A Comparison Between Different Microscopic Approaches to Neutron-rich Matter

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ECT* Workshop, June 10-14, 2013, Trento, Italy

Supported in part by the US Department of Energy.

OUTLINE

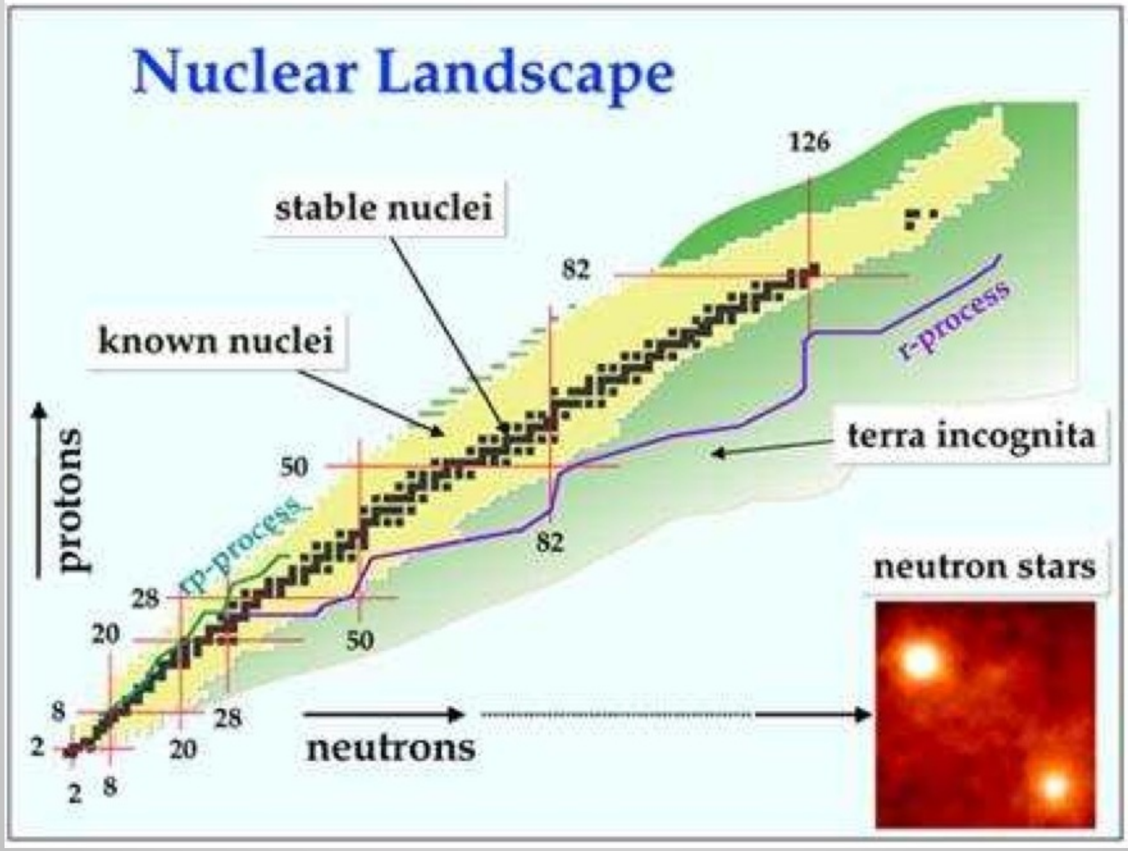
INTRODUCTION:
Broader context, fundamental relevance

OUR STANDARD THEORETICAL FRAMEWORK

WHAT WE HAVE DONE RECENTLY

CONCLUSIONS and OUTLOOK

After many decades of nuclear physics, still much mystery remains.



Neutron-rich nuclei are of great interest but not yet well studied

(Hopefully) the program at FRIB will have widespread impact, ranging from the physics of exotic nuclei to nuclear astrophysics.

Isospin-Asymmetric Nuclear Matter (IANM) is closely related to neutron-rich nuclei

Studies of IANM are now particularly timely, as they support rich on-going and future experimental effort.

The focal point is the symmetry energy contribution to the EoS of IANM .

Using our microscopic EoS, we have calculated symmetry-energy sensitive "observables" ranging from neutron skins to neutron star properties in a self-consistent manner.

We explored model dependence among different microscopic approaches.

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.

Our present 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).

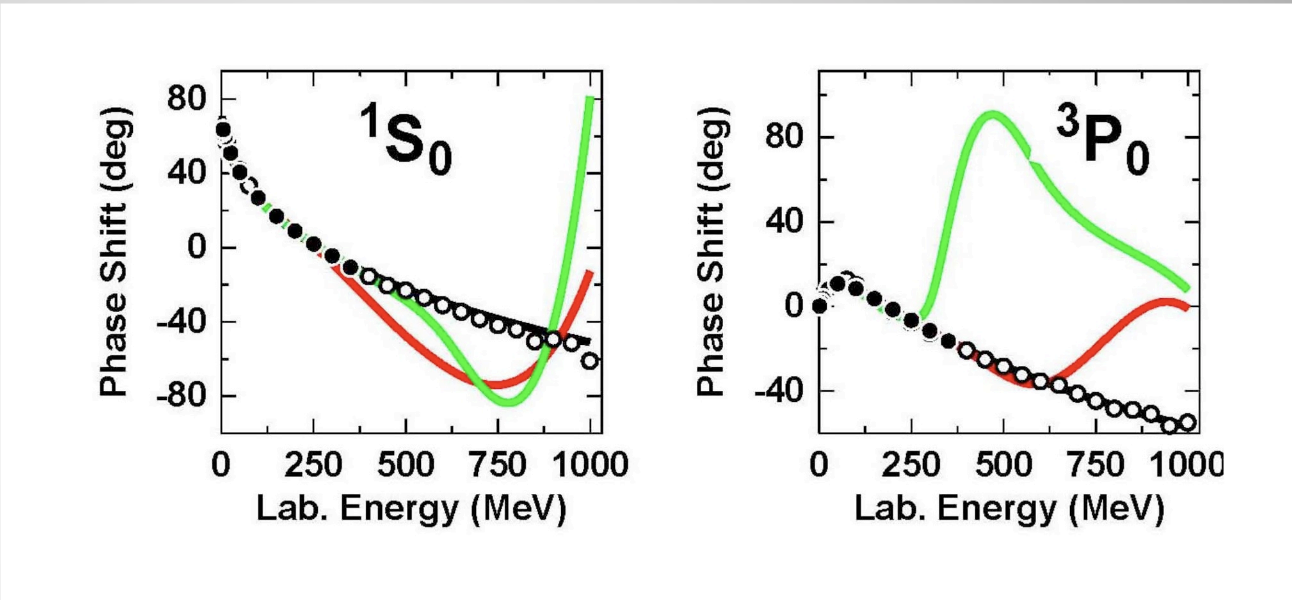
On the other hand, relativistic meson theory with a quantitative OBEP is a suitable choice.

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.

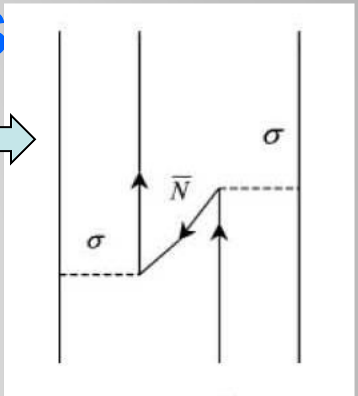
Microscopic DB gives validation to the success of RMF theories.

Microscopic relativistic nuclear physics: A paradigm which is important to pursue, in fact the only reliable one 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: ⇨

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

and the energy/particle

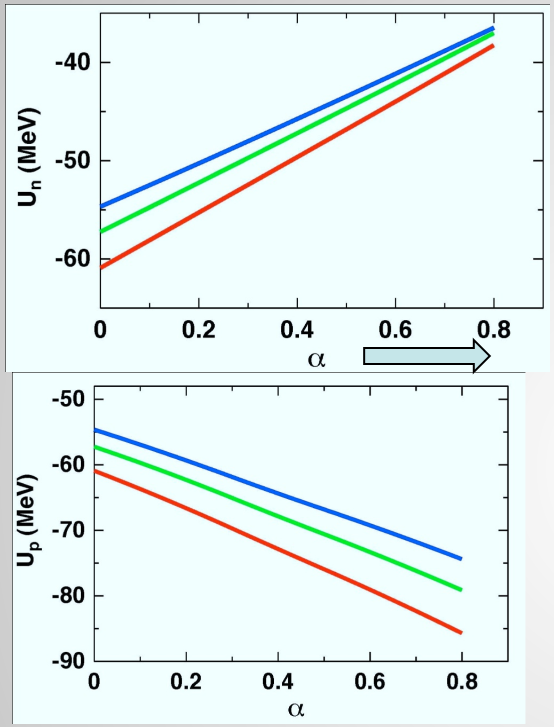
$$\bar{e}_i = \frac{1}{A}\langle T_i\rangle + \frac{1}{2A}\langle U_i\rangle - m.$$

The spp for neutrons and protons in IANM for three different potential models:

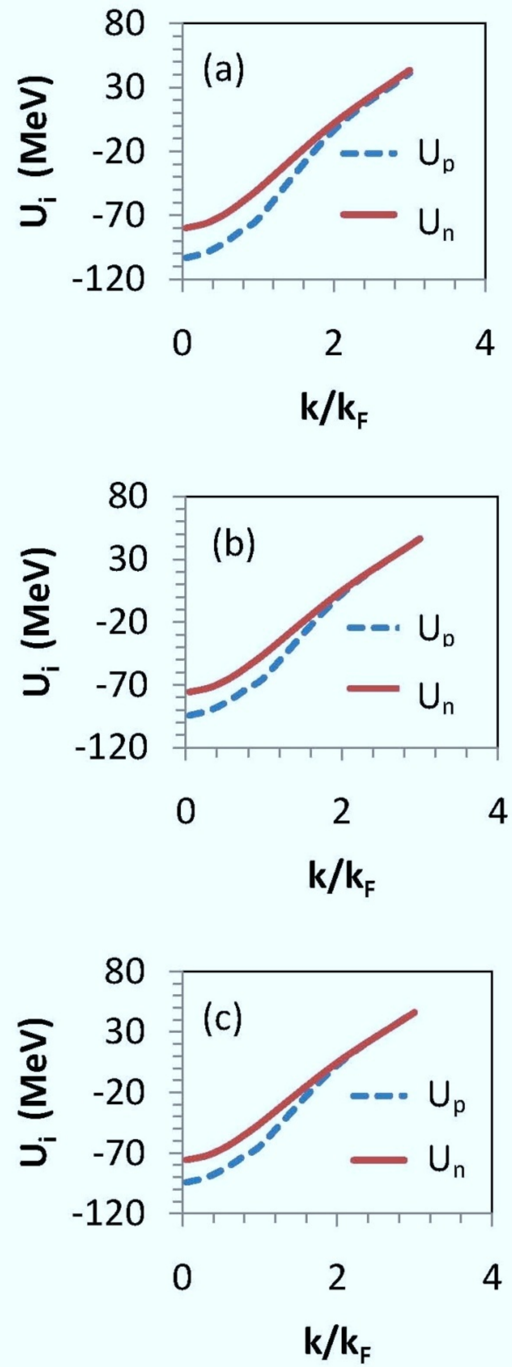
A

B

C



(neutron excess parameter)



A

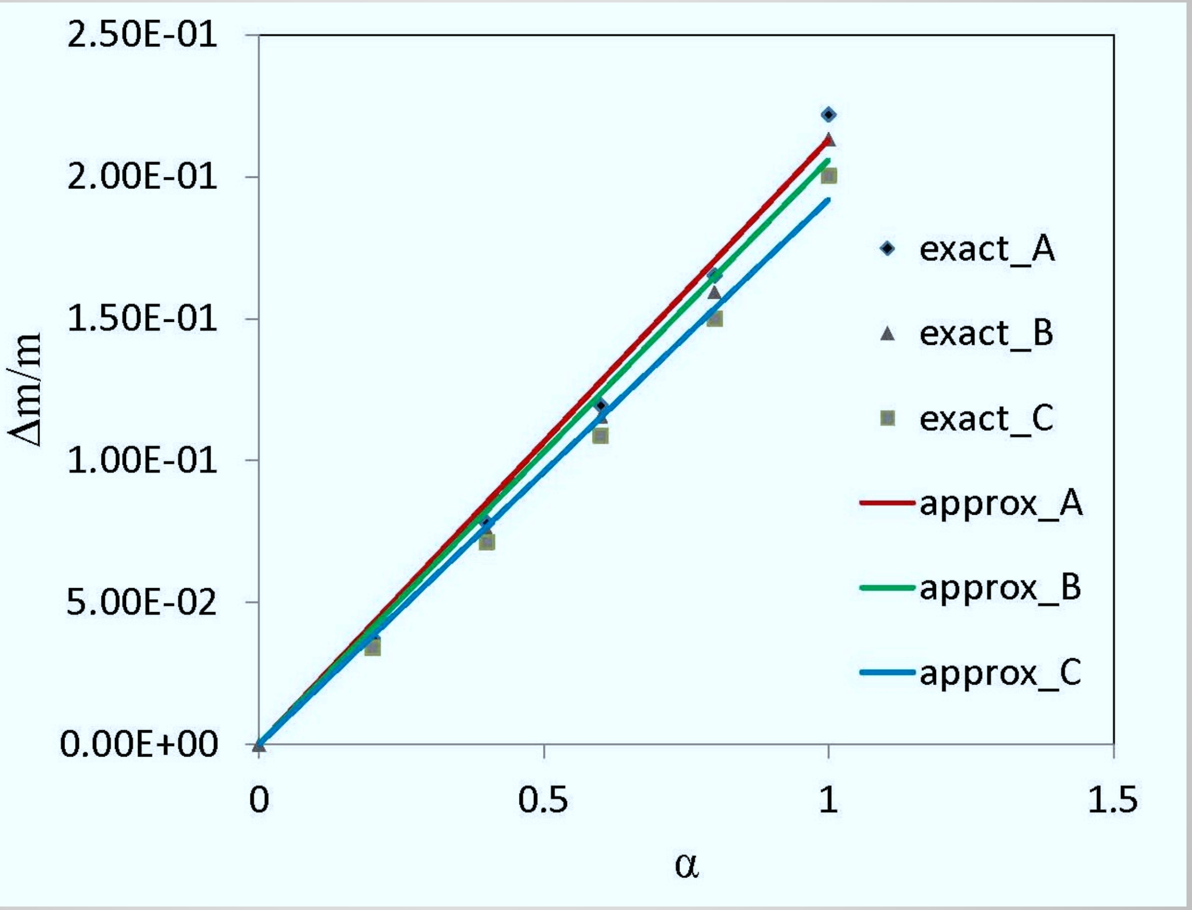
B

C

The "symmetry potential" is a crucial ingredient in HI collision simulations.

Neutron-proton mass splitting for three meson-theoretic potentials:

Slope:
A: 0.213
B: 0.206
C: 0.192



From analyses of GOP:
(Xu et al., PRC 82,054607 (2010)

$$\Delta m/m = (0.32 \pm 0.15)\alpha$$

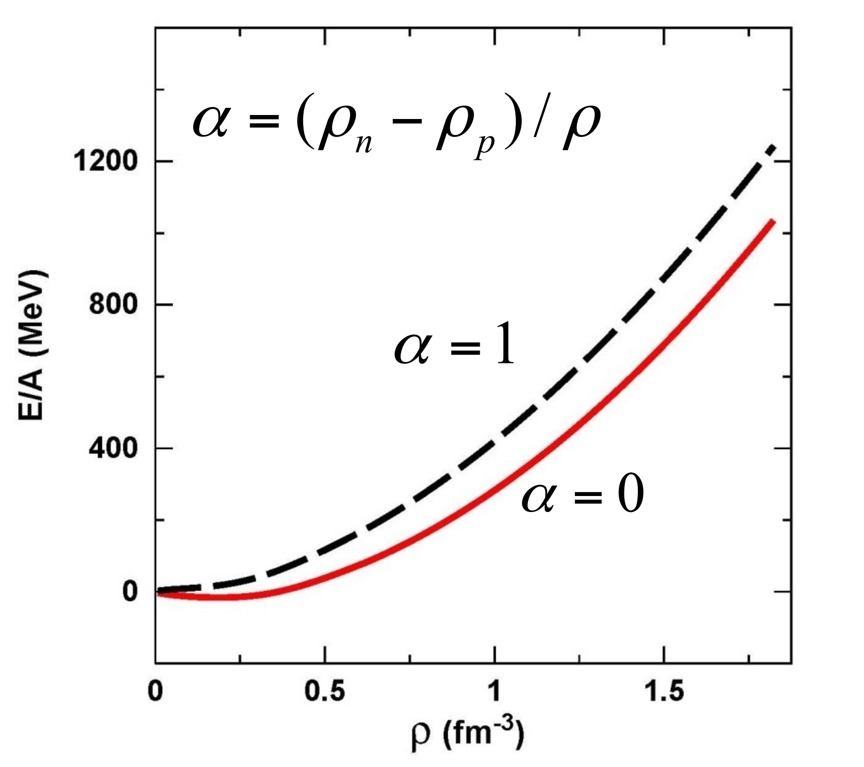
An overview of saturation properties:

$$e(\rho,\alpha) \approx e(\rho,0) + e_{sym}(\rho)\alpha^2$$

$$e_{sym} = e(\rho,1) - e(\rho,0)$$

$$e_s = -16.14 MeV$$
$$\rho_s = 0.185 fm^{-3}$$
$$K = 252 MeV$$

$$e_{sym}(\rho_0) = 33.7 MeV$$
$$L(\rho_0) = 69.6 MeV$$



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: ???

From recent analyses of p elastic scattering on Pb-208:
(J. Zenihiro et al., PRC82, 044611 (2010))

Neutron point radius : 5.653(+0.054,-0.063) fm
Proton point radius : 5.442(2) fm
Neutron skin : 0.211(+0.054,-0.063) fm

Our predictions:

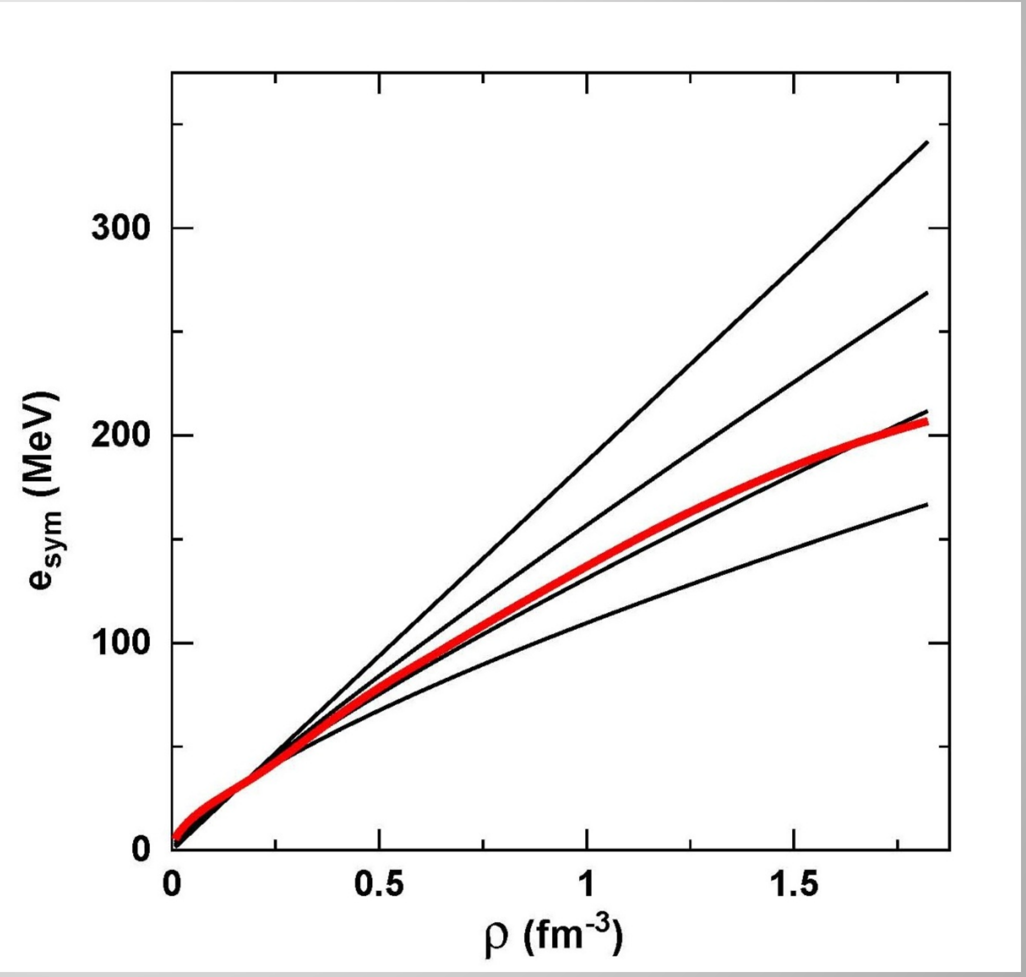
Neutron point radius : 5.56 fm
Proton point radius : 5.39 fm
Neutron skin : 0.17 fm

The density dependence of the symmetry energy is not well constrained:

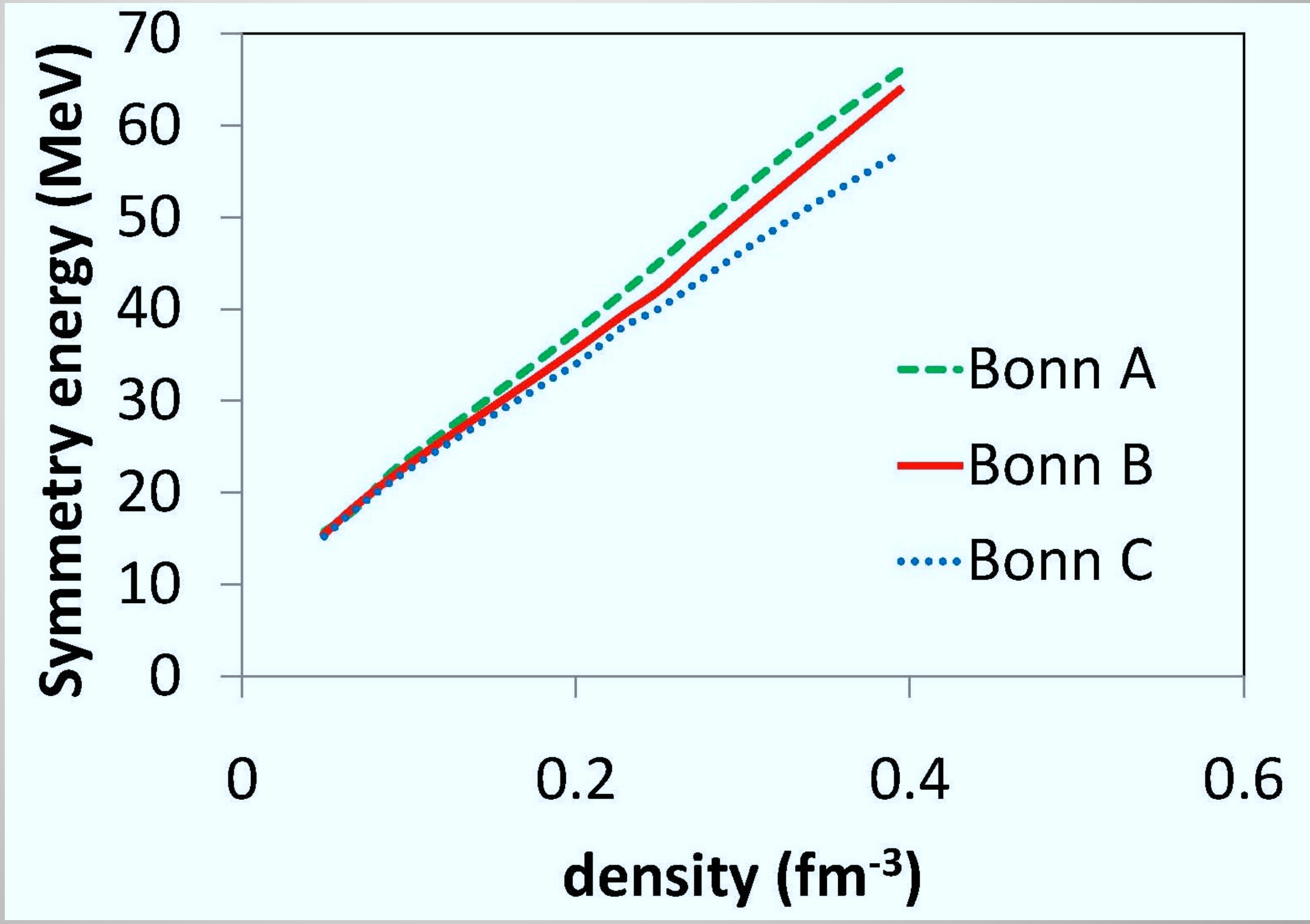
RED: DBHF predictions

Black: commonly used parametrizations

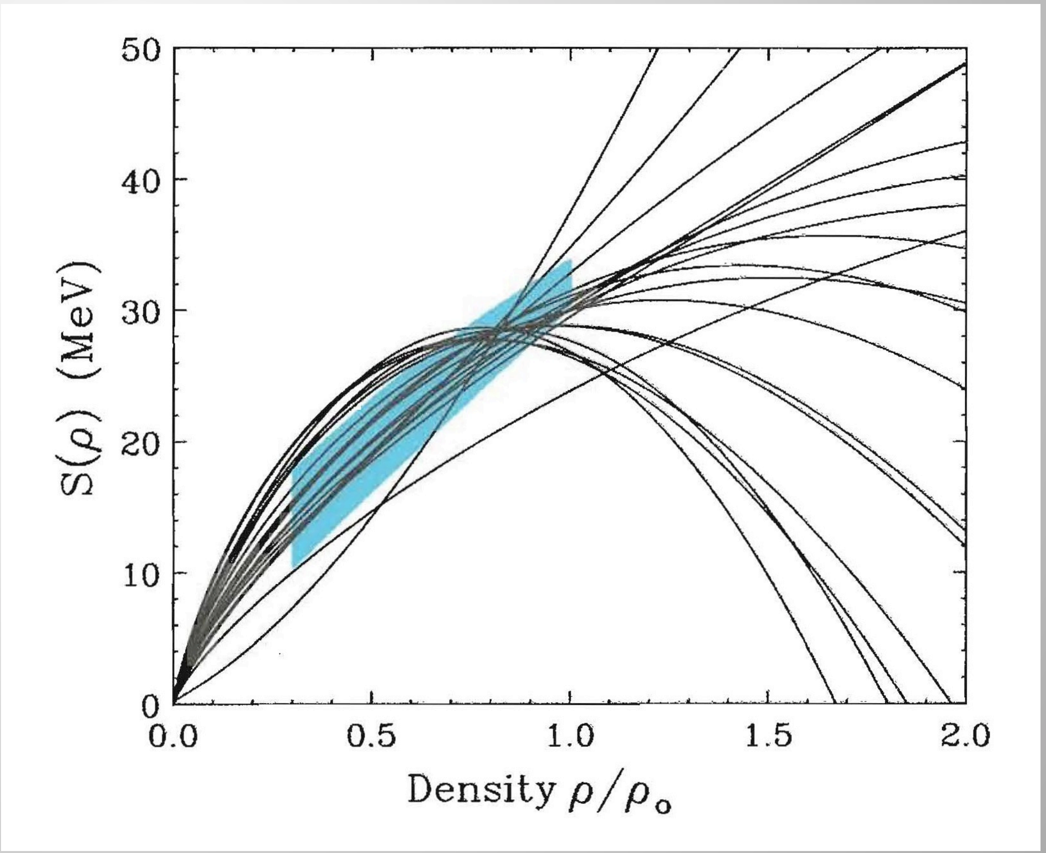
$$e_{sym} = C(\rho / \rho_0)^{\gamma}$$



The symmetry energy as predicted by three meson-theoretic potentials:
(F. Sammarruca , PRC84, 044307 (2011))



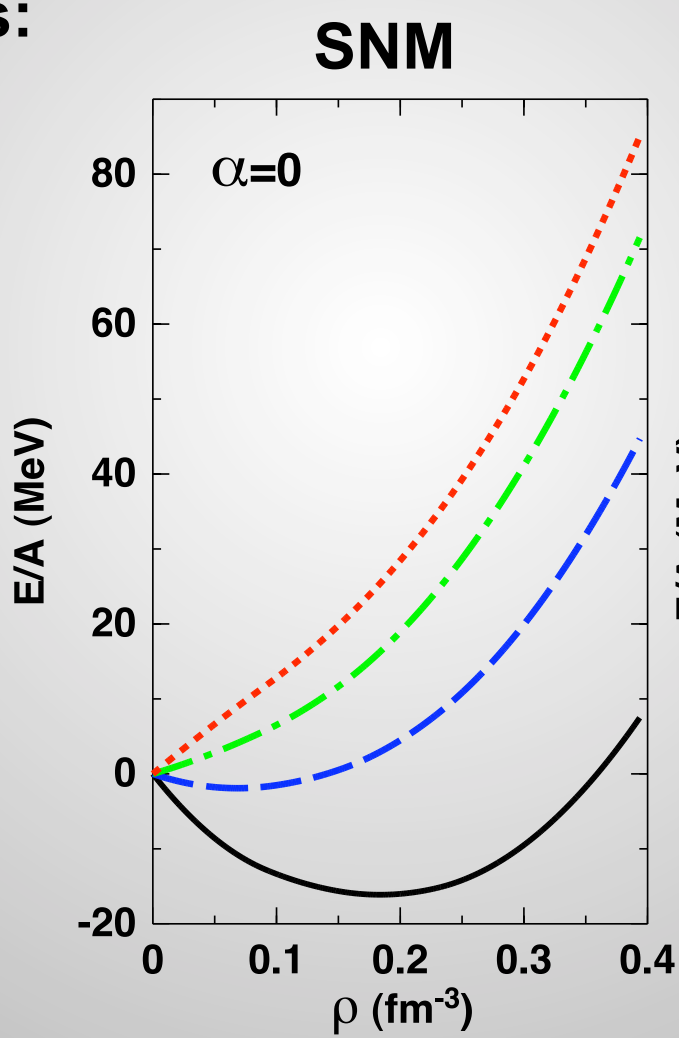
The density dependence of the symmetry energy from various parametrizations of the Skyrme models (B.A. Brown, PRL85, 5296 (2000)).
The shaded area corresponds to constraints from HI collisions.

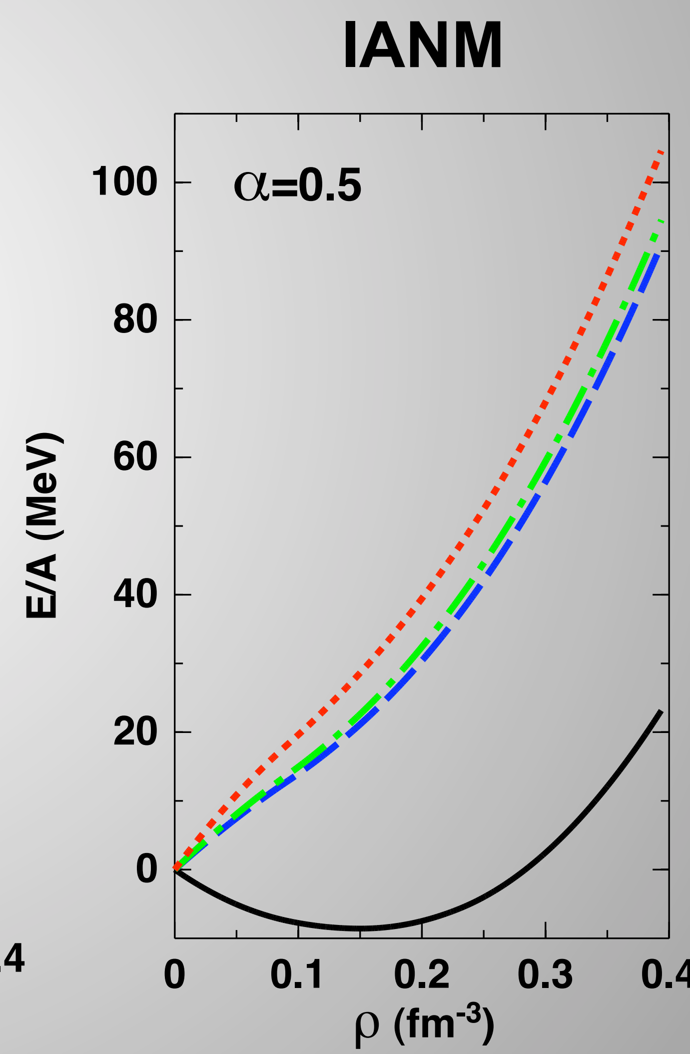


Polarized nuclear matter: an example where predictions from microscopic and non-microscopic models are in qualitative disagreement

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:

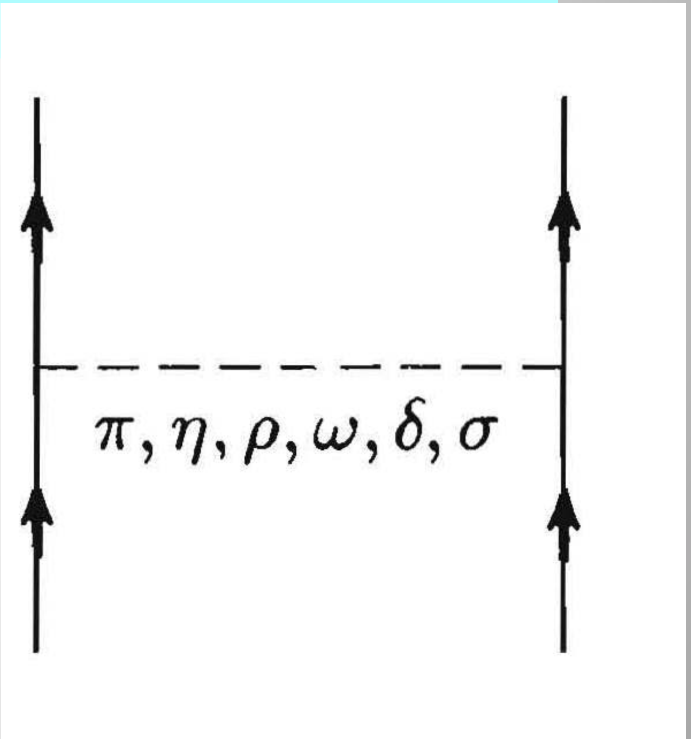
Gogny (D1S effective force) predicts transition to AFM state in SNM at some critical density (Isayev, Yang) and No transition to FM state.

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, 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.

Yet, some mean-field theories do not properly include all important mesons (with special emphasis on the pion).



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

Alternatively, nuclear forces can be derived from EFT.

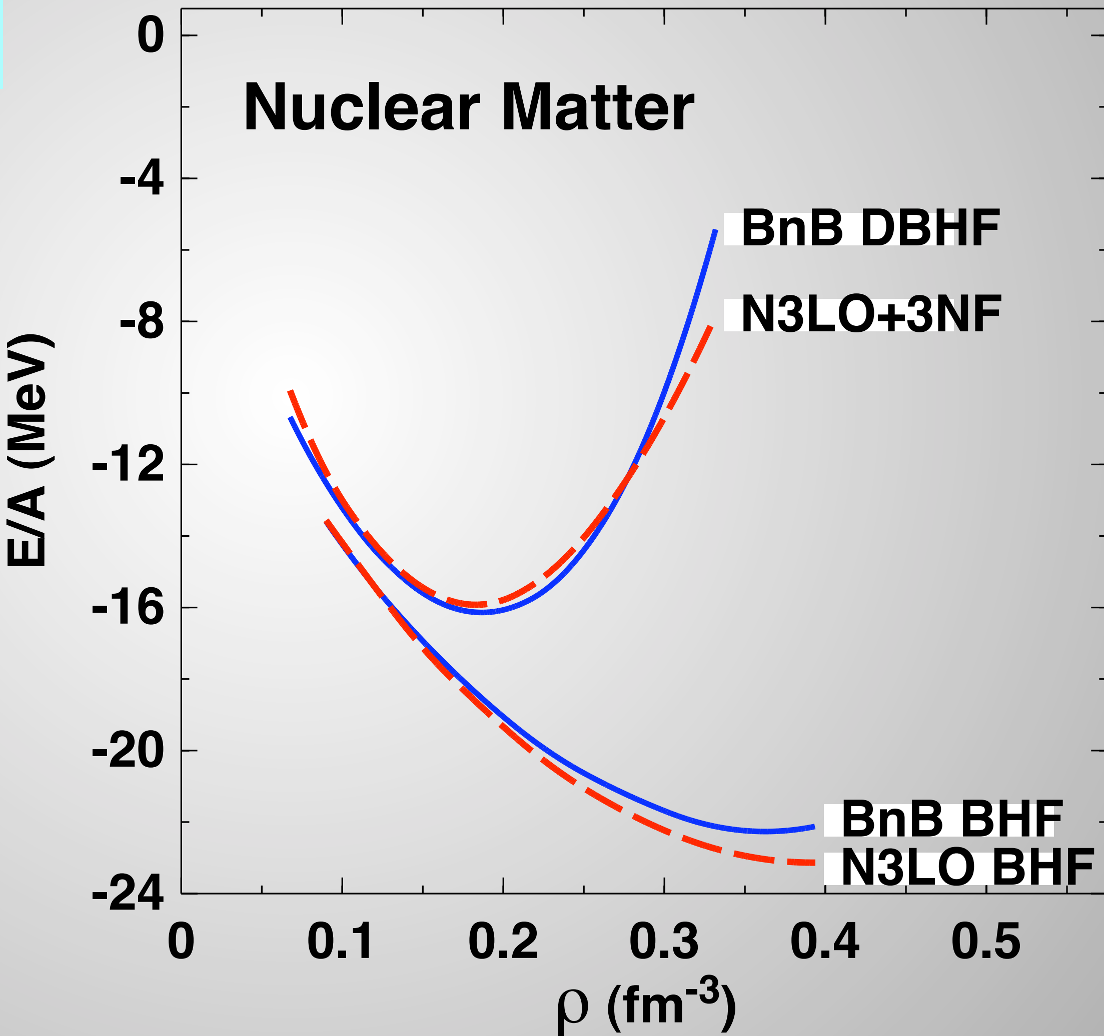
Next we will use chiral forces (up to moderate densities) and compare.

We will use:

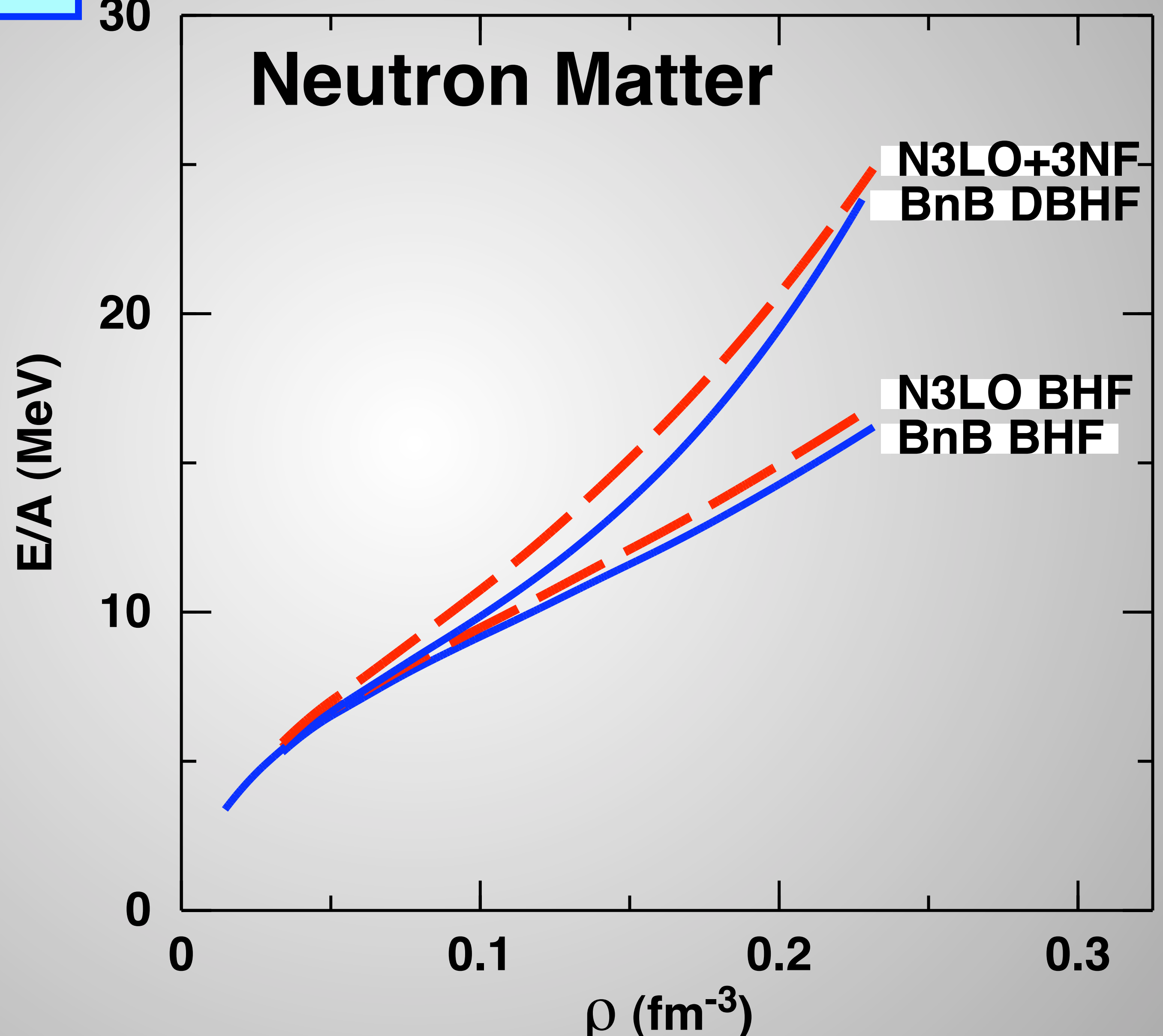
2NF at N3LO
3NF at N2LO

Effective 2N interactions reflecting the underlying leading order chiral 3NF have been constructed by Holt, Kaiser, and Weise.

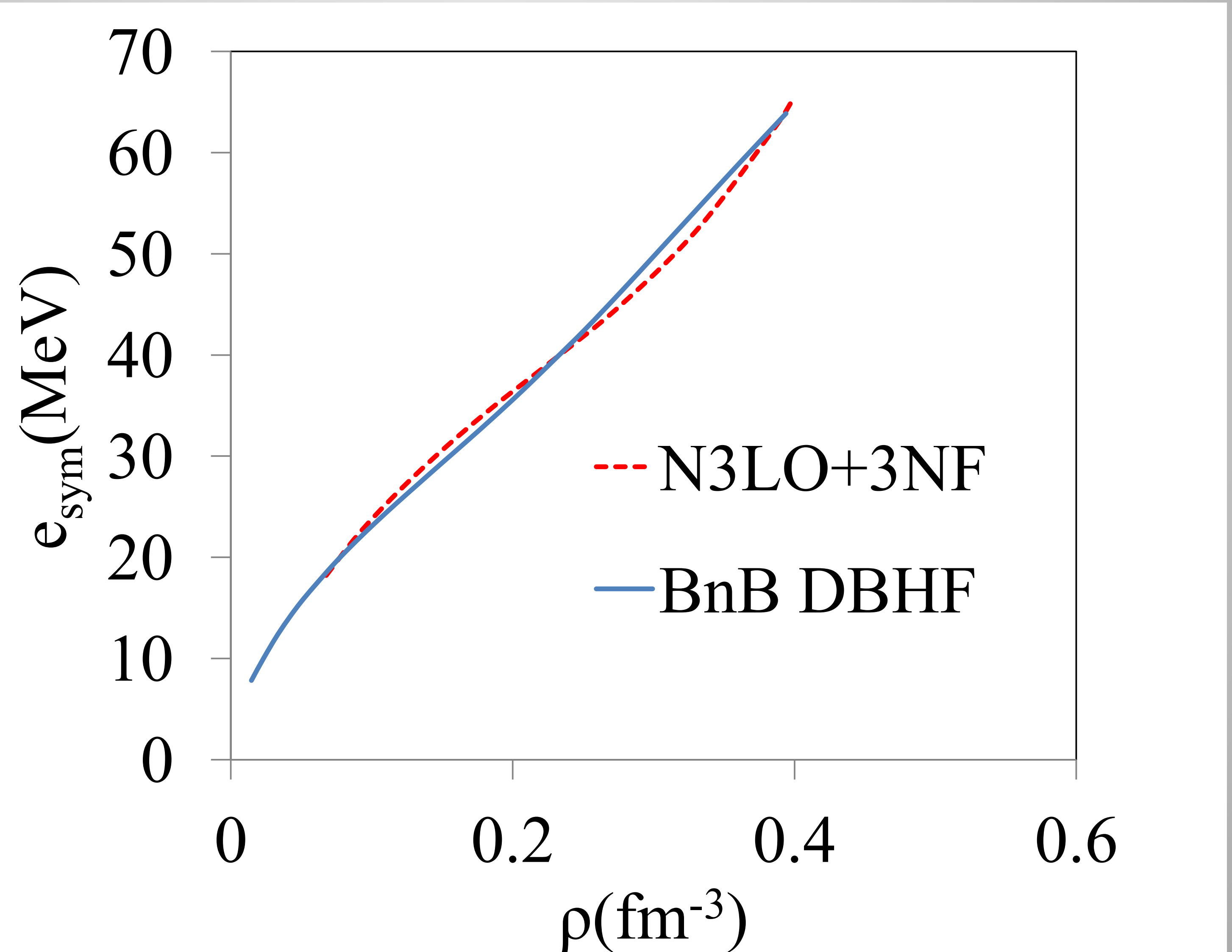
The EoS of Symmetric Nuclear Matter:



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 <u>relativistic meson exchange</u> or <u>chiral EFT</u>, 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.

I like to acknowledge my students:

Larz White (UI)

Boyu Chen (UI)