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COSMOLOGICAL NEUTRINOS AND THEIR INFLUENCE ON THE EVOLUTION OF THE UNIVERSE

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Being one of the most mysterious particles of the Standard Model, neutrinos have opened up new opportunities for astrophysical research. The high penetrating power of neutrinos provides insight into stellar interior and makes it possible to study the mechanisms of the origin of ultra-high energy cosmic rays. When a star explodes, a neutrino flare informs us about this event several hours earlier than electromagnetic radiation. Neutrino also plays a crucial role in cosmology, being the second most abundant known particle in the Universe. In the radiation-dominated epoch, neutrinos together with photons, determine the dynamics of the expansion of the Universe. Later, becoming nonrelativistic, the neutrinos increase the contribution $\Omega_{\rm m}$ *of nonrelativistic matter, which previously consisted of cold dark matter and baryonic matter. Since neutrinos affect the course of the evolution of the Universe, this fact should be taken into account when determining cosmological parameters. Recently, in addition to relic neutrinos from the Big Bang, antineutrinos of primordial nucleosynthesis have been theoretically predicted. Their detection could be additional evidence for baryon asymmetry of the Universe.*

Current results from a number of independent experiments indicate the possibility of the existence of a light sterile neutrino ($m_\nu \sim 1$–3 *eV*)*. The presence of such a neutrino is in poor agreement with the predictions of the Standard Cosmological Model, but these contradictions can be removed by its extension, for example, by the existence of a nonzero lepton asymmetry* $\xi_\nu \sim 10^{-2}$ *of the Universe. Nowadays, there are little doubts about the existence of cosmological neutrinos, but unfortunately it is not yet possible to detect them directly due to the extremely small cross section of their interaction at low energies. However, if this can be done in the future, we will obtain direct information about the first seconds, minutes, and hours of the evolution of the Universe after the Big Bang. A review of key aspects related to the influence of cosmological neutrinos on the evolution of the Universe at different stages from the early Universe (primordial nucleosynthesis and primordial recombination) to present days is given.*

1. INTRODUCTION

Every time humanity has a new way to look at the Universe, it sees not only the well-known phenomena in new colors, but also discovers previously unknown natural phenomena that enrich our understanding of the world, and sometimes radically change it. Thus, following optical astronomy, the development of radio astronomy, which started in the 1930s, highlighted the center, spiral arms, and the opposite edge of our galaxy, which is inaccessible to optical observations due to the huge amount of gas and dust in the interstellar space. Scientists discovered radio galaxies and pulsars, and cosmic microwave background radiation that was

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born in the first moments of the Big Bang and contained unique cosmological information both about the early periods of the Universe development and about its later evolution, up to the present day. Later the development of X-ray and gamma-ray astronomy made it possible to study both black holes as the most compact objects and galaxy clusters as the largest gravitationally bound structures in the Universe. However, all these studies refer to electromagnetic radiation. Although it gave a huge amount of information about the Universe, there are also other ways to penetrate in its secrets, including cosmic ray astrophysics and neutrino and gravitational wave astronomy. This paper discusses the achievements and prospects of exactly neutrino astronomy, which opens up new opportunities for studying the Universe.

2. MYSTERIOUS, PERVASIVE NEUTRINO

The modern concept of the structure of matter is based on the so-called Standard Model of elementary-particle physics and fundamental interactions. Its proof was successfully completed with the discovery of the latest fundamental "brick," the Higgs boson. A separate paper can be written about each particle of the Standard Model, but perhaps a neutrino still remains the most mysterious particle, since the explanation of its amazing properties may require to go beyond the Standard Model. A key characteristic is neutrino oscillations, which consist in the following: born in a certain flavor state, i. e., electron (ν_e), muonic (ν_μ), or tau (ν_τ) states, some time later, with a certain probability, a neutrino can be found in any of these three states, and such a transformation of a freely moving particle occurs without any external forcing. The oscillation phenomenon is also unambiguously related to the existence of neutrino mass. However, the mass generation mechanism is still unclear. Although the observed oscillations of neutrinos clearly indicate the existence of their mass, it has not been measured by direct methods so far, and only the lower and upper bounds for the total mass of neutrinos have been experimentally obtained: $0.06\,eV \lesssim \sum m_\nu \lesssim 0.12\,\mathrm{eV}$ (see, e. g., [1]). However, the unique properties of neutrinos do not end here: i) the neutrino is the second (after the photon) most common particle in the Universe; ii) it is the lightest known particle with nonzero mass (a neutrino is more than a million times lighter than an electron); iii) neutrinos explicitly break the left–right symmetry (neutrinos are left-handed, while antineutrinos are right-handed); iv) neutrino has one of the smallest interaction cross sections with matter ($\sigma \sim 10^{-44}\,\mathrm{cm}^2$ at energies of the order of several megaelectronvolts), which determines its enormous penetrating ability, allowing one to see stellar interior and, in the future, look into the first seconds, minutes, and hours of the birth of the Universe, opaque to electromagnetic radiation.

3. GRAND UNIFIED NEUTRINO SPECTRUM

For the first time in history, antineutrinos from nuclear reactors were detected in 1956 by Frederick Reines and Clyde Cowan, who sent a radiogram to Wolfgang Pauli from New York to Zürich. Subsequently, there were recorded solar neutrinos, atmospheric neutrinos resulting from the interaction of cosmic rays with atmospheric matter, and, finally, ultra-high energy neutrinos ($E_\nu \gtrsim 10^{14}\,\mathrm{eV}$), the active galactic nuclei being among their possible sources. The energy range in which neutrinos are now observed is really enormous, from megaelectronvolt to petaelectronvolt energies, but it is even more than ten orders of magnitude wider due to the theoretically predicted low-energy ($10^{-4} \lesssim E_\nu \lesssim 10$ eV) cosmological neutrinos[1] and ultra-high-energy ($E_\nu \gtrsim 10^{16}\,\mathrm{eV}$) cosmogenic neutrinos resulting from the interaction of cosmic rays with photons of the cosmic microwave background radiation. Figure 1 shows the so-called grand unified neutrino spectrum (the name was taken from [2]), which comprises theoretical and observational spectra of neutrinos of various nature (the data for constructing this spectrum can be found from the references in [3]). The present paper focuses on cosmological neutrinos and their influence on various stages of the evolution of the Universe.

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[1] In reality, cosmological neutrinos represent an equal mixture of neutrinos and antineutrinos. However, neutrinos and antineutrinos are generically called neutrinos in the scientific literature if it does not lead to confusion.

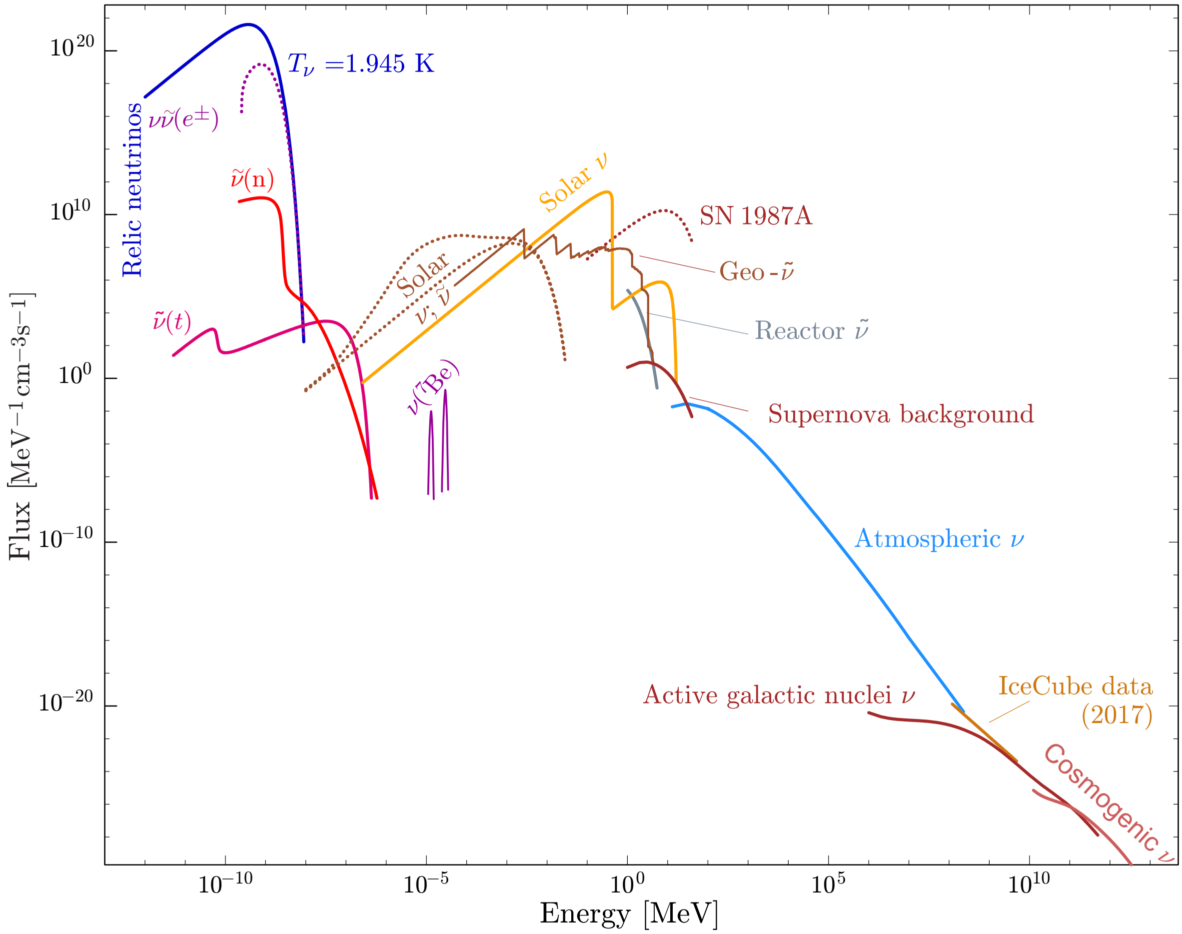

Fig. 1. Observed and theoretically calculated spectra of neutrinos and antineutrinos generated by various natural phenomena (local and cosmological) [3]. For a detailed discussion of all components of the grand unified neutrino spectrum, see [2].

4. RADIATION-DOMINATED EPOCH AND PRIMORDIAL NUCLEOSYNTHESIS

Fractions of a second after the Big Bang, the Universe enters the radiation-dominated stage of its evolution, which lasts about 50 thousand years, while neutrinos, along with photons, play a decisive role in the Universe expansion dynamics at this stage. This is the earliest moment in the history of the Universe that we can peek due to the primordial nucleosynthesis process, which took place in the first minutes and hours after the Big Bang and gave rise to the first lightest nuclei and their isotopes (D, He, and Li), which formed the primordial chemical composition of the Universe baryonic matter. Astronomical observations of the relative abundance of these elements and their comparison with theoretical predictions make it possible to estimate one of the key cosmological parameters, the baryon–photon ratio, $\eta = n_{\rm b}/n_\gamma$, and thereby give information about physical conditions that existed in this epoch. The most accurate estimates of the abundance of these elements have to date been obtained for ^{4}He by analyzing the spectra of dwarf metal-poor galaxies ($Y_p = 0.247 \pm 0.002$ [4, 5]) for D, by analyzing quasar spectra that contain absorption lines of damped Lyman-alpha systems associated with metal-poor intergalactic matter of the early Universe, the chemical composition of which is close to the primordial one (D/H= $(2.53 \pm 0.03) \cdot 10^{-5}$ and $(2.39 \pm 0.1) \cdot 10^{-5}$ [6, 7]), although there are circumstances that impede obtaining estimates and their errors on the abundance of primordial deuterium (this problem is discussed in [8]), and for ^{7}Li, by analyzing metal-poor star spectra in the halo of our galaxy (^{7}Li/H= $(1.6 \pm 0.3) \cdot 10^{-10}$ [9, 10]). Figure 2 shows the abundances of primordial ^{4}He, D, and ^{7}Li as functions of the baryon content in the Universe, which is characterized by the parameter

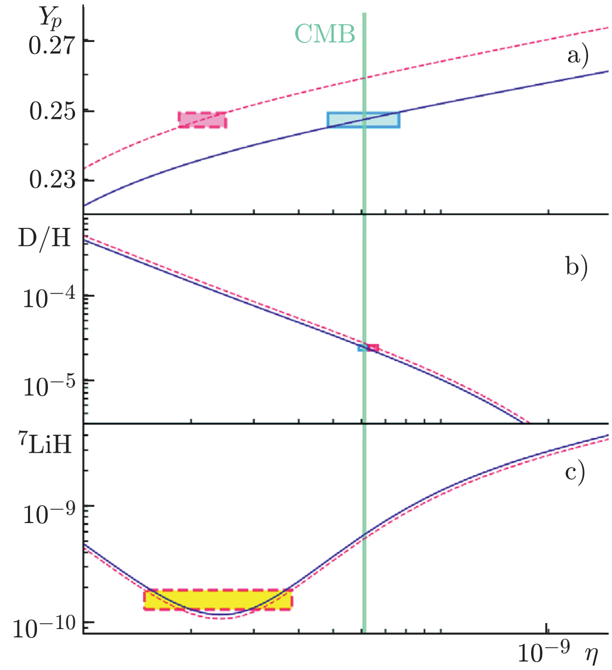

Fig. 2. Dependence of the primordial abundances of ^{4}He (Y_p), D (D/H), and ^{7}Li (^{7}Li/H) on the baryon–photon ratio η. Dark blue solid lines correspond to the standard theory of primordial nucleosynthesis with three species of active neutrinos ($\Delta N_{\rm eff} = 0$). Colored rectangles indicate the observed values of primordial abundance. The vertical turquoise line corresponds to the η value obtained due to the analysis of the cosmic microwave background radiation anisotropy data from the Planck satellite [11]. It can be seen that for ^{4}He and D, the observational data are consistent with the prediction based on the cosmic microwave background radiation anisotropy, while the observed value for ^{7}Li is significantly lower than the predicted one, which constitutes a lithium problem. The red dashed lines and the red rectangle correspond to the theory of nucleosynthesis if there is an additional species of neutrino ($\Delta N_{\rm eff} = 1$).

η (dark blue lines) and the observed values of the primordial abundances, marked by colored rectangles.

There is another way to estimate the baryon–photon ratio, namely, the analysis of cosmic microwave background radiation anisotropy which is formed in the course of primordial recombination that occurred 380 thousand years after the Big Bang. The primordial abundance values obtained from the cosmic microwave background radiation anisotropy analysis are also shown in Fig. 2 by the vertical turquoise line. It can be seen that the observational data for ^{4}He and D are consistent with the prediction based on the cosmic microwave background radiation anisotropy [11], while the observed value $^7\mathrm{Li/H} = (1.6 \pm 0.3) \cdot 10^{-10}$ [9, 10] is significantly lower than the predicted value $^7\mathrm{Li/H} = (4.7 \pm 0.7) \cdot 10^{-10}$ [12], which constitutes the so-called lithium problem that remains unsolved.

Independent estimates of the parameter $\eta = n_{\rm b}/n_\gamma$ on primordial nucleosynthesis and the cosmic microwave background radiation anisotropy belong to different cosmological epochs. Therefore they allow one not only to check the Standard Cosmological Model for self-consistency, but also, in the case of discrepancy, can serve as a tool for searching for physics beyond the Standard Model, which generalizes and extends the standard models of cosmology and elementary particle physics.

4.1. Neutrino role at the radiation-dominated stage

Born in the first moments of the Big Bang, photons and neutrinos are in thermal equilibrium in the primordial plasma with all Standard Model particles, whose birth is energetically allowed at a given temperature T of the Universe. However, as the Universe expands and cools, heavy particles annihilate and decay, so just in 0.1 s relativistic plasma consists of photons, neutrinos, electrons, positrons, and a small amount $\eta = n_{\rm b}/n_\gamma \simeq 6.1 \cdot 10^{-10}$ of baryonic matter that represents protons and neutrons by this time. At this stage, the contribution of baryons, as well as dark matter and dark energy, to the density of the universe energy is negligible. After about 100 s, only photons and neutrinos remain in significant amount as a result of electron–positron annihilation, and thus it is they that determine the further rate of expansion of the Universe till the end of the radiation-dominated stage (i. e., about another 50 thousand years). In this case, their spectra retain the thermodynamically equilibrium shape after the cessation of interaction with matter (neutrinos after 0.1 s and photons after 400 thousand years after the Big Bang) until today. They represent (see Fig. 3) a Planck spectrum of photons with the temperature $T(z) = T_{\gamma 0}(1+z)$ and a Fermi–Dirac spectrum of neutrinos with the temperature $T(z) = T_{\nu 0}(1+z)$. Before the electron–positron annihilation, the photon and neutrino temperatures coincided, and after that electron and positron energies converted mainly to the energy of photons, thereby increasing their temperature. The latter is related to the neutrino temperature by the formula $T_\nu = (4/11)^{1/3} T_\gamma$. The cosmological redshift z characterizes the ratio of the scale factor a of the Universe to its present-day value a_0, which is chosen equal to unity: $1 + z = 1/a$.

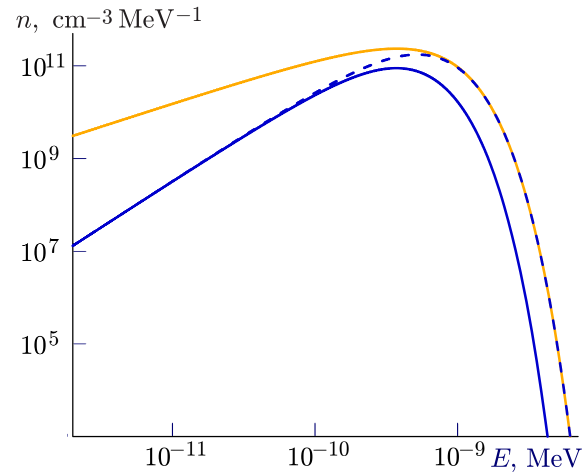

Fig. 3. Present-day Planck spectrum of relic photons (CMB) with the temperature $T_{\gamma 0} = 2.7255$ K (orange curve) and Fermi–Dirac spectrum of relic neutrinos (CνB) with the temperature $T_{\nu 0} = 1.9454$ K (blue solid line), which are related as $T_\nu = (4/11)^{1/3} T_\gamma$. The blue dashed line shows what the neutrino spectrum would be if the photon and neutrino temperatures coincide; the photon spectrum is hotter due to the electron–positron annihilation that occurred within the first hundred seconds after the Big Bang.

Thus, at least two[2] relic radiations, namely, the cosmic microwave background (CMB) of photons and the cosmic neutrino background (CνB), remained after the Big Bang. They almost uniformly and isotropically fill the whole Universe and propagate from all points of the Universe to all points of the Universe. The cosmic microwave background radiation of photons, predicted back in 1948 by George Gamow, was discovered in 1965 by Arno Penzias and Robert Woodrow Wilson (Nobel Prize 1971). Subsequently, the spectrum of the CMB radiation of photons with the temperature $T_{\gamma 0} = 2.7255 \pm 0.0006$ K in the modern epoch and the angular anisotropy of the CMB radiation temperature (over the celestial sphere) were measured by analyzing data from the COBE and WMAP space experiments [13, 14] (Nobel Prize 2006 to John C. Mather and George F. Smoot), while the detection of cosmic neutrino background radiation remains an impossible task to date. Nevertheless, the existence of cosmic neutrino background is not questioned, because without it the results of theoretical calculations of primordial nucleosynthesis and CMB anisotropy would be completely inconsistent with observations.

As a result, the particular role of neutrinos at the radiation-dominated stage and in the primordial nucleosynthesis is due to several circumstances. First, being an ultrarelativistic particle in this epoch, the neutrino gives a contribution comparable with that of photons to the energy density of the Universe, and thus the photons and neutrinos determine the rate of the Universe expansion at the radiation-dominated stage (after electron–positron annihilation and up to the transition to the stage of nonrelativistic matter dominance):

$$H(t) \equiv \frac{\dot{a}}{a} = \sqrt{\frac{8\pi G}{3}\rho(t)}, \qquad \rho(t) = g_* \frac{a_B T^4}{2}, \qquad g_* = 2_\gamma + \frac{7}{8} \cdot 3 \cdot 2_\nu \left(\frac{4}{11}\right)^{4/3}. \tag{1}$$

Here, $H(t)$ is the Hubble parameter that characterizes the Universe expansion rate, $\rho(t)$ is the Universe energy density proportional to the fourth degree of the relativistic-component temperature, and g_* is the effective number of relativistic degrees of freedom, which was contributed only by photons and neutrinos after electron–positron annihilation. From Eq. (1) is seen that the contribution of neutrinos to the Universe expansion rate will be about 40%. Second, in weak interactions, neutrinos determine the relative abundance n/p of neutrons that burn out during primordial nucleosynthesis, mostly joining with protons into ^{4}He nuclei, and thereby determine the primordial composition of ^{4}He. Thus, among three elements (D, ^{4}He, and ^{7}Li) for which astronomical observations make it possible to estimate their primordial composition, it is exactly ^{4}He that is the most sensitive to the rate of expansion of the Universe, the number of relativistic degrees of freedom, and the properties of neutrinos (the number of flavors and the possible existence of a sterile neutrino; see the text below).

[2] The existence of relic gravitational radiation is also possible.

4.2. Antineutrino of the primordial nucleosynthesis

Recently, in addition to the Big Bang relic neutrinos, antineutrinos of primordial nucleosynthesis have been predicted theoretically [3, 15].

Protons and neutrons are the initial construction materials of all nuclei synthesized in primordial nucleosynthesis. Besides the participation in the processes of nuclear transformations during collisions with other nuclei, neutrons are also subject to spontaneous β^- decay, i.e., $n \to p + e^- + \tilde{\nu}_e$, and the lifetime $\tau_{\rm n}$ of a neutron with respect to this process is $\tau_{\rm n} \simeq 880.2$ s [16]. The electron and the antineutrino, which are produced in the decay, carry away almost all of the decay energy $Q_{\rm n} \simeq 782.3$ keV distributed between them [17]. Most neutron decays occur after the neutrino hardening (which takes place about 0.1 s after the Big Bang), so the antineutrinos born in these decays are no longer thermalized. Thus, neutrons decaying during the epoch of primordial nucleosynthesis are the source of nonthermal antineutrino radiation, which will uniformly and isotropically fill the Universe at the end of the primordial nucleosynthesis process. The spectral flux $F(\varepsilon)$ of antineutrinos from neutron decays in the present-day Universe was calculated in [15] and is determined by the formula

$$F(\varepsilon) = -\frac{v(\varepsilon)}{4Q_{\rm n}\tau_{\rm n}} \int\limits_0^{z'} \frac{n_{\rm n}(z)}{(1+z)^3} f^0(\tilde{\varepsilon}) \frac{{\rm d}t}{{\rm d}z} {\rm d}z. \tag{2}$$

Here, ε is the antineutrino energy in the modern epoch ($\tilde{\varepsilon} = \varepsilon/Q_{\rm n}$), $v(\varepsilon)$ is the speed of the antineutrino with energy ε, $n_{\rm n}(z)$ is the neutron number density in the epoch where the redshift of the Universe was equal to z, $f^0(\tilde{\varepsilon})$ is β^--decay spectrum of antineutrinos born at redshift z (in the modern epoch, $z = 0$), the factor ${\rm d}t/{\rm d}z$ is due to the transition from integration over cosmological time t ($n_{\rm n}\,{\rm d}t/\tau_{\rm n}$ gives the number of neutrons decaying within the time ${\rm d}t$ per unit volume) to integration over the redshift quantity, and z' is the integration limit determined by the value of the decay energy.

Among the nuclei that are synthesized in the epoch of primordial nucleosynthesis with notable mass fractions, there is a nucleus that, like the neutron, is unstable with respect to the β^- decay. This is the tritium nucleus T. The lifetime of this nucleus $\tau_{\rm T} \simeq 17.66$ years [18] and the decay energy $Q_{\rm T} \approx 18.59$ keV [17]. The antineutrino flux from decays of tritium nuclei is also calculated using Eq. (2), where appropriate values of the lifetime and decay energy, as well as the redshift dependence of the mass fraction of the decaying element, should be used.

The calculated antineutrino spectra from the decays of neutrons and tritium nuclei in the early Universe are presented in Fig. 4. This figure shows the neutrino and antineutrino spectra from all sources generating the largest fluxes in the energy range depicted. It can be seen that the antineutrino fluxes of primordial nucleosynthesis in the energy range $[10^{-2}, \sim 10^{-1}]$ eV exceed the fluxes from any other sources of neutrinos and antineutrinos, which, if detected, will open a window to the early Universe.

4.3. Relic neutrino as indicators of the Universe baryon asymmetry

Direct observational facts suggesting that the observed part of the Universe is dominated by matter and lacks antimatter include the composition of cosmic rays, as well as the absence of significant annihilation radiation in the solar system, in our galaxy, and in galaxy clusters. The potential observation of relic antineutrinos would make it possible to see causally unrelated areas that are the farthest possible to date. The detection of relic antineutrinos of primordial nucleosynthesis could provide evidence for baryon asymmetry in most of the visible Universe, or help detect areas of antimatter predominance, since the existence of such areas would lead to the generation of relic neutrinos from antineutron and antitritium decays.

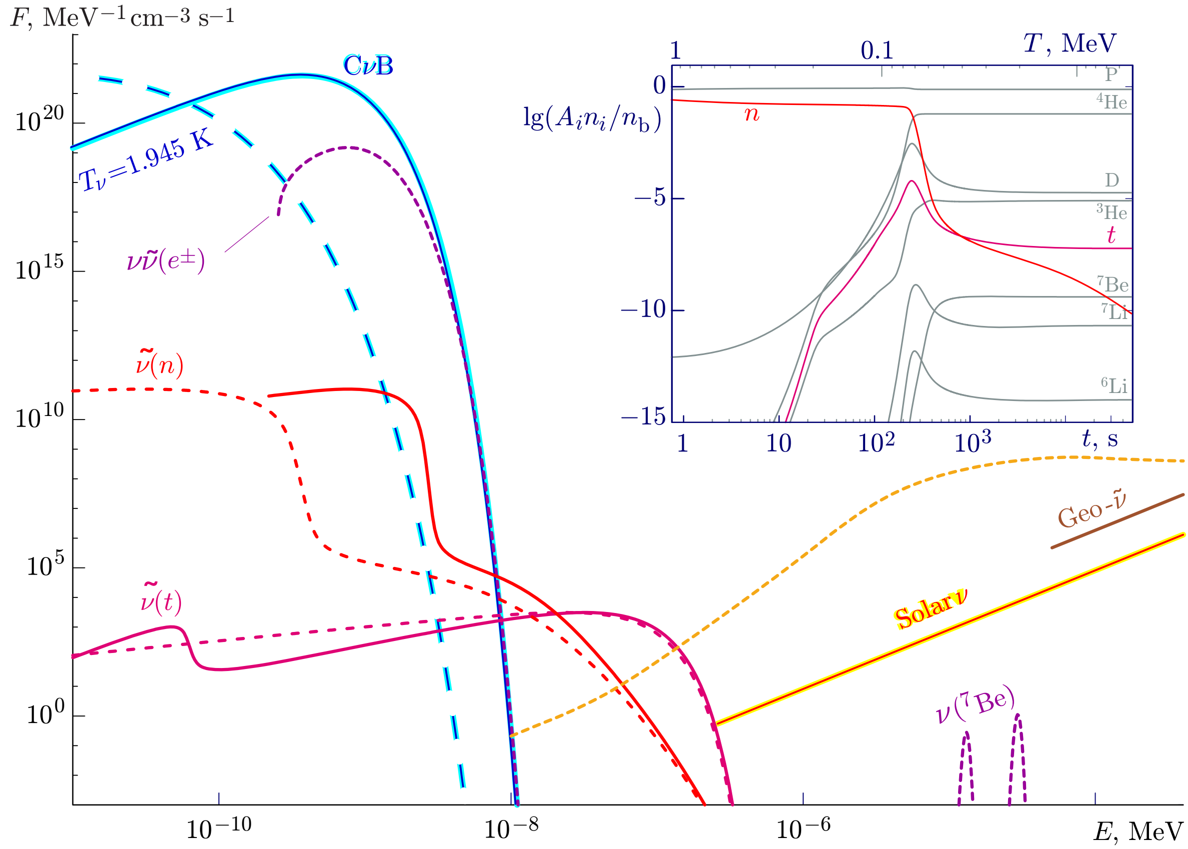

Fig. 4. Antineutrino spectra from the decays of neutrons and tritium nuclei (red and crimson lines). The solid lines show the spectra in the case of zerro neutrino mass. The dashed lines show the spectra for the case of neutrino mass 0.01 eV. It can be seen that there is a range of energies where the fluxes of antineutrinos of primordial nucleosynthesis exceed the fluxes of Big Bang neutrinos (blue line) and solar neutrinos (yellow line). Evolutionary curves of mass fractions of neutrons and tritium nuclei in the primordial nucleosynthesis are shown in the inset in the corresponding colors.

5. STERILE NEUTRINO AS AN EXPANSION OF THE STANDARD MODEL OF THE PHYSICS OF PARTICLES AND THE STANDARD COSMOLOGICAL MODEL

One of the options for extending the Standard Model of elementary particle physics is the introduction of sterile neutrinos. This provides a solution to several problems at once: the sterile neutrinos generate masses of active neutrino species (electron, muon, and tau neutrinos) by means of the swing mechanism, they are suitable for the role of dark matter, and they can also become a source of generation of the baryon asymmetry of the Universe (see [19, 20] for details). The mass range of sterile neutrinos is not determined. They can be light, with masses of the order of a few electronvolts, and very heavy, with masses of up to 10^{15} GeV. The role of sterile neutrinos in regard to cosmology is also determined by their mass. Ultraheavy sterile neutrinos with masses of 10^9–10^{15} GeV are capable of generating lepton and baryon asymmetry in the early Universe. Their lifetime is so short that they would decay before primordial nucleosynthesis, and thermodynamics would wipe out all traces of their existence; only the fact of the Universe baryon asymmetry could so far speak of such a possibility (not excluding others). Heavy sterile neutrinos, with masses of 10^2–10^9 GeV and lifetime comparable to or longer than the present age of the Universe, are good candidates for the role of cold dark matter. Finally, light sterile neutrinos with masses of the order of 1 eV can significantly affect the cosmology, which will be discussed in more detail below.

The signs of possible existence of sterile neutrinos appeared more than a decade ago in various independent experiments (see, e. g., references in [21]), the recent of which discuss the possible existence of light sterile neutrinos with masses about 1–3 eV [22, 23]. To date, the status of these experiments is rather controversial, since the results are not always consistent with each other, and sometimes they are said to be completely inconsistent. For example, a recent paper [24] rejects the hypothesis of the existence of a sterile neutrino. Nevertheless, there is still a range of parameters of light sterile neutrino oscillations that does not formally contradict the results of the STEREO [24] and Neutrino-4 [22] experiments, so the question about the existence of a light sterile neutrino cannot be considered to be finally solved.

The existence of a light sterile neutrino will lead to a change in the energy density in the radiation-dominated stage, which is convenient to parameterize using the so-called effective number N_{eff} of relativistic neutrino species, which, in turn, is determined by the relation

$$\frac{\rho_\nu}{\rho_\gamma} = \frac{7}{8} N_{\text{eff}} \left(\frac{4}{11}\right)^{4/3}. \tag{3}$$

Here, ρ_ν and ρ_γ are the neutrino and photon energy densities, respectively, the last factor is the fourth power of the neutrino-to-photon temperature ratio $T_\nu/T_\gamma = (4/11)^{1/3}$ [25], and $N_{\text{eff}} = 3.044$ in the standard model [26, 27]. By introducing the quantity ΔN_{eff}, which determines the addition to N_{eff} in the case of the presence of a light sterile neutrino, and considering that the temperatures of sterile and active neutrinos coincide, the total energy density can be written as

$$\rho_R = \rho_\gamma \left[1 + \frac{7}{8}(N_{\text{eff}} + \Delta N_{\text{eff}}) \left(\frac{4}{11}\right)^{4/3}\right], \tag{4}$$

from which it is easy to obtain the relation

$$\Delta N_{\text{eff}} = \left[\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]^{-1} \frac{\rho_\nu^{(s)}}{\rho_\gamma}, \tag{5}$$

where $\rho_\nu^{(s)}$ is the energy density of the sterile neutrino. Since sterile neutrinos are generated by oscillations from active neutrinos, which, in turn, are described by the Fermi–Dirac equilibrium cumulative distribution function, sterile neutrinos can also be expected to have an equilibrium distribution function. The calculations performed in [28, 29] using the actual measurements of neutrino mixing parameters show that light sterile neutrinos with masses of the order of a few electronvolts have time to fully thermalize by the moment of neutrino separation and remain in the expanding Universe as an additional relativistic degree of freedom with $\Delta N_{\text{eff}} = 1$. However, it should be noted that the parameters of light sterile neutrinos, obtained in the experiments (the difference Δm^2 of the squared masses and the mixing angle $\sin^2(2\theta)$), have fairly large uncertainty intervals, and the reliability of these results requires further corroboration. In the case of significantly lower mixing angles, the thermalization of sterile neutrinos will be incomplete, and therefore the number of relativistic degrees of freedom will be within the interval $0 \leq \Delta N_{\text{eff}} < 1$ (this case is considered in [21]). In the case of complete thermalization, we have $\Delta N_{\text{eff}} = 1$, and this fact significantly changes the expansion rate of the Universe and, consequently, the predictions of primordial nucleosynthesis. Figure 2*a* shows that the presence of a light sterile neutrino, which increases the effective number of neutrino species to four, leads to a radical change in the theoretical prediction of the relative abundance of ^{4}He, which is incompatible with observational data on deuterium and anisotropy of the cosmic microwave background radiation. To date, this is the most stringent constraint on the possible existence of a light sterile neutrino.

A solution to this problem can be found in the case of the existence of a nonzero lepton (neutrino) asymmetry $\xi_\nu = \mu/kT \sim 0.05$, where μ is the chemical potential of the neutrino. Figure 5 shows how the lepton asymmetry can compensate for the additional relativistic degrees of freedom (ΔN_{eff}).

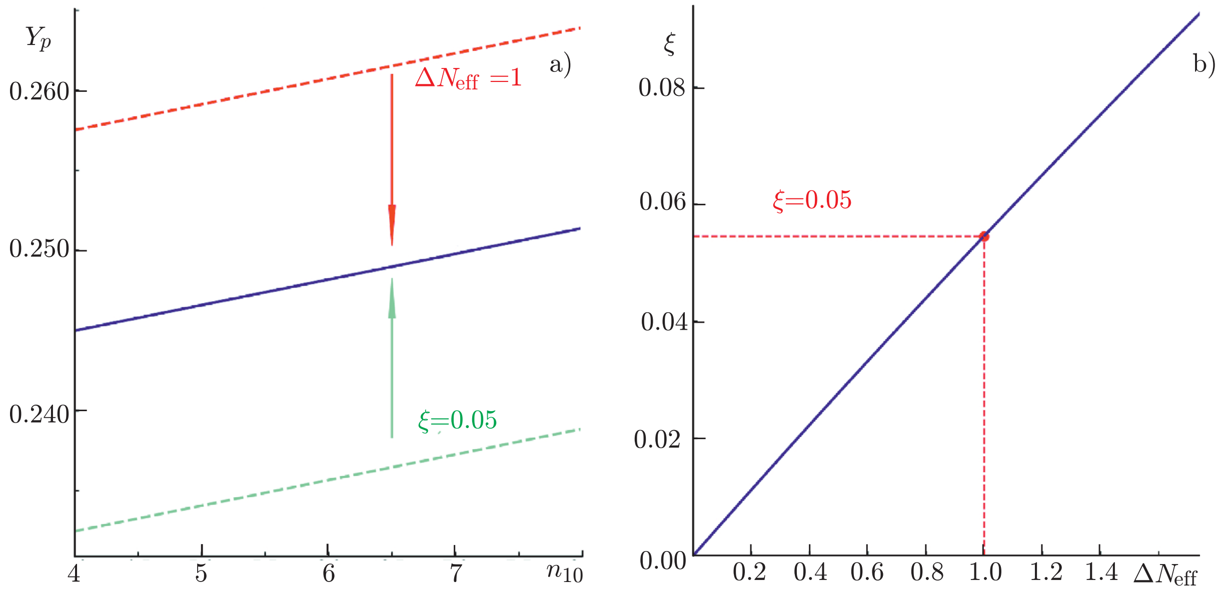

Fig. 5. Compensation for the influence of additional relativistic degrees of freedom $\Delta N_{\rm eff}$ on the abundance of ^{4}He (Y_p) by the nonzero lepton asymmetry ξ. Panel *a* shows the calculated dependences of Y_p on the baryon–photon ratio η_{10}. The red dashed curve shows the dependence $Y_p(\eta_{10})$ if one light sterile neutrino is present (see Fig. 2). The turquoise dashed curve shows the dependence $Y_p(\eta_{10})$ if the lepton asymmetry $\xi_e = 0.05$ is present. Panel *b* shows the lepton asymmetry ξ that fully compensates for the influence of the additional relativistic degree of freedom related to the light sterile neutrino.

6. THE INFLUENCE OF NEUTRINO ON THE NEXT STAGES OF THE UNIVERSE EVOLUTION

After the radiation-dominated epoch (in about 50 thousand years after the Big Bang), the epoch of nonrelativistic (dark and baryonic) matter dominance comes. Then, about 7 billion years later, the Universe changes its mode of expansion from slowed to accelerated, while neutrino affects the dynamics of the Universe expansion at each stage of evolution. The Universe expansion rate, characterized by the Hubble parameter, has the form

$$H(a) \equiv \frac{1}{a}\frac{\mathrm{d}a}{\mathrm{d}t} = H_0\sqrt{\Omega_\Lambda + \Omega_{\rm cdm}a^{-3} + \Omega_{\rm b}a^{-3} + \Omega_\gamma a^{-4} + \sum_\nu \Omega_\nu f_\nu(a)}. \tag{6}$$

Here, H_0 is the present-day value of the Hubble parameter, $\Omega_{\rm cdm}, \Omega_{\rm b}, \Omega_\gamma, \Omega_\nu$, and Ω_Λ are fractions of the energy densities of cold dark matter, baryons, photons, neutrinos, and dark energy in the Universe at the current moment, respectively, and the functions $f_\nu(a)$ determine the dependence of the neutrino contribution on the scale factor of the Universe, i. e., in the corresponding cosmological epoch. Figure 6, taken from our paper [21], shows the effective number of relativistic neutrino species with allowance for the possible existence of a light sterile neutrino. It can be seen that all neutrinos are relativistic at the early stages of the Universe evolution, and therefore they contribute significantly to the energy density, and hence to the Universe expansion rate, which, in turn, determines the size of the sound horizon by the time of primordial recombination. All these factors influence the formation of the anisotropy of cosmic microwave background radiation, the study of which allows cosmological parameters to be estimated with unprecedented accuracy. A detailed analysis of the influence of neutrino properties on the determination of cosmological parameters is presented in detail in our paper [21].

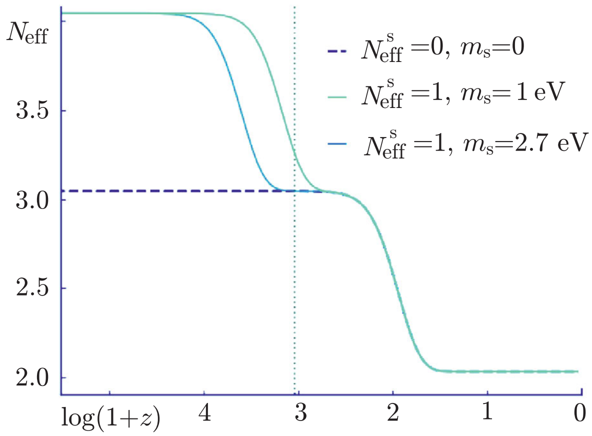

Fig. 6. Effective number of relativistic neutrino species with allowance for the possible existence of a light sterile neutrino as a function of the cosmological redshift z [21]. It can be seen that all neutrinos are relativistic at the early stages of the Universe evolution. Sterile neutrinos with a mass of 2.7 eV [22] become nonrelativistic before the recombination (vertical dotted line), those with a mass of 1 eV [23] become relativistic during the recombination, and active neutrinos with masses less than 0.1 eV become nonrelativistic after the recombination.

7. CONCLUSIONS

Neutrino astronomy has given a new opportunity for studying the Universe. Cosmological relic neutrinos, born in the very first moments of the Big Bang, participate in all stages of the evolution of the Universe, making an appreciable contribution to the dynamics of its expansion, unlike, for example, photons, whose energy density dominates only in the early stages of the Universe evolution, or dark matter and dark energy, whose contribution becomes significant only in the later epochs. Due to this circumstance, the spectrum of the anisotropy of cosmic microwave background radiation is sensitive to the properties of neutrinos, which significantly affects finding the values of key cosmological parameters, most accurately determined as a result of the neutrino analysis.

The recently predicted antineutrinos of primordial nucleosynthesis contain additional information about the nonequilibrium processes in the early Universe, in the first minutes and hours after the Big Bang. Their detection could provide evidence for the baryonic asymmetry of most of the visible Universe, since the existence of antimatter-dominated areas would lead to the generation of relic neutrinos from antineutron and antitritium decays.

The possible existence of a light sterile neutrino is poorly consistent with the predictions of the Standard Cosmological Model, but these contradictions can be removed if it is extended, for example, by introducing a nonzero lepton asymmetry $\xi_\nu \sim 10^{-2}$ of the Universe.

Due to the high penetrating power of neutrinos, if cosmological neutrinos can be recorded in the future, we will directly obtain information about the first seconds, minutes, and hours of the evolution of the Universe after the Big Bang.

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