Neutrino oscillations in the early Universe

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We discuss the oscillations effects on neutrinos in the early Universe and update the cosmological constraints on the oscillation parameters. It is shown that sterile LOW solution to the solar neutrino problem is almost completely excluded from cosmological nucleosynthesis considerations. Two possibilities for the relaxation of this constraint are discussed: high primordial ^4He yield and a relic lepton asymmetry present at nucleosynthesis epoch. The numerical analysis proved that $Y_p = 0.25$ only relaxes the constraints on LOW solution, while $L \geq 10^{-5}$ is capable to remove them.

1. Neutrino oscillation effects

Neutrino oscillations may play a considerable role in the early Universe. Cosmological nucleosynthesis (CN), baryogenesis, microwave background radiation, large scale structure formation, dark matter, lepton asymmetry, etc. could be essentially influenced by nonstandard neutrino properties, like nonzero mass and oscillations, presence of additional neutrino types, etc. The oscillations effect depends on the type of oscillations: oscillation channels, resonant transitions, the degree of equilibrium of oscillating neutrinos. Neutrino oscillations are capable to i)bring additional light particles into equilibrium [1], ii) deplete the neutrino number density [2], iii) distort the neutrino energy spectrum [3,4] and iv) affect neutrino-antineutrino asymmetry [4,5]. The effects i) and iv) are typical for active-sterile oscillations, and ii)-iv) are most considerable for nonequilibrium active-sterile oscillations. All these play crucial role for neutrino involved processes in the early Universe.

2. Cosmological constraints on neutrino oscillation parameters

Special attention is due to cosmological nucleosynthesis, which provides the strongest constraints on neutrino oscillation parameters [6–10]. Primordial yield of ^4He can be calculated with great accuracy within standard CN [11]. Helium-4 values, extracted from observation, although perhaps suffering from great systematic errors (of the order 0.05), are still the most reliable among the relic light element yields. Hence, the most reliable cosmological constraints are obtained in studies of that element. First CN constraints, based on effect i) were provided in refs. [1,2]. The best constraints available now on $\nu_{\mu,\tau} \leftrightarrow \nu_s$, accounting for i) and partially for ii), are provided in ref. [6]. They should be updated for the effects iii) and iv). [2]

The constraints on $\nu_e \leftrightarrow \nu_s$ have been recently updated. A recent analytical study of the nonresonant case, accounting for iii) to some acceptable approximation was provided [7]. Precise numerical analysis of nonresonant [8] and resonant [9] cases were performed, too. Exact kinetic equations for neutrino density matrix in momentum space were used to describe oscillating neutrinos in the high temperature Universe. Precise account for i) - iv) effects and selfconsistent analysis of neutrino and nucleons evolution was made [8–10]. In fig.1 the updated constraints on nonresonant and resonant $\nu_e \leftrightarrow \nu_s$ for different primordial ^4He values are plotted. The analytical fits to the exact constraints for primordial ^4He

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[2]An attempt to account for iii) was made in ref. [12], however, the work contains discontinuity in the results for the nonresonant and the resonant cases at maximal mixing, and hence is not reliable.

$Y_p = 0.24$ are:

$$\delta m^2 (\sin^2 2\vartheta)^4 \leq 1.5 \times 10^{-9}\mathrm{eV}^2 \qquad \delta m^2 > 0,$$
$$\text{and} \qquad |\delta m^2| < 8.2 \times 10^{-10}\mathrm{eV}^2 \qquad \delta m^2 < 0$$

at large mixing angles. These constraints are an order of magnitude stronger at large mixings than the previous due to the precise account of ii) and iii). In the resonant case they are less restrictive at small mixings, due to the account of neutrino-antineutrino asymmetry generated in oscillations.

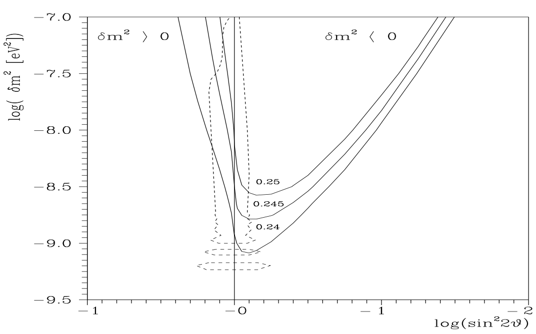

Figure 1. Cosmological constraints for $\nu_e \to \nu_s$ are presented for $Y_p = 0.24, 0.245, 0.25$. The dotted curve shows solar neutrino LOW solution.

According to these constraints, besides active-sterile LMA solution also LOW solution [13–15] to the solar neutrino problem is almost completely excluded. In fig.1 the LOW region, plotted by a dotted curve, is taken from ref. [13].

3. Relaxation of CN constraints

We have studied two possibilities for relaxing the cosmological constraints:

1. Higher Y_p. Having in mind the large systematic error of Y_p extracted from observations, $Y_p > 0.24$ looks possible. Therefore, we have calculated iso-helium contours $Y_p = 0.245, 0.25$ and compared them with the LOW solution. CN constraints then are relaxed, however, even $Y_p = 0.25$ cannot remove completely the constraints on LOW solution (fig.1).[3]

2. Relic lepton asymmetry L present before CN could relax the bounds. We have studied small asymmetries $L << 0.01$ that do not effect directly CN kinetics. They influence CN *indirectly* via oscillations: (a) effecting neutrino number densities, (b)neutrino spectrum distortion, and (c)neutrino oscillation pattern (suppressing or enhancing oscillations), which reflects in underproduction or overproduction of ^4He [16–18] in comparison with the case without L.

We have analyzed the effect of relic L on CN with oscillations, providing a precise selfconsistent study of CN and oscillating neutrinos for each set (δm^2, $\sin^2 2\vartheta$, L). The iso-helium contours $Y_p = 0.24$ for $L = 10^{-10}$ and $L = 10^{-6}$ are presented in fig.2. Relic lepton asymmetries

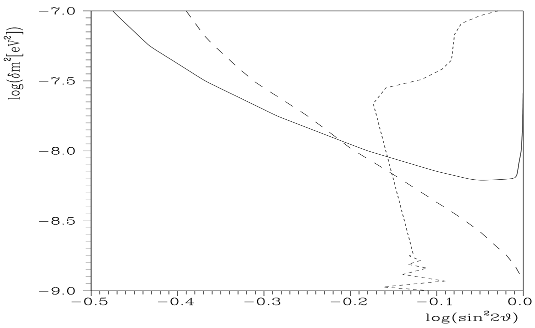

Figure 2. Iso-helium contours $Y_p = 0.24$ for $L = 10^{-6}$(solid curve) and $L = 10^{-10}$ are shown.

strengthen the bound at small ϑ and relax them at large mixings. The numerical analysis for $L = 10^{-6}, 10^{-5.5}$ showed that such L relax the constraints, while $L = 10^{-5}$ can remove the CN constraints on LOW solution.

Oscillations generated asymmetry. Lepton asymmetry can be dynamically generated due to resonant oscillations. Oscillations generated asymmetry can suppress oscillations and alleviate CN constraints [4,5,18]. We have several remarks concerning this possibility. Often very rough estimations of asymmetry growth is provided, without a precise kinetic account of the indirect asymmetry effects on CN and without account for the neutrino spectrum distortion [19]. Moreover, the asymmetry effect on CN is discussed separating artificially the processes of asymmetry growth and the CN: discussing first asymmetry growth till big $L \geq 0.01$ and afterwards exploring kinetic effect of big L on CN. We argue that the cor-

[3] Mind that the account only of i) does not constraint oscillations for high Y_p. To obtain exact constraints a precise account of ii)-iv) and a selfconsistent study of oscillations and CN is needed.

rect description of asymmetry evolution, its final value and sign, and its effect on oscillations and on CN, is possible in selfconsistent study of asymmetry, neutrino evolution and nucleosynthesis during asymmetry's *whole* evolution. As an illustration in fig.3 we present (dashed curve) the calculations $\delta Y_p(\delta m^2)$ of ref. [19], and the precisely provided calculations [18](solid curve). The

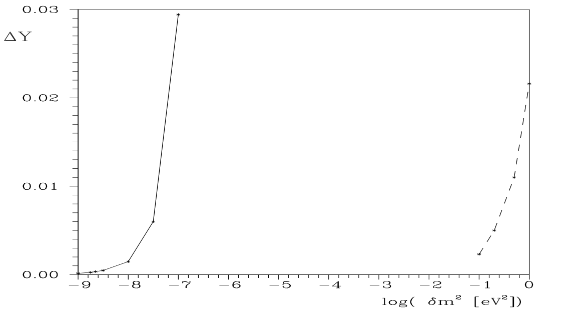

Figure 3. Relative increase of Y_p as a function of δm^2. The solid curve presents the precise results, the dashed one is from [19].

calculations [19] underestimate oscillation's and asymmetry's effects on Y_p by several orders of magnitude concerning δm^2.

4. Conclusions

Precise kinetic approach is obligatory for the study of neutrino oscillations in the early Universe, because neutrino depletion, spectrum distortion and oscillations generated asymmetry effects may be considerable. Accounting precisely for all oscillations effects we have reanalyzed CN with $\nu_e \leftrightarrow \nu_s$ and updated CN constraints on oscillation parameters. LOW sterile solution to the solar neutrino problem is almost completely excluded. This result is consistent with last analysis of the global data from SuperKamiokande, GALLEX+GNO, SAGE and Chlorine experiments, which does not favour $\nu_e \leftrightarrow \nu_s$ LOW solution [13,14].

Assumption of $Y_p = 0.25$ cannot remove CN bound on LOW solution, while relic lepton asymmetry $L > 10^{-5}$ evades this bound.

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