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BBN COSMOLOGICAL CONSTRAINTS ON PHYSICS BEYOND THE STANDARD MODEL

DANIELA KIRILOVA

Institute of Astronomy and NAO, Bulgarian Academy of Sciences
Blvd. Tsarigradsko Shosse 72, Sofia, 1784, Bulgaria
E-mail: dani@astro.bas.bg

Abstract. Big Bang Nucleosynthesis is the most reliable probe of the physical conditions of the early Universe during the cosmological nucleosynthesis epoch. Therefore, BBN is traditionally used as a cosmological test of physics beyond the Standard Model. We review several non-standard BBN models and the obtained cosmological constraints on the baryonic density, the number of neutrino families, neutrino mixing and neutrino masses, additional particles and interactions, in particular on chiral tensor particles coupling.

1. INTRODUCTION

Astrophysical and cosmological observations data requires the existence of beyond Standard Model (BSM) physics. For example, the contemporary cosmological model – Lambda Cold Dark Matter Model (LCDM) contains components called Dark Energy (DE) and Dark Matter (DM) with unknown nature, which constitute 95% of the Universe matter! The necessity of early inflationary period and the generation of the observed baryon asymmetry of the Universe also require BSM ingredients for their realization (to propose the DM, DE, inflaton candidates). The other possibility is to change the theoretical basis of the standard cosmological model – to propose an alternative gravitational theory, etc.

BSM physics in the neutrino sector – neutrino oscillations, is already experimentally firmly established. Neutrino oscillations experiments challenged the standard model assumptions of zero neutrino masses, no mixing, 3 light neutrino families, lepton number conservation, equilibrium Fermi Dirac distribution.

This review is mainly dedicated to the Big Bang Nucleosynthesis (BBN) constraints on BSM neutrino physics. In the next section I discuss contemporary status of BBN as the deepest reliable early Universe probe and BSM physics test.

The third section discusses BBN as Universe baryometer, which constrains the matter content of the Universe, points to the existence of hidden baryons, nonbaryonic dark matter and to the necessity of baryogenesis, in case the observed locally matter-antimatter asymmetry of the Universe is its global characteristic. Then BSM neutrinos and BBN constraints on inert neutrino, number of neutrino families and lepton asymmetry (L) in the neutrino sector are briefly discussed. The fourth section discusses BBN with neutrino oscillations and with L, neutrino oscillations - lepton asymmetry interplay and the possible solution to the dark radiation (DR) problem. The fifth section discusses BSM with chiral tensor particles and their cosmological influence and BBN constraints.

2. BBN - THE DEEPEST RELIABLE EARLY UNIVERSE PROBE

First ideas about BBN, that appeared in the period 1946-1948, belong to George Gamow. With his collaborators he developed BBN theory and predicted the existence of Cosmic Microwave Background (CMB). BBN describes the production of the light elements D, He-4, He-3 and Li-7 and some tiny traces of heavier nuclei Be-9, B-10, B-11 up to CNO isotopes during the early hot and dense radiation dominated stage (RD) of the Universe, corresponding to the period from the first second to the first 20 minutes. For recent reviews see Cyburt et al. (2016), Partignani et al. (2017), Pitrou et al (2018).

Contemporary BBN is theoretically well established - based on well-understood Standard Models physics, namely General Relativity, LCDM cosmology, Standard model of nuclear and particle physics. The primordially produced abundances are usually parameterized by the baryon-to-photon ratio $\eta=n_b/n_\gamma$, relativistic energy density (effective number of light neutrino families (N_{eff}) and neutron life time τ_n. All these have been already measured, namely, η was determined independently by the analysis of the anisotropies of the CMB (Ade et al., 2016):

$$\eta_{CMB} = (6.11\pm0.04).\ 10^{-10},\ \ 68\%\ \text{CL}.$$

LEP experiments at CERN determined:

$$N_{eff} = 2.984\pm0.008.$$

τ_n has been revised recently (Serebrov et al. 2017):

$$\tau_n = 879.5\pm0.8\ \text{s}.$$

Thus, contemporary BBN is a parameter free theory. The predicted abundances depend on the well measured cross sections of nuclear processes, which have been continuously updated and on the well measured neutron lifetime. Over 400 nuclear reactions are considered. Modern analyses of nuclear rates for BBN have been provided (see for example NACRE compilation of Angulo et al. 1999 and the updated NACRE-II compilation Xu et al. 2013). During the last decades more and more precise BBN codes have been invented, like PArthENoPE (Pisanti et al., 2008; Consiglio et al., 2017), AlterBBN (Arbey, 2012), PRIMAT (Pitrou et al., 2018), following the first BBN codes of Wagoner

(1967) and Kawano (1992). BBN calculations of the light elements by several different groups are in good agreement. BBN predicted abundances then are compared with the precise observational data on light elements abundances.

The primordially produced abundances are obtained from observational data in systems least contaminated by stellar evolution, after that the account for galactic chemical evolution is made. Namely, D is measured in high redshift z low-metallicity (low Z) H-rich clouds absorbing light from background QSA. He-4 is measured from emission lines in highly ionized H gas of the most metal-poor blue compact galaxies (extragalactic H II regions), after which a regression to zero Z is provided. Li is measured in Population II (metal-poor) stars in the spheroid of our Galaxy, which have $Z<1/10\,000\ Z_{Sun}$.

The last few years the precision of observational data on primordial abundances has been drastically improved. New observations of QAS have considerably improved the observational determination of D and lowered its uncertainty. The latest observational value for primordially produced D is (Cooke et al., 2017):

$$D/H=(2.527\pm0.03)\ 10^{-5}.$$

Recently, the emissivities of He-4 were updated and a new infra-red line was added (Izotov et al 2014), which led to more precise abundance determination in good agreement with BBN predicted one. He-4 primordial mass fraction is determined with 10^{-4} accuracy (Pitrou et al. (2018)):

$$Y_p=0{,}24709\pm 0{,}00017\ .$$

The primordial abundance of Li is given by (Sbordone et al. (2010)):

$$Li/H=(1.58\pm0.31)\ 10^{-10}.$$

It is by a factor of 3 less than the BBN predicted value. This Li-7 problem is considered as an indication for BSM physics. Some of the proposed BSM solutions include modified nuclear rates, new resonant interactions, new particles decaying before or during BBN (Dolgov&Kirilova, 1986), variation of fundamental constants (Dmitriev et al. 2004, Coc et al. 2007, 2012), etc.

It is remarkable that, the predicted abundances (except Li-7) are in good overall agreement with those inferred from observational data for $\Omega_B \sim 0.05$, and also with those “measured” by CMB. This allows the use of BBN as the earliest precision probe of physical conditions in the early Universe and also as the earliest test for BSM physics, corresponding to the BBN energy diapason (1 MeV- 10 KeV). Thus, BBN is used as precise Universe baryometer during BBN epoch, as the best speedometer at RD stage, as the most exact Universe leptometer (as will be discussed in the next sections), etc.

BBN is able to constrain physics beyond standard model thanks to the good concordance between BBN theory and observational data and thanks to the fact that BBN depend on all known interactions. Hence, it constrains the modification of those. Some of the often considered BBN constraints include: constraints on additional light (relativistic during BBN, i.e. m< MeV) particles species (generations) effecting radiation density (and correspondingly the Universe expansion rate H), pre-BBN nucleon kinetics or BBN itself; constraints on additional interactions or processes relevant at BBN epoch (decays of heavy particles, neutrino oscillations); constraints on the possible departure from equilibrium distributions of particle densities of nucleons and leptons (caused by neutrino oscillations, lepton asymmetry, inhomogeneous distribution of baryons, etc.); constraints on SUSY, string models, extradimensional models, etc.

3. BBN - BARYOMETER, SPEEDOMETER AND LEPTOMETER AT RADIATION DOMINATED STAGE

BBN was until recently considered the *unique universe baryometer*. The baryon density for which BBN predicted light element abundances values compatible with the ones obtained from observations is:

$5.8 \times 10^{-10} < \eta_{BBN} < 6.6 \times 10^{-10}$ 95%

corresponding to

$$0.021 \le \Omega_b h^2 \le 0.024 (95\% C.L.)$$

where

$$\Omega_b h^2 = 3.65 \times 10^7 \eta, \quad \Omega_b = \frac{\rho_b}{\rho_c}, \quad \rho_c = \frac{3H^2}{8\pi G_N}$$

Deuterium is the most sensitive element to the baryon density among the light elements produced primordially and is used as a powerful baryometer and a test of the concordance between BBN and CMB baryon measurements. The baryon density determined on the basis of D measurements and BBN is (Pitrou et al., 2018):

$$\Omega_b h^2 = 0.0219 \pm 0.00025 (95\% C.L.)$$

These results are in excellent agreement with the determinations of the baryon density by the latest CMB anisotropy measurements (Planck 2016) corresponding to a much later epoch of the Universe evolution (z~1000). Thus, BBN remains the best baryometer at the RD stage. Assuming that the baryon density has not changed between BBN and CMB epochs, the analysis of BBN and CMB together provides more precise determination:

$$\Omega_b h^2 = 0.0215 \pm 0.00014 (95\% C.L.)$$

The baryon density is much bigger than the luminous matter density, which means that most of the baryons are optically dark. It has been observationally found that half of the dark baryons are in the space between galaxies. Namely, in the spectra of distant quasars the absorption lines of ordinary baryonic matter were found (Danforth & Shull, 2008). The other half of dark baryons is supposed to be hidden in MACHOS, black holes, etc.

The baryon density is 0.049 of the total density. Besides, combined results of Hubble Space Telescope and CMB measurements and galaxy clusters data point to the existence of gravitating matter, constituting 26.8% of the total density, i.e. much bigger than the baryon density. BBN points to the existence of nonbaryonic dark matter, requiring BSM physics for the explanation of DM origin. The rest of the Universe density- 68.3% is in the form of DE, causing the observed by SNIa accelerated expansion of the Universe.

It is assumed that BSM physics must be invoked to answer the questions: Why baryonic matter is such a small fraction? What is the nature of nonbaryonic matter? Where are the antibaryons? How and when the net baryon number was generated? Is the asymmetry local or global?

BBN measured baryon density value is used as an observational constraint for baryogenesis models, aiming to explain the generation of the excess of baryons over antibaryons in the Universe. Standard cosmology predicts equal quantities at the hot stage and now the expected relic density is: $\beta \sim 10^{-18}$, which is by many orders of magnitude smaller than the observed value $\beta_{obs} \sim \eta$. The explanation of the measured value of the baryon asymmetry requires BSM physics. Most often baryogenesis models require B number violation and CP-violation BSM nonequilibrium processes.

Cosmic ray data from search of antiprotons, positrons and antinuclei indicate that there is no significant quantity of antimatter objects within a radius 1 Mpc. Gama ray data point that no significant amounts of antimatter exist up to galaxy cluster scales ~ 10 -20 Mpc. However, above that scale both theory and observations allow astronomically significant quantities antimatter. In case the baryon asymmetry is local, it is necessary to find acceptable separation mechanisms between the domains of matter and antimatter. Such kind of mechanisms also include BSM physics. See for example the inhomogeneous baryogenesis models of Dolgov&Kirilova (1989), Kirilova&Chizhov (2000), Kirilova(2002), Dolgov et al. (2008).

Besides being a unique baryometer at the RD stage, BBN is an *excellent speedometer*. He-4 is very sensitive element to the expansion rate of the Universe at the BBN epoch, which is usually parameterized by the effective number of the light neutrino types N_{eff} (Shvartsman 1969). Different types of BSM physics predict extra relativistic component ΔN_{eff} due to sterile neutrino, neutrino oscillations, lepton asymmetry, neutrino decays, nonstandard thermal history, etc

A maximum likelihood analysis by Cyburt et al. (2016), provided the following contemporary BBN constraints on N_{eff} and the baryon-to-photon ratio:

$$2.3 < N_{eff} < 3.4$$

$$5.6 < \eta < 6.6$$

Most recent stringent BBN constraint was obtained by Pitrou et al. (2018):

$$N_{eff} = 2.88^{+0.27}_{-0.27} \quad (95\%).$$

The CMB constraint (Planck Collaboration 2015) reads:

$$N_{eff} = 3.13^{+0.31}_{-0.31} \quad (95\%)$$

Now, as a result of the improved determination of D and the contemporary precision BBN, D provides more stringent constraints on N_{eff} than He-4. Using CMB plus D plus He-4 data allows a considerable reduction of the error (Cyburt, 2016):

$$N_{eff} = 2.88^{+0.16}_{-0.16} \quad (95\% \text{ Planck+D+He-4})$$

The most stringent constraint of CMB plus BBN now is:

$$N_{eff} = 3.01^{+0.15}_{-0.15} \quad (95\% \text{ Planck +BBN})$$

Thus, BBN and CMB constraint strongly all BSM physics introducing additional light species, as for example supersymmetric scenarios (lightest particle neutralino or gravitino), string theory, large dimensions theories, GUT with sterile (right handed) neutrinos, decaying particles, SUSY metastable particles, etc.

BBN is known also to be an exact *Universe leptometer*. Dynamical and kinetic effect of lepton asymmetry L on BBN lead to the BBN bound $|L|<0.1$. BBN bounds on L are changed in case of neutrino oscillations. Stringent BBN constraints on L in case of electron-sterile oscillations exist, namely L as small as 10^{-8} may be felt by BBN with oscillations (Kirilova 2012). In more detail BBN as a leptometer is discussed in 4.2.

4. BBN WITH NEUTRINO OSCILLATIONS AND LEPTON ASYMMETRY

4.1. BBN with Neutrino Oscillations

BSM physics of BBN with vacuum neutrino oscillations *proceeding before electron neutrino decoupling* was first studied by Dolgov (1981). In particular, it was found that active-sterile oscilltions may excite into equilibrium the sterile neutrino state, thus increasing the expansion rate of the Universe and influencing BBN. Cosmological effects of such fast neutrino oscillations in medium were first studied by Barbieri&Dolgov (1990, 1991), where besides the dynamical effect of neutrino oscillations also the depletion of the electron neutrinos due to oscillations was found. Cosmological constraints on neutrino oscillation parameters were obtained, which excluded large mixing angle (LMA) sterile solution to the solar neutrino problem.

BBN with non-equilibrium active-sterile neutrino oscillations in vacuum, *proceeding after electron neutrino decoupling*, was first studied by Kirilova (1988) and BBN with non-equilibrium matter active-sterile neutrino oscillations were first studied by Kirilova&Chizhov (1996,1997). It was found that active-sterile oscillations proceeding after decoupling may strongly distort neutrino energy spectrum from the equilibrium Fermi-Dirac form and enhance lepton asymmetry in the neutrino sector. BBN was determined to be a sensitive probe to additional species and to distortions in the neutrino distribution. First BBN constraints on neutrino oscillation parameters were obtained in these original papers accounting for the dynamical effect of neutrino oscillations and for the spectrum distortion effect and lepton asymmetry generation.

In several works (Kirilova&Chizhov, 1997, 1998a, 1998b, 2000; Kirilova, 2004, 2007, 2012; Kirilova&Panayotova, 2006) we have studied numerically the evolution of neutrino ensembles, evolution of L, and the evolution of nucleons during pre BBN epoch. Numerical analysis of the produced primordial helium-4 dependence on oscillation parameters (neutrino mixing and squared mass differences), lepton asymmetry value and the population of the sterile neutrino state Y_p ($\delta m^2, \theta$, L, δN_s) has been provided for $10^{-10}<L<0.01$, for the full parameter range of parameters of the oscillations model and for the BBN temperature range, namely

$$\delta m^2 \leq 10^{-7}\, eV^2 \qquad \textit{all mixing angles } \theta \quad 0 \leq \delta N_s \leq 1$$
$$2\, MeV \geq T \geq 0.3\, MeV$$

Precise BBN constraints on oscillation parameters were determined, accounting for all cosmological effects of neutrino oscillations discussed in this BSM of BBN.

The fit to these BBN constraints, corresponding to 3% He-4 overproduction and initially empty sterile neutrino state, reads:

$$\delta m^2 \left(\sin^2 2\theta\right)^4 \leq 1.5\times 10^{-9}\, eV^2 \quad \delta m^2 > 0$$
$$\delta m^2 < 8.2\times 10^{-10}\, eV^2 \quad \text{large } \theta,\ \delta m^2 < 0$$

These BBN constraints were by 4 orders of magnitude more stringent than experimental ones. They excluded LOW active-sterile solutions (1990, 1999) years before experimental results.

BSMs of BBN with neutrino oscillations excluded LMA and LOW active-sterile solutions years before experimental results of neutrino oscillations experiments managed to exclude the active-sterile solutions to the neutrino anomalies.

BSMs of BBN with neutrino oscillations and non-zero ν_s population were considered as well (Kirilova 2004, 2007 ; Kirilova&Panayotova 2006). It was found that additional ν_s population change non-trivially the BBN bounds on oscillation parameters due to the interplay between the dynamical and kinetic effects of non-zero initial population of ν_s (partially filled) on BBN. It may strengthen or relax BBN constraints. In case the dynamical effect dominates,

He-4 overproduction is enhanced and BBN constraints strengthen.

In case the kinetic effect dominates He-4 overproduction decreases with δN_s increase and BBN constraints relax.

4.2. BBN with Neutrino Oscillations and Lepton Asymmetry

BSMs of degenerate BBN have been considered since the original paper of Wagoner et al. (1967). Lepton asymmetry dynamical effect – the increase of the radiation energy density

$$L = \sum_i \frac{1}{12\zeta(3)} \frac{T_{\nu_i}^{\ 3}}{T_\gamma^{\ 3}} (\xi_{\nu_i}^3 + \pi^2 \xi_{\nu_i})$$

$$\Delta N_{eff} = 15/7((\xi/\pi)^4 + 2(\xi/\pi)^2)$$

has been studied. This leads to faster expansion $H = (8/3\pi G\rho)^{1/2}$, delay of matter/radiation equality epoch, influence BBN, CMB, evolution of perturbations i.e. LSS. For a review see Lesgourgues&Pastor (1999).

Besides, L in the electron neutrino sector has direct effect on neutron-proton kinetics in pre-BBN epoch. Therefore, BBN provides stringent constraints on L_e. In case of BBN with neutrino oscillations degeneracies in different sectors equilibrate due to oscillations before BBN (Dolgov et al. 2002). Then, the following BBN constraint on neutrino degeneracy parameter holds:

$$|\xi_\nu| < 0.1$$

More refined BBN constraints on L were discussed in the following works, see for example Miele et al. (2011), Steigman (2012), Mangano et al. (2013), which accounted for flavor oscillations and ν decoupling, Recent improvement on D and He-4 measurement allowed more stringent BBN constraints:

For comparison CMB $|\xi_\nu| < 0.016(68\% CL)$ $\quad L < 0.01$

Different *indirect kinetic effec* $|\xi_\nu| < 0.06(68\% CL)$ ı neutrino evolution, its number density, spectrum distribution distortion, oscillations pattern and hence on n/p kinetics and BBN was found and studied (Kirilova&Chizhov 1998, 2000; Kirilova, 2011, 2012). It was found that BBN with electron-sterile oscillations feels L<< 0.01.

An interesting interplay between ν oscillations and lepton asymmetry L was found possible in studies of BBN with active-sterile neutrino oscillations and L: (i) *Neutrino active-sterile oscillations change neutrino-antineutrino asymmetry of the medium:* they can suppress pre-existing asymmetry (Barbieri &Dolgov1991; Enqvist et al. 1992) or enhance L in MSW resonant active-sterile oscillations for $\delta m^2 \sin^4 2\theta < 10^{-7}\mathrm{eV}^2$ in the collisionless case (Kirilova&Chizhov 1996) and $\delta m^2 > 10^{-5}\mathrm{eV}^2$ in oscillations dominated by collisions (Foot et al. 1996).

For non-equilibrium neutrino oscillations between ν_e and ν_s, effective after ν_e decoupling, i.e. $\delta m^2 \sin^4 2\theta < 10^{-7}\mathrm{eV}^2$, the region of parameter space for which large generation of L is possible was determined (Kirilova, 2012) :

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

(ii)Lepton asymmetry effects neutrino oscillations: it may suppress oscillations (Foot&Volkas 1995; Kirilova&Chizhov 1998) *or enhance oscillations* (Kirilova&Chizhov 1998). On the basis of numerical analyses relations have been derived between L and neutrino oscillations parameters, corresponding to different L influence (Kirilova, 2012). Recently an update of this analysis was provided (Kirilova, 2018) allowing to derive the following relation connecting neutrino squared mass difference and L value necessary to inhibit neutrino oscillations.

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

In BBN with neutrino oscillations spectrum distortion and L generation lead to different nucleon kinetics, and modified BBN element production. Hence, modified BBN constraints on oscillation parameters in presence of L were obtained (Kirilova&Chizhov 1998b, 2000; Kirilova, 2012). The account of the neutrino-antineutrino asymmetry growth caused by resonant oscillations leads to relaxation of the BBN constraints for small mixings.

In case of small relic L, namely $10^{-11}<L<0.01$, due to its indirect kinetic effect L change primordial production of He-4 by enhancing or suppressing oscillations depending on the interplay between its value and the neutrino oscillation parameters. Hence, relic L may strengthen, relax or eliminate standard BBN bounds on oscillation parameters. This modified BBN model with late active sterile neutrino oscillations is very sensitive leptometer – it feels L as small as 10^{-8} (Kirilova, 2012).

4.3. Dark Radiation Problem and Its BSM Solution

Dark radiation (DR), i.e. the presence of non-zero ΔN_{eff} has been predicted by different BSM theories. DR is of particular interest today in view of experimental indications from neutrino oscillations short baseline (SBL) experiments for ν_s with mass in the eV range.

Anomalous results of neutrino oscillations SBL experiments data including reactor experiments+LSND+MiniBooNe+Gallium (GALLEX, SAGE) suggested the existence of light ν_s with 1.3 eV mass, with mixing with flavor neutrinos ν_a $\sin^2\theta_{14}$ in the range [0.01-0.03] (Giunti, 2017; Gariazzo et al. 2018; Capozzi et al, 2017).

However, stringent cosmological constraints on additional dark radiation ΔN_{eff} exist, as discussed in the previous section. It is known that eV sterile neutrino is brought into equilibrium in the early Universe due to fast oscillations between flavor and sterile neutrinos $\nu_a \leftrightarrow \nu_s$. This influences CMB and BBN through increasing the radiation density and the Universe expansion rate. Additional eV neutrinos lead to overproduction of He-4, i.e. BBN constraints additional light neutrinos (Dolgov 1981, Barbieri&Dolgov 1990). The same holds for CMB (see the contemporary BBN constraints on ΔN_{eff} discussed above). Besides, recently the following constraints have been obtained on the basis of Lyman Alpha forest BOSS data, CMB data from Planck, ACT, SPT, WMAP polarization (Rossi Yeche et al. 2015):

$$N_{eff} = 2.911^{+021.}_{-0.22} \quad 95\% \text{ C.L}$$
$$\Sigma m_\nu < 0.15 \text{ eV}$$

See also similar stringent constraints in case data from baryon acoustic oscillations are added, discussed by Sasankan et al. (2017). Thus, cosmology constraints severely the thermalized during BBN light sterile neutrinos.

Different BSM deviations from standard LCDM have been invented to solve the DR problem, including additional radiation, change in matter density, decaying particles during BBN, etc. We proposed the interplay between L and neutrino oscillations as a solution. Namely, L suppresses $\nu_s \leftrightarrow \nu_e$ oscillations, thus preventing ν_s thermalization, and avoiding cosmological constraints on eV sterile neutrinos (Kirilova 2012, 2013). See also the works by Mirizzi et al. (2012), Hannestad et al. (2012), dedicated to this type of DR problem solution.

Recently we updated the analysis of the interplay between $\nu_s \leftrightarrow \nu_e$ oscillations and L (Kirilova, 2018). It was found that

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

may suppress $\nu_s \leftrightarrow \nu_e$ and eliminate BBN bounds on neutrino $\nu_s \leftrightarrow \nu_e$ oscillations The DR problem may be solved applying this mechanism if L is big enough, namely : L>0.074.

5. BBN CONSTRAINTS ON BSM WITH CHIRAL TENSOR PARTICLES

Chiral tensor particles (CTP) have been proposed on theoretical grounds as an extension of Standard Model for completeness of the representation of the Lorentz group by Chizhov (1993). For more detail about the extended model with

CTP see also Chizhov (2011). Experimental search for these particles is conducted at present at the ATLAS experiment of the Large Hadron Collider, where first experimental constraints on their characteristics were obtained (Aad et al., 2014, 2014a).

The cosmological place of CTP was studied in several publications, see for example Kirilova et al. (1995), M. Chizhov&Kirilova (2009); Kirilova &V. Chizhov(2017), Kirilova&E.Chizhov(2018).Their characteristic interactions in the early Universe plasma, namely, their creation, scattering, annihilation and decay processes were studied and the corresponding time and energy intervals of their effective presence were obtained. The period of CTP effectiveness was determined to be:

$$6.10^{-42}\ \mathrm{s} < t < 6.5.10^{-27}\ \mathrm{s}$$

CTP dynamical cosmological effect was studied also. Due to their contribution to the matter tensor in the right-hand side of the Einstein--Hilbert equation, CTP increase Universe density and change the dynamical evolution of the Universe. Namely, the energy density increase caused by the additional degrees of freedom g_{CTP}=28 in the BSM physics model with CTP leads to speed up of the expansion of the Universe during the period of CTP presence:

$$H = \sqrt{\frac{8\pi^3 G_N g_*^{new}(T)}{90}}\, T^2$$

where $g^{new}=g_{SM}+g_{CTP}$.

The provided analysis of the cosmological place of the CTP showed, that cosmology allows their presence. Their direct interactions with the components of the high temperature plasma were effective for a very short early period during the Universe.

Recently reconsideration of the BBN constraint on the CTP coupling constant was provided (Kirilova&E.Chizhov, 2018). Using different BBN constraints on the additional relativistic particles and assuming that CTP interact with light sterile neutrinos, we have calculated the decoupling of right-handed neutrino production and obtained BBN cosmological constraints on CTP interaction strength for different cases. The constraints on CTP coupling in case of 3, 2 and 1 light ν_e and BBN constraint (Pitrou et al. 2018) $\delta N_{eff} < 0.3$, read correspondingly:

$$G_T \le 4.2\times10^{-4} G_F \qquad G_T \le 8.4.\times10^{-4} G_F \qquad G_T \le 1.4.\times10^{-3} G_F$$

Thus, BBN constrains CTP interaction strength to be milli weak or weaker, depending on the number of light right-handed neutrino species. These constraints can be interpreted also as an indication for absence of CTP interactions with light sterile neutrinos, or for absence of light sterile neutrinos.

CTP were present at energies typical for inflation, Universe reheating and leptogenesis and baryogenesis. Hence, it is interesting to explore further the role of CTP in the very early Universe.

6. CONCLUSIONS

Fruitful interplay between cosmology and particle physics exists. Cosmology can predict the influence of BSM characteristics and test them. In particular, BBN is the earliest and the most reliable and precision probe of BSM physics, relevant at energies typical for BBN (MeV-KeV). It measures neutrino mass differences, number of neutrino species, neutrino mixing patameters, deviations from equilibrium, baryon density and lepton asymmetry of the Universe, new interactions, additional particles, etc.

BBN is a reliable baryometer. The baryon density is measured with great precision and points to BSM physics – necessity of nonbaryonic dark matter. Its nature is still an open issue both in cosmology and in particle physics. Though baryon density is measured with a high accuracy today, the exact baryogenesis mechanism is not known. The problem of baryon asymmetry of the Universe is still fascinating and its explanation probably is in the realm of BSM physics. The possibility for astronomically large antimatter objects is experimentally and theoretically studied. This issue has gained more interest recently with the detection of anti He-3, -4 nuclei in cosmic rays. The separation mechanisms between matter and antimatter domains also imply BSM physics.

BBN is a very sensitive leptometer. Degenerate BBN constrains L : $|L|<0.1$, while in case of active-sterile neutrino oscillations L as small as 10^{-8} may be felt by BBN.

BBN is the most sensitive speedometer. It constrains additional light particle species N_{eff} thus, constraining SUSY, string, extradimensional models, etc. BBN bounds on N_{eff} are strengthened in case of neutrino oscillations.

BBN severely constrains CTP interaction strength in case CTP interact with light sterile neutrinos.

BBN constrains neutrino oscillations parameters. It provides the most stringent constraint on the neutrino mass differences δm^2. BBN constraints on neutrino oscillations parameters depend nontrivially on the population of sterile neutrino and L in the Universe. Additional initial population of the sterile state not always leads to strengthening of constraints (as can be naively thought) it may relax them. Relic L may provide relaxation or enhancement of BBN constraints on oscillations.

Large enough L may provide relaxation of BBN constraints on oscillations, by suppressing oscillations and causing incomplete thermalization of the sterile neutrino. Thus, dark radiation (1+3 oscillations models) might be allowed by BBN with L.

Future cosmic missions and observations and experiments at accelerators and colliders are expected to improve our knowledge about the Universe and, in particular, to solve the riddles of dark matter, dark energy, inflation, baryon asymmetry, lepton asymmetry, additional interactions and/or particles, dark radiation, etc. and hopefully detect the Nature chosen BSM physics.

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