NuSte: Global Light Sterile Neutrino Fits
Snowmass 2021 Letter of Interest

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Sterile neutrinos are one of the most likely manifestations of physics Beyond the Standard Model (BSM) in the lepton sector. Indeed, the existence of sterile neutrinos at different mass scales is predicted in most BSM models.

It is well established that there are three light neutrino masses with small squared-mass differences that generate the observed oscillations of solar, atmospheric, accelerator and reactor neutrinos in the standard framework of three-neutrino mixing. These three light neutrino masses are constrained below the eV scale by the results of the recent KATRIN experiment, by the bounds of neutrinoless double-beta decay experiments (assuming that the masses are of Majorana type), and by cosmological measurements (assuming the standard ΛCDM cosmological model). Moreover, the number of active neutrinos, that take part in standard model weak interactions, is well established to be three by the LEP measurement of the invisible decay of the Z^0 boson. Therefore, if there are more than three neutrino states, the additional ones must be sterile, i.e. not taking part in standard model weak interactions.

It is plausible that the smallness of the three light neutrino masses with respect to the charged lepton masses is explained by the seesaw mechanism, that requires the existence of Majorana sterile neutrinos and BSM physics at a high mass scale. These heavy sterile neutrinos have small mixing with the three active light neutrinos and cannot generate observable macroscopic neutrino oscillations because of the large mass difference. Their presence may be revealed by a small non-unitarity of the mixing matrix of the three light neutrinos, or by direct production in high-energy accelerator experiments if their mass is not too high. However, it is also possible that there is BSM physics at a low-mass scale, with non-standard fermions that have the right quantum numbers to mix with the three light neutrinos (see the review in Ref. [1]). In this case, the non-standard fermions are sterile neutrinos.

Light sterile neutrinos with masses at or below the eV scale can generate observable macroscopic neutrino oscillations in addition to those of the standard three-neutrino mixing. In particular, eV-scale sterile neutrinos can generate short-baseline oscillations that can be observed in reactor neutrino experiments with a source-detector distance of the order of 10 m and in accelerator neutrino experiments with a source-detector distance of the order of (E/GeV) km, where E is the neutrino energy. These oscillations have been searched in vain by the first generation of reactor and accelerator experiments in the 70's and 80's. However, in the 90's the LSND experiment [2, 3] observed a signal that can be due to short-baseline $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations. More recently, other indications in favor of short-baseline oscillations generated by light sterile neutrinos have been provided by the discoveries of the Gallium neutrino anomaly [4–6] and the reactor antineutrino anomaly [7–9].

An important role in the study of the implications of these anomalies has been played by "global fits", that are phenomenological analyses of all the available experimental data or a fair subset of them in the framework of active-sterile neutrino mixing (see the recent reviews in Refs. [10–12]). For example, the reactor antineutrino anomaly is the result of a global fit of the measurements of many reactor neutrino experiments, taking into account the theoretical predictions. Moreover, in order to be an evidence of the existence of light sterile neutrinos, an indication of short-baseline neutrino oscillations must be compatible with all the other experimental constraints in the framework of a model with active-sterile neutrino mixing. Checking this compatibility is the task of global fits. Another important outcome of global fits is the information on the allowed regions of the parameter space of active-sterile neutrino mixing that must be explored by new experiments in order to test the current indications.

The program of the NuSte group is to continue and improve the global fit studies that we have done in the past (see the review in Ref. [13] and the recent Refs. [14–19]). In particular, we plan to address the following open problems:

- It is well known that global fits of short-baseline neutrino oscillation data interpreted in the framework of active-sterile neutrino mixing suffer of a strong appearance-disappearance tension [13, 14, 16, 20–32]. If future

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experiments will confirm the short-baseline oscillation indications, it will be needed to understand the origin of the appearance-disappearance tension, that could be due to a misinterpretation of some experimental results.

- The measurements of the MiniBooNE experiment [33] carried out at Fermilab from 2002 to 2019 did not clarify the interpretation of the LSND result, adding instead the new problem of explaining a low-energy excess of ν_e-like events that is in tension with the data of other short-baseline neutrino oscillations experiments, as shown by the results of global fits [14, 30]. It is hoped that the interpretation of the LSND and MiniBooNE results will be clarified by the SBN program at Fermilab [34]. Our phenomenological studies will aim at the inspection of the MiniBooNE data analysis in search for a plausible explanation of the low-energy excess [35, 36].

- Several short- and long-baseline reactor neutrino experiments are giving detailed information on the reactor neutrino fluxes, including their spectral shape and their evolution with the fuel composition. This information must be analyzed in global fits in order to understand the implications for the reactor antineutrino anomaly [15, 17].

- It is necessary to analyze the combined implications of the new short-baseline reactor neutrino experiments that measure the neutrino spectrum at different distance from the reactor source (DANSS [37], PROSPECT [38], STEREO [39], Neutrino-4 [40], and SoLid [41]).

- The first observation of coherent neutrino-nucleus scattering (CEνNS) with the COHERENT CsI detector [42] and the recent CEνNS measurement of the COHERENT LAr detector [43] opened the way to precision CEνNS measurement that are expected to constrain or confirm the disappearance of active neutrinos into sterile states through neutral-current interactions. These results may give a crucial contribution to the global fits in the next years.

- Information on active-sterile mixing is provided also by the experiments on the direct measurement of the neutrino mass, as the tritium β-decay experiments Mainz [44], Troitsk [45, 46], KATRIN [47], and, in the future, the holmium electron capture experiments ECHo [48] and Holmes [49]. These experimental data must be taken into account in the global fits [18].

- The existence of sterile neutrinos at the eV mass scale have important implications for neutrinoless double-β decay, that must be discussed in the framework of global fits (see the reviews in Refs. [10, 12, 13]).

- Active-sterile neutrino mixing can generate relevant effects in long-baseline experiments [50–52], that must be calculated from the results of the global fits [53].

- There is a problem of compatibility between cosmological constraints on light sterile neutrinos and the existence of short-baseline neutrino oscillations generated by a light sterile neutrino [54, 55]. There are possible solutions involving non-standard cosmological effects that must be studied in the context of the global fits [56, 57].

- A problem in the analysis of neutrino oscillation data is that the χ^2 test statistic, in spite of its name, does not follow a χ^2 distribution [19, 58]. A correct analysis of the data of each experiment and their combination needs a complicated evaluation of the distribution of the χ^2 that requires a very large computer time. This is a very challenging task for which we will need to develop a smart computing framework.

Outlook. Global fits play a crucial role in the interpretation of the experimental data on the search for light sterile neutrinos. We commit to continue and improve our global fits in the next years. A major difficulty in performing a reliable global fit is the lack of sufficient information for the analysis of the experimental data. Therefore, we encourage the experimental collaborations to publish as much information as possible on their experiments and data analysis, preferably with detailed data releases.

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