Neutron stars:
a laboratory for nuclear physics

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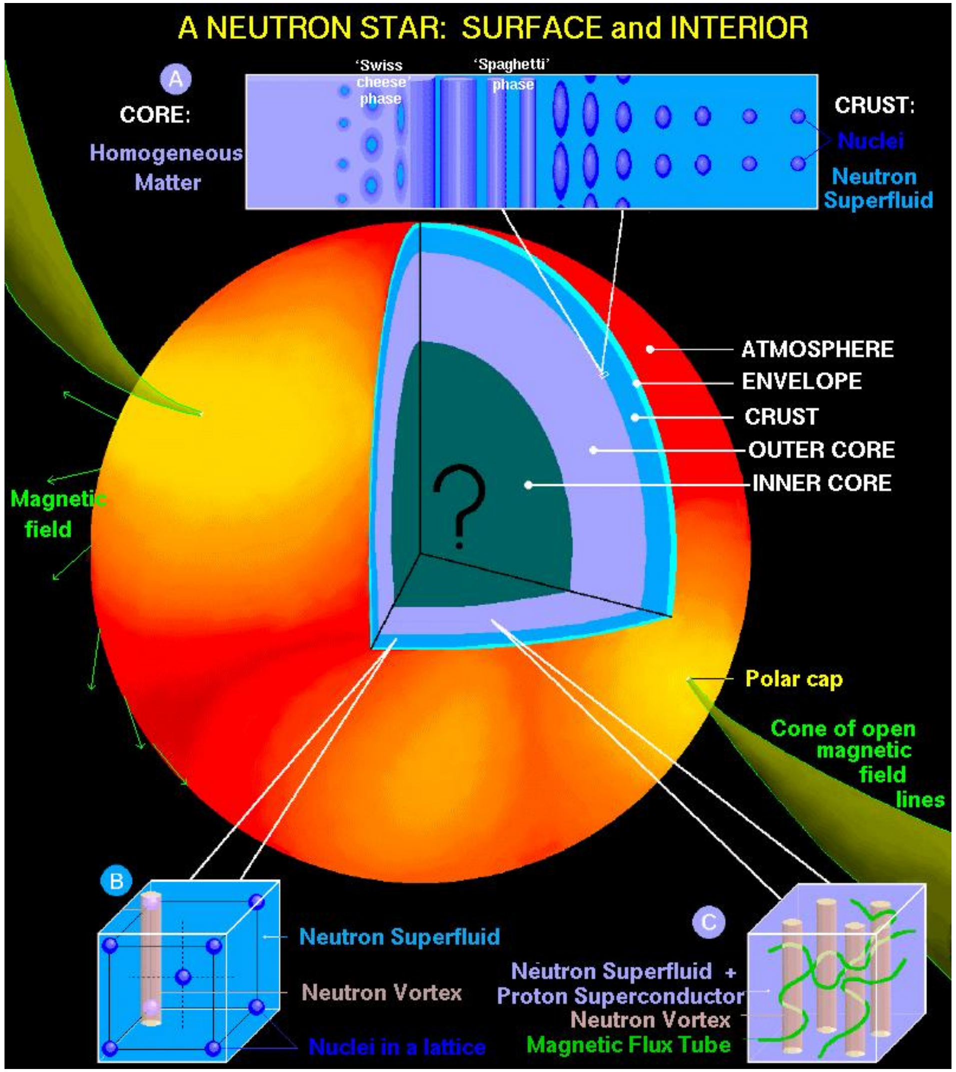
Introduction: Structure of neuton stars



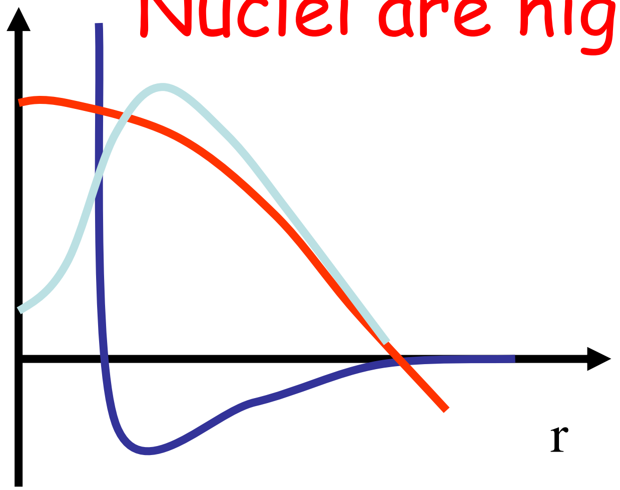
From the Crust to the Center:

- Nuclei plus degenerate e-Gas
- Neutron drip line: quasinuclei in a sea of neutrons
- Pasta Phase: Spaghetti, Lasagne
- Holes in continous matter
- Homogeneous Neutron Matter with small fraction of protons
- Further ingredients: Strange Baryons…
- Center ???

Outline

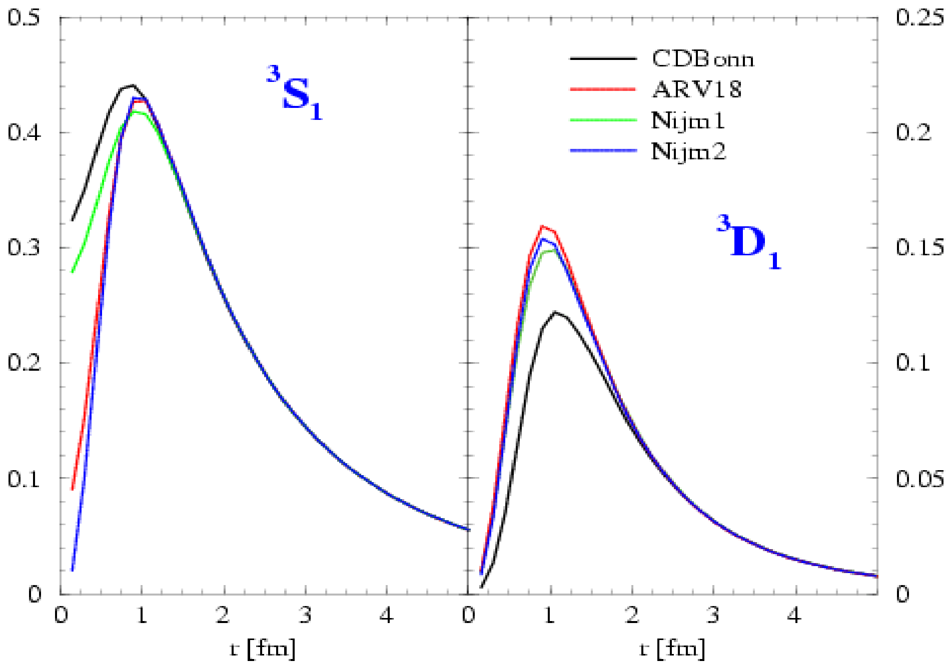
- Different approaches:
  - Microscopic: Fit NN scattering
    - predict normal nuclear systems and exotic
  - Phenomenologic: Fit normal nuclear systems
    - Predict exotic matter
- Compare for homogeneous matter
  - Pairing correlations: superfluidity
- Pasta Phase and Exotic Nuclei
- Propagation of Neutrinos

Nuclei are higly correlated Fermi liquids



strong short-range components in the NN interaction lead to correlations

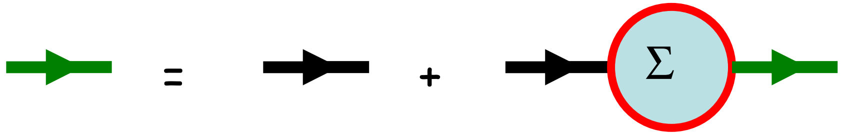
Hartree-Fock yields unbound nuclei



Green´s function and T-matrix approach

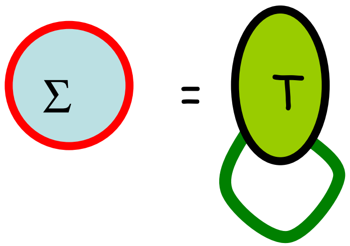
Single-particle Green´s function $g(k,t_1,t_2) = -i\langle T\, c_k(t_1)\, c_k^+(t_2)\rangle$

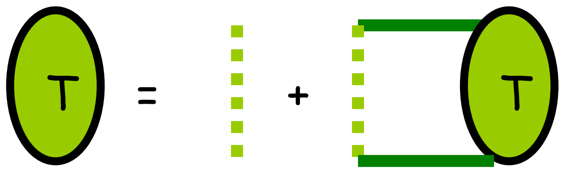
Dyson equation:



$$g(\omega) \;=\; g_0(\omega) \;+\; g_0(\omega)\, \Sigma(\omega)\, g(\omega)$$

$$g(k,\omega) \;=\; \frac{1}{\omega - k^2/2m - \Sigma(k,\omega)} \quad\Rightarrow\quad S(k,\omega) = -2\,\mathrm{Im}\, g(k,\omega)$$

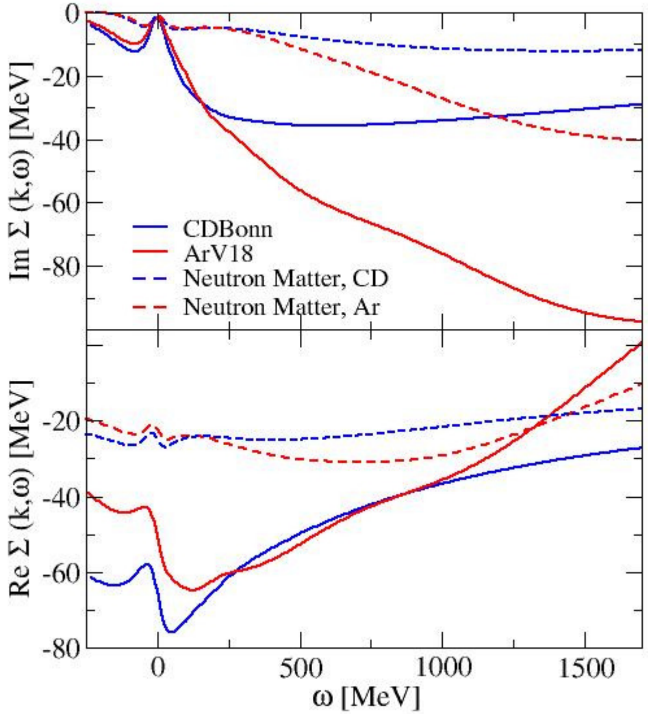
Self-energy 

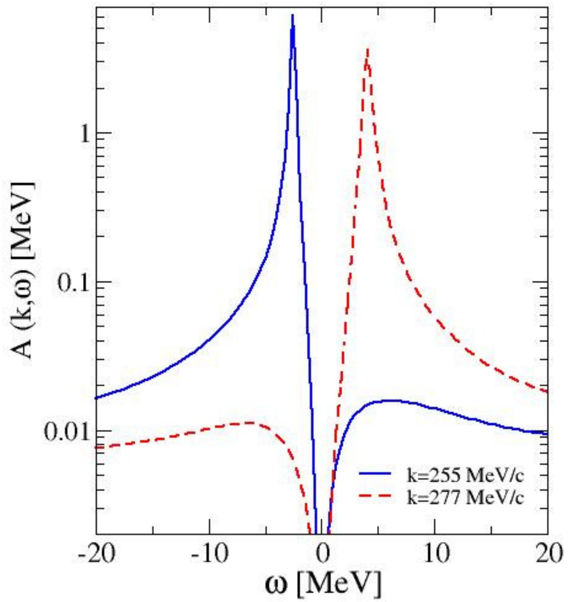
, T-matrix 

Finite temperature

Self-energy and spectral function

$$g(k,\omega) = \frac{1}{\omega - k^2/2m - \Sigma(k,\omega)} \quad \Rightarrow \quad S(k,\omega) = -2\,\mathrm{Im}\,g(k,\omega)$$





Real and imaginary part of the retarded self-energy

• k_F = 1.35 fm^{-1}, T = 5 MeV, k = 1.14 fm^{-1}

• Strength above and below the Fermi energy:

•partial occupation probabilities

BCS in the framework of SCGF

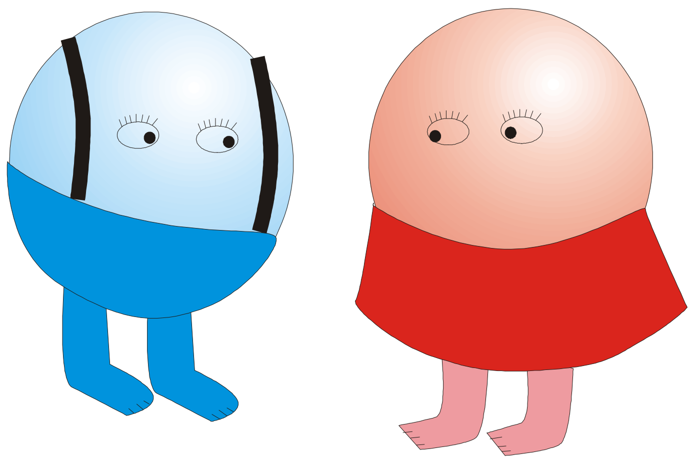
Generalized Greens function: Extend $g(k,t_1,t_2) = -i\langle T\, c_k(t_1)\, c_k^+(t_2)\rangle$

$$G(k,t_1,t_2) = \begin{pmatrix} -i\langle T\, cc^+\rangle & -i\langle Tcc\rangle \\ i\langle c^+c^+\rangle & i\langle Tc^+c\rangle \end{pmatrix} = \begin{pmatrix} g & f \\ f^+ & \overline{g} \end{pmatrix}$$

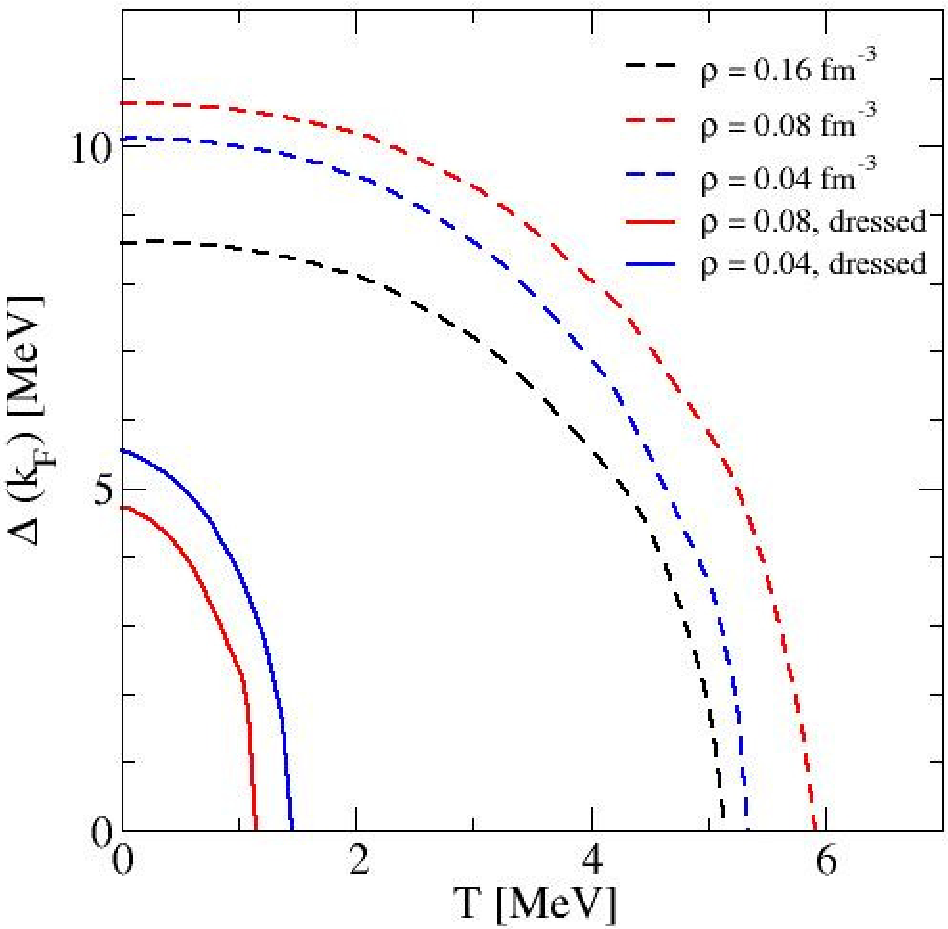
Generalized Dyson equation: Gorkov equation

$$\begin{pmatrix} \omega - t_k - \Sigma(k,\omega) & -\Delta(k,\omega) \\ -\Delta^+(k,\omega) & \omega + t_k + \Sigma(k,\omega) \end{pmatrix} \begin{pmatrix} g_{pair}(k,\omega) & f(k,\omega) \\ f^+(k,\omega) & \overline{g}_{pair}(k,\omega) \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Pairing of dressed nucleons:



Proton neutron pairing in nuclear matter



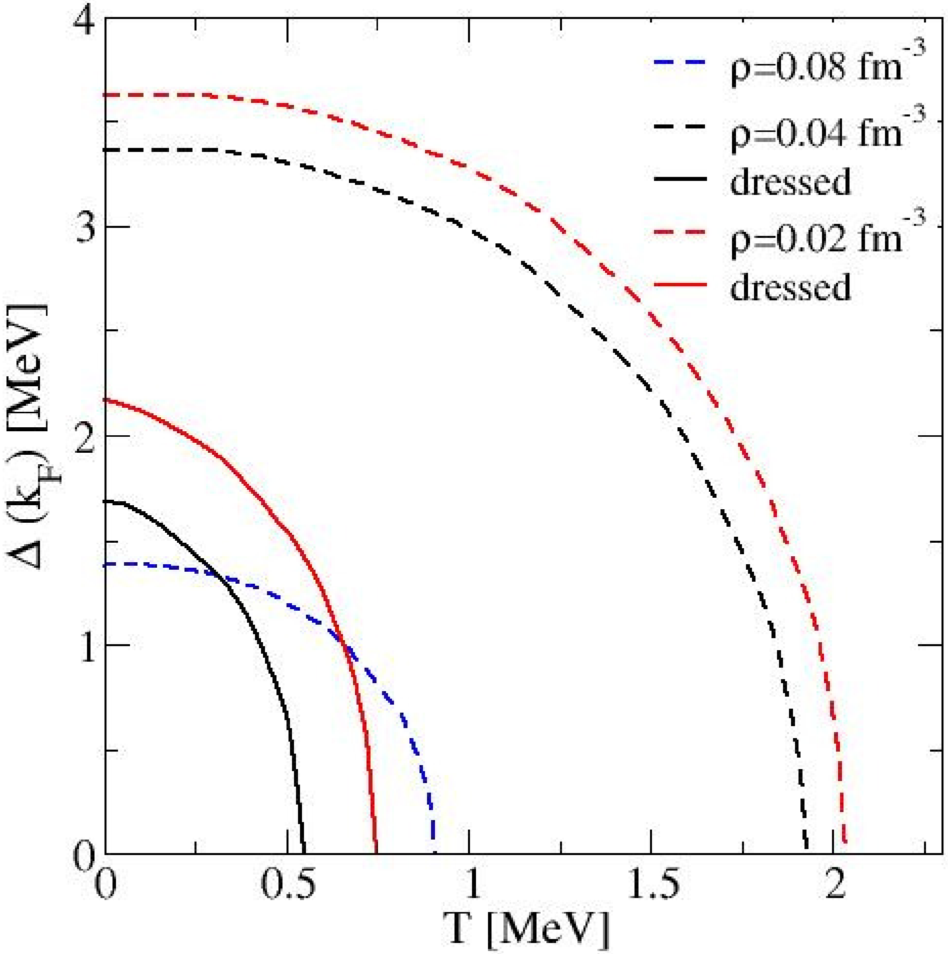
Using CDBonn

Dashed lines: quasiparticle poles

Solid lines: dressed nucleons

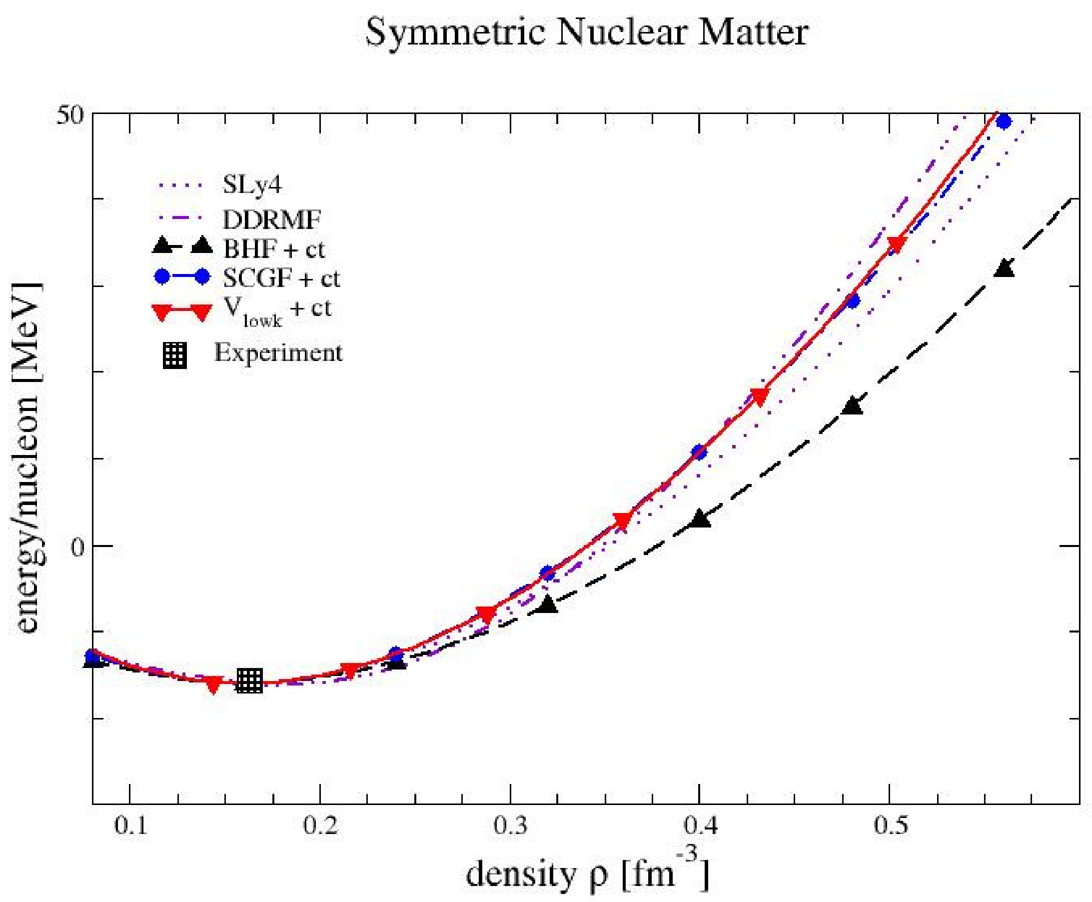
No pairing at saturation density

Pairing in neutron matter



Dressing effects weaker, but non-negligible

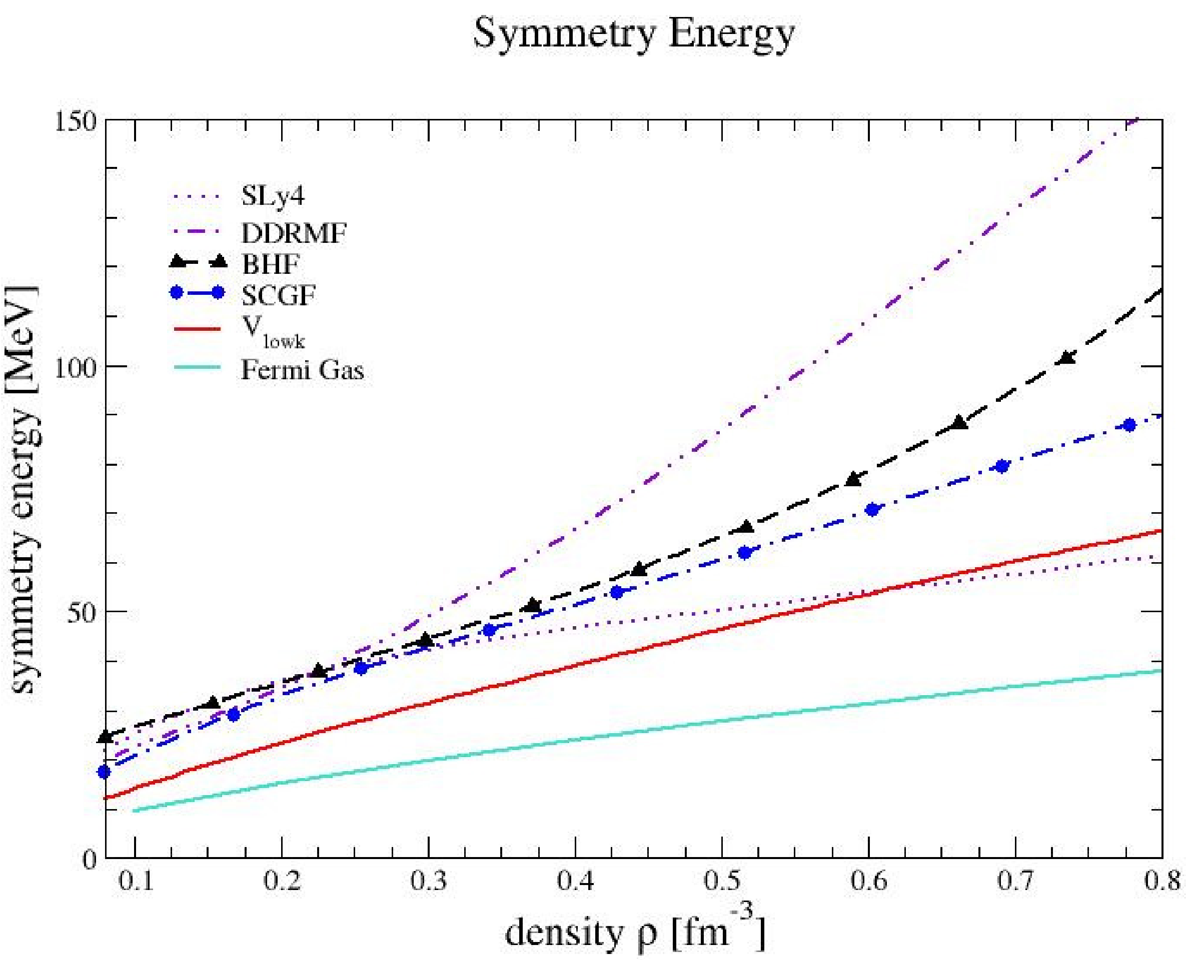
Compare Energies for Nuclear Matter



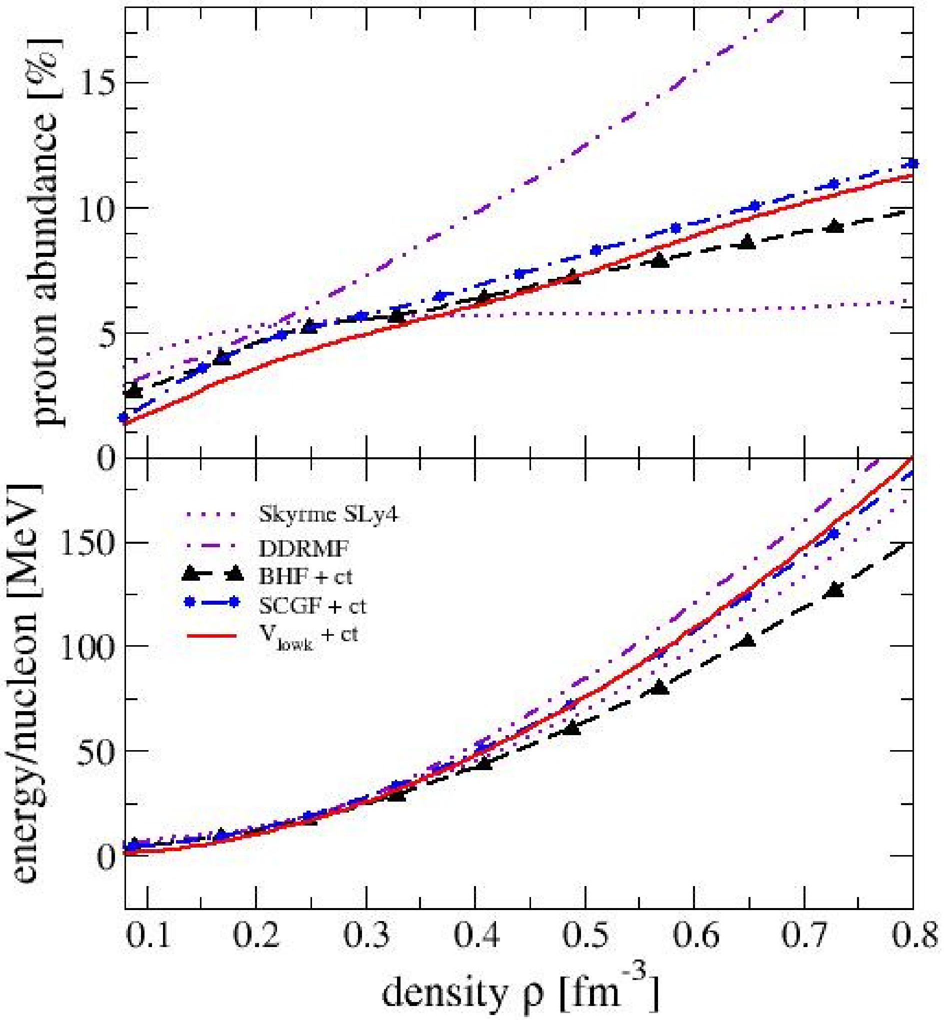
Microscopic calculations require adjustment:

Add contact interaction

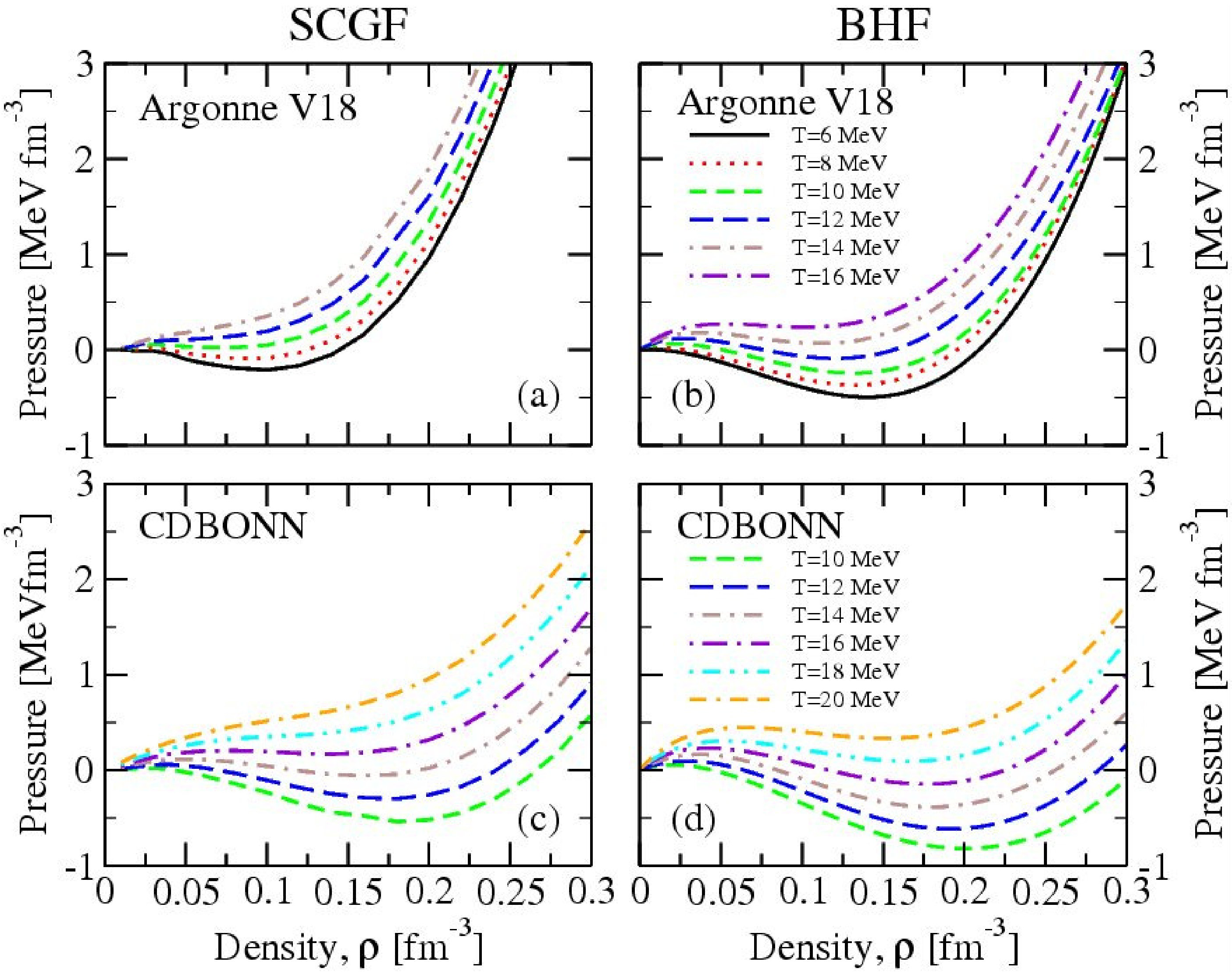
Compare Symmetry Energy



Results for Matter in β - Equilibrium

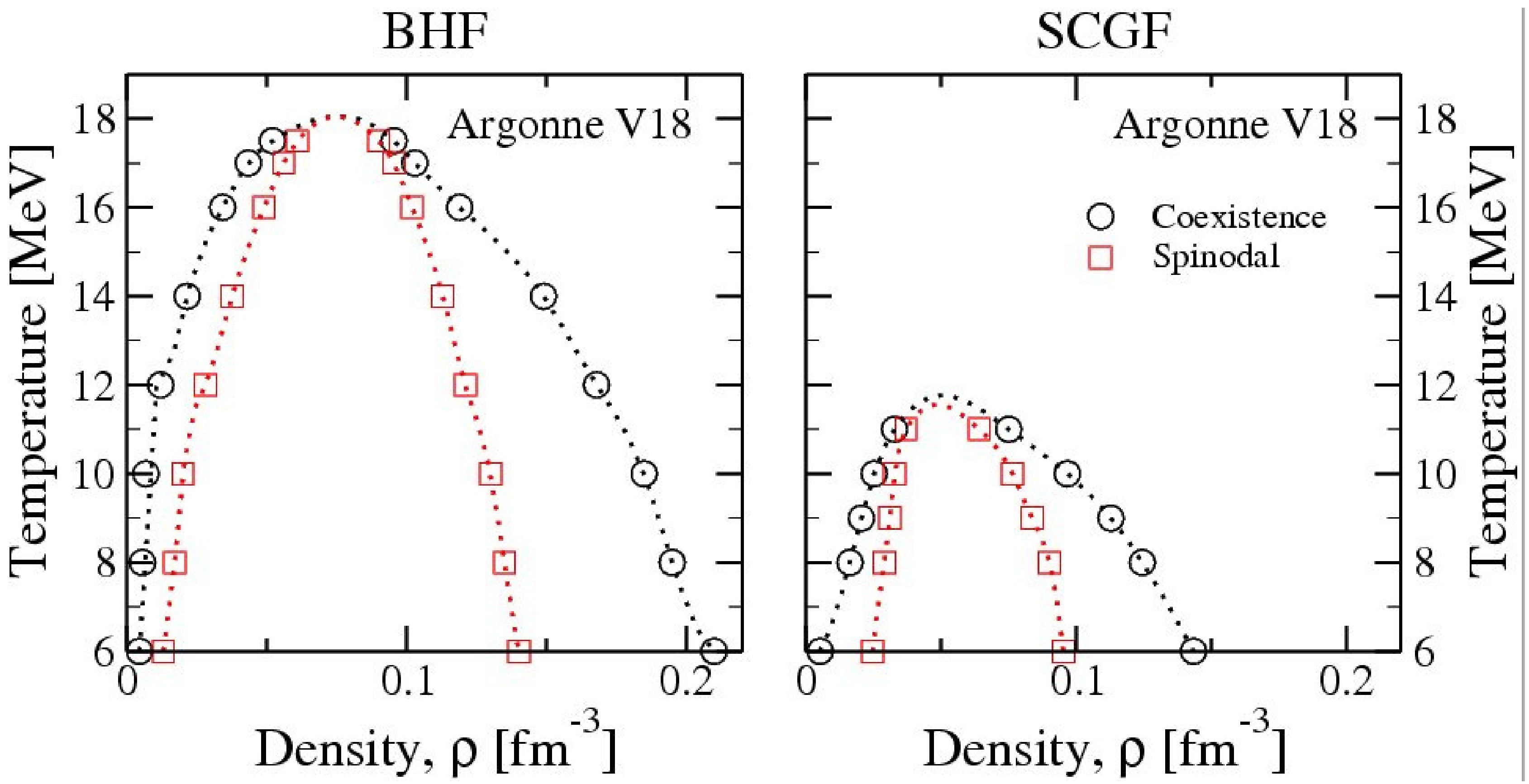


Liquid Gas

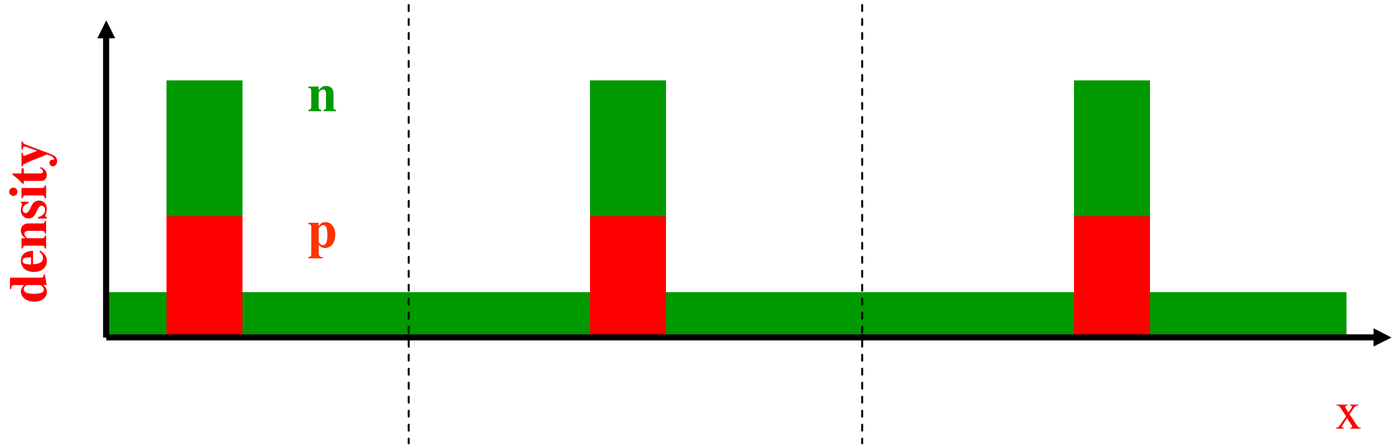


SCGF
BHF
Argonne V18
Argonne V18
T=6 MeV
T=8 MeV
T=10 MeV
T=12 MeV
T=14 MeV
T=16 MeV
(a)
(b)
CDBONN
CDBONN
T=10 MeV
T=12 MeV
T=14 MeV
T=16 MeV
T=18 MeV
T=20 MeV
(c)
(d)
Pressure [MeV fm^-3]
Pressure [MeVfm^-3]
Density, ρ [fm^-3]
0
0.05
0.1
0.15
0.2
0.25
0.3
-1
0
1
2
3

Coexistence



Between Nuclei and neutron matter: Pasta

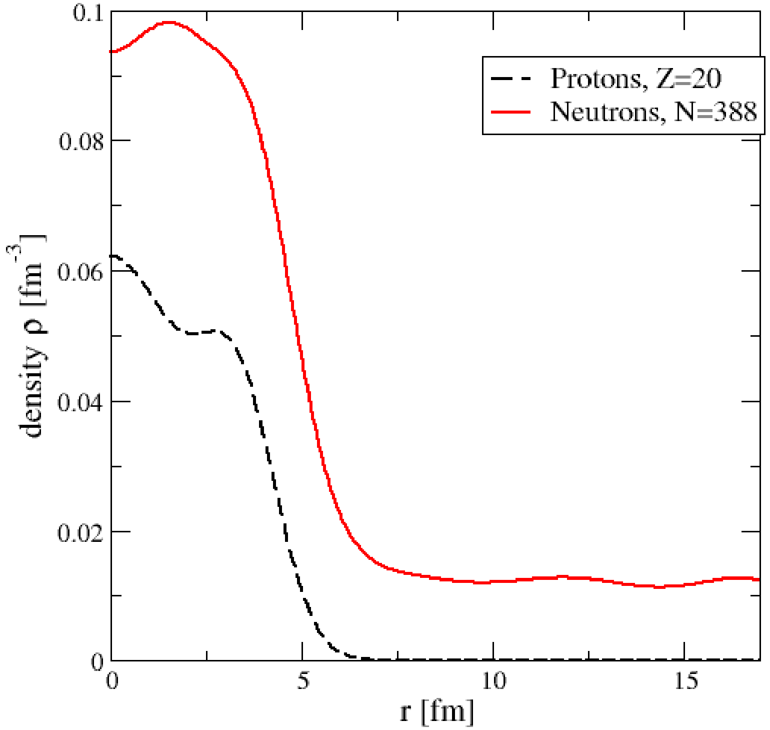


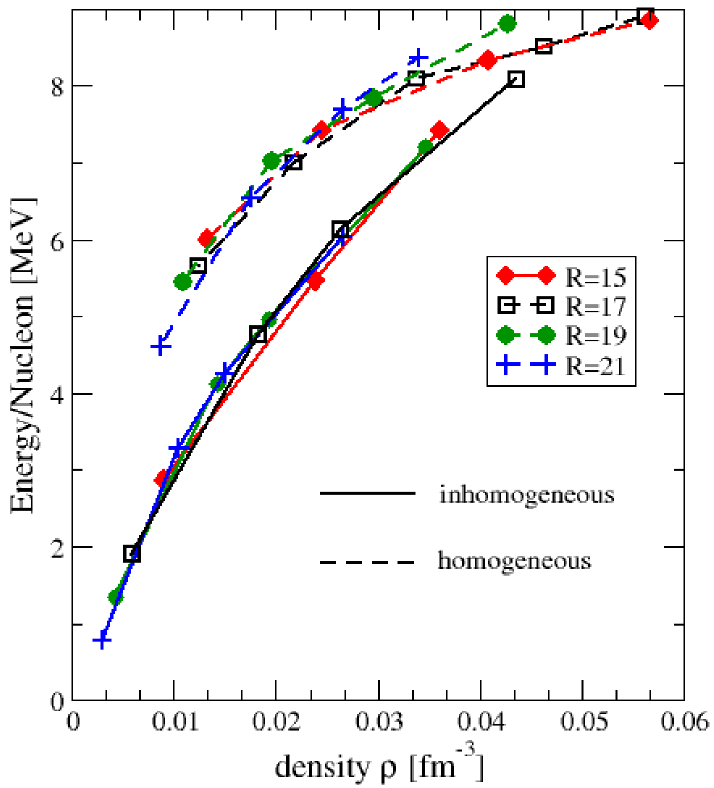
Thomas Fermi Approximation

versus

Direct calculation in a Wigner Seitz Box

Typical density profile

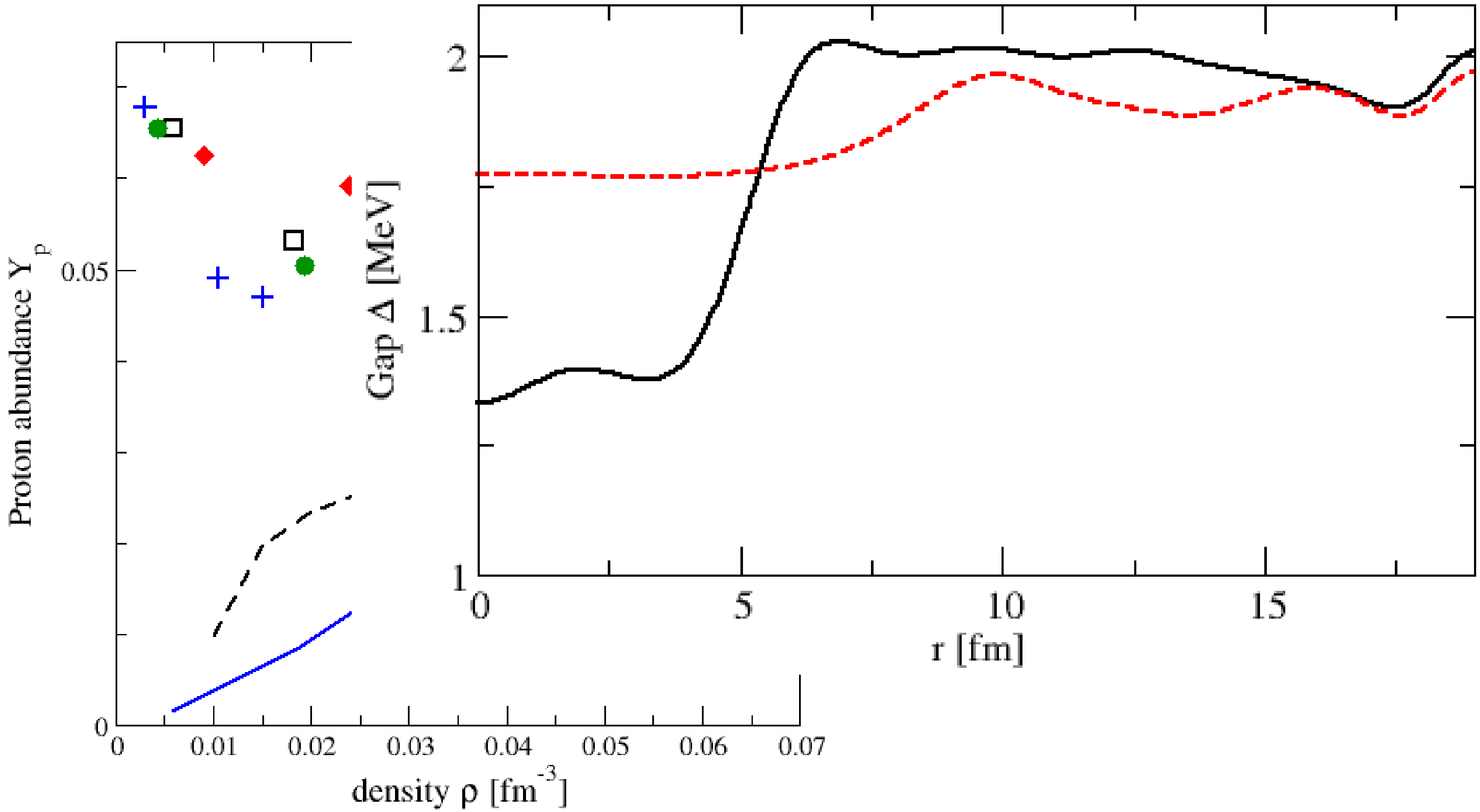




Energy versus density

(in various WS cells)

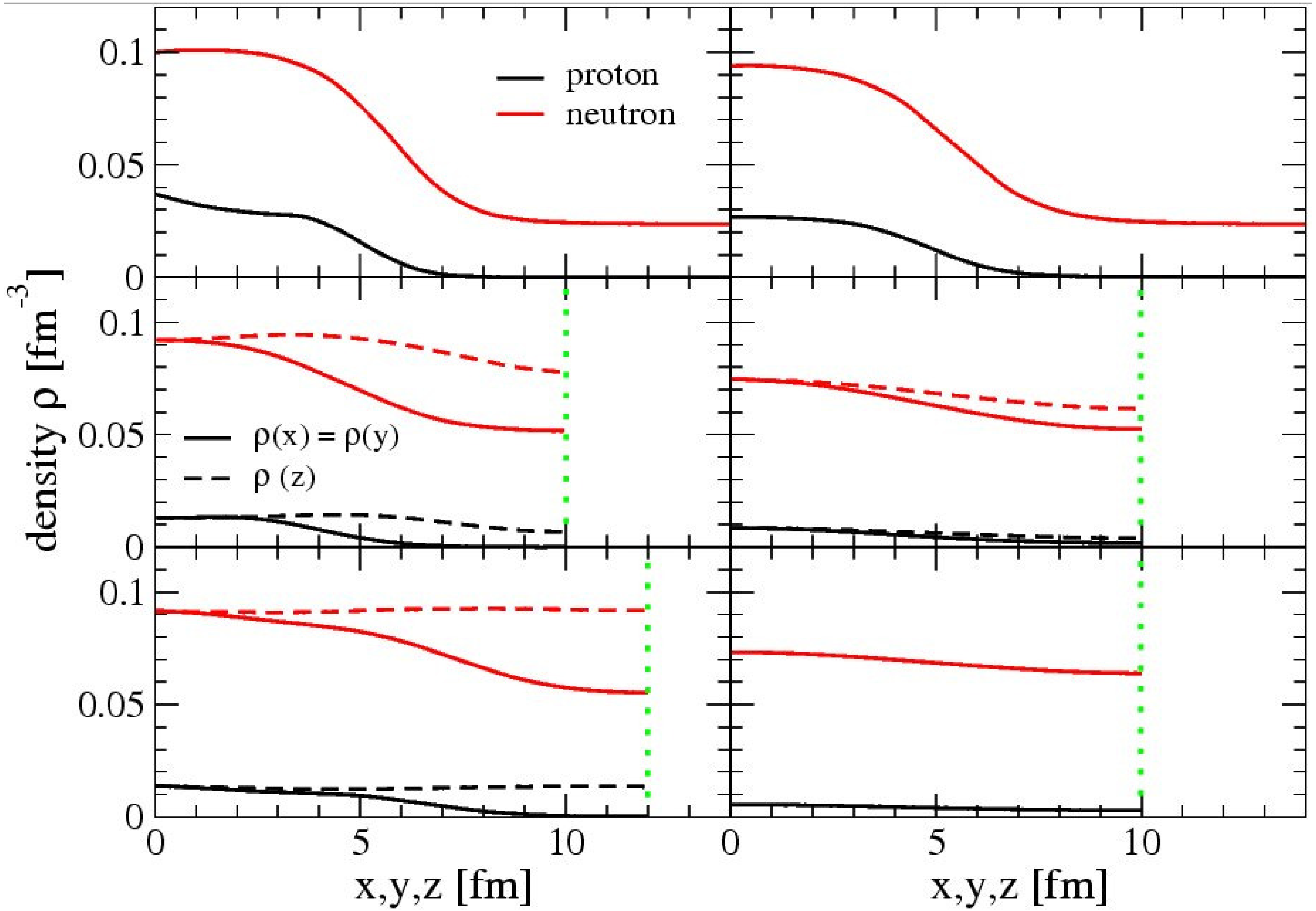
Shell Effects:



Enhance proton abundance

Reduce pairing gap

Shapes in Pasta Phase



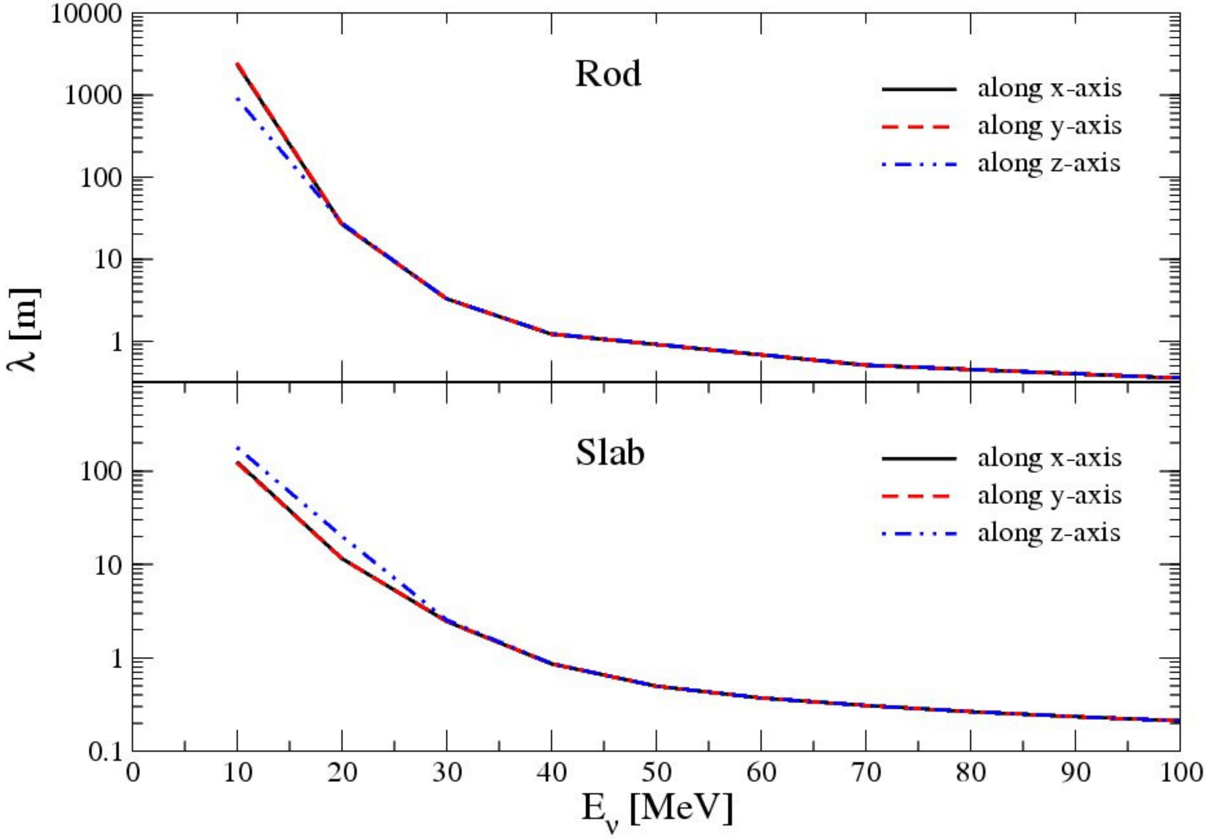
ρ = 0.02

ρ = 0.05

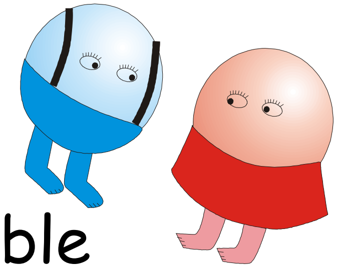
ρ = 0.06

T = 0 **T = 5 MeV**

Mean Free Path for Neutrinos



Conclusions



- Phenomenological approaches provide reasonable results for bulk properties of nuclear systems
- Microscopic studies are required for more sensitive observables like pairing correlations
- Consistent treatment of short-range and pairing correlations
- Short-range correlations quench pairing significantly
- Structures in the transition from homogeneous matter to isolated nuclei: „Pasta Phase“
- Effects on excitation modes and properties like mean free path for neutrinos