Sterile neutrino and dark matter

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Abstract

We consider the equation that describes the dynamics of the sterile neutrino density in primeval plasma. The analysis of this equation results in the ~5% contribution of the sterile neutrino with mixing parameters $\Delta m^2_{14} = 7.3 \text{ eV}^2$ and $\sin^2 2\theta_{14} = 0.33$ to the energy density of the Universe. The considered parameters of the sterile neutrino correspond to the warm dark matter.

1. Introduction

Starting from LSND in 2001 piled significant amount of evidences of the sterile neutrino existence. Anomalies were observed in several accelerator and reactor experiments: LSND at a confidence level of 3.8 $\sigma$ [1], MiniBooNE 4.7 $\sigma$ [2], reactor anomaly (RAA) 3 $\sigma$ [3,4], as well as in experiments with radioactive sources GALLEX/GNO, SAGE 3.2$\sigma$ and BEST [5-7].

In 2018, in the Neutrino-4 experiment [8], a direct process of oscillations with a sufficiently high frequency was observed. This was the first direct observation of the effect of oscillations of reactor antineutrinos into sterile neutrinos, in which it was possible to determine both the frequency and amplitude of the oscillations. The parameters of this process were $\Delta m^2_{14} \approx 7.26 \text{ eV}^2$ and $\sin^2 2\theta_{14} \approx 0.38$ at CL 3.5$\sigma$. A method of coherent addition of measurement results was proposed and implemented, which made it possible to directly observe the process of oscillations (see Fig. 1). In 2021, [9] a detailed description of the experiment was published, from preparatory operations to the final result, with a detailed analysis of possible systematic errors and MC simulations. The result was confirmed: at the level of 2.9$\sigma$ with parameters $\Delta m^2_{14} = (7.3 \pm 0.13_{\text{stat}} + 1.16_{\text{sys}}) \text{ eV}^2$ and $\sin^2 2\theta_{14} = 0.36 \pm 0.12_{\text{stat}}$ (2.9$\sigma$). Statistical analysis based on Monte Carlo gave a confidence level estimate of 2.7$\sigma$.

The 2022 paper [10] presents an analysis of the results obtained in the Neutrino-4 experiment in comparison with the results of the NEOS, DANSS, STEREO, PROSPECT experiments on reactors, the MiniBooNE, LSND, MicroBoone experiments on accelerators, with the IceCube experiment and the BEST experiment with $^{51}$Cr neutrino source. Combining the result of the “Neutrino-4” experiment and the result of the BEST experiment $\sin^2 2\theta_{14} = 0.32 \pm 0.08_{\text{stat}}$, one can obtain a refinement of the oscillation amplitude $\sin^2 2\theta_{14} = 0.33 \pm 0.07$ (4.9$\sigma$). It was shown that the results of the above-mentioned direct experiments on the search for sterile neutrinos are consistent within the framework of the 3+1 neutrino model with the available experimental accuracy. The sterile neutrino parameters make it possible to estimate the sterile neutrino mass $m_4 = (2.70 \pm 0.22) \text{ eV}$ and the effective electron neutrino mass $m_{4\nu_e} = (0.82 \pm 0.16)\text{eV}$. Finally, one can present the PMNS matrix of the 3+1 neutrino model and the flavor mixing scheme.

However, it should be noted that there is a difference in the values of $\sin^2 2\theta_{14}$ from the reactor experiments and the solar model. The main problem is the restriction on the sterile neutrino from cosmology. This paper is devoted to the possible role of the sterile neutrino in cosmology.

2. Results of the Neutrino-4 experiment in comparison to other experiments

A detailed comparison of the results of the Neutrino-4 experiment with the results of other experiments is presented in our paper [10]. Here we restrict ourselves to only two illustrations.

![Fig 1 Neutrino signal oscillation curve.](image)

In Fig. 2, the region of parameters of sterile neutrinos is highlighted in blue, and this region is determined by the experiments Troitsk, KATRIN, BEST, DANSS and The result of the experiment “Neutrino-4” is in this region: $\Delta m^2_{14} = (7.3 \pm 0.13_{\text{stat}} + 1.16_{\text{sys}}) \text{ eV}^2$, $\sin^2 2\theta_{14} = 0.36 \pm 0.12_{\text{stat}}$ The red ellipse indicates 95% confidence level in the
"Neutrino-4" experiment, taking into account the systematic error. The result of the KATRIN experiment [11,12] does not exclude the Neutrino-4 region.

Fig 2 Comparison of the results of the Neutrino-4 experiment with the results of other experiments.

3. PMNS matrix in 3+1 neutrino model

In [10] using the oscillation parameters, the PMNS matrix is presented in the 3+1 neutrino model. We plan to use the matrix parameters to further analysis the role of the sterile neutrino in cosmology:

\[
U^{(3+1)}_{PMNS} = \begin{pmatrix}
0.782^{+0.017}_{-0.016} & 0.524^{+0.017}_{-0.016} & 0.148^{+0.004}_{-0.004} \\
0.484^{+0.028}_{-0.034} & 0.473^{+0.027}_{-0.036} & 0.732^{+0.016}_{-0.025} \\
0.280^{+0.330}_{-0.120} & 0.678^{+0.705}_{-0.273} & 0.622^{+0.657}_{-0.194} \\
0.210^{+0.273}_{-0.060} & 0.060^{+0.203}_{-0.004} & 0.104^{+0.236}_{-0.035} \\
0.036^{+0.027}_{-0.016} & 0.027^{+0.035}_{-0.035} & 0.931^{+0.095}_{-0.017}
\end{pmatrix}
\]

The most important features of this scheme for mixing the flavors of active neutrinos and sterile neutrinos presented in Fig. 3 should be noted. First, the mass states \( m_1, m_2, m_3 \) are a mixture of electron, muon and tau flavors with a small fraction of the sterile state. Therefore, the \( m_1, m_2, m_3 \) mass states have a weak interaction, while the \( m_4 \) mass state is sterile in the ground state and has a weak interaction only due to the small contribution of electronic, muonic and tau flavors. As a result, the sterile neutrino \( m_4 \), after the appearance of active neutrinos as a result of oscillations and collisions with electrons, will propagate in the cosmic plasma for quite a long time before interaction and reverse transformation into an active neutrino. This circumstance creates the possibility of accumulation of sterile neutrinos and the possibility of their separation from the cosmic plasma at an early stage compared to active neutrinos.

4. Sterile neutrino role in cosmology

It is well known that the process of neutrino oscillations in matter changes as a result of the interaction of neutrinos with matter. This process is especially pronounced in space plasma. We begin our study of this process with the case of two neutrinos. Here and in the future, we will rely on the well-known review publication [13] and the monograph [14]. In the two-neutrino case, the effective mixing matrix is determined by one angle

\[
\begin{pmatrix}
|\nu_e\rangle \\
|\nu_x\rangle
\end{pmatrix} = \begin{pmatrix}
\cos \theta_m & \sin \theta_m \\
-\sin \theta_m & \cos \theta_m
\end{pmatrix} \begin{pmatrix}
|\nu_1\rangle \\
|\nu_4\rangle
\end{pmatrix}
\]

as well as neutrino flavor mixing and sterile neutrino for the direct mass hierarchy.

Fig 3 Scheme of mixing of active neutrinos and the sterile neutrino for normal mass hierarchy.

\[
\Delta m^2_{1}\approx 7.3 \text{ eV}^2
\]

\[
\Delta m^2_{3}\approx 2.45 \cdot 10^{-3} \text{ eV}^2
\]

\[
\Delta m^2_{2}\approx 7.39 \cdot 10^{-5} \text{ eV}^2
\]

The natural numbering is such, in which in vacuum the effective states pass into the corresponding mass states, like so, \(|\nu_1\rangle \rightarrow |\nu_{m1}\rangle \) and \(|\nu_4\rangle \rightarrow |\nu_{m4}\rangle\). Given that \( m_4 \gg m_1 \). In the mass basis, the neutrino Hamiltonian has the form:

\[
H = H_m + U^* V U
\]

Where \( H_m \) – energy difference related with mass, and in the mass basis the matrix has form:

\[
H_m = \text{diag}(m_1^2, m_2^2, m_3^2, m_4^2)
\]

\( V \) – interaction matrix which has the diagonal form in the flavor basis and \( U \) – mixing matrix.

For the two-neutrino case interaction matrix takes form:

\[
V = \text{diag}(V_{\nu e}, 0)
\]

\[
V_{\nu e} = -25 \cdot 3.5 \cdot m_e^2 \cdot T^4 \cdot E
\]

Here we consider only the second order part of the neutrino potential due to small value of the baryon asymmetry. The MSW effect in the Sun occurs with the potential proportional to the first order of \( G_F \) and has the form \( V = \sqrt{2} G_F (n_e - n_{\nu_e}) \) [13]. However, this potential appears in the assumption that there are no positrons in matter, which is true for the Sun, but in the early Universe the electron and positron densities are almost the same. Therefore, the first order term is cancelled out and one has to consider the second order term. In our calculations, we consider the value of the second order term (eq. 3) calculated in the work [14]. The main feature of the second order term is that it has the same negative sign for both neutrino and antineutrino. As a result, both particles have
suppressed mixing angles at the early stages, where potential energy dominates the kinetic part. That means the MSW resonance do not occur in the early Universe, the production of the sterile neutrino gradually increases with time, but mixing angle never exceed its vacuum value (see Fig 5).

The plasma parameters gradually change, and therefore the effective neutrino levels also change. At each moment of time, we consider that the neutrino energy is equal to $3.15T$, that is, the average energy for a ultra relativistic neutrino. The levels are the eigenvalues of the Hamiltonian and correspond to the states in the plasma at a given time. The difference between the levels, which determines the phase difference between propagating neutrino states in plasma, has the form:

$$E_2 - E_1 = \left( \frac{\Delta m^2 \cos(2\theta)}{2E} + V \right)^2 + \left( \frac{\Delta m^2 \sin(2\theta)}{2E} \right)^2 \right)^{1/2}$$

where $\Delta m^2_{14} = 7.3, \sin^2 2 \theta_{14} = 0.33$.

Since we consider neutrino energy to be variable quantity energy difference has a minimum in the range of $0.0025$ s.

Fig 5 The behavior of the amplitude of electron neutrino oscillation into sterile state in cosmic plasma, depending on time.

For the 4-neutrino case we consider the following potentials from the works [14,15]:

$$V_e = -3.5 \times 25 \times G_f^2 \times T^4 \times E$$
$$V_\mu = -2 \times 25 \times G_f^2 \times T^4 \times E$$
$$V_\tau = -25 \times G_f^2 \times T^4 \times E$$
$$V_s = 0$$

It is believed that only relative potential energies influence neutrino mixing. Therefore, it is possible to make all the contributions positive by setting 0 to the potential with the smallest value, that is, the potential $V_\mu$. Then the potentials will take a form:

$$V_e = 0$$
$$V_\mu = 1.5 \times 25 \times G_f^2 \times T^4 \times E$$
$$V_\tau = 2.5 \times 25 \times G_f^2 \times T^4 \times E$$
$$V_s = 3.5 \times 25 \times G_f^2 \times T^4 \times E$$

In fact, the muon potential on the temperature scale under consideration gradually changes. The multiplier is gradually converted from a value of 1 to 3.5 with a decrease in the number of muons in the plasma. For calculations, it is necessary to introduce vacuum angles of mixing and mass neutrino. For the masses, the values are taken: $m_1 = 0.003eV; m_2 = 0.0091eV; m_3 = 0.0502eV; m_4 = 2.7eV$, so that $m_2^2 - m_1^2 = 7.38 \cdot 10^{-5} eV^2$ and $m_3^2 - m_2^2 = 2.44 \cdot 10^{-3} eV^2$.

Introducing the mixing matrix:

$$\begin{pmatrix}
0.784 & 0.525 & 0.1432 & 0.301 \\
-0.481 & 0.476 & 0.733 & 0.073 \\
0.309 & -0.693 & 0.643 & 0.1 \\
-0.245 & -0.131 & -0.17 & 0.946
\end{pmatrix}$$

And considering its change due to the interactions in the cosmic plasma, we obtain the levels of neutrino energy listed in Fig 4. Matrix elements values are using without errors, which influence will be considered further. But it should be noted that main contribution to the uncertainty of result is due to error of the $\sin^2 2 \theta_{14}$. 

Fig 4 a) Adiabatic levels for two-neutrino case, b) Difference of the energy
The interaction of neutrino with cosmic plasma radically suppresses the process of oscillations, especially in the early universe. The effective mixing matrix gradually changes from the diagonal matrix at $t = 10^{-5}$ s.

\[
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(11)

To the form which almost coincide with the vacuum mixing matrix at $t = 1$ s:

\[
\begin{bmatrix}
0.784 & 0.525 & 0.1432 & 0.301 \\
0.481 & 0.476 & 0.733 & 0.073 \\
0.309 & 0.693 & 0.643 & 0.1 \\
0.245 & 0.131 & 0.17 & 0.946
\end{bmatrix}
\]

(12)

Intermediate values:

\[
U_{\text{ef}}(10^{-4} s) = \begin{bmatrix}
1.0 & 0.0 & 0.0 \\
0.0 & 1.0 & 0.0 \\
0.0 & 0.0 & 1.0 \\
0.0 & 0.0 & 0.1
\end{bmatrix}
\]

(13)

A sharp change occurs in the region $10^{-3} - 10^{-1}$ s, in which the contributions of potential and kinetic terms become comparable.

The density of the sterile neutrino generation is determined by collisions frequency $1/\tau$ or mean free path which is proportional to the cross section and concentration $1/\tau = n_\nu \sigma$. Neglecting baryon asymmetry total rate for the electron neutrino can be expressed as [14,15]:

\[
\frac{1}{\tau_{\nu_e}} = \Gamma_{\nu_e} = \frac{137 \pi}{9} \frac{G_F^2 T^4 E}{24}
\]

(17)

For the transition $\nu_\mu \rightarrow \nu_e$ for the process rate we use:

\[
\frac{1}{\tau_{\nu_\mu}} = \frac{1}{\tau_{\nu_e}} = \frac{7 \pi}{24} G_F^2 T^4 E
\]

(18)

The dynamics of the density of sterile neutrino are influenced by three processes: 1) the expansion of the universe, 2) transition of active neutrino into sterile and 3) inverse transition of sterile neutrino into active state.

The transition of the sterile neutrino in a unit of time is considered as a two steps process: at first step the sterile neutrino oscillate into the active state with corresponding probability and then the active component take part in interaction.

This equation is applicable up to the temperatures when the neutrino freeze-out, that is, to a temperature at which the density decreases so much that the interaction of neutrino with primordial plasma can be neglected. At this point, the interaction of neutrino with a substance is terminated and only the expansion of space affects the further density dynamics. Value of $\sin^2 2\theta_{m14}$ is related with the vacuum value $\sin^2 2\theta_{m14}$ via equation (7) where due to absence of the interaction of the sterile neutrino with matter $V_{14}$ is equal to the interaction potential of the electron neutrino with plasma. Since $V_{14}$ is negative there are no MSW-resonances.

Below we present equation which taking into account $\nu_\alpha$ generation and sink of them. The equation includes the effective interaction of sterile neutrino with plasma, due to oscillations:

![Fig 7 Stages of the Universe evolution.](Image)

Fig 6 Behavior of adiabatic energy levels in the 4-neutrino system

![Fig 6](Image)

Now we are interested in the density of sterile, tau, muon and electronic neutrino at different points in time. For this, it is necessary to consider the dynamics of the processes of birth and the destruction of various types of neutrino, solving the differential equation. We consider the behavior of neutrinos in the era after the annihilation of baryons and antibaryons. In this era, the contribution to the interaction of neutrino gives the processes of scattering on electrons, positrons, neutrinos and antineutrinos, as well as the process of the annihilation of neutrino and antineutrino.

Time average probability of neutrino appearance due to oscillation is $\frac{1}{2} \sin^2 2\theta$. Probability of
\[
\frac{dn_{\nu_e}}{dt} + 3Hn_{\nu_e} = \frac{1}{2} \left( \frac{\sin^2 2\theta_{m14} n_{\nu_e}}{\tau_{\nu_e}} + \frac{\sin^2 2\theta_{m24} n_{\nu_e}}{\tau_{\nu_\mu}} + \frac{\sin^2 2\theta_{m34} n_{\nu_e}}{\tau_{\nu_\tau}} \right) n_{\nu_e} \tag{19}
\]

where \( n_{\nu_e}, n_{\nu_\mu}, n_{\nu_\tau} \) and \( n_{\nu_e} \) are sterile, electron, muon and tau neutrino density corresponding to the Fermi-Dirac distribution with zero chemical [14]. We used for the squares of the sine of the double angle the following values \( \sin^2 2\theta_{14} = 0.33, \sin^2 2\theta_{24} = 0.024 \) and \( \sin^2 2\theta_{34} = 0.043 \).

The rate of increasing the density of sterile neutrino is determined by the difference in the probability of appearance and disappearance of sterile neutrino. Both processes are proportional to the amplitude of electron neutrino oscillation into sterile neutrino (or vice versa) with a factor \( \frac{1}{2} \). The process of appearance of the sterile neutrino is proportional to the density of electronic neutrinos \( n_{\nu_e} \) and the interaction frequency of electronic neutrinos \( \frac{1}{\tau_{\nu_e}} \). The process of transition of sterile neutrino into electronic neutrino is proportional to the density of sterile neutrinos \( n_{\nu_e} \) and the interaction frequency of electron neutrinos \( \frac{1}{\tau_{\nu_e}} \). Therefore, the factor \( \frac{1}{2} \) is included in both the generation and damping of the sterile neutrino.

Electron neutrino density depends on temperature:

\[
n_{\nu_e}(T) = \frac{3}{4} \frac{\xi(3)}{\pi^2} T^3 \tag{20}
\]

This equation has Hubble parameters \( H \) which depends on the relativistic degrees of freedom. We use value 43/4 from PDG review for temperature less than muon mass. For the ultra-relativistic case the Hubble constant is related with temperature as following [14]:

\[
H(T) = \frac{T^2}{M_P^2} \tag{21}
\]

where \( M_P^2 \) is the reduced planck mass [14].

The magnitude of the plasma oscillation time is calculated by the formula

\[
\tau_{osc} = \frac{\tau_0 \sin 2\theta_m}{\sin 2\theta_0} \tag{22}
\]

where \( \tau_0 \) — period of oscillations in vacuum

\[
\tau_0 = \frac{4\pi E}{\Delta m^2} \quad \Delta m^2 — \text{The difference of squares of masses neutrino, } \sin 2\theta_m = \text{Sinus of the double angle of mixing two neutrinos in the plasma, } \sin 2\theta_0 = \text{sinus of the double angle of mixing two neutrinos in vacuum.}
\]

Fig 8 illustrates the relationship between oscillation frequency and collision frequency for neutrinos of different flavors as a function of time. The lower part of the figure shows the dependence of the amplitude of oscillations between different flavors on time. We can note the presence of three critical moments — the setting of the oscillation amplitude onto the level of the oscillation amplitude in vacuum. These critical moments are also associated with the stabilization of the oscillation frequency at the level of the vacuum oscillation frequency, which begins to increase at this moment due to a decrease in the neutrino energy due to the expansion of space. These are the moments of splitting of neutrinos from plasma — the so-called moments of neutrino “freeze-out”.

The time and temperature of freeze-out for different neutrinos can be estimated from the minima in the adiabatic levels time dependencies in Fig. 6 and from the minima of the oscillation frequency time dependencies in Fig. 8. It is at this moment the frequency and amplitude of the oscillations almost reach the level of vacuum parameters. For a sterile neutrino, freeze-out occurs at \( 3 \cdot 10^{-3} \text{ s} \), the plasma temperature is \( 1.9 \cdot 10^{11} \text{ K} \). For tau neutrinos, freeze-out occurs at \( 3 \cdot 10^{-2} \text{ s} \), and the plasma temperature is \( 6 \cdot 10^{10} \text{ K} \). For the muon neutrino, “freeze-out” occurs at \( 1 \cdot 10^{-3} \text{ s} \), and the plasma temperature is \( 3.3 \cdot 10^{10} \text{ K} \). For electron neutrinos, freeze-out occurs at \( 2 \cdot 10^{-1} \text{ s} \), and plasma temperature \( 2.3 \cdot 10^{10} \text{ K} \).

Fig 9 illustrates the rate of creation and sink of different types of neutrinos: sterile, tau and muon. It can be seen that for active neutrinos, the generation and sink rates are the same for tau neutrinos or almost the same for muon neutrinos. There is a balance between the processes of birth and destruction. The same situation arises with a sterile neutrino.
As noted earlier, “the mass states \( m_1, m_2, m_3 \)
are a mixture of electronic, muonic and tau flavors with a small fraction of the sterile state. Therefore, the \( m_1, m_2, m_3 \) mass states have a weak interaction, while the \( m_4 \) mass state is mainly sterile and has a weak interaction only due to the small contribution of electronic, muonic and tau flavors. Ratio of the density of the sterile neutrinos to the density of electron neutrino at the 1s moment is \( \sim 1 \). Ratio value is calculated with oscillation parameters from the (8).

The consequence of the considered processes is a very important result: by the time of freeze out of all neutrinos, the density of sterile neutrinos turns out to be \( \sim 1 \) to the density of electron neutrinos, while the densities of tau and muon neutrinos turn out to be the same. This result is illustrated in Fig. 10, which shows the dynamics of ratios of the densities for various neutrino pairs. The obtained ratio of densities is correct for all types of relic neutrinos.

Now we should estimate the contribution of active and sterile neutrinos to the energy density of the Universe. It is quite obvious that the contribution of the sterile neutrino is dominant due to the high density of relic sterile neutrinos and the sterile neutrino mass \( m_{\nu_4} = 2.7 \text{eV} \). The ratio of the mass of a sterile neutrino to the sum of the masses of active neutrinos is \( m_{\nu_4}/\sum m_{\nu_1\nu_2\nu_3} \), and the contribution of active neutrinos to the energy density of the Universe is [14]:

\[
\Omega_{\nu_1\nu_2\nu_3} \approx (m_{\nu_1\nu_2\nu_3}/1\text{eV}) \cdot 0.01 h^{-2}, \text{where } h \text{ is the Hubble constant.}
\]

Thus, the contribution of the sterile neutrino to the energy density of the Universe is given by the equation:

\[
\Omega_{\nu_4} \approx (\sum m_{\nu}/1\text{eV})0.01 h^{-2} \cdot n_{\nu_4} m_{\nu_4}/(\sum n_{\nu_i} m_{\nu_i})
\]

\[
n_{\nu_i} = n_{\nu_e}, \quad (\sum n_{\nu_i} m_{\nu_i}) = n_{\nu_4} \sum m_{\nu_i}
\]

\[
\Omega_{\nu_4} \approx (2.7 \text{eV}/1\text{eV}) \cdot 0.01 h^{-2} \cdot 1 \approx 0.053
\]

and it equals to 5.3\% of the total energy density of the Universe.

The fig 11 illustrates the dependence of the \( \Omega_{\nu_4} \) on the sterile neutrino parameters obtained as a result of our analysis.

As a result of the above calculation we derive an estimation of contribution of the sterile neutrino with parameters \( \Delta m^2_{\nu_4} = 7.3 \text{eV}^2 \) and \( \sin^2 2\theta_{14} = 0.33 \) to the total energy density of the Universe. The obtained value is \( \sim 5\% \) and it should be considered as a warm dark matter contribution to the present energy density. Also, within the discussed framework of the sterile neutrino density analysis we obtained the dependence of this contribution on \( \Delta m^2_{\nu_4} \) and \( \sin^2 2\theta_{14} \).

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