XXXV International Workshop on High Energy Physics

The result of the Neutrino-4 experiment, sterile neutrinos, dark matter and the Standard Model

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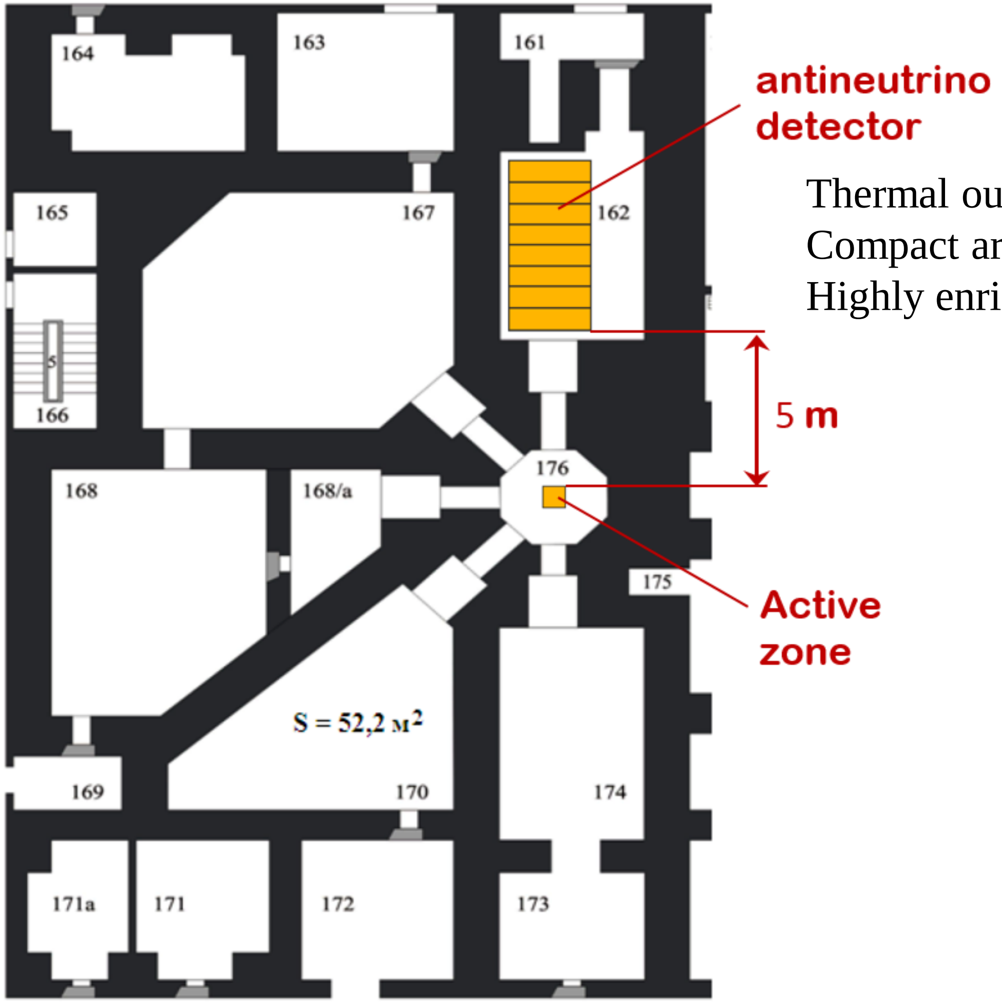
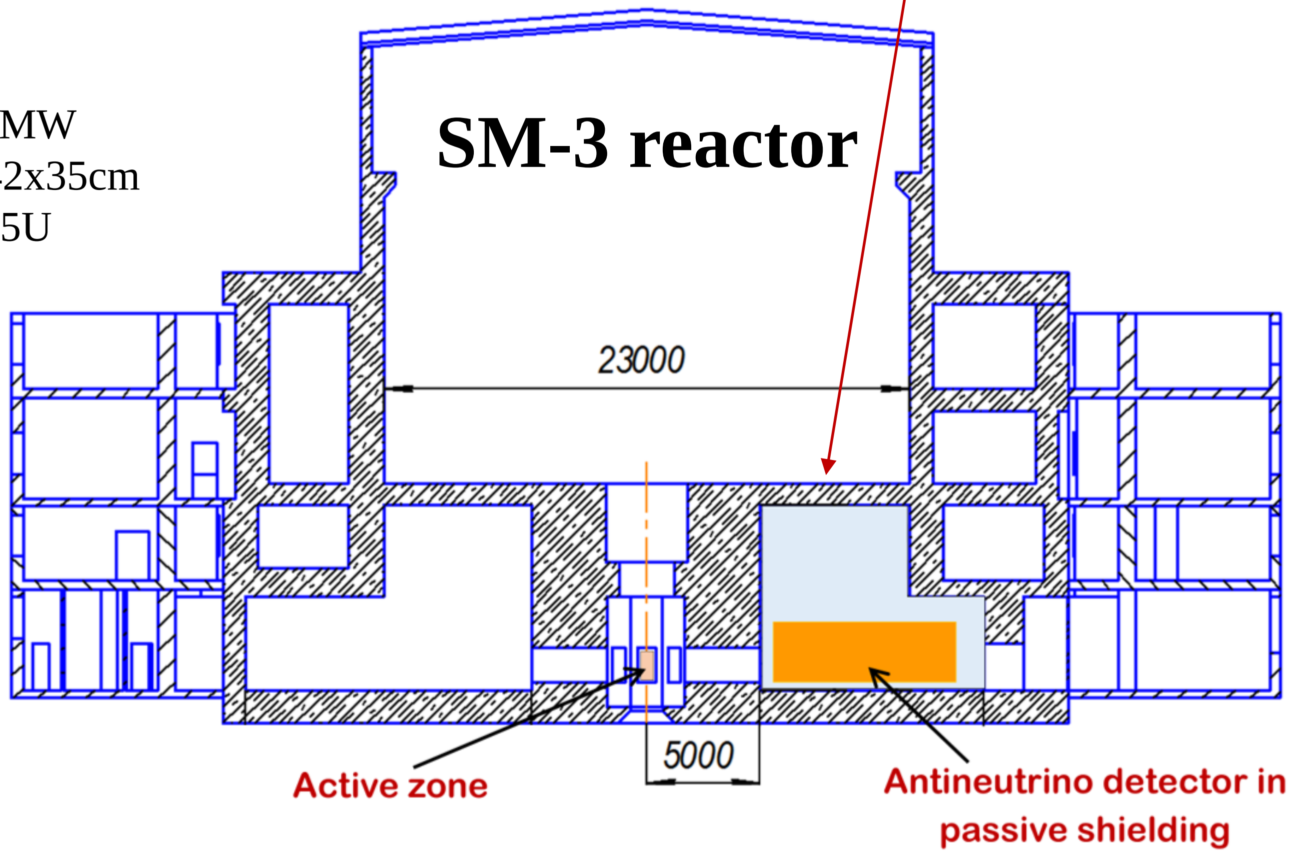
Neutrino-4 experiment at the SM-3 reactor



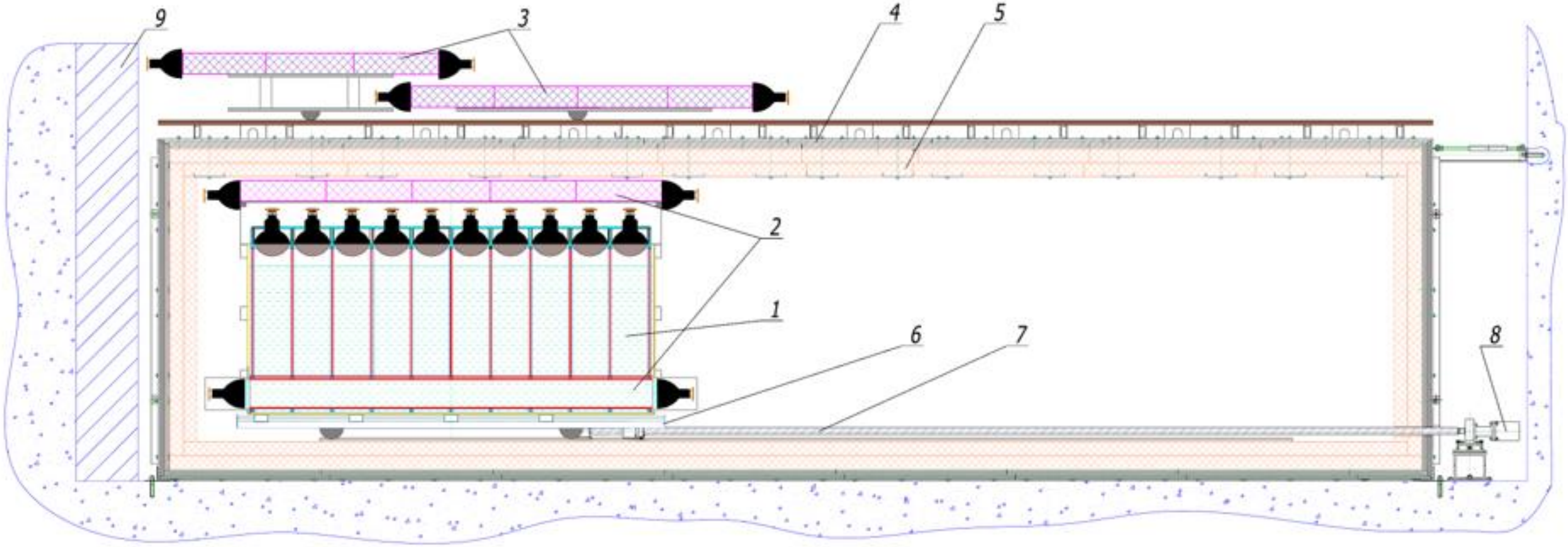
Thermal output 90 MW
Compact area 42x42x35cm
Highly enriched 235U

Week protection from cosmic rays (3-5 m w. e.)

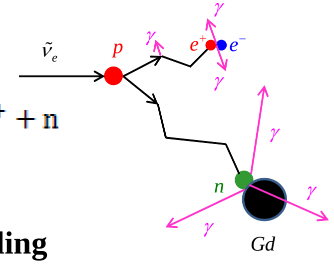


Due to the design features, the SM-3 reactor provides the most favorable conditions for searching for neutrino oscillations at short distances. However, the SM-3 reactor, like other research reactors, is located on the Earth's surface, so the cosmic background is the main difficulty in the experiment under consideration.

Mobile Spectrum-sensitive Antineutrino Detector at the SM-3 Reactor



$\bar{\nu}_e + p \rightarrow e^+ + n$



1. detector (5x10 cells)
2. internal active shielding
3. external active shielding
4. steel and lead
5. borated polyethylene
6. moveable platform
7. feed screw
8. step motor
9. shielding

Neutrino channel outside and inside

Detector prototype

Full-scale detector

Passive shielding - 60 tons

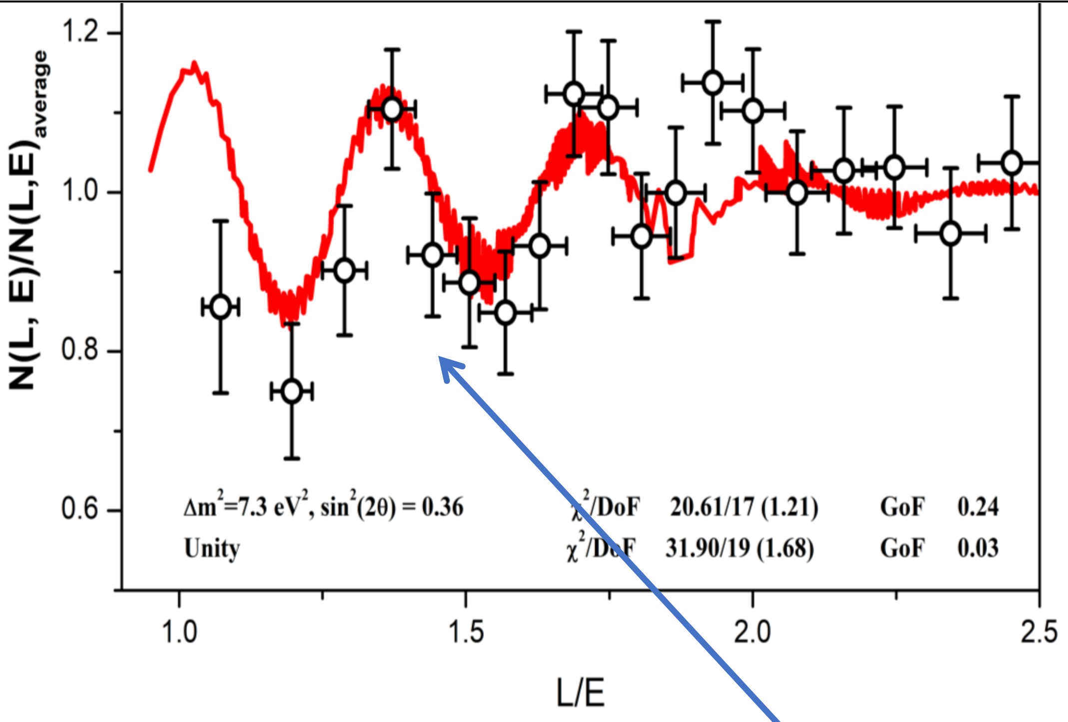
Range of measurements is 6 – 12 meters

Liquid scintillator detector 50 sections 0.235x0.235x0.85м³

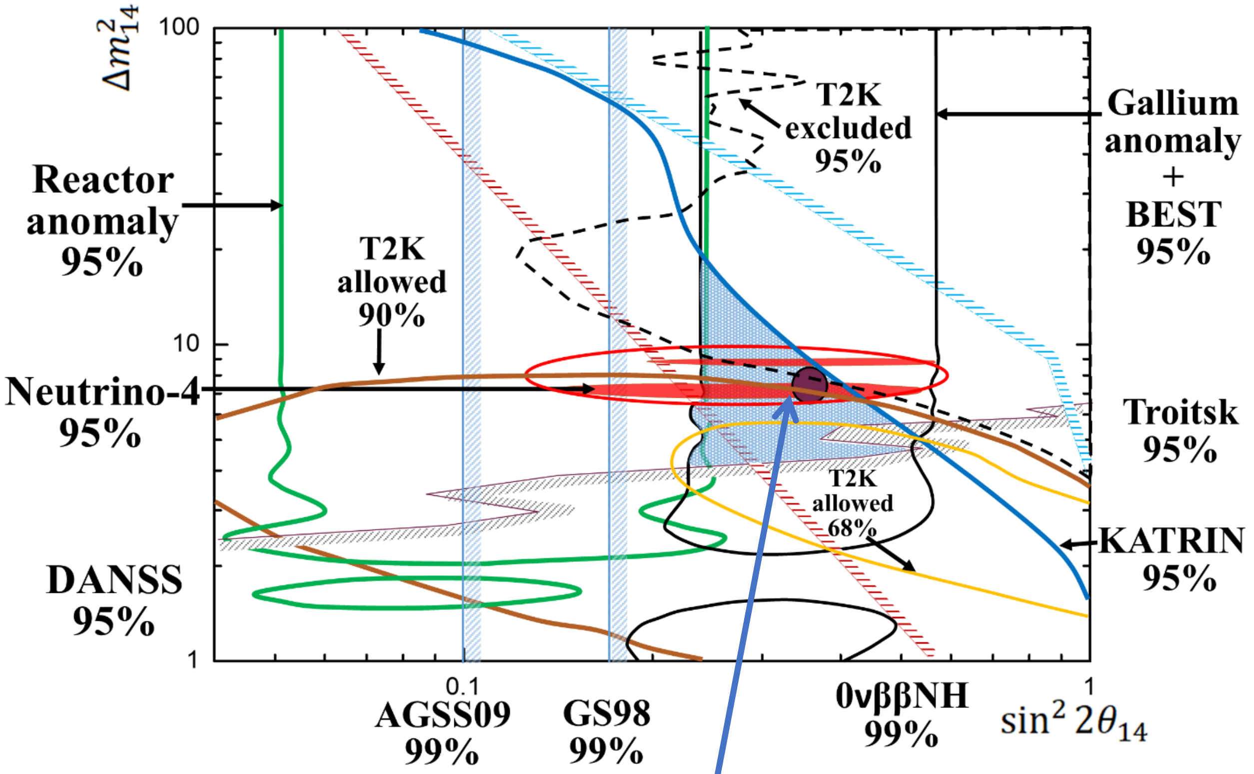
Curve of oscillations of the neutrino signal of the Neutrino-4 experiment

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

$$P(\tilde{\nu}_e \to \tilde{\nu}_e) = 1 - \sin^2 2\theta_{14}\ \sin^2\left(1.27\frac{\Delta m_{14}^2[eV^2]L[m]}{E_{\tilde{\nu}}[MeV]}\right)$$



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



$$m_4 = 2.7 \pm 0.2\ eV$$

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

A. P. Serebrov, et al, Physical Review D, 2021, 104(3), 032003

A. P. Serebrov, et al, JETP, 2023, Vol. 137, No. 1, pp. 55–70.

Analysis of the Result of the Neutrino-4 Experiment Together with Other Experiments on the Search for Sterile Neutrinos within the 3 + 1 Neutrino Model

Conclusions of the presented analysis.

The result of Neutrino-4 is not hidden by others experiments, but there is tension with some of them.

A. P. Serebrov, et al, JETP, 2023, Vol. 137, No. 1, pp. 55–70.

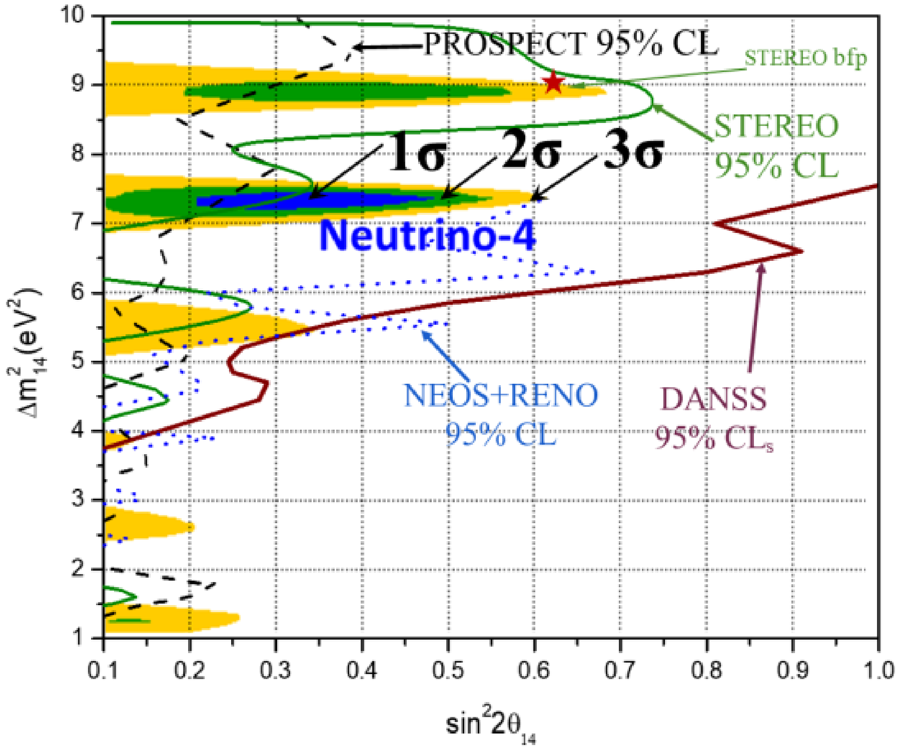
1. Experiments STEREO, PROSPECT for correct comparison of results with the results of the Neutrino-4 experiment **must examine the data in the form of the L/E dependence.** (Not precision enough to refute)

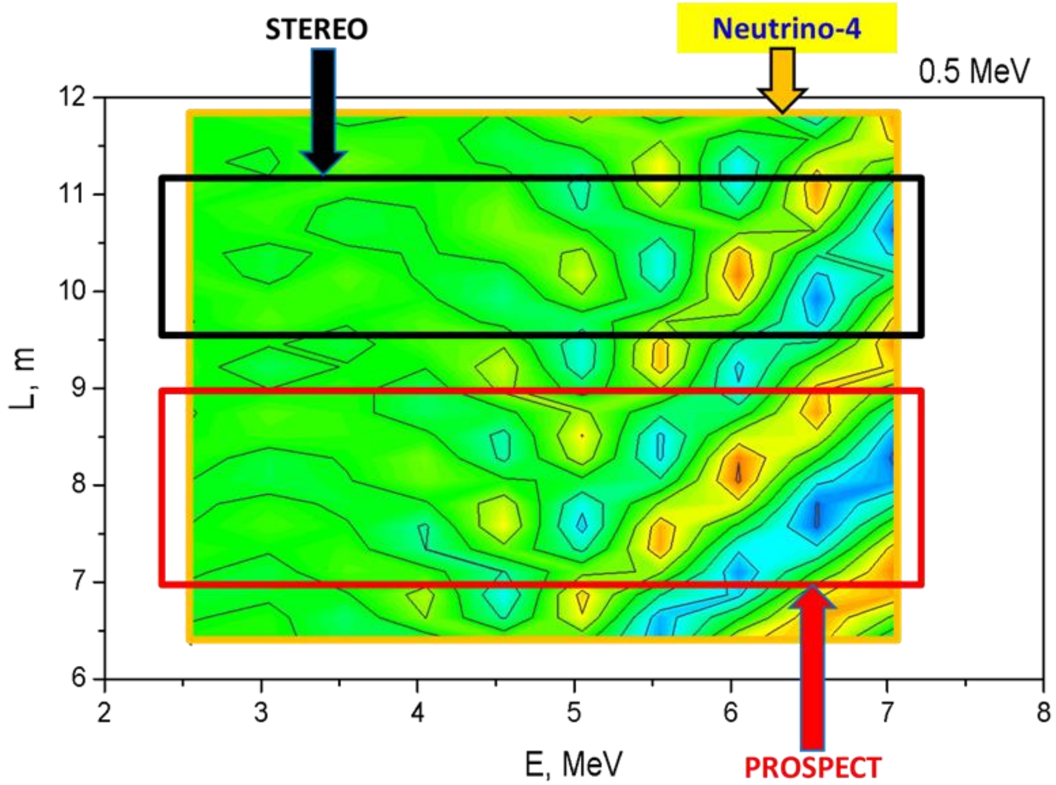
2. Reactor Antineutrino Anomaly (RAA) (Further analysis required, including reactor energy release) **Accounting for the energy carried away by antineutrinos? This is 5%. Residual power after turning off the reactor is 5%.**

3. Solar model. (Not precision enough to refute)

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

(There are not enough reasons to talk about the closure of the result of the Neutrino-4 experiment)

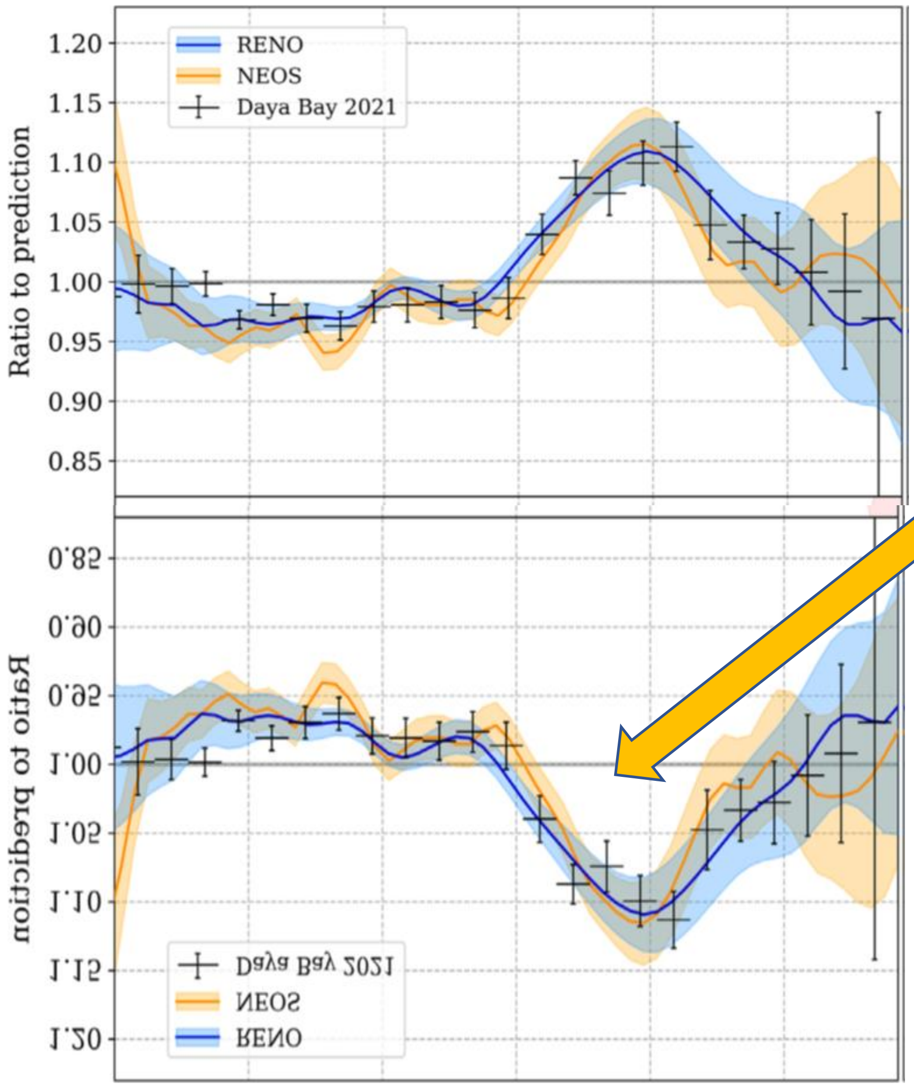


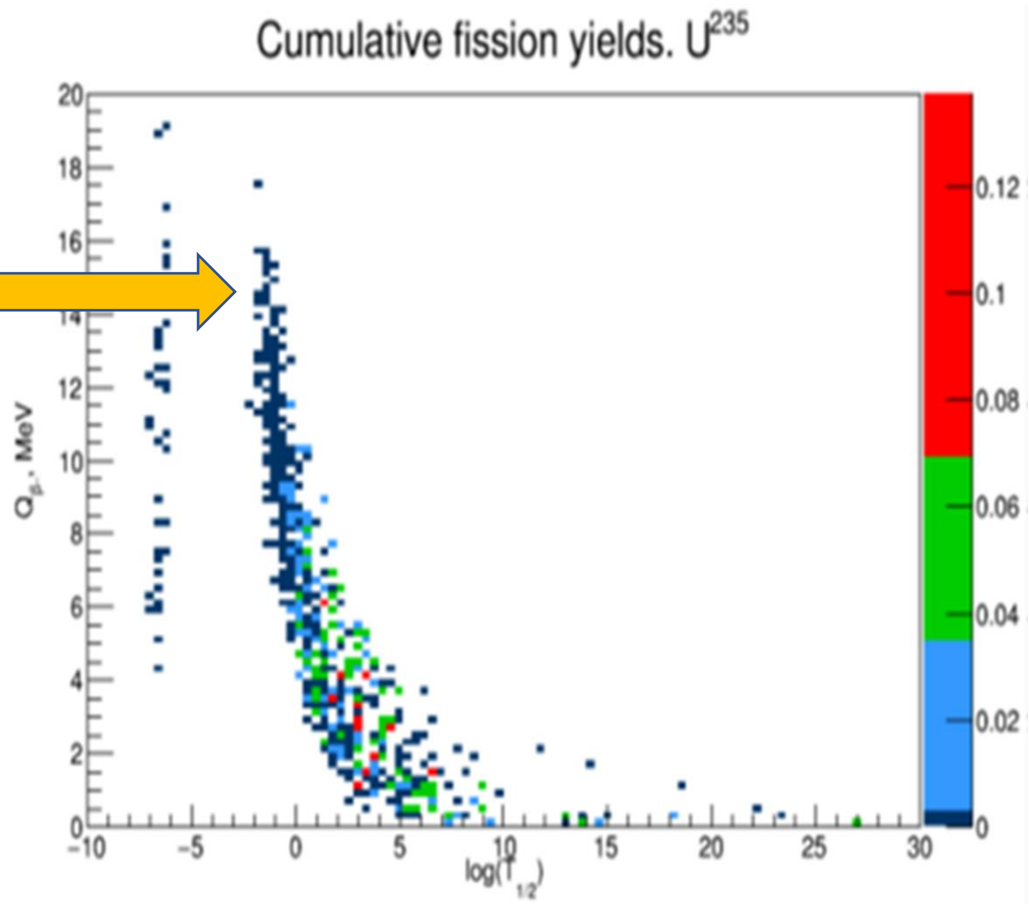


We believe that the STEREO and PROSPECT experiments should present data in the form of L/E relationship in order to correctly compare their results with the results of the Neutrino-4 experiment. Only then will it be possible to talk about closing the result of the Neutrino-4 experiment.

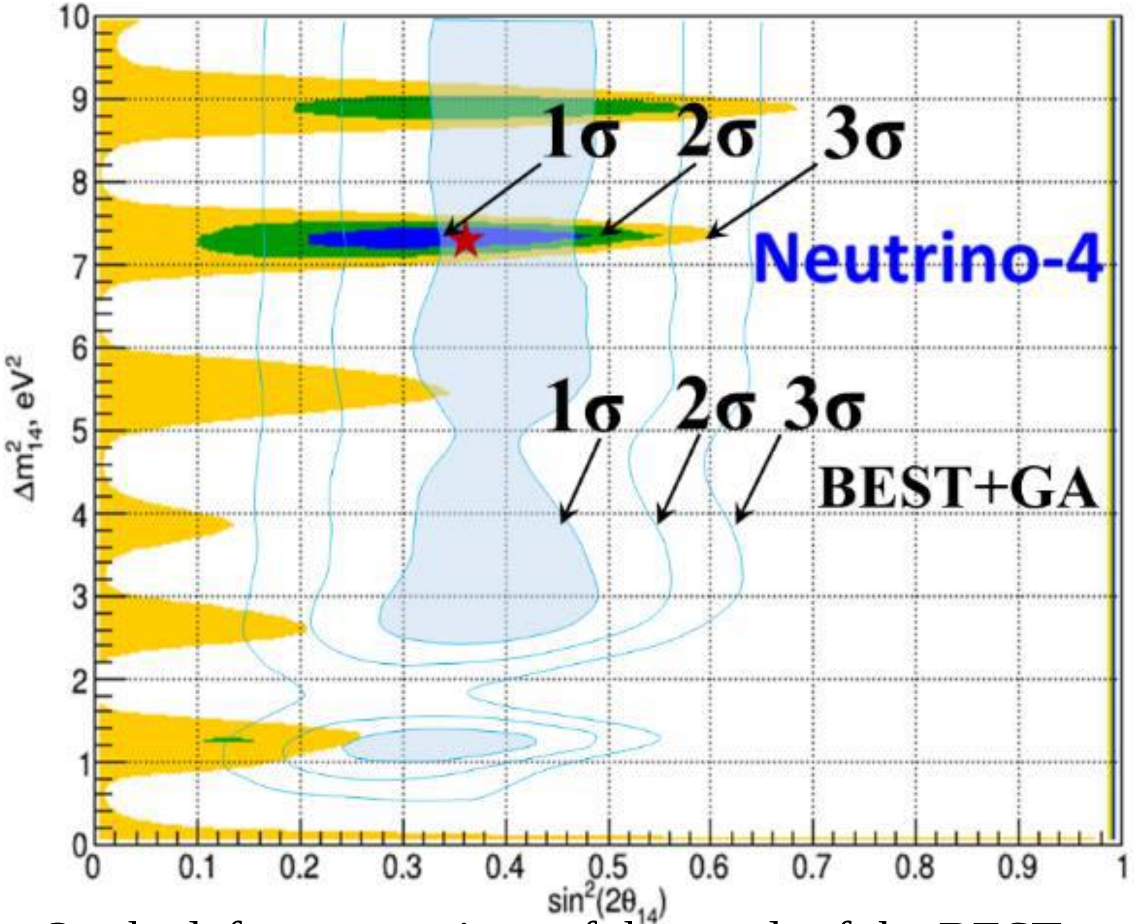
1. **The energy carried away by antineutrinos was not taken into account? This is 5%.**
2. **Residual power after turning off the reactor is 5%. Together 10%**

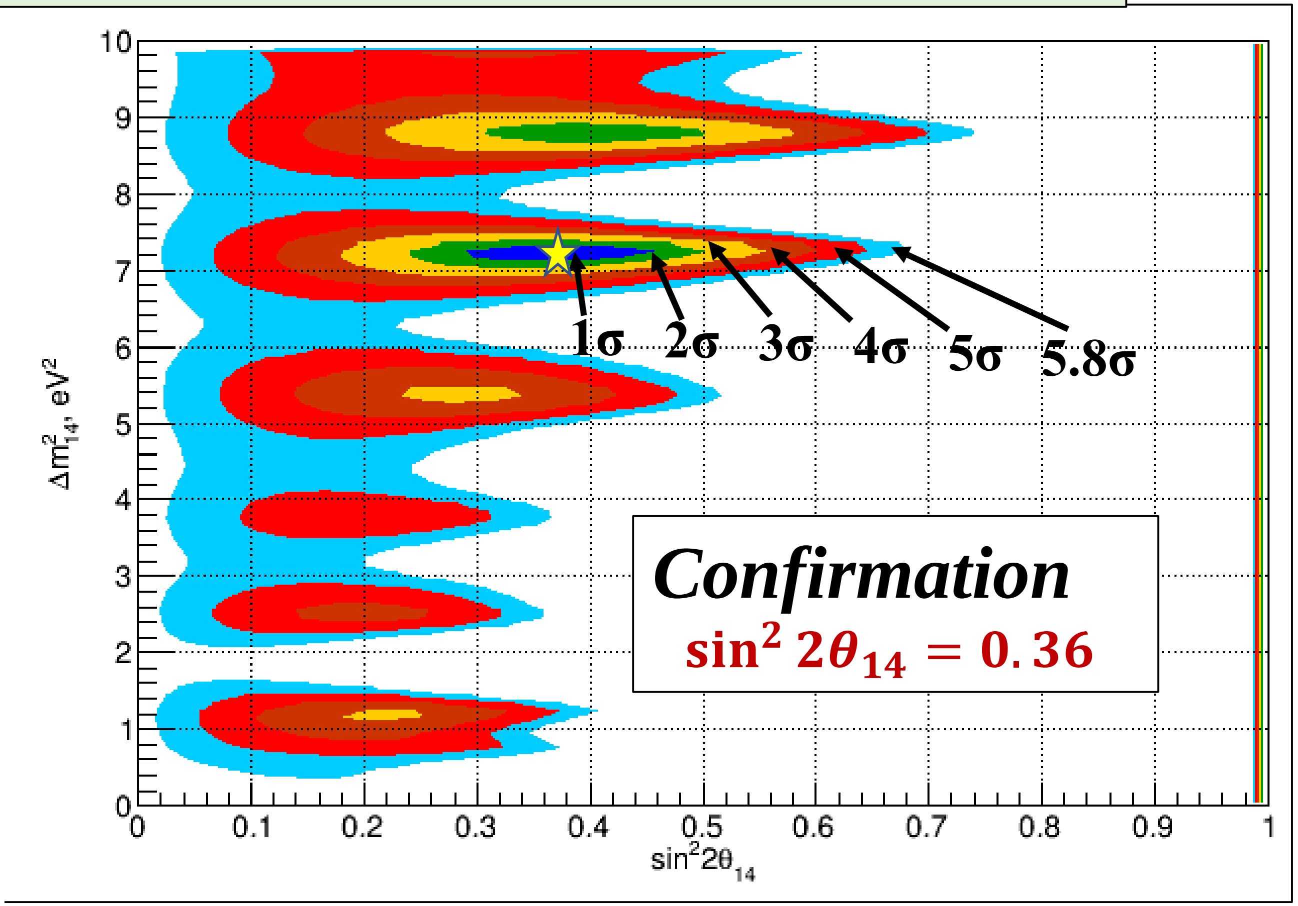
3.These are unaccounted beta decays with short lifetime and high decay energy.





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





On the left – comparison of the result of the BEST experiment with GA and the result of the Neutrino-4 experiment. On the right – The result of the combined analysis of GA, BEST and Neutrino-4, where blue indicates the area with a 1σ CL, green - 2σ, yellow - 3σ, dark red - 4σ, red - 5σ and blue - 5.8σ.

The results of direct experiments on the search for sterile neutrinos - Neutrino-4 and BEST with GA indicate the existence of sterile neutrinos with oscillation parameters: $\Delta m^2_{14} = 7.3\ eV^2, \sin^2 2\theta_{14} = 0.36, m_4 = 2.7 \pm 0.2\ eV$

Neutrino-4 and BEST with GA

The results of direct experiments to search for sterile neutrinos - Neutrino-4 and BEST with GA indicate the existence of a sterile neutrino with oscillation parameters:

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

Confirmation of $sin^2 2\theta_{14} = 0.36$ **(5.8σ)**

However, new confirmation are needed!

Two important implications for particle physics from Neutrino-4 result

1. Effective mass of electron neutrino: $\mathbf{m_{4\nu_e}^{eff} = (0.82 \pm 0.18)eV}$, $(m_4 = 2.7 \pm 0.2\ eV)$

2. Majorana or Dirac neutrino? More probable - **Dirac neutrino**!

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

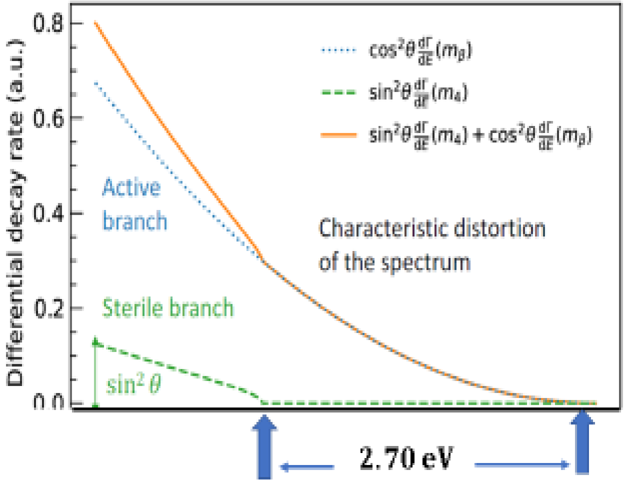
Effective mass of an electron neutrino from the Neutrino-4 experiment

$$m_{4\nu_e}^{eff} = (0.82 \pm 0.18)\text{eV}$$

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

$m_4 = (2.70 \pm 0.22)$eV

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



Comparison with neutrino mass constraints from experiments searching for double beta decay without neutrinos

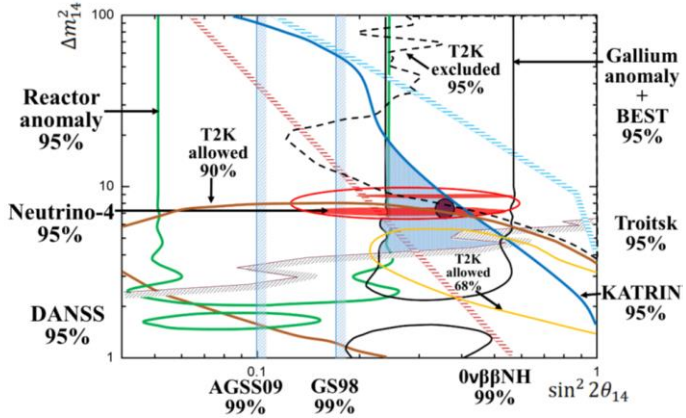
$m(0\nu\beta\beta) = (0.25 \pm 0.09)$eV our estimation

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

$m(0\nu\beta\beta) <[0.080-0.182]$eV experiments

The best weight limits for Marjoram were obtained in the GERDA experiment.

The value obtained with the Neutrino-4 oscillation parameters is $m\ (0\nu\beta\beta) = (0.25 \pm 0.09)\ eV$, which is three times the limit declared by the GERDA experiment. This is a significant discrepancy, but it is too early to draw reliable conclusions. If in the future the Majorana mass limit of the double beta decay experiment is lowered and the result of the Neutrino-4 experiment is confirmed, this will close the hypothesis that the neutrino is a Majorana-type particle.



Effective mass of an electron neutrino from the Neutrino-4 experiment

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

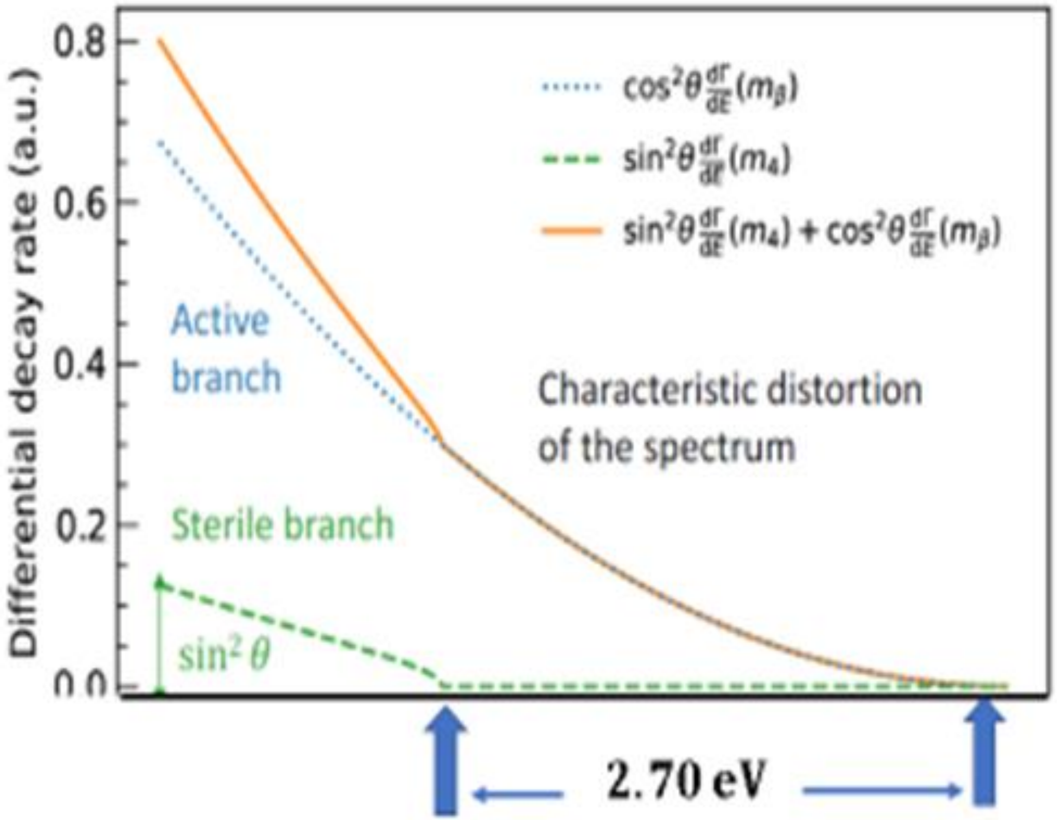
$$m_{4\nu_e}^{eff} = (0.82 \pm 0.18)\text{eV}$$

$$m_{4\nu_e}^{\text{eff}} \approx \sqrt{m_4^2 |U_{e4}|^2}$$

$$\approx \frac{1}{2}\sqrt{m_4^2 \sin^2 2\theta_{14}}$$

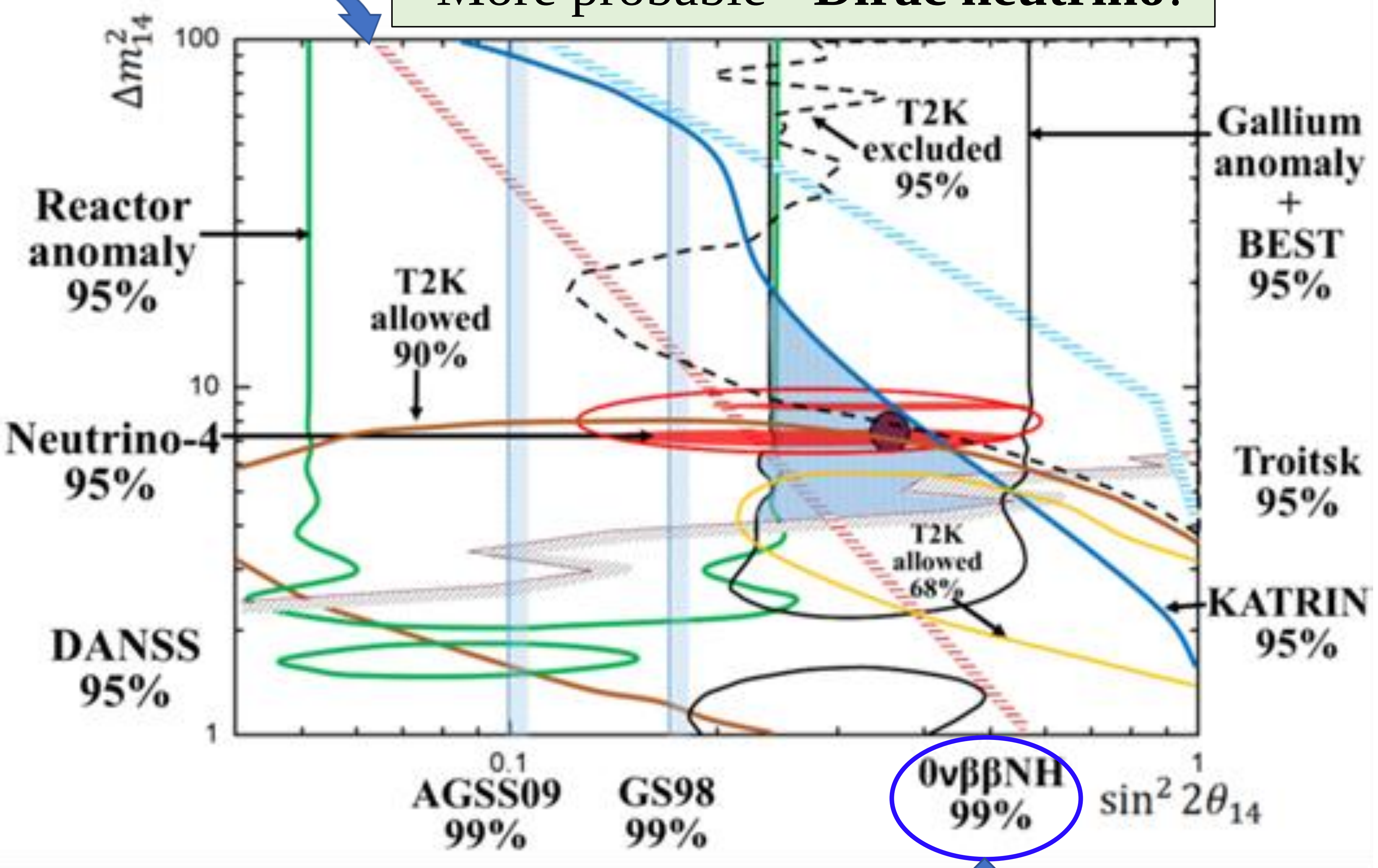
$$m_4 = (2.70 \pm 0.22)\text{eV}$$

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



Majorana or Dirac neutrino?
More probable - **Dirac neutrino**!

Double Beta Decay Without Neutrinos



Double Beta Decay

Cosmology and sterile neutrinos

Serebrov, A.P., Samoilov, R.M., Chaikovskii, M.E., Zherebtsov, O.M., Result of the Neutrino-4 Experiment and the Cosmological Constraints on the Sterile Neutrino (Brief Review) JETP Letters , 2022, 116(10), стр. 669–682

3+1 neutrino model and cosmology

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3} & U_{e4}\\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4}\\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4}\\ U_{s1} & U_{s2} & U_{s3} & U_{s4}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{bmatrix}$$

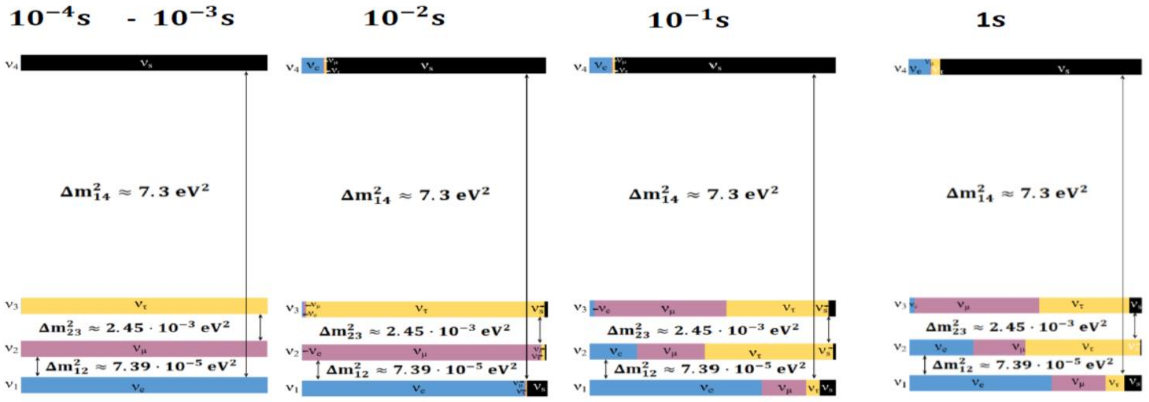
$$|U_{e4}|^2 = \sin^2(\theta_{14})$$
$$|U_{\mu4}|^2 = \sin^2(\theta_{24})\cdot\cos^2(\theta_{14})$$
$$|U_{\tau4}|^2 = \sin^2(\theta_{34})\cdot\cos^2(\theta_{24})\cdot\cos^2(\theta_{14})$$

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

$$P_{\nu_\mu\nu_\mu} = 1 - 4|U_{\mu4}|^2\left(1-|U_{\mu4}|^2\right)\sin^2\left(\frac{\Delta m_{14}^2 L}{4E_{\nu_\mu}}\right) = 1 - \sin^2 2\theta_{\mu\mu}\sin^2\left(\frac{\Delta m_{14}^2 L}{4E_{\nu_\mu}}\right)$$

$$P_{\nu_\mu\nu_e} = 4|U_{e4}|^2|U_{\mu4}|^2\sin^2\left(\frac{\Delta m_{14}^2 L}{4E_{\nu_e}}\right) = \sin^2 2\theta_{\mu e}\sin^2\left(\frac{\Delta m_{14}^2 L}{4E_{\nu_e}}\right)$$

$$U_{PMNS}^{(3+1)} = \begin{pmatrix} 0.782^{+0.017}_{-0.016} & 0.524^{+0.017}_{-0.016} & 0.148^{+0.004}_{-0.004} & 0.301^{+0.035}_{-0.035}\\ 0.484^{+0.028}_{-0.034} & 0.473^{+0.027}_{-0.036} & 0.732^{+0.016}_{-0.025} & 0.074^{+0.021}_{-0.021}\\ 0.280\div0.330 & 0.678\div0.705 & 0.622\div0.657 & 0\div0.194\\ 0.210\div0.273 & 0.060\div0.203 & 0.104\div0.236 & 0.931\div0.951 \end{pmatrix}$$

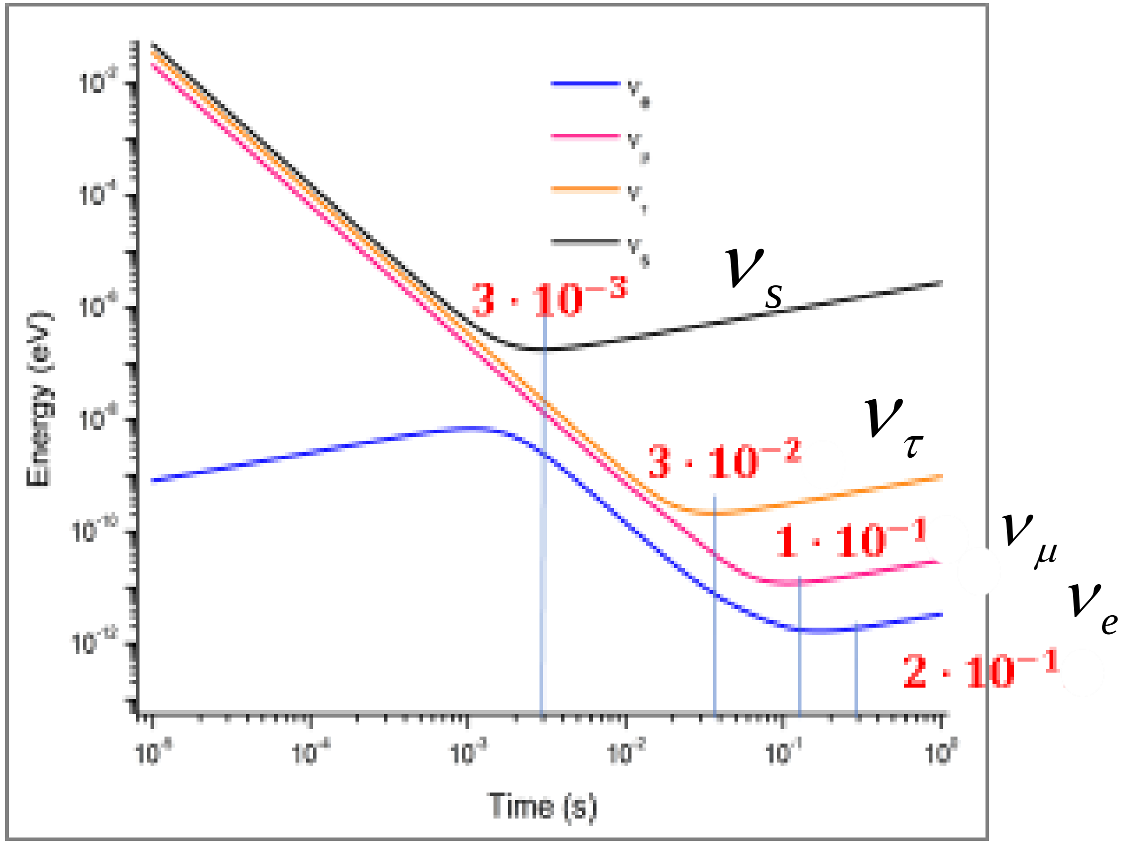


The neutrino potential in cosmic plasma

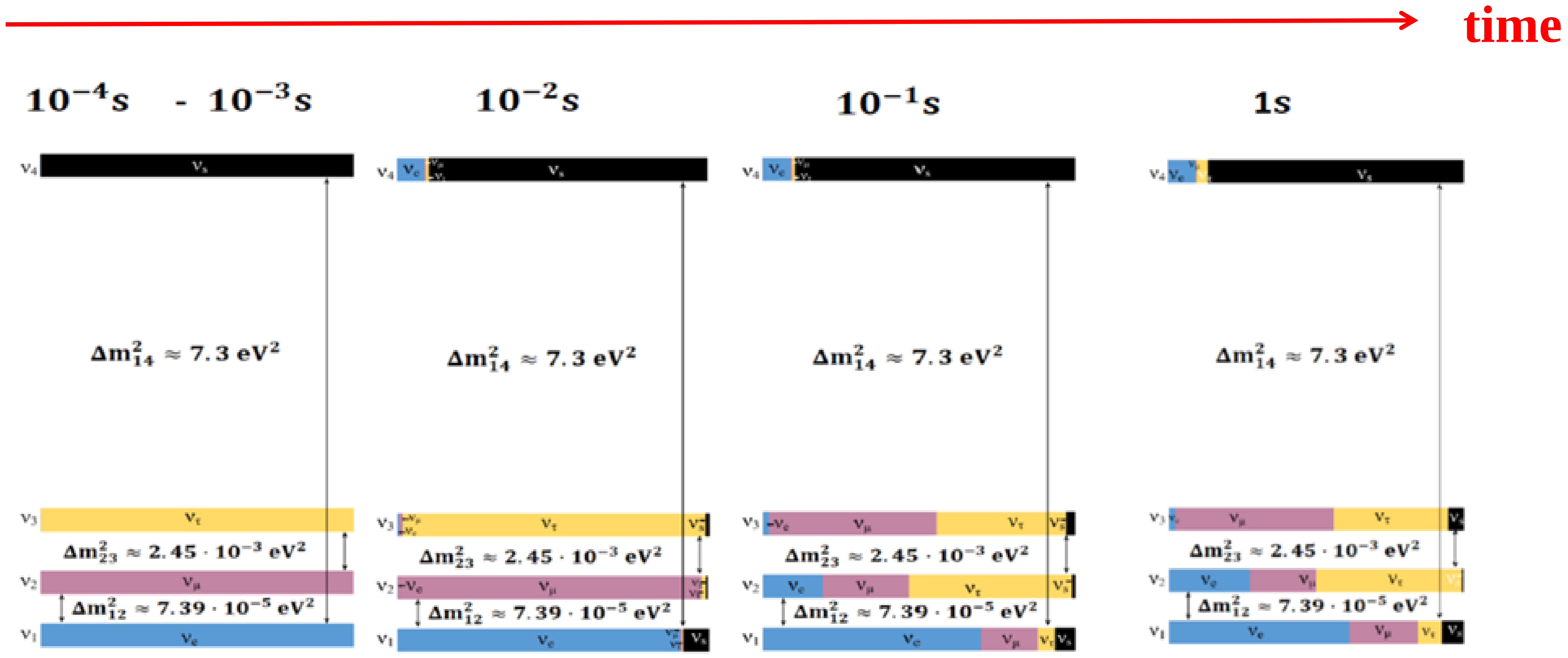
$$V = \pm C_1\eta G_F T^3 - C_2\frac{G_F^2 T^4 E}{\alpha}$$

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

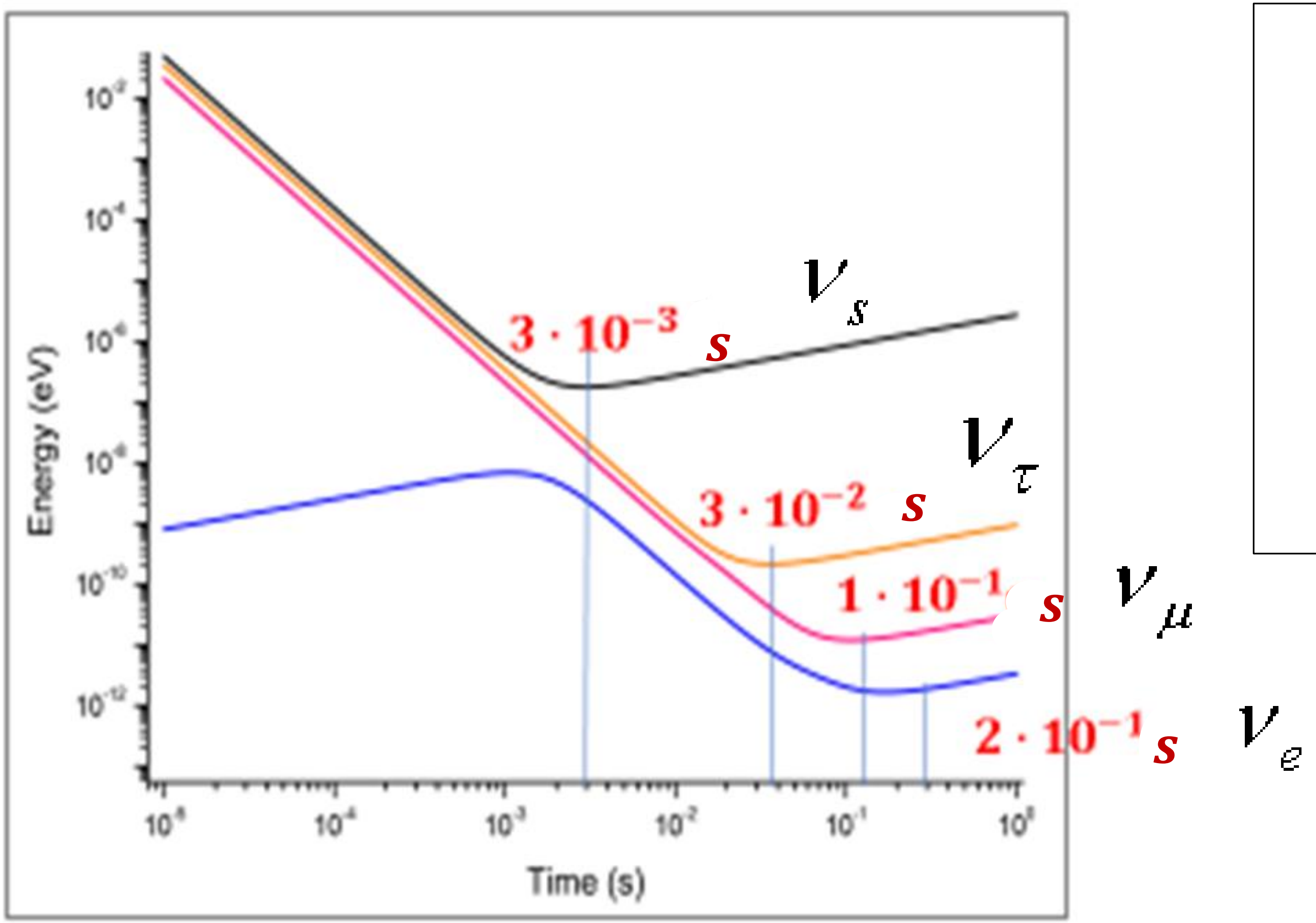
$$T[eV] \sim \frac{887734}{\sqrt{t[s]}}$$



Behavior of mixing between neutrinos in expanding Universe



Behavior of adiabatic energy levels in expanding Universe



For a sterile neutrino,
at $\mathbf{3 \cdot 10^{-3}}$ $\boldsymbol{s}$,
For tau neutrinos,
at $\mathbf{3 \cdot 10^{-2}}$ $\boldsymbol{s}$,
For the muon neutrino,
at $1 \cdot 10^{-1}$ s,
For electron neutrinos,
at $\mathbf{2 \cdot 10^{-1}}$ $\boldsymbol{s}$,

Equation for the generation and destruction of sterile neutrinos

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

$$E = 3.15T$$

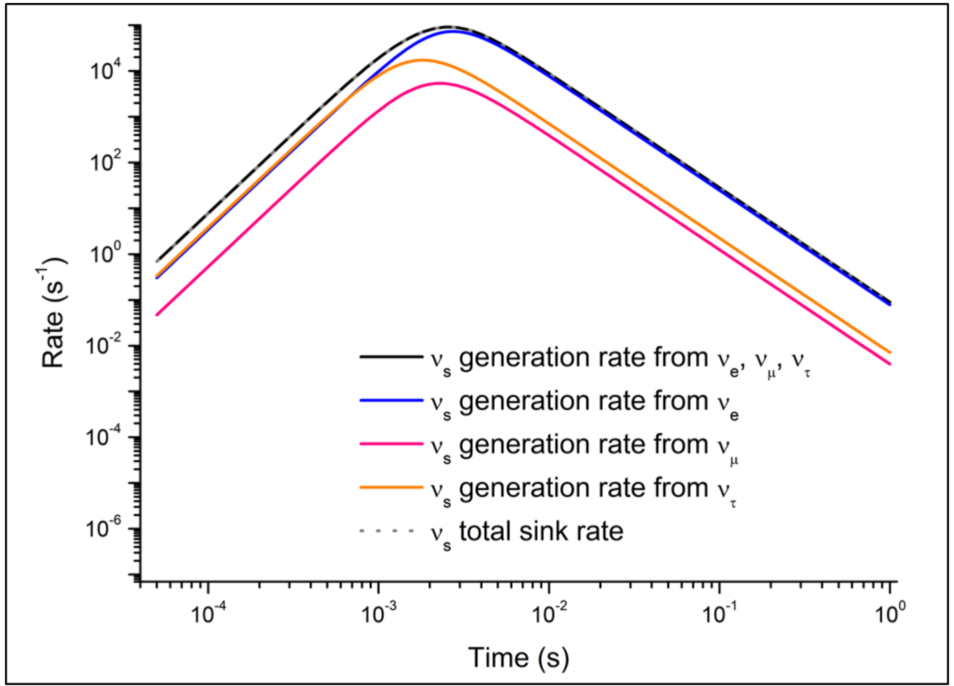
$$H(T) = \frac{T^2}{M^*_{Pl}}$$

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

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

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

Generation and destruction of sterile neutrinos

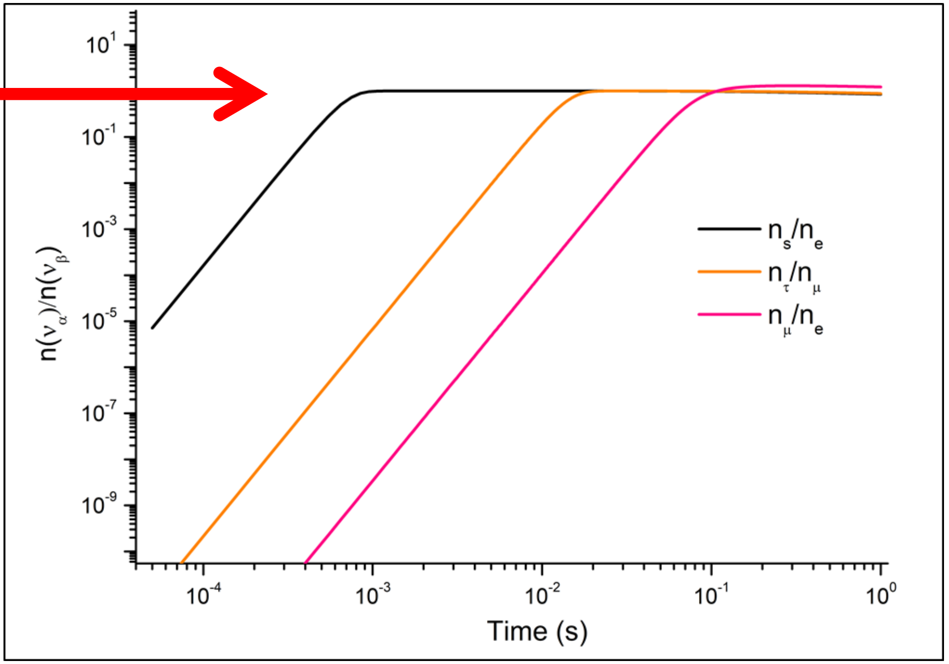


$$n_{\nu_s} / n_{\nu_e} = 1$$

Termalization of sterile neutrinos

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

The densities of different types of neutrinos are the same



RESULT

Contribution of the Sterile Neutrino ($m_4 = 2.7\ eV$)

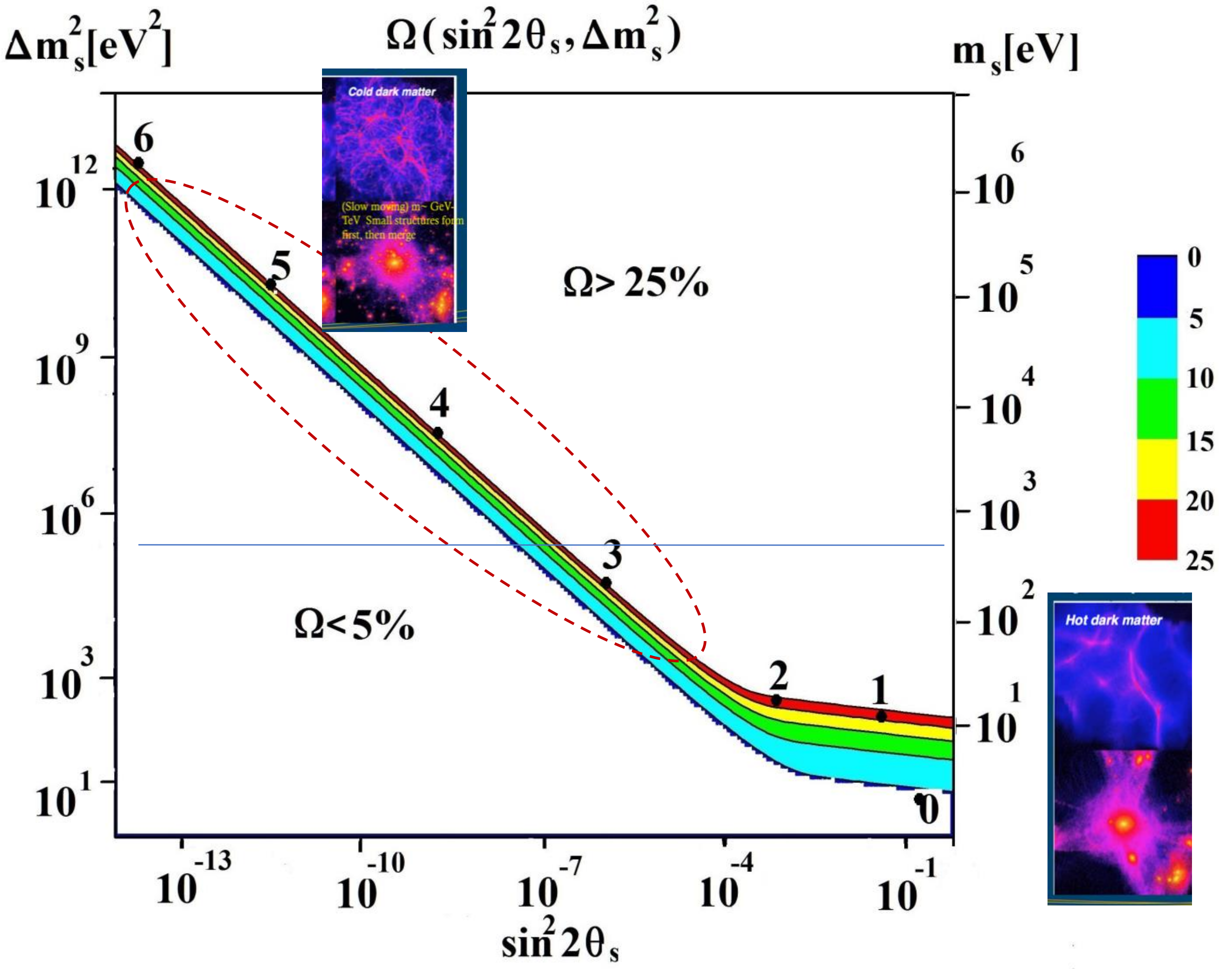
to the Energy Density of the Universe

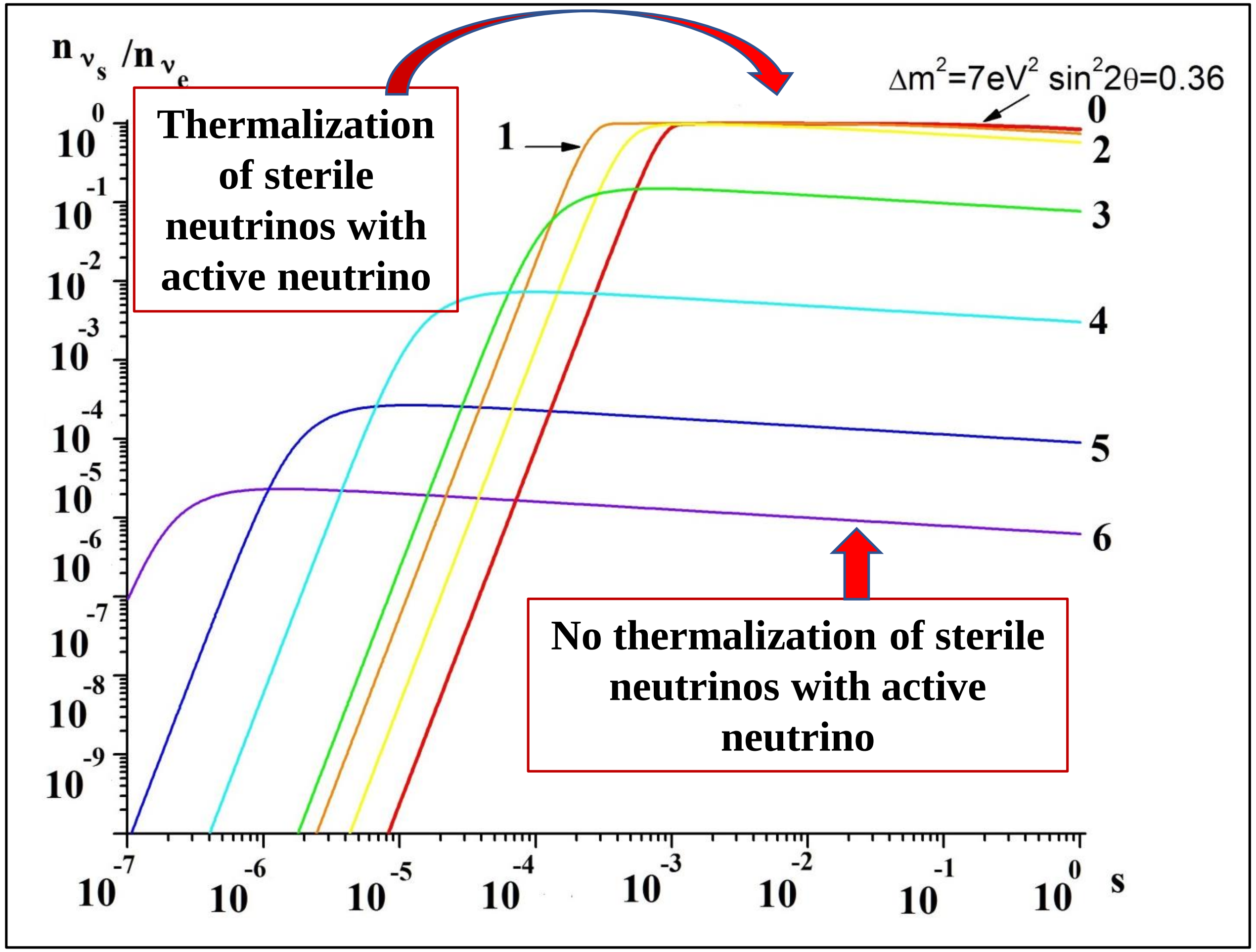
$$\Omega_{\nu_4} \approx \left(\sum m_{\nu_i}/1eV\right)0.01h^{-2} \cdot n_{\nu_4} m_{\nu_4}/\sum(n_{\nu_i} m_{\nu_i})$$

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

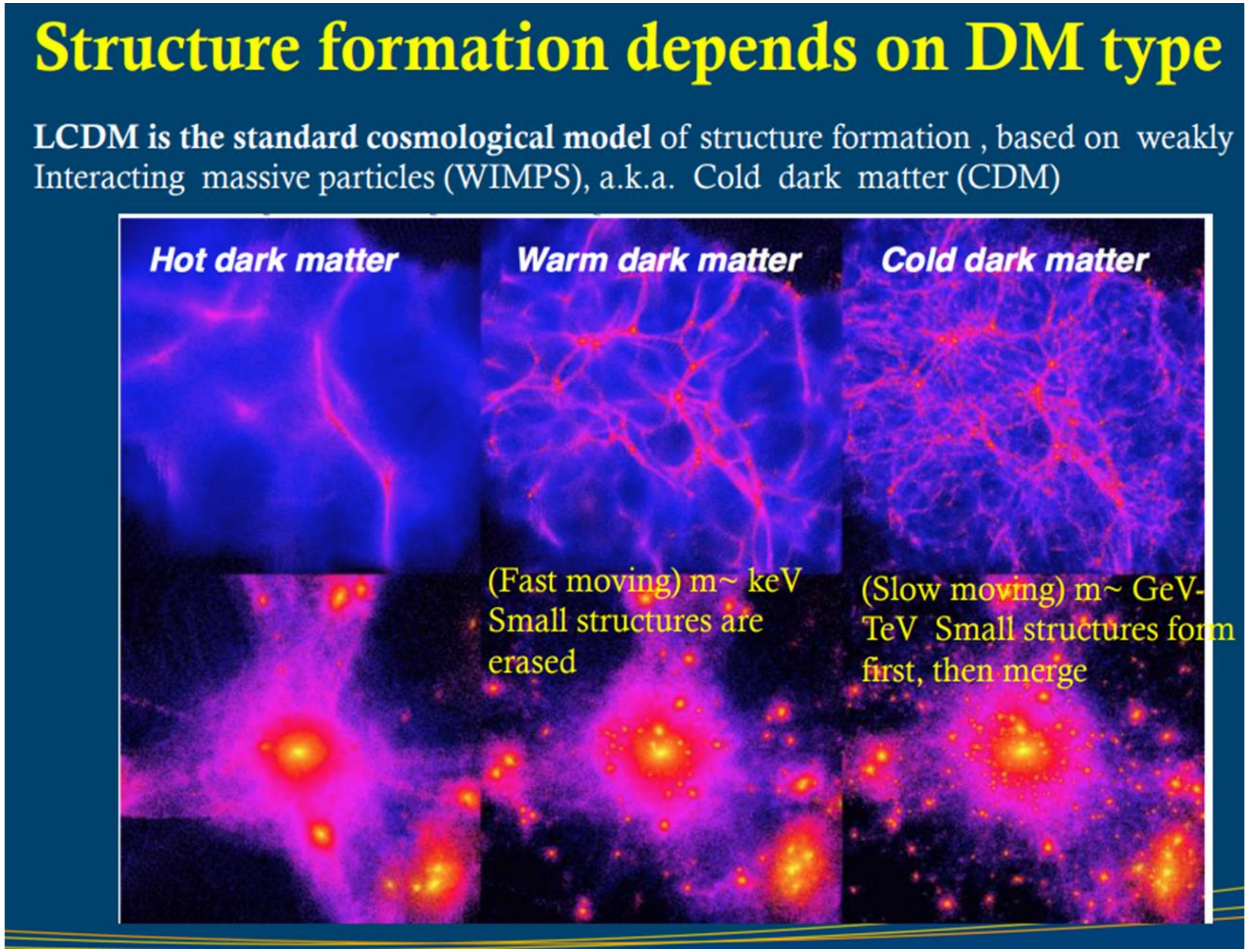
$$\Omega_{\nu_4} \approx (2.7eV/1eV) \cdot 0.01h^{-2} \cdot n_{\nu_4}/n_{\nu_e} = 5\%$$

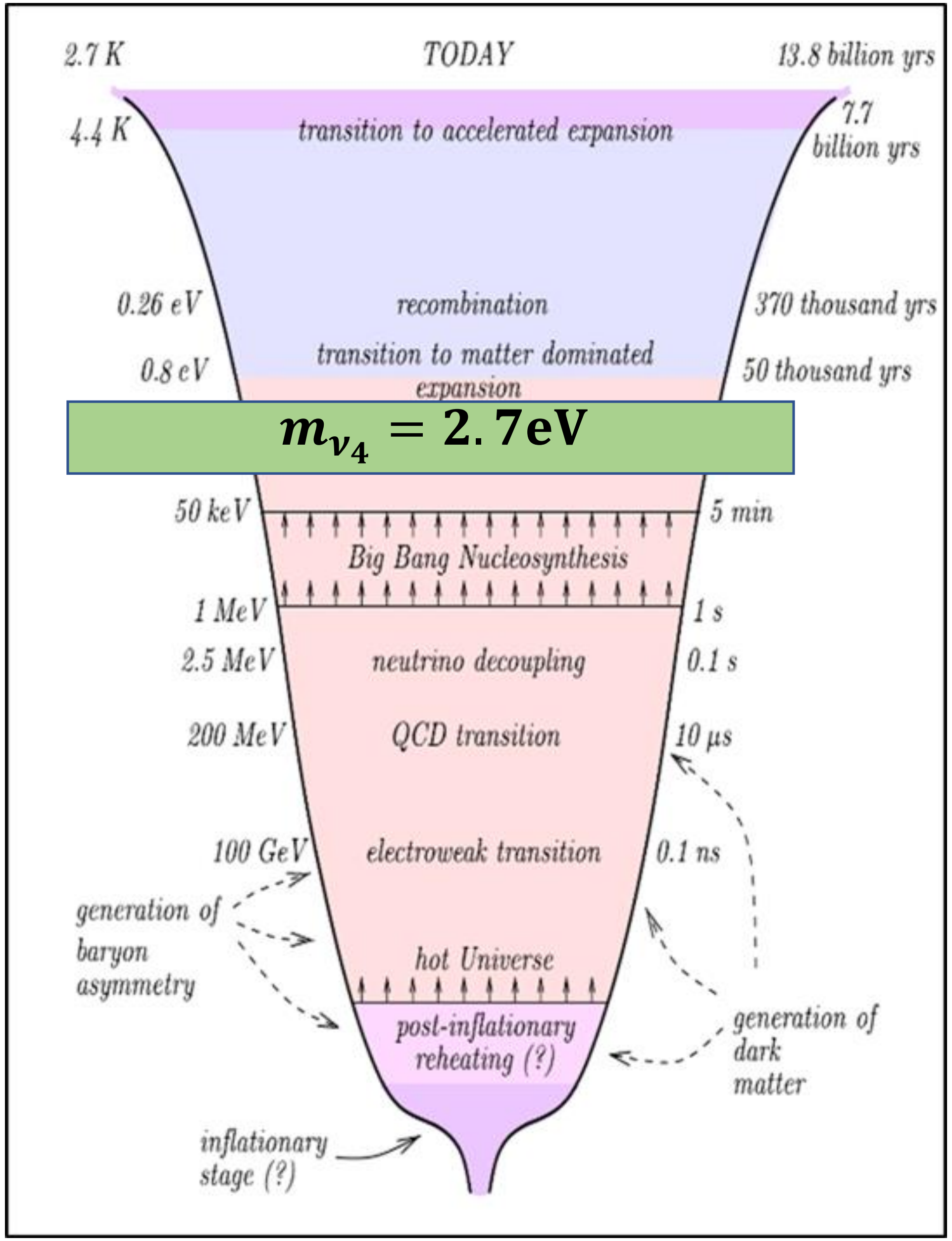
Heavy sterile (right-handed) neutrinos with very small mixing angles





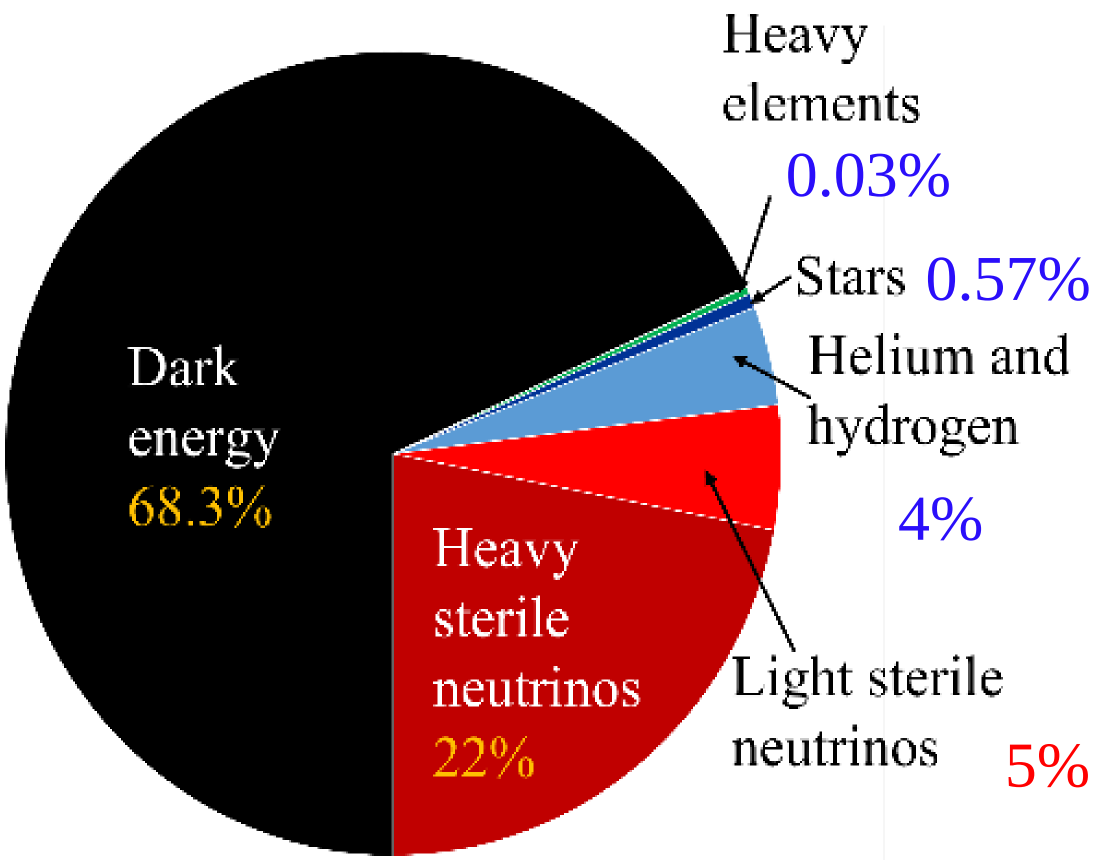
Heavy sterile (right-handed) neutrinos with very small mixing angles can be considered as dark matter and explain the structure of the Universe!

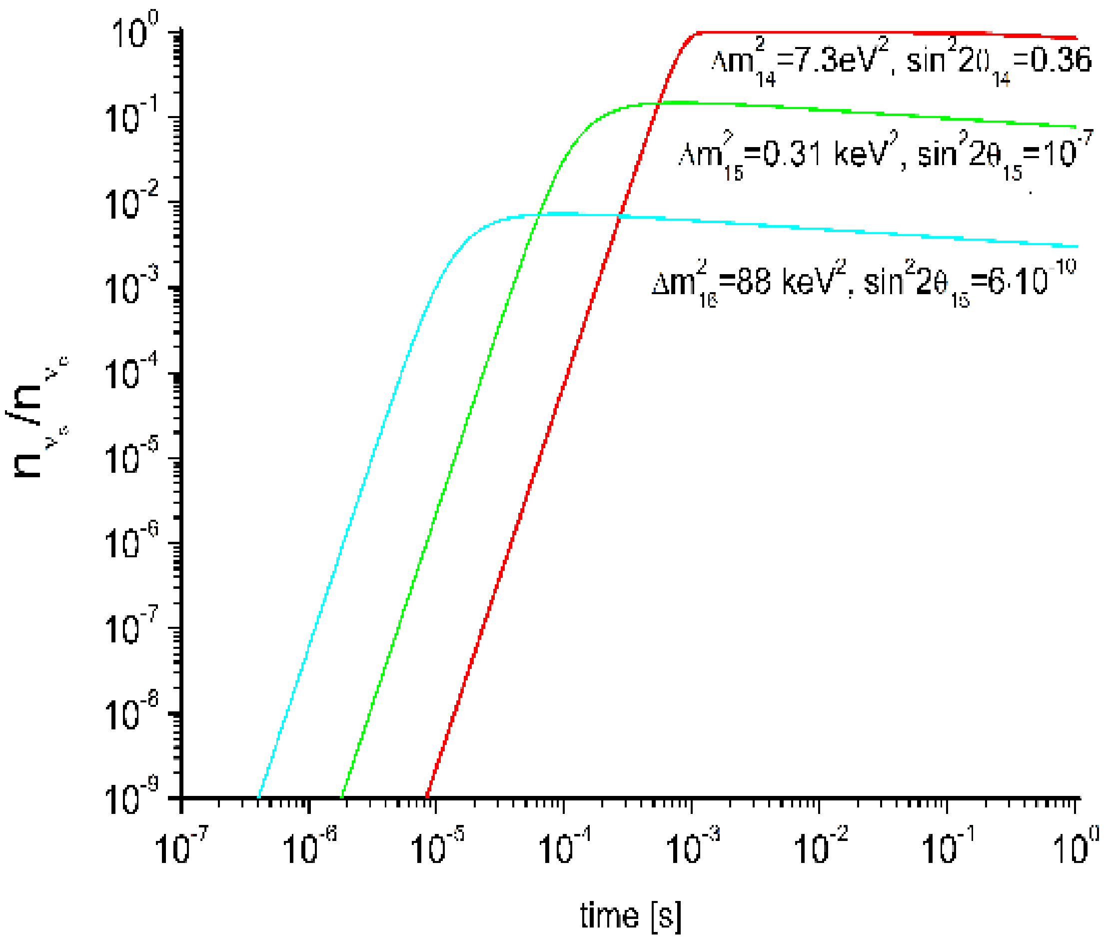




Heavy sterile (right-handed) neutrinos with a mass of several keV can form a structure due to gravitational forces and forces of attraction between right-handed neutrinos and right-handed antineutrinos.

General picture of the composition of the energy density and mass of the Universe

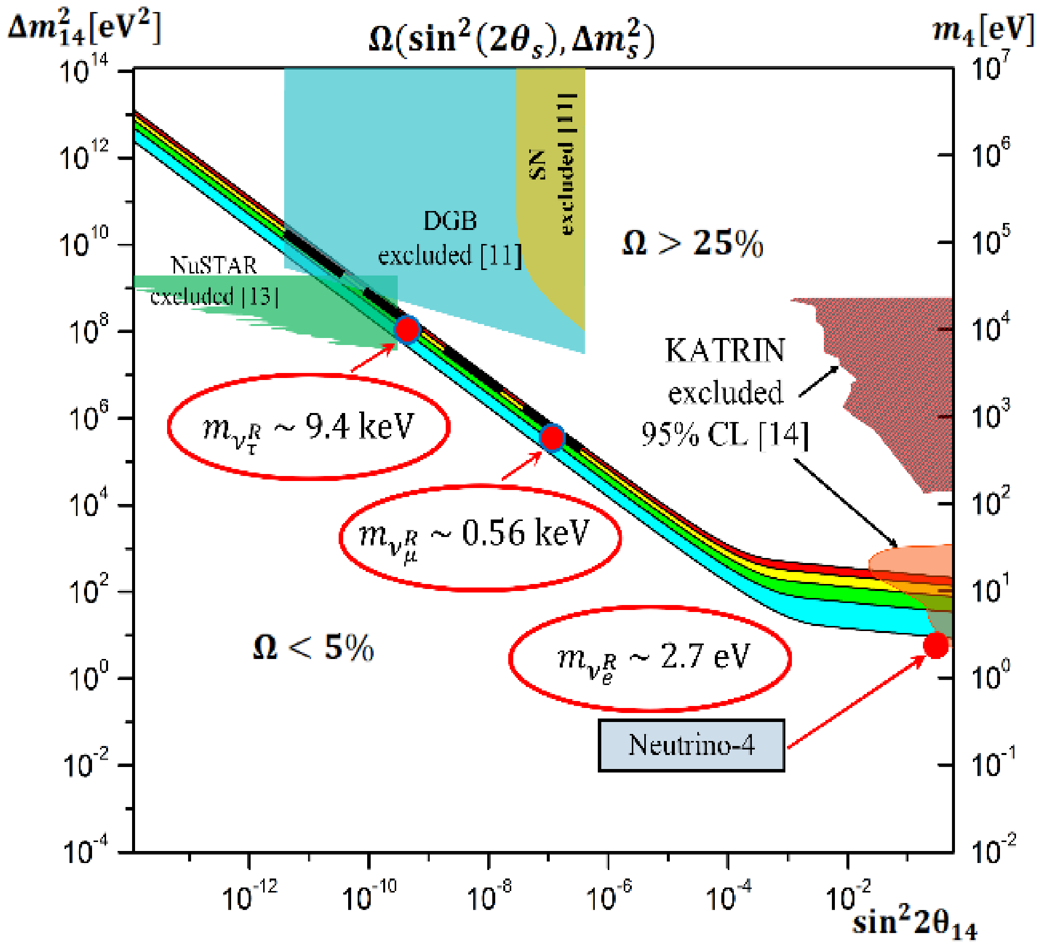


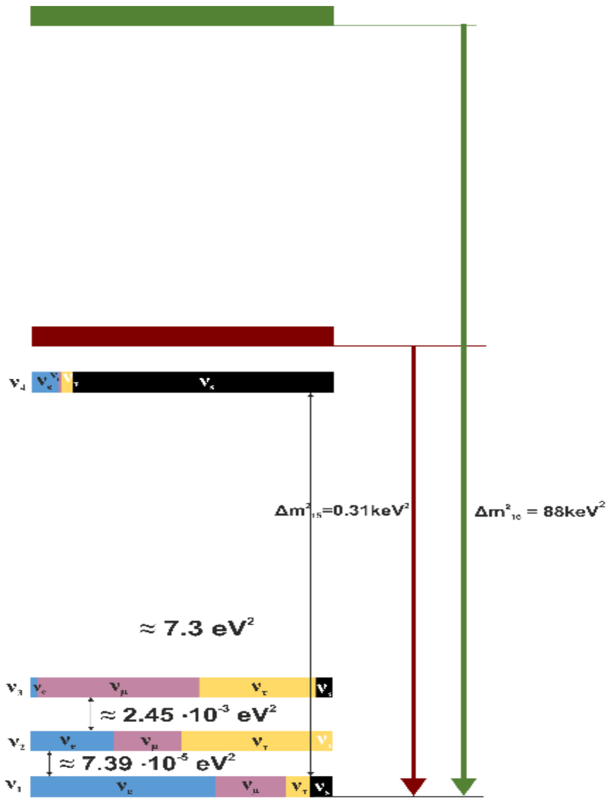


Dynamics of the generation of the dark matter consisted of three right-handed neutrinos and right-handed antineutrinos .

Hierarchy of right-handed neutrino masses ?

Hierarchy of right neutrino masses ?



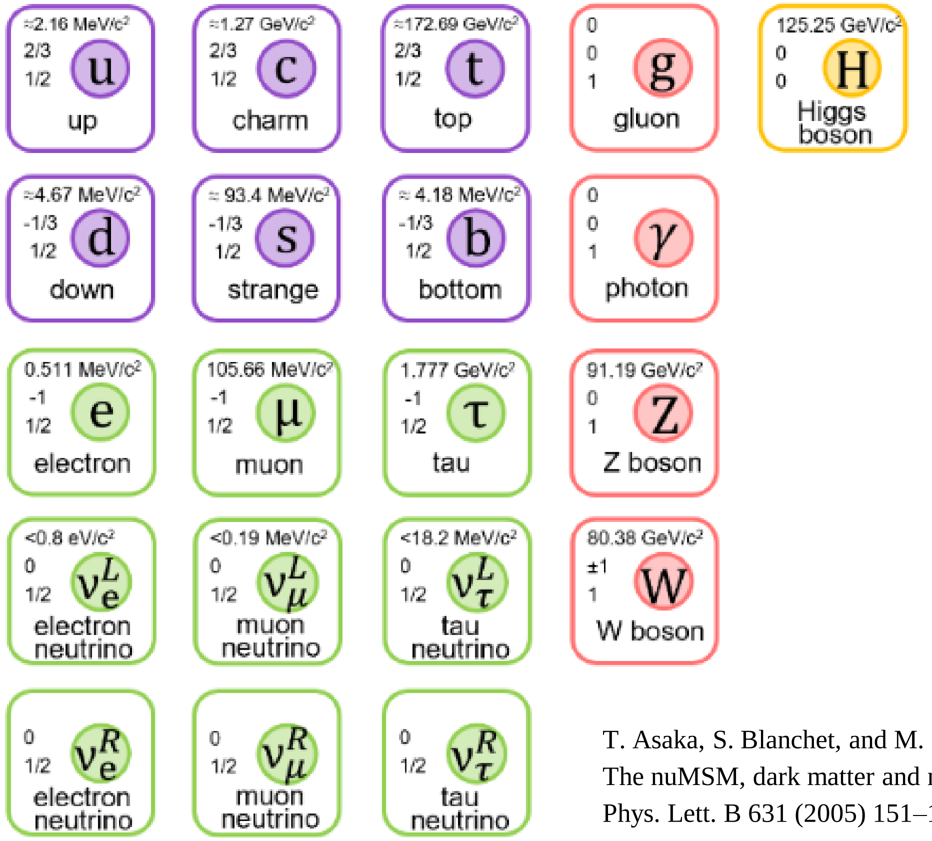


Mass hierarchy for left and right neutrinos. The direct hierarchy of mass active neutrinos is taken as a basis.

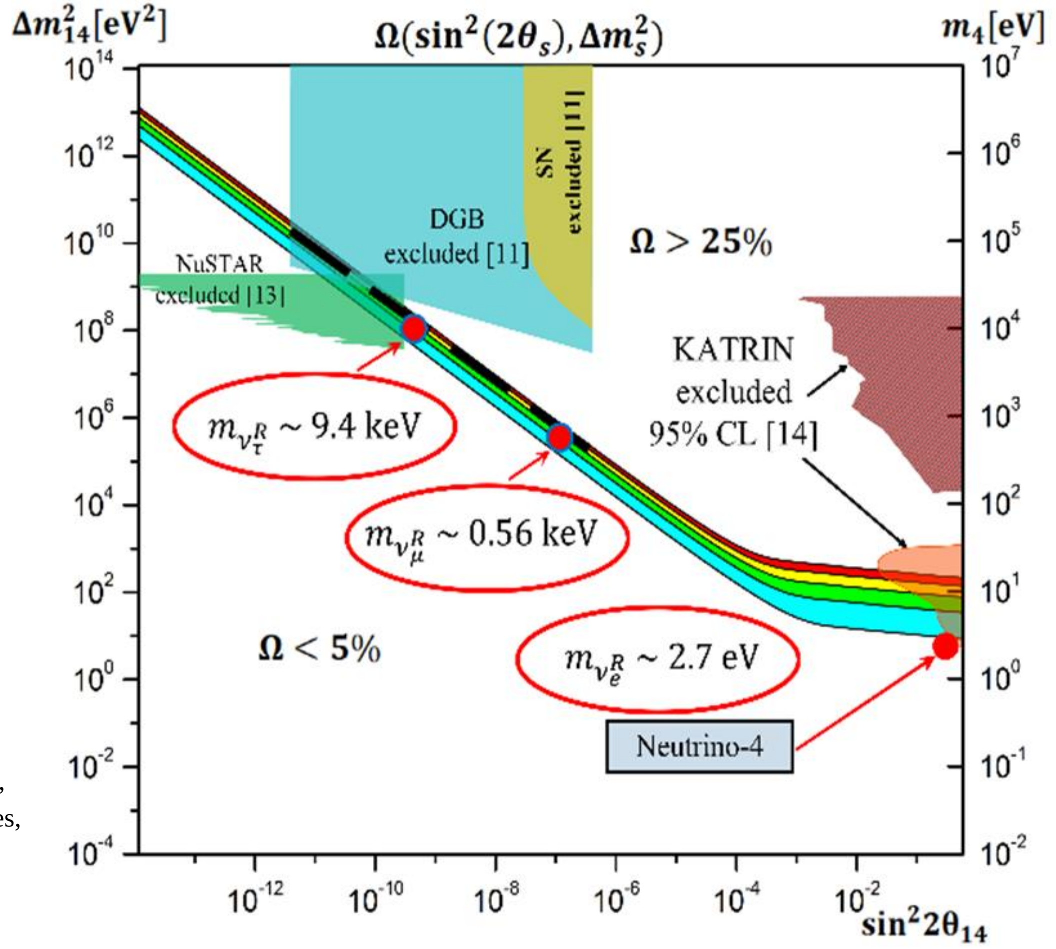
It can be assumed that the right neutrino mass hierarchy somehow correlates with the lepton mass hierarchy, i.e. m_e, m_μ, m_τ.

Laboratory and astrophysical constraints on the parameters of sterile neutrinos. 1) Red spots – result of the Neutrino-4 experiment and possible masses of the heavy right-handed neutrinos; 2) Ω_s range in 5-25%; 3) DGB – experimental constraints from gamma background [11]; 4) SN – experimental constraints from SN1987 observation, 5) constraints from NuSTAR experiment [12]; 6) KATRIN excluded 95% CL – constraints on eV-scale sterile neutrino from KATRIN experiment [13]; 7) excluded 95% CL – constraints from neutrino mass measurements experiment from [13];

Scheme of extending the Standard Model by introducing additional elementary particles - right-handed neutrinos, the so-called Neutrino Minimal Standard Model νMSM

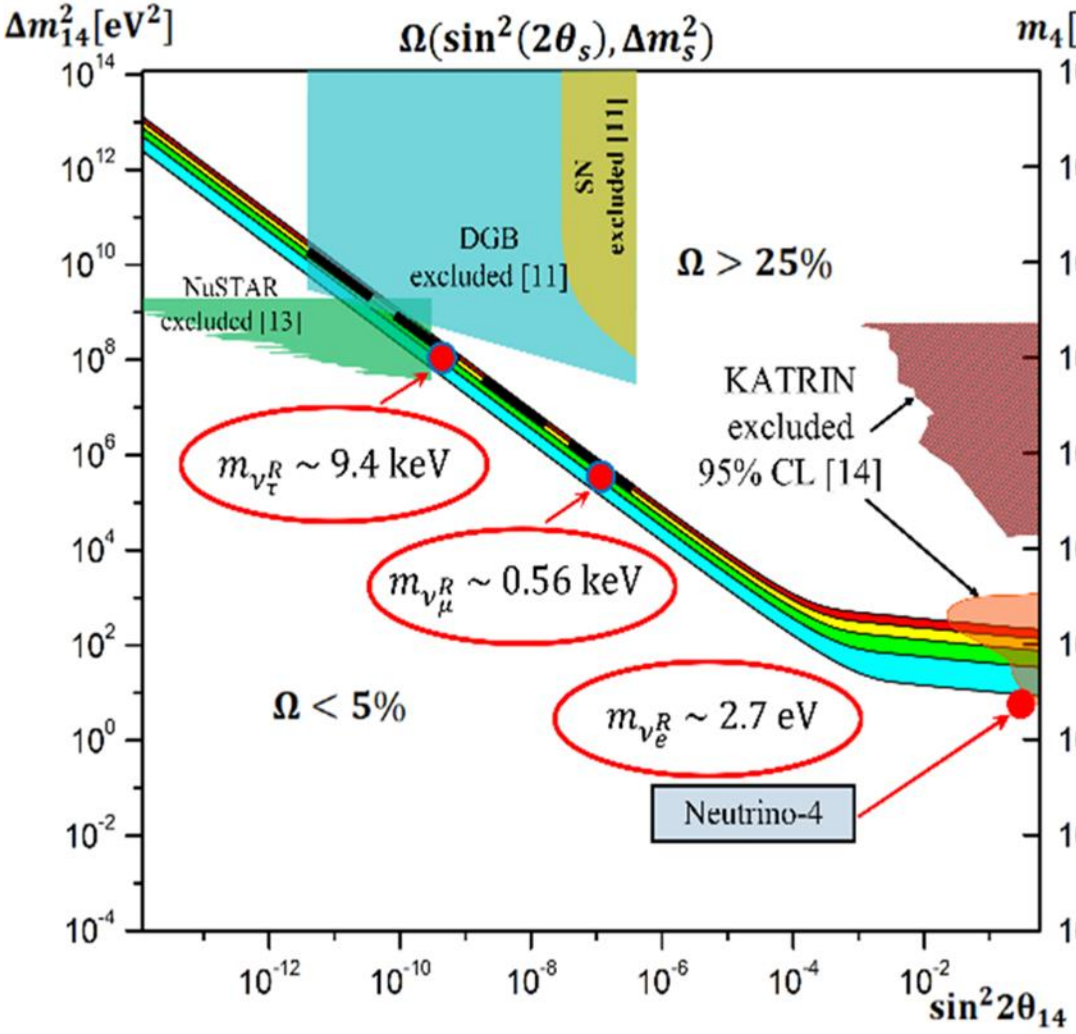


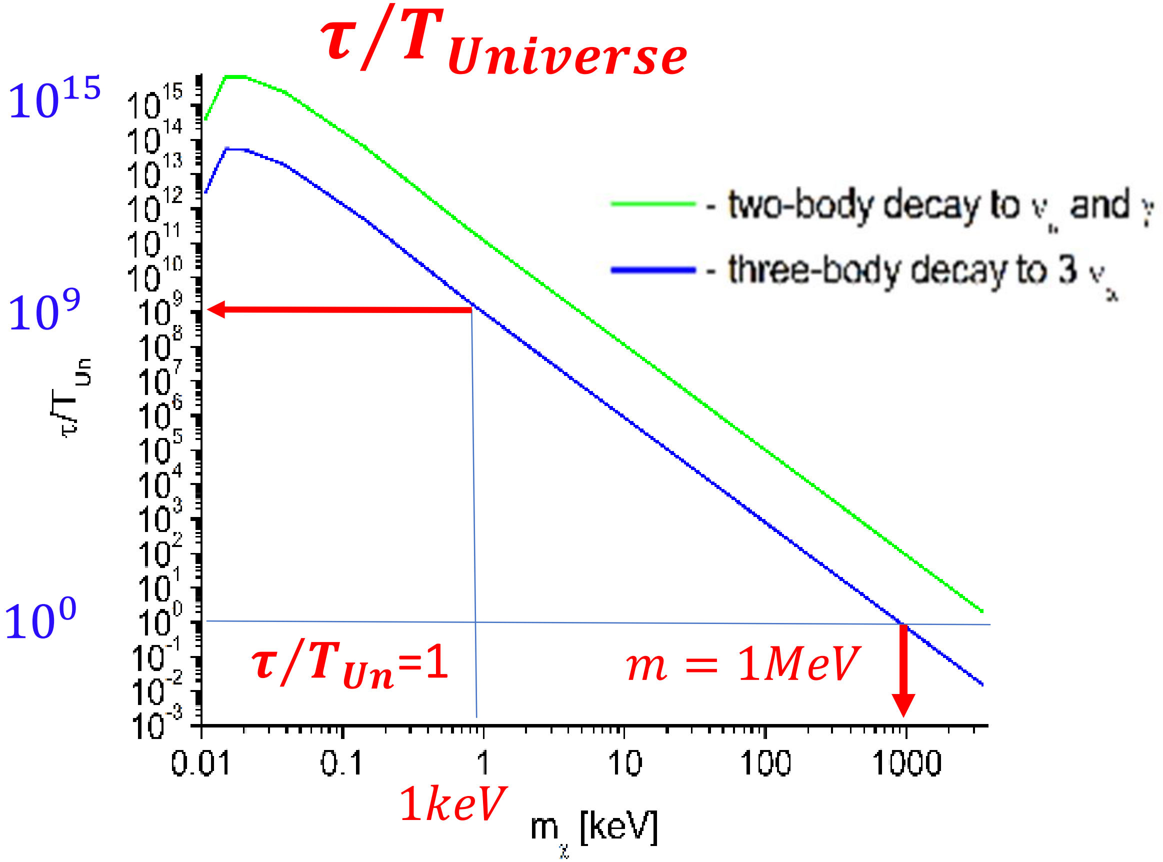
T. Asaka, S. Blanchet, and M. Shaposhnikov, The nuMSM, dark matter and neutrino masses, Phys. Lett. B 631 (2005) 151–156

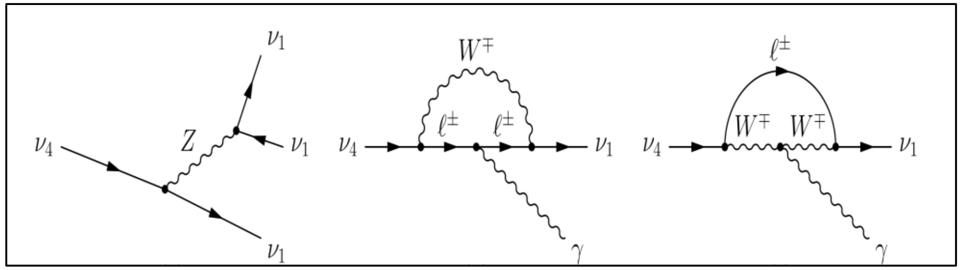


If we assume that the mass of the light right-handed neutrino is determined, then the masses of heavy right-handed neutrinos are unknown. It can be assumed that the right neutrino mass hierarchy somehow correlates with the lepton mass hierarchy, i.e. m_e, m_μ, m_τ. Then we can assume the following direct hierarchy of right neutrino masses: $\boldsymbol{m_{\nu_e^R} = 2.7\,\mathrm{eV}}$, $m_{\nu_\mu^R} = 0.56$ keV, $m_{\nu_\tau^R} = 9.4$ keV .

Decay time of right-handed neutrinos in the channel of two-body and three-body decay.







Lifetime of heavy neutrino as function of its mass.
The lifetimes are reduced to the time of the Universe.

Dasgupta and J. Kopp, Phys. Rept. **928** (2021) 1-63, arXiv:2106.05913v1

arxiv.2306.09962
The result of the Neutrino-4 experiment, sterile neutrinos, dark matter and the Standard Model A. P. Serebrov, R. M. Samoilov, O. M. Zherebtsov

Does the light right-handed neutrino ($2.7eV$) contradict astrophysical data on the measurement of the mass content of 4He?

How accurate are the experimental limits on the number of neutrinos based on astrophysical data on measuring the mass content of 4He?

When passing from *N_ν*=3 to *N_ν*=4, the mass content of 4He increases by 4.9%

The number of degrees of freedom at the moment of neutron hardening is equal to: $g_*^{T_n} = 2 + \frac{7}{8} \cdot 4 + \frac{7}{8} \cdot 2 \cdot N_\nu$

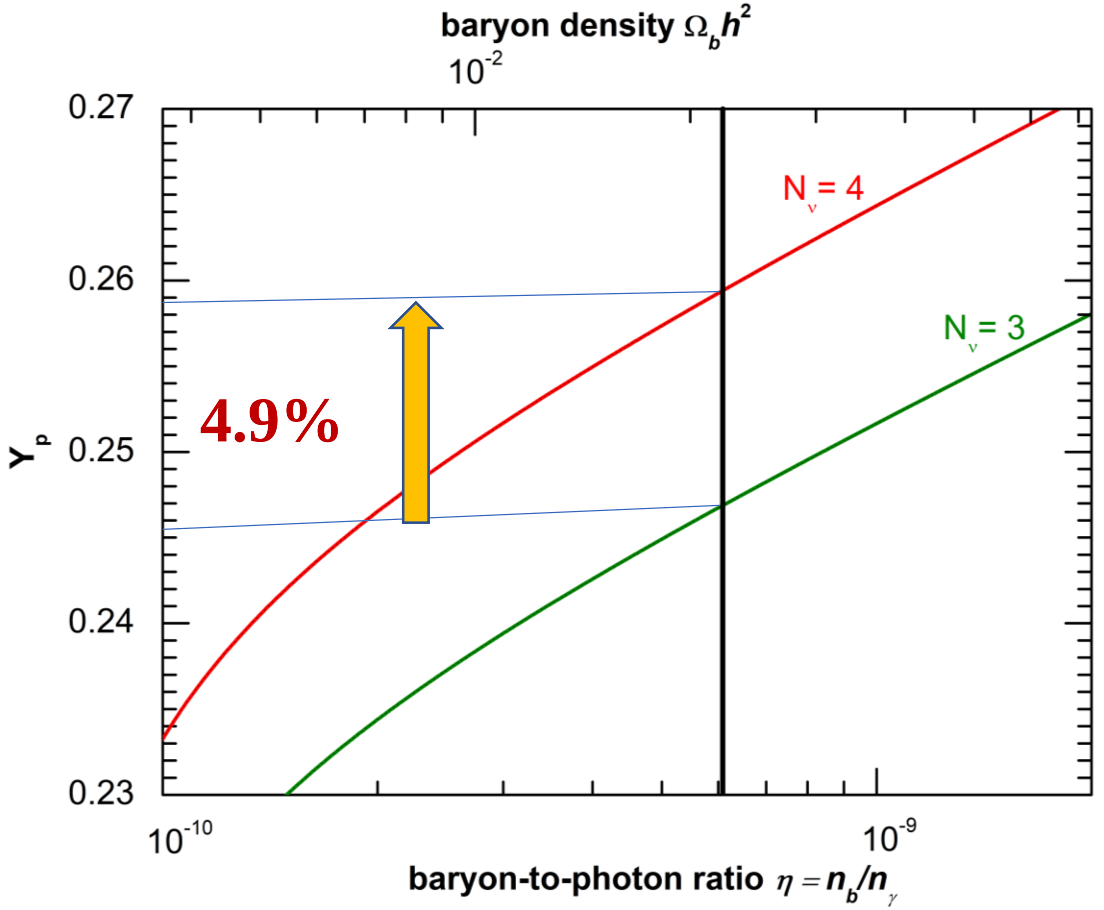
The first contribution arises due to photons, the second due to electrons and positrons, the third is associated with light neutrinos that have managed to thermalize.

Accordingly, for $\boldsymbol{N_\nu = 3}$, $\boldsymbol{g_*^{T_n} = 10.75}$ and for $\boldsymbol{N_\nu = 4}$, $\boldsymbol{g_*^{T_n} = 12.5}$. Although the number of degrees of freedom increases by 16.3%, the rate of plasma expansion increases by 7.8%, because root dependency

The number of degrees of freedom at the time of nucleosynthesis is:

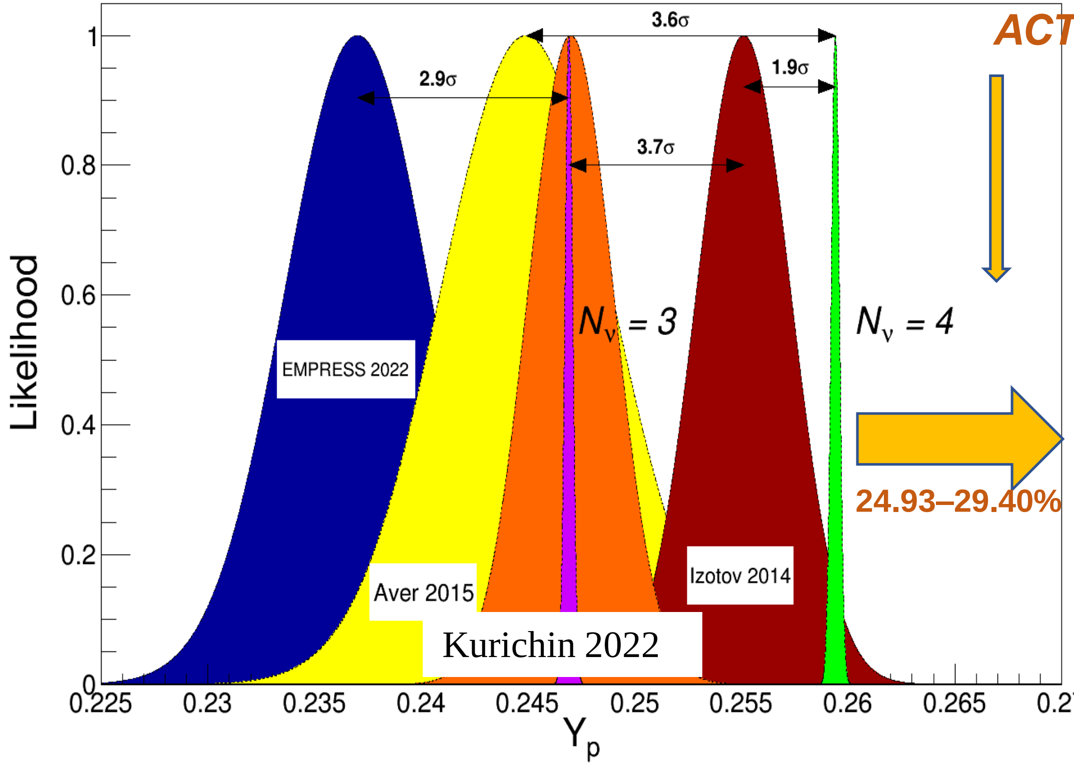
$$g_*^{T_n} = 2 + \frac{7}{8} \cdot 2 \cdot N_\nu \cdot \left(\frac{4}{13}\right)^{4/3}$$

Accordingly, for ***Nν=3***, ***g*Tn=3.36***, and for***Nν=4***, ***g*Tn=3.81***. Although the number of degrees of freedom increases by 13.5%, the plasma expansion rate increases by 6.5%, because root dependency. Thus, the rate of plasma expansion during nucleosynthesis increases by 6.5% when passing from the analysis of the scheme with three neutrinos to the scheme with four neutrinos. The average value of the increase in the number of degrees of freedom over the interval from 1.2 s to 265 s is approximately 7%.



Y_p abundances as a function of baryon asymmetry at $N_\nu = 3$ and 4 respectively. The line thickness is determined by the experimental accuracy of measuring the neutron lifetime ($\tau_n = 879.4 \pm 0.6$ s). The vertical line corresponds to the value of the baryon asymmetry (6.090 ± 0.060)·10^{-1}, and its thickness corresponds to one standard deviation. Data taken from [24].

The experimental estimations on the number of neutrinos based on astrophysical data on measuring the mass content of 4He



Comparison of the calculated predictions of the abundance of ^{4}He with the known neutron lifetime and the value of the baryon asymmetry in the model $N_\nu = 3$ and $N_\nu = 4$ (purple and green peaks, respectively) with the results of astrophysical observations: Izotov 2014, Aver 2015, Kurichin 2022 and EMPRESS 2022 (red, yellow, orange and blue distribution respectively)

АСТРОНОМИЧЕСКИЙ ЖУРНАЛ, 2023, том 100, № 3, с. 258–271

К ВОПРОСУ О ПЕРВОНАЧАЛЬНОМ СОДЕРЖАНИИ ГЕЛИЯ ПО НАБЛЮДЕНИЯМ РРЛ В ОРИОНЕ А

© 2023 г. А. П. Цивилев[1], *, В. В. Краснов[1]

Следовательно, можно ожидать, что первичное содержание гелия (*Yp*, отношение He/H по массе) может составлять не менее интервала значений ≈24.93–29.40%, что допускает отклонения от выводов Стандартной модели, например, допускает присутствие неизвестных легких частиц во время первичного нуклеосинтеза

ON THE QUESTION OF THE ORIGINAL HELIUM CONTENT ACCORDING TO RRL OBSERVATIONS IN ORION A

Therefore, it can be expected that the primordial helium abundance (Yp, He/H ratio by mass) may be **at least in the range of values of ≈24.93–29.40%, which allows for deviations from the conclusions of the Standard Model, for example, allowing for the presence of unknown light particles during primordial nucleosynthesis**

It is impossible to draw a definite conclusion in favor of models of three or four neutrinos, based on the presented astrophysical data.

Role of lepton asymmetry in BBN analysis

Assumption that the lepton asymmetry is as small as the baryon asymmetry.
However, this condition may be violated.

At the beginning of BBN, neutrons and protons are in equilibrium until the equilibrium is disturbed by a weak interaction. If the process $\boldsymbol{p + \bar{\nu}_e \to n + e^+}$ is suppressed with respect to the process $\boldsymbol{n + \nu_e \to p + e^-}$ due to a smaller number of electron antineutrinos, then this suppresses the neutron-proton ratio and, as a result, Y_P decreases. This decrease in Y_{P} can be compensated by increasing the number of degrees of freedom N_ν^{eff} to keep the same value of Y_{P}. **Thus, the presence of lepton asymmetry masks the presence of the fourth neutrino.**

lepton asymmetry
decrease Y_{P}

$$\boldsymbol{p + \bar{\nu}_e \to n + e^+ \neq n + \nu_e \to p + e^-}$$

$$\frac{n_\nu - n_{\bar{\nu}}}{n_\nu + n_{\bar{\nu}}} = \frac{\pi^2}{9\zeta(3)} \frac{\mu_\nu}{T} \approx \quad \xi_a = \mu_{\nu_a}/T_\nu$$

$$\frac{n_n}{n_p} = \exp\left\{-\frac{\Delta m}{T_n} - \frac{\mu_{\nu_e}}{T_n}\right\}$$

lepton asymmetry $\boldsymbol{\xi_a = \mu_{\nu_a}/T_\nu}$

Role of lepton asymmetry in BBN analysis

At a non-zero chemical potential, the Fermi–Dirac distributions for neutrinos (antineutrinos) are written as

$$f_{\nu_e}(p,\xi_e) = \frac{1}{\exp\left(\frac{p}{T_\nu} - \xi_{\nu_e}\right)+1}, \qquad f_{\bar{\nu}_e}(p,\xi_e) = \frac{1}{\exp\left(\frac{p}{T_\nu} + \xi_e\right)+1},$$

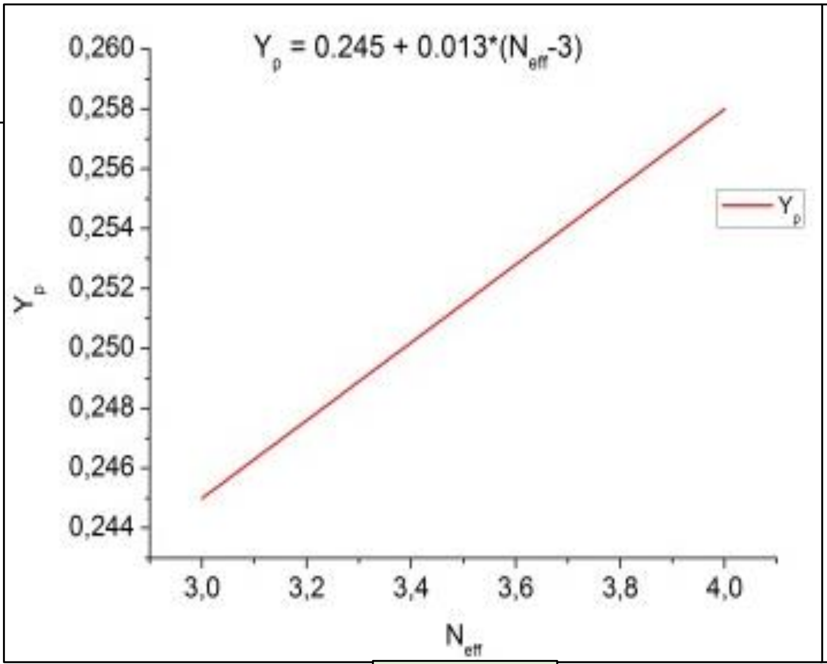
where $\xi_e = \mu_{\nu_e}/T_\nu$ and μ_{ν_e} – is the chemical electron neutrino potential, ξ_e is asymmetry of the electron neutrino.

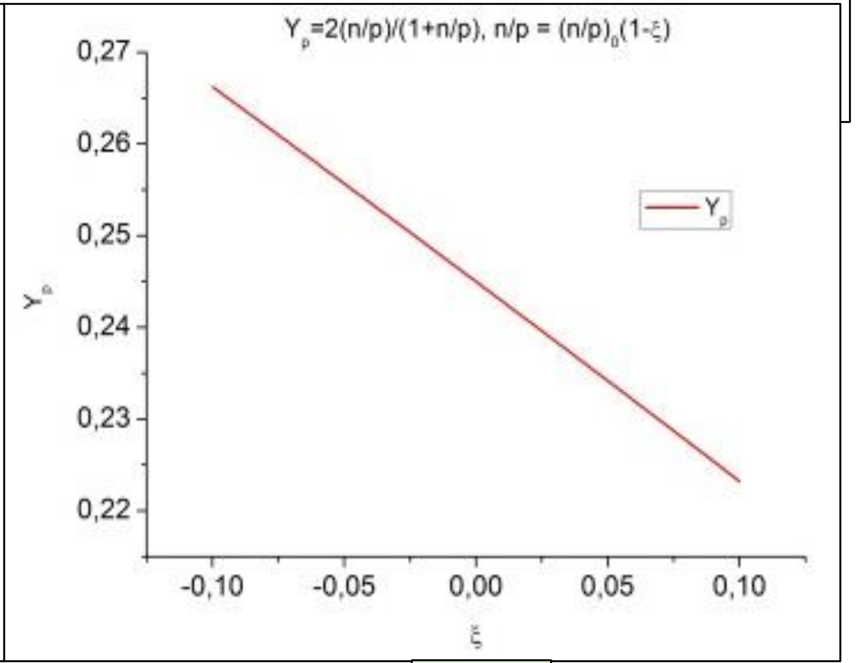
$$\xi_e \approx \frac{n_{\nu_e} - n_{\bar{\nu}_e}}{n_{\nu_e} + n_{\bar{\nu}_e}}.$$

$$\xi_a = \mu_{\nu_a}/T_\nu$$

$$\frac{n_n}{n_p} = \exp\left\{-\frac{\Delta m}{T_n} - \frac{\mu_{\nu_e}}{T_n}\right\}$$

Dependence of Y_P on ξ_{ν_e}, and N_{eff}





N_{eff} $\qquad$ ξ_{ν_e}

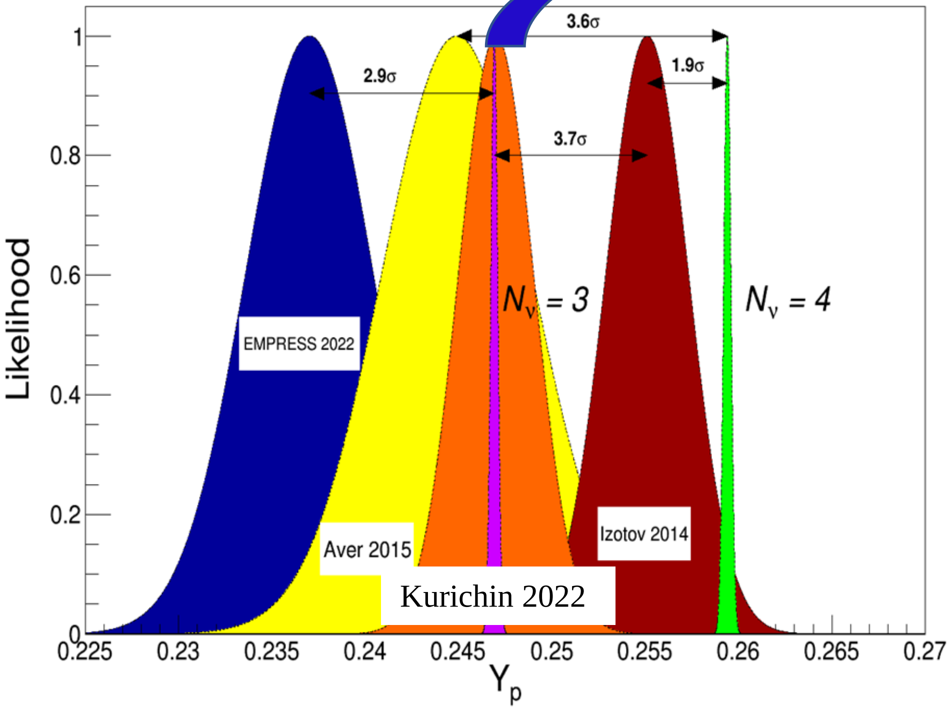
From the definition of the mass content of He4 $Y_p = 0.2462 \pm 0.0022$ и $N_\nu = 4$ $\xi \approx 0.05$

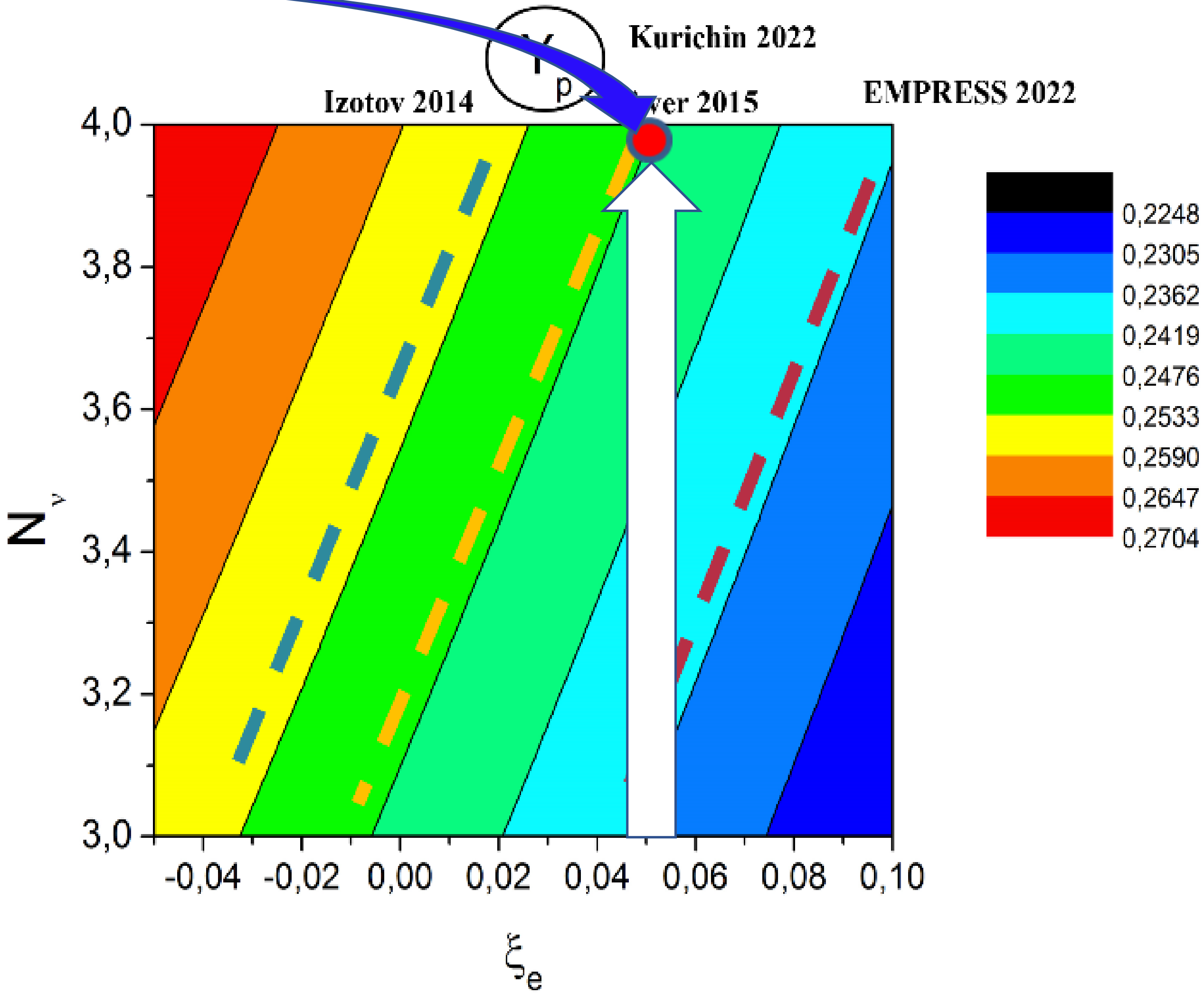
$\xi = 0$

$Y_p = 0.2462 \pm 0.0022$

$\xi \approx 5\%$ $N_\nu = 4$

$\xi \neq 0$





arxiv.2306.09962

The result of the Neutrino-4 experiment, sterile neutrinos, dark matter and the Standard Model A. P. Serebrov, R. M. Samoilov, O. M. Zherebtsov

The appearance of neutrino-antineutrino asymmetry in the process of primary nucleosynthesis

(Result of our calculations in progress)

CONCLUSIONS

1. The joint analysis of the results of the Neutrino-4 experiment and the data of the GALLEX, SAGE and BEST experiments confirm the parameters of neutrino oscillations declared by the Neutrino-4 experiment ($7.3\ eV^2$ and $sin^2 2\theta_{14} \approx 0.36$) and increases the confidence level to 5.8σ. ($m_4 = 2.7\ eV$)

2. Estimation of the contribution of sterile neutrinos with mass $2.7 eV$ is 5% of the energy density of the Universe.

3. Extension of the neutrino model by introducing two more heavy sterile neutrinos in accordance with the number of types of active 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%. Dark matter can be explained by heavy right-handed neutrinos within the framework of the extended Standard Mode νMSM.

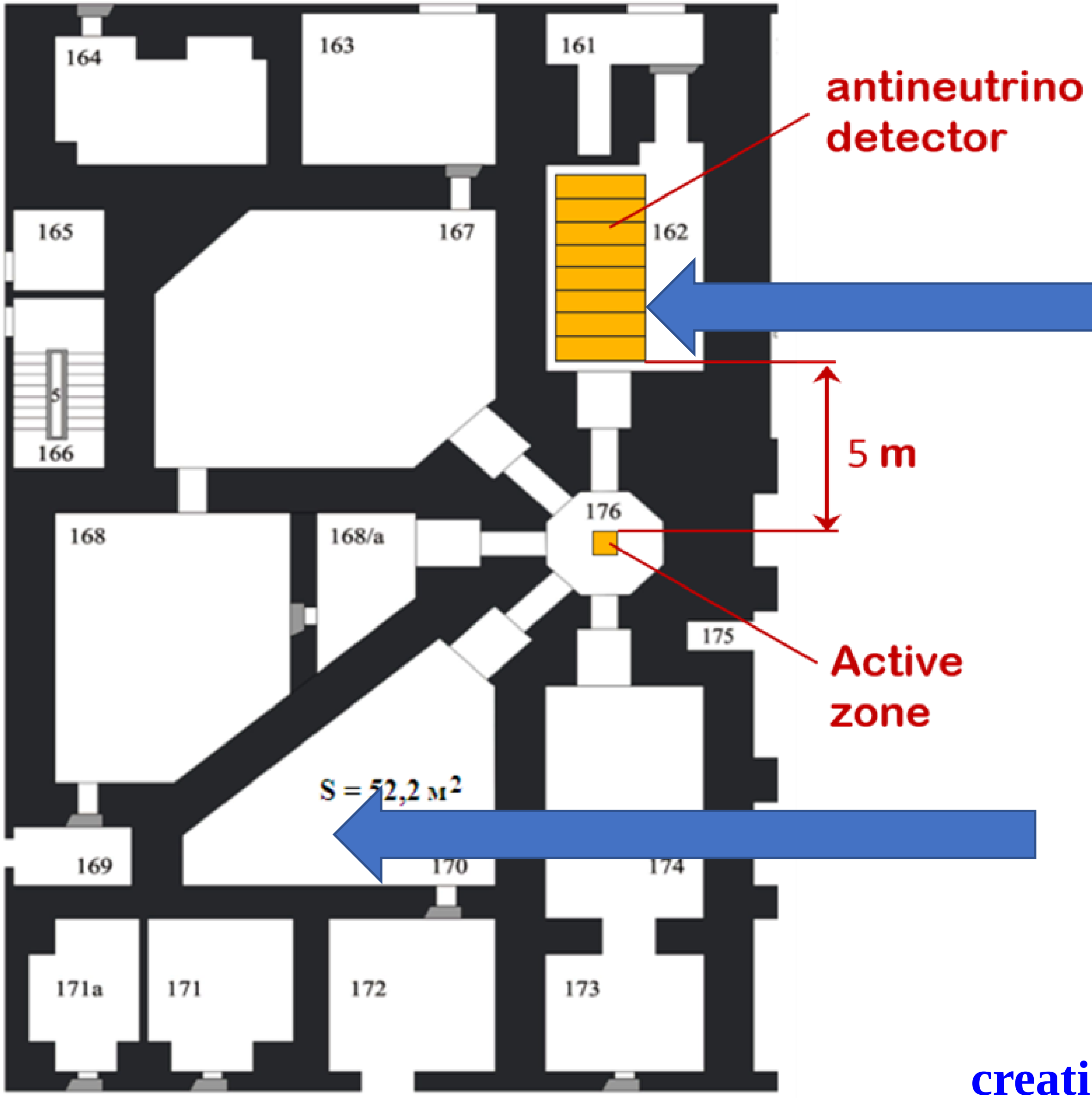
4. It is shown that, based on modern astrophysical data, it is impossible to draw a definite conclusion in favor of the model of three or four neutrinos.

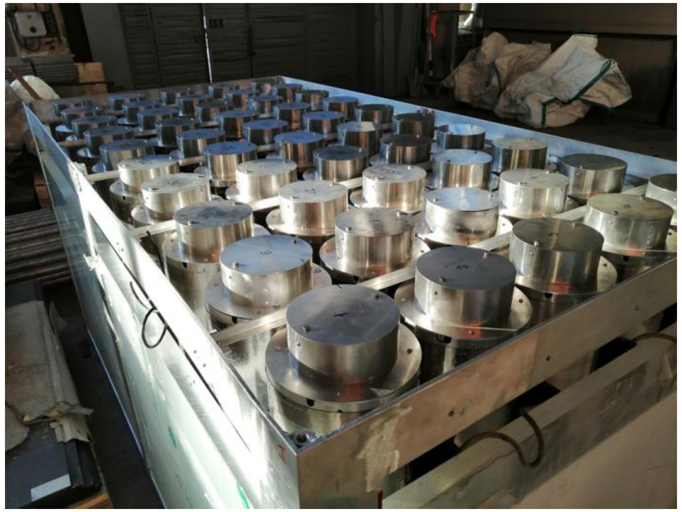
In general,

it was shown that there is enough room to introduce the light right-handed neutrino to cosmology,

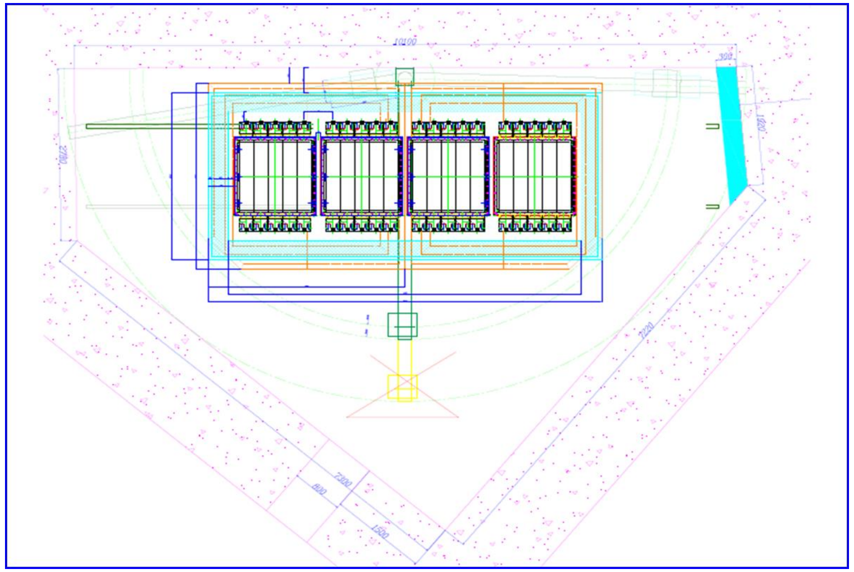
moreover, dark matter can be explained by heavy right-handed neutrinos within the framework of the extended Standard Model.

Prospects for confirmation of Neutrino-4 result by our new experiments





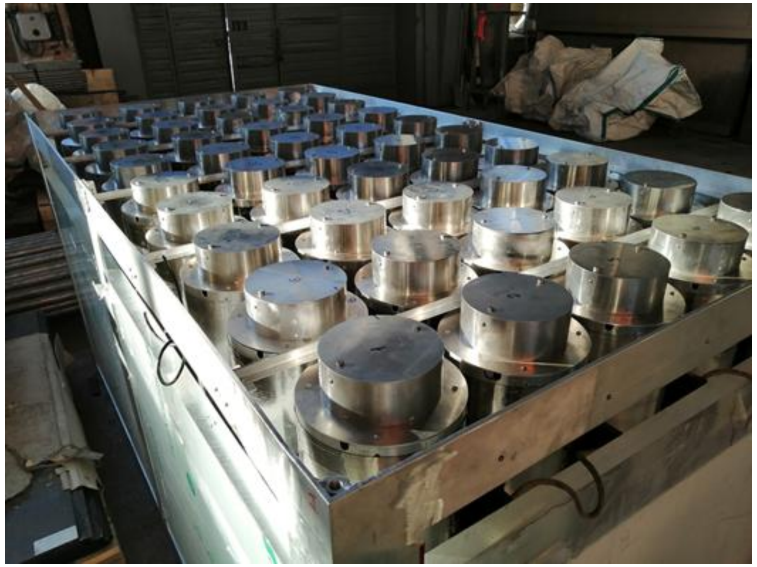
second option for Neutrino-4

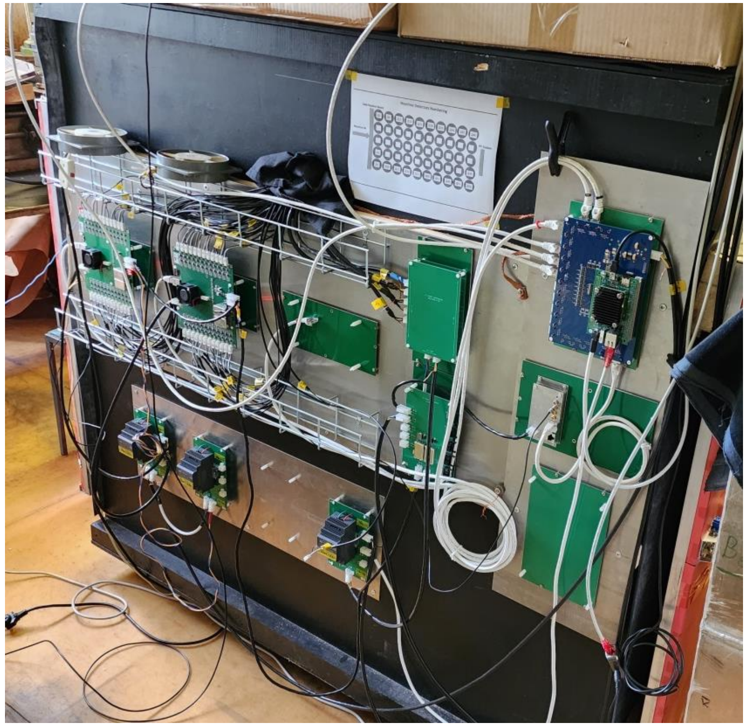


creation of a second neutrino laboratory and a new installation

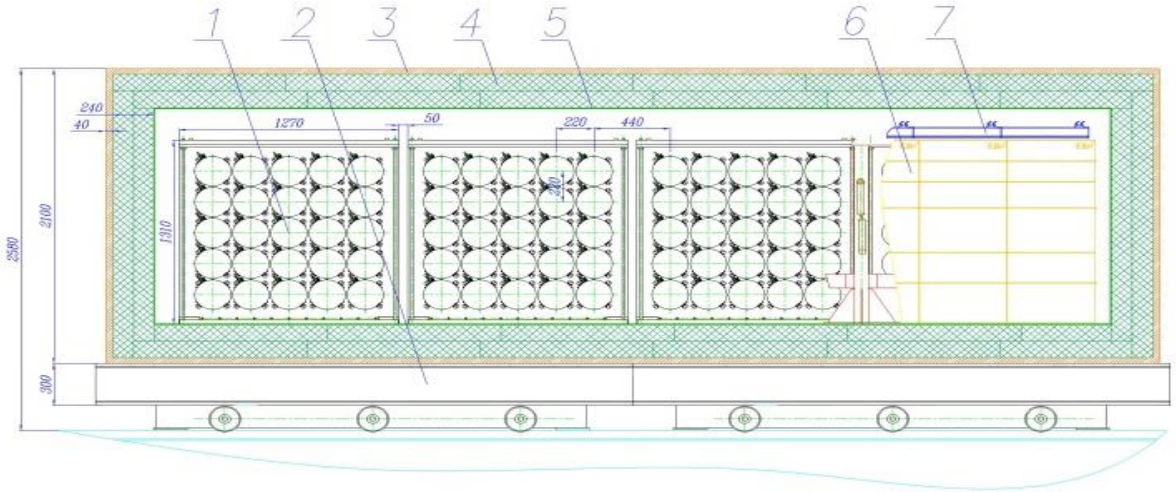
New installation (Neutrino-4M) for the first neutrino laboratory

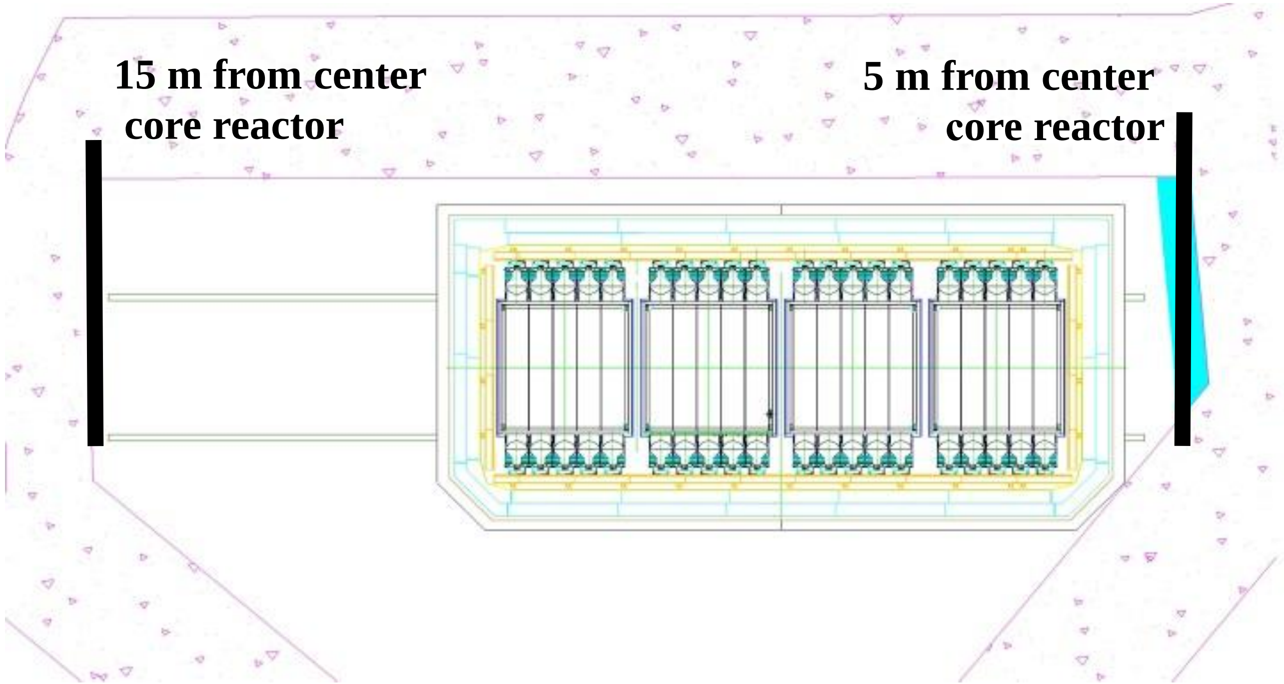
1. The installation was manufactured and transported to the SM-3 reactor.
2. Measurements are started recently.
3. The expected measurement accuracy is 2 times higher, than for the Neutrino-4 installation due to improvement signal/background ratio.



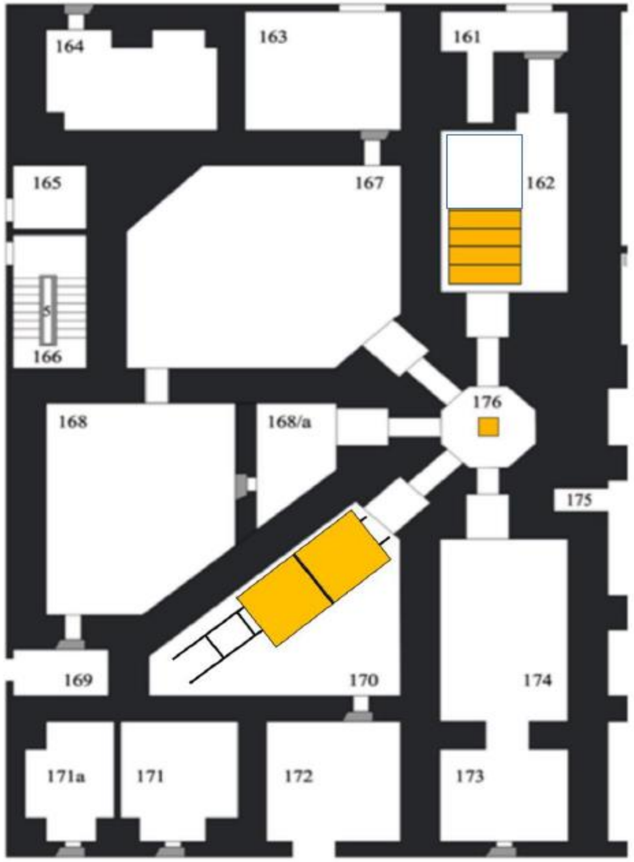


Installation Neutrino-6





Second neutrino laboratory at the SM-3 reactor



1st neutrino laboratory

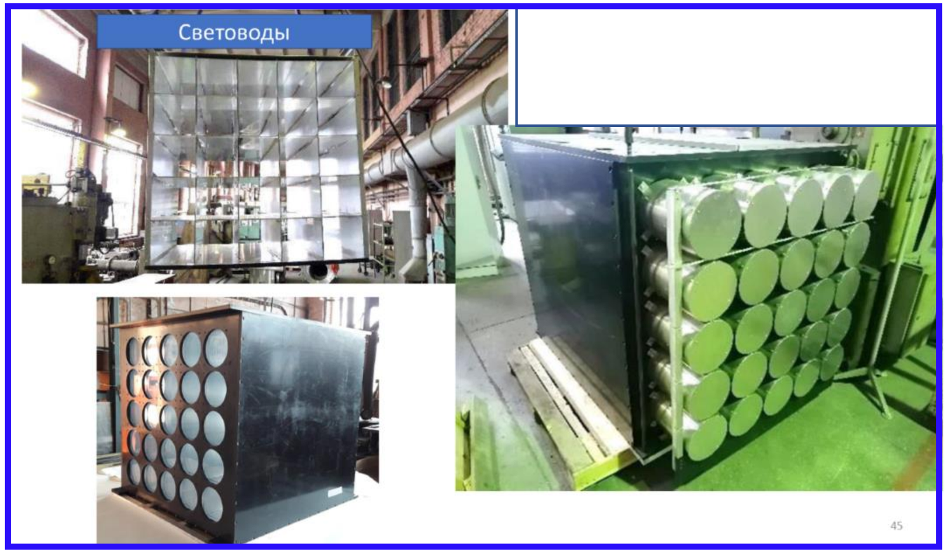
Neutrino-4M

2nd neutrino laboratory

Neutrino-6

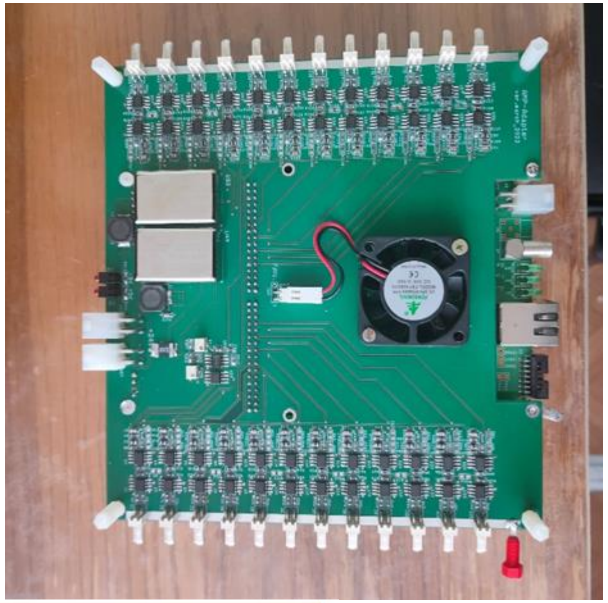
New installation (Neutrino-6) for the second neutrino laboratory

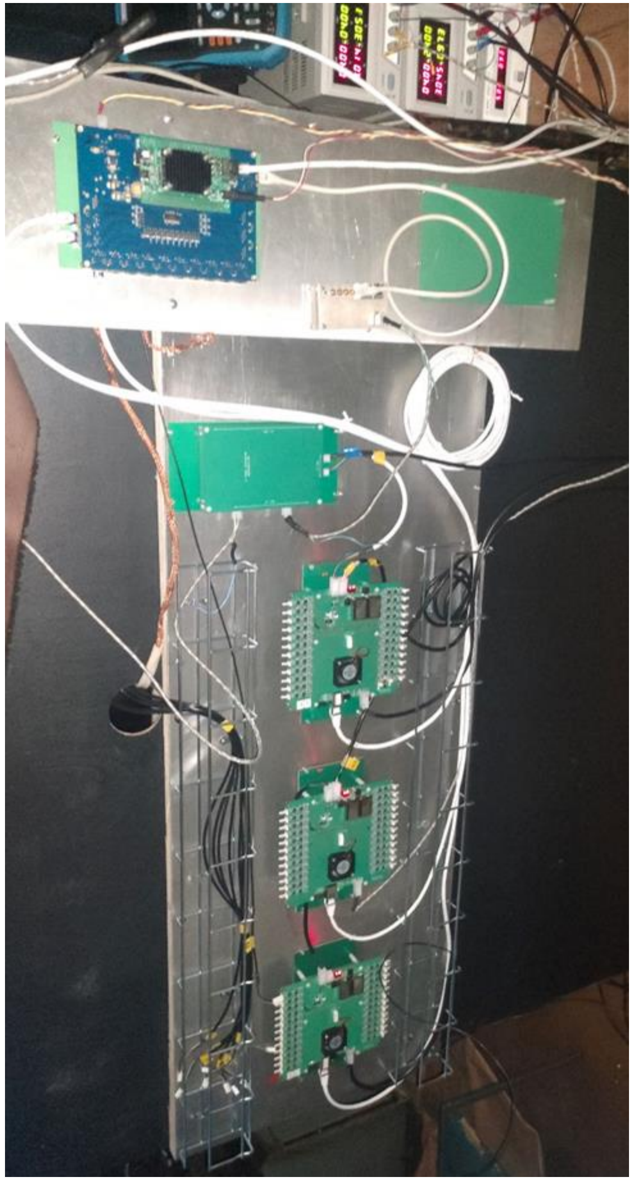
In Gatchina. Manufacturing of installation components is completed.



Passive protection is being installed **at the SM-3 reactor**

In Gatchina. Manufacturing and testing electronics and photomultipliers (200 pcs.) is being completed.



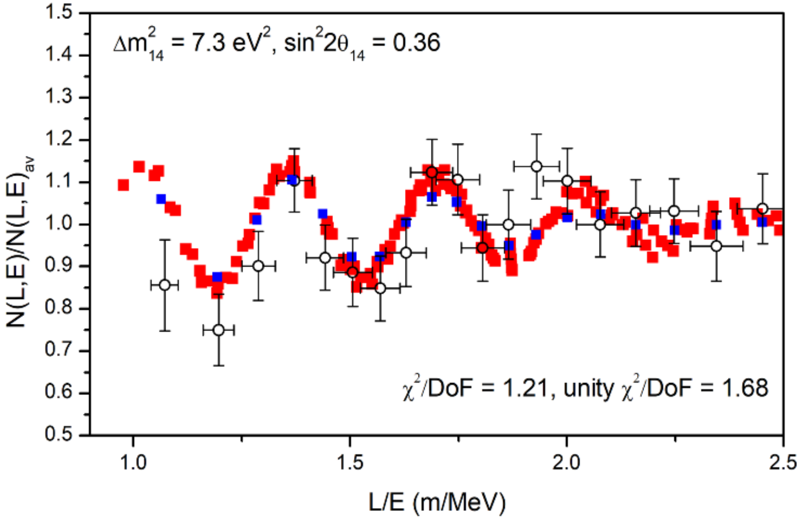


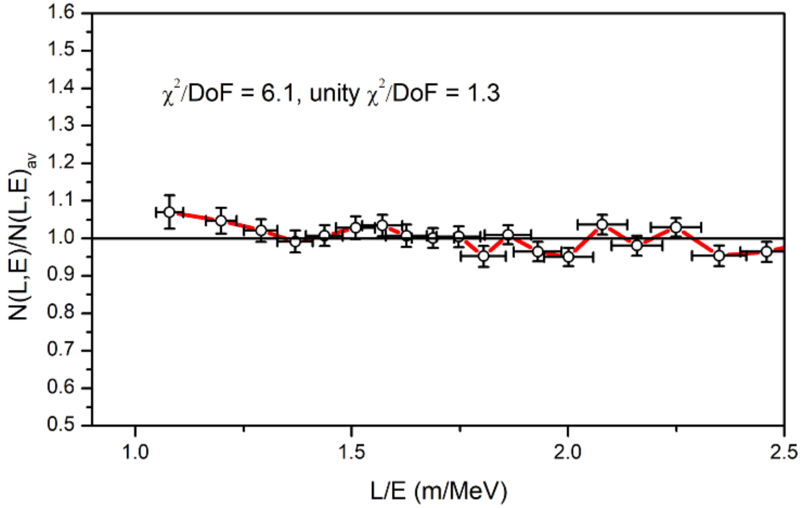
The statistical accuracy of the Neutrino-6 installation is expected to improve by 3 times compared to the Neutrino-4 installation
Achieving 5 sigma confidence level

Method	Parameter improvement factor	Accuracy increase factor
4 detectors	3 times larger volume	**1.6**
Gd concentration 0.2%	4 times less random coensidens	**1.5**
PSD	4 times less correlated background	**1.3**
Overall accuracy increase factor ……………………………… Effect/Background = 2 (was 0.5)	……………………………………………… **4 times less likelihood of systematic error**	**3.1**

What will happen next
will be shown by the experiment

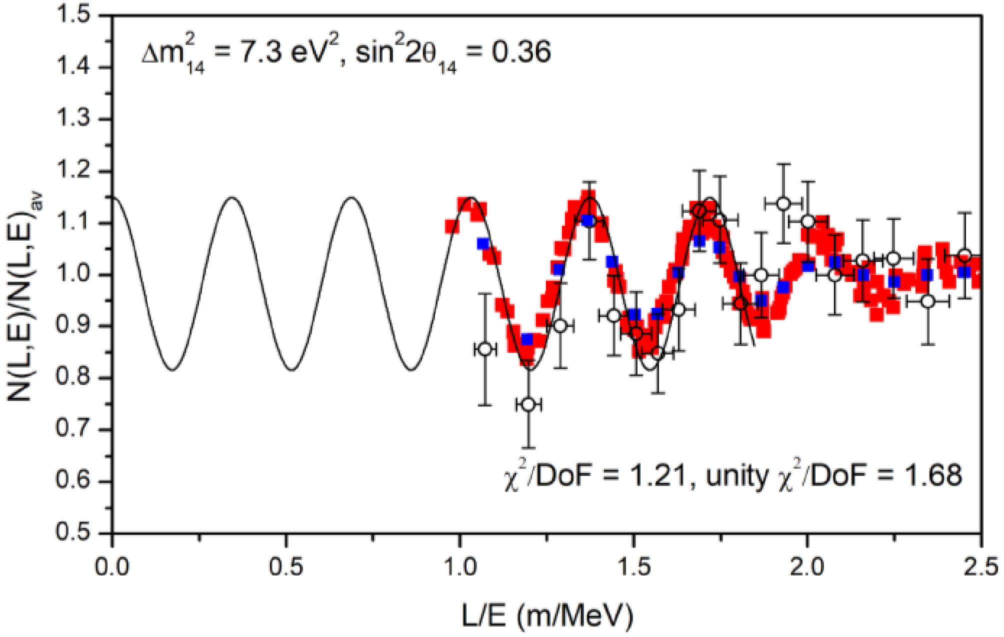
Thank you
for your attention



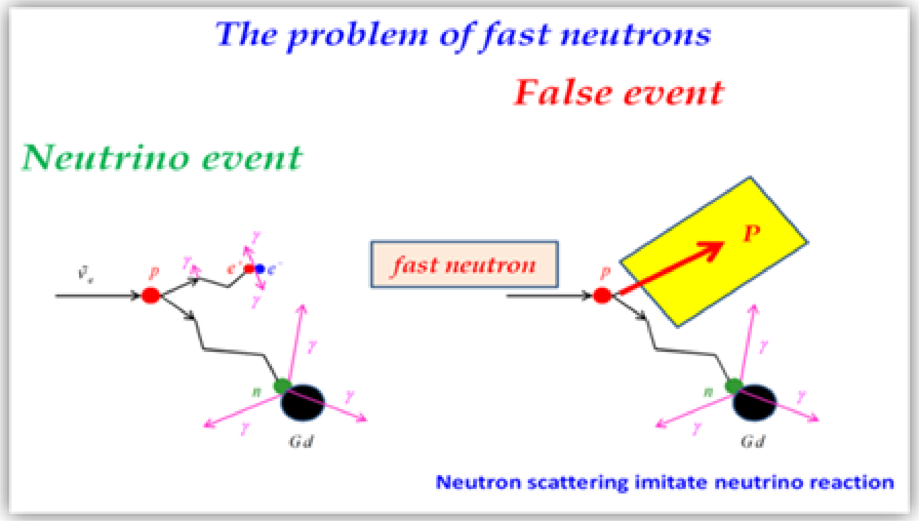


Comparison of the R ratio versus L/E for the neutrino signal (top) and
the R ratio versus L/E for the background (bottom).

Systematic error control

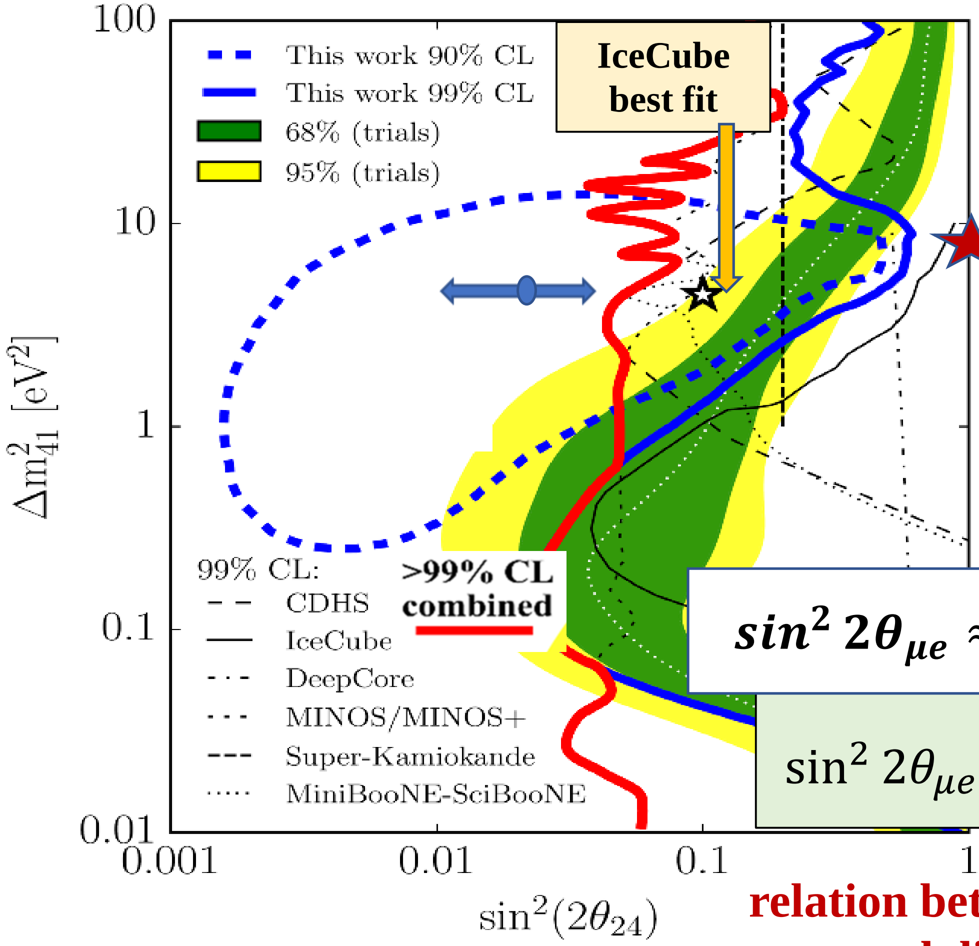


Complete oscillation curve from the center of the reactor core.



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

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

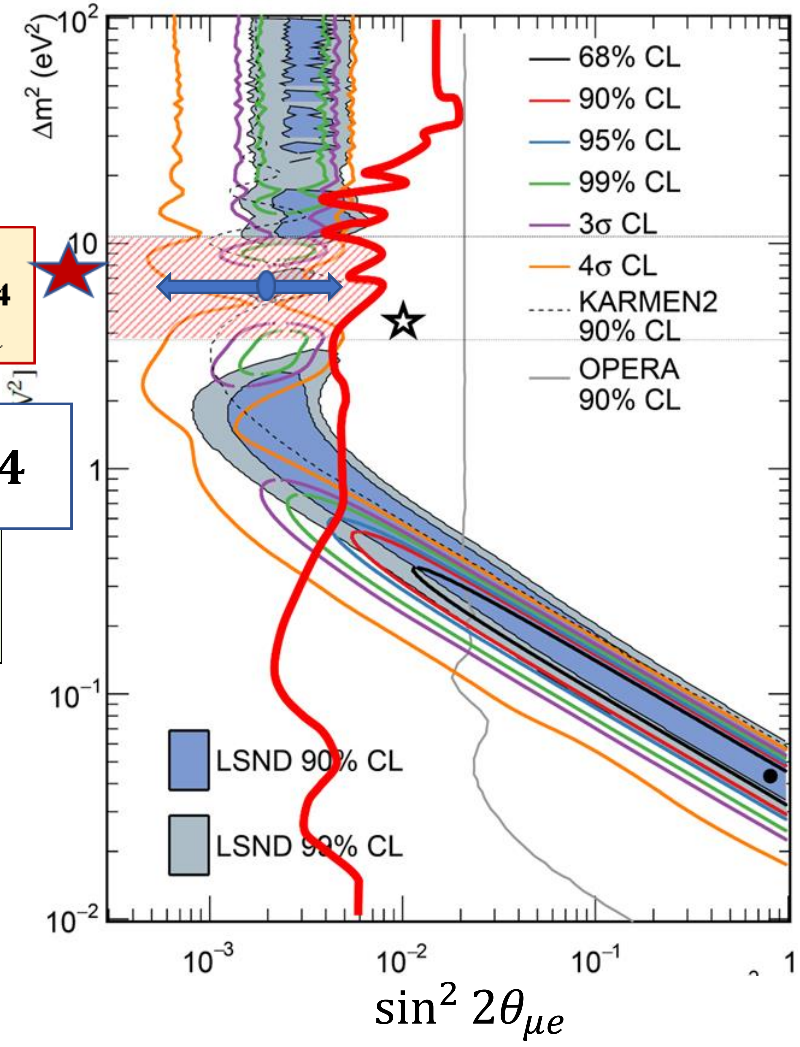


Best fit Neutrino-4 for Δm^2_{14}

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

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

Best fit Neutrino-4 for Δm^2_{14}



relation between appearance and disappearance

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

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

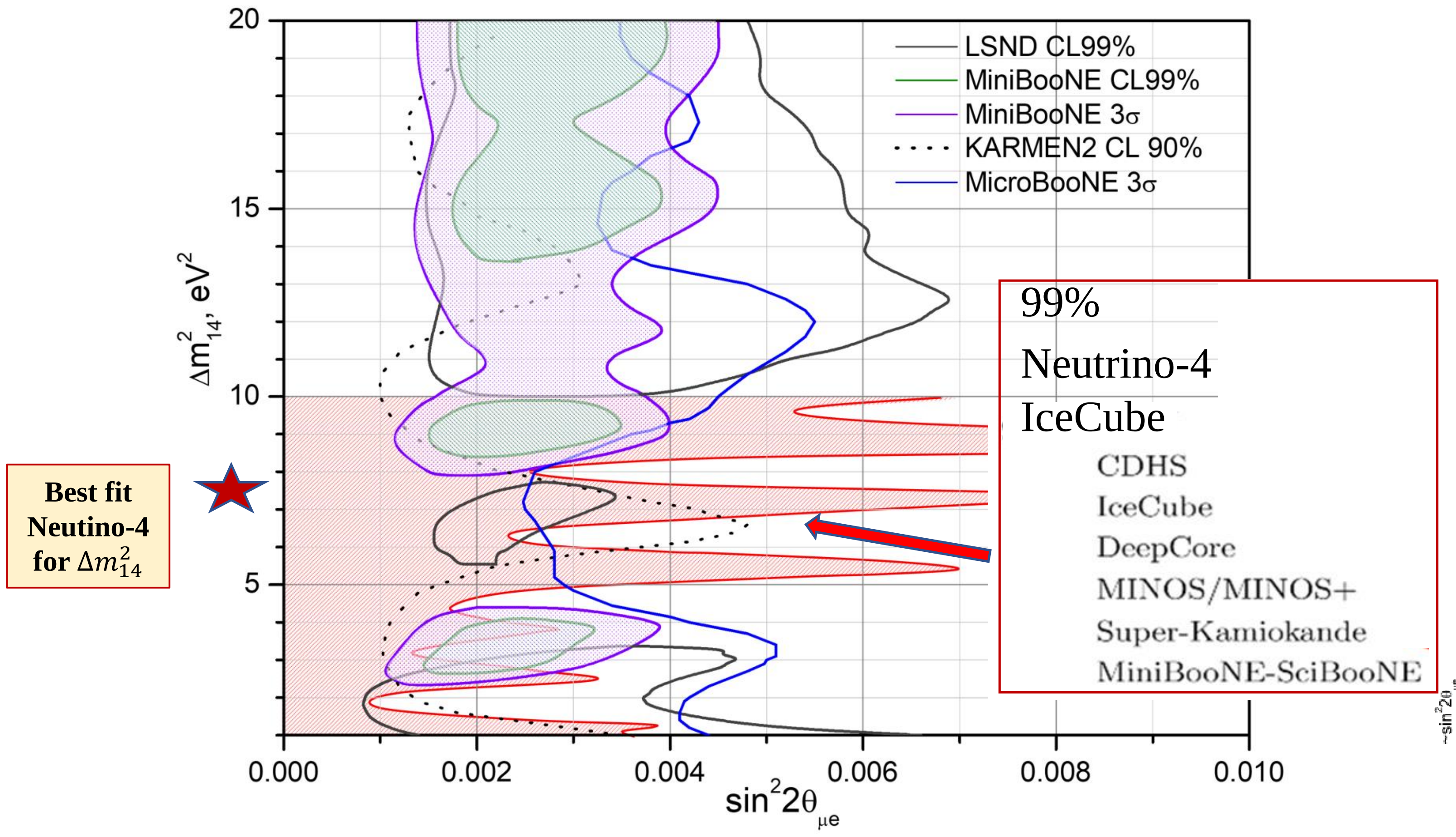
$\boldsymbol{\sin^2 2\theta_{\mu e} \approx 0.0024 \pm 0.0016}$

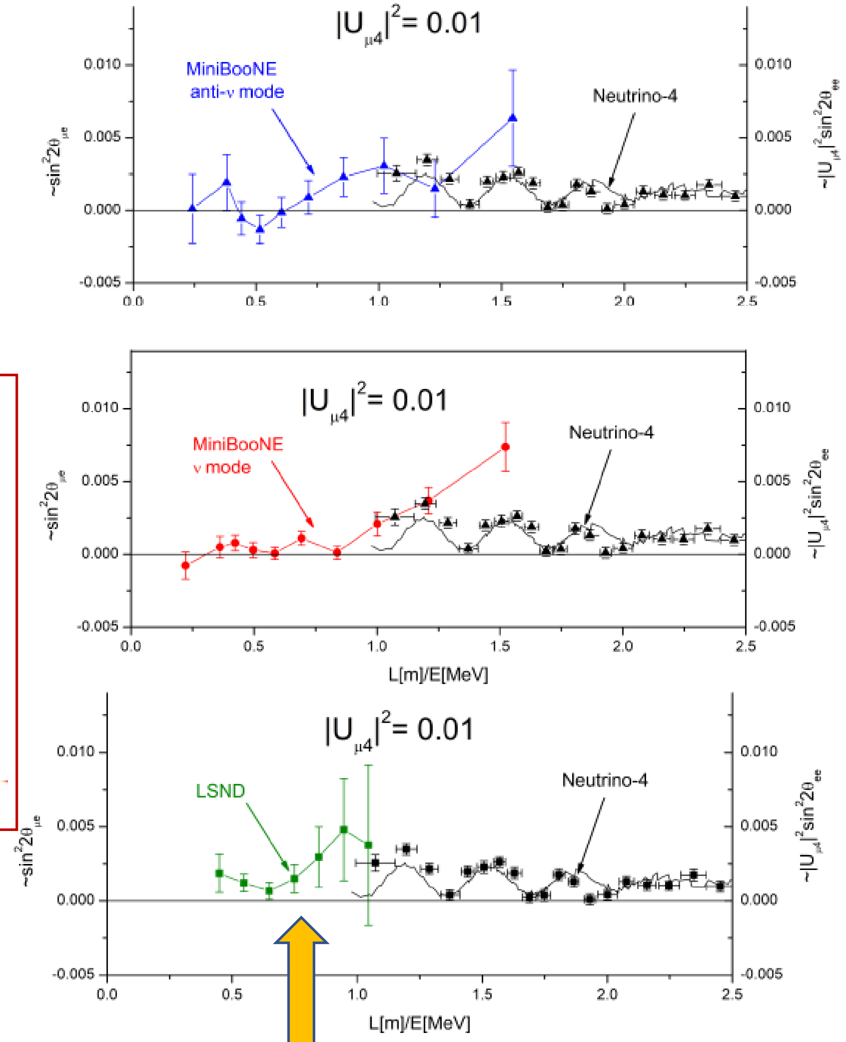
$\sin^2 2\theta_{14} \approx 0.36 \pm 0.12$

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

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

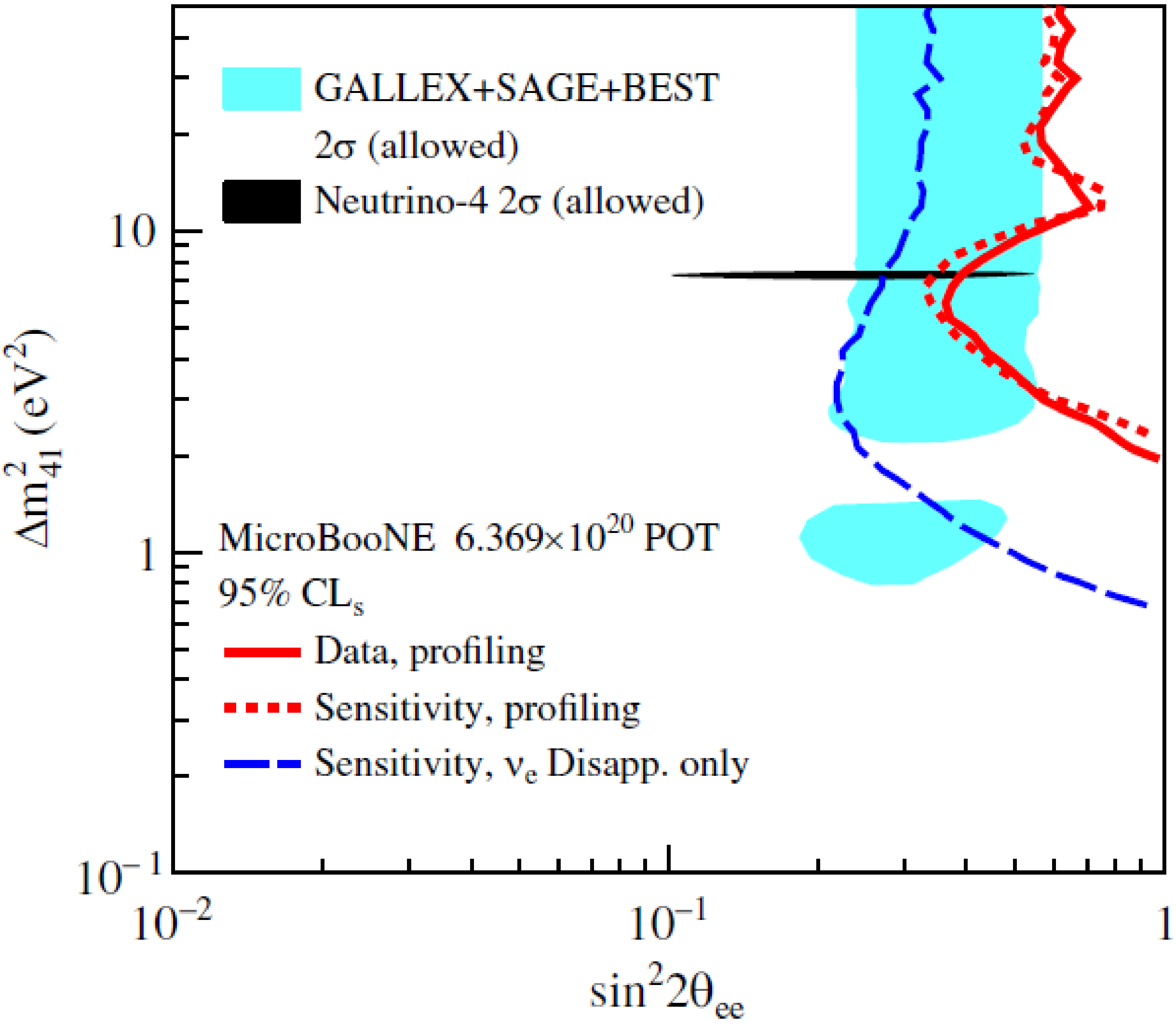
(At least it doesn't contradict)





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

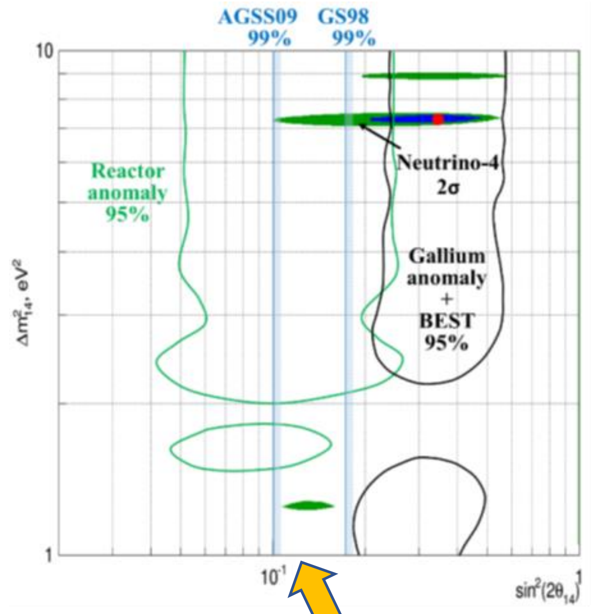
To get confirmation you need to have a similar sinusoidal dependence here



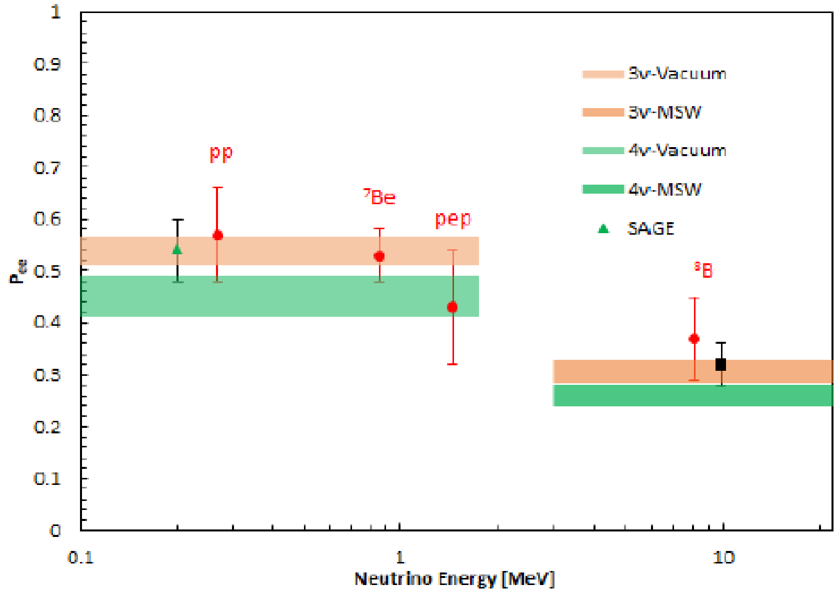
GALLEX+SAGE+BEST
2σ (allowed)
Neutrino-4 2σ (allowed)
MicroBooNE 6.369×10^20 POT
95% CL_s
Data, profiling
Sensitivity, profiling
Sensitivity, ν_e Disapp. only
Δm²_41 (eV²)
sin²2θ_ee
10
1
10^−1
10^−2
10^−1
1

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

(Insufficient accuracy to refute)



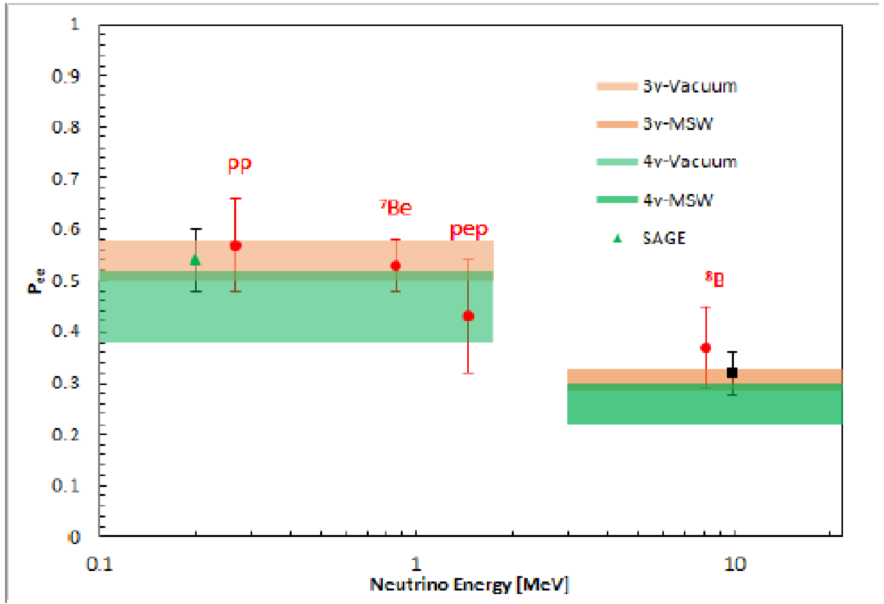
Comparison of Neutrino-4 and GA+ BEST results with the solar model[16].



3ν fit 0.13σ

4ν fit 1.67σ

For quadratic adding errors



3ν fit 0.12σ

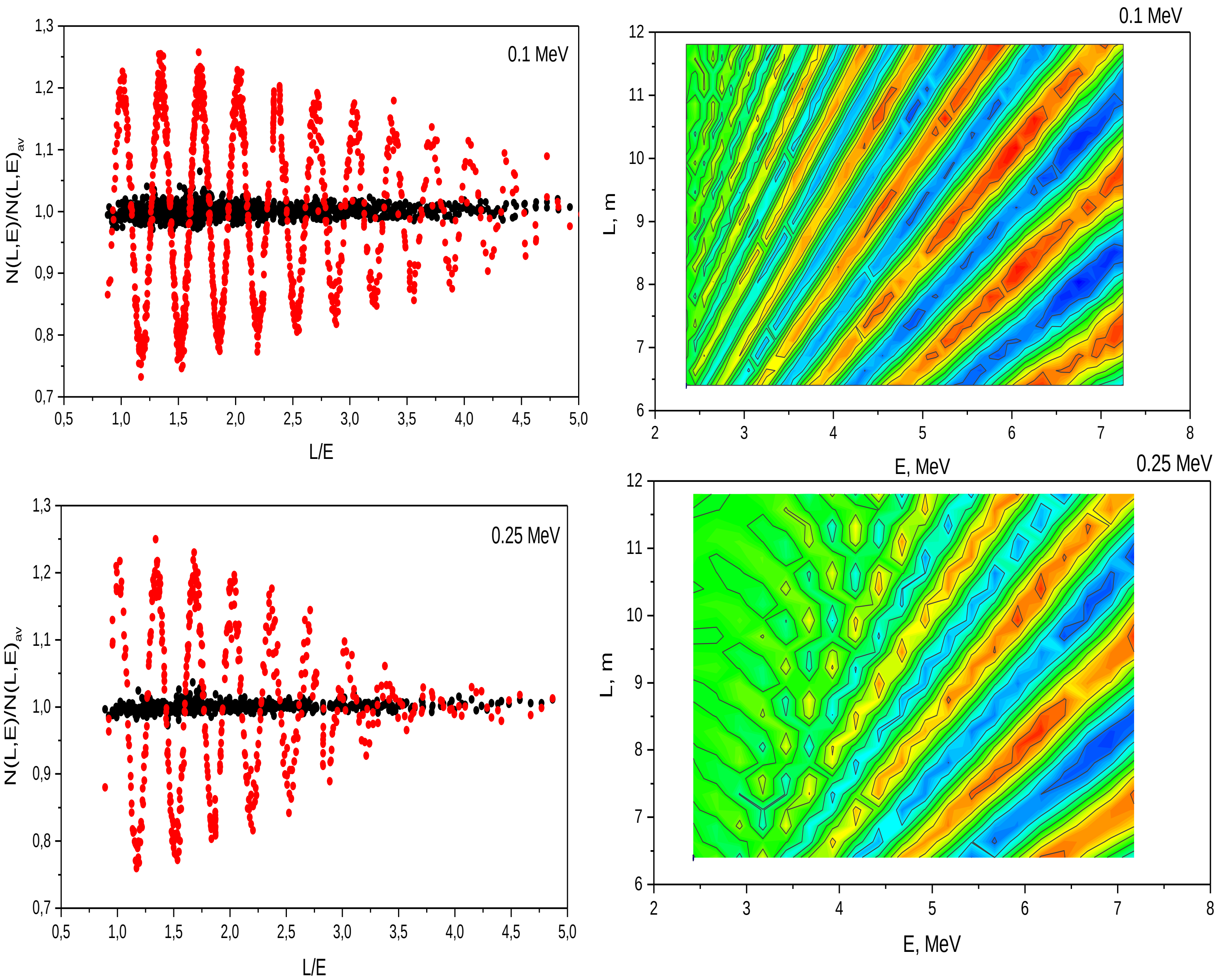
4ν fit 0.43σ

For linear adding errors

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

The stated contradiction with solar models does not have sufficient accuracy.

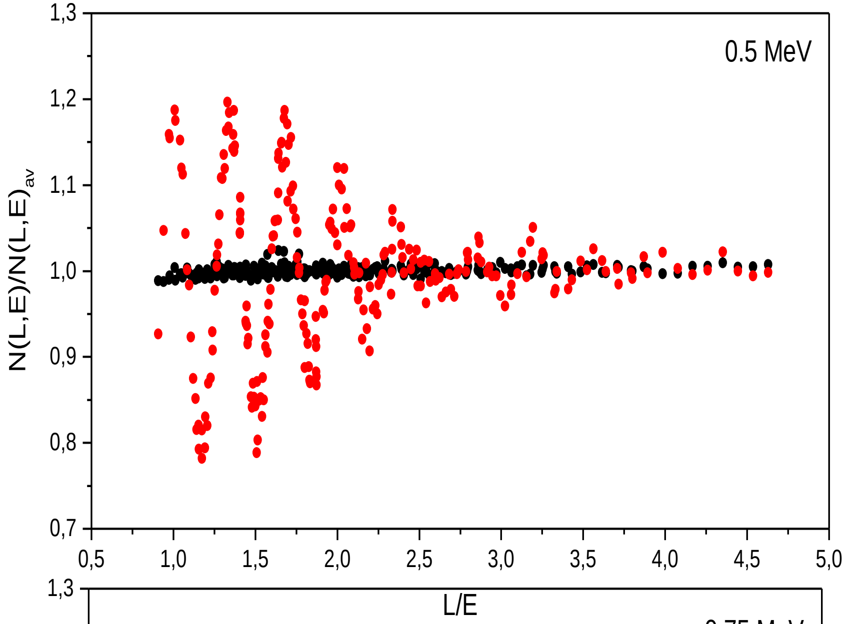
Expected effect for different energy resolutions

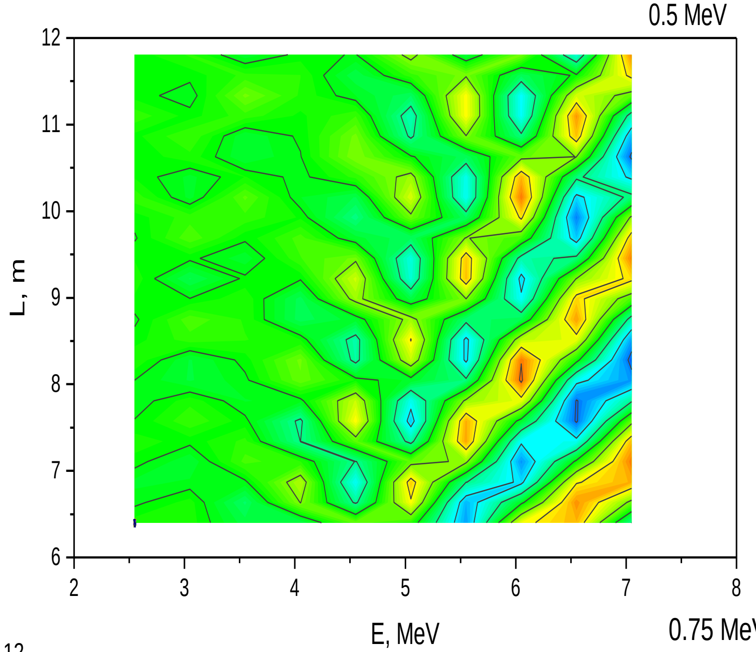


Energy resolution 0.1 MeV

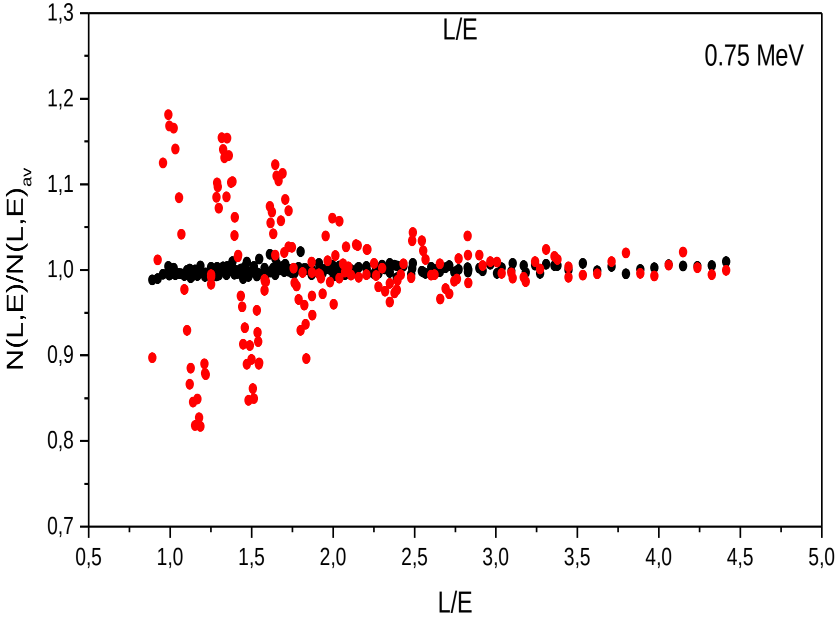
Energy resolution 0.25 MeV

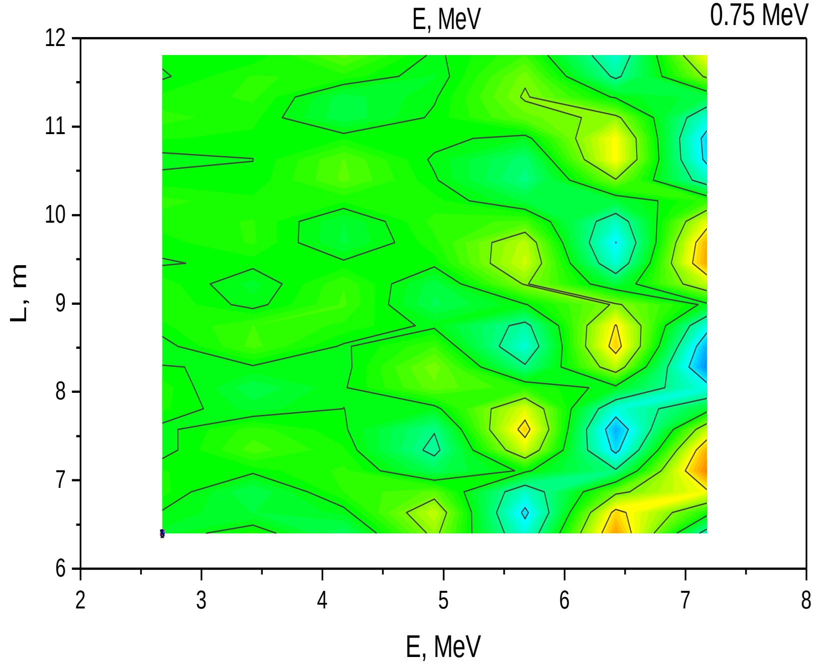
Expected effect for different energy resolutions





Energy resolution 0.50 MeV





Energy resolution 0.75 MeV

Perhaps taking into account the fourth neutrino will solve the Hubble Tension problem?

The introduction of a fourth neutrino removes the Hubble Tension problem

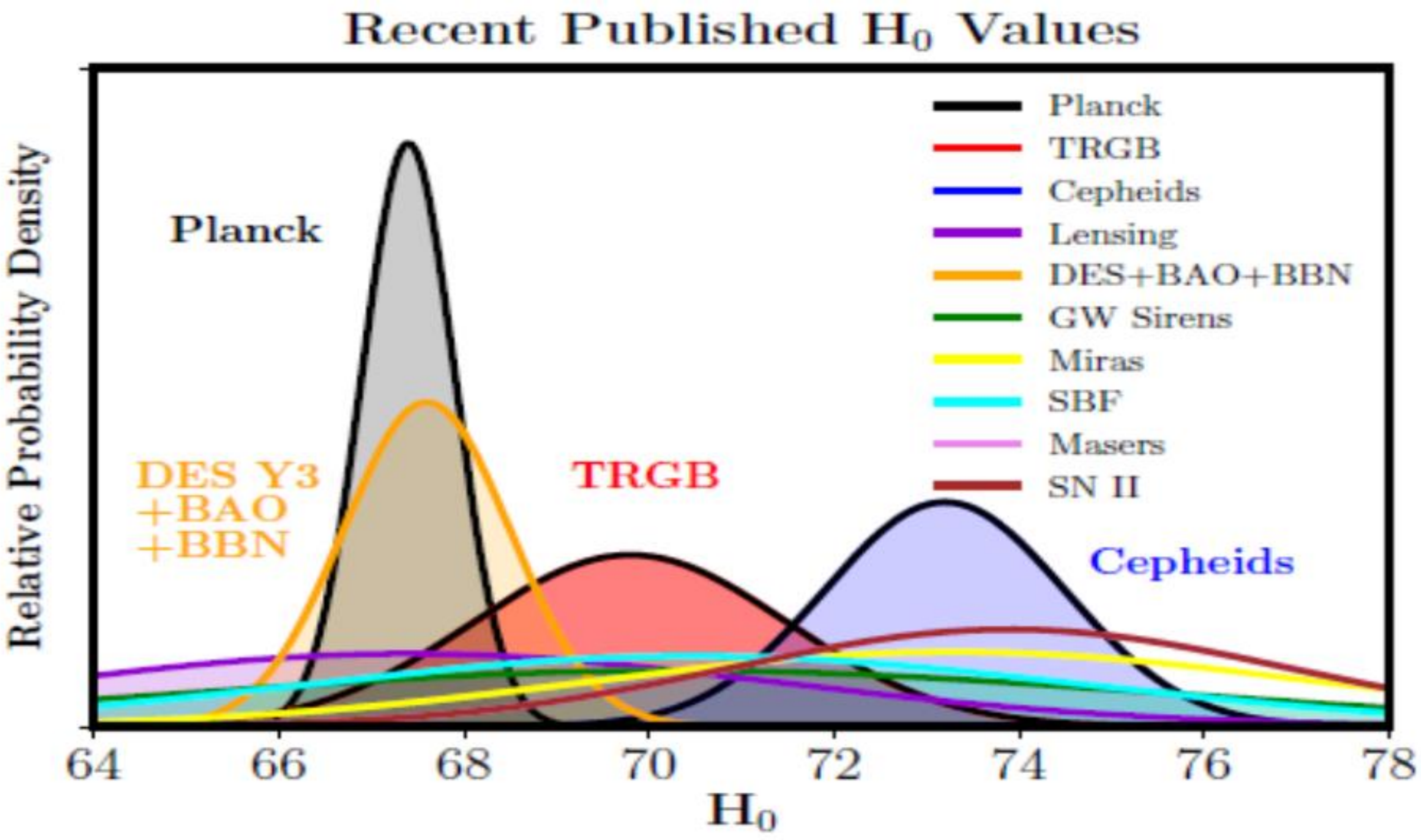


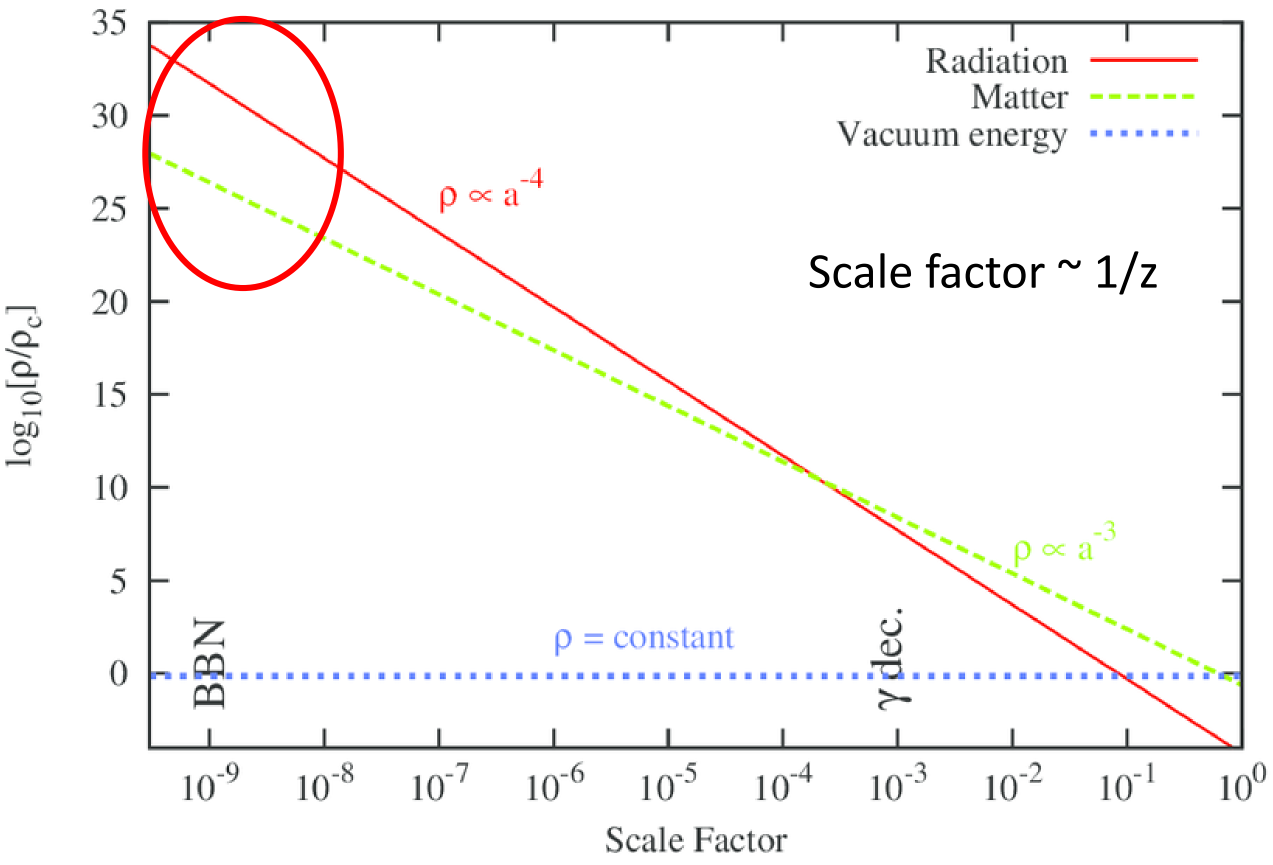
Figure 10. Relative probability density functions for several current methods for measuring H_0. The CMB, BAO, strong lensing and TRGB methods currently yield lower values of H_0, while Cepheids yield the highest values. The uncertainties associated with H_0 measurements from gravitational wave sirens, strong lensing, Miras, masers, and SBF are currently significantly larger than the errors quoted for the TRGB and Cepheids. See text for details. (CMB: Planck Collaboration 2018; TRGB: this paper; Cepheids: R21; Lensing: Birrer et al. (2020); DES Y3 + BAO + BBN: DES Collaboration et al. (2021); GW sirens: Hotokezaka et al. (2019) Miras: Huang et al. (2018); SBF: Khetan et al. (2021); Masers: Reid et al. (2019)).

When moving from $N\_\nu=3$ to $N\_\nu=4$ the Hubble constant can be increased by 7% to obtain an equivalent process

$$H^2 = \frac{8\pi^3}{90} G g_* T^4$$

$$H(z)^2 = H_0^2 \times (\Omega_R \times (1+z)^4 + \Omega_m \times (1+z)^3 + \Omega_\Lambda + \Omega_{Cur} \times (1+z)^2),$$

$$\Omega_R \times (1+z)^4 \gg \Omega_m \times (1+z)^3 + \Omega_\Lambda \quad Z > 10\ 000$$



The entire process is determined by temperature. Therefore, equating the temperatures in the model of three and four neutrinos,

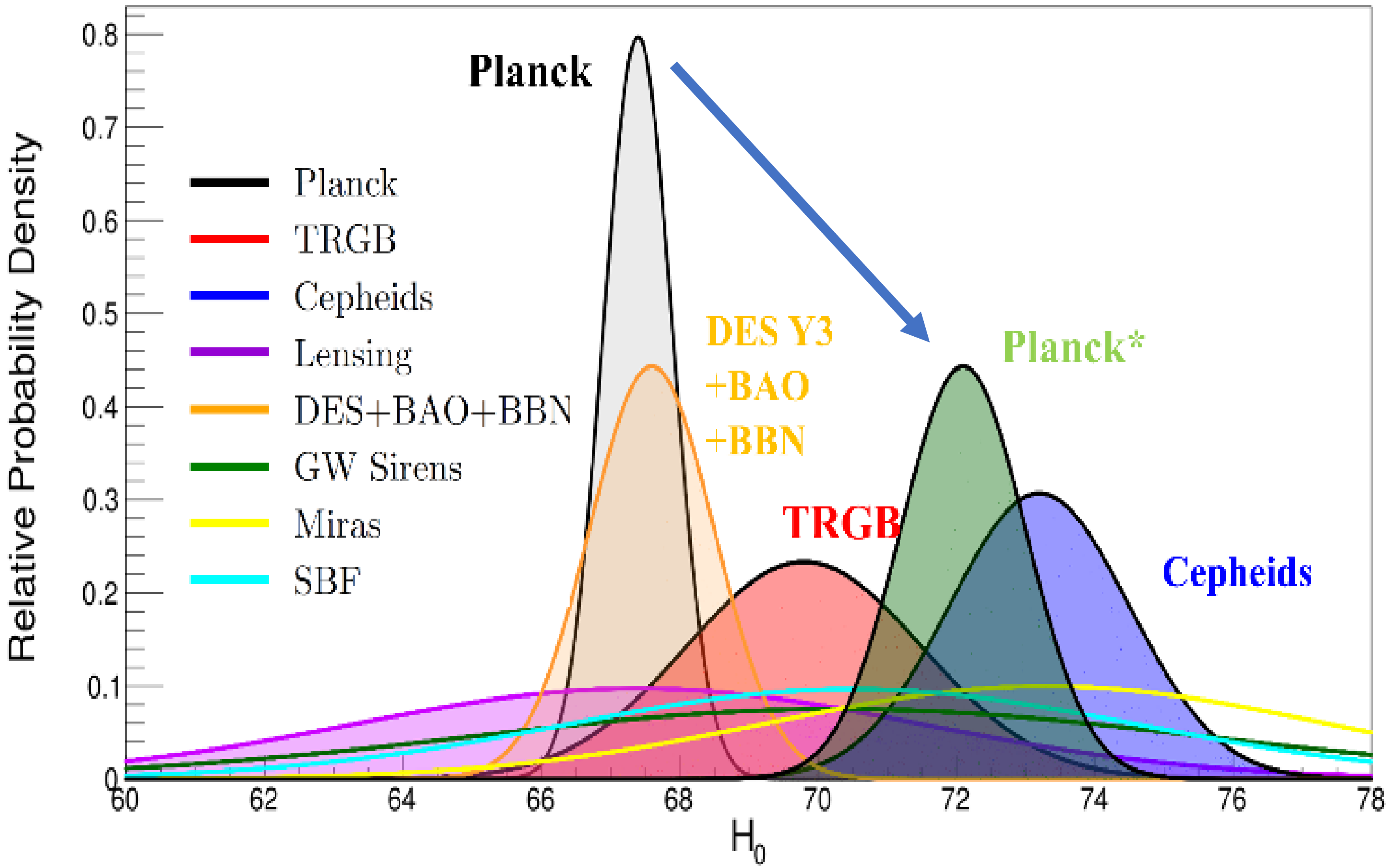
$$T^4 = \frac{H_0^2(3)(\Omega_R \times (1+z)^4)}{8\pi^3/90\, G g_*(3)} = \frac{H_0^2(4)(\Omega_R \times (1+z)^4)}{8\pi^3/90\, G g_*(4)}$$

we find that when moving from $N\_\nu=3$ to $N_\nu=4$The same processes can be obtained with:

$$\frac{H_0(4)}{H_0(3)} = \sqrt{\frac{g_*(4)}{g_*(3)}} = 1.07$$

The Hubble constant needs to be increased by 7% when moving from $N\_\nu=3$ to $N\_\nu=4$.

The introduction of a fourth neutrino removes the Hubble Tenshen problem



NEUTRINO DISPERSION AT FINITE TEMPERATURE AND DENSITY

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Received 9 February 1988

Neutrino optics in space plasma

Real part of the potential

$$V_{\nu_e} = \pm 0.95\left(2\eta_{\nu_e} + \eta_{\nu_\mu} + \eta_{\nu_\tau} + \eta_e - \frac{1}{2}\eta_n\right) G_F T^3 - 0.61\alpha^{-1} G_F^2 T^4 E_\nu$$

$$V_{\nu_\mu} = \pm 0.95\left(\eta_{\nu_e} + 2\eta_{\nu_\mu} + \eta_{\nu_\tau} - \frac{1}{2}\eta_n\right) G_F T^3 - 0.17\alpha^{-1} G_F^2 T^4 E_\nu$$

$$V_{\nu_\tau} = \pm 0.95\left(\eta_{\nu_e} + \eta_{\nu_\mu} + 2\eta_{\nu_\tau} - \frac{1}{2}\eta_n\right) G_F T^3 - 0.17\alpha^{-1} G_F^2 T^4 E_\nu$$

$$\eta = \frac{n - \bar{n}}{n_\gamma}$$

$$\xi = \frac{n - \bar{n}}{n + \bar{n}}$$

$$\xi = \frac{4}{3}\eta$$

Imaginary part

$$\omega = 13/9\,(7\pi/24)(G_F^2 T^4 E + \xi^2 \alpha\, G_F T^3)$$