Probing active-sterile neutrino oscillations in long-baseline experiments for a wide mass-squared range

Pragyanprasu Swain

Institute of Physics, Bhubaneswar, India

Collab: Sanjib Kumar Agarwalla, Suprabh Prakash, Samiran Roy

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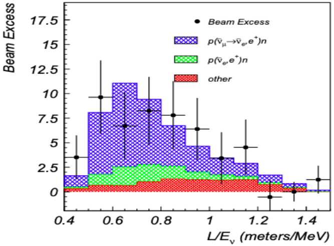
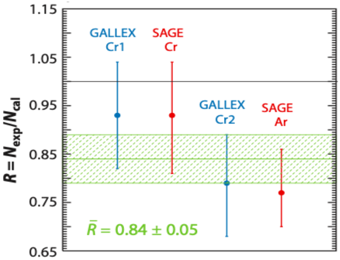
Anomalies pointing towards existence of eV-scale sterile neutrino

LSND Anomaly



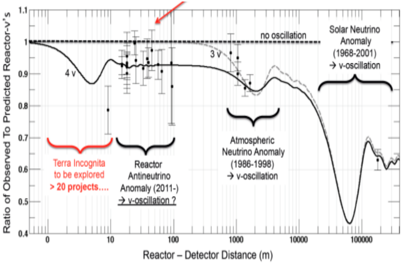
3.8σ excess of $\bar{\nu}_e$ events in a beam of $\bar{\nu}_\mu$

Gallium Anomaly



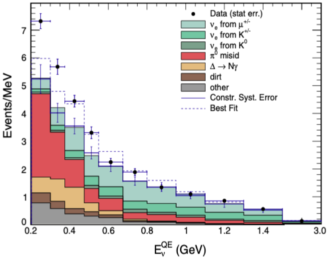
Deficit in ν_e survival events at $\sim 3\sigma$

Reactor Antineutrino Anomaly



$\sim$7% deficit in reactor antineutrino flux (2.5σ)

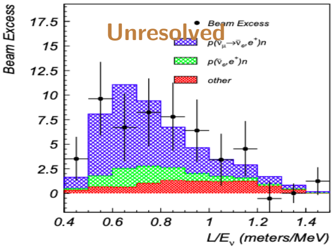
MiniBooNE LEE



4.8σ excess of ν_e events in ν_μ beam at low energies

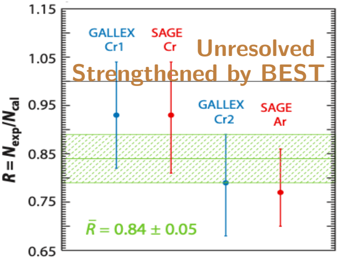
Anomalies pointing towards existence of eV-scale sterile neutrino

LSND Anomaly



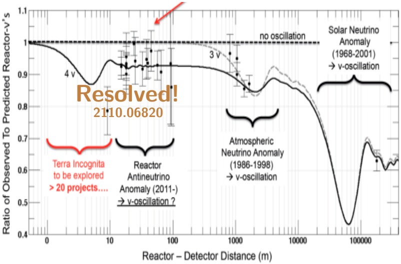
3.8σ excess of $\bar{\nu}_e$ events in a beam of $\bar{\nu}_\mu$

Gallium Anomaly



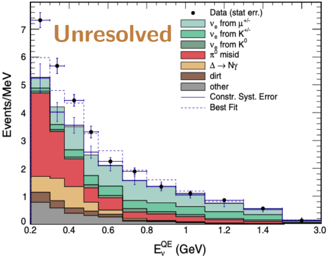
Deficit in ν_e survival events at $\sim 3\sigma$

Reactor Antineutrino Anomaly



~7% deficit in reactor antineutrino flux (2.5σ)

MiniBooNE LEE



4.8σ excess of ν_e events in ν_μ beam at low energies

Motivation to search for light sterile neutrino of mass other than eV-scale

- The possible existence of super light sterile neutrino of mass very close to active ones ($\Delta m_{41}^2 = 10^{-5}$ eV^2).
  Can explain the suppressed upturn in the solar neutrino energy spectrum below 8 MeV.
  Phys. Rev. D69 (2004) 113002, Phys. Rev. D83 (2011) 113011
- Existence of very light sterile neutrino of mass less than 0.1 eV^2.
  Affects the oscillation of reactor antineutrinos.
  Phys. Rev. D88 (2013) 073012, JHEP 08 (2014) 057
- A light sterile neutrino having a mass of a few eV.
  Can help in nucleosynthesis of heavy elements inside the supernova.
  arXiv:1110.2104, astro-ph/9910175, arXiv:1305.2382
- A relatively heavy sterile neutrino with mass around keV scale.
  Can act as warm dark matter in the context of the Neutrino Minimal Standard Model (νMSM).
  hep-ph/0503065, hep-ph/0505013, arXiv:0901.0011, arXiv:1602.04816

⇒ motivations to investigate the presence of light sterile neutrino over a wide range of mass-squared difference.

$$\boxed{\mathbf{10^{-5}}\ \text{eV}^2 \leq \mathbf{\Delta m_{41}^2} \leq \mathbf{10^2}\ \text{eV}^2}$$

3+1 scheme of neutrino oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

- U$=R_{34}(\theta_{34},\delta_{34})R_{24}(\theta_{24})R_{14}(\theta_{14},\delta_{14})R_{23}(\theta_{23})R_{13}(\theta_{13},\delta_{13})R_{12}(\theta_{12})$
- Six mixing angles, 3 Dirac CP phases, and 3 Majorana CP phases
- Three independent mass-squared splittings Δm^2_{31}, Δm^2_{21}, and Δm^2_{41}
- $|U_{e4}|^2 << 1$, $|U_{\mu 4}|^2 << 1$, $|U_{\tau 4}|^2 << 1$, and $|U_{s4}|^2 \approx 1$

$$\Downarrow$$

4ν mixing acts as a small perturbation to the 3ν scenario.

Probability expressions

$$
\begin{aligned}
P_{\mu e}^{3\nu} \;\simeq\;& 4 s_{23}^2 s_{13}^2 \sin^2\Delta \\
+\;& 4 c_{12}^2 c_{23}^2 s_{12}^2 (\alpha\Delta)^2 \\
+\;& 8 s_{13} s_{12} c_{12} s_{23} c_{23} (\alpha\Delta) \sin\Delta \cos(\Delta + \delta_{13}) \\
-\;& 4 s_{13}^2 s_{23}^2 s_{12}^2 (\alpha\Delta) \sin(2\Delta)
\end{aligned}
$$

$\Uparrow$

3ν scenario

$$
\begin{aligned}
P_{\mu e}^{4\nu}\big|_{\text{avg.}} \;\simeq\;& (1 - s_{14}^2 - s_{24}^2) P_{\mu e}^{3\nu} \\
+\;& 4 s_{14} s_{24} s_{13} s_{23} \sin\Delta \sin(\Delta + \delta_{13} - \delta_{14}) \\
-\;& 4 s_{14} s_{24} c_{23} s_{12} c_{12} (\alpha\Delta) \sin\delta_{14} \\
+\;& 2 s_{14}^2 s_{24}^2
\end{aligned}
$$

$\Uparrow$

$\Delta\mathrm{m}_{41}^2 \sim \mathrm{O}\ (\mathrm{eV}^2)$

$$
\begin{aligned}
P_{\mu e}^{4\nu}\big|_{\text{atm.}} \;\simeq\;& (1 - s_{14}^2 - s_{24}^2) P_{\mu e}^{3\nu} \\
+\;& 8 s_{14} s_{24} s_{13} s_{23} \cos(\delta_{13} - \delta_{14}) \sin^2\Delta \\
-\;& 8 s_{14} s_{24} c_{23} s_{12} c_{12} (\alpha\Delta) \sin(\delta_{14}) \sin^2\Delta \\
+\;& 4 s_{14}^2 s_{24}^2 \sin^2\Delta
\end{aligned}
$$

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$\Delta\mathrm{m}_{41}^2 = \Delta\mathrm{m}_{31}^2$

$$
P_{\mu e}^{4\nu}\big|_{\text{sol.}} \simeq (1 - s_{14}^2 - s_{24}^2) P_{\mu e}^{3\nu}
$$

$\Uparrow$

$\Delta\mathrm{m}_{41}^2 = \Delta\mathrm{m}_{21}^2$

$\boxed{\Delta = 1.27 \times \Delta m_{31}^2[\mathrm{eV}^2] \times L[\mathrm{km}]/E[\mathrm{GeV}]}$ $\boxed{\alpha = \Delta\mathrm{m}_{21}^2/\Delta\mathrm{m}_{31}^2 \simeq \pm 0.03}$ $\boxed{\cos\theta_{ij} \equiv c_{ij},\ \sin\theta_{ij} \equiv s_{ij}}$

The interference terms get doubled in atm. scale than those in the avg. out scale.

Benchmark values of oscillation parameters

Parameter	Benchmark Value	Marginalization Range
$\sin^2\theta_{12}$	0.304	Not marginalized
$\sin^2 2\theta_{13}$	0.085	Not marginalized
$\sin^2\theta_{23}$	0.50	[0.4, 0.6]
$\theta_{14}/^\circ$	$=\theta_{13}$	[0, 10]
$\theta_{24}/^\circ$	$=\theta_{13}$	[0, 10]
$\theta_{34}/^\circ$	0	Not marginalized
$\delta_{13}/^\circ$	[- 180, 180]	[- 180, 180]
$\delta_{14}/^\circ$	[- 180, 180]	[- 180, 180]
$\delta_{34}/^\circ$	0	Not marginalized
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	7.50	Not marginalized
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (NMO)	2.475	Not marginalized
$\frac{\Delta m^2_{41}}{\mathrm{eV}^2}$	$10^{-5} - 10^{2}$	Not marginalized

We consider Normal Mass Ordering (NMO) for our analysis.

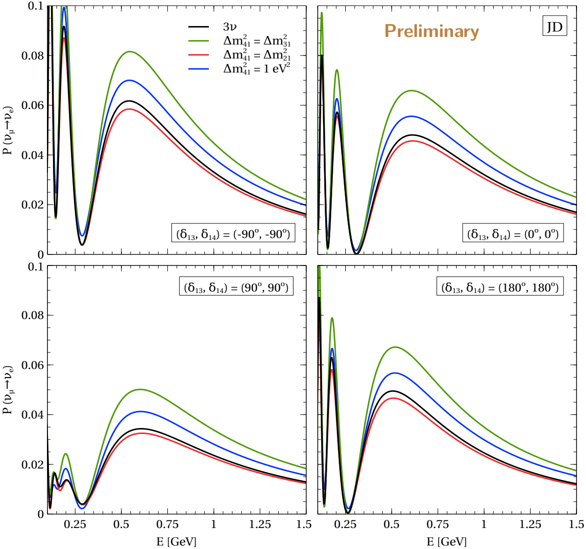
Details of experimental setups

	JD/KD (IWCD)	DUNE FD (ND)
Detector Mass	187 kt/187 kt (1 kt) WC	40 kt (67.2 t) LArTPC
Baseline length	295 km/1100 km (1 km)	1285 km (574 m)
Proton Energy	80 GeV	120 GeV
Beam type	Narrow-band, off-axis (2.5°)	Wide-band, on-axis
Beam power	1.3 MW	1.2 MW
P.O.T./year	27×10^{21}	1.1×10^{21}
Run time (ν+$\bar{\nu}$)	2.5 yrs + 7.5 yrs	3.5 yrs + 3.5 yrs

arXiv: 1502.05199 **arXiv: 2002.02967**

JD → Japanese detector
KD → Korean detector
IWCD → Intermediate Water Cherenkov detector

Oscillation probability at JD



L = 295 km

- The enhancement in the oscillation probability for $\Delta m^2_{41} = \Delta m^2_{31}$ is attributed to the doubling of the interference terms at this scale.
- For $\Delta m^2_{41} = \Delta m^2_{21}$, the deviation of the oscillation probability from that of the standard 3ν case, is negligible.

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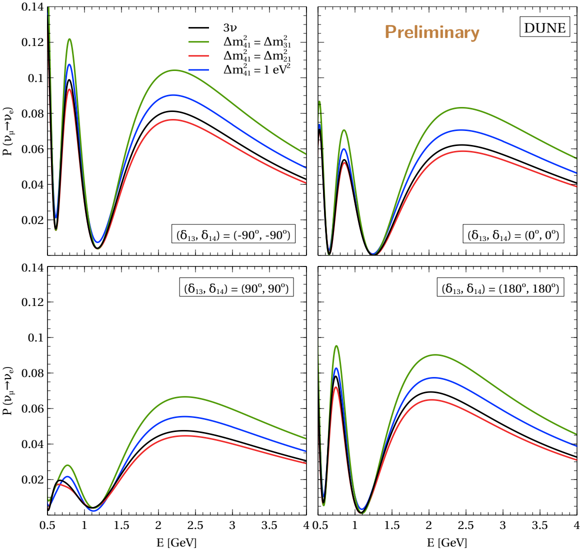
Absence of interference terms between the standard and sterile frequencies at the leading orders.

Oscillation probability at DUNE



L = 1285 km

- The enhancement in the oscillation probability for $\Delta m^2_{41} = \Delta m^2_{31}$ is attributed to the doubling of the interference terms at this scale.
- For $\Delta m^2_{41} = \Delta m^2_{21}$, the deviation of the oscillation probability from that of the standard 3ν case, is negligible.

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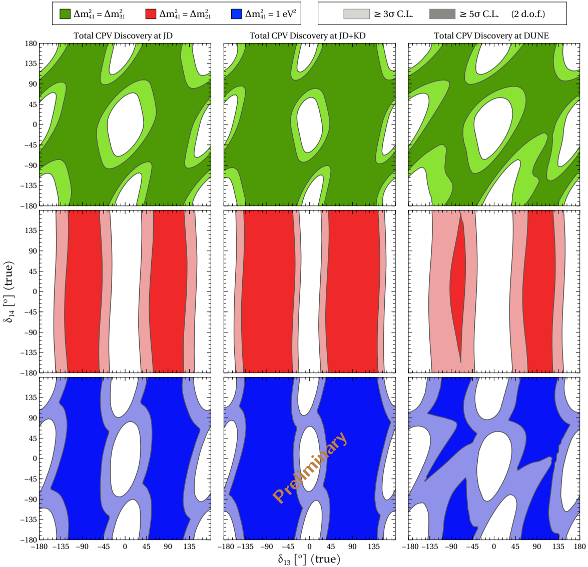
Absence of interference terms between the standard and sterile frequencies at the leading orders.

Total CP-violation discovery potential at JD, JD+KD, and DUNE

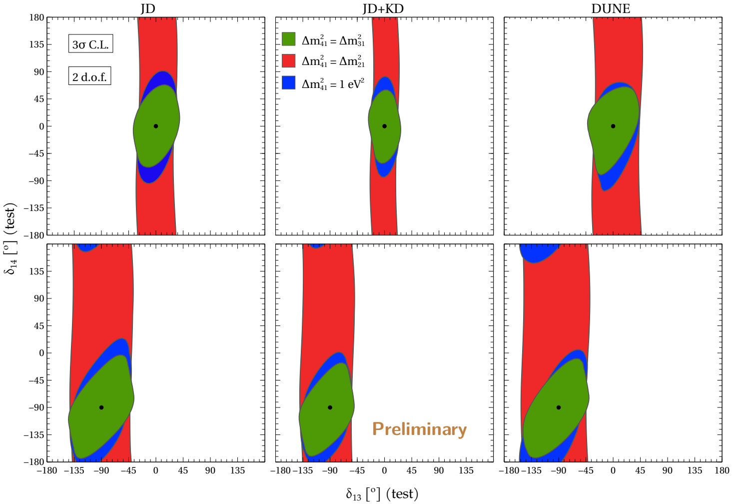


δ_{13} (test) $= 0^\circ$ and 180°

δ_{14} (test) $= 0^\circ$ and 180°

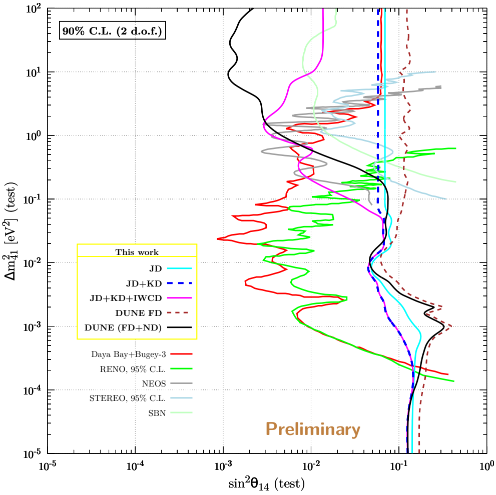
- JD+KD outperforms the standalone JD and DUNE.
- JD performs relatively better than DUNE, because JD with a relatively smaller baseline measures the CP phases with less interference from the fake CP asymmetry due to Earth matter effect.
- CP-violation discovery potential is maximum when $\Delta m^2_{41} = \Delta m^2_{31}$.
- For $\Delta m^2_{41} = \Delta m^2_{21}$, all the three experimental setups become almost insensitive to δ_{14}.

Reconstruction of CP phases at JD, JD+KD, and DUNE



- True values of CP phases are indicated by the black dots.
- Same conclusions hold as in case of CP-violation discovery potential.

Exclusion plots in $\Delta m^2_{41} - \sin^2\theta_{14}$ plane



$$\boxed{\Delta\chi^2 = \min_{\vec{\rho}}\left[\chi^2(3+1) - \chi^2(3+0)\right]}$$

$\vec{\rho}$ = marginalization parameters

Marginalized over: δ_{13}, δ_{14}, θ_{24}, and θ_{23} in theory

θ_{34} and δ_{34}: 0° in both data and theory

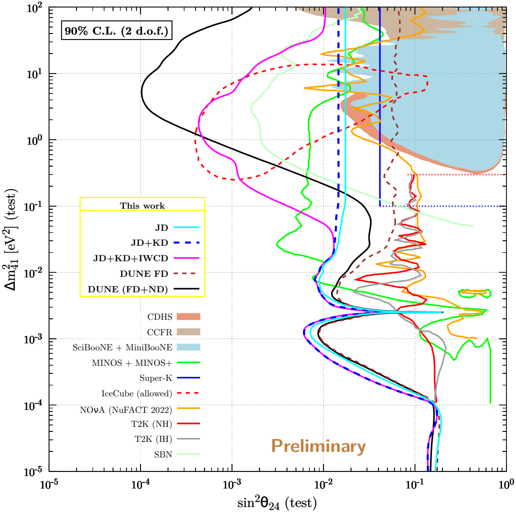
- For the higher Δm^2_{41} range, oscillations at FD gets averaged out.
- NDs start seeing the active-sterile oscillations at $\Delta m^2_{41} \gtrsim 0.1$ eV^2.
- For 2×10^{-3} eV$^2 \lesssim \Delta m^2_{41} \lesssim 2\times10^{-2}$ eV^2, sensitivity increases due to interference between the sterile and atmospheric frequency.

Maximal sensitivity

DUNE FD+ND: $\theta_{14} \lesssim 2.5^\circ$ ($\Delta m^2_{41} \sim 10$ eV^2)

JD+KD+IWCD: $\theta_{14} \lesssim 3^\circ$ ($\Delta m^2_{41} \sim 1$ eV^2)

Exclusion plots in $\Delta m^2_{41} - \sin^2\theta_{24}$ plane



Marginalized over: δ_{13}, δ_{14}, θ_{14} and θ_{23} in theory

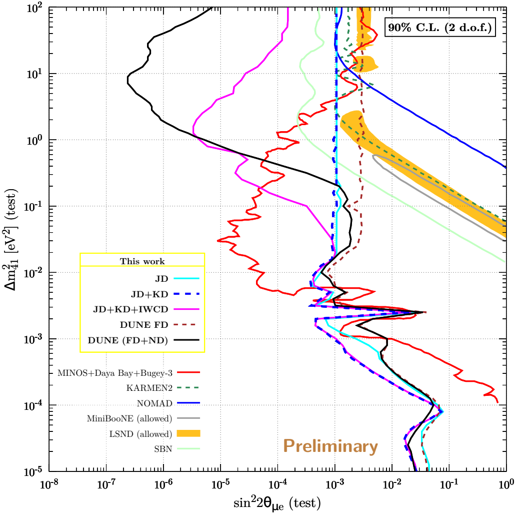
θ_{34} and δ_{34}: 0° in both data and theory

Maximal sensitivity

DUNE FD+ND: $\theta_{24} \lesssim 0.5^\circ$ ($\Delta m^2_{41} \sim 10$ eV^2)

JD+KD+IWCD: $\theta_{24} \lesssim 1.5^\circ$ ($\Delta m^2_{41} \sim 1$ eV^2)

Exclusion plots in $\Delta m^2_{41} - \sin^2 2\theta_{\mu e}$ plane



$$\boxed{\sin^2 2\theta_{\mu e} = 4 \sin^2 \theta_{14} \cos^2 \theta_{14} \sin^2 \theta_{24}}$$

Marginalized over: δ_{13}, δ_{14}, and θ_{23} in theory

θ_{34} and δ_{34}: 0° in both data and theory

- JD alone would cover almost all the LSND and MiniBooNE allowed regions.
- DUNE (FD+ND) and JD+KD+IWCD would improve the existing limits on $\sin^2 2\theta_{\mu e}$ in the higher Δm^2_{41} (0.2 to 100 eV^2) range.
- All the experimental setups considered in our work improve the existing limits on $\sin^2 2\theta_{\mu e}$ in the lower Δm^2_{41} (10^{-5} to 10^{-3} eV^2) region.

Summary

- The two future LBL experiments, DUNE and T2HK/T2HKK (JD/JD+KD), will be sensitive to the sterile CP phases and hence are complementary to the SBL experiments in the context of active-sterile neutrino oscillation.

- We explore the CP-violation discovery potential and the CP phase reconstruction capability of DUNE and JD/JD+KD at three different scales, namely, $\Delta m^2_{41} = 1\ \mathrm{eV}^2$, $\Delta m^2_{41} = \Delta m^2_{31}$, and $\Delta m^2_{41} = \Delta m^2_{21}$. The CP-sensitivity is maximum when the sterile frequency becomes comparable to the atmospheric one.

- For the first time, we explore the potential of IWCD in constraining the parameter space of active-sterile neutrino oscillations. Inclusion of near detectors increases the sensitivity to the active-sterile mixing angles in the high Δm^2_{41} region.

Thank You!