From Nuclear Matter to Nuclear Reactions

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Applications of nuclear forces in the medium include:

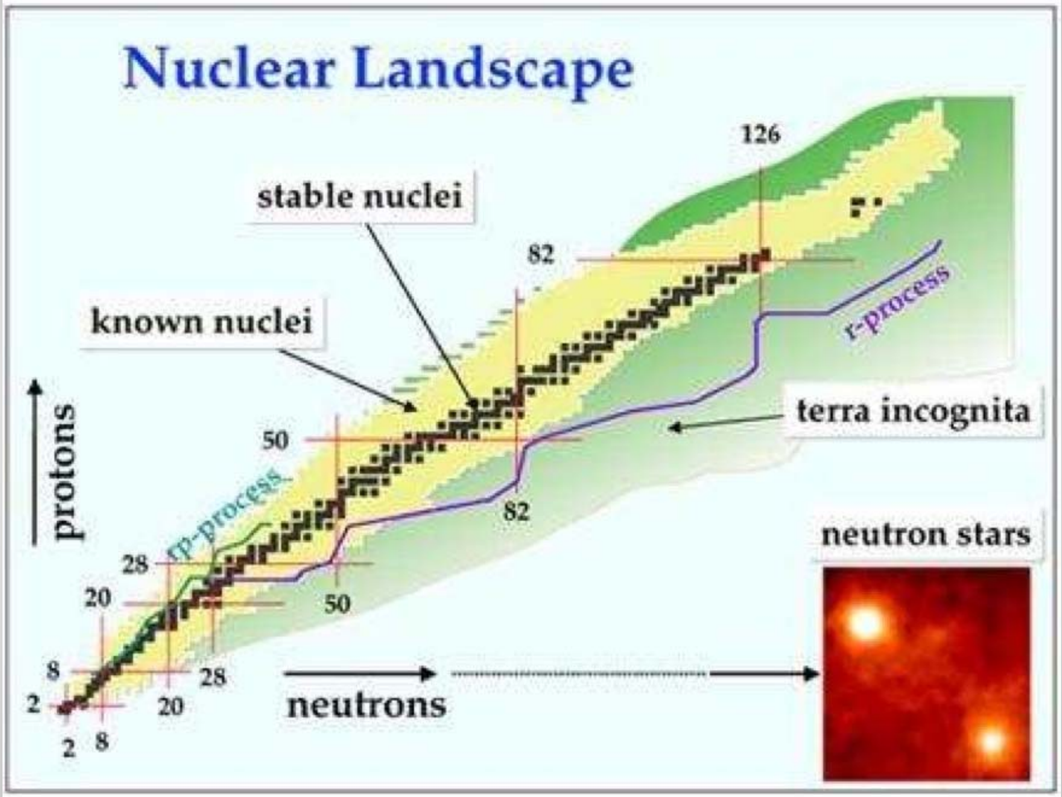
Nuclear/neutron matter

Reactions

Structure of nuclei

After more than 8 decades of nuclear physics, still a lot is unknown about the nuclear chart.

Particularly so for systems with large isospin asymmetry

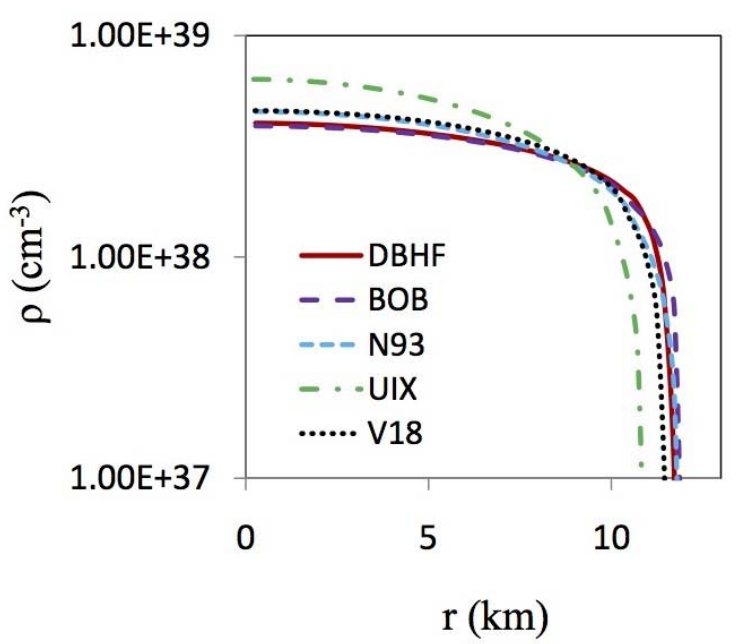


Isospin-asymmetric nuclear matter (IANM) is closely related to neutron-rich nuclei and is a convenient theoretical laboratory.

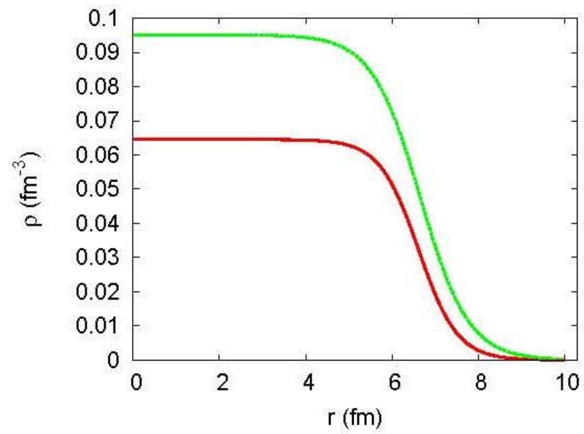
Studies of IANM are far-reaching:

(Predictions from the same equation of state)

The density profile of a “canonical”mass NS



Neutron and proton densities in 208Pb.



The philosophy of modern ab-initio calculations:

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The parameters of the two- and many-body forces are constrained by the properties of the two- and few-nucleon systems and not readjusted in the many-body system.

Then, one can claim PREDICTIVE POWER

How to develop basic interactions?

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.

ChPT: well-defined organizational scheme from which 2BF and many-body forces emerge on the same footing (the chiral expansion).

How good is the rate of convergence of the chiral expansion?

(More on this point later..)

Our traditional approach:
Two-body sector: **a realistic meson-theoretic potential developed within a relativistic scattering equation (Bonn B).**

For the nuclear matter sector:

Dirac-Brueckner-Hartree-Fock (DBHF).

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 (whereas ChPT is a low-momentum expansion).

The symmetry energy has a long history:
The “mass formula”, Bethe-Weizaecker:

$$\frac{B}{A} = a_V - \frac{a_{sym}(A-2Z)^2}{A^2} - \frac{a_s}{A^{1/3}} - \frac{a_C Z(Z-1)}{A^{4/3}} - \frac{\Delta E}{A}.$$

B/A = Binding energy/nucleon

(N – Z)/A = neutron excess or isospin asymmetry

NOW LET THE SYSTEM BE INFINITE, AT SOME DENSITY ρ, AND IGNORE COULOMB INTERACTIONS:

$$N \rightarrow \rho_n$$

$$Z \rightarrow \rho_p$$

$$\frac{N-Z}{A} \rightarrow \alpha = \frac{\rho_n - \rho_p}{\rho}$$

THEN:

$$\frac{E}{A} = e_0(\rho) + e_{sym}(\rho)\alpha^2$$

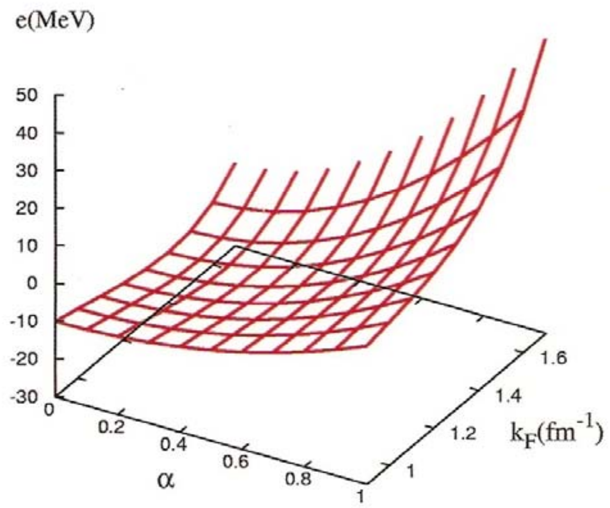
Symmetry energy

This is consistent with the results of a proper (microscopic) calculation of the energy/particle in nuclear matter:

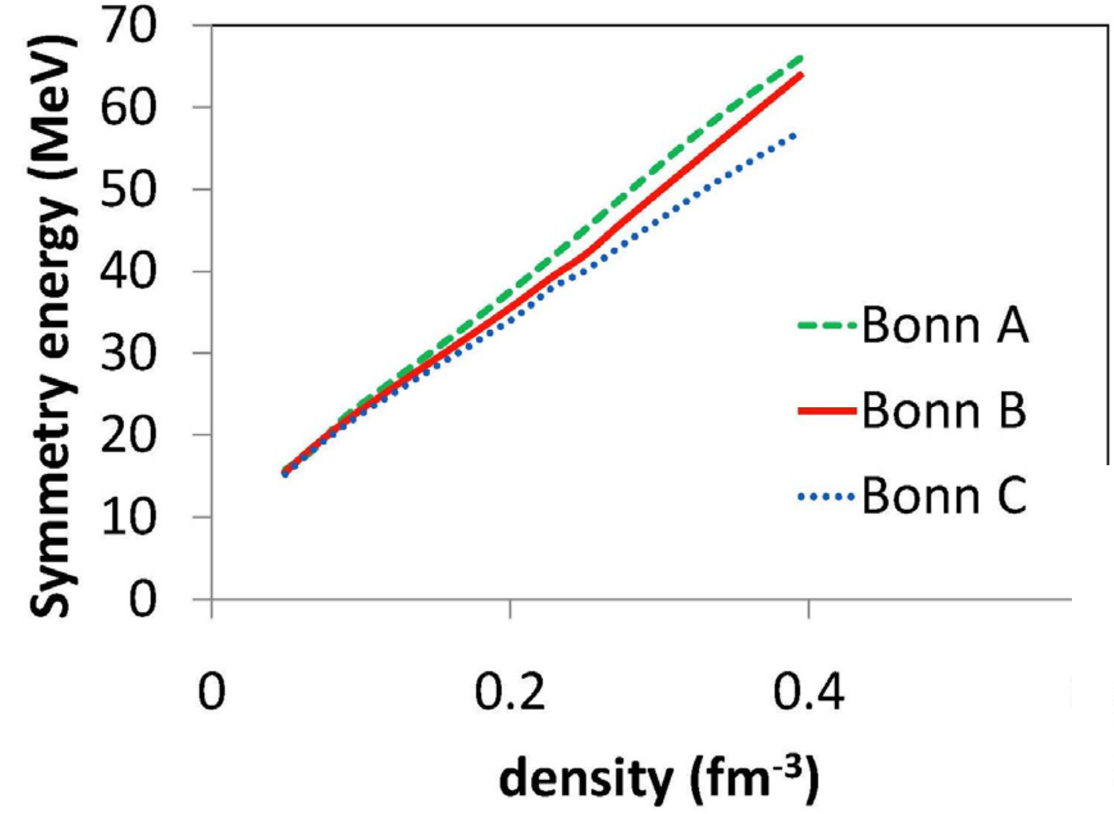
THE ASYMMETRIC MATTER EOS

Energy/nucleon vs. density (or Fermi momentum) and the neutron excess parameter, α

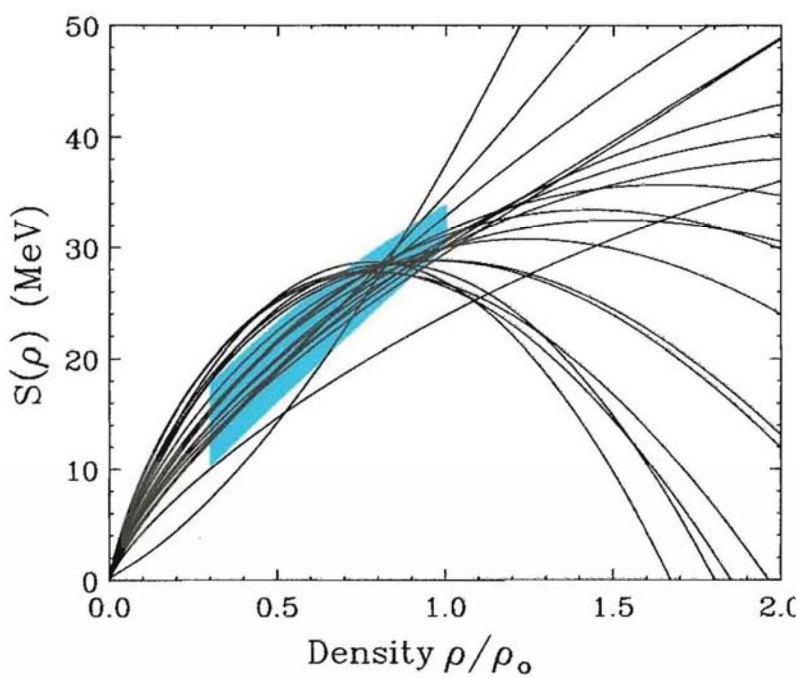
$$\rho = \rho_n + \rho_p \qquad \alpha = \frac{\rho_n - \rho_p}{\rho}$$



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



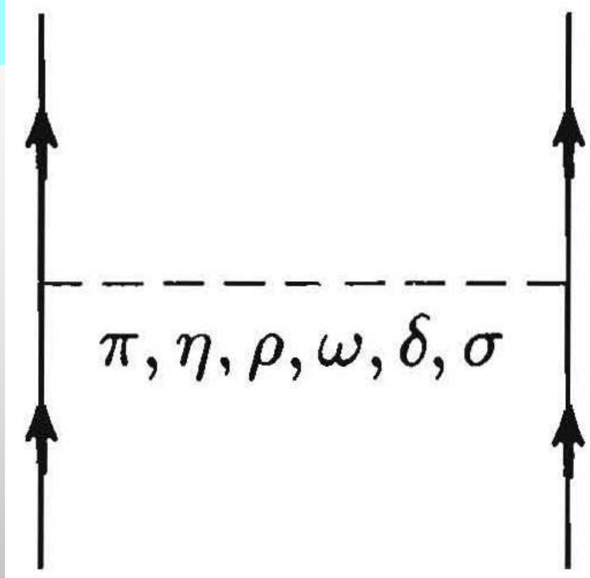
..and from various parameterizations of the Skyrme model:



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.

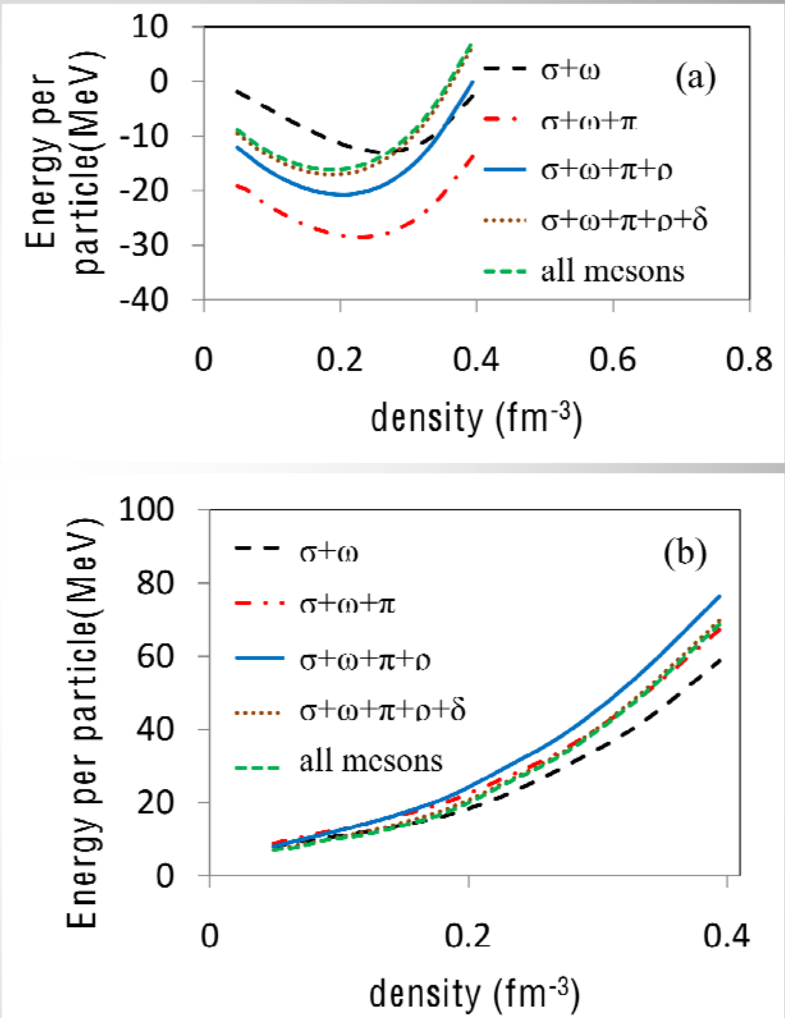
Tensor force at short range:
requires a proper description of the rho-meson, with both its vector and tensor coupling to the nucleon.



The role of the tensor force in nuclear matter as a powerful saturation mechanism is well known:

$$G = V + V\frac{Q}{E - E_0}G$$

$$G \approx V_C +$$



A discussion on tensor force effects that does not start from a microscopic foundation is, to a large extent, arbitrary.

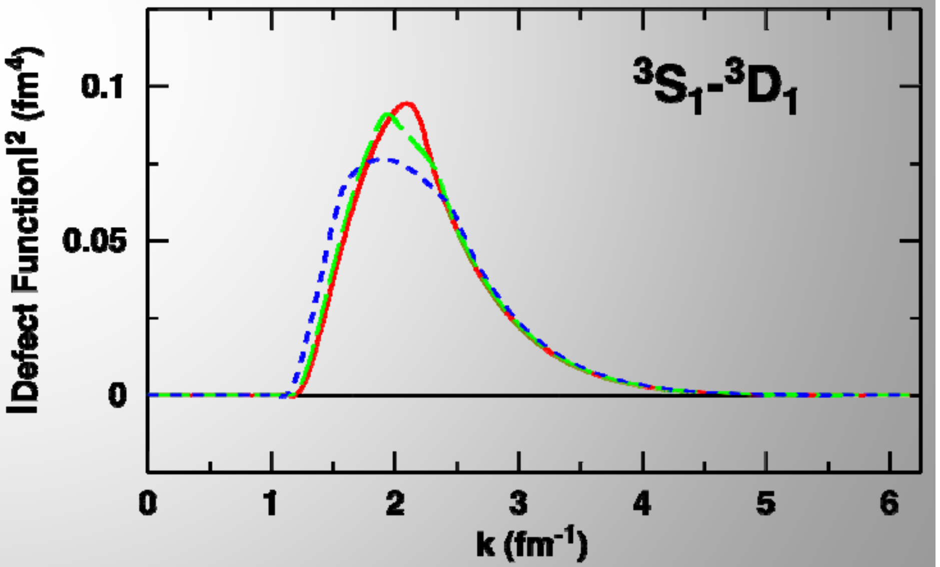
Tensor SRC can be investigated through the correlated wave function in the 3S1-3D1 channel:

$$G\phi = V\psi$$

$$\psi = \phi + \frac{Q}{E - E_0} G\phi$$

$\psi - \phi$ is the defect function.

Defect function vs. momentum near saturation density at three levels of isospin asymmetry (DBHF predictions)



A study of SRC including modern 2- and 3-body chiral interactions is coming soon.

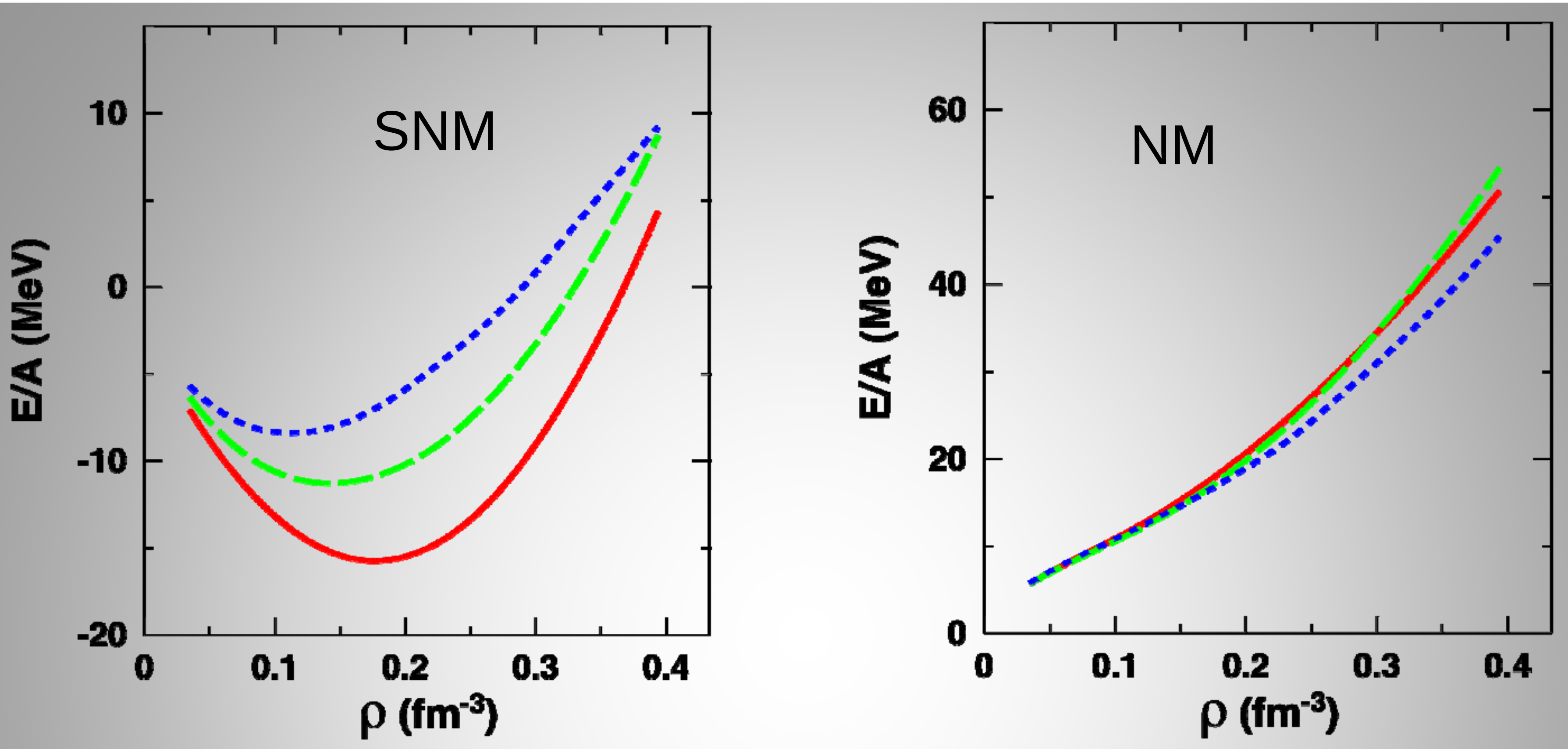
Key to improved understanding of the many-body system: Comparative studies with ab initio approaches.

Recent calculations with consistent chiral 2BF and 3BF:
(with L. Coraggio, N. Itaco, L.E. Marcucci, J. Holt, R. Machleidt)

2BF constrained by the NN system
3BF constrained by the A=3 system

Predictions at N3LO of the chiral 2BF, varying the cutoff in the regulator function applied to the chiral NN potential.

$$f(p,p') = e^{[-(\frac{p}{\Lambda})^{2n} - (\frac{p'}{\Lambda})^{2n}]}$$



Red: 450 MeV

Green: 500 MeV

Blue: 600 MeV

Preliminary conclusions:

Realistic saturation properties <u>can</u> be obtained with consistent 2BF and 3BF in a parameter-free calculation. Not a trivial task!

A systematic analysis of order-by-order convergence is in progress in our group.

Improved cutoff independence with increasing order is crucial for the success of EFT.

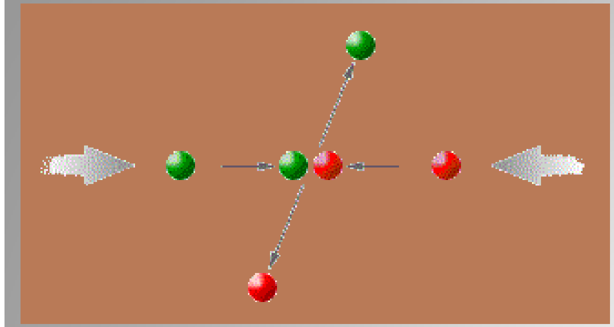
Applications of nuclear forces in the medium include:

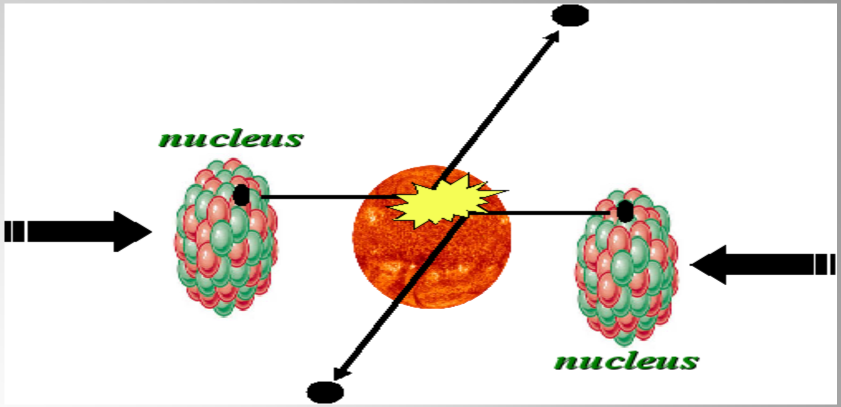
Nuclear/neutron matter (considered so far)

Reactions

Structure of nuclei

Our link with reactions: In-medium NN collision





Transport models of HI collisions are sensitive to both NN collisions and the average nuclear matter potential.

NN collisions are described by NN effective xsections.
Our in-medium NN xsections are microscopic
(i.e. driven by the NN scattering amplitudes.)

Using microscopic input has the advantage that different ingredients are internally consistent, as they all originate from the NN scattering amplitudes in the medium.

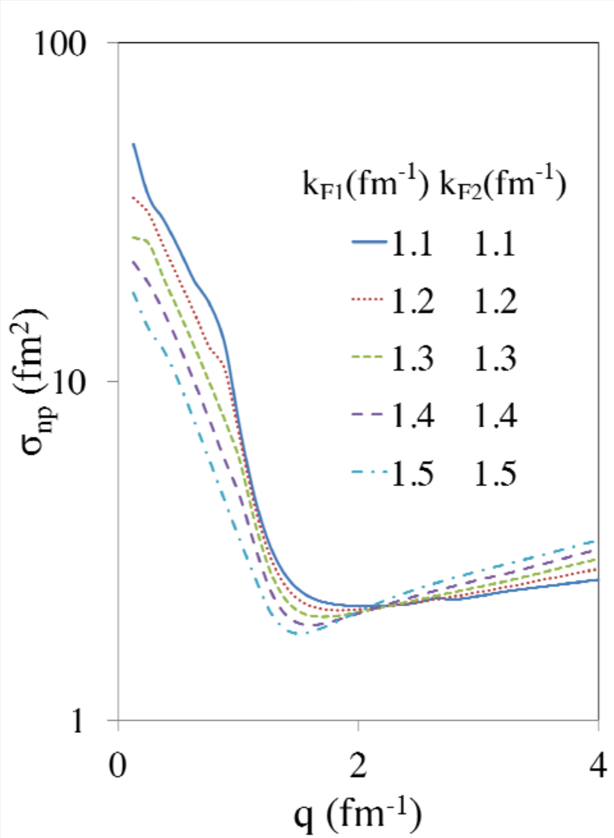
Single-nucleon knockout reactions at intermediate energies involving unstable beams:

(c + N) + T --------> c + X

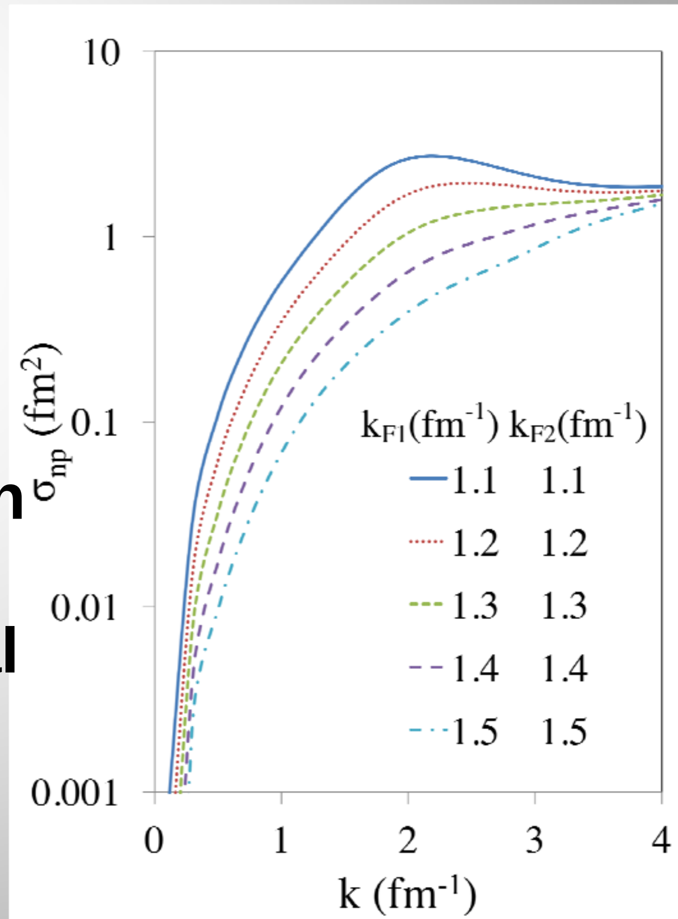
(A very sensitive tool to study s.p. occupancies in the shell model through measurements of the momentum distribution.)

In the Glauber model, NN scattering amplitudes enter through the eikonal phase as effective scattering cross sections.

Microscopic in-medium NN cross sections as from DBHF G-matrix calculations.



Average in-medium NN cross section for collision of two Fermi spheres, including Pauli restriction of the final scattering states.



Summary and Conclusions:

We reviewed some aspects of our previous work with IANM and the symmetry energy.

We reported on work in progress to explore SRC with modern interactions.

We reported on on-going investigations of order-by-order convergence of SNM and NM predictions with chiral two- and three-body forces.

Link with reactions: in the description of in-medium NN collisions. Effective NN xsections can be very model-dependent. **Suggestion**: uitilize reactions suitable as clean probes of the NN collision input.

In all of the above, we stressed the importance of the ab initio approach.