NEUTRINO PROPAGATION IN HOT NUCLEAR MATTER AND ITS APPLICATIONS TO THE SUPERNOVAE EXPLOSION

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INTRODUCTION

After forty years of investigation, mechanism of supernovae explosion is still unknown. Although qualitative model of core collapse seems to be correct, numerical calculations do not lead to the explosion. This result is a straightforward consequence of lack in understanding of processes, which transfer energy from the inner core to the outer mantle of the massive star. Major mediators of this energy transfer are neutrinos, which are produced in abundance during the explosion. Therefore, to correctly understand mechanism of supernova explosion it is necessary to firmly deal with the physics of neutrino processes in nuclear medium.

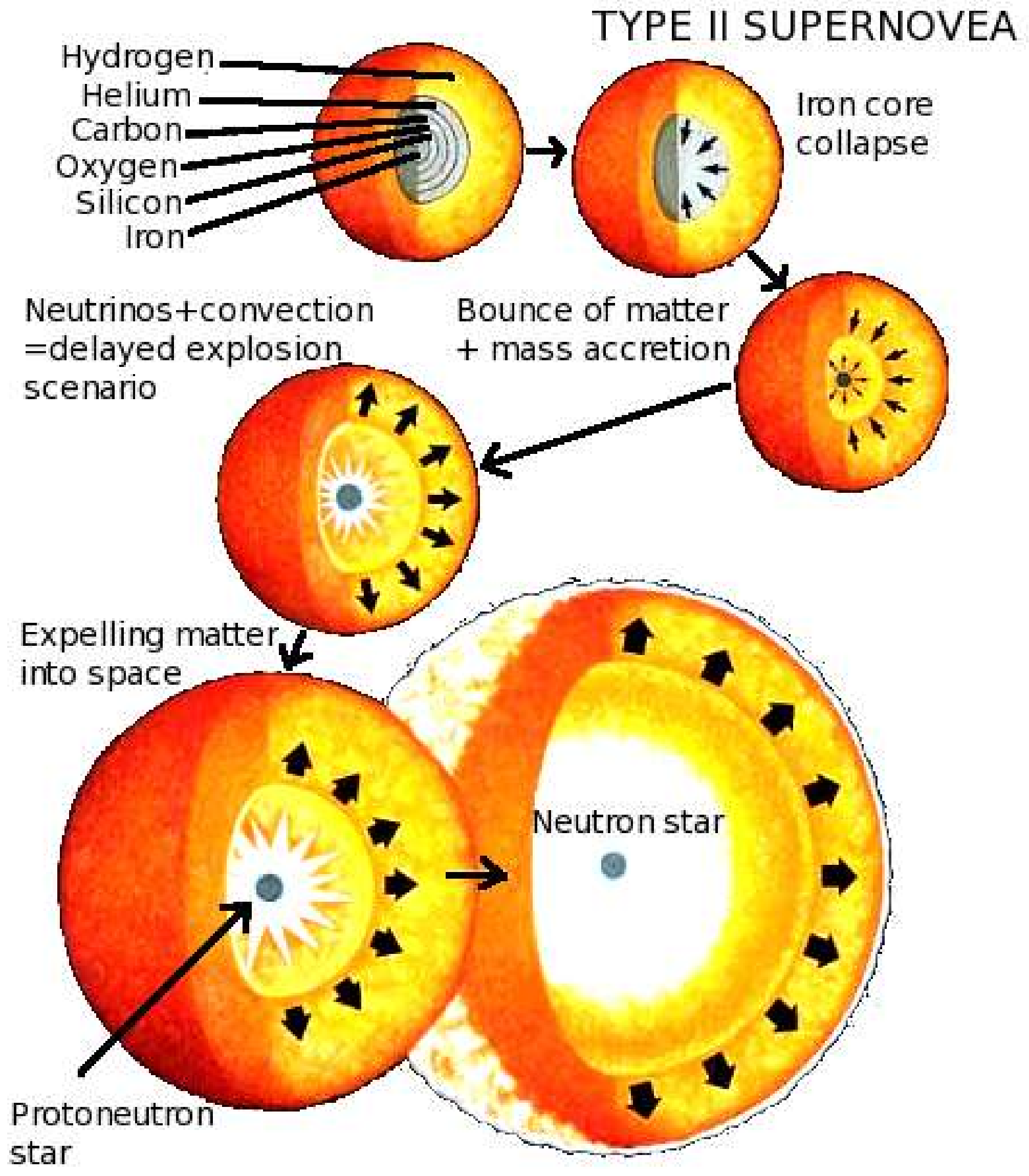

Figure 1: The main stages of supernova explosion.

Current theory of supernova explosion is based upon the fact that high-energetic neutrinos streaming up from the hot interior have to transfer energy to outer layers and convert this energy into kinetic energy of expelling mass. Without additional source of energy, "shock wave" stalls after propagation of a few hundred kilometres, due to energy dissipation by the dissociation of nuclei, encounter during it moves outward. The mechanism of "re-juvenated" stagnating shock wave was first proposed in the early 1980s by Bethe and Wilson and now is known as "delayed explosion scenario". Understanding of mechanism of deposition neutrinos energy to the outer layers is crucial to reach explosion in numerical simulation. It is obvious that this issue comes to solve a problem of neutrino transport in nuclear medium. In fact it is a problem of nuclear physics and it is strongly connected with our knowledge of properties of hot & dense nuclear matter.

PHYSICAL APPROACH

Main ingredient needed to solve problem of neutrino transport is opacity of dense nuclear mater for neutrinos. This quantity can be expressed in terms of cross section for various processes or, what it is equivalent, by neutrino mean free path in nuclear medium.

Interaction of neutrino with nucleus is described by Wienberg-Salam theory. Neutrino mean free path in nonrelativistic limit can be expressed in terms of so-called dynamic form factors or structural functions, characterizes the isospin response of the nonrelativistic system. These functions contain all information about nuclear system and strongly depend on nuclear interaction.

$$1/\lambda(\mathrm{k}_\nu, T) = \frac{G_F^2}{16\pi^2}\int d\mathbf{k}_3 \left(c_V^2(1+\cos\theta)\ \mathcal{S}_V(q,T) \right.$$
$$\left. + c_A^2(3-\cos\theta)\ \mathcal{S}_A(q,T)\right),$$

Equation 1: Neutrino mean free path in nonrelativistic approximation. G_F is the Fermi constant, C_V (C_A) the vector (axial) coupling constant, S_V and S_A the structural functions.

To incorporate strong interactions Hartree-Fock approach with the effective Skyrme SLy4 interaction is used. Simplicity of density energy functional in limit of infinity nuclear matter makes that H-F approximation can be efficiently solved in case of finite temperatures.

$$\begin{aligned}\mathcal{H} \ = \ & \frac{\tau_B}{2M_N} + \frac{t_0}{2}\left[\left(1+\frac{x_0}{2}\right)\rho_B^2 - \left(\frac{1}{2}+x_0\right)(\rho_n^2+\rho_p^2)\right] \\ & + \frac{t_3}{12}\rho_B^\alpha\left[\left(1+\frac{x_3}{2}\right)\rho_B^2 - \left(\frac{1}{2}+x_3\right)(\rho_n^2+\rho_p^2)\right] \\ & + \frac{1}{8}\left[t_1(2+x_1)+t_2(2+x_2)\right]\rho_B\tau_B \\ & - \frac{1}{8}\left[t_1(2x_1+1)-t_2(2x_2+1)\right](\rho_n\tau_n+\rho_p\tau_p).\end{aligned}$$

Equation 2: Density energy functional for effective the Skyrme interaction in limit of infinity, uniform nuclear matter. ρ indicates density of particles, τ kinetic density.

In general exact composition of matter inside (proto) neutron star is unknown. Astrophysics gives only constrains for densities and chemical potentials of ingredients i.e. condition for β-equilibrium and charge neutrality of the system. To find the composition of medium (densities and chemical potentials of ingredients) is required formula of nuclear interaction, which depends on densities of particles. This problem can by solved only in self-consistent way.

$$E_q(p) = \frac{p^2}{2M_q^*} + U_q^{eff}.$$

Equation 3:Idea of H-F approximation. Each particle of the system with effective mass M moves independently in the single-particle potential U^{eff} which represents the mean field "felt" by the particle due to its interaction the other particle of the medium.*

NUCLEAR MATTER COMPOSITION

Figure 2 presents the composition of nuclear matter for cases of protoneutron and neutron matter in H-F approximation. Temperatures are chosen as representative for newly born protoneutron star (30 MeV) and neutron star (5 MeV). It is clearly shown that cooling process by neutrinos emission leads to increasing neutrons concentration. For temperature below 1 MeV protons concentration can be neglected and matter can be treated as pure neutron matter. Figure 3 shows chemical potentials of constituents for presented cases.

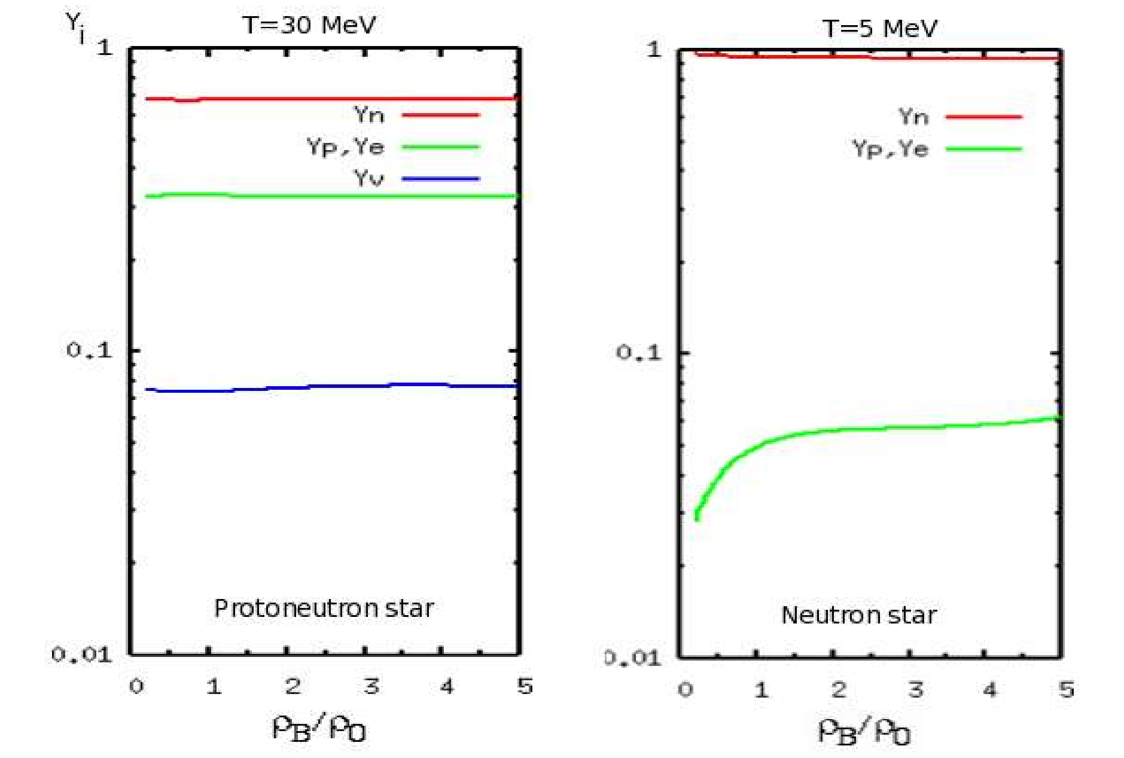

Figure 2:Individual concentrations of neutrons, protons and neutrinos for case of protoneutron matter (left panel) and neutron matter (right panel) versus density of nucleus (in units of the nuclear equilibrium density) for two arbitrary temperatures. In case of neutron matter concentration of neutrinos is zero.

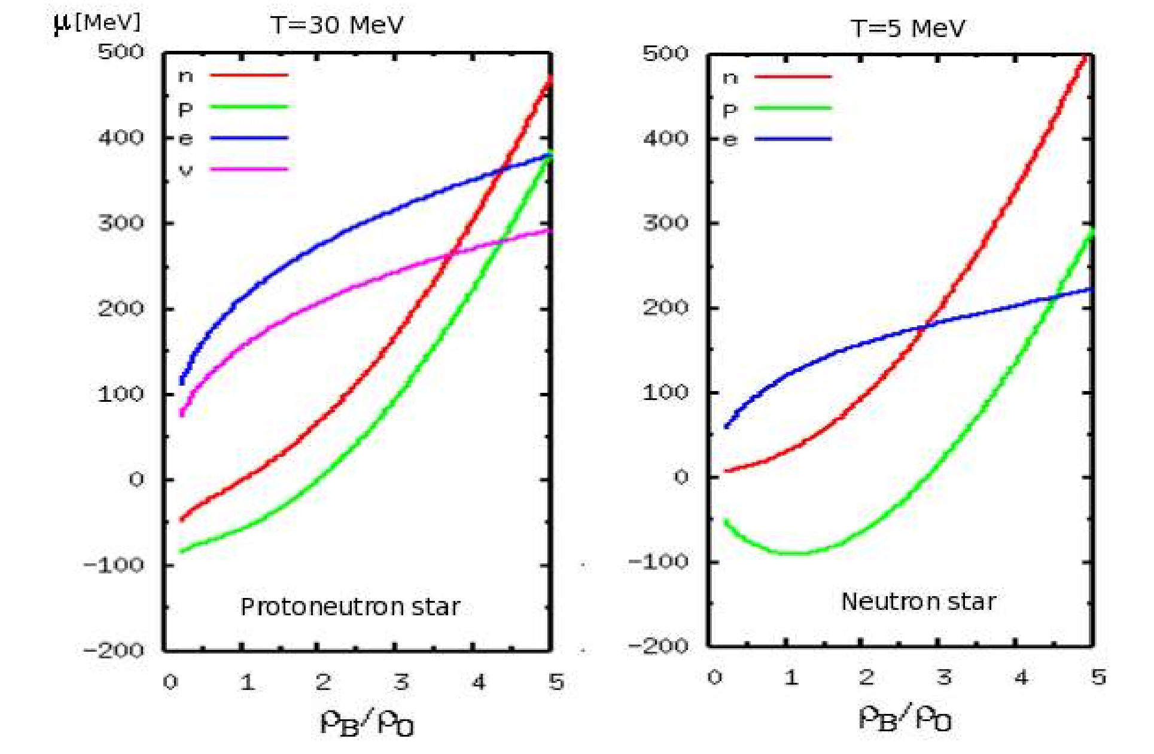

Figure 3: Chemical potentials of particles for case of protoneutron matter (left panel) and neutron matter (right panel) versus density of nucleus for two arbitrary temperatures. In case of neutron matter chemical potential of neutrinos is zero.

EQUATION OF STATE

Figure 4 presents energy per particle asymmetric nuclear matter for three arbitrary temperatures. In case of protoneutron matter we observe that increasing temperature of system leads to appearance of minimum for density very close to saturation density. In case of neutron matter such minimum does not appear what has a very simple explanation. Neutron systems cannot create bound objects. In case of neutron stars force, which binds all particles, is gravitational force.

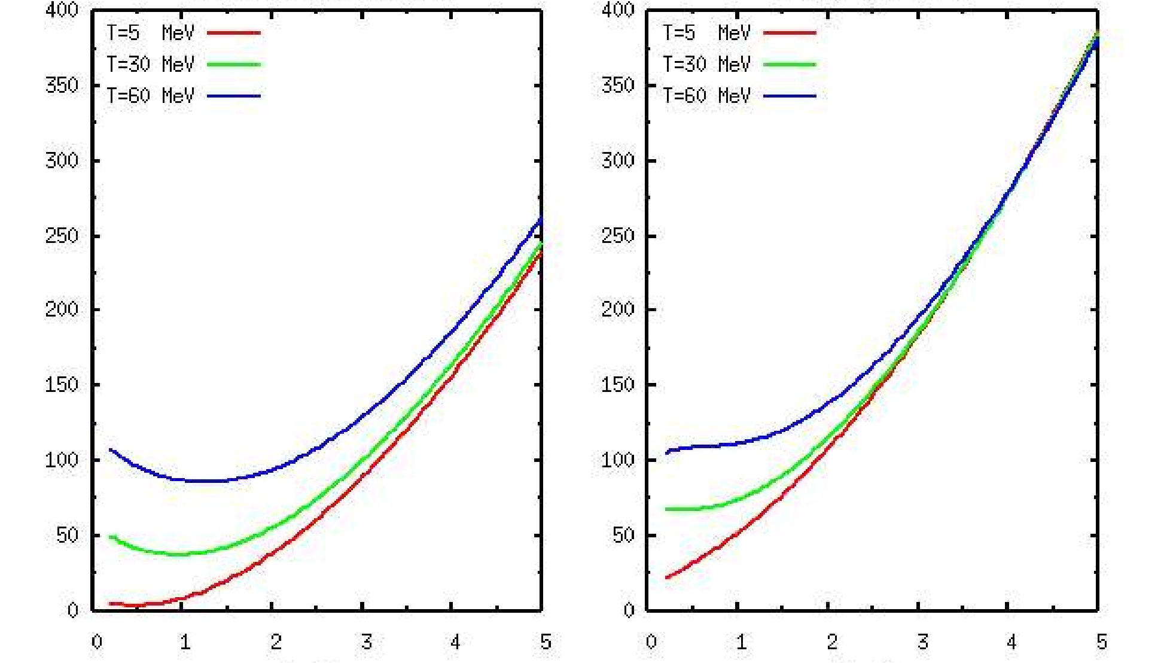

Figure 4: Energy per particle of protoneutron matter (left panel) and neutron matter (right panel) as a function of density for three arbitrary temperatures. Results are obtained for Skyrme effective interaction SLy4.

Figure 5 presents ratio of effective mass to bare nucleon mass in two cases of nuclear medium. Calculation shows that effective masses are independent of the temperature. Effective mass depends only on composition of the nuclear medium.

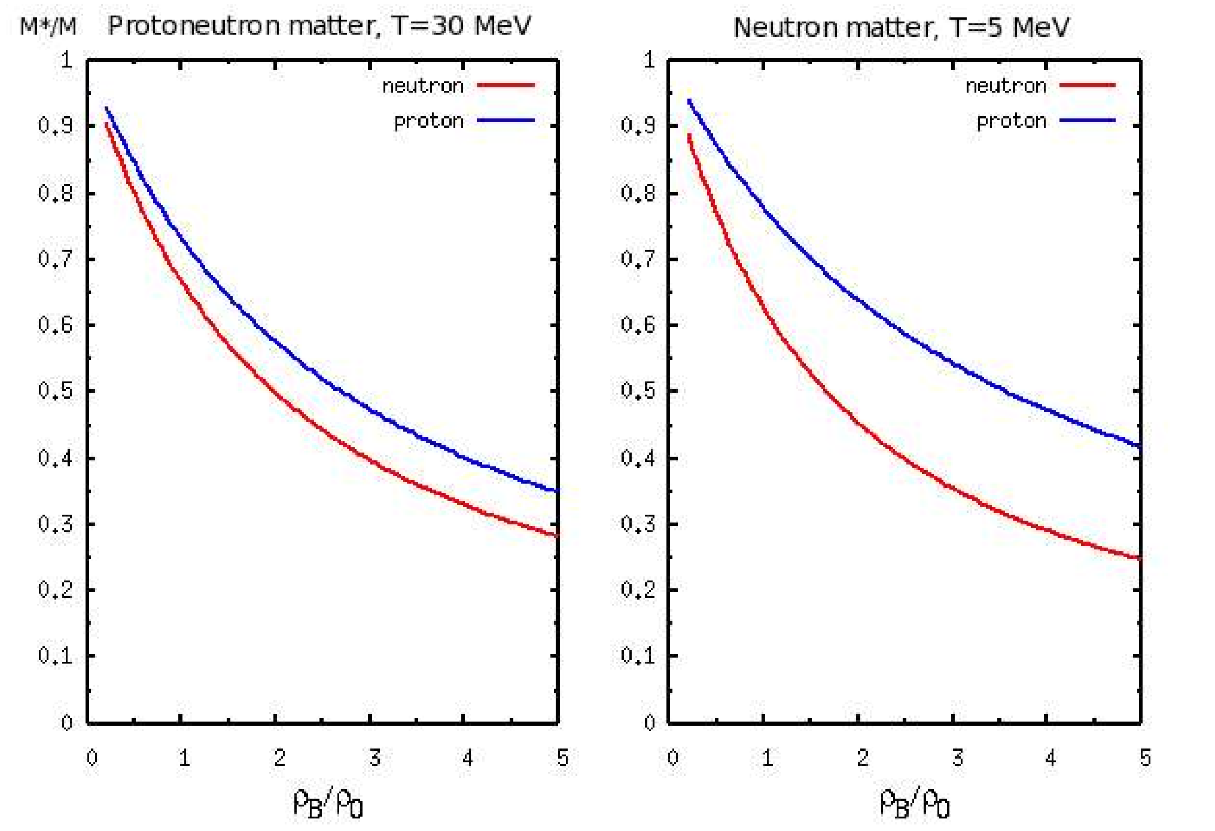

Figure 5: Neutron and proton effective masses in protoneutron matter (left panel) and neutron matter as a function of density in the Skyrme model.

NEUTRINO MEAN FREE PATH

We investigate both scattering and absorption neutrino mean free path. Figure 6 depicts neutrino mean free path in the protoneutron matter for neutrinos near Fermi surface. In this case the most efficiency reaction is absorption of neutrinos on neutrons (cross section is equal inverse of mean free path). Cross section for the absorption is three times larger than for scattering process. Reaction this is known as direct URCA process and it is major process inside protoneutron and hot neutron star. Process this determines intensity of neutrino flux which carry energy to the outer layers. Because the size of protoneutron star (R≈10 km) is much more grater than mean free path we say that neutrinos are trapped in the core of the star.

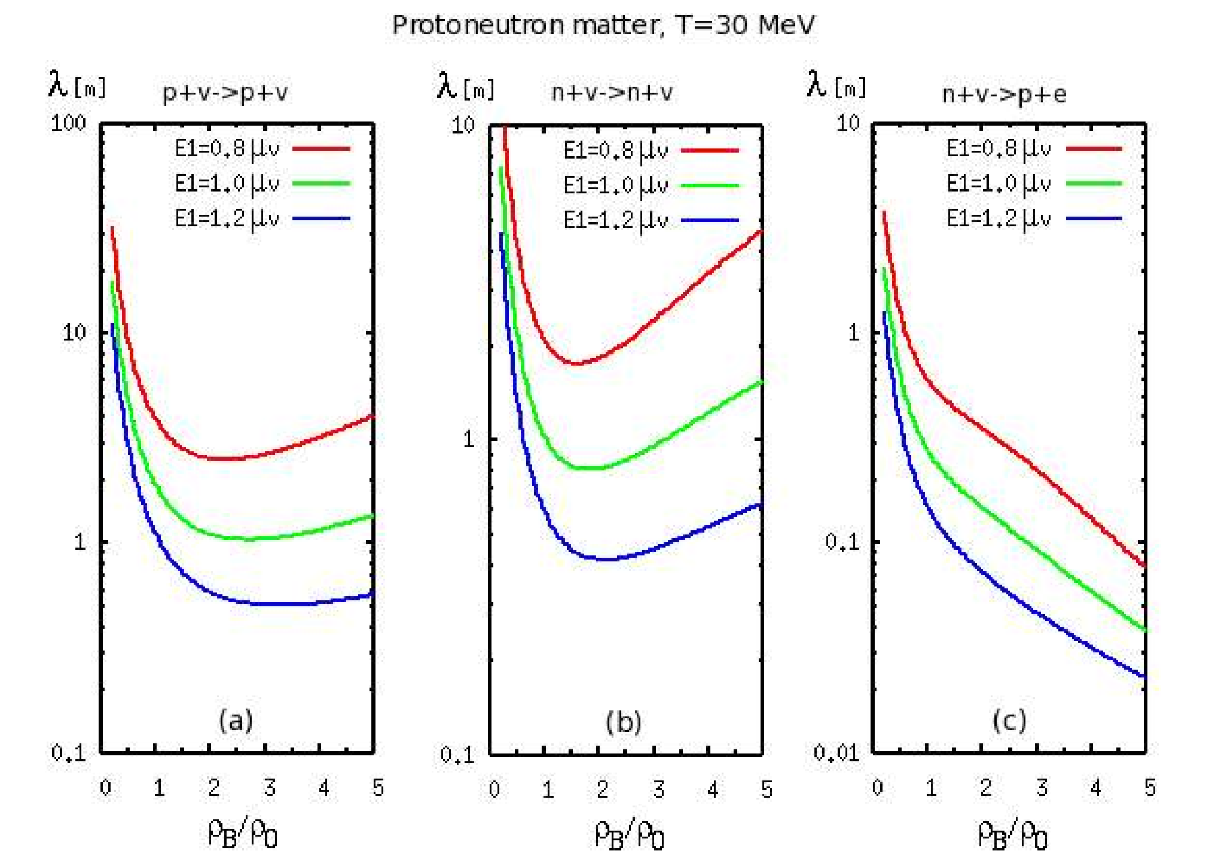

Figure 6: Neutrino mean free path in protoneutron matter with respect to scattering reactions on protons (a), neutrons (b) and absorption reactions on protons (c) as a function of nuclear matter density.

Figure 7 presents neutrino mean free path for neutrinos propagating in neutron matter. In this case mean free path is calculated for thermal neutrinos which energy is of order ~3 T. Main feature for this case is totally different behaves of cross section for absorption. Large difference of neutron and proton Fermi momenta makes simultaneous energy and momentum conservation impossible. Thus at low temperatures direct URCA process is suppressed and scattering becomes dominant process.

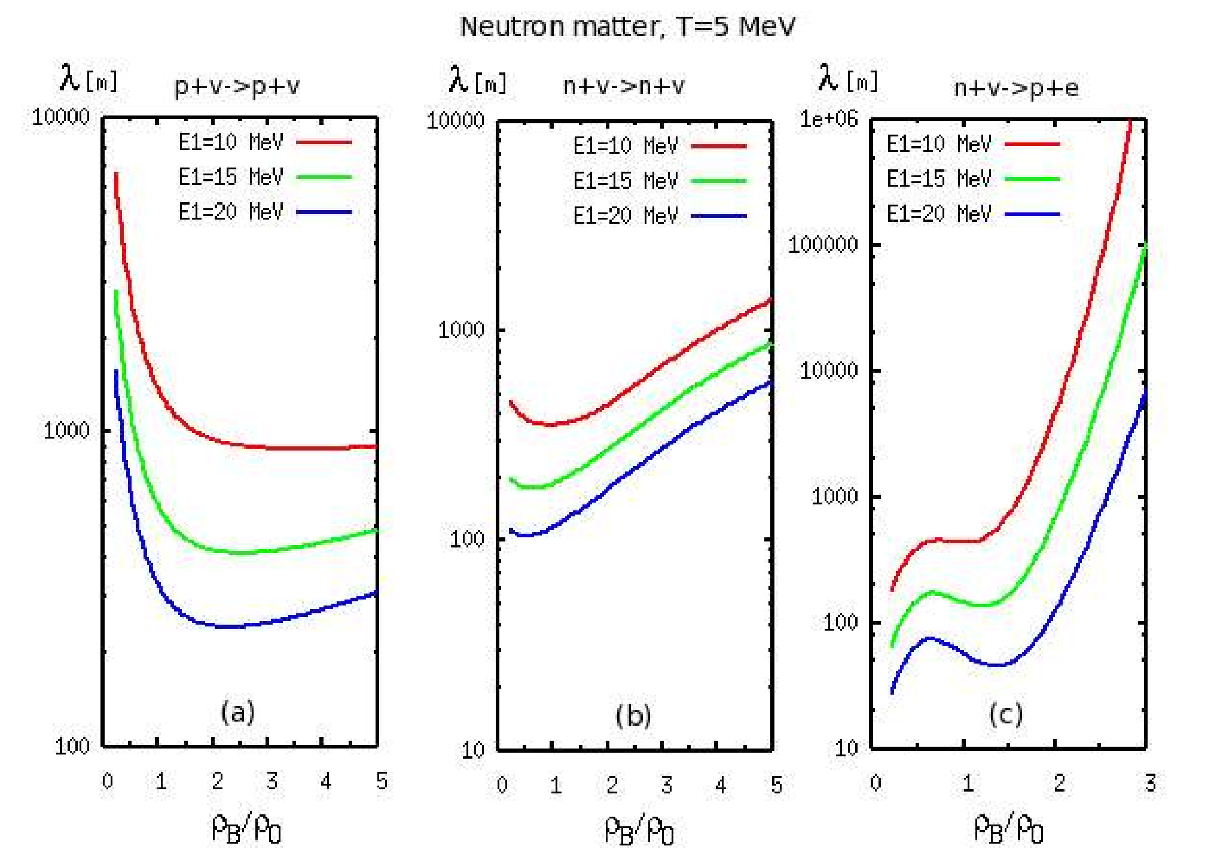

Figure 7: Neutrino mean free path in neutron matter with respect to scattering reactions on protons (a), neutrons (b) and absorption reactions on protons (c) as a function of nuclear matter density.

In case of scattering starting from density ~2 ρ_0 mean free path increasing. Intuitive mean free path should decrease with increasing density. This anomalous result at high density can be indication of borders of usage Skyrme effective interaction. Such results are common for all calculations based on nonrelativistic nuclear interactions.