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NEUTRINO IN COSMOLOGY

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Abstract. The relic neutrinos from the Big Bang or the Cosmic Neutrino Background (CNB) neutrinos are expected to be the most abundant particles in our universe after the relic photons of the Cosmic Microwave Background (CMB). They carry precious information from the early epoch when our universe was only 1 sec old. Although not yet directly detected, CNB may be revealed indirectly through cosmological observations due to their important cosmological influence.

I review the cosmological role of neutrinos and the present cosmological constraints on neutrino characteristics. Namely, I discuss the impact of neutrinos in the cosmic expansion, neutrino decoupling, the role of neutrinos in the primordial production of light elements, their effect on CMB anisotropies, LSS formation, the possible neutrino contribution to the Dark Matter in the universe, leptogenesis, etc. Due to the considerable cosmological influence of neutrinos, cosmological bounds on neutrino properties from observational data exist. I review the cosmological constraints on the neutrino characteristics, such as the effective number of neutrino species, neutrino mass and mixing parameters, lepton number of the universe, gravitational clustering of neutrinos, presence of sterile neutrino, etc.

1. INTRODUCTION

During the last two decades cosmology has experienced a tremendous progress, and has become a precision science, providing us with information about universe characteristics and laws. Mainly due to the detection and investigation of Cosmic Microwave Background (CMB), which together with Big Bang Nucleosynthesis (BBN) model and light elements abundance measurements and large scale structure (LSS) formation studies and LSS surveys provided precise knowledge about the main universe characteristics. *Cosmology provided* also *knowledge about* the properties of the very elusive particle - *neutrino.*

On the other hand *the role of neutrino in cosmology* has been intensively studied already for more than 20 years: it has been understood that neutrino had a considerable role in universe evolution during its early stages, namely universe dynamics, big bang nucleosynthesis (BBN), leptogenesis and baryogenesis, the formation of CMB. The neutrino role during later stages of the universe concerning the formation and evolution of the large scale structure, its eventual role for the dark matter (DM) in the universe, etc. has been studied, as well. In this connection it is relevant to note that the future detection of the cosmic neutrino will provide precious information about the first seconds of the universe evolution. For comparison the earliest observational information which we have today corresponds to the first minutes of the universe thanks to light element abundance measurements, CMB data give an insight of the epoch when universe was 300 000 years old, while the reach of the contemporary telescopes gives a glimpse of the galaxy formation epoch, corresponding to 11-12 billion years old universe.

Meanwhile *neutrino physics and astrophysics has achieved serious results*: Since the first idea about neutrino existence, presented in the now famous Pauli's letter of 1930, and since neutrinos first direct detection in 1953 by Reines and Cowan, neutrino physics has passed a long and fruitful path. To mention just several of its road marks: neutrino helicity measurements first made in 1957 by Goldhaber et al.; the existence of 2 types of neutrinos predicted in 1960 by Lee and Yang and the detection of muon neutrino in 1962 by L. Lederman, M. Schwartz and J. Steinberger; the participation of neutrino in weak neutral currents, found in 1973; the existence of 3 light flavor neutrino types, confirmed by LEP experiments in 1993; studies of neutrino mass by double beta decay experiments; studies of neutrino oscillations by LSND, K2K, KamLand, MiniBoone experiments, etc.

Besides neutrinos from earth reactors and accelerators, we have detected and studied neutrinos from astrophysical sources, namely from the Sun, from the atmosphere, from supernova SN1987 and geo-neutrinos from the Earth interiors. And we hope to detect neutrinos coming from the neutrino decoupling epoch of the early universe, corresponding to cosmic time 1 sec and energies several MeV, which constitute the cosmic neutrino background (CNB). Neutrinos from the Sun and the atmosphere were intensively studied. Since the first solar neutrino Homestake experiment by R. Davis in 1960's it was found (and confirmed by the following solar neutrino experiments like Gallex, SAGE, Kamiokande) that there exist an energy dependent deficit of electron neutrinos coming from the Sun, compared to the predictions of the standard solar model. Another anomaly, atmospheric neutrino anomaly, was found in neutrino fluxes from the atmosphere by IMB, and confirmed by Kamiokande, MACRO and SOUDAN experiments. These solar and atmospheric neutrino anomalies were successfully explained in terms of neutrino oscillations. In 1998 Super-Kamiokande obtained the evidence of atmospheric neutrino oscillations, which pointed also to non-zero neutrino mass.

The neutrino oscillations suggested by solar and atmospheric neutrino experiments, were confirmed by terrestrial experiments. The atmospheric neutrino oscillations were confirmed by the earth based experiment K2K and Minos. In 2002 SNO detected the evidence of flavor-transformation of solar neutrinos, thus pointing to second non-zero mass difference and at least to one more neutrino flavor with a finite mass. The ground based experiment KamLAND gave an evidence of reactor antineutrino oscillations. [1] Thus, a strong evidence for *non-zero neutrino masses and mixing* has been provided by solar, atmospheric and terrestrial neutrino oscillation experiments in resent years. A detail review of the main experimental and theoretical results of neutrino physics may be found in e.g. Strumia and Vissani 2006. The discovery of non-zero neutrino mass and mixing provided the first evidence for physics beyond the standard electroweak model. This success of neutrino physics and astrophysics was marked by several Nobel prizes. Therefore, it is extremely interesting to discuss the

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[1] Other terrestrial experiment LSND and MiniBoon are suggesting other oscillation possibilities, yet unconfirmed by other experiments.

cosmological influence of neutrino and the cosmological information and constraints on its characteristics.

1. 1. WHAT ARE NEUTRINOS

Now we know that neutrinos are spin 1/2 fermions, they have weak interactions, i.e. they belong to SU$(2)_W$ doublets, there exist 3 neutrino families of weakly interacting light neutrinos[2], namely electron neutrino ν_e, muon neutrino ν_μ and tau neutrino ν_τ. Other types of neutrinos (if present) should be sterile [3], i.e. SU$(2)_W$ singlets, not having the ordinary weak interactions. Recently it was found that, unlike the expectations of the standard electroweak model, neutrinos oscillate, i.e. their mass eigenstates ν_j do not coincide with the flavor eigenstates ν_f, there exist neutrino mixing and non-zero neutrino mass differences

$$\nu_f = \sum_{i=1}^{3} U_{fi}\nu_i, \qquad \delta m^2_{ij} = m^2_j - m^2_i \neq 0, \quad (i \neq j)$$

The dominant oscillation channels have been proved to be flavor neutrino oscillations. The role of sterile neutrinos and the active-sterile subdominant oscillation possibilities are explored at present. The experimental data point to the following: ν_e from the Sun oscillate into ν_μ and ν_τ, and the corresponding oscillating parameters are the squared mass difference $\delta m^2_{12} \sim 8.10^{-5}$ eV^2 and mixing $\sin^2 \vartheta_{12} \sim 0.3$; atmospheric muon neutrinos oscillate mainly into tau neutrinos with $\delta m^2_{23} \sim 3.10^{-3}$ eV^2 and almost maximal mixing. Since 1998 the neutrino oscillation data firmly established that neutrinos have non-zero mass, however, it cannot determine the absolute mass scale. From atmospheric neutrino oscillations data we may only conclude that at least one type of neutrino has mass exceeding 0.05 eV. The absolute neutrino mass has not been directly measured yet, neutrinoless double beta decay and beta decay experiments set an upper limit to the neutrino mass. For example the Mainz (see e.g. Krauz et al. 2005) and Troitsk (see e.g. Lobashev 2003) Tritium decay experiments limit the single electron neutrino mass correspondingly $m < 2.05$ eV and $m < 2.3$ eV, at 95% C.L. Much more stringent mass limits are due to cosmology, which measures indirectly neutrino mass and has provided the most stringent available now constraints on the total neutrino mass (to be discussed in more detail in the following Sec. 4 and Sec. 5). Just the mass differences and mixing, with the exclusion of θ_{13}, are well measured, the ordering of neutrino masses is not known because of the unknown sign of δm_{13}. So there exist the following possibilities for the neutrino mass ordering: the *normal hierarchy* $m_1 < m_2 << m_3$ and the *inverted hierarchy* $m_3 << m_1 < m_2$. Neutrino masses may be very small - of the order of δm_{23} but also they may be big and degenerate: $m_1 \sim m_2 \sim m_3 >> \delta m_{23}$.

On the other hand, due to the existence of degeneracies of neutrino mass and N_ν with other cosmological parameters, the uncertainty of neutrino characteristics leads to large systematic errors in the estimation of cosmological parameters. Therefore, precise determination of neutrino properties is of cosmological importance, as well.

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[2] The most precise experimental measurement of the number of light (with $m < m_Z/2$) neutrino types comes from four LEP experiments, and gives $N_\nu = 2.984 \pm 0.008$.

[3] There exist BBN and other cosmological bounds on the number of neutrino families, which we will discuss in detail in Sec. 3 and Sec. 4

The next section is dedicated to relic neutrino characteristics and the formation of the cosmic neutrino background and its evolution from the early universe stages till today. The following three sections discuss neutrino cosmological influence during universe evolution and the constraints on neutrino properties from BBN, CMB, LSS cosmological data. The last section provides a summary of the review.

2. NEUTRINO HISTORY. COSMIC NEUTRINO BACKGROUND

According to the standard cosmological model (SCM) at early radiation dominated stage neutrinos were kept in thermal equilibrium due to their standard weak interactions with other particles while their interaction rates were faster than the expansion rate of the universe $\Gamma \sim \sigma(E)n_\nu(T) > H$. Hence, neutrino had an equilibrium Fermi-Dirac energy distribution

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

The energy contribution of the 3 neutrino species ρ_ν to the energy density of the universe in relativistic species at that stage was comparable with the CMB photons one:

$$\rho_\nu = [3 \times 7/8(T_\nu/T)^4]\rho_\gamma.$$

Hence, at early stages neutrino influenced the expansion rate of the universe $H \sim \sqrt{8\pi G_N \rho/3}$ considerably. The dynamical effect of neutrino is usually parameterized by the effective number of the relativistic neutrino species N_{eff}:

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

As the universe expanded and cooled, particle densities diluted and the weak interactions became slower than expansion, i.e. ineffective to keep neutrino in good thermal contact with the plasma. Thus, at ~ 3 MeV muon and tau neutrino decoupled and at ~ 2 MeV electron neutrino decoupled and since then they were free streaming, i.e. formed the cosmic neutrino background (CNB). Due to their negligible masses they kept their equilibrium Fermi-Dirac (FD) spectrum while their temperature decreased with further expansion and cooling of the universe.

During e^+e^- - annihilation, the photons were heated and since then neutrino temperature is lower than the CMB one $T_\nu = (4/11)^{1/3}T$, the number density per flavor is $n_\nu = 3/11 n_\gamma$, neutrino density is: $\rho = 7/8(4/11)^{4/3}N_{eff}\rho_\gamma(T)$. Since the neutrino decoupling was close to e^+e^- - annihilation, which proceeded at ~ 0.5 MeV, neutrinos shared a small part of the released entropy [4] due to non-instantaneous ν decoupling and flavor oscillations, and thus neutrinos were slightly heated (see e.g. Dolgov et al. 1997, Mangano et al. 05). The neutrino distribution was negligibly distorted, the change may be described by changing the effective number of relativistic neutrino species

$$N_{eff} = 3.046.$$

Thus relic neutrinos contributed considerably to the universe dynamics while $m_\nu << T_\nu$. Today CNB is expected with number densities $n_\nu + n_{\bar{\nu}} = 3 \times 3/11 n_{cmb} = 339.3$

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[4] this is still unobservable by present observations

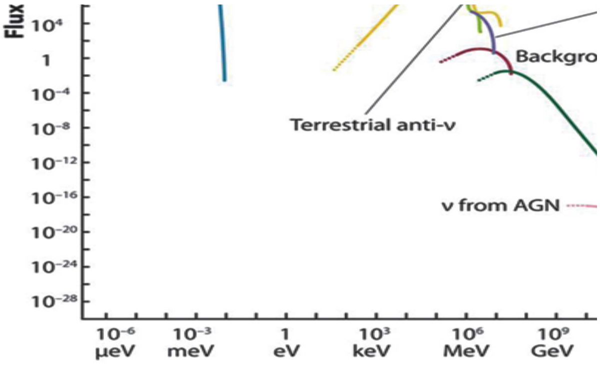

Figure 1: The expected cosmic neutrino background in comparison with other neutrino sources.

cm^{-3} (per 3 neutrino species), i.e. as numerous as CMB photons $n_{CMB} = 411$ cm^{-3}, and temperature $T_\nu = (4/11)^{1/3} T_{cmb} \sim 1.9$ K, slightly smaller than cosmic microwave background (CMB) temperature.

Summarizing, the standard cosmological model predicts CNB, which has formed close to BBN epoch, with a temperature today slightly smaller than the CMB one, negligible chemical potential, and negligible nonthermal features. Recent reviews of primordial neutrinos can be found in e.g. Dolgov 2002, Hannestad 2006, Lesgourgues and Pastor 2006. On Fig. 1 (see e.g. ASPERA roadmap 2007) the expected CNB is presented together with already detected neutrinos from other sources, like solar neutrino, neutrino from supernova burst in 1987, atmospheric neutrino, reactor neutrino, as well as not yet detected neutrinos from Active Galactic Nuclei and GZK neutrinos.

Though numerous, *direct CNB detection* has not been performed, it is difficult because of neutrinos weak interactions and low energy today $\sim 10^{-4}$ eV. In some near future, hopefully, appropriate detector facilities will be able to study the cosmological neutrinos, which will provide a glimpse into the first seconds of the universe existence (the epoch of CNB formation). Fortunately, at present *indirect CNB detection* is possible due to CNB effects on Big Bang Nucleosynthesis (BBN), CMB, Large Scale Structure (LSS), etc.

The closeness of neutrino decoupling epoch to the BBN one is one of the reasons for the big influence of neutrino on BBN and the numerous BBN constraints on neutrino properties, which will be discussed in the following section.

2. 1. POSSIBLE DISTORTIONS OF CNB

There exist different possibilities for deviations of the expected CNB from standard cosmology predictions. Here we list some of the possible deviations from the FD distribution of CNB. One possible source of ν spectrum distortion (SD) is the existence of *non-zero relic neutrino asymmetry*. However, this possibility has been strongly constrained recently by BBN considerations: It was found that flavor ν oscillations with parameters favored by the atmospheric and solar neutrino data establish an equilibrium among active neutrino species before BBN epoch (see e.g. Dolgov et al. 2002). Hence the stringent BBN limit to ν_e degeneracy applies to all flavors.

However, there still exists a possibility of lepton asymmetry in the post-BBN epoch, which has not been much explored. A mechanism of neutrino-antineutrino asymmetry generation in resonant MSW active-sterile oscillations after neutrino decoupling was found (see e.g. Kirilova and Chizhov 1996, 2000), which leads to a growth of the asymmetry up to 4 orders of magnitude during the BBN epoch. Further investigation is necessary to reveal how big the lepton asymmetry may grow in the post-BBN epoch.

Active and active-sterile neutrino oscillations present another source of deviation of neutrino distribution from the equilibrium FD form. It is known that flavor oscillations slightly shift neutrino FD distribution (see e.g. Dolgov 1981). Active-sterile oscillations effective before neutrino decoupling also slightly influence active neutrino distributions, because the states are refilled due to interactions with the plasma (see e.g. Barbieri and Dolgov 1991), and may bring sterile neutrino into equilibrium.

In contrast, active-sterile ν oscillations proceeding after ν_e decoupling $\delta m^2 \sin^4(2\vartheta) \leq 10^{-7}$ eV^2 and provided that ν_s state is not in equilibrium $\delta N_s = \rho_{\nu_s}/\rho_{\nu_e} < 1$ [5] may cause strong energy SD and ν_e depletion (see e.g. Kirilova 1988, Chizhov and Kirilova 1996, 1997, Kirilova 2004) and generate $\nu_e - \bar{\nu_e}$ asymmetry (see e.g. Chizhov and Kirilova 1996, Foot et al. 1996, Volkas and Wang 2000). It was found that mainly via SD $\nu_e \leftrightarrow \nu_s$ oscillations considerably influence nucleons kinetics during BBN (to be discussed in more detail below).

Hence, due to $\nu_e \leftrightarrow \nu_s$, CNB may be expected to be considerably depleted and less energetic with an energy spectrum distorted from the equilibrium FD one (Kirilova 2009). In the case of such oscillations future prospects of observing CNB may be even worse than the predicted by standard cosmological paradigm. On the other hand they will allow to peek into the well hidden realm of sterile neutrino.

3. NEUTRINO AND BIG BANG NUCLEOSYNTHESIS

BBN is the most early ($t \sim 1$ s, $T \sim 10^{10}$ K) and precision physical test (see e.g. Iocco et al. 2009). According to the Standard Big Bang Nucleosynthesis 4 light elements: D, He-3, He-4, Li-7 were produced during the early hot stage of the universe evolution. The predicted primordially produced abundances of these elements are functions of only one parameter - the baryon-to-photon ratio $\eta = n_B/n_\gamma$ (see Fig. 2.) BBN predicted abundances are in excellent agreement with the observational data, spanning 9 orders of magnitude. Namely D is measured in high-redshift, low-metallicity quasar absorption systems $D/H \sim 3.10^{-5}$ and is considered the best baryometer among the light elements, because of the very high sensitivity of its productions to the density of baryons. He-4 is measured in clouds of ionized hydrogen (H II regions), with small post-BBN chemical evolution, i.e. in the most metal-poor dwarf galaxies, and then is extrapolated to zero metallicity. Thus determined primordial mass fraction of helium-4 is $Y_p \sim 0.25$. Due to the high sensitivity of He production to the expansion rate it is considered the best speedometer. Besides, as will be discussed below in more detail, He-4 is very sensitive to neutrino properties and, therefore, it is the preferred among light elements for constraining neutrino physics. Li is measured in Pop II (metal-poor) stars in the spheroid of our Galaxy, which have metallicities going down

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[5] which is natural, because ν_s decouples earlier in the universe evolution and since then flavor neutrinos have been heated by the annihilation processes, taking place till flavor neutrino's later decoupling

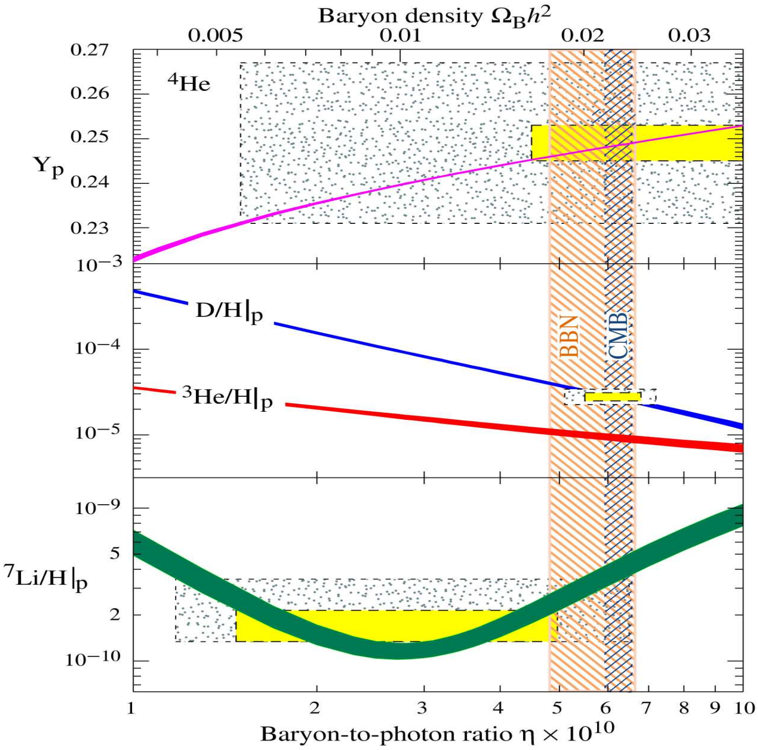

Figure 2: BBN predicted abundances of the light elements as a function of the baryon-to-photon ratio compared with the observational data. Y denotes the mass fraction of He. The vertical shaded band is the CMB measure of the cosmic baryon density (see e.g. Fields and Sarkar, Review of Particle Physics, 2008)

to at least 10^{-4} and perhaps 10^{-5} of the Solar value, $Li/H \sim 2.10^{-10}$. BBN considerations and observational data (mainly based on D) provide constraints on the baryon density of the universe $0.017 \leq \Omega_b \leq 0.024$, which point to the existence of optically dark baryons, $\Omega_{lum} < \Omega_b$ ($\Omega_{lum} < 0.003$ is the luminous matter) and to the fact that matter in the universe is mainly non-baryonic, $\Omega_b < \Omega_m$, i.e. non-baryonic Dark Matter (DM) exists.

Primordial helium-4 Y_p is sensitive to universe dynamics and kinetics of nucleons during neutron-proton freezing, in which ν_e participate, because it is defined essentially by neutron-to-proton freezing ratio, $(n/p)_f$, which depends on the equilibration of expansion rate $H = \sqrt{8\pi\rho/3M_P^2}$ and weak interactions rates $\Gamma_w \sim G_F^2 E_\nu^2 n_\nu^3$, which on its turn depend also on neutrino characteristics. The primordially produced mass fraction of He-4, to a good approximation, is

$$Y_p(\text{He-4}) \sim 2(n/p)_f/(1+n/p)_f \exp(-t/\tau_n).$$

Being calculated with great precision ($Y_p = 0.2482 \pm 0.0007$, uncertainty $< 0.1\%$ within a wide range of baryon density), most precisely measured among light elements (less than 3-5% uncertainty) (see e.g. Izotov et al. 2007), and with a simple post-BBN evolution, He is a reliable cosmological probe of ν characteristics.

BBN conservative bound, mainly based on Y_p, reads $\delta N_{eff} < 1$. (N_{eff} is the effective number of relativistic during BBN species.) Hence, there follows the BBN constraint (see e.g. Lisi et al. 1999, Barger at al. 2003) on the number of ν families $N_\nu < 4$. Recent analysis of BBN data points that much stringent bound may hold, $\delta N_{eff} < 0.3$. BBN bounds on the effective number of ν depend on the concrete analysis of the data, and data sets used. For comparison present WMAP CMB bounds are much looser even than BBN conservative limit.

In case of 3 standard neutrino flavors without extra relativistic component, the effective number of neutrinos is expected to be 3.046. So, BBN bound allows some room for extra relativistic components (like sterile neutrino, lepton asymmetry, neutrino oscillations, etc.) and/or nonstandard thermal history (distortions of the neutrino energy distributions, neutrino decays, low-reheating temperature scenario, etc.) usually parameterized by δN_{eff}. Their effect on Y_p can be easily understood from the empirical relation $\delta Y \sim 0.013 \delta N_{eff}$. However, BBN may distinguish between their effect and the pure dynamical effect of additional relativistic species during BBN, due to their specific signatures and because of their effects on nucleons kinetics. For obtaining precise BBN constraints, of course, a precise analysis of each concrete case is provided.

Assumed that the extra relativistic component is due completely to lepton asymmetry $\delta N_{eff} = \sum_f 15/7[(\mu/T)^4/\pi^4 + 2(\mu/T)^2/\pi^2]$ and taking for oscillation parameters the values of atmospheric and LMA solar solutions, leading to equilibrium between ν species before BBN epoch, BBN constrains severely neutrino chemical potential in any ν flavor $\mu/T < 0.07$ (see e.g. Dolgov et al. 2002). Since the lepton asymmetry is not known, this limit provides valuable information about leptogenesis of our universe. BBN constrins also sterile neutrino, namely ν_s decoupling temperature $T_s > 130$ MeV and ν_s exotic interactions. Recently BBN was used to constrain new exotic interaction of ν_s with chiral tensor particles, which appear in an extention of standard elecroweak model and can explain anomalies in radiative pion decay and two pion decay of the tau lepton (see e.g. Chizhov and Kirilova 2009). The obtained constraint is in agreement with particle physics estimations of M_T and points to centiweak interactions $G_T \leq 10^{-2} G_F$. BBN provides as well the most stringent constraint on ν magnetic moment $\mu_\nu < 10^{-12}\mu_B$; on active-sterile ν oscillations (see e.g. Kirilova 1988, Barbieri and Dolgov 1990, Kirilova 2001) discussed in more detail in the following subsection.

BBN bounds considerably tighten in case of active-sterile oscillations during BBN mainly due to the neutrino spectrum distortion and positive kinetic effect of oscillations on BBN, discussed in more detail below.

3. 1. BBN AND OSCILLATING NEUTRINO

BBN predictions and constraints may considerably differ if active-sterile oscillations took place during BBN. Flavor oscillations influence BBN negligibly, because flavor neutrinos differ slightly due to their close decoupling temperatures. While active-sterile oscillations lead to overproduction of Y_p, due to their dynamical δN_s and kinetic δN_{kin} (only for $\nu_e \leftrightarrow \nu_s$) effect on BBN, which mimics an increase of the relativistic degrees of freedom

$$\delta N_{eff}^{BBN+osc} = \delta N_{eff} + \delta N_{kin} + \delta N_s,$$

i.e. BBN constraints on ν characteristics become more stringent than standard BBN ones and dependent on oscillation parameters. For example, the bound $\delta N_{eff} < 1$ changes to

$$\delta N_{eff} < 1 - \delta N_{kin}(\vartheta, \delta m^2) - \delta N_s.$$

It was found that $\nu_e \leftrightarrow \nu_s$ oscillations considerably influence nucleons kinetics during BBN mainly via spectrum distortion of neutrino caused by oscillations. Namely, they lead to decrease of weak interaction rates, causing earlier n/p freezing and He-overproduction. SD and its kinetic effect decrease with the increase of initial population of ν_s. The interplay between the kinetic effect of oscillations and the dynamical effect of the additional sterile state on BBN has been thoroughly studied (see e.g. Chizhov and Kirilova 1996, 1997, 1998, 2000; Kirilova and Panayotova 2006, Kirilova 2007). A good fit to the exact (numerically calculated) interplay between the effects is (see e.g. Kirilova 2004):

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

where δN_{kin}^{max} is the maximal kinetic oscillations effect numerically calculated for $\delta N_s = 0$.

Precise numerical account of SD caused by $\nu_e \leftrightarrow \nu_s$ oscillations revealed the possibility for 6 times higher He-4 overproduction than the obtained in previous studies, accounting mainly for the dynamical effect of oscillations. On the basis of the analysis of neutrino oscillations effect on He production and the observational data on He more precise BBN constraints on neutrino oscillation parameters were obtained (see e.g. Chizhov and Kirilova 1996, 1997, 1998, 2000; Kirilova and Panayotova 2006, Kirilova 2007). The analytical fits to the exact constraints for the $\delta N_s = 0$ case are:

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

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

The bounds on ν mass differences are strengthened by an order of magnitude at large mixing angles, due to precise SD account, and relaxed at small mixing angles, due to account of asymmetry growth (compared with previous studies, see e.g. Barbieri and Dolgov 91, Enqvist et al. 1992). BBN bounds are several orders of magnitude better than the existing experimental constraints. BBN considerations were the first to exclude two of the possible solutions of the solar neutrino problem - large mixing angle solution and low mixing angle solution, years before the analysis of solar neutrino oscillations experiments data pointed to the preferred flavor oscillation channels.

For contemporary BBN constraints on oscillation parameters, accounting for the flavor mixing see e.g. Dolgov 2002, Dolgov and Villante 2004. In the non-resonant case they can be approximated by

$$(\delta m^2_{\nu_e \nu_s}/eV^2) sin^4 2\theta^{\nu_e \nu_s} = 3.16.10^{-5} (\delta N_\nu)^2$$

$$(\delta m^2_{\nu_\mu \nu_s}/eV^2) sin^4 2\theta^{\nu_\mu \nu_s} = 1.74.10^{-5} (\delta N_\nu)^2$$

assuming kinetic equilibrium and using stationary point approximation. The bounds are reasonably accurate for large mass differences in case of efficient repopulation of active neutrinos. For the exact constraints in the resonant case see (Dolgov and Villante, 2004).

Additional sterile population, present before oscillatons become effective, may either strengthen or relax BBN constraints on $\nu_e \leftrightarrow \nu_s$ oscillations parameters due to the interplay between its dynamical and kinetic effect. The calculated BBN constraints for different population values are presented in refs. (see e.g. Kirilova 2004, Kirilova and Panayotova 2006, Kirilova 2007).

Role of lepton asymmetry L and relaxation of the BBN constraints: Small lepton asymmetry, that do not effect directly BBN may influence it indirectly via ν oscillations by changing ν number densities, its energy distribution and SD, ν oscillation pattern. It may suppress or enhance oscillations. Accurate numerical modelling of BBN with L and oscillations, has shown that lepton asymmetry is able to relax BBN constraints at large mixings and strengthen them at small mixings. [6] While large enough initial lepton asymmetry may alleviate BBN constraints (see e.g. Kirilova and Chizhov 1998).

4. COSMIC MICROWAVE BACKGROUND AND NEUTRINO

Cosmic Microwave Background, predicted in the 40ies of the previous century by George Gamow, as the relic background left from the epoch when the universe was hot and dense, was first detected by R. Penzias and Wilson in 1965. Since then it is known that the universe today is filled with highly isotropic radiation, with temperature $T = 2.725 \pm 0.001$ K (1σ), which is actually the best black body radiation ever measured. During the 70's of the previous century its dipole was measured and in 1992 thanks to the cosmic missions Relikt and COBE the quadrupole anisotropy of CMB was measured as well (see e.g. Strukov et al. 1992, Smoot, g. et al 1992). CMB anisotropy measurements allow to look back into the infancy of the universe 300 000 years from the Big Bang - the recombination epoch. The CMB angular power spectrum allows to measure the main universe characteristics and gain some understanding of the origin of structures. Namely, CMB anisotropy corresponds to the density fluctuations at the recombination epoch $\delta T/T \sim \delta\rho/\rho$, which were the seeds of universe structure formation. Since first Relikt and COBE results, which found CMB anisotropy at a level $\delta T/T \leq 10^{-5}$, and at angular scale 7°, the angular resolution and precision have considerably increased. The BOOMERang balloon experiment measured the anisotropy spectrum up to the 3rd peak. Archeops balloon experiment was able to reach a resolution of 8' and very high sensitivity of 10^{-4} K. DASI was the first to register the polarization of the CMB. WMAP measured the anisotropy and polarization of CMB with great precision. Its angular resolution was $15'$ and the sensitivity was better than 2.10^{-5} K. In future Planck mission even better precision is forseen $\delta T/T \sim 2.10^{-6}$ at an angular scale $5'$. The great importance of CMB achievements for physics and cosmology was granted the Physics Nobel prize for 2006, given to the Cosmic Background Explorer (COBE) team.

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[6] in contrast to the dynamically generated asymmetry in oscillations, which account leads to relaxation of constraints at small mixings.

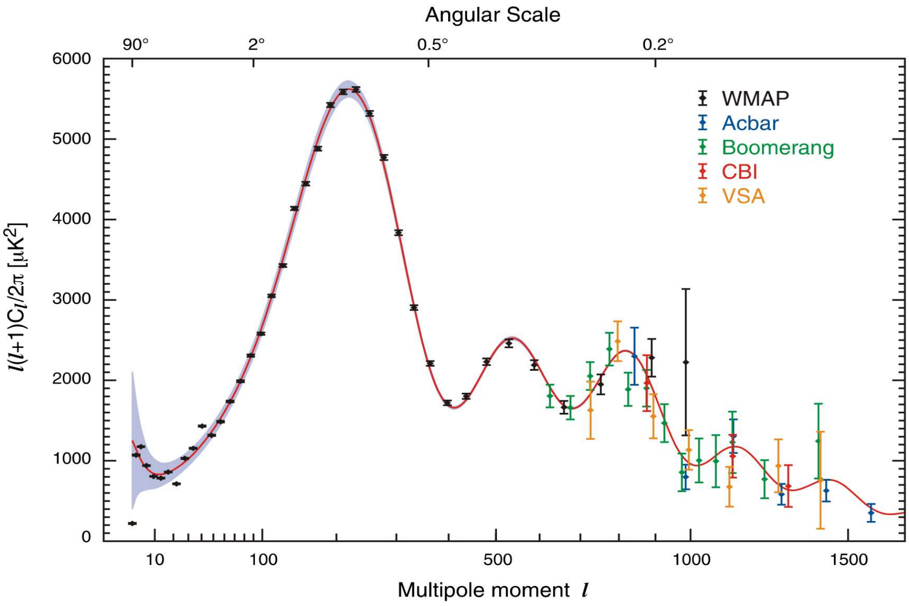

Figure 3: Predicted CMB power spectrum compared with the observational data (see e.g. Hinshaw, G. et al. 2007).

The CMB angular power spectrum allows to measure the main universe characteristics. The location and the heights of the peaks depend on the different cosmological parameters values but also depend on the data sets used. Thus WMAP five years data (see e.g. Komatsu 2009, Spergel et al. 2007) plus Hubble Space Telescope (HST) and SN-Ia Supernovae observations (see e.g. Riess et al 2004, Astier at al. 2006) combined with baryonic oscillations data (BAO) (see e.g. Percival et al. 2007) provide the following information about the main universe characteristics: the age of the universe is estimated to be $t = 13.72 \pm 0.12$ Gyr, $h = 0.705 \pm 0.013$, the total density $-0.0179 < \Omega_0 - 1 < 0.0081$ (95% C.L.) points to a spatially flat universe, the baryon density $\Omega_b = 0.0456 \pm 0.0015$ and the matter density $\Omega_m = 0.274 \pm 0.013$, affirming the need for DM and Dark Energy.

CMB constrains the relativistic particles at photon decoupling epoch. The effect of N_{eff} on CMB comes mainly from the change of the epoch of radiation-matter equality: increasing N_{eff} the radiation-matter equality occurs later, which reflects into enhancion of the first acoustic peak due to the early integrated Sachs-Wolfe effect, shift in the positions of the acoustic peaks towards smaller scales (higher multipoles) and increased separation between the peaks (see e.g. Ichikawa et al. 2008).

The effects of N_{eff} on CMB are strongly degenerate with other cosmological parameters, such as matter energy density Ω_m, the Hubble constant h and the scalar spectral index. The degeneracy is significant up to 2nd/3rd peak of the CMB power spectrum, hence it is impossible to constrain N_{eff} by WMAP5 alone. BAO and SN provide independent constraint on $\Omega_m h^2$, which helps to reduce the degeneracy. Thus concerning neutrino properties, WMAP5 plus SN, HST and BAO constrains the effective number of neutrino types $N_{eff} = 4.4 \pm 1.5$ (68% C.L.) (see e.g. Komatsu 2009, Cirelli et al. 2006, Hannestad and Raffelt 2006). Future Planck results, however, are expected to provide accuracy comparable to BBN, namely $\Delta N_{eff} \sim 0.2$.

To measure N_{eff} by CMB alone we need information at higher multipoles, beyond the 3rd peak. Recently it was provided by ACBAR, BOOMERANG and CBI and allowed to obtain the constraint (see Ichikawa et al. 2008) $0.96 \geq N_{eff} \geq 7.94$ at 95% C.L. Addopting a prior $N_\nu > 3.046$ the constraint on extra radiation becomes $N_\nu < 8.19$.

CMB constrains also the sum of the neutrino masses, for a review on the subject see e.g. Lesgourgues and Pastor 2006. The contribution of neutrinos to the total energy density today (in case of 3 degenerate masses and neutrino masses larger than the present cosmic temperature $m >> T \sim 10^{-4}$ eV) is

$$\Omega_\nu = 3m_0/(93.14h^2 \;\; eV^2),$$

where $\Omega_\nu = \rho_\nu/\rho_0$ is neutrino density today relative to the critical density $\rho_c = 3H^2/8\pi G_N$. CMB is sensitive to the density of massive neutrinos, i.e. to their total mass. [7] For small neutrino masses $m < 0.5$ eV, which remain relativistic at the time of recombination, the main effect on CMB is related to the delay of matter-radiation equality, which causes a small shift in the peaks of the power spectrum and a slight increase in their heights due to the longer duration of the Sachs-Wolfe effect. The effect of free streaming of these neutrino is negligible. Considerable impact of fast moving neutrinos, by preventing the early clumping of gas in the universe, would have delayed also the emergence of the first stars, in conflict with the new WMAP data.

The CMB constraint reads: $\sum_{k=1}^{3} m_k < 1.2$ eV. The constraint on m_ν is fairly robust and does not vary much even if lepton asymmetry is allowed, and in that case is given by $\sum m_\nu < 1.3$ eV (95%C.L.) (see e.g. Shiraishi et al. 2009). However, due to CMB degeneracies massive neutrinos can hide in CMB spectrum, their effect can be compensated by appropriately chosen values of h for example. Combined analysis with other cosmological data helps to lift the degeneracy. CMB WMAP5 plus BAO and SN data reaches twice stronger bound $\sum_{k=1}^{3} m_k < 0.67$ eV at 95% C.L. (see e.g. Komatsu et al. 2009). Neutrino density today is constrained from several independent sets of observational data $\Omega_\nu h^2 \leq 0.0076$ at 95 % CL.

Combined analysis of CMB, LSS and other cosmological data provides several times stronger constraint (see next section).

5. NEUTRINO AND LARGE SCALE STRUCTURE FORMATION

According to CMB data, when the universe was 300 000 years old it was almost perfectly uniform spatially, with density variations from place to place at 10^{-5} level. These tiny density fluctuations grew in amplitude due to gravitational instability till they formed the galaxies and the large-scale structure that we observe today.

Massive neutrinos influence the growth of cosmic clustering. Namely massive neutrinos at low redshift when they are no longer relativistic ($z < z_{nonr} \sim 2.10^3 m_\nu/eV$) effect the power spectrum $P(k)$, suppressing it on small scales (smaller than the so

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[7] However, forecast analysis (se e.g. Bernardis et al. 2009) show that measurements of matter power spectrum from Euclid, combined with CMB data from Planck may be able to constrain single neutrino masses as well.

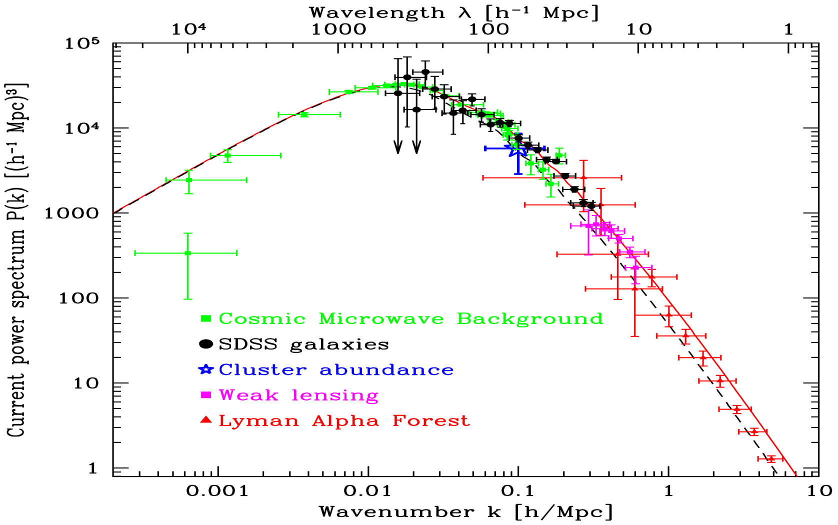

Figure 4: Predicted matter power spectrum compared to observational data (see e.g. Tegmark et al. 2004)

called free-streaming length of neutrinos $\lambda_{fs} = 2\pi/k_{fs}$, which depends on neutrinos mass $k_{fs}(z) = f(\Omega_m, \Omega_\Lambda, z) \times (m/eV)hMpc^{-1}$ and thus changing its overall shape in a characteristic way (see Fig. 4). The suppression depends on the neutrino energy fraction of the matter density in the form of massive neutrinos Ω_ν/Ω_m

$$\Delta P(k)/P(k) \sim -8\Omega_\nu/\Omega_m, \qquad \Omega_\nu \sim \sum m_\nu/93.14h^2eV$$

Thus, the suppression mainly depends on the total mass, but also to a smaller amount on the single masses, due to the dependences of the transition time to non-relativistic regime and the dependence of λ_{fs} on single masses. Hence, on the basis of the available rich contemporary data on large scale structures in the universe, it is possible to constrain neutrino density. In general neutrino density depends on neutrino number density and its mass, thus the cosmological constraints on neutrino masses from LSS can be derived.

It was found that light neutrinos must not play any major role in the evolution of structure in the universe, because neutrinos prevent clustering at small scales, i.e. prevent early galaxy formation, in conflict with the LSS data power spectrum of density fluctuations (see e.g. Hu et al. 1998).

The figure (see e.g. Tegmark et al., 2004) shows the predicted matter power spectrum by the currently accepted ΛCDM model (solid curve) and by a model with 1 eV neutrino (constituting 7% of DM) (dashed curve). Combined analysis of CMB, galaxy surveys data and other cosmological data provides better constraints on the sum of neutrino masses (see e.g. Fogli et al. 2008).

As seen from the table, depending on the choice of data sets, the cosmological constraints on neutrino masses vary within $0.2 - 1.2$ eV range. So, although indirect

Table 1: 2σ (95% C.L.) constraints on the sum of neutrino masses from different data set analysis in flat ΛCDM models. From analysis of Fogli et al. 2008.

Cosmological data set	$\sum m$ (at 2σ)
CMB	<1.19 eV
CMB + LSS	<0.71 eV
CMB + HST + SN-Ia	<0.75 eV
CMB + HST + SN-Ia +BAO	<0.60 eV
CMB + HST + SN-Ia +BAO + Lyα	<0.19 eV

and model dependent, cosmological constraints on neutrino mass are an order of magnitude stronger than the available present experimental limit. On the other hand there is almost an order of magnitude between these cosmological limits and lower limit $m > 0.05$ eV, set at SNO and Kamiokande. It is expected that ~ 0.1 eV mass values could be reached with Planck data and enable precise determination of neutrino mass.

The sensitivity to measure single neutrino masses and provide evidence for neutrino mass splitting (against neutrino degenerate mass model) is expected in future weak lensing survey Euclid and CMB Planck experiment (see e.g. De Bernandis et al. 2009).

6. NEUTRINOS AS DARK MATTER CANDIDATES

There exist numerous observational indications and evidences, pointing to the existence of Dark Matter component in our universe. Namely, observational results coming from *dynamical studies* of different systems, *gravitational lensing*, *theoretical simulations*, etc. points that DM is required in order to enable gravity to amplify enough the small fluctuations found in CMB to form the structures that we see in the universe today. *Combined CMB, SN and cluster measurements analysis* points also to the existence of considerable amount of DM. It constitutes major matter fraction today $\Omega_{DM}h^2 \sim 0.1$.

DM has not been directly detected and we do not yet know the nature of DM. [8] BBN considerations together with the observational data on light element abundances constrain the eventual baryonic component of the dark matter, i.e. DM should be predominantly non-baryonic. Analysis of structure formation points that DM is predominantly cold. There exist different possible DM candidates, like axions, primordial black holes and WIMPS (Weakly Interacting Massive Particles). Massive neutrino is WIMP DM candidate. Depending on its interactions and mass it can constitute the whole DM or just a part of it.

LSS data power spectrum of density fluctuations, however, constrains light neutrino contribution to several % of the DM. In contrast, sterile neutrino may be the particle accounting for considerable part of DM or for all (worm or cold) DM in case its mass is in the KeV range ($m_s < 3.5KeV$ if MSM produced)(see e.g. Kusenko 2009).

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[8] It may indicate our ignorance about the appropriate gravitational laws at large scales or/and the lack of knowledge about particles representing DM.

7. SUMMARY

Contemporary cosmology predicts the existence of relic neutrino background, with total number density $n_\nu = 339.3$ cm^{-3} and temperature 1.9 K, slightly smaller than the CMB ones. This CNB, though not yet directly detected, is indirectly detected due to its cosmological role.

At early stages neutrinos are dynamically important constituent of the universe. Therefore, stringent cosmological constraints on neutrino density and the number of neutrino species exist.

There exist robust experimental and observational evidence for the existence of neutrino oscillations pointing to at least 2 non-zero neutrino masses and $m > 0.05$ eV. Massive light neutrinos may effect clustering in the universe and CMB anisotropy spectrum, and constitute small part of the DM. CMB and LSS are sensitive to total neutrino density. CMB, LSS, HST, SN and BAO data stringent limit on the sum of neutrino masses $\sum m < 0.2 - 0.7$ eV follows from the requirement neutrinos not to spoil the observed clustering at small scales. This cosmological constraint is an order of magnitude stronger than the existing experimental limits.

While CMB and LSS at the present state of our observational facilities are flavor blind, and not sensitive enough to distinguish between nonthermal distortions of neutrino and extra relativistic degrees of freedom, BBN provides a more precise probe. Namely, it is sensitive to different flavors contribution (and especially to ν_e characteristics), neutrino energy distributions, neutrino total density, mass differences and mixing, chemical potentials, etc. BBN provides the most stringent bounds on many ν characteristics: the number of neutrino species $N_{eff} < 0.3$, lepton asymmetry $\mu/T < 0.07$ in any neutrino flavor, distortions in the energy distribution of neutrinos, ν mass differences and mixing (notably BBN is sensitive to extremely small $\delta m^2 \sim 10^{-10}$ eV^2), sterile neutrino characteristics.

BBN bounds considerably tighten in case of active-sterile oscillations during BBN, mainly due to positive kinetic effect of oscillations on primordially produced helium-4, resultant mainly from oscillations caused neutrino spectrum distortion. BBN constraints on $\nu_e \leftrightarrow \nu_s$ oscillation parameters depend nontrivially on the population of ν_s, δN_s and on the lepton asymmetry. In case of active-sterile ν oscillations, CNB neutrinos may be expected considerably depleted and less energetic with an energy spectrum considerably distorted from FD equilibrium one.

The study of relic neutrinos cosmological effects provides cosmological information about neutrino properties which in many cases is complimentary to and more precise than the experimental one. On the other hand precise determination of neutrino properties is of cosmological importance.

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