1 Sterile neutrinos

1.1 Sterile neutrinos in extensions of the Standard Model

Sterile neutrinos—fermions that are uncharged under the $SU(3)\times SU(2)\times U(1)$ gauge group—arise naturally in many extensions of the Standard Model and even where they are not an integral part of a model, they can usually be accomodates easily. A detailed overview of the phenomenology of sterile neutrino and of related model building considerations is given in **[WHITEPAPER]**.

For instance, in Grand Unified Theories (GUTs), fermions are grouped into multiplets of a large gauge group, of which $SU(3) \times SU(2) \times U(1)$ is a subgroup. If these multiplets contain not only the known quarks and leptons, but also additional fermions, these new fermions will, after the breaking of the GUT symmetry, often behave like gauge singlets (see for instance [1–4] for GUT models with sterile neutrinos).

Models attempting to explain the smallness of neutrino masses through a seesaw mechanism generically contain sterile neutrinos. While in the most generic seesaw scenarios, these sterile neutrinos are extremely heavy ($\sim 10^{14}$ GeV) and have very small mixing angles ($\sim 10^{-12}$) with the active neutrinos, slightly non-minimal seesaw models can easily feature sterile neutrinos with eV-scale masses and with per cent level mixing with the active neutrinos. Examples for non-minimal seesaw models with relatively light sterile neutrinos include the split seesaw scenario [5], seesaw models with additional flavor symmetries (see e.g. [6]), models with a Froggatt-Nielsen mechanism [7, 8], and extended seesaw models that augment the mechanism by introducing more than three singlet fermions, as well as additional symmetries [9–11].

Finally, sterile neutrinos arise naturally in "mirror models", in which the existence of an extended "dark sector", with nontrivial dynamics of its own, is postulated. If the dark sector is similar to the visible sector—as is the case, for instance in string-inspired $E_8 \times E_8$ models—it is natural to assume that it also contains neutrinos [12–14].

1.2 Experimental hints for light sterile neutrinos

While the theoretical motivation for the existence of sterile neutrinos is certainly strong, what has mostly prompted the interest of the scientific community in this topic is is the fact that there are several experimental results that show significant deviations from the Standard Model predictions which can be interpreted as hints for oscillations involving sterile neutrinos.

The first of these hints was obtained by the **LSND** collaboration, who carried out a search for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations over a baseline of ~ 30 m [15]. Neutrinos were produced in a stopped pion source in the decay $\pi^+ \to \mu^+ + \nu_\mu$ of pions at rest and the subsequent decay $\mu^+ \to e^+\bar{\nu}_\mu\nu_e$. Electro antineutrinos are detected through the inverse beta decay reaction $\bar{\nu}_e p \to e^+ n$ in a liquid scintillator detector. Backgrounds to this search arise from the decay chain $\pi^- \to \bar{\nu}_\mu + (\mu^- \to \nu_\mu\bar{\nu}_e e^-)$ if negative pions produced in the target decay before they are captured by a nucleus, and from the reaction $\bar{\nu}_\mu p \to \mu^+ n$, which is only allowed for the small fraction of muon antineutrinos produced by pion decay *in flight* rather than stopped pion decay. The LSND collaboration finds an excess of $\bar{\nu}_e$ candidate events above this background with a significance of more than 3σ. When interpreted as $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations through an intermediate sterile state $\bar{\nu}_s$, this result is best explained by sterile neutrinos with an effective mass squared splitting $\Delta m^2 \gtrsim 0.1$ eV^2 relative to the active neutrinos, and with an effective sterile-induced $\bar{\nu}_\mu$–$\bar{\nu}_e$ mixing angle $\sin^2 2\theta_{e\mu,\mathrm{eff}} \gtrsim 2 \times 10^{-3}$, depending on Δm^2.

The **MiniBooNE experiment** [16, 17] was designed to test the neutrino oscillation interpretation of the LSND result using a different technique, namely neutrinos from a horn-focused pion beam. While a MiniBooNE search for $\nu_\mu \to \nu_e$ oscillations indeed disfavors most (but not all) of the parameter region preferred by LSND in the simplest model with only one sterile neutrino [16], the experiment obtains results *consistent* with LSND when running in antineutrino mode and searching for $\bar{\nu}_\mu \to \bar{\nu}_e$. Due to low statistics, however, the antineutrino data favors LSND-like oscillations over the null hypothesis only at the 90% confidence level. Moreover, MiniBooNE observes a yet unexplained 3.0σ excess of ν_e-like events (and, with smaller significance also of $\bar{\nu}_e$ events) at low energies, 200 MeV $\lesssim E_\nu \lesssim$ 475 MeV, outside the energy range where LSND-like oscillations would be expected.

A third hint for the possible existence of sterile neutrinos is provided by the so-called **reactor antineutrino anomaly**. In 2011, Mueller et al. published a new ab initio computation of the expected neutrino fluxes from nuclear reactors [18]. Their results improve upon a 1985 calculation by Schreckenbach [19] by using up-to-date nuclear databases, a careful treatment of systematic uncertainties and various other corrections and improvements that were neglected in the earlier calculation. Mueller et al. find that the predicted antineutrino flux from a nuclear reactor is about 3% higher than previously thought. This result, which was later confirmed by Huber [20], implies that short baseline reactor experiments have observed a 3σ *deficit* of antineutrinos compared to the prediction [21]. **CITE STERILE NEUTRINO WHITEPAPER, SINCE IN THE OLDER PUBLICATION, THE SIGNIFICANCE IS STILL BELOW 3σ.** It needs to be emphasized that the significance of the deficit depends crucially on the systematic uncertainties associated with the theoretical prediction, some of which are difficult to estimate reliably. If the reactor antineutrino deficit is interpreted as $\bar{\nu}_e \to \bar{\nu}_s$ disappearance via oscillation, the required 2-flavor oscillation parameters are $\Delta m^2 \gtrsim$ 1 eV^2 and $\sin^2 2\theta_{ee,\mathrm{eff}} \sim 0.1$.

Such short-baseline oscillations could also explain another experimental result: The **Gallium anomaly**. The GALLEX and SAGE solar neutrino experiments used electron neutrinos from intense artifical radioactive sources to test their radiochemical detection principle [22–26]. Both experiments observed fewer ν_e from the source than expected. The statistical significance of the deficit is above 99% and can be interpreted in terms of short-baseline $\bar{\nu}_e \to \bar{\nu}_s$ disappearance with $\Delta m^2 \gtrsim 1$ eV^2 and $\sin^2 2\theta_{ee,\mathrm{eff}} \sim 0.1$–$0.8$. [27–29].

1.3 Constraints and global fit

While the previous section shows that there is an intriguing accumulation of hints for the existence of new oscillations effects—possibly related to sterile neutrinos—in short-baseline experiments, these hints are not undisputed. Several short-baseline oscillation experiments did *not* confirm the observations from LSND, MiniBooNE, reactor experiments, and Gallium experiments, and place very strong limits on the rel-

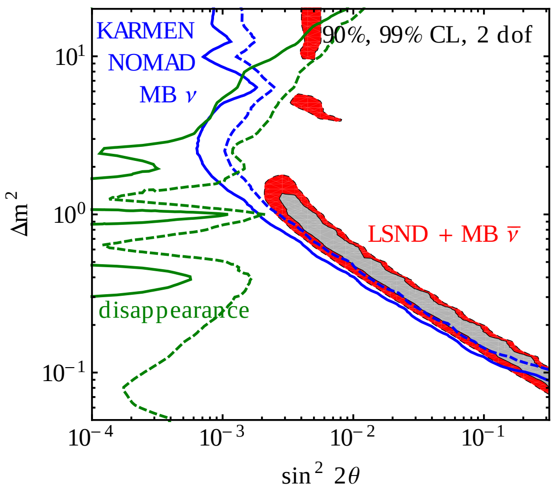

Figure 1: Global constraints on sterile neutrinos in a 3+1 model. We show the allowed regions at 90% and 99% CL from a combined analysis of the LSND [15] and MiniBooNE antineutrino [17] signals (filled regions), as well as the constraints from the null results of KARMEN [35], NOMAD [36] and MiniBooNE neutrino [16] appearance searches (blue contour). The limit from disappearance experiments (green contours) includes data from CDHS [37], atmospheric neutrinos [38], MINOS [39, 40], and from SBL reactor experiments [41–48]. For the latter, we have used the new reactor flux predictions from [18], but we have checked that the results, especially regarding consistency with LSND and MiniBooNE $\bar{\nu}$ data, are qualitatively unchanged when the old reactor fluxes are used. Fits have been carried out in the GLoBES framework [49, 50] using external modules discussed in [51–53].

evant regions of parameter space in sterile neutrino models. To assess the viability of these models it is necessary to carry out a global fit to all relevant experimental data sets, and several groups have endeavored to do so [30–34] **CITE WHITEPAPER**. In figure 1 [30] **WHITEPAPER**, we show the current constraints on the parameter space of a $3+1$ model (a model with three active neutrinos and one sterile neutrino). We have projected the parameter space onto a plane spanned by the mass squared difference Δm^2 between the heavy, mostly sterile mass eigenstate and the light, most active ones and by the effective amplitude $\sin^2 2\theta_{e\mu,\mathrm{eff}}$ for $\nu_\mu \to \nu_e$ 2-flavor oscillations to which LSND and MiniBooNE are sensitive.

We see that there is severe tension in the global data set: The parameter region favored by LSND and MiniBooNE antineutrino data is disfavored at more than 99% confidence level by searches for $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$ disappearance. Using a parameter goodness of fit test [54] to quantity this tension, p-values on the order of few $\times\, 10^{-6}$ are found for the comparibility of LSND and MiniBooNe $\bar{\nu}$ data with the rest of the global data set, and p-values smaller than 10^{-3} are found for the compatibility of appearance data and disappearance data **WHITEPAPER**. The global fit improves somewhat in models with more than one sterile neutrino, but significant tension remains [30] **WHITEPAPER**.

One can imagine several possible resolutions to this puzzle:

1. One or several of the apparent deviations from the standard three neutrino oscillation framework discussed in section 1.2 have explanations not related to sterile neutrinos.

2. One or several of the null results that favor the no-oscillation hypothesis are in error.

3. There are more than two sterile neutrino flavors. Note that already scenarios with one sterile neutrino with an eV scale mass are in some tension with cosmology, even though the existence of one sterile neutrino with a mass well below 1 eV is actually preferred by cosmological fits [55–58]. Cosmological bounds on sterile neutrinos can be avoided in non-standard cosmologies [59] or by invoking mechanisms that suppress sterile neutrino production in the early universe [60, 61].

4. There are sterile neutrinos plus some other kind of new physics at the eV scale. (See for instance [53, 62] for an attempt in this direction.)

We conclude that our understanding of short baseline neutrino oscillations is currently in a rather unsatisfactory state. On the one hand, several experiments indicate deviations from the established three-neutrino framework. However, none of these hints can be considered conclusive, and moreover, when interpreted in the simplest sterile neutrino models, they are in severe tension with existing constraints on the parameter space of these models. An experiment searching for short-baseline neutrino oscillations with good sensitivity and well-controlled systematic uncertainties has great potential to clarify the situation by either finding a new type of neutrino oscillation or by deriving a strong and robust constraint on any such oscillation. While the former outcome would constitute a major discovery, also the latter one would certainly receive a lot of attention since it would provide the world's strongest constraints on a large variety of theoretical models postulating "new physics" in the neutrino sector at the eV scale.

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