

Review Article

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Neutrinos from the Early Universe and physics beyond standard models

Abstract: Neutrino oscillations present the only robust example of experimentally detected physics beyond the standard model. This review discusses the established and several hypothetical beyond standard models neutrino characteristics and their cosmological effects and constraints. Particularly, the contemporary cosmological constraints on the number of neutrino families, neutrino mass differences and mixing, lepton asymmetry in the neutrino sector, neutrino masses, light sterile neutrino are briefly reviewed.

Keywords: neutrino; beyond standard model; cosmology; cosmological constraints; BBN

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1 Introduction

Physics Beyond the Standard Models (BSMs), i.e. beyond Electro Weak Model and beyond Standard Cosmological Model (SCM, also called λ Cold Dark Matter model) is required for the explanation of the astrophysical and cosmological observational data. Namely, the contemporary SCM, contains considerable BSMs components - the so called dark energy (DE) and dark matter (DM), both with yet unrevealed nature, alas. These constitute 96% of the matter in the universe today, and play a considerable role at the matter dominated epoch, i.e. at later stages of the Universe evolution!

BSMs physics is needed also for revealing the nature and the characteristics of the inflaton (the particle/field responsible for inflationary expansion stage) and CP-violation (CPV) or/and B-violation (BV) mechanisms. These are expected necessary ingredients in the theories of inflation and baryon asymmetry generation, which are the

most widely accepted today hypotheses providing natural explanations of numerous intriguing observational characteristics of our universe.

The inflationary theory explains naturally and elegantly the initial conditions of the universe in the pre-Friedmann epoch, namely: the extraordinary homogeneity and isotropy at large scales of the universe at its present epoch; its unique isotropy at the Cosmic Microwave Background (CMB) formation epoch (when the universe was ~ 380000 years old); its unique flatness and the pattern of structures. Besides, the inflationary early stage explains the lack of topological defects in the universe. Meanwhile the baryon asymmetry generation models explain the locally observed matter-antimatter asymmetry of the universe.

To understand these cosmological puzzles *physics BSMs* is required either to propose the candidates for DM, DE, inflation and baryon charge carrying field, or to change/extend the theoretical basis of SMs (propose alternative gravitational theory, extended standard model or grand unified theory), etc. Alas, after many years of research there are no firm experimental detection of these BSM candidates, only experimental and observational constraints on the hypothetical candidates or/and theories exist.

On the other hand, we have been already the lucky witnesses of the *experimental establishment of the BSM physics* in the neutrino sector. Experimental data on neutrino oscillations firmly determined three neutrino mixing angles and three mass differences, corresponding to the existence of at least two non-zero neutrino masses. The concrete neutrino mass pattern and possible CPV mechanism are to be detected in the near future. Thus, the neutrino experimental data ruled out the Standard Models assumptions about zero neutrino masses and mixing and about flavor lepton number (L) conservation.

Cosmology provides complementary knowledge about neutrino and BSM physics in the neutrino sector, because the neutrino had a considerable influence on the processes during different epochs of the universe evolution. At the hot early universe stage, radiation dominated (RD) stage,

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light neutrinos were essential ingredients of the universe density, determining the dynamics of the universe ¹.

Neutrinos played also an essential role in different processes as for example Big Bang Nucleosynthesis (BBN). In particular, electron neutrino participated in the pre-BBN neutron-proton transitions, that took place during the first seconds, and nucleons freezing, and thus they influenced considerably the primordial production of the light elements (BBN) during the first minutes of the universe. Hence, BBN is very sensitive to the number of the light neutrino types, neutrino characteristics, neutrino chemical potentials, the possible presence of sterile neutrino, etc. BBN is capable of differentiating neutrino flavors, because ν_e participates in proton-neutron transitions in the pre-BBN epoch, essential for yields of the primordially produced elements, while ν_μ and ν_τ do not exert kinetic effect on BBN.

At later stages of the universe evolution ($T < \text{eV}$) relic neutrinos, contributing to the matter density, influenced CMB anisotropies, ² played a role in the formation of galaxies and their structures. CMB and LSS, being sensitive to the total neutrino density provide information about the neutrino masses and number of neutrino species ³.

Hence, although the relic neutrinos, called Cosmic Neutrino Background (CNB) are not yet directly detected, strong observational evidence for CNB and stringent cosmological constraints on relic neutrino characteristics exist from BBN, CMB and LSS data. In particular, the determinations of light elements abundances and BBN theory predictions are used to put stringent constraints on neutrino characteristics (the effective number of relativistic particles, lepton asymmetry, sterile neutrino characteristics, neutrino mass differences and mixings). While CMB and LSS data provide constraints on neutrino masses and neutrino number density corresponding to CMB and LSS formation epochs.

In summary: It is important to explore the cosmological constraints on neutrino on one hand, because neutrinos are messengers from the very young hot universe (CNB formation epoch corresponds to the first seconds of universe when the universe plasma had $T \sim \text{MeV}$) and thus they provide information about the physical conditions of the early universe; on the other hand cosmology pro-

vides knowledge about the properties of neutrino, which is complementary to the information coming from particle physics.

This review discusses the already established and also several hypothetical BSMs neutrino characteristics and their cosmological effects and constraints. Namely, we review the cosmological role of light neutrino, neutrino oscillations and possible lepton asymmetry in the neutrino sector. We present contemporary cosmological constraints on neutrino properties, obtained on the basis of astrophysical and cosmological data. Particularly, the cosmological constraints on the number of neutrino families, neutrino mass differences and mixing, lepton asymmetry hidden in the neutrino sector, neutrino masses, sterile neutrino possible characteristics, etc. are reviewed.

In the next section we discuss SCM predictions concerning relic neutrino. In the third section established BSMs neutrino physics and some hypothetical BSMs neutrino characteristics are discussed. Fourth and fifth sections review BBN constraints on neutrino BSMs characteristics, in particular the constraints on sterile neutrino, active-sterile neutrino oscillations, neutrino-antineutrino asymmetry, the dark radiation problem.

2 Neutrino predicted by SMs

2.1 Neutrino in Standard Electro Weak Model

In the Standard Electro Weak Model neutrinos are massless, spin 1/2 fermions with weak interactions, i.e. $\text{SU}(2)_W$ doublets. There exist 3 neutrino flavors of light neutrinos, namely electron neutrino ν_e , muon neutrino ν_μ and tau neutrino ν_τ . The number of light neutrino types (with masses $m < m_Z/2$) was experimentally measured by four LEP experiments to be: $N_\nu = 2.984 \pm 0.008$.

However, there is robust experimental evidence for BSMs physics in the neutrino sector: Neutrinos oscillate, i.e. their mass eigenstates do not coincide with their flavor eigenstates, there exist neutrino mixing and non-zero neutrino mass differences. Neutrino oscillations data proved that neutrinos are massive. The origin of neutrino masses is still unknown. Various mass generation mechanisms, usually involving the introduction of extra particles, are discussed.

Besides, BSMs physics predicts other types of neutrinos, not coupled to Z , called "sterile" ν_s , i.e. $\text{SU}(2)_W$ singlets, not having the ordinary weak interactions. Sterile neutrinos may be produced in GUT models, in models with

¹ DE and DM had negligible dynamical influence at RD stage

² as far as at least one of the neutrino species became non-relativistic (using the information about neutrino mass differences from the neutrino oscillations data)

³ with present day accuracy the CMB and the LSS data are flavor blind.

large extra dimensions, Manyfold Universe models, mirror matter models, or by neutrino oscillations, etc. Cosmological effects of ν_s and bounds on light ν_s will be discussed in more detail in the following sections.

2.2 Relic neutrino characteristics predicted in SCM

According to the SCM at radiation dominated stage of the universe neutrinos were dynamically important component, because their energy density was comparable to that of photons:

$$\rho_\nu = 7/8(T_\nu/T)^4 N_{\text{eff}} \rho_\gamma(T), \quad (1)$$

where N_{eff} is the effective number of the relativistic neutrino species. Hence, ν_e , ν_μ and ν_τ influenced considerably the expansion rate of the universe $H \sim \sqrt{8\pi G_N \rho/3}$.

At $T > 1$ MeV neutrinos were kept in equilibrium because their interactions with other particles of the hot universe plasma, were faster than the expansion rate of the universe: $\Gamma_W \sim \sigma(E_\nu) n_\nu(T) > H$. Hence, neutrinos had an equilibrium Fermi-Dirac (FD) energy distribution

$$n_\nu^{eq} = (1 + \exp((E - \mu)/T))^{-1} \quad (2)$$

and their temperature coincided with that of electrons and photons.

As the Universe expanded and cooled Γ decreased faster than H , due to the decrease of energy and the dilution of particle densities. Hence, roughly at $T \leq 1$ MeV the interactions of neutrino could no longer keep neutrino in equilibrium and neutrinos "froze out", i.e. neutrino species decoupled. Since then neutrinos propagated freely, i.e. cosmic neutrino background was formed. In SCM neutrinos were assumed massless and, therefore, they kept their FD distribution after decoupling. In the SCM the lepton asymmetry in the neutrino sector was assumed zero.

The decoupling T slightly differed for different types of neutrino. Namely $T_{\nu_e}^{dec} \sim 2$ MeV, while $T_{\nu_\mu, \tau}^{dec} \sim 3$ MeV. This is due to the fact that electron neutrino, besides neutral current interactions experienced also charged current interactions (as far as electrons and positrons were still present in the universe plasma at the time of neutrino decoupling, while muons and tau leptons have already disappeared). Neutrinos kept their equilibrium FD distribution after decoupling because of the extreme smallness of neutrino mass.

At $T_e \sim m_e$ only photons were heated by e^+e^- - annihilation. Since then neutrino temperature remained lower than the temperature of the photons T_γ by a factor $(4/11)^{1/3}$.

Actually, neutrinos shared a small part of the entropy release because neutrino decoupling epoch was close to m_e and also because the decoupling was not instantaneous. The account for non-instantaneous decoupling, for QED finite temperature effects and for flavor neutrino oscillations slightly changes the predicted neutrino particle and energy densities [1, 2]. Thus, the expected number of neutrino species is $N_\nu = 3.046$ not 3, the neutrino number density is $n_\nu = 339.3 \text{ cm}^{-3}$ (per three neutrino species), not 335.7 cm^{-3} . The temperature of CNB today is predicted to be $T = 1.9$ K.

Hence, CNB neutrinos are expected to be the most numerous particles after CMB photons. The relic neutrinos today contribute a negligible part to the total density due to their low temperature:

$$\Omega_\nu(t_0) = 2 \times 7/8 \times (\pi^2/30) T_{\nu,0}^4/\rho_c \sim 10^{-5}.$$

Thus, *SCM predicts massless relic neutrinos, with equilibrium Fermi-Dirac distribution, zero chemical potential and effective number of the relativistic neutrino species $N_{\text{eff}} = 3.046$.*

Though numerous, CNB neutrinos have not been directly detected yet, because of neutrinos weak interactions and extremely low energy of the CNB neutrinos today. However, due to the cosmological effects of neutrinos on processes which have left observable today relics, *CNB has been detected indirectly* and numerous constraints on relic neutrino and on BSM neutrino characteristics have been obtained. For more details see for example the review papers [3–8]. The constraints on light neutrinos will be discussed in the following sections.

3 Neutrino beyond standard models - established and hypothetical

Here we discuss several examples of BSM neutrino physics: deviations from FD distribution, neutrino oscillations, neutrino masses, neutrino-antineutrino asymmetry.

3.1 Deviations from Fermi-Dirac distribution

Different BSM models predict deviations from FD distribution of the CNB neutrino. Among them are neutrino oscillations, models with non-zero lepton asymmetry, models with additional decaying particles into neutrinos or decays of heavy neutrinos.

Flavor neutrino oscillations lead to a slight change of the FD distribution [9, 10]. Flavor oscillations with parameters favored by the atmospheric and solar neutrino data establish an equilibrium between active neutrino species before BBN epoch. Thus, the number density of one neutrino species with the account of flavor oscillations becomes 113 cm^{-3} instead 112^{-3} (predicted by the SCM).

The presence of non-zero *lepton asymmetry* is capable to distort strongly the neutrino spectrum. However, the value of the neutrino-antineutrino asymmetry is now strongly constrained by BBN in all sectors due to the presence of flavor oscillations [11] (see section 5).

Fast active-sterile neutrino oscillations, which could have been effective before the epoch of neutrino decoupling, slightly influence active neutrino distributions, because the active neutrino states can be refilled due to interactions with the plasma.

However, *active-sterile neutrino oscillations, proceeding after ν_e decoupling*, i.e. with oscillation parameters:

$$\delta m^2 \sin^4(2\theta) \leq 10^{-7} \text{ eV}^2$$

and provided that ν_s state was not in equilibrium before the start of oscillations $\delta N_s = \rho_{\nu_s}/\rho_{\nu_e} < 1$, may strongly distort neutrino energy spectrum and deplete neutrino number density [13–15].

Thus, relic neutrino may have strongly distorted non-equilibrium spectrum today [16].

Besides, resonant neutrino active-sterile oscillations may generate neutrino-antineutrino asymmetry [14, 15, 17, 18], which also may lead to distortions of the FD neutrino distribution.

Eventual *decays of neutrino and into neutrinos* are another source for deviations from the equilibrium neutrino spectrum.

Possible *violation of spin statistics* and the cosmological constraints on it were also explored [19, 20].

3.2 Neutrino oscillations

Solar neutrino problem and atmospheric neutrino anomaly were resolved by the phenomenon of neutrino oscillations, confirmed by the data of terrestrial neutrino oscillations experiments. The dominant neutrino oscillation channels to solve the atmospheric and solar neutrino problems have been proved to be flavor neutrino oscillations.

Thus, it has been observationally and experimentally proved that neutrinos oscillate, i.e. there exists flavor neutrino mixing in vacuum and neutrino mass eigenstates ν_j

do not coincide with the flavor eigenstates ν_f ,

$$\nu_f = \sum_{i=1}^3 U_{fi} \nu_i, \quad \delta m_{ij}^2 = m_j^2 - m_i^2 \neq 0, \quad (i \neq j). \quad (3)$$

Namely,

$$\delta m_{12}^2 \sim 7.5 \times 10^{-5} \text{ eV}^2$$

$$|\delta m_{31}^2| \sim 2.4 \times 10^{-3} \text{ eV}^2$$

and $\sin^2 \theta_{12} \sim 0.3$, $\sin^2 \theta_{23} \sim 0.39$, $\sin^2 \theta_{13} \sim 0.024$. This implies non-zero neutrino mass and mixing and non-conservation of the individual lepton charges L_f , which are BSMs characteristics for neutrino.

In general neutrino oscillations occur in medium (matter oscillations) inside stars, planets, universe plasma, etc. For example the data from solar neutrino detectors showed evidence for matter effects in the solar ν_e transitions. Matter oscillations in the early universe plasma were studied as well [21]. The medium distinguishes between different neutrino types due to different interactions, which lead to different average potentials V_f for different neutrino types:

$$V_f = Q \pm L, \quad (4)$$

where $f = e, \mu, \tau$, $Q = -bET^4/(\delta m^2 M_W^2)$ is the so called non-local term, $L = -aET^3 L^a/(\delta m^2)$ is the local term and L^a is given through the fermion asymmetries of the plasma, a and b are positive constants different for the different neutrino types, $-L$ corresponds to the neutrino and $+L$ to the antineutrino case.

Thus, due to the medium the oscillation pattern may change: In general the medium suppresses oscillations by decreasing their amplitude, in comparison with the vacuum oscillations. However, the mixing in matter may become maximal, independently of the value of the vacuum mixing angle, i.e. enhanced oscillation transfer may occur in medium when a resonant condition holds.

For neutrino in equilibrium in the early Universe, when working in terms of mean neutrino energy is acceptable, the resonant condition reads:

$$Q \mp L = \cos 2\theta. \quad (5)$$

For $Q = 0$ this is the well known Mikheev-Smirnov-Wolfenstein effect [22–24]. For naturally small lepton asymmetry of the order of the baryon one at high temperature of the early Universe when $Q > L$ resonant neutrino transfer is possible both for neutrino and antineutrino ensembles for $\delta m^2 < 0$. At low T , when $L > Q$, resonance in the neutrino ensemble occurs at $\delta m^2 > 0$, while in antineutrino ensemble the resonant is possible for $\delta m^2 < 0$.

In non-equilibrium case when the distortion in the spectrum distribution of neutrino in the early universe is considerable the resonance condition and the description of neutrino propagation become more complicated [25, 26].

3.3 Neutrino masses

Two non-zero mass differences have been measured by neutrino oscillation experiments, therefore at least two neutrino types have different and non-zero masses. Neutrinos with a definite mass can be Dirac fermions or Majorana particles. However, whatever their nature, SMs cannot accommodate neutrino masses without considerable extensions (additional particles and/or extra interactions).

From atmospheric neutrino oscillations data a lower mass limit follows: at least one type of neutrino has mass exceeding 0.048 eV. For three massive neutrinos with mass m , the energy density today is expected to be:

$$\Omega_\nu = 3m/(93.14h^2 \text{ eV}^2).$$

Hence, the neutrino oscillations data put lower limit on the energy density of relic neutrino: $\Omega_\nu > 0.003$.

The pattern of neutrino mass is not known. The following possibilities for the neutrino mass spectrum exist, namely *normal hierarchy*: $m_1 < m_2 \ll m_3$ and *inverted hierarchy*: $m_3 \ll m_1 < m_2$.

The absolute neutrino masses have not been directly measured yet, neutrinoless double beta decay and beta decay experiments set an upper limit to the neutrino mass $m < 2.05 \text{ eV}$ at 95% C.L.

Cosmology provides the most stringent constraints on the total neutrino mass. Having very tiny masses, flavor neutrino should not play an important role as a dark matter candidate, because they are hot dark matter and predicted LSS in a Universe filled with hot DM is incompatible with observations. On this cosmological consideration the upper limit on the neutrino relative density and on the neutrino masses are obtained:

$$\Omega_\nu < 0.02, m < 0.66 \text{ eV}.$$

3.4 Sterile neutrino and active-sterile neutrino oscillations

Recent reviews on the phenomenology of sterile (right handed) neutrino and the experimental, astrophysical and cosmological constraints on them can be found in refs. [27, 28].

In case of presence of sterile neutrinos active-sterile neutrino oscillations may also have place. Although neutrino anomalies are well described in terms of flavor neutrino oscillations, it has been pointed out that sub-leading active-sterile neutrino oscillations may provide a better fit [29].

In case active-sterile neutrino oscillations occur, the following beyond SM physics may be expected:

- i) Active-sterile oscillations (effective before neutrino decoupling) may excite sterile neutrinos into equilibrium [10, 30, 31], i.e. four or more light neutrino families, instead of three may exist;
- ii) Active-sterile oscillations (effective after flavor neutrino decoupling) may lead to strong distortion of the neutrino energy spectrum from its equilibrium FD form [13, 14]; This neutrino energy spectrum distortion, caused by neutrino oscillations, and its dependence on the level of initial population of the sterile neutrino was discussed in detail also in ref. [32]. Depending on the concrete oscillation parameters, this may be very strong effect - up to six times stronger than the dynamical effect of neutrino oscillations.
- iii) Active-sterile oscillations may change neutrino-antineutrino asymmetry of the medium (suppress or enhance preexisting asymmetry) [14, 15, 17, 18, 33–36];
- iv) Sterile neutrinos, produced by neutrino oscillations, in the 1 – 2 KeV mass range may be viable candidates for warm DM [37, 38];

Such WDM models with sterile neutrinos are as compatible to cosmological observational data as CDM ones [39]. For a recent review of the status of sterile neutrino as DM candidates, see ref. [40].

v) Sterile neutrinos are employed in leptogenesis models, where CP-violating decays of ν_s produce the locally observed baryon asymmetry of the Universe.

Sterile neutrinos and active-sterile neutrino oscillations may play important role for neutrino involved processes during different epochs of the Universe, from which observable relics have been already found, like BBN epoch and CMB and LSS formation epochs, or from which observable relics are expected - like CNB formation epoch.

The most stringent limits on sterile neutrino and on active-sterile oscillation parameters have been obtained from BBN considerations [41–46], and will be discussed in detail the next sections.

3.5 The interplay between neutrino-antineutrino asymmetry and oscillations

There exists interplay between neutrino oscillations and the lepton asymmetry L of the medium in the early uni-

verse [48]. On one hand, neutrino oscillations change neutrino-antineutrino asymmetry of the medium, on the other hand L effects neutrino oscillations.

Flavor neutrino oscillations with the oscillation parameters fixed from the experimental measurements are able to equalize possible relic asymmetry L_f in different flavors before BBN epoch [11, 12].

Active-sterile neutrino oscillations, depending on the concrete values of the oscillation parameters and the characteristics of the medium, may either *suppress pre-existing asymmetry* [30, 31] or *enhance it* (in MSW resonant active-sterile oscillations). L enhancement in MSW resonant active-sterile neutrino oscillations was found possible both in collisions dominated oscillations [17, 18] for $\delta m^2 > 10^{-5} \text{ eV}^2$ and in the collisionless case [14, 15] for $\delta m^2 < 10^{-7} \text{ eV}^2$.

Relic L effects active-sterile neutrino oscillations. Depending on the concrete values of the parameters, describing oscillations and the medium L may *suppress oscillations* [17, 18, 25] or *enhance them* [25, 26].

In BBN with active-sterile neutrino oscillations spectrum distortion and L generation lead to different nucleon kinetics, and modified BBN element production. These cosmological effects and the cosmological constraints on BSM neutrino physics will be discussed in more detail in the following section.

3.6 Neutrino-antineutrino asymmetry

Lepton asymmetry of the Universe L , usually defined as $L = (n_l - n_{\bar{l}}/n_\gamma)$, is not measured yet and may be considerably bigger than the baryon asymmetry $\beta \sim 6 \cdot 10^{-10}$, which has been already measured with great precision from CMB anisotropy data and BBN light elements abundances data. Considerable L might be contained in ν sector, hence future detection of the CNB would provide the possibility for L direct measurement.

Today L may be measured/constrained only indirectly: through its effect on other processes, which have left observable traces in the universe: light element abundances from BBN, CMB, LSS, etc.

Non-zero L has the following effect: it increases the radiation energy density, hence it leads to faster universe expansion and delays matter/radiation equality epoch. CMB, BBN and LSS feel the total neutrino density, thus they constrain L due to its dynamical effect.

Besides this effect, BBN feels also *the kinetic effect of non-zero electron neutrino asymmetry* exerted on the pre-BBN n-p transitions. Thus, more restrictive BBN constraints on L_e exist.

In case of electron-sterile oscillations there exists *indirect kinetic effect of L due to L -neutrino oscillations interplay*: even very small $L < 0.01$, for which dynamical and kinetic effect can be neglected, lead to changes in electron neutrino number density, energy distribution, and oscillations pattern, and hence, to changes of n/p kinetics and BBN [25, 26].

The cosmological effects of L and the stringent cosmological constraints on neutrino-antineutrino asymmetry are discussed in the last section. Extra neutrino species, as well as cosmological effects of BSMs neutrino and the BBN constraints on it are discussed in the next section.

4 BBN - Early Universe probe and standard model physics test

Big Bang Nucleosynthesis is the most early and precision probe for physical conditions in early Universe and it presents also the most reliable test for new physics at BBN energies. In particular, it constrains BSMs characteristics of neutrinos.

According to standard BBN four light nuclides: deuterium D, helium isotopes He-3 and He-4 and lithium Li-7, were produced in non-negligible quantities during the hot stage of the Universe evolution, in the brief period between the first seconds and the first few minutes. The corresponding energy interval is 1 - 0.01 MeV. Then the conditions (particle densities and energy) were appropriate for the cosmic nuclear reactor to work. Later due to universe expansion the temperature and the particle densities decreased and the production of heavier elements was hindered.⁴

Standard BBN is theoretically well established and observationally and experimentally supported. The theoretical inputs include: the neutron lifetime τ_n , the gravitational constant G_N , the baryon-to-photon number density $\eta = n_B/n_\gamma$, the nuclear rates. τ_n and G_N are precisely measured: $\tau_n = 880.0 \pm 0.9 \text{ s}$ and $G_N = 6.7087 \pm 0.001 \times 10^{-39} \text{ GeV}^{-2}$. Precise data on nuclear processes rates from laboratory experiments at low energy (10 KeV - 1 MeV) is available. Until recently η was considered as the only parameter of the standard BBN and was estimated from the data on the primordial abundances of the four elements, produced in considerable quantities during BBN. Today precise determination of η

⁴ The latter were produced much later in stars and processes in cosmic rays.

was made from the data of CMB anisotropies (which corresponds, however, to the much later epoch - the epoch of CMB formation). I.e. there exists independent on BBN measurement of η .

Besides, precise astrophysical data on the predicted by standard BBN abundances of the light elements exists. Light elements D, He-3, He-4, Li-7 were measured in different pristine environments, i.e. in systems least contaminated by stellar evolution.⁵

Namely, D is measured in high redshift, low metallicity H-rich clouds absorbing light from background QSA. He is measured in clouds of ionized H (H II regions) of the most metal-poor blue compact galaxies. Li is measured in old Population II (metal-poor) stars in the spheroid of our Galaxy, which have very small metallicity: $Z < 1/10000Z_{\text{Sun}}$.

Then, the observed abundances are analyzed, accounting for different processes that might have changed their primordial values. It is known that D is only destroyed after its BBN formation, He-4 is only enriched in stars, while He-3 and Li-7 have more complicated evolution being both destroyed and produced in different processes after BBN (He-3 in stars, Li-7 - destroyed in stars, produced in CR interactions).⁶

In standard BBN primordial yields of the elements depend on the baryon-to photon ratio η . The predictions of standard BBN for η value determined from CMB are in excellent agreement with observational data of D, He-3, He-4. For Li-7 the consistency is not so good the observational data is by factor three lower than the standard BBN predictions (the so called lithium problem). Hence, D and He-4 are used as reliable probes for BSMs physics, relevant at BBN energies. (He-3 has a complicated post BBN evolution, therefore it is not used as a cosmological probe.)

The primordial values, obtained from the analysis of an astrophysical data of these elements are [47, 49]:

$$D/H = (2.53 \pm 0.04) \times 10^{-5}$$

$$Y_p = 0.254 \pm 0.003.$$

In general BBN depends on all known interactions and, thus, constrains their BSMs modifications. The primordial yields, depend strongly on nucleons freezing, which is determined by the competition between weak rates Γ_w of n-p transitions and the expansion rate $H(N_{\text{eff}})$. Therefore, BBN is used as a probe of non-standard physics leading

to changes in H , Γ_w , pre-BBN nucleon kinetics or BBN itself. In particular, BBN probes i) any additional light i.e. $m < \text{MeV}$, relativistic during BBN, particles species (generations), N_{eff} ii) nonstandard interactions relevant at BBN epoch, iii) departures from equilibrium distributions of particle densities of nucleons and leptons (caused by neutrino oscillations, lepton asymmetry, inhomogeneous distribution of baryons, etc.)

BBN produced He-4 is known to be the best speedometer and is usually used to constrain additional radiation. It is also the most exact leptometer at the RD stage [51].

Because of the closeness of the BBN epoch and the epoch of formation of the cosmic neutrino background, relic neutrino characteristics are most strongly constrained by BBN. In the following the effects of neutrino on BBN and several BBN cosmological constraints on BSMs neutrino characteristics will be reviewed.

4.1 Cosmological effects and BBN constraints on neutrino

Neutrinos of all flavors influence considerably H during pre-BBN epoch and during BBN. Neutrino BSMs characteristics, like extra neutrino species, chemical potentials or/and lepton asymmetries in the neutrino sector, neutrino active-sterile oscillations bringing into equilibrium additional species, all lead to the increase of H , i.e. exert *dynamical effect on BBN*. Thus BBN feels BSM physics leading to the effective number of neutrinos bigger than the standard value 3, i.e. extra neutrino species, neutrino non standard interactions, neutrino oscillations, nonequilibrium energy distribution, neutrino chemical potentials, neutrino asymmetry, etc.

Besides, electron neutrino and antineutrino have *direct kinetic effect on BBN*, participating in the n-p transitions in the pre-BBN epoch. Due to that, BSM physics in the electron neutrino sector, like chemical potentials and/or neutrino-antineutrino asymmetry, neutrino electron-sterile oscillations, electron neutrino decays or decays into electron neutrinos, etc., have stronger effect on BBN than the corresponding ones in the muon or tau neutrino sectors, which lead only to the dynamical effects on BBN.

4.1.1 Cosmological constraints on N_{eff}

The effective number of relativistic species N_{eff} is strongly constrained by cosmological considerations of the BBN produced He-4 [52].

⁵ Primordial abundances cannot be observed directly, because chemical evolution after BBN has changed the primordial yields.

⁶ Thus, primordial He-4 for example is obtained by regression to zero metallicity.

BBN cosmological constraints, using He-4 data [50] read: $N_{eff} = 3.8^{+0.8}_{-0.7}$ at 95% C.L. More stringent constraint follows from recent D data [49].

Using conservative approach an upper bound $\delta N_{eff} < 1$ at 95 % CL has been obtained in ref. [53]. A much more stringent bound was achieved recently, based on BBN produced D abundance and CMB data [54]:

$$N_{eff} = 3.53^{+0.66}_{-0.63}.$$

Recent BBN analysis [55], based on $Y = 0.2565 \pm 0.006$ provide the constraint $\delta N_{eff} = 0.66 \pm 0.46$, which is consistent with $\delta N_{eff} = 0$ at 95% C.L. According to that analysis:

$$N_{eff} = 3.71^{+0.47}_{-0.45}.$$

$\delta N_{eff} \sim 1$ is favored, while $\delta N_{eff} \sim 2$ is disfavored at more than 95% C.L.

Mind however, that the standard BBN bounds on N_{eff} are tightened in the presence of active sterile oscillations, which lead to overproduction of He-4 [16].

Before Planck CMB measurements had larger errors than BBN in determining δN_{eff} . The cosmological data based on WMAP7, BAO and H_0 measurements provided much looser constraints $2.7 < N_{eff} < 6.2$ [56]. Besides, in contrast to BBN, CMB data are not sensitive to neutrino flavor content and cannot distinguish the deviations of neutrino distribution from equilibrium from dynamical effects [57, 58].

Recent Planck measurements combined with other CMB data (Planck, WMAP and other CMB high l experiments provide the following constraints [59]:

$$N_{eff} = 3.361^{+0.68}_{-0.64} \text{ at 95\% C.L.}$$

Adding to the analysis H and BAO data (95% Planck +WP+high l+H0+BAO), the errors are comparable to the BBN ones:

$$N_{eff} = 3.52^{+0.48}_{-0.45}.$$

Again higher than the standard value $\delta N_{eff} > 0$ is favored. I.e. there are some indications both from BBN and CMB epochs for extra radiation.⁷

Assuming no entropy release between BBN and CMB epochs simultaneous CMB+BBN constraints (68% Planck +WP+high l+Y(Aver et al.)) can be obtained, namely:

$$N_{eff} = 3.41 \pm 0.3.$$

If CMB plus BBN D data are combined (68% Planck +WP+high l+D(Pettini+Cooke)) the following stringent

constrained holds:

$$N_{eff} = 3.02 \pm 0.27.$$

Besides, CMB data allow simultaneous constraints on extra radiation and the total flavor neutrino mass or sterile neutrino mass. Namely the bounds in case of *massless sterile neutrino* read:

$$N_{eff} = 3.29^{+0.67}_{-0.64} \text{ (95\% Planck +WP+high l) and}$$

$$m < 0.6 \text{ eV.}$$

When BAO data are added, the bounds on extra radiation slightly tighten, but then the bounds on the mass of the flavor neutrinos tightens considerably: $m < 0.28$ eV, which presents the most stringent bound today on the total flavor neutrino mass.

Accepting $m = 0.6$ eV and allowing for *massive sterile neutrino* the presence of which was indicated by Mini-Boone, reactor and Gallium anomalies) the following constraints on extra radiation and sterile neutrino mass have been obtained:

$$N_{eff} < 3.91 \text{ (95\% Planck +WP+high l) and}$$

$$m_s < 0.59 \text{ eV.}$$

The latter bounds are marginally compatible with fully thermalized sterile neutrino with sub-eV mass $m_s < 0.5$ eV, necessary to explain the oscillations anomalies, called "dark radiation". This puzzle and possible solutions to it are discussed in more detail below.

4.1.2 Dark radiation and eV neutrino saga

Different types of cosmological indications suggested additional relativistic density: BBN and especially the abundance of He-4 [50, 60], preferred higher radiation density than the standard cosmological model prediction, namely $3 < N_{eff}^{BBN} < 5$. The CMB and LSS data, as well as their combined analysis also pointed to excess radiation [61–64].

Besides, *different neutrino oscillations experiments (reactor, LSND, MiniBooNe, Gallium) data with different neutrino sources and different detector technology presented indications for neutrino oscillations with 1 or 2 sterile neutrinos with sub-eV masses* [65]. Phenomenological studies and global fits, taking into account all relevant data have been provided [66–69]. Recent analyses of neutrino data prefer 3+1 neutrino oscillation models [66].

Non-standard BBN models including extra neutrinos were discussed. Analysis of different type of cosmological data provided during the last years showed that the sub-eV

⁷ Besides, the observed tension b/n H direct measurements and CMB and BAO data is relieved if extra radiation exists, the best fit being $N_{eff} = 3.37$ (for low l power spectrum).

neutrinos would have been brought into thermal equilibrium before BBN [70–73], and thus it is restricted by standard BBN. Besides, sterile neutrinos in the sub-eV range would produce unacceptably big amount of hot dark matter (inconsistent with LSS data) [74–77].

Thus, the presence of two additional ν_s is in tension both with BBN and with LSS requirements [54, 64, 78]. Recent cosmological data show slight preference for extra radiation and showed that 3+2 are difficult to realize in Λ CDM [74–76].

Thus, CMB, LSS and BBN disfavored two additional thermalized extra neutrino. As discussed in the previous subsection, cosmology favors one additional sterile neutrino, but prefers it to be lighter than eV [59, 78]. Recent Planck results, however, showed no convincing evidence for extra relativistic neutrino species.

Deviations from the minimal cosmological model have been discussed. To relax the cosmological constraints on DR modifications of Λ CDM including additional radiation, change in matter density, lepton asymmetry in the electron ν sector, etc. have been explored.

L dynamical and direct kinetic effects have been considered as an explanation of the excess radiation. It was shown that excess radiation cannot be explained by degenerate BBN [79]. However, in case its value is large enough to suppress active-sterile oscillations the presence of L may prevent complete thermalization of the sterile neutrinos and help to circumvent BBN and LSS constraints.

It has been shown that additional sub-eV sterile neutrino may be allowed by BBN with $L \geq 0.08$ [48]. Lower values $|L| > 10^{-2}$ were obtained in ref. [80]. The difference might be due to different approximations used.

Other possibilities of DR problem solution, including modified BBN with decays of heavy neutrinos, were discussed as well [81–83].

4.2 Cosmological effects and constraints of neutrino oscillations

Flavor oscillations have no considerable cosmological effect, because of the close decoupling temperature, and hence almost equal population of the different neutrino flavors. However, in case of non-zero neutrino asymmetries, flavor oscillations lead to redistribution and equilibration of the asymmetries in the different sectors [11, 12, 79]. Hence, the restrictive BBN constraints to the asymmetry in the electron neutrino sector applies to the other sectors as well.

Hypothetical neutrino-antineutrino mass differences may reproduce baryon asymmetry of the universe [84]. There exist CPT violation scenarios generating difference between neutrino and antineutrino populations. Via subsequent sphaleron processes or B-L conserving GUT symmetries the observable baryon asymmetry can be produced.

Fast *active-sterile neutrino oscillation*, effective before neutrino decoupling, increase the expansion rate H by introducing additional relativistic particle - ν_s , i.e. they exert *dynamical effect*. First idea about the dynamical effect of extra relativistic species belongs to Shvartsman (1969). This effect caused by oscillations was precisely studied in numerous publications, starting with the pioneer one [9], where the vacuum oscillation case was considered, and ref. [30], where matter neutrino oscillations were considered.

The dynamical effect of oscillations have been explored in numerous publications, see for example the pioneer papers [9, 30, 31]. He-4 mass fraction serves as the best speedometer at BBN epoch.

Neutrino oscillations have also *adirect kinetic effect on BBN* processes. Namely *oscillations influence electron neutrino and antineutrino number densities and/or spectrum*, thus effecting the weak rates of n-p transitions $\Gamma_w \sim G_F E_\nu n_{\nu_e}$. This direct kinetic effect of oscillations may be due to

- i) the *change of the particle densities of electron neutrino and antineutrino* by fast electron-sterile neutrino oscillations [30, 31];
- ii) the *distortion of the energy spectrum distribution of electron neutrino* caused by late electron-sterile neutrino oscillations, proceeding after decoupling [13–15, 32];
- iii) the *change of the neutrino-antineutrino asymmetry*: production of a considerable asymmetry ($L > 0.01$ (capable to influence n-p kinetics) in the electron neutrino sector by fast resonant electron-sterile oscillations [14, 15, 17, 18], or suppression of a preexisting L.

Late active-sterile oscillations, effective after decoupling of ν_f , may have also *indirect kinetic effect on BBN* due to generation of small asymmetry in the electron neutrino sector [15, 42] (as already discussed in previous sections). Although in this case the generated L is too small to have direct influence on BBN kinetics, *oscillations produced L influence the oscillations pattern - suppresses or enhances oscillations, which reflects in change of BBN*.⁸

⁸ Tiny relic asymmetry, $L \ll 0.01$, may also influence indirectly the kinetics of BBN due to the neutrino oscillations-asymmetry interplay [25, 26, 85].

Due to the different effects of neutrino oscillations on BBN, it is a sensitive probe of neutrino oscillation parameters and of neutrino characteristics.

Most precise constraints on the neutrino active-sterile oscillation parameters in case of fast oscillations have been obtained in ref. [43].

The case of electron-sterile oscillations, effective after neutrino decoupling, was considered in refs. [15, 41, 42, 44–46]. The precise account of the energy spectrum distribution of oscillating neutrino allowed to extend the BBN constraints towards very small mass differences - down to 10^{-9} . The constraints relax at small mixings due to the exact simultaneous account of the asymmetry generated in oscillations. The change of the BBN constraints due to initially non-zero sterile neutrino state was considered as well.

5 Lepton asymmetry - cosmological effects and constraints

5.1 Cosmological effects of L

Several well studied cosmological effects of L are known:

The dynamical effect of L: It consists in the increase of the radiation energy density due to non-zero L:

$$\Delta N_{\text{eff}} = 15/7 \left[(\xi/\pi)^4 + 2(\xi/\pi)^2 \right],$$

where $\xi = \mu/T$ is the ν degeneracy parameter. This effect leads to faster expansion, delaying matter/radiation equality epoch, thus influencing BBN, CMB, evolution of perturbations and LSS.

The kinetic effect of L: It is noticeable for big enough asymmetry in the ν_e sector $|L_e| > 0.01$. Then the different number densities of ν_e and $\bar{\nu}_e$, lead to changes in neutron-proton transfers in the pre-BBN epoch:

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

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

$$n \rightarrow p + e^- + \bar{\nu}_e$$

and, correspondingly, change the BBN yields. (See for example ref. [86] and refs there in.)

L with much smaller values, $L \ll 0.01$ may influence BBN through its interplay with neutrino oscillations, *indirect kinetic effect*.

5.2 Cosmological constraints on L

BBN provides the most stringent constraints on L. In BBN with the known flavor neutrino oscillations, degenera-

cies in different neutrino sectors equilibrate before BBN due to flavor neutrino oscillations. Hence, the more stringent BBN constraint on L_e is distributed to other neutrino types [11, 12, 87]. Thus BBN provides the stringent cosmological bound:

$$|L| < 0.1.$$

See also recent analysis [55].

CMB and LSS provide looser bounds [88]. Future CMB experiments will be more sensitive to neutrino asymmetry and provide comparable or better limits on L than the BBN ones.

In the case of modified BBN with active-sterile neutrino oscillations, due to the interplay between L and these oscillations very stringent constraints on L can be obtained [25, 26, 89]. BBN with late electron-sterile neutrino oscillations may be the most precise leptometer: it provides the possibility to measure and/or constrain L with values close to baryon asymmetry value [26].

In case of BBN with non-zero L the limits on active-sterile oscillation parameters are changed. Namely, due to the capability of L to suppress or enhance oscillations, it may eliminate, relax or strengthen BBN constraints on neutrino oscillations.

It has been found that big enough L inhibits oscillations, and thus in case active-sterile neutrino oscillations are detected, this relation between L and oscillations parameters may be interpreted as an upper bound on L [26, 48]:

$$L < \left(\delta m^2 (eV^2) \right)^{2/3}.$$

For example, taking the indications for active-sterile oscillations with $\delta m^2 \sim 10^{-5}$ [90] the following estimate of the upper limit on L follows: $L < 10^{-3.3}$.

6 Conclusions

Cosmology provides a powerful test for BSMs neutrino characteristics. In particular, cosmological constraints on the number of neutrino families, neutrino mass differences and mixing, lepton asymmetry hidden in the neutrino sector, neutrino masses, sterile neutrino possible characteristics, etc. exist. These contemporary cosmological bounds on light neutrino properties, obtained on the basis of astrophysical and cosmological data, are much stronger than the experimentally available ones and hence, provide precious information about neutrino.

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