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To cite this article: Yury Kudenko and David Wark 2017 *J. Phys.: Conf. Ser.* **934** 012001

IOP Conf. Series: Journal of Physics: Conf. Series **934** (2017) 012001 doi:10.1088/1742-6596/934/1/012001

Neutrino oscillations: status and prospects of accelerator and reactor experiments

Yury Kudenko[1,2,3] **and David Wark**[4,5]

[1] Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
[2] Moscow Institute of Physics and Technology, Moscow Region, Russia
[3] National Research Nuclear University "MEPhI" (Moscow Engineering Physics Institute) Moscow, Russia
[4] Oxford University, Department of Physics, Oxford, United Kingdom
[5] STFC, Rutherford Appleton Laboratory, Harwell Oxford, and Daresbury Laboratory, Warrington, United Kingdom

E-mail: `kudenko@inr.ru`, `david.wark@stfc.ac.uk`

Abstract. A brief overview of recent results from accelerator and reactor neutrino experiments and future prospects are presented. The experimental status of sterile neutrinos is also discussed.

1. Introduction

The discovery of neutrino oscillations [1, 2] has provided convincing evidence for non-zero neutrino masses and leptonic mixing. This phenomenon is the first clear example of the new physics beyond the Standard Model (SM). Oscillation data obtained by now in atmospheric, solar, accelerator and reactor experiments are well described in the framework of three active massive neutrinos which flavour eigenstates ν_e, ν_μ, ν_τ and mass eigenstates ν_1, ν_2, ν_3 with masses m_1, m_2, m_3 are related by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) 3×3 unitary mixing matrix. This matrix is parametrized by three mixing angles $\theta_{12} \sim 34°$, $\theta_{23} \sim 45°$, $\theta_{13} \sim 9°$ and a CP-violating phase $\delta_{\rm CP}$. Non-zero masses appear in oscillations as two independent squared-mass differences between mass eigenstates $\Delta m^2_{21} = m^2_2 - m^2_1 \simeq 7.5 \times 10^{-5}$ eV^2 and $|\Delta m^2_{32}| = |m^2_3 - m^2_2| \simeq 2.4 \times 10^{-3}$ eV^2.

The number of light neutrinos constrained by LEP experiments is $N_\nu = 2.9840 \pm 0.0082$. However, this result does not exclude existence of sterile neutrinos which could mix with active neutrinos and therefore could modify the 3×3 mixing matrix. There are three exceptions - short baseline neutrino oscillation anomalies - which are not described by the PMNS matrix. 1.The observation of a $\bar{\nu}_e$ excess in a $\bar{\nu}_\mu$ beam by the LSND experiment [3]. 2.The Gallium anomaly - a deficit of ν_e found in measurements with a radioactive neutrino source by the SAGE [4] and GALLEX [5] experiments. 3.The reactor antineutrino anomaly - an observed in several short baseline experiments deficit of reactor antineutrinos relative to the calculated flux [6]. These results, if correct, could be explained by introducing at least one additional squared-mass difference $\Delta m^2 \geq 1$ eV^2. This requires the existence of at least one extra massive neutrino ν_4 which corresponds to a sterile neutrino in flavour basis.

This brief review covers the recent progress in study of neutrino oscillations with an emphasis on a search for CP violation. The new results on sterile neutrinos obtained in various

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disappearance experiments and expectations from running and future experiments are discussed. Next decade projects aiming at the discovery of CP violation and measurement of $\delta_{\rm CP}$ and determination of the neutrino mass hierarchy are also outlined.

2. Active neutrinos

2.1. New T2K result

The T2K (Tokai-to-Kamioka) experiment [7] collects data since 2010 and released a new preliminary result reported at several conferences this Summer. The result is based on 14.7×10^{20} protons on target (POT) for neutrino mode and 7.6×10^{20} POT for antineutrino mode. For details, one can see Ref. [8]. Statistics accumulated in T2K is summarized in Table 1. As seen

Table 1. Number of electron and muon neutrino and antineutrino detected in T2K and predicted for several values of $\delta_{\rm CP}$. The normal mass hierarchy is assumed.

	T2K data	$\delta=-\pi/2$	$\delta=0$	$\delta=\pi/2$	$\delta=\pi$
ν_e	74	73.5	61.5	49.9	62.0
$\nu_e+1\pi$	15	6.92	6.01	4.87	5.78
$\bar{\nu}_e$	7	7.93	9.04	10.04	8.93
ν_μ	240	267.8	267.4	267.7	268.2
$\bar{\nu}_\mu$	68	63.1	62.9	63.1	63.1

from Table 1, T2K observed 89 ν_e and 7 $\bar{\nu}_e$ events while 67 ν_e and 9 $\bar{\nu}_e$ are expected in case of CP conservation. The experimental data show some excess of ν_e events and deficit for $\bar{\nu}_e$ events relative to Monte Carlo data for all values of $\delta_{\rm CP}$. T2K already reached the sensitivity to $\delta_{\rm CP}$ without using reactor information on θ_{13}. The results of the oscillation analysis obtained combining data taken with neutrino and antineutrino beams are shown in Fig. 1.

T2K obtained that the CP conservation hypothesis ($\sin\delta_{\ rmCP}=0$ or π) is excluded at the confidence level of 2σ. The best fit value $\delta_{\rm CP}=-1.83^{+0.60}_{-0.66}$ rad and a 90% CL interval for allowed $\delta_{\rm CP}$ values is $[-161^\circ,\ -48^\circ]$. T2K data favor the maximal CP violation ($\delta_{\rm CP}\sim-\pi/2$) and the normal mass hierarchy.

It is expected that T2K will accumulate 7.8×10^{21} POT according to the plan to reach the J-PARC beam power about 1 MW by 2021 and then icrease up to 1.3 MW by 2026. An upgrade of near detectors is also needed to reduce the systematic uncertainties from the current level of $\sim6\%$ to 4%. T2K collaboration proposed to extend the experiment to the second phase T2K-II with the goal to accumulate 20×10^{21} POT by 2026 and to reach a 3σ sensitivity to CP violation in case of $\delta_{\rm CP}\sim-\pi/2$.

2.2. Results from NOνA

The NOνA experiment has measured a ν_μ disappearance using 6.05×10^{20} POT [10] and selecting μ-like candidates at the far detector observed 78 events, while 473 ± 30 were expected without oscillations. NOνA found an indication on a non-maximal value of θ_{23} [9], with two best fit points, both for normal mass hierarchy: $\sin^2\theta_{23}=0.404$, $\delta_{\rm CP}=1.48\pi$ and $\sin^2\theta_{23}=0.623$, $\delta_{\rm CP}=0.72\pi$, as shown in Fig. 2. The inverted mass hierarchy in the lower octant ($\theta_{23}<45^\circ$) is disfavored at greater than 93% C.L. for all values of $\delta_{\rm CP}$, and excluded at $>3\sigma$ significance outside the range $0.97\pi<\delta_{\rm CP}<1.94\pi$. In general, NO$\nu$A results are in agreement with T2K data, but more statistics is needed to conclude if θ_{23} is maximal or not. It should be also noted

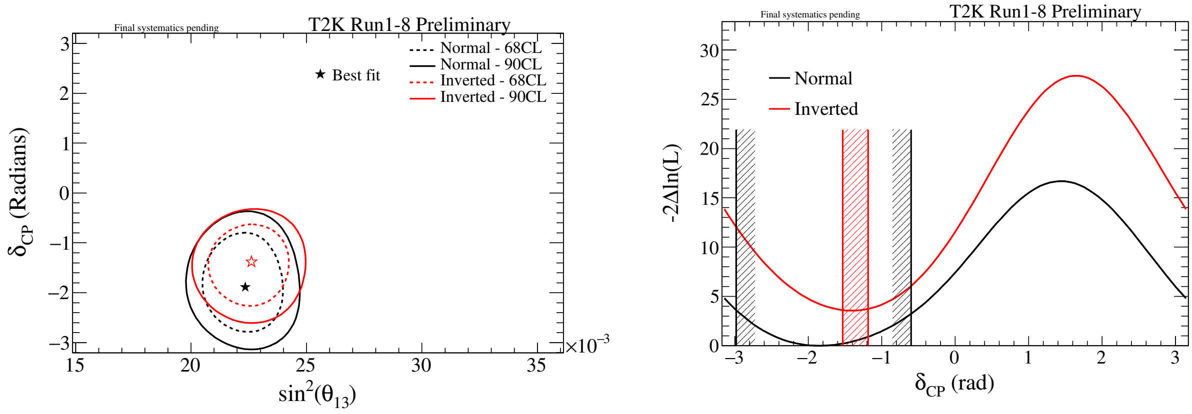

Figure 1. Left: best fit points (stars) and allowed 68% and 90% CL regions of $\sin^2\theta_{13}$ and δ_{CP} for the normal (black) and inverted (red) mass hierarchy obtained in the T2K experiment. Reactor constraint $\pm 1\sigma$ on θ_{13} is used. Right: black and red curves show $2\Delta\ln(L)$ significance at which each value of $\delta_{\rm CP}$ is disfavored for normal and inverted mass hierarchy, respectively. Vertical lines limit the allowed regions for $\delta_{\rm CP}$ values by the 2σ confidence level. The best fit point is $\delta_{\rm CP} = -1.83$ rad for the normal mass hierarchy. The reactor constraint on θ_{13} is used.

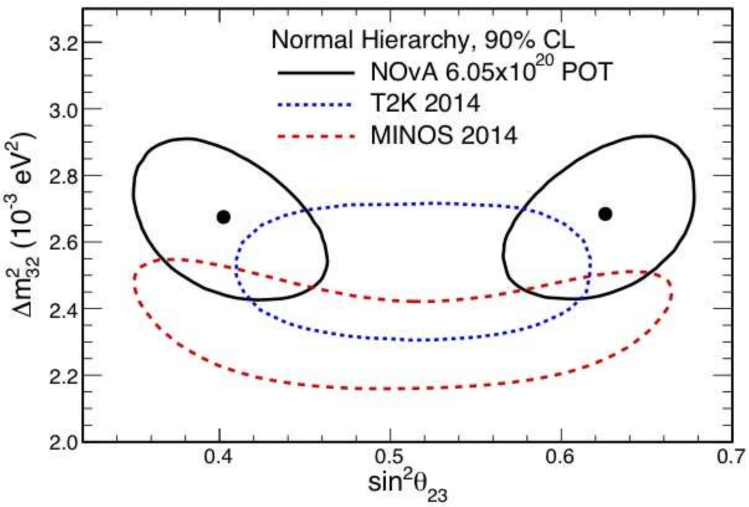

Figure 2. Confidence regions in the plane $|\Delta m^2_{32}|$ - $\sin^2\theta_{23}$ obtained in oscillation experiments NOν, T2K, and MINOS. Black dots show the best fit of the NOνA data.

that the θ_{23} values measured by Super-Kamiokande [11] and IceCube [12] are consistent with the maximal mixing.

2.3. θ_{13} from reactor experiments

The disappearance probability of reactor antineutrinos, as a function of neutrino propagation distance L and energy E can be written:

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2(\frac{\Delta m^2_{31} L}{4E}). \quad (1)$$

For the antineutrino average energy of 4 MeV, the disappearance of $\bar{\nu}_e$ reaches a maximum at $L \simeq 2$ km. Three reactor experiments, Daya Bay, RENO, and Double Chooz, have been built to measure θ_{13}. Their first results released in 2012 discovered the large value of $\theta_{13} \sim 9^{circ}$. The most precise measurement of θ_{13} was provided by Daya Bay [13]: $\sin 2\theta_{13} = 0.0841 \pm 0 : 0027(\text{stat}) \pm 0.0019(\text{syst})$. Combined analysis of the data from three reactor experiments obtained in [14] is shown in Fig. 3.

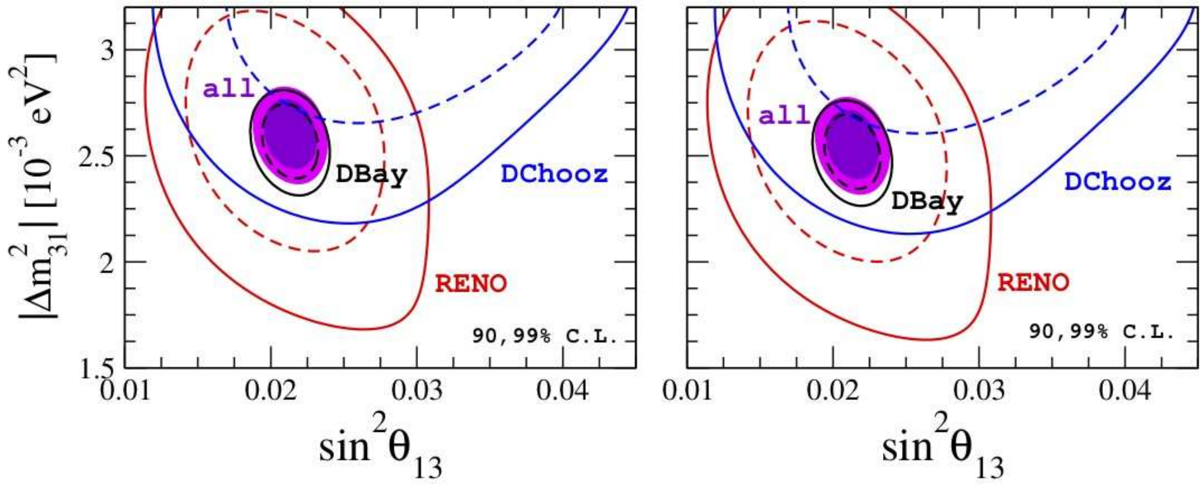

Figure 3. Allowed regions in the plane $|\Delta m^2_{31}|$ - $\sin^2\theta_{13}$ from reactor experiments. The dashed line shows 90% CL, the solid line corresponds to 99% CL. Colored regions show the combination of all experiments. The left (right) panel corresponds to the normal (inverted) mass hierarchy.

3. Future long baseline projects

A rich oscillation experimental program is under preparation to answer the fundamental questions. Is leptonic CP violating or not? What is the neutrino mass hierarchy? What is the value of θ_{23}? Some answers, or hints, can be obtained from running experiments T2K, NOνA, IceCube, Super-Kamiokande, and reactor experiments. However, only the next generation of long baseline accelerator experiments, DUNE, T2HK and reactor experiment JUNO can establish CP violation and determine the mass hierarchy.

3.1. JUNO

The JUNO (Jiangmen Underground Neutrino Observatory) experiment [15] has two main goals: the determination of mass hierarchy and precise measurement of oscillation parameters Δm^2_{21}, $\Delta m^2 31$, and $\sin^2\theta_{12}$. The JUNO detector, a 20 kt spherical unsegmented liquid scintillator detector, will be located at a distance of 53 km from two sites of Yangon and Tanisha, where 6 and 4 nuclear reactors are to be built, respectively. According to the construction plan, the total power of 35.8 GW will be available. The detector will be instrumented by more than 17000 20-inch and about 34000 3-inch photo multiplies (PMTs) ensuring a 77% photocathode coverage. To discriminate between the neutrino hierarchies at a $\geq 3\sigma$ level, the detector energy resolution is required to be $3\%/\sqrt{E(\text{MeV})}$ and the absolute energy scale should be calibrated with a precision of 1%. It is expected that after 6 years of data taking JUNO can distinguish between the true and wrong hierarchy hypothesis at a 4σ significance, assuming no systematics. If systematic uncertainties are considered (non equal baselines from reactors to the detector, backgrounds, the shape of the reactor antineutrino spectrum), the significance to determine the mass hierarchy is reduced to about 3σ. The civil construction begun in 2015 and the experimental hall is expected to be ready in 2018. JUNO plans to start data taking in 2020.

3.2. DUNE

The main scientific goals of the Deep Underground Neutrino Experiment (DUNE) [16] are the sensitive test of CP violation in the leptonic sector, determination the neutrino mass hierarchy, and precise measurements of neutrino oscillation parameters. The proposed liquid Argon far neutrino detector will be built deep underground, at a depth of about 1500 m, in the Sanford Underground Research Facility (South Dakota, USA), about 1300 km from Fermilab where a high intensity wide band on-axis neutrino beam with neutrino energies of 1-6 GeV will be formed. This neutrino beam will cover the first and the second oscillation maxima which correspond to the neutrino energy of 2.5 GeV and 0.8 GeV, respectively. The far detector will consist of four cryostats instrumented with Liquid Argon Time Projection Chambers (LAr TPCs) with a fiducial mass of 40 kt. The first 10 kt DUNE liquid argon module adopts a single-phase technology pioneered by the ICARUS T600 detector. The second DUNE far detector module can be constructed on the basis of a dual-phase TPC if its performance is confirmed as a result of activities at the CERN Neutrino Platform. The LAr TPC technology offers excellent capabilities for position and energy resolution and for high-precision reconstruction of complex interaction topologies over a broad neutrino energy range and will provide a powerful complementarity to the large, underground water Cherenkov or scintillator-based detectors. According to the present timescale, DUNE begins data taking with the first 10 kton module in 2026 and the full configuration will be ready by 2029. The expected sensitivity of DUNE is shown in Fig. 4.

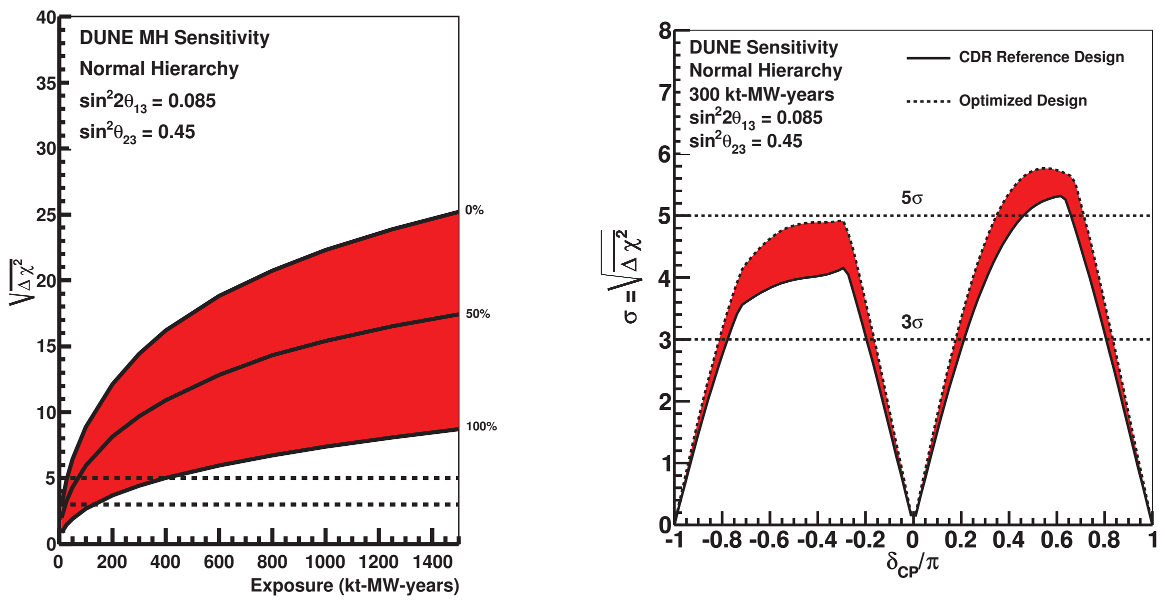

Figure 4. DUNE sensitivities to the mass hierarchy and δ_{CP} [16]. Left: minimal significance with which the mass hierarchy can be determined for all values of δ_{CP}. Right: significance with which the CP violation can be determined for an exposure of $300\mathrm{kt} \cdot \mathrm{MW} \cdot \mathrm{year}$ assuming the normal mass hierarchy.

3.3. T2HK

The main goal of the T2HK (Tokai-to-Hyper-Kamiokande) experiment is the sensitive search for CP violation in neutrino oscillations [17]. A gigantic water Cherenkov Hyper-Kamiokande detector equipped with newly developed high efficiency and high-resolution PMTs will serve as a far detector in this experiment which will use neutrino and antineutrino beams produced at J-PARC upgraded to the power of ~ 1.3 MW. The baseline design includes one 260 kt Cherenkov detector at a distance of 295 km from J-PARC. The inner detector region of the tank is viewed by 40,000 PMTs that provides a 40% photo-cathode coverage. As in T2K, the 2.5° off-axis beam tuned to the first oscillation maximum will be used. Hyper-Kamiokande is expected to collect about 1000 ν_e and $\bar{\nu}_e$ events after 10 years of data taking with one tank, assuming a 2:1 ratio between running time of neutrino and antineutrino modes. Fig.5 shows the expected significance

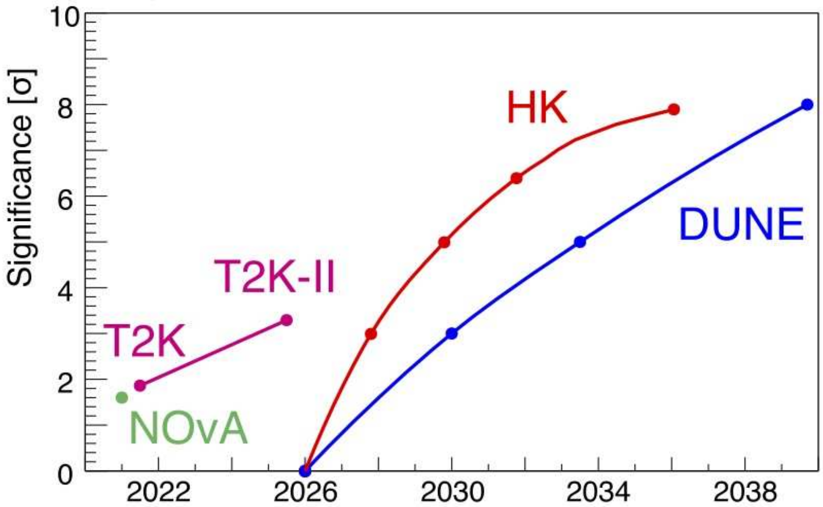

Figure 5. The expected significance of measurement of CP violation in T2HK (denoted as HK) as a function of running time with the beam power of 1.3 MW. The normal mass hierarchy, $\delta_{\rm CP} = -\pi/2$, and a 2:1 ratio of neutrino:antineutrino modes are assumed. Other experiments are also shown.

of measurement of CP violation in T2HK with one far detector as a function of running time with the beam power of 1.3 MW, for the normal mass hierarchy and $\delta_{\rm CP} = -\pi/2$. The expected sensitivities of other long baseline experiments are also shown.

4. Sterile neutrinos

A few experiments released their new results on searches for sterile neutrinos during the year.

4.1. IceCube

The IceCube experiment reported the result of the first search for atmospheric $\nu_\mu + \nu_e$ disappearance in the energy range from about 320 GeV to 20 TV [18]. At these energies, sterile neutrinos would produce distortions in the measured zenith angle distributions due to a resonant matter-enhanced oscillations during neutrino propagation through the Earth for the mass splitting of $0.01\text{eV}^2 \leq \Delta m^2 \leq 10\text{eV}^2$. Fig. 6 shows the IceCube result at 99% CL. The allowed region from the appearance experiments LSND and MiniBooNE is excluded at approximately 99% CL further increasing tensions between the appearance and disappearance results.

4.2. Daya Bay and MINOS

The combined analysis [19] of the MINOS and Daya Bay sterile neutrino search data is shown in Fig. 7. In this analysis muon neutrino disappearance data from MINOS are combined with

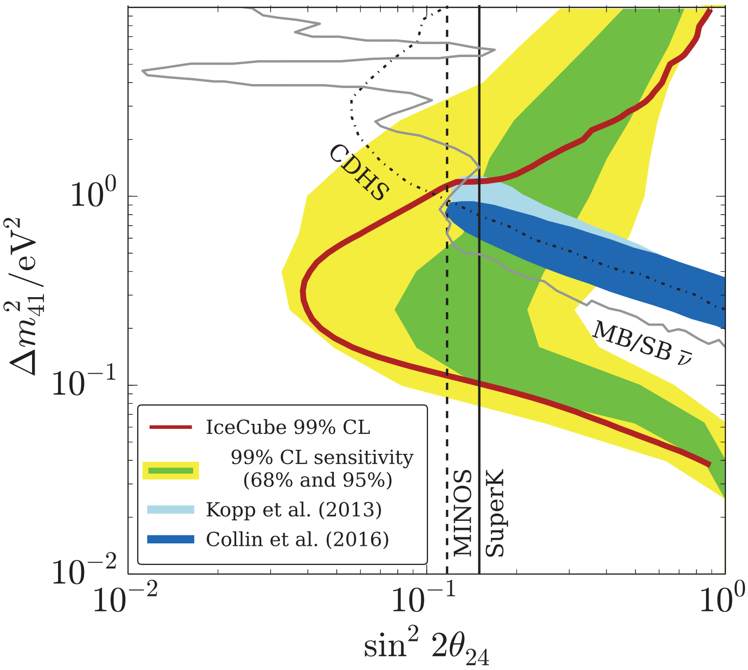

Figure 6. The IceCube 99% CL contour (red solid line) excludes the regions to the right. Also shown the allowed region from LSND/MiniBooNE.

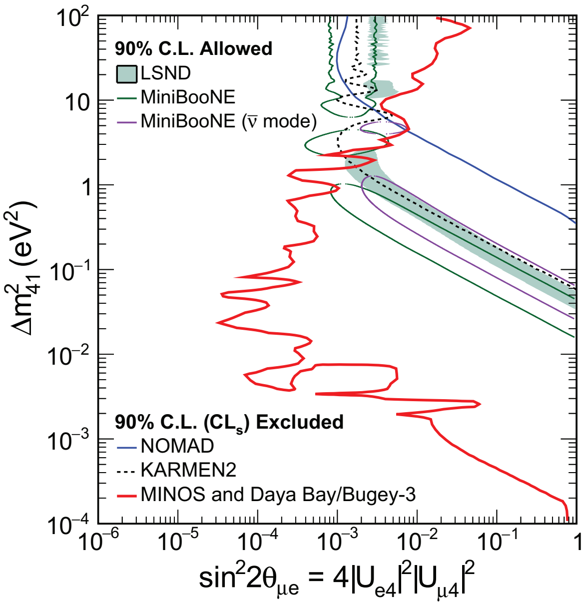

Figure 7. MINOS and Daya Bay + Bugey-3 combined 90% CL limit on $\sin^2 2\theta_{\mu e}$ compared to LSND and MiniBooNE 90% allowed regions. Regions of parameter space to the right of the red contour are excluded.

electron antineutrino disappearance data from Daya Bay and Bugey-3. As seen from Fig. 7, this result excludes at 95% CL the sterile neutrino mixing phase space allowed by LSND and MiniBooNe for $\Delta m^2 14 < 0.8$ eV^2.

4.3. NEOS
The NEOS experiment (Korea) measured the flux of $\bar{\nu}_e$ at a distance of about 22 m from a core of a 2.8 GW reactor for a period of 8 months with a signal-to-background ratio of about 22:1 [20]. The measured energy spectrum of reactor antineutrinos was compared with the simulated spectrum obtained for the 3+1 hypothesis and with the spectrum measured in the Daya Bay experiment. The result of the oscillation analysis is shown in Fig 8.

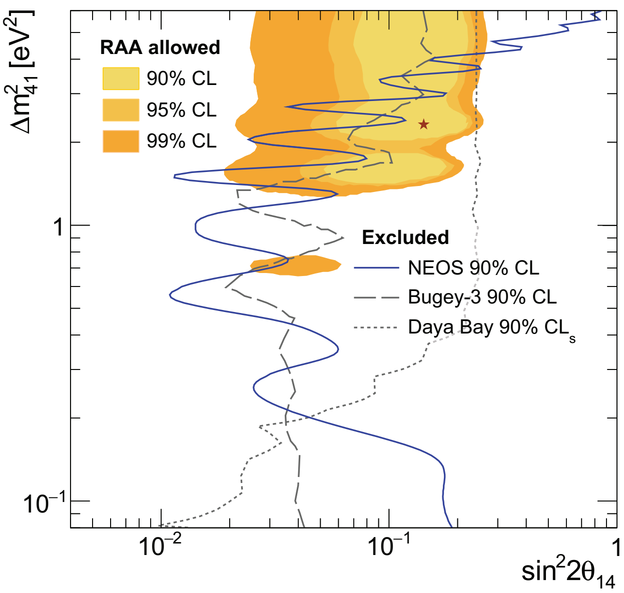

Figure 8. The NEOS 90% CL exclusion curve (solid blue line). The shaded area is the allowed region from the reactor anomaly.

No strong evidence for $3+1$ oscillations is observed and the new upper limit on θ_{14} in the region of Δm^2_{41} is obtained. The sensitivity is expected to be further increased if the reference spectrum from the RENO experiment will be used in the analysis. It should be noted the reactor experiment DANSS recently obtained the preliminary result [21] which is similar to the NEOS one shown in Fig. 8.

5. Conclusion
The known oscillation data is successfully described by the standard 3-flavor neutrino paradigm. Still missing information about unknown parameters - $\delta_{\rm CP}$, mass hierarchy - is expected to be obtained in current and future accelerator and reactor experiments. Anomalies which point to existence of sterile neutrinos are being addressed by many experiments at reactors, accelerators and with intensive neutrino sources. Very interesting physics and new surprises are ahead of us.

5.1. Acknowledgments
This work was supported in part by the RFBR/JSPS grant # 17-52-50038.

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