Comparing Different Microscopic Approaches to Neutron-rich Matter

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OUTLINE

INTRODUCTION:
Broader context,
fundamental relevance

ADVANTAGES OF OUR STANDARD THEORETICAL FRAMEWORK

WHAT WE HAVE DONE RECENTLY

CONCLUSIONS and OUTLOOK

After 8 decades of nuclear physics, much is still unknown

(Hopefully) the program at FRIB will have widespread impact, filling some of the gaps in our incomplete knowledge of the nuclear chart.

Isospin-Asymmetric Nuclear Matter (IANM) is closely related to neutron-rich nuclei and is a convenient theoretical laboratory.

Studies of IANM (particularly the symmetry energy contribution to the EoS), are now particularly timely, as they support rich on-going and future experimental effort.

Ab initio:

realistic free-space NN forces, potentially complemented by many-body forces, are applied in the nuclear many-body problem.

Most important aspect of the *ab initio* approach:

No free parameters in the medium.

Which forces to use?

Our present (incomplete) knowledge of the nuclear force is the results of decades of struggle.

QCD and its symmetries led to the development of chiral effective theories.

Chiral potentials are based on a low-momentum expansion and are of limited use for applications in dense matter (this issue will be revisited later in the talk).

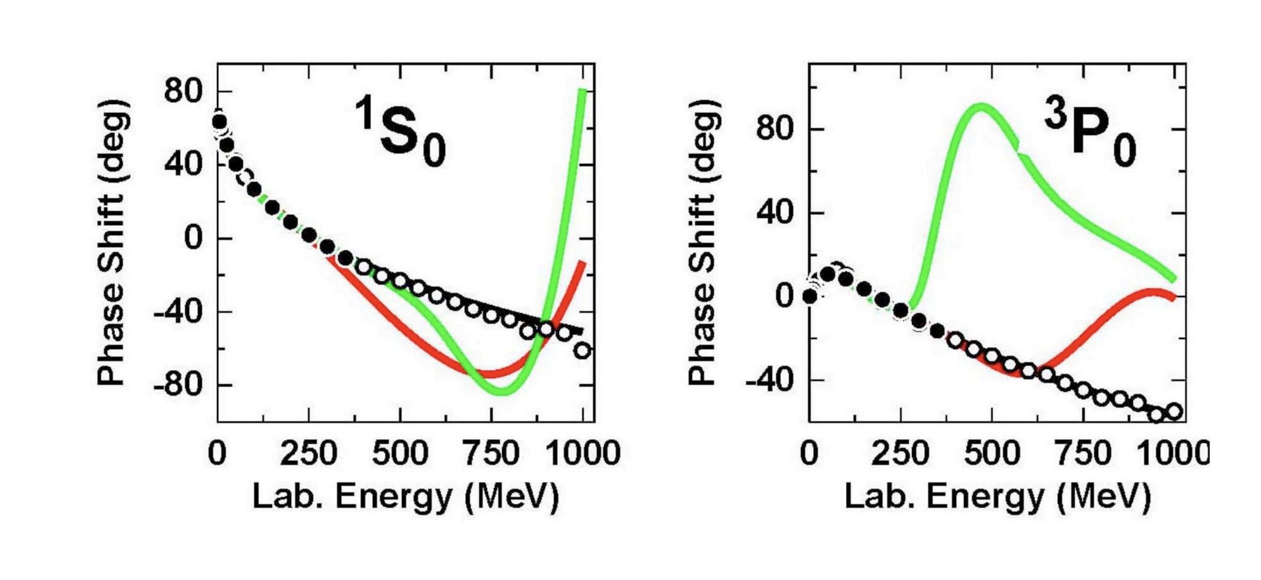
On the other hand, relativistic meson theory with a quantitative OBEP is a suitable choice.

Some NN phase shifts as predicted with CD-Bonn and two chiral potentials:

Black: CD-Bonn (behind data points, the circles)

Green: Epelbaum chi. pot. (N3LO)

Red: Idaho N3LO



Thus, a quantitative OBE potential does very well with NN elastic phase shifts up to high energy.

Two-body sector: a realistic OBE developed within a relativistic scattering equation (Bonn B)

Our traditional many-body framework:

The Dirac-Brueckner-Hartree-Fock (DBHF) approach to (symmetric and asymmetric) nuclear matter.

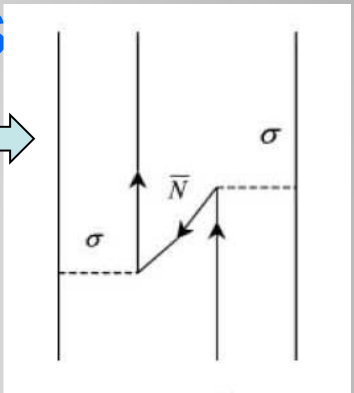
Microscopic DB gives validation to the success of RMF theories.

Microscopic relativistic nuclear physics:
A paradigm which is important to pursue, reliable over a broad range of momenta/densities.

The typical feature of the DBHF method:

Via dressed Dirac spinors, effectively takes into account virtual excitations of pair terms

Z-diagram



$$u^*(p,\lambda) = \left(\frac{E_p^{\,*} + m^*}{2m^*}\right)^{1/2} \begin{pmatrix} 1 \\ \dfrac{\sigma \bullet p}{E_p^{\,*} + m^*} \end{pmatrix} \chi_\lambda$$

Repulsive, density-dependent saturation effect

$$\Delta E / A \propto (\rho / \rho_0)^{(8/3)}$$

…at the end of our calculation of IANM:

We obtain nuclear matter potentials self-consistently with the effective interaction.

For isospin-asymmetric matter:

$$U_n = \int G_{np} + \int G_{nn}$$

$$U_p = \int G_{pn} + \int G_{pp}$$

$$k_F^{\,n} \neq k_F^{\,p}$$

and, finally, the total energy/particle…

THE BRUECKNER G-MATRIX

$$G_{ij}(\mathbf{q}',\mathbf{q},\mathbf{P},(\epsilon^*_{ij})_0) = V^*_{ij}(\mathbf{q}',\mathbf{q}) + \int \frac{d^3K}{(2\pi)^3} V^*_{ij}(\mathbf{q}',\mathbf{K}) \frac{Q_{ij}(\mathbf{K},\mathbf{P})}{(\epsilon^*_{ij})_0 - \epsilon^*_{ij}(\mathbf{P},\mathbf{K})} G_{ij}(\mathbf{K},\mathbf{q},\mathbf{P},(\epsilon^*_{ij})_0),$$

yields the nucleon potential in nuclear matter

spp: ⇨

$$U_i(p) = \sum_{p'_j \le k^i_F} G_{ij}(\mathbf{p}_i,\mathbf{p}'_j),$$

and the energy/particle

$$\bar{e}_i = \frac{1}{A}\langle T_i\rangle + \frac{1}{2A}\langle U_i\rangle - m.$$

In a microscopic approach, nuclear matter properties, and all related quantities, are a by-product of the NN amplitudes in the medium.

For instance, NN in-medium xsections (an important input for reaction calculations<u>**) are driven by the NN scattering amplitudes**</u>**.**

The isospin dependence of our in-medium NN xsections has <u>**everything to do with the EoS of IANM (and thus the symmetry energy),**</u> **as they originate from the same source.**

We considered the ratio of the pp and np xsections in the medium as well as the splitting between pp and nn xsections in IANM (arxiv/1307.5373, review to appear soon in EPJA)

There is more to transport models than the symmetry energy!

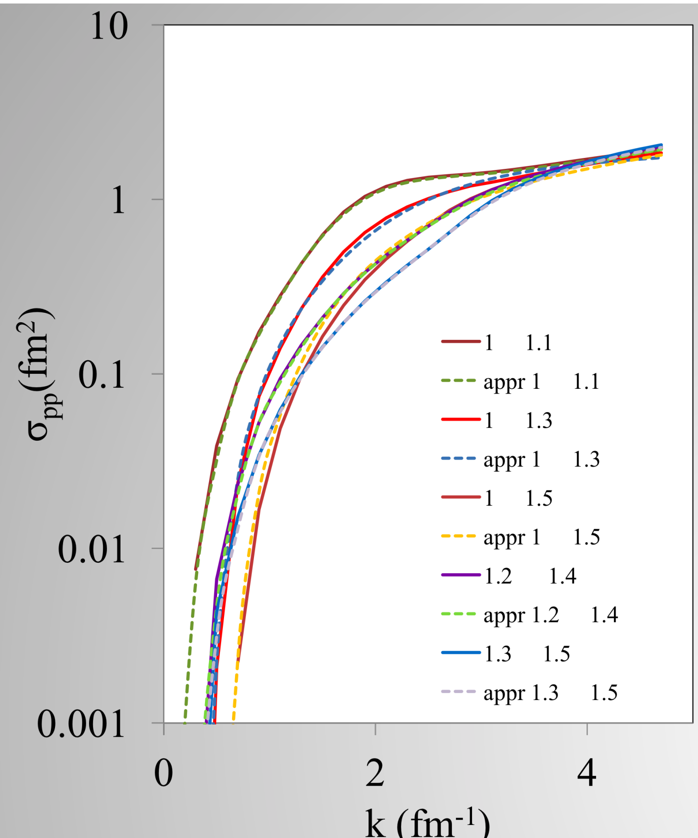
Using microscopic input has several advantages:

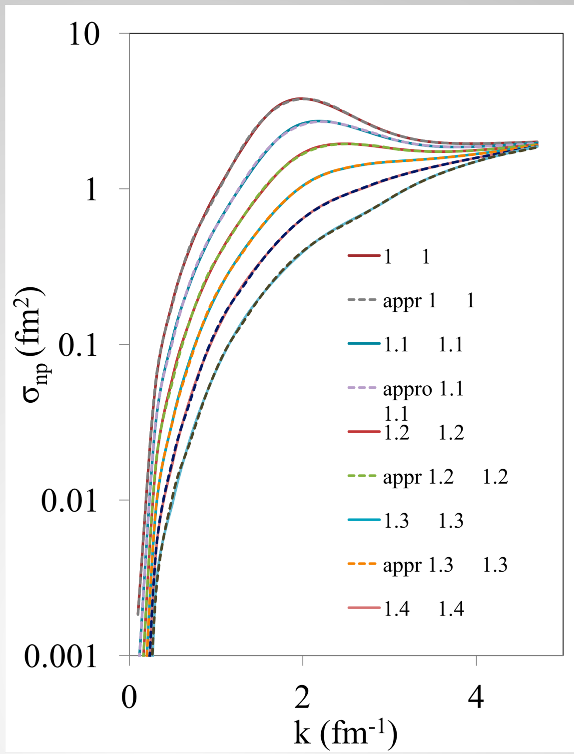
Internal consistency of different ingredients

Better insight into the physics

All microscopic models have at least one thing in common…..

….they describe the NN system





pp and np in-medium cross sections suitable for scattering of two Fermi spheres vs. the relative momentum of the two spheres. The pair of numbers associated with each curve shows the radii of the two Fermi spheres.
(Cross sections calculated as in:
Chen, Sammarruca, Bertulani, PRC87, 054616 (2013))

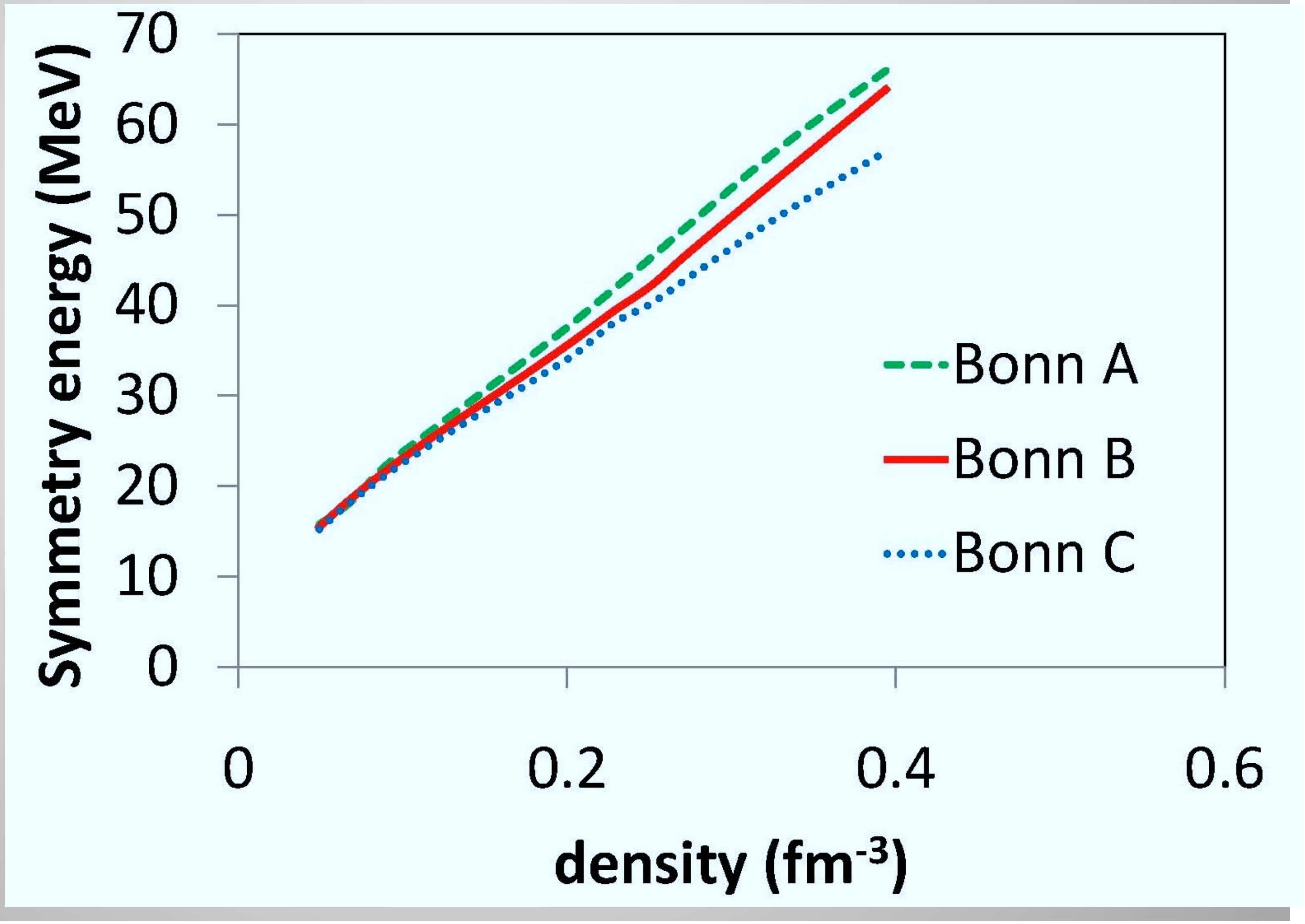
(The curves labeled as “appr” are a parametrization of the exact results.)

Variuos experiments agree that the acceptable range of values for the symmetry energy and its slope are centered around 32.5 MeV and 70 MeV, respectively.

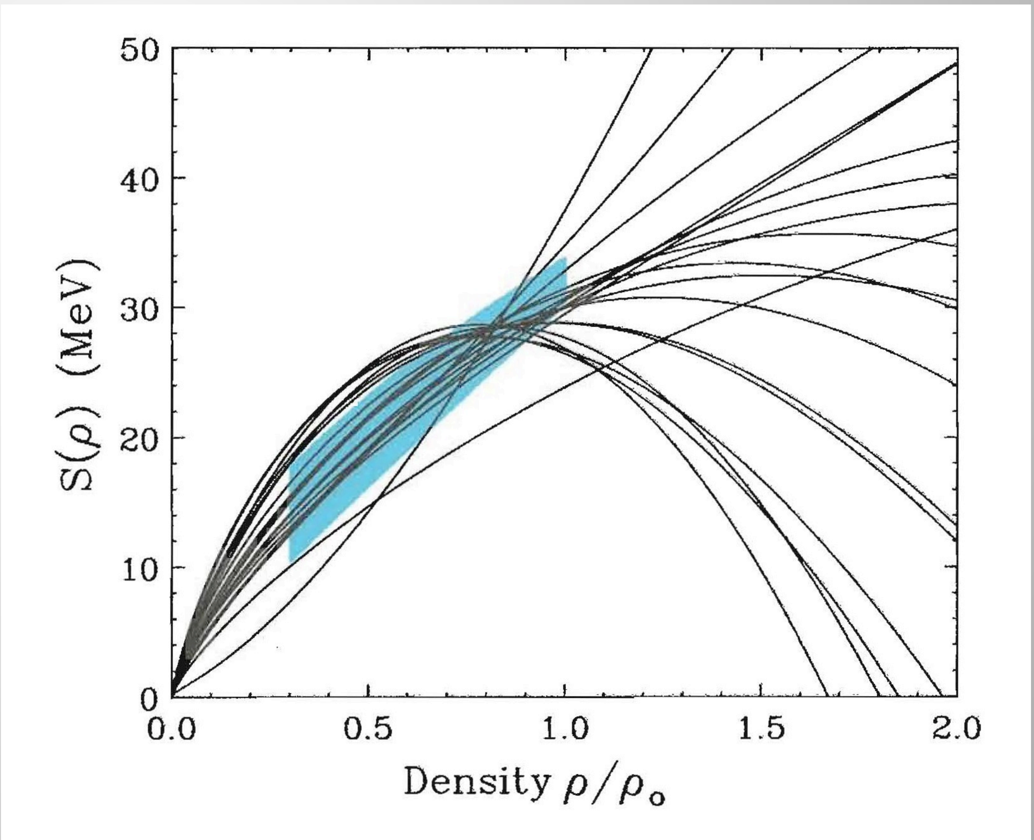
These constraints are consistent with a value of 0.18(0.027) fm for the neutron skin of 208-Pb

PREX: S=0.33(+0.16,-0.18)fm
PREXII: ???

The symmetry energy as predicted by three meson-theoretic potentials:



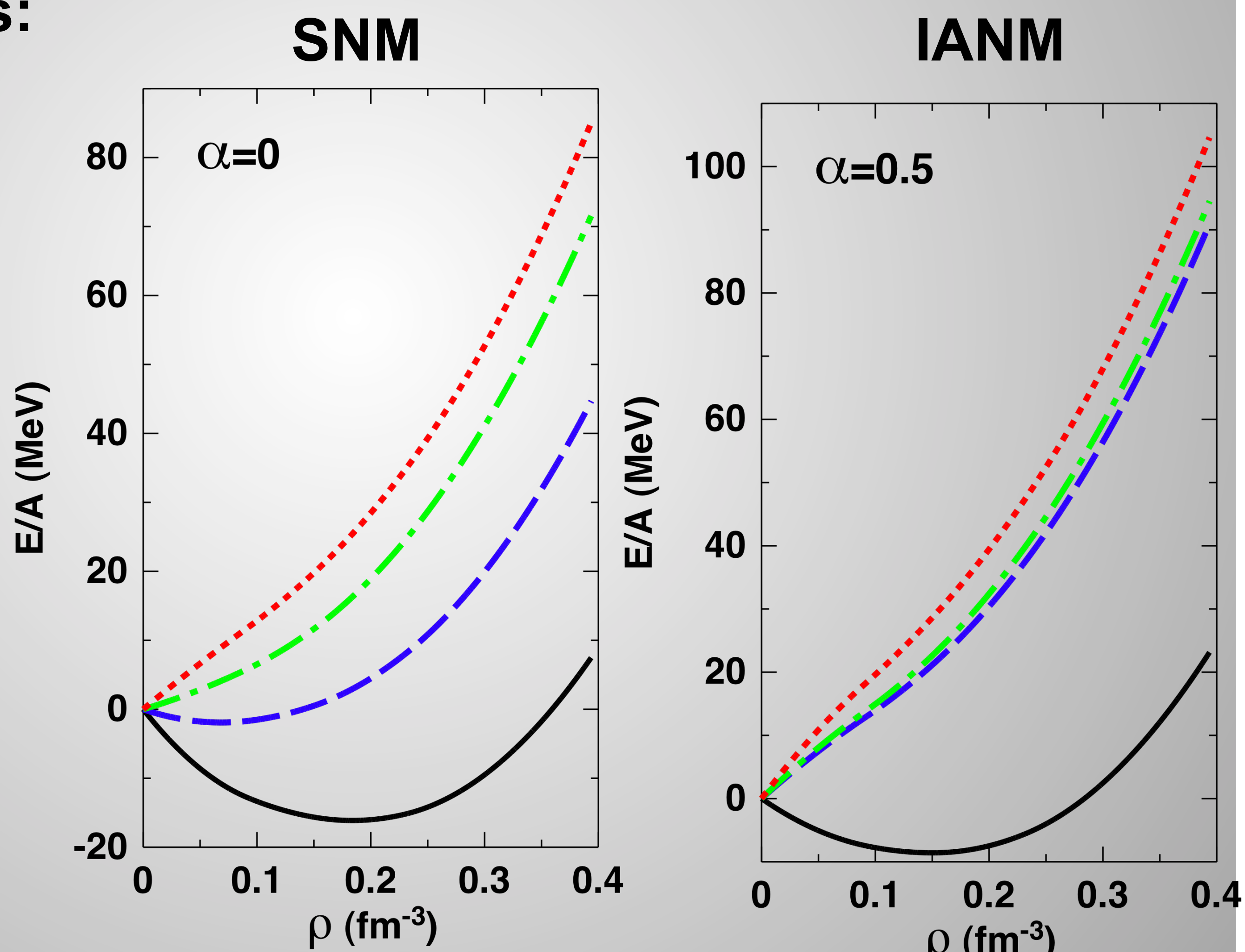
The density dependence of the symmetry energy from various parametrizations of the Skyrme models.
The shaded area corresponds to constraints from HI collisions.



Polarized nuclear matter: an example where predictions from microscopic and non-microscopic models are in qualitative disagreement

Our predictions:

Blue: Polarized neutrons, unpol. protons;
Green: FM state
Red: AFM state



The issue of a spontaneous transition to spin polarized states is controversial and broadly separates microscopic vs. non-microscopic models:

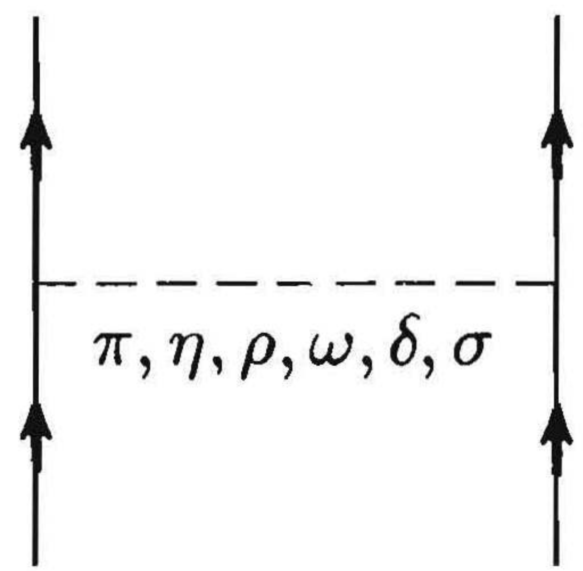
Gogny (D1S effective force) predicts transition to AFM state in SNM at some critical density (Isayev, Yang) and No transition to FM state.

Skyrme effective forces predict FM instabilities in SNM (Viduarre, Navarro, Bernabeu) and in NM (Reddy, Prakash, Lattimer, Pons) at some critical density.

Relativistic HF based on effective meson-nucleon Lagrangians predict that the onset of FM transition in NM is determined by the inclusion of isovector mesons and the nature of their coupling. (Marcos, Niembro, Quelle, Navarro)

In any fundamental theory of nuclear forces, the pion is the most important ingredient (crucial for NN scattering data or the deuteron!), followed by heavier mesons.

As demonstrated in F.S., PRC84, 044307 (2011), the pion gives the main contribution to the symmetry energy.



Relativistic nuclear physics with realistic meson-theoretic potentials is a valid approach.

Alternatively, nuclear forces can be derived from EFT.

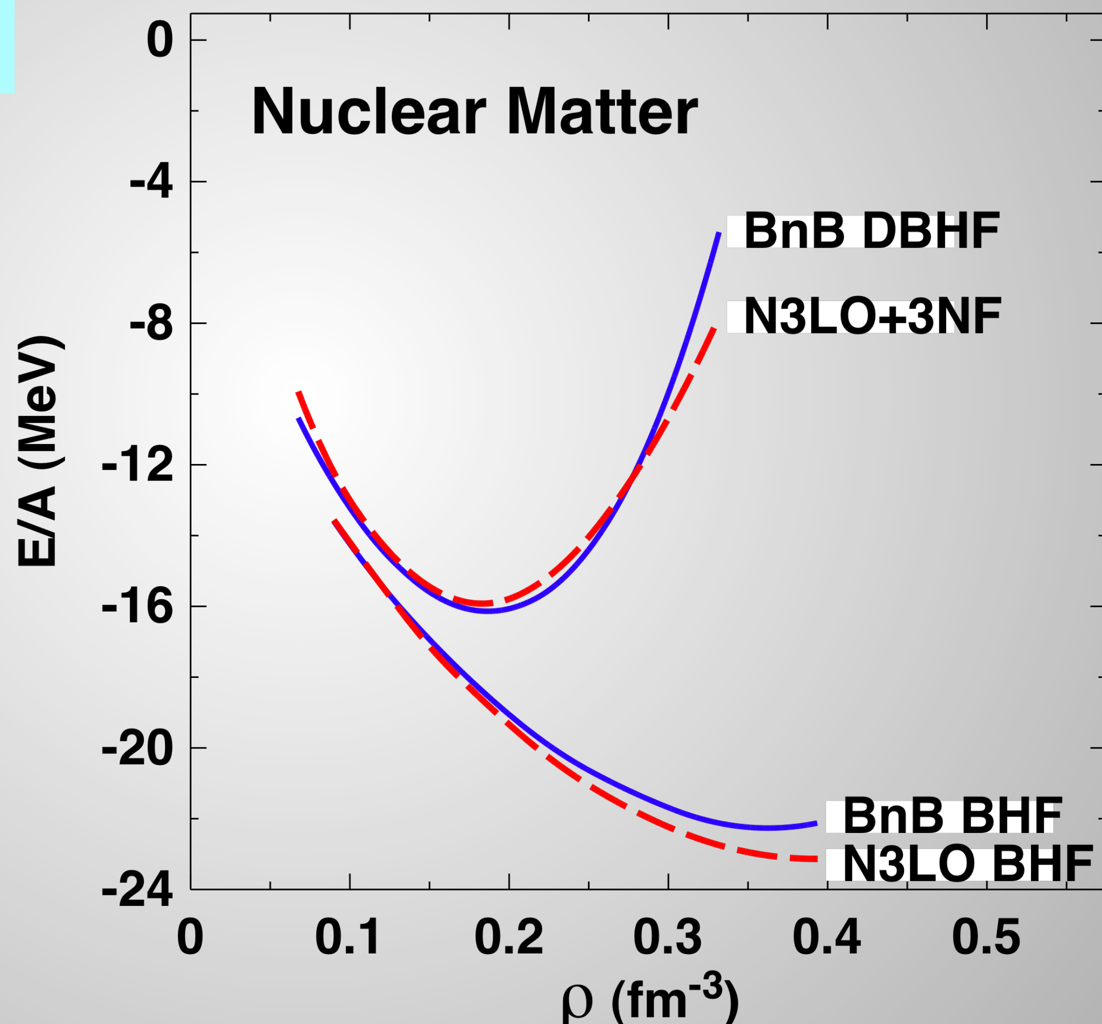
Next we will use chiral forces (up to moderate densities) and compare.

We will use:

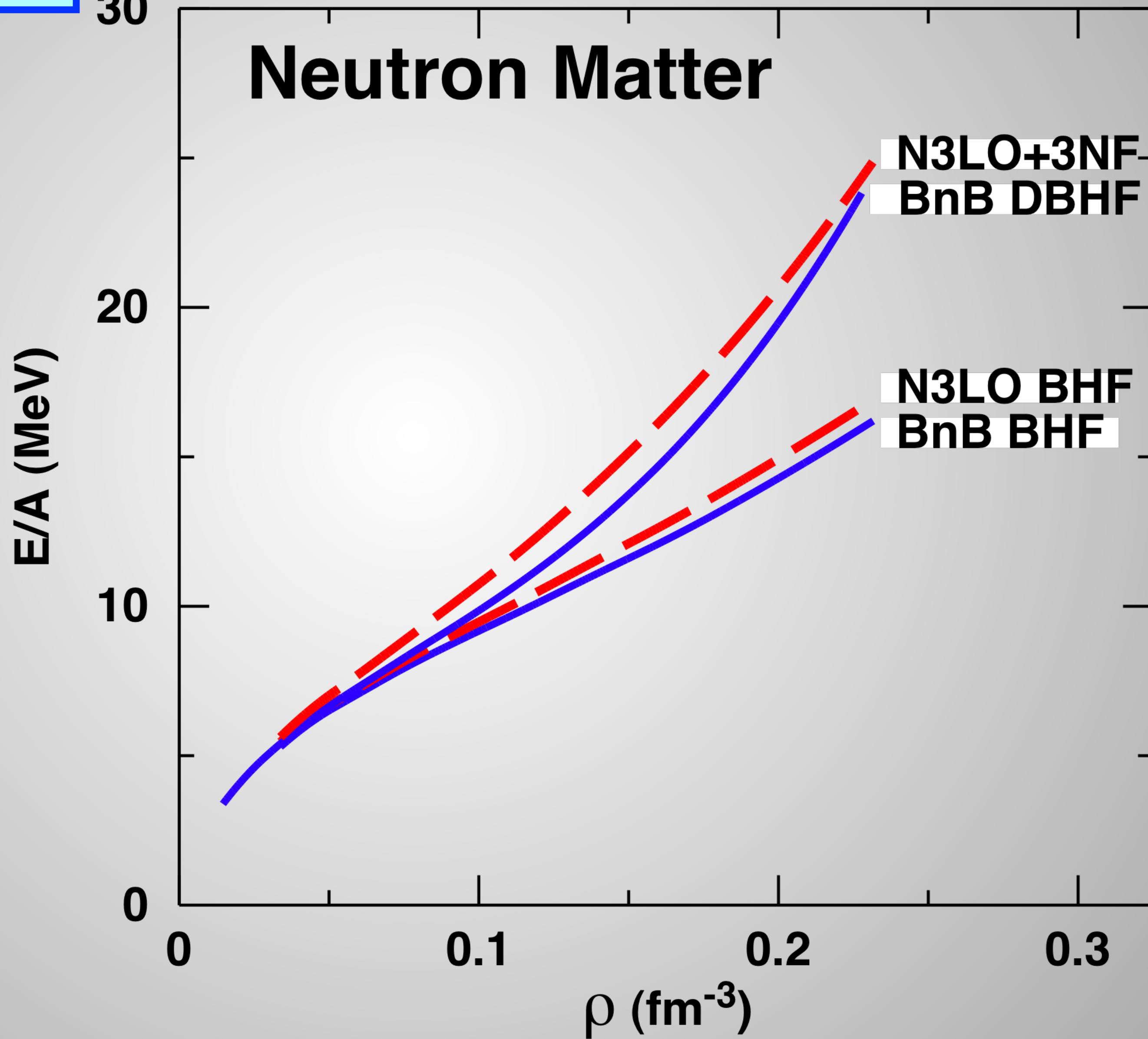
2NF at N3LO
3NF at N2LO

Effective DD interactions reflecting the underlying leading order chiral 3NF have been constructed by Holt, Kaiser, and Weise.
(PRC81, 024002 (2010))

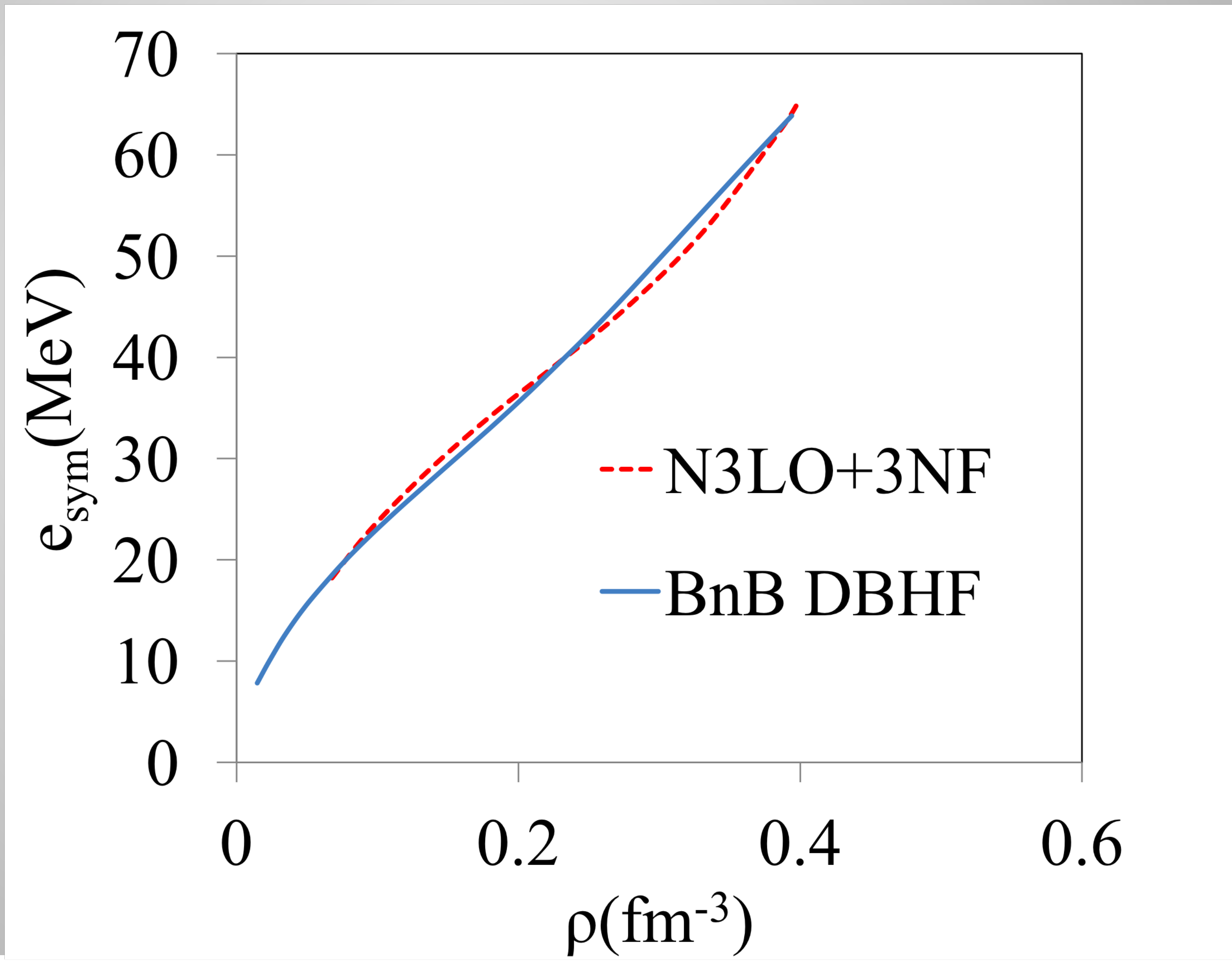
The EoS of Symmetric Nuclear Matter:



The EoS of Neutron Matter:



Density dependence of the symmetry energy:



In summary :

We considered two different microscopic methods to study the properties of nucleonic matter.

Whether the interactions applied are based on relativistic meson exchange or chiral EFT, the results are very similar.

Concerning the choice of DBHF as the theoretical framework:

Its major strength is in the additional density dependence generated by the use of a self-consistent Dirac spinor basis.

Relativistic OBEP + DBHF is a reliable framework for probing systems where high-momenta are involved.

The common denominator is the ab-initio approach. This is crucial to have true predictive power.

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