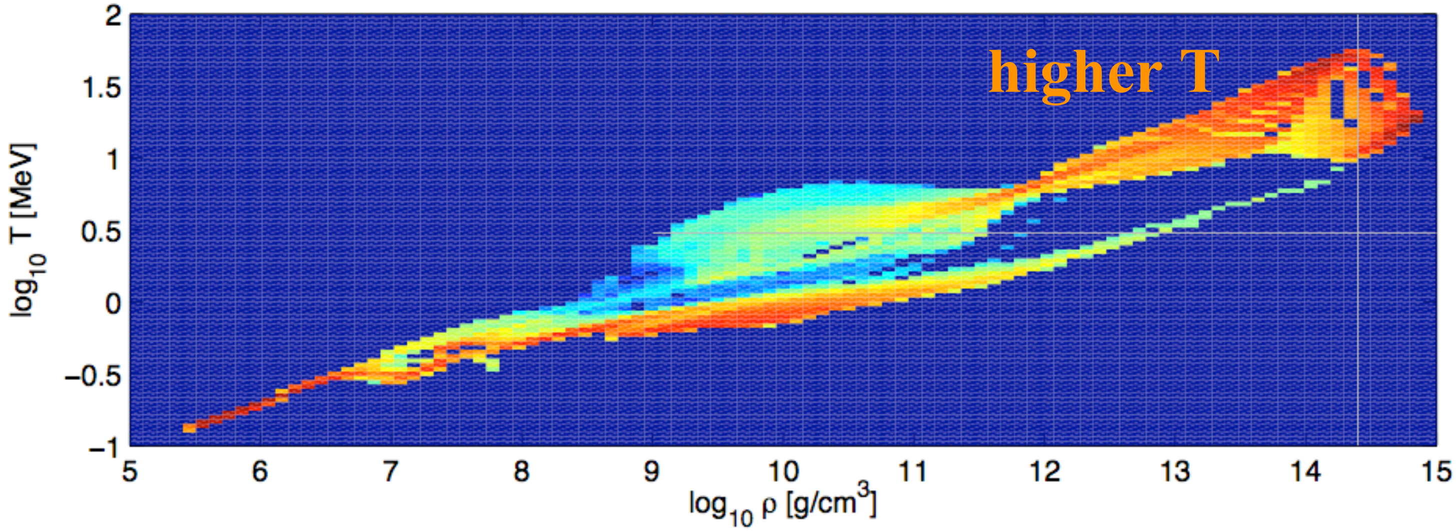
and for equilibrating neutrino number densities

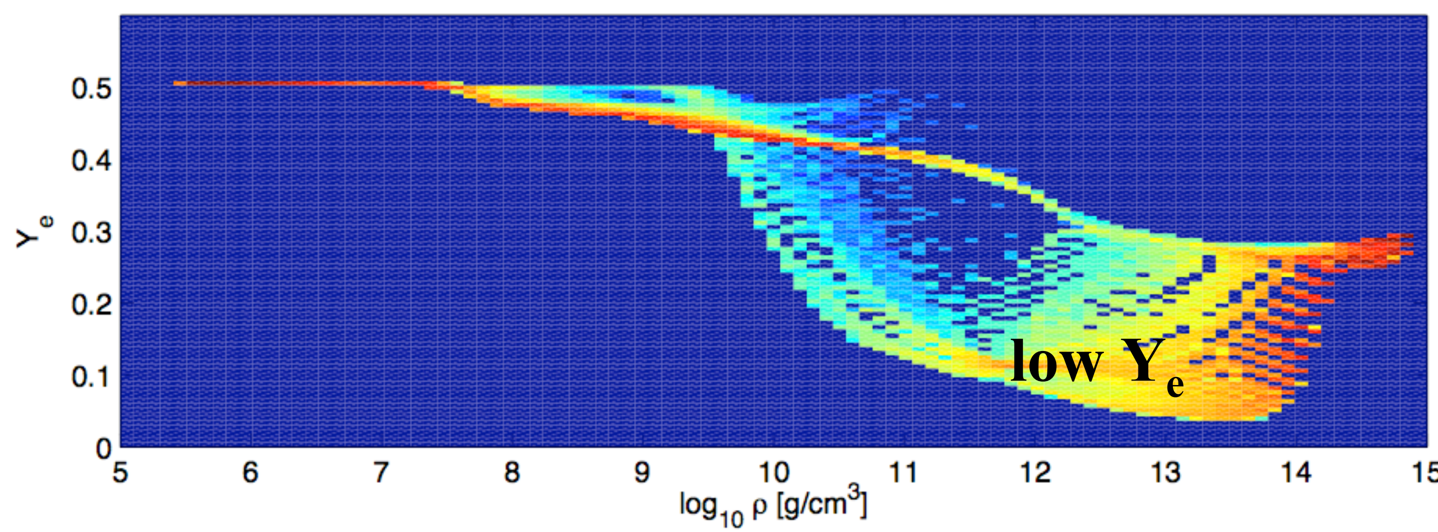
at subnuclear densities $\rho < 10^{14}\,\mathrm{g\,cm}^{-3}$ no systematic calculations beyond one-pion exchange (OPE) approximation for nuclear interactions

can calculate systematically using
chiral effective field theory, electroweak interactions, many-body theory

Relevant conditions

crucial densities below nuclear matter density $\rho \sim \rho_0/10$
(high densities: neutrinos trap; low densities: few interactions)

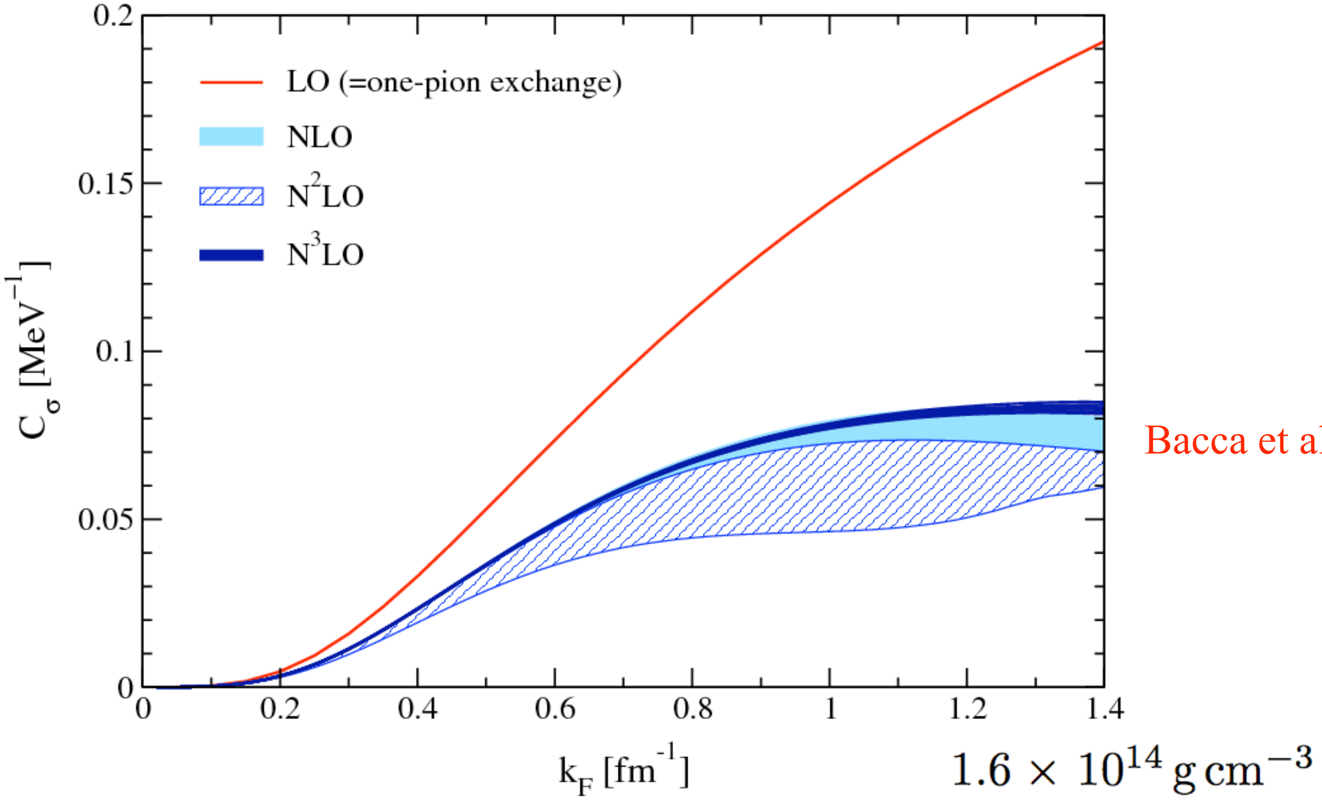




from A. Perego

Main results: chiral EFT

neutrino rates in 2N processes determined by spin relaxation time
= rate of change of nucleon spin through collisions with other nucleons



shorter-range interactions significantly reduce neutrino rates (compared to OPE) in neutron matter for all relevant densities

first calculation of neutrino processes in dense matter from chiral EFT

Many-body theory: single- and two-nucleon processes

elastic scattering from nucleons (space-like $\omega<q$)

initial and final state interactions, inelastic scattering $\nu nn \leftrightarrow \nu nn$

collisional damping - Landau-Pomeranchuk-Migdal effect

neutrino-pair bremsstrahlung/absorption $nn \leftrightarrow nn\nu\overline{\nu}$ (time-like $\omega>q$)

need collisions between nucleons for the latter processes

noncentral contributions, due to tensor forces from pion exchanges and spin-orbit forces, are essential for the two-neutron response

follows from direct calculations Friman, Maxwell (1979)
and from conservation laws Olsson, Pethick (2002)

developed a unified treatment that consistently includes one- and two-nucleon response in a strongly-interacting many-body system (Boltzmann eqn for collisions, spin-dependent mean-field effects,…)

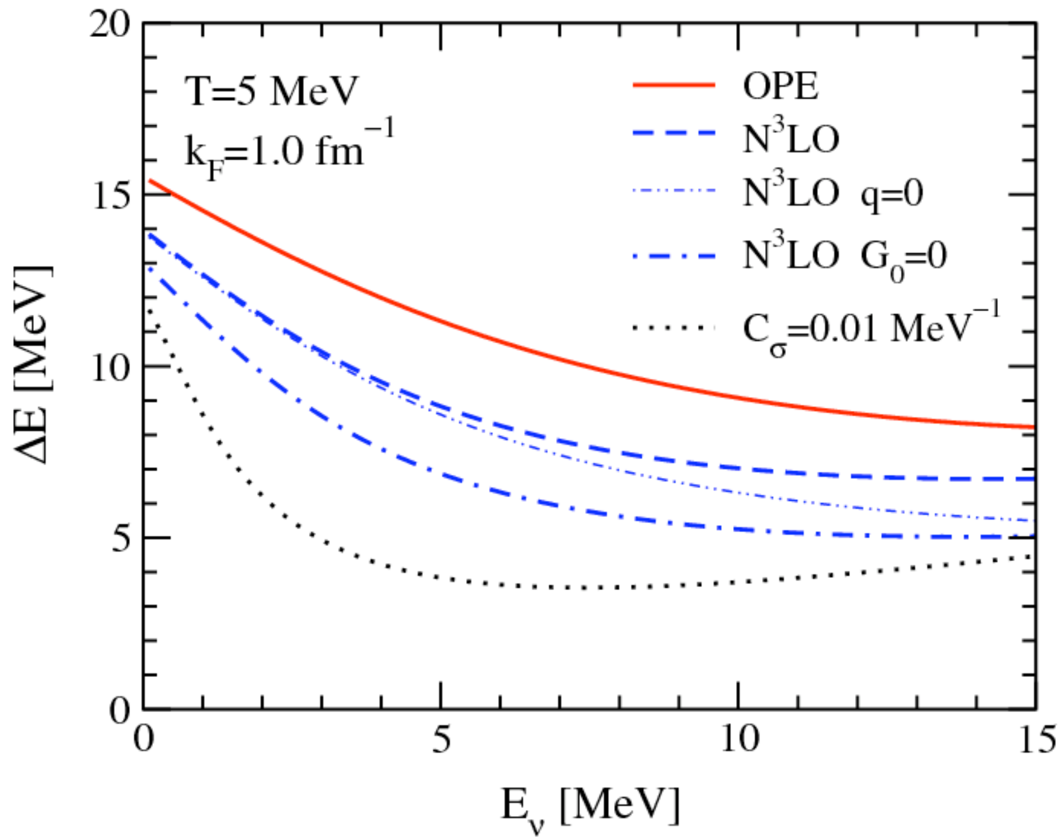
Energy transfer in neutrino scattering from nucleons

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

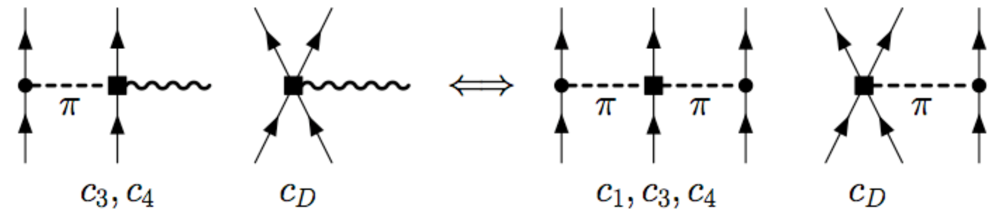


collision processes and spin-dependent mean-field effects (G_0)
dominate over energy transfer due to recoil, nonzero momentum transfers

Chiral EFT for electroweak transitions Menendez, Gazit, AS, PRL in press.

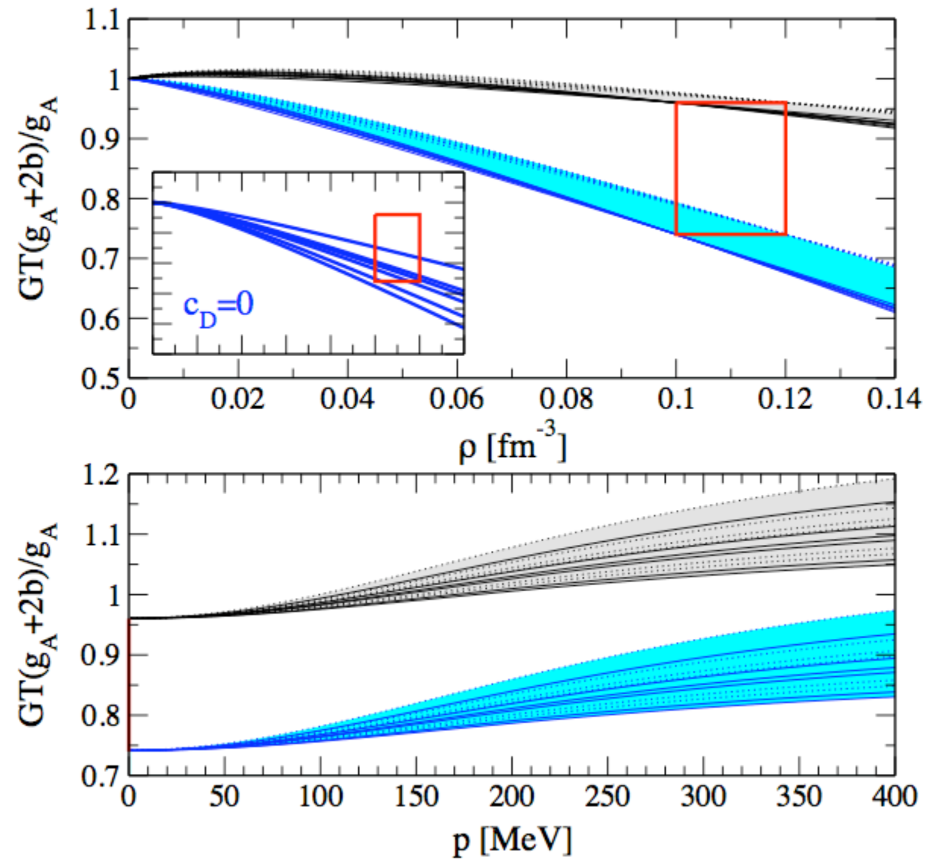
two-body currents lead to important contributions in nuclei (Q~100 MeV) especially for Gamow-Teller transitions

two-body currents determined by NN, 3N couplings to N^3LO
Park et al., Phillips,…



explains part of quenching of g_A (dominated by long-range part)

+ predict momentum dependence (weaker quenching for larger p)



Thanks to collaborators!

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Summary

Exciting era with advances on many fronts,
exciting interactions with experiments and observations!

chiral effective field theory and the renormalization group,
enable a unified description from nuclei to matter in astrophysics

3N forces are a frontier

dominant uncertainty of neutron (star) matter below nuclear densities,
constrains pressure of neutron star matter and neutron star radii

key to explain why ^{24}O is the heaviest oxygen isotope,
Ca isotopes and N=28 magic number, key for neutron-rich nuclei!

opportunities: neutrino-matter interactions based on chiral EFT