The result of the Neutrino-4 experiment and cosmological restrictions on sterile neutrinos

A.P. Serebrov, R.M. Samoilov, M.E. Chaikovsky, O.M. Zherebtsov

Petersburg Institute of Nuclear Physics, NRC Kurchatov Institute, 188300, Gatchina, Russia

Письма в ЖЭТФ, том 116, вып. 10, с. 644 – 658 с 2022 г. 25 ноября

ISSN 0021-3640, JETP Letters.

The 6th International Conference on Particle Physics and Astrophysics (ICPPA-2022)
Moscow, Russia, from the 29th of November to the 2nd of December

Analysis of the result of the Neutrino-4 experiment in conjunction with other experiments on the search for sterile neutrinos within the framework of the 3 + 1 neutrino model

A.P. Serebrov, R.M. Samoilov, M.E. Chaikovskii

Petersburg Nuclear Physics Institute, National Research Center Kurchatov Institute, 188300, Gatchina, Russia

hep-ex > arXiv:2112.14856

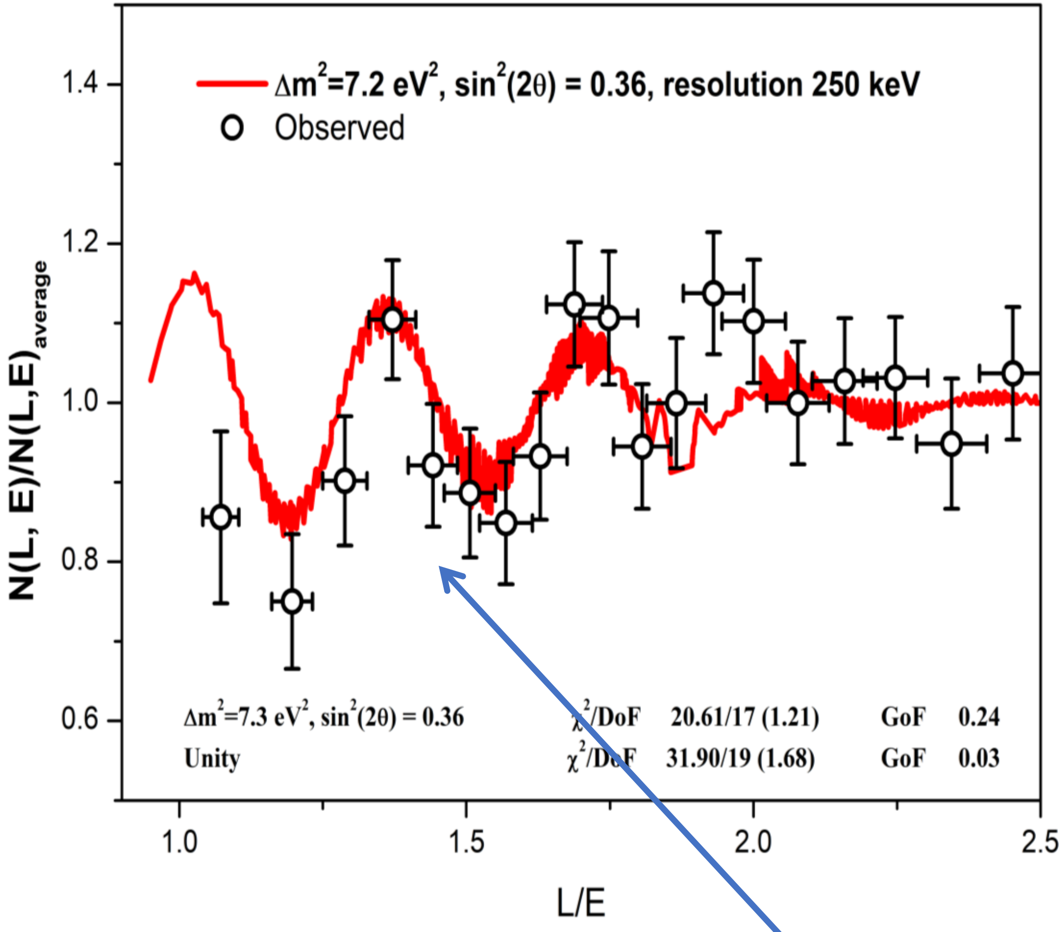
last revised 17 Nov 2022 (this version, v2)]

Submitted to JETF

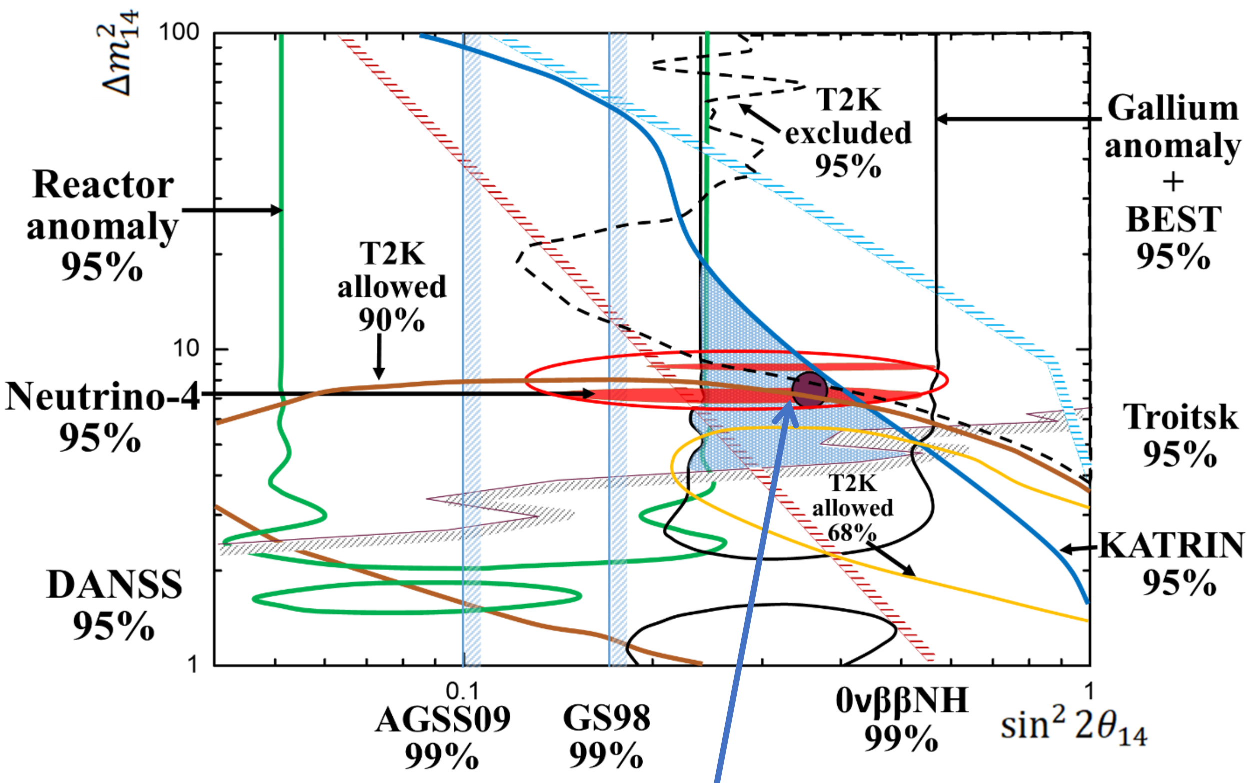
The 6th International Conference on Particle Physics and Astrophysics (ICPPA-2022)
Moscow, Russia, from the 29th of November to the 2nd of December

Oscillation curve of neutrino signal from the Neutrino-4 experiment

$$\Delta m^2_{14} = (7.3 \pm 0.13_{st} + 1.16_{sys})\ eV^2$$
$$\sin^2 2\theta_{14} = 0.36 \pm\ 0.12_{stat}\ (2.9\sigma).$$

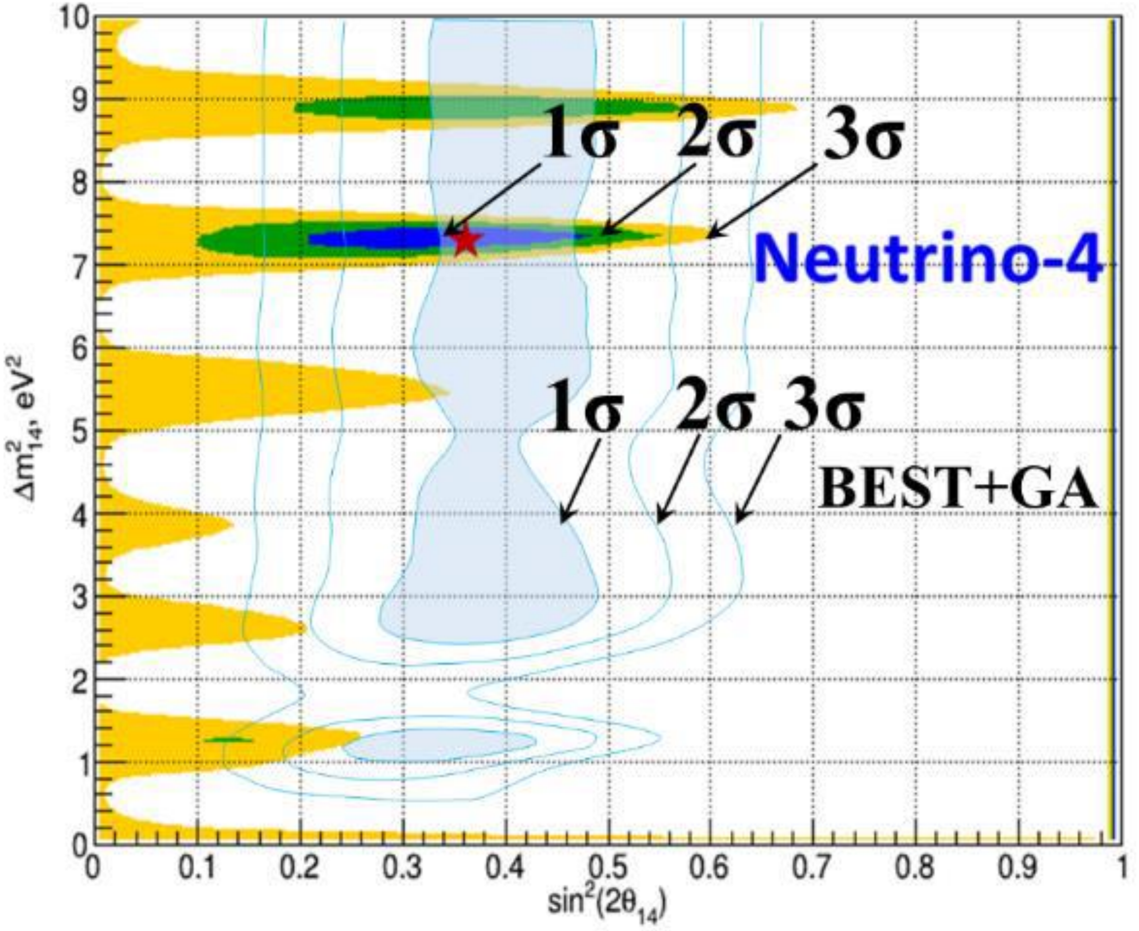


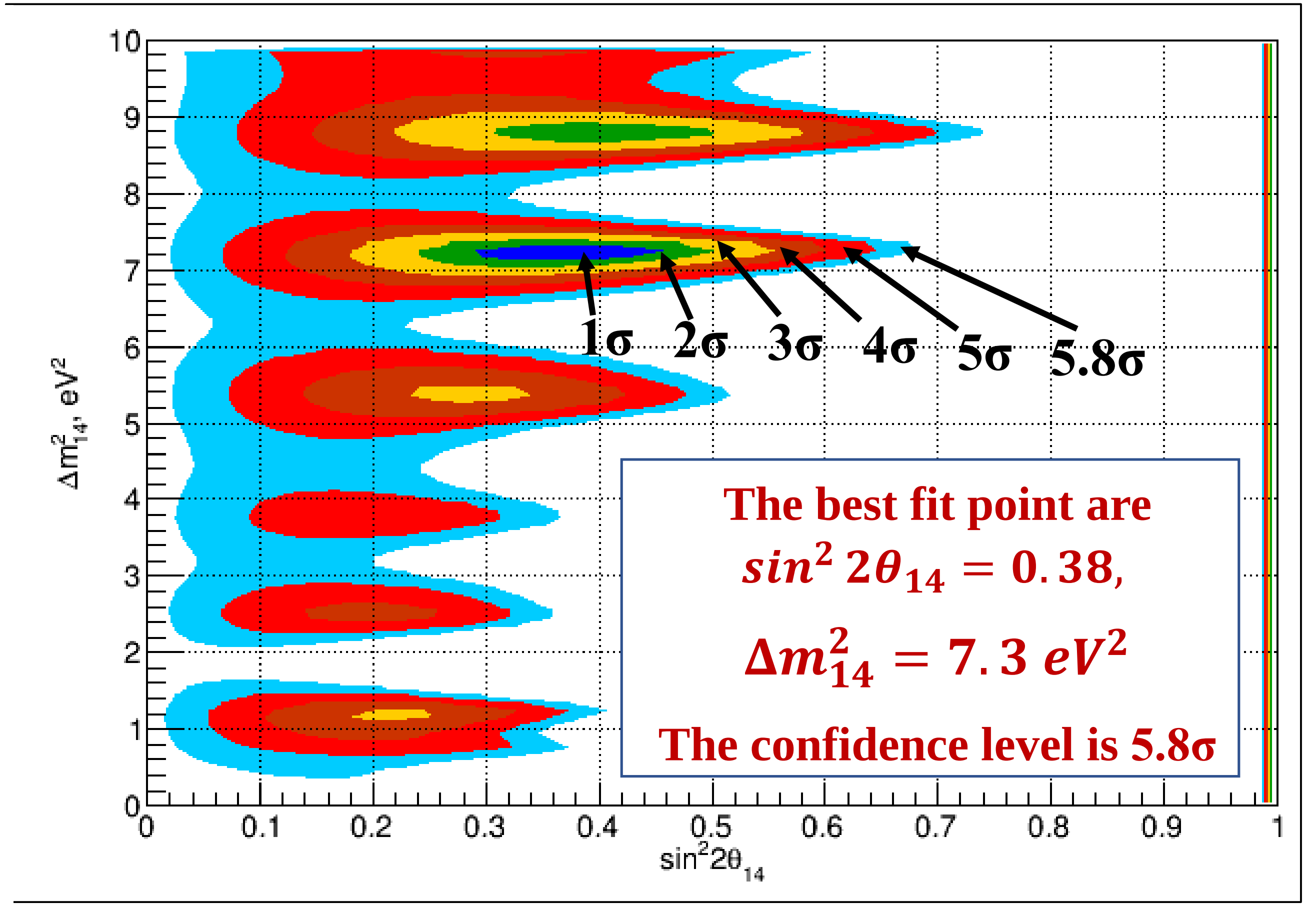
Comparison of the results of the Neutrino-4 experiment with the results of other experiments.



$\Delta m^2_{14} = 7.3\ eV^2, \sin^2 2\theta_{14} = 0.36$

Comparison of the results of the experiment Neutrino-4 with gallium anomaly (GA),

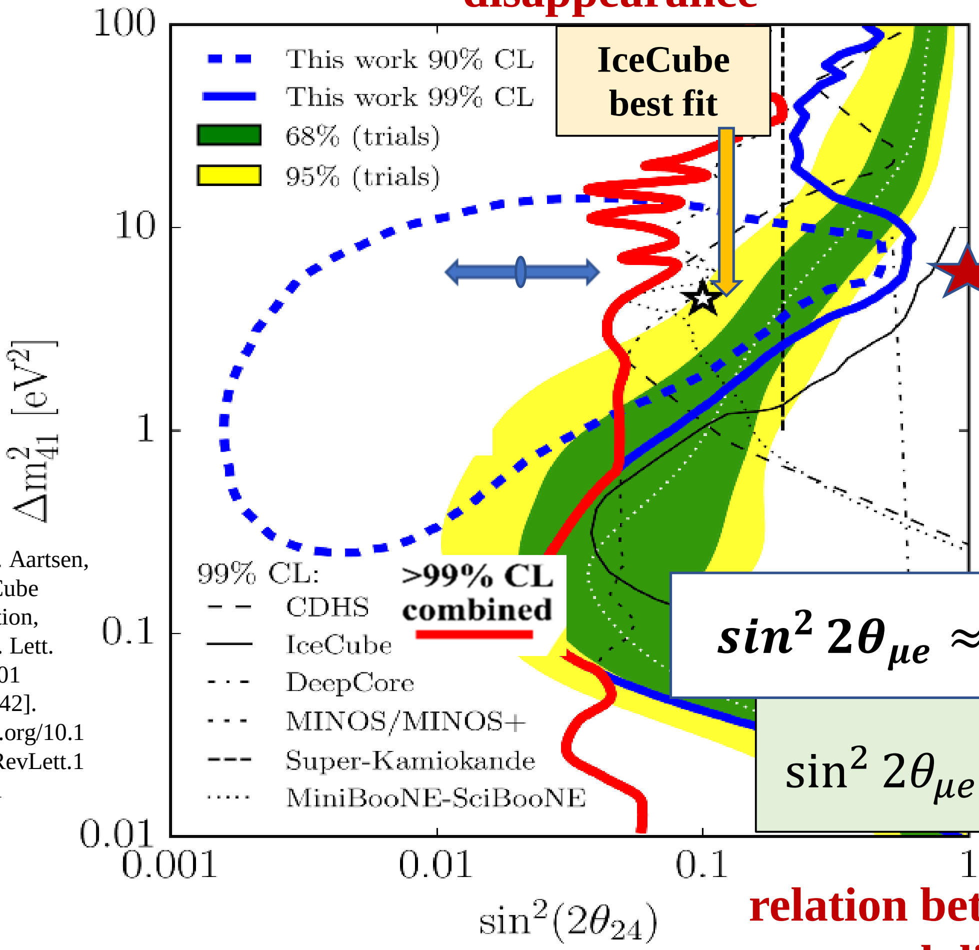




Neutrino-4 and BEST with GA **indicate the existence of sterile neutrino** with oscillation parameters: $\Delta m^2_{14} = (7.30 \pm 0.13_{st} \pm 1.16_{syst})\ eV^2$, $sin^2 2\theta_{14} = 0.35^{+0.09}_{-0.07}$

Comparison of Neutrino-4 results with IceCube and LSND, MiniBooNE results

disappearance



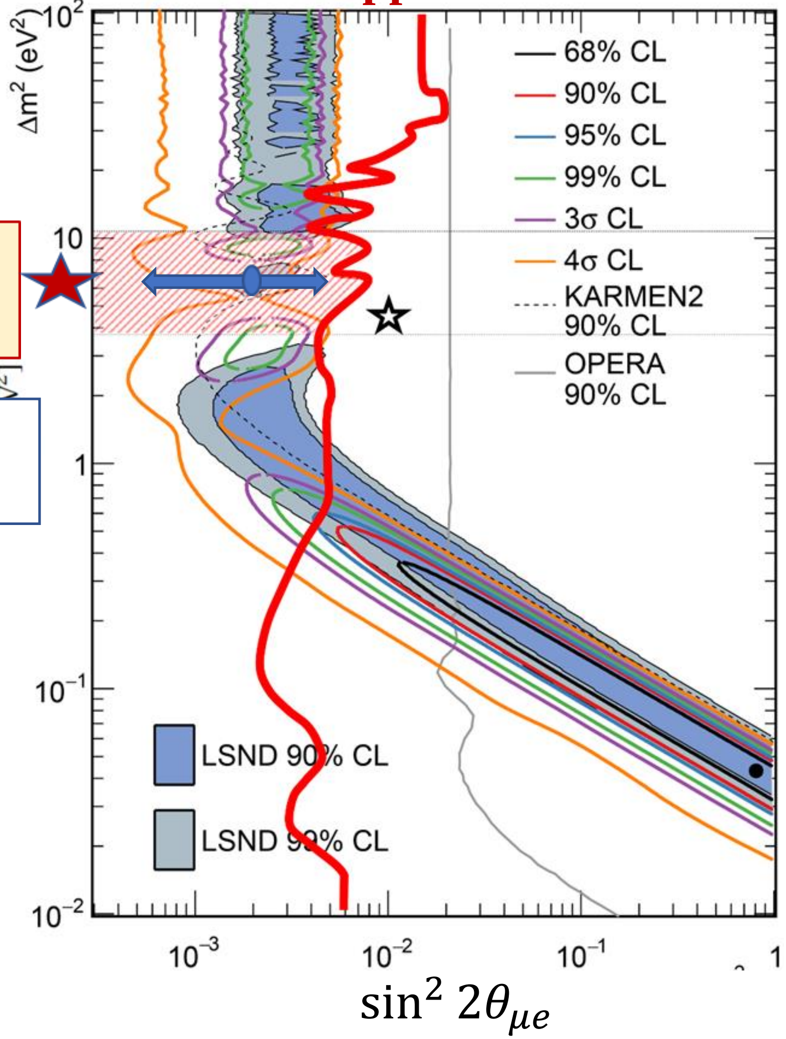
Best fit Neutrino-4 for Δm^2_{14}

[28] M. G. Aartsen, et al., IceCube Collaboration, Phys. Rev. Lett. 125, 141801 [2005.12942]. https://doi.org/10.1103/PhysRevLett.125.141801

$$\Delta m_{24} = \mathbf{4.47^{+3.53}_{-2.08}\ eV^2},\ \sin^2 2\theta_{24} = 0.10^{+0.10}_{-0.07}$$

appearance

Best fit Neutrino-4 for Δm^2_{14}



$$\boldsymbol{\sin^2 2\theta_{\mu e} \approx \frac{1}{4}\,0.027\text{x}0.36 = 0.0024}$$

$$\sin^2 2\theta_{\mu e} \approx \frac{1}{4}\sin^2 2\theta_{14}\sin^2 2\theta_{24}$$

relation between appearance and disappearance

$$\sin^2 2\theta_{24} = 0.027 \pm 0.014$$

$$\sin^2 2\theta_{24} = 0.041 \div 0.013$$

$$\sin^2 2\theta_{14} \approx 0.36 \pm 0.12$$

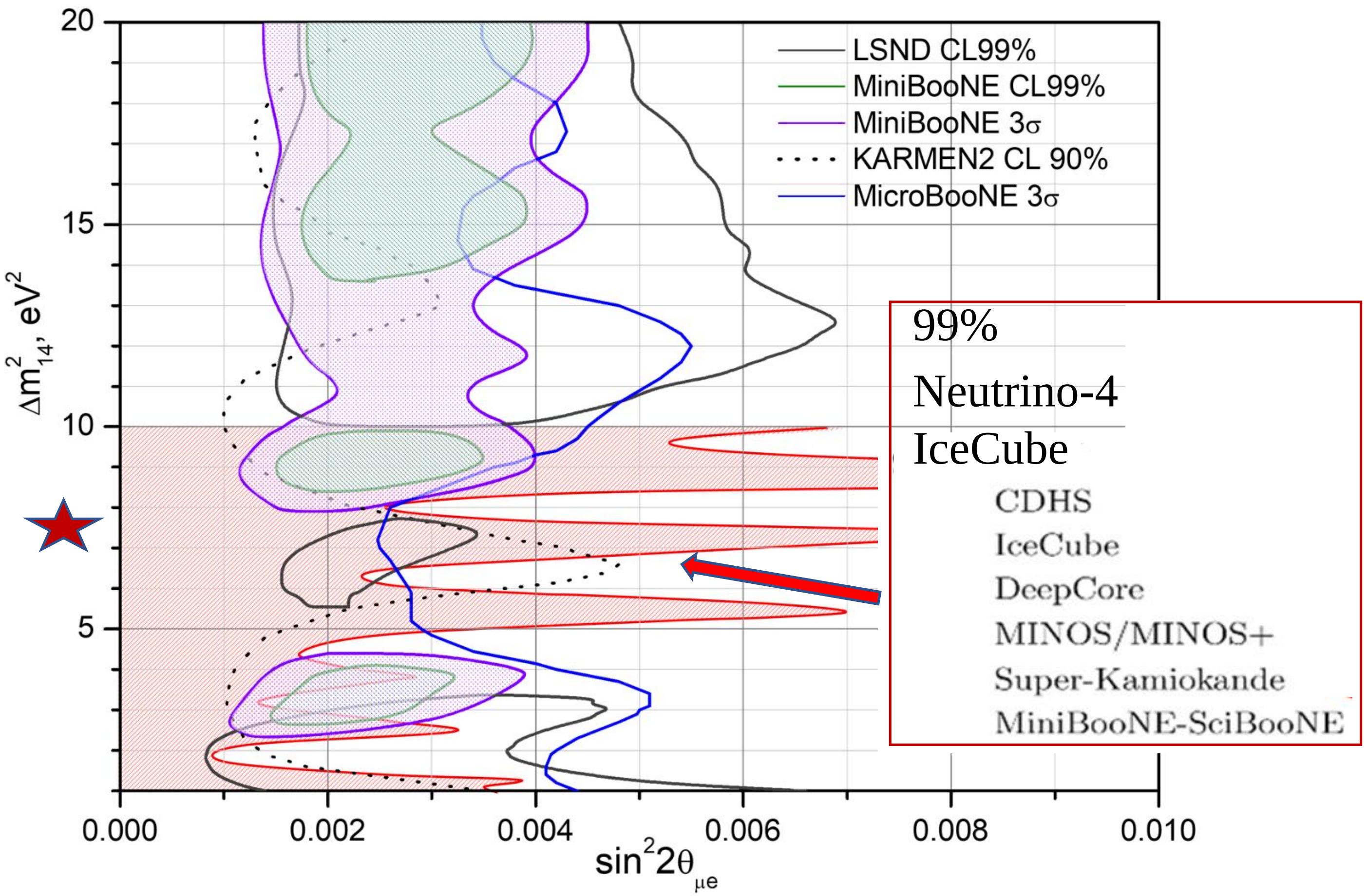
$$\boldsymbol{\sin^2 2\theta_{\mu e} \approx 0.0024 \pm 0.0016}$$

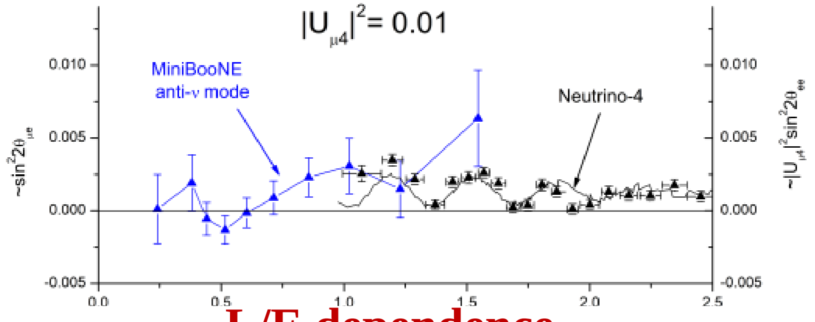
$$\boldsymbol{\sin^2 2\theta_{\mu e} \approx 0.0040 \div 0.0008}$$

[3] A. A. Aguilar-Arevalo et al., MiniBooNE collaboration, Phys. Rev. Lett. 121, 221801. https://doi.org/10.1103/PhysRevLett.121.221801.

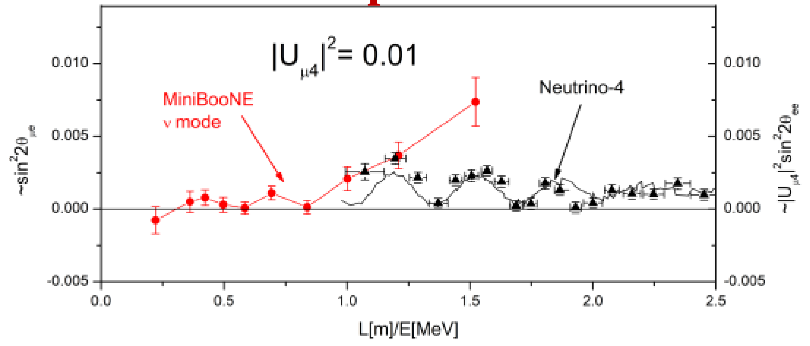
Comparison of Neutrino-4 results with LSND, MiniBooNE and MicroBooNE results

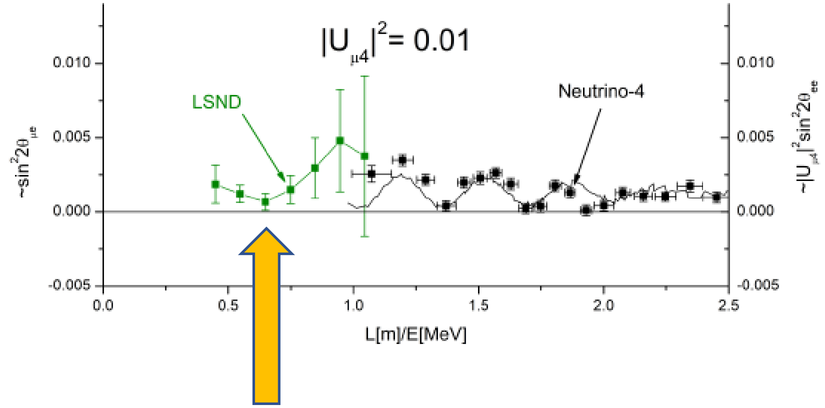
Best fit Neutino-4 for Δm^2_{14}





L/E dependence

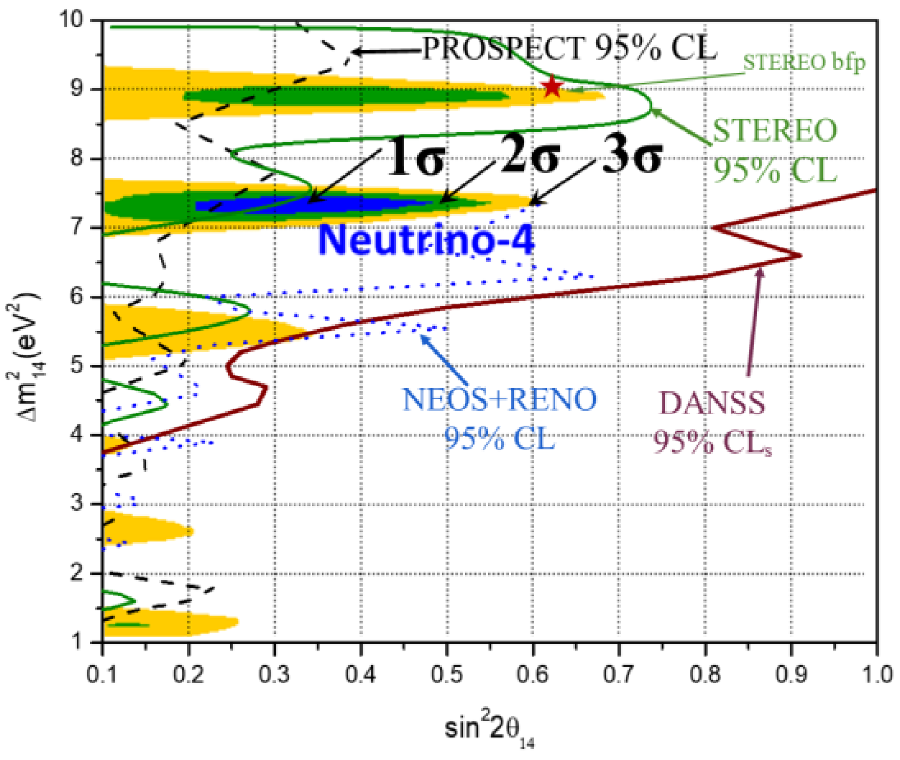


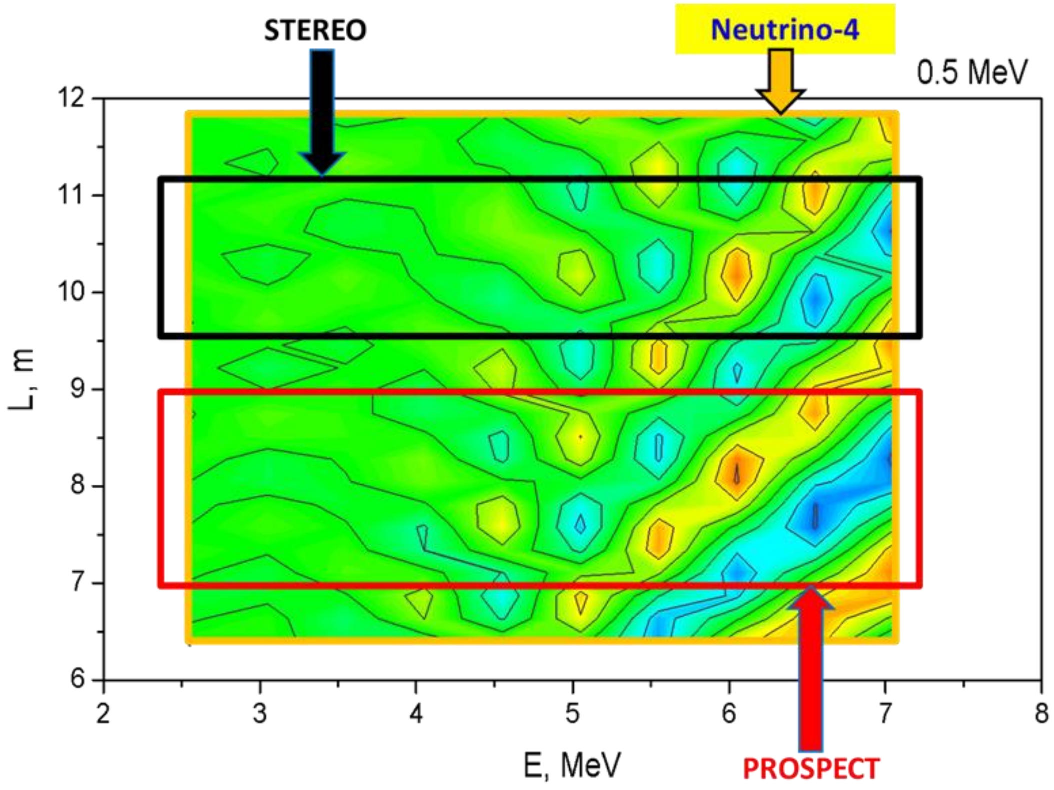


The effect of neutrino appearance in the MiniBooNE, LSND experiments with $\Delta m^2_{14} = 7.3\ eV^2, sin^2 2\theta_{14} = 0.36$ **is not excluded.**

To obtain confirmation it is necessary to have the **similar sine dependence here**

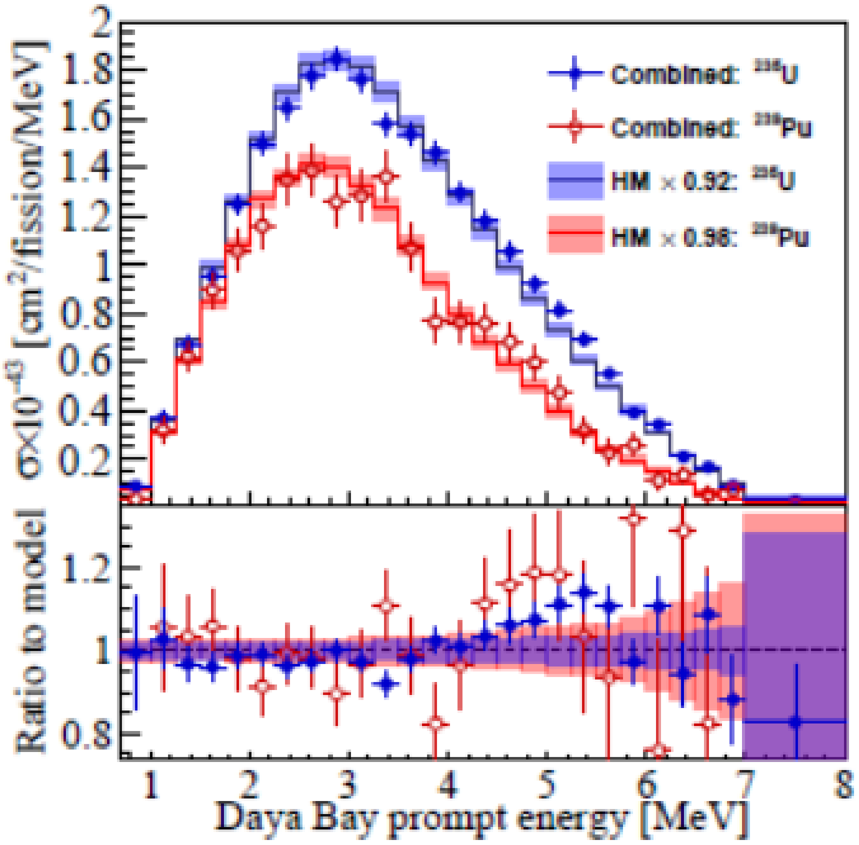
Comparison of the results of Neutrino-4 with the results of the PROSPECT, STEREO, DANSS and NEOS experiments





The talk [23] reports that the new results of the STEREO experiment exclude the 1σ region of the Neutrino-4 experiment. **We believe that the STEREO, PROSPECT experiments, should present the data in the form of the L/E dependence to compare their own results with the results of the Neutrino-4 experiment correctly. Only then the closing of the result of the Neutrino-4 experiment can be discussed.**

Reactor Antineutrino Anomaly (RAA)

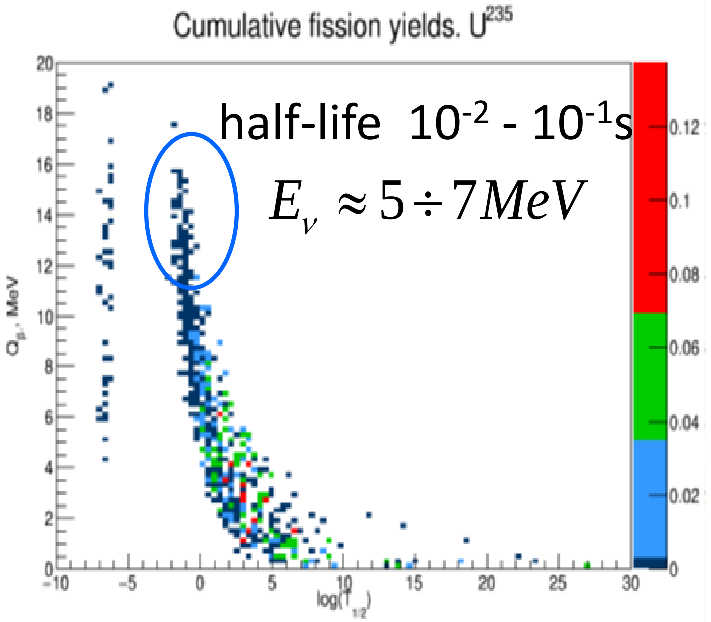


[17] F.P. An *et al.* (PROSPECT,

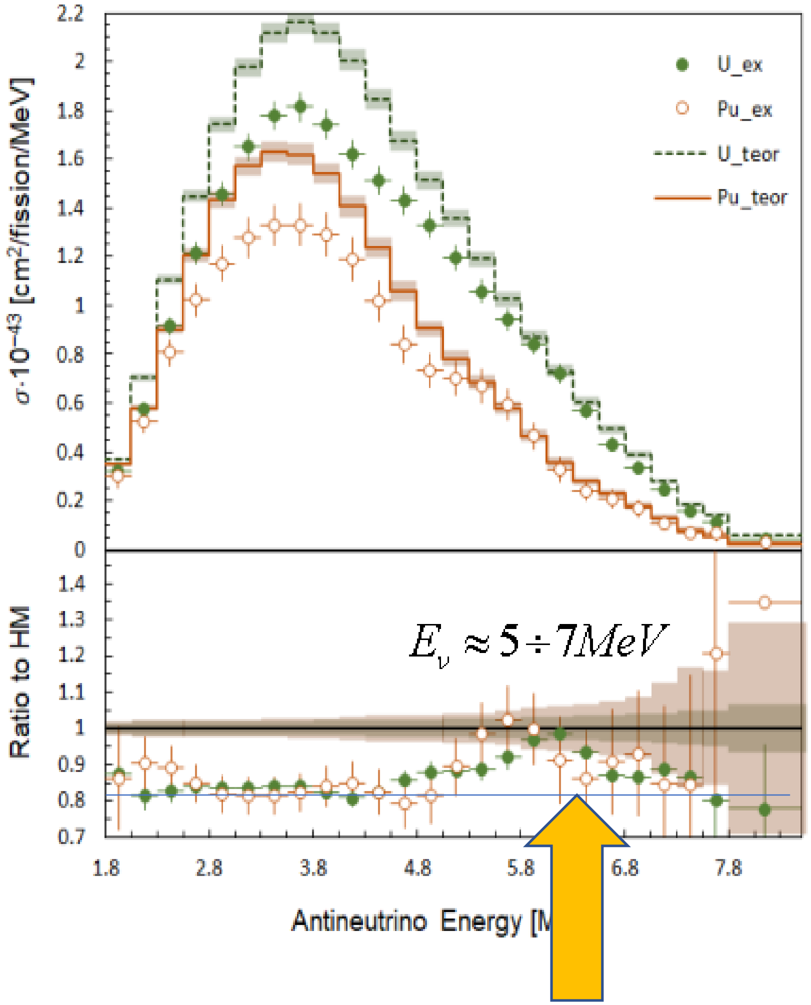
Daya Bay collaborations)

arXiv:2106.12251

Comparison of the spectra if the parameter $\sin^2 2\theta_{14} = 0.36$ is taken into consideration.

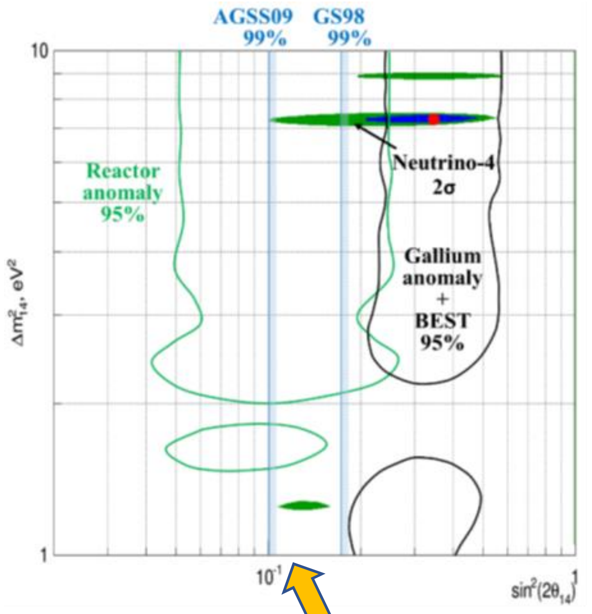


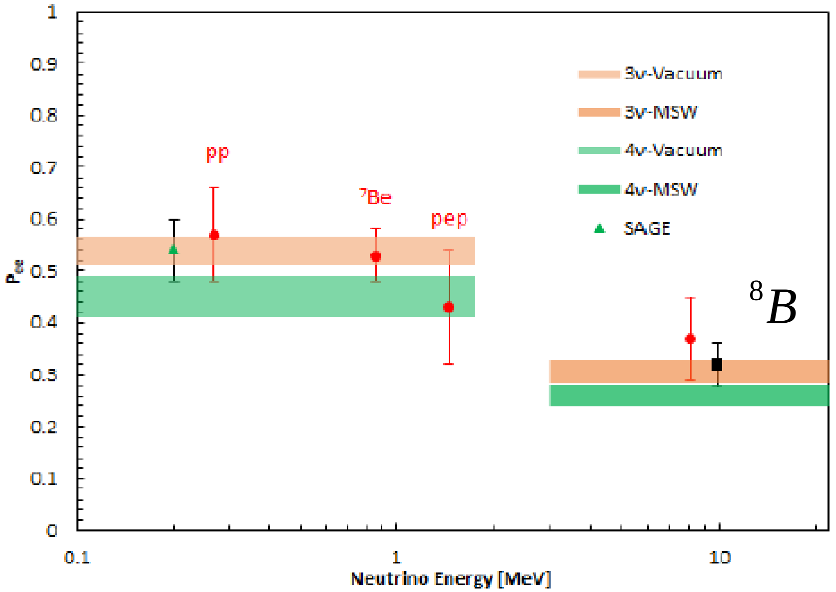
Cumulative yield of nuclides during fission of 235U depending on the decay energy and half-life.

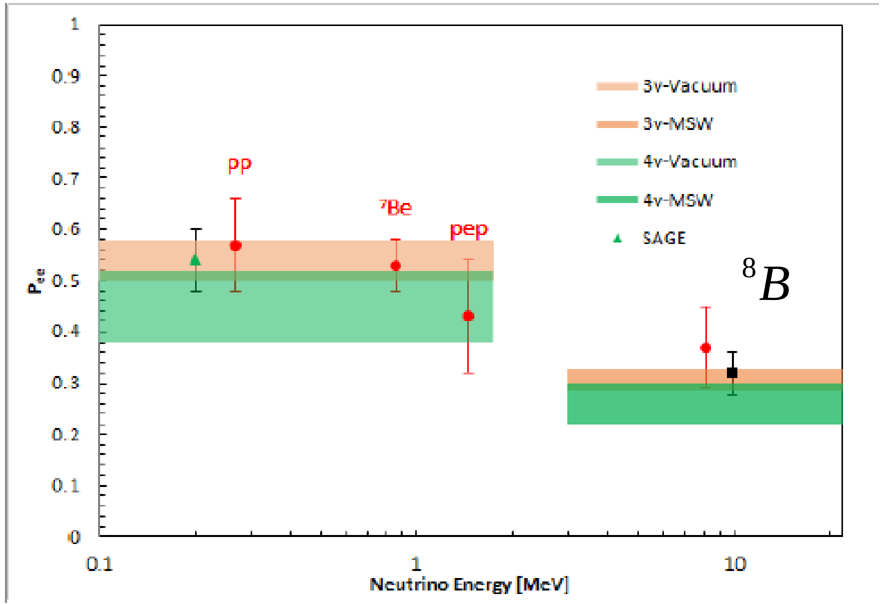


There is a socalled "bump". If there is an excess in the spectrum in the 5 MeV region, can be assumed some isotopes and decays are not taken into account.

Comparison of the results of the experiment Neutrino-4 and the solar model







Comparison of the results of the Neutrino-4 and GA with BEST experiments with **the solar model** [16].

	For quadratic addition of errors	For linear addition of errors
3ν fit	**0.13σ**	**0.12σ**
4ν fit	**1.67σ**	**0.43σ**

For quadratic addition of errors **For linear addition of errors**

[16] Kim Goldhagen, Michele Maltoni, Shayne Reichard and Thomas Schwetz, arXiv:2109.14898

Conclusions of the presented analysis

1. The results of direct experiments on the search for sterile neutrinos - **Neutrino-4 and BEST with GA indicate the existence of a sterile neutrino** with oscillation parameters: $\boldsymbol{\Delta m_{14}^2 = 7.3\ eV^2, \sin^2 2\theta_{14} = 0.38}$. **The confidence level is 5.8σ**

2. The range of values of the effect of neutrino appearance in the **MiniBooNE, LSND experiments is not excluded the existence of a sterile neutrino** with oscillation parameters: $\boldsymbol{\Delta m_{14}^2 = 7.3\ eV^2, \sin^2 2\theta_{14} = 0.38}$

3. **STEREO, PROSPECT experiments** for a correct comparison of their own results with the results of the Neutrino-4 experiment **should present the data in the form of the L/E dependence.** Only then we can discuss the closure or confirmation of the result of the Neutrino-4 experiment.

4. The claimed contradiction with **solar models still contain significant uncertainties**

The result of the Neutrino-4 experiment and cosmological restrictions on sterile neutrinos

A.P. Serebrov, R.M. Samoilov, M.E. Chaikovsky, O.M. Zherebtsov

Petersburg Institute of Nuclear Physics, NRC Kurchatov Institute, 188300, Gatchina, Russia

Письма в ЖЭТФ, том 116, вып. 10, с. 644 – 658 с 2022 г. 25 ноября

ISSN 0021-3640, JETP Letters.

The 6th International Conference on Particle Physics and Astrophysics (ICPPA-2022)
Moscow, Russia, from the 29th of November to the 2nd of December

STRUCTURE OF THE 3 + 1 NEUTRINO MODEL AND PRESENTATION OF THE PROBABILITIES OF DIFFERENT OSCILLATIONS

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

$$|U_{e4}|^2 = \sin^2(\theta_{14})$$
$$|U_{\mu 4}|^2 = \sin^2(\theta_{24}) \cdot \cos^2(\theta_{14})$$
$$|U_{\tau 4}|^2 = \sin^2(\theta_{34}) \cdot \cos^2(\theta_{24}) \cdot \cos^2(\theta_{14})$$

$$P_{\nu_e \nu_e} = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2) \sin^2\left(\frac{\Delta m_{14}^2 L}{4E_{\nu_e}}\right) = 1 - \sin^2 2\theta_{ee} \sin^2\left(\frac{\Delta m_{14}^2 L}{4E_{\nu_e}}\right)$$

$$P_{\nu_\mu \nu_\mu} = 1 - 4|U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right) \sin^2\left(\frac{\Delta m_{14}^2 L}{4E_{\nu_\mu}}\right) = 1 - \sin^2 2\theta_{\mu\mu} \sin^2\left(\frac{\Delta m_{14}^2 L}{4E_{\nu_\mu}}\right)$$

$$P_{\nu_\mu \nu_e} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m_{14}^2 L}{4E_{\nu_e}}\right) = \sin^2 2\theta_{\mu e} \sin^2\left(\frac{\Delta m_{14}^2 L}{4E_{\nu_e}}\right)$$

Oscillation parameter required for comparative analysis of experimental results:

experiment $\longrightarrow$ $\boxed{\sin^2 2\theta_{ee}} \equiv \boxed{\sin^2 2\theta_{14}}$ $\longleftarrow$ **theory**

$$\boxed{\sin^2 2\theta_{\mu\mu}} = 4 \sin^2 \theta_{24} \cos^2 \theta_{14} (1 - \sin^2 \theta_{24} \cos^2 \theta_{14}) \approx \boxed{\sin^2 2\theta_{24}}$$

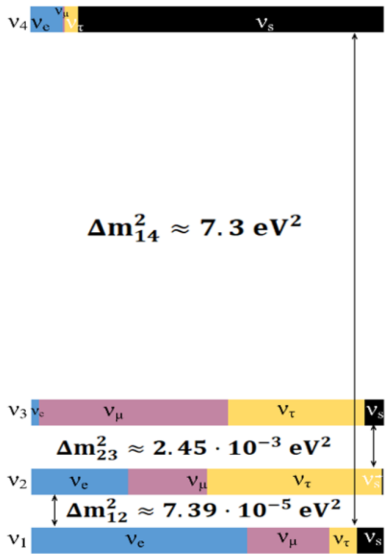
$$\boxed{\sin^2 2\theta_{\mu e}} = 4 \sin^2 \theta_{14} \sin^2 \theta_{24} \cos^2 \theta_{14} \approx \boxed{\frac{1}{4} \sin^2 2\theta_{14} \sin^2 2\theta_{24}}$$

PMNS matrix in the 3+1 neutrino model

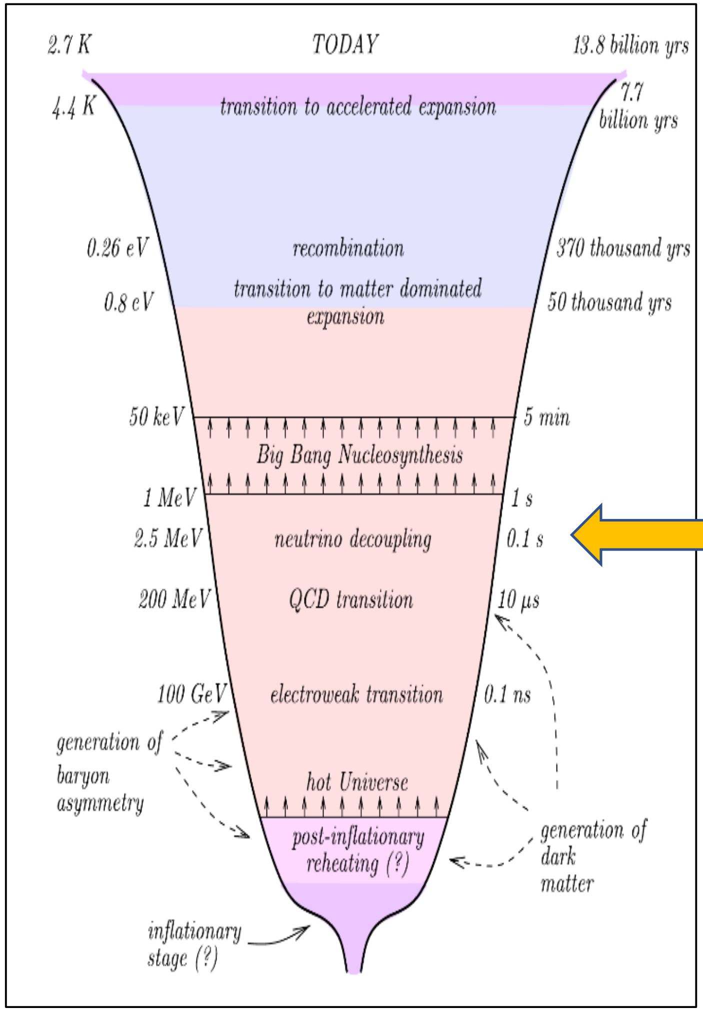
Stages of development of the Universe

Our calculations

$$U_{PMNS}^{(3+1)} = \begin{pmatrix} 0.782^{+0.017}_{-0.016} & 0.524^{+0.017}_{-0.016} & 0.148^{+0.004}_{-0.004} & \boxed{0.301^{+0.035}_{-0.035}} \\ 0.484^{+0.028}_{-0.034} & 0.473^{+0.027}_{-0.036} & 0.732^{+0.016}_{-0.025} & \boxed{0.074^{+0.021}_{-0.021}} \\ 0.280 \div 0.330 & 0.678 \div 0.705 & 0.622 \div 0.657 & \boxed{0 \div 0.194} \\ 0.210 \div 0.273 & 0.060 \div 0.203 & 0.104 \div 0.236 & \boxed{0.931 \div 0.951} \end{pmatrix}$$



The sterile neutrino m_{ν_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.



The process of neutrino oscillations in matter changes as result of the interaction of neutrinos with matter. **This process is especially pronounced in plasma.**

General statements

We begin our study of this process with the case of two neutrinos.

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_s\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m & \cos\theta_m \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_4\rangle \end{pmatrix}$$

$$|\nu_e(t)\rangle = \exp(-iE_i t)|\nu_e(0)\rangle = \exp(-iE_1 t)\cos\theta|\nu_1\rangle +$$

$$+ \exp(-iE_2 t)\sin\theta|\nu_2\rangle\,,$$

$$P(\nu_e \leftrightarrow \nu_e) = |\langle\nu_e|\nu_e\rangle|^2 = 1 - \sin^2(2\theta)\sin^2\left[\frac{1}{2}(E_2 - E_1)t\right]$$

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

in the matter

$$\frac{\Delta m^2\cos(2\theta)}{2E} >> V$$

$$E_2 - E_1 = \frac{m_2^2 - m_1^2}{2E_\nu} = \pm\frac{\Delta m^2}{2E_\nu}\,,$$

in a vacuum

The neutrino potential is formed from the contributions of the first and secondorder by constant G_F

$$\boxed{T[eV] \sim \frac{887734}{\sqrt{t[s]}}}$$

$$V = \pm C_1 \eta G_F T^3 - C_2 \frac{G_F^2 T^4 E}{\alpha}$$

$$E = 3.15T$$

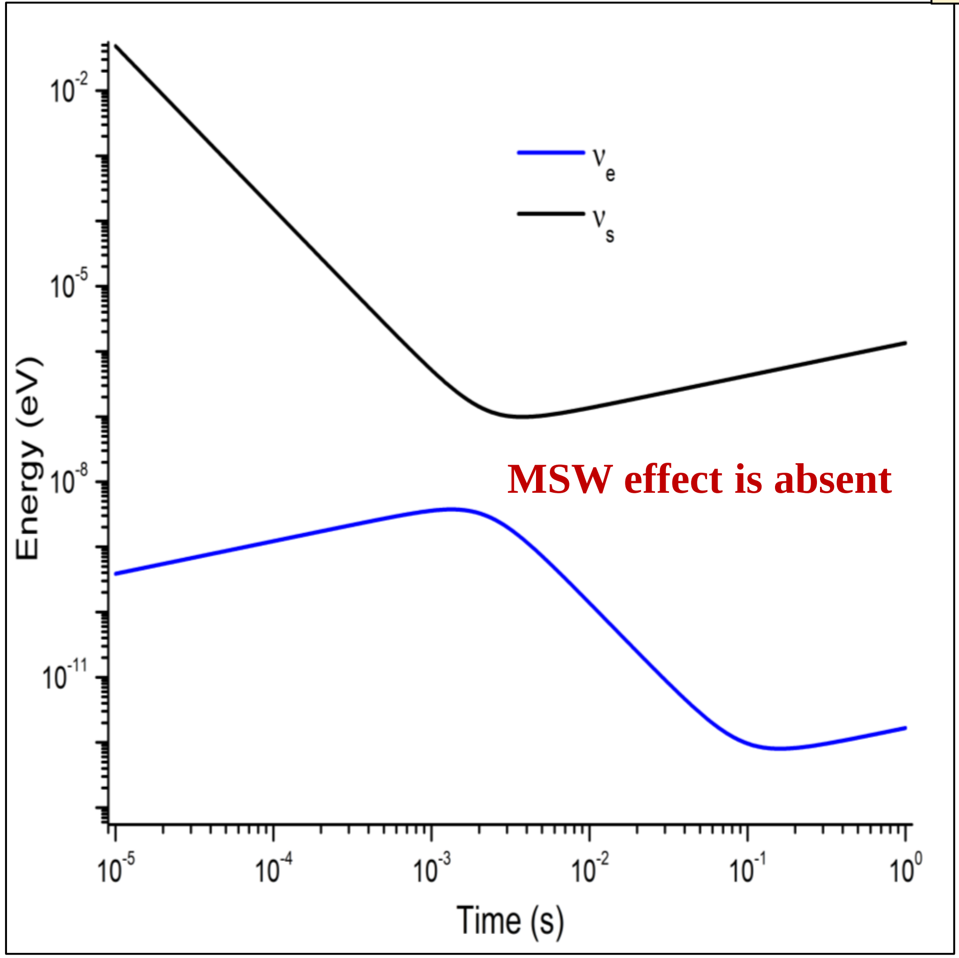
The sign of the first term is different for particles and antiparticles, but it depends on parameter η, which is responsible for the difference between particles and antiparticles. This contribution dominates in the Sun and leads to the resonant MSW effect. **But in the primary plasma, particles and antiparticles are approximately the same, therefore, in the region we are considering, we can restrict ourselves to the second-order contribution in G_F^2.**

The negative potential suppresses oscillations in the region where it significantly exceeds the contribution from the mass matrix $V \gg \frac{\Delta m^2}{E}$

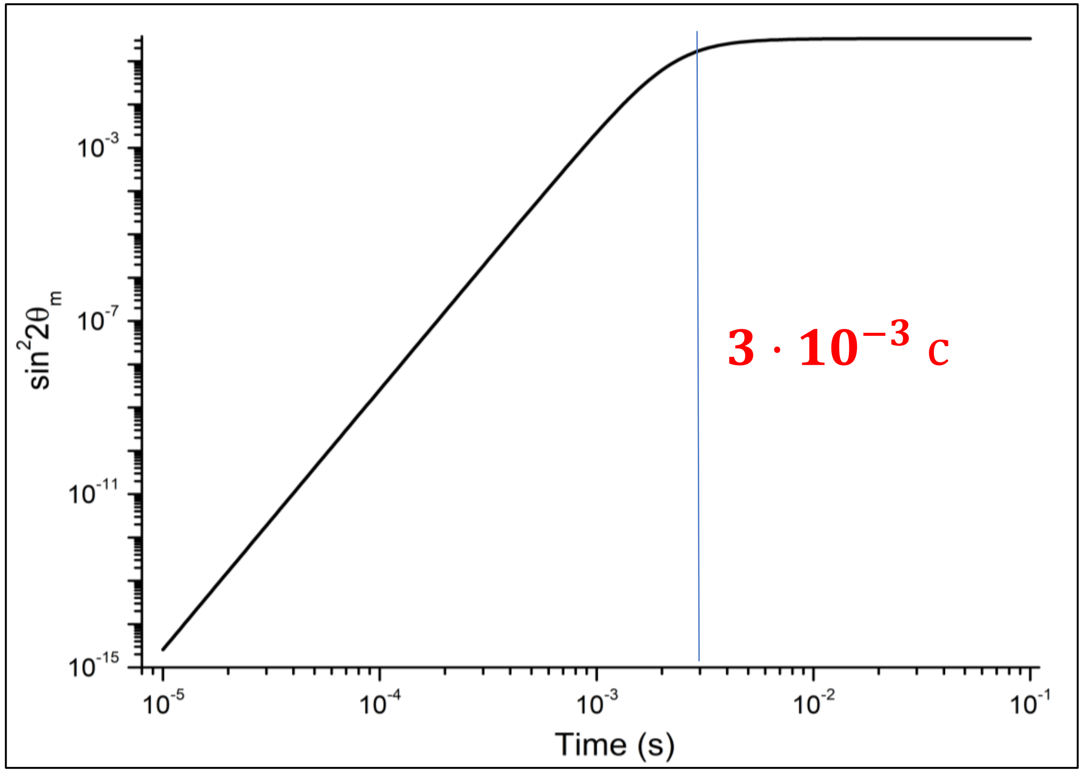
MSW effect is absent

Adiabatic energy levels in a two-neutrino system

$$\sin^2 2\theta_m = \sin^2 2\theta \cdot \left(\left(\cos 2\theta - \frac{2 \cdot E \cdot V_e}{\Delta m^2} \right)^2 + \sin^2 2\theta \right)^{-1}$$



где $\Delta m_{14}^2 = 7.3,$
$\sin^2 2\theta_{14} = 0.36.$



Behavior of the amplitude of electron neutrino oscillations to a sterile state in space plasma as a function of time.

$$U_{ef}(10^{-4}s) = \begin{pmatrix} 1. & 0. & 0. & 0. \\ 0. & 1. & 0. & 0. \\ 0. & 0. & 1. & 0. \\ 0. & 0. & 0. & 1. \end{pmatrix}$$

$$U_{ef}(10^{-3}s) = \begin{pmatrix} 0.999 & 0.007 & 0.005 & 0.044 \\ 0.008 & 1. & 0.003 & 0.017 \\ 0.006 & 0.004 & 0.999 & 0.038 \\ 0.044 & 0.017 & 0.038 & 0.998 \end{pmatrix}$$

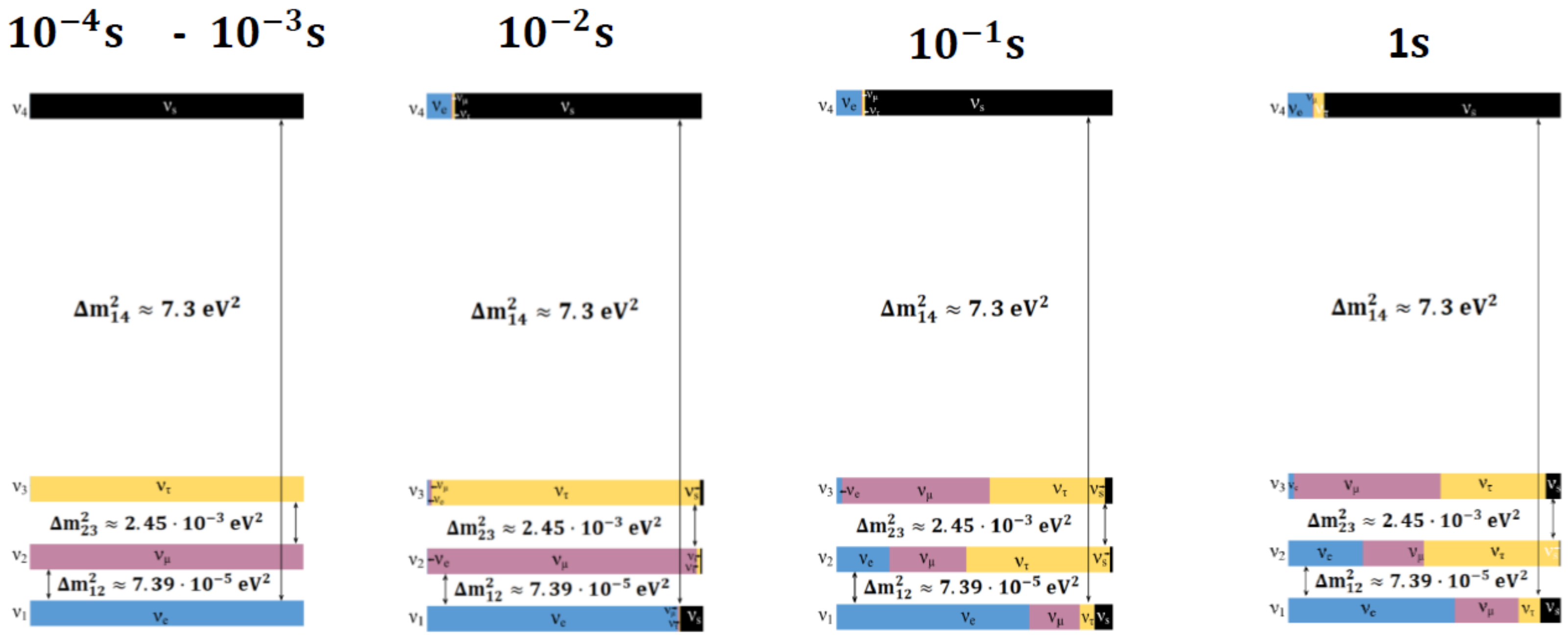
$$U_{ef}(10^{-2}s) = \begin{pmatrix} 0.953 & 0.048 & 0.024 & 0.299 \\ 0.075 & 0.988 & 0.11 & 0.073 \\ 0.05 & 0.121 & 0.986 & 0.1 \\ 0.29 & 0.079 & 0.12 & 0.946 \end{pmatrix}$$

$$U_{ef}(10^{-1}s) = \begin{pmatrix} 0.835 & 0.438 & 0.142 & 0.301 \\ 0.427 & 0.527 & 0.731 & 0.073 \\ 0.233 & 0.721 & 0.645 & 0.1 \\ 0.257 & 0.104 & 0.17 & 0.946 \end{pmatrix}$$

The interaction of neutrino with cosmic plasma radically suppresses the process of oscillations, especially at the early stages.

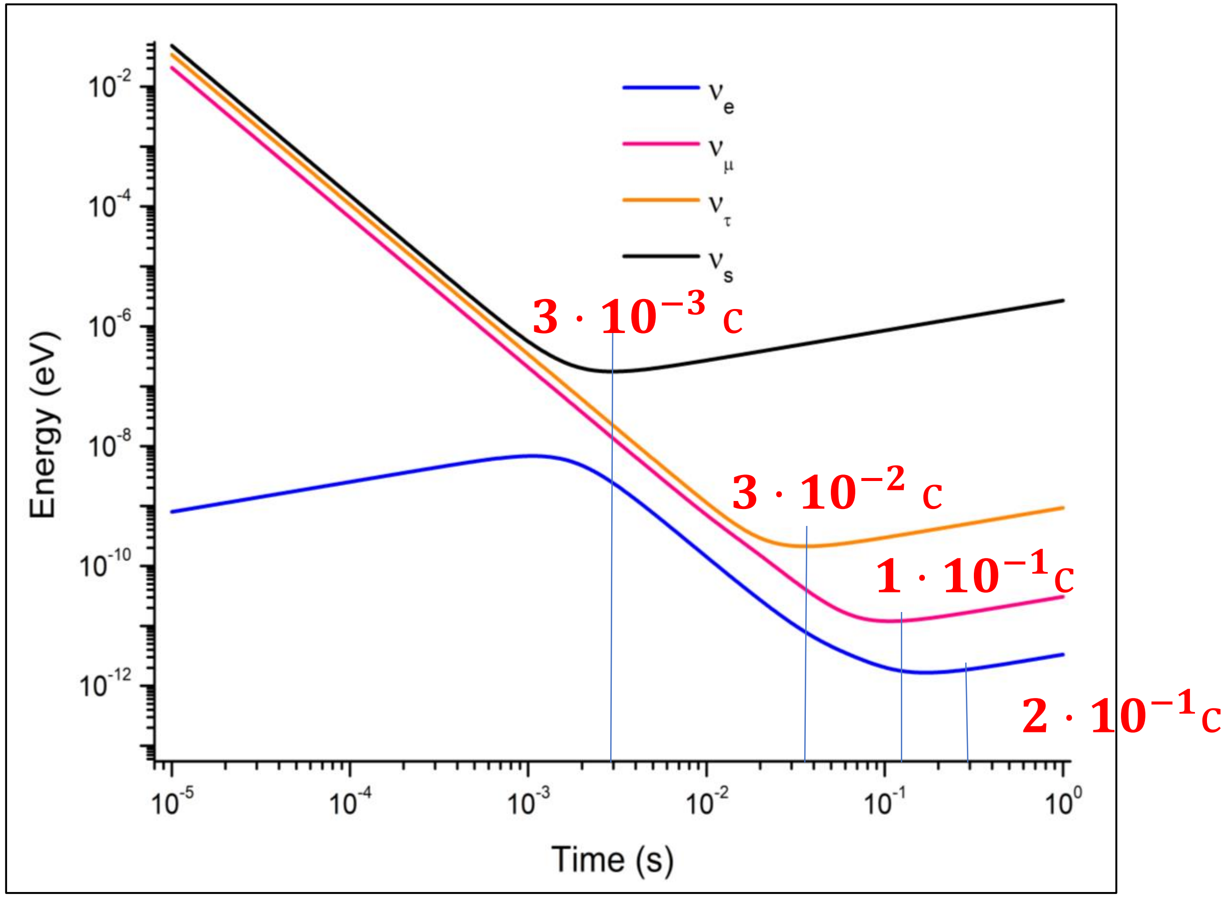
The effective mixing matrix gradually changes from the diagonal matrix at $t = 10^{-5}$ s to the form which almost coincide with the vacuum mixing matrix at $t = 1\ s$:

Scheme of mixing of active neutrinos and the sterile neutrino in time



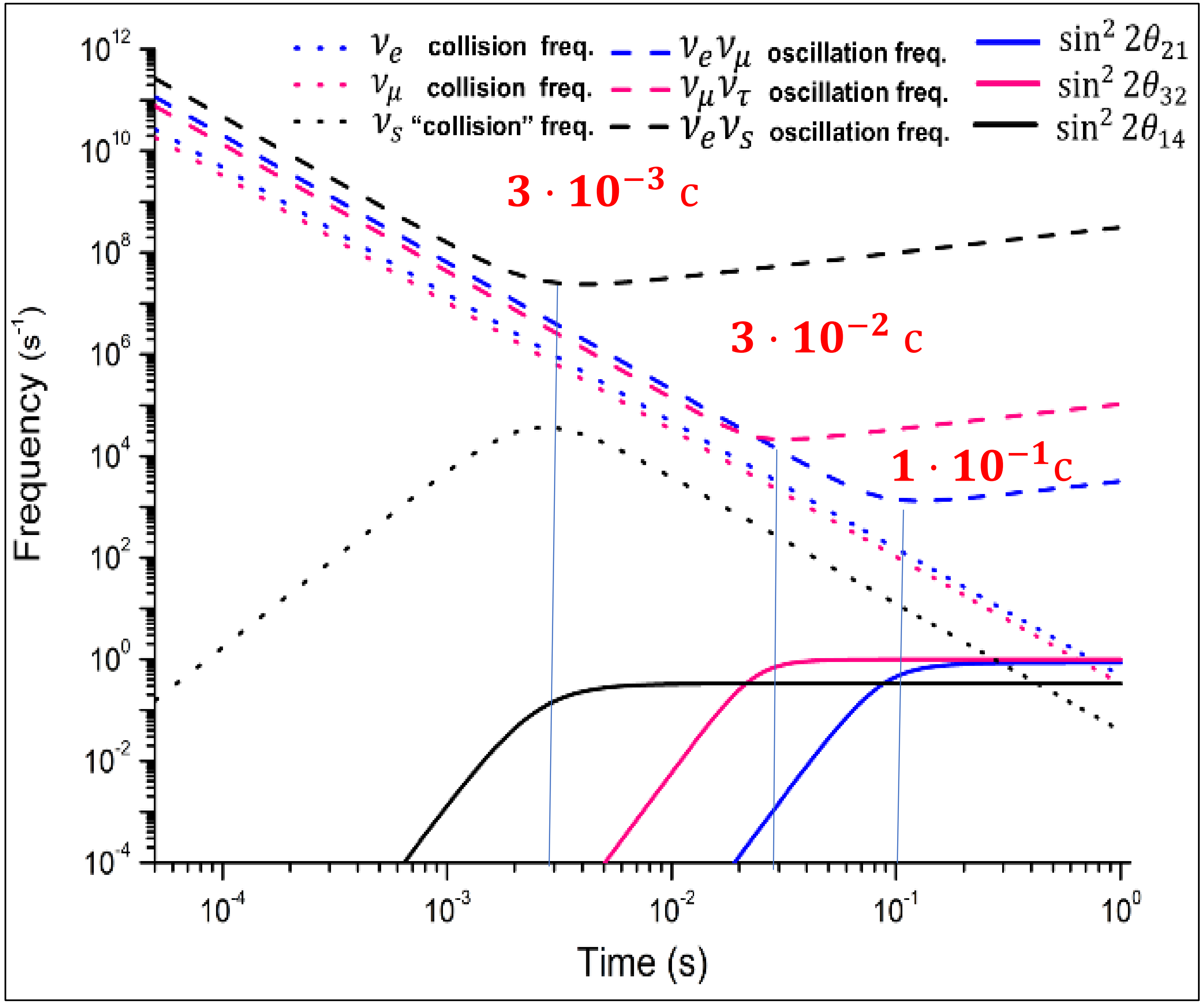
Interactions of neutrinos with cosmic plasma radically suppress the process of oscillations, especially in the early Universe.The effective mixing matrix gradually changes from a diagonal matrix $t = 10^{-5}$ s.

For a sterile neutrino, freeze-out occurs at $\mathbf{3 \cdot 10^{-3}}$ $\boldsymbol{s}$, when the plasma temperature is $1.9 \cdot 10^{11}$ K. For tau neutrinos, freeze-out occurs at $\mathbf{3 \cdot 10^{-2}}$ $\boldsymbol{s}$, when the plasma temperature is $6 \cdot 10^{10}$ K. For the muon neutrino, "freeze-out" occurs at $1 \cdot 10^{-1}$ s, when the plasma temperature is $3.3 \cdot 10^{10}$ K. For electron neutrinos, freeze-out occurs at $\mathbf{2 \cdot 10^{-1}}$ $\boldsymbol{s}$, when the plasma temperature is $2.3 \cdot 10^{10}$ K.



Behavior of adiabatic energy levels in a system of 4 neutrinos.

Collision frequency, oscillation frequency, oscillation amplitude, neutrino hardening times.



For a sterile neutrino, hardening occurs at $3 \cdot 10^{-3}$ c, and plasma temperature $1.9 \cdot 10^{11}$ K.

For tau neutrinos, hardening occurs at $3 \cdot 10^{-2}$ c and plasma temperature $6 \cdot 10^{10}$ K.

For the muon neutrino, the hardening occurs at $1 \cdot 10^{-1}$c and plasma temperature $3.3 \cdot 10^{10}$ K.

For an electron neutrino, hardening occurs at $2 \cdot 10^{-1}$c, и температуре плазмы $2.3 \cdot 10^{10}$ K.

Equality of inflow and outflow of sterile neutrino

$$\frac{dn_{\nu_s}}{dt} + 3Hn_{\nu_s} = \frac{1}{2}\left(\frac{\sin^2 2\theta_{m\,14}\, n_{\nu_e}}{\tau_{\nu_e}} + \frac{\sin^2 2\theta_{m\,24}\, n_{\nu_\mu}}{\tau_{\nu_\mu}} + \frac{\sin^2 2\theta_{m\,34}\, n_{\nu_\tau}}{\tau_{\nu_\tau}}\right) -$$

inflow

$$\frac{1}{2}\left(\frac{\sin^2 2\theta_{m\,14}}{\tau_{\nu_e}} + \frac{\sin^2 2\theta_{m\,24}}{\tau_{\nu_\mu}} + \frac{\sin^2 2\theta_{m\,34}}{\tau_{\nu_\tau}}\right) n_{\nu_s}$$

outflow

$n_{\nu_s}, n_{\nu_e}, n_{\nu_\mu}$ и n_{ν_τ} are the densities of sterile, electron, muon and tau neutrinos.

$sin^2 2\theta_{14} = 0.33$, $sin^2 2\theta_{24} = 0.024$ и $sin^2 2\theta_{34} = 0.043$.

This equation can be applied over a wide range of times if there is an equilibrium between inflow and outflow

$$\frac{dn_{\nu_s}}{dt} + 3Hn_{\nu_s} = \frac{1}{2}\left(\frac{\sin^2 2\theta_{m\,14}\, n_{\nu_e}}{\tau_{\nu_e}} + \frac{\sin^2 2\theta_{m\,24}\, n_{\nu_\mu}}{\tau_{\nu_\mu}} + \frac{\sin^2 2\theta_{m\,34}\, n_{\nu_\tau}}{\tau_{\nu_\tau}}\right) - \frac{1}{2}\left(\frac{\sin^2 2\theta_{m\,14}}{\tau_{\nu_e}} + \frac{\sin^2 2\theta_{m\,24}}{\tau_{\nu_\mu}} + \frac{\sin^2 2\theta_{m\,34}}{\tau_{\nu_\tau}}\right) n_{\nu_s}$$

$$n_{\nu_e}(T) = \frac{3}{4}\frac{\zeta(3)}{\pi^2}T^3$$

$$T[eV] \sim \frac{887734}{\sqrt{t[s]}}$$

$$\frac{1}{\tau_{\nu_e}} = \Gamma_{\nu_e} = \frac{13}{9}\frac{7\pi}{24}G_f^2 T^4 E$$

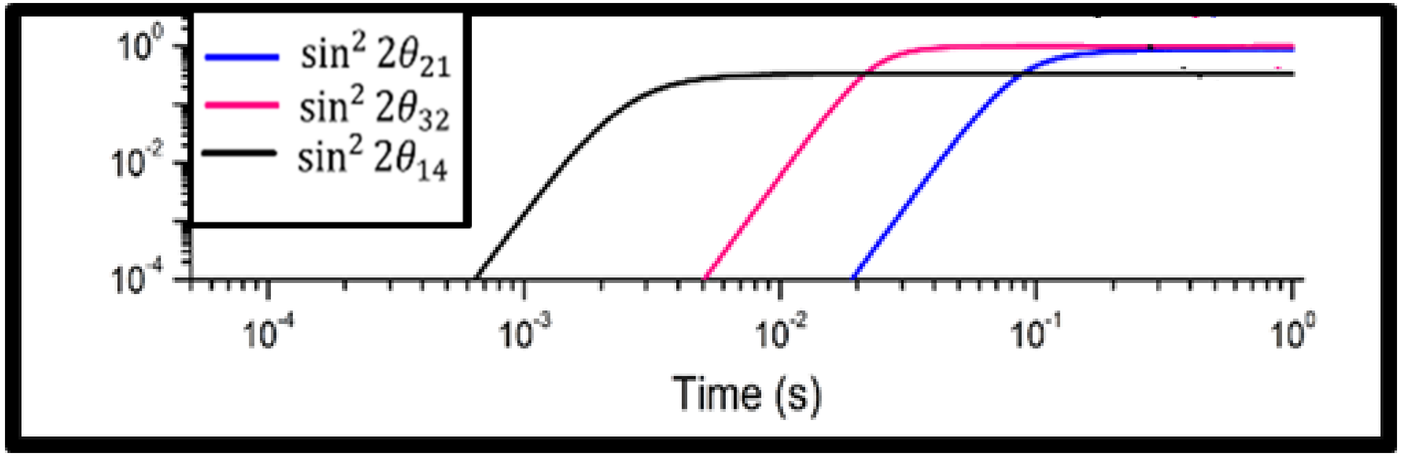
$$E = 3.15T$$

$$H(T) = \frac{T^2}{M_{Pl}^*}$$

$$T[eV] \sim \frac{887734}{\sqrt{t[s]}}$$

$$\frac{1}{\tau_{\nu_\mu}} = \frac{1}{\tau_{\nu_\tau}} = \Gamma_{\nu_\mu} = \frac{7\pi}{24}G_f^2 T^4 E$$

$$E = 3.15T$$

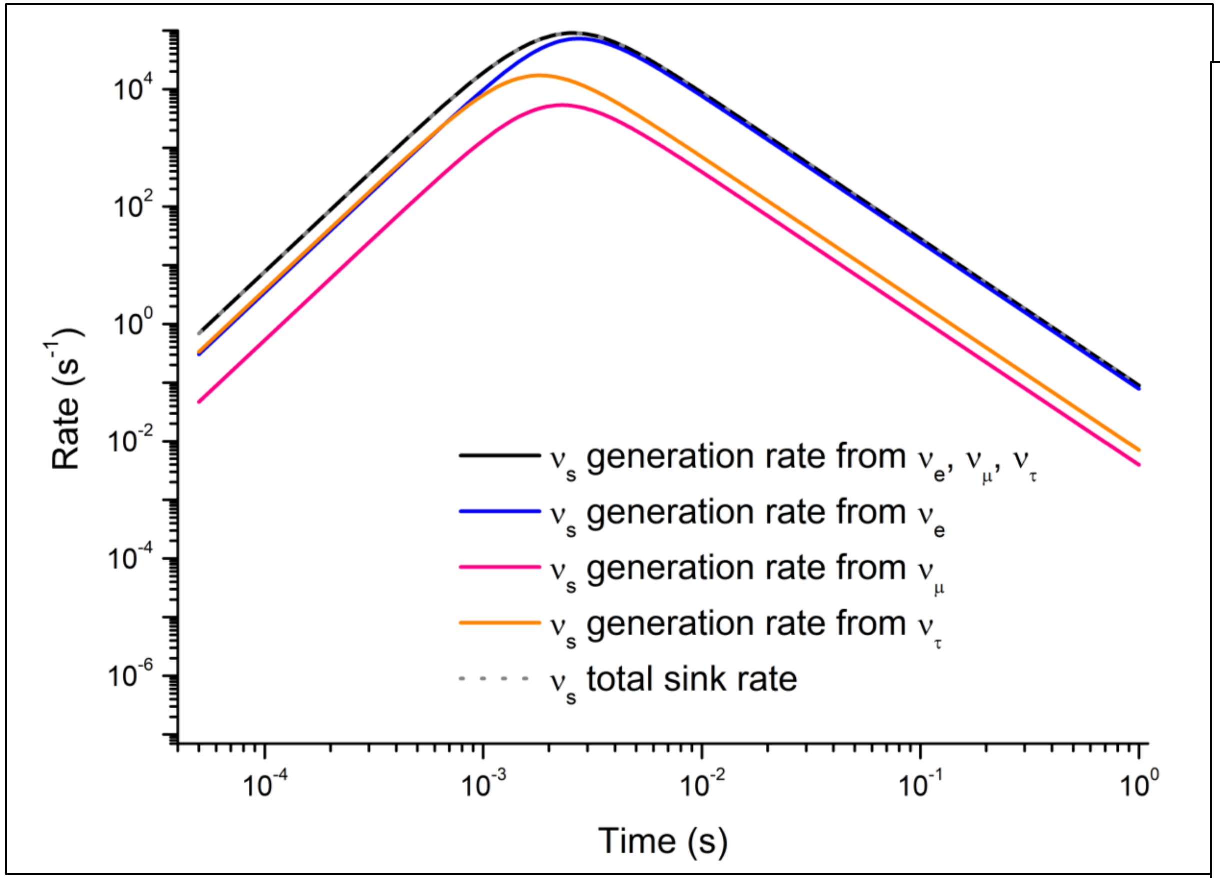


$$\tau_{osc} = \tau_0 \frac{\sin 2\theta_m}{\sin 2\theta_0}$$

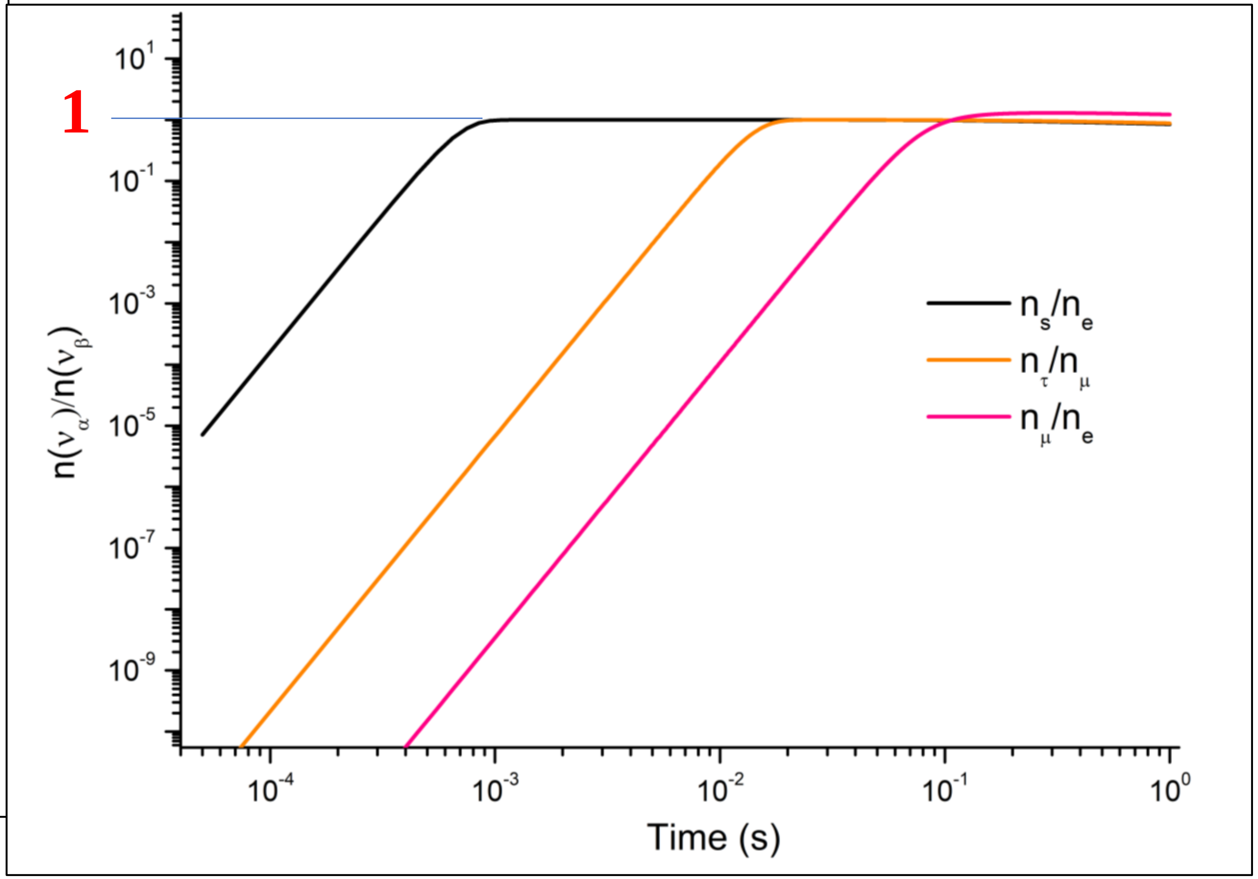
$$\tau_0 = \frac{4\pi E}{\Delta m^2}$$

$$\sin^2 2\theta_m = \sin^2 2\theta \cdot \left(\left(\cos^2 2\theta - \frac{2\cdot E \cdot V_e}{\Delta m^2}\right)^2 + \sin^2 2\theta\right)^{-1}$$

Generation and sink of sterile neutrinos



Relative neutrino densities



The generation and sink of sterile neutrinos are equal to each other. There is no pumping effect.

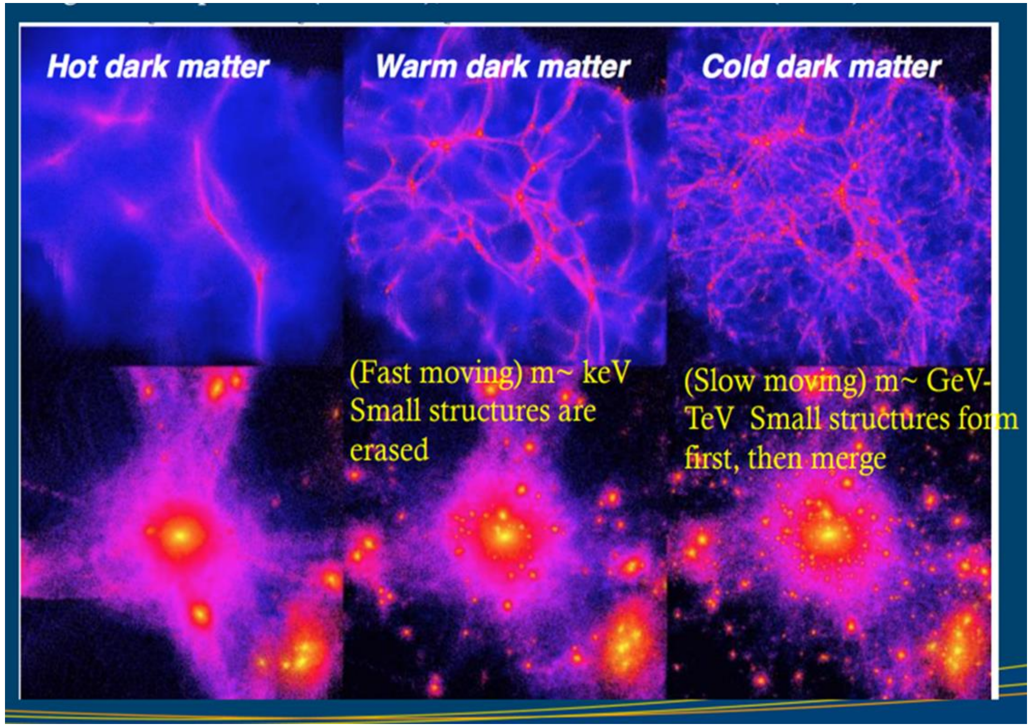
The densities of different types of neutrinos are the same.

Contribution of the Sterile Neutrino to the Energy Density of the Universe

$$\Omega_{\nu_4} \approx \left(\sum m_{\nu_i}/1eV\right)0.01h^{-2}\cdot n_{\nu_4}\, m_{\nu_4}/\sum(n_{\nu_i} m_{\nu_i})$$

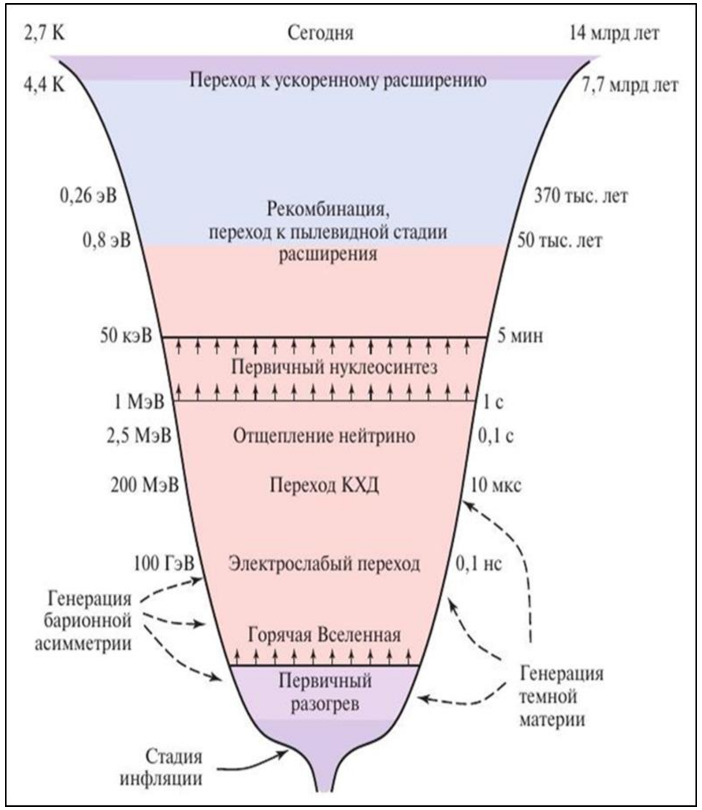
$$n_{\nu_i} = n_{\nu_e}\ , \qquad \sum(n_{\nu_i} m_{\nu_i}) = n_{\nu_e}\sum m_{\nu_i}$$

$$\Omega_{\nu_4} \approx (2.7eV/1eV)\cdot 0.01h^{-2}\cdot n_{\nu_4}/n_{\nu_e} = 5\% \qquad \boxed{n_{\nu_4}/n_{\nu_e}=1}$$

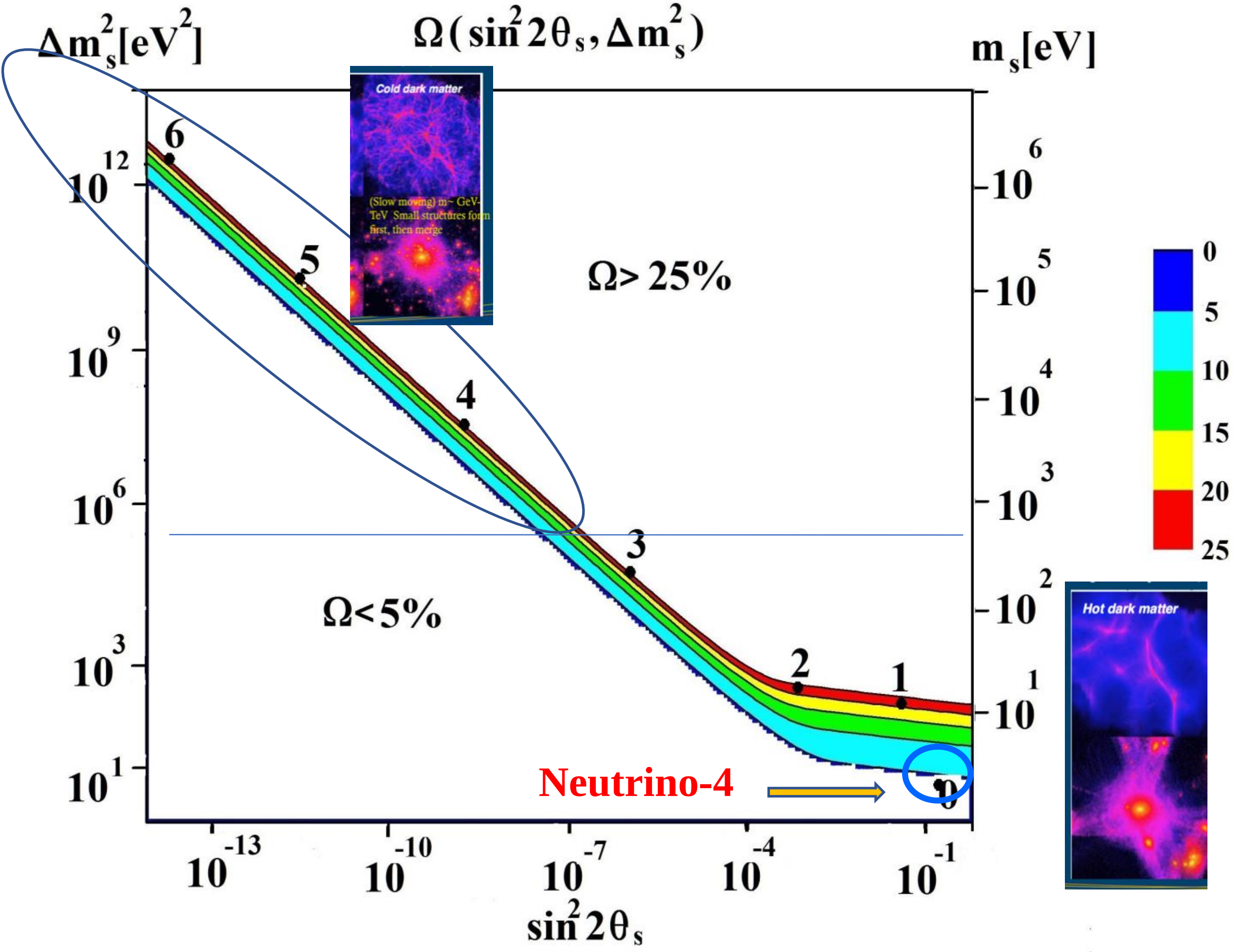


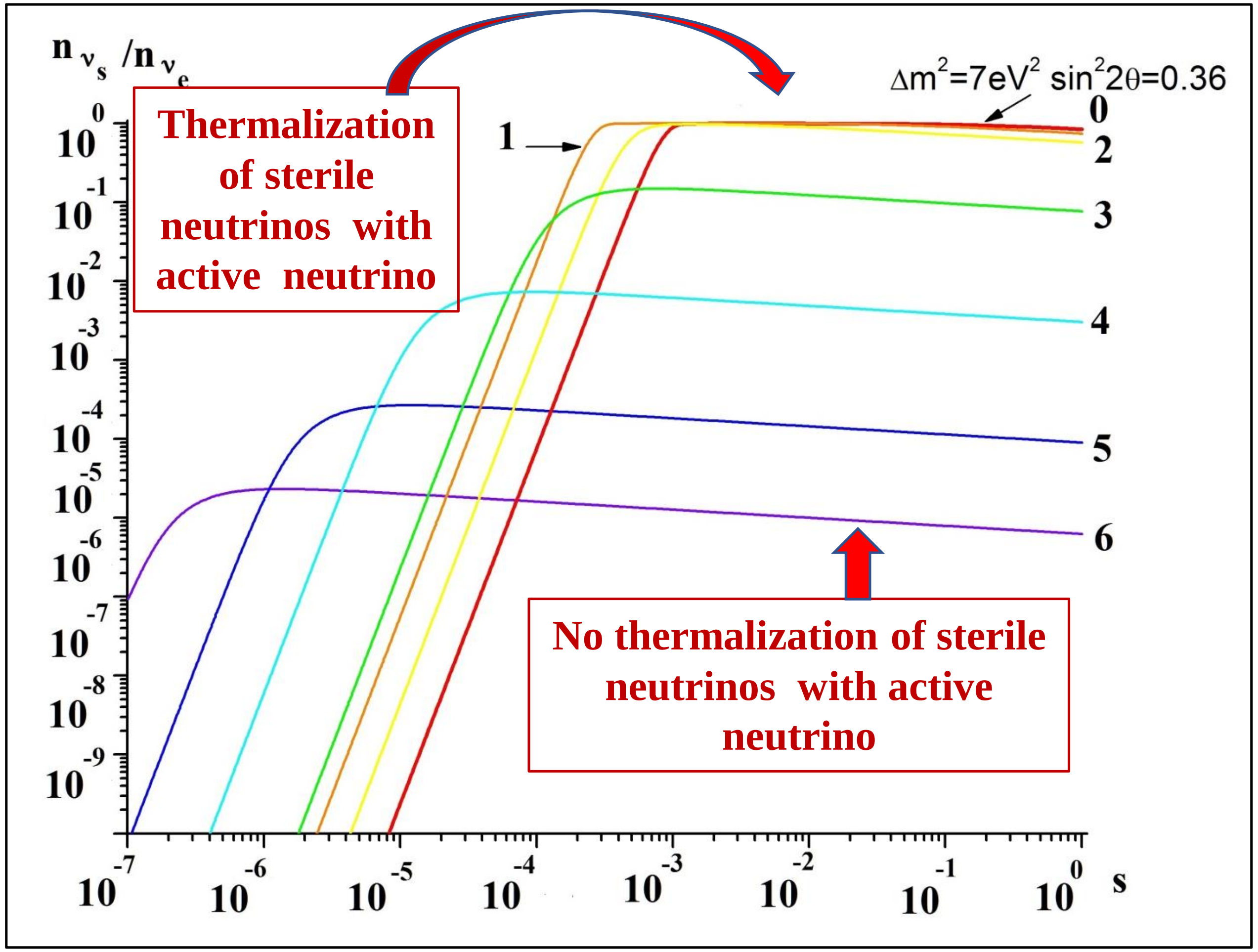
sterile neutrino with parameters $\Delta m_{14}^2 = 7.3\ eV^2$, $\sin^2 2\theta_{14} = 0.36$ does not contradict cosmology, but does not explain the structure of the universe.

We need heavy sterile neutrinos with very small mixing angles



Heavy sterile neutrinos with very small mixing angles





Heavy sterile neutrinos with very small mixing angles can be considered as warm dark matter and explain the structure of the Universe??

From the above analysis, we can conclude that heavy Dirac neutrinos should have a small mixing angle due to cosmological limitations. This means that heavy sterile neutrinos do not contribute to reactor neutrino experiments.

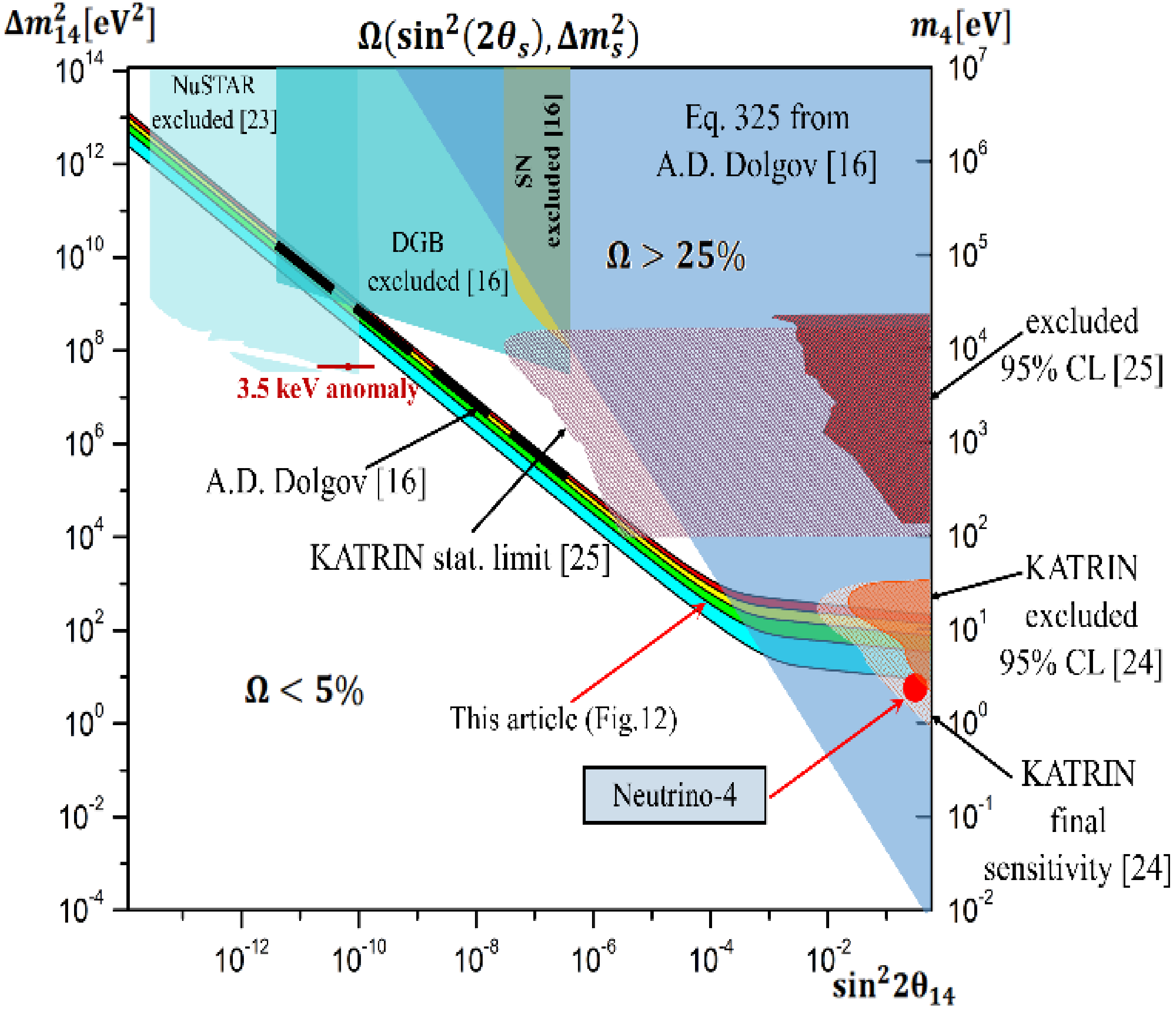
The following conclusions can also be drawn from this analysis.

1. Sterile neutrino with parameters $\Delta m_{14}^2 = 7.3\ eV^2$, $\sin^2 2\theta_{14} = 0.36$ contributes approximately 5% to dark matter, but is relativistic and does not explain the structure of the universe.

2. To explain the structure of the Universe, heavy sterile neutrinos with very small mixing angles are needed.

3. Extension of the neutrino model by introducing two more heavy sterile neutrinos will make it possible to explain the structure of the Universe and bring the contribution of sterile neutrinos to the dark matter of the Universe to the level of 27%.

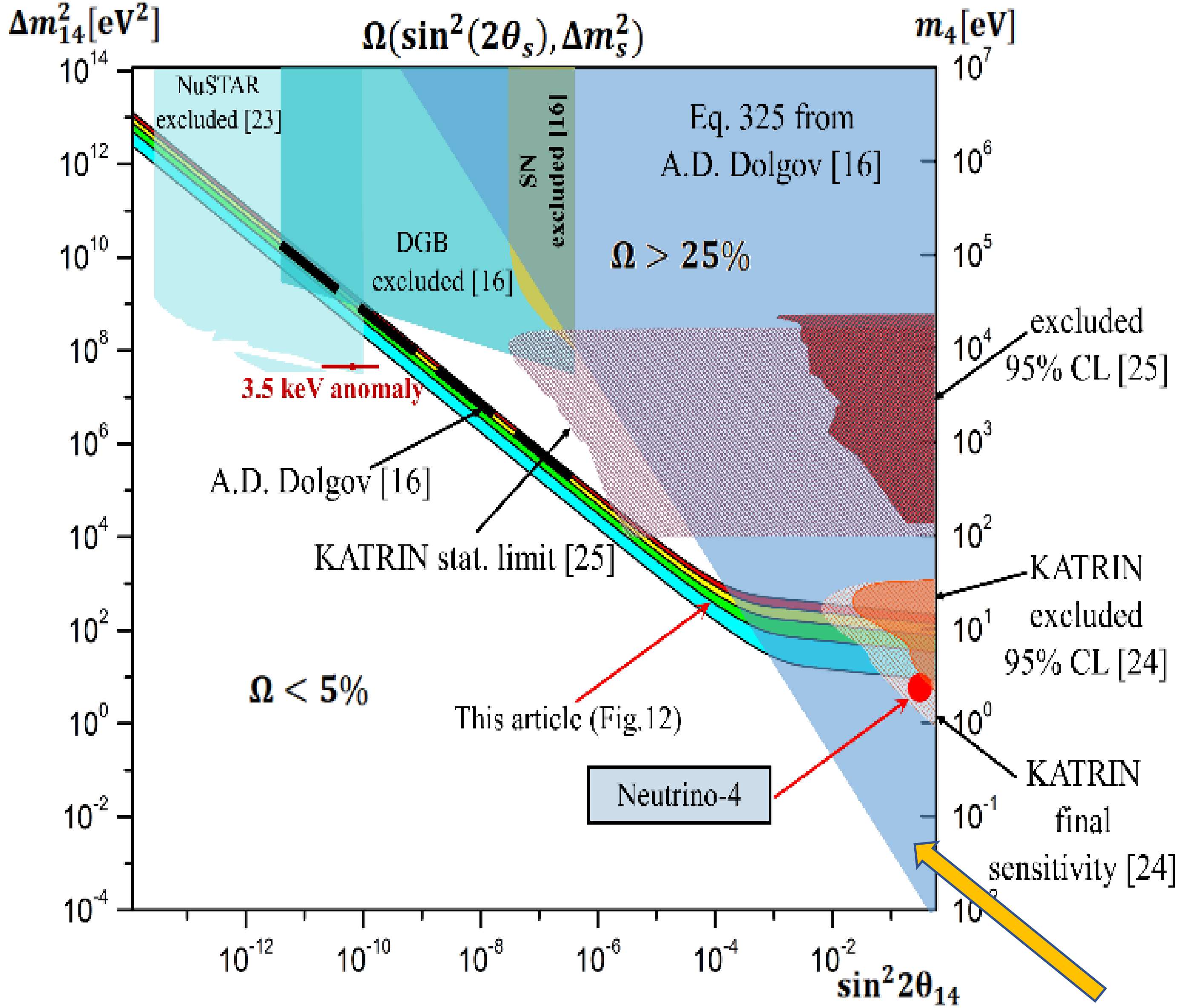
Restrictions on the sterile neutrino parameters.



Constraints on the sterile neutrino parameters.

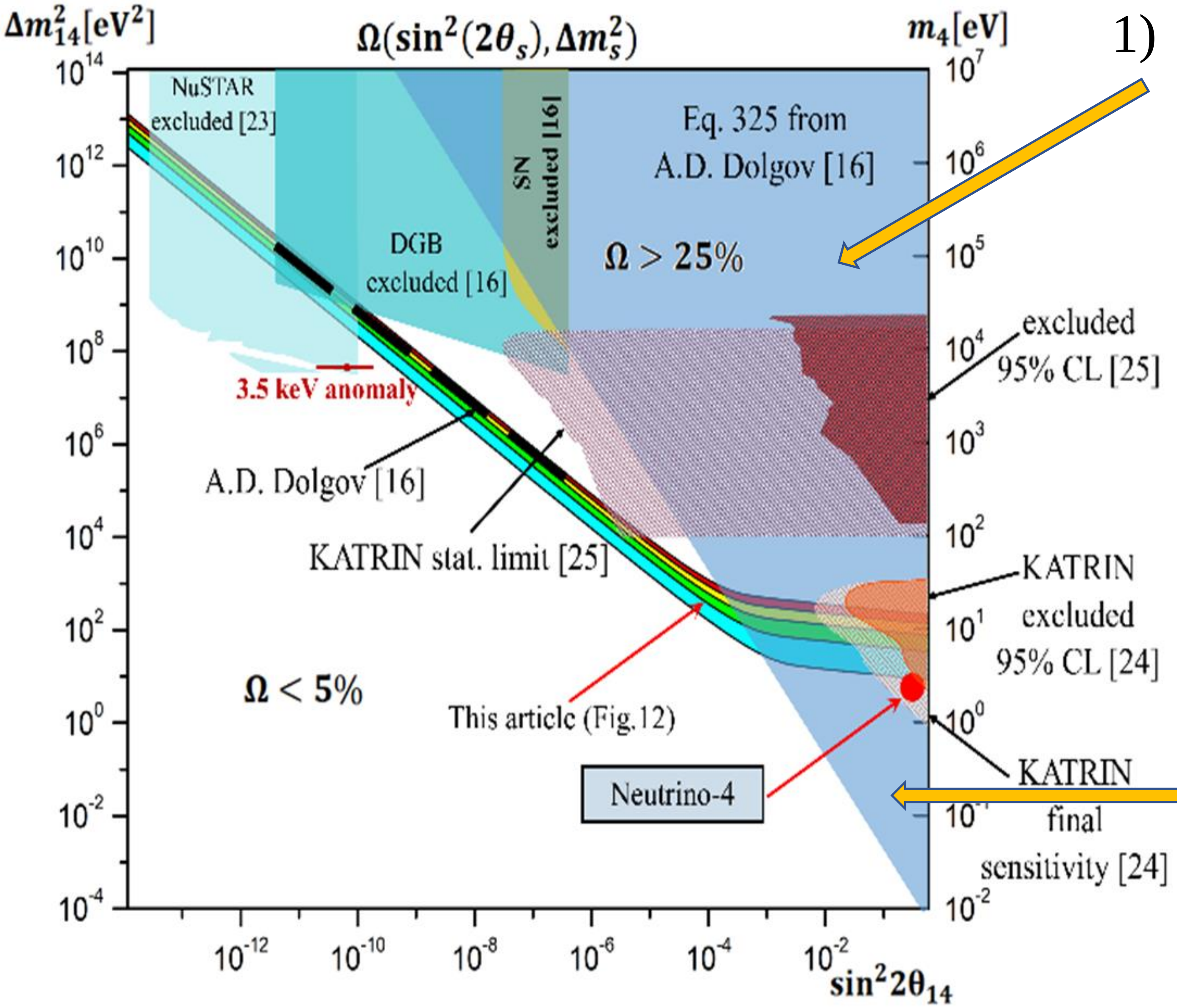
1) Red spot – result of the Neutrino-4 experiment; 2) This article (Fig.12) – area of the Ω_s values in 5-25% range; 3) A.D. Dolgov [16] – result from the Ref.[16] for $\nu_e - \nu_s$mixing with $\Omega_s = 30\%$ (it should be noted that result of calculation presented in this work based on equation (19) is consistent with A.D. Dolgov results presented in Ref.[16]; 4) Eq.(325) from A.D. Dolgov [16] – constraints from equation (325) in Ref.[16]; 5) DGB – experimental constraints based on diffuse gamma background; 6) experimental constraints from SN1987 observation; 7) constraints from NuSTAR experiment [23]; 8) KATRIN excluded 95% CL – constraints on eV-scale sterile neutrino from KATRIN experiment; 9) KATRIN final sensitivity – sensitivity limit of the KATRIN experiment for eV-scale sterile neutrino; 10) excluded 95% CL – constraints from neutrino mass measurements experiment from Ref. [24]; 11) KATRIN stat. limit[24] – statistical limit of the KATRIN experiment for keV-scale sterile neutrino

Restrictions on the sterile neutrino parameters.



Constraints on the sterile neutrino parameters.

1) Red spot – result of the Neutrino-4 experiment;
2) This article (Fig.12) – area of the Ω_s values in 5-25% range;
3) ---- A.D. Dolgov [16] – result from the Ref.[16] for $\nu_e - \nu_s$ mixing with $\Omega_s = 30\%$ (it should be noted that result of calculation presented in this work based on equation (19) is consistent with A.D. Dolgov results presented in Ref.[16];



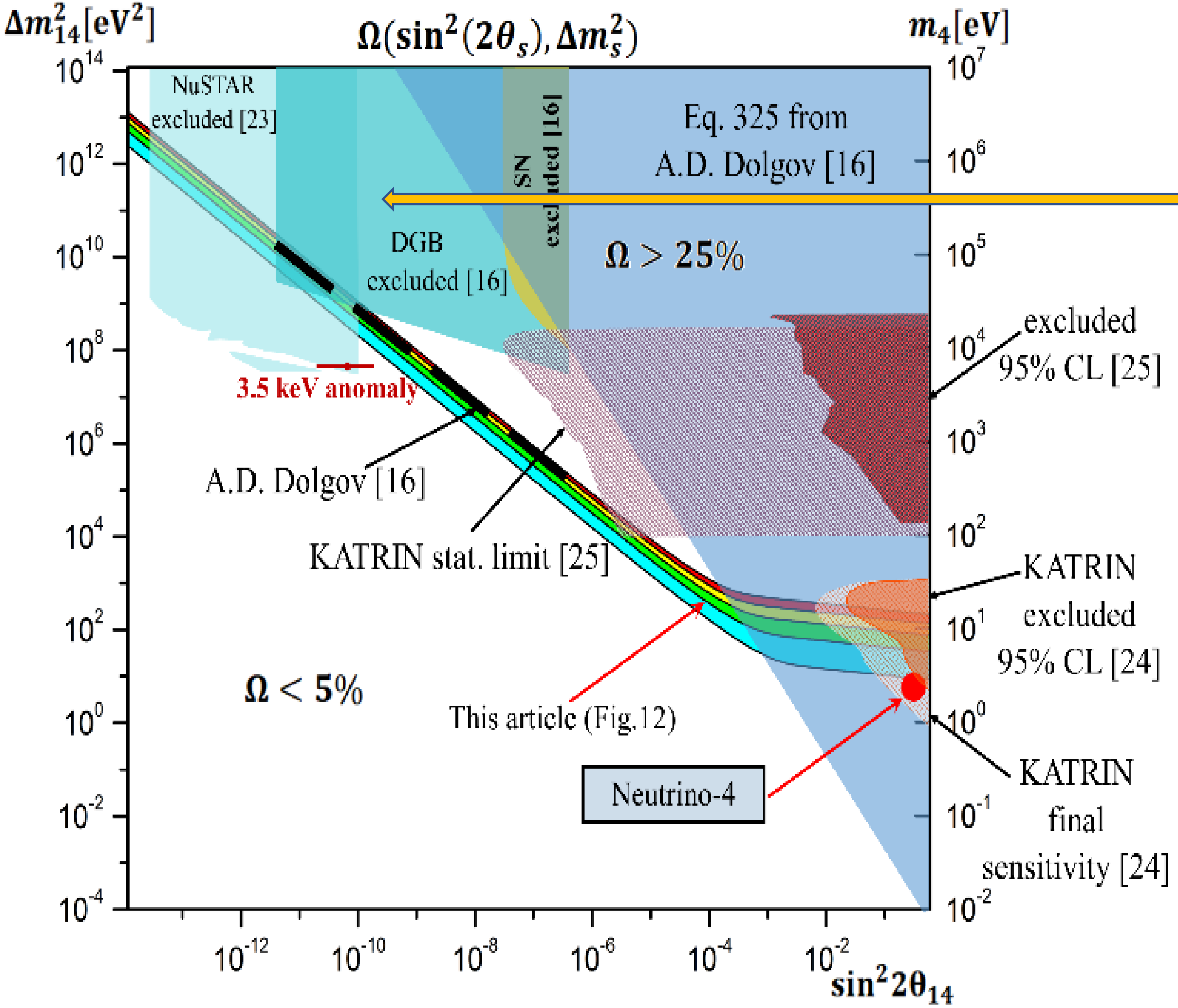
1) primordial nucleosynthesis and distribution of light nuclei [16, 17]

1) Eq.(325) from A.D. Dolgov [16] – constraints from equation (325) in Ref.[16];

$$\left(\frac{\Delta m_{es}^2}{eV^2}\right)\cdot \sin^4 2\theta_{vac}^{\nu_e\nu_s} = $$

$$= 3.16\cdot 10^{-5}\left(\frac{g_*\left(T_{prod}^{\nu_s}\right)}{10.75}\right)^3 \Delta N_\nu^2$$

Restrictions on the sterile neutrino parameters.



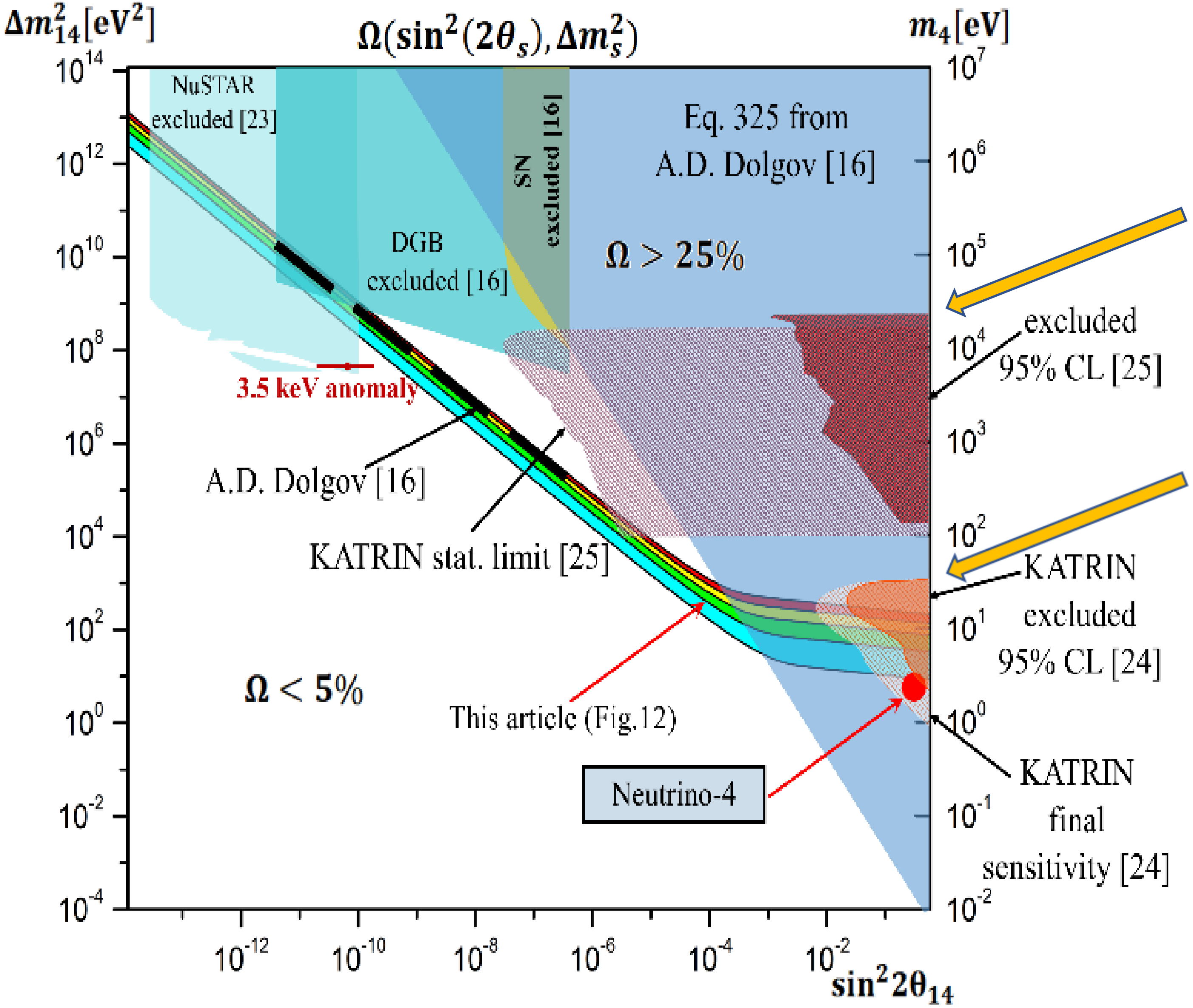
Constraints on the sterile neutrino parameters.

5) DGB – experimental constraints based on diffuse gamma background;

6) experimental constraints from SN1987 observation;

7) constraints from NuSTAR experiment [23];

Restrictions on the sterile neutrino parameters.



Constraints on the sterile neutrino parameters.

8) KATRIN excluded 95% CL – constraints on eV-scale sterile neutrino from KATRIN experiment;

9) KATRIN final sensitivity – sensitivity limit of the KATRIN experiment for eV-scale sterile neutrino;

10) excluded 95% CL – constraints from neutrino mass measurements experiment from Ref. [24];

11) KATRIN stat. limit[24] – statistical limit of the KATRIN experiment for keV-scale sterile neutrino

Large lepton asymmetry

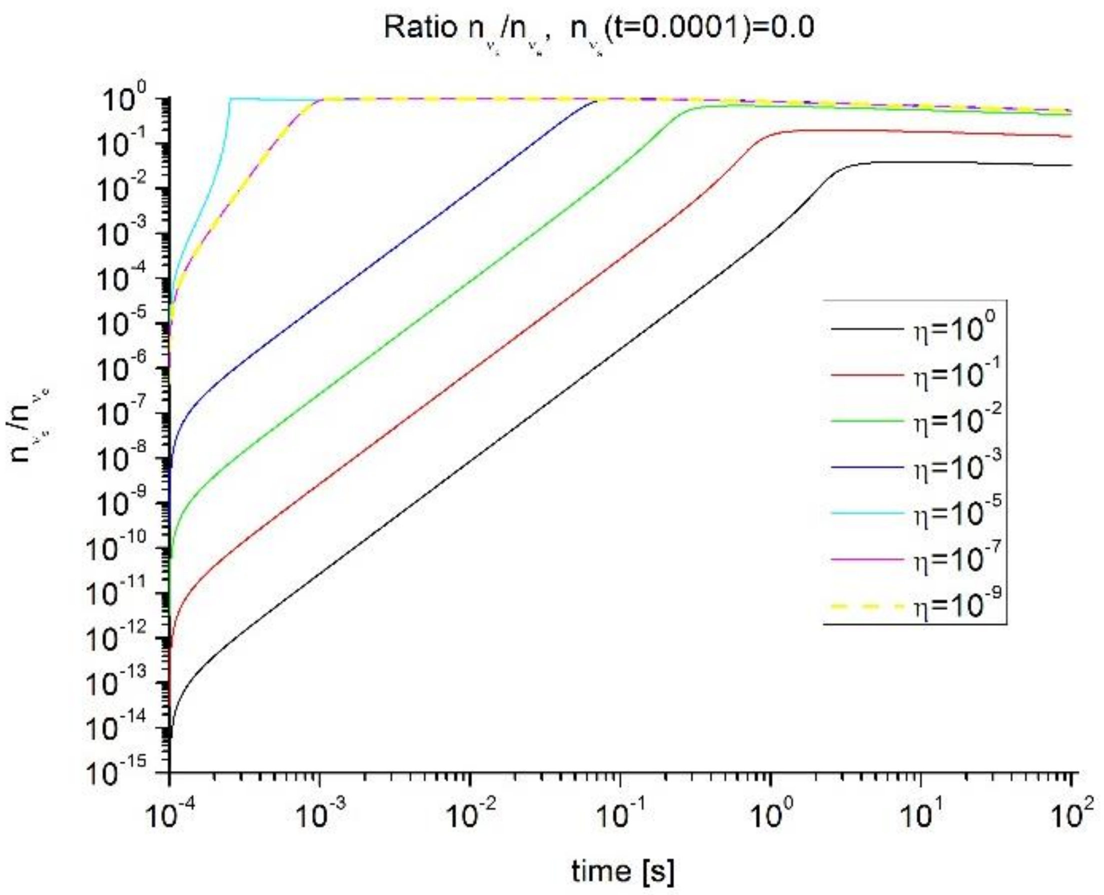
If we consider a sufficiently large asymmetry, then the diabatic energy levels of active and sterile neutrinos can intersect, which will lead to resonant oscillations into a sterile state, by analogy with resonant oscillations between electron and muon neutrinos in the Sun (MSW resonance).

Considering the potentials of the form:

$$\mathrm{V_e} = 0{,}95 \times G_f \boldsymbol{\eta} T^3 - 3.5 \times 25 \times \mathrm{G_f^2} \times \mathrm{T^4} \times \mathrm{E}$$

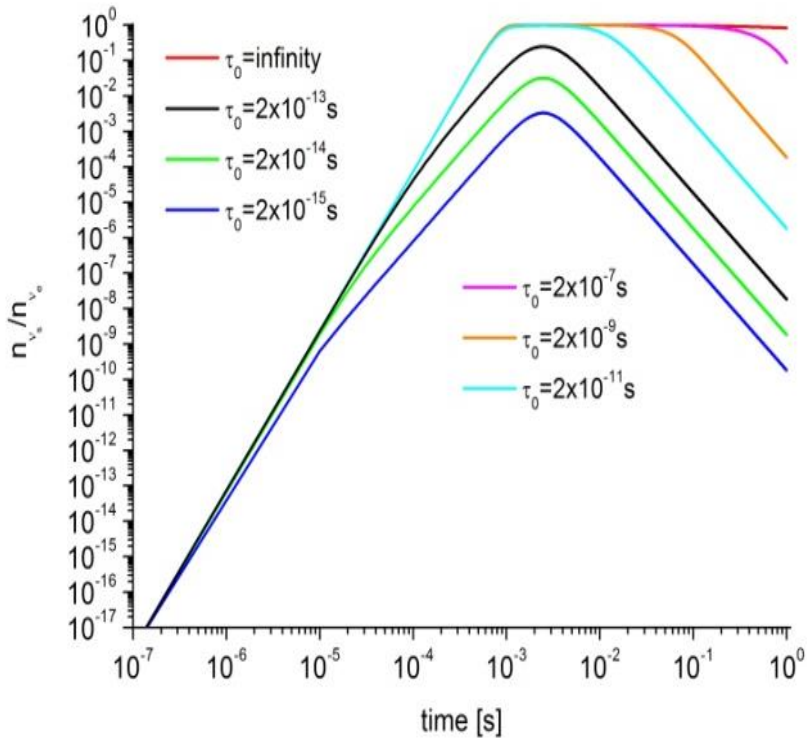
$$\mathrm{V_s} = 0$$

for different values of $\boldsymbol{\eta}$, we obtain dependence curves for the ratio of the density of the number of sterile and active neutrinos.



In this regard, it can be noted that in the work of A. D. Dolgov “Neutrino oscillations in the early Universe. Resonance case” [25] similar situation was considered. The idea of that work is the transition $\nu_\alpha \rightarrow \nu_s$ may be more favorable than the transition of the corresponding antineutrinos. The feedback is positive and leads to a further increase in asymmetry and makes the transition $\nu_\alpha \rightarrow \nu_s$ more and more efficient compared to $\bar{\nu}_\alpha \rightarrow \bar{\nu}_s$. The lepton asymmetry generated in the early Universe by neutrino oscillations on sterile partners reaches the asymptotic values of the asymmetry at the 0.2 – 0.3 [25]. Of course, a detailed consideration of such a scenario with experimental oscillation parameters is required.

The decay of a sterile neutrino.



The ratio of sterile neutrino density to the electron neutrino density, taking into account the decay of a sterile neutrino. The lifetime of a sterile neutrino in the comoving coordinate system is τ_0 . Oscillation parameters are $\sin^2 2\theta_{14} = 0.36$, $\Delta m^2_{14} \approx 7 \text{ eV}^2$.

Substituting the decay time into equation as an additional channel for sterile neutrino losses, we arrive at a value of $n_s/n_e \ll 0.01$ by the start of nucleosynthesis at approximately 1s.

Figure shows the behavior of the density ratios of the sterile neutrino to the electron neutrino for various decay times. The result of the calculations shows that in a wide range of possible values of $\boldsymbol{\tau_0}$ it is possible to achieve the contribution of the sterile neutrino to dark matter at a level that does not contradict cosmological limitations. For example, at $\boldsymbol{\tau_0 = 2 \times 10^{-7}\, s}$ s the ratio n_s/n_e is 0.1.

The value $\boldsymbol{\tau_0 > 2 \times 10^{-7}\, s}$ can be considered as the upper limit on the sterile neutrino decay time, established from the cosmological constraints on nucleosynthesis.

Experimental the lower limit of sterile neutrino decay time

A natural limitation from the experiment is the fact that the neutrino leaves an oscillatory signal in our experimental setup, so it does not decay over a length of about 10 meters. From this we get the lower limit of the decay period of the order $\boldsymbol{\tau_0 > 2 \times 10^{-14}\ s}$. . If in addition we consider that reactor anomaly can be observed at distances up to 1 km, then the lower limit can be increased to $\boldsymbol{\tau_0 > 2 \times 10^{-12}\ s}$**.**

Finally, an estimate can be made if we assume that the effect of oscillations is also observed in the IceCube [26] experiment, then considering the distance (diameter of the Earth) and neutrino energy (~100 GeV) we get $\boldsymbol{\tau_0 > 2 \times 10^{-12}\ s}$.

The upper limit of sterile neutrino decay time from cosmological constraints

The value $\boldsymbol{\tau_0 < 2 \times 10^{-7}\ s}$ can be considered as the **upper limit** on the sterile neutrino decay time, established from the cosmological constraints on nucleosynthesis.

Conclusion

If the Neutrino-4 result is confirmed at a confidence level of more than 5σ at our new experimental facility with three times the sensitivity, as well as by other scientific groups, then the above **theoretical limitations will have to be revised.**

Since direct observation of a sterile neutrino in a laboratory experiment can become the defining criterion,

significant revision of the entire model of the dynamics of the early universe will be required.

Thank you for your attention

Предсказание эффективной массы электронного нейтрино из эксперимента Нейтрино-4 и сравнение с экспериментами по измерению массы нейтрино: KATRIN и GERDA

$$m_{4\nu_e}^{eff} = \sqrt{\sum m_i^2 |U_{ei}|^2}\,; \quad sin^2 2\theta_{14} \approx 4|U_{14}|^2;$$

$$\sum m_\nu = m_1 + m_2 + m_3 \approx 0.54 \div 0.11\text{eV}$$

$$\Delta m_{14}^2 \approx m_4^2 \approx 7.3\ eV^2, \quad m_1^2, m_2^2, m_3^2 \ll m_4^2$$

$$\boxed{m_4 = (2.70 \pm 0.22)\text{eV}} \qquad \boxed{sin^2 2\theta_{14} \approx 0.35 \pm 0.07\ (4.9\sigma)}$$

$$m_{4\nu_e}^{\text{eff}} \approx \sqrt{\text{m}_4^2 |U_{e4}|^2} \boxed{\approx \frac{1}{2}\sqrt{m_4^2 \sin^2 2\theta_{14}}.}$$

$$\boxed{m_{4\nu_e}^{eff} = (0.82 \pm 0.18)\text{eV}} \qquad m_{4\nu_e}^2 = 0.68 \pm 0.29$$

В экспериментах по двойному β-распаду масса майораны определяется соотношением:

$$m(0\nu\beta\beta) = /\sum U_{ei}^2 m_i\, / \qquad m(0\nu\beta\beta) \approx m_4 U_{14}^2 \qquad \boxed{m(0\nu\beta\beta) = (0.25 \pm 0.09)\text{eV}}$$

СРАВНЕНИЕ ПРОГНОЗА МАССЫ НЕЙТРИНО-4 С ИЗМЕРЕНИЕМ МАССЫ НЕЙТРИНО

	Neutrino-4	KATRIN
$m^{eff}_{\nu_e} = \sqrt{\sum m_i^2 \lvert U_{ei}\rvert^2}$ $\Delta m^2_{14} \approx m^2_4$ Effective mass and mass squared: $m^{eff}_{\nu_e}$, m^2_ν	$m^{eff}_{4\nu_e} = 0.82 \pm 0.18$ $\boxed{\left(m^{eff}_{4\nu_e}\right)^2 = 0.68 \pm 0.29}$ $m_1^2, m_2^2, m_3^2 \ll m_4^2$	$m^{eff}_{3\nu_e} < 0.8$ eV (90%) $m^{eff\,2}_{3\nu_e} = 0.26 \pm 0.34$ $m^{eff\,2}_{4\nu_e} =$ **?**

Параметры четвертого нейтрино, полученные в эксперименте «Нейтрино-4» $sin^2 2\theta_{14} \approx 0.35 \pm 0.07 (4.9\sigma)$ и $m_4^2 \approx 7.3\ eV^2$, должны быть использованы в качестве таких дополнительных параметров. Мы думаем, что коллаборация KATRIN представит такой анализ в одной из своих будущих публикаций для получения оценки $m^2_{1,2,3}$

KATRIN

$m^{\mathrm{eff}}_{3\nu_e} < 0.8$ eV (90%)

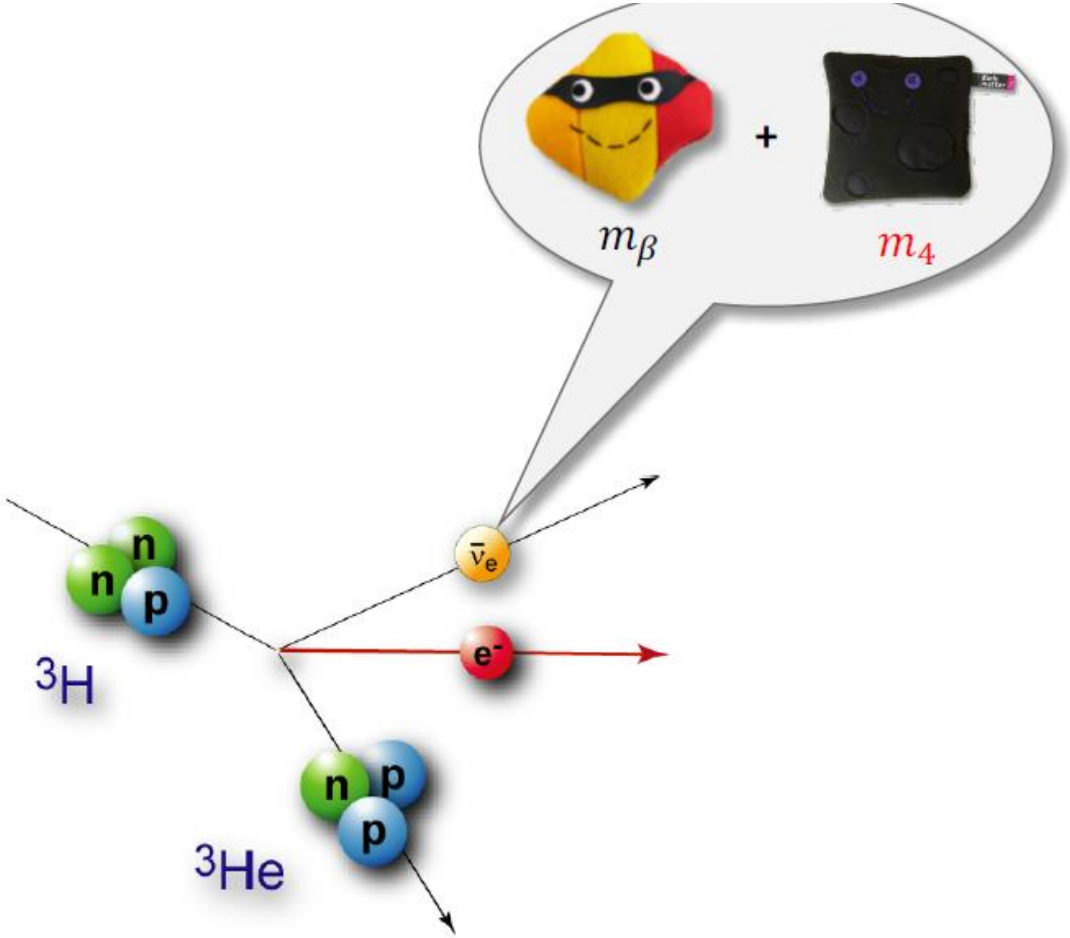
$$\left(m^{eff}_{3\nu_e}\right)^2 = \mathbf{0.26 \pm 0.34}$$

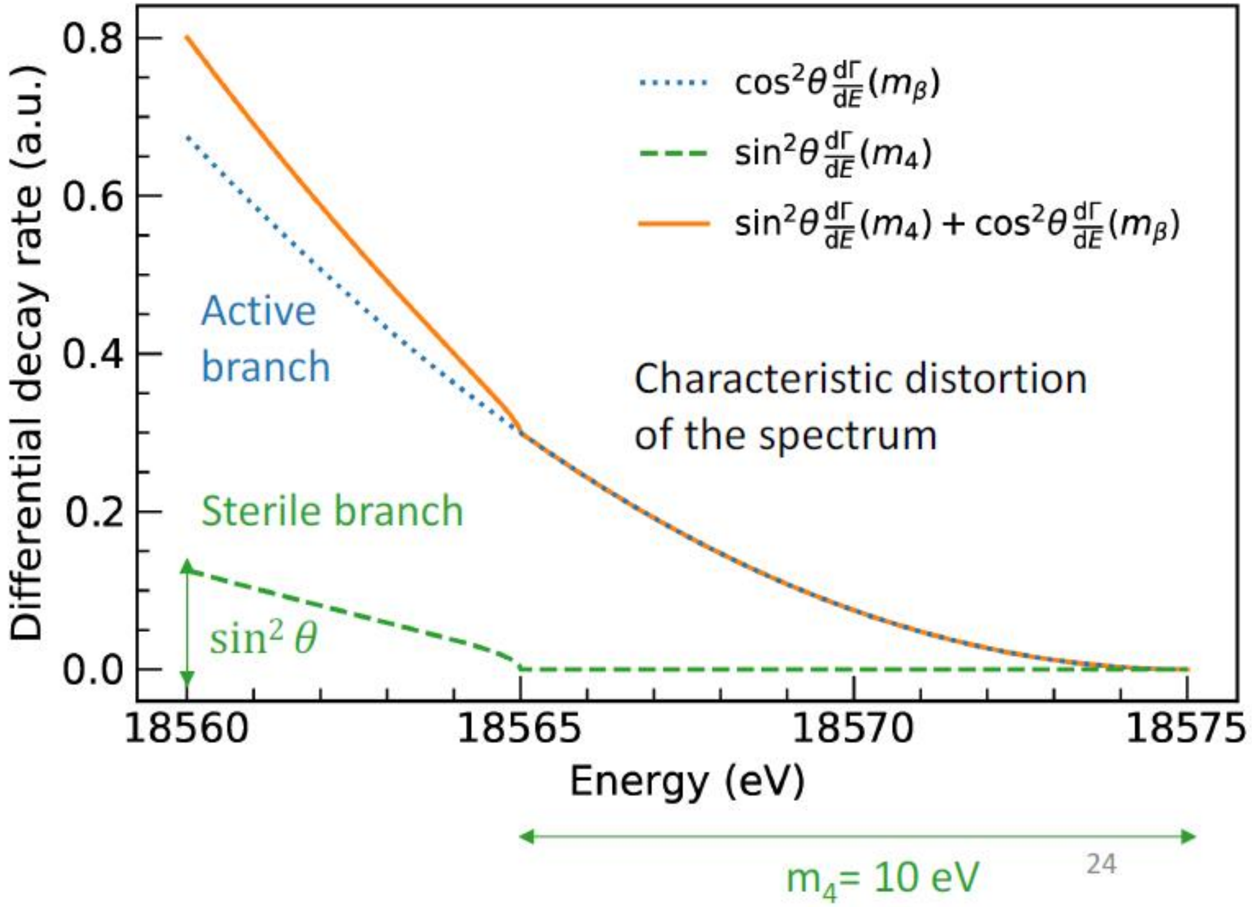
$$m^{eff\,2}_{4\nu_e} = ?$$

$$\boxed{\mathbf{m^{eff}_{4\nu_e} = (0.82 \pm 0.18)eV}}$$

Neutrino4

$$\boxed{\left(m^{eff}_{4\nu_e}\right)^2 = \mathbf{0.68 \pm 0.29}}$$



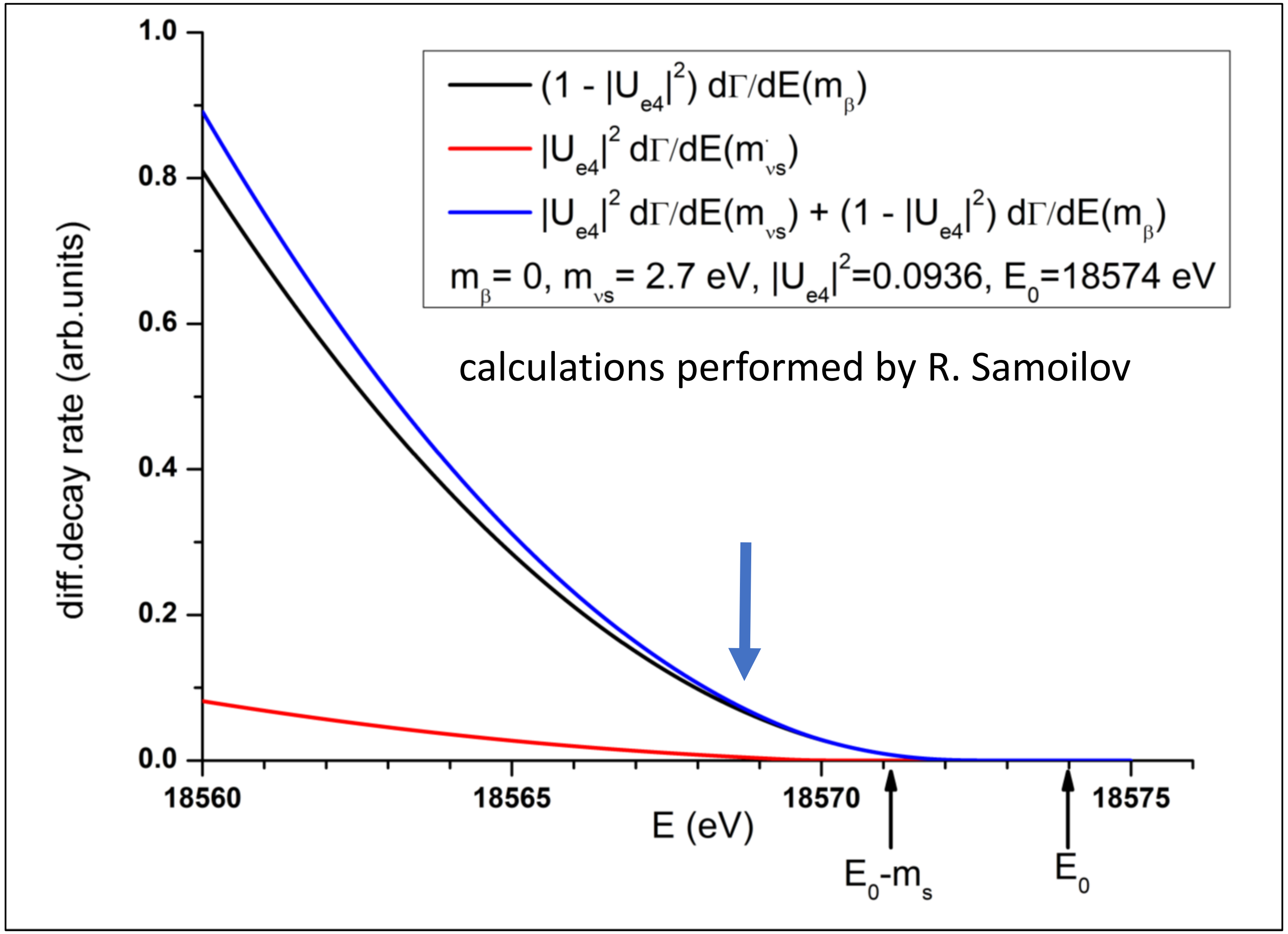


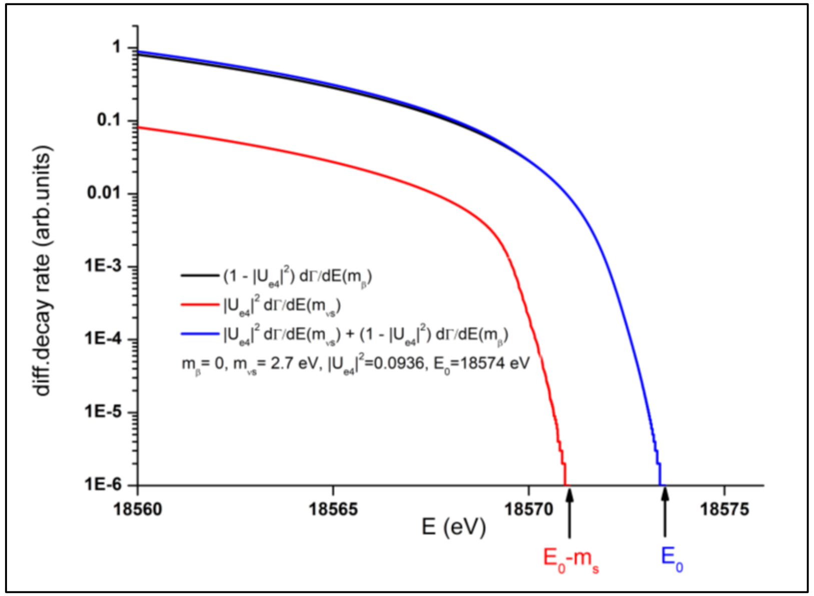
Susanne Mertens

Что должна видеть ***KATRIN*** с учетом стерильного нейтрино с параметрами:

$$m_4 = (2.70 \pm 0.22)\mathrm{eV}$$

$$sin^2 2\theta_{14} \approx 0.35 \pm 0.07\ (4.9\sigma)$$





Сравнение с ограничениями на массу нейтрино из экспериментов по поиску двойного бета-распада без нейтрино

Это выражение для модели 3 + 1 и с предположением $m1$, $m2$, $m3 \ll m4$ можно упростить:

$$m_{ee} = \left|\sum_i m_i U_{ei}^2\right| = \begin{cases} \left|m_0 c_{12}^2 c_{13}^2 + \sqrt{\Delta m_{21}^2 + m_0^2}\, s_{12}^2 c_{13}^2 e^{2i(\eta_2-\eta_1)} + \sqrt{\Delta m_{32}^2 + \Delta m_{21}^2 + m_0^2}\, s_{13}^2 e^{-2i(\delta_{CP}+\eta_1)}\right| & \text{in NO}, \\ \left|m_0 s_{13}^2 + \sqrt{m_0^2 - \Delta m_{32}^2}\, s_{12}^2 c_{13}^2 e^{2i(\eta_2+\delta_{CP})} + \sqrt{m_0^2 - \Delta m_{32}^2 - \Delta m_{21}^2}\, c_{12}^2 c_{13}^2 e^{2i(\eta_1+\delta_{CP})}\right| & \text{in IO}, \end{cases}$$

Численный результат в показан ниже.

$\boldsymbol{m(0\nu\beta\beta) = (0.25 \pm 0.09)}$**eV**
our estimation

$$m(0\nu\beta\beta) \approx m_4 U_{14}^2$$

$\boldsymbol{m(0\nu\beta\beta)}$ **<[0.080–0.182]eV**
experiments

Наилучшие ограничения на массу Майораны были получены в эксперименте GERDA.

Значение, полученное с параметрами осцилляций Нейтрино-4, составляет $\boldsymbol{m\,(0\nu\beta\beta)} = (\mathbf{0.25} \pm \mathbf{0.09})\ \boldsymbol{eV}$, что в три раза превышает предел, заявленный экспериментом GERDA. Это существенное несоответствие, но делать достоверные выводы пока рано. **Если в будущем предел майорановской массы эксперимента по двойному бета-распаду будет понижен и результат эксперимента Нейтрино-4 подтвердится, это закроет гипотезу о том, что нейтрино является частицей майорановского типа.**