

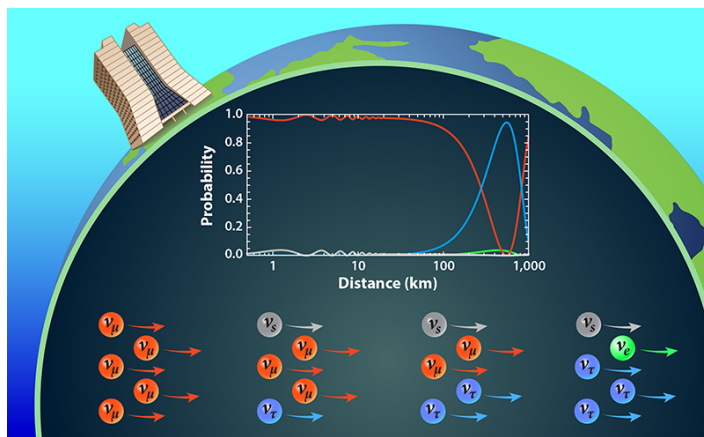
# Sterile Neutrino Down but Not Completely Out

Neutrino experiments place the most stringent limits to date on a hypothetical fourth neutrino, but the possibility that such a particle exists remains open.

By **Viviana Niro** and **Pedro Machado**

Physicists know a lot about neutrinos. These elementary particles exist everywhere yet rarely interact with matter. They are produced in three different types—electron, muon, and tau—known in the field as flavors. And they can oscillate between these flavors, periodically changing from one to another as they travel. But despite this knowledge, neutrinos are shrouded in some big mysteries. For example, that neutrinos oscillate implies that at least two of the particles have a nonzero mass, but the exact mass has yet to be determined (oscillation experiments provide only information on the squared mass difference between neutrinos, and cosmological

experiments are sensitive only to the sum of all three masses). Additionally, experiments hint at the existence of an enigmatic fourth neutrino, called the sterile neutrino (see [Viewpoint: The Plot Thickens for a Fourth Neutrino](#)). But the results are controversial, and the signals from this particle are inconsistent (see [Viewpoint: Getting to the Bottom of an Antineutrino Anomaly](#), and [Viewpoint: Hunting the Sterile Neutrino](#)). Now the collaborations behind the MINOS and MINOS+ experiments at Fermilab in the US and the Daya Bay Reactor Neutrino Experiment in China have released an analysis that eliminates a large portion of the remaining parameter space in which sterile neutrinos could exist [1]. But the teams have not yet studied all their data, and other experiments do see possible signals, leaving the door ajar for the existence of this disputed particle.



**Figure 1:** As neutrinos travel through Earth their flavor oscillates. The graph shows the probability that a muon neutrino (red) produced at Fermilab oscillates into a tau neutrino (blue), an electron neutrino (green), or the hypothetical sterile neutrino (gray).

Credit: APS/Carin Cain

The oscillation of neutrinos between flavors is a quantum effect. It comes from the fact that each neutrino flavor,  $\nu_e$  (electron),  $\nu_\mu$  (muon), and  $\nu_\tau$  (tau), is a linear superposition of three states,  $\nu_1$ ,  $\nu_2$ , and  $\nu_3$  with masses  $m_1$ ,  $m_2$ , and  $m_3$  (see [Focus: Nobel Prize—Neutrinos Oscillate](#)). Precision measurements show that the distance it takes for one neutrino to turn into another—the neutrino oscillation baseline—depends on the energies of the participating states and the difference between their squared masses. For example, a 1-GeV muon neutrino from the neutrino beam at Fermilab typically takes 500 km to oscillate into a tau neutrino. A 3-MeV electron antineutrino from a nuclear reactor, on the other hand, takes only 1 km to switch flavors. Both oscillations are consistent with  $\Delta m_{31}^2 = m_3^2 - m_1^2 = 2.5 \times 10^{-3} \text{ eV}^2$ .

However, some experiments have found a number of puzzling results that don't fit with the three-neutrino framework. The

oldest of these results comes from the Liquid Scintillator Neutrino Detector (LSND) experiment at Los Alamos National Laboratory, where in 2001 they obtained data consistent with muon antineutrinos converting into electron antineutrinos over shorter distances than expected for three-flavor neutrino oscillations [2]. Later, the Mini Booster Neutrino Experiment (MiniBooNE), which was built to test the LSND anomaly, observed a similar signal [3].

One explanation for these short oscillations is that there exists a fourth “sterile” neutrino,  $\nu_s$ , which does not interact via any of the fundamental interactions of the standard model of particle physics. The LSND and MiniBooNE data suggest that such a particle would have oscillations with a mass splitting of  $\Delta m_{41}^2 = 1 \text{ eV}^2$ . Other results from some reactor neutrino experiments also fit with a  $1\text{-eV}^2$  mass splitting or more [4]. The new analysis from the MINOS, MINOS+, and Daya Bay collaborations, which includes old data from Bugey-3—an experiment that ended in 1996—searched for signals with these mass splittings. But the teams found no hints of sterile neutrinos where other experiments have seen one.

MINOS and MINOS+ are long-baseline experiments, where the neutrinos travel hundreds of kilometers before they are detected. The two experiments study the disappearance of muon neutrinos produced at Fermilab using detectors placed 1.04 km and 735 km from the lab [5]. Daya Bay is a medium-baseline experiment. Their electron antineutrinos are produced at six nuclear reactors and detected with eight antineutrino detectors that are in three different underground halls, which are at distances ranging from 365 m to 1.9 km from the reactor [6]. Bugey-3 was a short-baseline experiment that detected muon neutrino oscillations at distances of 15, 40, and 95 m from the reactor core, where the neutrinos were produced.

Analyzing their combined data, the collaborations have been able to set new constraints on the probability that the muon neutrino oscillates into an electron neutrino via a sterile one over these distances. They eliminate the sterile neutrino region of interest for mass splittings between  $10^{-4}$  to  $10^3 \text{ eV}^2$ .

These new constraints exacerbate tension surrounding the sterile neutrino. This tension comes because they exclude mass splittings values for sterile neutrino signals that could explain both the early LSND and MiniBooNE experiments [7] and also in

new unpublished MiniBooNE experiments that analyze a 17-year-long dataset [8]. Other unpublished results, this time from the IceCube Collaboration, which analyzes eight years of atmospheric muon neutrino data, also question the existence of a sterile neutrino [9]. And the absence of a sterile neutrino fits with data from the Planck satellites that measure the energy density of the early Universe [10].

These conflicts mean that additional data are still needed to resolve the sterile neutrino problem, particularly from the Short Baseline Neutrino Program at Fermilab. Moreover, the MINOS+ Collaboration still has to analyze the last year of data from their experiments and the Daya Bay Collaboration has two additional years of data-taking to look at. That further data could provide valuable evidence in favor of or against the existence of sterile neutrinos.

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