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Future Neutrino Experiments & Outlook

Sowjanya Gollapinni[a,b]

[a] *Physics Division, Los Alamos National Laboratory,*
P.O. Box 1663, Los Alamos, New Mexico, United States 87545
[b] *Department of Physics & Astronomy, University of Tennessee, Knoxville,*
1408 Circle Dr, Knoxville, Tennessee, United States, 37996

E-mail: `sowjanya@lanl.gov`

The past two decades have brought several remarkable neutrino-related discoveries indicating that one may answer the most sought after question of our matter dominated universe from within the neutrino sector. Although neutrinos have been studied for over 70 years now, much is still unknown such as the absolute scale of neutrino masses, neutrino mass ordering, Dirac or Majorana nature of neutrinos, neutrino charge-parity violation, and beyond standard model 3-flavor mixing. Addressing all of these open questions with technological advances is the focus of current and future neutrino experiments. This document briefly reviews the status and reach of current experiments and provides a detailed outlook on future neutrino experiments and facilities. In particular, the document focuses on next generation long-baseline experiments that have broad physics programs beyond just oscillation measurements. Beyond next generation experiments are also briefly discussed.

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1. Introduction

Neutrinos provide a promising window to probe a wide range of fundamental physics, from the physics of the nucleus to the astrophysical structure of a supernova. The discovery that neutrinos can transition between different flavors, which implies they must have a non-zero mass, has revolutionized the field of neutrino physics. The past two decades have brought several remarkable neutrino-related discoveries indicating that one may answer the most sought after question of our matter dominated universe from within the neutrino sector. The global neutrino physics program is currently focused on studying neutrino oscillations, and to understand the implications of this phenomena on the evolution of the universe. Experimental evidence indicates that neutrino oscillations are governed by the Pontecorvo-Maki-Nakagawa-Sakata mixing matrix [1] which contains three mixing angles θ_{12}, θ_{23} and θ_{13} and a Charge-Parity (CP) violating phase, δ_{CP}, the indicator of a possible explanation for our matter dominated universe. All the mixing angles are measured, but the size of the CP violating phase is still unknown. Also unknown is which of the three neutrino mass eigenstates is the heaviest and which is the lightest. The absolute masses of neutrinos and whether they are Dirac or Majorana type is also an open question.

Additionally, in the last two decades, several short-baseline oscillation and reactor experiments reported anomalous results [2, 3] that do not fit the standard model (SM) three neutrino scenario indicating the possibility that there may be additional "sterile" neutrino mass states. Addressing all of these open questions by employing novel technologies and diverse experimental techniques to achieve the required precision is the focus of current and future neutrino experiments. The field of neutrinos offers a very broad physics program with overlapping physics and technological goals that are synergistic allowing for valuable cross checks. This document briefly reviews the current neutrino experimental landscape and provides an outlook on future experiments with a particular focus on next generation long-baseline oscillation searches. There are many other important topics that this document was unable to cover due to page limit constraints such as solar and geo-neutrinos, astrophysics, cosmology, and high energy astrophysics for which neutrinos are extensively used, and neutrinos for nuclear non-proliferation applications. The reader is advised to look elsewhere for progress and outlook on these topics.

2. Direct Mass Measurements

Constraints from cosmological and astrophysical data and precision measurements from β-decay experiments provide direct measurements of absolute mass of neutrinos. The current upper limit on the effective mass of neutrinos $m_{\nu_e} < 1.1$ eV at 90% confidence level (CL) comes from KATRIN [4], a 70 m Tritium β-decay tagging experiment (see Fig. 1, left). KATRIN continues to collect more data with a goal to reach 0.2 eV in the next three years. Future experiments for direct mass measurements include Project8, ECHo and HOLMES. Project8 is a Tritium β-decay experiment using a new technique called Cyclotron Radiation Emission Spectroscopy. ECHo and HOLMES are complementary to tritium-based searches and use ^{163}Ho whose decay via electron capture determines the effective electron neutrino mass as opposed to anti-neutrino in Tritium. Both experiments use cryogenic bolometers. All current and future experiments are aiming for sub-eV sensitivity with staged goals to reach from eV to sub-eV scale (see Fig. 1, right). Project8 aims to

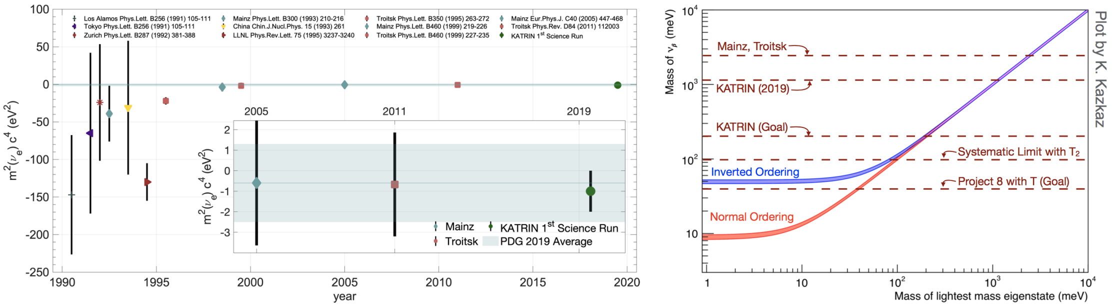

Figure 1: (left) Squared neutrino mass values obtained from tritium β-decay in the period 1990-2019 [5]. (right) Projected sensitivities for KATRIN and Project8

reach 0.04 eV sensitivity after 2022. ECHo and HOLMES are aiming to reach 0.2 eV sensitivity after 2022.

3. Neutrinoless Double Beta Decay

Observation of neutrinoless double beta decay ($0\nu\beta\beta$) provides evidence for Lepton Number Violation (LNV) and "Majorana" nature of neutrinos. The observable determined by $0\nu\beta\beta$ experiments is the half-life of the decay ($T_{1/2}$) of the isotope under study. The current best limits come from the Xe-doped liquid scintillator experiment, KamLAND-Zen [6], with a $T_{1/2}$ >1.07 × 10^{26} yr at 90% CL on ^{136}Xe. Future experiments are aiming for ∼2 orders of magnitude improvement in $T_{1/2}$ along with covering neutrino inverted ordering region, see Fig. 2 (left). Achieving this requires building large mass detectors in order to offset long half lifes along with excellent tracking and energy resolution while achieving low backgrounds. In addition, discovery in more than one isotope is crucial. The future $0\nu\beta\beta$ experimental program is one of the most vibrant programs with detectors ranging from tonne-scale to multi-tonne scale. In order to achieve the needed precision, multiple experimental techniques such as bolometers, scintillators, trackers, time projection chambers (TPCs) and semiconductors are being actively developed and demonstrated. In addition, multiple isotopes such as ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{130}Te, and ^{136}Xe, are being employed. Future $0\nu\beta\beta$ experiments [7] include LEGEND-200, LEGEND-1000, KamLAND2-Zen, SuperNEMO, nEXO (Fig. 2, right), CUPID, PandaX, DARWIN, and LZ to name a few.

4. Atmospheric Sector & CP Violation

Long-baseline oscillation experiments where the distance between the neutrino source and the detector is ∼1000 km, can address many important questions about neutrino oscillations. They can provide precision measurements of neutrino mixing parameters, determine the neutrino mass ordering, discriminate the θ_{23} octant, and discover CP-violating effects in the neutrino sector. In particular, ν_e appearance experiments in matter will be sensitive to rich physics (θ_{23}, θ_{13}, δ_{CP}, and matter effects). Electron density in matter causes asymmetry through forward week scattering resulting in a hierarchy dependent effect and CP violating effects can be probed by comparing neutrino and anti-neutrino oscillations. The current status of oscillation parameter measurements can be found in Particle Data Group (PDG) 2020 [8].

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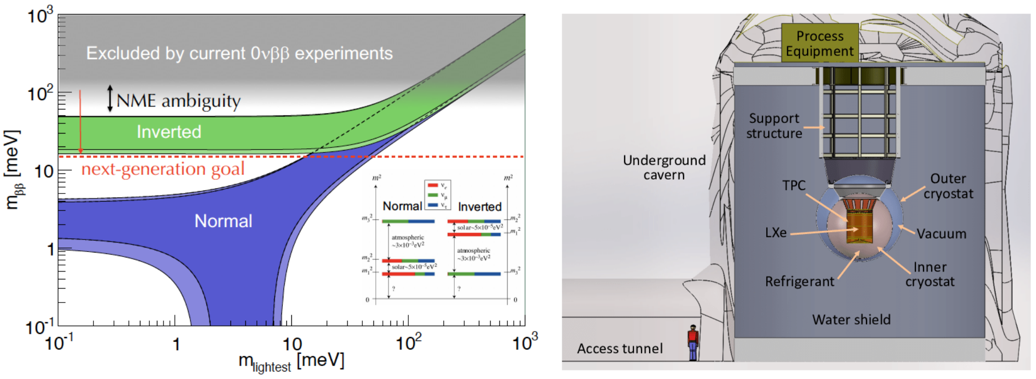

Figure 2: (left) Sensitivity of current and future $0\nu\beta\beta$ experiments [7]. (right) Engineering design of the nEXO experiment concept showing a cross-section of the TPC.

Figure 3 shows the current and future long-baseline experiments in United States and Asia. NOνA with 735 km baseline in U.S. and T2K with 295 km baseline in JPARC, Japan, are long-baseline experiments currently taking data. Latest results from these experiments show that the picture of atmospheric sector is consistent across experiments. The results also show preference for normal mass ordering and non-maximal mixing. Joint oscillation fits are underway between T2K and NOνA, and T2K and Super-K to understand differences observed in δ_{CP} measurements. Together T2K an NOνA can reach ~2-3 σ sensitivity for CP violation (CPV) and mass hierarchy (MH) depending on parameter choices and systematics reach. Figure 4 shows the sensitivity reach from both experiments for δ_{CP}. Extended run from T2K (T2K-II) collecting a total statistics of 20E21 protons on target (POT) can result in 3 σ reach for δ_{CP}. T2K is upgrading its near detector ND280 with WAGASCI and BabyMIND to reduce neutrino interaction uncertainties. In addition, Gadolinium (Gd) doping is also planned for efficient neutron tagging to enhance ν and anti-ν discrimination. NOνA with an upgraded neutrino beam and full dataset can reach 3σ for CP sensitivity and 3σ MH sensitivity for 30-50% of δ_{CP} values. Test beam experiments are being planned to reduce largest systematics coming from detector energy scale.

New technologies, high intensity MW-scale neutrino beams, multi-kiloton-scale detectors with fine-grained tracking and calorimetry are needed in order to reach the sensitivity goals for MH and δ_{CP} with needed precision. The Deep Underground Neutrino Experiment (DUNE) [11] in U.S. and Hyper-Kamiokande (Hyper-K) [12] experiment in Japan are next generation long-baseline oscillation experiments aiming to measure δ_{CP}. The physics program of these massive detectors

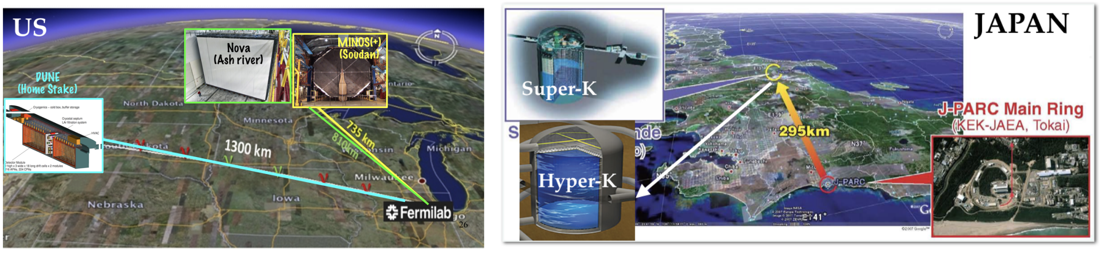

Figure 3: Current and future long-baseline facilities in United States (left) and Japan (right)

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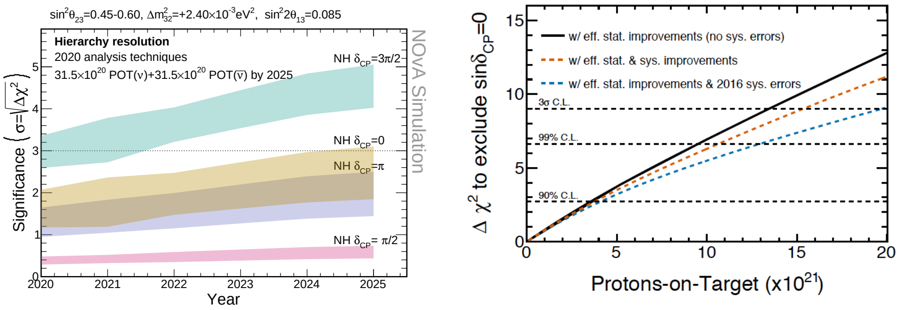

Figure 4: (left) NOνA's mass hierarchy sensitivity [9] as a function of time assuming 50% ν and 50% anti-ν data corresponding to a total of 63E20 POT. Projected beam intensity improvements and reduced systematic uncertainties from test beam efforts are also included. (right) T2K's sensitivity to CPV [10] as a function of POT with a 50% improvement in the effective statistics, assuming the true MH is the normal MH but unknown and the true value of $\delta_{CP} = -\pi/2$. The plot compares different assumptions for the T2K-II systematic errors with $\sin^2_{\theta_{23}} = 0.50$.

will be incredibly rich. In addition to addressing the important questions in oscillation physics, they will also simultaneously search for signatures of nucleon decay, supernova and beyond the SM physics.

DUNE will consist of two neutrino detectors, one detector installed at Fermilab (the near site) and a second, much larger, detector will be installed more than a kilometer underground at the Sanford Underground Research Facility (SURF) in Lead, South Dakota (the far site) 1300 km from Fermilab. Dual site facilities are provided by the Long Baseline Neutrino Facility (LBNF). The Proton Improvement Project (PIP-II) at Fermilab will provide DUNE with a 1.2 MW neutrino beam in late 2020s and will later be upgraded to 2.4 MW. Following the first MW-scale neutrino beam, DUNE is scheduled to collect first physics data in late 2020s. The DUNE near detector (ND) hall will be located 574 m from the neutrino beam target at Fermilab and will employ multiple technologies. The primary goal of the ND is to characterize the neutrino beam and constrain flux and cross section uncertainties for the far detector (FD). The DUNE ND will consist of 1) a modular, pixelated liquid argon time projection chamber (LArTPC), most similar to the FD, called

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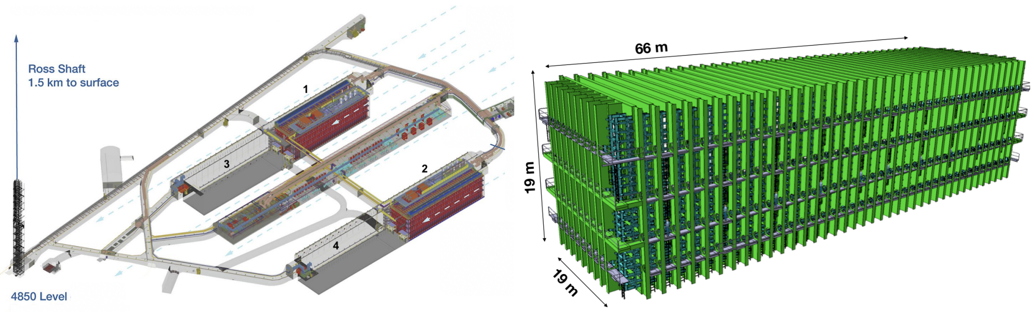

Figure 5: (left) The LBNF caverns for the DUNE experiment. The north and south caverns are identical and will house the four far detector modules. The central cavern will accommodate cryogenic equipment and other utilities needed for DUNE. (right) One of the four DUNE far detector modules showing a 17 kton cryostat with 10 kton active volume.

"ND-LAr", 2) a high-pressure gaseous argon TPC (GArTPC) with magnet and electromagnetic calorimeter (ECAL), referred to as "ND-GAr" and, 3) a 3D plastic scintillator target with tracker, ECAL, and magnets, called "SAND". ND-LAr and ND-GAr can move off-axis to observe varied beam spectra, a concept referred to as "DUNE-PRISM".

The DUNE far detector will use the cutting-edge LArTPC technology and will consist of four massive LArTPC modules (see Fig. 5, left), each with a fiducial mass of 10-kt, accounting to a total of 40-kt fiducial mass. The four separate caverns allow for flexibility in design. Each 10-kt detector (see Fig. 5, right) will be installed in a cryostat containing a total LAr mass of 17.5-kt. DUNE is currently exploring two technologies for the FD, single-phase (SP) and dual-phase (DP) LArTPCs. In a SP-LArTPC, the drift and collection of ionization electron signals is all in LAr whereas in the case of a DP, ionization signals are drifted vertically in LAr and transferred into the gas above the liquid for collection. For both technologies, full-scale engineering prototype program (ProtoDUNE) is actively underway at CERN in Switzerland at the CERN neutrino platform. Each prototype is approximately one-twentieth of a DUNE far detector module, but uses components identical in size to those of the full-scale module. The ProtoDUNE-SP was successfully built and commissioned in 2018 and collected test beam data between 2018 and 2020. ProtoDUNE-SP achieved exceptional noise operation and very good LAr purity [13]. ProtoDUNE-DP is currently taking data and both prototype demonstrators are being prepared for phase-2 upgrades and data taking. As noted in the European strategy update for particle physics [14], Europe and CERN through the CERN neutrino platform will continue to support long-baseline experiments in Japan and the United States, especially towards successful implementation of LBNF and DUNE. In addition to DUNE prototypes, CERN neutrino platform also includes near detector R&D activities for T2K and Hyper-K.

The Hyper-Kamiokande detector will be located in the Tochibora mine, about 295 km away from the J-PARC proton accelerator research complex in Tokai, Japan. It will be the largest underground water cherenkov detector (see Fig. 6, left) with a fiducial volume that is 8.4 times larger than the Super-K detector. Hyper-K will have 20 times more statistics than Super-K. The currently existing J-PARC accelerator will be steadily upgraded to reach a 1.3 MW beam by the

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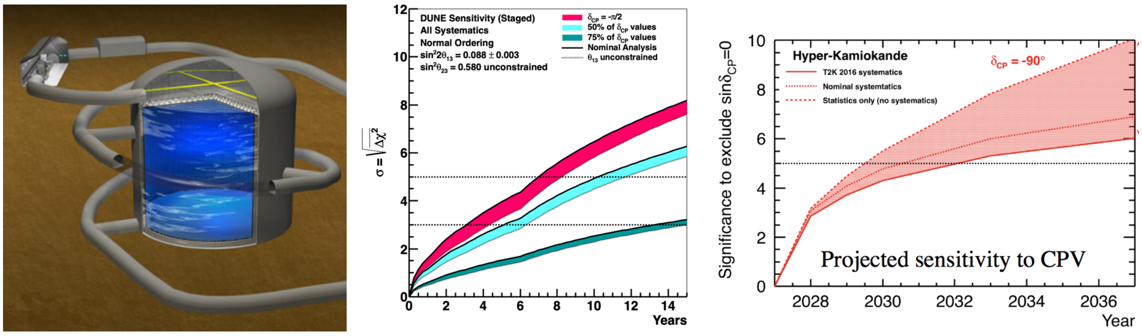

Figure 6: (left) Illustration of the Hyper-K first cylindrical tank in Japan. (middle) DUNE CPV sensitivity [16] as a function of time. The width of the band shows the impact of applying an external constraint on $\sin^2 2\theta_{13}$. (right) Hyper-K CPV sensitivity [15] as a function of time. The band shows the impact of systematic uncertainties.

start of the experiment. Hyper-Kamiokande is currently under construction and is scheduled to start operation in 2027. As of Feb. 2020, the first year construction budget has been approved and in May 2020, U. of Tokyo and the Japanese High Energy Accelerator Research Organization (KEK) signed the memorandum of understanding (MOU) in support of Hyper-K. Hyper-K will consist of two near detectors designed to significantly reduce systematics: 1) T2K's near detector ND280 will be upgraded to use super fine grained detectors (SuperFGDs) to improve short track efficiency and high angle acceptance, and 2) a new 1 kton-scale water cherenkov detector called "Intermediate Water Cherenkov Detector (IWCD)" will be located at $\sim$1 km baseline that can move vertically allowing for different off-axis angle measurements. A lot of R&D for near and far detectors of Hyper-K is actively underway. Figure 6 (right) shows Hyper-K's prospects for CPV measurement and the impact of systematic uncertainties. Uncertainties on neutrino interaction models are currently major contributors and as mentioned above, near detectors are designed to reduce the systematics. Figure 6 (middle) shows DUNE's CPV sensitivity assuming a staged deployment of the four far detector modules and equal running of neutrino and anti-neutrino modes.

Other next generation large-scale neutrino detectors that are observatories like DUNE and Hyper-K are JUNO, ORCA and PINGU. The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton liquid scintillator detector located in China (see Fig. 7, left). It will be capable of detecting neutrinos from reactor, supernova, atmospheric, solar and geophysical sources, and can perform exotic searches. JUNO is scheduled to take data in 2022. The major goal of JUNO is determining neutrino mass hierarchy. It can achieve 3σ MH sensitivity within 6 years and greater than 5σ sensitivity from a combined analysis with IceCube within 3-7 years or with PINGU in 2 years. The Oscillation Research with Cosmics in the Abyss (ORCA) experiment in the Mediterranean sea and the Precision IceCube Next Generation Upgrade (PINGU) experiment at South Pole will study atmospheric neutrino oscillations deep in water and ice, respectively, thus enhancing the matter effects. They are optimised for a measurement of the neutrino mass hierarchy, providing a sensitivity of 3σ in 3-4 years.

Beyond next generation neutrino observatories include Tokai to Hyper-Kamiokande to Korea or Korean Neutrino Observatory (T2HKK/KNO), Indian Neutrino Observatory (INO), Neutrino SuperBeam at European Spallation Source (ESSνSB), and THEIA (see Fig. 7). These experiments have very broad program with rich physics and the exact goals will depend on what we will find with next generation experiments. In the case of T2HKK/KNO, the far detector in Korea will

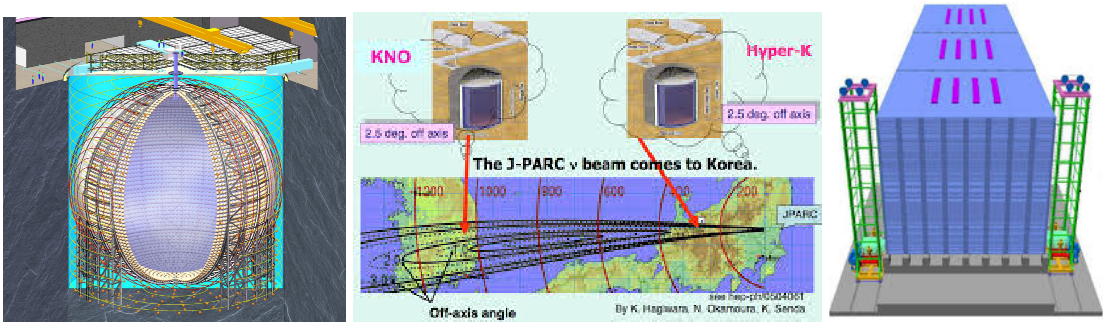

Figure 7: (left) The JUNO detector. (middle) The T2HKK/KNO experiment. (right) The INO experiment.

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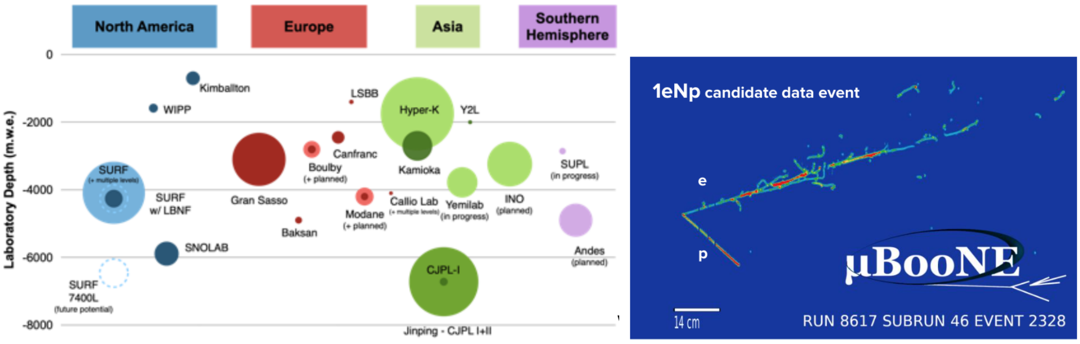

Figure 8: (left) Current and future Underground facilities across the map [17]. Circles represent the volume of the science space. (right) A ν_e candidate event from MicroBooNE.

receive ν beam from J-PARC in Japan and the massive Hyper-K will become the near detector. With the onset of many large-scale experiments favoring deep underground locations to reduce cosmic-ray backgrounds, the underground facility initiatives are also growing worldwide. Figure 8 shows worldwide current and future underground neutrino facilities.

5. Beyond 3-flavor Mixing

Anomalous results from short-baseline accelerator (e.g. LSND, MiniBooNE), radioactive source (e.g. Gallex, SAGE) and reactor (e.g. Bugey, Daya Bay) neutrino experiments in the recent years provide hints for high Δm^2 neutrino oscillations with one (or more) additional sterile neutrino states with masses at or below a few eV. Accelerator-based experiments saw anomalies in ν_e and anti-ν_e appearance channels but no evidence so far in ν_μ disappearance channels (e.g. in NOνA or MINOS). MiniBooNE's most recent results [3] show an excess of electron-like events at 4.8σ significance in the neutrino mode and a 6.1σ excess when combined with LSND. LSND and MiniBooNE anomalies remain unsolved to this day. Radioactive source & reactor experiments perform oscillation searches in the ν_e and anti-ν_e disappearance channels. Many results from reactor experiments such as NEOS, RENO, Double CHOOZ, Daya Bay, DANSS, PROSPECT, STEREO, and Neutrino-4 were reported in 2020 and no precise indication for sterile neutrino oscillations has been observed from anti-ν_e flux measurements at reactors. There are many important prospects in the future from very short-baseline reactor experiments such as PROSPECT, Neutrino-4, STEREO, DANSS, NEOS, and SoLid, decay-at-rest experiments such as IsoDAR and Coherent Captain Mills (CCM), and source experiments such as SAGE and BEST. Updated and improved results from PROSPECT, SoLid, and NEOS are expected in the near future along with joint analysis from PROSPECT, Daya Bay and STEREO. The CCM experiment is currently analyzing neutrino beam data and results are expected soon. The BEST experiment will address the Ga anomaly by 2020.

Addressing the MiniBooNE anomaly requires highly granular detectors that can unambiguously distinguish electrons from photons. The MicroBooNE experiment at Fermilab is utilizing the LArTPC technology to address the MiniBooNE anomaly along with performing high-statistics neutrino cross section measurements in argon in the ~1 GeV range. MicroBooNE has been collecting data since 2015 and is currently at the cusp of unblinding the data to produce first results

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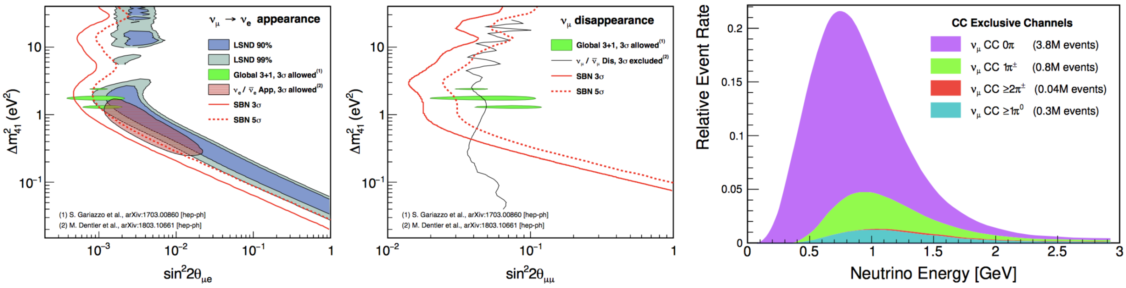

Figure 9: The SBN 3σ (solid red line) and 5σ (dotted red line) sensitivities [21] to a light sterile neutrino in the $\nu_\mu \to \nu_e$ appearance channel (left) and $\nu_\mu \to \nu_\mu$ disappearance channel (middle). (right) Neutrino induced charged-current (CC) event rates in SBND.

soon. Figure 8 (right) shows an ν_e candidate event from MicroBooNE. MicroBooNE is performing the MiniBooNE low energy excess analysis in both electron [18] and photon channels [19]. The Short-Baseline Neutrino (SBN) [20] program at Fermilab which builds upon the already existing MicroBooNE detector by adding additional detectors along the Booster Neutrino Beam (BNB) at Fermilab will more definitively address the sterile neutrino question where there are existing hints. The Short-baseline near detector (SBND) with 112 tons of active LAr mass will sit closest to the booster neutrino source at 110 m. The ICARUS detector with 476 tons of active LAr mass will act as the far detector sitting at 600 m on the BNB. This multiple-detector arrangement using the same neutrino source and same detector technology is expected to reduce the systematic uncertainties significantly. In addition, SBN can perform oscillation searches in both ν_e appearance and ν_μ disappearance modes. As shown in Figure 9 (left, middle), SBN can cover much of the parameters allowed by past anomalies at greater than 5σ significance [21]. The SBND detector is currently being constructed and the ICARUS detector is in the commissioning phase. Besides SBN, the JSNS^2 at J-PARC (Japan) just started taking data and aims for a direct test of LSND.

6. Neutrino-Nucleus Interactions

Needless to say, with experiments using denser nuclear targets, understanding neutrino-nucleus interactions is critical for current and future oscillation experiments. Especially, with next generation neutrino experiments favoring LArTPCs, ν-Ar cross section measurements are even more important to improve nuclear modeling and provide crucial inputs to oscillation analyses along with reducing systematics. Cross section measurements from T2K, NOνA, MINERνA, COHERENT, ArgoNeuT and MicroBooNE experiments are significantly contributing to our understanding of neutrino-nucleus interactions and this is only expected to grow steadily in the future. More measurements are expected from LArIAT, ProtoDUNEs, SBND, ICARUS and next generation long-baseline near detectors such as IWCD and DUNE ND along with off-axis measurements. For example, SBND will collect the world's highest statistics (see Fig. 9, right) for ν-Ar cross section measurements and ICARUS will collect high statistics for electron neutrino cross section measurements on argon using the off-axis beam at Fermilab. In addition, experimentalists are closely partnering with neutrino theorists and phenomenologists to improve nuclear models and implementation of neutrino generators in the simulation along with interpreting oscillation results using new physics.

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7. Summary & Outlook

The neutrino community has witnessed enormous progress across all fronts this year and as highlighted in the document, there are many exciting prospects to look forward to in the future. Next generation experiments are bigger, technologically superior and have broad physics program beyond just being oscillation experiments. Together the community is striving globally to understand the full picture of neutrinos and is already thinking about beyond the next generation experiments.

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