Properties of Asymmetric Nuclear Matter within the EBHF approach

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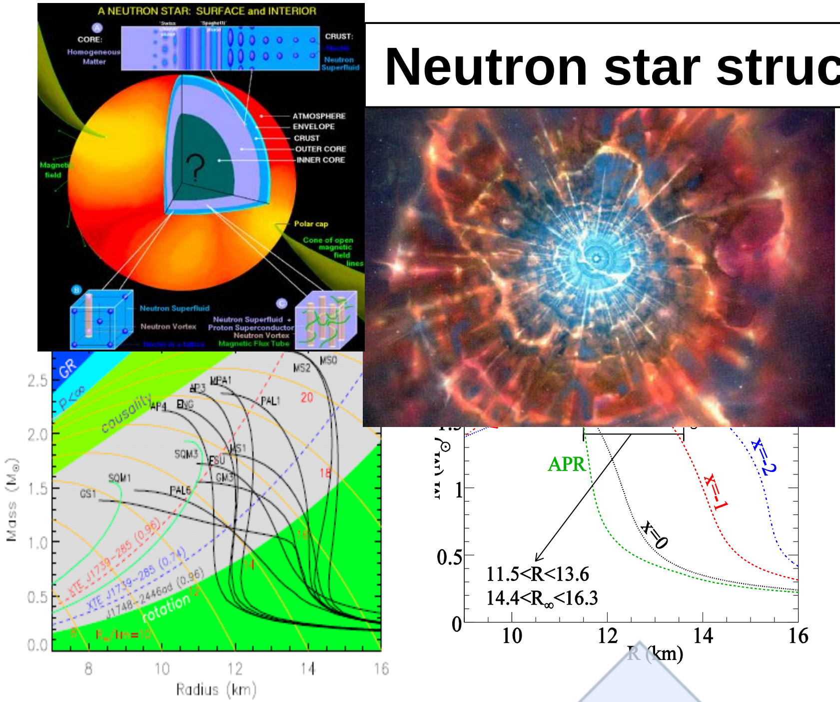
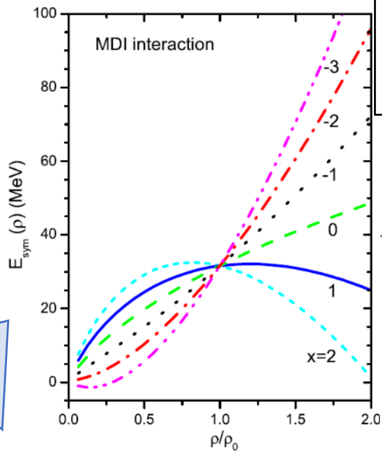
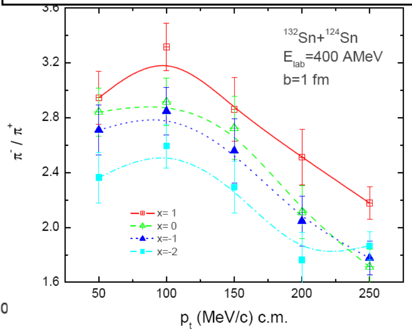
Neutron star structure



Nuclear many-body model

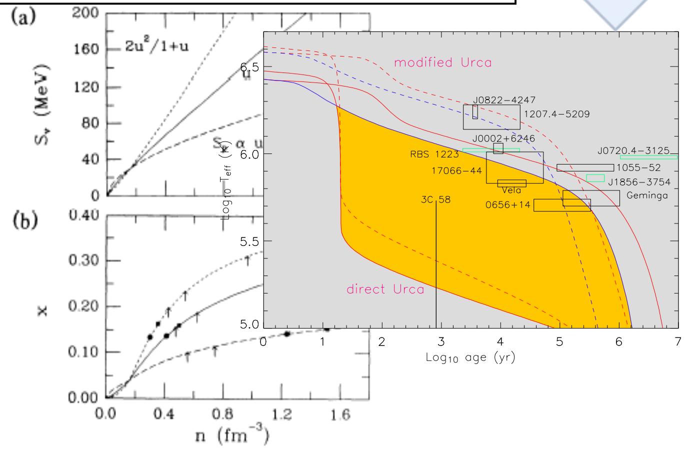
Isospin transport in HIC





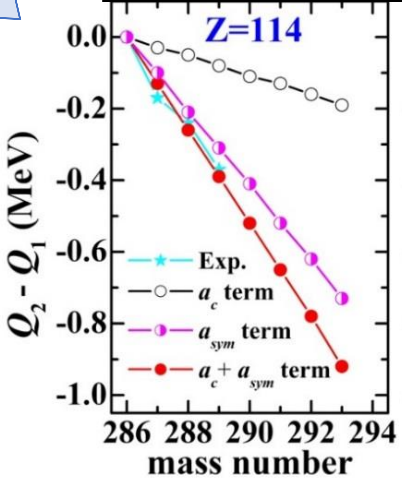
Properties of ANM

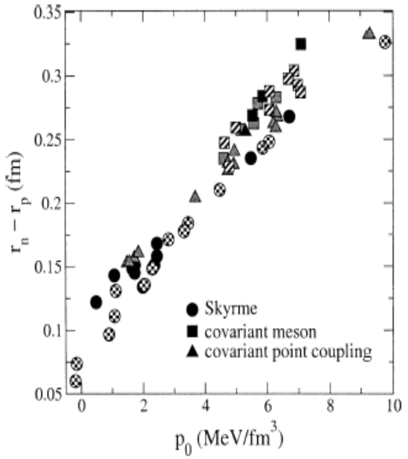
Neutron star cooling



Effective NN interaction in nuclear medium

Properties of neutron-rich nuclei and heavy nuclei





Theoretical Approaches

- Skyrme-Hartree-Fock Approach
- Relativistic Mean Field Theory
- Relativistic Hartree-Fock Theory

- Variational Approach
- Green’s Function Theory
- Brueckner Theory
- Dirac-Brueckner Approach
- Effective Field Theory

Bethe-Goldstone Theory

Bethe-Goldstone equation and effective ***G***-matrix

$$G(\rho,\beta;\omega)=v_{NN}+v_{NN}\sum_{k_1k_2}\frac{|k_1k_2\rangle Q(k_1,k_2)\langle k_1k_2|}{\omega-\varepsilon(k_1)-\varepsilon(k_2)+i\eta}G(\rho,\beta;\omega)$$

→ v_{NN} is the realistic nucleon-nucleon interaction. In our calculation: $v_{NN}=v_2+V_3^{eff}$

- ★ Two-body interaction v_2: AV18 (isospin dependent)
- ★ Effective three-body force V_3^{eff}

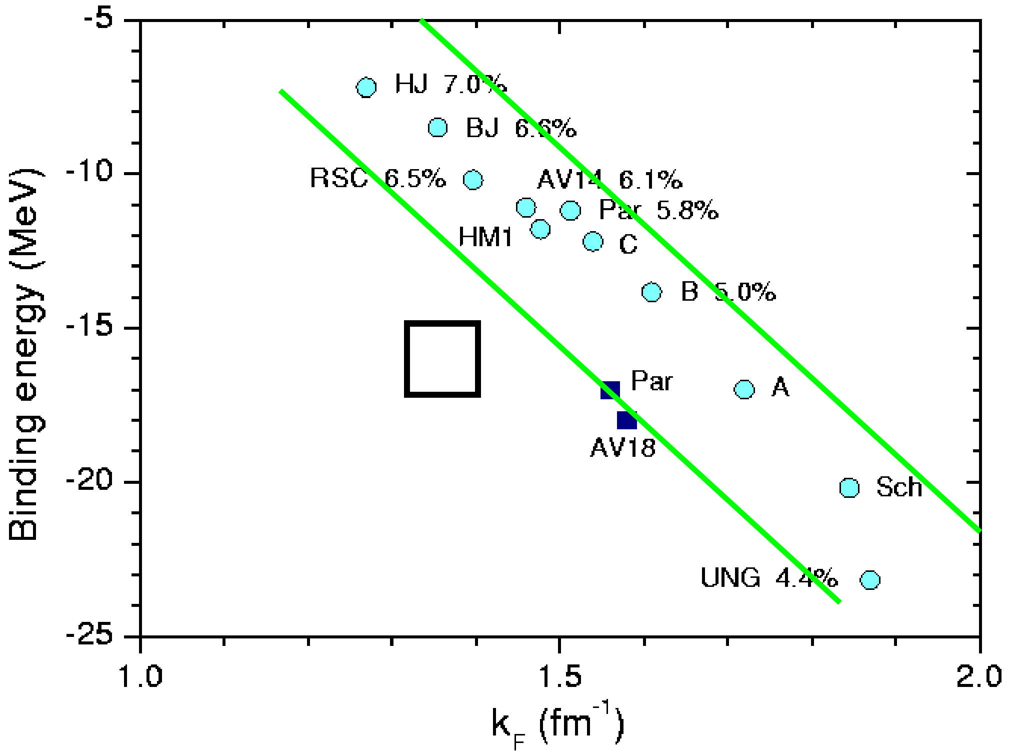
→ Pauli operator : $Q(k_1,k_2)=[1-n(k_1)][1-n(k_2)]$

→ Single particle energy : $\varepsilon(k)=\frac{\hbar^2k^2}{2m}+U_{BHF}(k)$

→ “Auxiliary” potential : continuous choice $U(k)=\sum_{k'}n(k')\,\mathrm{Re}\langle kk'|G[\varepsilon(k)+\varepsilon(k')]|kk'\rangle_A$

Nuclear Matter Saturation Problem

The model of rigid nucleons interacting via realistic two-body forces fitting in-vacuum nucleon-nucleon scattering data can not reproduce the empirical saturation properties of nuclear matter (Coestor band, Coestor et al., PRC1(1970)765)



Effective NN interaction

- **Dirac-Brueckner approach** [R.Machleidt, Adv. Nucl. Phys. **16** (1989) 189; Serot andWalecka, Int. Journ. Mod. Phys. E6(1997) 515]

- There are on the market different ways on how to introduce the medium effects:
  - Phenomenologocal three-body force

$$V_{ijk} = V_{ijk}^{2\pi} + V_{ijk}^{R}$$

--- Two or few adjustable parameters, which are adjusted simultaneously on nuclear saturation point and light nuclei (^{3}He)properties.

--- Extensively applied to neutron star physics within both variational approach [Wiringa et al., PRC38(1988) 1010; Akmal et al., PRC56 (1997)2261; C58(98) 1804.] and BHF approach [Baldo et al., Astron. Astrophys. 328(1997) 274.]

  - Microscopic three-body force

At the lowest mean field approximation, two problems of BHF approach for predicting nuclear s.p. properties:

1. At densities around the saturation density, the predicted optical potential depth is too deep as compared to the empirical value, and it destroy the Hugenholtz-Van Hove (HVH) theorem.

   Solution: to include the effect of ground state correlations

   J. P. Jeukenne *et al.*, Phys. Rep. **25** (1976) 83

   M. Baldo *et al.*, Phys. Lett. **209** (1988) 135; **215** (1988) 19

2. At high densities, the predicted potential is too attractive and its momentum dependence turns out to be too weak for describing the experimental elliptic flow data.

   P. Danielewicz, Nucl. Phys. **A673** (2000) 375

Improvement in three aspects:

1. Extend the calculation of the effect of ground state correlations to asymmetric nuclear matter

   Zuo, Bombaci, Lombardo, PRC 60 (1999) 024605

2. Include a microscopic three-body force (TBF) in the BHF calculation

   Zuo, Lejeune, Lombardo, Mothiot, NPA706 (2002) 418; EPJA 14(2002)469;

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

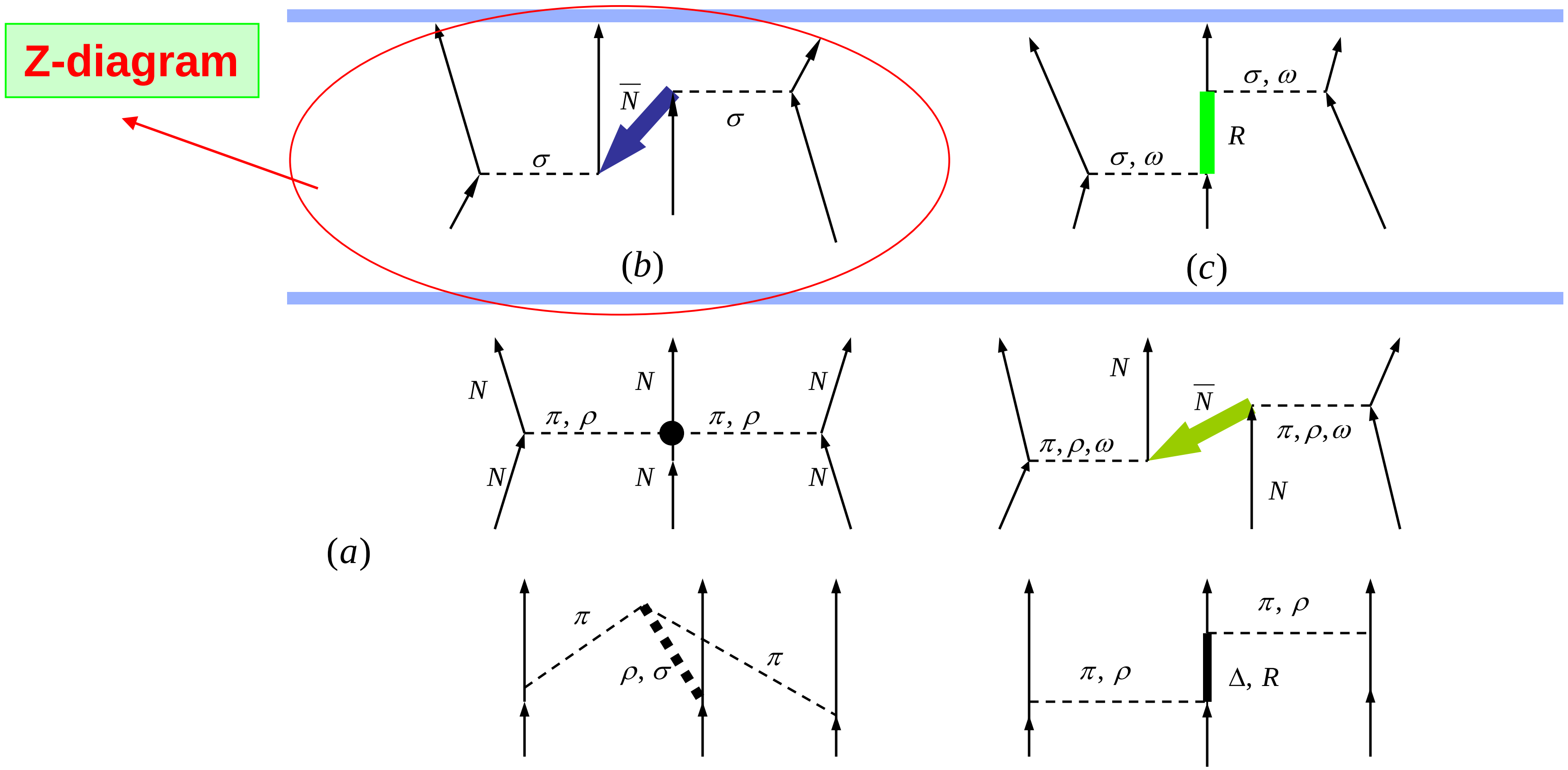
3. The TBF-induced rearrangement contribution for calculating the s.p. properties in Bruckner theory

   W. Zuo *et al.*, PRC72 (2005)014005; PRC74 (2006) 014317

Microscopic Three-body Forces

- **Based on meson exchange approach**
- **Be constructed in a consistent way with the adopted two-body force ----- microscopic TBF !**

Grange *et al.*, PRC40(1989)1040



Z-diagram

Effective Microscopic Three-body Force

Effective three-body force

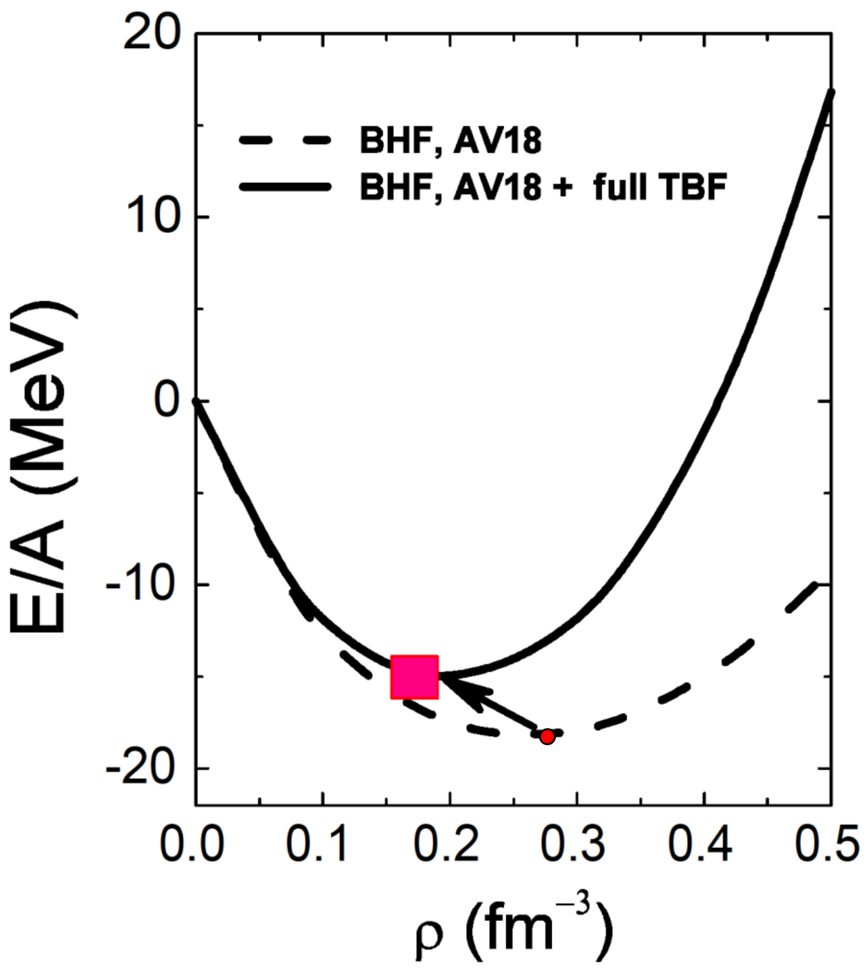
$$V_3^{eff}(\vec{r}_1', \vec{r}_2' | \vec{r}_1, \vec{r}_2) = \frac{1}{4} Tr \sum_n \int d\vec{r}_3 d\vec{r}_3' \, \varphi_n^*(\vec{r}_3')[1 - \eta(r_{13}')][1 - \eta(r_{23}')]$$
$$\times W_3(\vec{r}_1', \vec{r}_2', \vec{r}_3' \, | \vec{r}_1, \vec{r}_2, \vec{r}_3 \,) \varphi_n(\vec{r}_3)[1 - \eta(r_{13})][1 - \eta(r_{23})]$$

→ Defect function: $\eta(r_{12}) = \Phi(r_{12}) - \Psi(r_{12})$

- ★ Short-range nucleon correlations (Ladder correlations)
- ★ Evaluated self-consistently at each iteration

- ➢ **Effective TBF ---- Density dependent**
- ➢ **Effective TBF ---- Isospin dependent for asymmetric nuclear matter**

EOS of SNM & saturation properties



TBF is necessary for reproducing the empirical saturation property of nuclear matter in a non-relativistic microscopic framework.

Saturation properties:

ρ (fm^{-3})	E_A (MeV)	K (MeV)
0.19	–15.0	210
0.26	–18.0	230

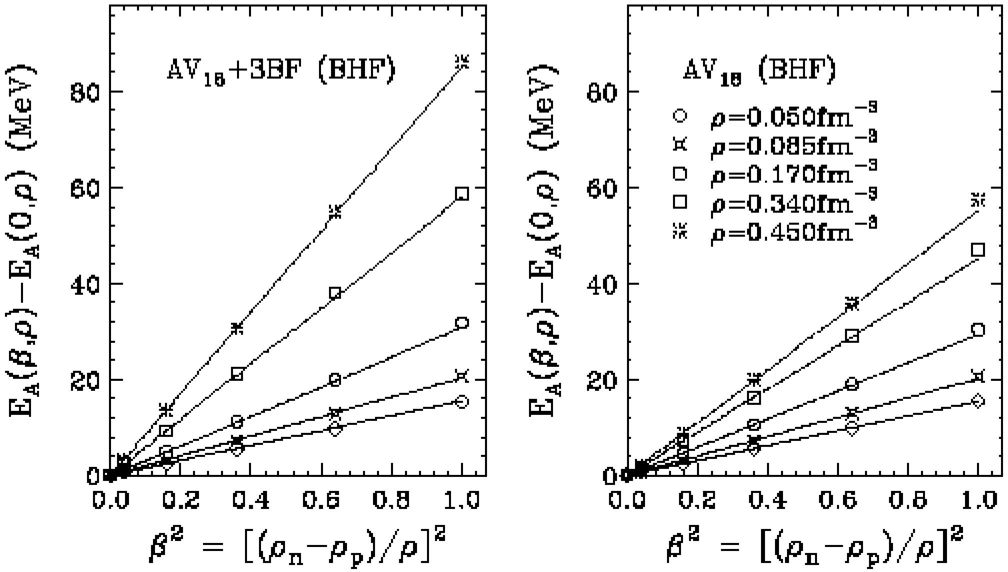
W. Zuo, A. Lejeune, U.Lombardo, J.F.Mothiot, NPA706(2002)418

Isospin dependence of the EOS

Parabolic law : linear dependence on β^2

$$E_A(\rho, T, \beta) = E_A(\rho, T, 0) + E_{sym}(\rho, T)\beta^2$$

Bombaci, Lombardo, *PRC* 44 (1991) 1892
Zuo, bombarci, Lombardo, PRC 60 (1999) 024605



W. Zuo, A. Lejeune, U.Lombardo, J.F.Mothiot,
Nucl.Phys.A706(2002)418

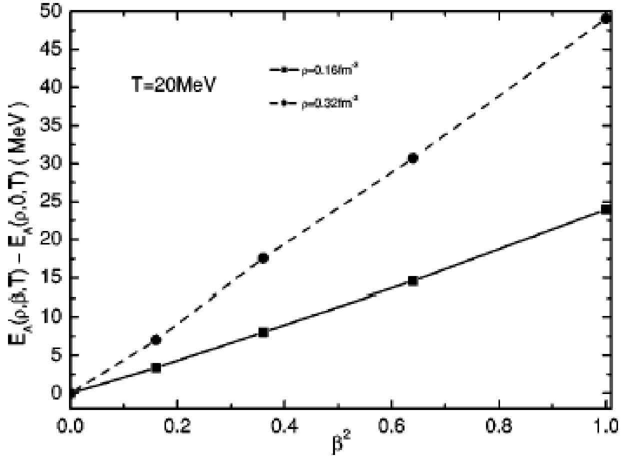
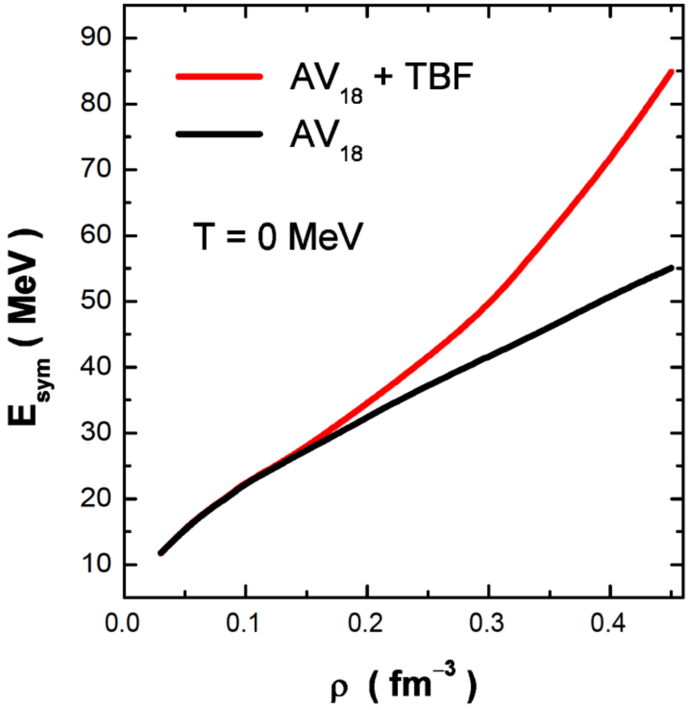


FIG. 5. Energy per nucleon $E_A(\rho, \beta, T) - E_A(\rho, \beta=0, T)$ versus β^2 in the range $0 \leqslant \beta \leqslant 1$ for two different densities. The results are obtained by including the TBF.

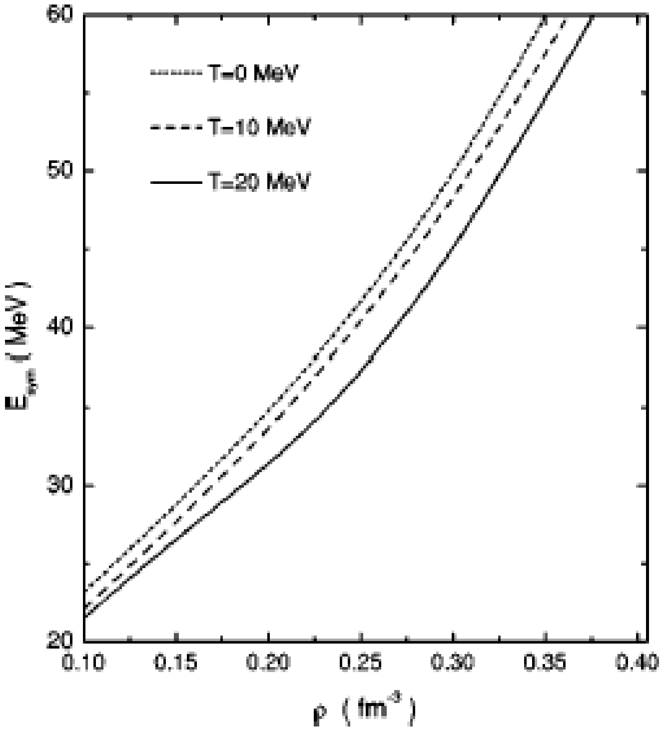
W. Zuo et al., Phys. Rev. C69 (2004) 064001

Density dependence of symmetry energy

TBF effect

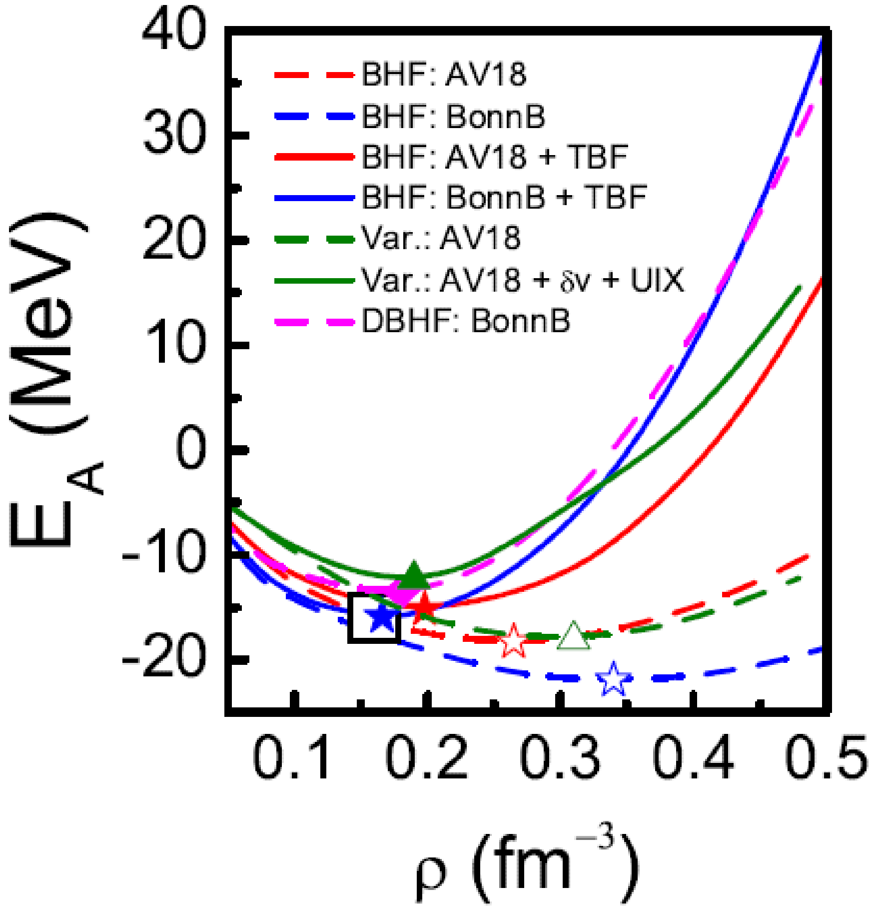


Thermal effect

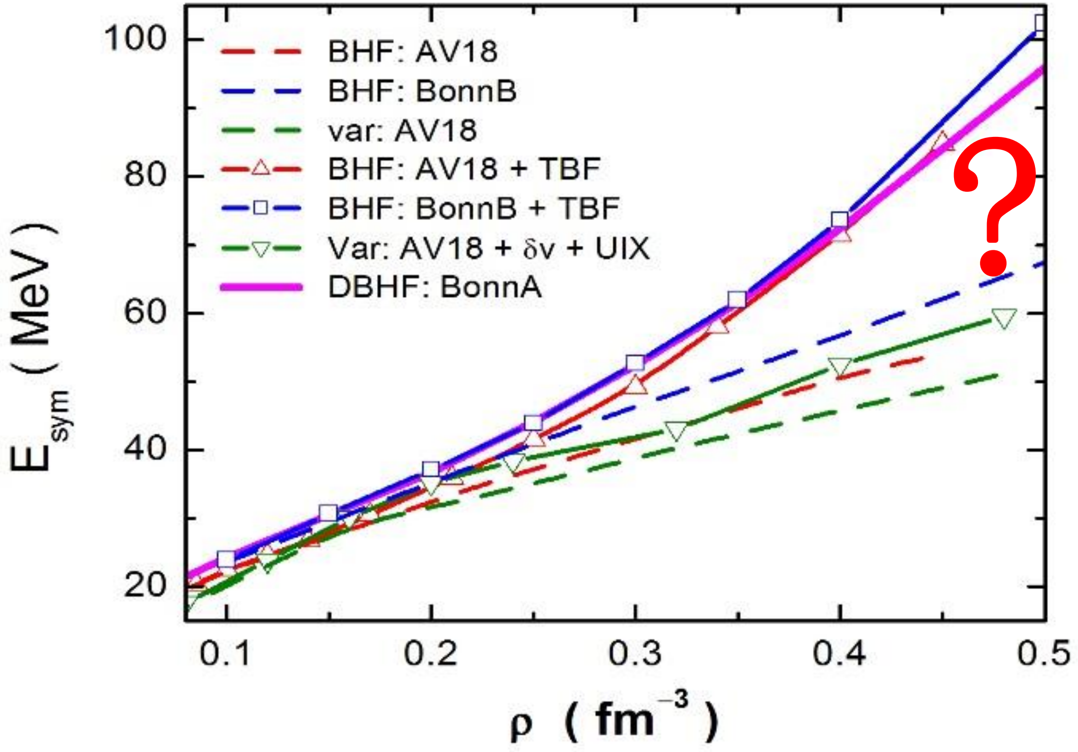


Predictions from different *ab. initio* approaches

EOS of symmetric nuclear matter



Density dependence of symmetry energy

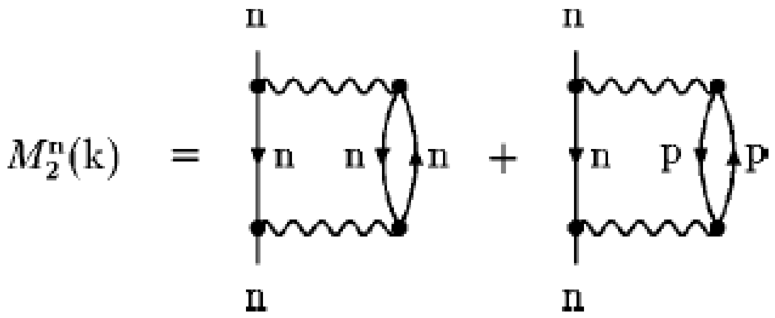


Single Particle Potential beyond the mean field approximation:

1. Single particle potential at lowest BHF level

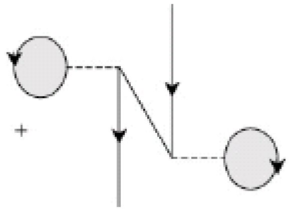
$$U_{BHF}(k)=\sum_{k'} n(k')\,\mathrm{Re}\langle kk'|G[\varepsilon(k)+\varepsilon(k')]|kk'\rangle_A$$

2. Ground state correlation



3. TBF rearrangement

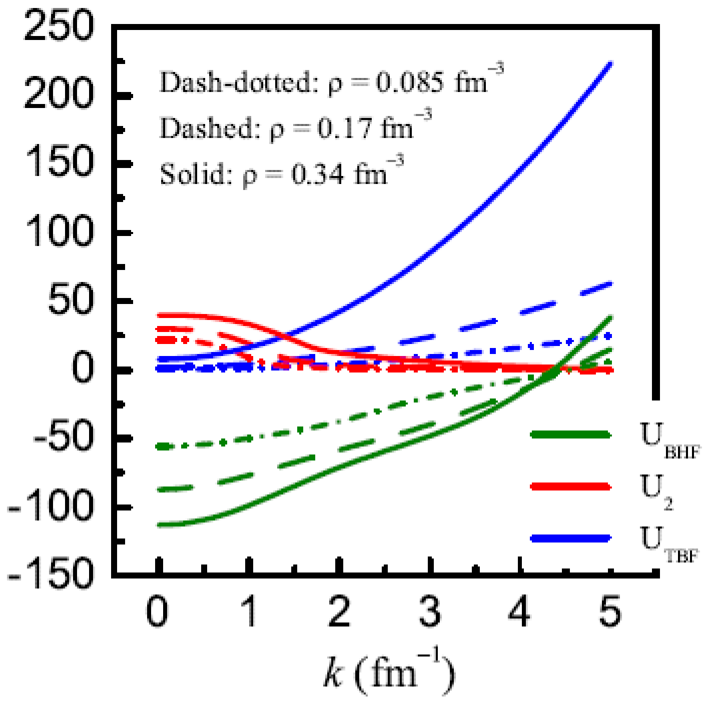
$$\Sigma_{\mathrm{TBF}}(k)=\frac{1}{2}\sum_{ij}\left\langle ij\left|\frac{\delta V_3^{\mathrm{eff}}}{\delta n_k}\right|ij\right\rangle_A n_i n_j$$



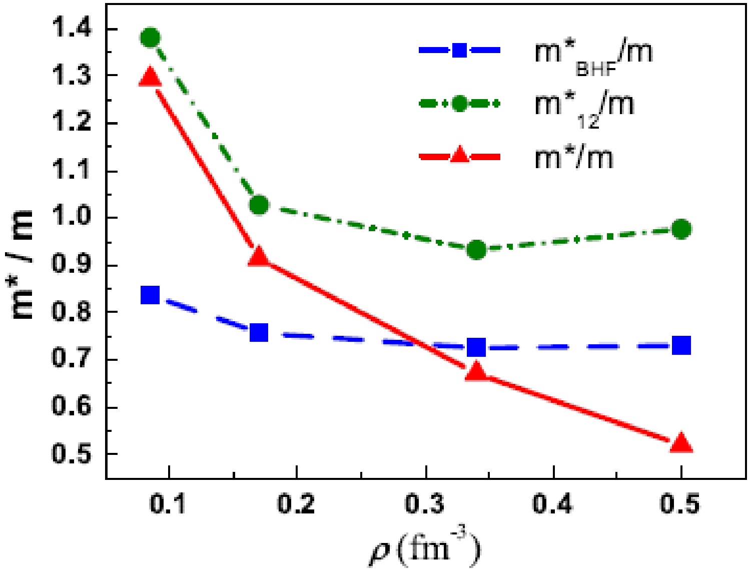
Full s.p. potential: $U(k)=U_{BHF}(k)+U_2(k)+U_{TBF}(k)$

Single particle properties in SNM (TBF effect and g.s. correlation effect)

Single particle potential

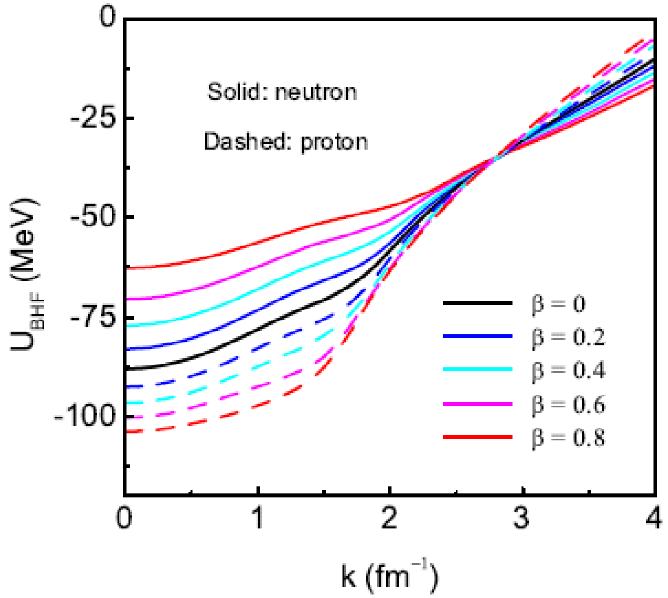


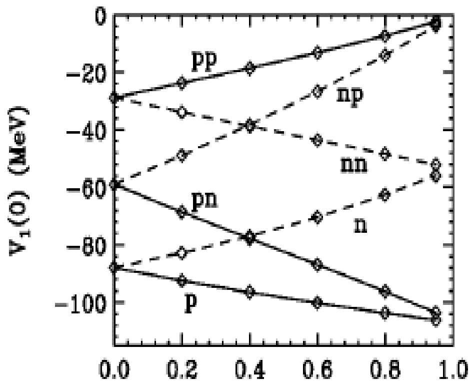
Effective mass



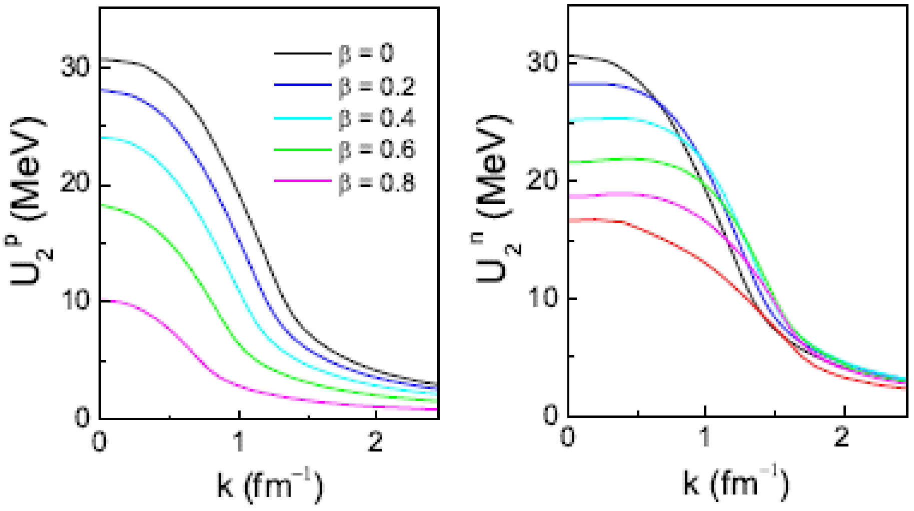
Single particle potentials in ANM (TBF contribution and the effect of g.s. correlations)

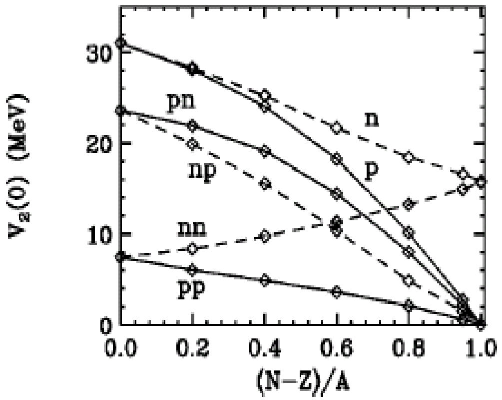
Lowest BHF approximation



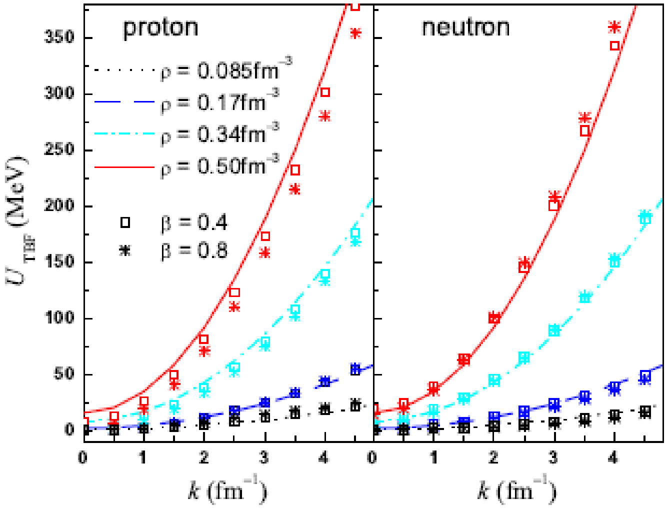


Pauli rearrangement contribution



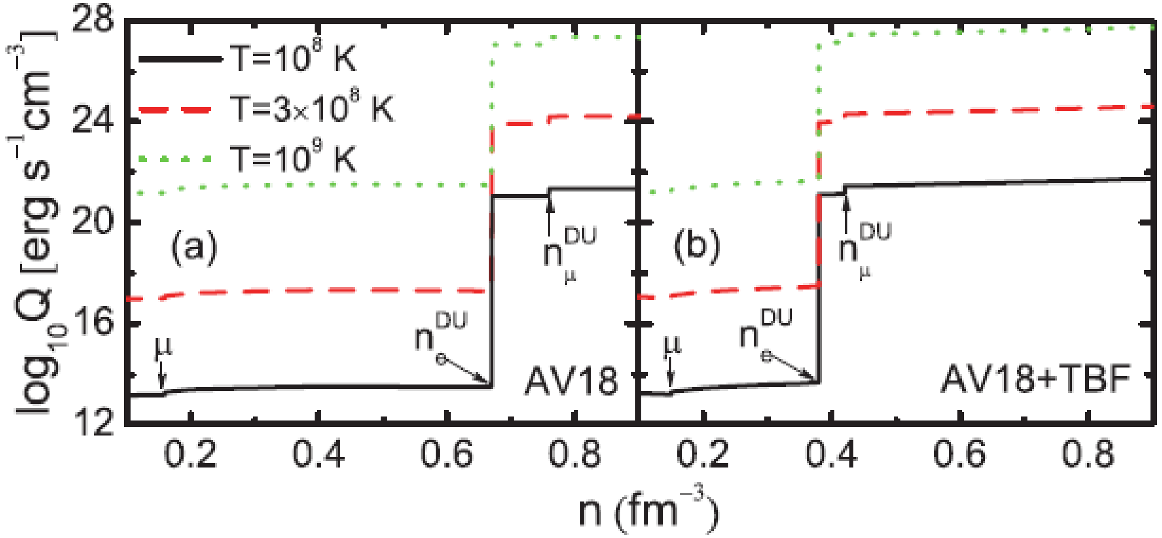


TBF rearrangement contribution



TBF effect on Neutrino emissivity of neutron star matter

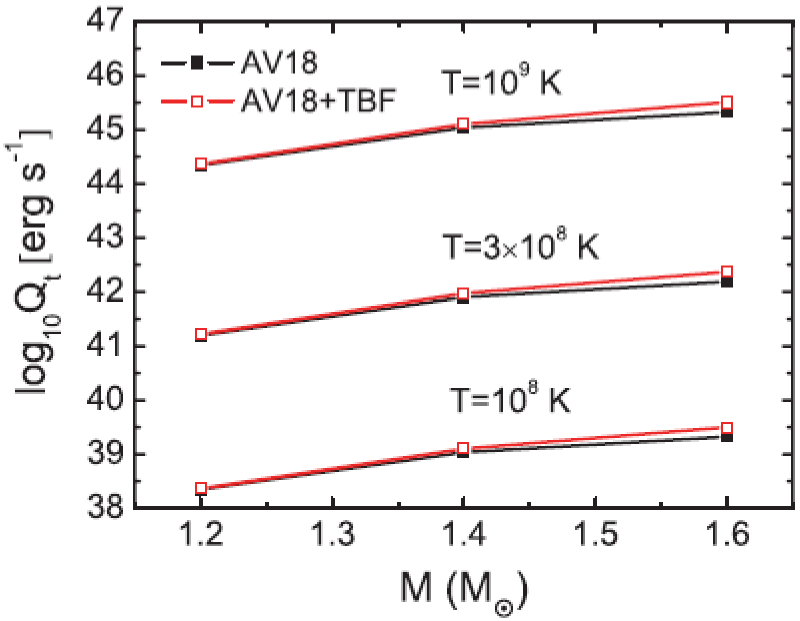
Density dependence of the neutrino emissivity in neutron star matter



Critical density for DU process
Without three-body force $n_e^{DU} = 0.67\ \text{fm}^{-3}$

Critical density for DU process
With three-body force $n_e^{DU} = 0.38\ \text{fm}^{-3}$

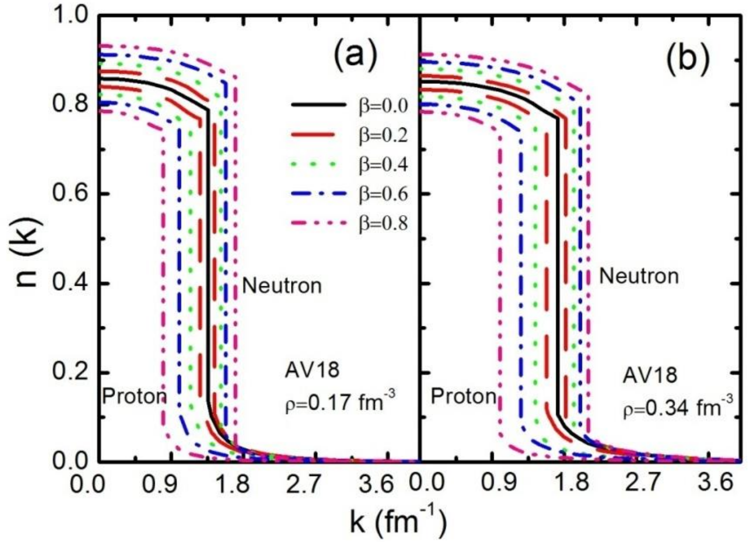
Total neutrino emissivity of neutron stars



The TBF effect on the total neutrino emissivity is not as strong as expected, and it leads an enhancement of the total neutrino emissivity of a neutron star with a given mass of 1.6*M by* only about 50%.

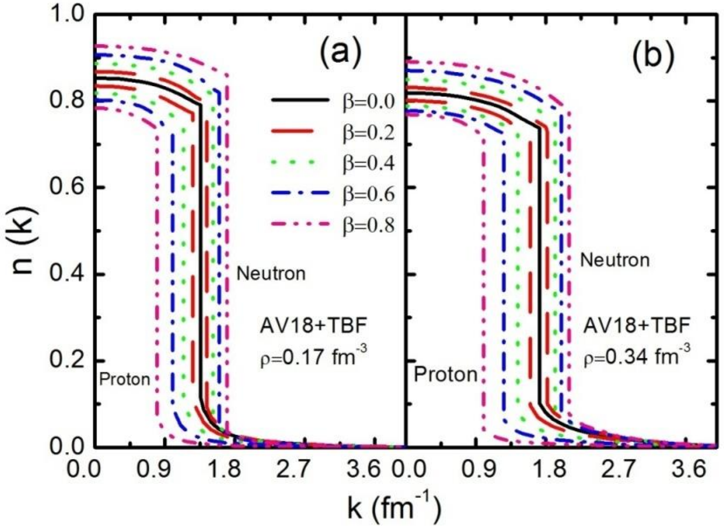
Yin Peng, W. Zuo， Phys. Rev. C **88**, 015804 (2013)

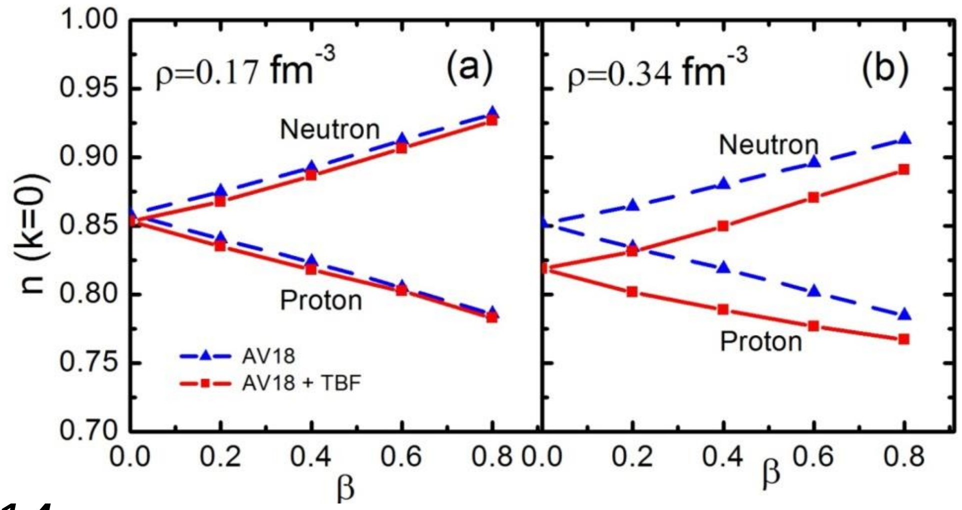
TBF effect on Nucleon momentum distribution in ANM



Without TBF

With TBF



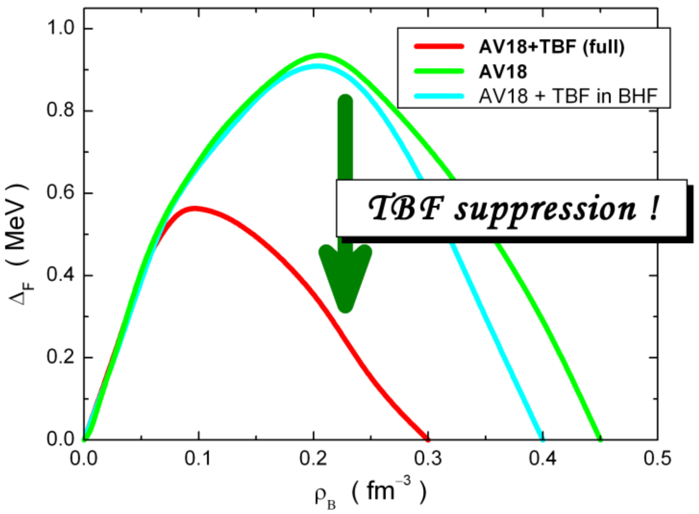


At high densities well above the saturation density, the TBF lead to an enhancement of the depletion of nuclear Fermi sea.

YIN, li, Wang, and Zuo, Phys. Rev. 87 (2013) 014314

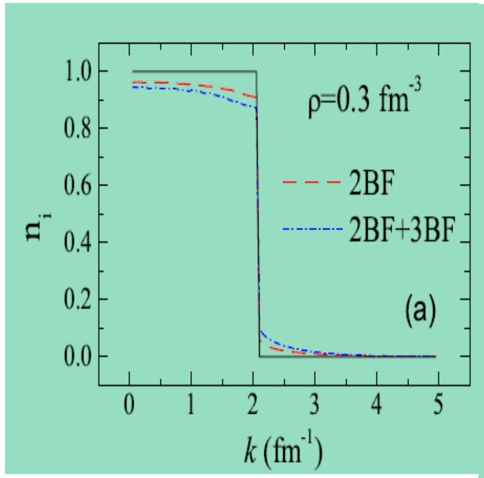
Effects of TBF and short-range correlations (SRC) on nucleon superfluidity in neutron star matter

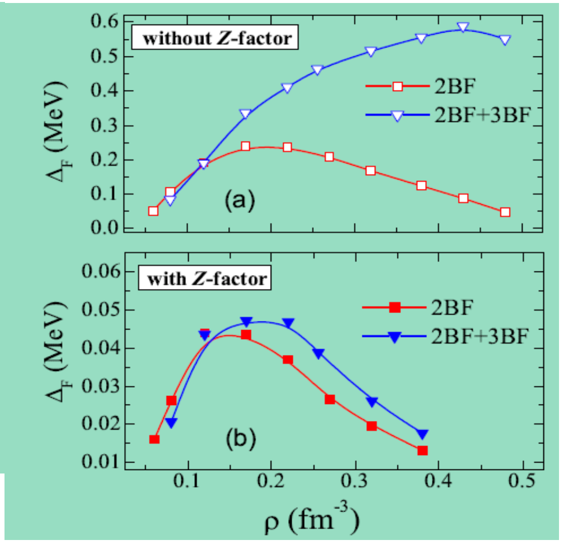
1S0 proton superfluidity in neutron star matter



W. Zuo *et al*., PLB 595(2004)44

3PF2 neutron superfluidity in neutron matter and neutron star matter





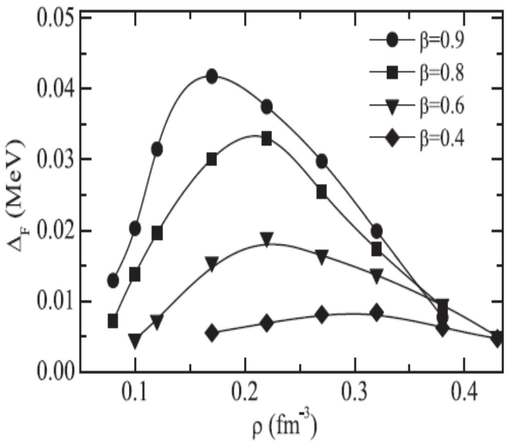
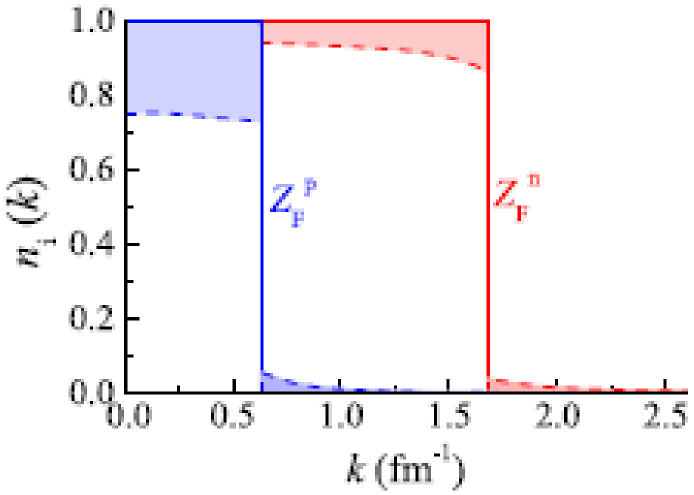


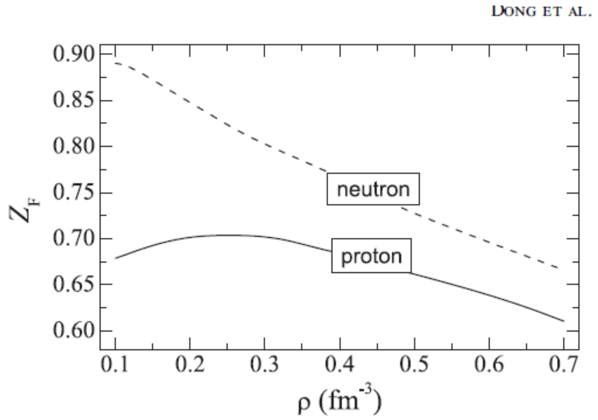
Figure 4. Neutron $^3PF_2$ gap as a function of nucleonic density in asymmetric matter for various isospin asymmetries β.

Dong, Lombardo and Zuo, PRC **87**, 062801(R) (2013)

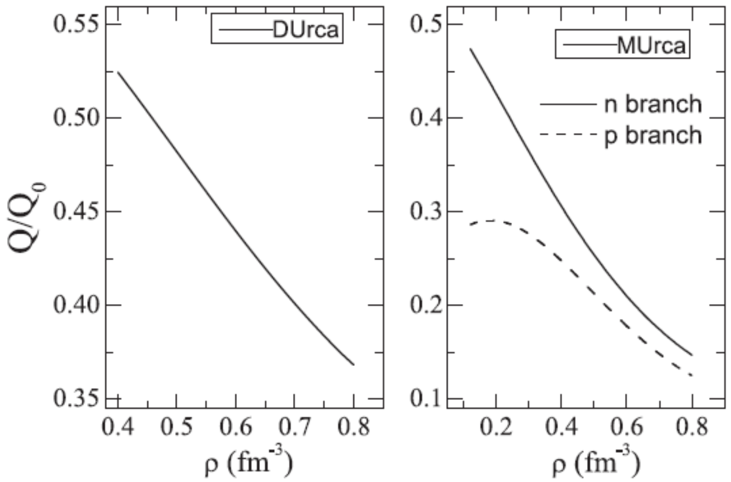
Effect of SRC on neutron star cooling



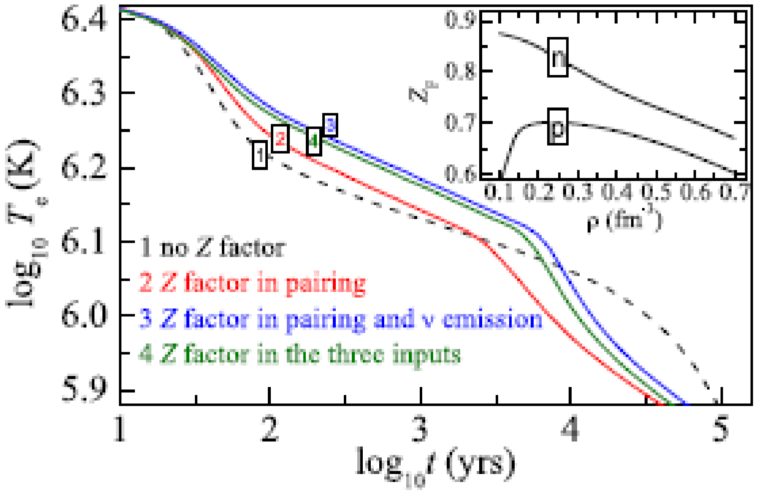
Depletion of Fermi surface in neutron star matter



Neutrino emissivity for DU and MU processes in neutron stars



Cooling curve of neutron stars



~ The SRC reduces the neutrino emissivity of DU process by more than 50%, which is in complete contrast to the previous expectation.

~ The cooling rates of young NSs are significantly slowed due to the SRC

Dong et al., APJv817(2016)6

Summary

TBF provides a repulsive contribution to the EOS of nuclear matter and improves remarkably the predicted saturation properties.

TBF and thermal effect do not alter he empirical parabolic law fulfilled by the EOS of ANM.

TBF may lead to a strong enhancement of the stiffness of symmetry energy at high densities.

TBF induces a strongly repulsive and momentum-dependent rearrangement contribution to the s.p. potential at high densities.

At high densities, TBF may lead to an enhancement of the depletion of nuclear Fermi sea.

The TBF effect on the total neutrino emissivity is not as strong as expected.

SRC may suppress strongly the nucleon superfludities inside neutron stars.

SRC may reduce significantly the cooling rates of young neutron stars.

Thank you for attention！