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KATRIN tightens the net around the elusive sterile neutrino

The KATRIN experiment has searched with unprecedented precision for signs of a fourth type of neutrino, that could reveal new physics beyond the Standard Model. No signal was found, tightening the constraints on one of the most debated puzzles in neutrino research.

Neutrinos, though nearly invisible, are among the most numerous matter particles in the Universe. The Standard Model recognizes three types, but the discovery of neutrino oscillations revealed they have mass and can change identity while propagating. For decades, puzzling experimental anomalies have suggested the presence of a fourth, *sterile* neutrino, one that interacts even more weakly. Finding it would transform our understanding of particle physics.

In a new study, published in *Nature*, the KATRIN collaboration presents the most precise direct search for sterile neutrinos through measurements of tritium β-decay.

The KATRIN (Karlsruhe Tritium Neutrino) experiment, built to determine the neutrino mass, measures the energy spectrum of electrons emitted in the β-decay of tritium. In this process, the energy carried away by the neutrino subtly shapes the detected electron spectrum. If an additional sterile neutrino existed, it would occasionally be emitted in the decay, producing a distinct distortion, or “kink”, in the electron energy spectrum. KATRIN, located at the Karlsruhe Institute of Technology in Germany, is a large experiment extending over 70 meters. It comprises three main components: a high-luminosity windowless gaseous tritium source that emits electrons, a high-resolution spectrometer system that measures their energy, and a detector that counts them. Since 2019, KATRIN has measured the tritium β-decay spectrum with unmatched precision, looking for small deviations, especially the characteristic kink expected from a sterile neutrino.

The new *Nature* publication presents the most sensitive search to date for sterile neutrinos using the β-decay of tritium. KATRIN collected 36 million electrons over 259 days from 2019 to 2021 and compared them to a β-decay model, reaching sub-percent measurement accuracy. No sign of a sterile neutrino was found. The result excludes a large region of parameter space suggested by earlier anomalies: small but significant deficits observed in reactor-neutrino and gallium-source experiments that had hinted at a fourth neutrino state. It also fully rules out the Neutrino-4 experiment claim, which had reported evidence for such a signal. With an excellent signal-to-background ratio ensuring that almost all detected electrons come from tritium β-decay, KATRIN achieves a remarkably clean measurement of the spectral shape. In contrast to oscillation experiments, which study how neutrinos change flavor after traveling some distance, KATRIN probes the energy distribution at the point of creation. Relying on distinct detection methods, the two approaches complement each other and jointly deliver a powerful test that disfavors the sterile-neutrino hypothesis.

“Our new result is fully complementary to reactor experiments such as STEREO,” explains Thierry Lasserre (Max-Planck-Institut für Kernphysik) in Heidelberg, who led the analysis. “While reactor experiments are most sensitive to sterile–active mass splittings below a few eV^2, KATRIN explores the range from a few to several hundred eV^2. Together, the two approaches now consistently rule out light sterile neutrinos that would noticeably mix with the known neutrino types.”

With data collection continuing through 2025, KATRIN’s sensitivity will further increase, enabling even more stringent searches for light sterile neutrinos. “By the completion of data taking in 2025, KATRIN will have recorded more than 220 million electrons in the region of interest, increasing the statistics by over a factor of six,” says KATRIN co-spokesperson Kathrin Valerius (KIT). “This will allow us to push the boundaries of precision and probe mixing angles below the present limits.” In 2026, the KATRIN experiment will be upgraded with the TRISTAN detector, capable of recording the full tritium β-decay spectrum with unprecedented statistics. By bypassing the main spectrometer and measuring electron energies directly, TRISTAN will be able to explore much higher sterile-neutrino masses. “This next-generation setup will open a new window into the keV-mass range, where sterile neutrinos might even form the Universe’s dark matter,” says co-spokesperson Susanne Mertens (Max-Planck-Institut für Kernphysik).

The KATRIN Collaboration
Scientists from over 20 institutions across 7 countries are working on the KATRIN project.

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KATRIN Website: http://www.katrin.kit.edu

Illustration: The KATRIN experiment

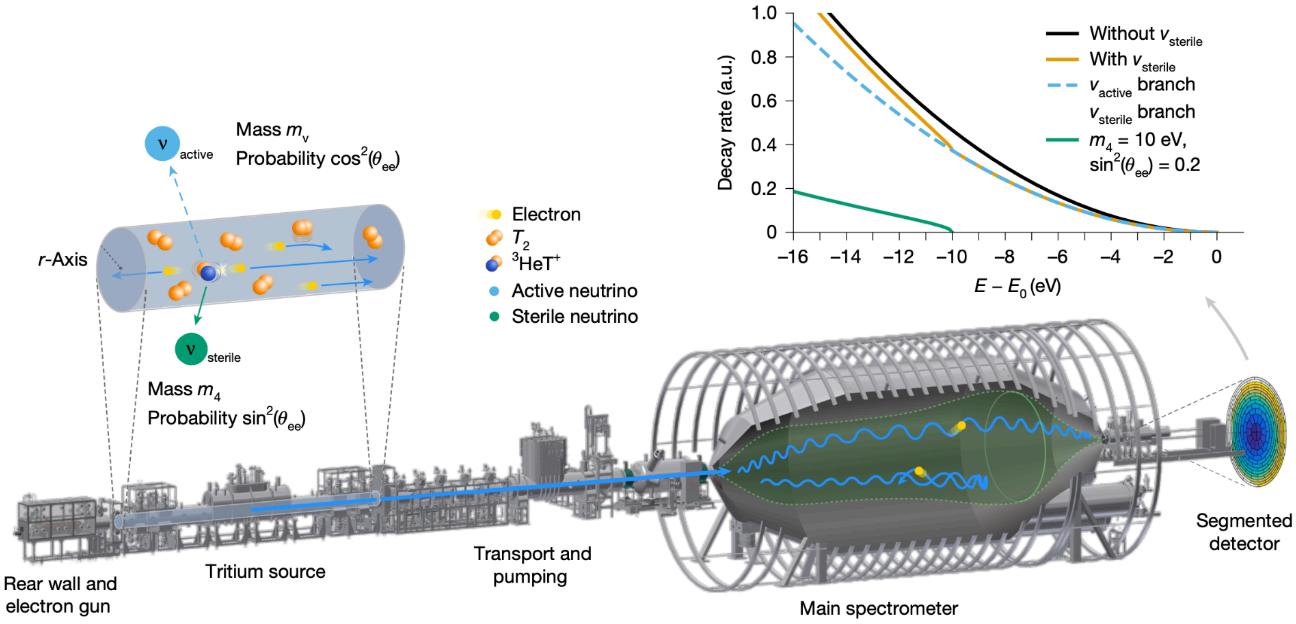

Figure 1: The KATRIN experiment. From left to right, the rear wall and electron gun, the windowless gaseous tritium source, the transport and pumping section, the pre- and main spectrometers, and the focal-plane detector in which the electrons are detected and counted.

Illustration: Sterile Neutrino Imprint in KATRIN

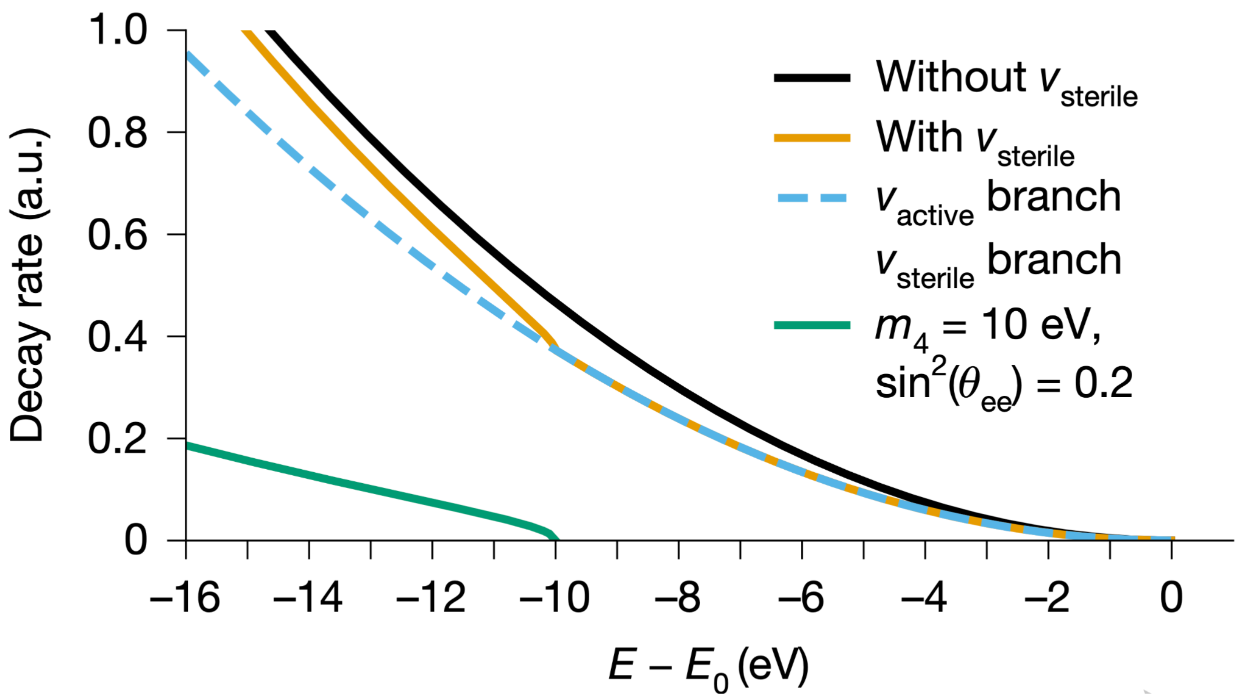

Figure: Anticipated imprint of a 10 eV fourth neutrino mass state in the tritium β-decay spectrum. The associated kink emerges at E0−m4, while the amplitude of the modification of the spectrum is set by the mixing strength sin2(θee). The mixing effect is intentionally amplified here for visibility.

Illustration: KATRIN picture

Figure: Transport of the KATRIN main spectrometer vessel, a major component of the experiment, to KIT's Campus North site.

Illustration: KATRIN Collaboration - October 2024

Illustration: Main Result

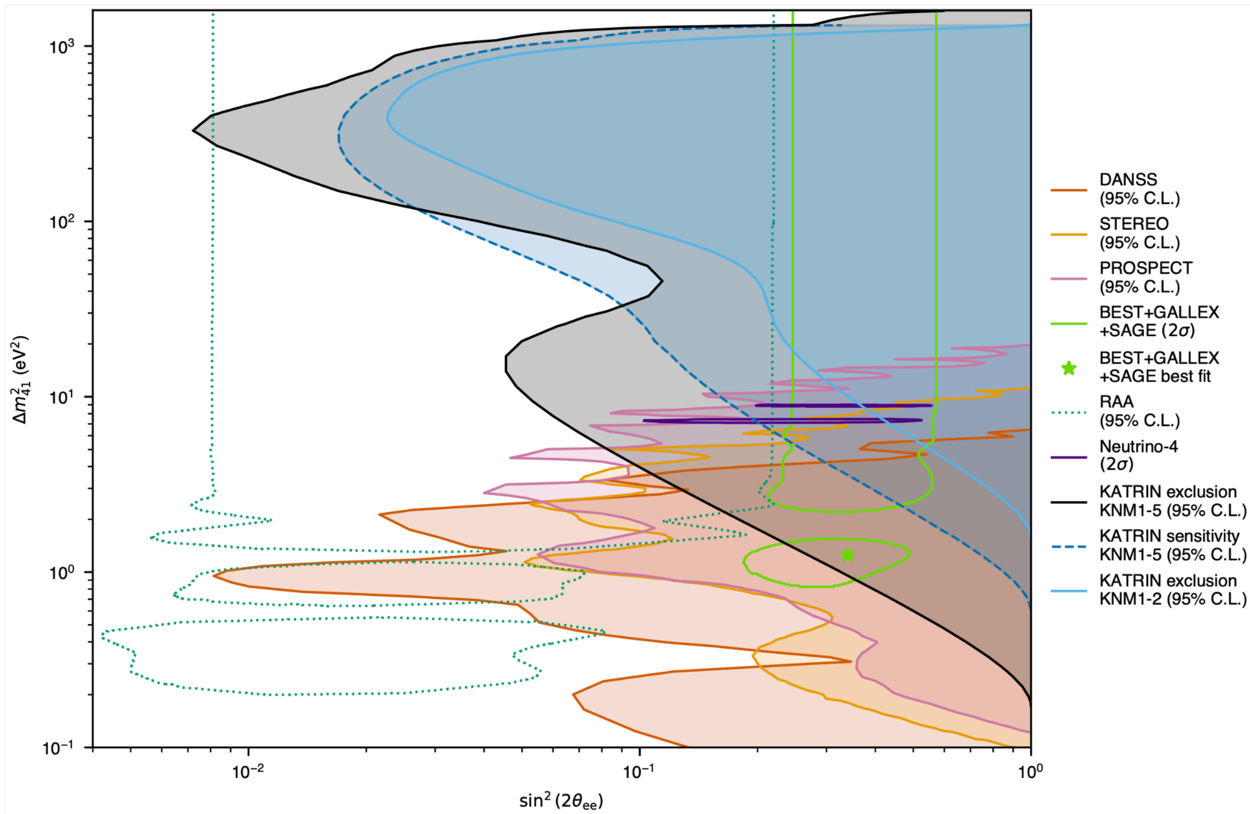

Figure: KATRIN's new data (black) largely rule out the sterile-neutrino hints suggested by earlier reactor and gallium anomalies.