Status of Hyper-Kamiokande experiment

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Abstract

The Hyper-Kamiokande experiment is a next-generation water Cherenkov detector aiming to advance neutrino and astrophysics research. With a 188-kiloton fiducial volume and 40% photo-coverage, Hyper-K will enable precise studies of neutrino oscillations, CP violation, and proton decay. Its sensitivity to cosmic neutrinos positions it to observe solar, supernova, and relic neutrinos, enhancing our understanding of stellar phenomena and cosmic evolution. Anticipated to begin in 2027, Hyper-K will play a pivotal role in multimessenger astrophysics, contributing transformative insights into particle physics and astrophysical events.

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1 Introduction

The Hyper-Kamiokande (Hyper-K) project [1] [2] [3] represents a major advancement in neutrino and astrophysics research, building on the legacy of Kamiokande and Super-Kamiokande. Currently under construction in Japan, Hyper-K features a 188-kiloton water tank with 20-inch photomultiplier tubes (PMTs) and multi-PMT modules, offering a fiducial volume eight times larger than Super-K and 40% photo-coverage for efficient Cherenkov radiation detection (Figure 1). Hyper-K's far detector is being constructed at Gifu, Japan, 295 km downstream from J-PARC. The tank will provide the fiducial volume of 0.188 Mt ultra pure water, with the dimensions of the 71 m (D) × 60 m (H).

Using J-PARC's neutrino beam, Hyper-K's primary focus is the precise measurement of neutrino oscillation parameters, including the determination of the CP-violating phase (δ_{CP}) in the lepton sector. By measuring differences in oscillation probabilities (Figure 2 (a)) between neutrinos and antineutrinos, Hyper-K aims to provide critical insights into the matter-antimatter asymmetry in the universe. Over the next decade, it is projected to achieve 5σ sensitivity to CP violation for a wide range of δ_{CP} values (Figure 2 (b)), significantly advancing our understanding of this fundamental phenomenon.

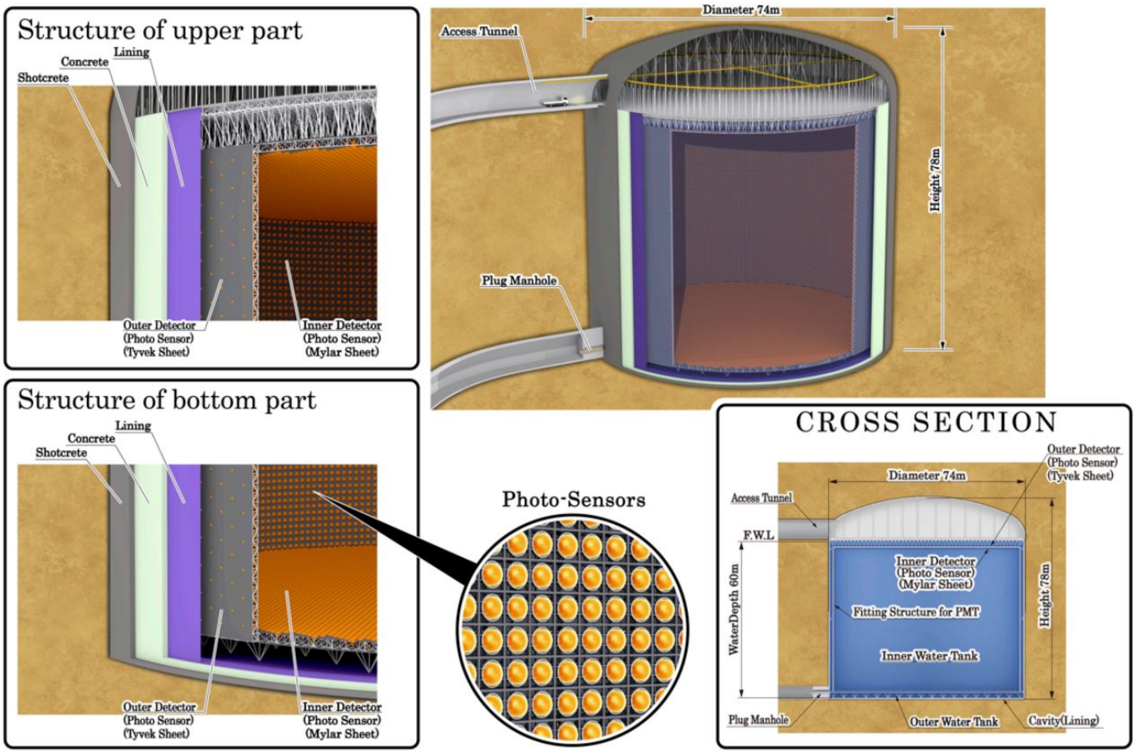


Figure 1: Hyper-K's far detector design [3]. Copyright Hyper-Kamiokande collaboration.

Hyper-K's enhanced sensitivity to neutrino mass hierarchy will resolve the ordering of neutrino masses (Figure 2 (c)), a long-standing question in particle physics. By analyzing the interaction of atmospheric neutrinos, which traverse different path lengths and densities through the Earth, Hyper-K will discriminate between the normal and inverted mass orderings. Additionally, precise measurements of the θ_{23} mixing angle octant will refine the three-flavor oscillation framework, potentially revealing new physics beyond the Standard Model.

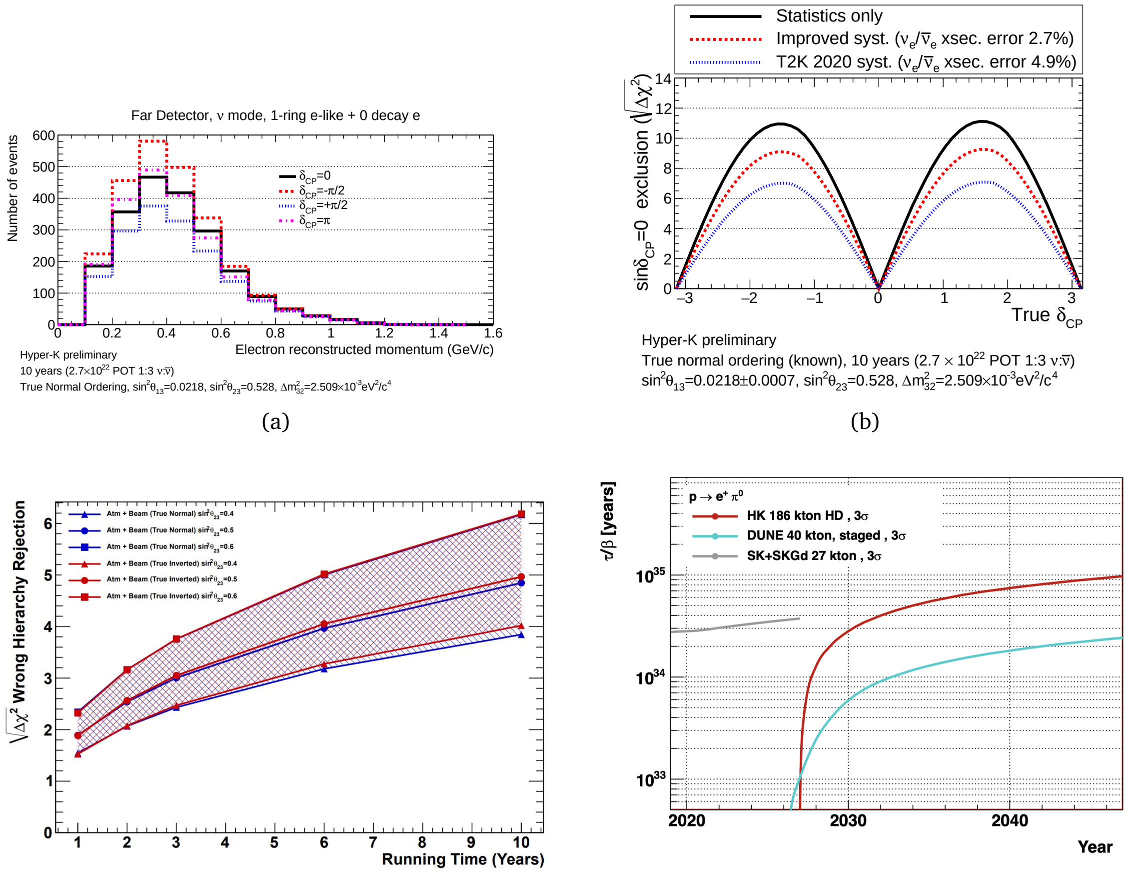
In addition to oscillation studies, Hyper-K is uniquely equipped to search for proton decay, a key prediction of Grand Unified Theories (GUTs). Over the next 10 years, it is expected to improve the lower limits on the proton lifetime by an order of magnitude, particularly for decay channels such as $p \to e^+\pi^0$ (Figure 2 (d)) and $p \to \bar{\nu}K^+$. The discovery of proton decay would have profound implications for understanding the unification of fundamental forces and the early universe.

In astrophysics, Hyper-K will study neutrinos from solar and supernova sources, refining models of solar neutrino oscillations and investigating stellar collapse dynamics. Its ability to detect supernova relic neutrinos will provide insights into star formation and cosmic evolution.

Key construction milestones include excavation of the access tunnel and cavern, with scientific operations expected to begin in 2027 (Table 1). Hyper-Kamiokande is positioned to drive transformative discoveries in both particle physics and astrophysics.

2 Supernova, Relic, and Multimessenger Astrophysics Neutrino Detection

The Hyper-Kamiokande (Hyper-K) experiment is uniquely equipped to detect neutrinos from supernovae and relic neutrinos, offering insights into stellar collapse and cosmic star forma-

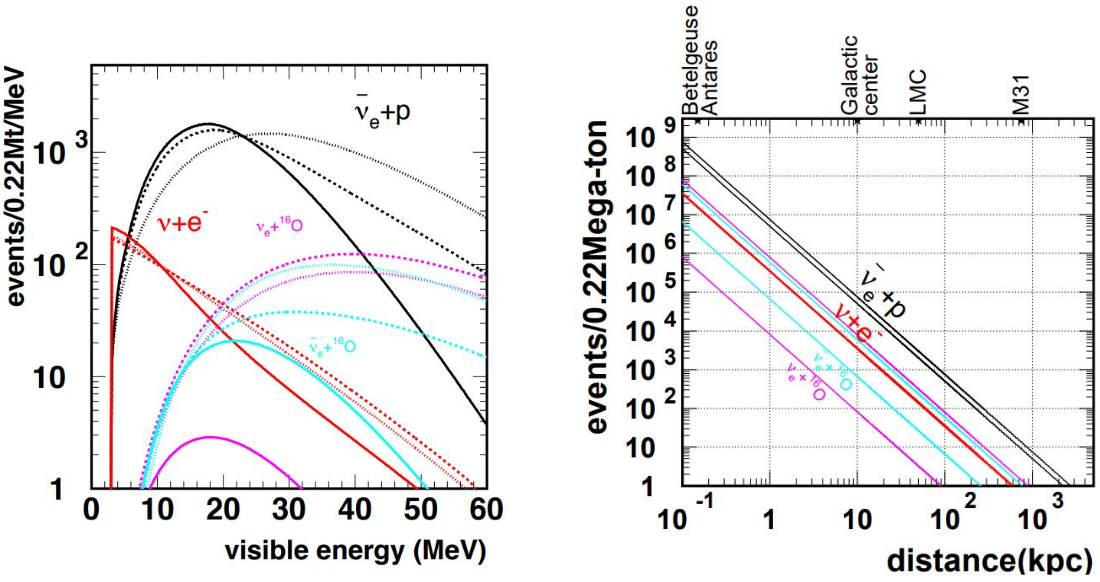


(a) (b) (c) (d)

Figure 2: Hyper-K's sensitivities, Copyright Hyper-Kamiokande collaboration. a) Reconstructed electron momentum spectrum for the ν-mode beam, showing the effect of changing values of δ_{CP} (2023). b) $sin\delta_{CP} = 0$ exclusion as a function of true δ_{CP} for 10 HK-years and different systematics models (2023). c) The wrong hierarchy rejection sensitivity for atmospheric neutrino observation as a function of running time [3]. d) The $p \rightarrow e^+\pi^0$ life time with 3σ discovery as a function of running time (2020).

	Activity Timeline (Summary)
Cavern	Excavation finished in 2024
Water Tank	Structure Construction in 2026
50-cm PMTs	Assembly 2026-2027
PMT Covers	Assembly 2026–2027
mPMTs	Assembly 2025–2026
Outer Detector (OD)	Assembly 2026
Electronics	Assembly 2025–2026
	Installation 2026-2027 → Water filling 2027
Accelerator/Beam	Upgrade 2024 - 2027
IWCD	Construction 2025-2027
	Operation and Data Taking 2027-2028

Table 1: Summary of Hyper-Kamiokande Construction Activities and Timeline.



(a) (b)

Figure 3: (a) Energy spectra of events from a supernova neutrino burst in Hyper-K assuming the Totani [4] model and a fiducial distance of 10 kpc [3]. (b) Expected number of supernova burst events for each interaction as a function of the distance to a supernova with 1 tank. The band of each line shows the possible variation due to the assumption of neutrino oscillations. Copyright Hyper-K collaboration [3].

tion history. Its design also integrates with multimessenger networks, enabling collaborative observations with gravitational wave and electromagnetic detectors.

Hyper-K's large volume and sensitivity allow detection of tens of thousands of neutrinos from nearby supernovae within seconds, primarily via inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$) and neutrino-electron elastic scattering ($\nu + e^- \rightarrow \nu + e^-$). In Figure 3 (left) energy spectra of events from a supernova neutrino burst in Hyper-Kamiokande assuming the Totani [4] model and a fiducial distance of 10 kpc. Different colours stand for inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ (black), ve-scattering $\nu + e^- \rightarrow \nu + e^-$ (red), $\nu_e + {}^{16}\mathrm{O}\,\mathrm{CC}(\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}^*)$ (purple) and $\bar{\nu}_e + {}^{16}\mathrm{O}\,\mathrm{CC}(\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N}^*)$ (light blue), while solid, dashed and dotted lines correspond to no oscillation, normal ordering and inverted ordering, respectively [3]. In Figure 3 (right) expected number of supernova burst events for each interaction as a function of the distance to a supernova with 1 tank. The band of each line shows the possible variation due to the assumption of neutrino oscillations [3].

These measurements reconstruct supernova dynamics and probe the formation of neutron stars or black holes. Hyper-K's reach extends to supernovae in the Milky Way, Andromeda (M31), and beyond, providing critical data on supernova mechanisms and neutrino behavior.

Hyper-K will also detect diffuse supernova neutrino background (DSNB), capturing relic neutrinos from past cosmic supernovae. Its Gadolinium-doped water future update, will enable the detection of tens of DSNB events annually in the 16-30 MeV range, refining models of supernovae, star formation rates, and cosmic energy output.

As part of the multimessenger framework, Hyper-K's real-time neutrino detection can trigger follow-up observations in gravitational wave and electromagnetic observatories, such as LIGO, Virgo, and KAGRA. This synergy helps uncover connections between neutrino emissions and gravitational waves during core collapse. Hyper-K's ability to measure neutrino flavor composition further enriches insights into dense astrophysical environments.

(a) (b)

Figure 4: (a) A mockup of 50 cm PMTs with covers for the Hyper-K Far Detector Inner Detector. Copyright CC BY 4.0, Jan Kisiel (Silesia U.) for the Hyper-K collaboration [6]. (b) Top and side view of early version of the mPMT. Copyright Saul Cuen-Rochin.

Hyper-Kamiokande's capacity to detect supernova neutrinos, relic neutrinos, and support multimessenger efforts positions it as a vital tool for studying stellar evolution, cosmic history, and fundamental physics.

3 Towards completing construction

The Hyper-Kamiokande (Hyper-K) project is progressing steadily since its approval in 2020, with key milestones achieved in excavation and detector assembly. This includes the development of photodetectors, tank infrastructure, and near detector systems.

The main tank, a cylindrical structure 71 meters in diameter and 64 meters in height, will house 20,000 newly developed 50-cm PMTs (Hamamatsu R12860), which offer double the detection efficiency of their predecessors due to improved photon detection and timing resolution (Figure 4 (a)). Over 10,000 PMTs have been inspected and delivered at Kamioka. Complementing these are 800 multi-PMT (mPMT) modules (Figure 4 (b)) [5], each with 19 3-inch PMTs, enhancing directional sensitivity and Cherenkov ring reconstruction. These modules, alongside 3,600 3-inch PMTs in the outer detector, are undergoing rigorous testing for long-term stability. Signals will be digitized with underwater electronics to avoid long cabling, a crucial factor given the extensive cabling required for the detector's thousands of PMTs.

Efforts are ongoing to finalize underwater electronics, which digitize PMT signals and transmit data efficiently from the detector. These systems, housed in pressure-resistant vessels, are critical for long-term underwater operations. Cavern excavation, including the access tunnel and main detector chamber, is well underway, with rock overburden shielding from cosmic rays. Mockup frames (Figure 4 (a)) for PMTs have been tested to ensure structural stability and streamline underwater cabling, improving efficiency for the thousands of PMTs installed.

The ND280 detector suite shown in Figure 5 (a), is a key near detector system for Hyper-Kamiokande, located 280 meters downstream from J-PARC, designed to monitor the neutrino beam and reduce systematic uncertainties in neutrino oscillation measurements. It comprises multiple subsystems, including INGRID, an on-axis detector that measures the beam direction and intensity, and a magnetized tracker for off-axis measurements of neutrino interaction rates and energy spectra. Recent upgrades to ND280 include the Super Fine-Grained Detector (SuperFGD), a high-resolution 3D tracking detector, and new horizontal Time Projection Chambers (TPCs), which improve the angular acceptance and particle identification capabilities. These advancements enhance ND280's ability to measure neutrino cross-sections and flux properties before they reach the far detector. The Intermediate Water Cherenkov Detector (IWCD), shown in Figure 5 (b) is a near detector designed to enhance the precision of neutrino oscillation measurements for the Hyper-Kamiokande experiment. Positioned approximately 750 meters downstream of the neutrino beam source at J-PARC, IWCD is capable of adjusting its vertical position within its water-filled tank to sample neutrino interactions at different off-axis angles. This enables it to measure the neutrino energy spectrum across a wide range, reducing systematic uncertainties associated with neutrino flux and interaction modeling. By improving the characterization of the neutrino beam and cross-section properties, the IWCD plays a crucial role in refining Hyper-K's sensitivity to CP violation, mass hierarchy, and other key neutrino oscillation parameters.

With the far detector excavation, photodetector production, and near detector upgrades progressing on schedule, Hyper-K remains on track to begin operations in 2027, promising transformative contributions to neutrino physics and astrophysics.

4 Conclusion

The Hyper-Kamiokande project is set to revolutionize neutrino physics and astrophysics through advanced technology and a massive detection volume. Progress in excavation, photodetector assembly, and electronics development is on schedule, with near detector upgrades enhancing precision in neutrino studies.

This global collaboration, involving scientists from over 22 countries, is on track to begin operations in 2027. Hyper-K will enable groundbreaking discoveries in CP violation, proton decay, and astrophysical neutrinos, establishing itself as a flagship experiment in particle physics. Its multidisciplinary approach promises transformative insights into the universe's fundamental processes.

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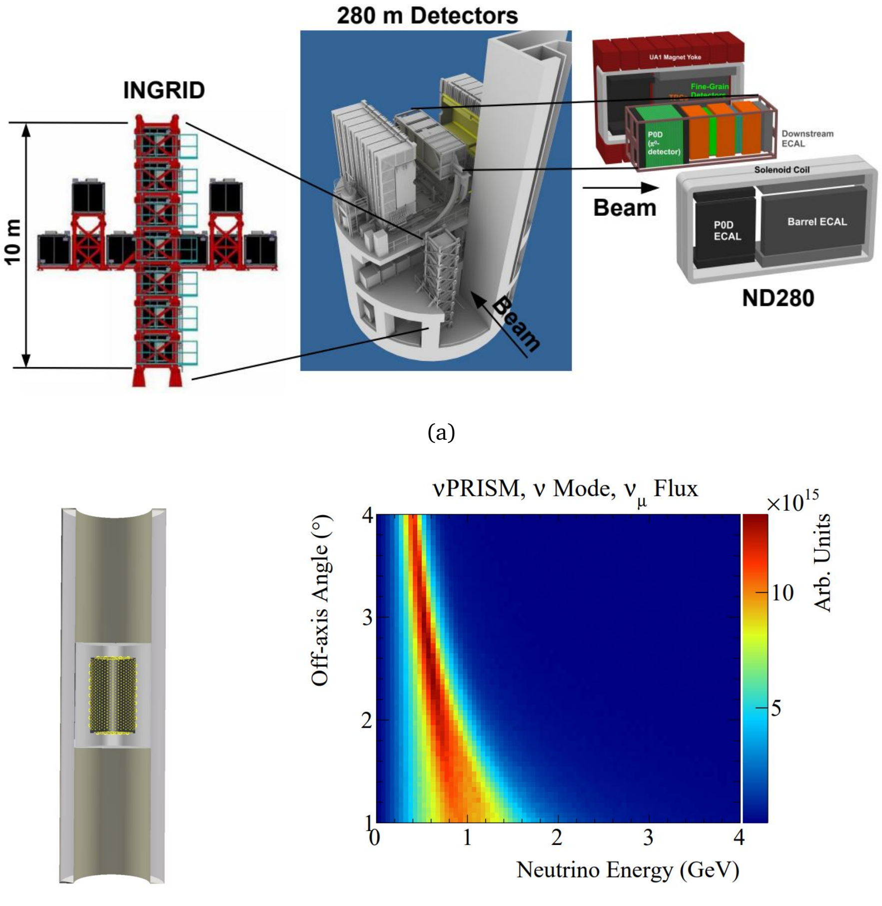

(a)

(b)

Figure 5: (a) ND280 detector suite includes INGRID an on-axis detector to measure beam direction and event rate, also an off-axis magnetized tracker to measure primary (anti)neutrino interaction rates, spectrum, and properties. (b) Left: A conceptual drawing of the IWCD (νPRISM). Right: the ν_μ flux energy dependence for the $1° - 4°$ off-axis angle range. Copyright Hyper-K collaboration [3].

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