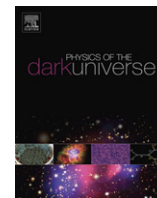


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Light sterile neutrinos in particle physics: Experimental status



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ABSTRACT

Most of the neutrino oscillation results can be explained by the three-neutrino paradigm. However several anomalies in short baseline oscillation data, corresponding to an L/E of about 1 m/MeV, could be interpreted by invoking a hypothetical fourth neutrino. This new state would be separated from the three standard neutrinos by a squared mass difference $\Delta m_{new}^2 \sim 0.1\text{--}1\text{ eV}^2$ and would have mixing angles of $\sin^2 2\theta_{ee} \gtrsim 0.01$ and $\sin^2 2\theta_{\mu e} \gtrsim 0.001$, in the electron disappearance and appearance channels, respectively. This new neutrino, often called sterile, would not feel standard model interactions but mix with the others. Such a scenario calling for new physics beyond the standard model has to be either ruled out or confirmed with new data. After a brief review of the anomalous oscillation results we discuss the forthcoming laboratory experiments aiming to clarify the situation.

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1. Introduction

The well established standard neutrino oscillation framework satisfactorily explains most of neutrino data. It relies on three flavors (ν_e , ν_μ , ν_τ), mixture of three mass states (ν_1 , ν_2 , ν_3) separated by squared mass differences of $\Delta m_{21}^2 = \Delta m_{sol}^2 = 7.50_{-0.20}^{+0.19} \times 10^{-5}\text{ eV}^2$ and $|\Delta m_{31}^2| \approx |\Delta m_{32}^2| = \Delta m_{atm}^2 = 2.32_{-0.08}^{+0.12} \times 10^{-3}\text{ eV}^2$ [1], where “sol” and “atm” stand historically for solar and atmospheric experiments providing compelling evidence for neutrino oscillation (see [2] and references therein for a recent review). Beyond this minimal extension of the standard model, anomalous results have been reported in LSND [3], MiniBooNE [4,5], and radioactive source experiments [6–9]. In addition a new evaluation of the reactor neutrino fluxes [10,11] led to a reinterpretation of the results of short baseline reactor experiments [12], the so-called Reactor Antineutrino Anomaly.

If not related to non understood experimental issues, results of the global fit of short-baseline neutrino oscillation experiments (see [13] for instance) show that the data can be explained by the addition of one or two sterile neutrinos to the three active neutrinos of the standard model, the so-called (3 + 1) and (3 + 2) scenarios, respectively. However some tension remains between appearance and disappearance data in the global fits, see [14].

It is worth noting that sterile neutrinos would affect the oscillation probabilities of the active flavors and therefore could influence cosmological processes [15]. These aspects will not be further discussed in this experimental review focusing on terrestrial experiments, but more details can be found in [16].

2. Anomalous oscillation results and sterile neutrinos

In this section we focus on neutrino oscillation results with an L/E of about 1 m/MeV. A comprehensive review of all short baseline oscillation results and detailed statements on the current oscillation anomalies can be found in [17].

In 1995 the LSND experiment reported an excess in the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance channel [3]. A similar experiment, KARMEN [18], did not report such an excess, however. In 2002 the MiniBooNE experiment confirmed this excess in both ν_e to ν_μ and $\bar{\nu}_e$ to $\bar{\nu}_\mu$ channels [4,5]. The MiniBooNE results will be soon complemented by using a 170-ton LAr TPC in the same neutrino beam; the MicroBooNE experiment [19] will check if the low-energy excess is due to ν_e charged current quasielastic events. Event rates measured by many reactor experiments at short distances, when compared with a newly evaluated antineutrino flux, are indicating the disappearance of $\bar{\nu}_e$ [12]. In addition the results from the gallium solar neutrino calibration experiments reported also a deficit of ν_e in a similar L/E range [7–9].

The individual significances of these anomalies lie between 2.5 to 3.8 σ , and these results, not fitting the three-neutrino-flavor framework, are difficult to explain by systematics effects. If not experimental artifacts it is puzzling that each of them could be

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explained by oscillation to sterile neutrinos with a large mass squared difference, $\Delta m_{\text{new}}^2 \gtrsim 0.1 \text{ eV}^2$, corresponding to an L/E of about 1 m/MeV.

Indeed the minimal neutrino mixing scheme provides only two squared-mass differences. A third one would be required for new short-baseline neutrino oscillations. It then requires the introduction of a sterile neutrino ν_s [20–23]. The minimal model consists of a hierarchical $3 + 1$ neutrino mixing, acting as a perturbation of the standard three-neutrino mixing in which the three active neutrinos ν_e, ν_μ, ν_τ are mainly composed of three massive neutrinos ν_1, ν_2, ν_3 with light masses m_1, m_2, m_3 . The sterile neutrino would mainly be composed of a heavy neutrino ν_4 with mass m_4 such that $\Delta m_{\text{new}}^2 = \Delta m_{41}^2$, and $m_1, m_2, m_3 \ll m_4$.

In $3 + 1$ neutrino mixing, the effective flavor transition and survival probabilities in short-baseline neutrino oscillation experiments are given by

$$P_{\nu_\alpha \rightarrow \nu_\beta}^{(\text{--})} = \sin^2 2\theta_{\alpha\beta} \Delta_{41} \quad (\alpha \neq \beta), \quad (1)$$

$$P_{\nu_\alpha \rightarrow \nu_\alpha}^{(\text{--})} = 1 - \sin^2 2\theta_{\alpha\alpha} \Delta_{41}$$

where $\Delta_{41} = \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$, and for $\alpha, \beta = e, \mu, \tau, s$, with the transition amplitudes

$$\sin^2 2\theta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2, \quad (2)$$

$$\sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2).$$

The interpretation of both LSND and MiniBooNE anomalies in terms of light sterile neutrino oscillations requires mixing of the sterile neutrino with both electron and muon neutrinos. In addition, both OPERA and ICARUS experiments recently reported negative results for the search ν_e from the ν_μ CNGS beam [24,25], although not testing fully the relevant space of oscillation parameters. Therefore when considering all data together no satisfactory global fit can be obtained (see [14] for instance). This is mainly due to the non-observation of ν_μ disappearance at the eV-scale [26], that is a generic prediction if the LSND signal implies a sterile neutrino. This negative results is not strong enough to rule out this hypothesis, however.

All these facts motivate the experimental program being briefly summarized in this review. In what follows, we focus on the 3 active $+1$ sterile neutrino mixing scheme with Δm_{new}^2 of the order of $0.1\text{--}1 \text{ eV}^2$.

3. Clarification of the anomalies: experimental program

To definitively test the short baseline oscillation hypothesis the new experiments must be sensitive to an oscillation pattern either in the energy spectrum, or in the spatial distribution of the neutrino interactions, or both. To cover the Δm^2 region of $0.1\text{--}1 \text{ eV}^2$ with MeV/GeV neutrinos the distance between the emitter and the detector has to be on the scale of $1\text{--}10 \text{ m}/1\text{--}10 \text{ km}$, respectively. Statistical and systematics uncertainties must be at the level of a few percents or less. Such an experiment could be performed close to nuclear reactors, with intense radioactive sources used as neutrino emitters, or with accelerator based experiments. We review below the various projects that have been proposed to clarify the neutrino anomalies, leaving out R&D efforts.

3.1. Reactor-based proposals

Nuclear reactors are very intense sources of $1\text{--}10 \text{ MeV}$ electron antineutrinos. In the 1980s their expected fluxes were obtained with a precision of 5% through the measurement of the integral

β -spectra of uranium and plutonium isotopes irradiated into a reactor core, followed by their phenomenological conversion into $\bar{\nu}_e$ spectra [27,28]. But in 2011 this prediction was corrected leading to an increase of the emitted flux by about 4%, with a similar precision [10,11]. The revised comparison of the latest with the measured rate of interactions in detectors located at 100 m or less from the cores revealed the Reactor Antineutrino Anomaly [12]. It is worth noting that there remains some lack of knowledge of the reactor neutrino fluxes. It has been recently pointed out that the detailed treatment of forbidden transitions in the computation of reactor neutrino spectra may lead to an increase of the systematic uncertainty by a few percents [29]. Moreover, while writing this article a new deviation with respect to the expected reactor neutrino spectral shape predictions [27,28,10,11] has been announced by the RENO and Double Chooz collaborations at the Neutrino 2014 conference [30–32], and confirmed later by the Daya Bay collaboration at the ICHEP 2014 conference [33]. This deviation in the prompt signal energy spectrum is being observed between about 4 to 7 MeV (visible energy) with a significance of more than 3 standard deviations. The origin of this structure is still unknown. Therefore further investigations of reactor neutrino spectra as well as more precise data are needed.

New reactor experiments searching for short baseline oscillation, with $L/E \sim 1 \text{ m/MeV}$, should first look for an oscillation pattern imprinted in the energy distribution of events. Of course the analysis must be complemented by an integral rate measurement. According to global fits the relevant range of oscillation lengths, $L_{\text{osc}} \sim 2.5E/\Delta m_{\text{new}}^2$ is between 1 and 10 m. Therefore short baselines, a few ten's of meters, are mandatory and compact reactor cores, with typical dimensions of 1 m, are preferable in comparison with larger commercial reactors to prevent washing out the hypothetical oscillation pattern at the L/E's of interest. Experimentally the detection technique of most experiments in preparation relies on the inverse β -decay (IBD) reaction, $\bar{\nu}_e + p \rightarrow e^+ + n$, where the positron carries out the $\bar{\nu}_e$ energy while the neutron tagging provides a discriminant signature against backgrounds. Indeed an accidental pair from γ -ray radioactivity contaminants or induced by the reactor core, followed by a neutron capture or a high energy γ from the core could easily mimic the signal. This background can partially be suppressed through passive shielding while the remaining contribution can be measured in-situ at the analysis stage, leading to an increase of the uncertainty due to statistical fluctuations of the background rate, however. Correlated backgrounds induced by cosmic rays can also alter the signal. By definition a single correlated event can mimic the IBD process. All current projects are foreseen at shallow depths or even at the surface, the latter case being extremely challenging and not yet experimentally demonstrated at the desired precision. More problematic could be the possible correlated backgrounds induced by the reactor core itself. It must be suppressed through passive shielding, depending strongly on the site configuration and on the type of reactor core. This background superimposes on the top of the signal and it cannot be measured in situ, unfortunately. It is therefore mandatory to optimize the experimental setup through simulation to minimize it, while taking large safety margins due to the difficulty of assessing the remaining contribution in the fiducial volume. Table 1 provides a list of current projects being carried out at reactors. The Nucifer experiment [34] is currently taking data close to the Osiris nuclear reactor in Saclay. Though not optimized for a sterile neutrino search it could provide first new constraints by 2015. The Stereo experiment [17] will be constructed next to the ILL reactor in Grenoble in 2014 and aims taking data middle of 2015. The DANSS [35] and Neutrino4 [36] experiments are under construction in Russia and should provide first data in 2015. Finally a comprehensive project for searching sterile neutrinos at reactor in US is currently in its R&D phase [37]; depending on its

Table 1
Main features of proposed reactor experiments.

Projects	Ref.	P_{th} (MW)	M_{target} (tons)	L (m)	Depth (m.w.e.)
Nucifer	[34]	70	0.75	7	13
Stereo	[17]	50	1.75	[8.8–11.2]	18
Neutrino 4	[36]	100	2.2	[6–12]	Few
DANSS	[35]	3	0.9	[9.7–12.2]	50
Solid	[38]	[45–80]	3	[6–8]	10
Hanaro		30	0.5	6	Few
US project	[37]	20–120	1 & 10	4 & 18	Few
CARR	[39]	60	–	7 & 15	Few

approval schedule it could provide first results by 2016. All these experiments are designed to test the space of parameters deduced from the interpretation of reactor antineutrino anomaly through the existence of light sterile neutrinos.

3.2. Neutrino generator proposals

In the experiments performed to calibrate the radiochemical solar neutrino detectors SAGE and GALLEX the number of measured capture events for neutrinos from artificial sources of ^{51}Cr and ^{37}Ar are below the expectations, the average ratio of the measured-to-expected capture-rate being 0.87 ± 0.05 [5]. New experiments have been proposed to clarify this anomaly, using a very intense ^{51}Cr neutrino generator at Baksan (3 MCi) or next to the Borexino detector (10 MCi). On the other hand an experiment using 100 kCi of ^{144}Ce – ^{144}Pr could be used next to a large liquid scintillator detector, such as Borexino or KamLAND, to directly test the reactor antineutrino anomaly.

Those projects aims to search for an energy-dependent oscillating pattern in event spatial distribution of active neutrino interactions that would unambiguously determine neutrino mass differences and mixing angles if oscillation to light sterile neutrinos is the explanation of the gallium and/or reactor neutrino anomalies. We review below these proposals.

3.2.1. ^{51}Cr -based neutrino generator

A neutrino source uses the electron capture process to produce monoenergetic neutrinos. Several neutrino sources have already been produced to calibrate radiochemical solar neutrino experiments. Two nuclei are usually considered: ^{51}Cr and ^{37}Ar . The ^{51}Cr decays with a 27.7 day half-life, producing mainly 753 keV neutrinos, and in 10% of decays 433 keV neutrinos with a 320 keV gamma, while the ^{37}Ar produces 814 keV neutrinos in any case with a 35 day half-life. The ^{37}Ar is therefore more suitable from the point of view of heat and shielding issues, and benefits also of slightly longer half-life and slightly higher energy. Still chromium is much easier to handle. Both isotopes have to be produced by neutron irradiation in a nuclear reactor, through $^{50}\text{Cr}(n, \gamma)^{51}\text{Cr}$ process and $^{40}\text{Na}(n, \alpha)^{37}\text{Ar}$ process respectively. Moreover, the (n, α) reaction has a threshold requiring irradiation with fast neutron.

The main drawback of neutrino source relies in the detection process, elastic scattering off electrons. The cross section of this process is low and the detection is very sensitive to backgrounds. Currently only Borexino, design to study solar neutrinos, has shown a low enough background control. The unique extreme radiopurity achieved in the liquid scintillator medium allows to control the irreducible contribution of ^7Be solar neutrinos. The experiment will consist in counting the number of observed events at each detector location and to compare it to the expectation without oscillations. The position of each event can be reconstructed with a precision of ~ 12 cm at 1 MeV, which is enough for the range of Δm^2 of interest and smaller than the size of the source, a few tens of centimeters. The SOX experiment [41] will perform such a measurement with a 10 MCi ^{51}C source irradiated either in Russia (PA

Mayak) or in US, and deployed at 8.25 m from the center of the Borexino detector in 2016/17.

At Baksan another technique is being pursued. Based on the technology developed for the SAGE solar neutrinos experiment a ^{51}Cr source could be placed at the center of a target, containing 50 ton of liquid metallic gallium divided into two areas, an inner 8-ton zone and an outer 42-ton zone. The ratio of the two measured capture rate to its expectation could sign an oscillation, although not as precisely as for the oscillometry performed in a liquid scintillator detector. This is a well-proven technique free of backgrounds, however. Furthermore it would necessitate a lower activity, 3 MCi, more easy to achieve from standard irradiation in research reactors and logistic issues would be easier to organize since both the source and the detector would remain in Russia.

3.2.2. ^{144}Ce – ^{144}Pr -based antineutrino generator

An antineutrino source uses the β^- decay process to produce a non monoenergetic neutrino spectrum. Antineutrinos allow the use of Inverse Beta Decay (IBD) as detection process: $\bar{\nu}_e + p \rightarrow e^+ + n$. At a few MeV's it has the advantage of a higher cross-section with respect to neutrino scattering off electrons, by roughly one order of magnitude. Furthermore the time and space coincidence between positron and neutron allow a very effective tagging of the process, leading to much easier background rejection.

The main drawback is the 1.8 MeV energy threshold requiring a high Q-value β^- decay. Since the period and the Q-value are strongly anticorrelated for β^- decay, this requirement leads to nuclei with a period shorter than the day, preventing the effective production and use of an antineutrino source based on a single isotope. The solution relies on the use of a cascade of two β^- decays, the father having a long period (month or year scale) and the daughter having a Q-value above the IBD threshold, as high as possible to maximize the event rate. Several pairs of isotope have been identified but we will focus on the best option.

The CeLAND and CeSOX experiments plan to use 100 kCi of ^{144}Ce in KamLAND [42,43] and Borexino [42,44]. Cerium was chosen because of its high Q_β , its $\sim 4\%$ abundance in fission products of uranium and plutonium, and finally for engineering considerations related to its possible extraction of rare earth from regularly spent nuclear fuel reprocessing followed by a customized column chromatography. While not minimizing the difficulty of doing this, the nuclear industry does have the technology to produce sources of the appropriate intensity, at a high purity level. The goal is to deploy the ^{144}Ce radioisotope about 10 m away from the detector center and to search for an oscillating pattern in both event spatial and energy distributions that would determine neutrino mass differences and mixing angles through an unambiguously. Thanks to available pressing techniques the source fits inside a < 15 cm-scale capsule, small enough to consider the Cerium volume as a point-like source. For comparison the vertex reconstruction is < 15 cm. ^{144}Ce has a low production rate of high-energy γ rays (> 1 MeV) from which the $\bar{\nu}_e$ detector must be shielded to limit background events. Backgrounds are of two types, those induced by the environment or detector, and those due to the source (attenuated by a 20 cm tungsten shielding). Eventually backgrounds are expected to be negligible thanks to the strong IBD signature.

The logistic for transporting the source from the production site, PA Mayak in Russia, to the detector site is a major issue for such an experiment due to the necessary time required to certify the transport containers. This is a drawback for deploying quickly a 100 kCi ^{144}Ce source in KamLAND. Since transportation to Italy is easier the CeSOX experiment could take data as early as end of 2015.

3.2.3. Tritium-based experiments

A new neutrino ν_4 heavier than the three active neutrinos should leave an imprint in the β -spectrum of experiments

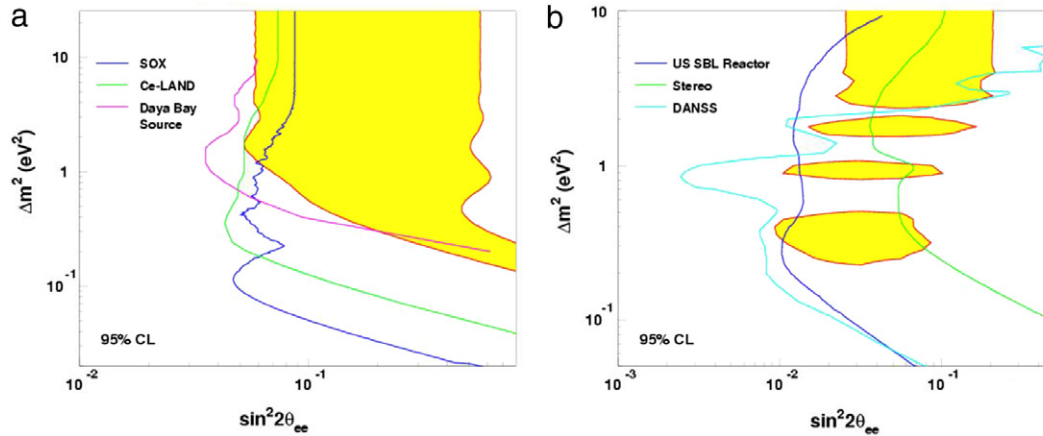


Fig. 1. Projected sensitivity curves for proposed neutrino generator and reactor experiments plotted against the global fits for the gallium anomaly and reactor anomaly respectively, based on the compilation of [40].

measuring the absolute masses of active neutrinos, such as the forthcoming KATRIN experiment [45]. The detectors aim at measuring precisely the high energy tail of the tritium β -decay spectrum by combining an intense molecular tritium source with an integrating high-resolution spectrometer. The projected sensitivity of the experiment on the effective electron neutrino mass is 200 meV at 90% C.L. The detection principle is to search for a distortion at the high energy endpoint of the electron spectrum of tritium β -decay, since its shape is a priori very precisely understood. Any shape distortion due to decays involving a heavier neutrino could sign the existence of a sterile neutrino state. As designed the KATRIN experiment can probe part of the current allowed region of the reactor antineutrino anomaly, especially for $\Delta m_{\text{new}}^2 > 1 \text{ eV}^2$, with 3 years of data-taking [46,47]. First results are expected in 2016.

3.3. New accelerator-based proposals

Over the last years a large experimental program is being prepared to search for sterile neutrinos using neutrino beams at CERN or Fermilab, or the spallation neutron source at Oak Ridge. We briefly review the various projects, sorting them by the processes creating the neutrinos.

3.3.1. Isotope decay at rest

A huge statistics of $\bar{\nu}_e$ from the β -decay of ^8He could be obtained through the development of a high-power cyclotron with low energy. The IsoDAR project [48] proposes to place such a device underground in the Kamioka mine to search for an oscillation pattern in the KamLAND 13-m diameter detector. This would be a disappearance experiment directly testing both the reactor and the gallium anomalies starting from a well known $\bar{\nu}_e$ spectrum. In case of positive results it would have the ability to disentangle different oscillation models, potentially involving more than one sterile neutrino.

3.3.2. Pion and Kaon decay at rest

For 20 years the puzzling LSND results carried out at LAMPF was never directly tested. This could reliably be achieved by locating a detector upstream to a spallation neutron source beam dump. This kind of facility has the advantage to produce a well-understood source of electron and muon neutrinos from π^+ and μ^+ decays-at-rest. The OscSNS project [49] proposes to locate a 800 ton gadolinium-doped scintillator detector 60 m away from the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory. The main channel would be the search of the appearance of $\bar{\nu}_e$, taking advantage of the low duty factor of SNS to reduce cosmic induced backgrounds.

3.3.3. Pion decay in flight

To reliably test the LSND and Miniboone anomalies using pion decay in flight neutrinos one would need a setup with two identical detectors located at different baselines. The ICARUS/NESSIE project [50] proposes to relocate the 600 tons ICARUS LAr TPC at 1600 m away from a new neutrino beam line at CERN, extracted from the SPS. The near detector would consist of new LAr TPC of 150 tons, to be built at 300 m away from the target. This experiment could address both ν_e and $\bar{\nu}_e$ appearance and disappearance channels. It could be complemented by two muon spectrometers behind each TPC to enhance the ability to constrain ν_μ disappearance, a signal expected if the LSND/MiniBooNE anomalies are due to oscillation into sterile neutrino. A similar multi-baseline project is being proposed at Fermilab in the Booster Neutrino Beam line. The LAr1 project [51] aims to build two LAr TPC, a 40 ton and a 1 kton detector at 100 m and a 1 km for the target, respectively. We note that those two projects could be merged in a single experiment, by installing the ICARUS T600 LAr TPC at Fermilab [52].

3.3.4. Low energy neutrino factory

Ultimately precision physics of sterile neutrinos could be done by using a clean and well-understood beam of ν_e and $\bar{\nu}_\mu$ produced by the decay of muons stored into a long storage ring with two straight arms pointing to two similar detectors. Furthermore this facility could prototype a future neutrino factory. As a matter of fact such a neutrino beam could probe precisely both appearance and disappearance processes, the golden channel being the search for ν_μ appearance from a muon free electron neutrino beam, that is impossible with in meson decay-in-flight beams. The nuSTORM project, based on existing technologies, has been proposed both at CERN [53] and Fermilab [54]. Two magnetized iron detectors could be deployed at two different baselines to study the golden channel without polluted by wrong sign muons from the beam.

4. Summary and conclusion

The significance of each short baseline oscillation anomaly is moderate, but the concordance of their possible explanation with non-standard neutrino oscillation cannot be neglected and calls for new data. The projected sensitivity of the experimental proposal discussed in this review is shown in Fig. 1 for the reactor and neutrino generator proposals, and in Fig. 2 for the accelerator based projects. Data used for these plots have been compiled by the authors of [40] from the collaborations, as well as from the comprehensive light sterile neutrino white paper [17]. From these

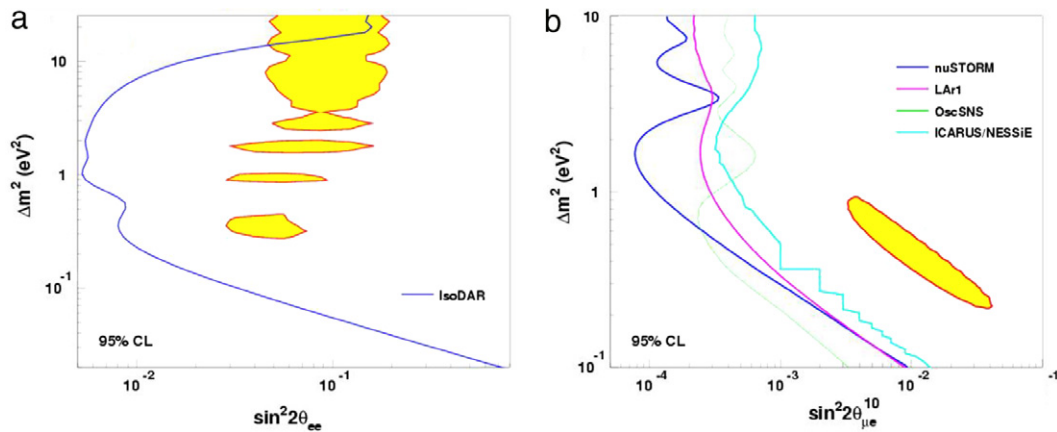


Fig. 2. Projected sensitivity curves for proposed accelerator-based experiments, plotted against the global fits [40].

summary plots we see that there is a broad range of sensitivities addressed by the various proposals in the appearance and disappearance oscillation channels. It is likely that reactor and neutrino generator based experiments will provide first results since they require less funding and resources. The proposed experiments have the potential to test neutrino oscillation transitions with mass-squared difference $\Delta m^2 > 0.1 \text{ eV}^2$ and mixing angle such that $\sin^2 2\theta_{ee} > 0.05$ (see in Fig. 1). However if sterile neutrino oscillations would be confirmed by these first data, then it would be mandatory to study this new physics with a vast accelerator-based experimental program, leading to more precise results and accessing to all possible appearance channels, as can be seen in Fig. 2. It is worth noting that the observation of neutrino oscillations in at least two independent detectors employing different physics channels, detection methods, and neutrino targets would be a necessary indication to sign the existence of sterile neutrinos. First results on the clarification of the short baseline neutrino oscillation anomalies might come as early as 2015. The situation should be definitively clarified by 2020, with potential surprises that could lead to major breakthroughs in particle physics, astrophysics, and cosmology.

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