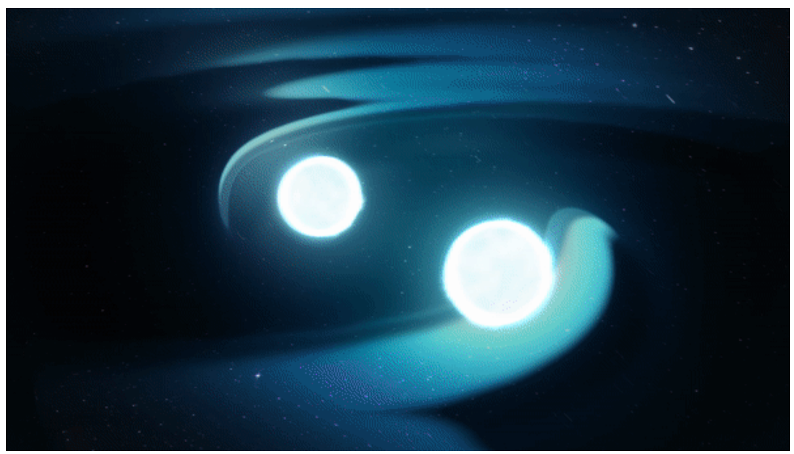
The short-range correlation effect on the properties of neutron star



Jinniu Hu

School of Physics, Nankai University

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Outline

- Introduction
- Relativistic Hartree-Fock method with UCOM
- Numerical results
- Summary

Symmetry energy

Semi-empirical mass formula

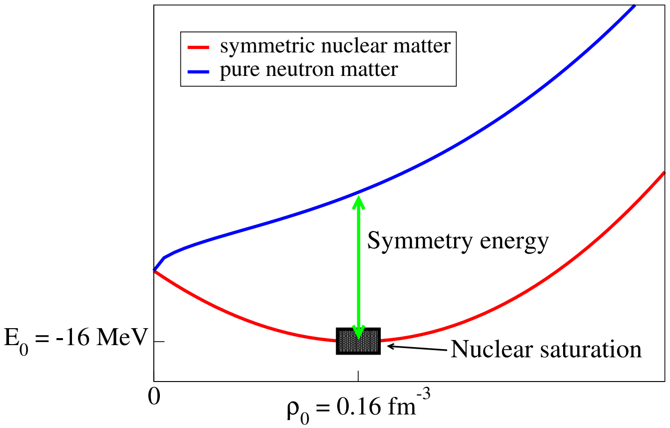
$$B(Z,A) = a_V A - a_S A^{2/3} - a_C Z(Z-1)A^{-1/3} - a_{sym}\frac{(A-2Z)^2}{A} + a_p \frac{(-1)^Z[1+(-1)^A]}{2}A^{-3/4}$$

Symmetry energy in nuclear matter

$$E_{sym}(\rho) = S_0 + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{K_{sym}}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \cdots$$

The slope of symmetry energy

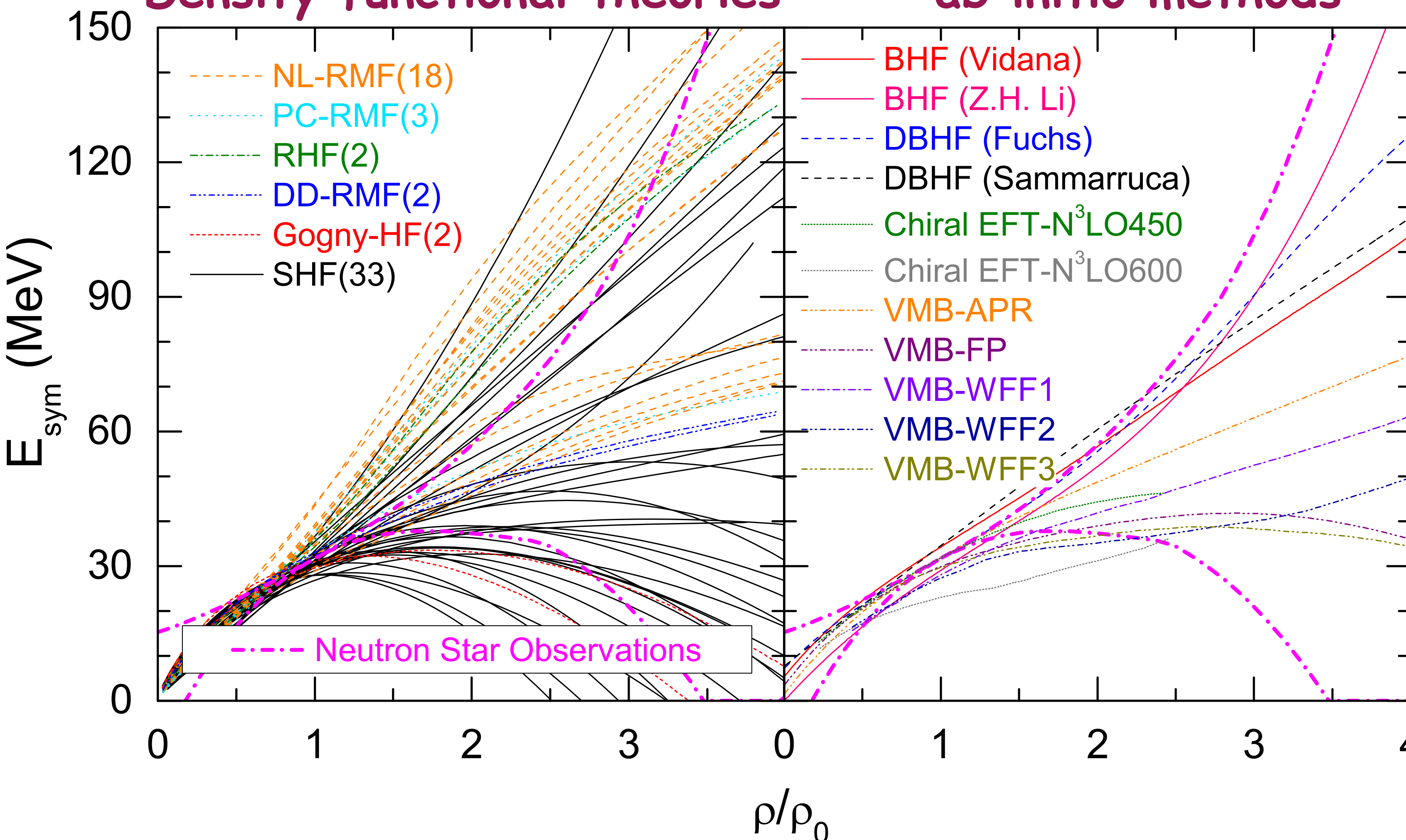
$$L = 3\rho_0 \frac{\partial E_{sym}(\rho)}{\partial \rho}\Big|_{\rho=\rho_0}$$



The density dependence

The uncertainty of symmetry energy at high density

Density functional theories ab initio methods



N. B. Zhang and B. A. Li, Euro. Phys. J. A 55(2019)39

The ab initio calculations

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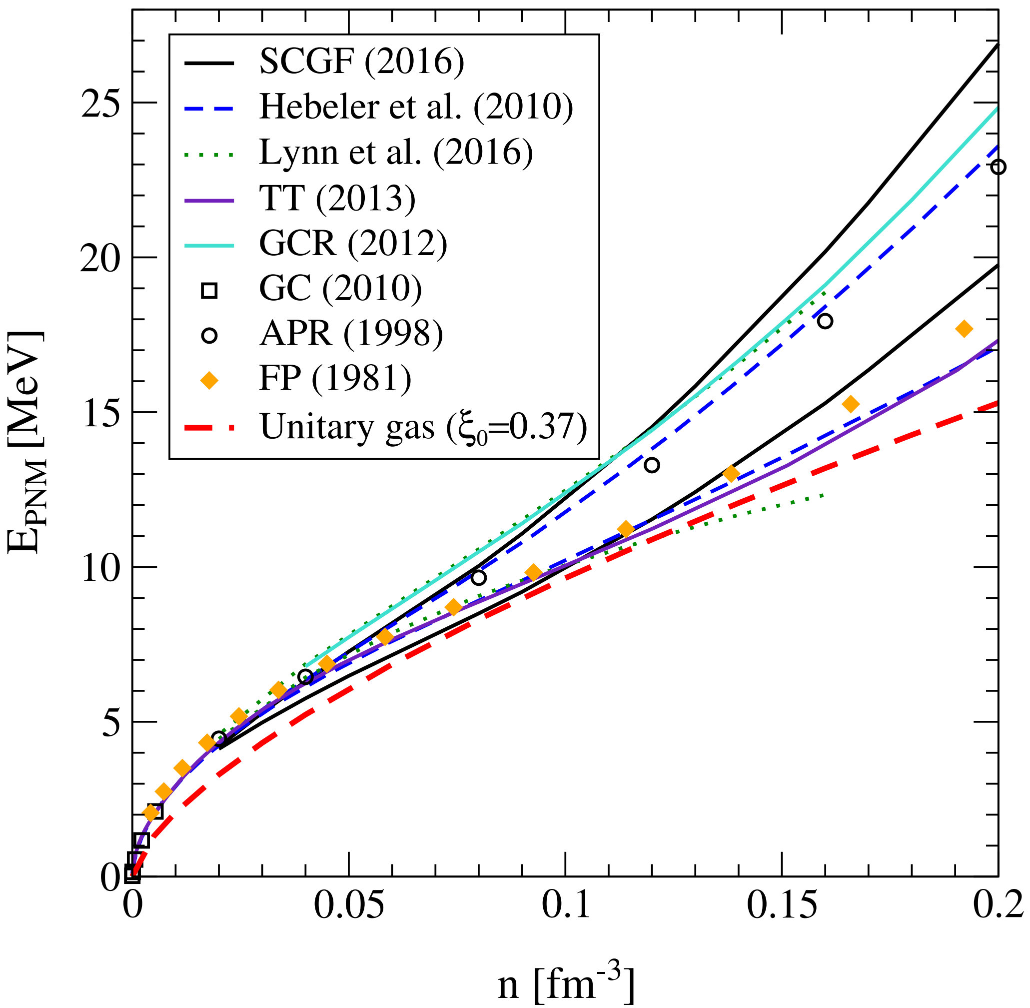

I. Tews , J. M. Lattimer, A. Ohnishi, and E. E. Kolomeitsev, Astrophy. J. 848(2017)105

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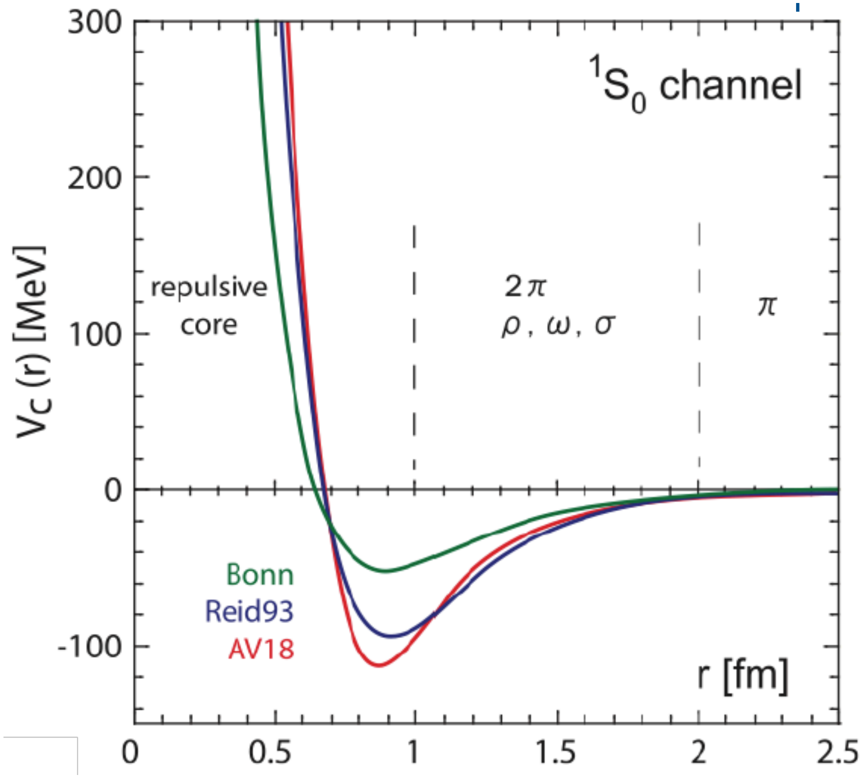
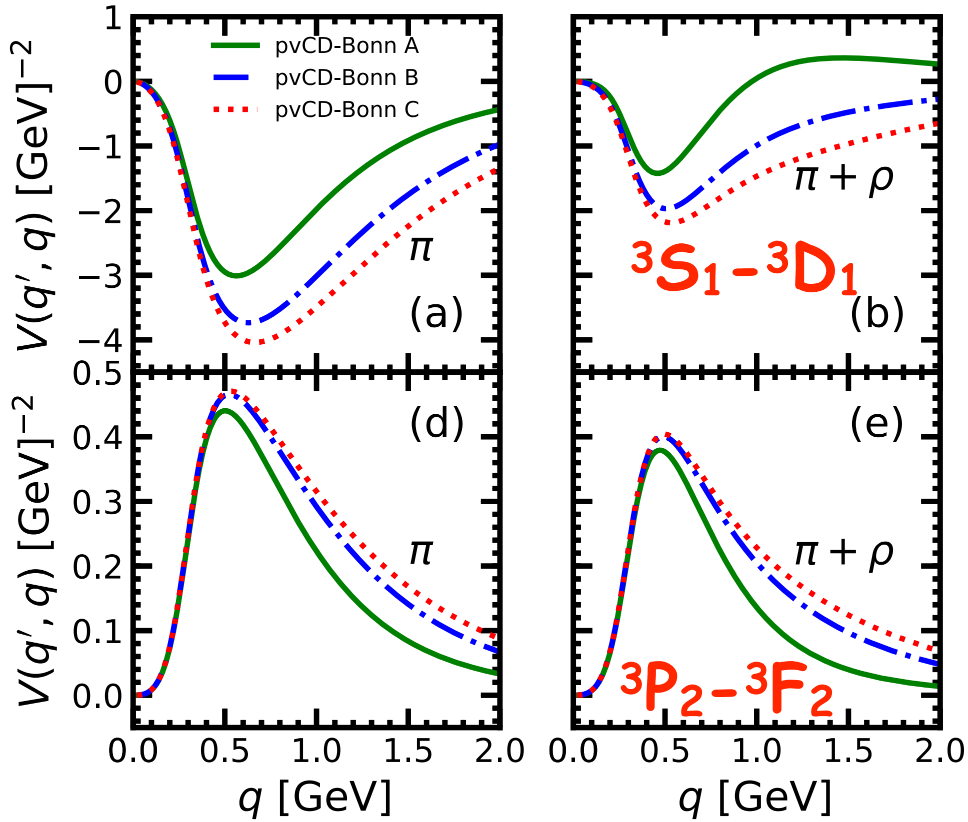
The repulsion at short range distance

The strong tensor force at intermediate range





C. Wang, J. Hu, Y. Zhang, H. Shen, Chin. Phys. C, accepted

The tensor force is very weak in T=1

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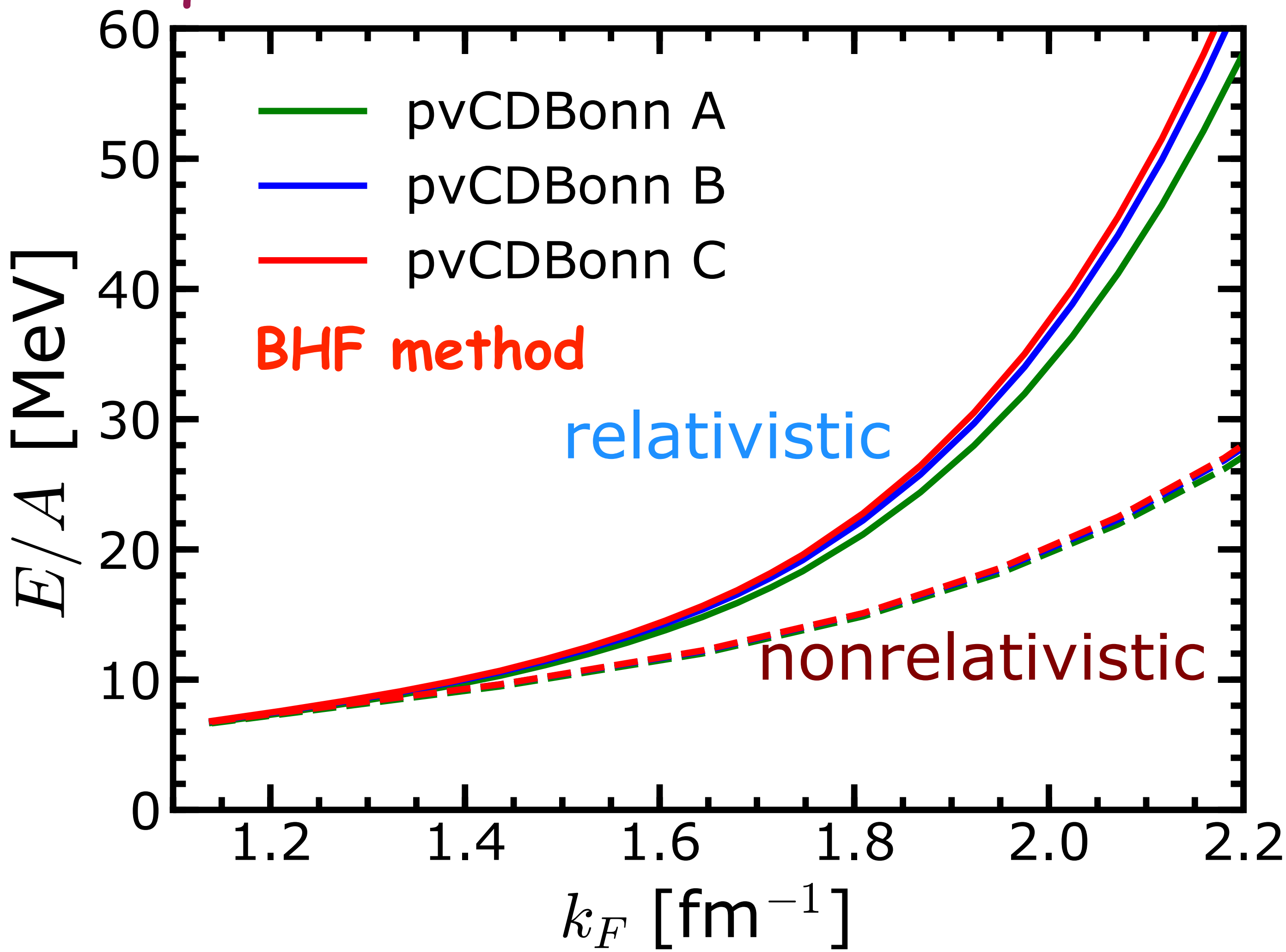
Equation of states of Pure neutron matter



The tensor effect in pure neutron matter is very weak

The short range correlation

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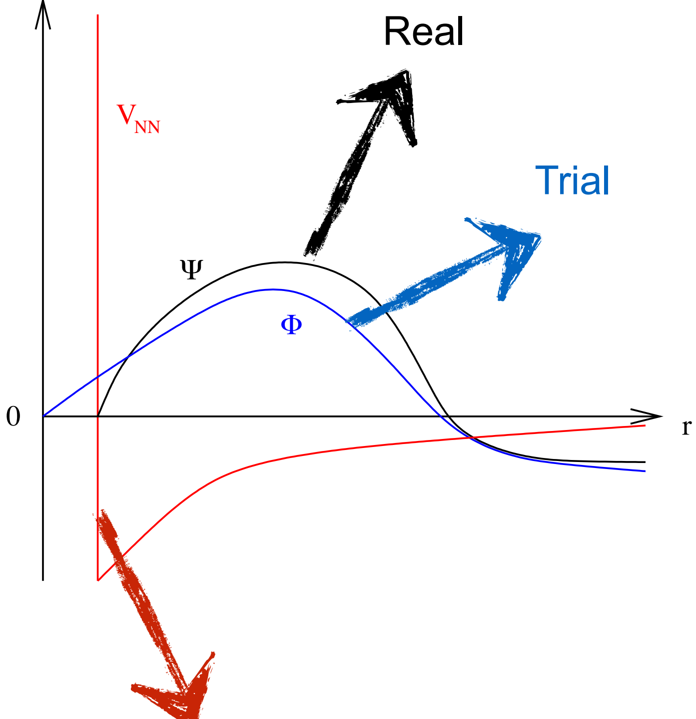
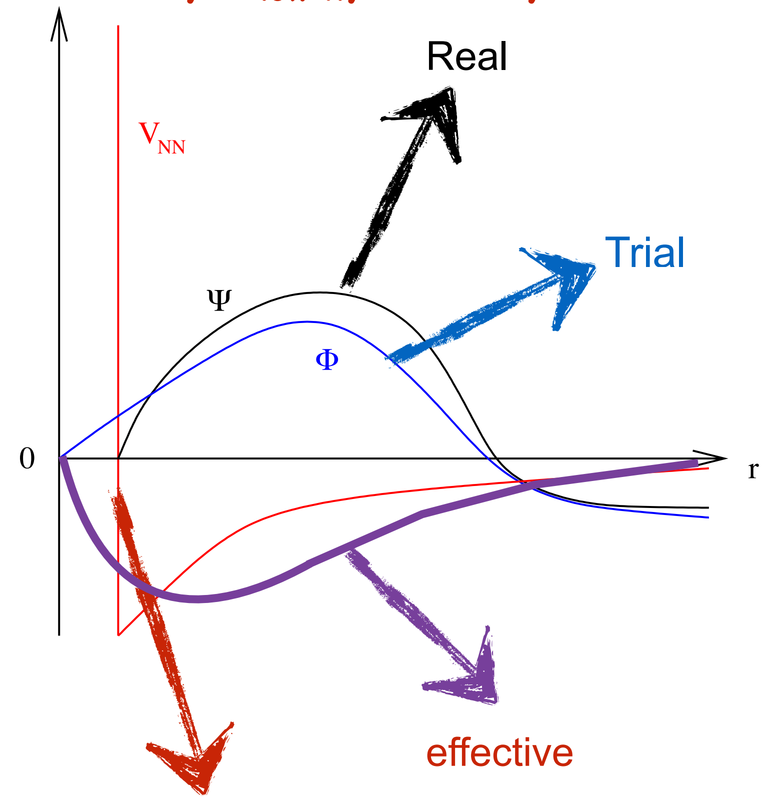
Correlation function:

Jastrow function,
coupled-cluster method…



Renormalize interaction:

G-matrix, $V_{low\ k}$, SRG…,UCOM



J. Hu, H. Toki, W. Wen, and H. Shen, Phys. Lett. B 687(2010)271
J. Hu, H. Toki, and H. Shen, J. Phys. G 38(2011)08515
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J. Hu, H. Shen and H. Toki, Phys. Rev. C, 95(2017)025804
J. Hu, Y. Zhang, E. Epelbaum, U. G. Meissner, and J. Meng, Phys. Rev. C 96(2017)034307

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The Lagrangian of Bonn potentials

$$
\begin{aligned}
\mathcal{L}_{\text{int}} = \bar{\psi}\Big[& -g_\sigma \sigma - g_\delta \tau_a \delta^a - \frac{f_\eta}{m_\eta}\gamma_5\gamma_\mu \partial^\mu \eta - \frac{f_\pi}{m_\pi}\gamma_5\gamma_\mu \tau_a \partial^\mu \pi^a \\
& - g_\omega \gamma_\mu \omega^\mu + \frac{f_\omega}{2M}\sigma_{\mu\nu}\partial^\nu \omega^\mu - g_\rho \gamma_\mu \tau_a \rho^{a\mu} + \frac{f_\rho}{2M}\sigma_{\mu\nu}\partial^\nu \tau_a \rho^{a\mu}\Big]\psi \\
& + \frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma - \frac{1}{2}m_\sigma^2 \sigma^2 + \frac{1}{2}\partial_\mu \delta^a \partial^\mu \delta^a - \frac{1}{2}m_\delta^2 \delta^{a2} \\
& + \frac{1}{2}\partial_\mu \eta \partial^\mu \eta - \frac{1}{2}m_\eta^2 \eta^2 + \frac{1}{2}\partial_\mu \pi^a \partial^\mu \pi^a - \frac{1}{2}m_\pi^2 \pi^{a2} \\
& - \frac{1}{4}W_{\mu\nu}W^{\mu\nu} + \frac{1}{2}m_\omega^2 \omega_\mu \omega^\mu - \frac{1}{4}R^a_{\mu\nu}R^{a\mu\nu} + \frac{1}{2}m_\rho^2 \rho^a_\mu \rho^{a\mu} ,
\end{aligned}
$$

R. Machleidt. Avd. Nucl. Phys. 19(1989)189

Unitary correlation operator method

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Correlation operator

$$\psi = U\phi.$$

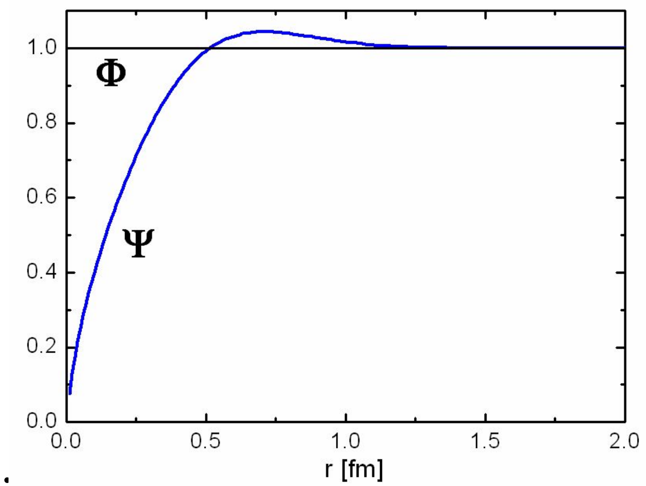
Unitary

$$\mathcal{H}\psi = E\psi,$$

$$U^\dagger \mathcal{H} U \psi = E\psi.$$

The Hamiltonian of NN interaction

$$\mathcal{H} = \sum_i^A T_i + \sum_{i<j}^A V(i,j),$$



The Hamiltonian after correlated

$$\widetilde{\mathcal{H}} = u^\dagger(i,j)\mathcal{H}u(i,j)$$

$$= \sum_i^A T_i + \sum_{i<j}^A \widetilde{V}(i,j),$$

The effective interaction

$$\widetilde{V}(i,j) = u^\dagger(i,j)Vu(i,j) + u^\dagger(i,j)(T_i + T_j)u(i,j) - (T_i + T_j).$$

H. Feldmeier, T. Neff, R. Roth, J. Schnack, Nucl. Phys. A 632(1998)61

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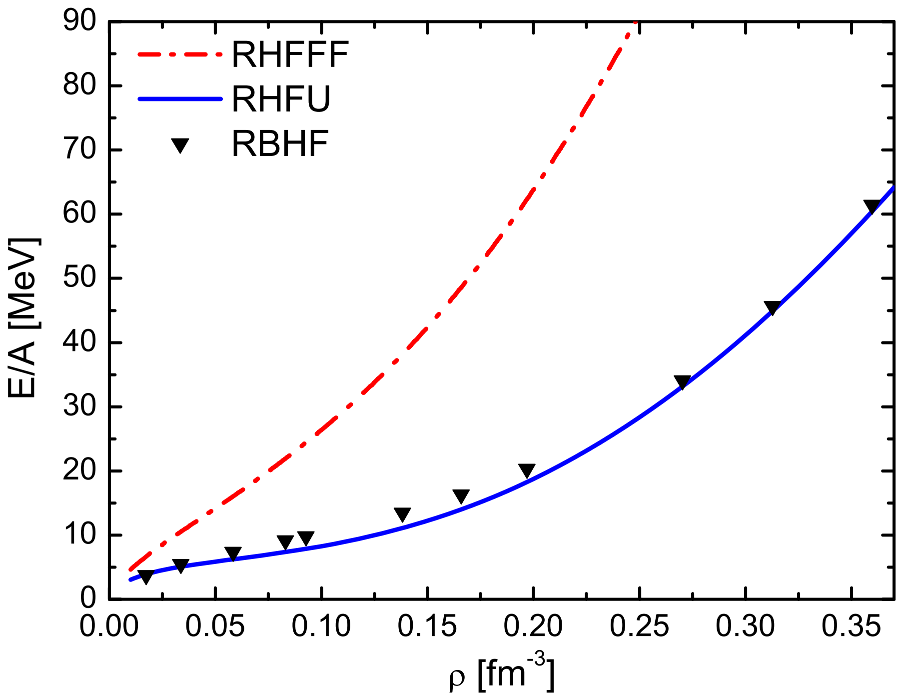
The infinite nuclear matter

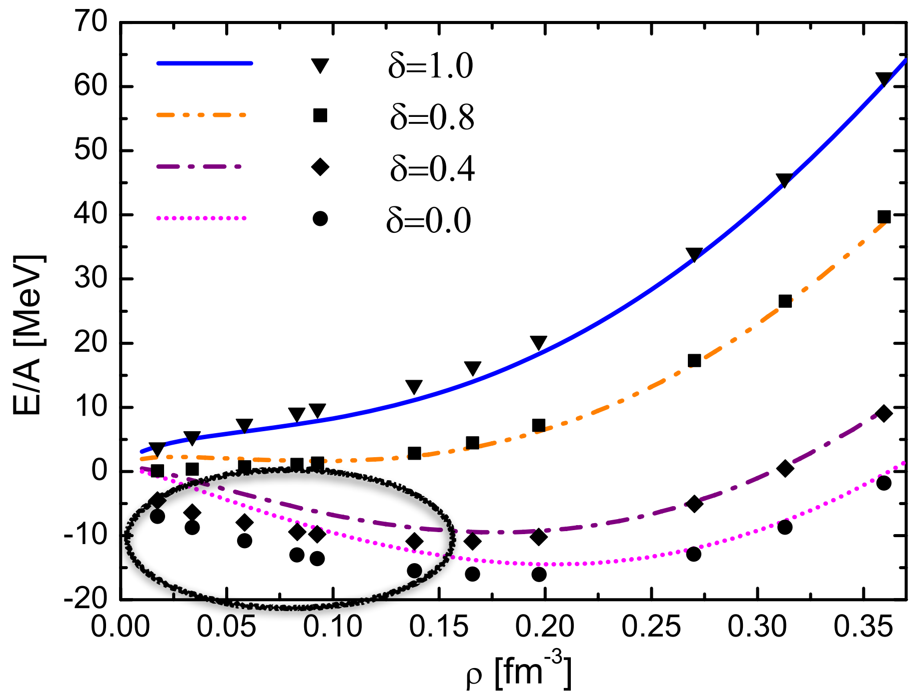
The equations of state of nuclear matter

J. Hu, H. Toki, W. Wen, and H. Shen, Phys. Lett. B 687(2010)271

Pure neutron matter



Asymmetry nuclear matter



The present framework can reproduce the results of RBHF for PNM

For SNM, the tensor correlation is important at low density region

The properties of nuclear matter

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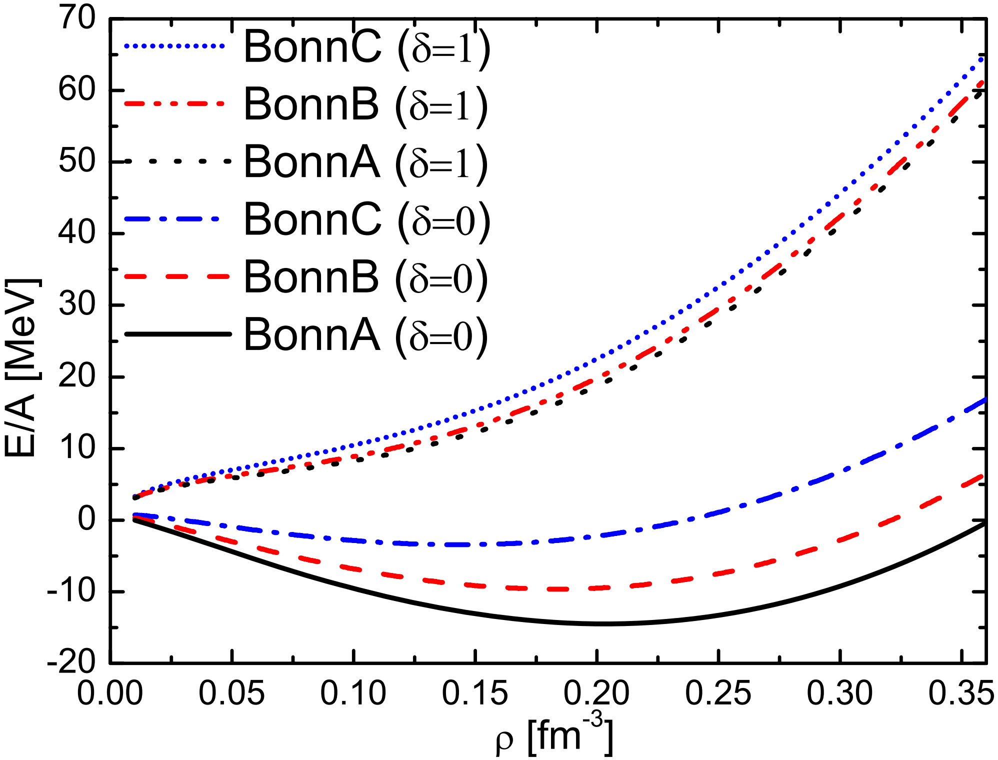
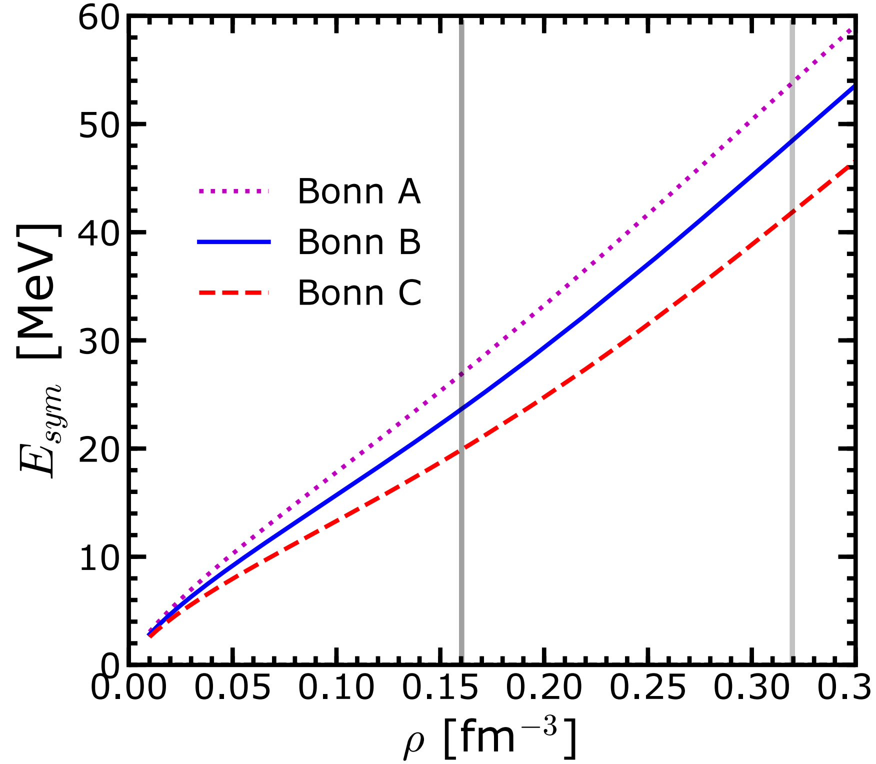
J. Hu, H. Toki, W. Wen, and H. Shen, Phys. Lett. B 687(2010)271

Asymmetry nuclear matter



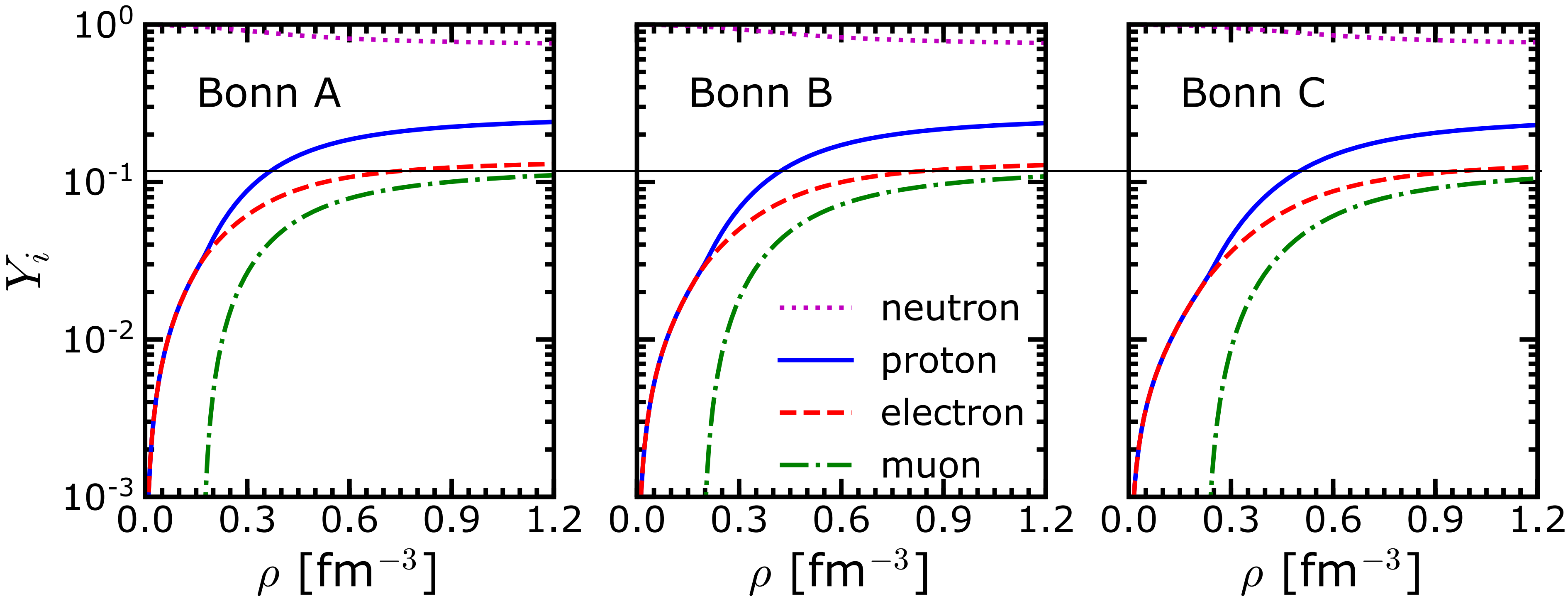
Symmetry energy



The symmetry energies from three Bonn potentials are different due to the tensor effects on SNM

The components of neutron star

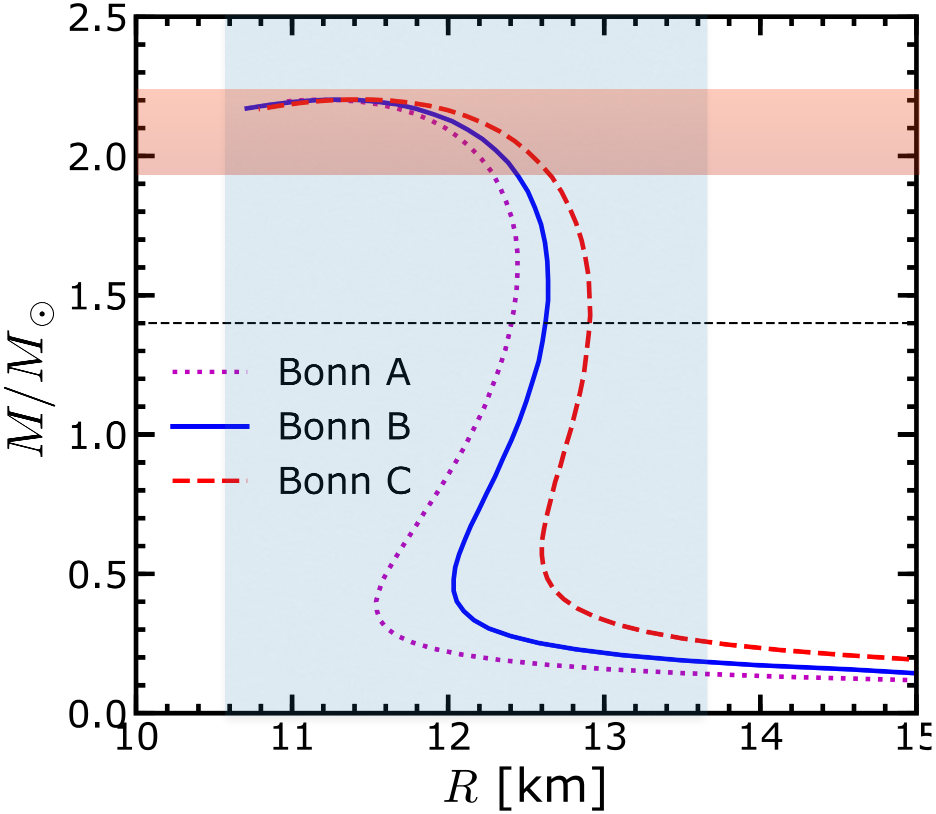
The fractions of baryons and leptons



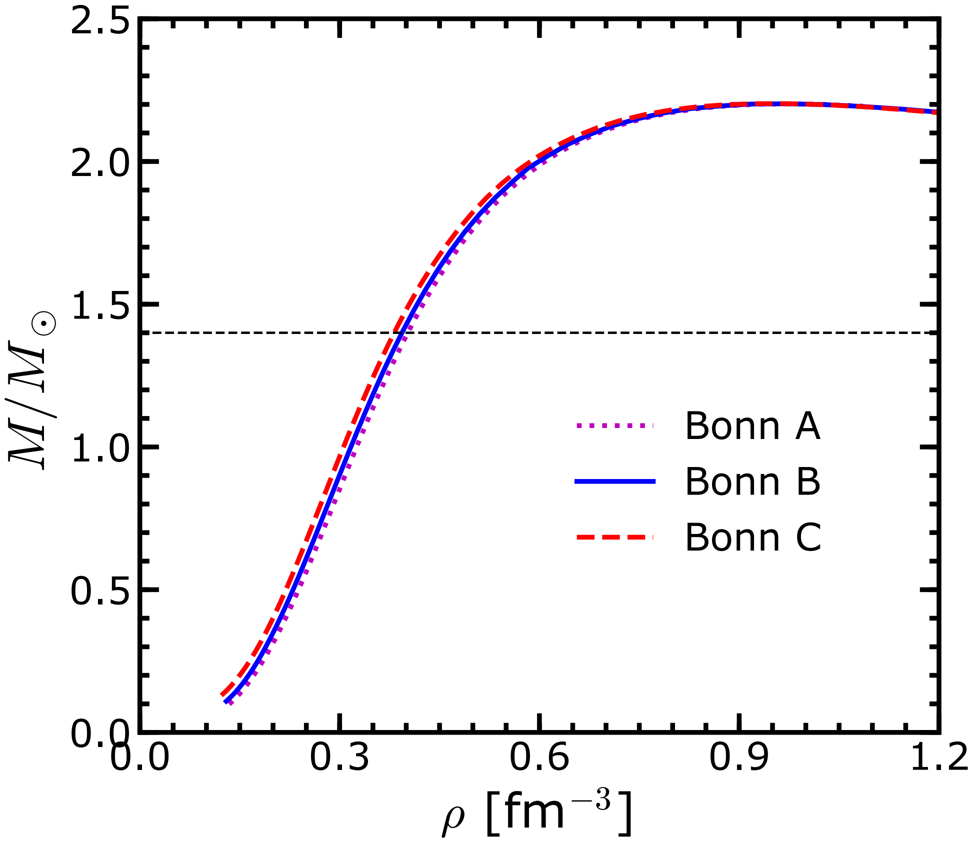
The Direct URCA process will firstly occur at Bonn A potential due to its largest symmetry energy.

The properties of neutron star

Mass-radii relation



Mass-density relation



The maximum masses of neutron star are about 2.2M⊙

The radii at 1.4M⊙ are less than 13 km

The binary star merger

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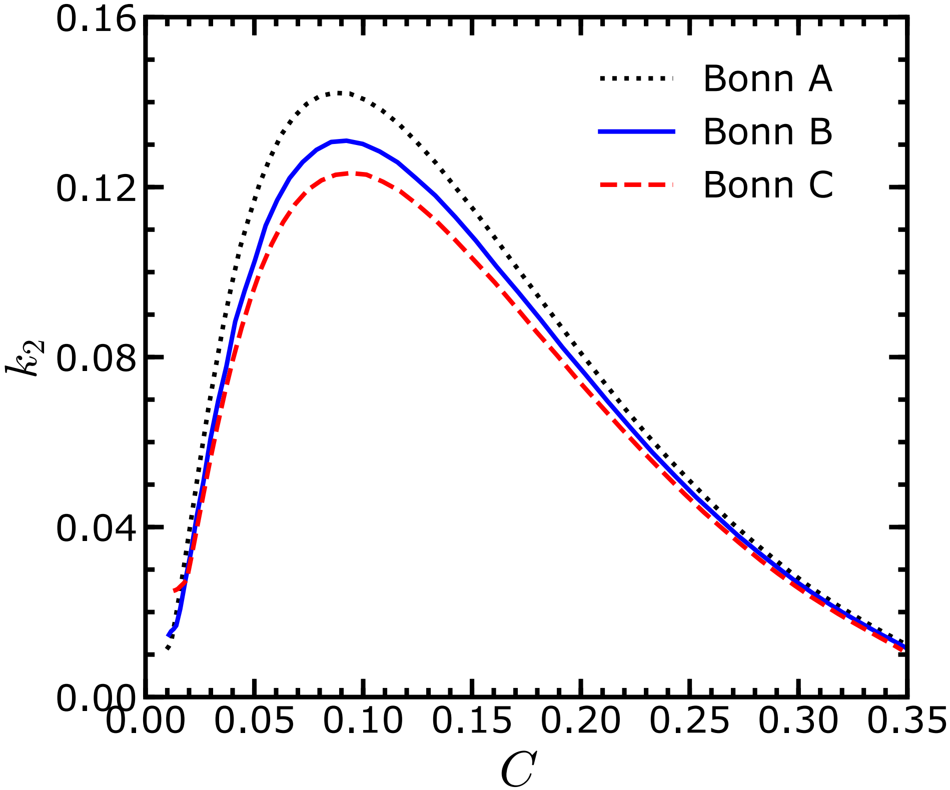
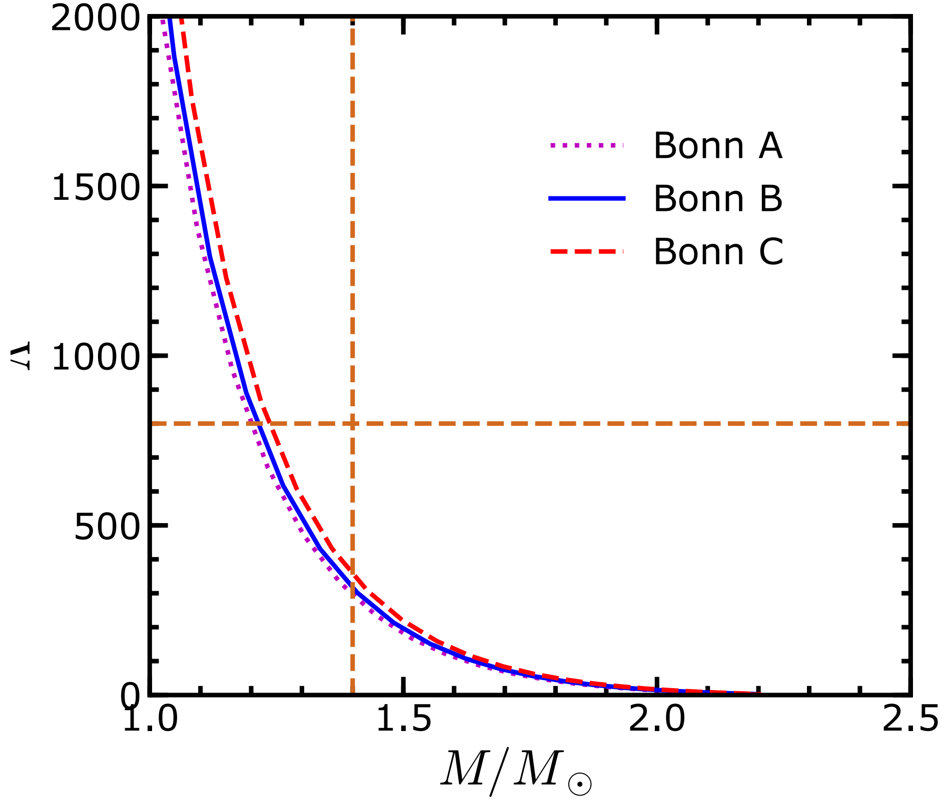
Love number

Tidal deformability

$$\Lambda = \frac{2}{3} k_2 C^{-5}, \qquad C = GM/Rc^2$$





The tidal deformabilities at 1.4M⊙ are less than 400

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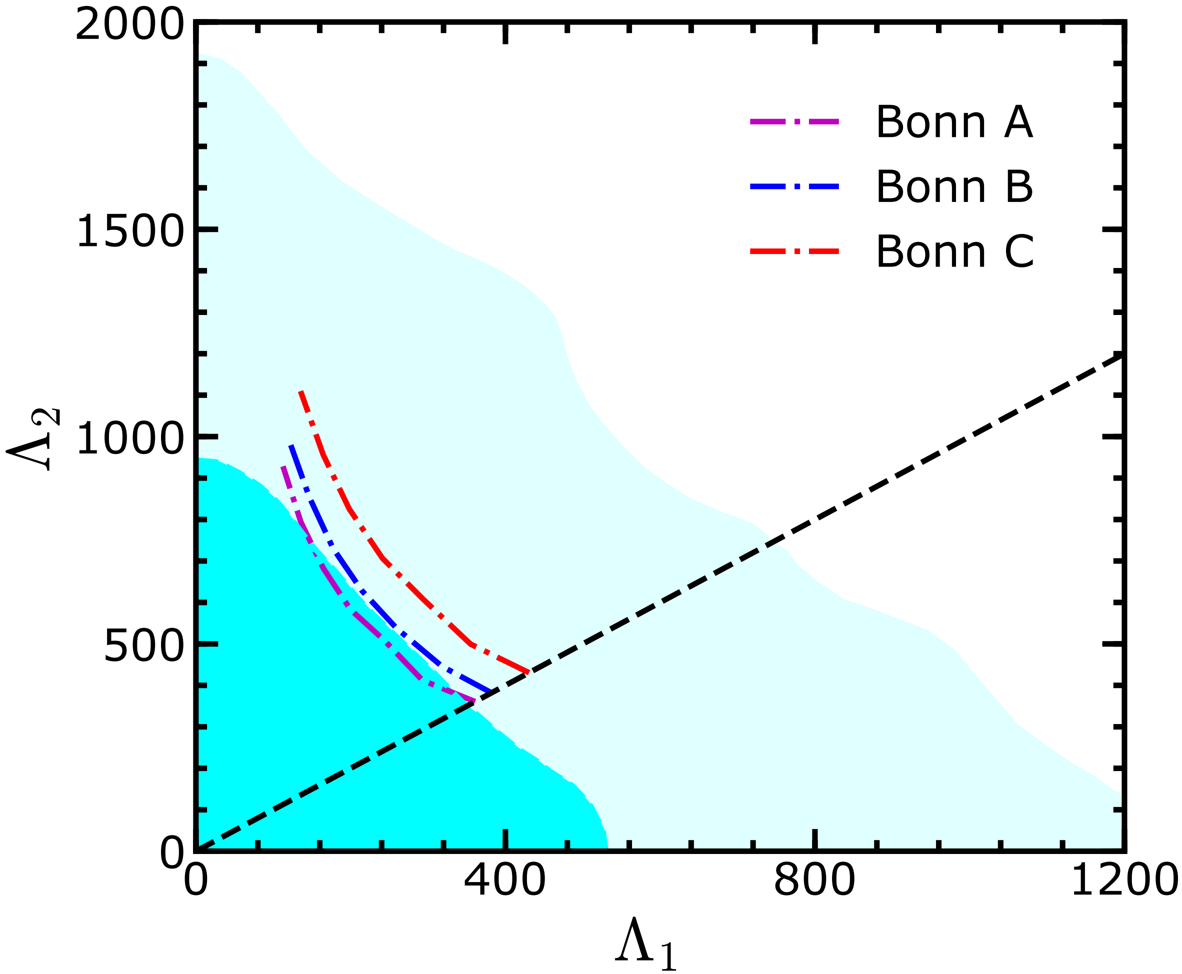
The tidal deformabilities with constraint of GW170817



Data from: B. P. Abbott et al. Phys. Rev. Lett. 121(2018)161101

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The summary

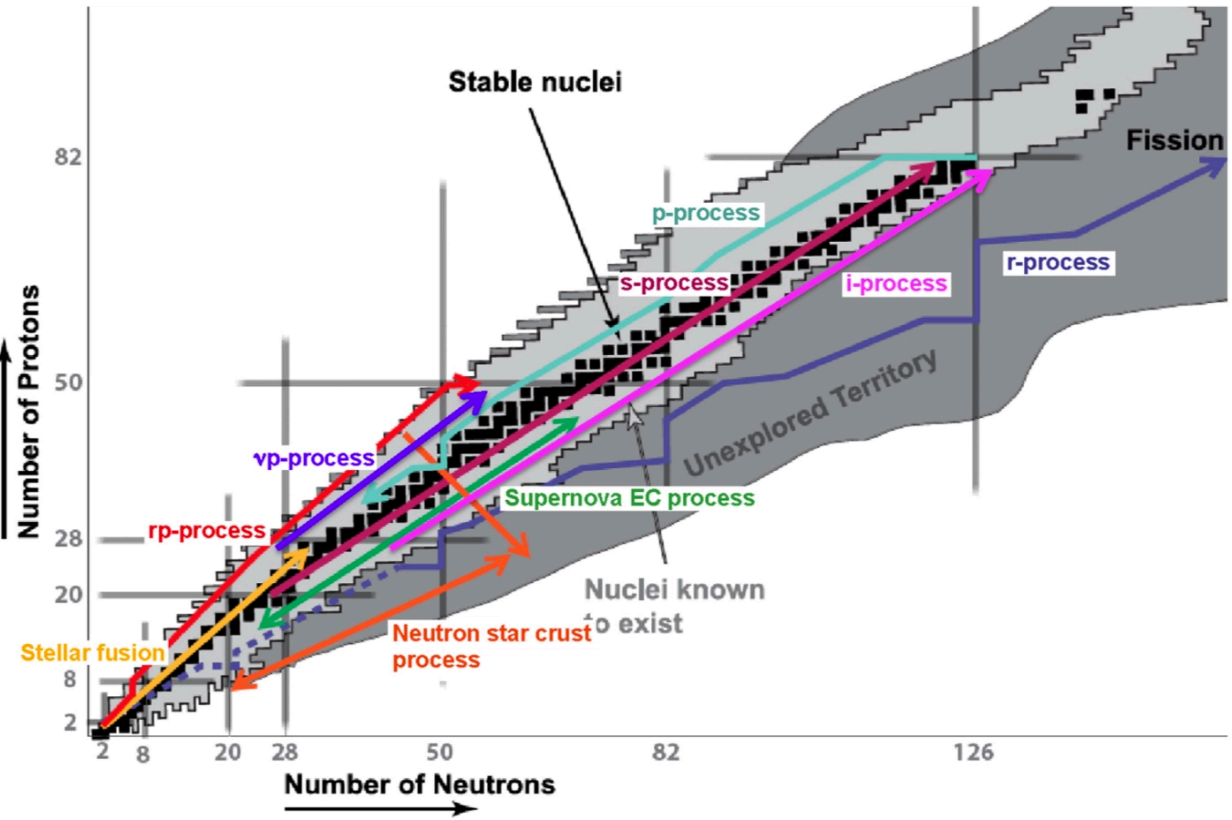
The properties of neutron star were calculated in framework relativistic Hartree-Fock model with UCOM

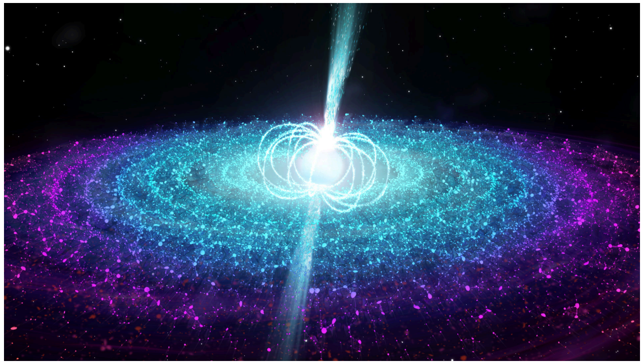
The maximum masses and radius from Bonn potentials are almost identical.

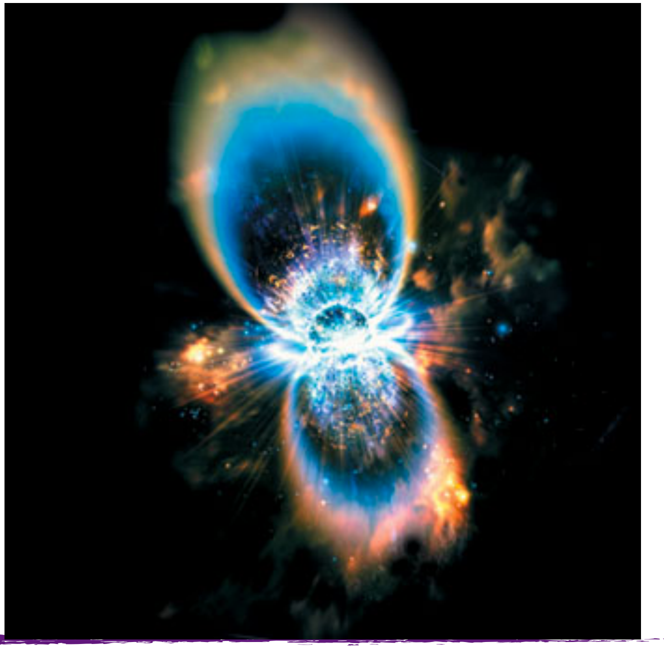
The properties of neutron star at $1.4M_\odot$ from three Bonn potentials are distinguished due to their different density dependences of symmetry energy.

Thank you very much
for your attention!

Neutron rich system







H. Schatz, J. Phys. G 43(2016)064001

Nuclear matter

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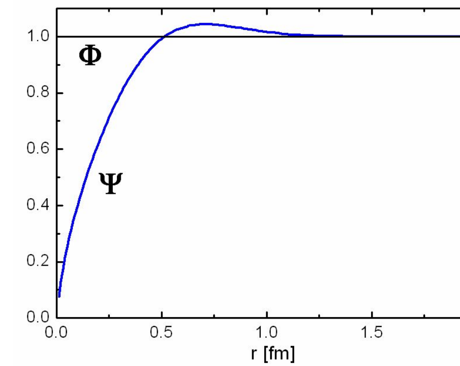
The parameterization correlation function



$$R_+(r) = r + \alpha \left(\frac{r}{\beta}\right)^\eta \exp(-\exp(r/\beta)).$$

The correlations on quantum operator

$$u^\dagger(i,j) r u(i,j) = R_+(r)$$

$$u^\dagger(i,j) V(r) u(i,j) = V(R_+(r))$$

$$u^\dagger(i,j) p_r u(i,j) = \frac{1}{\sqrt{R'_+(r)}} \frac{1}{r} p_r \frac{1}{\sqrt{R'_+(r)}},$$

The correlation on kinetic energy

$$c^\dagger(i,j) T(i,j) - T = \sum_{i<j} (\vec{\alpha}_i - \vec{\alpha}_j) \cdot \frac{\vec{r}}{r} \frac{1}{\sqrt{R'_+(r)}} \frac{1}{r} q_r \frac{r}{\sqrt{R'_+(r)}}$$

$$+ (\vec{\alpha}_i - \vec{\alpha}_j) \cdot \frac{\vec{r}}{r} \left(\frac{1}{R'_+(r)} - \frac{r}{R_+(r)} \right) q_r + \left(\frac{r}{R_+(r)} - 1 \right) (\vec{\alpha}_i - \vec{\alpha}_j) \cdot \vec{q}.$$

Symmetry energy

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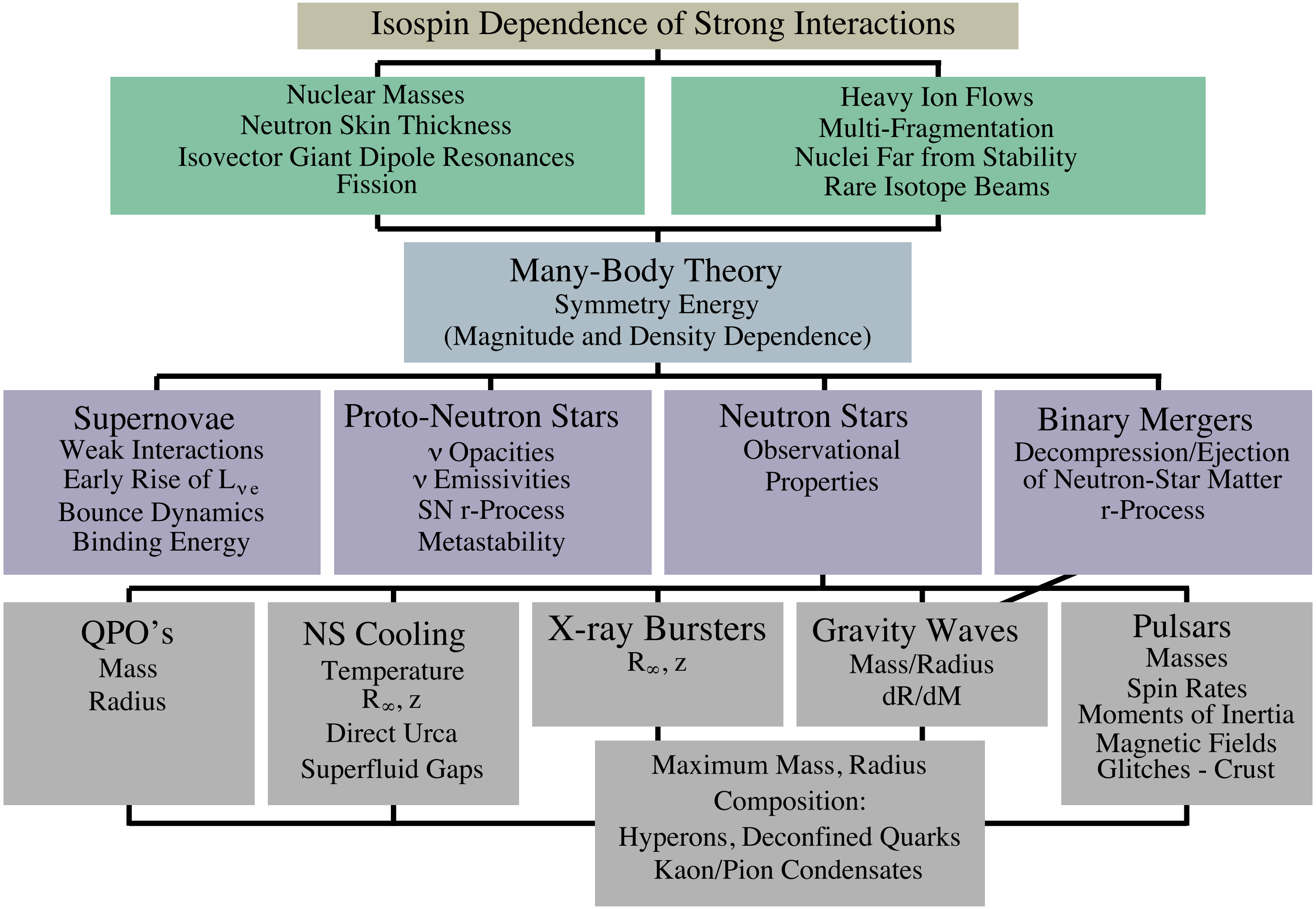

A. Steiner, M. Prakash, J. Lattimer and P. Ellis, Phys. Rep. 411(2005)325

np potential T=0 case