PROCEEDINGS OF SCIENCE

Status of the Hyper-Kamiokande Experiment

Ajmi Ali*
On behalf of the **Hyper-K** Collaboration
Department of Physics, University of Winnipeg,
515, Portage Avenue, Winnipeg, Manitoba, Canada
E-mail: a.ajmi-ra@uwinnipeg.ca

Hyper-Kamiokande or Hyper-K is the next generation Water Cherenkov detector being constructed in Kamioka, Japan, following the successful running Super-Kamiokande experiment. The Hyper-Kamiokande will not only measure neutrinos from the accelerator at J-PARC, Tokai in Japan, as a long-baseline neutrino experiment but also from the natural sources like the sun and the atmosphere. The design and construction of the detector is progressing currently, and the experiment is expected to start taking data in 2027. Apart from advanced PMT configurations, the Hyper-K will also have an Intermediate Water Cherenkov Detector (IWCD) at a distance of approximately a km from the neutrino-source, while the far detector will be located 295 km away. The designs and status of this enormous detector Hyper-K, which is currently under-construction, the status of the near or intermediate detectors, and the main and expected physics capabilities of the experiment are described in this report.

16th International Conference on Heavy Quarks and Leptons (HQL2023)
28 November-2 December 2023
TIFR, Mumbai, Maharashtra, India

*Speaker

PoS(HQL2023)098

1. Introduction

The Hyper-Kamiokande (Hyper-K) detector [1] is the next generation Water Cherenkov (WC) detector in Japan, the youngest yet the largest member in the Kamiokande family of WC detectors. The Hyper-K will be the far detector of the Tokai-to-Kamioka (now called T2K [2]) long baseline experiment, besides observing neutrinos from natural sources. The accelerator and the near detector complex are at J-PARC in Tokai, Ibaraki Prefecture, 295 km away from the site of the far detector, Hyper-K which is at Kamioka, on the west coast of Japan.

The Hyper-K detector, 71 m tall, and 68 m in diameter, will contain ∼260 kton of water, with a fiducial mass of ∼190 kton, which is about 8 times larger than the Super-Kamiokande. The detector will be instrumented with 20,000 50 cm photomultiplier tubes (PMTs) and more (discussed later).

The (anti)neutrino beam, produced at the J-PARC accelerator facility, will be measured by the near detectors and the intermediate WC detector at Tokai, before it reaches the far detector Hyper-K, as depicted in the Fig. 1.

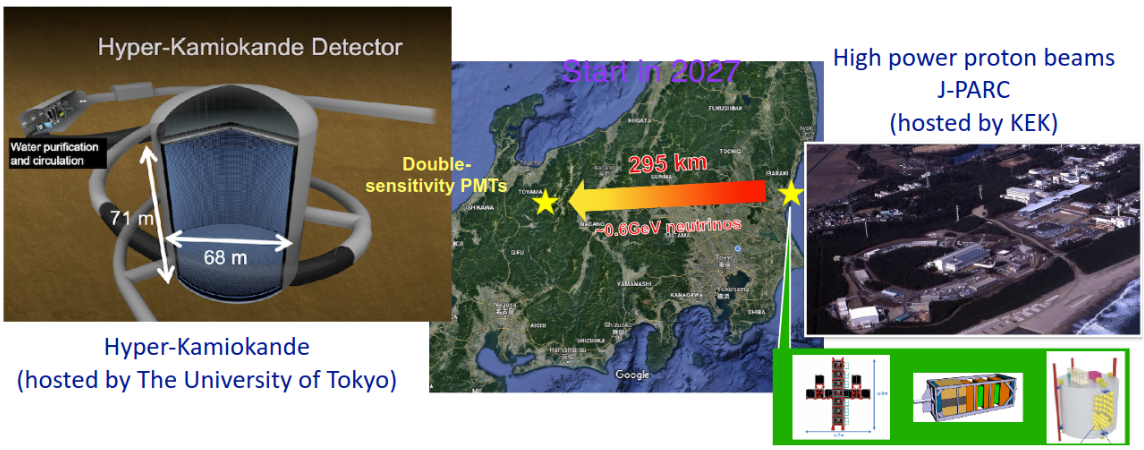

Figure 1: Schematic Diagram of the Hyper-K detector, the J-PARC accelerator and the near /intermediate detectors of the Hyper-K experiment, and the neutrino beam direction from the east coast to the west coast of Japan, travelling 295 km.

Neutrino oscillations is primarily characterised by the elements in the PMNS matrix, which lists them as follows:

$$U=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

The probabilty of the neutrino oscillation is then calculated as a function of the mixing angles (θ_{ij}), L (distance travelled), the neutrino energy (E) and the differences in their mass-squares, Δm_{ij}.

The values of θ_{12} and θ_{13} have already been determined to significant precision by the solar, reactor and accelerator neutrinos, and θ_{23} to some extent by the atmospheric/accelerator neutrinos [3–5]. The important questions still waiting to be answered are the phase of CP violation (δ_{CP}), the ordering of ν-mass hierarchy (sign of Δm^2_{13}); and the octant or prescision of the θ_{23}.

Hyper-K will study the neutrino oscillations phenomenon using both, the accelerator neutrinos, as well as the atmospheric neutrinos. The main physics goals of the Hyper-K and the status of progress in building of the experiment are discussed in the following report.

2. Physics Sensitivities

The Tokai-to-Hyper-K Long baseline experiment will use the 2.5° off-axis ν_μ and $\bar{\nu}_\mu$ beam peaked at 0.6 GeV (oscillation maximum at 295 km) and measure neutrinos in the $\nu_\mu/\bar{\nu}_\mu$ disappearance channel, as well as the $\nu_e/\bar{\nu}_e$ appearance channel.

With (anti)neutrino beam data in the ratio of 1:3 ($\nu : \bar{\nu}$), running over a period of 10 years, the Hyper-K can exclude CP conservation to 5σ for >60% of true δ_{CP} values, and to 3σ for >75% values, as shown in Fig. 2. Despite the expected high statistics in Hyper-K, it's critical to improve systematic errors on the beam, neutrino interactions and the detector related parameters. Analysis of the events rate from the neutrino beam and the atmospherics, combined, improves its sensitivity over that with beam alone when the ordering of the mass hierarchy (MO) is unknown, as can be seen from Fig. 3. It is also sensitive to the octant determination of θ_{23} and the ordering of the neutrino mass hierarchy, to approximately beyond 3.6σ and 3.8σ respectively.

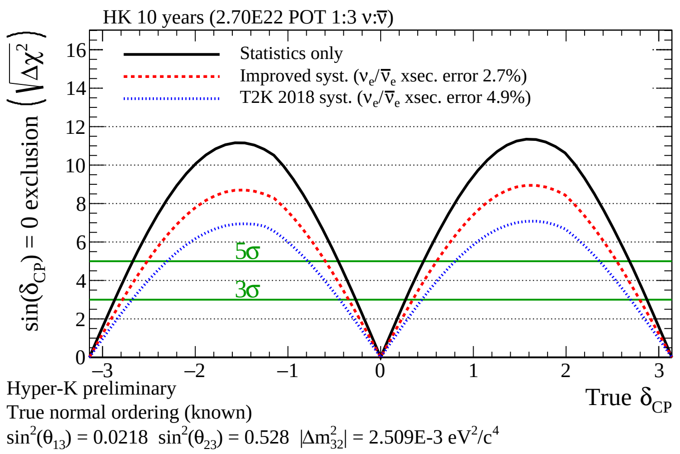

Figure 2: Sensitivity to determining the δ_{CP}, at the Hyper-K, with and without considering the systematic uncertainties. Effect of better estimated uncertainties (improved) due to different aspects like the improved cross section measurements of $\nu_e/\bar{\nu}_e$, including estimated contraints from the upgraded ND280 and IWCD, etc., also shown in red.

Hyper-K is sensitive to neutrinos from core-collapse supernova bursts, pre-supernova neutrinos and to the integrated supernova relic neutrino (SRN) background [7, 8]. It expects to see 50-90k neutrinos from SN-bursts 10 kpc away. It's sensitivity to the neutrinos from the pre-supernova phase of the stars, due to silicon burning, approximately two days before the core collapse, is also an added advantage to the entire physics community. Hyper-K can measure the diffused rate of neutrinos coming from the past supernovae, mostly in the

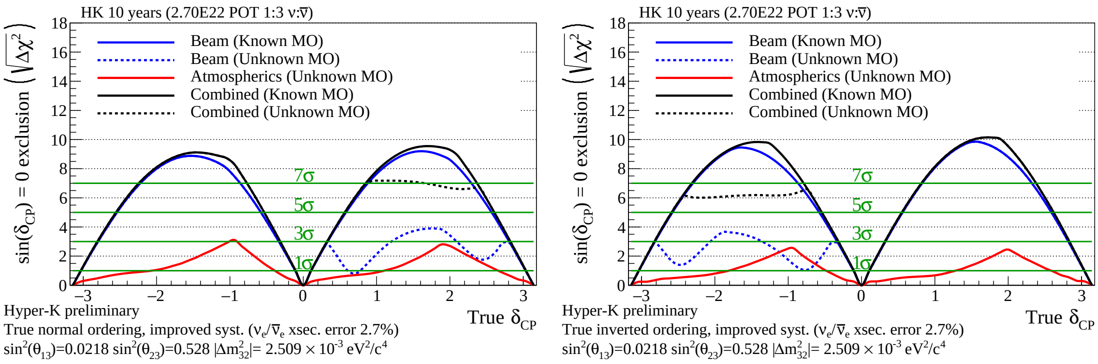

Figure 3: Sensitivity to determining the δ_{CP}, at the Hyper-K, assuming known/unknown MO, using events from the beam and with/without adding the atmospheric contribution. The true values of the oscillation parameters are specified at the bottom left of the plots.

energy window between 16-30 MeV, and the corresponding sensitivity is shown in Fig. 4-left with/without considering 30% of the backgrounds from black hole remnants.

Oscillations in the solar neutrinos are enhanced by matter (MSW) effects as a function of the neutrino energy. Low-energy solar neutrinos from the pp chain, ^{7}Be and proton-electron capture (pep-chain) have higher survival probability than those from ^{8}B decay, which is in the higher energy range and dominated by the MSW effect. Hyper-K will collect data in this intermediate energy region, between 2 MeV and 7 MeV. This region, as known as the upturn curve, is also expected to be sensitive to new physics models, such as the inclusion of sterile neutrinos or non-standard interactions [6]. The extent of the upturn discovery sensitivity (5σ or 3σ) at Hyper-K depends on the energy threshold (3.5 MeV or 4.5 MeV respectively), as shown in Fig. 4-right.

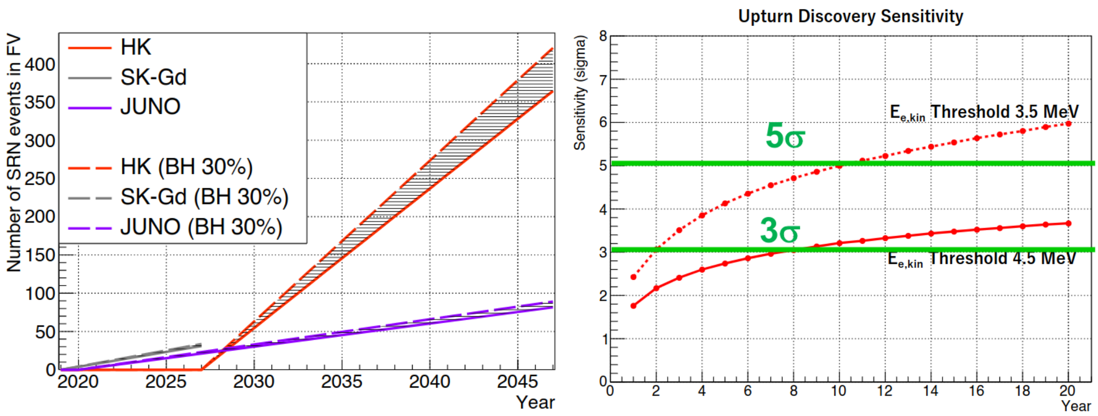

Figure 4: Left: SRN detection sensitivity with/without black hole remnants background. Right: Solar neutrino upturn sensitivity at Hyper-K.

The Hyper-K will also look for the proton decays in the two channels, the $p \to e^+ + \pi^0$ and $p \to K^+ + \bar{\nu}_\mu$ decay modes, and their estimated sensitivities are shown in Fig. 5. The proton decay lifetime could be reached beyond 10^{35} years with 10 years of data taking at the Hyper-K.

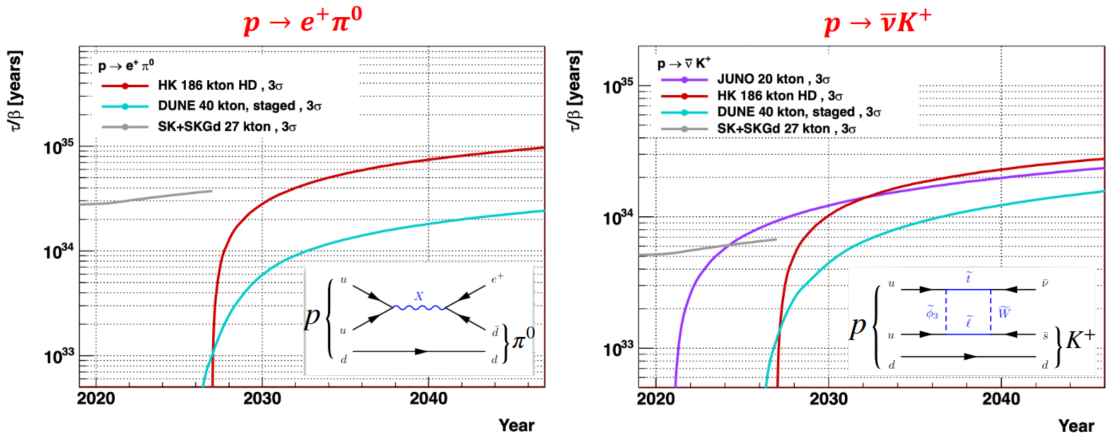

Figure 5: Proton decay sensitivities of Hyper-K in the two most significant modes $p \to e^+ + \pi^0$ (left) and $p \to K^+ + \bar{\nu}_\mu$ (right).

3. Far-Detector Status

The site of the Hyper-K detector is very close to that of the Super-K, and will be under a rock-covering of 600 m under the Mt. Nijugoyama, in Kamioka, Japan. Excavations and civil engineering have been in full swing since 2021. The access tunnels have already been completed and the cavern excavation is ongoing. Excavation of the huge dome section, measuring 69 m in diameter and 21 m in height, has also been completed, in Oct. 2023, a glimpse of which is shown in Fig. 6. The cylindrical section of the cavern is being excavated currently, as all scheduled. The data taking at the Hyper-K is scheduled to start in 2027.

The detector will be read out by 20,000 Hamamatsu 50 cm box-and-line-dynode (BL) PMTs installed on the Inner Detector (ID), and 3600 8 inch PMTs with Wavelength-shifting plates (WLS) on the Outer detector (OD), to veto the cosmic muons and other radioactive and cosmogenic backgrounds. The new BL-PMTs will provide improved photodetection efficiency, better pressure tolerance, better charge and timing resolution, as compared to the PMTs used in the SuperK. The PMT productions, delivery and quality checks are ongoing. Furthermore, there will also be about ∼800 multi-PMT modules for the ID, consisting of 19 8 cm Hamamatsu PMTs per module, to aid in better timing and vertex resolution.

The front-end electronics will be installed underwater, given the large number of detector units/modules. There are two types of underwater-electronics vessels to be employed: one to tend to the ID PMTs exclusively (24 channels per vessel), while the other is of a hybrid kind that will each support 20 ID and 12 OD channels. The vessels will accommodate both the high-voltage and the low-voltage power supplies, the data processing and timing boards to connect to the external Global Positioning Systems. Tests to finalise the designs of these components are ongoing at different collaborating institutes.

Figure 6: Excavation of the dome section of the cavern that will house the Hyper-K detector, completed on 3rd Oct. 2023. The dome is 69 m in diameter and 21 m in height.

4. Neutrino-Beam Status

The neutrino beam is produced by the proton beam hitting a graphite target, followed by selection of mainly the π^+/π^- by magnetic horns and letting them decay into muons and neutrinos. All charged particles are then dumped or absorbed, allowing the neutrinos only to beam through, as known as the neutrino beam.

The neutrino beam at the J-PARC accelerator centre will also be upgraded for the Hyper-K experiment. The objective is hence to achieve 1.3 MW of proton beam power by 2027. Increasing the proton beam power from 515 kW to ~750 kW and then to 1.3 MW involves several upgrades or improvements, all aiming to mainly increasefor the ID the frequency of beam spills and boosting the number of protons per spill. New power supplies for the magnetic horns are being implemented in order to enhance the repetition cycle from 2.48 s/cycle to 1.32 s/cycle to 1.16 s/cycle respectively, as planned in Fig. 7. New RF (Resonance Frequency) cavities too are being installed to achieve this objective. A new horn magnet is designed and being tested for this purpose. Re-designing the configuration of the graphite target is also underway to cope with the higher intensity proton beam which will be incident on it, to mention just a few from the long list of steps.

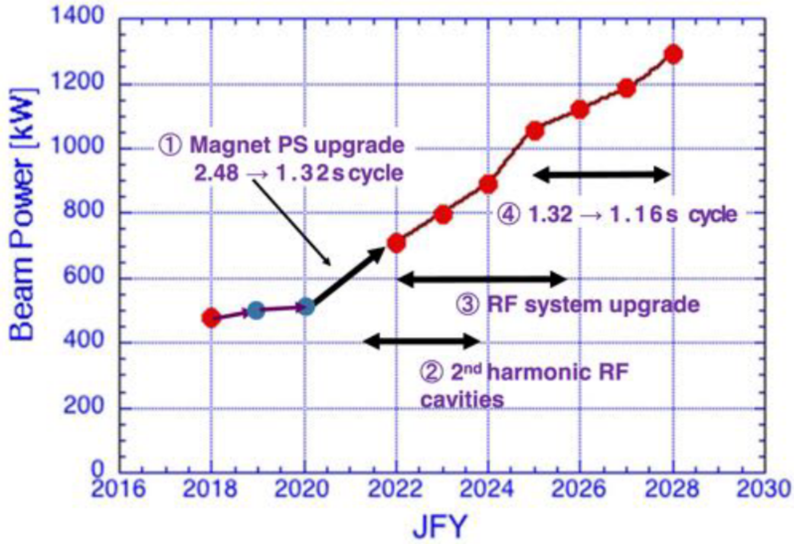

Figure 7: Planned schedule of the neutrino beam upgrade at J-PARC, aiming to achieve 1.3 MW by 2027.

5. Status of the Near-Detectors

Besides the existing near detectors of the T2K experiment [2], a new Intermediate WC detector (IWCD) will also be built along the Tokai-to-Hyper-K baseline.

The array of the T2K near detectors at 280 m, comprises of the on-axis "INGRID" detector, and the off-axis magnetised tracker detector "ND280", which is being upgraded currently, to include a High-Angle TPC (Time Projection Chamber), Super-FGD (Fine Grain Detector) and a Time-of-Flight detector. The upgraded version has already been installed and is being tested with the neutrino beam. This upgrade will enable the ND280 with higher particle detection efficiency, wider phase space coverage and better proton/neutron acceptance.

A movable mini-WC-Detector (IWCD) (∼800 t) will be built ∼1 km from the J-PARC, to further constrain the systematic uncertainties.

The IWCD will be read out by the multi-PMT modules, and the detector position will be movable along vertical direction. This is to probe the neutrino spectra peaking at different energies, due to the off-axis angle effect (1-4°), as depicted in Fig. 8. Designing the details of the detector system and the site finalisation are underway.

A beam test using a 50 ton scale WC detector exposed to a charged particles beam at CERN, is planned next year to validate the performance of the mPMT detection systems and the various calibration devices to be deployed in the IWCD.

6. Calibration

Adequate calibration of the detector-systems is an essential component in every experiment. A number of systematic parameters need to be understood well for the more efficient

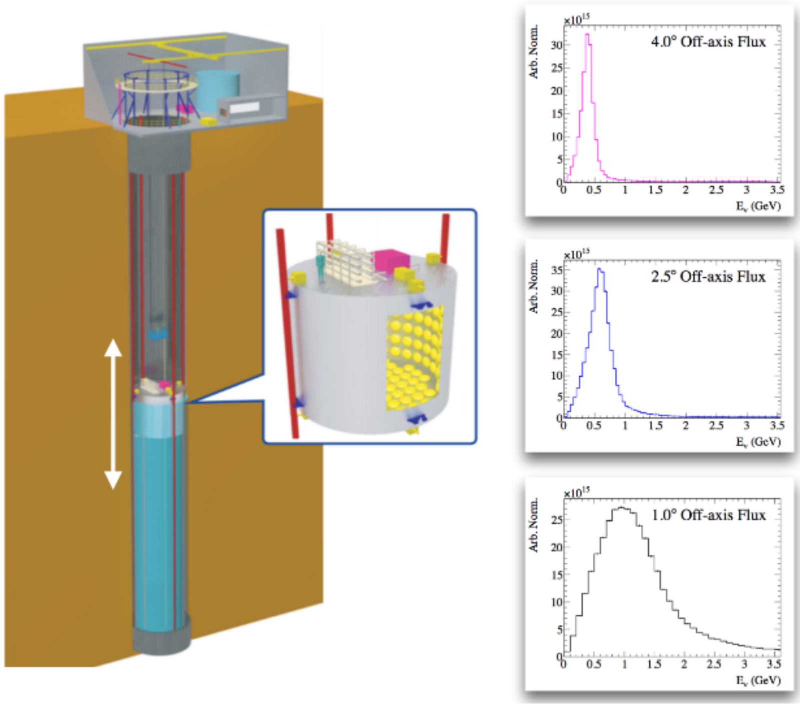

Figure 8: A schematic diagram of the IWCD, that will move along the vertical direction spanning the neutrino beam over 1-4° off-axis (anti)neutrino beam.

WC detector measurements, like: geometry, water quality, reflections, timing, PMT response, PMT Single-Photon-Efficiency/Quantum Efficiency, Cherenkov radiation features, etc. For precise measurements, accurate calibration of all detector properties becomes more crucial for smaller WC detectors. Hence, extensive precalibration programme and photogrammetry are being worked upon in this perspective. A number of different calibration sources/devices are being tested to finalise designs, like the light injection systems (includes diffusers, colllimators etc.), the Electron Linac system, which will use 3-24 MeV electrons and a number of different radioactive sources like the DT Source $_{16}$N, AmBe + BGO-tagged neutrons, Ni/Cf source (9 MeV γ cascade) etc. The photogrammetry project aims to correct for the shifts in the geometry and position of the detection units and the deployed calibration sources.

7. Conclusion

The Hyper-Kamiokande or Hyper-K, the next generation neutrino experiment is under construction, and proceeding as scheduled, and will start operation in 2027. The primary physics objectives of the Hyper-K are discovering the Neutrino CP violation with 5σ sensitivity for $\sim$60% parameter δ_{CP} regions, the ordering of the neutrino mass hierarchy and the θ_{23} octant determination. It will also look for nucleon decay search (p-decay) besides measuring neutrinos from the atmosphere, the solar neutrinos and astrophysical sources like the supernovae.

The experiment is under construction and the production phase is ongoing as planned. The access tunnels, and dome construction have been completed, and the barrel excavation is ongoing. The inner detector is planned with a hybrid configuration of 20,000 improved PMTs and 800 mPMTs, the production of which is ongoing. Finalising designs and tests of the different other components at the far detector, the details of the new intermediate detector, and various calibration methods are ongoing at the different collborating institutes of the Hyper-K, and all expected to converge in time.

References

[1] K. Abe et al. "Hyper-Kamiokande Design Report", (May 2018). arXiv: 1805.04163

[2] K. Abe et al. (T2K), Nucl. Inst. Meth. A 659, 106 (2011).

[3] K. Abe et al. "Observation of Electron Neutrino Appearance in a Muon Neutrino Beam", Phys. Rev. Lett. 112 (2014), p. 061802. doi: 10 . 1103 / PhysRevLett . 112 . 061802.

[4] K. Abe et al. "Atmospheric neutrino oscillation analysis with external constraints in Super-Kamiokande I-IV", Phys. Rev. D 97.7 (2018), p. 072001. doi: 10 . 1103 / PhysRevD . 97 . 072001.

[5] S. Fukuda et al. "Solar B-8 and hep neutrino measurements from 1258 days of Super-Kamiokande data", Phys. Rev. Lett. 86 (2001), pp. 5651–5655. doi: 10.1103/PhysRevLett.86.5651.

[6] Michele Maltoni and Alexei Yu. Smirnov. : "Solar neutrinos and neutrino physics", Eur. Phys. J. A 52.4 (2016), p. 87. doi: 10.1140/epja/i2016-16087-0. arXiv: 1507.05287 [hep-ph].

[7] K. Abe et al. "Supernova Model Discrimination with Hyper-Kamiokande", Astrophys. J. 916.1 (2021), p. 15. doi: 10.3847/1538-4357/abf7c4. arXiv: 2101.05269 [astro-ph.IM]

[8] L. N. Machado et al. "Pre-supernova Alert System for Super-Kamiokande", Astrophys. J. 935.1 (2022), p. 40. doi: 10.3847/1538-4357/ac7f9c.