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The Hyper-Kamiokande Experiment

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*on behalf of the Hyper-Kamiokande Collaboration

Hyper-K

XX INTERNATIONAL WORKSHOP ON NEUTRINO TELESCOPES

Venice, October 26th, 2023

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UAM Universidad Autónoma de Madrid

Kamioka water detector experiments

Hyper-Kamiokande

- 2027 onwards

➢ Extended search for proton decay
➢ Precision measurement of neutrino oscillation (CPV and MO)
➢ Neutrino Astrophysics
Explore new physics

Super-Kamiokande

x8.4

- 1996 onwards

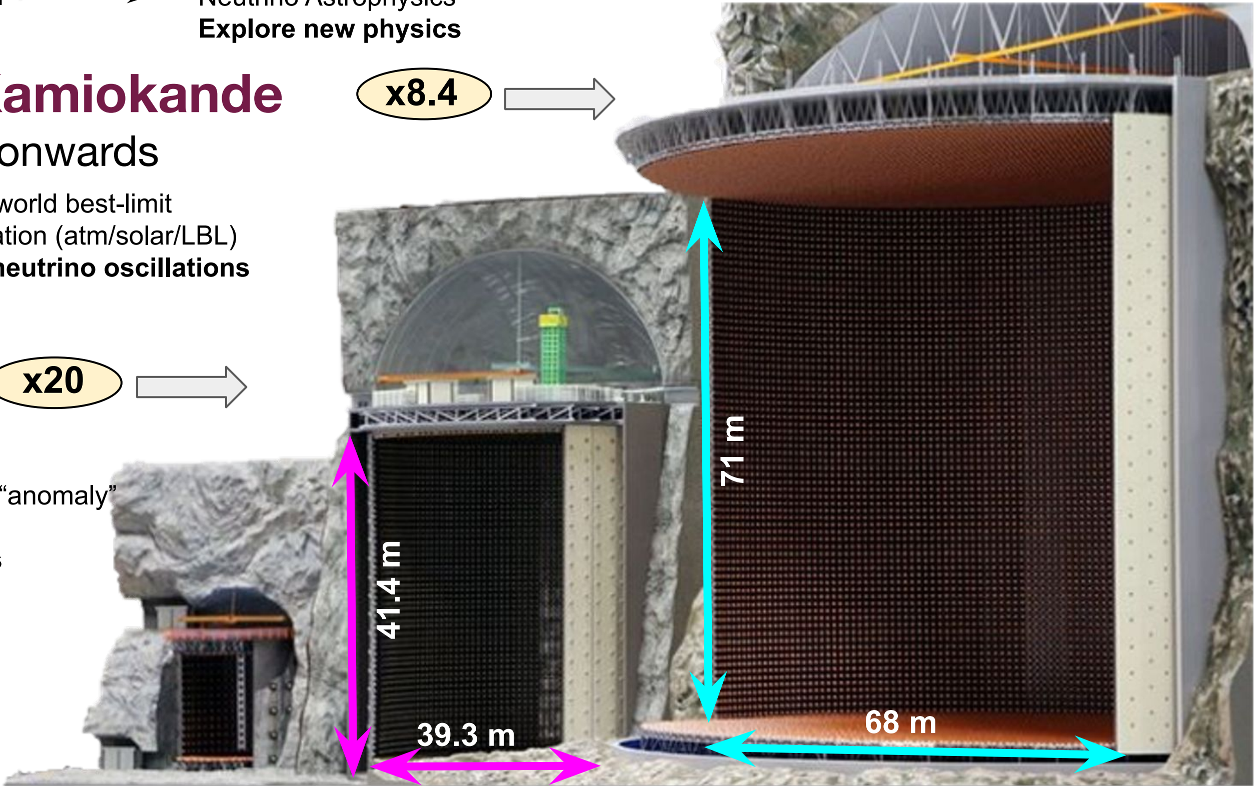
➢ Proton decay: world best-limit
➢ Neutrino oscillation (atm/solar/LBL)
Discovery of neutrino oscillations

Kamiokande

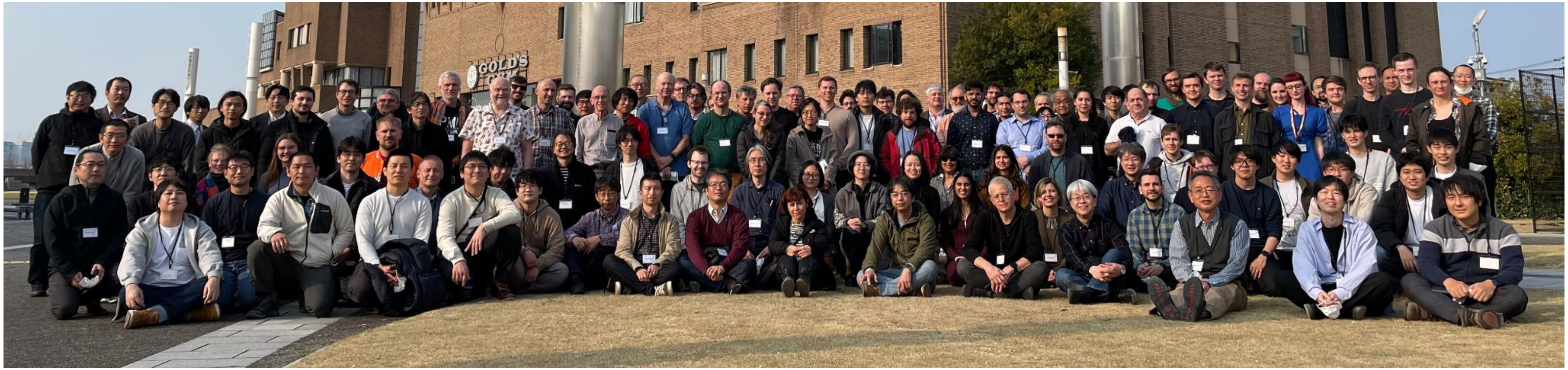
x20

- 1983-1996

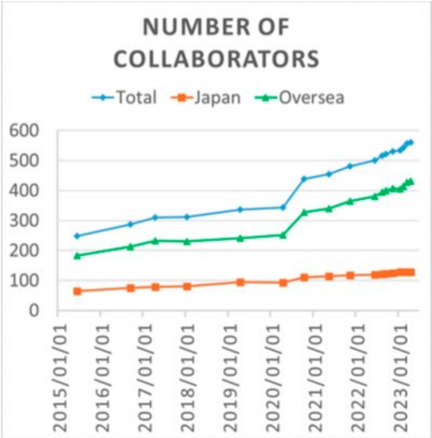
➢ Atmospheric and solar neutrino “anomaly”
➢ Supernova 1987A
Birth of neutrino astrophysics



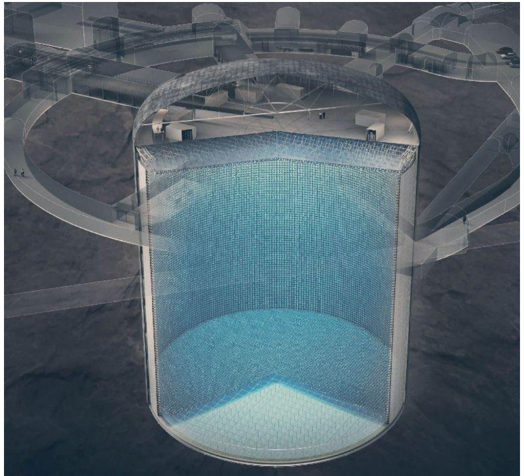
The Hyper-Kamiokande collaboration



~600 researchers from 102 institutions in 22 countries as of October 2023, and growing!

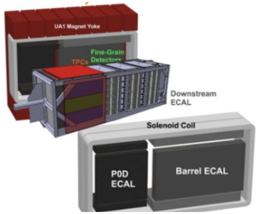


The Hyper-Kamiokande project


Hyper-Kamiokande detector (Far Detector)

HK project includes: **a far detector, a neutrino beam, and a neutrino near detector complex**

- ➔ Construct the Hyper-Kamiokande detector at Kamioka.
- ➔ Upgrade the J-PARC neutrino beam.
- ➔ Construct the Intermediate Water Cherenkov Detector (IWCD) at Tokai.

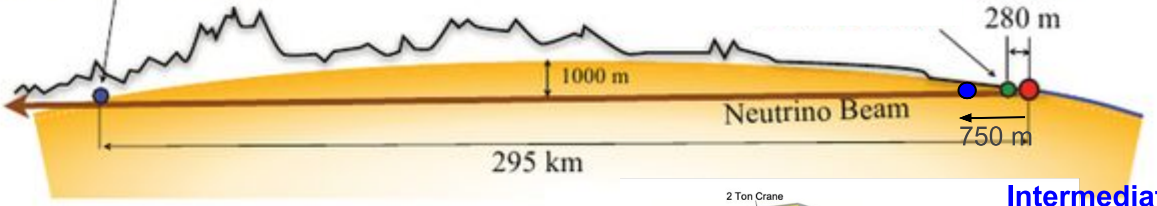


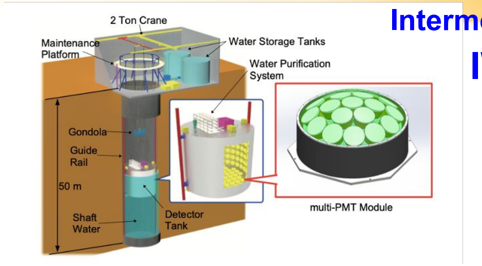
ND280


INGRID

Near Detector

J-PARC

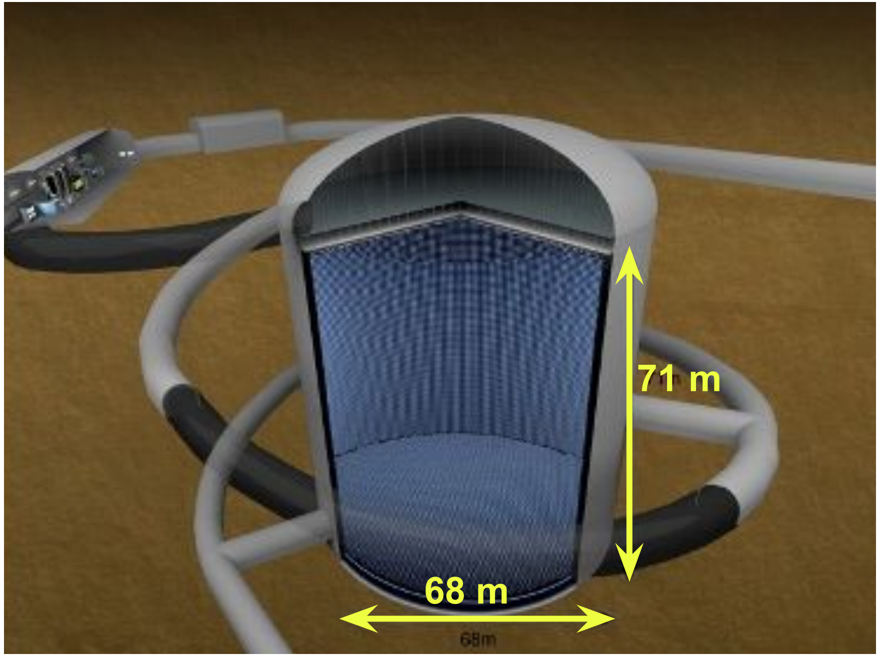


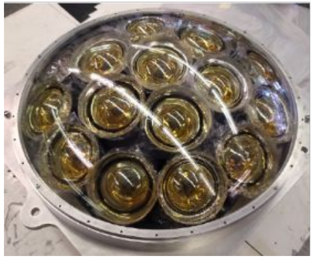


Intermediate Detector

IWCD

Far detector: The Hyper-Kamiokande detector





- ★ A water Cherenkov detector located 600 m under the mountains.
- ★ **258 kton** of ultrapure water (**216 kton** inner detector).
- ★ Fiducial volume: ~**188 kton**.

Inner detector (ID):

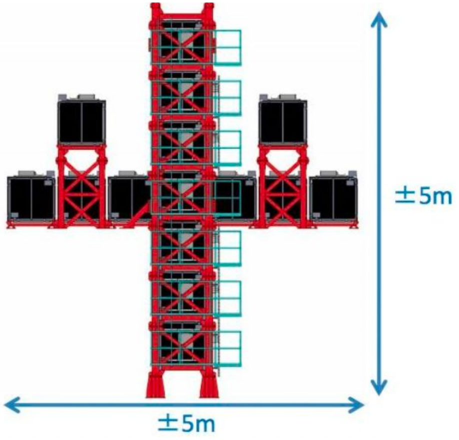
- 64.8 m diameter, 65.8 m height.
- 20000 50 cm PMTs will be installed.
- ~800 mPMTs modules will be integrated as hybrid configuration.

Outer detector (OD):

- 1 m barrel or 2m top/bottom thick.
- ~3600 8 cm PMTs + WLS plates.
- Walls are covered with high-reflectivity Tyvek sheets.

Near detectors

On-axis Detector
(INGRID)

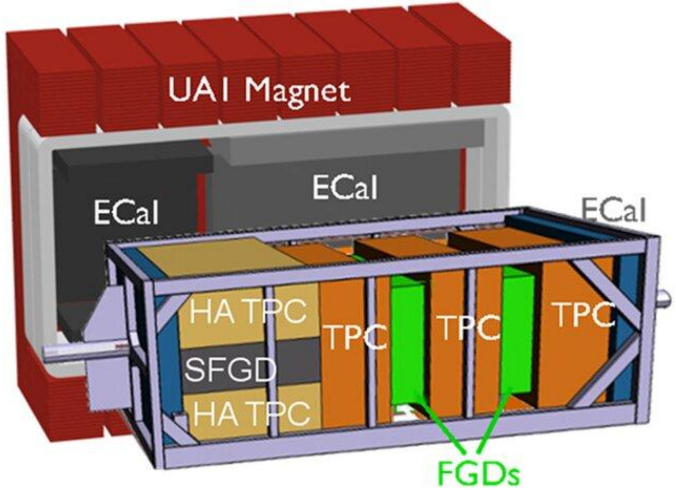


Suite of near detectors to constrain flux and measure event rates before oscillation.

On-axis detector: Measure beam direction and event rate.

Off-axis Magnetized Tracker

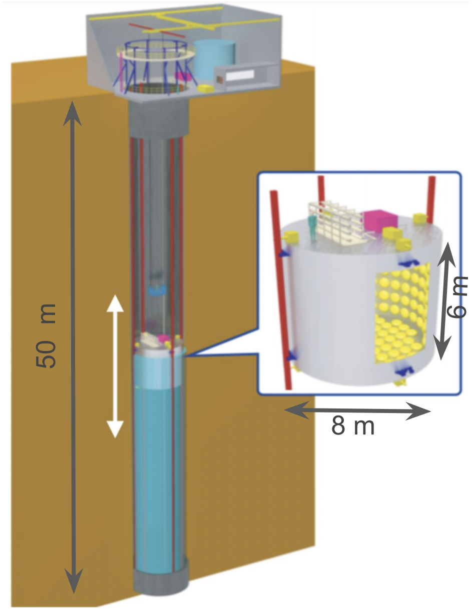
(ND280 → Upgrade for T2K → Upgrade for Hyper-K)

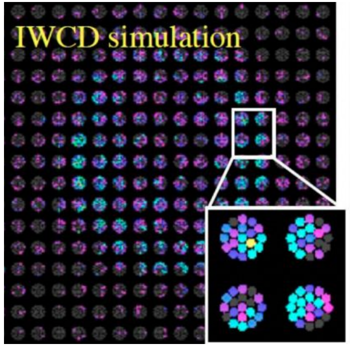


Off-axis magnetized tracker: Measure primary (anti) neutrino interaction rates, spectrum and properties. Charge separation to measure wrong-sign background.

Upgrade by T2K experiment and intensive discussion for further upgrade in Hyper-K era is on-going.

Intermediate Detector: IWCD



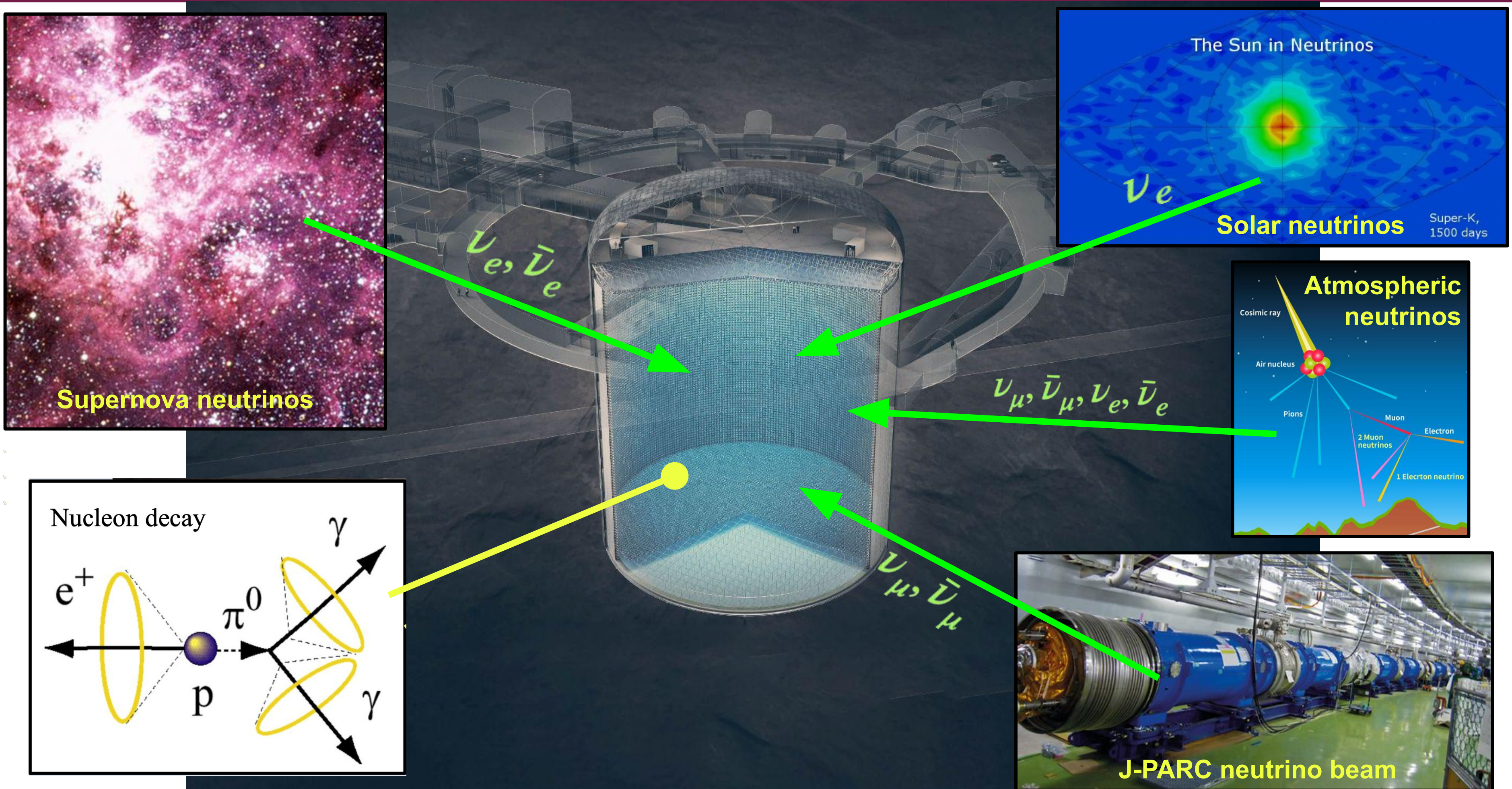


- 1 kton water Cherenkov detector, Diameter ~8 m, height ~6 m at 750 m from neutrino target.
- Use mPMTs for readout:
  - ~400 19x8 cm PMTs in a 50 cm PMT housing.
  - High granularity and timing resolution.
- Move detector up and down shaft to sample different off-axis angles.

→ Constrain neutrino energy mis-reconstruction.

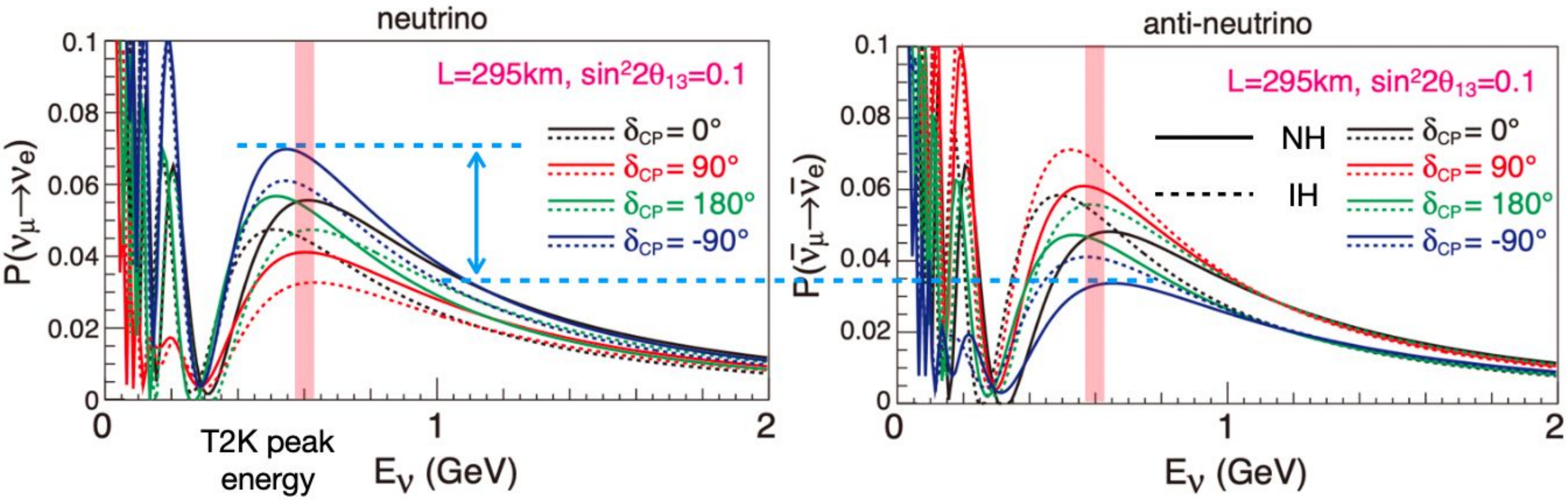
→ Measure electron neutrino cross sections.

Hyper-Kamiokande observation target



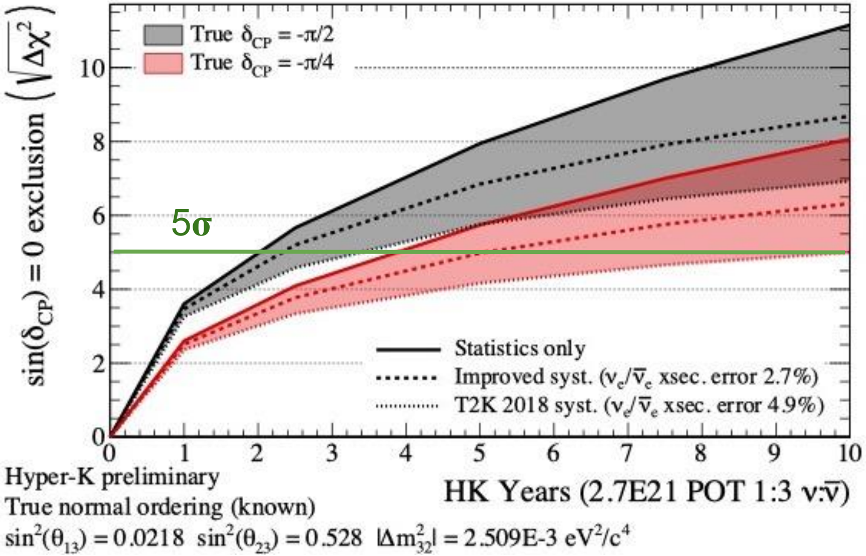
Measurements of oscillations

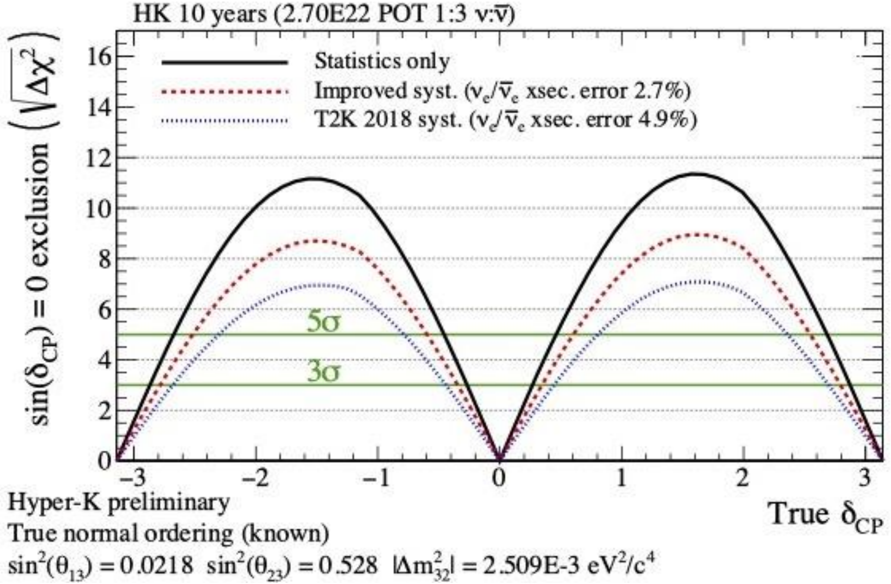
- Measure CP violation in neutrinos through ν_e and $\bar{\nu}_e$ appearance differences.
- Few % statistical uncertainty after 10 years operation with > 1000 ν_e and $\bar{\nu}_e$ signal event:
  - Systematics limited.
- Near detectors crucial to constrain far detector expectation.



CP violation sensitivity

- Sensitivity CP violation with 1:3 ν : $\bar{\nu}$ beam.





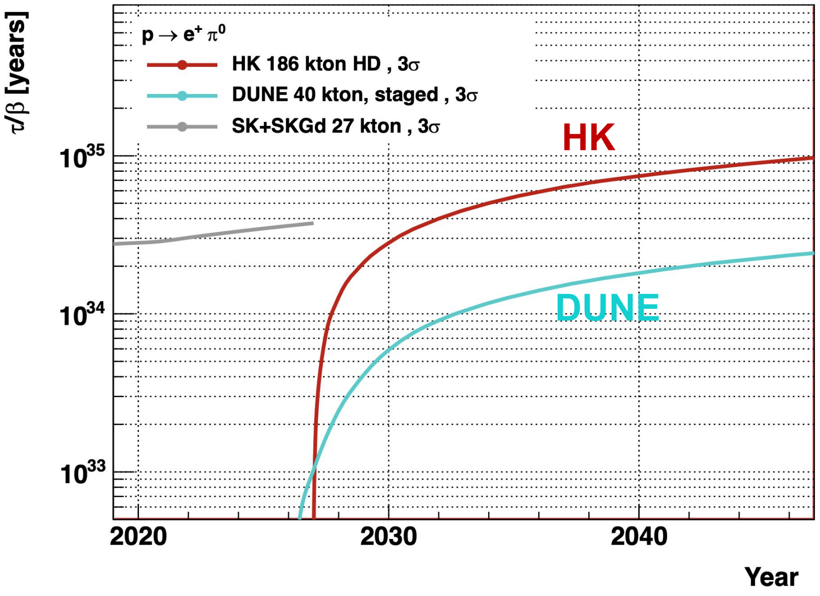
- With optimistic systematics and known mass ordering (MO): 2-3 years for 5 sensitivity to exclude CP conservation for true $\delta CP = -\pi/2$.
- After 10-year operation, 60% of δCP values excluded at > 5.

Proton decay

- Nucleon decay is evidence of Beyond Standard Model (BSM) and Grand Unified Theories (GUT).
- Examples of proton decay sensitivity in two modes:

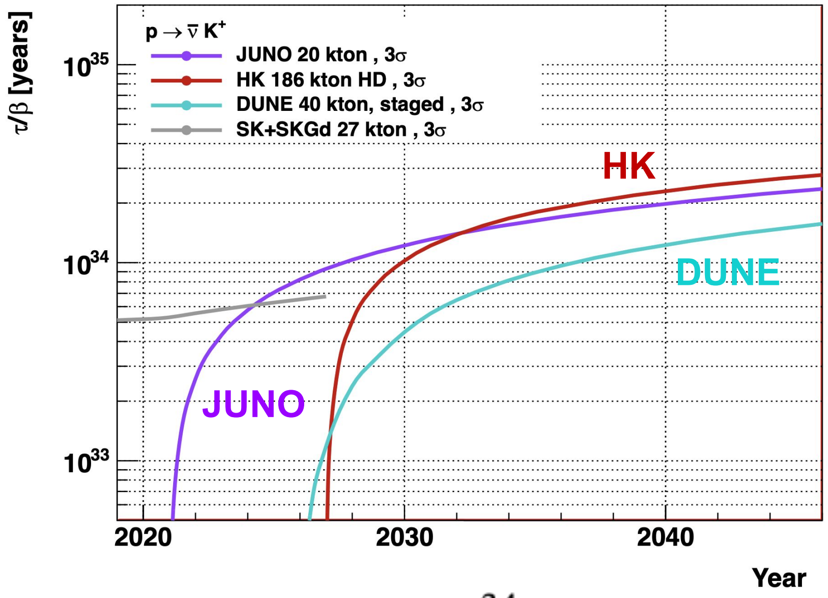
[HK] arXiv:1805 04163
[DUNE] arXiv:2002.03005
[JUNO] arXiv:1508.07166

$p \rightarrow e^+\pi^0$



$\tau \sim 10^{35}$ years (3σ)

$p \rightarrow \bar{\nu} + K^+$



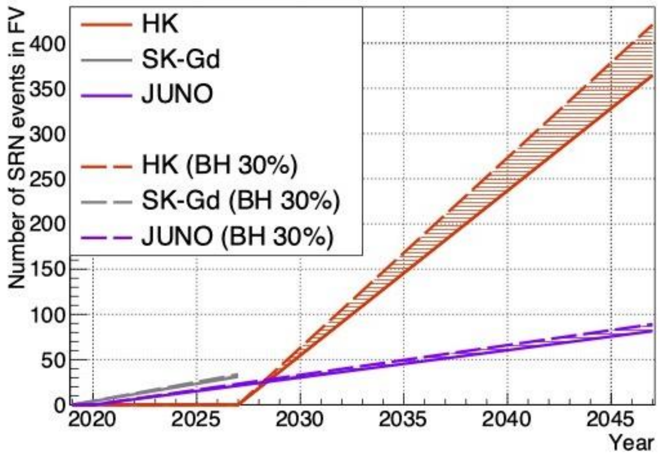
$\tau \sim 3 \times 10^{34}$ years (3σ)

Astrophysics neutrinos

- Observation of a few ~10 MeV neutrinos with time, energy and direction information

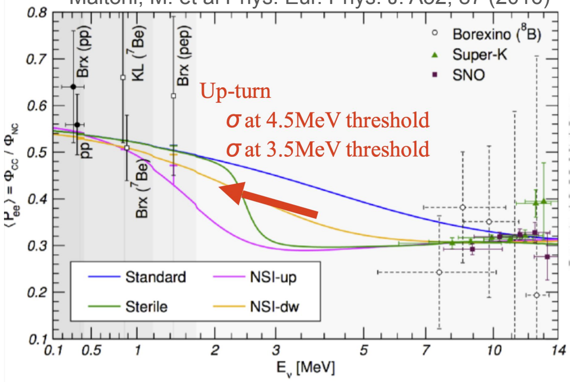
  - Unique role in multi-messenger observation.

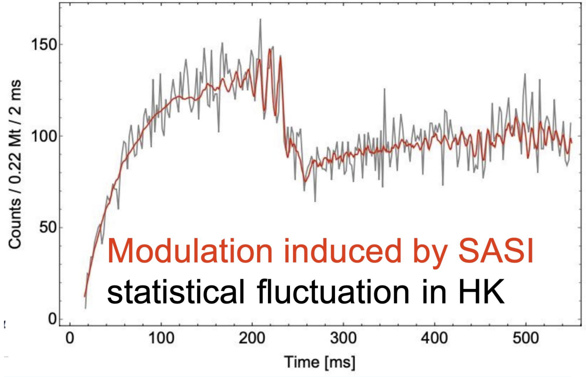
- **Solar neutrinos:** up-turn at vacuum-MSW transition, Day/Night asymmetry, hep neutrino observation.
- **Supernova burst neutrinos:** explosion mechanism, BH/NS formation, alert with ~1º pointing.
- **Supernova Relic Neutrinos (SRN):** stellar collapse, nucleosynthesis and history of the universe

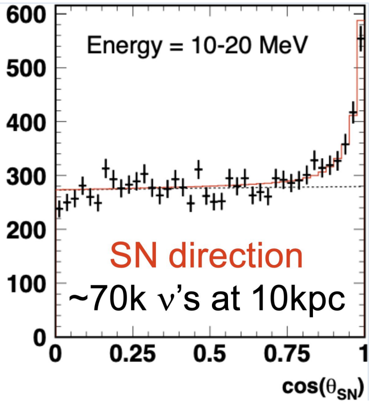


SRN rate: Calculation from FV and E_{th}
Efficiency is not accounted

Maltoni, M. et al Phys. Eur. Phys. J. A52, 87 (2016)

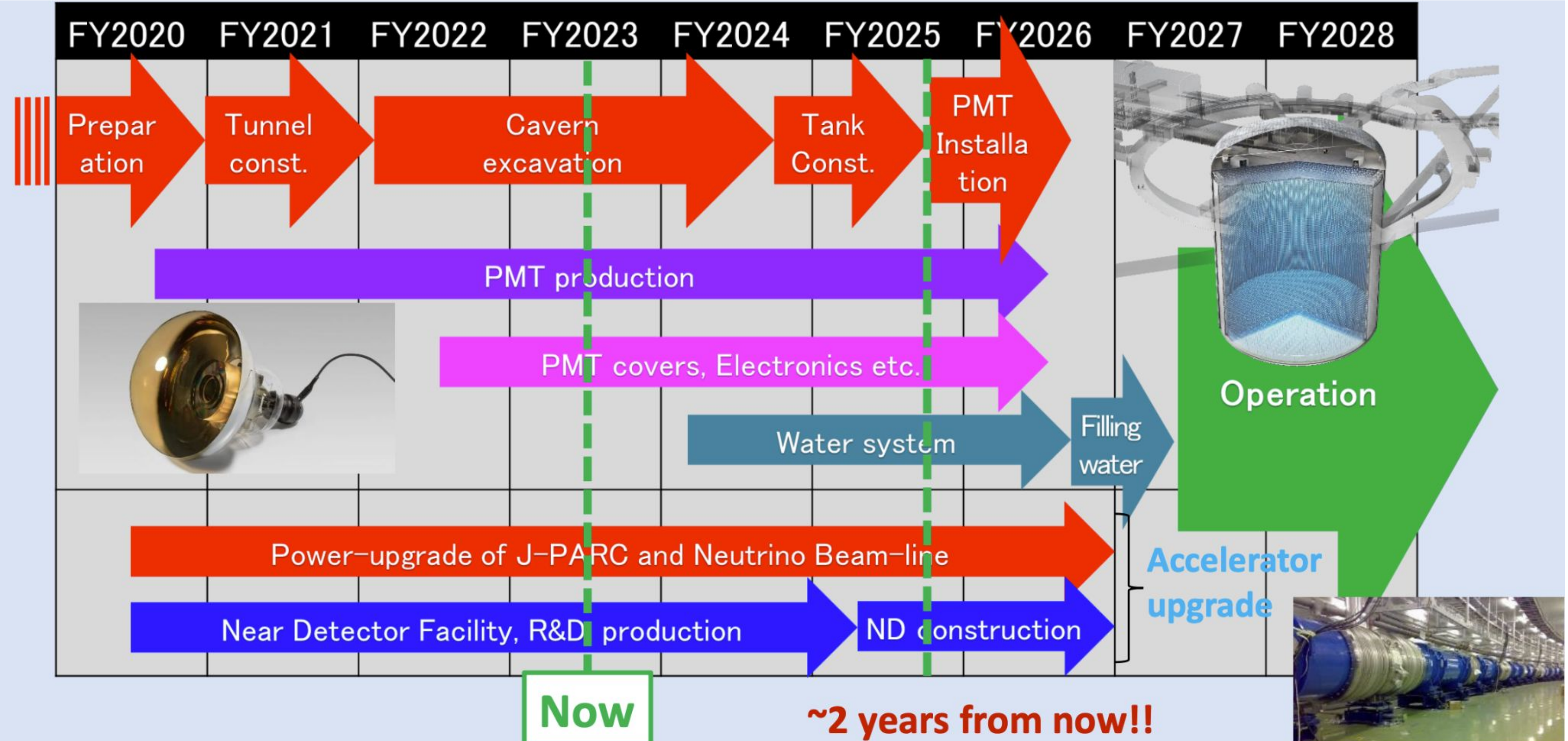






Detector construction

7 years construction from year 2020; start operation in 2027.
We are in the middle of the civil construction and starting to produce detector components.

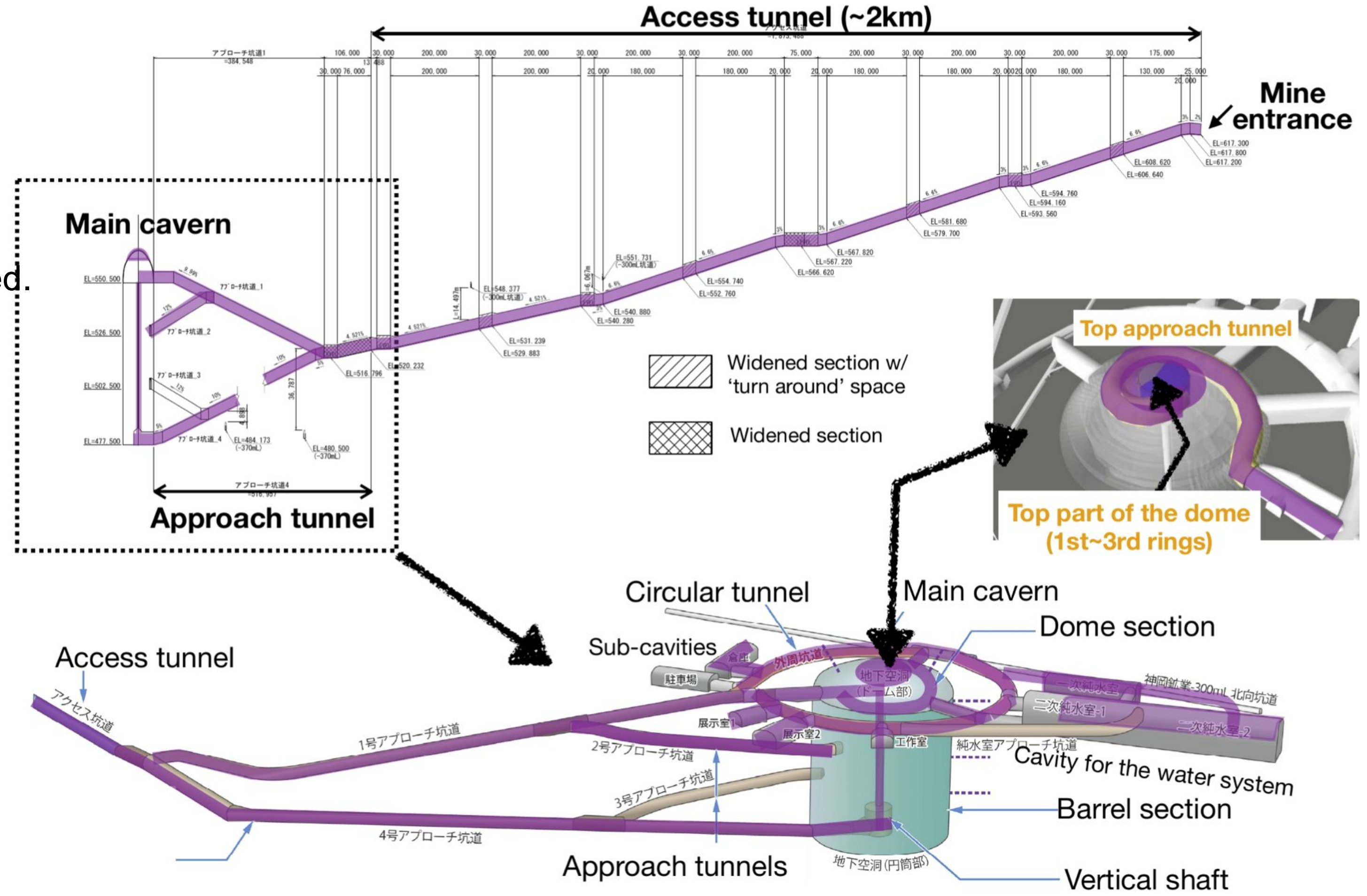


Hyper-K caverns excavation

★ Access tunnel excavation completed.

★ Approach & circular tunnel excavation completed.

★ Main cavern excavation has started on-time!



Hyper-K access tunnel excavation

Groundbreaking ceremony held online on May 28, 2021

Access tunnel entrance

April 20, 2021

Access tunnel → Access tunnel excavation completed on schedule

November 1, 2021

1.87 km completed

February 25, 2022

Center of the Hyper-K Main Cavern's Dome reached on June 23, 2022

April 12, 2022

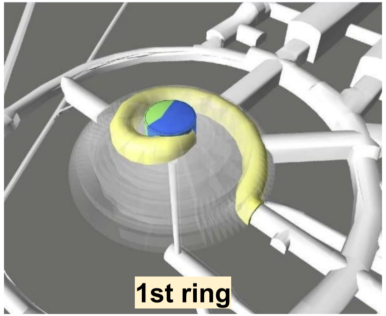
May 10, 2022

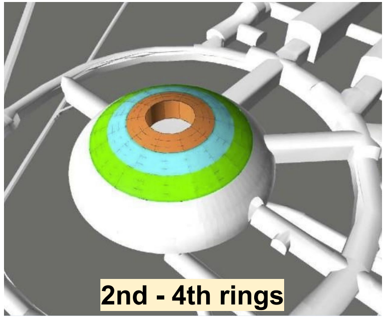
June 23, 2022

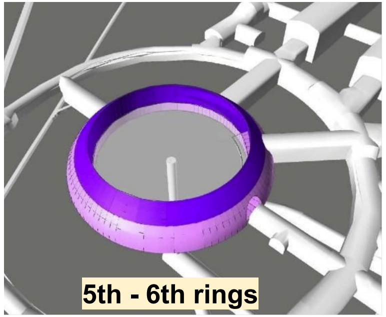
June 23, 2022

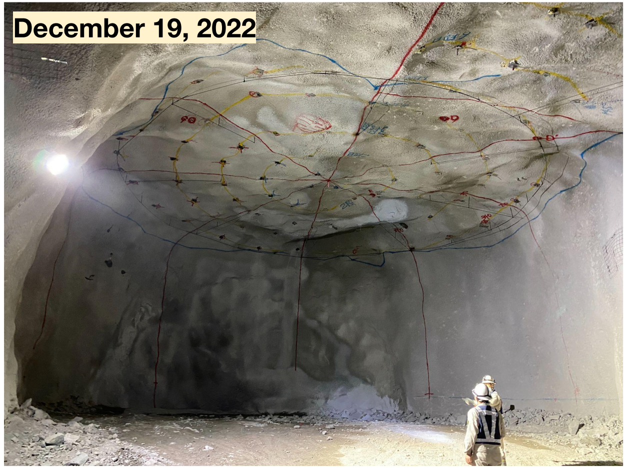
Hyper-K main cavern excavation

➔ Cavern dome constructed in consecutive rings









Hyper-K main cavern excavation

October 3, 2023:
excavation of the dome section completed.

- ➢ 69m diameter, 21m height.
- ➢ One of the largest human-made underground space.

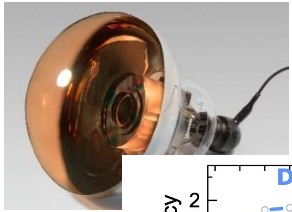
Now, the excavation of the barrel section is ongoing.

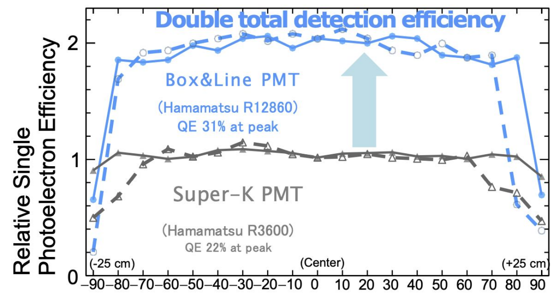
Photomultiplier Tubes

20,000 Hamamatsu 50 cm box-and-line PMTs require for ID.

Same size as used in Super-K but performance is largely improved:

- Twice higher photo-efficiency compared to Super-K.
- Twice better charge and timing resolutions.

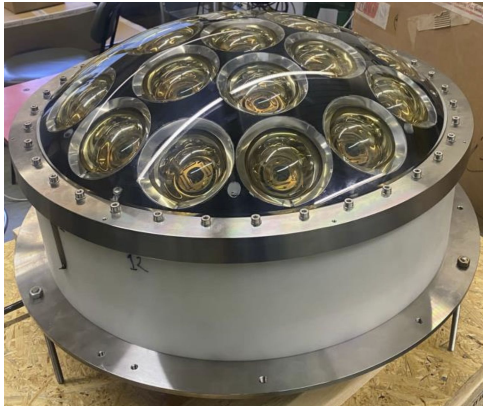




~800 mPMTs, providing improved vertex reconstruction.

19x8 cm PMTs in a 50 cm PMT:

➢ Review of internal LED calibration system being finalized.



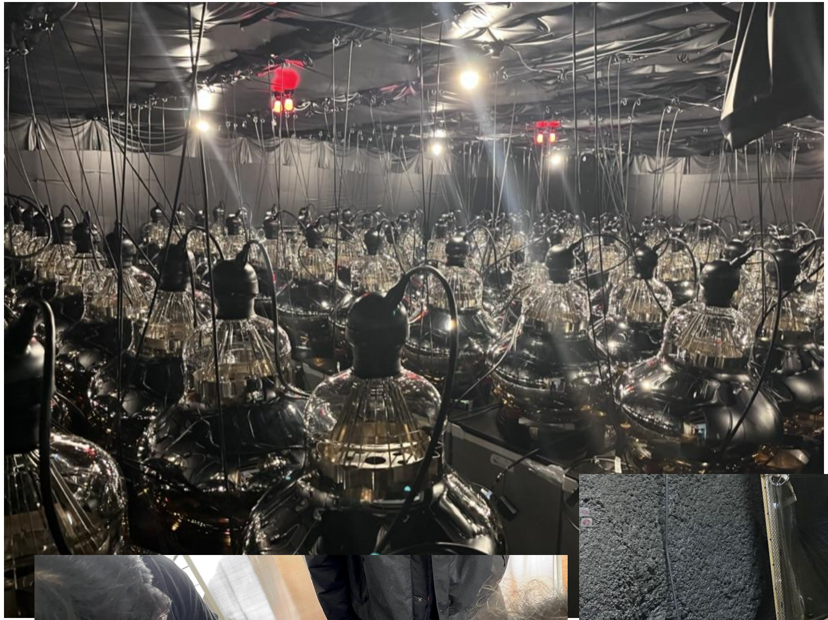
~3600 8 cm OD PMTs with wavelength shifting plates.

To veto cosmic-ray muons.

➢ Design finalization is ongoing.

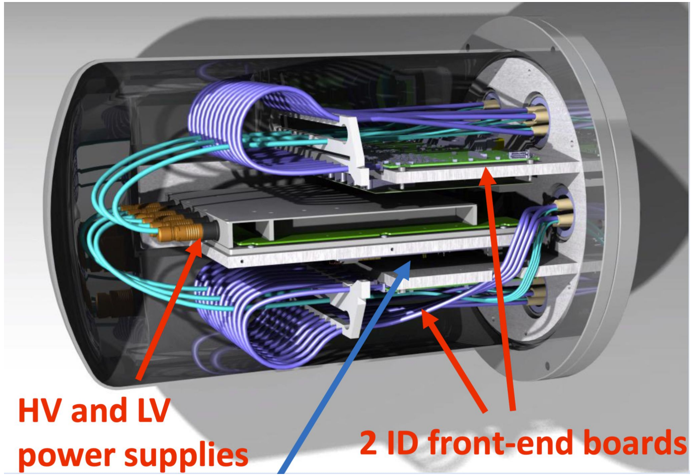
50 cm PMT production status

- Mass production started in Dec. 2020.
- Production was suspended to investigate their defect rate in April 2022.
- From May 2023, production resumed after improvement and screening by manufacturer.
- Delivery completion remains unchanged as originally scheduled.
- Constant quality inspections at Kamioka are ongoing.



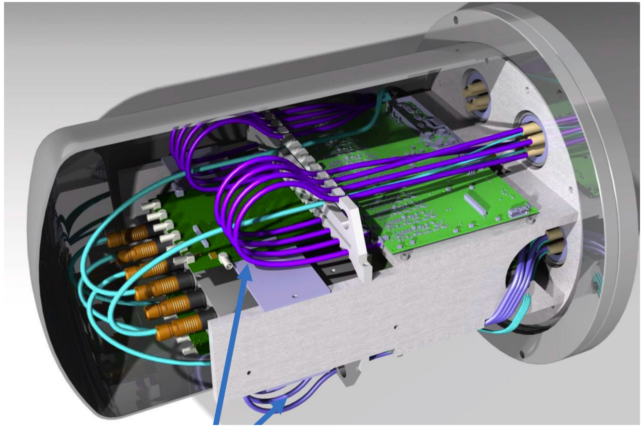
Electronics

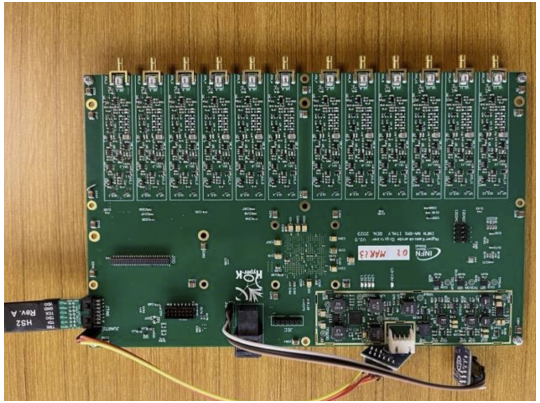
- Front-end electronics placed in underwater vessels.
- Two types of underwater electronics vessels:
  - Inner detector vessels: 24 ID channels read out by two PCBs.
  - Hybrid outer + inner detector vessels: 20 ID + 12 OD channels.

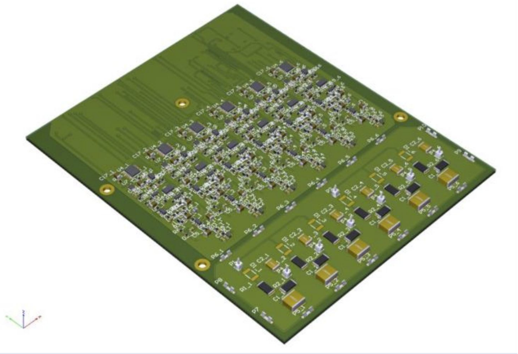


Data processing and timing boards

Preliminary


2 OD front-end boards

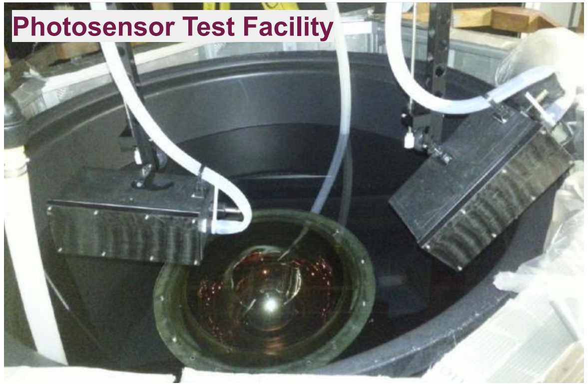

ID 12-channel front end board

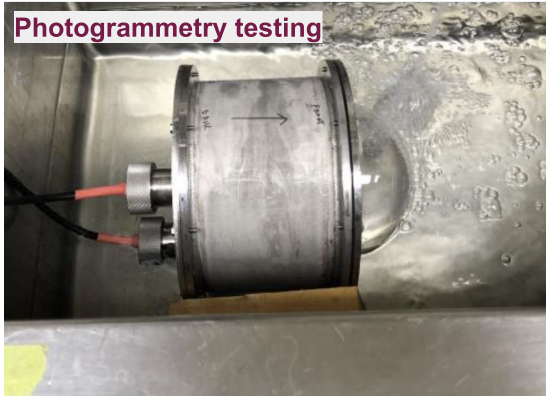

OD 6-channel FE board

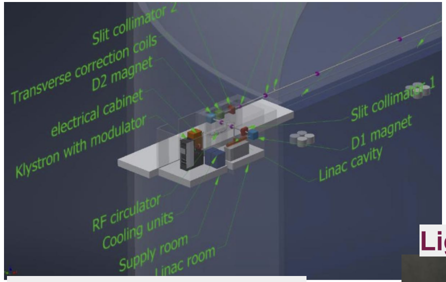
Calibration

Extensive program of calibration sources to determine detector parameters and measure systematics.

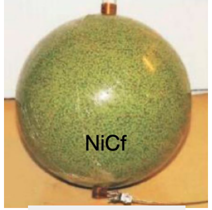
- Pre-calibration of photosensors.
- Photogrammetry.
- Light injection.
  - Diffusers and collimators.
  - mPMT system.
  - OD injections.
- Electron LINAC.
  - 3-24 MeV electrons.
- Radioactive sources
  - DT source - ^{16}N
  - AmBe + BGO - tagged neutrons.
  - Ni/Cf - 9 MeV γ cascade.


Photosensor Test Facility

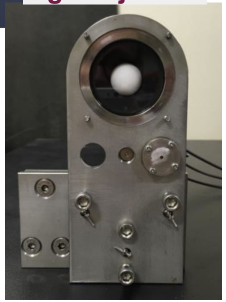

Photogrammetry testing



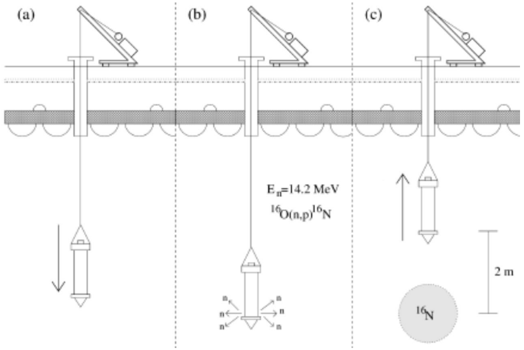
LINAC beam simulation



Ni/Cf source


Light injectors

DT operation



Summary

- Hyper-Kamiokande is the next generation neutrino experiment and the world's largest underground facility.

  Construction is underway, on schedule to start operation in **2027.**

- Physics targets:
  - Neutrino CP violation: Discovery with 5 σ for ~60% parameter regions.
  - Nucleon Decay Search for testing GUT: $\boldsymbol{\tau} > 10^{35}$ years for $p \rightarrow e^{+}\pi^{0}$
  - Neutrino Astrophysics: Supernova neutrinos
- Hyper-Kamiokande construction on schedule:
  - Access tunnel and cavern construction on track.
  - 50 cm PMT production underway.
  - Other detector component designs being finalized.
  - Neutrino beam upgrade to 1.3 MW.
  - Near detector upgrade and design of intermediate detector being finalized.

Hyper-Kamiokande

Abstract: Hyper-Kamiokande, the next generation of water Cherenkov neutrino detector, will take a unique role in neutrino physics and astrophysics. Its construction started in 2020 and the experiment is expected to start operations in 2027. It will serve as a far detector of a long-baseline neutrino experiment and an observatory for astrophysical neutrinos and rare decays. The baseline design has a fiducial volume 8 times the size of its predecessor, Super-Kamiokande, and is instrumented with new photosensors that offer significant performance improvements. Combined with the upgraded J-PARC neutrino beam produced 295 km away, as well as a near detector suite, Hyper-Kamiokande will be able to measure neutrino oscillation with unprecedented statistical precision, enabling the determination of the CP violation and the precise measurement of atmospheric neutrino oscillation. The large detector size will greatly improve the study of astrophysical neutrinos, such as supernova burst, supernova relic neutrinos, and solar neutrinos. It will also enable the search for proton decays in a variety of final-state decays. In this talk, an overview of the Hyper-Kamiokande experiment will be provided, highlighting its significance in the neutrino physics and astrophysics field, and its construction status will be presented.

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Affiliation of primary author and respective role: Department of Theoretical Physics, University Autonoma of Madrid, postdoctoral researcher.

Eventual Organization: The Hyper-Kamiokande Collaboration.

Key-word and topic of your presentation: Hyper-Kamiokande, neutrinos, astrophysics neutrinos, water cherenkov detector, PMTs, multi-PMTs, neutrino beam, far detector, near detectors, oscillations, CP violation, proton decay.

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