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Oscillations Beyond Three-Neutrino Mixing

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Oscillations Beyond Three-Neutrino Mixing

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Abstract. The current status of the phenomenology of short-baseline neutrino oscillations induced by light sterile neutrinos in the framework of 3+1 mixing is reviewed.

The current experimental and theoretical research of the physics of massive neutrinos is based on the standard paradigm of three-neutrino (3ν) mixing which describes the oscillations of neutrino flavors measured in solar, atmospheric and long-baseline experiments [1–3]. In this framework, the three left-handed active neutrino fields ν_{eL} , $\nu_{\mu L}$, $\nu_{\tau L}$ are unitary linear combinations of three left-handed massive neutrino fields ν_{1L} , ν_{2L} , ν_{3L} with respective masses m_1 , m_2 , m_3 :

$$\nu_{\alpha L} = \sum_{k=1}^N U_{\alpha k} \nu_{kL} \quad (\alpha = e, \mu, \tau), \quad (1)$$

for $N = 3$, where U is the 3×3 unitary mixing matrix. There are two independent squared-mass differences: the small solar squared-mass difference

$$\Delta m_{\text{SOL}}^2 = \Delta m_{21}^2 \simeq 7.4 \times 10^{-5} \text{ eV}^2, \quad (2)$$

and the larger atmospheric squared-mass difference

$$\Delta m_{\text{ATM}}^2 = |\Delta m_{31}^2| \simeq |\Delta m_{32}^2| \simeq 2.5 \times 10^{-3} \text{ eV}^2, \quad (3)$$

with $\Delta m_{kj}^2 = m_k^2 - m_j^2$.

Although the standard 3ν framework is very successful at explaining the currently well-established neutrino data, it is interesting to explore non-standard effects in neutrino oscillations, which are expected from the new physics beyond the Standard Model. In this review we consider the current short-baseline neutrino oscillation anomalies and we discuss their explanation in the framework of the 3+1 mixing scheme. There are three short-baseline neutrino oscillation anomalies:

1. The LSND observation of a short-baseline excess of $\bar{\nu}_e$ -induced events in a $\bar{\nu}_\mu$ beam [4, 5].
2. The Gallium neutrino anomaly [6–10], consisting in a short-baseline disappearance of ν_e measured in the Gallium radioactive source experiments GALLEX [11] and SAGE [12].
3. The reactor antineutrino anomaly [13], which is a deficit of the rate of $\bar{\nu}_e$ observed in several short-baseline reactor neutrino experiments in comparison with that expected from the calculation of the reactor neutrino fluxes [14, 15].



A neutrino oscillation explanation of these anomalies requires the existence of at least one additional squared-mass difference

$$\Delta m_{\text{SBL}}^2 \gtrsim 1 \text{ eV}^2, \quad (4)$$

which is much larger than Δm_{ATM}^2 and requires the existence of at least one massive neutrino ν_4 in addition to the three standard massive neutrinos ν_1, ν_2, ν_3 (see the review in Ref. [16]). Since from the LEP measurement of the invisible width of the Z boson we know that there are only three active neutrinos, in the flavor basis the additional massive neutrinos correspond to sterile neutrinos [17], which do not have standard weak interactions.

In the general case of $N > 3$ massive neutrinos, the mixing of the three active neutrino fields which are observable through weak interactions is given by Eq. (1) with $N \geq 4$ and U is a $3 \times N$ rectangular mixing matrix which is obtained by keeping only the first three rows of a unitary $N \times N$ unitary matrix. Moreover, the mixing of the standard active neutrinos with the non-standard massive neutrinos must be very small, in order not to spoil the successful 3ν mixing explanation of solar, atmospheric and long-baseline neutrino oscillation measurements [1–3]:

$$|U_{\alpha k}|^2 \ll 1 \quad (\alpha = e, \mu, \tau; k = 4, \dots, N). \quad (5)$$

In other words, the non-standard massive neutrinos must be mostly sterile.

In this review we consider the so-called 3+1 scheme¹ in which there is a non-standard massive neutrino (mostly sterile) at the eV scale which generates the new squared-mass difference in Eq. (4) and the three standard massive neutrinos are much lighter than the eV scale². Let us emphasize that the 3+1 mixing scheme must be considered as effective, in the sense that the existence of more non-standard massive neutrinos is allowed, as long as their mixing with the three active neutrinos is sufficiently small to be negligible in the analysis of the data of current experiments.

In the case of 3+1 neutrino mixing [18–20, 23], we have $\Delta m_{41}^2 = \Delta m_{\text{SBL}}^2$. The oscillation probabilities of the flavor neutrinos in short-baseline experiments are given by

$$P_{\nu_{\alpha} \rightarrow \nu_{\beta}}^{(-) \quad (-) \text{ (SBL)}} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right) \quad (\alpha \neq \beta), \quad P_{\nu_{\alpha} \rightarrow \nu_{\alpha}}^{(-) \quad (-) \text{ (SBL)}} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right), \quad (6)$$

where L is the source-detector distance and E is the neutrino energy. The oscillation amplitudes depend only on the absolute values of the elements in the fourth column of the mixing matrix:

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \quad (\alpha \neq \beta), \quad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2). \quad (7)$$

Hence, even if there are CP-violating phases in the mixing matrix, CP violation cannot be measured in short-baseline experiments. However, the effects of the non-standard CP-violating phases are observable in the experiments sensitive to the oscillations generated by the smaller squared-mass differences Δm_{ATM}^2 [44–51] and Δm_{SOL}^2 [52]. The dependence on the same elements of the mixing matrix of the different amplitudes of the oscillations in short-baseline appearance and disappearance experiments generates the appearance-disappearance constraint [18, 19]

$$\sin^2 2\vartheta_{\alpha\beta} \simeq \frac{1}{4} \sin^2 2\vartheta_{\alpha\alpha} \sin^2 2\vartheta_{\beta\beta} \quad (\alpha = e, \mu, \tau). \quad (8)$$

¹ The 2+2 mixing schemes which were favorite in the 90's after the results of the LSND experiment [18–21] are excluded by solar and atmospheric neutrino oscillation data [22, 23]. In the literature one can also find studies of the 3+2 [24–32], 3+3 [26, 33], 3+1+1 [34–38], and 1+3+1 [39, 40] schemes.

² We do not consider the 1+3 scheme in which Δm_{SBL}^2 is obtained with a very light (or massless) non-standard neutrinos and the three standard massive neutrinos have almost degenerate masses at the eV scale, because this possibility is strongly disfavored by cosmological measurements [41] and by the experimental bounds on neutrinoless double- β decay if the massive neutrinos are Majorana particles (see Refs. [42, 43]).

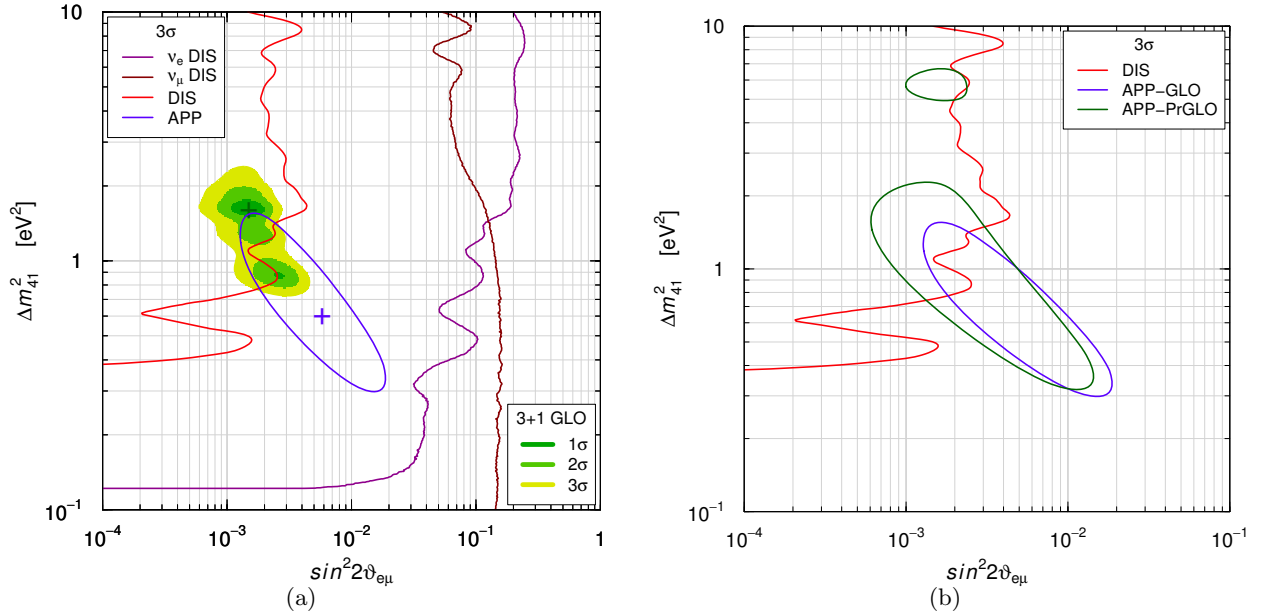


Figure 1. (a) Allowed regions in the $\sin^2 2\vartheta_{e\mu}$ - Δm_{41}^2 plane obtained in the 3+1 global (GLO) fit of short-baseline neutrino oscillation data compared with the 3σ allowed regions obtained from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ short-baseline appearance data (APP) and the 3σ constraints obtained from $\bar{\nu}_e$ short-baseline disappearance data (ν_e DIS), $\bar{\nu}_\mu$ short-baseline disappearance data (ν_μ DIS) and the combined short-baseline disappearance data (DIS). The best-fit points of the GLO and APP fits are indicated by crosses. (b) Comparison of the allowed regions obtained in the global (APP-GLO) and pragmatic (APP-PrGLO) fits of short-baseline appearance data.

The most recent global fits of short-baseline neutrino oscillation data [16, 53, 54] indicate that the most likely values of the 3+1 mixing parameters lie in a region around

$$\Delta m_{41}^2 \approx 1\text{--}2 \text{ eV}^2, \quad |U_{e4}|^2 \approx 0.03, \quad |U_{\mu 4}|^2 \approx 0.01. \quad (9)$$

Figure 1(a) shows the allowed regions in the $\sin^2 2\vartheta_{e\mu}$ - Δm_{41}^2 plane obtained in the 3+1 global (GLO) fit of short-baseline neutrino oscillation data compared with the bounds from the data of disappearance experiments. The best-fit values of the oscillation parameters are $(\Delta m_{41}^2)_{\text{bf}} = 1.6 \text{ eV}^2$, $(|U_{e4}|^2)_{\text{bf}} = 0.028$, $(|U_{\mu 4}|^2)_{\text{bf}} = 0.014$, which imply $(\sin^2 2\vartheta_{e\mu})_{\text{bf}} = 0.0015$, $(\sin^2 2\vartheta_{ee})_{\text{bf}} = 0.11$ and $(\sin^2 2\vartheta_{\mu\mu})_{\text{bf}} = 0.054$.

Figure 2(a) shows the allowed regions in the $\sin^2 2\vartheta_{e\mu}$ - Δm_{41}^2 plane obtained in the 3+1 global fits of Ref. [54]. Comparing figures 1(a) and 2(a) one can see that there is an approximate agreement of the results of the two different global fits. The differences are mainly due to different ways of analyzing old data on which there is limited information. The best-fit values of the oscillation parameters obtained in Ref. [54] are in approximate agreement with those above: $(\Delta m_{41}^2)_{\text{bf}} = 1.75 \text{ eV}^2$, $(|U_{e4}|^2)_{\text{bf}} = 0.027$, $(|U_{\mu 4}|^2)_{\text{bf}} = 0.014$, which imply $(\sin^2 2\vartheta_{e\mu})_{\text{bf}} = 0.0015$, $(\sin^2 2\vartheta_{ee})_{\text{bf}} = 0.11$ and $(\sin^2 2\vartheta_{\mu\mu})_{\text{bf}} = 0.54$.

From Figure 1(a) one can see that the separate 3σ exclusion curves obtained from $\bar{\nu}_e$ and $\bar{\nu}_\mu$ short-baseline disappearance data do not exclude any area of the region that is allowed at 3σ by the analysis of the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ short-baseline appearance data. These bounds are simply obtained taking into account that from the unitarity of the mixing matrix $|U_{\alpha 4}|^2 \leq 1 - |U_{\beta 4}|^2$ for $\alpha \neq \beta$, which implies that $\sin^2 2\vartheta_{\alpha\beta} \leq 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2) = \sin^2 2\vartheta_{\alpha\alpha}$. On the other hand, when the

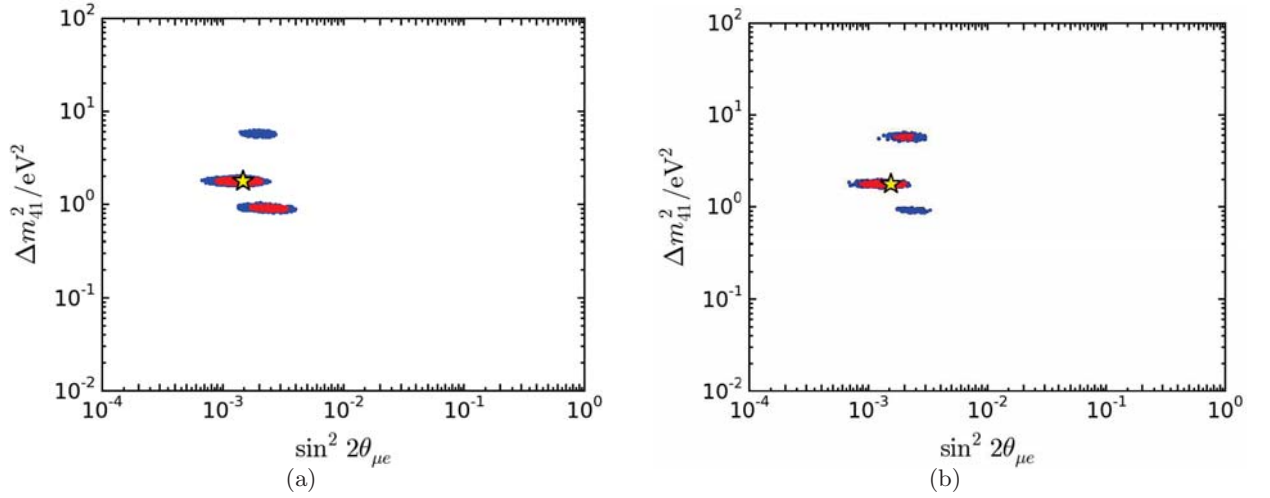


Figure 2. (a) Allowed regions in the $\sin^2 2\vartheta_{e\mu}$ – Δm_{41}^2 plane obtained in the 3+1 global fits of Ref. [54] (a) and Ref. [53] (b). The red and blue regions correspond, respectively to 90% and 99% C.L. The best-fit point is marked by a yellow star.

$\nu_e^{(-)}$ and $\nu_\mu^{(-)}$ bounds are combined through the appearance-disappearance constraint in Eq. (8) the disappearance exclusion curve excludes most of the appearance allowed region. Hence, there is a strong appearance-disappearance tension³ [16, 29, 31, 32, 38–40, 55–58].

The appearance-disappearance tension can be alleviated by excluding from the fit the low-energy bins of the MiniBooNE experiment [59, 60] which have an anomalous excess of ν_e -like events. This is the pragmatic approach (PrGLO) advocated in Ref. [38]. The motivation is that the MiniBooNE low-energy excess requires a small value of Δm_{41}^2 and a large value of $\sin^2 2\vartheta_{e\mu}$ [56, 57], which are excluded by the data of other experiments (see Ref. [38] for further details). This is illustrated in Figure 1(b) where one can see that the region allowed by appearance data shifts towards larger values of Δm_{41}^2 and smaller values of $\sin^2 2\vartheta_{e\mu}$ when the MiniBooNE low-energy bins are omitted from the fit. As a result, the overlap of the appearance and disappearance allowed regions increases, relieving the appearance-disappearance tension. Therefore, it is reasonable to adopt the pragmatic approach, waiting for a clarification of the cause of the MiniBooNE low-energy excess by the MicroBooNE⁴ experiment at Fermilab [61].

Figure 3 shows the allowed regions in the $\sin^2 2\vartheta_{e\mu}$ – Δm_{41}^2 , $\sin^2 2\vartheta_{ee}$ – Δm_{41}^2 and $\sin^2 2\vartheta_{\mu\mu}$ – Δm_{41}^2 planes obtained from an update of the analysis in Ref. [16] with an improved treatment of the MiniBooNE background disappearance due to neutrino oscillations [62]. These regions are relevant, respectively, for $\nu_\mu^{(-)} \rightarrow \nu_e^{(-)}$ appearance, $\nu_e^{(-)}$ disappearance and $\nu_\mu^{(-)}$ disappearance searches. Figure 3 shows also the region allowed by $\nu_\mu^{(-)} \rightarrow \nu_e^{(-)}$ appearance data and the constraints from $\nu_e^{(-)}$ disappearance and $\nu_\mu^{(-)}$ disappearance data. The best-fit values of the oscillation parameters are $(\Delta m_{41}^2)_{\text{bf}} = 1.6 \text{ eV}^2$, $(|U_{e4}|^2)_{\text{bf}} = 0.027$, $(|U_{\mu 4}|^2)_{\text{bf}} = 0.012$, which imply $(\sin^2 2\vartheta_{e\mu})_{\text{bf}} = 0.0013$, $(\sin^2 2\vartheta_{ee})_{\text{bf}} = 0.10$ and $(\sin^2 2\vartheta_{\mu\mu})_{\text{bf}} = 0.050$.

³ This tension is unavoidable in any 3+ N_s scheme with N_s sterile neutrinos [55], because the mixing of ν_e and ν_μ with the sterile neutrinos required by the appearance data implies ν_e and ν_μ disappearances that are larger than the respective experimental bounds.

⁴ In the MiniBooNE mineral-oil Cherenkov detector ν_e -induced events cannot be distinguished from ν_μ -induced events which produce only a visible photon (for example neutral-current π^0 production in which only one of the two decay photons is visible). On the other hand, MicroBooNE is a large Liquid Argon Time Projection Chamber (LArTPC) in which electrons and photons can be distinguished.

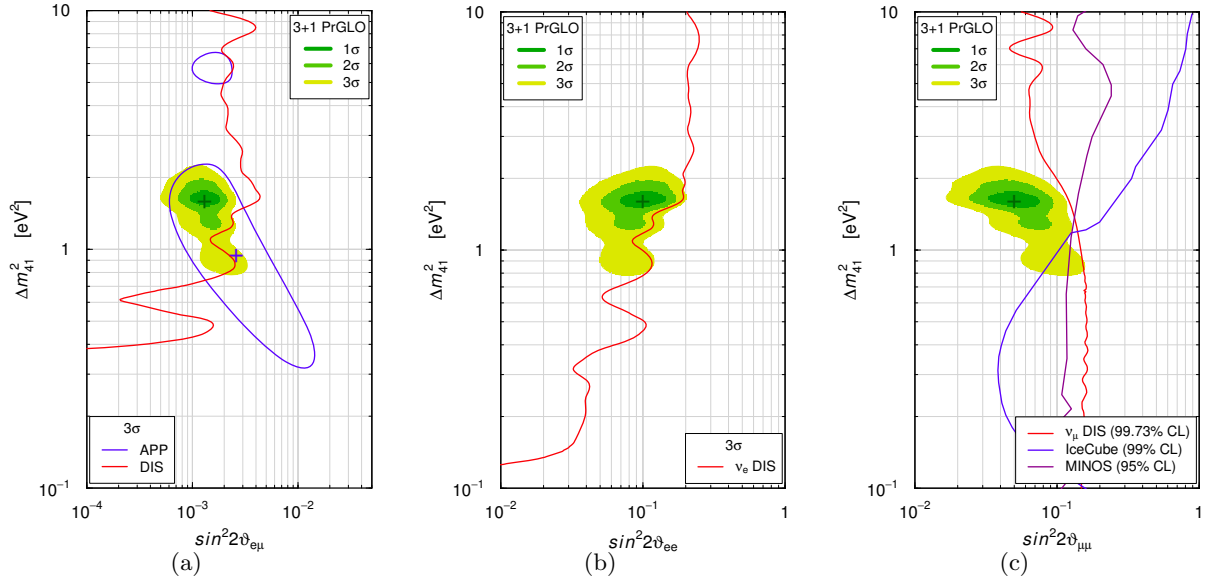


Figure 3. Allowed regions in the $\sin^2 2\vartheta_{e\mu}-\Delta m_{41}^2$ (a), $\sin^2 2\vartheta_{ee}-\Delta m_{41}^2$ (b), and $\sin^2 2\vartheta_{\mu\mu}-\Delta m_{41}^2$ (c) planes obtained in the pragmatic 3+1 global fit PrGLO of short-baseline neutrino oscillation data compared with the 3σ allowed regions obtained from $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$ short-baseline appearance data (APP) and the 3σ constraints obtained from $\bar{\nu}_e$ short-baseline disappearance data (ν_e DIS), $\bar{\nu}_{\mu}$ short-baseline disappearance data (ν_{μ} DIS) and the combined short-baseline disappearance data (DIS). The best-fit points of the global (PrGLO) and APP fits are indicated by crosses.

Figure 3(c) shows a comparison of the allowed regions in the $\sin^2 2\vartheta_{\mu\mu}-\Delta m_{41}^2$ plane with the exclusion curves obtained recently by the IceCube [63] and MINOS [64] experiments. One can see that they disfavor the low- Δm_{41}^2 and high- $\sin^2 2\vartheta_{\mu\mu}$ part of the allowed region. This is confirmed by the results presented in Ref. [53], where the 3+1 global fit of Ref. [54] was updated with the addition of the IceCube data. The resulting allowed regions in the $\sin^2 2\vartheta_{\mu\mu}-\Delta m_{41}^2$ plane are shown in Figure 2(b). Comparing Figures 2(a) and 2(b) one can see that the effect of including the IceCube data in the fit is to disfavor the low- Δm_{41}^2 region. The main allowed region around the best-fit point remains stable and there is a slight improvement of the likelihood of the high- Δm_{41}^2 region.

Because of the scarcity of sensitive data, of the possible existence of unknown systematic errors, and of the appearance-disappearance tension, the possible existence of light sterile neutrinos at the eV scale is controversial and needs new reliable experimental checks. Fortunately, there is an impressive program of new experiments which are planned to check the existence of eV sterile neutrinos (see the reviews in Refs. [16, 65–67]). Figure 4 shows a comparison of the sensitivities of future experiments with the PrGLO allowed regions of Fig. 3 for (a) $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$ transitions (SBN [68], nuPRISM [69], JSNS² [70]), (b) $\bar{\nu}_e$ disappearance (CeSOX [71], BEST [72], IsoDAR@KamLAND [73], IsoDAR@C-ADS [74], DANSS [75], NEOS [76], Neutrino-4 [77], PROSPECT [78], SoLid [79], STEREO [80], KATRIN [81]), and (c) $\bar{\nu}_{\mu}$ disappearance (SBN [68], KPipe [82]).

Moreover, light sterile neutrinos have important effects that could be observed in β decay experiments [83–87], in neutrinoless double- β decay experiments [10, 88–96], in solar neutrino experiments [10, 40, 52, 97–100], in long-baseline neutrino oscillation experiments [44–50, 101, 102], in atmospheric neutrino experiments [103–111], in supernova neutrino experiments [112–115], in

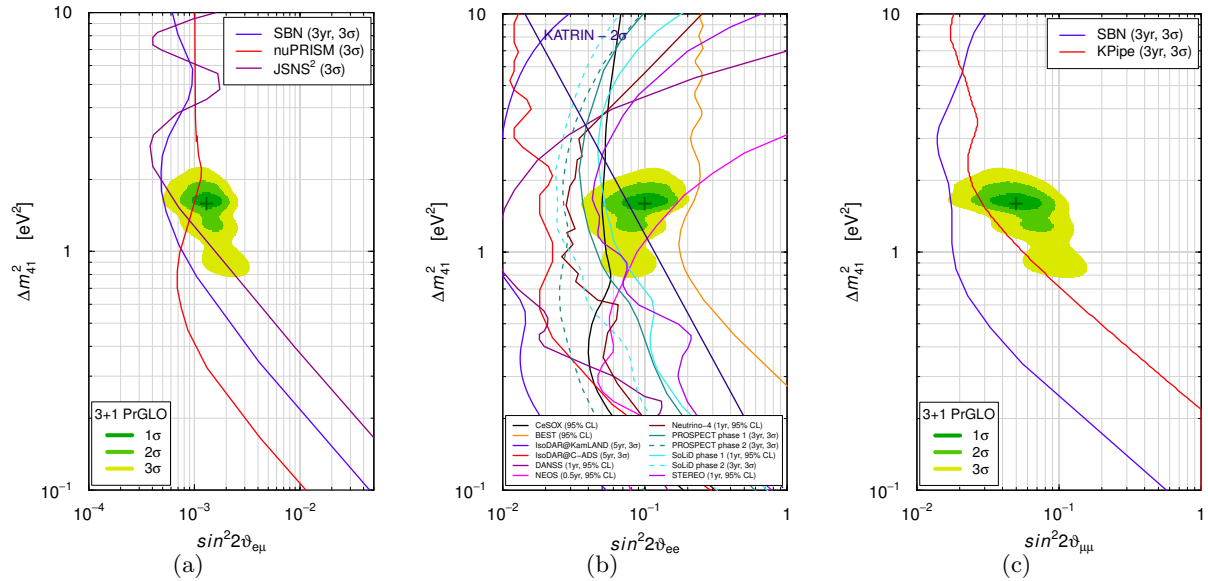


Figure 4. Sensitivities of future experiments compared with the PrGLO allowed regions of Fig. 3.

indirect dark matter detection [116]), in high-energy cosmic neutrinos experiments [117], and in cosmology (see Refs. [16, 118, 119]).

Let us finally emphasize that the discovery of the existence of sterile neutrinos would be a major discovery which would have a profound impact not only on neutrino physics, but on our whole view of fundamental physics, because sterile neutrinos are elementary particles beyond the Standard Model. The existence of light sterile neutrinos would prove that there is new physics beyond the Standard Model at low-energies and their properties can give important information on this new physics (see Refs. [120, 121]).

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