Opacidade de neutrinos e a estrutura da fase pasta

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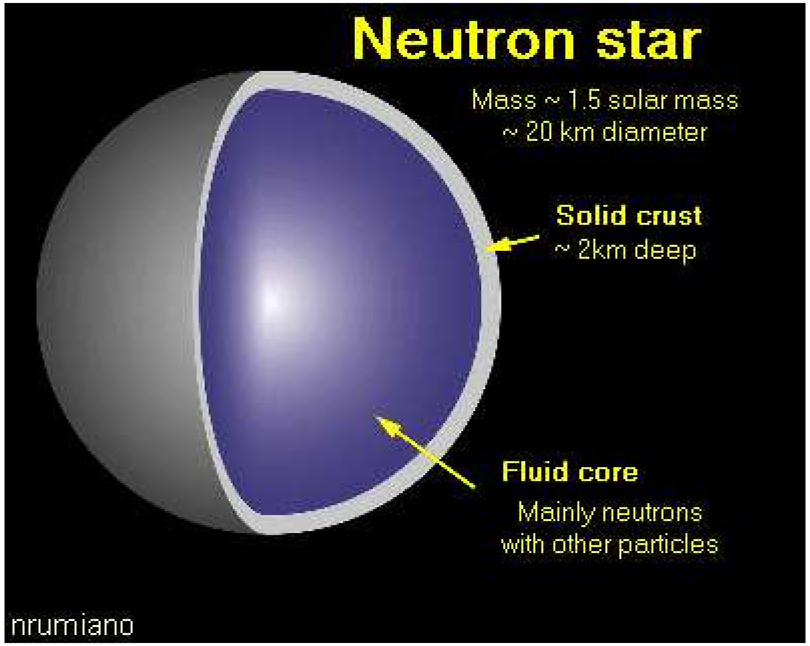
Building the Pasta Phase



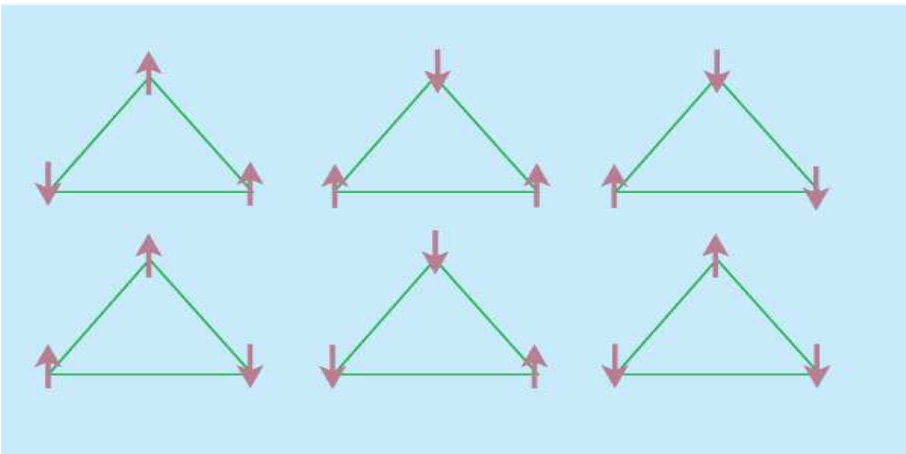
The solid crust insulates thermally the neutron star cold surface from its hot liquid interior and because of this fact, it is of vital importance in the understanding of neutron star cooling and evolution.



Does the existence of the pasta phase on the crust influence neutrino opacities in stellar matter?

What is the pasta phase probably present in the crust of NS?

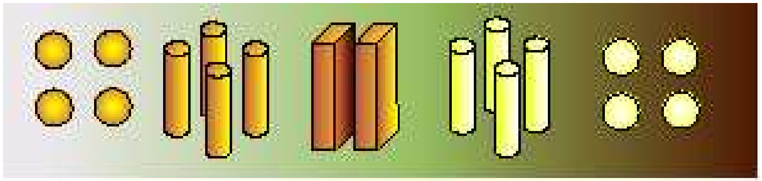
- It is the result of a frustrated system. At low densities a competition between the strong and the electromagnetic interactions takes place leading to a frustrated system.



- The individual interaction energies among the three types of pairing cannot be minimised simultaneously: the system is frustrated (P. Schiffer, Nature **420** (2002) 35).

- Normally the short and large distance scales related to the nuclear and Coulomb interactions are well separated so that nucleons bind into nuclei but at densities of the order of $10^{13} - 10^{14}$ g/cm^3 these length scales are comparable.

- A variety of complex structures exist: droplet (meatball, 3D), rod (spaghetti, 2D), lazagna (slab, 1D), penne (tube, 2D), Swiss cheese (bubble, 3D).



- The pasta phase is the ground state configuration if its free energy is lower than the corresponding homogeneous phase.

Different models - *npe* matter

Variations of quantum hadrodynamics (non-linear Walecka model)

$$\mathcal{L} = \sum_{i=p,n} \mathcal{L}_i + \mathcal{L}_e + \mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\rho + \mathcal{L}_\delta + \mathcal{L}_\gamma, \tag{1}$$

with fixed couplings (coupling constants):

$$\mathcal{L}(\psi, g_s\phi, g_v V^\mu, g_\rho \vec{b}^\mu, eA^\mu, \kappa\phi^3, \lambda\phi^4, \xi(V_\mu V^\mu)^2) \tag{2}$$

or with density dependent couplings (non-linear terms are not present):

$$\mathcal{L}(\psi, \Gamma_s\phi, \Gamma_v V^\mu, \Gamma_\rho \vec{b}^\mu, eA^\mu) \tag{3}$$

$$\Gamma_i(\rho) = \Gamma_i(\rho_0) h_i(x), \quad x = \rho/\rho_0 \tag{4}$$

These parameters are fitted to give especific nuclear matter properties

NL3: G. A. Lalazissis, J. König and P. Ring, Phys. Rev. C **55**, 540 (1997)

TM1: K. Sumiyoshi, H. Kuwabara, H. Toki, Nucl. Phys. **A 581**, 725 (1995)

NLδ: B. Liu, V. Greco, V. Baran, M. Colonna and M. Di Toro, Phys. Rev. **C 65**, 045201 (2002)

GM1,GM3: N. K. Glendenning, Compact Stars, Springer-Verlag, New-York, 2000

TW: S. Typel and H. H. Wolter, Nucl. Phys. **A656**, 331 (1999)

DDME1: T. Niksic, D. Vretenar, P. Finelli and P. Ring, Phys. Rev. **C 66**, 024306 (2002)

DDHδ: T. Gaitanos, M. Di Toro, S. Typel, V. Baran, C. Fuchs,V. Greco and H. H. Wolter, Nucl. Phys. **A 732**, 24 (2004); S.S. Avancini, L. Brito, D. P. Menezes and C. Providência, Phys. Rev. C **70**, 015203 (2004)

GDFM: P. Gögelein, E.N.E. van Dalen, C. Fuchs and H. Müther, Phys. Rev. **C 77**, 025802 (2008)

Two methods are used: TF and CP.

The Thomas-Fermi Approximation

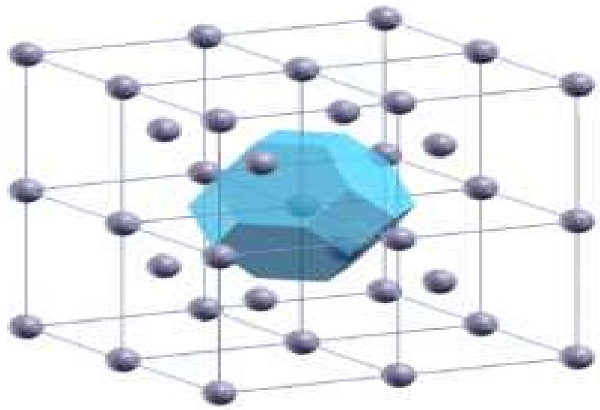
The densities are obtained by minimising the functional:

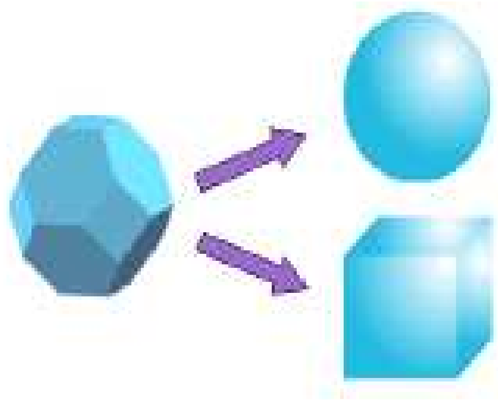
$$\Omega = \int_{V_{WZ}} d^3x \ \epsilon_{TF}[\rho_p(\vec{x}), \rho_n(\vec{x}), \rho_e(\vec{x})] - \sum_{i=n,p,e} \mu_i \int_{V_{WZ}} d^3r \rho_i(\vec{x}) \ .$$

with adequate boundary conditions.

Numerical technique: All mesonic fields are expanded in a HO basis for 1D, 2D or 3D and the differential equations become matrix equations solved self-consitently.

Wigner-Seitz Cell Geometry





TF: Inside the WS cell *npe* matter is considered locally homogeneous and described by a degenerate Fermi gas:

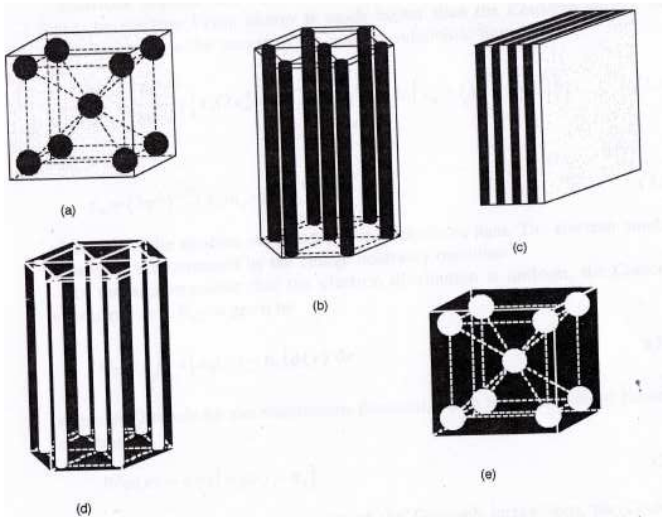
$$N_i = \int d^3x \ \rho_i(\vec{x}) \quad , \quad i = p, n, e$$

$$E_{TF} = \int d^3x \ \{\epsilon(\rho_p(\vec{x}), \rho_n(\vec{x}), \phi(\vec{x}), V_0(\vec{x}), b_0(\vec{x}), \delta_0(\vec{x})) + \epsilon_{COUL}(\rho_p(\vec{x}), \rho_e(\vec{x}))\}$$

- Body centered cubic crystal lattice (bcc) - spherical structures (3D) - $\rho_i(r,\theta,\phi) = \rho_i(r)$

- Hexagonal lattice - cylindrical structures (2D) - $\rho_i(\rho,\theta,z) = \rho_i(\rho)$

- Unidimensional lattice - slab structure - $\rho_i(x,y,z) = \rho_i(z)$



K. Oyamatsu, Nucl. Phys. **A**561 (1993) 431.

We fix ρ_B and calculate the energies related to the 3 Wigner-Seitz cell geometries. The lower one is the preferential pasta structure. It is then compared with the energy of a homogeneous system.

Coexisting Phases Method / MFA

Nuclear matter

ρ, $Y_p = \rho_p/\rho$ (global proton fraction) are fixed; the pasta structures are built with different geometrical forms in a background nucleon gas.

Gibbs' conditions :

$$P^I(\nu_p^I, \nu_n^I, M_n^{*I}, M_p^{*I}) = P^{II}(\nu_p^{II}, \nu_n^{II}, M_n^{*II}, M_p^{*II}), \tag{5}$$

$$\mu_i^I = \mu_i^{II}, \quad i = p, n \tag{6}$$

$$m_s^2 \phi_0^I = \Gamma_s \rho_s^I, \qquad m_s^2 \phi_0^{II} = \Gamma_s \rho_s^{II}, \tag{7}$$

$$m_\delta^2 \delta_3^I = \Gamma_\delta \rho_{s3}^I, \qquad m_\delta^2 \delta_3^{II} = \Gamma_\delta \rho_{s3}^{II}, \tag{8}$$

$$f \rho_p^I + (1 - f)\rho_p^{II} = \rho_p = Y_p \rho, \tag{9}$$

I,II = labels of the phases, f = volume fraction of phase I:

$$f = \frac{\rho - \rho^{II}}{\rho^I - \rho^{II}} \tag{10}$$

$$P = P^I + P_e \tag{11}$$

$$\mathcal{E} = f\mathcal{E}^I + (1-f)\mathcal{E}^{II} + \mathcal{E}_e + \mathcal{E}_{surf} + \mathcal{E}_{Coul}, \qquad \mathcal{E}_{surf} = 2\mathcal{E}_{Coul} \tag{12}$$

$$\mathcal{E}_{Coul} = \frac{2\alpha}{4^{2/3}}(e^2\pi\Phi)^{1/3}\left(\sigma D(\rho_p^I - \rho_p^{II})\right)^{2/3}, \tag{13}$$

$\alpha = f$ for droplets/rods, $\alpha = 1-f$ for bubbles/tubes; $\sigma =$ surface energy coefficient; $D =$ dimension of the system.

$$\Phi = \begin{cases} \left(\frac{2-Df^{1-2/D}}{D-2} + f\right)\frac{1}{D+2}, & D = 1,3; \\ \frac{f-1-ln(f)}{D+2}, & D = 2. \end{cases} \tag{14}$$

σ is AN IMPORTANT QUANTITY, which we parametrize.

Stellar matter

$$\mu_p = \mu_n - \mu_e + \mu_\nu, \quad \mu_e = \mu_\mu \tag{15}$$

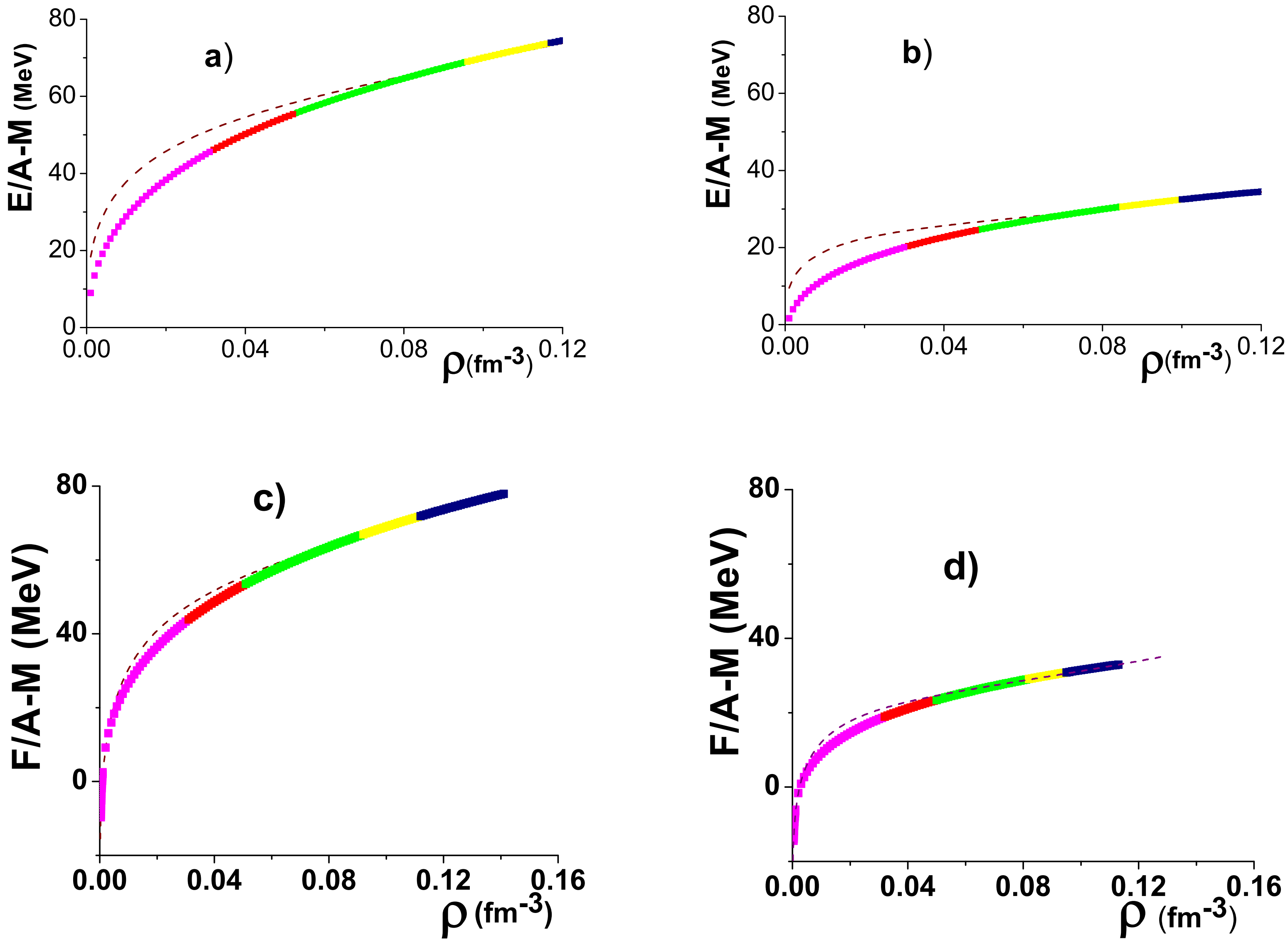
$$\rho_p = \rho_e + \rho_\mu \tag{16}$$

$$Y_L = \frac{\rho_e + \rho_\nu + \rho_\mu}{\rho_B} \tag{17}$$

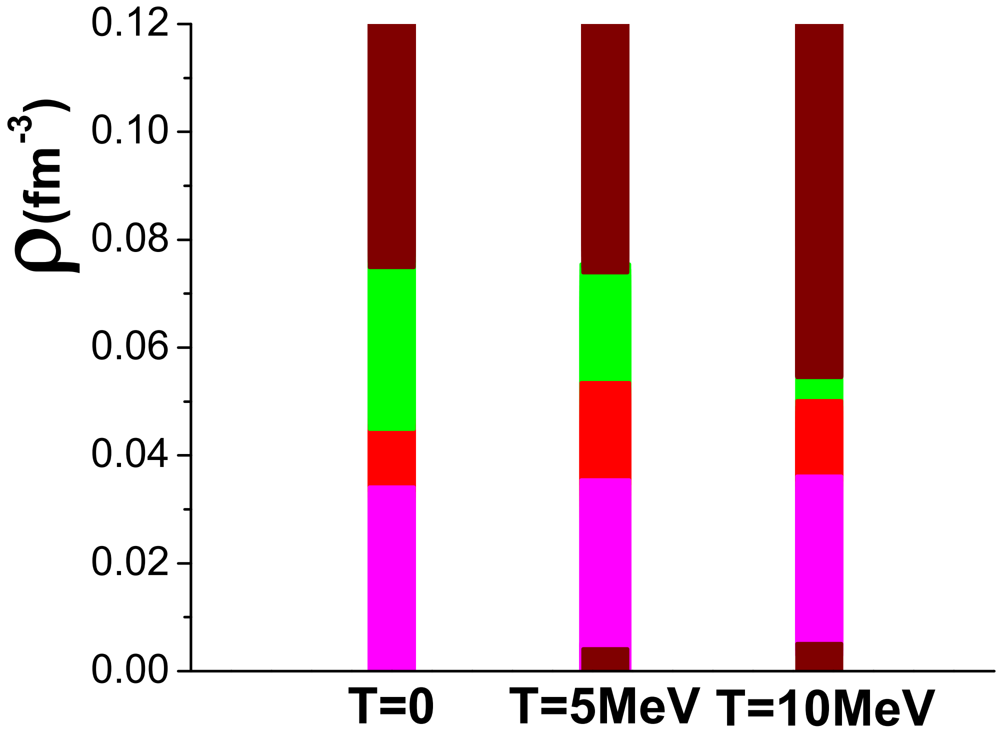
The Gibbs' conditions:

$$\mu_n^I = \mu_n^{II}, \quad \mu_e^I = \mu_e^{II}, \quad \mu_\nu^I = \mu_\nu^{II}, \tag{18}$$

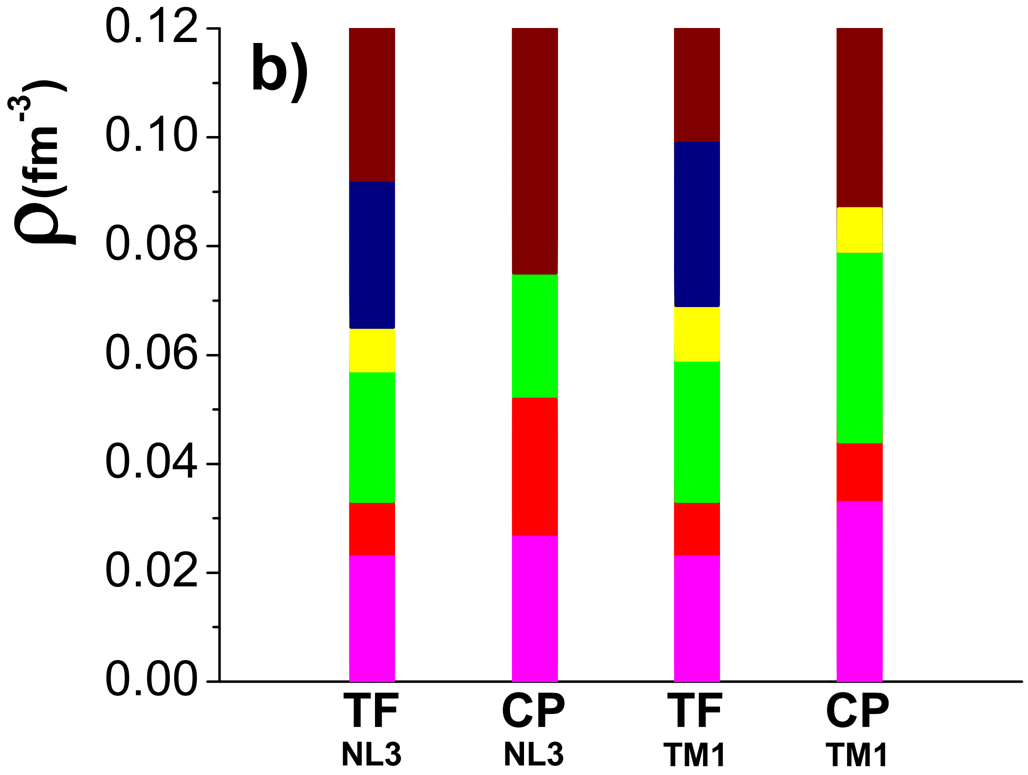
$$f\left(\rho_p^I - \rho_e^I - \rho_\mu^I\right) + (1-f)\left(\rho_p^{II} - \rho_e^{II} - \rho_\mu^{II}\right) = 0 \tag{19}$$



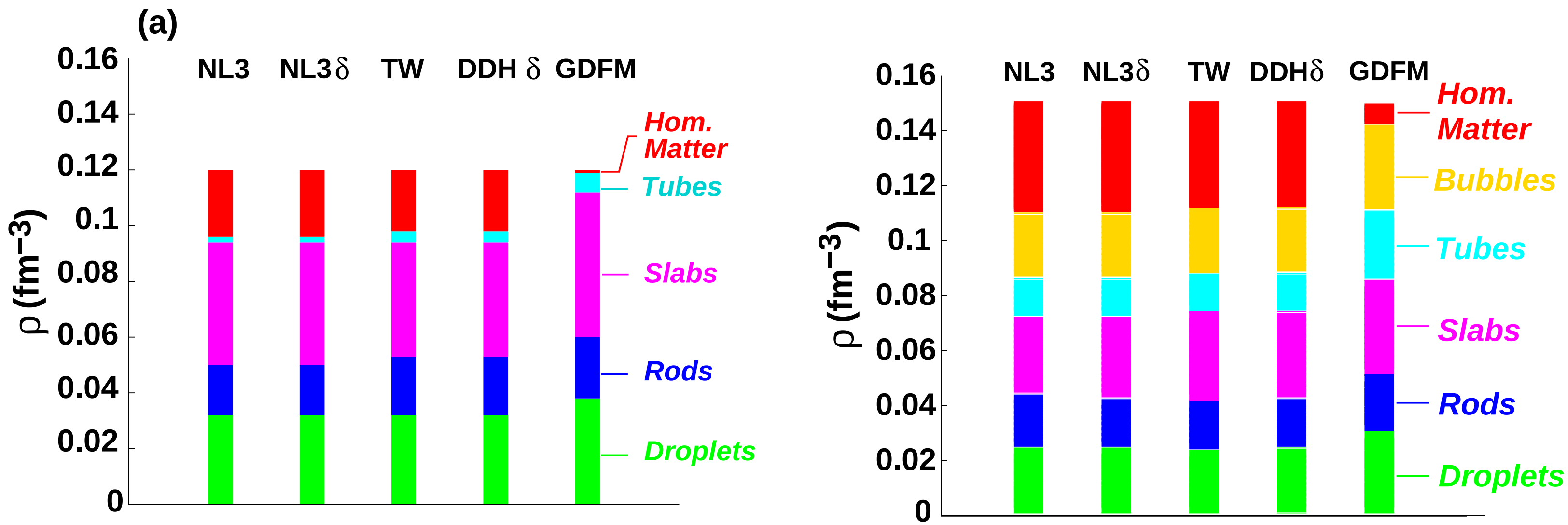
npe matter (CP method) with NL3 and a) T=0, $Y_p = 0.5$, b) T=0 $Y_p = 0.3$; c) T=5 MeV, $Y_p = 0.5$, d) T=5 MeV, $Y_p = 0.3$. The different structures of the pasta are represented by different colors and the dashed line stands for homogenous matter.



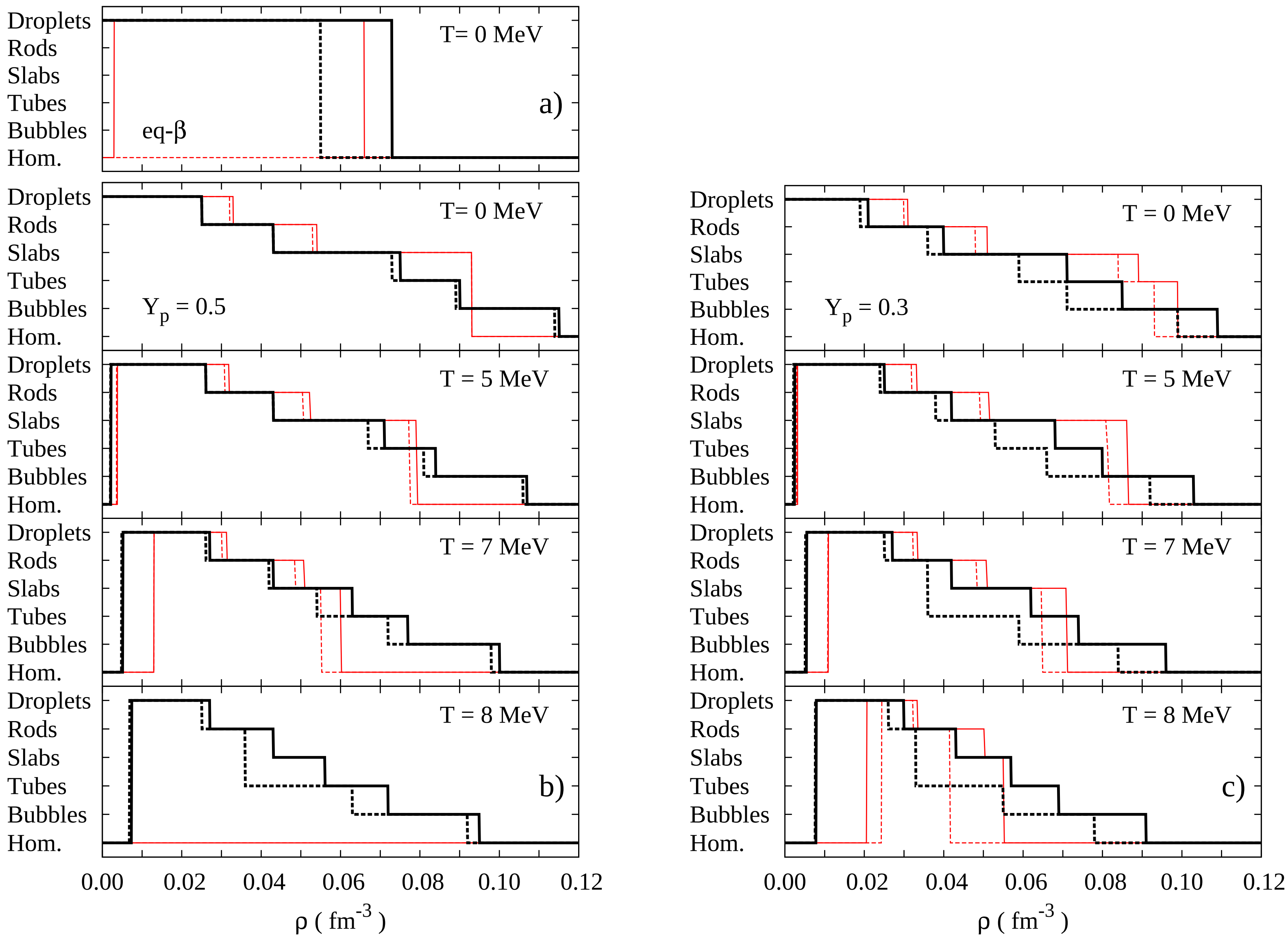
Comparison of the phase diagrams, NL3, $Y_p = 0.3$, CP method. From bottom to top the colours represent droplets, rods, slabs and the homogeneous phase for $T = 0$ MeV, and homogeneous phase, droplets, rods, slabs and the homogeneous phase for $T = 5$ MeV and $T = 10$ MeV.



Phase diagrams, T=0, obtained both with CP and TF approximation for NL3 and TM1 with $Y_p = 0.3$. From bottom to top the colours represent droplets, rods, slabs, tubes, bubbles and the homogeneous phase, whenever present.



Phase diagrams at $T = 0$ MeV for $Y_p = 0.5$ obtained with a) the coexisting phases method (CP) and b) obtained with the TF method for several models.



Pasta phases: comparison between NL3 (dashed line) and TW (full line). The thick lines - Thomas-Fermi (TF) calculation and the thin red lines - coexisting-phases (CP) calculation.

Comments on the pasta phase

- While the final EOS obtained with the different methods do not vary much, the internal structure varies considerably.

- The TF approximation was performed to test the much simpler CP calculation. It was shown that the success of the CP calculation depends on the parametrisation of the surface energy.

- The pasta phase shrinks with the increase of the temperature and the homogeneous matter can be the preferential phase also at very low densities depending on the temperature and the proton fraction.

Neutrino cross sections

To calculate neutrino opacities and mean free paths we consider neutral current scattering reactions:

$$\nu_e + n \to \nu_e + n, \qquad (20)$$
$$\nu_e + p \to \nu_e + p, \qquad (21)$$

and charged current absorption reactions:

$$\nu_e + n \to e^- + p. \qquad (22)$$
$$\overline{\nu}_e + p \to e^+ + n. \qquad (23)$$

for which we need cross sections σ_n, σ_p and σ_a (huge expressions...)

The total neutrino mean free path in dense matter is given by

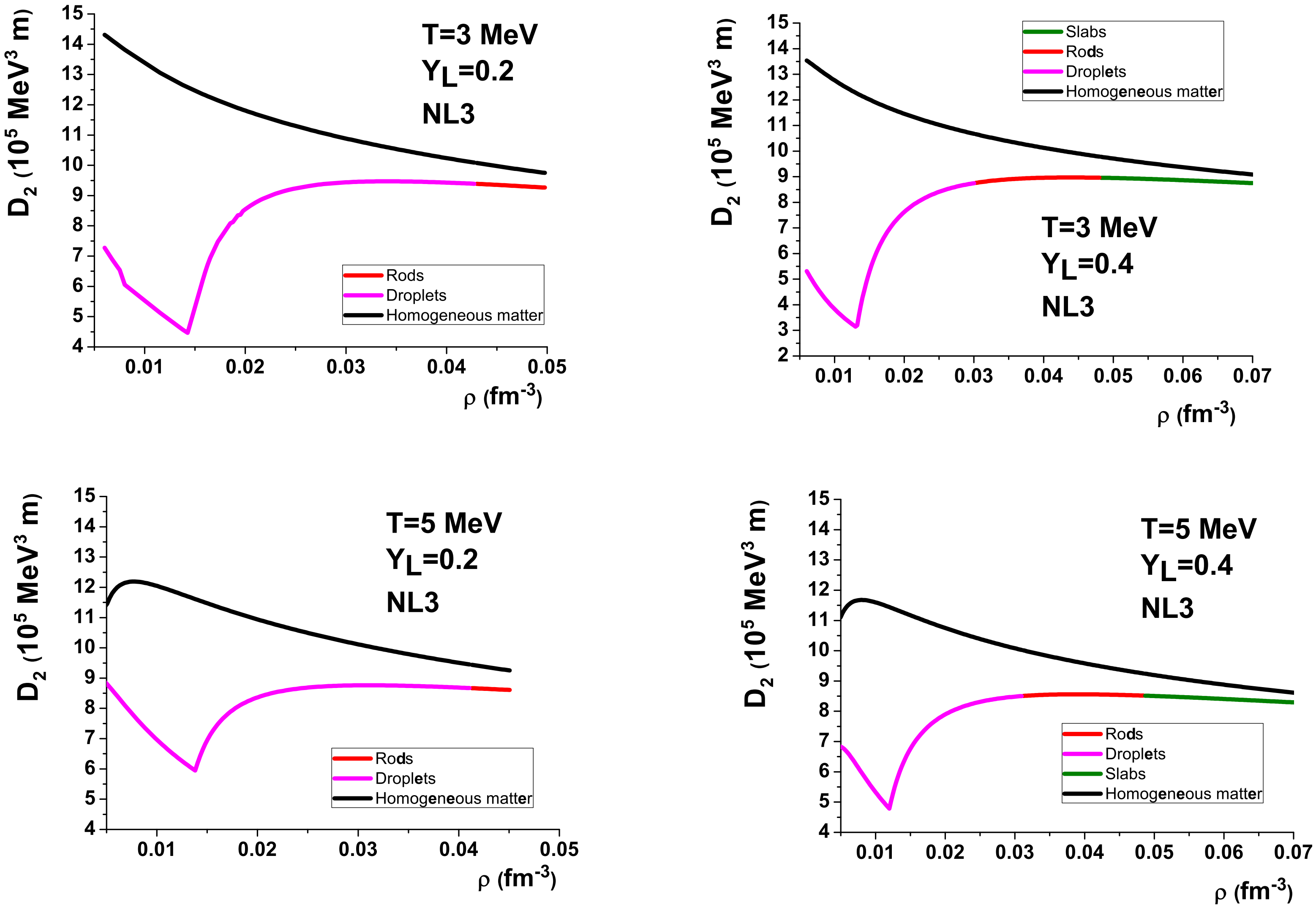
$$\lambda_\nu = \frac{1}{\rho_n \sigma_n + \rho_p \sigma_p + \rho_B \sigma_a}. \tag{24}$$

Rosseland neutrino mean free paths are related with diffusion coefficients D_j by

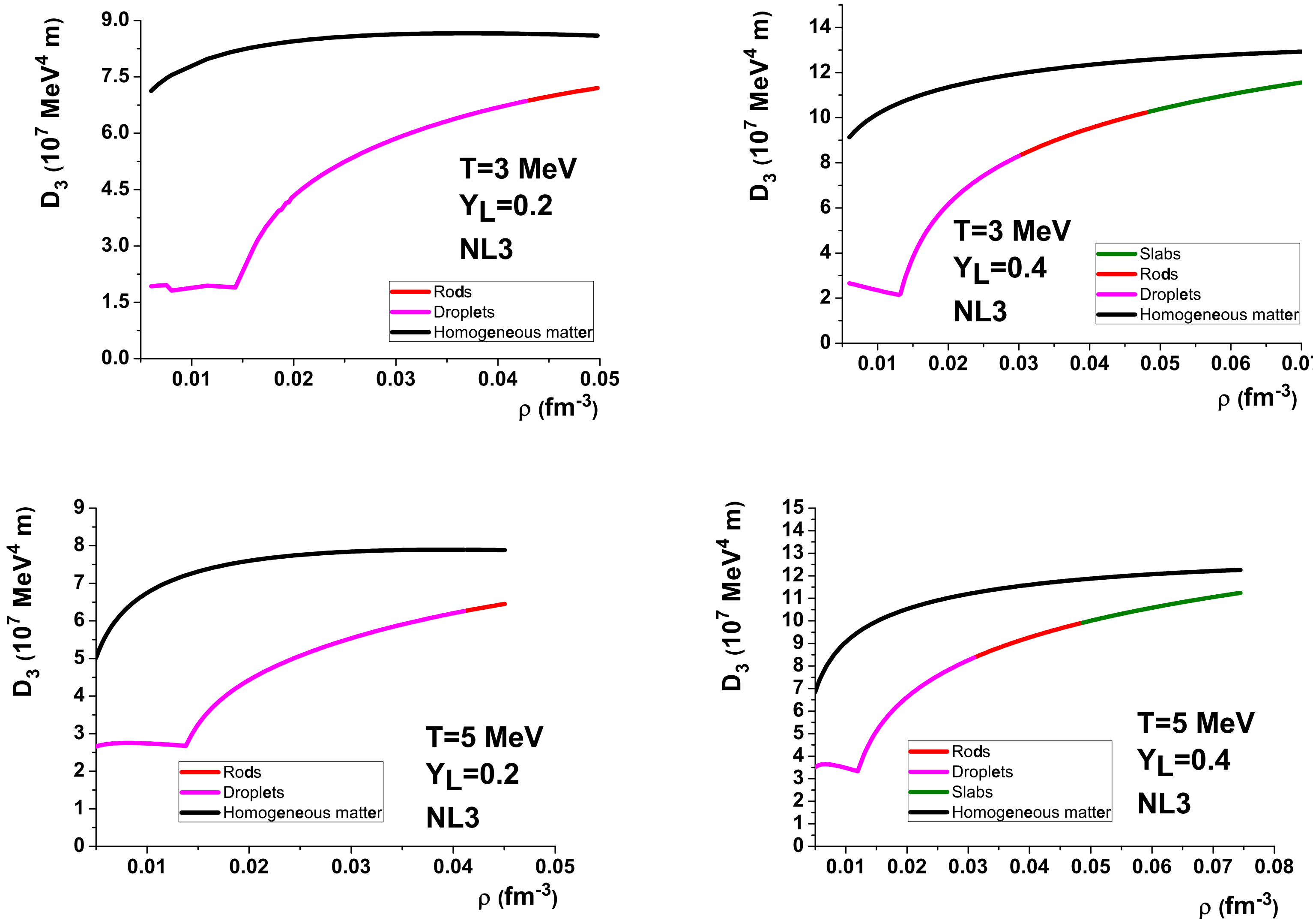
$$\lambda_\nu^k = \frac{D_k}{\int_0^\infty d\epsilon_\nu \ \epsilon_\nu^k f_\nu (1 - f_\nu)}, \tag{25}$$

where

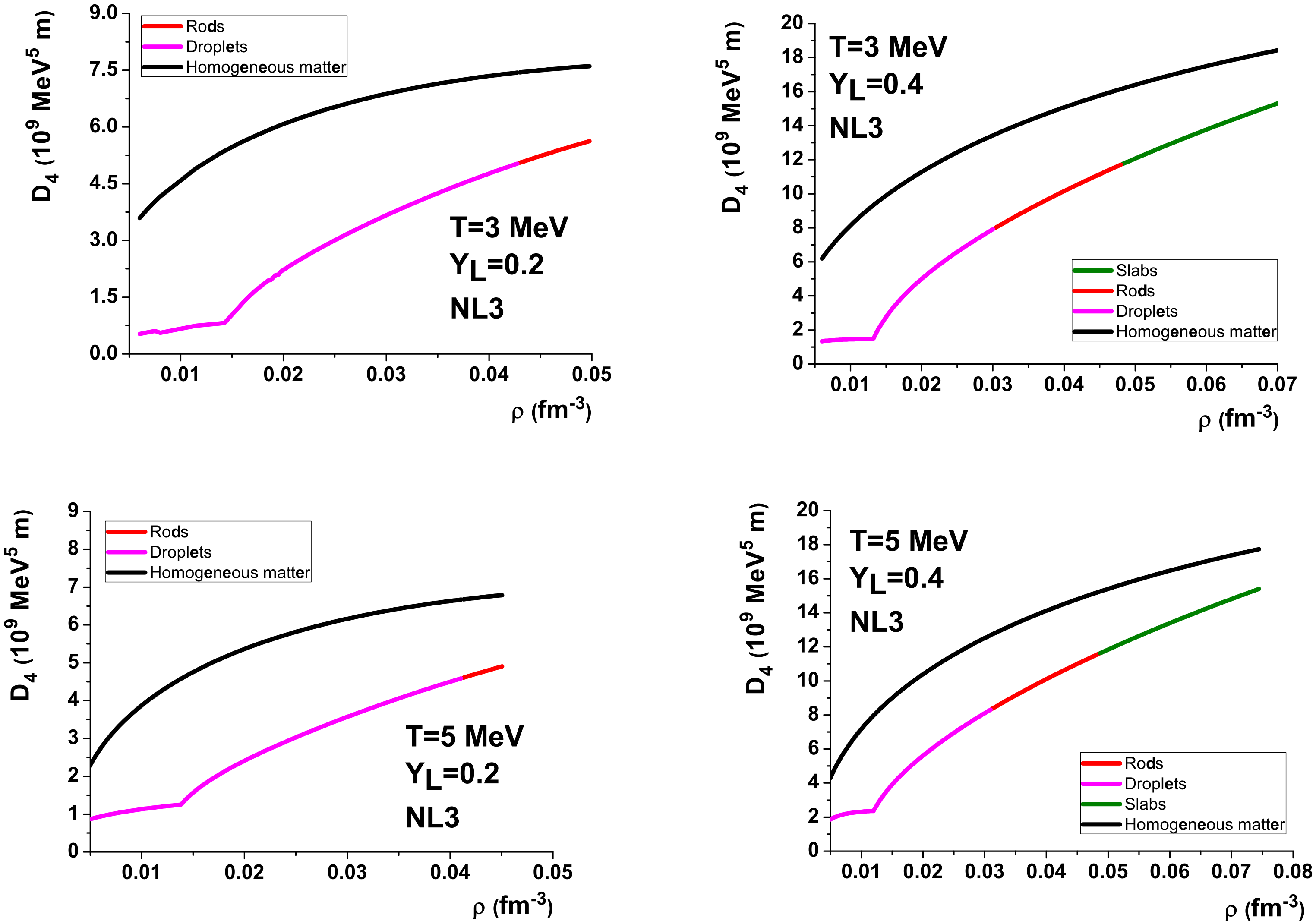
$$D_k = \int_0^\infty d\epsilon_\nu \ \epsilon_\nu^k \lambda_\nu f_\nu (1 - f_\nu). \quad k = 2, 3, 4 \tag{26}$$



Diffusion coefficient D_2 as function of baryon density for different temperature and lepton fraction values for homogeneous matter and pasta phase.



Diffusion coefficient D_3 as function of baryon density for different temperature and lepton fraction values for homogeneous matter and pasta phase.



Diffusion coefficient D_4 as function of baryon density for different temperature and lepton fraction values for homogeneous matter and pasta phase.

Conclusions

- Just NL3 obtained with CP; other parametrizations may give slightly different results for the diffusion coefficients.

- The differences in the diffusion coefficients due to the existence of the pasta phase have consequences in neutrino opacities.

- Neutrino opacities are used as input to the solution of the transport equations in the equilibrium diffusion approximation, which simulates the Kelvin-Helmholtz phase of the protoneutron stars.

- The existence of the pasta phase in the crust of protoneutron stars will probably influence their cooling mechanism.

Collaborators

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Thank you for your attention