

BEST impact on sterile neutrino hypothesisVladislav Barinov^{1,2,*} and Dmitry Gorbunov^{1,3,†}¹*Institute for Nuclear Research of the Russian Academy of Sciences, Moscow 117312, Russia*²*Physics Department, Moscow State University, Vorobievsky Gory, Moscow 119991, Russia*³*Moscow Institute of Physics and Technology, Dolgoprudny 141700, Russia*

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Recently, the Baksan Experiment on Sterile Transitions (BEST) has presented results [1] confirming the *gallium anomaly*—a lack of electron neutrinos ν_e at calibrations of SAGE [2,3] and GALLEX [4]—at the statistical significance exceeding 5σ . This result is consistent with explanation of the gallium anomaly as electron neutrino oscillations into a sterile neutrino, ν_s . Within this explanation, the BEST experiment itself provides the strongest evidence for the sterile neutrino among all the previous anomalous results in the neutrino sector. We combine the results of gallium experiments with searches for sterile neutrinos in reactor antineutrino experiments (assuming *CPT* conservation in the $3 + 1$ neutrino sector). While the “gallium” best-fit point in the model parameter space (sterile neutrino mass squared $m_{\nu_s}^2 \approx 1.25 \text{ eV}^2$, sterile-electron neutrino mixing $\sin^2 2\theta \approx 0.34$) is excluded by these searches, a part of the BEST-favored 2σ region with $m_{\nu_s}^2 > 5 \text{ eV}^2$ is consistent with all of them. Remarkably, the regions advertised by anomalous results of the NEUTRINO-4 experiment [5] overlap with those of the BEST experiment: the best-fit point of the joint analysis is $\sin^2 2\theta \approx 0.38$, $m_{\nu_s}^2 \approx 7.3 \text{ eV}^2$, and the favored region will be explored by the KATRIN experiment [6]. The sterile neutrino explanation of the BEST results would suggest not only the extension of the Standard Model of particle physics but also either serious modifications of the Standard Cosmological Model and Solar Model, or a specific modification of the sterile sector needed to suppress the sterile neutrino production in the early Universe and in the Sun.

DOI: [10.1103/PhysRevD.105.L051703](https://doi.org/10.1103/PhysRevD.105.L051703)**I. INTRODUCTION**

Neutrino oscillations provide us with the only direct evidence for incompleteness of the Standard Model of particle physics (SM), which fails to explain them. While the fundamental physics responsible for the oscillations is still elusive, results of the majority of neutrino experiments can be phenomenologically described by introducing neutrino mass matrix. The joint analysis (see, e.g., Ref. [7] for a recent one) of the oscillation data determines three mixing angles between the mass and flavor neutrino eigenstates and two squared-mass differences.

However, results of several experiments [2–5,8–12] apparently cannot be described in this way [13,14] and within the oscillation picture ask for neutrino states additional to those three of the SM. These results are commonly known as *neutrino anomalies*, and the new states are

known as *sterile neutrinos*, see, e.g., Ref. [15], since they mix with the SM (or *active*) neutrinos but do not participate in the SM gauge interactions.

All the neutrino anomalies must be thoroughly investigated [16,17]. Indeed, any unrecognized systematics constrain the application of the neutrino as, e.g., Refs. [18,19], a tool in studying the inner structures of the Earth and Sun. On the other side, the possible presence of sterile neutrinos in nature will be the first example of the non-SM physics for which we have been looking for decades. Moreover, the sterile neutrinos with mixing parameters required to explain the anomalies [17] are expected to be produced in the early Universe and be in equilibrium with the primordial plasma before the epoch of big bang nucleosynthesis. They would change the standard predictions for the primordial abundance of the light chemical elements as well as the subsequent late-time history of our Universe, including the recombination and formation of the large-scale cosmic structures. Thus, in the present concordance Λ CDM (for Λ -term and Cold Dark Matter) cosmological model, these sterile neutrinos are forbidden [20]. The situation was quite the opposite about ten years ago, when both state-of-the-art analyses of the big bang nucleosynthesis [21] and cosmic microwave background anisotropy [22] favored the sterile neutrino

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hypothesis. Anyway, with more complicated sterile neutrino sector, they can be safe for cosmology; see, e.g., Refs. [23–25]. Moreover, presently, we have several tensions in consistent description of the cosmological data; the most serious are so-called the Hubble tension and σ_8 tension. So far, we have no natural straightforward resolutions, but some suggestions in literature, see, e.g., Refs. [26,27], involve sterile neutrinos as one of the necessary ingredients.

II. RESULTS OF THE BEST EXPERIMENT

Therefore, both particle physics and cosmology would benefit from settling this issue with neutrino anomalies, and there are various projects and ongoing experiments dedicated to clarification of particular anomalous results. One of these experiments is Baksan Experiment on Sterile Transitions (BEST) aimed at exploring the *gallium anomaly* [28], which is the lack of electron neutrino events from compact artificial chromium and argon sources observed by four (in total) calibrations of SAGE [2,3] and GALLEX [4] solar neutrino experiments. BEST was placed in the Baksan Neutrino Observatory of INR RAS and operated in 2019. Closely following the scheme of the original SAGE calibration, its geometry has been specifically designed to achieve the highest sensitivity to the sterile neutrino model with parameters tuned to explain the gallium anomaly via $\nu_e \leftrightarrow \nu_s$ oscillations.

BEST exploited an artificial chromium source simultaneously irradiating two volumes filled with gallium, which allowed one to measure the neutrino flux at two different distances. The BEST experiment has published results [1], which confirm the gallium anomaly and are consistent with its explanation as electron neutrino oscillations into the sterile components. In the BEST experiment, the artificial source was very compact and placed in the center of the inner spherical volume, which was placed in the center of the outer cylindrical volume. The neutrino fluxes were measured as $R_{\text{in}} = 0.791 \pm 0.05$ and $R_{\text{out}} = 0.766 \pm 0.05$ from what are expected, which implies more than 5σ evidence for the disappearance of electron neutrinos. Within the sterile neutrino hypothesis, this disappearance is explained as oscillations into sterile neutrino states so that the electron neutrino flux at a given distance r from the pointlike source is suppressed by the survival probability

$$P(E_\nu, r) = 1 - \sin^2 2\theta \sin^2 \left(1.27 \times \frac{\Delta m^2 [\text{eV}^2] r [\text{m}]}{E_\nu [\text{MeV}]} \right).$$

With the detector size of about a meter and the neutrino energy of about 750 keV (the dominant line of the chromium source), it allows for testing the oscillations with $\Delta m^2 \sim 1 \text{ eV}^2$. The geometry details are presented in Ref. [1], and the sterile neutrino parameters (mass and mixing angle) are defined from the likelihood function

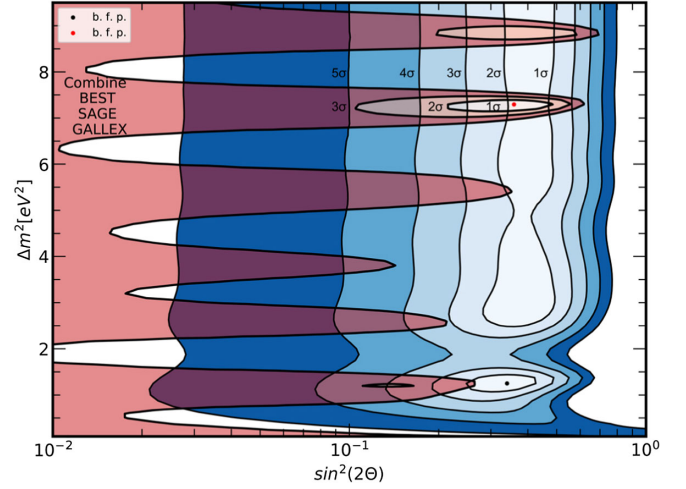


FIG. 1. The regions (in shades of blue) favored by all the gallium experiments [1] for mixing with electron neutrinos. Assuming the same mixing with electron antineutrinos, there are also regions (in shades of pink) favored by NEUTRINO-4 [29].

given by Eqs. (3)–(5) of Ref. [1]. Then, repeating the joint analysis for the all gallium experiments, one obtains the favorable region in the model parameter space outlined in Fig. 1; the 1-, 2-, and 3- σ contours coincide with those in Fig. 3 of Ref. [1]. We observe that *within the sterile neutrino hypothesis* the gallium experiments provides higher than 5σ evidence for the presence of sterile neutrinos. Actually, one can find that even the single BEST result exceeds 5σ level.

III. JOINT ANALYSIS

The results obtained by the BEST experiment favor rather large mixing angle and either the region of $\Delta m^2 \simeq 1 \text{ eV}^2$ or noticeably larger masses $\Delta m^2 \gtrsim 3 \text{ eV}^2$. The likelihood contours on the plot of Fig. 1 show that in the region of large masses the BEST has no sensitivity to the sterile neutrino masses, which correspond to the oscillation lengths shorter than the typical meter-scale size of the BEST detector volumes. Remarkably, parts of this region have been favored by the anomalous results (2.8σ) of one of the reactor neutrino experiments, NEUTRINO-4 [5,29]. We plot these regions in Fig. 1 for comparison. Note that the Neutrino-4 likelihood exhibits a local minimum in the region of the best-fit point of the joint gallium anomaly, $\Delta m^2 \simeq 1 \text{ eV}^2$. There are also minima at large masses and the global minimum at $\Delta m^2 \simeq 7 \text{ eV}^2$, where 1- σ contours of NEUTRINO-4 and gallium experiments overlap.

The region of masses $\Delta m^2 \simeq 1 \text{ eV}^2$ has been thoroughly explored by searches for sterile neutrino in the reactor antineutrino experiments, see Fig. 2, the strongest constraint obtained by the DANSS experiment [30,31]. Note that, while at small masses the favored by gallium anomaly region is heavily constrained by these searches, at large

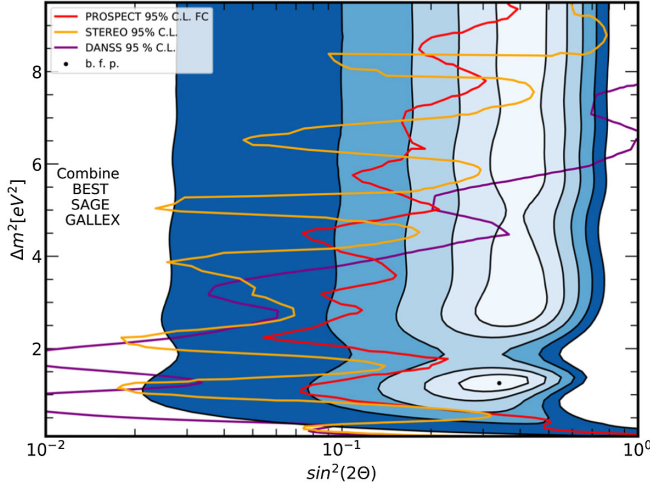


FIG. 2. The regions favored by all the gallium experiments [1] (the same as in Fig. 1) for mixing with electron neutrinos and limits from searches for sterile neutrinos at reactor antineutrino experiments STEREO [32], PROSPECT [33], and DANSS [30]. The regions of large mixing are excluded by each experiment at 95% C.L.

masses, $\Delta m^2 > 5 \text{ eV}^2$, there are $2\text{-}\sigma$ and even $1\text{-}\sigma$ patches favored by gallium experiment and consistent with all these bounds.

Encouraged by the overlap presented on the plot of Fig. 1, we perform a joint analysis of the all gallium experiments, NEUTRINO-4 and DANSS, which yields the likelihood contours depicted in Fig. 3. We utilize here the original DANSS likelihood¹ and the NEUTRINO-4 likelihood² somewhat corrected as advertised in Ref. [34] to be conservative (the NEUTRINO-4 anomaly becomes then at 2.2σ level). The joint anomaly inferred from this analysis is at about 5.7σ , and it favors the region of large sterile neutrino masses, $\Delta m^2 > 5 \text{ eV}^2$. The significance level is dominated by the BEST anomalous result, while the positions of the local minima of the joint likelihood at particular values of the sterile neutrino mass are mostly determined by those of the NEUTRINO-4 experiment.

We also plot in Fig. 3 limits from sterile neutrino searches at STEREO and PROSPECT experiments (the regions of large mixing are *excluded* at 95% C.L.), and the green contour that outlines the region *favored* at 95% C.L. by the reactor antineutrino anomaly (RAA); see, e.g., Ref. [16]. One observes that the STEREO limits are consistent with the joint anomaly presented in Fig. 3, while the limits from PROSPECT disfavor $2\text{-}\sigma$ regions except a small part at $\Delta m^2 \approx 9 \text{ eV}^2$. The reactor antineutrino anomaly region also has a small spot with $2\text{-}\sigma$ regions of the joint anomaly.

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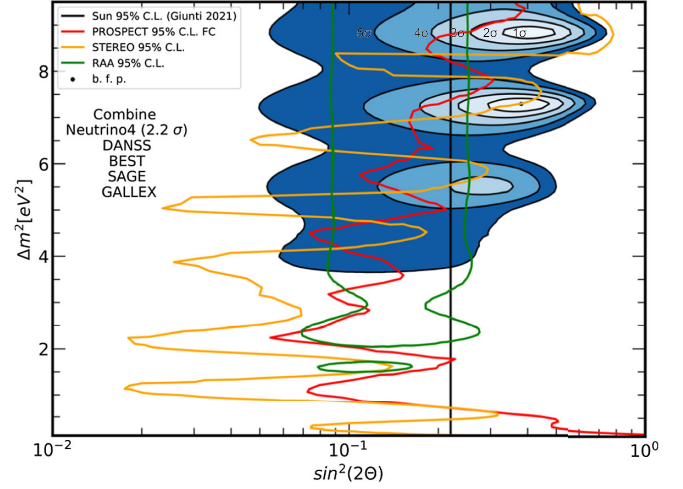


FIG. 3. The regions (in shades of blue) favored by the joint analysis of the gallium experiments, DANSS [30] and NEUTRINO-4 [29]. There are also regions excluded at 95% C.L. from sterile neutrino searches at reactor antineutrino experiments STEREO [32] and PROSPECT [33]. The regions outlined by the green line is favored at 95% C.L. by the RAA [16]. The region to the right of the black vertical line is excluded at 95% C.L. from observations of solar neutrinos [34].

The analysis above shows that the BEST anomalous result, if explained within the hypothesis of a single sterile neutrino (dubbed $3 + 1$ scheme), points at the region of large mixing and masses, which will be explored at the next operation stages of the upgraded reactor neutrino experiments and KATRIN experiment on tritium β decay; see Ref. [6]. The position of the best fit point and the likelihood contours may be refined with a joint statistical analysis including the likelihoods of other reactor antineutrino experiments relevant for the task.

Finally, recall that, apart from the direct limits, the typical $3 + 1$ neutrino model is strongly constrained from astrophysics and excluded by cosmological observations within simple extensions of the Standard Cosmological Model. Indeed, measurements of the solar neutrino flux exclude the models with large mixing [34]; the black vertical line in Fig. 3 refers to the corresponding 95% C.L. bound. Likewise, the large sterile-active neutrino mixing produces sterile neutrinos in the plasma of the early Universe in the amount forbidden from the analysis of present cosmological data [20]. It is tempting to suggest a modification of the simple $3 + 1$ scheme, which would circumvent the both indirect constraints.

IV. CONCLUSIONS

To summarize, we investigate how the recent results of BEST experiment can affect the hypothesis of the “ $3 + 1$ ” scheme in the neutrino sector. Note in passing that the explanation of the observed lack of neutrino events as oscillations to the sterile neutrino is not the only possibility

involving new physics. Moreover, an overall error in neutrino cross section on gallium or some issues in extraction efficiency cannot be ruled out, though all the aspects of experimental procedure have been verified and many have been double-checked [1].

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- [1] V. V. Barinov *et al.*, [arXiv:2109.11482](#).
 - [2] J. N. Abdurashitov *et al.* (SAGE Collaboration), *Phys. Rev. C* **59**, 2246 (1999).
 - [3] J. N. Abdurashitov *et al.*, *Phys. Rev. C* **73**, 045805 (2006).
 - [4] F. Kaether, W. Hampel, G. Heusser, J. Kiko, and T. Kirsten, *Phys. Lett. B* **685**, 47 (2010).
 - [5] A. P. Serebrov *et al.* (NEUTRINO-4 Collaboration), *Pis'ma Zh. Eksp. Teor. Fiz.* **109**, 209 (2019).
 - [6] M. Aker *et al.* (KATRIN Collaboration), *Phys. Rev. Lett.* **126**, 091803 (2021).
 - [7] I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, and A. Zhou, *J. High Energy Phys.* **09** (2020) 178.
 - [8] C. Athanassopoulos *et al.* (LSND Collaboration), *Phys. Rev. Lett.* **77**, 3082 (1996).
 - [9] T. A. Mueller *et al.*, *Phys. Rev. C* **83**, 054615 (2011).
 - [10] P. Huber, *Phys. Rev. C* **84**, 024617 (2011); **85**, 029901(E) (2012).
 - [11] A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), *Phys. Rev. Lett.* **121**, 221801 (2018).
 - [12] M. G. Aartsen *et al.* (IceCube Collaboration), *Phys. Rev. Lett.* **125**, 141801 (2020).
 - [13] J. Kopp, P. A. N. Machado, M. Maltoni, and T. Schwetz, *J. High Energy Phys.* **05** (2013) 050.
 - [14] M. Dentler, A. Hernández-Cabezudo, J. Kopp, P. A. N. Machado, M. Maltoni, I. Martinez-Soler, and T. Schwetz, *J. High Energy Phys.* **08** (2018) 010.
 - [15] C. Giunti and T. Lasserre, *Annu. Rev. Nucl. Part. Sci.* **69**, 163 (2019).
 - [16] K. N. Abazajian *et al.*, [arXiv:1204.5379](#).
 - [17] S. Böser, C. Buck, C. Giunti, J. Lesgourgues, L. Ludhova, S. Mertens, A. Schukraft, and M. Wurm, *Prog. Part. Nucl. Phys.* **111**, 103736 (2020).
 - [18] O. Sramek, W. F. McDonough, E. S. Kite, V. Lekic, S. Dye, and S. Zhong, *Earth Planet. Sci. Lett.* **361**, 356 (2013).
 - [19] E. G. Adelberger *et al.*, *Rev. Mod. Phys.* **83**, 195 (2011).
 - [20] N. Aghanim *et al.* (Planck Collaboration), *Astron. Astrophys.* **641**, A6 (2020); **652**, C4(E) (2021).
 - [21] Y. I. Izotov and T. X. Thuan, *Astrophys. J.* **710**, L67 (2010).
 - [22] E. Komatsu *et al.* (WMAP Collaboration), *Astrophys. J. Suppl. Ser.* **192**, 18 (2011).
 - [23] S. Hannestad, R. S. Hansen, and T. Tram, *Phys. Rev. Lett.* **112**, 031802 (2014).
 - [24] B. Dasgupta and J. Kopp, *Phys. Rev. Lett.* **112**, 031803 (2014).
 - [25] X. Chu, B. Dasgupta, and J. Kopp, *J. Cosmol. Astropart. Phys.* **10** (2015) 011.
 - [26] M.-M. Zhao, D.-Z. He, J.-F. Zhang, and X. Zhang, *Phys. Rev. D* **96**, 043520 (2017).
 - [27] M. Archidiacono, S. Gariazzo, C. Giunti, S. Hannestad, and T. Tram, *J. Cosmol. Astropart. Phys.* **12** (2020) 029.
 - [28] M. Laveder, *Nucl. Phys. B, Proc. Suppl.* **168**, 344 (2007).
 - [29] A. P. Serebrov *et al.*, *Phys. Rev. D* **104**, 032003 (2021).
 - [30] M. Danilov, *Proc. Sci. ICHEP2020* (2021) 121.
 - [31] I. Alekseev *et al.* (DANSS Collaboration), *Phys. Lett. B* **787**, 56 (2018).
 - [32] H. Almazán *et al.* (STEREO Collaboration), *Phys. Rev. D* **102**, 052002 (2020).
 - [33] M. Andriamirado *et al.* (PROSPECT Collaboration), *Phys. Rev. D* **103**, 032001 (2021).
 - [34] C. Giunti, Y. F. Li, C. A. Ternes, and Y. Y. Zhang, *Phys. Lett. B* **816**, 136214 (2021).