More General BBN Constraints on Neutrino Oscillations Parameters
Relaxed or Strengthened

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Abstract

I discuss BBN with nonequilibrium $\nu_e \leftrightarrow \nu_s$ oscillations in the more general case of non-zero population of $\nu_s$ before oscillations $\delta N_s \neq 0$. I calculate $^4$He primordial production $Y_p(\delta N_s)$ in the presence of $\nu_e \leftrightarrow \nu_s$ oscillations for different initial populations of the sterile neutrino state $0 \leq \delta N_s \leq 1$ and the full range of oscillation parameters.

Non-zero $\delta N_s$ has two-fold effect on $^4$He: (i) it enhances the energy density and hence increases the cosmic expansion rate, leading to $Y_p$ overproduction and (ii) it suppresses the kinetic effects of oscillations on BBN, namely the effects on pre-BBN nucleon kinetics caused by the $\nu_e$ energy spectrum distortion and the $\nu_e - \bar{\nu}_e$ asymmetry generation by oscillations, leading to decreased $Y_p$ overproduction. Depending on oscillation parameters one or the other effect may dominate, causing correspondingly either a relaxation of the cosmological constraints or their strengthening with the increase of $\delta N_s$.

I calculate more general BBN constraints on $\nu_e \leftrightarrow \nu_s$ oscillation parameters, corresponding to 3% $Y_p$ overproduction, for different initial populations of the sterile state. Previous BBN constraints were derived assuming empty sterile state before oscillations. The cosmological constraints for that case strengthen with the increase of $\delta N_s$ value, the change being more considerable for nonresonant oscillations.

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1 Introduction

Big Bang Nucleosynthesis (BBN) provides one of the most sensitive probes of the physical conditions of the early Universe and is often used to constrain neutrino oscillations.

Active-sterile neutrino oscillations may considerably effect the early Universe, and in particular BBN. They are capable of exciting additional light particles into equilibrium, thus, affecting the expansion rate $H$, and they may also distort neutrino energy spectrum and generate neutrino-antineutrino asymmetry, thus, in case of electron-sterile oscillations $\nu_e \leftrightarrow \nu_s$, influencing the weak interaction rates of $\nu_e$ and, hence, the kinetics of nucleons at the pre-BBN epoch and the primordial nucleosynthesis.

Among the light elements produced primordially, $^4$He is the most abundantly produced, most precisely measured and calculated [1, 2, 3, 4, 5], and usually it is the chosen element for putting BBN constraints on oscillations. Cosmological constraints on neutrino oscillations parameters, based on BBN and $^4$He observational data, have been discussed in numerous publications, see for example refs. [6, 7, 8, 9, 10, 11, 12, 13, 14], the review papers [15, 16, 17] and the references there in.

All available constraints were obtained assuming that the sterile state was empty before oscillations $\delta N_s = N_\nu - 3 = 0$, i.e. that it has been filled only due to active-sterile mixing during oscillations. $N_\nu$ is the number of neutrino species in equilibrium.

In general, however, $\nu_s$ state may not be initially empty. There exist numerous possibilities of producing $\nu_s$ before $\nu_e \leftrightarrow \nu_s$ oscillations: from GUT models, large extra dimensions models, Manyfold Universe models, mirror matter models, etc. They may be also produced in preceding $\nu_{\mu,\tau} \leftrightarrow \nu_s$ oscillations in 4-neutrino and 5-neutrino mixing schemes. \(^2\) The degree of initial population of $\nu_s$, $\delta N_s$, and its energy spectrum depends on the concrete model of $\nu_s$ production.

Non-zero initially $\delta N_s$ can influence the dynamical and the kinetic effects of oscillations on BBN [19] and change the cosmological limits on oscillations. The aim of this work is to define how and to what extend the available cosmological constraints on $\nu_e \leftrightarrow \nu_s$ oscillation parameters, obtained with the assumption $\delta N_s = 0$, are changed in the more general case of initially non-zero sterile population $\delta N_s \neq 0$.

In the next section I discuss how $\delta N_s \neq 0$ influences oscillations effects on BBN and provide qualitative considerations of the expected change of cosmological constraints. In section 3 I present the results of the numerical analysis of $^4$He production in BBN with

\(^2\)The analysis of experimental oscillations data provides some constraints on the sterile neutrino impact in the oscillations explaining atmospheric and solar neutrino anomalies [18], and hence, provides some indications about the possible values of $\delta N_s$, which could have been eventually produced by oscillations.
nonequilibrium $\nu_e \leftrightarrow \nu_s$ oscillations and initially nonzero $\nu_s$ population $0 < \delta N_s < 1$ and discuss the generalized cosmological constraints on oscillation parameters. In the last section the results and the assumptions of the model are resumed and possibilities of relaxing the cosmological constraints are discussed.

2 Generalizing BBN Constraints on Oscillations

I discuss the generalization of BBN constraints on $\nu_e \leftrightarrow \nu_s$ neutrino oscillations parameters for the case of oscillations effective after electron neutrino decoupling. It is known that at lower mass differences, when sterile neutrino production takes place after active neutrino decoupling, due to $\nu_e \leftrightarrow \nu_s$ oscillations between initially empty $\nu_s$ and electron neutrino, i.e. for $(\delta m^2/eV^2) \sin^4 2\theta < 10^{-7}$, the re-population of active neutrino becomes slow and kinetic equilibrium may be strongly broken by $\nu_e \leftrightarrow \nu_s$ oscillations. I will denote these oscillations with an initially non-equilibrium sterile neutrino further on 'nonequilibrium oscillations' for short. They may cause considerable deviations of the $\nu_e$ energy spectrum from the equilibrium Fermi-Dirac form [7, 10] (called further 'spectrum distortion') and generate neutrino-antineutrino asymmetry $^3$, thus influencing the weak interaction rates of the processes governing pre-BBN nucleon kinetics $\nu_e + p \leftrightarrow n + e^+$, $\bar{\nu}_e + n \leftrightarrow p + e$, $n \leftrightarrow p + e + \nu_e$ the nucleons freezing and correspondingly the primordial elements production. $^4$

For that oscillation case a numerical analysis of the evolution of the neutrino and nucleons, using the kinetic equations for the neutrino density matrix and neutrino number densities in momentum space was provided to make a proper account for the neutrino spectrum distortion, depletion and neutrino asymmetry growth at each momentum [10]. The analysis of such oscillations, accounting precisely for the kinetic effect, allowed to put stringent constraints on oscillations effective after active neutrino decoupling [10, 11, 16].

The analytical fits to the exact constraints, corresponding to 3% $^4$He overproduction, are [10, 11, 16]:

$$\delta m^2 (\sin^2 2\theta)^4 \leq 1.5 \times 10^{-9} eV^2 \quad \delta m^2 > 0$$

$$|\delta m^2| < 8.2 \times 10^{-10} eV^2 \quad \delta m^2 < 0, \quad \text{large } \vartheta,$$

$^3$The asymmetry effect at large mixings and small mass differences, discussed here, is subdominant [10] and leads to a slight suppression of the spectrum distortion effect. This is in contrast to the case of generation of lepton asymmetry by oscillations at relatively high $\delta m^2$ and small mixings [20], where it may play the dominant role.

$^4$The effect of distortions on the energy distributions of neutrinos caused by residual interactions of neutrinos after 2 MeV during electron-positron annihilations was not considered, because it leads to a negligibly small change in $Y_p$. [23]
These constraints, as well as all existing in literature BBN constraints, concern the case of empty sterile neutrino state at the start of oscillations.

The presence of a nonzero $\delta N_s$ before oscillations exerts two types of effects on BBN [19]:

(i) It increases the energy density by $\delta \rho = 7/8 (T_\nu / T_\gamma)^4 \delta N_s \rho_\gamma$, thus modifying the cosmic expansion rate $H = \sqrt{8\pi \rho / 3M_p^2}$, which reflects into higher freezing temperature of the nucleons and overproduction of $^4\text{He}$ [21]. The dynamical effect of initially present $\delta N_s$ on primordial $^4\text{He}$ production will be denoted further on by $\delta Y_d$. Due to this effect strongeining of the cosmological bounds with respect to the ones calculated at $\delta N_s = 0$ should be expected.

In case of $\nu_{\mu,\tau} \leftrightarrow \nu_s$ oscillations the dynamical effect is the only effect of non-zero $\delta N_s$ present before oscillations. In the case of $\nu_e \leftrightarrow \nu_s$ oscillations with almost equilibrium neutrino energy distribution, i.e. oscillations taking place before neutrino decoupling, this is the leading effect as well. This effect can be accounted for simply by adding the initial $\delta N_s$ value to the one produced in oscillations. So, in both these cases the rescaling of the existing constraints is rather straightforward.

(ii) In the nonequilibrium $\nu_e \leftrightarrow \nu_s$ oscillations case, the presence of partially populated $\nu_s$ suppresses the oscillations effects on pre-BBN nucleons kinetics [19]. Further on this kinetic effect is denoted by $\delta Y^k_s$, while the kinetic effects of oscillations are denoted by $\delta Y_k$ (or in terms of the effective degrees of freedom $\delta N_k$, where $\delta Y_k \sim 0.013 \times \delta N_k$).

Kinetic effects are a result of the generated energy spectrum distortion of $\nu_e$ in oscillations between active and sterile neutrino, and to a smaller degree are due to the neutrino-antineutrino asymmetry, generated by oscillations. Both are very sensitive to the degree of population of $\nu_s$ because the rate of oscillations is energy dependent. The spectrum distortion effect plays however the dominant role, so it will be discussed in more detail further on, although we have accounted precisely for both.

The distortion of $\nu_e$ spectrum leads both to a depletion of the active neutrino number densities $N_\nu$: $N_\nu \sim \int dE E^2 n_\nu(E)$ and a decrease of the $\Gamma_w$, causing an earlier $n/p$-freezing and an overproduction of $^4\text{He}$ yield. The spectrum distortion is the greatest in the case the sterile state is empty at the start of oscillations, $\delta N_s = N_{\nu_e} / N_{\nu_s} = 0$. It decreases with the increase of the degree of population of the sterile state at the onset of oscillations.

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$^5$Neutrino-antineutrino asymmetry generated during the resonant transfer of neutrinos exerts back effect on oscillating neutrino. Although its value is too small to have a direct kinetic effect on the synthesis of light elements, i.e. $L < 0.01$, it effects indirectly BBN by suppressing oscillations at small mixing angles, leading to less overproduction of $^4\text{He}$ compared to the case without the account of asymmetry growth [10].
as illustrated in the following figure from ref. [19].

Fig.1. The figure gives a snapshot of the spectrum distortion of the electron neutrino energy spectrum $x^2 \rho_{LL}(x)$, where $x = E/T$ at a characteristic temperature 0.7 MeV, caused by resonant oscillations with a mass difference $\delta m^2 = 10^{-7}$ eV$^2$ and mixing $\sin^2 2\vartheta = 0.1$ for different degrees of initial sterile neutrino population, namely $\delta N_s = 0$ (lower curve), $\delta N_s = 0.5$ and $\delta N_s = 0.8$ (upper curve). The dashed curve gives the equilibrium spectrum for comparison.

So, larger $\delta N_s$ leads to a decrease of the kinetic effects of oscillations and to a decrease of the overproduction of $^4$He by oscillations with respect to the case of initially zero $\delta N_s$, i.e. $\delta N_k < \delta N_{k\text{kin}}^0$, where $\delta N_{k\text{kin}}^0$ is the kinetic effect corresponding to zero initial population of the sterile state, which presents in fact the maximal kinetic effect at a given set of oscillation parameters. \footnote{For $\nu_e \leftrightarrow \nu_s$ oscillations effective after $\nu_e$ decoupling, these kinetic effects $\delta N_{k}^0$ can be considerable, as large as $\delta N_{k}^0 = 6$ [22].} Due to the decrease $\delta Y_p^s$ in the overproduction of $Y_p$, caused by the suppression of $\delta N_k$ by the initially present $\delta N_s \neq 0$, relaxation of the cosmological bounds with respect to the ones corresponding to an initially empty $\nu_s$ state should be expected.

Obviously, there is an interplay between the two types of effects (i) and (ii) induced by non-zero $\delta N_s$. The total effect depends on the concrete values of the oscillation parameters and $\delta N_s$. The shift of the constraints may be expected in either direction (relaxing or constraining the existing constraints) and its analysis requires numerical study, accounting precisely for $\nu_e$ energy spectrum distortion and the suppression of the kinetic effects, which is essential.

Using the approximate empirical formula giving the dependence of $Y_p$ production on...
the two effects, obtained in ref. [19]:

\[
\delta Y_p = \delta Y_d + \delta Y_k^0 + \delta Y_k^s \sim 0.013 \times (\delta N_s + \delta N_k^{0\text{kin}} - \delta N_s \times \delta N_k^{0\text{kin}})
\]

it is possible to make some predictions concerning the value and the sign of the $^4$He overproduction and the direction of the shift of the BBN. Here $\delta Y_p = Y_p - Y_p^{\text{stand}}, \delta Y_d = 0.013 \times \delta N_s, \delta Y_k^0 = 0.013 \times \delta N_k^{0\text{kin}},$ while $\delta Y_k^s = -0.013 \times \delta N_s \times \delta N_k^{0\text{kin}}.$

**First:** The total effect of oscillations for initially non-zero $\delta N_s$ on $^4$He production is smaller than the sum of the energy density increase effect (i) $\delta Y_d$ and the maximum kinetic effect of oscillations (ii) $\delta Y_k^0$ corresponding to zero $\delta N_s,$ due to the term $\delta N_s \times \delta N_k^{0\text{kin}}$ expressing the decrease of oscillations kinetic effect with $\delta N_s.$

The results of the exact numerical study of the effects (i) and (ii) on $^4$He overproduction, illustrated in the following figures, confirm this estimation. In Fig.2a and Fig.2b the contribution of the different effects on neutron-to-nucleon freezing ratio $X_n = n_n^f/n_{\text{nuc}}$ is presented. (The $Y_p$ production mainly depends on $X_n, Y_p \sim X_n \times \exp(-t/\tau_n),$ where $\tau_n$ is the neutron lifetime.) The dotted curve shows the kinetic effect dependence on $\delta N_s,$ the lower dashed curve gives the energy increase effect. The total effect is presented by the solid curve, which although has different behavior in the two cases (decreasing or increasing), is situated considerably lower than the uppermost long-dashed curve presenting the sum of the effects (i) and (ii).

![Fig.2a](image-url)

Fig.2a. The solid curve presents the frozen neutron number density relative to nucleons $X_n = n_n^f/n_{\text{nuc}}$ as a function of the sterile neutrino initial population, at $\delta m = \pm 10^{-8}$ eV$^2$, $\sin^2 2\theta = 1.$ The dotted curve presents the kinetic effect, while the lower dashed curve presents energy density increase effect. The uppermost long dashed curve corresponds to the total effect when the decrease of the kinetic effect is not
accounted for, as if the initial $\delta N_s$ were stored in a state not participating in oscillations with electron neutrino, and the effects were simply additive.

**Hence, the cosmological constraints will be less stringent than in the case of simply additive effects.** The latter case will have place when the enhancement of the energy density $\delta N_s$ is due to other additional particles brought partially into equilibrium (like sterile neutrinos in the muon or tau-sectors, or other relic relativistic particles) while the sterile state, which participates further in oscillations with the electron neutrino is initially empty. In that case the two effects will be simply additive, and the uppermost long-dashed curve in Figs.2 presents the overproduction of $^4$He for such specific situation.

![Graph showing neutron number density](image)

Fig.2b. The solid curve presents the frozen neutron number density relative to nucleons $X_n^f = n_n^f / n_{nuc}$ as a function of the sterile neutrino initial population, at $\delta m = \pm 10^{-9}$ eV$^2$, $\sin^2 2\theta = 1$. The dotted curve presents the kinetic effect, while the lower dashed curve presents energy density increase effect. The uppermost long dashed curve corresponds to the total effect if the effects were simply additive.

However, due to the fact that $\delta N_{kin}$ is a decreasing function of $\delta N_s$, naively adding the two effects exaggerates $Y_p$ overproduction, and hence would define stronger bounds than the real ones.

**Second**: The direction of the shift of the constraints should be as follows: in case $\delta N_{kin}^0 \delta N_s < \delta N_s$ the constraints will be strengthened in comparison with the $\delta N_s = 0$ constraints, while in the opposite case they will be relaxed.

In fig.2a the solid curve, presenting the total effect, is a decreasing function of $\delta N_s$ because $\delta N_{kin}^0 > 1$, i.e. for that set of oscillation parameters the overproduction of $^4$He due to oscillations decreases with the increase of the initial population of the sterile neutrino.
state. Obviously the suppression effect (ii) dominates. In that case we expect relaxation of the cosmological constraints compared to the case of initially zero population of $\nu_s$.

Fig. 2b presents the results for a set of oscillation parameters for which $\delta N_{\text{kin}}^0 < 1$, then as it is illustrated the total effect is an increasing function of $\delta N_s$, the dynamical effect (i) dominates over (ii), thus the overproduction of $^4\text{He}$ increases in respect to the case of $\delta N_s = 0$ and hence, the cosmological constraints must become more stringent with the increase of $\delta N_s$. And as far as $\delta N_{\text{kin}}^0 = \delta N_{\text{tot}}$ at $\delta N_s = 0$, the BBN constraints, corresponding to $^4\text{He}$ observational uncertainty expressed as $\delta N_{\text{tot}} < 1$, will be strengthened. For example, $^4\text{He}$ uncertainty $\delta Y_p \sim 0.007$ corresponds to $\delta N_{\text{tot}} \sim 0.54$. Thus at $\delta N_s = 0$ $\delta N_{\text{kin}}^0 \sim 0.54 < 1$, and hence strengthening of the cosmological constraints is expected.

The exact form of the cosmological constraints obtained by a detail numerical study of the effects (i) and (ii) and corresponding to such $^4\text{He}$ overproduction and different $\delta N_s$ values is presented in the next section.

In case of bigger $^4\text{He}$ uncertainty, parametrized by $\delta N_{\text{tot}} > 1$, the term (ii) dominates (as illustrated in Fig. 2a), leading to a decrease of the $^4\text{He}$ overproduction due to oscillations and hence, relaxation of the cosmological constraints should be expected. It is interesting to note that contrary to some prejudice, even for $^4\text{He}$ uncertainty equivalent to $\delta N_{\text{tot}} > 1$ cosmological constraints on oscillation parameters still persist, provided that $\delta N_s < 1$ and that a proper description of the neutrino energy spectrum distortion is made.

3 BBN constraints for partially filled $\nu_s$

For calculating cosmological constraints on oscillation parameters, I have followed the kinetic approach described in detail in ref. [19]. The case of $\nu_e \leftrightarrow \nu_s$ oscillations effective after electron neutrino decoupling is considered. For simplicity mixing just in the electron sector is assumed. The more general case of a sterile neutrino state being partially filled before the oscillations become effective is studied. In a previous work [19] it was shown that for a wide range of $\delta N_s$ values the kinetic effects of oscillations, namely spectrum distortion of the electron neutrino and lepton asymmetry growth, play a considerable role, hence rough analytical estimations of the kinetic effects are not applicable [25, 10]. Therefore, here an exact numerical analysis of $\delta N_s$ effects (i) and (ii) on pre-BBN nucleons freezing and the production of $^4\text{He}$ in BBN with oscillations is provided.

The kinetic equations for the density matrix of neutrino and antineutrino ensembles are simultaneously and selfconsistently solved with the kinetic equations governing the

\footnote{In more detail this case will be discussed in a following paper [24].}
evolutions of nucleons from the period of neutrino decoupling $T \sim 2$ MeV till the nucleons freezing epoch, down to $T \sim 0.3$ MeV. The neutrino spectrum is described by 1000 bins for the nonresonant case, and by more than 5000 bins (depending on the asymmetry growth region of oscillation parameters). This detail study, performed for a wider range of parameters, confirms the importance of the kinetic effect at non-zero $\delta N_s$, found in ref. [19]. I calculate primordial $^4$He yield $Y_p(\delta N_s, \delta m^2, sin^22\theta)$ at different $\delta N_s$ values for the full set of oscillations parameters of the model: for all mixing angles $\theta$ and mass differences $\delta m^2 \leq 10^{-7}$ eV$^2$.

For the analysis of the constraints the observational uncertainty of the primordially produced $^4$He is assumed $\delta Y_p < 0.007$ in correspondence with the accepted systematic error in the $^4$He measurements [1]. Then the maximum possible value of $\delta N_s$ at BBN epoch is constrained on the basis of BBN considerations: Using the approximate empirical formula $\delta Y_p \sim 0.013\delta N_{\text{tot}}$, $\delta Y_p < 0.007$ corresponds to $\delta N_s < 0.54$. So, in our analysis we have varied $\delta N_s$ in the range $0.0 \leq \delta N_s \leq 0.5$ with a step 0.1. The case $\delta N_s > 0.54$ corresponds to higher $^4$He uncertainty and will not be studied here.

This choice of maximum $\delta N_s$ is also supported by the results of the recent standard BBN analysis + $^4$He observational data with an input the baryon density value from WMAP data, which provide bounds on the number of additional neutrino species at BBN in the range $\delta N_s < 0.1 - 0.5$ [2, 3, 26, 27, 28].

Uncertainty $\delta Y_p = 0.007$ corresponds to $\delta Y_p/Y_p \sim 3\%$, so in this analysis, I have assumed that primordial $^4$He abundance is known with an accuracy better than 3\%, and will call the isohelium contours corresponding to $\delta Y_p = 0.007$ '3\% $^4$He overproduction contours', and the obtained BBN constraints '3\% $^4$He constraints'.

In Fig. 2 I present the calculated cosmological constraints on oscillation parameters for the $\delta N_s = 0.1$, and $\delta N_s = 0.5$ for the resonant (to the left) and the non-resonant (to the right) oscillation cases. The region upwards of the corresponding curves is the cosmologically excluded. The upper curve is for $\delta N_s = 0.1$ case, the lower one – for $\delta N_s = 0.5$. $\delta N_s = 0$ constraints are given for comparison by the dashed contours.
Figure 3: BBN constraints on oscillation parameters for the resonant (l.h.s.) and the non-resonant $\nu_e \leftrightarrow \nu_s$ oscillations and for initial degrees of population of the sterile neutrino state $\delta N_s = 0.1$ and $\delta N_s = 0.5$. The dashed contours present the constraints for $\delta N_s = 0$ case for comparison.

The analysis shows that the two effects (i) and (ii) of $\delta N_s$, nearly compensate each other for small $\delta N_s$ values. Hence, the cosmological constraints for $\delta N_s = 0.1$ slightly differ from the ones for $\delta N_s = 0$, as illustrated in Fig.3. For $\delta N_s > 0.1 \delta Y_d$ dominates over the suppression term $\delta Y^s_k$, so the constraints are strengthened. As a whole the cosmological constraints in the resonant case are slightly changed compared to the case with initially zero sterile state, while in the non-resonant case the change is more noticeable, and the constraints are becoming more stringent with the increase of $\delta N_s$.

The precise account of the kinetic effects of oscillations on BBN, i.e. the study of the distorted spectrum distribution of neutrinos and its effect on nucleons kinetics, allows strengthening the cosmological constraints by an order of magnitude towards smaller mass differences in comparison with calculations considering just the integral effect like neutrino number density depletion.
4 Discussion

The presence of a *non-empty* sterile state before $\nu_e \leftrightarrow \nu_s$ oscillations was not considered in previous cosmological constraints on oscillation parameters. This work is a step towards generalizing the cosmological constraints on oscillation parameters of neutrino. It discusses the effect of partially filled sterile state before oscillations on primordial production of $^4$He and on the BBN oscillations constraints.

It is shown that initially non-zero $\nu_s$ state has two fold effect on $^4$He: on one hand it affects Universe dynamics leading to overproduction of $Y_p$, while on the other hand its presence suppresses oscillations kinetic effects causing a decrease of $Y_p$ overproduction. Thus, depending which effect dominates, non-zero initially $\nu_s$ may cause strengthening or relaxation of the cosmological constraints on oscillation parameters.

I have calculated the isohelium contours corresponding to 3% overproduction of $^4$He, in a model of BBN with electron–sterile oscillations effective after neutrino decoupling and for the general case of the sterile neutrino state being partially populated before oscillations, $0.0 < \delta N_s \leq 0.54$. The constraints become more stringent with the increase of $\delta N_s$ value. So, the presence of non-zero initial population $\delta N_s \leq 0.54$ strengthens the 3% $^4$He cosmological constraints.

These cosmological constraints are obtained for the case of 2-neutrino mixing. Further generalization of the constraints includes the account of mixing between active neutrinos, which has been proved important in the resonant oscillation case for oscillations proceeding before neutrino decoupling [14].

The constraints are obtained for the natural assumption that at BBN epoch the initial lepton asymmetry is of the order of the baryon one. However, in fact the lepton asymmetry in the neutrino sector is not strongly constrained [29]. We expect that, provided a small lepton asymmetry $L << 0.1$ is present, it may be large enough to relax or alleviate the discussed BBN bounds on neutrino oscillations. For $\delta N_s = 0$ case it was proven that larger than $10^{-7}$ lepton asymmetry may strongly suppress oscillations effective after neutrino decoupling and change the constraints, while initial lepton asymmetry larger than $10^{-5} - 10^{-4}$ can alleviate them [30, 11].

Cosmological constraints can be relaxed also if the systematic error of $Y_p$ is higher than 0.007. However, it is interesting to note that even for $\delta Y_p \sim 0.01$, and a considerable initial population of $\nu_s \delta N_s < 1$, the constraints may not be removed, but just relaxed, as the results of ref. [24] suggest.
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