



10-7-2022

Search for Unstable Sterile Neutrinos with the IceCube Neutrino Observatory

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Recommended Citation

Abbasi, R.; Ackermann, M.; Adams, J.; Aguilar, J. A.; Ahlers, M.; Ahrens, M.; Alameddine, J. M.; Alves, A. A.; Amin, N. M.; Andeen, K.; Anderson, T.; Anton, G.; Argüelles, C.; Ashida, Y.; Axani, S.; Bai, X.; Balagopal V, A.; Barwick, S. W.; Bastian, B.; Basu, V.; Baur, S.; Bay, R.; Beatty, J. J.; Becker, K. H.; and Becker Tjus, J., "Search for Unstable Sterile Neutrinos with the IceCube Neutrino Observatory" (2022). *Physics: Faculty Publications and Other Works*. 76.

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Search for Unstable Sterile Neutrinos with the IceCube Neutrino Observatory

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We present a search for an unstable sterile neutrino by looking for a resonant signal in eight years of atmospheric ν_μ data collected from 2011 to 2019 at the IceCube Neutrino Observatory. Both the (stable) three-neutrino and the $3 + 1$ sterile neutrino models are disfavored relative to the unstable sterile neutrino model, though with p values of 2.8% and 0.81%, respectively, we do not observe evidence for $3 + 1$ neutrinos with neutrino decay. The best-fit parameters for the sterile neutrino with decay model from this study are $\Delta m_{41}^2 = 6.7_{-2.5}^{+3.9}$ eV², $\sin^2 2\theta_{24} = 0.33_{-0.17}^{+0.20}$, and $g^2 = 2.5\pi \pm 1.5\pi$, where g is the decay-mediating coupling. The preferred regions of the $3 + 1 +$ decay model from short-baseline oscillation searches are excluded at 90% C.L.

DOI: [10.1103/PhysRevLett.129.151801](https://doi.org/10.1103/PhysRevLett.129.151801)

Long-standing anomalies in short-baseline (SBL) neutrino experiments [1,2] have been interpreted in the standard oscillation framework of three known flavors and one or more hypothetical sterile neutrinos, referred to as “ $3 + N$ ” models. The “ $3 + 1$ ” model, which involves only one sterile neutrino, has been extensively studied through global fits to datasets sensitive to vacuum oscillations involving a dominant mass splitting of ~ 1 eV² [3–5]. These fits find a strong preference for $3 + 1$ over the three neutrino hypothesis [4]. However, the allowed regions from these fits suffer from internal inconsistencies between datasets [4,6]. In particular, no experiment has found evidence of ν_μ disappearance, which is expected in a $3 + 1$ model. This is one motivation to consider alternative models to the $3 + 1$; another is to evade cosmological bounds on light sterile neutrinos [7–11] and possibly resolve the Hubble tension [12–16].

Other explanations for the observed anomalies include misestimation of standard model backgrounds in the experiments with anomalies [2,17–20], alternative models that do not involve light sterile neutrinos [21–32], and extensions to the $3 + 1$ model that address the internal tension [33–35]. In the latter case, models wherein the sterile neutrino is unstable (“ $3 + 1 +$ decay”) reduce the tension compared to the $3 + 1$ model [4,35,36]. However, to be seen as a well-motivated improvement, the $3 + 1 +$ decay model should be tested through entirely different processes than vacuum oscillations.

The IceCube Neutrino Observatory has the unique capability of performing such a test. IceCube is a cubic-kilometer neutrino detector buried 1.5–2.5 km beneath the surface of the Antarctic glacier at the South Pole [37]. Muon tracks from charged current (CC) muon (anti)neutrino interactions are reconstructed based on observation of emitted Cherenkov light that is collected by “digital optical modules” (DOMs) [38] arranged in vertical strings on a hexagonal lattice. Specifically, the track fitting [39] utilizes signals from two detector arrays: (i) the main array of 78 strings spaced 125 m apart, each carrying 60 DOMs with a vertical separation of 17 m between them; and (ii) the DeepCore [40] eight-string array, with lateral spacing varying from 42 to 72 m, and vertical DOM separation of 7 m.

The existence of an eV-scale sterile neutrino can manifest itself as a resonant, matter-enhanced flavor transition for either muon antineutrinos or muon neutrinos traversing the core of the Earth [41–46]. This causes a deficit of “up-going” muon (anti)neutrinos at TeV-scale energies. IceCube cannot distinguish between neutrinos and antineutrinos. Therefore, the only signature is a deficit in the combined muon neutrino and muon antineutrino ($\nu_\mu + \bar{\nu}_\mu$) CC event distribution at TeV energies. A search in the framework of the $3 + 1$ model using eight years of IceCube data has recently been published [47,48]. This dataset offers an excellent platform to test the hypothesis that the $3 + 1 +$ decay model provides a better description of the data than the $3 + 1$ model without relying upon the vacuum oscillation signature.

In the $3 + 1 +$ decay model, the three-neutrino mixing matrix, U_{PNMS} , which is parametrized by three mixing angles and one CP -violating phase, δ_{CP} , is extended by one row and column, adding one sterile flavor state, ν_s , and one heavy mass state, ν_4 . This introduces three new mixing angles, θ_{14} , θ_{24} , and θ_{34} , two new CP -violating phases, δ_{14}

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and δ_{24} , and one additional mass splitting, Δm_{41}^2 . Lastly, instability of the fourth mass state is introduced as in Ref. [4], governed by the strength of a coupling constant g . For nonzero values of g , ν_4 can decay into invisible particles beyond the standard model, while $g = 0$ returns the $3 + 1$ model. The relationship between this coupling, g , the ν_4 mass, m_4 , and its lifetime, τ , is [49]

$$\tau = \frac{16\pi}{g^2 m_4}. \quad (1)$$

Most of the parameters involved in three-neutrino mixing are well known; these include the light, active neutrino mass splittings and the PMNS matrix elements [50]. However, this Letter is insensitive to these parameters as well as to the neutrino mass ordering and δ_{CP} because, for the relevant neutrino energies ($E_\nu > 100$ GeV) and baselines (order the diameter of the Earth or smaller), oscillation probabilities between the three active flavors are insignificant. For the present study, the normal mass ordering is assumed and δ_{CP} is assumed to be zero. Furthermore θ_{14} , δ_{14} , and δ_{24} are set to zero since they have subleading effects [51]; θ_{34} is set to zero as this yields conservative results [51,52] and m_1 is set to zero since only mass differences are relevant. This leaves three free parameters in the model to be tested: Δm_{41}^2 , $\sin^2 2\theta_{24}$, and g^2 . It is assumed that $\theta_{24} < \pi/4$, which causes the resonance to appear in the antineutrino flux; larger values of θ_{24} are heavily constrained [4] and since there are more atmospheric neutrinos than antineutrinos [53], this choice is also conservative.

At IceCube, the ν_μ and $\bar{\nu}_\mu$ disappearance probabilities vary as a function of energy and zenith angle (θ_z), where $\cos \theta_z = 0$ corresponds to neutrinos arriving from the horizon and $\cos \theta_z = -1$ corresponds to neutrinos arriving from the direction of the North Pole. This study uses a dataset collected over a live time of 2786 days and an event selection that has been described in detail in Refs. [48,54]. The predicted resonance occurs at TeV scales, hence the analysis focuses on muons from CC neutrino interactions with energies between 500 GeV and 10 TeV. Relevant neutrino interactions occur below or within IceCube. Because the signature of the analysis relies on matter effects in the Earth, this analysis requires muon tracks to have up-going zenith angle ($-1.0 < \cos \theta_z < 0.0$). The angular resolution of the tracks, $\sigma_{\cos \theta_z}$, lies between 0.005 and 0.015, and the track energy resolution, $\sigma_{\log_{10}(E_\mu/\text{GeV})}$, is ~ 0.5 [39]. The selected sample comprises 305 735 CC ν_μ and $\bar{\nu}_\mu$ events.

The expected neutrino flux is primarily atmospheric neutrinos, with approximately a 3% overall contribution from astrophysical neutrinos, determined by extrapolating from measurements at higher energies [55–61]. The atmospheric flux arises predominantly from the decays of kaons and pions, and to a much lesser extent, muons, in cosmic-ray air showers [62]. The decays of heavier mesons contribute minimally to the atmospheric flux in the energy

range relevant to this analysis [63–69]. The atmospheric and astrophysical fluxes fall steeply with energy, with spectral indices of approximately -3.7 and -2.5 , respectively [61,70].

The physics under study affects the flavors of the neutrinos as they propagate through the Earth. This is described using the nuSQUIDS neutrino evolution code [71,72] which accounts for both coherent and incoherent interactions [73–78], as well as tau neutrino regeneration [79,80]. This analysis uses nuSQUIDSDecay, which incorporates the effect of ν_4 decay [34]. The Earth density profile is parametrized by the spherically symmetric PREM model [81]. The CSMS [82] neutrino-nucleon cross section is used to describe the CC interactions below and within the detector.

This analysis builds on the $3 + 1$ analysis in Ref. [48]. The data are binned in reconstructed muon energy and $\cos \theta_z$, and a modified Poisson likelihood that accounts for finite simulation statistics is used to evaluate the data given sterile neutrino parameters [83]. Eighteen systematic effects related to the atmospheric and astrophysical flux, detector, and cross section uncertainties are incorporated into the likelihood function as nuisance parameters; these are described further in Ref. [48]. The treatment of most systematic uncertainties is unchanged. The dominant category of uncertainties had been identified as those associated with the atmospheric neutrino flux.

Two improvements were made over the $3 + 1$ analysis: (i) the uncertainty in the atmospheric neutrino flux corresponding to the uncertainty in the production of charged mesons in atmospheric showers is calculated using atmospheric data from the NASA Atmospheric InfraRed Sounder satellite [84], rather than the atmospheric model from Ref. [85]; and (ii) the astrophysical and prompt neutrino fluxes are calculated using a corrected depth setting of the glacial ice, compared to Ref. [48], which had little impact on the current or previous results. Combined, these changes increase the likelihood of the data for the three-neutrino model and best-fit $3 + 1$ model by, respectively, 0.09 and 0.18 log-likelihood (LLH) units.

Both a frequentist parameter estimation and a pointwise Bayesian model comparison [86] are performed, following the same procedure as in Ref. [48]. The likelihood function and Bayes factor [87] are evaluated over a grid scan of the three physics parameters— Δm_{41}^2 , $\sin^2 2\theta_{24}$, and g^2 —where Δm_{41}^2 and $\sin^2 2\theta_{24}$ are sampled log uniformly with ten samples per decade in the ranges 0.01–47 eV² and 0.01–1.0, respectively, and the parameter g^2 is sampled in steps of $(\pi/2)$ in the range $0 - 4\pi$.

The best-fit parameters are found to be $\Delta m_{41}^2 = 6.7_{-2.5}^{+3.9}$ eV², $\sin^2 2\theta_{24} = 0.33_{-0.17}^{+0.20}$, and $g^2 = 2.5\pi \pm 1.5\pi$. The $\bar{\nu}_\mu$ disappearance probabilities are given in Fig. 1 for the parameters $\Delta m_{41}^2 = 6.7$ eV² and $\sin^2 2\theta_{24} = 0.33$, and for two values of g^2 ; the top panel shows the situation for $g^2 = 0$, which corresponds to the $3 + 1$ model, while the bottom panel is for the case $g^2 = 2.5\pi$. The bottom panel

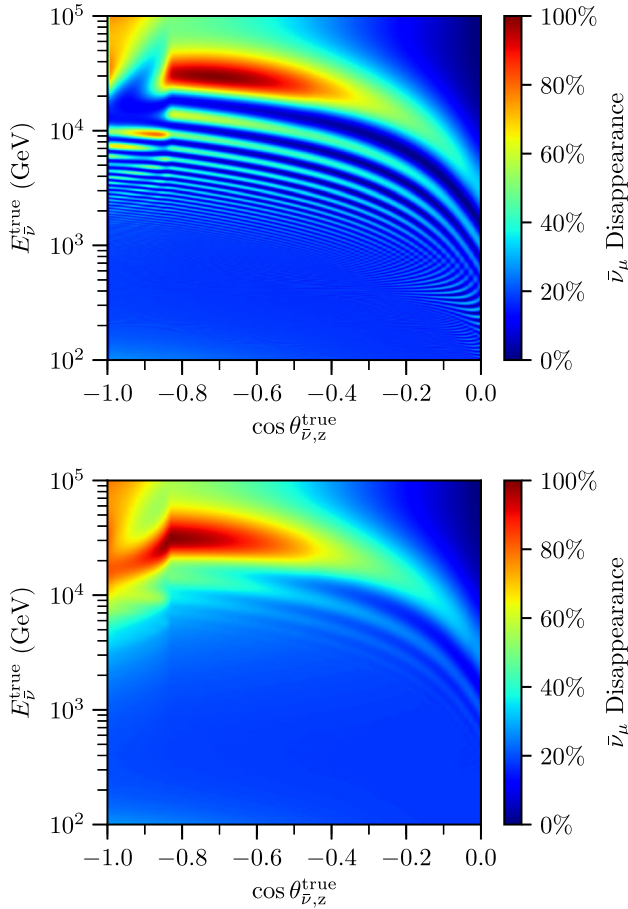


FIG. 1. Muon antineutrino disappearance probabilities for the sterile parameters $\Delta m_{41}^2 = 6.7 \text{ eV}^2$, $\sin^2 2\theta_{24} = 0.33$, and two values of g^2 . Top: $g^2 = 0$, which corresponds to infinite ν_4 lifetime, i.e., the $3 + 1$ model. Bottom: $g^2 = 2.5\pi$; this is the best-fit point.

represents the best-fit point of the frequentist analysis. Muon neutrino disappearance probabilities do not feature the resonant deficit and make subleading contributions to the sterile signature, so they are not shown.

The best-fit signal expectation and data are both compared to the three-neutrino model expectation in Fig. 2. In these plots, both the signal expectation and the three-neutrino model expectation include systematic uncertainties estimated adopting the respective physics parameters. Both the data and the best-fit signal shapes have a deficit of events for through-going neutrinos at the highest energies and a relative excess for horizon-skimming events at the highest energies. The fit values of all systematic uncertainties are within 1σ of their prior centers, with the exception of the cosmic-ray spectral index. The fit value of this systematic uncertainty deviates by 2.4σ , which is similar to both the result from the $3 + 1$ search [47,48], as well as the fit value assuming no sterile neutrino.

The frequentist confidence regions sliced at the best-fit value of g^2 are shown in Fig. 3. The contours are drawn

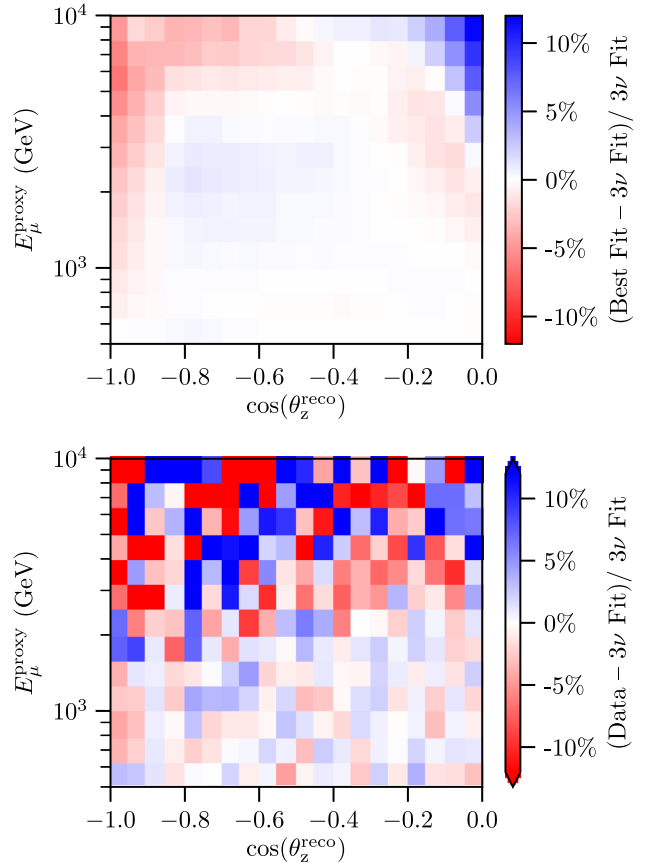


FIG. 2. Top: Comparison of best-fit signal expectation to the three-neutrino fit. Bottom: Comparison of the binned data to the three-neutrino fit. Distributions are binned in reconstructed muon energy (E_μ^{Proxy}) and cosine zenith angle.

assuming Wilks' theorem and three degrees of freedom (DOF). Fits to simulated datasets for several points in the parameter space showed the effective DOF was consistent with three or fewer. The slices of the confidence regions for the other values of g^2 are approximately the same in the 2D space of $[\Delta m_{41}^2, \sin^2 2\theta_{24}]$, with two deviations: the 90% C.L. (confidence level) region for $g^2 = 0$ excludes any point with $\sin^2 2\theta_{24} \gtrsim 0.2$, and above $\Delta m_{41}^2 \sim 7 \text{ eV}^2$, the confidence regions extend to higher Δm_{41}^2 values for larger values of g^2 . This is shown in the Supplemental Material [88]. The effective DOF at the null hypothesis (only three neutrinos) was determined to be 2.86 ± 0.14 , obtained by fitting 300 simulated datasets generated assuming this hypothesis. The null hypothesis is disfavored in favor of the $3 + 1 + \text{decay}$ model with $-2\Delta\text{LLH} = 9.1$ and a p value of 2.8%. This p value was obtained using Wilks' theorem and three DOF, which is conservative and consistent with the DOF assumed for the contours.

The Bayesian analysis finds the best model to have the parameters $\Delta m_{41}^2 = 6.7 \text{ eV}^2$, $\sin^2 \theta_{24} = 0.33$, and $g^2 = 1.5\pi$; this model has a Bayes factor (BF) with respect to the three-neutrino model of 0.025. The Bayes factor of

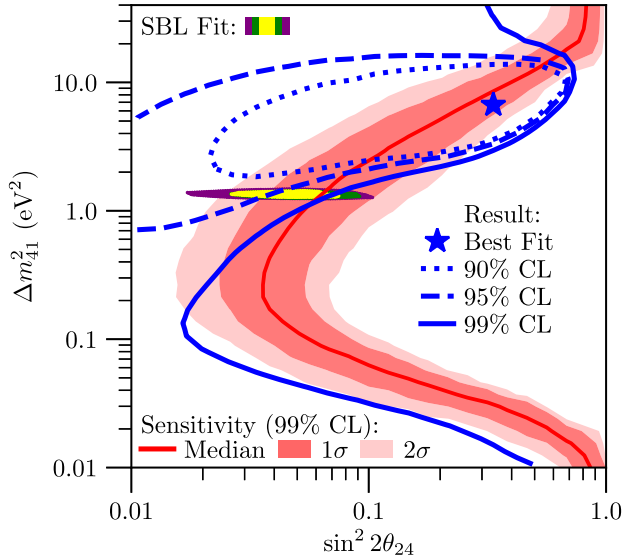


FIG. 3. The result of the frequentist analysis for $g^2 = 2.5\pi$. The 90%, 95%, and 99% C.L. contours are shown as blue dotted, dashed, and solid curves, respectively. The best-fit point is marked with a blue star. The median sensitivity at 99% C.L., determined from 300 simulated datasets, is shown as a red curve. The medium and light pink bands indicate the 1σ and 2σ regions for the sensitivity. The 2D projection of the SBL fit results from [4] for the range $2.25\pi \leq g^2 \leq 2.75\pi$ at 90% C.L., 95% C.L., and 99% C.L. are shown as the solid yellow, green, and purple islands around $\Delta m^2_{41} = 1.3 \text{ eV}^2$.

the frequentist best-fit point is 0.027. The Bayesian result for $g^2 = 2.5\pi$ is shown in Fig. 4. As with the frequentist confidence regions, Bayesian preferred regions sliced at the varying values of g^2 are very similar, with a few exceptions. For $g^2 = 0$, the region $\log_{10}(\text{BF}) \leq -0.5$ excludes points with $\sin^2 2\theta_{24} \gtrsim 0.2$. The regions with $\log_{10}(\text{BF}) = -1.5$ only occur for $1.5\pi \leq g^2 \leq 2.5\pi$. This is shown in the Supplemental Material [88].

The frequentist and Bayesian results profiled over the parameters Δm^2_{41} and $\sin^2 2\theta_{24}$ are shown in Fig. 5. Both analyses find some preference for nonzero g^2 . In the frequentist analysis, $g^2 = 0$ is disfavored in favor of nonzero g^2 with $-2\Delta\text{LLH} = 3.9$ and a p value of 0.81%. This p value was obtained using Wilks' theorem and 0.26 effective DOF. The effective DOF was determined by fitting 500 simulated datasets generated assuming the best-fit 3 + 1 parameters, i.e., fixing $g^2 = 0$. The uncertainty of the value of the effective DOF is 0.02.

The 95% C.L. allowed region found in this Letter overlaps that of the SBL fits, as seen in Fig. 3. This overlap occurs to some extent for all nonzero values of g^2 , but is larger for g^2 values above π . This overlap remains fixed in Δm^2_{41} and $\sin^2 2\theta_{24}$ for varying g^2 . At and above $g^2 = \pi$, there is some overlap between the 95% C.L. region of this Letter and the 90% C.L. allowed region from the SBL fits.

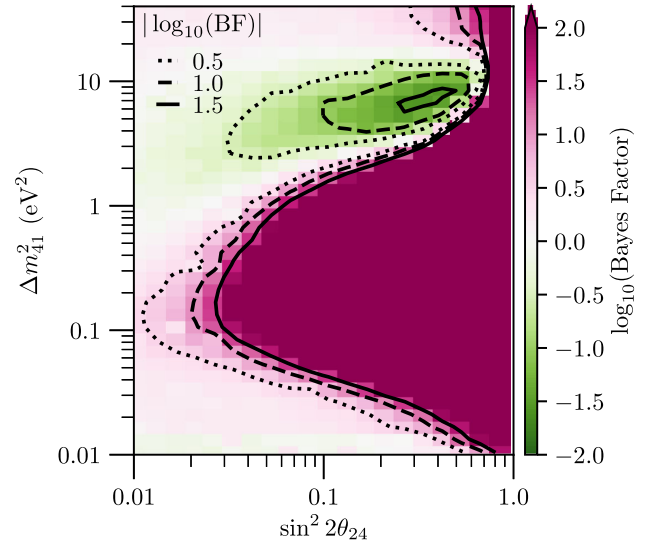


FIG. 4. The result of the Bayesian analysis for $g^2 = 2.5\pi$. The color indicates the logarithm of the Bayes factor with respect to the three-neutrino model; magenta regions have strong preference for the three-neutrino model, while green regions have preference for the sterile neutrino model. The dotted, dashed, and solid black contours correspond to $\log_{10}(\text{BF})$ equaling ± 0.5 , ± 1.0 , and ± 1.5 , respectively.

In conclusion, we have found no substantive evidence for the 3 + 1 + decay model. The null hypothesis of only three neutrinos is disfavored with a p value of 2.8%, and the 3 + 1 model disfavored with a p value of 0.81%. The

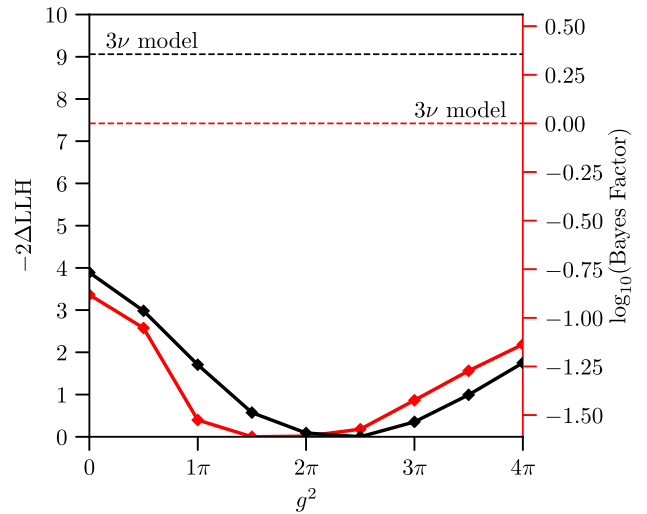


FIG. 5. The frequentist and Bayesian results profiled over two of the sterile parameters, Δm^2_{41} and $\sin^2 2\theta_{24}$. The frequentist test statistic, $-2\Delta\text{LLH}$ is shown in black and is plotted on the left y axis. The logarithm of the Bayes factor is shown in red and is plotted on the right y axis. The diamond markers joined by the thick lines show the results for the sterile model as a function of the third sterile parameter, g^2 . The results for the null hypothesis—that there are only three neutrino species—are shown in the dashed horizontal lines at the top of the plot.

best-fit parameters are $\Delta m_{41}^2 = 6.7^{+3.9}_{-2.5} \text{ eV}^2$, $\sin^2 2\theta_{24} = 0.33^{+0.20}_{-0.17}$, and $g^2 = 2.5\pi \pm 1.5\pi$. While we have reported valuable new input to global studies, further work, both within and beyond IceCube, is needed to clarify the picture [89]. In particular, in IceCube, the track energy reconstruction can be improved by using machine learning algorithms [90] and the dataset can be expanded to use a new event morphology [91,92].

The IceCube Collaboration acknowledges the significant contributions to this manuscript from the Massachusetts Institute of Technology, University of Texas at Arlington, and Harvard University groups. The authors gratefully acknowledge the support from the following agencies and institutions: USA—U.S. National Science Foundation—Office of Polar Programs, U.S. National Science Foundation—Physics Division, U.S. National Science Foundation—EPSCoR, Wisconsin Alumni Research Foundation, Center for High Throughput Computing (CHTC) at the University of Wisconsin—Madison, Open Science Grid (OSG), Extreme Science and Engineering Discovery Environment (XSEDE), Frontera computing project at the Texas Advanced Computing Center, U.S. Department of Energy—National Energy Research Scientific Computing Center, Particle astrophysics research computing center at the University of Maryland, Institute for Cyber-Enabled Research at Michigan State University, and Astroparticle physics computational facility at Marquette University; Belgium—Funds for Scientific Research (FRS-FNRS and FWO), FWO Odysseus and Big Science programmes, and Belgian Federal Science Policy Office (Belspo); Germany—Bundesministerium für Bildung und Forschung (BMBF), Deutsche Forschungsgemeinschaft (DFG), Helmholtz Alliance for Astroparticle Physics (HAP), Initiative and Networking Fund of the Helmholtz Association, Deutsches Elektronen Synchrotron (DESY), and High Performance Computing cluster of the RWTH Aachen; Sweden—Swedish Research Council, Swedish Polar Research Secretariat, Swedish National Infrastructure for Computing (SNIC), and Knut and Alice Wallenberg Foundation; Australia—Australian Research Council; Canada—Natural Sciences and Engineering Research Council of Canada, Calcul Québec, Compute Ontario, Canada Foundation for Innovation, WestGrid, and Compute Canada; Denmark—Villum Fonden and Carlsberg Foundation; New Zealand—Marsden Fund; Japan—Japan Society for Promotion of Science (JSPS) and Institute for Global Prominent Research (IGPR) of Chiba University; Korea—National Research Foundation of Korea (NRF); Switzerland—Swiss National Science Foundation (SNSF); United Kingdom—Department of Physics, University of Oxford.

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