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BBN Cosmological Constraints on Beyond Standard Model Neutrino

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Big Bang Nucleosynthesis is a reliable cosmological test of physics beyond the Standard Model and in particular of possible non-standard neutrino characteristics. We present a short review of several modified BBN models including beyond Standard Model neutrino physics. First we present a short review of cosmological effects of additional relativistic sterile neutrino ν_s and constraints on it following from the standard BBN model and from BBN with non-equilibrium $\nu_e \leftrightarrow \nu_s$ oscillations. Then we discuss BBN model with $\nu_e \leftrightarrow \nu_s$ oscillations and the cosmological constraints on oscillations parameters. Finally BBN with $\nu_e \leftrightarrow \nu_s$ oscillations and lepton asymmetry bigger than the baryon one is described. The interplay between $\nu_e \leftrightarrow \nu_s$ oscillations and lepton asymmetry in the neutrino sector and its BBN effect are presented. In particular, we discuss asymmetry generation by non-equilibrium resonant $\nu_e \leftrightarrow \nu_s$ neutrino oscillation. We discuss also the capability of relic lepton asymmetry to enhance neutrino oscillations due to spectrum wave resonance of neutrinos. The cosmological constraints on active-sterile neutrino oscillations for different values of the lepton asymmetry and for different initial population of ν_s are presented.

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1. Introduction

Cosmology provides valuable information about neutrinos and BSM physics in the neutrino sector due to the considerable effect neutrinos exert in different epochs of the universe evolution. In particular, neutrinos played an essential role in cosmological nucleosynthesis - Big Bang Nucleosynthesis (BBN). Hence, BBN put stringent constraints on established and hypothetical BSM neutrino characteristics.

Sterile neutrino (right-handed neutrino), proposed by many BSM theories, presents the simplest extension of SM particle content and may have many important applications. We have studied modified BBN models with additional light sterile neutrinos, with active-sterile neutrino oscillations, with asymmetry in the neutrino sector considerably bigger than the baryon asymmetry. On the basis of the effects, which these BSM components exert on the cosmological synthesis of light elements, we have obtained stringent cosmological constraints on BSM physics in the neutrino sector [1].

In the next section the contemporary BBN as the most reliable early Universe probe of BSM neutrino physics is briefly presented. In particular, the contemporary standard BBN constraints on additional relativistic neutrino and on the lepton asymmetry are given. The third section is dedicated to BBN models with BSM neutrino, namely: BBN with non-equilibrium $\nu_e \leftrightarrow \nu_s$ oscillations with empty or partially filled ν_s state; BBN with $\nu_e \leftrightarrow \nu_s$ oscillations and with lepton asymmetry $10^{-11} < |L| < 0.01$; The interplay between $\nu_e \leftrightarrow \nu_s$ oscillations and L in the neutrino sector and its BBN effect is discussed; BBN constraints on active-sterile neutrino oscillations and their change by non-zero initially present sterile neutrino and by lepton asymmetry (generated by neutrino oscillations or initially present) are described. The possibility to solve dark radiation problem by BSM physics in the neutrino sector is discussed. The fourth section contains the conclusion.

2. Contemporary BBN - the deepest reliable early Universe probe and SMP test

BBN is a precise quantitative theory of cosmological nucleosynthesis that describes the period from the first second to the first 20 minutes in the early Universe evolution, corresponding to the BBN energy diapason (1 MeV- 10 KeV). During BBN the light elements D, He-4, He-3 and Li-7 and some tiny traces of Be-9, B-10, B-11 up to CNO isotopes were produced. [2, 3, 4]

Contemporary BBN is a parameter free theory, because its parameters at present are determined with good accuracy, namely the baryon-to-photon ratio $\eta = n_b/n_\gamma$ is independently measured by CMB (Ade et al., 2016), the effective number of light neutrino families N_{eff} was determined with high accuracy at LEP experiments at CERN and the neutron life time τ_n was recently measured with better precision [6]. The cross sections of nuclear processes essential for the formation of light elements have been updated, as well [7, 8]. Precise BBN codes like PArthENoPE [9, 10], AlterBBN [11], PRIMAT [4] are used.

The precision of observational data on primordial abundances has also been improved considerably. Namely, the observational determination of D has improved thanks to new observations of QAS [12], precise abundance determination of He-4 was made due to the updated emisivities of He-4 and the recently observed infra-red line [13]. There exists good overall agreement between the predicted abundances (except Li-7) and those inferred from observational data. This allows to use of BBN as the earliest precision probe of physical conditions in the early Universe and also as the most precision cosmological test of fundamental and BSM physics. In particular, it is a precise Universe baryometer during BBN epoch, the best speedometer at radiation dominated stage and the most exact Universe leptometer.

BBN constraints on BSM neutrino physics include: constraints on additional right handed (sterile) light (relativistic during BBN, i.e. $m < 1$ MeV) neutrino due to their effect on the Universe dynamics, pre-BBN nucleon kinetics or BBN itself; constraints on BSM processes relevant at BBN epoch, like decays of heavy particles, neutrino oscillations, constraints on possible departures from equilibrium distributions of particle densities due to neutrino oscillations, lepton asymmetry, etc.

2.1 Standard BBN constraints on relativistic sterile neutrino

At the radiation dominated stage neutrinos were dynamically important component with energy density comparable to that of photons:

$$\rho_\nu = 7/8(T_\nu/T)^4 N_{eff}\rho_\gamma(T). \tag{2.1}$$

where T is the photons temperature, ρ_γ is the photons density, N_{eff} denotes the effective number of the light neutrino types. In the standard BBN scenario $N_{eff} = 3.046$, which implies 3 flavor neutrino types and accounts for the non-instantaneous neutrino decoupling and QED finite temperature corrections. Many BSM physics models predict extra relativistic component $\delta N_{eff} = N_{eff} - 3.046$ (GUT models with sterile (right handed) neutrino ν_s, neutrino oscillations, lepton asymmetry, SUSY, string models, extra dimensional models, etc.) Such models may be restricted by cosmological constraints on N_{eff}.

BBN is very sensitive to the expansion rate of the Universe $H = \sqrt{8\pi\rho(N_{eff})/3M_p^2}$ and N_{eff} [14]. Most recent stringent BBN constraint is obtained by Pitrou et al. (2018) [4]:

$N_{eff} = 2.88 \pm 0.27$ at 95% CL.

For comparison the CMB constraint (Planck Collaboration 2015) reads:

$N_{eff} = 3.13 \pm 0.31$ at 95% CL.

More stringent cosmological constraint on δN_{eff} is that of CMB plus BBN considerations:

$N_{eff} = 3.01 \pm 0.15$ at 95%.

BBN bounds on N_{eff} are used to constrain BSM physics models leading to increase of the radiation density during the BBN epoch, as those discussed in the next section.

2.2 Standard BBN constraints on lepton asymmetry.

L has not been directly measured, because cosmic neutrino background has not been directly detected. Nevertheless, due to L influence on BBN stringent cosmological constraints on L value are available.

The role of $L > 0.01$ in BBN have been studied systematically since the original paper of Wagoner et al. (1967) [16]. Two different effects of L have been considered. Namely:

(i)*Lepton asymmetry dynamical effect:* L leads to the increase of the radiation energy density by $\delta N_eff = 15/7((\zeta/\pi)^4 + 2(\zeta/\pi)^2)$, where ζ is the degeneracy parameter. Hence, L fastens H, delays matter/radiation equality epoch, influences BBN (in particular leads to overproduction of

He-4), influences the Cosmic Microwave Background (CMB), the evolution of perturbations i.e. LSS [17].

(i)*Lepton asymmetry direct kinetic effect:* $L > 0.01$ in the electron neutrino sector may effect considerably the weak interaction rates of the processes governing pre-BBN nucleon kinetics:

$$\nu_e + p \leftrightarrow n + e^+,$$

$$\bar{\nu}_e + n \leftrightarrow p + e,$$

$$n \leftrightarrow p + e + \nu_e$$

and, correspondingly, BBN element production. Flavor neutrino oscillations equilibrate the degeneracies in different neutrino sectors before BBN [18, 19, 20, 21]. Contemporary BBN constraint on L based on the dynamical and direct kinetic effect of L reads: $|L| < 0.01$.

Small $L << 0.01$ is capable to influence BBN in case of non-equilibrium electron-sterile neutrino oscillations due to its indirect kinetic effect on BBN through neutrino oscillations, as will be discussed in 3.2

Different modified BBN models (with additional ν_s, with $\nu_e \leftrightarrow \nu_s$ neutrino oscillations, with lepton asymmetry $10^{-11} < |L| << 0.01$) and the BBN constraints on BSM of these models are presented in the next section.

3. BBN constraints on BSM neutrino physics

3.1 BBN and neutrino oscillations

BBN with vacuum neutrino oscillations was first studied by Dolgov [22]. It was found that flavor neutrino oscillations negligibly influence BBN, while active-sterile oscillations may excite into equilibrium ν_s state, which increases the Universe expansion rate and overproduces He-4 during BBN.

In refs.[23] BBN with matter electron-sterile neutrino oscillations effective before neutrino decoupling were first studied, the dynamical effect of neutrino oscillations and the depletion of the electron neutrinos due to oscillations was found. Cosmological constraints on neutrino oscillation parameters excluding electron-sterile neutrino oscillation solution to the LSND experiment and large mixing angle (LMA) sterile solution to the solar neutrino problem were derived. See also refs. [25, 26].

At lower mass differences, when sterile neutrino production due to $\nu_e \leftrightarrow \nu_s$ oscillations between initially empty ν_s and electron neutrino, i.e. for $(\delta m^2/eV^2)\sin^4 2\theta < 10^{-7}$, takes place after active neutrino decoupling, the re-population of active neutrino is slow and the kinetic equilibrium may be strongly broken by $\nu_e \leftrightarrow \nu_s$ oscillations [27].

First analysis of BBN with $\nu_e \leftrightarrow \nu_s$ neutrino oscillations between initially empty ν_s and electron neutrino, in vacuum, proceeding after electron neutrino decoupling, was provided for the vacuum neutrino oscillation case in ref. [24] and for matter oscillation case in refs. [27].It was found that these late oscillations may distort considerably the ν_e energy spectrum from the equilibrium Fermi-Dirac form and enhance L.

The effect on BBN of the asymmetry generated by these oscillations was shown to be subdominant and it causes a slight suppression of the spectrum distortion effect at smaller mixings. [1]

A numerical analysis of the evolution of the oscillating neutrino and nucleons was provided, using the exact kinetic equations for the neutrino density matrix and neutrino number densities in momentum. The following set of kinetic equations for neutrino density matrix $\rho(t)$, L in the electron neutrino sector L_{ν_e} and neutron number densities $n_n(t)$ in momentum space were used to describe the evolution of the system of oscillating neutrinos in the high temperature Universe and the lepton asymmetry role during BBN:

$$\begin{aligned} \partial\rho(t)/\partial t &= Hp_\nu\ (\partial\rho(t)/\partial p_\nu) + \\ &\quad + i[\mathcal{H}_o,\rho(t)] + i\sqrt{2}G_F\left(\mathcal{L} - Q/M_W^2\right)N_\gamma[\alpha,\rho(t)] + \mathrm{O}\left(G_F^2\right), \\ \partial\bar{\rho}(t)/\partial t &= Hp_\nu\ (\partial\bar{\rho}(t)/\partial p_\nu) + \\ &\quad + i[\mathcal{H}_o,\bar{\rho}(t)] + i\sqrt{2}G_F\left(-\mathcal{L} - Q/M_W^2\right)N_\gamma[\alpha,\bar{\rho}(t)] + \mathrm{O}\left(G_F^2\right), \end{aligned}$$

$$L_{\nu_e} = \int \mathrm{d}^3p(\rho_{LL} - \bar{\rho}_{LL})/N_\gamma$$

$$\begin{aligned} \partial n_n/\partial t &= Hp_n\ (\partial n_n/\partial p_n) + \\ &\quad + \int \mathrm{d}\Omega(e^-,p,\nu)|\mathcal{A}(e^-p\to\nu n)|^2\left[n_{e^-}n_p(1-\rho_{LL}) - n_n\rho_{LL}(1-n_{e^-})\right] \\ &\quad - \int \mathrm{d}\Omega(e^+,p,\tilde{\nu})|\mathcal{A}(e^+n\to p\tilde{\nu})|^2\left[n_{e^+}n_n(1-\bar{\rho}_{LL}) - n_p\bar{\rho}_{LL}(1-n_{e^+})\right], \end{aligned}$$

where $\alpha_{ij} = U^*_{ie}U_{je}$, $\nu_i = U_{il}\nu_l(l=e,s)$. $\mathcal{H}_o$ is the free neutrino Hamiltonian. Q presents the W/Z propagator effect,$Q \sim E_\nu\ T$. $\mathcal{L} \sim 2L_{\nu_e} + L_{\nu_\mu} + L_{\nu_\tau}$, $L_{\mu,\tau} \sim (N_{\mu,\tau} - N_{\bar{\mu},\bar{\tau}})/N_\gamma$ $L_{\nu_e} \sim \int \mathrm{d}^3p(\rho_{LL} - \bar{\rho}_{LL})/N_\gamma$.

The first two equations describe the evolution of neutrino and antineutrino ensembles. They provide a *simultaneous account* of the following processes: expansion (first term), neutrino oscillations (second term), neutrino forward scattering and weak interaction processes. The number densities of nucleons and electron neutrino were assumed the equilibrium ones.

These equations account precisely for the kinetic effects of neutrino oscillations - distortion of the neutrino energy distribution, depletion of electron neutrino and for neutrino asymmetry growth at each momentum. It was found that $\nu_e \leftrightarrow \nu_s$ oscillations lead to overproduction of He-4. An enormous overproduction in BBN produced He-4 (up to 6 times bigger than the effect of an additional

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[1] In case of L generation by fast oscillations, proceeding at relatively high $\delta m^2 > 10^{-5}$ eV^2 and small mixing, as discussed first in ref. [28], asymmetry may grow considerably to effect the weak interaction rates of the processes governing pre-BBN nucleon kinetics and, correspondingly, BBN.

light neutrino species!) is possible for some oscillation parameters [29]. I.e. $\delta N_{kin}^{max} > 6$. Figure 1 illustrates this result. The overproduction of He-4 in BBN with oscillations as a function of the mixing angle and for two different mass differences is presented in Fig.1.

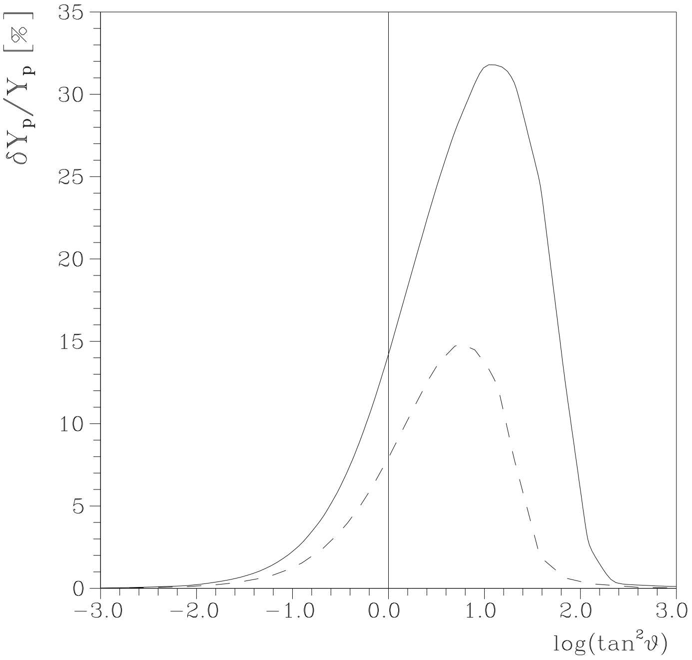

Figure 1: The figure illustrates the overproduction of He-4 in BBN with neutrino oscillations as a function of the mixing angle and for two different mass differences, namely the upper curve for $\delta m^2 = 10^{-7}$ eV^2, the lower curve for $\delta m^2 = 10^{-8}$ eV^2. Figure from [1].

This strong overproduction allowed to put stringent BBN constraints on oscillations effective after active neutrino decoupling [30]. (See dotted blue constraint on Fig.2.) These BBN constraints accounting for the dynamical effect, the spectrum distortion effect and lepton asymmetry growth by neutrino oscillations excluded almost completely the low mixing angle (LOW) sterile solution to the solar neutrino problem.

The analytical fits to the numerically calculated BBN constraints on $\nu_e \leftrightarrow \nu_s$, corresponding to 3% He-4 overproduction and initially empty sterile neutrino state, read:

$$\begin{gathered}\delta m^2(\sin^2 2\vartheta)^4 \leq 1.5\times 10^{-9}\mathrm{eV}^2 \quad \delta m^2 > 0 \\ |\delta m^2| < 8.2\times 10^{-10}\mathrm{eV}^2 \quad \delta m^2 < 0,\ \ large\ \ \vartheta, \end{gathered} \tag{3.1}$$

Thus, BBN constraints excluded LMA and LOW active-sterile solutions years before neutrino oscillations experiments managed to exclude them.

Inspired by the better contemporary accuracy of He-4 measurement, we are working on BBN constraints corresponding to 1% He-4 overproduction contour.

3.2 BBN with neutrino oscillations and initially non-zero partially filled ν_s state.

BBN with $\nu_e \leftrightarrow \nu_s$ and with initially non-zero partially filled ν_s state were studied as well [31, 32, 33]. The presence of a nonzero δN_s (before neutrino oscillations become effective) exerts two types of effects on BBN [31]:

(i) *Dynamical effect:* It increases the energy density $\delta\rho = 7/8(T_\nu/T_\gamma)^4 \delta N_s \rho_\gamma$, thus speeding the expansion $H = \sqrt{8\pi\rho/3M_p^2}$, which reflects into overproduction of He-4. [2]

(ii) *Kinetic effect:* In case of non-equilibrium $\nu_e \leftrightarrow \nu_s$, the partially populated ν_s suppresses the kinetic effects of $\nu_e \leftrightarrow \nu_s$ oscillations $\delta N_{kin}(\theta, \delta m^2)$, namely the energy spectrum distortion of ν_e and the neutrino-antineutrino asymmetry growth.

The dynamical and kinetic effects of such ν_s were numerically analyzed and the following relation between them was revealed. The dynamical effect increases the overproduction of He-4 thus strengthening the cosmological bounds on oscillation parameters, while the kinetic effect decrease it, correspondingly relaxing BBN bounds on oscillation parameters with respect to the ones calculated at $\delta N_s = 0$. On the basis of numerical analysis the following empirical relation describing the interplay between these effects was derived [31, 32]:

$$\delta N_{kin}(\theta, \delta m^2) = \delta N_{kin}^{max}(\theta, \delta m^2)(1 - \delta N_s),$$

where δN_{kin}^{max} is the maximal kinetic effect corresponding to $\delta N_s = 0$. The total effect of initially present partially filled sterile neutrino state can be very precisely fitted with the following relation:

$$\delta N_{tot}(\theta, \delta m^2) = \delta N_{kin}(\theta, \delta m^2) + \delta N_s = \delta N_{kin}^{max}(\theta, \delta m^2) + \delta N_s(1 - \delta N_{kin}^{max}(\theta, \delta m^2)).$$

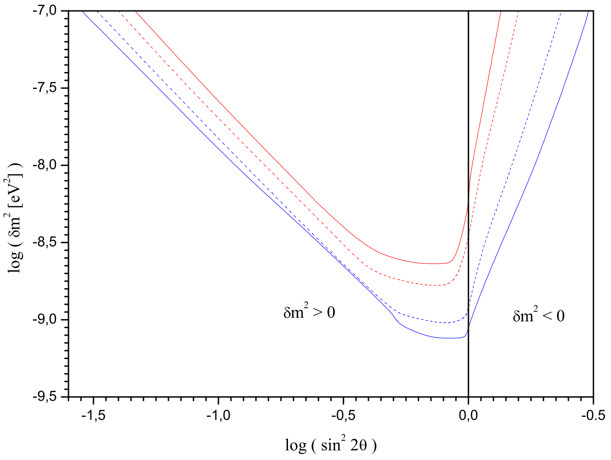

Figure 2: The BBN constraints on neutrino oscillation parameters for different He-4 overproduction and different initial population of the sterile neutrino state are presented. Upper curves correspond to 5.2% He-4 overproduction, lower curves - to 3% He-4 overproduction. The dotted curves correspond to initially zero populated sterile state, while the other curves to initially half filled ν_s. Figure from ref.[33].

The dependence of the cosmological constraints on the initial population of the sterile neutrino state was studied numerically. It was found that non-zero initial population of ν_s strengthens BBN

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[2] For $\nu_{\mu,\tau} \leftrightarrow \nu_s$ oscillations this dynamical effect is the only one of initially non-zero δN_s. It is also the major effect as well for electron-sterile oscillations occurring before neutrino decoupling.

constraints when the dynamical effect dominates and relaxes them when its kinetic effect dominates (Fig.2). Thus, BBN constraints on neutrino oscillations can be relaxed or strengthened depending on the interplay between the kinetic and dynamical effect of the additional sterile state.

3.3 BBN with neutrino oscillations and tiny lepton asymmetry.

The cosmological effects of tiny lepton asymmetries $|L| << 0.01$ on n/p kinetics of BBN with $\nu_e \leftrightarrow \nu_s$ oscillations was studied in refs. [34, 35, 1, 36]. It was found that tiny asymmetry $10^{-8} < |L| << 0.01$ is able to influence BBN with $\nu_e \leftrightarrow \nu_s$ neutrino oscillations due to L indirect kinetic effect via neutrino oscillations on neutrino evolution, its number density, spectrum distribution distortion, oscillations pattern.

It is known that small relic L, depending on its value and on the neutrino oscillations parameters is able to suppress [37, 34] or enhance [34] neutrino oscillations. The interplay between L and neutrino oscillations and its effect on BBN and on BBN constraints on neutrino oscillations parameters was numerically analyzed. Empirical relations between the values of the oscillation parameters and L, corresponding to different L effect have been obtained [35, 1]. The relation connecting neutrino squared mass difference and L value necessary to inhibit neutrino oscillations was recently updated [36]:

$$L > (0.01\delta m^2/eV^2)^{3/5}.$$

Relic L change BBN production of light elements by enhancing or suppressing neutrino oscillations (for illustration see Fig.3.). Hence, relic L may strengthen or relax standard BBN constraints on oscillation parameters. The parameter range where cosmological constraints on oscillation parameters are strengthened, relaxed or evaded was found. L influence on BBN and BBN constraints on neutrino oscillation parameters is illustrated in Fig.3 and Fig.4, correspondingly.

On the other side, neutrino active-sterile oscillations are capable to change neutrino-antineutrino asymmetry of the medium. It was found that they can suppress pre-existing asymmetry [23, 25] or enhance L in MSW resonant active-sterile oscillations for $\delta m^2 sin^4 2\theta < 10^{-7}$eV^2 in the collisionless case [27] and $\delta m^2 > 10^{-5}$eV^2 in oscillations dominated by collisions [28].

Enhancement of L was found possible by non-equilibrium resonant neutrino oscillations between ν_e and ν_s, effective after ν_e decoupling, i.e. for $\delta m^2 sin^4 2\theta < 10^{-7}$ eV^2 in ref. [34]. The instability region, corresponding to asymmetry growth of L (up to 4-5 orders of magnitude), is [35]:

$$|\delta m^2| sin^4 2\theta \leq 10^{-9.5} (\mathrm{eV})^2.$$

This effect was revealed thanks to the precise kinetic approach used for the description of oscillating neutrino and lepton asymmetry. The effect is caused by the phenomenon of "spectrum wave resonance", discovered in ref.[34].

Neutrino-antineutrino asymmetry growth caused by resonant oscillations leads to relaxation of the BBN constraints at small mixing. Fig.4 presents the change of BBN constraints on neutrino oscillations parameters in case the L is considerably bigger than the baryon asymmetry. As illustrated, $L = 10^{-6}$ relaxes the constraints on neutrino mass differences at large mixing and strengthens them at small mixing in comparison with the usually accepted L value of the order of the baryon asymmetry $L = 10^{-10}$ (see also refs.[35, 1].

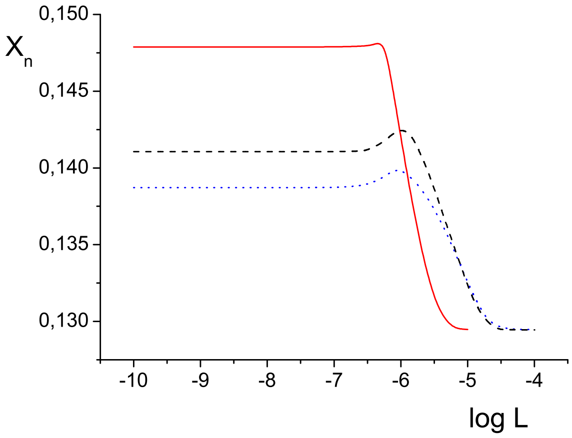

Figure 3: Dependence of the frozen neutron number density (essential for BBN produced He-4) on the value of the initially present lepton asymmetry. The solid curve corresponds to maximal mixing, the dashed curve to $\sin^2\theta = 10^{-0.05}$, the dotted curve to $\sin^2\theta = 10^{-0.1}$. The Figure from ref. [35].

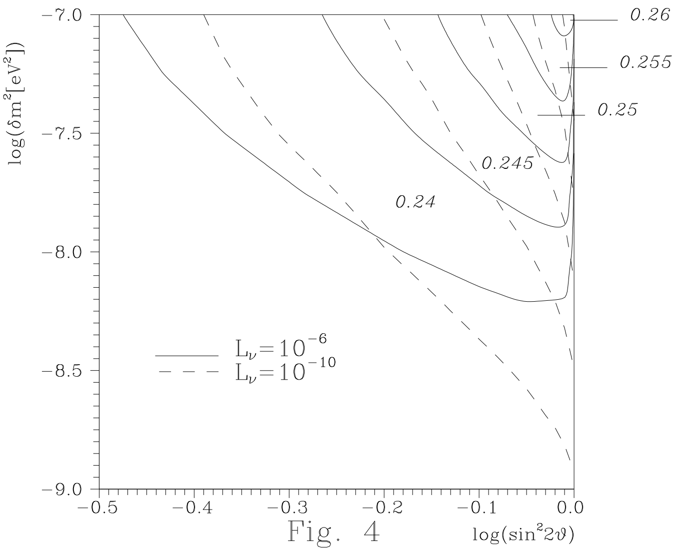

Figure 4: The BBN constraints on neutrino oscillations parameters corresponding to different constant He-4 contours for different values of the initially present lepton asymmetry $L = 10^{-6}$ (solid curves) and $L = 10^{-10}$ (dashed curves. Figure from ref.[34]

3.4 BSM Neutrino and Dark Radiation Problem

Dark Radiation (DR) problem is of particular interest because of the experimental indications from neutrino oscillations short baseline experiments including reactor experiments, LSND, MiniBooNe and Gallium experiment (GALLEX, SAGE) for presence of ν_s with mass in the eV range and mixing with flavor neutrinos $sin\theta_{14}^2$ in the range $[0.01 - 0.03]$ [38, 39].

However, such eV sterile neutrino is brought into equilibrium by the active-sterile neutrino oscillations in the early Universe. It fastens the Universe expansion, thus influencing CMB and BBN.

Hence, BBN and CMB exclude the thermalized during BBN light sterile neutrinos and constrains $\nu_e \leftrightarrow \nu_s$ oscillations. Constraints on eV oscillating ν_s exist also on the basis of Lyman Alpha forest BOSS data, CMB data from Planck, ACT, SPT, WMAP polarization [40], and baryon acoustic oscillations data [41], as well. These cosmological constraints rule out the possibility of thermalized eV sterile neutrino.

Different solutions to the DR problem have been proposed including: additional radiation, change in matter density, decaying particles during BBN, degenerate BBN, etc. As an explanation of the excess radiation most thoroughly was studied the case of degenerate BBN with big enough L to change the Universe dynamics and the nucleons kinetics in the pre-BBN epoch. It was found that DR cannot be explained by such model [19].

We discussed two possible solutions to DR problem, using BSM physics in the neutrino sector: (i) An explanation employing the interplay between neutrino-antineutrino asymmetry and neutrino oscillations, i.e.: large enough L suppresses oscillations preventing the thermalization of ν_s and thus avoiding cosmological constraints [35, 42, 43, 44, 36]. DR problem may be solved by this mechanism for $L > 0.074$ [36]. That big asymmetry exerts, however, dynamical and in case it is in ν_e sector, direct kinetic effect on BBN. Although small, these effects may be non-negligible, having in mind the better precission of contemporary BBN. I.e. more precise analysis accounting for these effects is required.

(ii) An explanation employing the *decays of heavy particles into neutrino* was discussed in refs. [45, 46]. Namely, additional non-radiatively decaying particles during or before n-p freezing lead to faster expansion than in the standard BBN model and change the nucleons kinetics in the pre-BBN epoch due to their decay products. It is possible to achieve underproduction of primordial He-4 for decaying particles with masses $m < 7$ MeV in case these particles decouple while relativistic [47]. Hence, the dynamical effect of the DR may be compensated by the effect of the decay products on nucleons kinetics during BBN.

Both models allow a relaxation of the BBN bounds on the number of relativistic neutrino species, and correspondingly on 3+1 and 3+2 neutrino models.

4. Conclusion

BBN is the earliest and the most robust test of beyond Standard Model neutrino. It "measures" the number of neutrino species, neutrino mass differences and mixing, deviations from equilibrium Fermi-Dirac distribution, lepton asymmetry, possible new interactions, etc.

Being sensitive speedometer BBN provides stringent constraints on additional light particle species N_{eff}. These constraints are strengthened in case of active-sterile neutrino oscillations.

BBN with nonequilibrium electron-sterile neutrino oscillations constrains oscillation parameters for He-4 uncertainty up to $32\%(14\%)$ in resonant (non-resonant) case. It provides the most stringent constraint on neutrino mass differences δm^2. Oscillations generated L relaxes BBN constraints at small mixings.

BBN constraints on neutrino oscillations parameters depend nontrivially on the population of ν_s and L in the Universe. Additional initial population of ν_s not always leads to strengthening of constraints, it relaxes them in case its kinetic effect dominates over its dynamical effect.

BBN with electron-sterile neutrino oscillations is a very sensitive leptometer. Relic L as small as 10^{-8} may be felt by BBN via electron-sterile neutrino oscillations. Relic L may lead to reduction or increase of He-4 overproduction in models of BBN with electron-sterile neutrino oscillations. Hence, it may provide relaxation or enhancement of BBN constraints on neutrino oscillation parameters.

$L > 0.07$ may provide relaxation of BBN constraints on neutrino oscillations with eV sterile neutrino because it can suppress these oscillations and cause ν_s incomplete thermalization, i.e. help to solve the DR problem. Models with additional decaying particles with masses $m < 7$ MeV into neutrino, which effects pre-BBN kinetics, also have been considered as a possible solution of DR problem.

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