

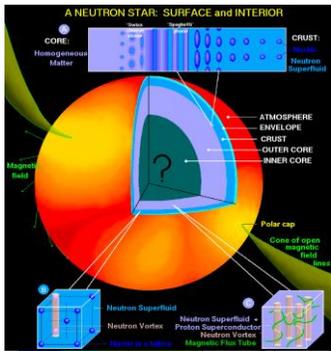
NN2015, June 21-27, 2015

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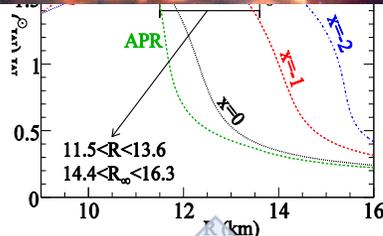
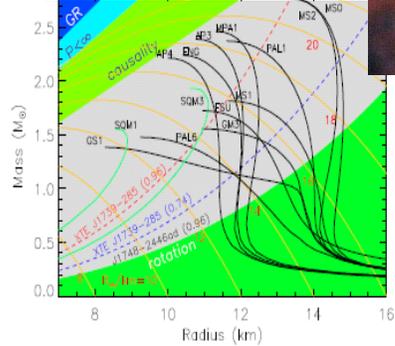
# Three-body force effect on the properties of neutron-rich nuclear matter

Wei Zuo

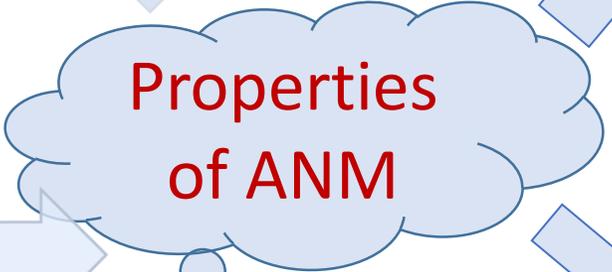
Institute of Modern Physics, Lanzhou, China



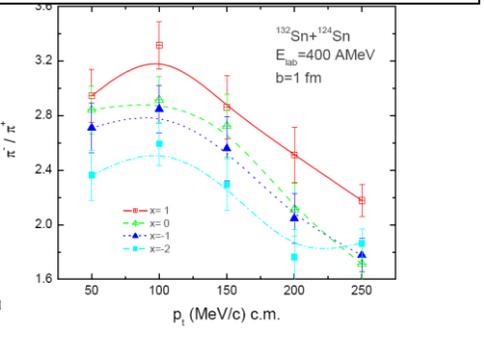
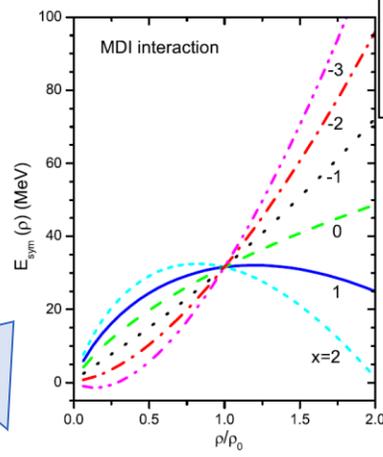
# Neutron star structure



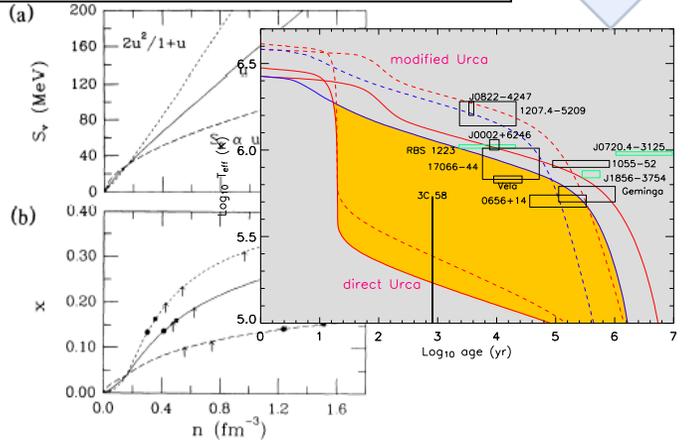
# Nuclear many-body model



# Isospin transport in HIC

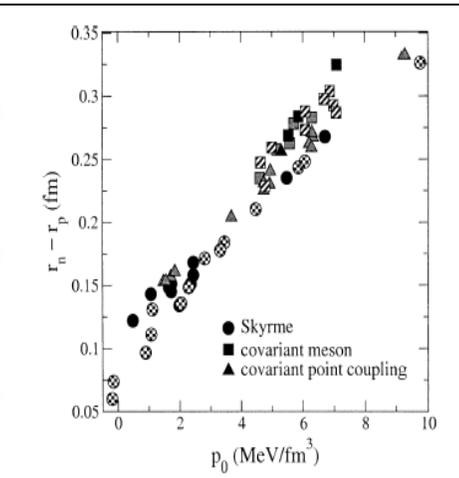
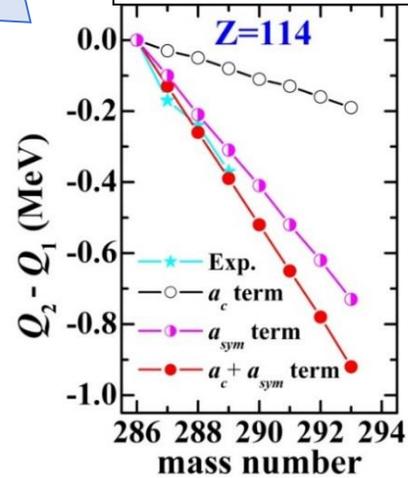


# Neutron star cooling



# Effective NN interaction in nuclear medium

# Properties of neutron-rich nuclei and heavy nuclei



# Theoretical Approaches

- Skyrme-Hartree-Fock
- Relativistic Mean Field Theory
- Relativistic Hartree-Fock
  
- Variational Approach
- Green's Function Theory
- Brueckner Theory
- Dirac-Brueckner Approach
- Effective Field Theory

# Bethe-Goldstone Theory

Bethe-Goldstone equation and effective  $\mathbf{G}$ -matrix

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

→  $v_{NN}$  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  $V_3^{eff}$

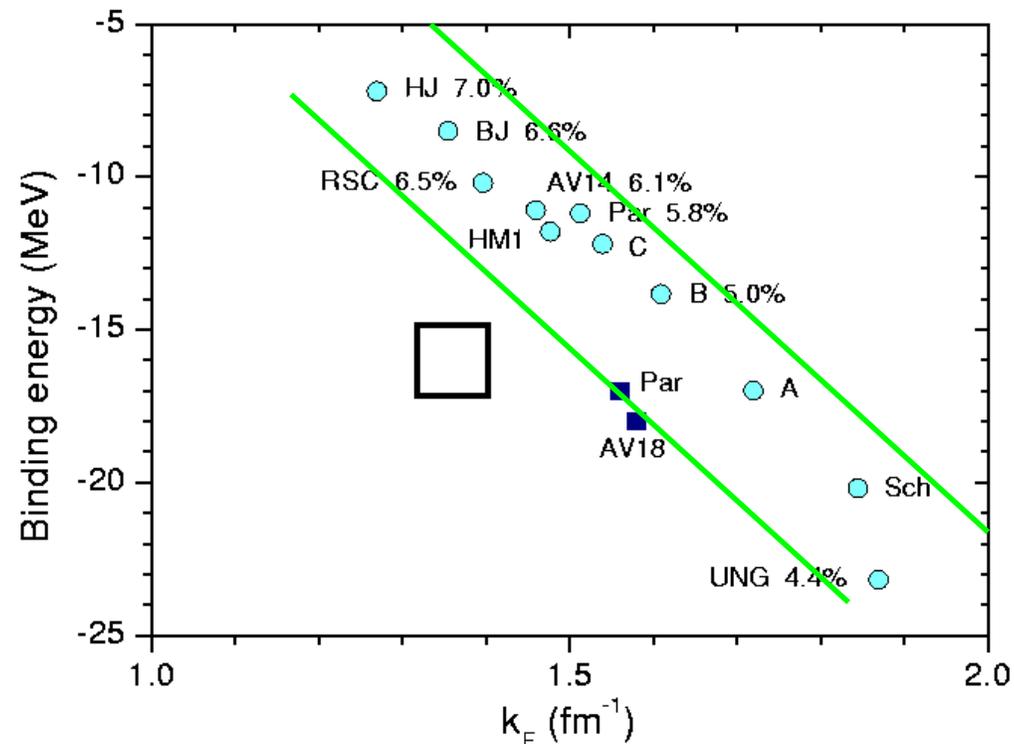
→ Pauli operator :  $Q(k_1, k_2) = [1 - n(k_1)][1 - n(k_2)]$

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

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

# 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 (**Coester band**, Coester et al., PRC1(1970)765)



# Effective NN interaction

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➤ 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:

## ◆ Phenomenological 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 (<sup>3</sup>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:

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1. At densities around the saturation density, the predicted optical potential depth is too deep as compared to the empirical value, and it destroys 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:

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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;

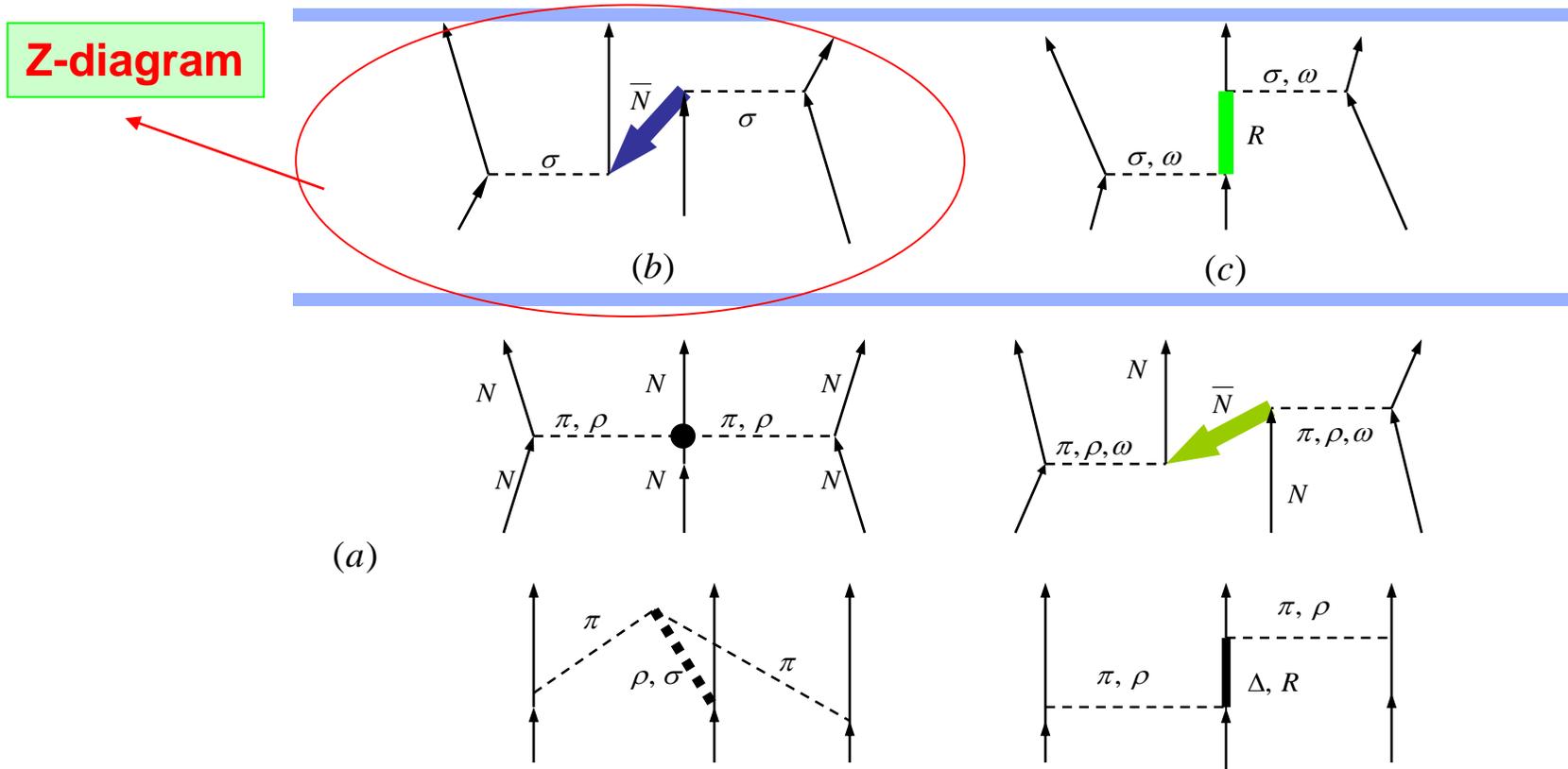
Z. H. Li *et al.*, PRC 77 (2008) 034316

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



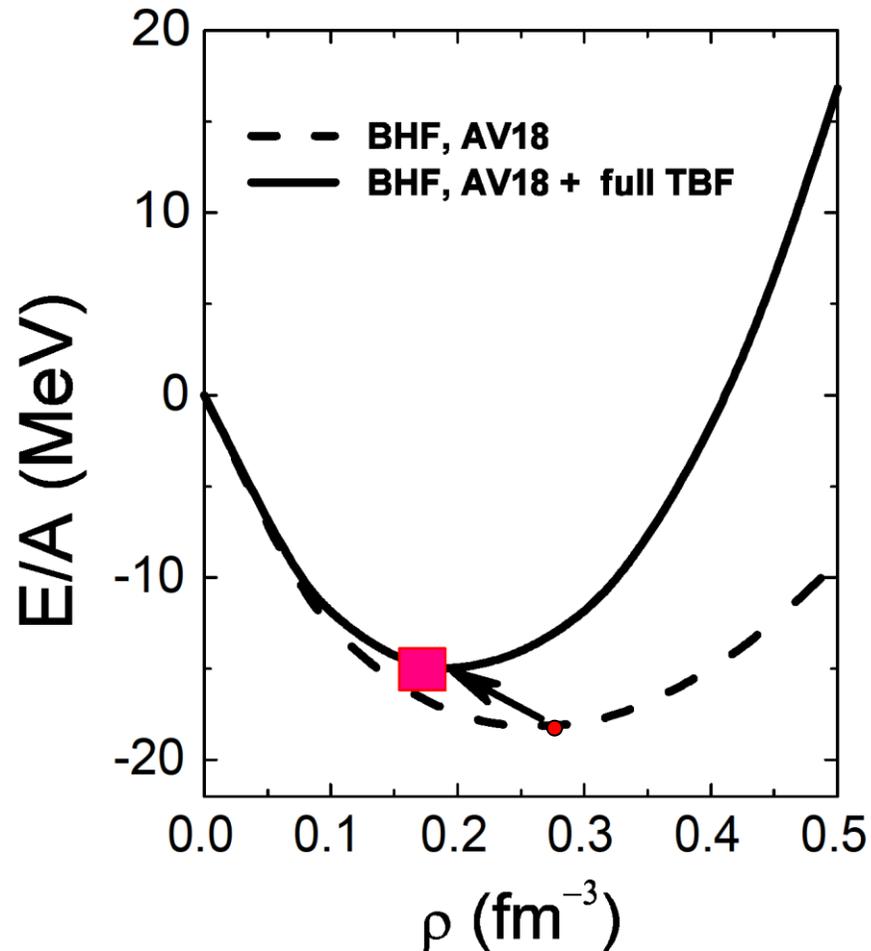
# Effective Microscopic Three-body Force

## 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:

$\rho$ (fm <sup>-3</sup> )	$E_A$ (MeV)	$K$ (MeV)
0.19	-15.0	210
0.26	-18.0	230

# Isospin dependence of the EOS

Parabolic law : linear dependence on  $\beta^2$

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

Bombaci, Lombardo, *PRC* 44 (1991) 1892

Zuo, bombarci, Lombardo, *PRC* 60 (1999) 024605

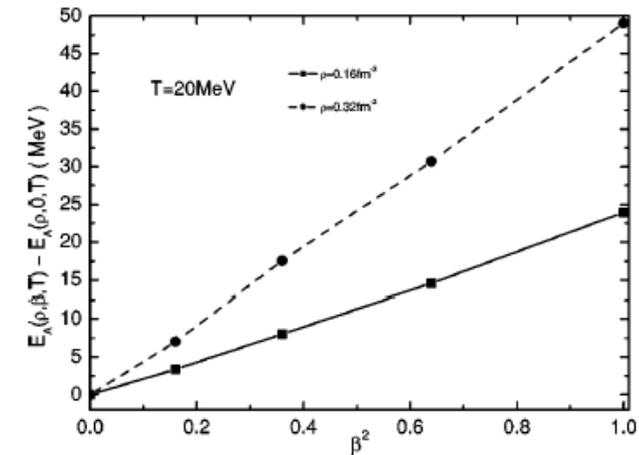
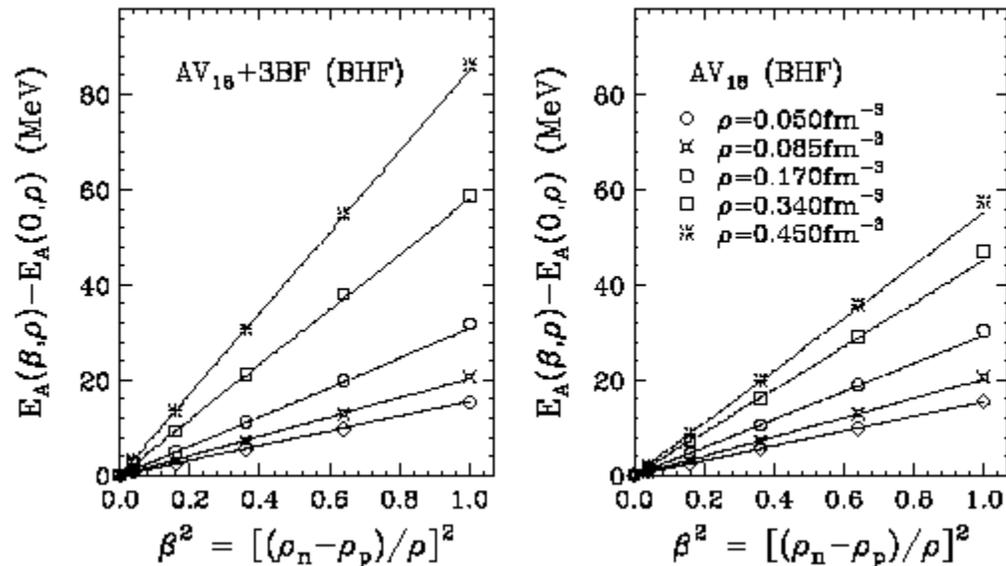


FIG. 5. Energy per nucleon  $E_A(\rho, \beta, T) - E_A(\rho, 0, T)$  versus  $\beta^2$  in the range  $0 \leq \beta \leq 1$  for two different densities. The results are obtained by including the TBF.

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

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

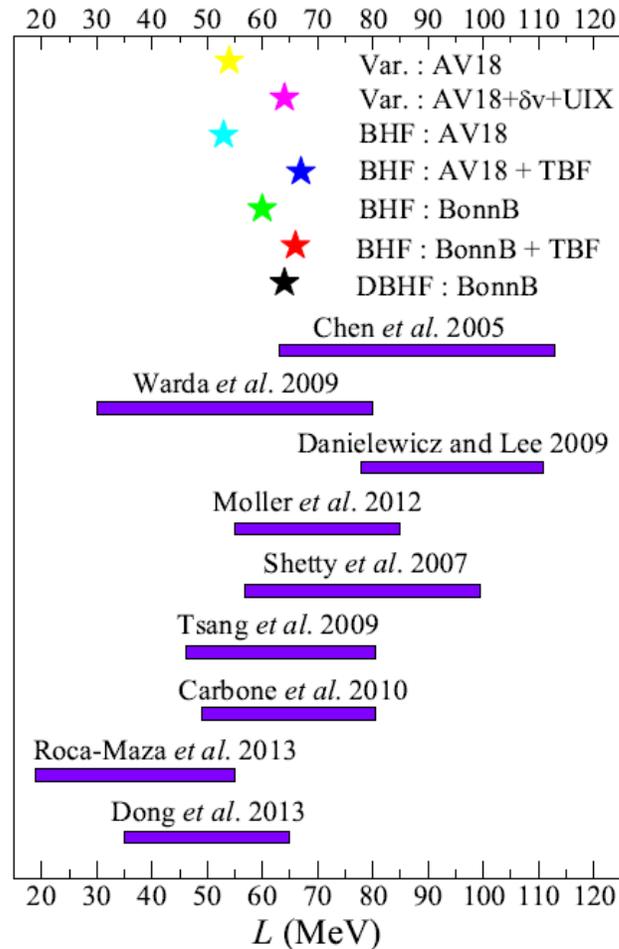
# Density dependence of symmetry energy: Slope parameter around saturation density

Experimental constraints:

$$20\text{MeV} < \bar{L} < 120\text{MeV}$$

Microscopic predictions:

$$50\text{MeV} < L < 70\text{MeV}$$



Microscopic predictions

Neutron skin thickness

Surface symmetry energy

Nuclear mass

Isospin diffusion & isoscaling

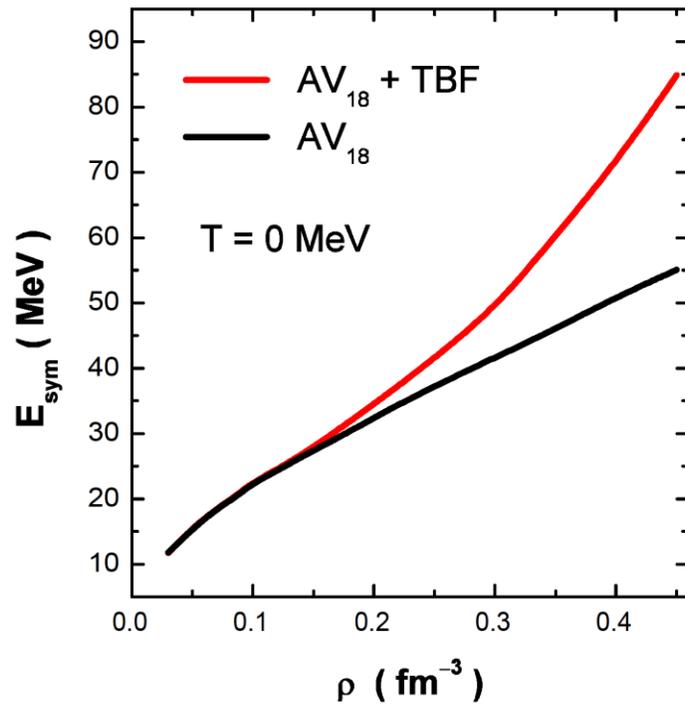
Pymgy dipole resonance

IVGQR

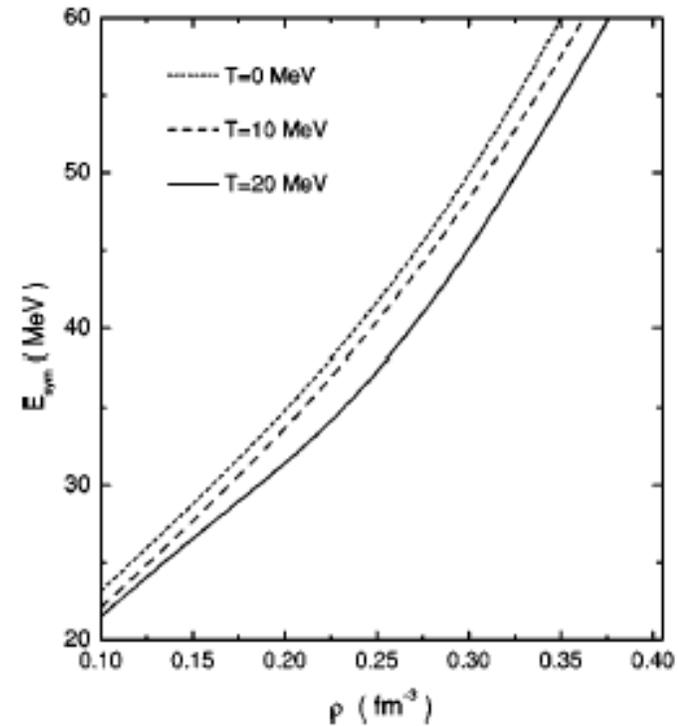
$\beta$ -decay energy of heavy nuclei

# Density dependence of symmetry energy

## TBF effect

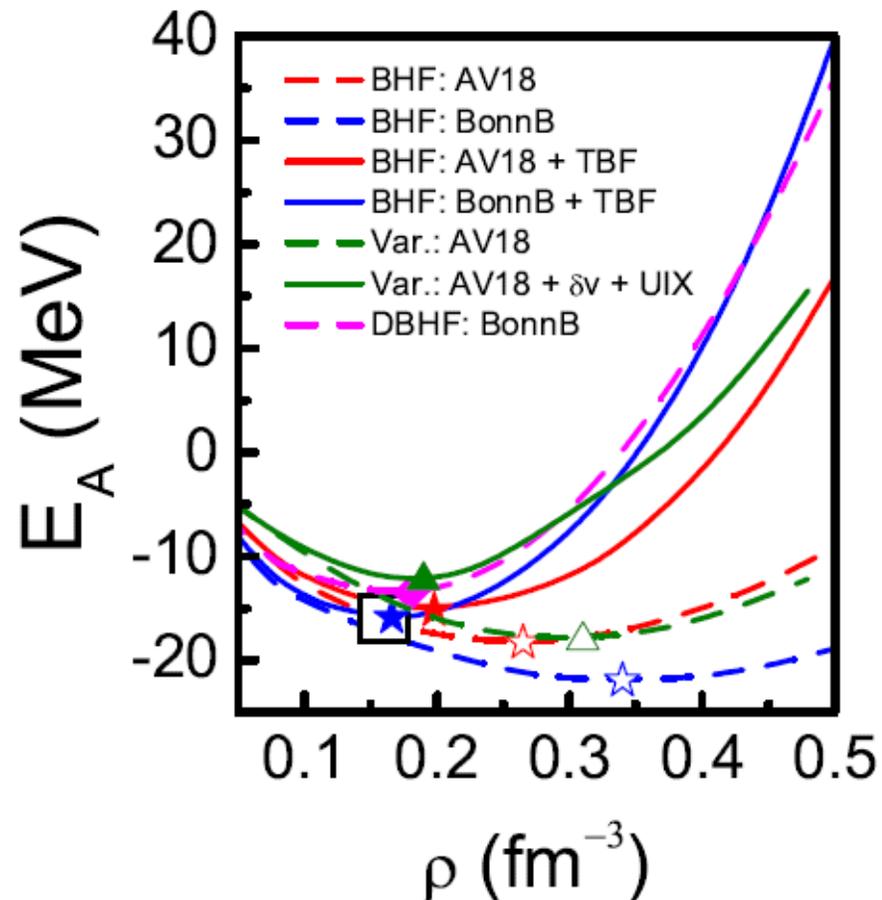


## Thermal effect

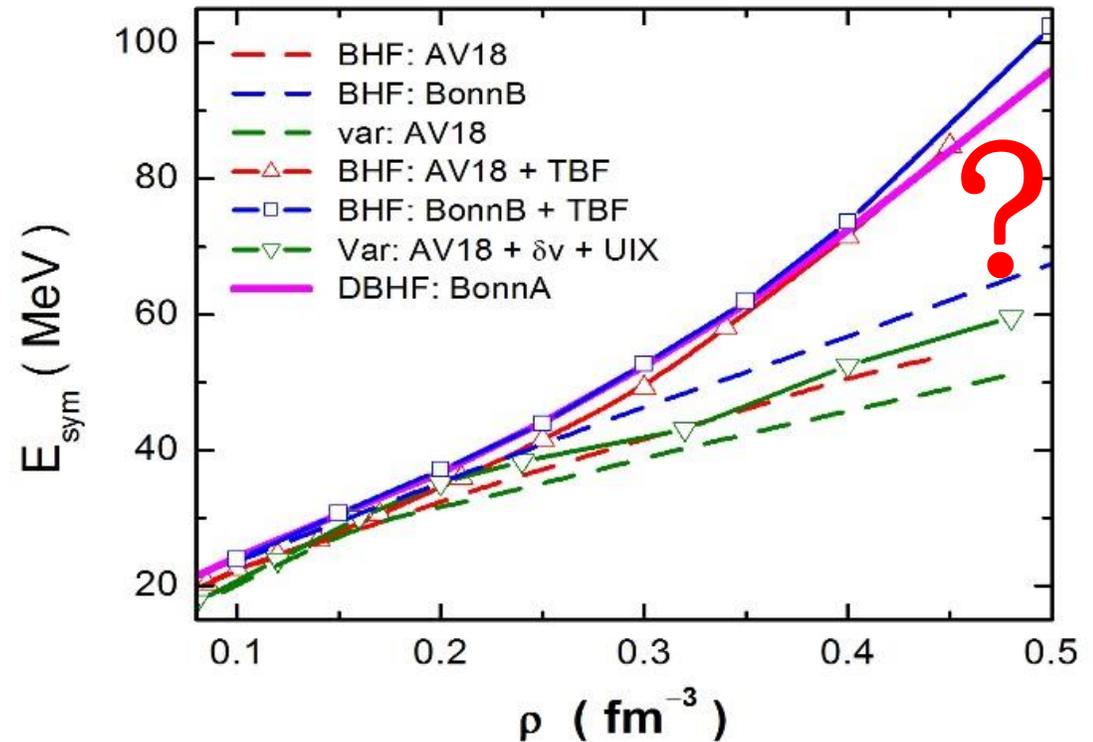


# Predictions from different *ab. initio* approaches

## 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

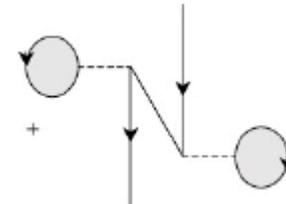
$$U_{BHF}(k) = \sum_{k'} n(k') \text{Re} \langle kk' | G[\varepsilon(k) + \varepsilon(k')] | kk' \rangle_A$$

## 2. Ground state correlation

$$M_2^n(k) = \text{Diagram 1} + \text{Diagram 2}$$

## 3. TBF rearrangement

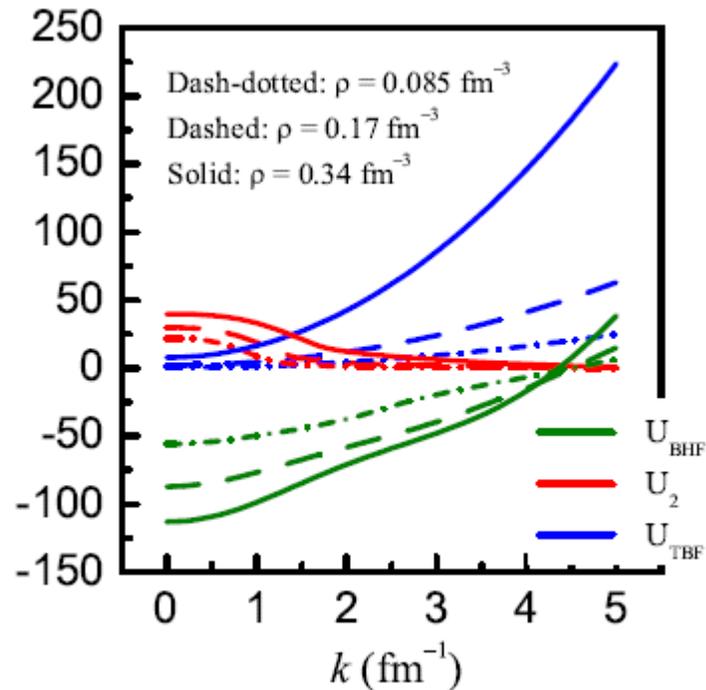
$$\Sigma_{TBF}(k) = \frac{1}{2} \sum_{ij} \left\langle ij \left| \frac{\delta V_3^{\text{eff}}}{\delta n_k} \right| ij \right\rangle_A n_i n_j$$



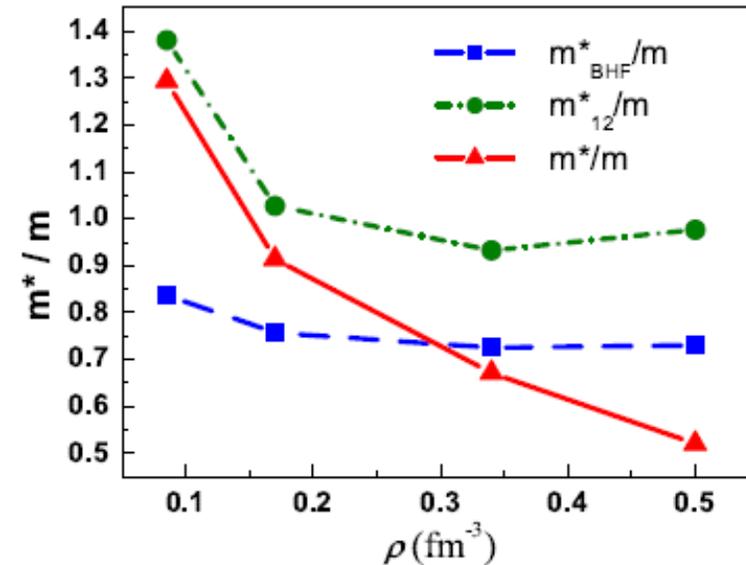
**Full s.p. potential:**  $U(k) = U_{BHF}(k) + U_2(k) + U_{TBF}(k)$

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

## Single particle potential

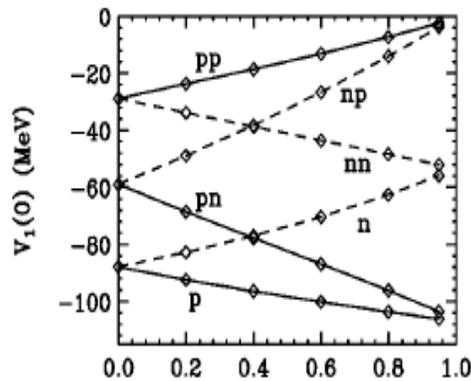
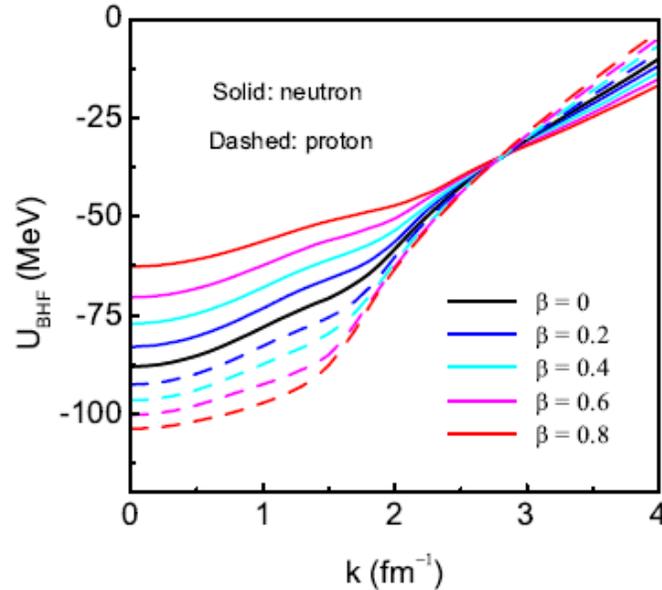


## Effective mass

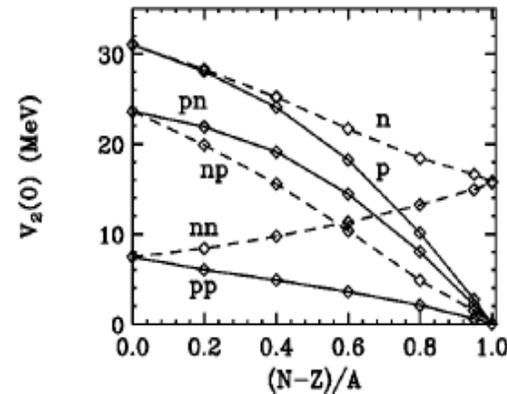
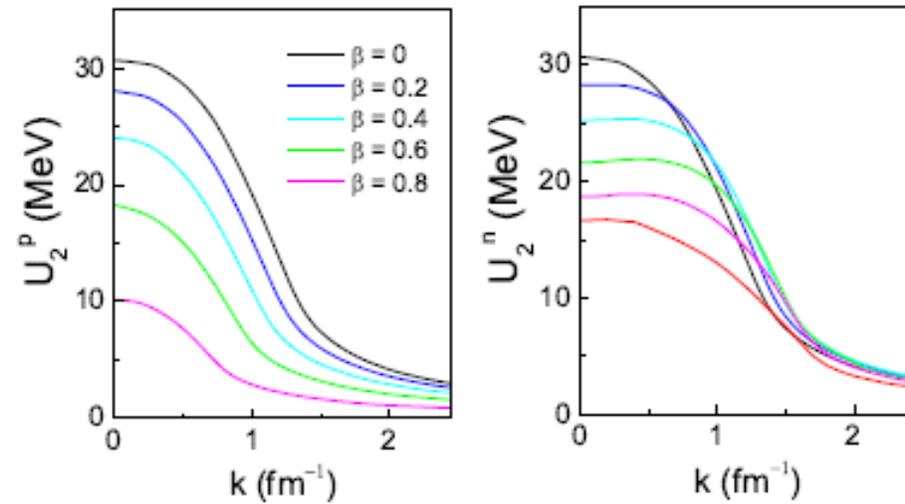


# Single particle potentials in ANM ( TBF contribution and the effect of g.s. correlations )

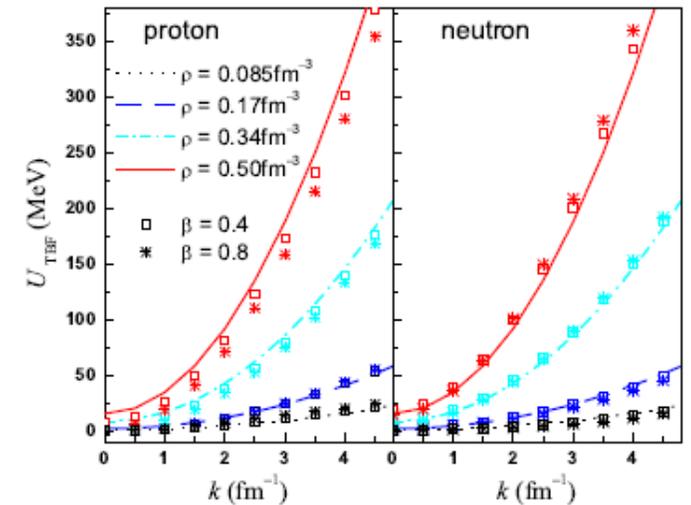
## Lowest BHF approximation



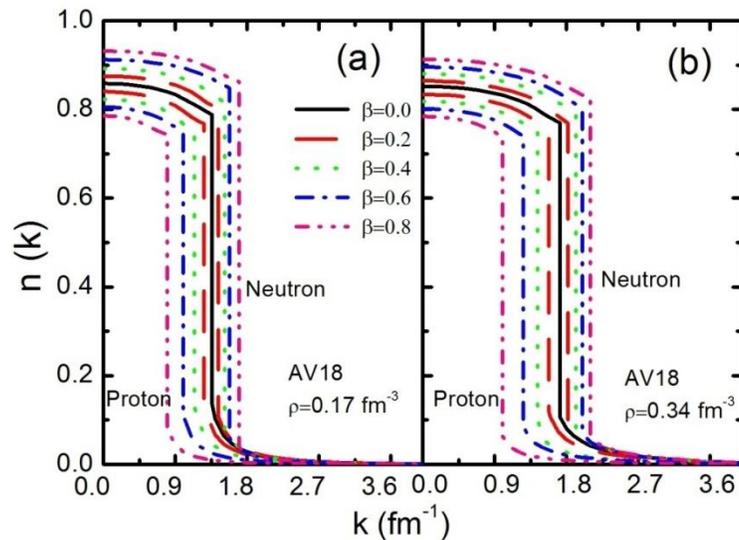
## Pauli rearrangement contribution



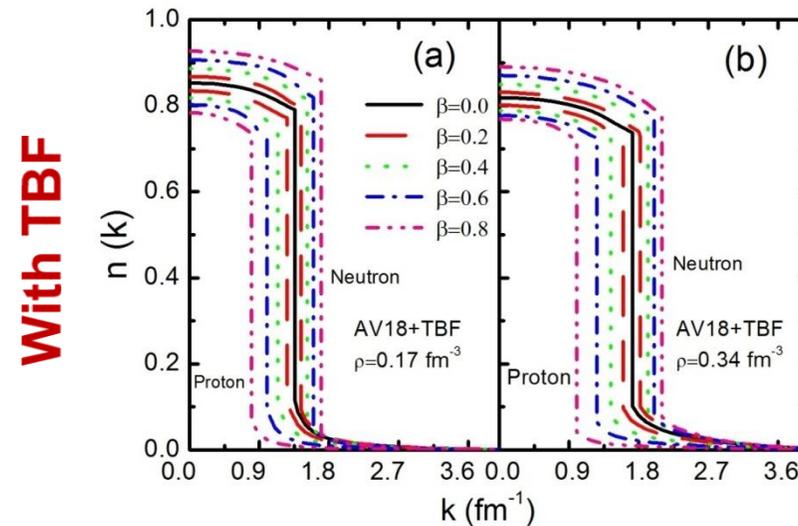
## TBF rearrangement contribution



# TBF effect on Nucleon momentum distribution in ANM

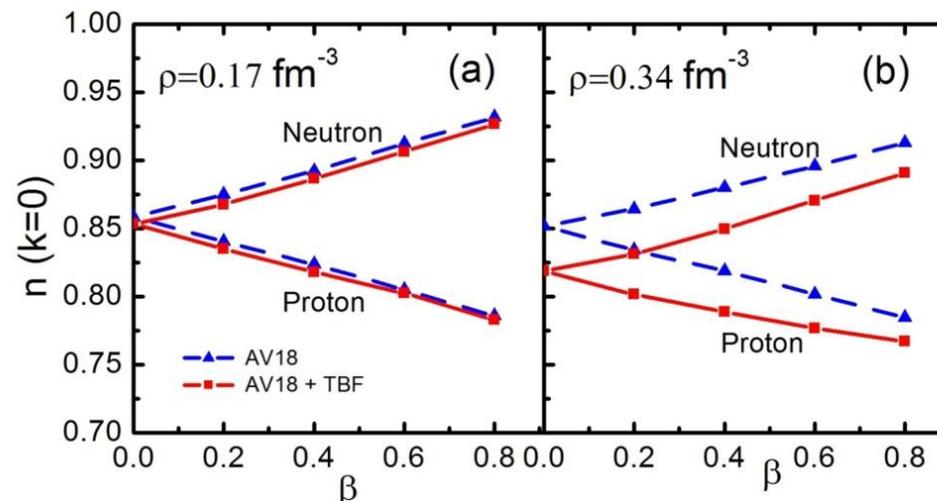


Without TBF



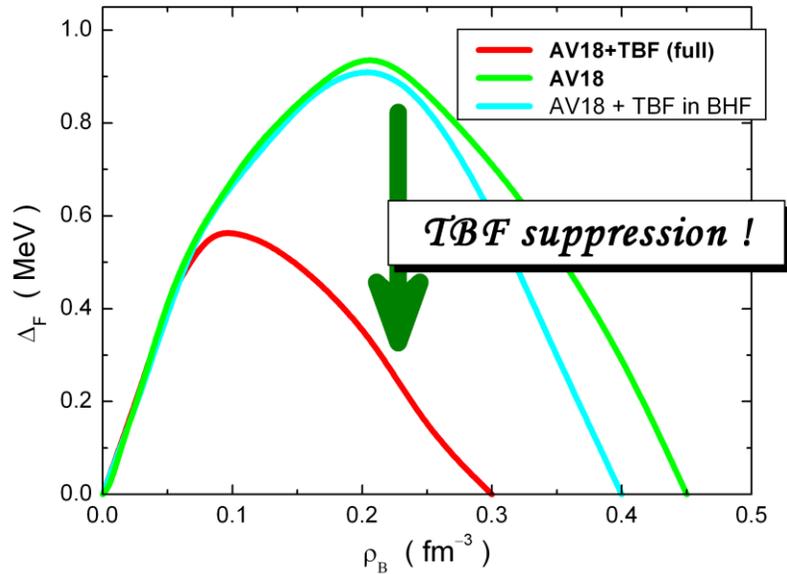
With TBF

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



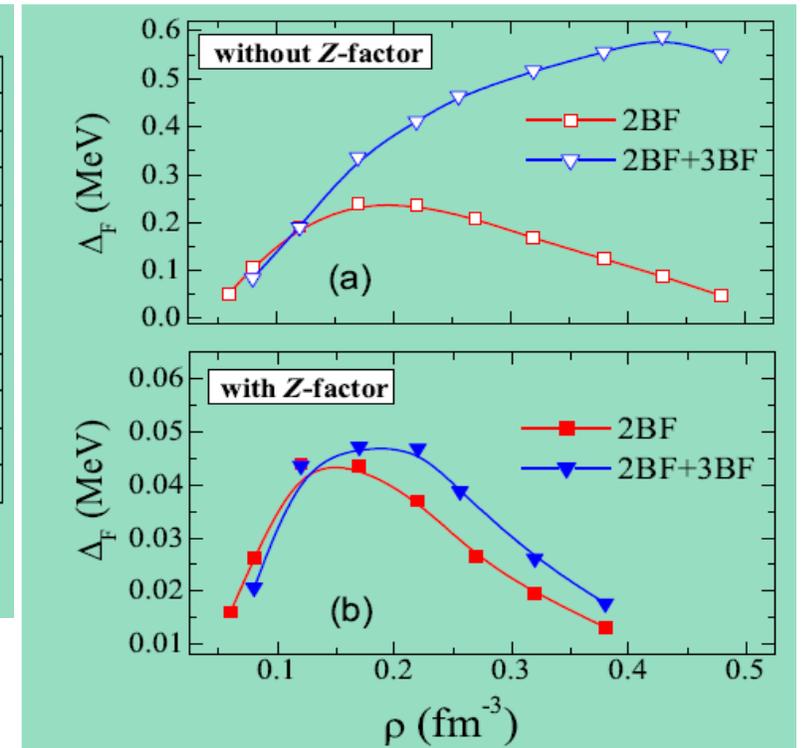
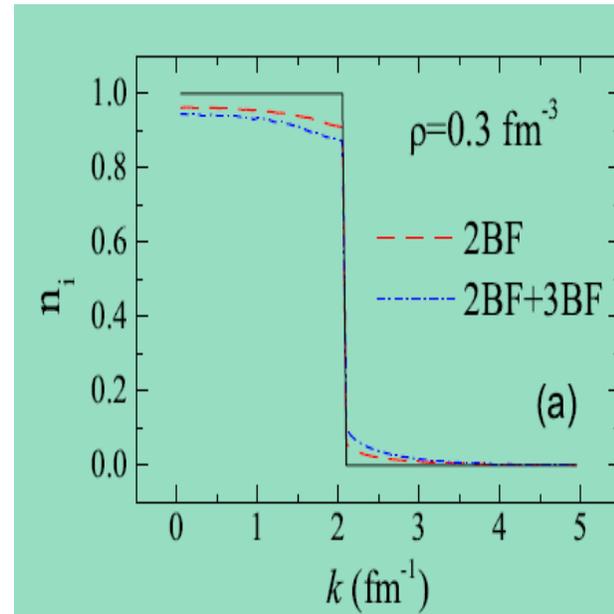
# TBF effect on nucleon superfluidity in neutron star matter

## 1S0 proton superfluidity in neutron star matter



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

## 3PF2 neutron superfluidity in neutron matter



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

# Summary

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- 1. TBF provides a repulsive contribution to the EOS of nuclear matter and improves remarkably the predicted saturation properties.**
- 2. TBF and thermal effect do not alter the empirical parabolic law fulfilled by the EOS of ANM.**
- 3. TBF may lead to a strong enhancement of the stiffness of symmetry energy at high densities.**
- 4. TBF induces a strongly repulsive and momentum-dependent rearrangement contribution to the s.p. potential at high densities.**
- 5. At high densities, TBF may lead to an enhancement of the depletion of nuclear Fermi sea.**

*Thank you for attention !*

谢谢大家!