Properties of nuclear matter with modern nucleon-nucleon potentials

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content

Theoretical method:

Brueckner theory

Results I:

Equation of state

Symmetry energy

Neutron skin thickness

Results II:

Momentum distribution and correlation strength

Bruckner theory

$$G = v_{NN} + v_{NN} \sum_{k_1 k_2} \frac{\left| k_1 k_2 \right\rangle Q(k_1, k_2) \left\langle k_1 k_2 \right|}{\omega - e(k_1) - e(k_2) + i\eta} G$$

$$V_{NN} = V_2 + \boxed{V_3}$$

V_2: AV18; Paris; Bonn A,B,C; CDBonn;

Reid93; Nij93; NijI; NijII ; N3LO.

$$e_k = \frac{k^2}{2m} + \mathrm{Re}\,\boxed{M}_1(k)$$

Brueckner-Hartree-Fock

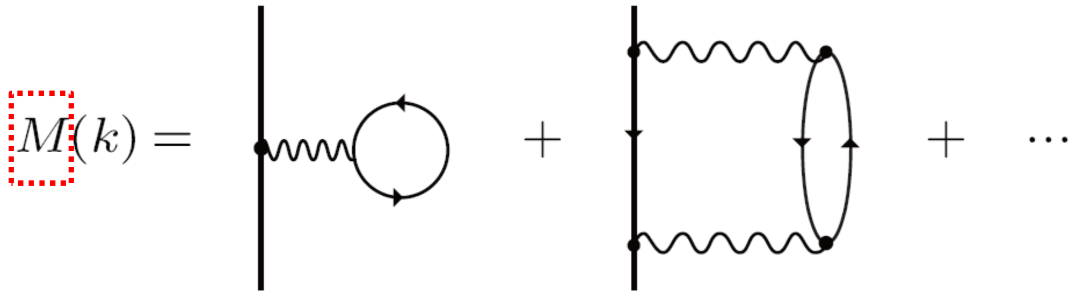
$$\eta_\alpha = \frac{QG_\alpha}{e}$$

Defect function denoting the difference between the correlated wave functions and the uncorrelated ones.

$$\kappa = \rho \sum_\alpha \int d^3 r \left| \eta_\alpha(r) \right|^2$$

Correlation strength - an indicator for the convergence of BBG hole-line expansion.

Mass operator



M_1 M_2

$$n(k < k_F) = 1 + \frac{\partial M_1(k,\omega)}{\partial \omega}\bigg|_{\omega = e_k}$$

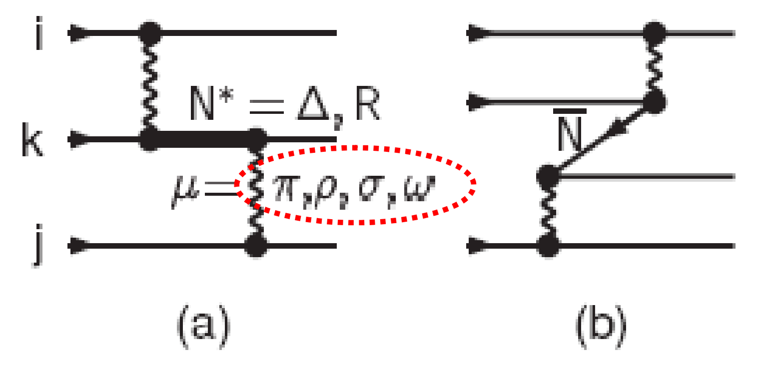
$$n(k > k_F) = -\frac{\partial M_2(k,\omega)}{\partial \omega}\bigg|_{\omega = e_k}$$

$$\kappa \equiv \sum_k n(k > k_F) / \sum_k n(k < k_F)$$

depletion parameter
or
correlation strength

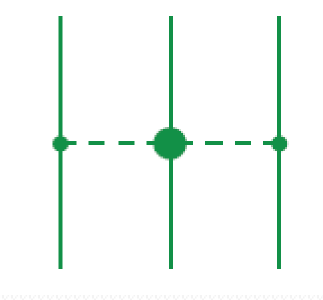
Phenomenological 3NF: fitted to the saturation point of nuclear matter and the binding energy of the tritium, involving at most 2π exchange and containing two free parameters, like Urbana model.

Microscopic 3NF: based on one - boson - exchange picture of nucleon-nucleon interaction involving the four important mesons π,ρ,σ, ω.

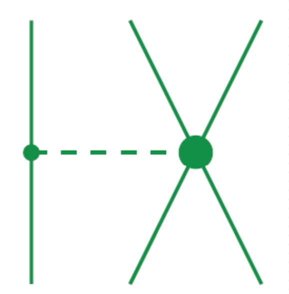


Chiral 3NF: N2LO

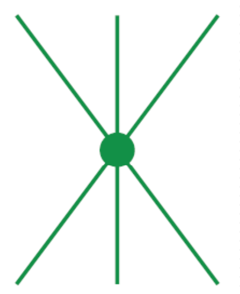
R. Machleidt, Phys. Rep. 503 (2011) 1



long-range 2π-exchange force

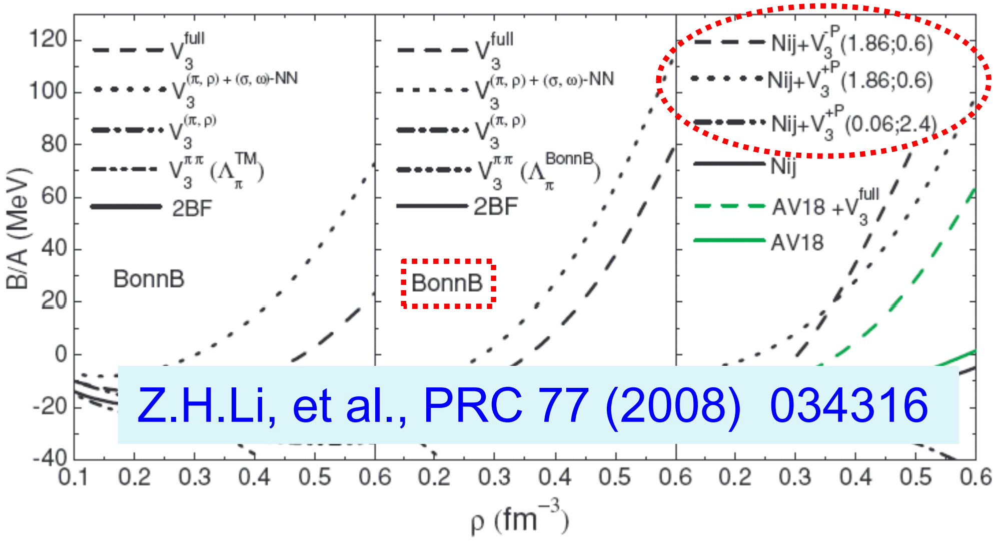


medium-range 1π-exchange force

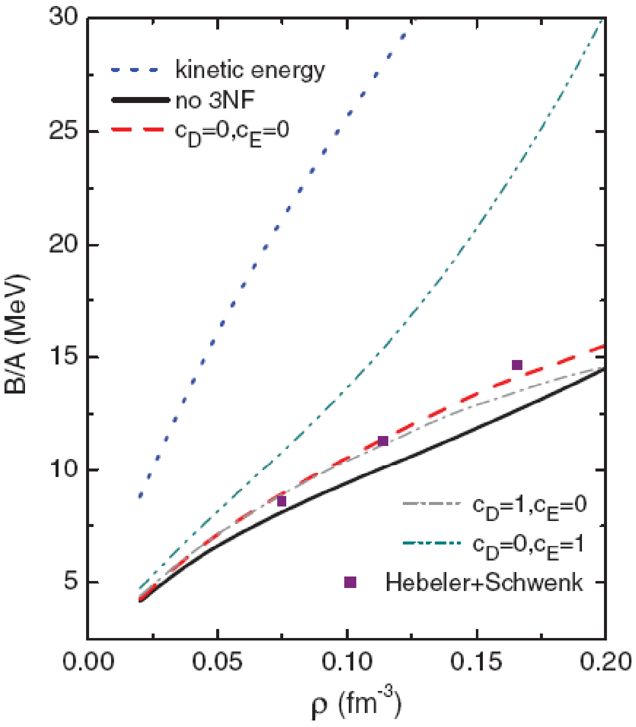


short-range contact interaction

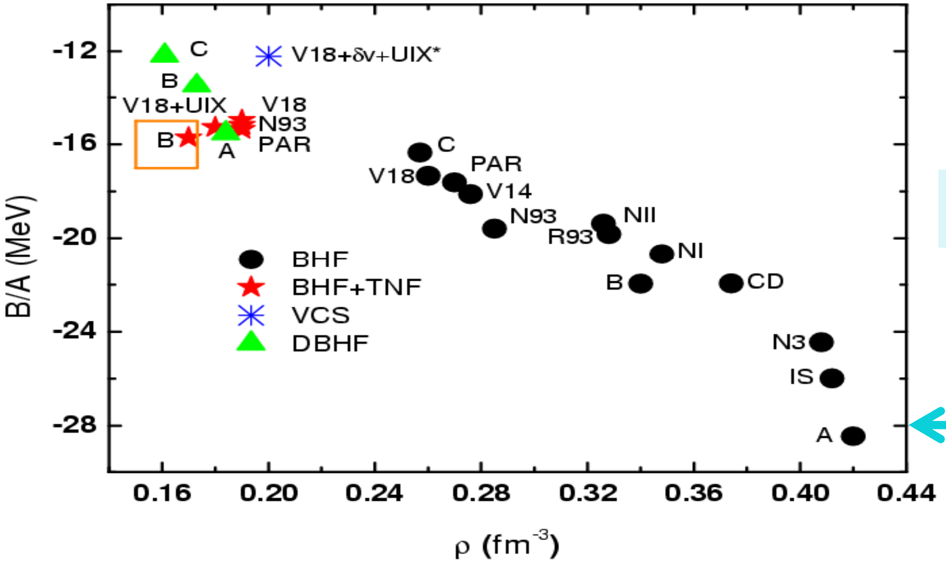
Results I: Equation of state



Z.H.Li, et al., PRC 77 (2008) 034316

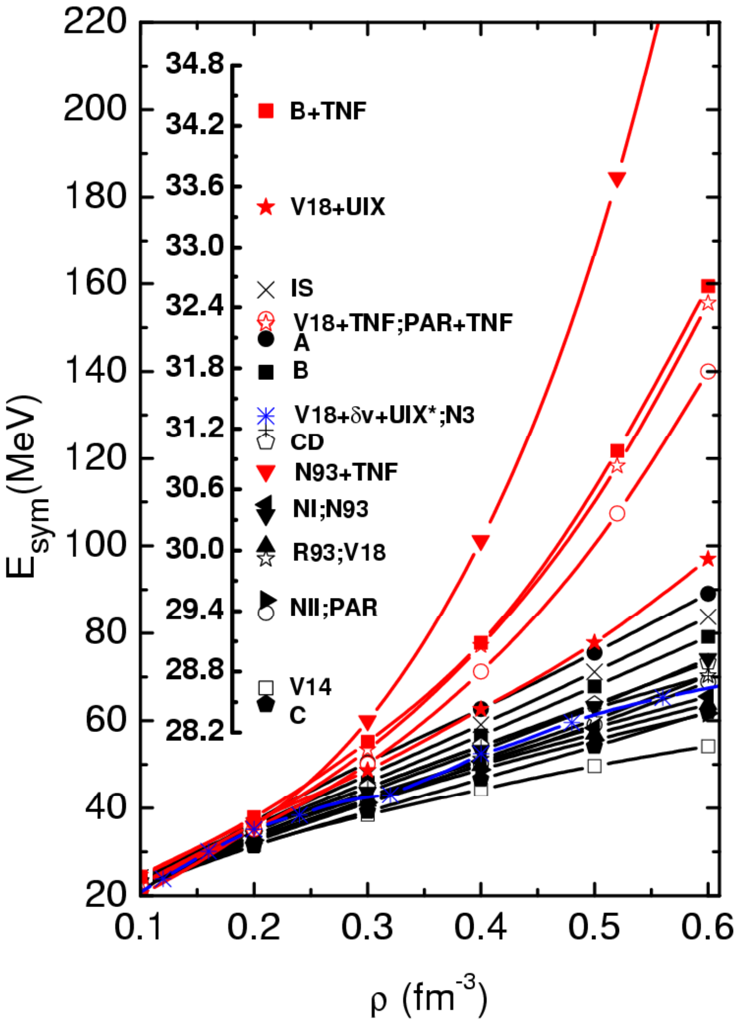


Z.H.Li, et al., PRC 85 (2012) 064002

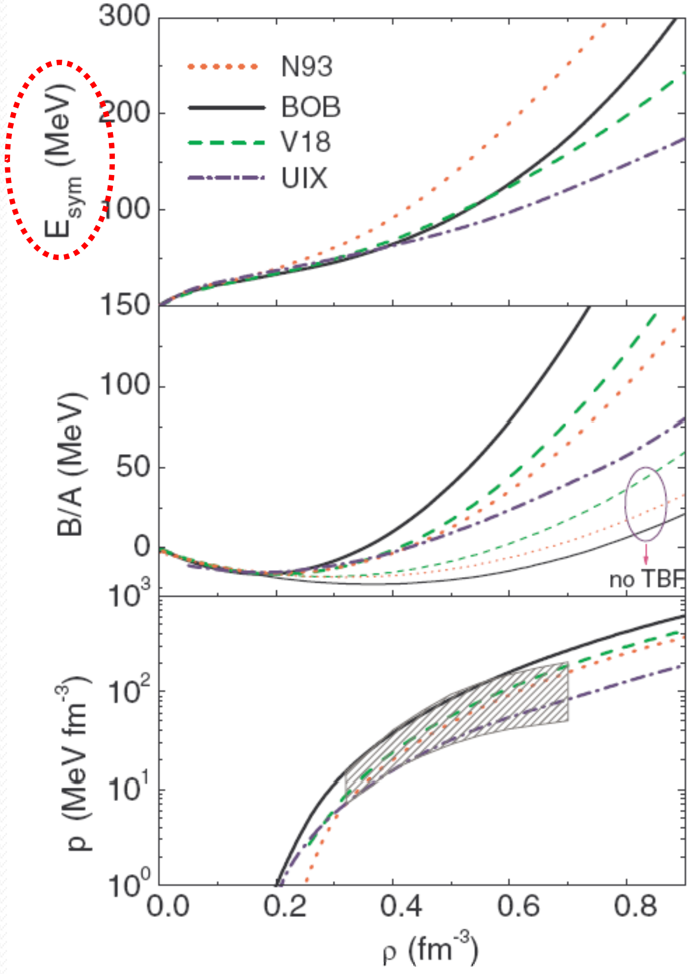


Updated Coester line based on our work in PRC74(2006)047304

Results I: Symmetry Energy

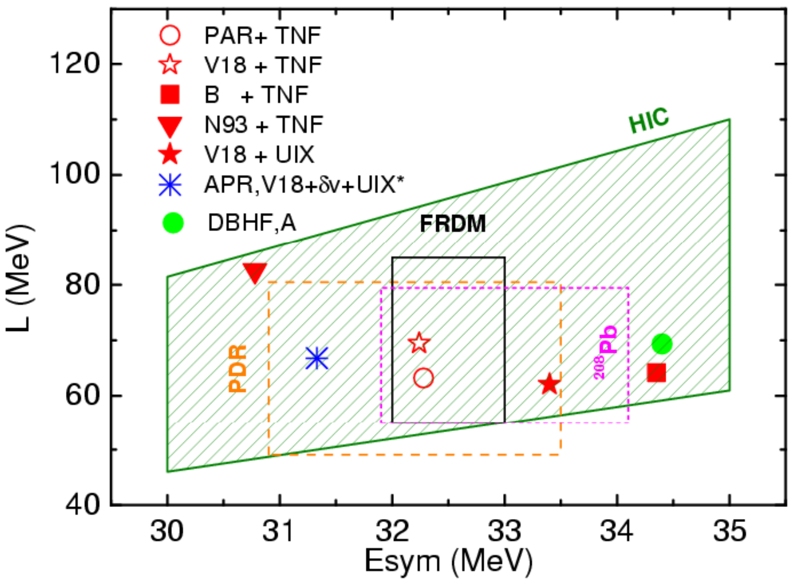


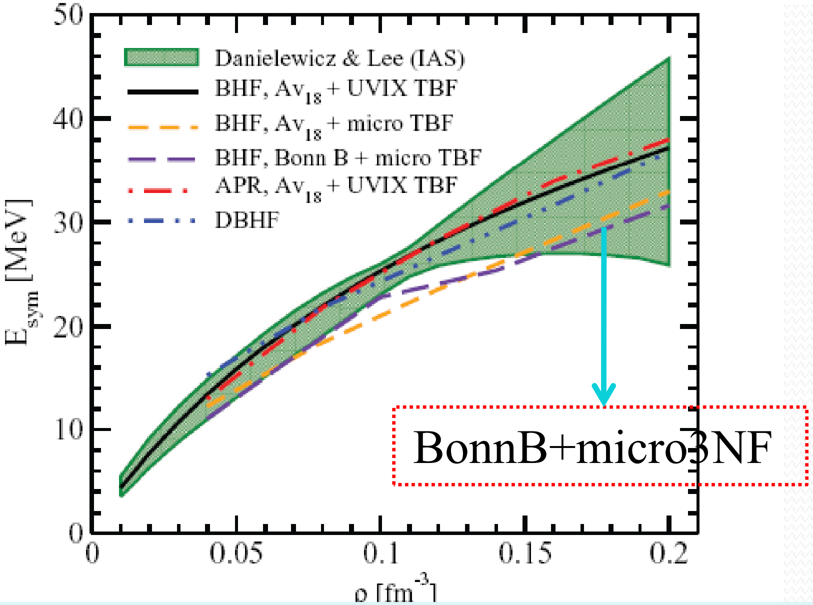
Z.H.Li, et al.,PRC 74(2006)047304



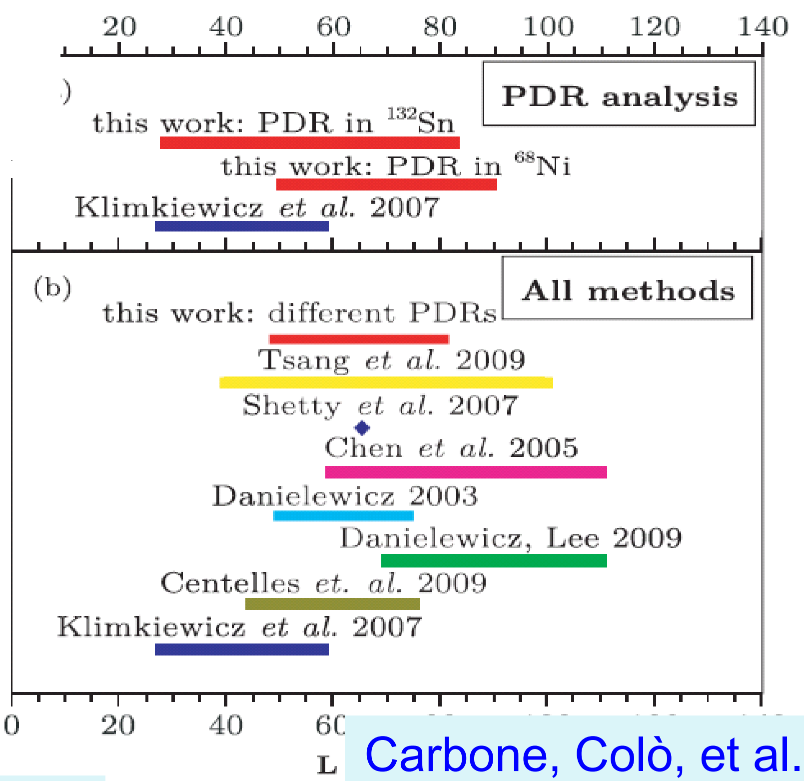
Z.H.Li, et al., PRC 78 (2008) 028801

L and symmetry energy at the normal density with theoretical models and recent experimental data: HIC, FRDM(Finite Range Droplet Model), PDR(Pygmy Dipole Resonance), Pb(Zenihiro)





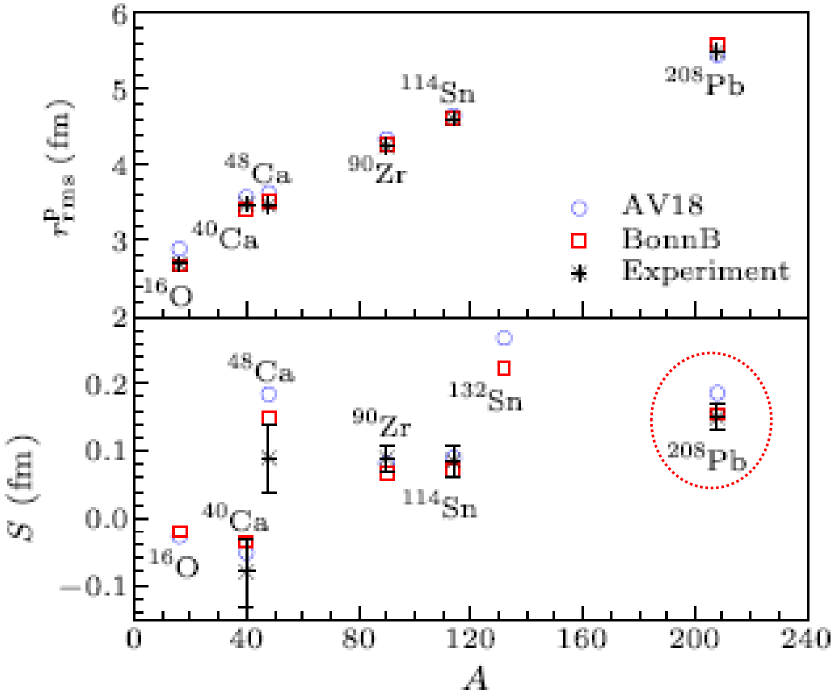
Taranto, Baldo, Burgio, PRC 87(2013) 045803

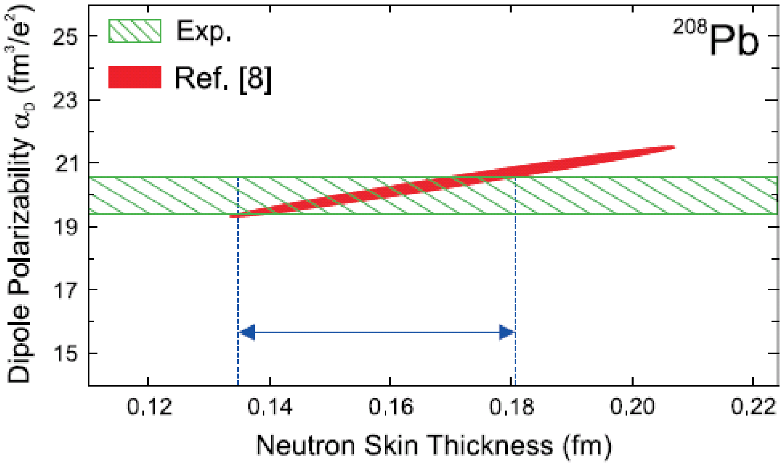


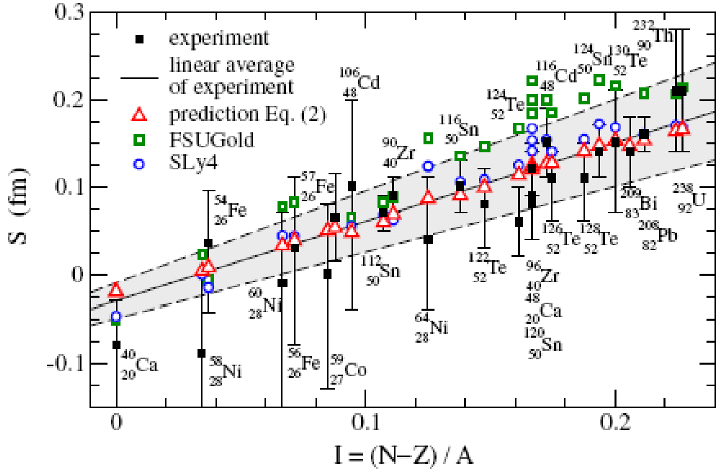
Carbone, Colò, et al.
PRC 81 (2010) 041301(R)

Results I: Neutron skin thickness

Proton radius





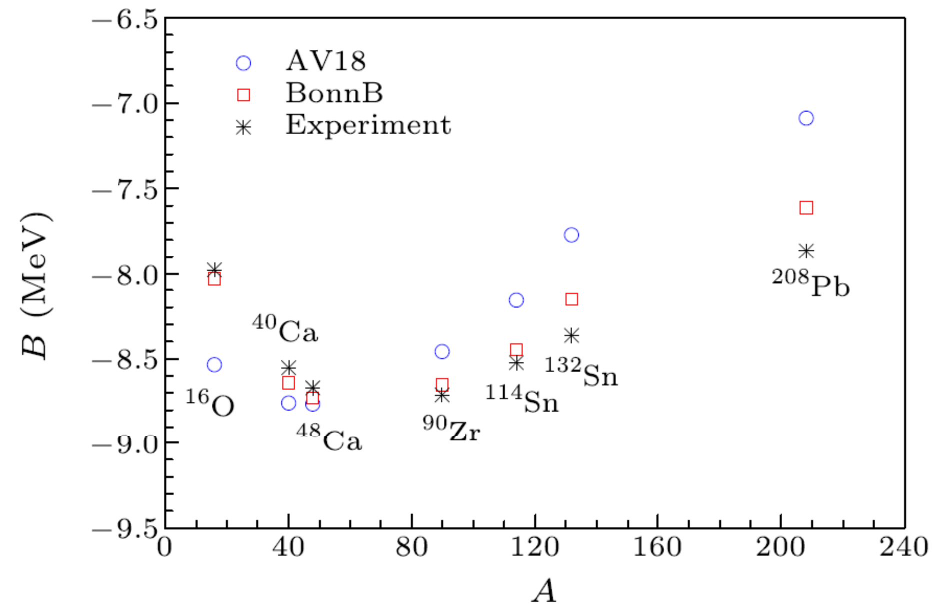


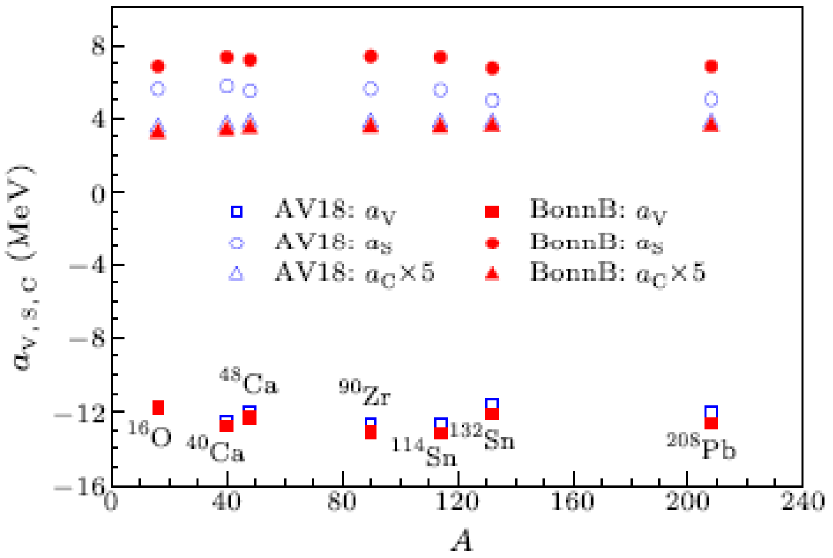
Pb: S_n=0.16~0.19 fm

Q.Y.Bu, Z.H.Li, et al.,
CPL 33(2016) 032101

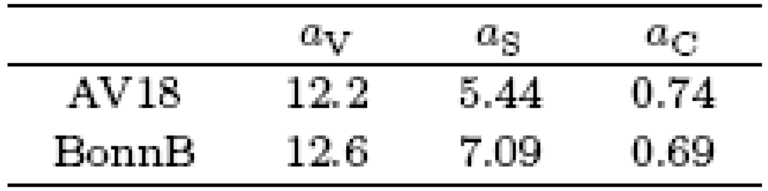
M. Centelles, et al., PRL 102 (2009) 122502;
PRL 107 (2011) 062502

$$B = \boxed{a_V}\,A - \boxed{a_S}\,A^{2/3} - \boxed{a_C}\,\frac{Z^2}{A^{1/3}} - a_A\frac{(A-2Z)^2}{A} + \delta(A,Z)$$





Nuclear binding energy is obtained using the different EOS from the modern 2NF+3NF, and compared to the semi-empirical mass formula. Due to the smaller volume term contribution from EOS of nuclear matter, so it needs less contribution from the surface energy to be compensated.



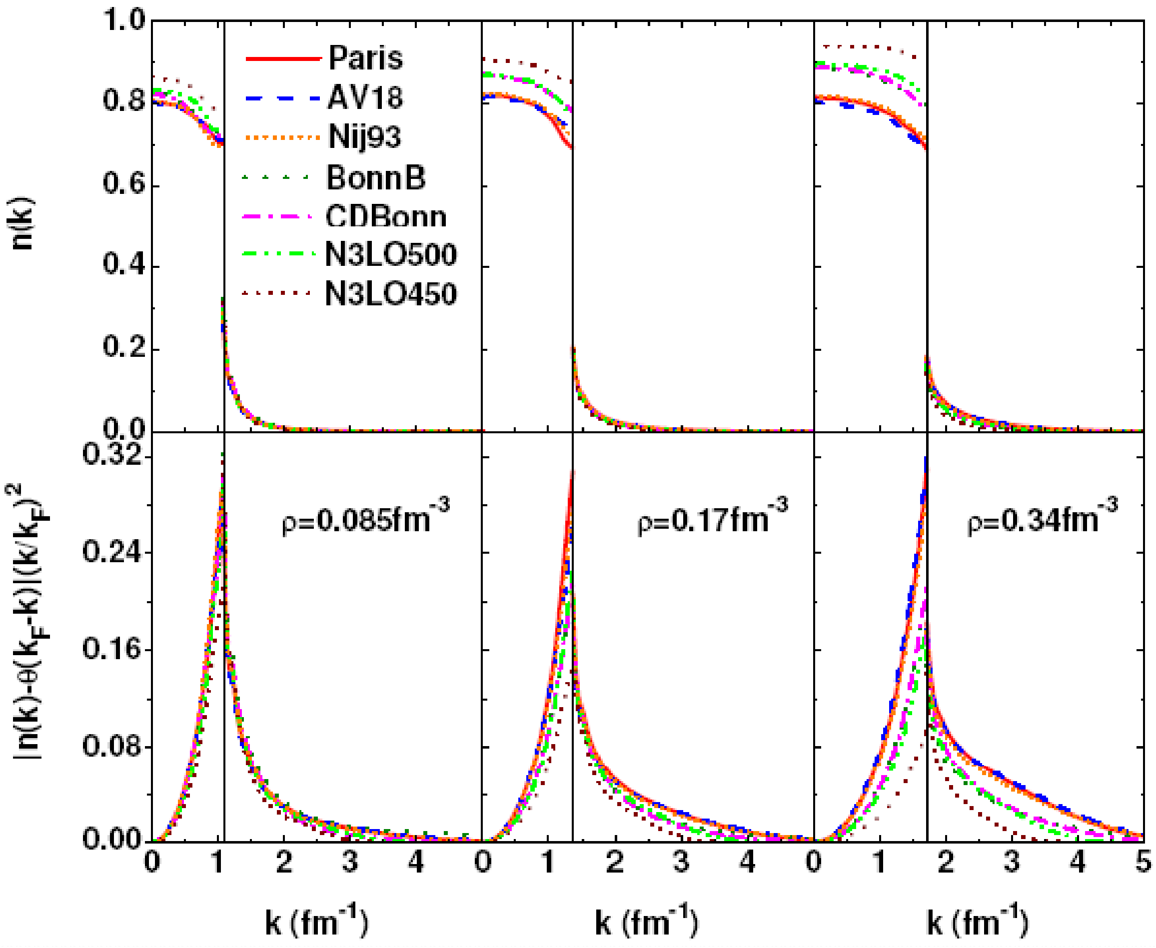
	a_V	a_S	a_C
AV18	12.2	5.44	0.74
BonnB	12.6	7.09	0.69

$$a_V = 16MeV;\ a_S = 15MeV;$$

$$a_C = 0.7MeV$$

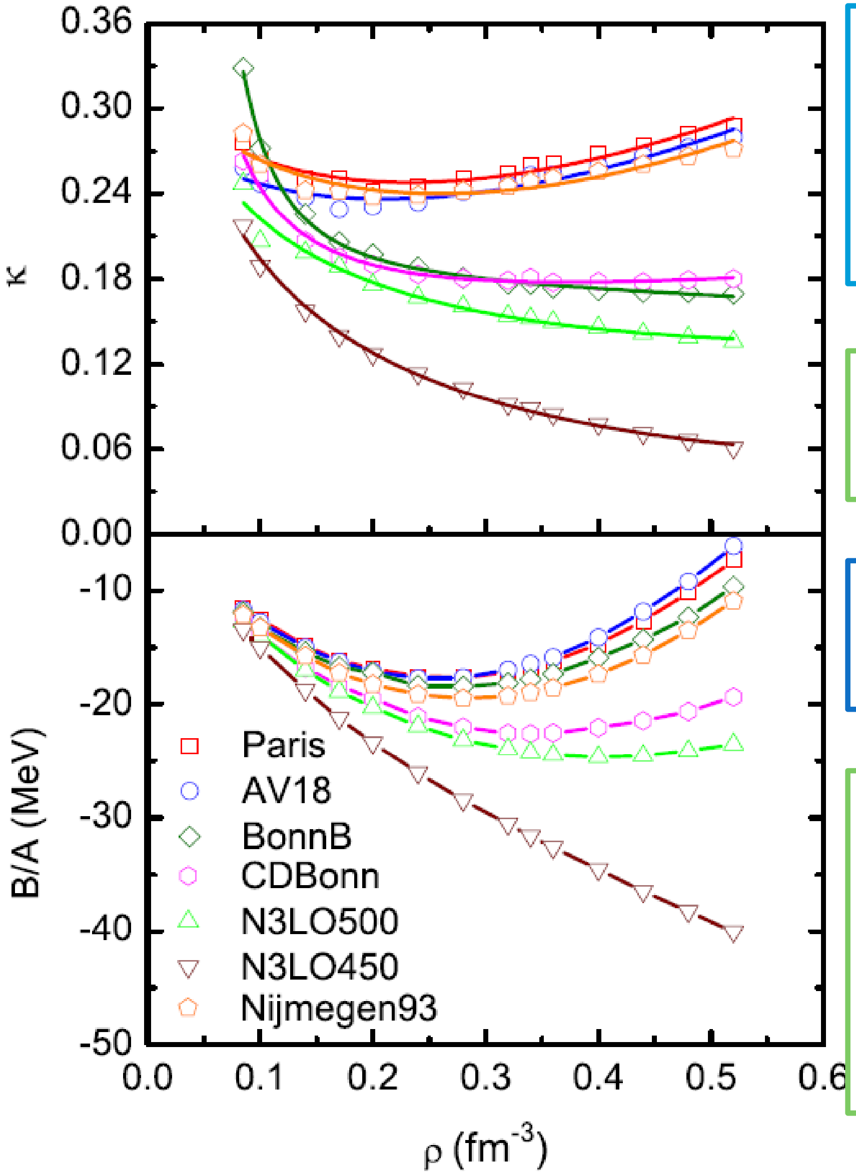
P. Möller et al. , PRL 108 (2012) 052501

Results II: Correlation strength κ



Momentum distribution

The weighted deviations from the free Fermi distribution

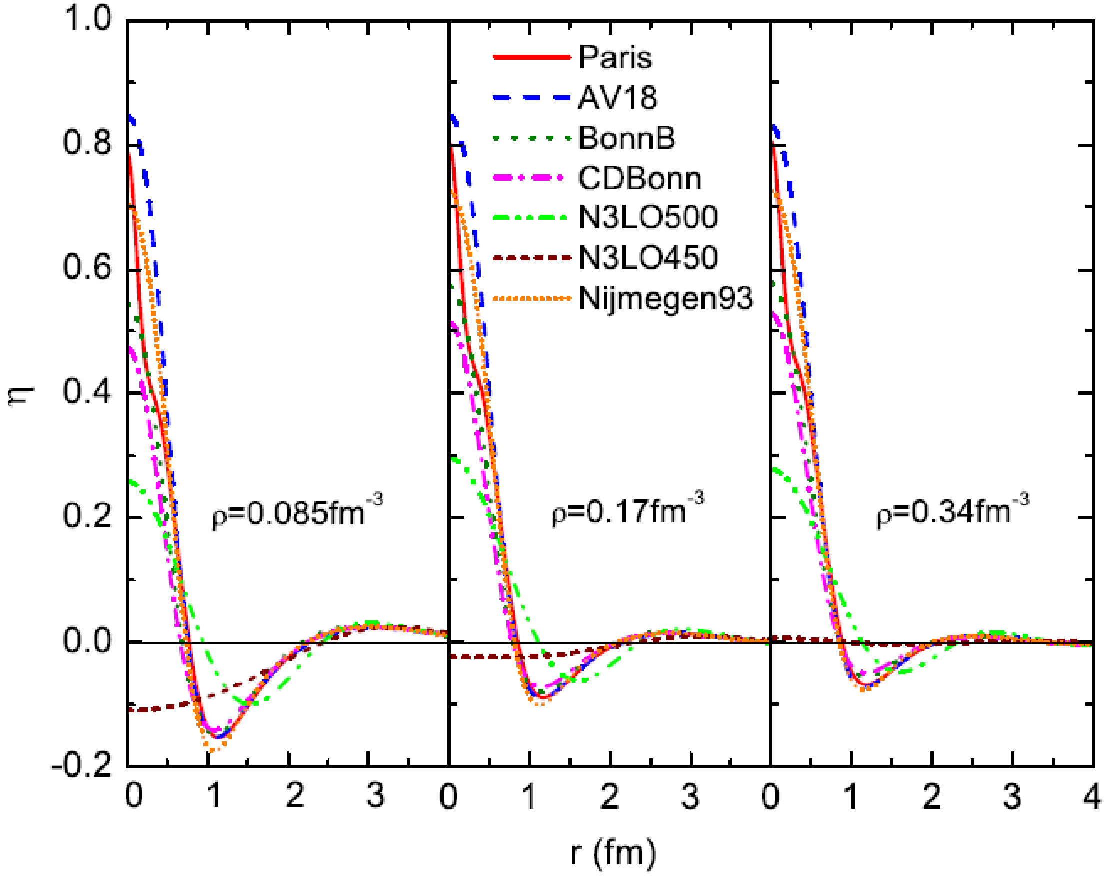


The depletion at high density is determined by the repulsive core of the NN interaction, which is very strong in the r space potentials and very weak in the chiral potentials .

For the chiral potentials, the depletion has a strong dependence on the cutoff.

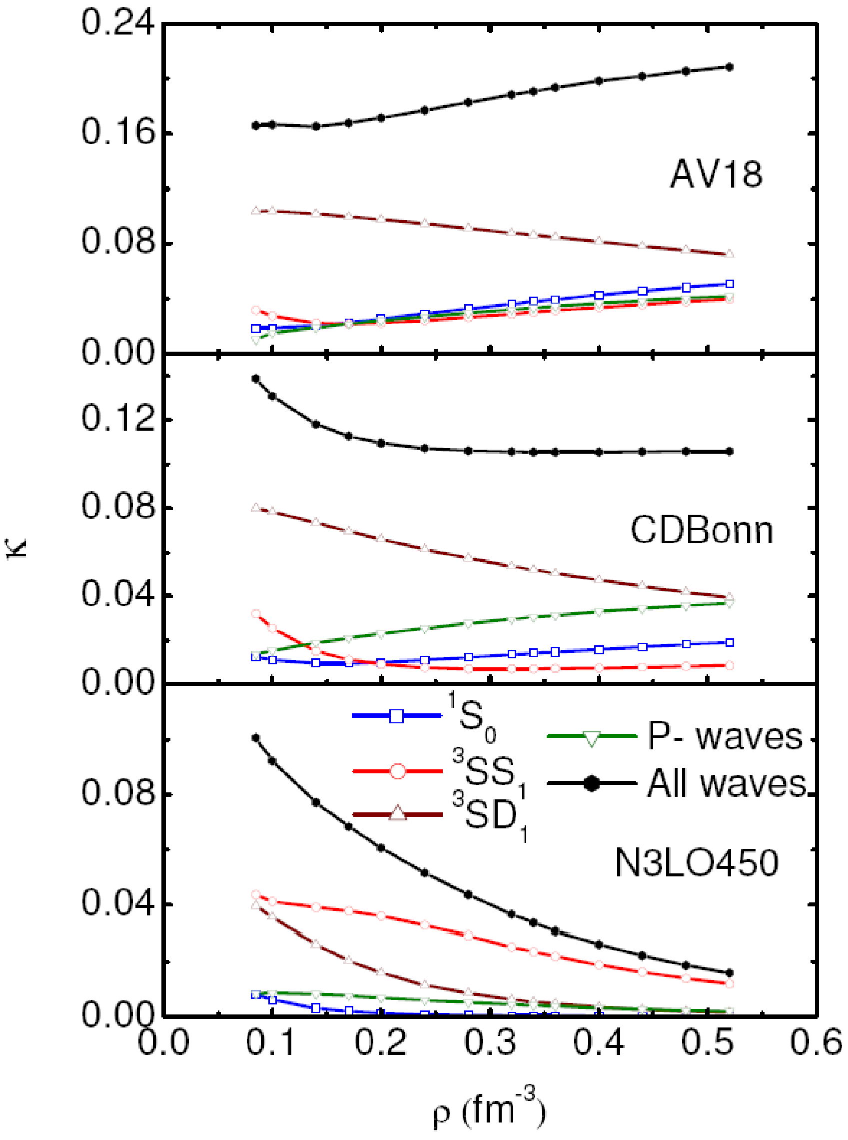
The “weakest” chiral potentials saturate only at very large density, or not at all.

However, for the chiral potentials, with the density increasing the correlation parameter κ becomes very small, thus any corrections to the saturation curve in the hole-line expansion are expected to be small.



Defect function

The r-space potentials are very “hard”, with a large “defect” at small distance, while the chiral potentials are extremely “soft”.



Regardless of a typical "hard" potential (AV18), an intermediate one (CDBonn) or a very "soft" one (N3LO), the largest contributor to the depletion κ is the deuteron channel, especially at the low density. Thus the important role of the tensor force is emphasized.

With increasing density for the "hard" potentials the correlation strength increase again due to the dominance of the persistent p-wave contributions at high density, whereas for "soft" potentials the parameters κ_α disappear fast.

Summary

1. With the various modern NN potentials in Brueckner calculations, we showed the equation of state of nuclear matter, symmetry energy, and the neutron skin thickness of some spherical nuclei.
2. We also examined the correlation strength of various modern NN potentials and pointed out the connection to momentum distributions and defect functions. We found qualitatively different behaviors for “hard” and “soft” potentials.
3. The results imply that the hole-line expansion is well converged already at BHF level. For chiral potentials with small cutoff, very strong nuclear 3NF is required in order to achieve satisfactory saturation properties of nuclear matter.

Thanks for your attention!