Letter of Interest: Neutrino Physics with IsoDAR

NF Topical Groups: (check all that apply ☐/■)
■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
☐ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
■ (NF7) Applications
■ (TF11) Theory of neutrino physics
■ (NF9) Artificial neutrino sources
☐ (NF10) Neutrino detectors
☐ (Other) *[Please specify frontier/topical group(s)]*

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A well-known and long history of anomalies reported in short baseline (SBL) neutrino experiments may be indicative of at least one new type of neutrino [1–3]. By placing a novel, high power cyclotron[1] close to a kiloton-scale scintillator-based detector, the IsoDAR experiment will probe the anomalous experimental results with unmatched sensitivity to possible neutrino oscillations near $\Delta m^2 \sim 1$ eV^2 [4]. No other proposed technology permits the reconstruction of the $\bar{\nu}_e$ disappearance oscillation wave at the level of IsoDAR, as illustrated in Fig. 1 (for the case of IsoDAR@KamLAND), which has the potential to reveal the underlying physics associated with the anomalies.

The simplest explanation of the existing anomalies introduces one additional light-mass and "sterile" (*i.e.* non-interacting) neutrino flavor state. A model with three active and one sterile flavor, called "3+1", connects results between disappearance and appearance oscillation data through a common mixing matrix. In a 3+1 model, for vacuum oscillations observed through charged-current scattering, two matrix elements, $|U_{e4}|^2$ and $|U_{\mu 4}|^2$, connect to three mixing angles that characterize the amplitude of ν_e disappearance, ν_μ disappearance, and $\nu_\mu \to \nu_e$ appearance:

$$\sin^2 2\theta_{ee} = 4(1 - |U_{e4}|^2)|U_{e4}|^2; \quad \sin^2 2\theta_{\mu\mu} = 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2; \quad \sin^2 2\theta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2. \tag{1}$$

Thus, the mixing angles measured in the three types of searches, as well as the squared mass splitting, Δm^2, are not independent. An allowed signature in IsoDAR for a 3+1 model from our group's global fit to the world's SBL data [5] is shown in Fig. 1, left. As can be seen, the high statistics and wide energy range lead to the possibility of a striking oscillatory signature.

Unfortunately, as the number of reported SBL-related anomalies grows (see, e.g., Refs. [6, 7]), so does tension with disappearance limits within 3+1 global fits, especially muon neutrino disappearance results. Numerous potentially sensitive experiments have published highly-constraining null results [5] and, in general, there are serious complications with obtaining a strong global fit to the complete set of oscillation measurements. There are cases of observed behavior where the parameters do not agree, and there are experiments that exhibit unexpected features in the data, beyond that which is expected from a signal consistent with oscillations. Further, limits set by a wide range of experiments restrict the allowed parameters in contradictory ways (see, e.g., Ref. [8]). As a result, it seems likely that if the SBL results are due to new physics, then the model must be more complex than 3+1. For simplicity, however, one can use 3+1 global fits to investigate the possible oscillation parameters compatible between the electron and muon neutrino disappearance measurements plus the electron neutrino appearance measurements. Our SBL global fit allowed regions as of 2018 are shown in magenta and 2019 update [8] in black in Fig. 2. Unfortunately, it seems unlikely that the "next generation" reactor experiments, PROSPECT [9], STEREO [10] and SOLID [11], can address the possibility of $\bar{\nu}_e$ disappearance definitively. To illustrate their future sensitivities, which are all similar, we project the present PROSPECT 5σ limit to 5 years (Fig. 2, green, dashed).

The probability that all SBL data (anomalies and null results) fit a 3+1 model is extremely small: $p < 10^{-4}$ [12], indicating that either this explanation is too simplistic, or the anomalies are due to unknown (and probably uncorrelated) experimental issues. Because of the similarity of the general features of the anomalies, theorists have been actively exploring more complex explanations [13]. While there is excitement about these models, there is no consensus on which matches the multi-layered and complicated data most accurately. As an example, one commonly explored model features "3+2" neutrinos, and is shown in Fig. 1, middle [5]. This model addresses inconsistencies within the anomalies, but does not relieve the tension from the comparison to the experiments with null results. In Fig. 1, right, we show a model that incorporates both 3+1 sterile neutrino

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[1] Please see the other IsoDAR LOIs for a description of the accelerator, underground, and medical science opportunities enabled by such a device.

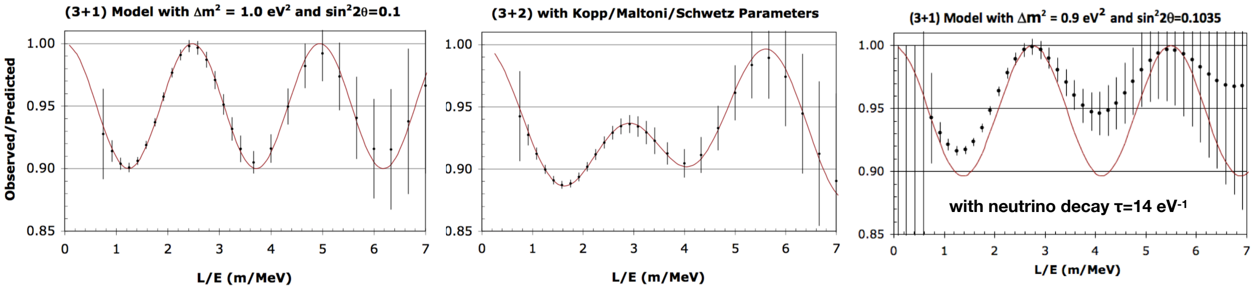

Figure 1: *IsoDAR@KamLAND L/E dependence, 5 years of running, for 3+1 (left) and 3+2 (middle) sterile neutrinos, and 3+1 with decay (right). Solid curve shows no smearing in the reconstructed position and energy. Data points with error bars include smearing.*

oscillation and also neutrino decay [14]. This model relieves the tension between the data sets in the global fits and addresses cosmological models. Still, a consensus has not been reached on what, if any, new physics explanations are correct.

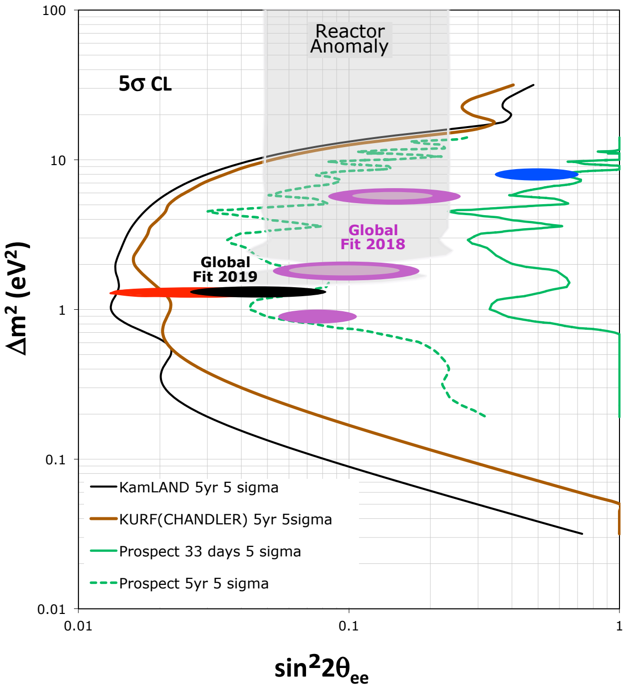

Figure 2: *Black line: IsoDAR@KamLAND capability at 5σ. Gray area: RAA signal; Magenta area: Global fit allowed signal; Red area: DANSS/NEOS combined signal; Blue area: Neutrino-4 signal. Green lines: PROSPECT at 5σ, solid–present, dashed – 5 year projection.*

In general, and while the global experimental and phenomenological situation is complicated, it is clear that a definitive experiment, capable of discerning a distinct oscillation/decay/other wave for a large swath of possible parameters, in whatever model, is required for "real" progress on this front. The confused situation motivates a major change of approach, rather than more of the same. IsoDAR@KamLAND covers all allowed regions with 5σ sensitivity in 5 years (Fig. 2, black) with a higher-energy, better-controlled, and better-understood $\bar{\nu}_e$ source than that of reactors. The L/E dependence (Fig. 1) allows models to be clearly differentiated, and the ability to "trace the wave" extends to $\sin^2 2\theta_{ee} \sim 0.01$ in the simplest 3+1 model. Thus, IsoDAR can both decisively confirm or refute the anomalies and *explain* them in the context of a number of possible scenarios.

In addition to world-leading sensitivity to possible SBL oscillations, IsoDAR will also probe non-standard neutrino interactions via $\bar{\nu}_e$-electron scattering [15]. IsoDAR@KamLAND will collect 2400 events in 5 years, a sample which would allow for a 3.2% measurement of $\sin^2\theta_W$. This would be the most precise measurement of $\sin^2\theta_W$ from neutrino-electron data and, as such, would represent a unique and precision elecroweak test with sensitivity to new physics.

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