LIGHT STERILE NEUTRINOS: OSCILLATIONS AND COSMOLOGY*

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Light sterile neutrinos with a mass around 1 eV have been studied for many years as a possible explanation of the so-called short-baseline neutrino oscillation anomalies. Recently, several neutrino oscillation experiments reported preferences for non-zero values of the mixing angles and squared mass differences for active–sterile mixing which are, however, not always in agreement. I review our current knowledge on the light sterile neutrino in the 3+1 model, starting with a separate discussion on the status of the most relevant searches and then analyzing the problems that arise when combining different probes in a global fit. A short summary on the tension with cosmological observations is also provided.

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1. Introduction

Our current knowledge of the oscillation parameters in the three-neutrino scheme has improved noticeably in the last twenty years, see, *e.g.*, [1]. Yet, several anomalous experimental results remain unexplained. Among these, we find the measurements by LSND [2], plus the gallium [3, 4] and reactor anomalies [5–7]. These anomalies, better discussed in the following sections, might have a common explanation if a new neutrino eigenstate exists. Oscillations between the three standard and the fourth neutrino, driven by a new squared mass difference between the first and the fourth neutrino mass eigenstates $\Delta m^2_{41} = m^2_4 - m^2_1 \simeq 1$ eV^2, were proposed in order to give a common explanation of these anomalies. The new neutrino, which cannot have the Standard Model interactions [8], is denoted as sterile.

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The range at which oscillations between active and sterile neutrinos are dominant is defined by the relation

$$\frac{\Delta m^2_{41} L}{E} \simeq 1\,, \tag{1}$$

where the quantity on the left-hand side enters the neutrino oscillation formulas (see below). For the distances L and neutrino energies E that match the above relation, defining what are called Short BaseLine (SBL) oscillations, the terms due to the solar and atmospheric mass splittings cannot develop, and only the effect of Δm^2_{41} must be considered. At SBL, therefore, one can write the transition probability between a neutrino or antineutrino of flavor α and one of flavor β in the following way (see, *e.g.*, [9]):

$$P^{\rm SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)\,, \qquad (\alpha \neq \beta)\,, \tag{2}$$

$$P^{\rm SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)\,, \tag{3}$$

where the effective angles $\vartheta_{\alpha\alpha}$ and $\vartheta_{\alpha\beta}$ depend on some elements of the fourth column of the (four-by-four) neutrino mixing matrix

$$\sin^2 2\vartheta_{\alpha\beta} = 4\,|U_{\alpha 4}|^2\,|U_{\beta 4}|^2\,, \qquad (\alpha \neq \beta)\,, \tag{4}$$

$$\sin^2 2\vartheta_{\alpha\alpha} = 4\,|U_{\alpha 4}|^2\,\left(1 - |U_{\alpha 4}|^2\right)\,. \tag{5}$$

Since we generally expect the mixing matrix elements $|U_{\alpha 4}|^2$ ($\alpha = e, \mu, \tau$) to be small, in order not to alter excessively the phenomenology of three-neutrino oscillations observed in non-SBL experiments, we expect the *appearance* effective mixing angles $\vartheta_{\alpha\beta}$ ($\alpha \neq \beta$) to be quadratically suppressed with respect to the *disappearance* ones, $\vartheta_{\alpha\alpha}$. As we will discuss in the following, this is the reason for the existence of the so-called appearance–disappearance tension.

2. Disappearance constraints

Let us now discuss more in details the various classes of experiments, starting from disappearance probes.

2.1. Electron (anti)neutrino disappearance

The first anomaly in the electron neutrino disappearance channel has been reported by the GALLEX and SAGE experiments [3], which observed a deficit of electron neutrinos at distances of the order of 1 m from the radioactive source. The anomaly has a statistical significance slightly smaller than 3σ, see also the recent analysis [4].

In 2011, the updated calculations of the electron antineutrino fluxes from nuclear reactors [6, 7] lead to the discovery of a new anomaly, coming from a smaller observed event rate in a number of existing neutrino experiments at reactors [5] with respect to the predicted one. Also in this case, the combination of the various experiments gives a $\sim 3\sigma$ significance.

A common solution of the two anomalies could come from a suppression of the measured flux due to a non-zero effective disappearance angle ϑ_{ee}, but errors in the calculation of the unoscillated fluxes could also be viable explanations. If the theoretical estimates of the reactor antineutrino flux were wrong, for instance, the reactor anomaly would also be wrong. Similar arguments could apply the gallium anomaly.

In order to better investigate if neutrino oscillations could be the possible explanation of these anomalies and to reconstruct the reactor antineutrino flux with more precision, in the recent years several experiments at SBL started to measure the antineutrino flux at different distances from the reactor cores. The obtained fluxes can then be used to compute ratios that, in principle, only depend on neutrino oscillation effects and not on distance-independent systematics related, for example to the normalization or shape of the unoscillated flux: for this reason, the experiments of this class provide *model-independent* results (*i.e.* the theoretical model for the unoscillated flux is nearly irrelevant when computing the fit).

The first experiment to provide results obtained with a ratio method was NEOS [10] in South Korea which, however, has only one fixed detector at $\sim$ 25 m from the reactor core and uses the DayaBay flux observations at much bigger distances (the reactor composition is similar) in order to obtain the ratio. A second experiment of this kind is DANSS [11] in Russia, which instead has a movable detector that can be moved to three different positions, at distances between $\sim$ 10.5 and 12.5 m from the reactor core. From the fluxes at these three positions, two ratios can be computed.

The combined results of NEOS and DANSS, until few months ago, were indicating a preference in favor of the existence of new oscillations described by $\Delta m^2_{41} \simeq 1.3$ eV^2 and $|U_{e4}|^2 \simeq 0.01$ over the standard three-neutrinos case, with a global significance of $\sim 3.5\sigma$ [12] (see also [13]). Considering also the new set of data by the DANSS experiment shown for the first time in the EPS-HEP conference [14], together with NEOS [10], PROSPECT [15] and the previous DANSS [11] observations, the global model-independent preference in favor of the light sterile neutrino decreases to a $\sim 2.5\sigma$ significance and the new best-fit point, nearly degenerate with the one mentioned above, corresponds to $\Delta m^2_{41} \simeq 0.4$ eV^2 and $|U_{e4}|^2 \simeq 0.01$ [16].

Finally, the Neutrino-4 experiment [17] also provided results that indicate a strong preference in favor of a light sterile neutrino, with a mass defined by a large $\Delta m^2_{41} \simeq 7$ eV^2. The best-fit of Neutrino-4, however, is in direct tension with the constraints obtained by PROSPECT [15] with the first 33 days of observations.

2.2. Muon (anti)neutrino disappearance

Considering muon (anti)neutrino disappearance, no anomaly was ever observed. Therefore, current experiments only provide strong upper bounds, mainly on the matrix element $|U_{\mu 4}|^2$.

The bounds come from two classes of experiments: atmospheric neutrino oscillation measurements, mainly driven by the IceCube [18, 19] observations, and probes using accelerator neutrinos, such as in the MINOS+ case [20]. Atmospheric data, thanks to the strong matter effects that influence neutrino oscillations through Earth, can constrain $|U_{\mu 4}|^2$ and to a minor extent also $|U_{\tau 4}|^2$, in particular thanks to the low-energy data by the DeepCore section of the IceCube detector [18]. Bounds on $|U_{\mu 4}|^2$ are, however, approximately one order of magnitude stronger than those on $|U_{\tau 4}|^2$.

MINOS+ data [20], obtained by means of a near ($\sim$ 500 m from the source) and a far ($\sim$ 800 km) detector, currently provide the strongest bounds on $|U_{\mu 4}|^2$ in a wide range of Δm^2_{41} values. Due to the distance between the source and the near detector, MINOS+ can use a far-to-near flux ratio to constrain the neutrino mixing in a model-independent way only for $\Delta m^2_{41} \lesssim 1$ eV^2: for larger mass splittings, there may be active–sterile neutrino oscillations already in the near detector and it is impossible to measure the unoscillated flux. For this reason, in the latest analyses, the MINOS+ Collaboration decided to use a full two-detectors fit instead of a ratio fit. In the high Δm^2_{41} range, the bounds have a significant dependence on cross-section systematics. We have checked that below $\Delta m^2_{41} \lesssim 10$ eV^2, which is the most interesting region given the results of reactor experiments, a far-to-near ratio analysis gives results very similar to those obtained with the full two-detectors fit [16]. The treatment of systematic uncertainties, therefore, does not affect significantly the obtained bound in the range of $1 \lesssim \Delta m^2_{41}/\text{eV}^2 \lesssim 10$. We have also verified that the bounds on $|U_{\mu 4}|^2$ do not vary significantly when the three-neutrino mixing parameters or the other active–sterile mixing angles are varied in the analysis [16].

3. Appearance constraints

The most controversial anomalies in SBL oscillations until now have been obtained by (anti)neutrino appearance experiments, such as LSND [2] and MiniBooNE [21].

The LSND experiment was the first one to report the anomalous appearance of electron antineutrinos in a beam of muon antineutrinos with a significance of $\sim 3.8\sigma$. Such anomaly was not confirmed by the KARMEN experiment, working at slightly smaller distances [22].

In order to test the LSND anomaly, the MiniBooNE experiment was built. MiniBooNE uses neutrinos at higher energies with respect to LSND, but it preserves the same L/E of the anomaly. The most recent MiniBooNE results [21] are in partial agreement with the LSND ones. The preferred best-fit by MiniBooNE, however, corresponds to maximal mixing between active and sterile states, and is in direct tension with the ICARUS [23] and OPERA [24] results. Moreover, even maximal mixing is not really sufficient to fully explain the excess in the two bins at the lowest studied energies. For this reason, a new experiment, MicroBooNE [25], was proposed to check the LSND and MiniBooNE excess, using liquid argon time projection chamber (LArTPC) technology in order to be able to achieve a better level of signal/background separation and, therefore, understand if the anomalous events are really due to neutrino oscillations or to some other kind of new physics. MicroBooNE is also one of the three facilities that will constitute the SBL program at FermiLAB: it will be the intermediate detector of the SBN experiment [26].

4. Global fit

As already anticipated in the introduction, the three effective mixing angles which are mostly relevant for electron (anti)neutrino disappearance (ϑ_{ee}), muon (anti)neutrino disappearance ($\vartheta_{\mu\mu}$) and electron (anti)neutrino appearance ($\vartheta_{e\mu}$) can be written in terms of two elements of the fourth column of the mixing matrix: $|U_{e4}|^2$ and $|U_{\mu4}|^2$. In the ideal case, appearance and disappearance data would indicate a common preferred region for such matrix elements and we would have a single explanation for all the observed anomalies. Unfortunately, this is not the case.

From the model-independent fit of NEOS and DANSS data, we obtain $|U_{e4}|^2 \simeq 10^{-2}$ with a 3σ upper limit of about $|U_{e4}|^2 \lesssim 3 \times 10^{-2}$. From the muon disappearance channel, mainly driven by MINOS+ and IceCube, we have a 3σ upper bound of $|U_{\mu4}|^2 \lesssim 10^{-2}$ on the second entry of the last column of the mixing matrix. Combining these two bounds from disappearance probes, we expect $\sin^2 2\vartheta_{e\mu} \lesssim 10^{-3}$ at 3σ. In order to explain the anomaly observed by LSND and MiniBooNE, on the other hand, we would need a mixing angle $\sin^2 2\vartheta_{e\mu} \gtrsim 10^{-3}$, again at 3σ. Although these are approximate numbers, they are sufficient to see that there is a tension between appearance and disappearance observations.

In order to quantify the tension between the two sets of constraints, the easiest way is to adopt a parameter goodness of fit (PG) test on the best-fit point. The p-value of the PG for the full combination of appearance and disappearance data, taking into account, in particular, the most recent results from MINOS+ and MiniBooNE, is around 10^{-9} [16], certainly too small to be due to random realizations of the same underlying model. We must conclude that nowadays there is no common sterile neutrino solution for the SBL anomalies and some additional explanation is required in order to reconcile appearance and disappearance probes.

Using the PG, we can also test which experiment is mostly responsible for the tension [16] (see also [27]). Since the muon disappearance experiments observe no anomaly, and assuming that the model-independent observations of NEOS and DANSS are not influenced by unaccounted systematics or new physics[1], we considered the effect of removing LSND, MiniBooNE or both of them from the analysis. When the global fit is performed excluding MiniBooNE, which claims to have a preference of 4.8σ in favor of the sterile neutrino presence, the p-value becomes of the order of 10^{-6}: a significant improvement, but not sufficient to claim that the remaining appearance measurements are compatible with disappearance probes. On the other hand, we can remove LSND, which reports a global preference of 3.8σ in favor of the 3+1 neutrinos case, and in this case the p-value becomes approximately 10^{-5}: nearly an order of magnitude larger than in the case without MiniBooNE. These numbers teach us that the preference for the 3+1 model from each experiment alone does not reflect their role in the global fit: LSND has a bigger effect on the global analysis because its best-fit is not as much in tension with other experiments as the MiniBooNE best-fit. It is, therefore, inaccurate to claim that MiniBooNE currently gives the strongest preference in favor of the new neutrino: this is true only if all the other data are ignored.

The last test consists in removing both LSND and MiniBooNE from the global analysis. In this case, there is no anomalous signal in the appearance channel, so that the tension vanishes and the remaining experiments give a consistent fit, where $|U_{\mu4}|^2$ is compatible with zero and $|U_{e4}|^2$ is given by reactor experiments. The fit obtained in this way can be motivated by the possible existence of new physics beyond the light sterile neutrino: if the LSND and MiniBooNE anomalies are not entirely due to active–sterile neutrino oscillations, it is incorrect to include their data in a global fit of the 3+1 mixing parameters. As already mentioned, the MicroBooNE experiment and the SBN program are expected to provide a conclusive result on the subject in the next years.

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[1] Since their constraints are computed using ratio of spectra at different distances, it is unlikely that some problem in the evaluation of the initial flux or some new interactions can produce a distance-dependent effect that simulates neutrino oscillations.

5. Light sterile neutrino and early Universe

In addition to the tensions in neutrino oscillations, another problem arises when a light sterile neutrino is considered. The problem is related to the fact that, if it exists, a light sterile neutrino affects the evolution of the Universe and cosmological observations can be used to put bounds on its properties. In order to obtain these bounds, one has to compute the effects of active–sterile neutrino oscillations in the early Universe and determine if the sterile neutrino can reach equilibrium with the active flavors. The thermalization process must be described in an environment which contains the thermal plasma, composed by muons, electrons, photons and neutrinos. The calculation must take into account the expansion of the Universe, annihilation processes which transfer energy from muons and electrons to the rest of the thermal plasma, energy transfer between neutrinos, and electrons and, of course, neutrino oscillations.

When the various particles are in equilibrium, they have a Fermi–Dirac or Bose–Einstein distribution function, but the crucial point is that the neutrino momentum distribution is not necessarily the equilibrium one, for two reasons. First, the sterile neutrino is not expected to exist in the very early Universe, because it cannot be generated by the electroweak processes that keep the plasma in equilibrium: it must be produced by oscillations once the matter effects become small enough to allow active–sterile neutrino oscillations. This means that the distribution function of the fourth neutrino is initially zero and evolves in a non-trivial way towards its final shape, which can be different from a pure Fermi–Dirac. Second, after most of the neutrinos have decoupled from the thermal plasma, electrons annihilate and transfer energy to the photons and to the few neutrinos still coupled to them, those in the high-momentum tail of the momentum distribution, which is distorted by the energy transfer. In order to compute these effects, one possible approach is to discretise the neutrino distribution function using a grid of momenta, and evolve its value in each point of such a grid independently [28].

In practice, in order to obtain the final momentum distribution function of the various particles in the thermal plasma, one has to solve a differential equation that governs the evolution of the photon temperature plus a set of equations which describe the evolution of the neutrino momentum distribution for the various flavors, as a function of the neutrino momentum [28]. Solving these equations taking into account the preferred mass splitting and mixing angles that emerge from SBL observations, for example the values obtained combining DANSS and NEOS results, one obtains that the additional neutrino reaches a full thermalization before the interactions between neutrinos and electrons become weak enough and the neutrinos decouple from the thermal plasma. In terms of the widely used effective number of relativistic species, $N_{\rm eff}$, all the points within the preferred region at 3σ from the DANSS+NEOS experiments correspond to $N_{\rm eff} \simeq 4$ [28].

Cosmological bounds, however, prefer a much smaller $N_{\rm eff}$. For instance, Big Bang Nucleosynthesis data constrain $N_{\rm eff} \simeq 2.9 \pm 0.2$ [29], while from Cosmic Microwave Background (CMB) observations, one obtains $N_{\rm eff} \lesssim 3.3$ [30]. Going more into details, CMB data are compatible with a sterile-neutrino-like particle with a mass around 1 eV only if its contribution to $N_{\rm eff}$ is very small, or with a somewhat larger $N_{\rm eff}$ only if it comes from nearly massless particles (see, *e.g.* [30, 31]).

If the future reactor neutrino experiments will confirm the current best-fit point, then, some new physics will be required in order to reconcile the presence of the light sterile neutrino in the early Universe with the current observations. Such new physics may be in the form of new interactions (see, *e.g.* [31]), preventing the thermalization of the new neutrino thanks to the presence of additional matter effects, which suppress neutrino oscillations between the active and the sterile states at the relevant times.

6. Prospects and conclusions

In the incoming months, many experiments are expected to publish more results. In particular, apart for the DANSS experiment that is still taking data [14], results are expected from STEREO [32, 33] and PROSPECT [15]. Currently, the limits from STEREO and PROSPECT are not competitive enough to confirm or reject the preferred oscillation parameters by DANSS and NEOS, but they are expected to reach soon the required sensitivity. If within the next few years the different experiment will not converge towards a common best-fit point, the light sterile neutrino explanation of the anomalies will need to be discarded. On the other hand, if many of them will independently observe oscillations involving a new neutrino state, with the same mixing parameters, we will have the cleanest signal ever observed in favor of new physics beyond the Standard Model.

In the same way, the already mentioned MicroBooNE [25] and SBN [26] experiments will soon be able to give a final confirmation or disproval of the sterile neutrino interpretation of the LSND and MiniBooNE results.

A confirmation of the light sterile neutrino from oscillation experiments, moreover, will require some new mechanism in order to reconcile the presence of the new particle in the early Universe with the current observational bounds. All together, these new experiments will, therefore, allow us to understand whether a consistent explanation of the SBL anomalies can exist or not, and, if it may involve a light sterile neutrino, which are the mixing parameters associated to it, shedding light on what stands beyond the Standard Model of particle physics.

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