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Updated BBN cosmological constraints on Beyond Standard Model physics

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Big Bang Nucleosynthesis (BBN) is one of the most reliable tests of Beyond Standard Model (BSM) physics due to the remarkable concordance between the theoretically predicted and the derived from observations abundances of light elements produced primordially. Recently the primordial light elements D and He-4 were determined with higher accuracy. This allows to update and strengthen the Big Bang Nucleosynthesis constraints on physics beyond Standard Model. We consider several models representing BSM physics. We derived updated more stringent BBN constraints on electron-sterile neutrino oscillations parameters corresponding to 1 percent accuracy of the determination of the primordial produced Helium-4. We present new cosmological constraints on the number of the effective degrees of freedom of light particles during the BBN epoch and updated the BBN constraints on the freezing temperature of the light sterile neutrinos.

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1. Introduction

The chemical content of the baryonic component of the Universe now is mainly 24.7% ^{4}He and the rest is hydrogen H. This content is known to be synthesized during the hot early stage of the Universe evolution when its temperature T and density were suitable for nuclear reactions to proceed, i.e. during primordial nucleosynthesis - Big Bang Nucleosynthesis (BBN). BBN occurred during the first minutes of the evolution of our Universe, in the temperature range 1 MeV - 0.1 MeV. Besides ^{4}He 24.7% by mass to nucleons, several light elements with negligible quantities were synthesized namely: deuterium D, D/H $\sim 3 \times 10^{-5}$, ^{3}He, ^{3}He/H $\sim 3 \times 10^{-5}$ and ^{7}Li , ^{7}Li/H $\sim 2 \times 10^{-10}$. Some even less significant quantities of carbon C, nitrogen N and oxygen O were produced as well. In contemporary BBN models over 400 reactions are considered, leading mainly to the synthesis of the discussed elements.

Heavier than ^{7}Li nuclei were not produced during BBN in considerable quantities mainly because of the fast decrease of the baryon density and temperature due to Universe expansion. They were produced much later in star cores, during Super Novae bursts and in Cosmic Rays.

Big Bang Nucleosynthesis is theoretically well established. Precise data on nuclear processes rates from laboratory experiments at low energies, corresponding to these during BBN (10 KeV - MeV) exist and are used in BBN codes, like PArthENoPE, AlterBBN, PRIMAT [1–6].

Light element primordial abundances depend on the baryon number density usually given by the baryon-to-photon ratio η, neutron life-time τ_n, the number of the effective degrees of freedom of light particles N_{eff}, all of which are determined with high precision. Namely: The baryon-to-photon ratio is measured independently by CMB with high precision: $\eta_{CMB} = (6.14 \pm 0.04) \times 10^{10}$, which is in agreement with the BBN value. The neutron lifetime has been also measured with higher accuracy $\tau = 879.5 \pm 0.8$ s [7]. N_{eff} during the BBN epoch is known with a high precision: $N_{eff} = 2.88 \pm 0.154$ at 95% C.L. [5, 8]. The cosmological constraint based on BBN+CMB [9] is more restrictive: $N_{eff} = 2.898 \pm 0.141$, i.e. $N_{eff} < 3.18$ at 95% CL. Thus, BBN is now considered a parameter free theory.

The observational abundances of the primordial elements are derived from astrophysical observations of different objects in our Universe, usually at high redshift and with low metalicity with an account for the post BBN chemical evolution. Precise data on D, He, Li are available and during the last years the precision of determination of primordial D and He-4 has increased considerably [5, 8, 10]. D observational data improved due to new observations of QAS [8]. The precision of He-4 data improved due to the inclusion of new observations of HeI λ 10830He infrared emission line measured in the extremely metal poor galaxy Leo P. These observations combined with previous ones allowed to derive an improved primordial helium abundance Y_p :

$$Y_p = 0.2453 \pm 0.0034.$$

More details can be found in refs [10–12].

There is a remarkable concordance between theoretically predicted and derived from observations abundances of light elements produced primordially. Hence, BBN is used as the most reliable precision probe for physical conditions in early Universe and a unique test for new physics.

The post BBN evolution of ^{4}He is simple: it is only produced in the stellar and galactic chemical evolution. It is the most abundant (after H), most precisely calculated and measured element and it is very sensitive to nucleons kinetics before BBN. Hence, ^{4}He is the preferred element for obtaining the BBN constraints on Physics beyond the Standard model, like, in particular, beyond SM neutrino.

The primordial abundance of ^{4}He is obtained from observations of He and H emission lines from metal poor HII regions, like compact blue dwarf galaxies. Linear fit of all the data obtained from spectra of HII regions is made and then extrapolated to zero metallicity. The linear correlation between ^{4}He, produced in stars and metals Z (C, N and O) is used to derive the primordial mass fraction of helium. The accuracy of the determination is limited by systematic errors. Many systematic effects are corrected in recent observations in order to derive from the observed intensities of He spectral lines its primordial value. In the previous decade primordial ^{4}He was known with 3-5% precision, and the constraints on beyond standard model physical models used this precision. During the last decade the precision of helium measurements increased. Hence, this allows to update and strengthen BBN constraints on physics beyond Standard Model.

In this work we consider several models representing beyond SM physics including sterile neutrinos and present updated cosmological constraints on them. (For a contemporary review on theoretical and experimental science of sterile neutrinos see ref [13].) The work is including updates of refs. [15–17]. Namely, first in the following section we discuss how BBN constraints on neutrino oscillations parameters change[14] as a result of the higher precission of the latest data on primordially produced ^{4}He, which correspond to 1-3% uncertainty; in section 2, using recent cosmological constraints on the number of the effective degrees of freedom of relativistic particles, we provide an update of the cosmological constraints on the freezing temperature of the light sterile neutrinos [16, 17] and update the BBN constraints on the interaction strength of eventual beyond SM interactions of sterile neutrino.

2. BBN with neutrino oscillations. Updated BBN constraints on oscillation parameters.

Today there exist experimental and observational evidence that neutrinos oscillate, i.e it changes its flavour and neutrino mass eigenstates are distinct from the flavor eigenstates. Solar neutrino problem, atmospheric neutrino anomaly and the results of terrestrial neutrino oscillations experiments were resolved by flavor neutrino oscillations.

Neutrino oscillations influence Universe processes and consequently Cosmology constrains oscillations. Hence, in BBN with neutrino oscillations between electron neutrino and sterile neutrino $\nu_e \leftrightarrow \nu_s$ the energy distribution and the density of the electron neutrino may strongly differ from the one of the standard BBN - the number density of electron neutrino is reduced and the energy spectrum distribution may be very distorted from its equilibrium Fermi-Dirac form, leading to the reduction both of the number density of eletron neutrino and to reduction of its energy. These lead to changes in the kinetics of the nucleons during BBN and influences the cosmological synthesis of the light elements.

The reduction of the neutrino density and energy spectrum distortion caused by the non-equilibrium oscillations lead to reduction of the weak interaction rates of electron neutrino and to overproduction of ^{4}He. In the 90ies ^{4}He primordial abundance Y_p was determined with 3-7% accuracy, which allowed to put BBN constraints on neutrino oscillation parameters – the neutrino squared mass differences and neutrino mixing, corresponding to 3-7% overproduction of ^{4}He. [18–20]. We have calculated combined iso-helium contours for 3-7% ^{4}He overproduction, accounting for all oscillations effects on BBN, for zero initial population of the sterile neutrino. Precise BBN constraints, orders of magnitude more stringent than previous ones, due to account for spectrum distortion were obtained.

2.1 Updated BBN constraints on neutrino oscillation parameters.

Recently the primordial abundance of ^{4}He was determined with 1% accuracy. Hence, it is possible to obtain more stringent BBN constraints on neutrino oscillations.

We have provided numerical analysis of 135 BBN models with neutrino oscillations with different oscillation parameters. In models of BBN with late neutrino oscillations helium-4 is overproduced. We have calculated numerically the produced helium-4 values in our BSM model of BBN of helium-4 in the presence of neutrino oscillations for different sets of neutrino oscillation parameters. We have compared the obtained helium-4 value in each model corresponding to concrete neutrino oscillations values to the observational value for primordially produced helium-4. Thus, we have found the oscillation parameters values corresponding to 3% and 1% overpoduction of helium-4. On the basis of the numerical results we have determined the contours in the plane δm^2 –- $sin^2 2\theta$, corresponding to 1% and 3% overproduction of helium due to neutrino oscillations [14]. See Fig.1 from ref. [14] and Fig.1 and the discussion in the following section. We have updated also the data on baryon density and the neutron life time.

3. BBN constraints on the freezing temperature of sterile neutrino and on sterile neutrino interactions.

3.1 Recent constraints on light neutrino types

BBN constrains the effective number of relativistic species N_{eff} or light neutrino types because additional light particles into equilibrium increase the expansion rate of the universe $H \sim (G_N \rho)^{1/2}$, where $\rho = \rho_\gamma + \rho_\nu$ is the relativistic density, and effective number of relativistic species N_{eff} is defined by $\rho_\nu = 7/8T/T_\nu)^4 N_{eff} \rho_\gamma(T)$. Non-zero $\delta N_{eff} = N_{eff} - 3.045$ will indicate any extra relativistic component. BBN is a sensitive probe to additional species and it tests and constrains new physics.

Among the light elements produced primordially He-4 is the best speedometer, because it is a strong function of the effective number of light stable particles at BBN epoch. As mentioned in the previous section recent stringent constraints on the number of light neutrino types during BBN epoch read: $N_{eff} < 3.18$ at 95% C.L. [9]. And this is in accordance with the Planck data gives the constraint: $N_{eff} = 3.01 \pm 0.15$ at 95% C.L. [5] .

Thus, although BBN and CMB neutrino numbers are consistent with the standard model value $N_{eff} = 3.045$ within uncertainties, the deviations from it can be interpreted as indications for beyond SM physics and can be used to put constraints on the parameters of beyond SM physics models. We will use $\delta N_{eff} < 0.2$ for obtaining BBN constraints on new physics in the following subsections.

3.2 Change in the cosmological constraints on neutrino oscillations in presence of non-zero sterile neutrino

In BSM with additional sterile neutrino partially filled sterile neutrino at BBN epoch may influence electron-sterle neutrino oscillations and change BBN constraints on neutrino oscillations compared with the case of initially zero populated sterile neutrino state. It has been proved both analytically and numerically that the distortion due to active-sterile oscillations and the kinetic effect caused by additional partially filled sterile neutrino depends on the degree of initial population of ν_s δN_s. due to the interplay between the dynamical and kinetic oscillation effects [21, 22]. Additional inert population may strengthen or relax BBN constraints. In particular, the constraints corresponding to 5% overproduction of helium-4 relax with the increase of the initial population of sterile neutrino, while BBN constraints corresponding to 3% overproduction of helium-4 strengthen with the increase of δN_s.

On the basis of general results of our previous analysis it is expected *strengthening of the BBN constraints* on neutrino oscillations, corresponding to 1% He-4 overproduction with the increase of the initial popularion of ν_s. The results from our numerical analysis of BBN with neutrino oscillations confirm this expectation [14]. In Fig.1 we present the updated BBN contraints on neutrino oscillations parameters, based on 1% uncertainty of ^{4}He for the case of initial population of the sterile neutrino equivalent to $\delta N_s = 0.2$.

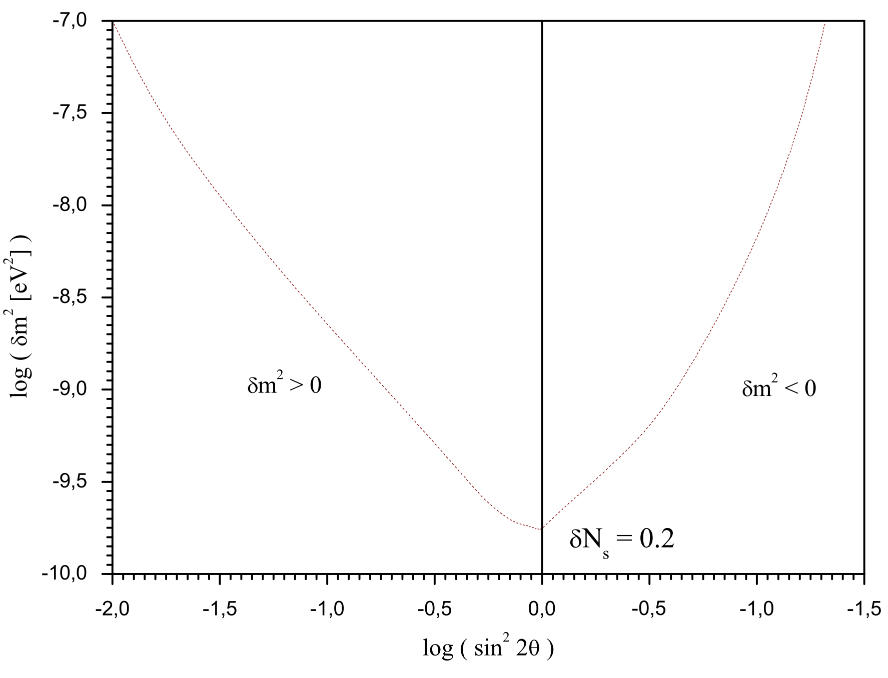

Figure 1: BBN constraints on neutrino oscillation parameters, corresponding to 1% He-4 uncertainty and $\delta N_s = 0.2$

3.3 Excess radiation density and BBN constraints on additional light neutrino

Combined neutrino oscillations data (including MiniBoone and LSND) require additional light sterile neutrino in equillibrium before BBN, participating into oscillations with flavor neutrinos with higher mass differences values, than the ones required by solar and atmospheric neutrino oscillations experiments. They hint to sterile neutrino with eV mass.

Recently updated global analysis of neutrino scillations with eV-scale sterile neutrinos was provided including the results of reactor experiments+LSND+MiniBooNe+Gallium expt+SAGE [23, 24].

Neutrino search using eight years of atmospheric muon neutrino data from the IceCube Neutrino Observatory hints to:

$sin^2(2\theta_{24}) = 0.10$ and $\delta m^2_{41} = 4.5$ eV^2 [25]

Tension exists between data from T2K and NOvA: there a preference is obtained for $\delta m^2_{41} = 10^{-2}$ eV^2 and $sin^2(2\theta_{24}) = 0.07$ [26].

The global analysis shows significant tension between groups of different data sets, and between appearance and disappearance results [24]. However, the sterile neutrino with the masses and mixings indicated by all these experiments will come to equilibrium during BBN.

BBN strongly constrains the presence of fully thermalized light sterile neutrino, as already discussed. And sterile neutrino with the mass and mixing indicated by the mensioned experiments is also constrained by the BBN exclusion plots on neutrino oscillations parameters.

Possible solutions were discussed by several authors. For example in BBN with neutrino oscillations and degenerate neutrino, i.e. with relic lepton asymmetry in the neutrino sector, which is high enough to suppress neutrino oscillations and thus prevent the sterile neutrino thermalization and solve the contradiction between the experiments pointing to dark radiation and cosmological constraints [27, 28]. Hence, the additional rediation density, found in neutrino oscillation experiments may point to the necessity of presence of lepton asymmetry during BBN epoch. Estimations of its value show that it should be much larger than the baryon astmmetry of the local universe [17, 29].

3.4 BBN constraint on sterile neutrino decoupling

In the expanding Universe particles are kept in thermal equilibrium while their interaction rates $\Gamma(T)$ are higher than the expansion rate H(T). Freeze-out occurs when they become comparable $\Gamma(T) \sim H(T)$.

We updated the cosmological constraint on the freezing temperature of sterile neutrino T_f using recent BBN constraint $\delta N_{eff} < 0.2$ [5], and the fact that the total entropy is conserved if the evolution of the universe is adiabatic [15–17, 30]. For the relation between the the effective degrees of freedom in the early universe and the temperature we used the data provided in ref. [31].

For the case of 3 light sterile neutrino types and $\delta N_{eff} < 0.2$ we have determined $T_f > 1600$ MeV. In case of 2 light sterile neutrino $T_f > 200$ MeV, for 1 light sterile neutrino $T_f > 170$ MeV. These values are slightly lower than previously estimated in ref. [16].

These constraints on T_f can be interpreted as constraints on any new interactions with right-handed neutrinos because $(T_f/2MeV)^3 = (G_w/G_{new})^2$, where 2 MeV is the freezing temeperature of the electron neutrino, G_w is the week interaction strength and G_{new} is the interaction strength of any new interactions sterile neutrino may participate in. Then the following constraints follow: in case of 3 light right handed neutrinos $G_{new}/G_w < 4.4 \times 10^{-5}$, for 2 light right handed neutrinos $G_{new}/G_w < 1.10^{-6}$, for 1 light right handed neutrinos $G_{new}/G_w < 1.3 \times 10^{-3}$. These constraints on G_{new} are much stronger than estimated in previous works. Such interactions should be at least thousands times weeker than the week interactions.

4. Conclusions

We derived improved BBN constraints on electron-sterile neutrino oscillations parameters corresponding to 1 percent accuracy of the the primordial produced Helium-4 and initial population of the sterile neutrino equal to 0.2. BBN constraints forbid the presence of sterile neutrino with big mass differences indicated by several neutrino oscillation experiments, unless large enough lepton asymmetry suppresses neutrino oscillations during BBN.

We updated the BBN constraints on the freezing temperature of the light sterile neutrinos and the interaction strength of eventual interactions in which this neutrino participates.

These results are important not only from cosmological point of view for clarifying the role of neutrino in the early Universe but also for neutrino oscillations theory, for studies of the sterile neutrino and new physics in general.

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