Chiral three-nucleon forces: From neutron matter to neutron stars

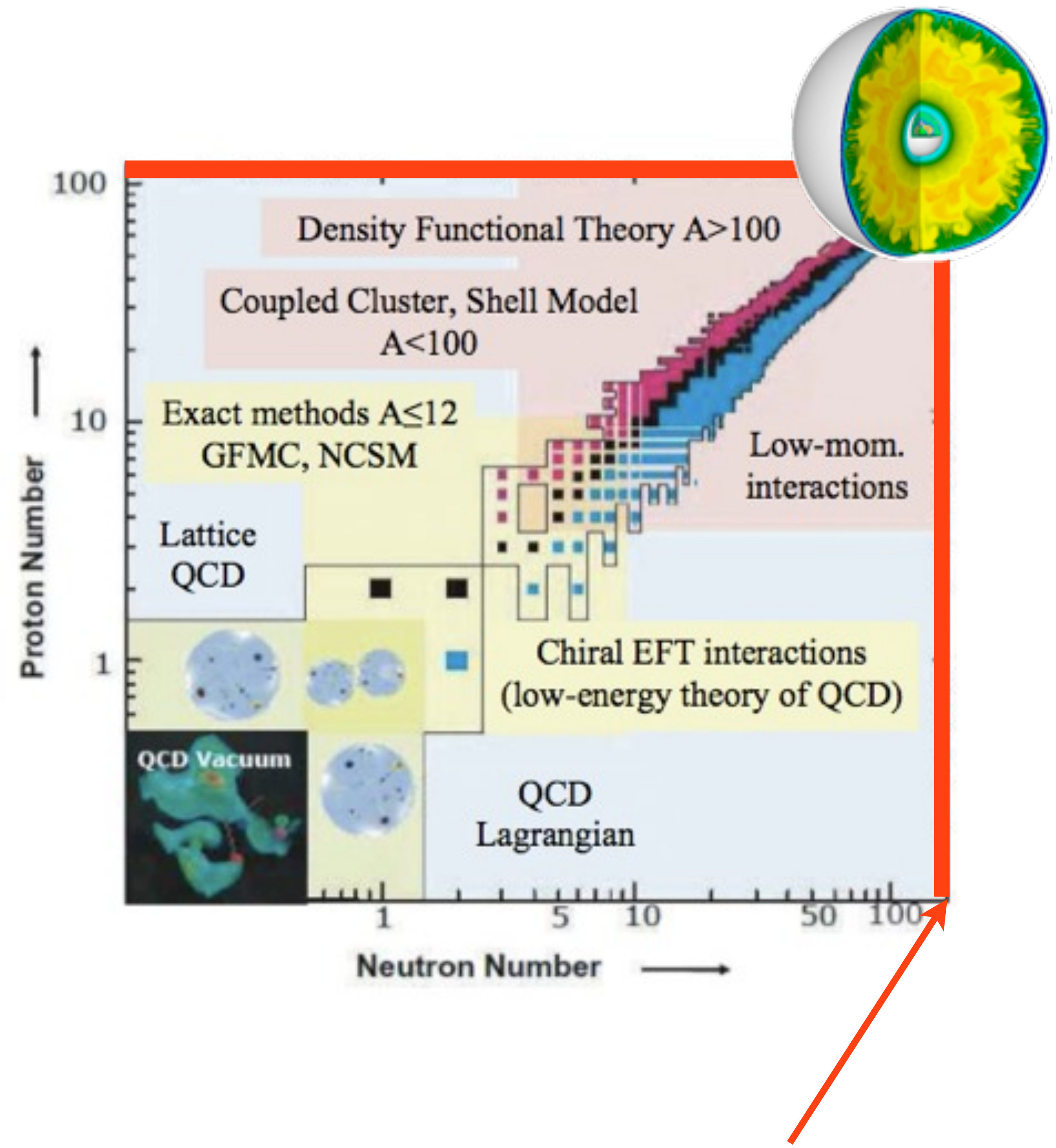
Kai Hebeler (OSU)

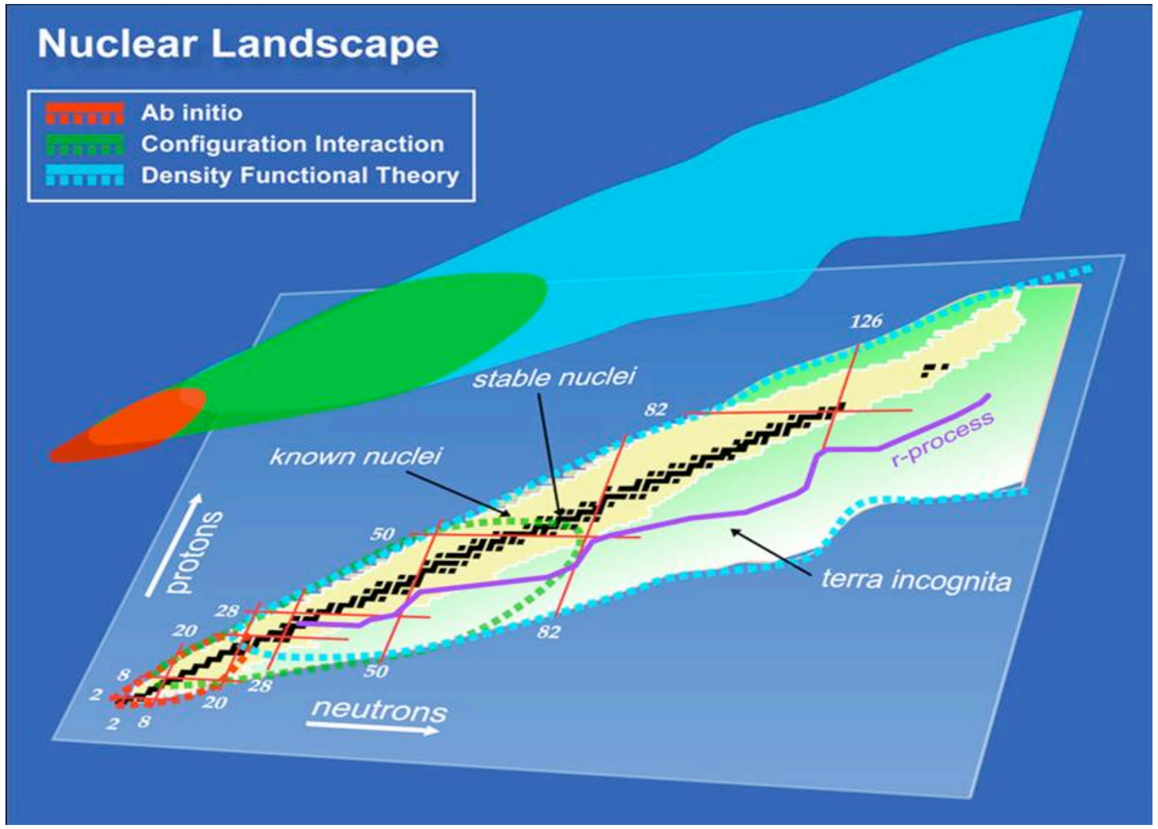
Seattle, May 2, 2011

Fermions from Cold Atoms to Neutron Stars:
Benchmarking the Many-Body Problem

The nuclear landscape

- Nuclear systems are complex many-body systems with rich properties
- No "one size fits all" method
- All theoretical approaches need to be linked





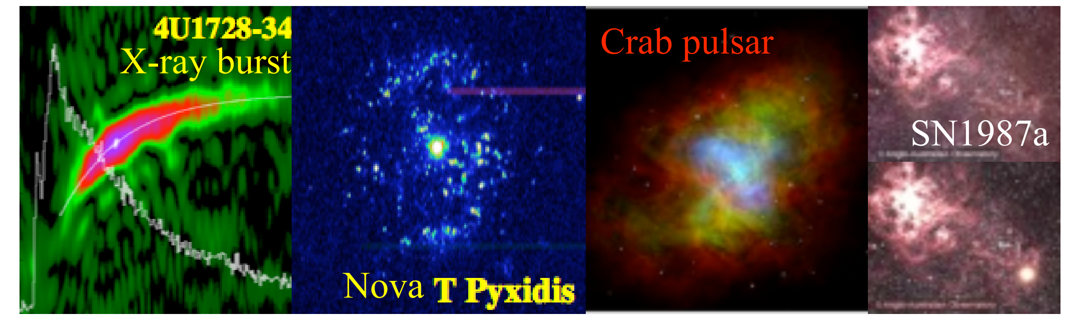
Nucleonic matter:
Infinite system of interacting neutrons and protons in the thermodynamic limit.

Significance of nuclear/neutron matter results

- for the extremes of astrophysics:

neutron stars, supernovae,

neutrino interactions with nuclear matter



- constraining microscopically energy-density functionals, next-generation Skyrme functionals, density matrix expansion

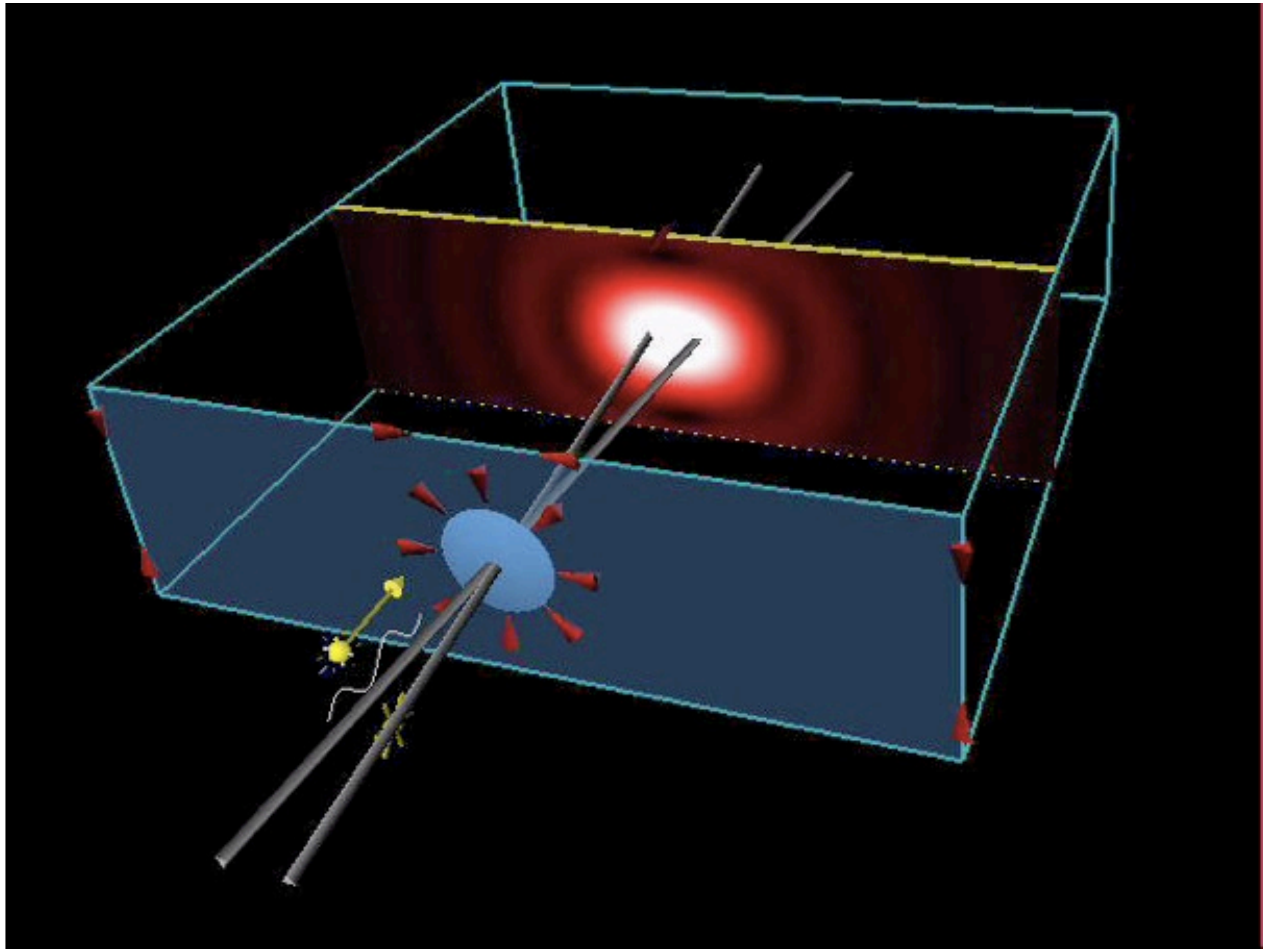
UNEDF

$$\mathcal{E} = \frac{\tau}{2M} + A[\rho] + B[\rho]\tau + C[\rho]|\nabla\rho|^2 + \cdots$$

- universal properties at low densities, can be probed in experiments with ultracold Fermi gases

- my focus: development of efficient methods to include 3N forces in microscopic many-body calculations of neutron/nuclear matter and finite nuclei

Wavelength and resolution



size of resolvable structures depends on the wavelength

Question: Which resolution should we choose?

Depends on the system and phenomena we are interested in!

Resolution: The higher the better?

in the nuclear physics here we are interested in low-energy observables

(long-wavelength information!)

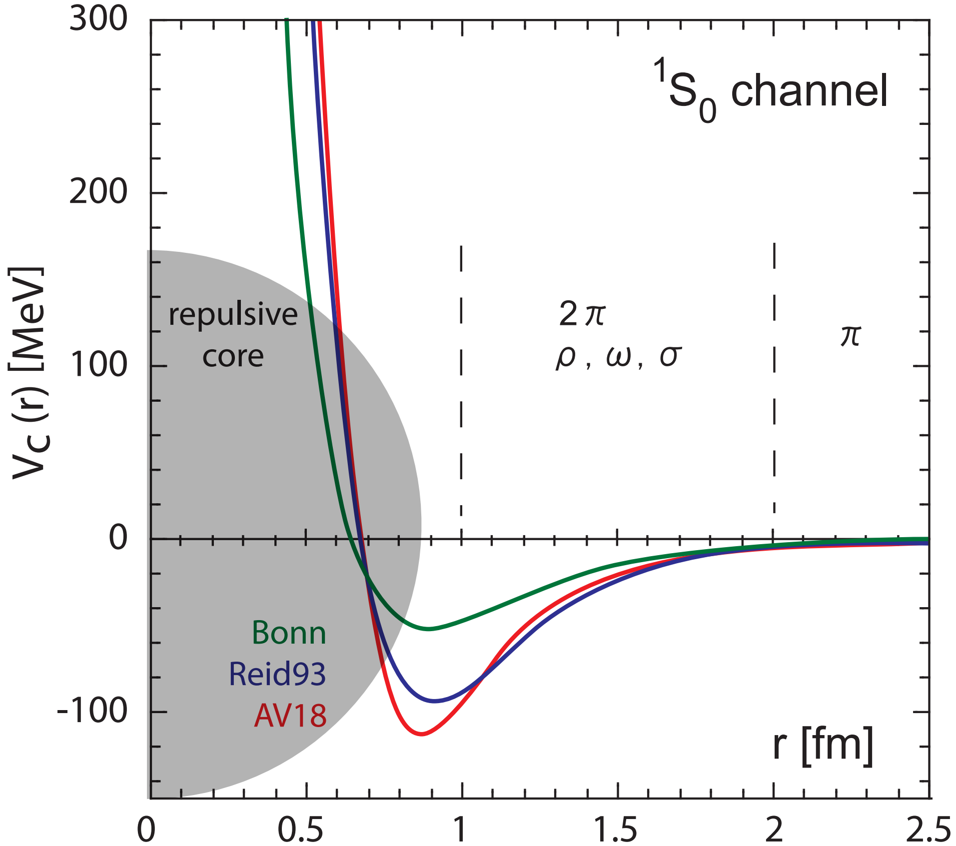
- resolution of very small (irrelevant) structures can obscure this information
- small details have nothing to do with long-wavelength information!

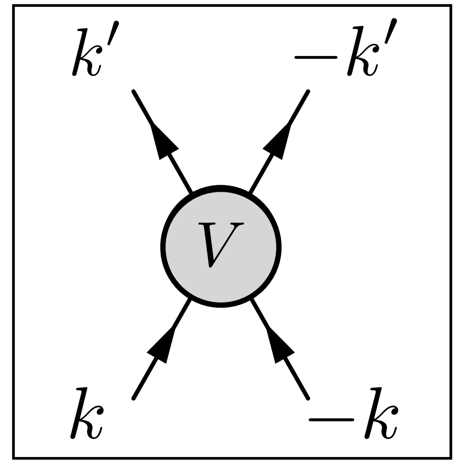
Strategy: Use a low-resolution version

- long-wavelength information is preserved
- distortion at small distance significantly reduced
- much less information necessary

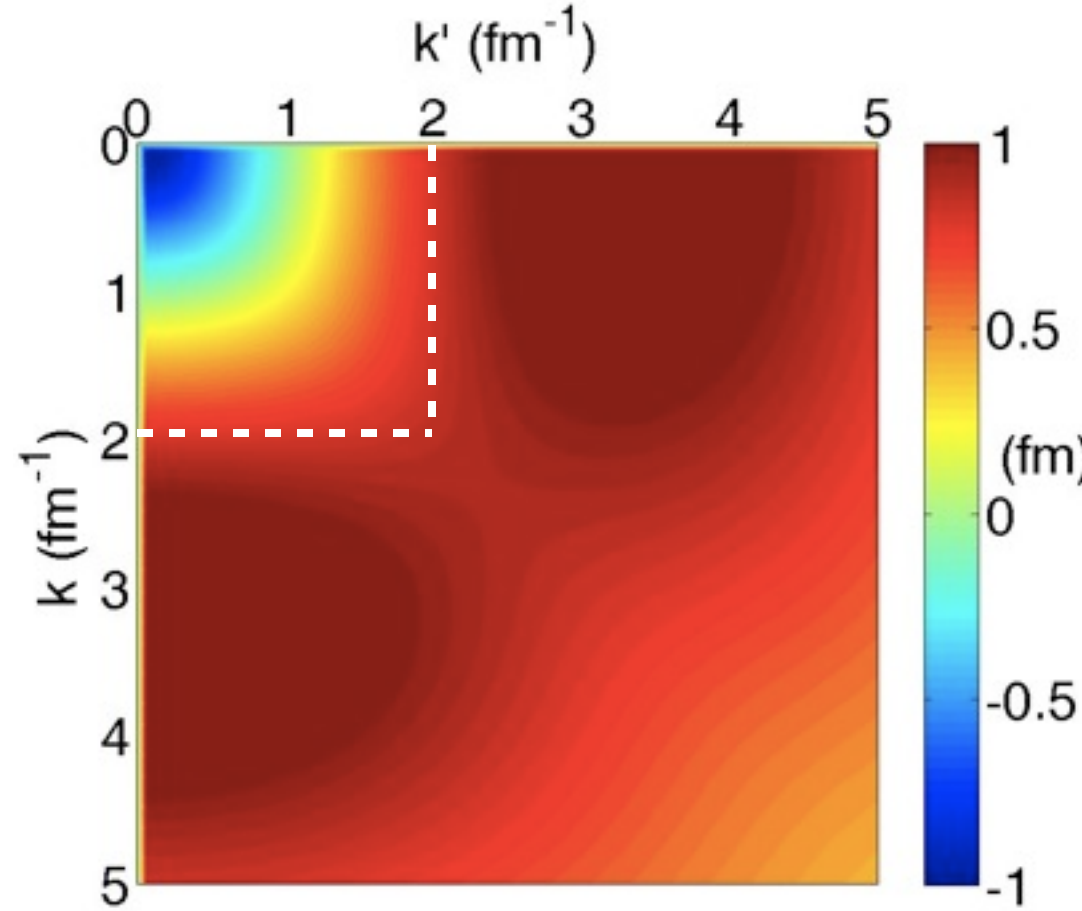
In nuclear physics:
Use renormalization group (RG) to change resolution!

Problem: Traditional “hard” NN interactions





$\langle k'|V|k\rangle$



- constructed to fit scattering data (long-wavelength information!)
- “hard” NN interactions contain repulsive core at small relative distance
- strong coupling between low and high-momentum components, hard to solve!

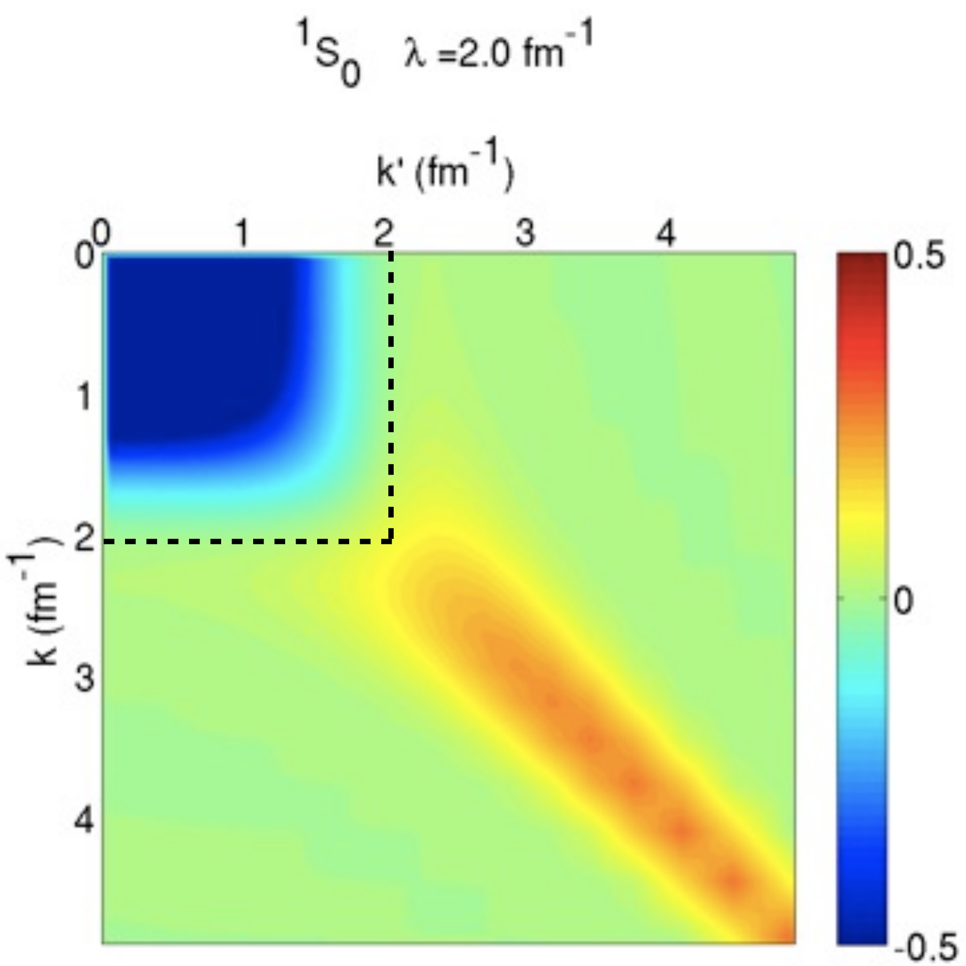
Claim:
Problems due to high resolution from interaction.
These interactions correspond to using beer coasters.

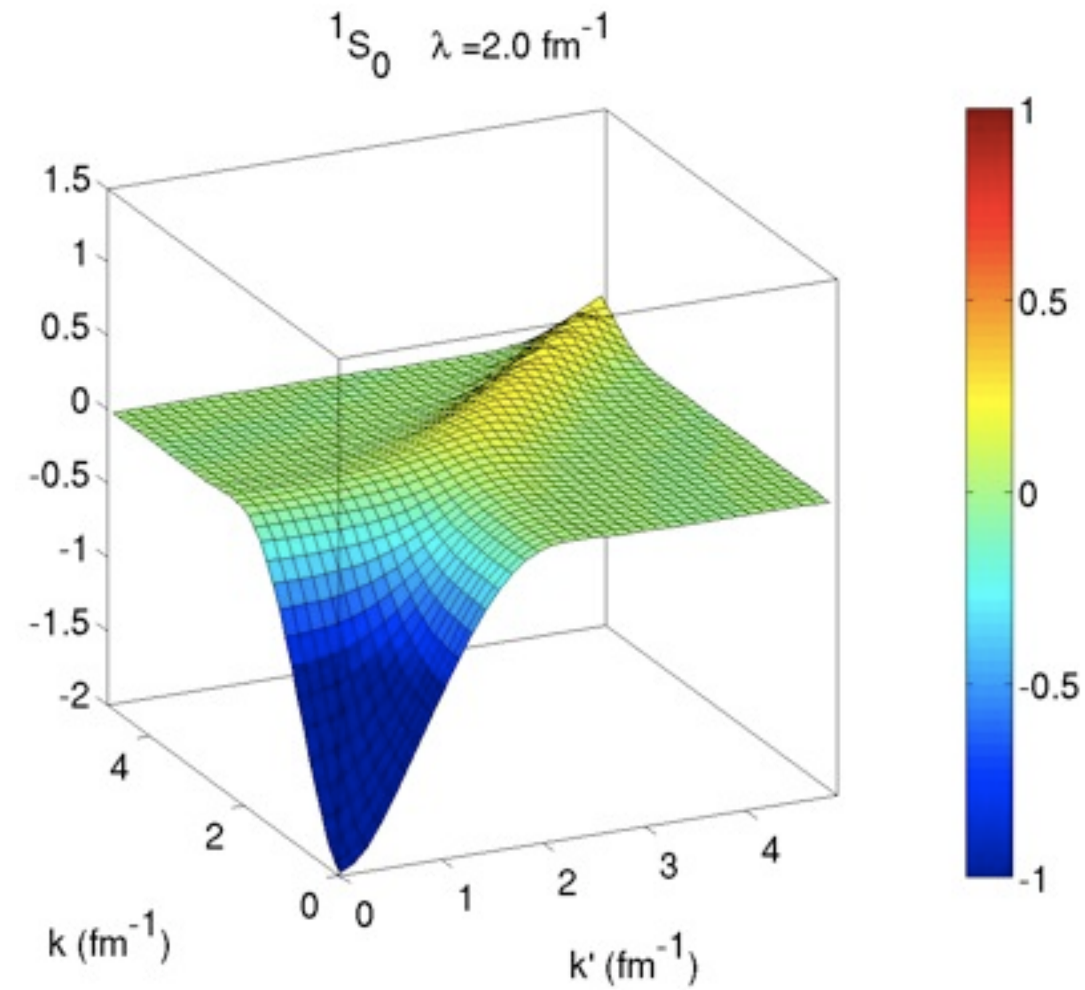
Changing the resolution: The (Similarity) Renormalization Group

- goal: generate unitary transformation of "hard" Hamiltonian

$$H_\lambda = U_\lambda H U_\lambda^\dagger \quad \text{with the resolution parameter } \lambda$$

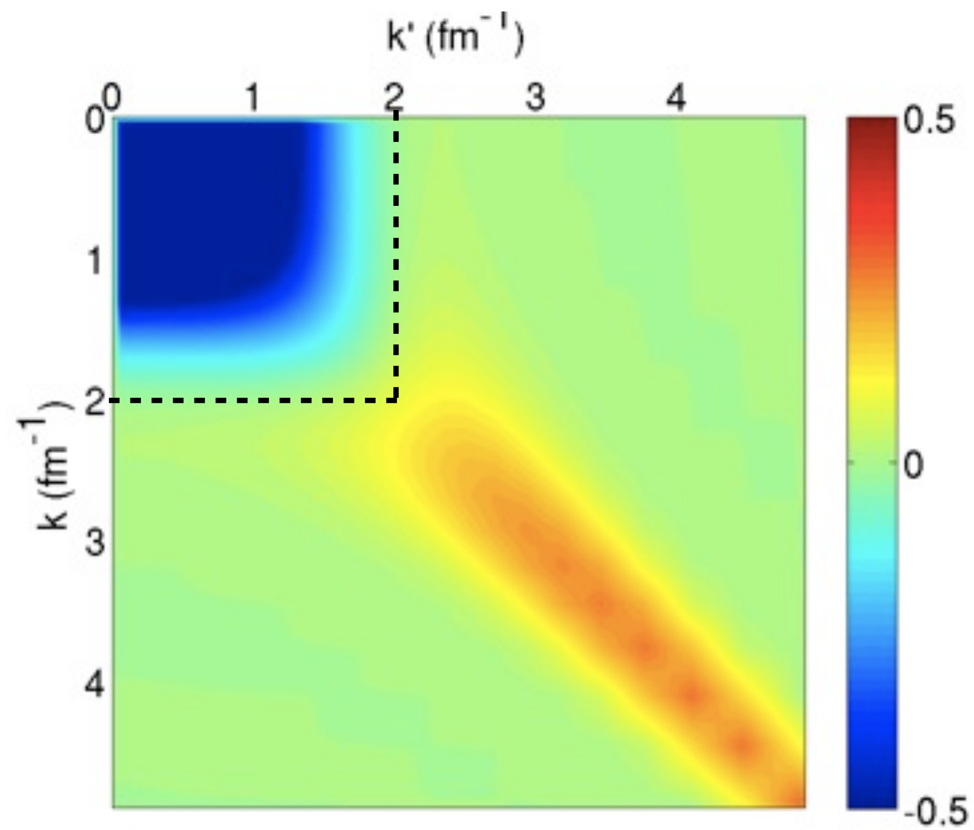
- basic idea: change resolution in small steps: $\frac{dH_\lambda}{d\lambda} = [\eta_\lambda, H_\lambda]$





- SRG only one possibility, also: $V_{\text{low k}}$, UCOM, Lee-Suzuki...

Changing the resolution: The (Similarity) Renormalization Group



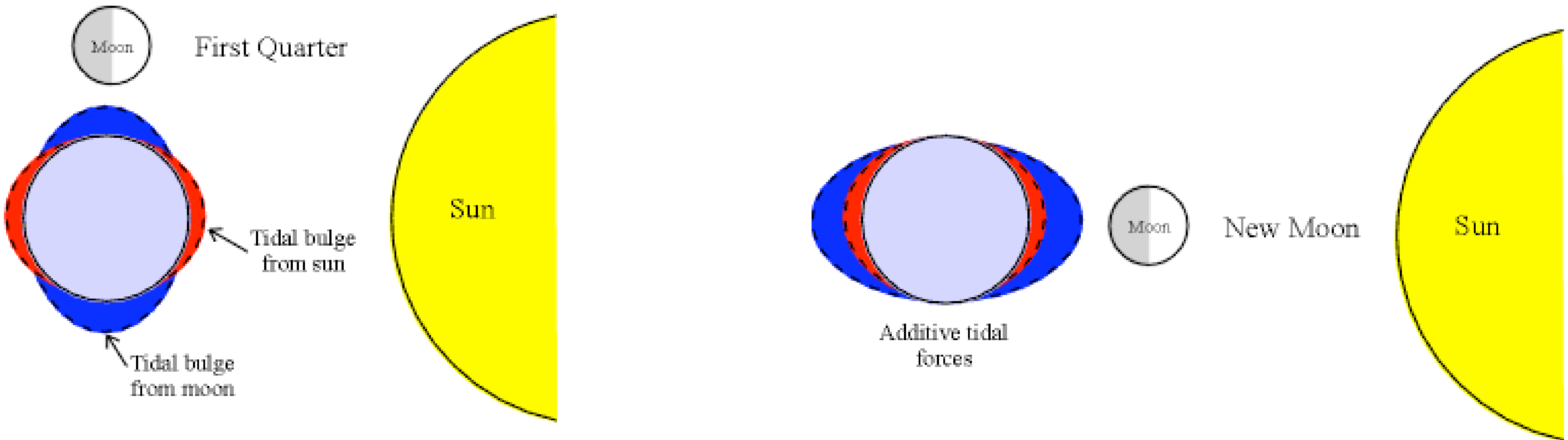
- elimination of coupling between low- and high momentum components, calculations much easier!
- observables unaffected by resolution change (for exact calculations)
- residual resolution dependences can be used as tool to test calculations

Not the full story:
RG transformation also changes three-body (and higher-body) interactions!

Why are there 3N forces?

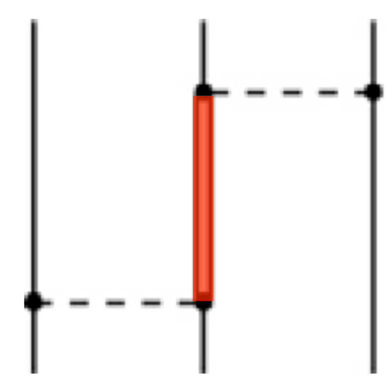
Classical analog

Tidal effects lead to 3N forces in earth-sun-moon system:



- force between earth and moon depends on the position of sun
- tidal deformations are internal excitations

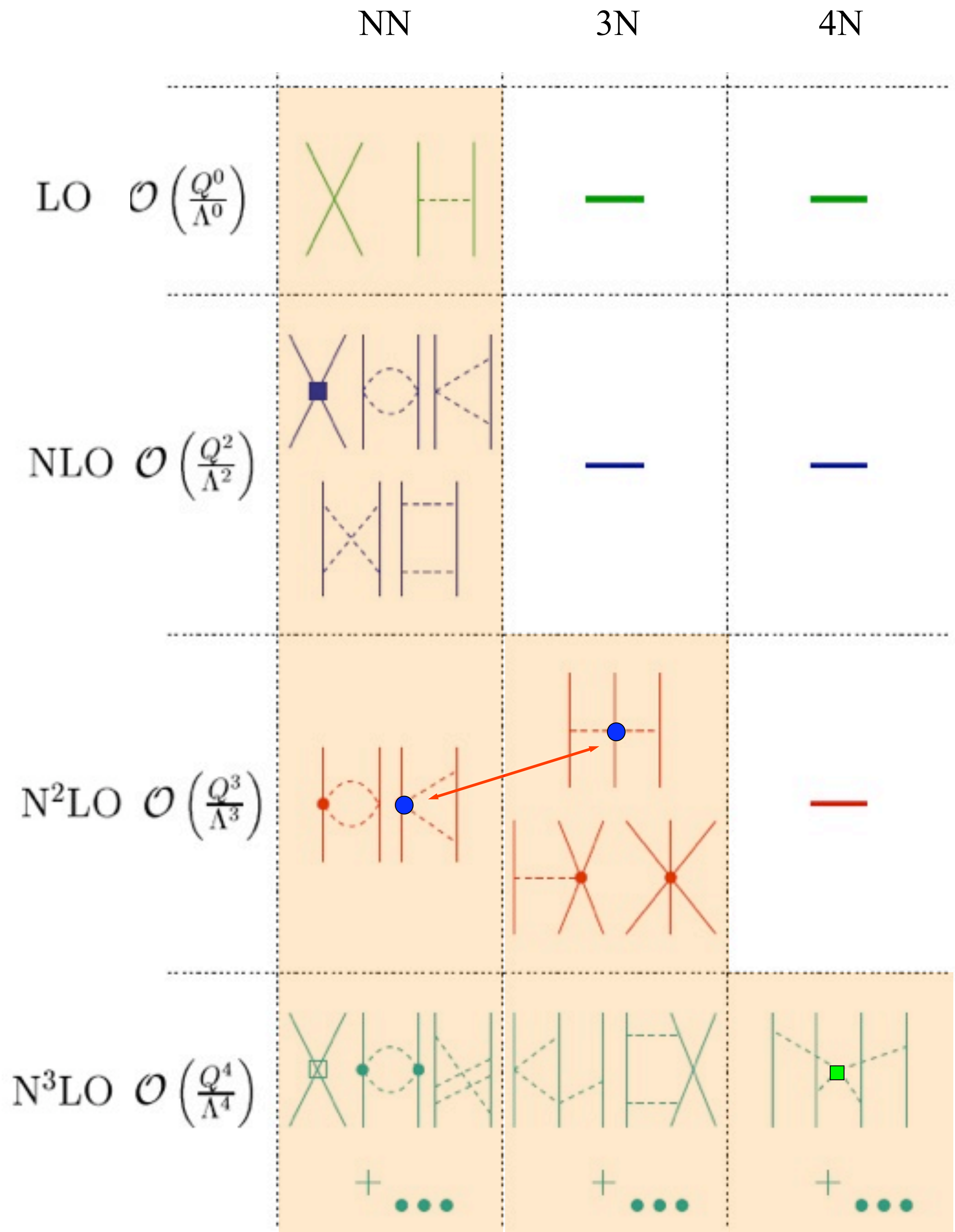
- nucleons are composite particles, can also be excited
- change of resolution changes the excitations that can be described explicitly ⟶ change of 3N force
- three-nucleon forces are crucial at low resolutions!



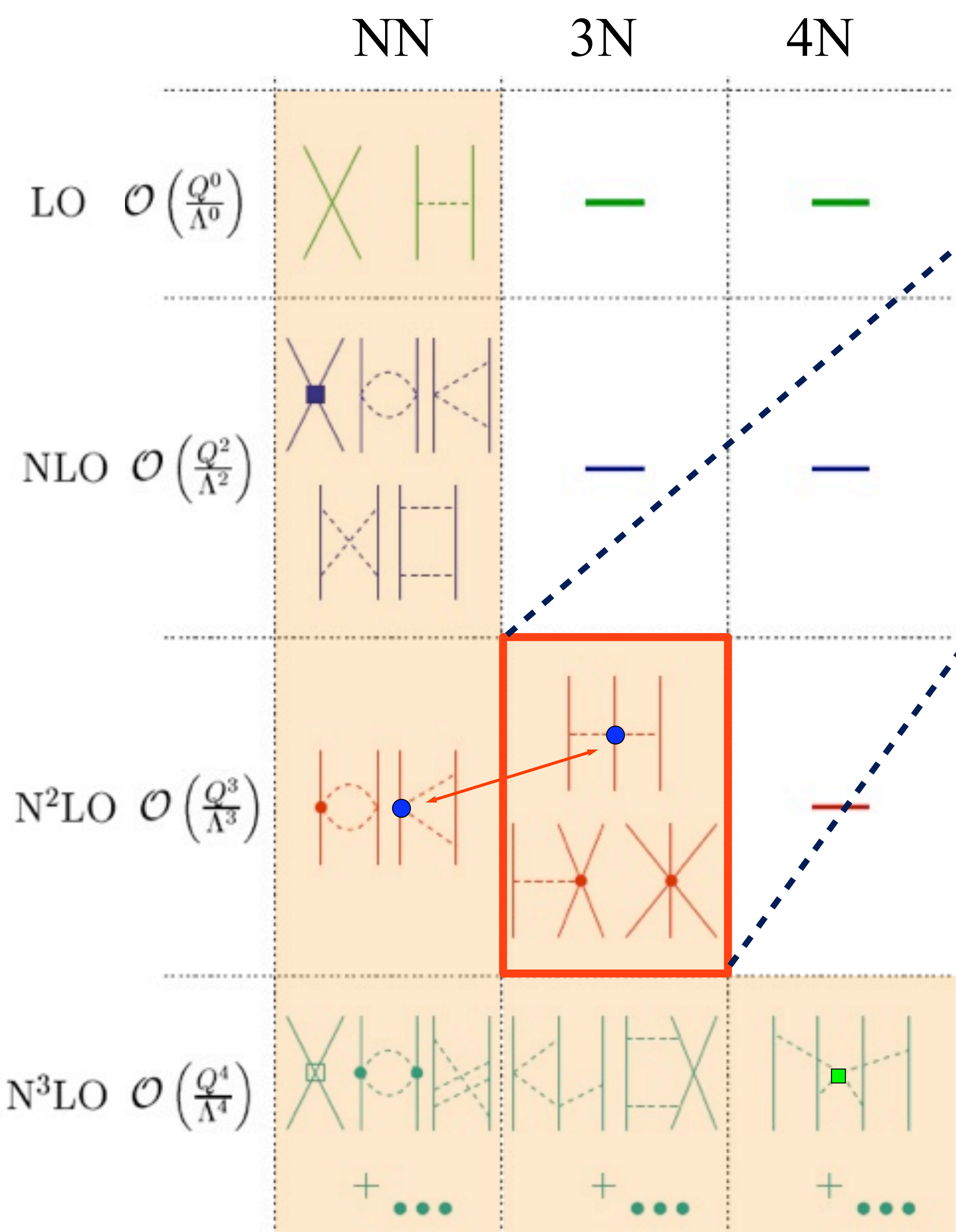
Basics concepts of chiral effective field theory

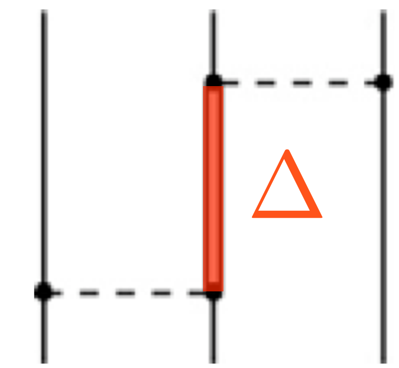
- choose effective degrees of freedom: here nucleons and pions
- short-range physics captured in few short-range couplings
- separation of scales: $Q \ll \Lambda_b$, breakdown scale $\Lambda_b \sim 500$ MeV
- power-counting: expand in powers Q/Λ_b
- systematic: work to desired accuracy, obtain error estimates

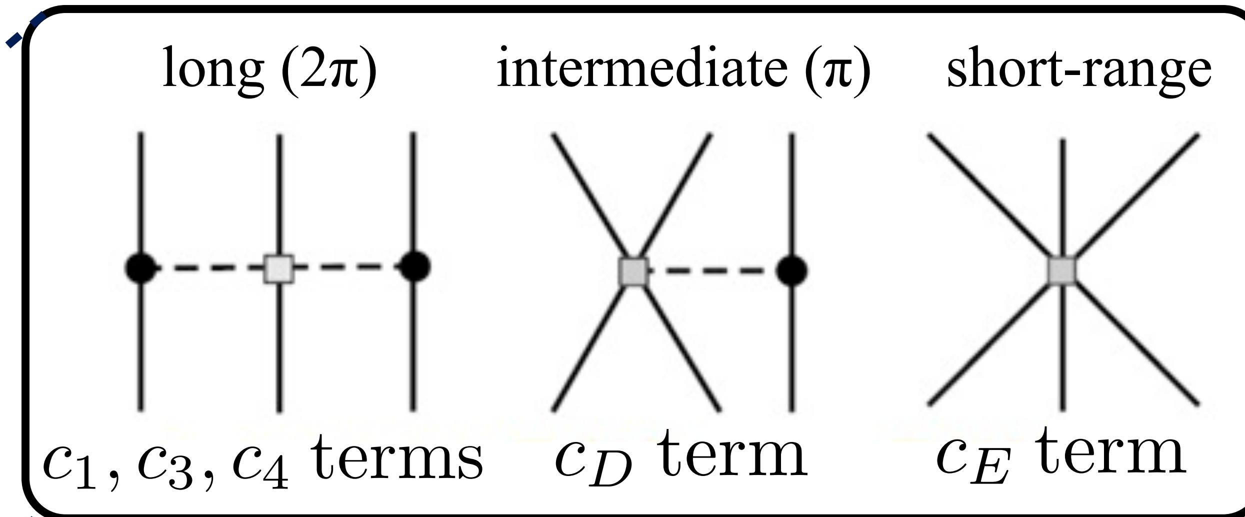
Plan: Use EFT interactions as input to RG evolution.



Leading order chiral 3N forces







- large uncertainties in 2π coupling constants at present:

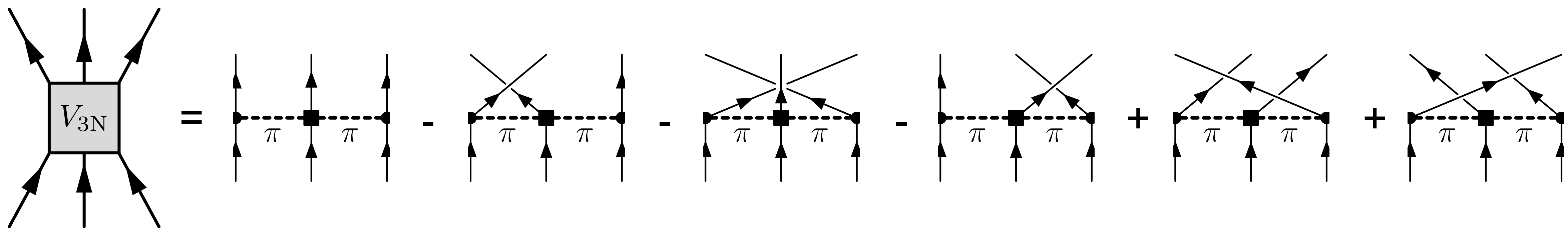
$$c_1 = -0.9^{+0.2}_{-0.5}\ ,\ c_3 = -4.7^{+1.5}_{-1.0}\ ,\ c_4 = 3.5^{+0.5}_{-0.2}$$

leads to theoretical uncertainties in many-body observables

- c_D and c_E have to be determined in $A \geq 3$ systems

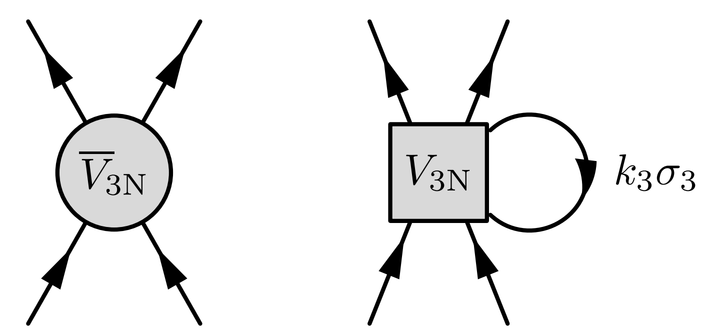
Chiral 3N interaction as density-dependent two-body interaction

(1) calculate antisymmetrized 3N interaction



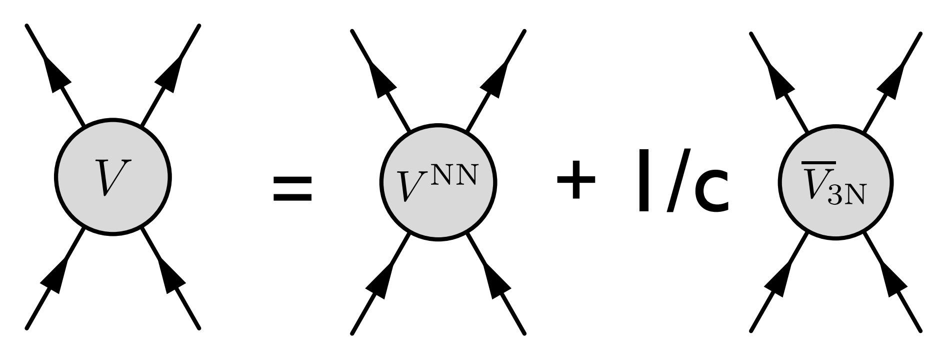
(2) construct effective density-dependent NN interaction

Basic idea:
Sum one particle over occupied states in the Fermi sea



(3) combine with free-space NN interaction

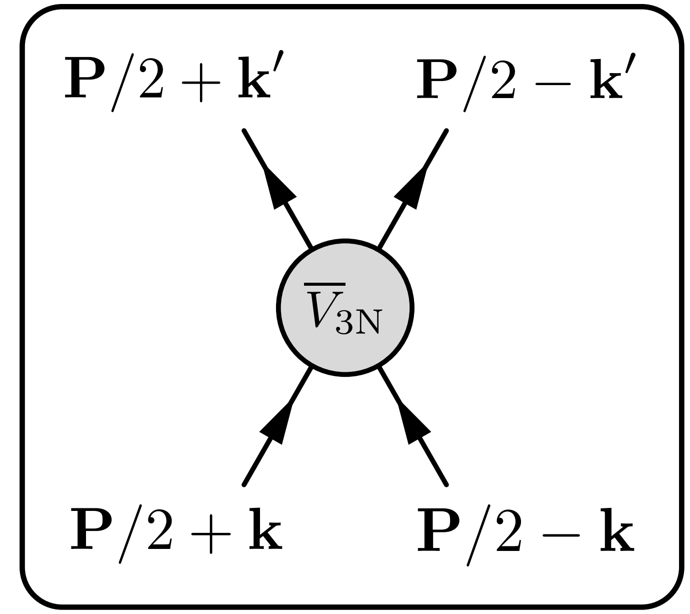
combinatorial factor c depends on type of diagram!



Properties of the effective interaction $\overline{V}_{3N}$

General momentum dependence:

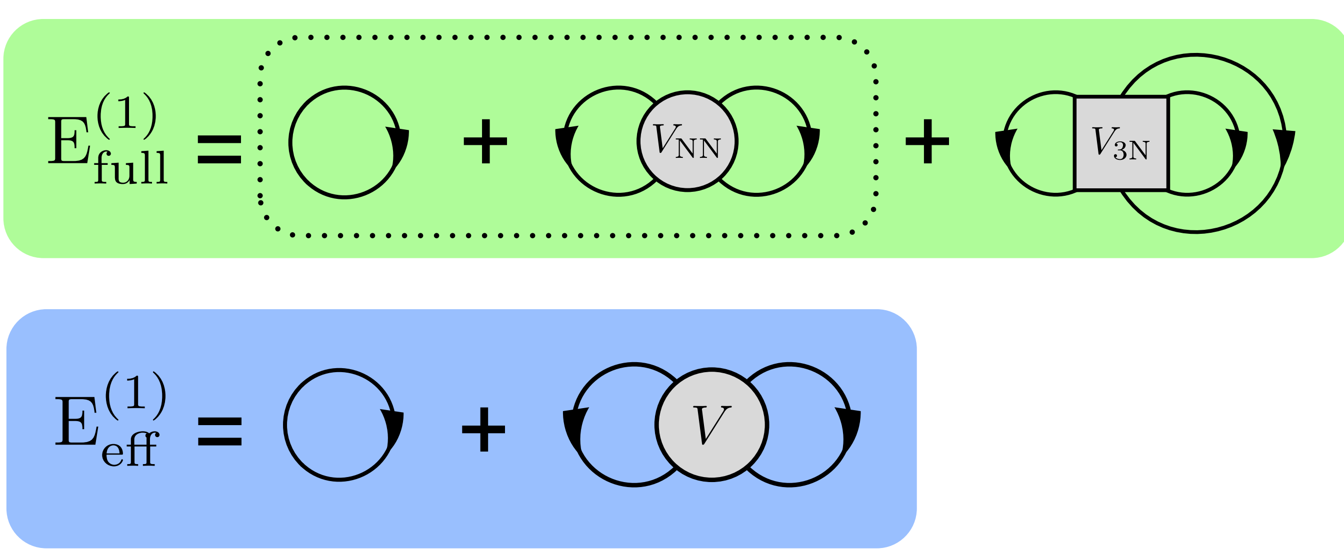
$$\overline{V}_{3N} = \overline{V}_{3N}(\mathbf{k}, \mathbf{k}', \mathbf{P})$$

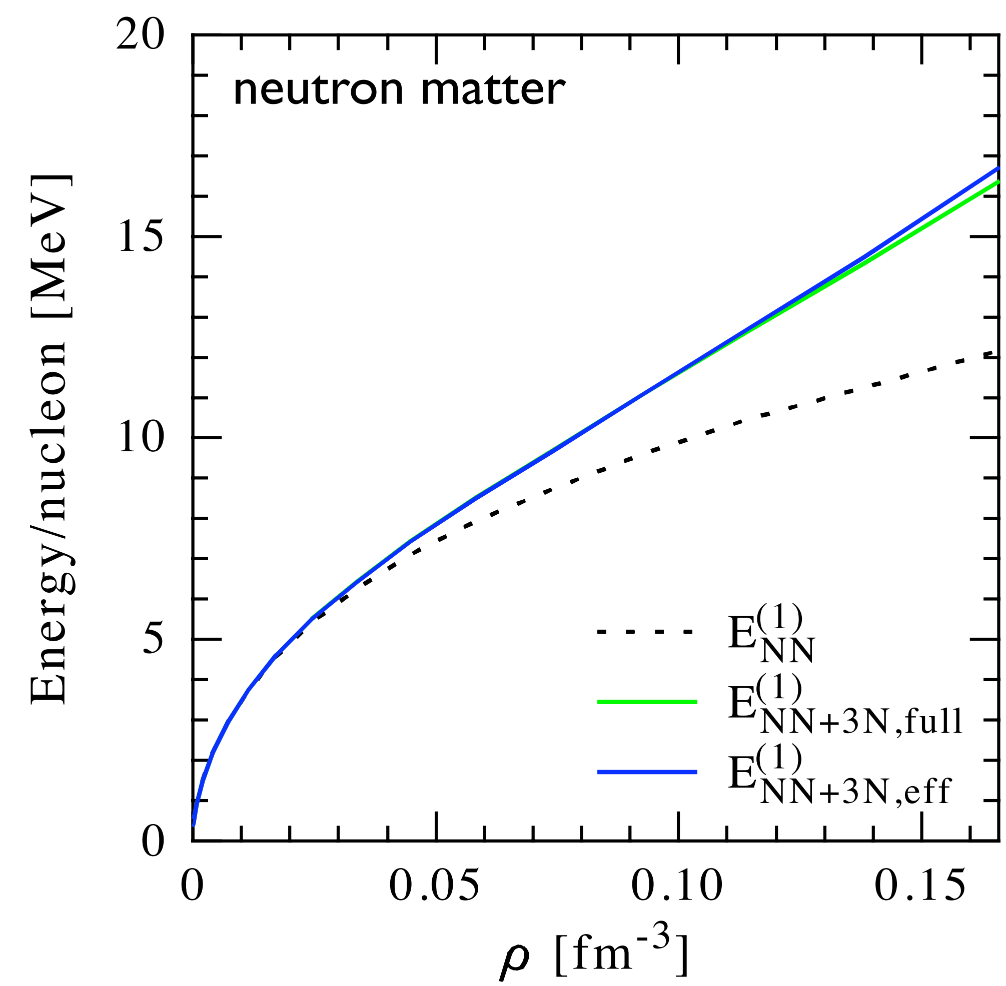


- $\mathbf{P}$-dependence much weaker than $\mathbf{k}, \mathbf{k}'$-dependence!
- neglect $\mathbf{P}$-dependence, set $\mathbf{P} = \mathbf{0}$
- matrix elements have the same form like free-space

NN interaction matrix elements

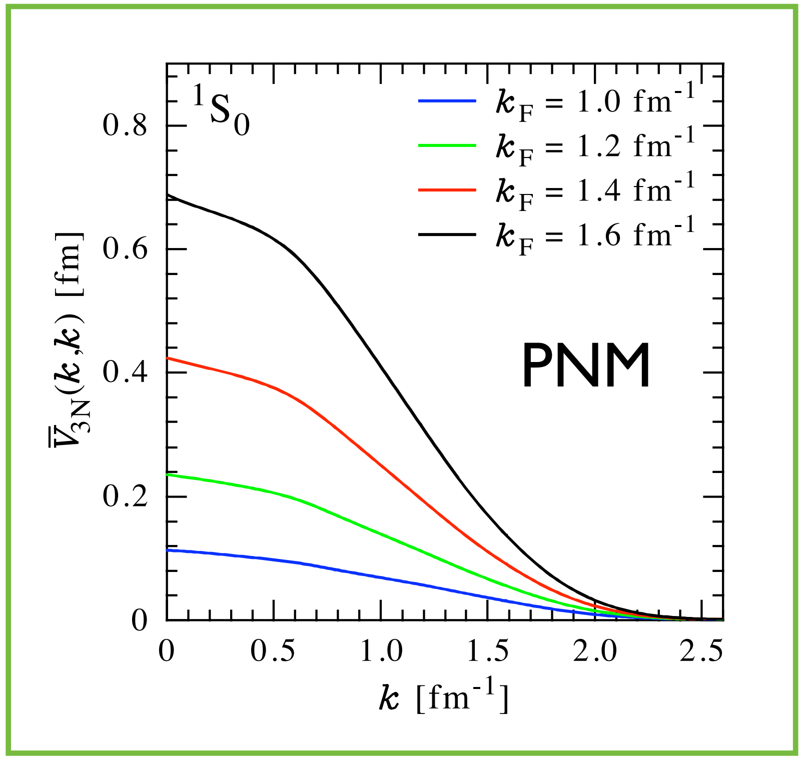
- straightforward to include in existing many-body schemes

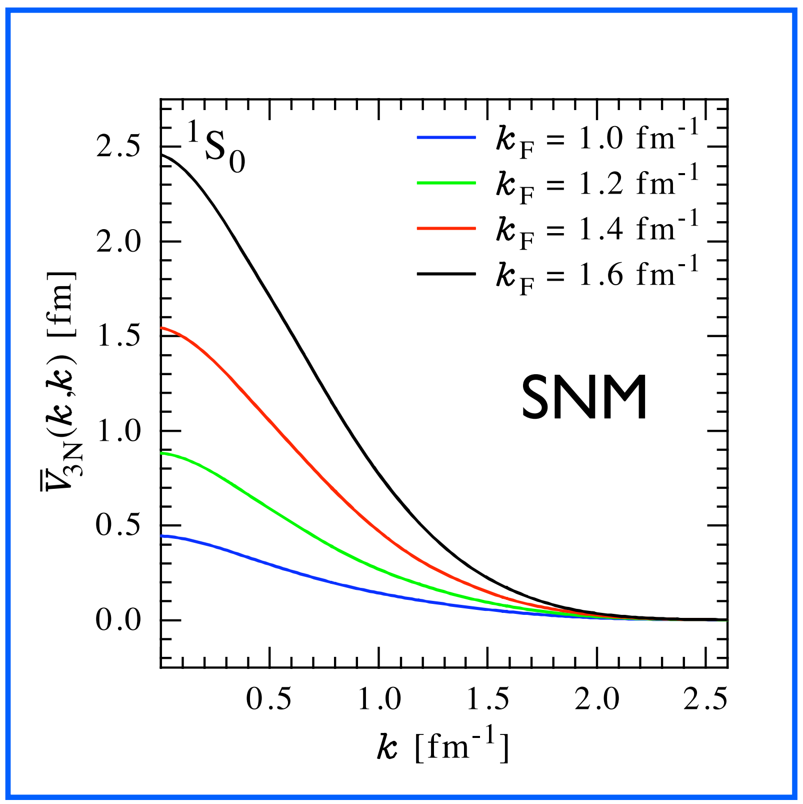


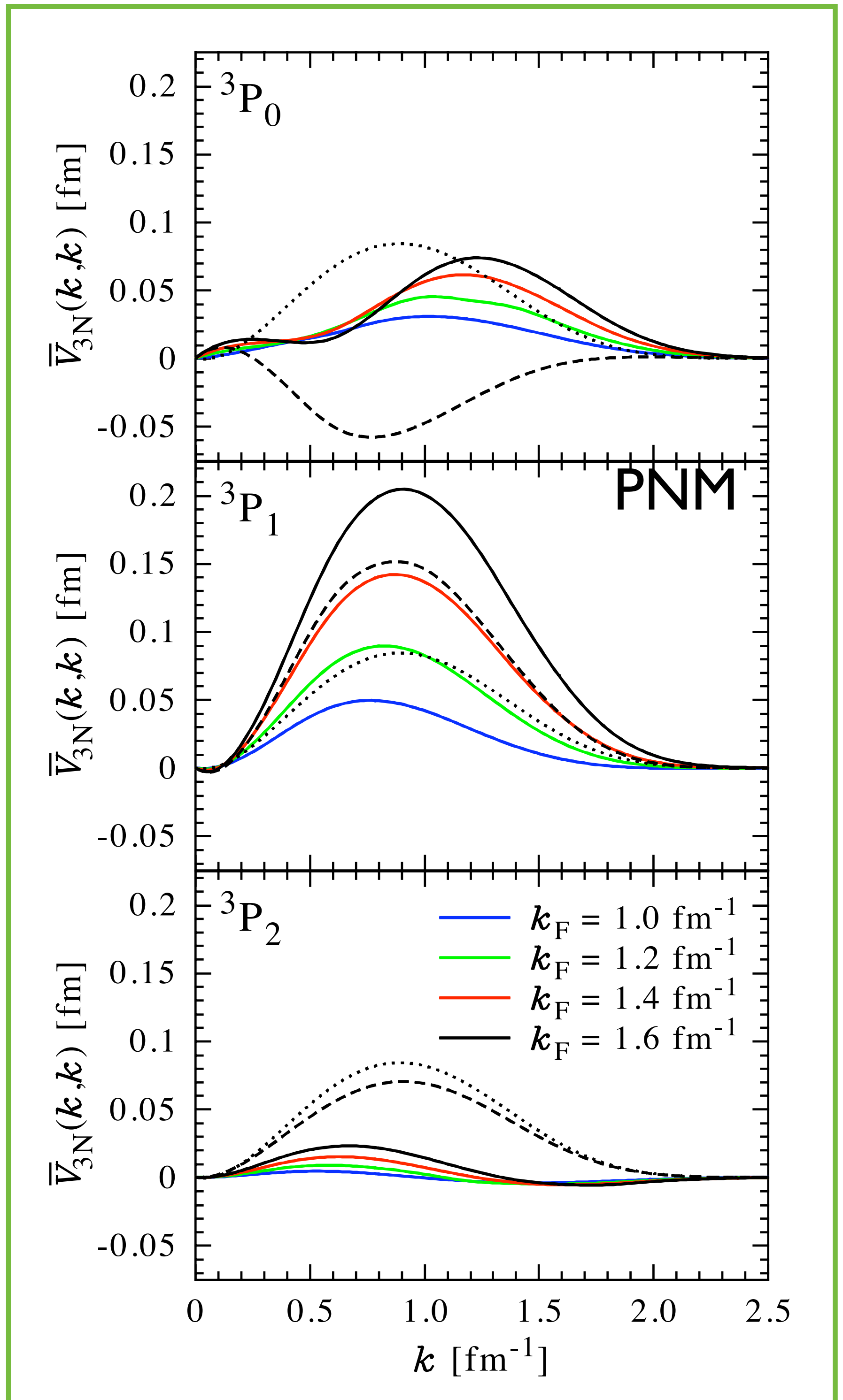


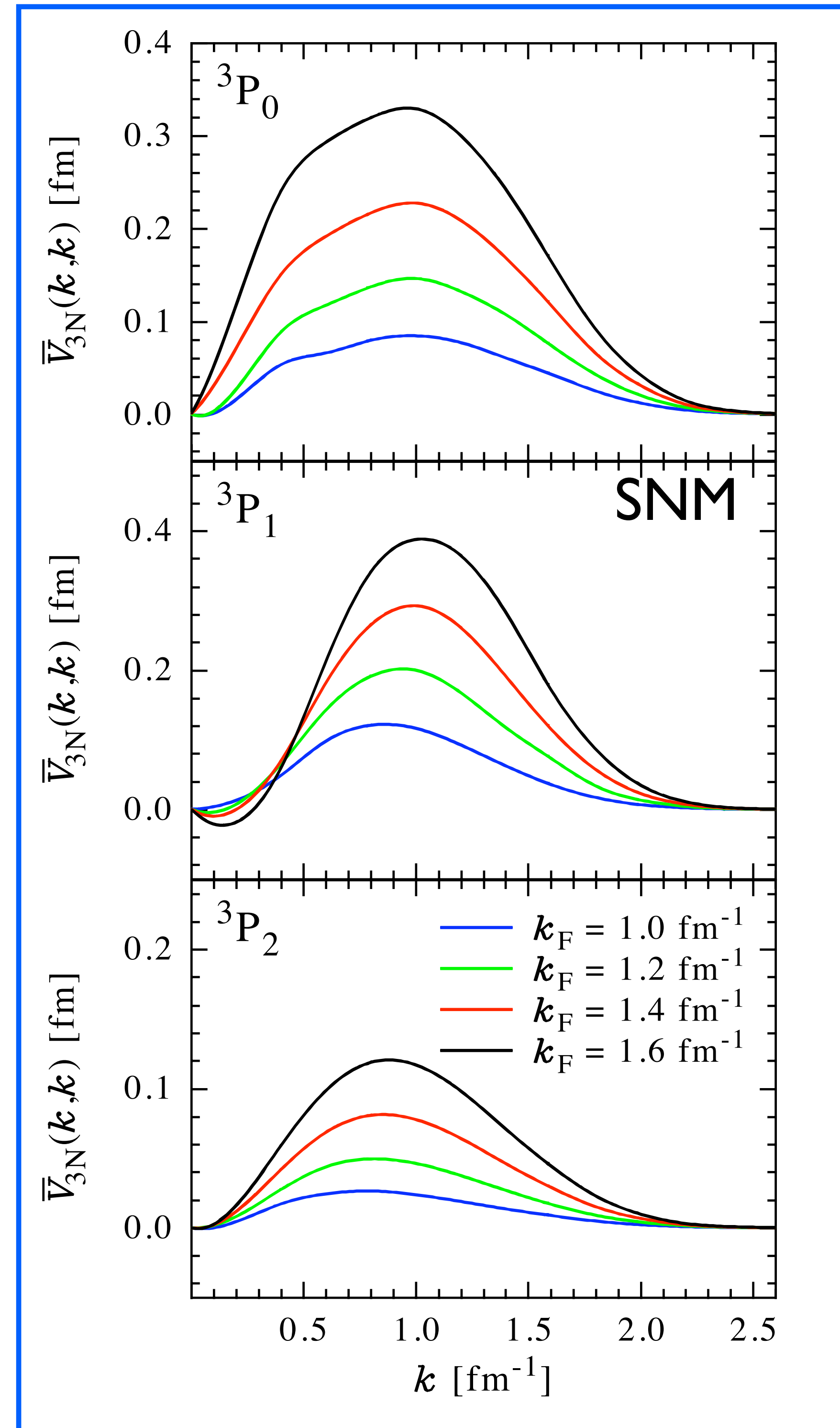
Properties of the effective interaction $\overline{V}_{3N}$

$(\Lambda_{3N} = 2.0\,\mathrm{fm}^{-1})$





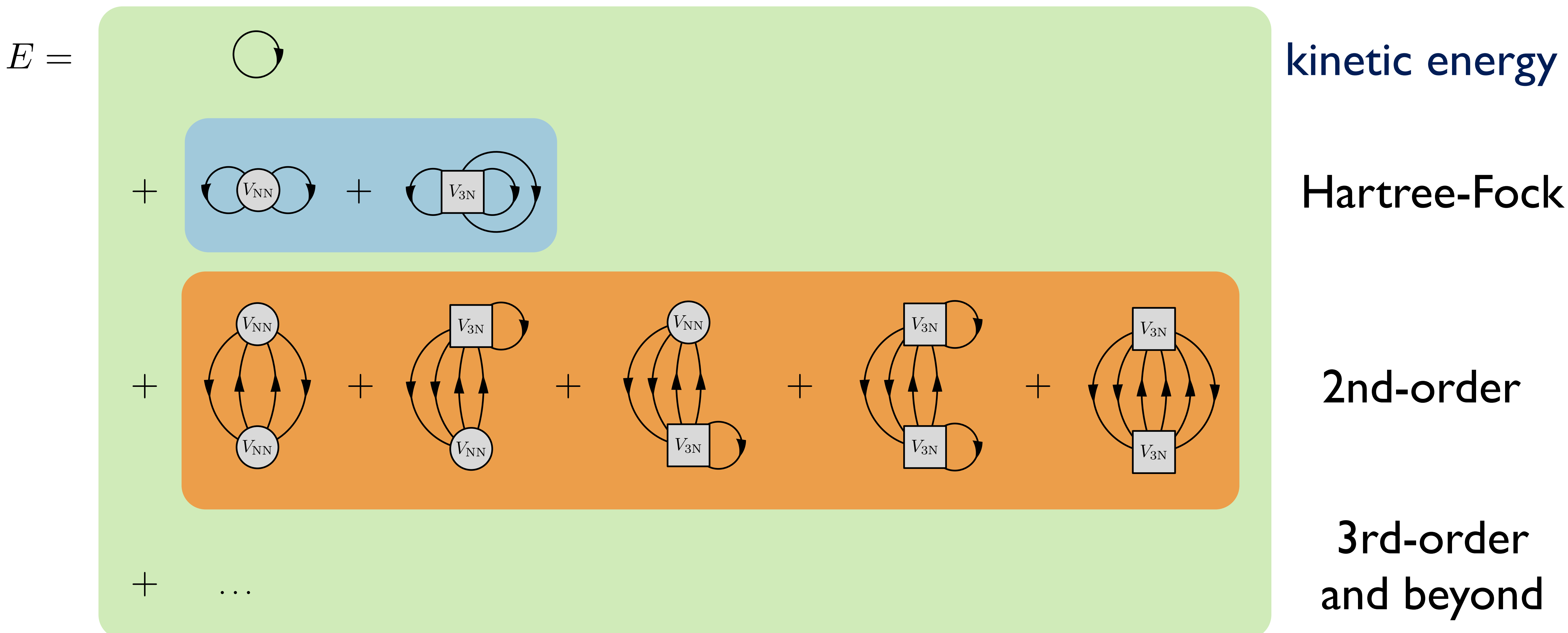




Equation of state: Many-body perturbation theory

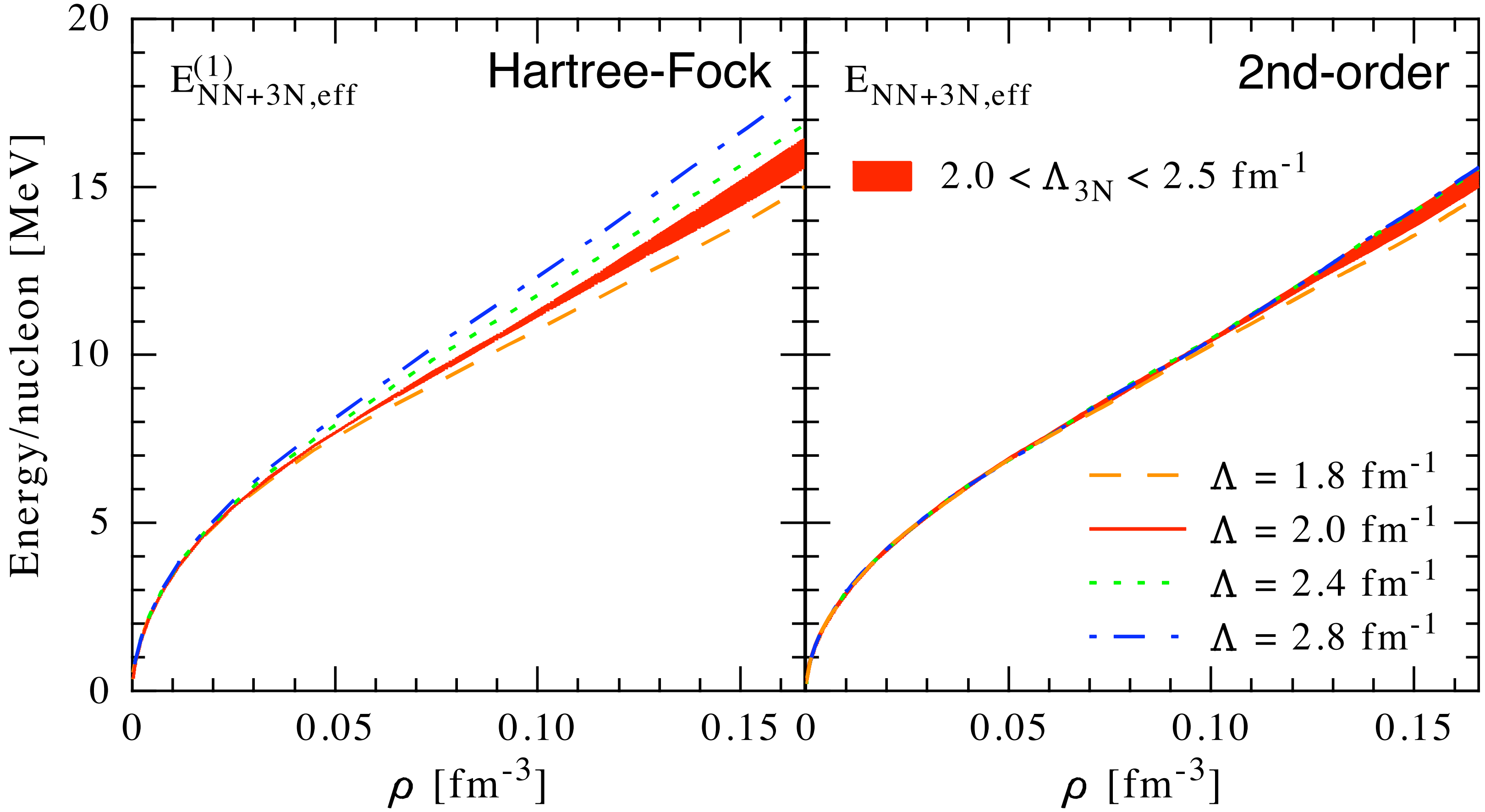
central quantity of interest: energy per particle E/N

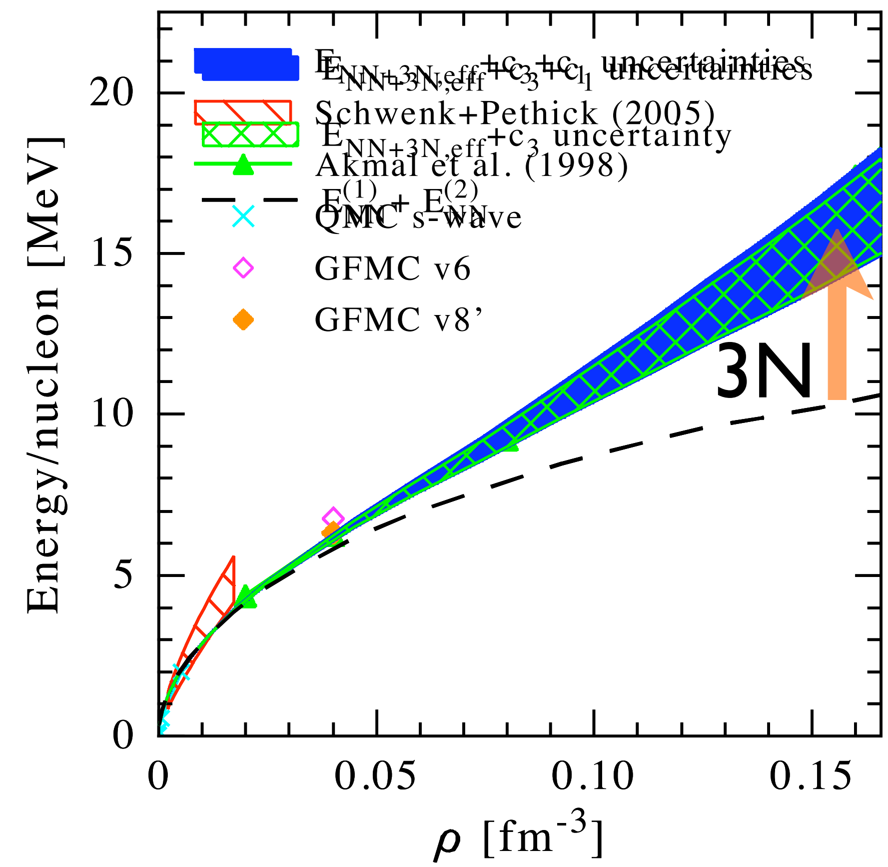
$$H(\lambda) = T + V_{\rm NN}(\lambda) + V_{\rm 3N}(\lambda) + \ldots$$



- "hard" interactions require non-perturbative summation of diagrams
- with low-momentum interactions much more perturbative
- inclusion of 3N interaction contributions

Equation of state of pure neutron matter





KH and Schwenk PRC 82, 014314 (2010)

- significantly reduced cutoff dependence at 2nd order perturbation theory
- small resolution dependence indicates converged calculation
- energy sensitive to uncertainties in 3N interaction
- variation due to 3N input uncertainty much larger than resolution dependence
- good agreement with other approaches (different NN interactions)

Neutron matter: Symmetry energy

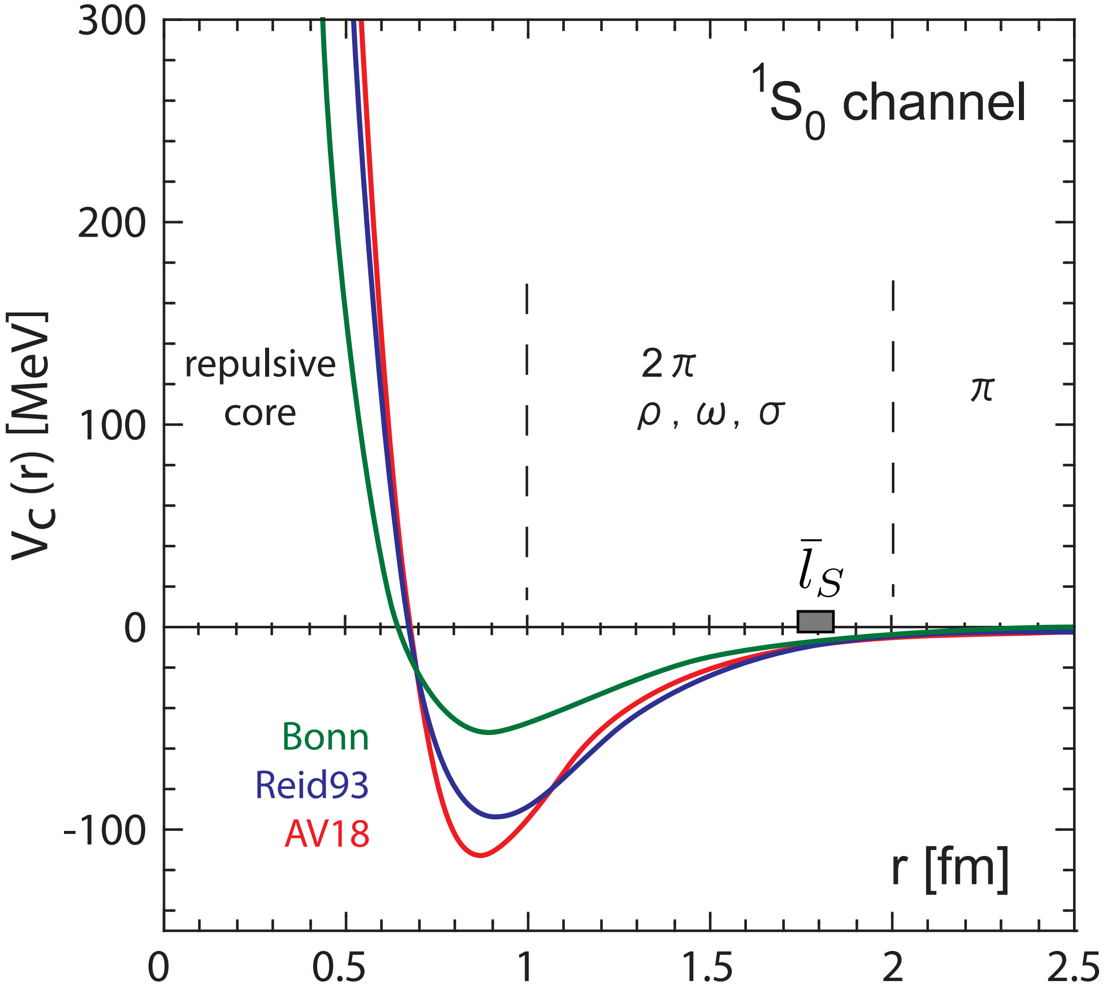
$$E(\rho, \alpha = 1) = -a_V + \frac{K_0}{18\rho_0^2}(\rho - \rho_0)^2 + S_2(\rho)$$

$$S_2(\rho) = a_4 + \frac{p_0}{\rho_0^2}(\rho - \rho_0)$$

c_1 [GeV]	c_3 [GeV]	a_4 [MeV]	p_0 [MeV fm^{-3}]
-0.81	-3.2	31.7	$2.4/2.5$
-0.81	-5.7	33.7	$2.9/3.0$
-0.7	-3.2	31.7	$2.4/2.5$
-1.4	-5.7	34.5	$3.3/3.4$

- uncertainties in c_i couplings lead to uncertainties in symmetry energy
- given the experimental constraint $a_4 = 30 \pm 4\,\mathrm{MeV}$
  smaller absolute values of c_3 seem to be preferred from our results

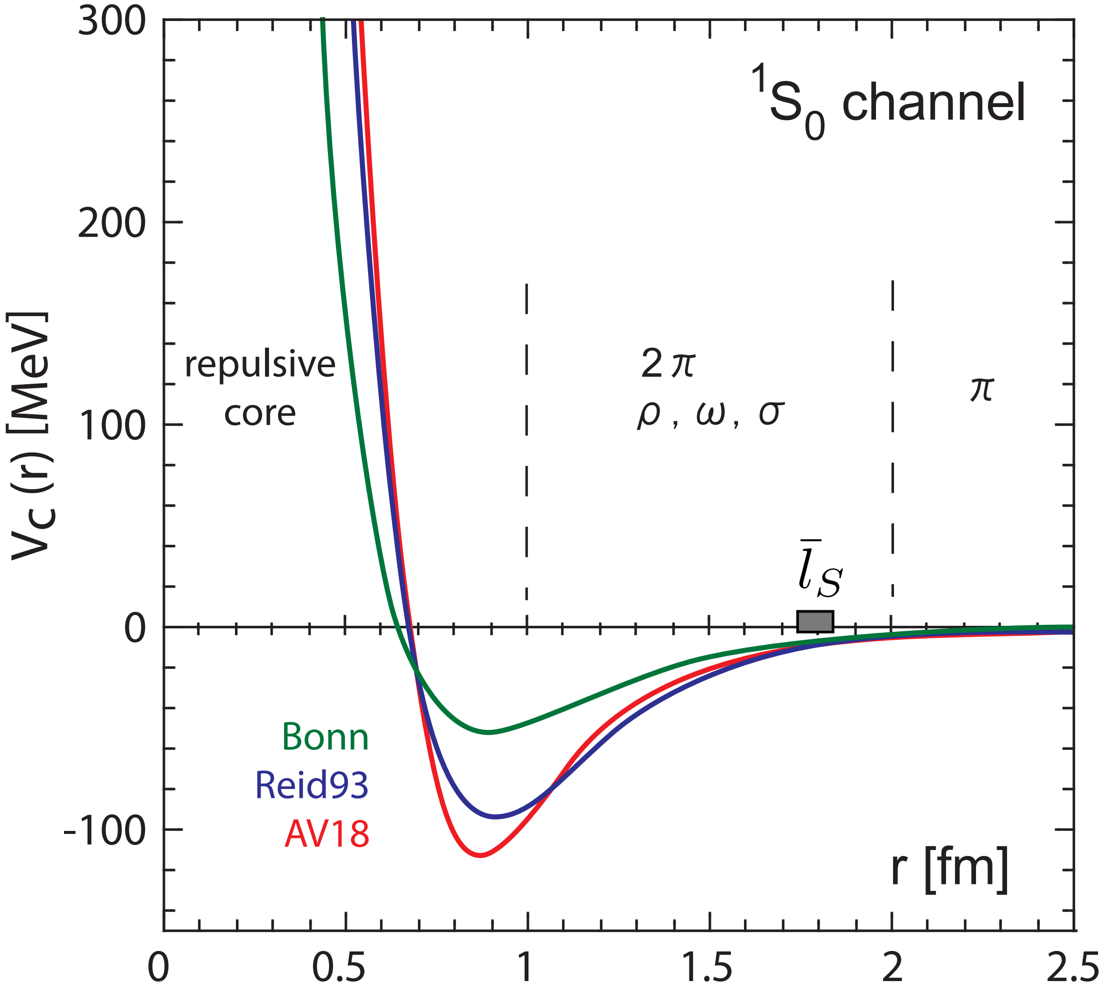
Equation of state of symmetric nuclear matter

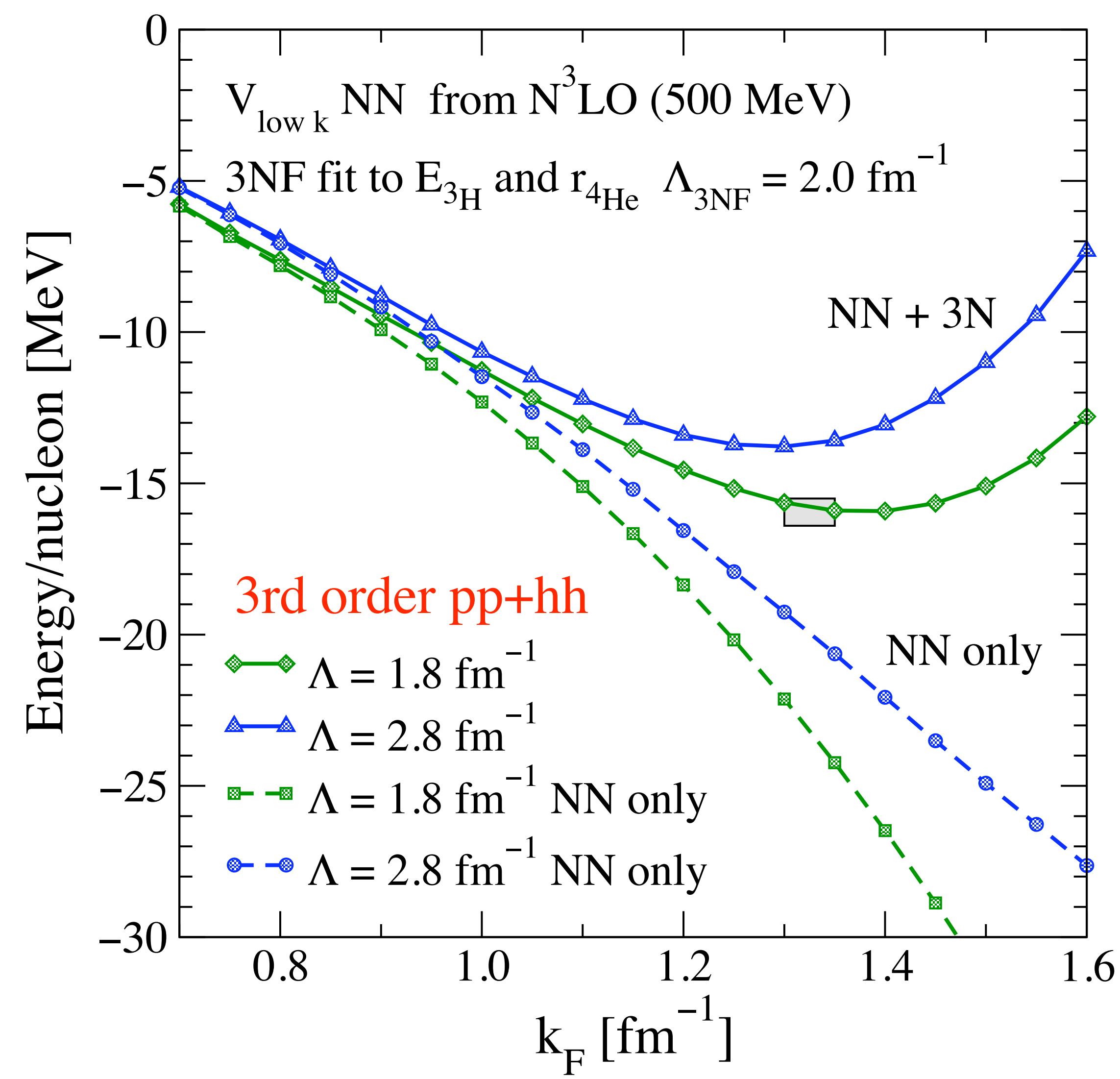


"Very soft potentials must be excluded because they do not give saturation; they give too much binding and too high density. In particular, a substantial tensor force is required."
Hans Bethe (1971)

- empirical saturation at $n_S \sim 0.16\,\mathrm{fm}^{-3}$ and $E_{\mathrm{binding}}/N \sim -16\,\mathrm{MeV}$

Equation of state of symmetric nuclear matter

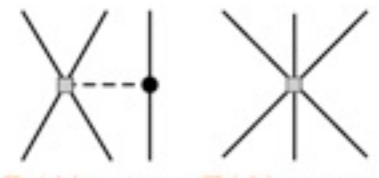




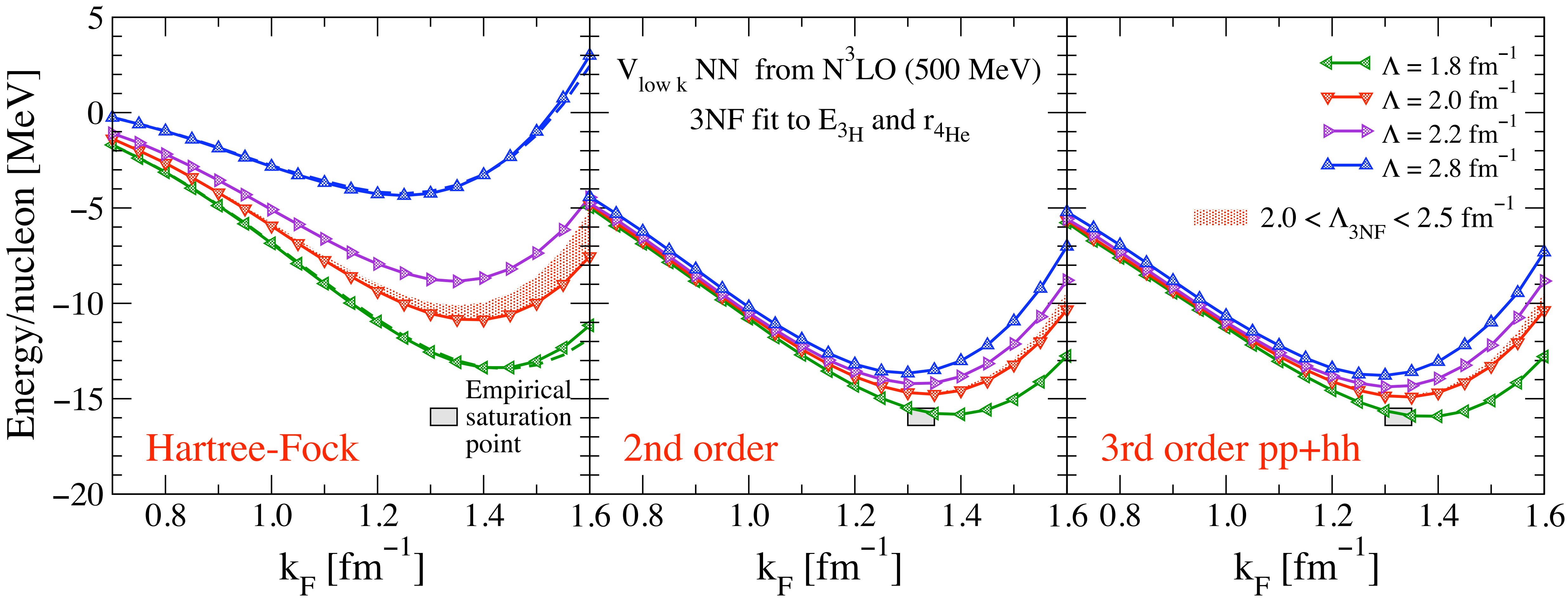
KH et al., PRC(R) 83, 031301 (2011)

- empirical saturation at $n_S \sim 0.16\,\mathrm{fm}^{-3}$ and $E_{\mathrm{binding}}/N \sim -16\,\mathrm{MeV}$
- nuclear saturation delicate due to cancellations of large kinetic and potential energy contributions
- 3N forces are essential! Here: fit 3NF couplings to few-body systems:

$$E_{^3\mathrm{H}} = -8.482\,\mathrm{MeV} \quad \text{and} \quad r_{^4\mathrm{He}} = 1.95 - 1.96\,\mathrm{fm}$$



Equation of state of symmetric nuclear matter



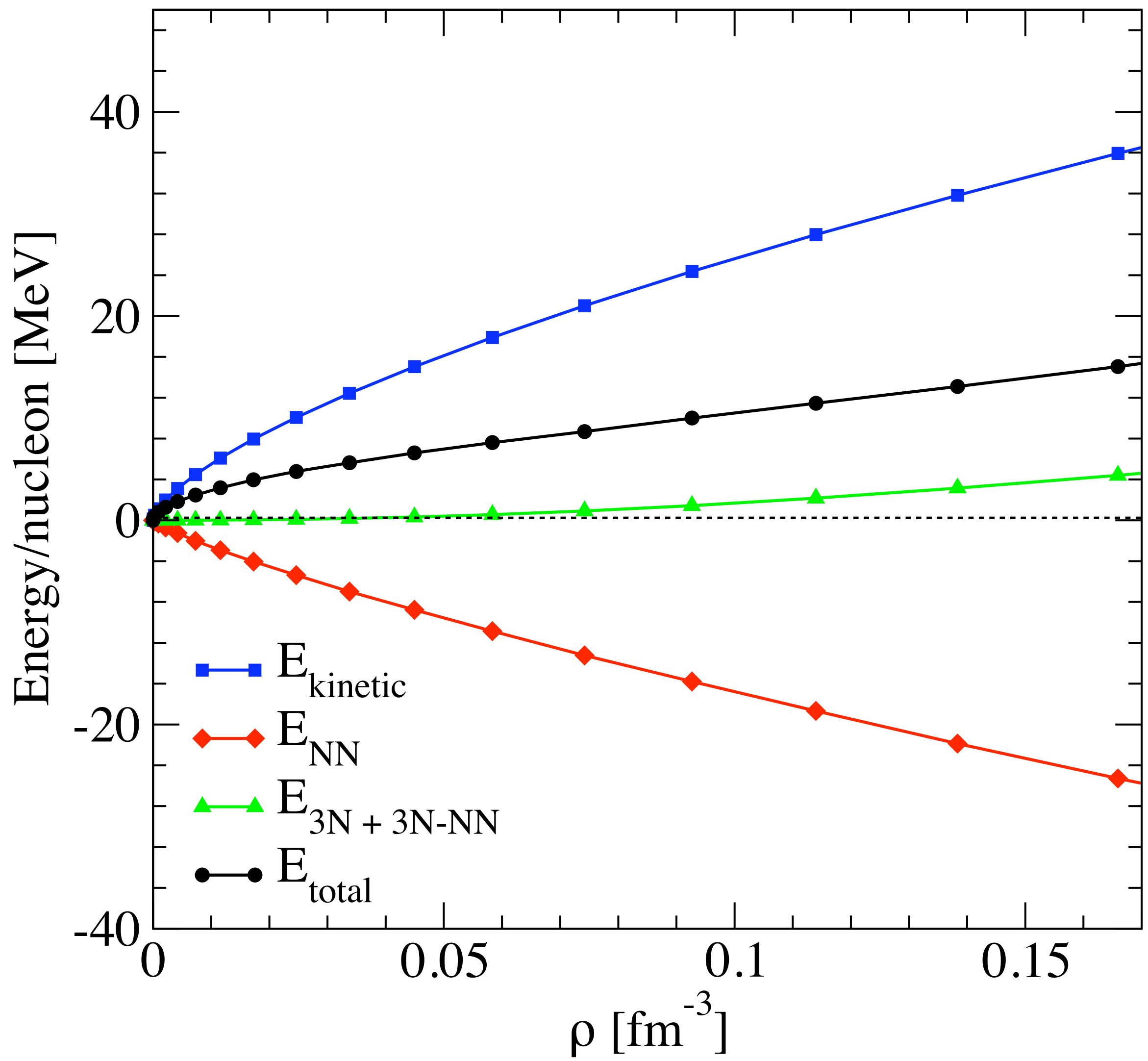
KH et al., PRC(R) 83, 031301 (2011)

- saturation point consistent with experiment, without new free parameters
- cutoff dependence at 2nd order significantly reduced
- 3rd order contributions small
- cutoff dependence consistent with expected size of 4N force contributions

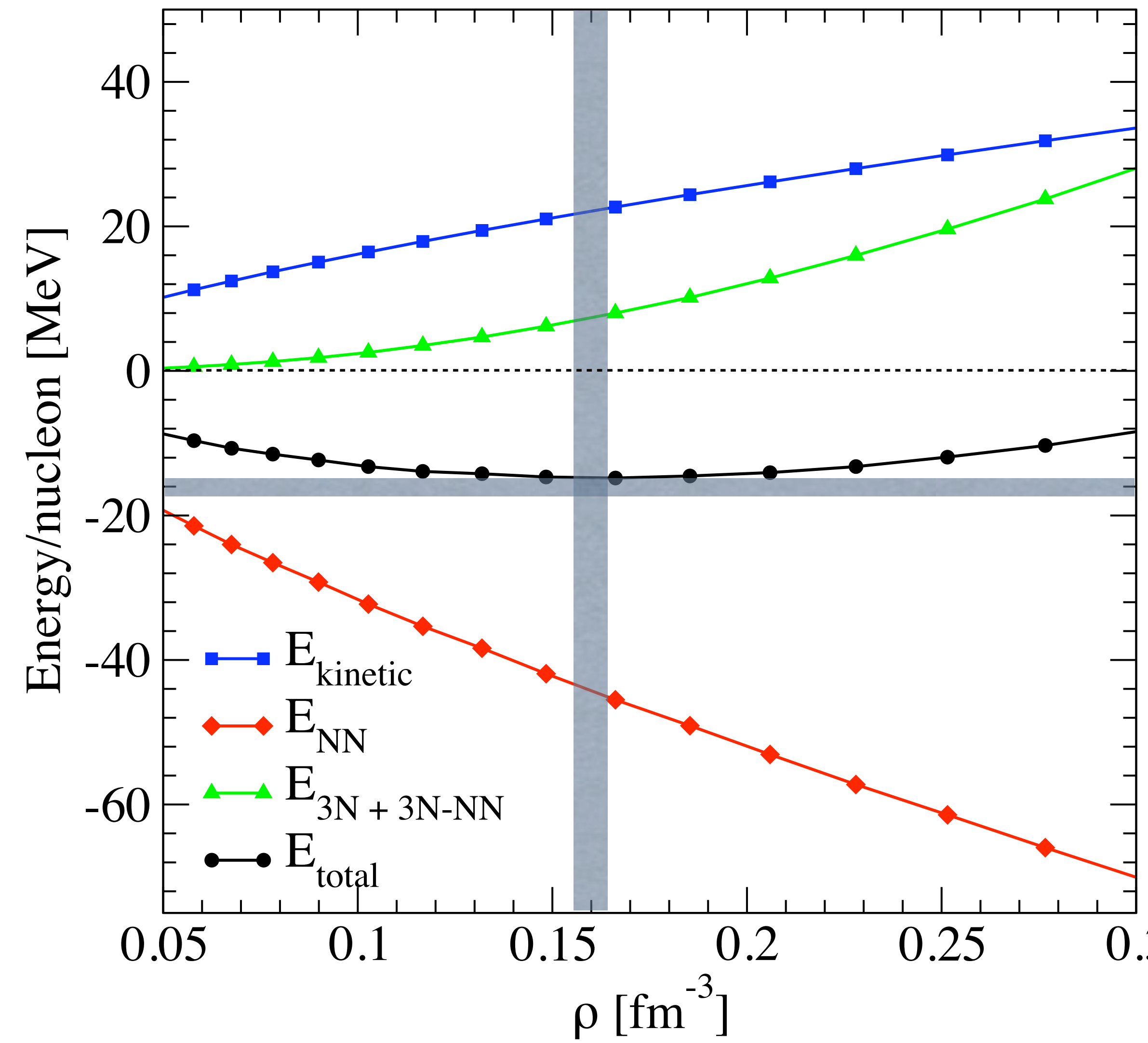
Bulk nuclear properties
efficiently described at low resolution!

Hierarchy of many-body contributions

neutron matter



nuclear matter



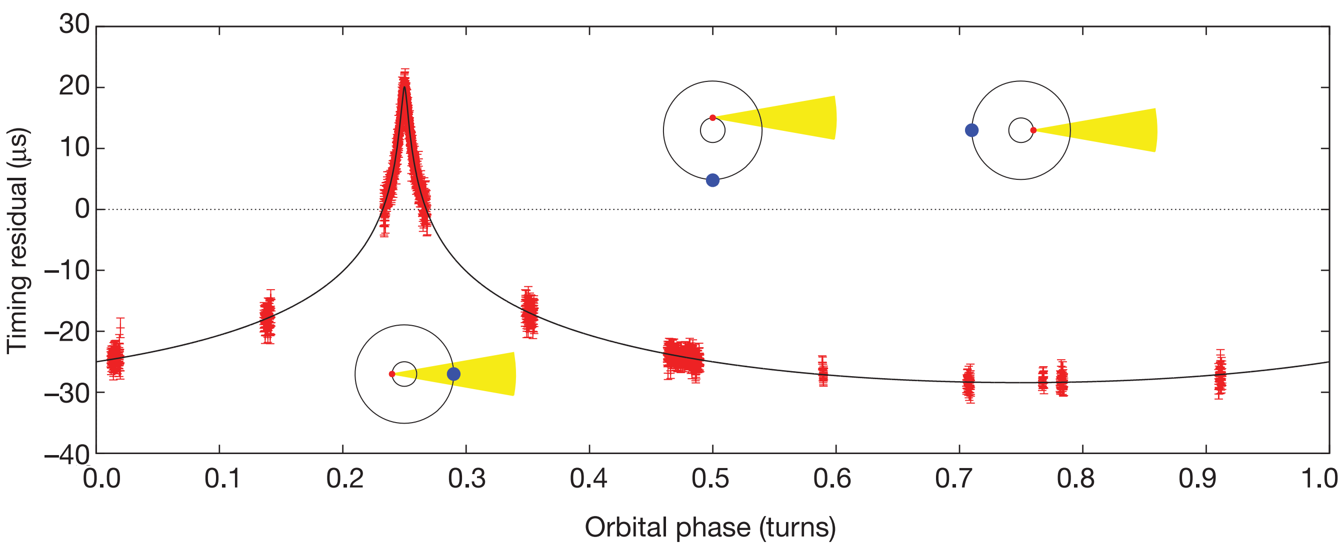
- binding energy results from cancellations of much larger kinetic and potential energy contributions
- chiral hierarchy of many-body terms preserved for considered density range
- cutoff dependence of natural size, consistent with chiral exp. parameter $\sim 1/3$

Constraints on the nuclear equation of state (EOS)

nature

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]



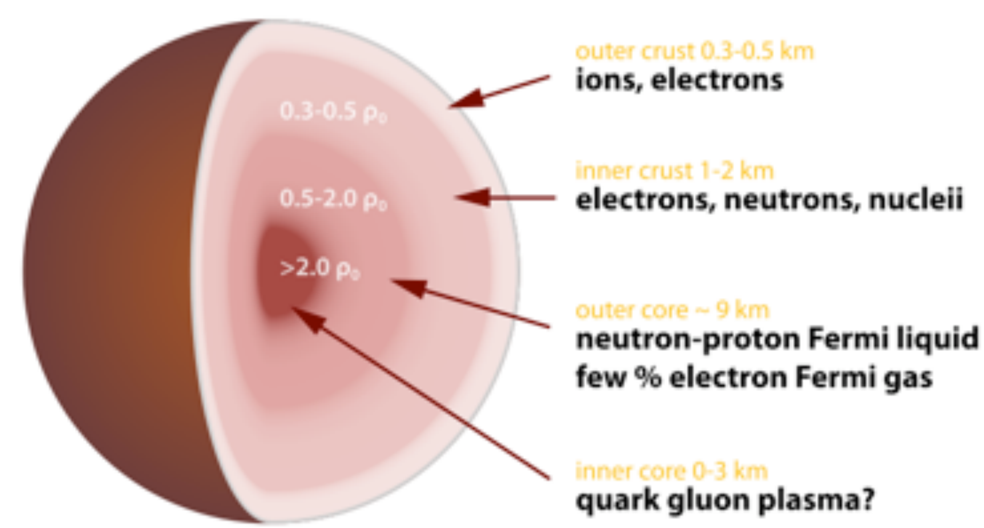
Demorest et al., Nature 467, 1081 (2010)

$$M_{\rm max} = 1.65 M_\odot \rightarrow 1.97 \pm 0.04\, M_\odot$$

Credit: NASA/Dana Berry

Structure of a neutron star is determined by Tolman-Oppenheimer-Volkov (TOV) equation:

$$\frac{dP}{dr} = -\frac{GM\epsilon}{r^2}\left[1+\frac{P}{\epsilon c^2}\right]\left[1+\frac{4\pi r^3 P}{Mc^2}\right]\left[1-\frac{2GM}{c^2 r}\right]^{-1}$$



crucial ingredient: energy density $\epsilon = \epsilon(P)$

Neutron star radius constraints

Problem: Solution of TOV equation requires EOS up to very high densities. Radius of a typical NS (M~1.4 $M_\odot$) theoretically not well constrained.

But: Radius of NS is relatively insensitive to high density region.

---

incorporation of beta-equilibrium: neutron matter $\longrightarrow$ neutron star matter

parametrize piecewise high-density extensions of EOS:

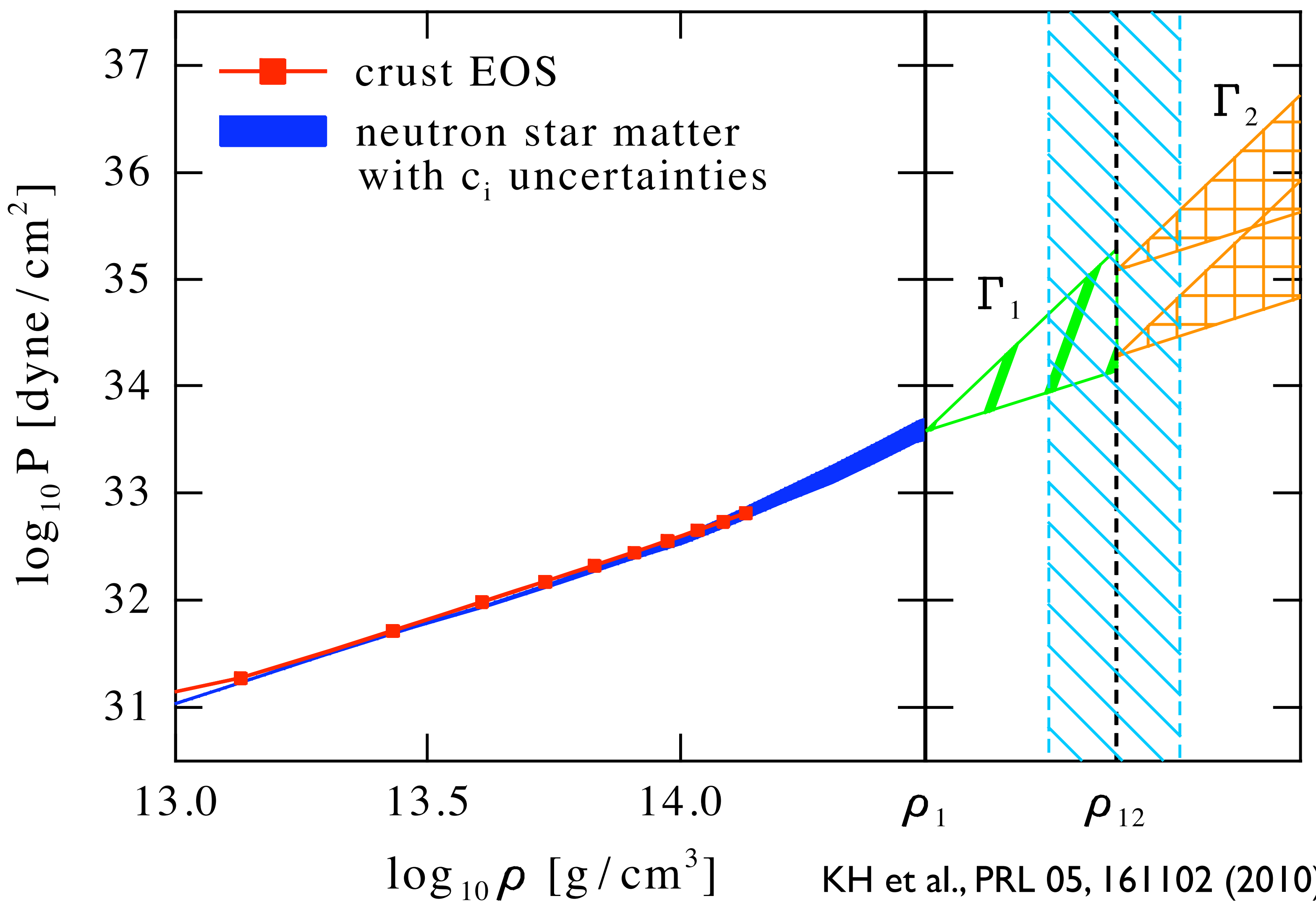
- use polytropic ansatz

$$p \sim \rho^\Gamma$$

- range of parameters

$$\Gamma_1, \rho_{12}, \Gamma_2$$

limited by physics!



KH et al., PRL 05, 161102 (2010)

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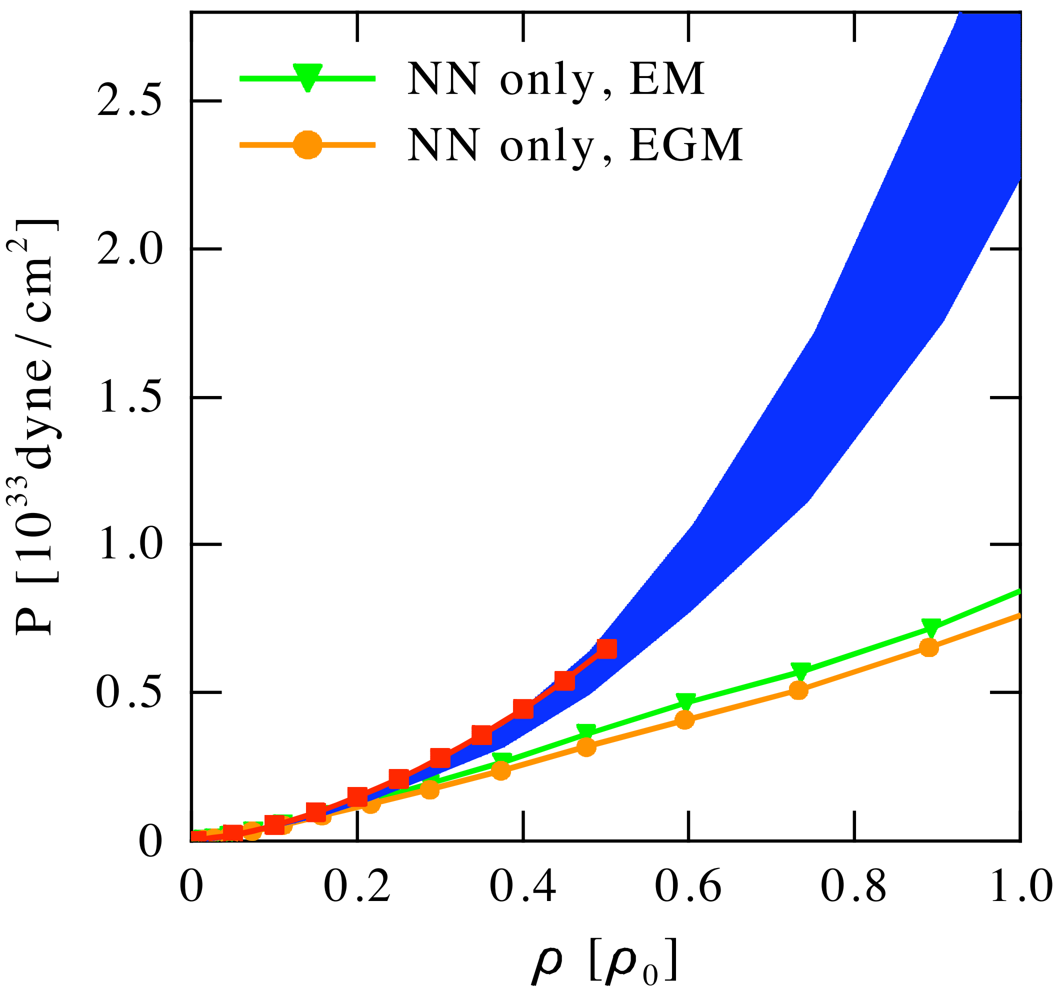
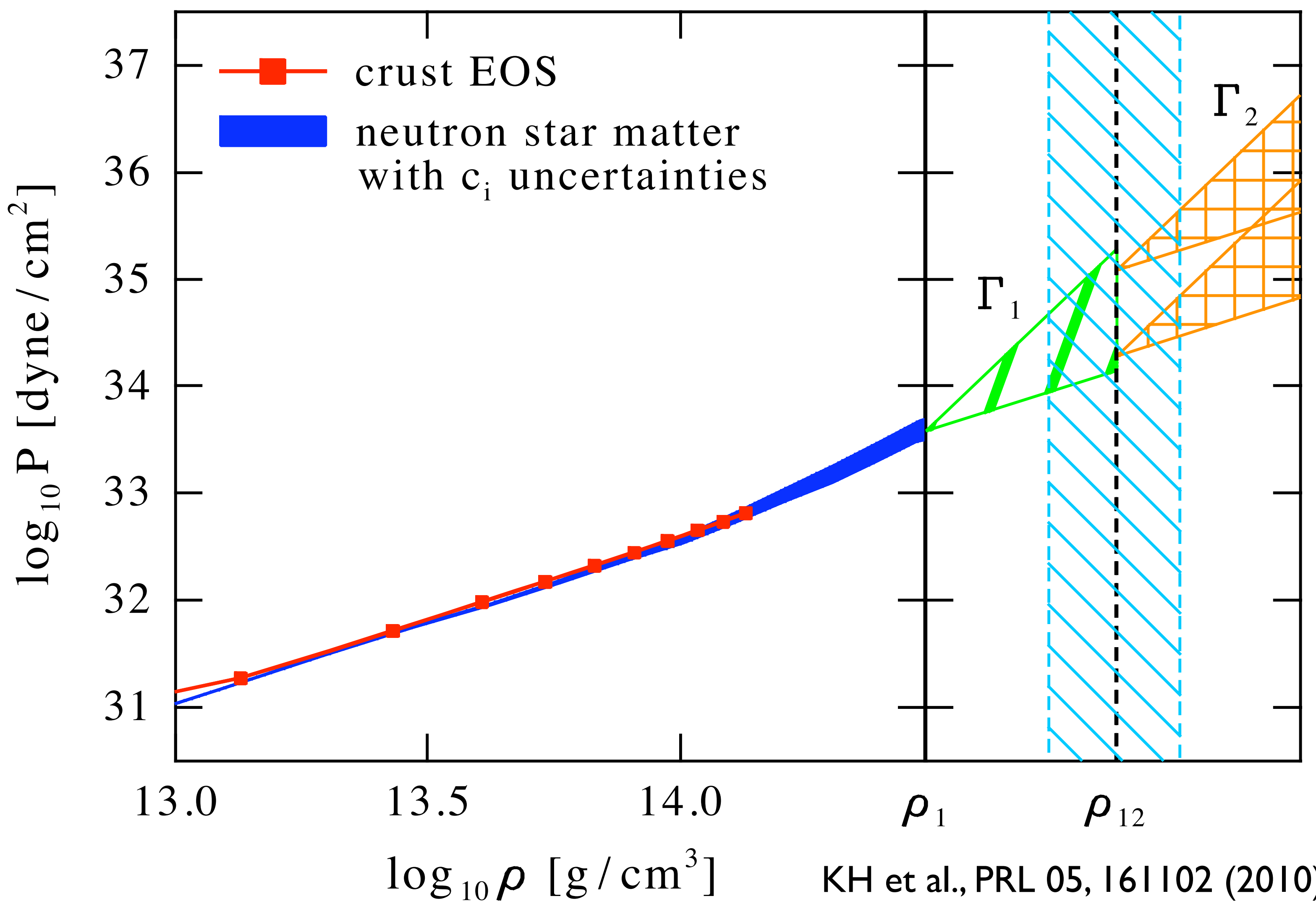




KH et al., PRL 05, 161102 (2010)

without 3N forces EOS differs significantly from crust EOS around $\rho_0/2$

Neutron star radius constraints

use the constraints:

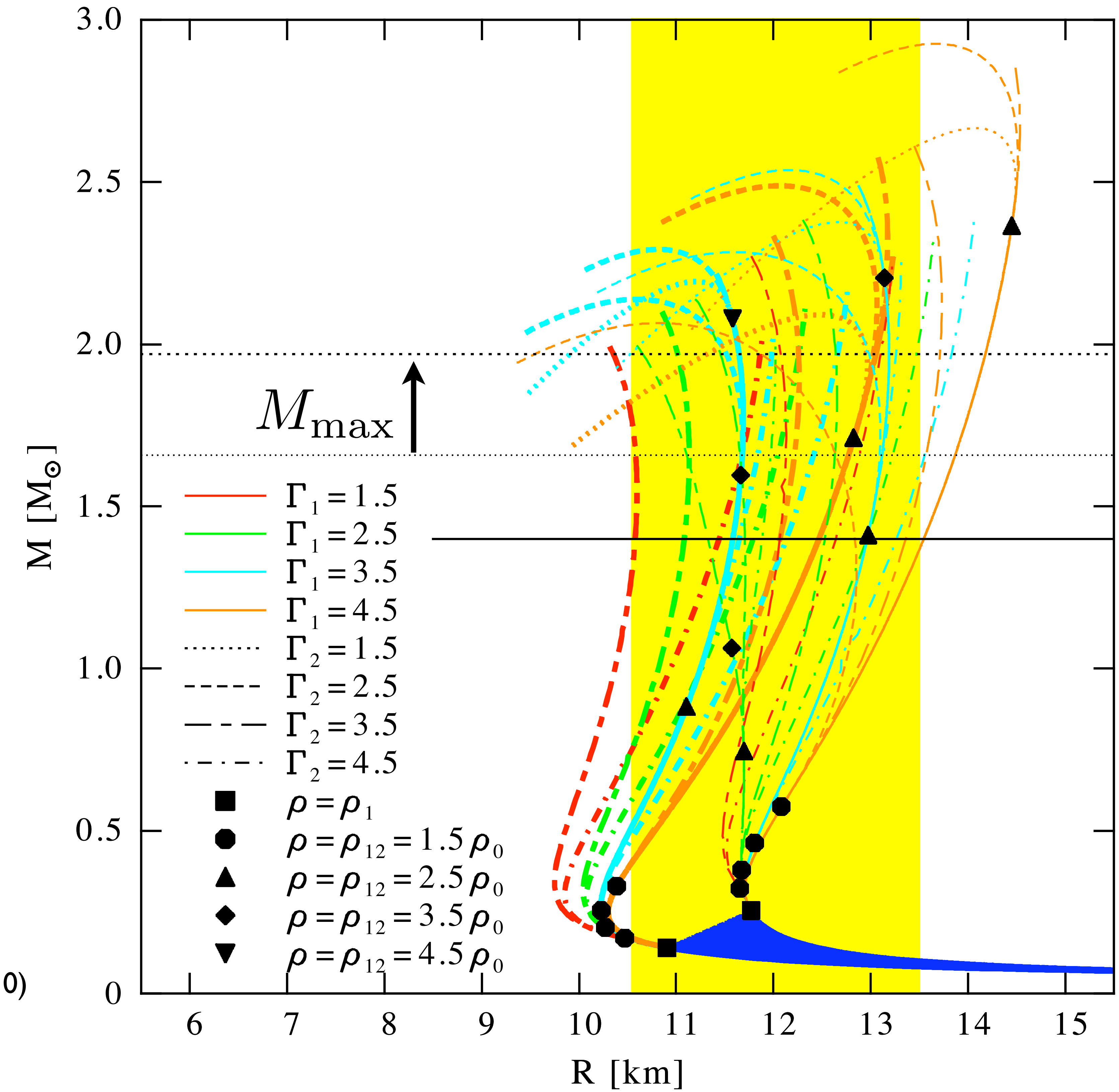
recent NS observation

$$M_{\max} > 1.97\, M_\odot$$

causality

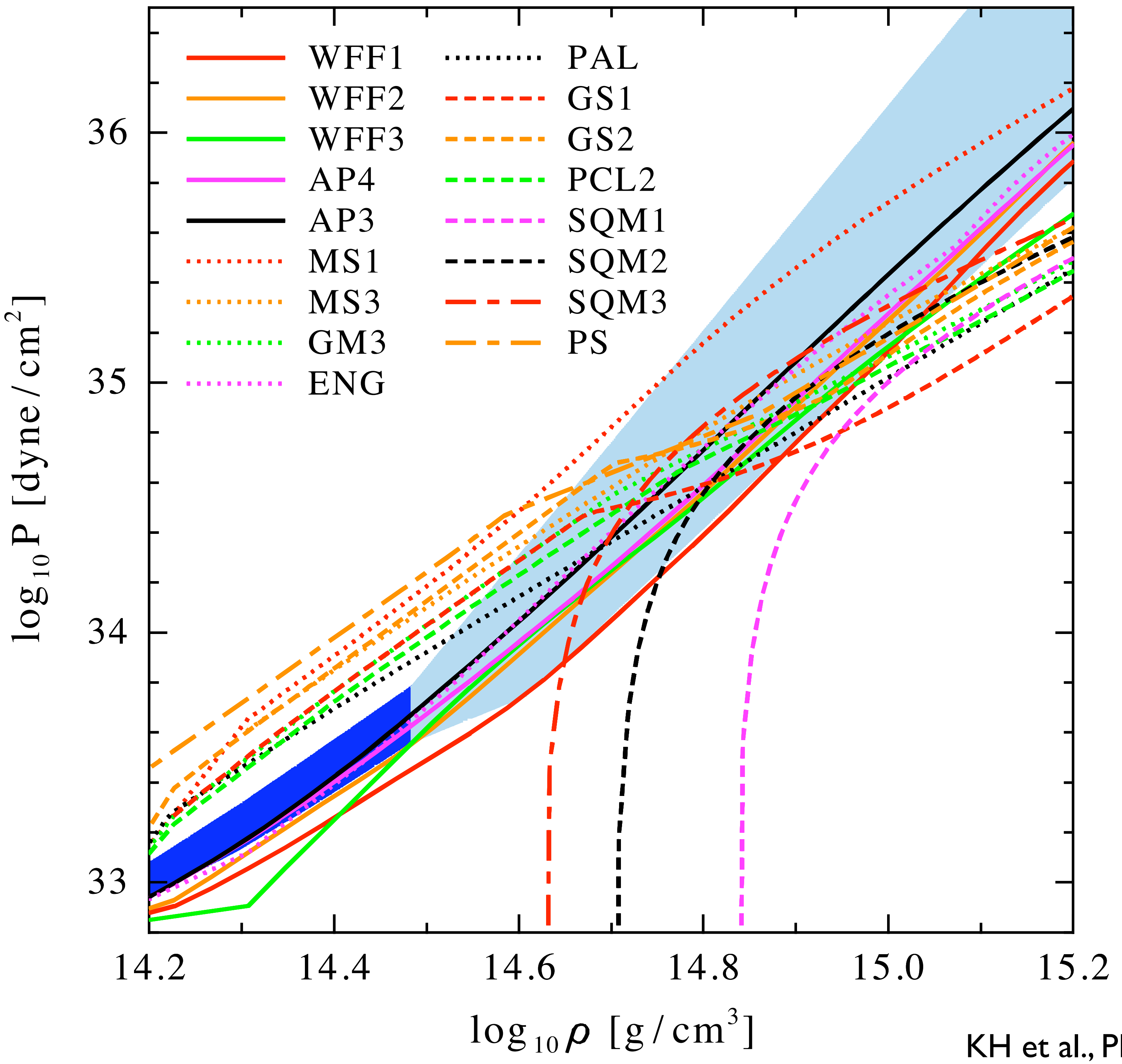
$$v_s(\rho) = \sqrt{dP/d\varepsilon} < c$$

KH et al., PRL 05, 161102 (2010)



- low-density part of EOS sets scale for allowed high-density extensions
- radius constraint after incorporating crust corrections: $10.5 - 13.5\,\mathrm{km}$

Constraints on neutron star equations of state



KH et al., PRL 05, 161102 (2010)

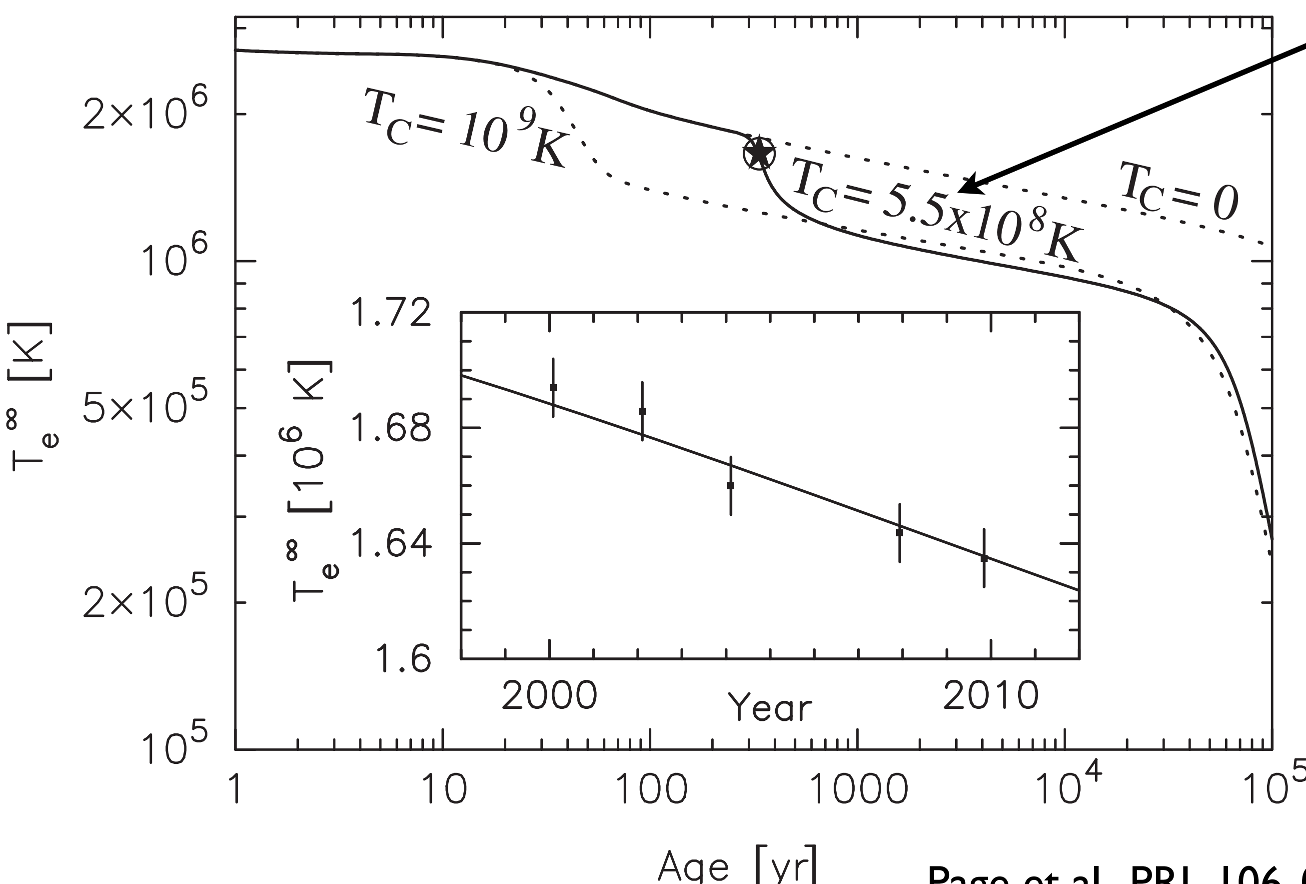
- $1.97 M_\odot$ neutron star and causality constrain nuclear equation of state at high densities (esp. lower bound)
- very stiff EOS lead to low central densities in typical ns ($\rho \sim (2-2.5)\rho_0$)

Cooling of neutron stars

- neutron star transparent to neutrinos ⟶ neutrino emission dominates cooling process for about 10^5 years after formation
- Cooper pair formation dominant cooling process in young neutron stars, superfluidity allows process $n + n \rightarrow [nn] + \nu + \bar{\nu}$

Spectacular 4% temperature drop in young neutron star within only 10 years!

extraction of approximate pairing gap size



Page et al., PRL 106, 081101 (2011)

PRL **106,** 081101 (2011) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 25 FEBRUARY 2011

Rapid Cooling of the Neutron Star in Cassiopeia A Triggered by Neutron Superfluidity in Dense Matter

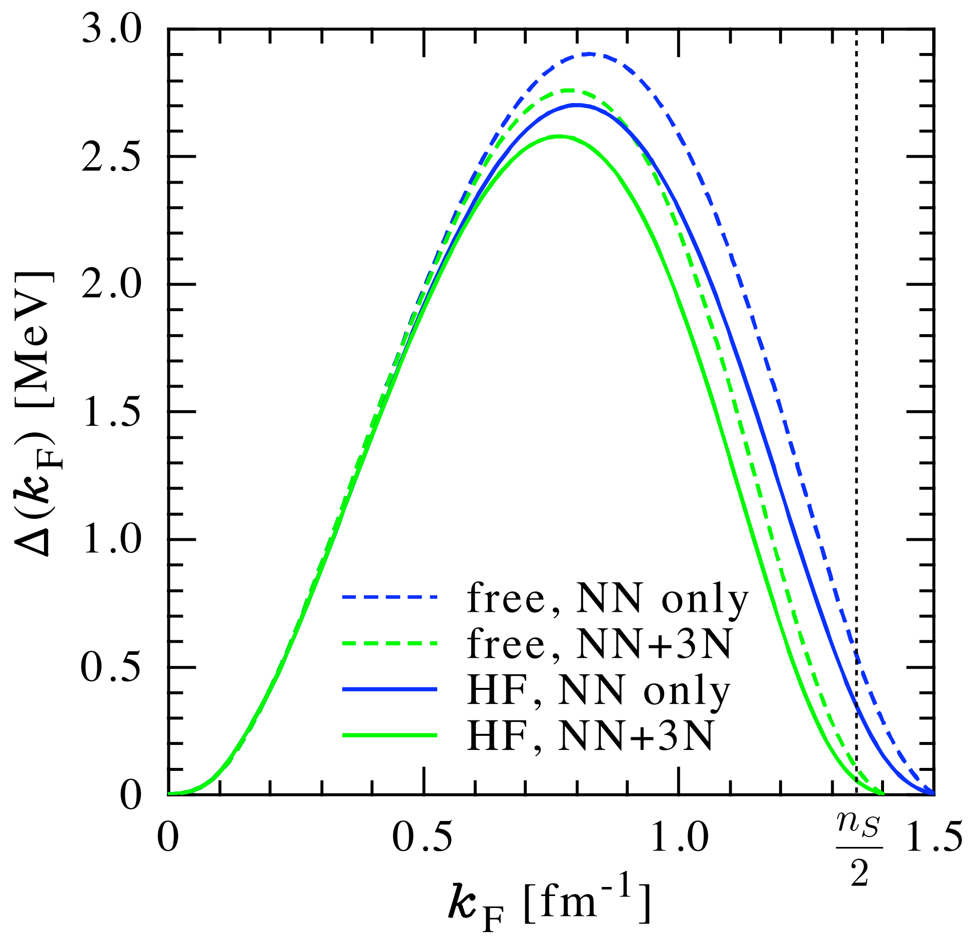
Dany Page,[1] Madappa Prakash,[2] James M. Lattimer,[3] and Andrew W. Steiner[4]

Science NOW Adrian Cho, 25 February 2011

Neutron Star Provides Direct Evidence for Bizarre Type of Nuclear Matter

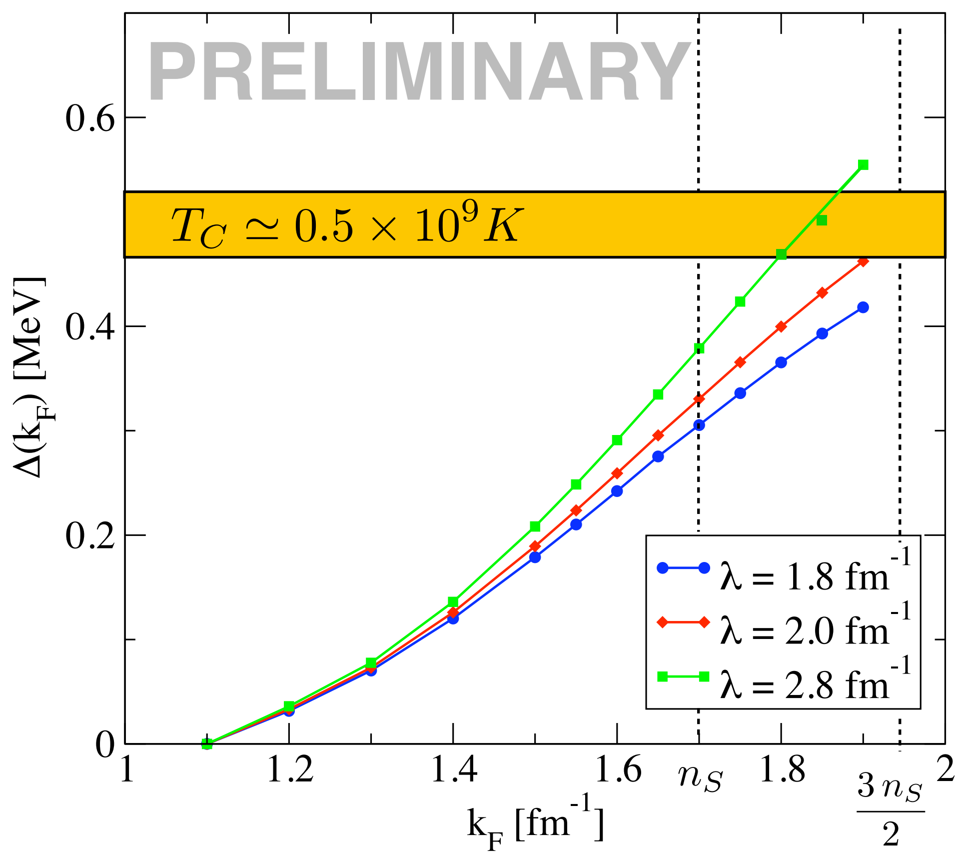
Superfluidity in neutron and cooling of neutron stars

spin-singlet ($^1S_0$):



KH and Schwenk PRC 82, 014314 (2010)

spin-triplet ($^3P_2$-$^3F_2$):



T_C extracted in Page et al., PRL 106, 081101 (2011)

- pairing gap rather well constrained
- active at low densities
- 3N force contributions moderate
- only weakly affects cooling

(crustal cooling)

- only loosely constrained so far
- active at higher densities
- 3N force contributions important
- crucial for cooling

(core cooling)

Conclusions

- derivation of density-dependent effective NN interactions from 3N interactions

- effective NN interaction efficient to use and accounts for 3N effects in neutron and nuclear matter to good approximation

- good agreement with empirical symmetry energy and nuclear saturation properties

- constraints for the neuton star equation of state and radii of neutron stars

- first investigation of triplet pairing in neutron stars including 3N forces

In collaboration with:

S. Bogner

B. Friman

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