25th International Workshop on Neutrinos from Accelerators

Hyper-Kamiokande Status

C. Bronner on behalf of the Hyper-Kamiokande collaboration
September 20th, 2024

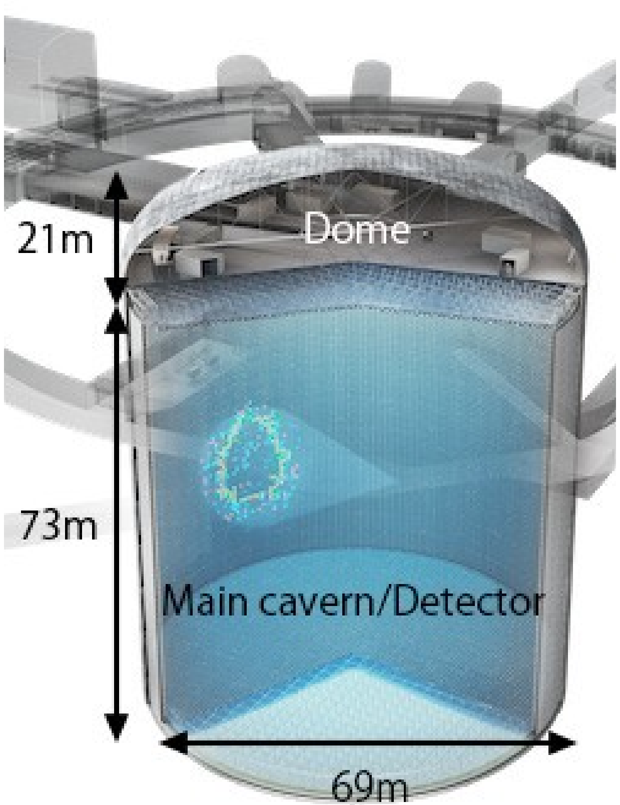
Hyper-Kamiokande

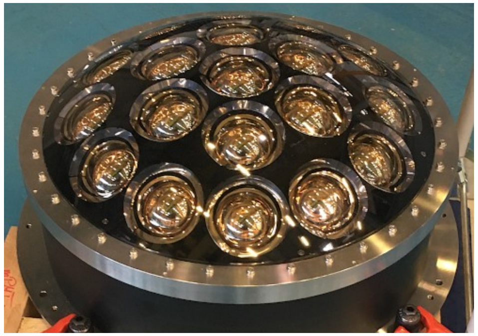
ICRR
Institute for Cosmic Ray Research
University of Tokyo

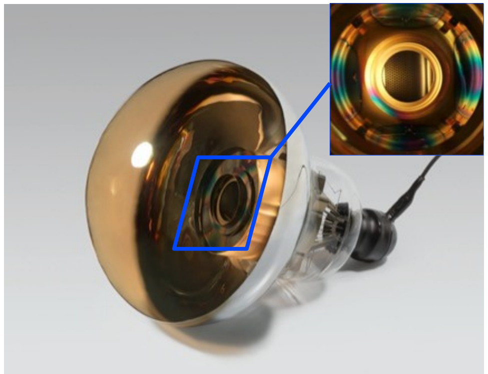
KAMIOKA OBSERVATORY

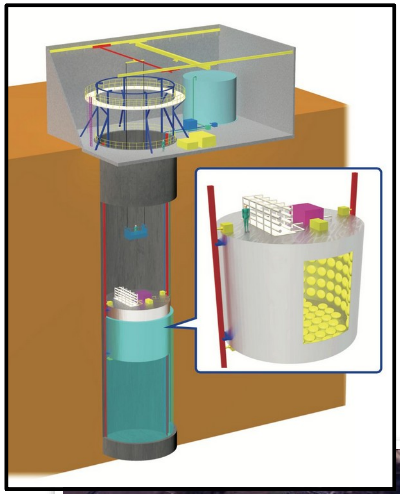
The Hyper-Kamiokande experiment Overview

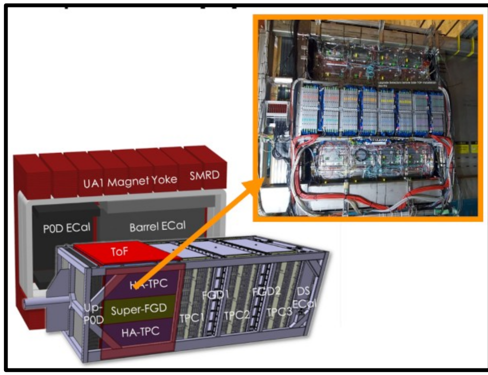
- Hyper-Kamiokande is the next generation Water Cerenkov experiment in Japan
- Builds on the successful approaches used in T2K and Super-Kamiokande
- A number of improvements for increased sensitivity:
  - Larger Water Cerenkov detector for increased statistics
  - Improved light detection system
  - Increased beam intensity and additional near detector for long baseline part



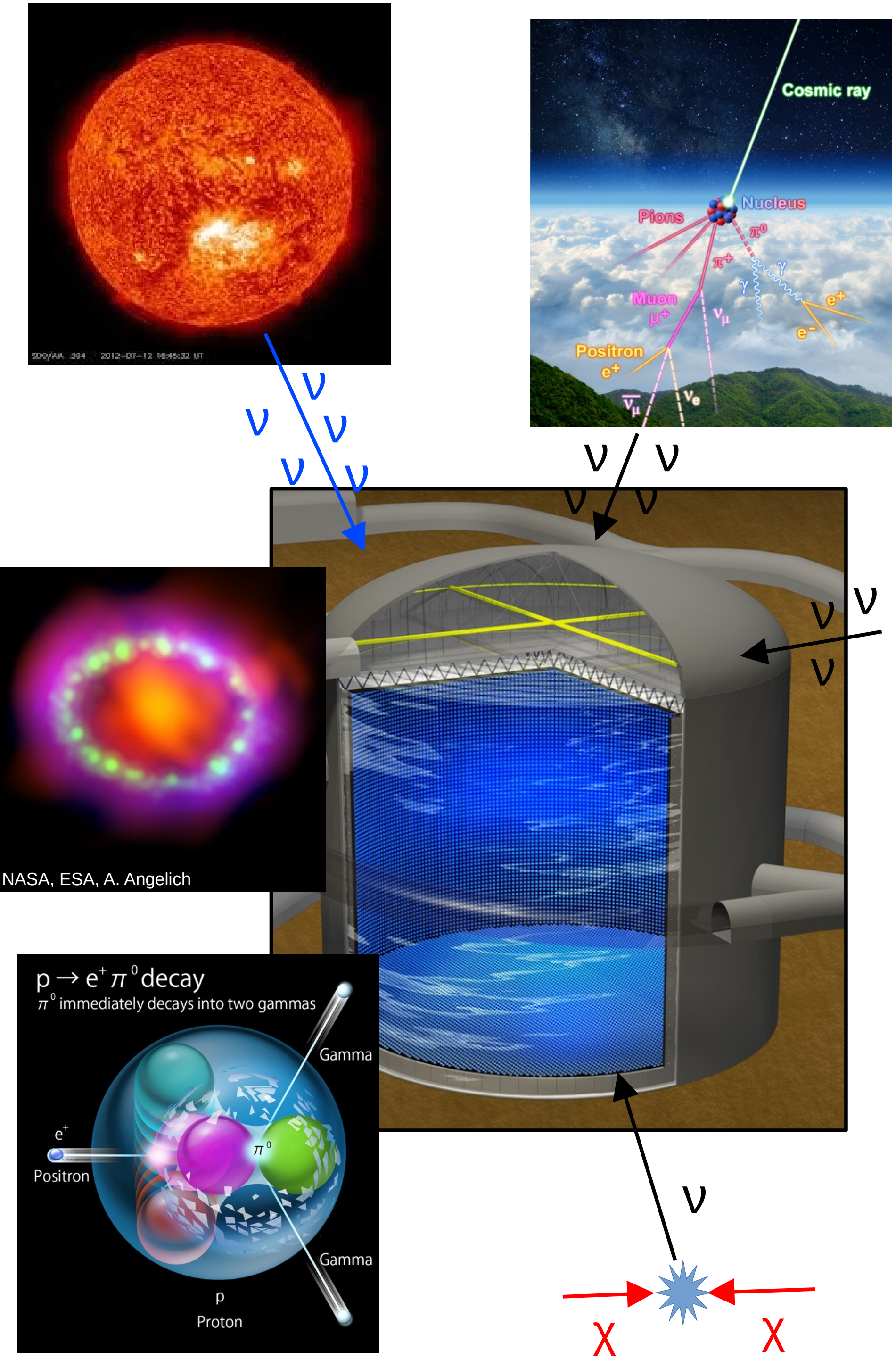






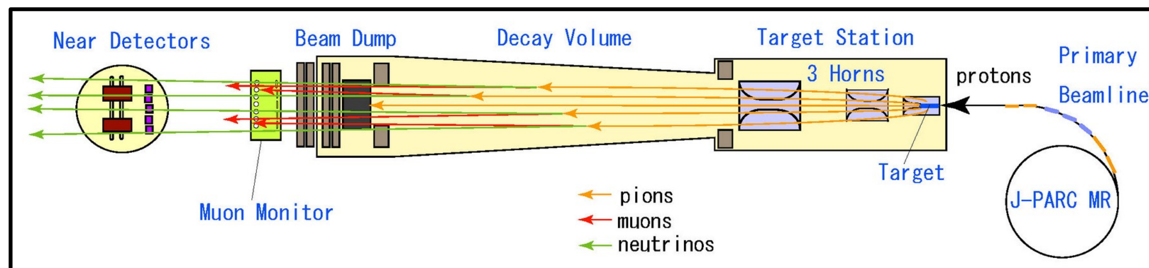


Physics goals



Broad physics program:

- Oscillations of atmospheric, accelerator and solar neutrinos
- Supernova neutrinos
- Search for proton decay
- Dark matter indirect detection

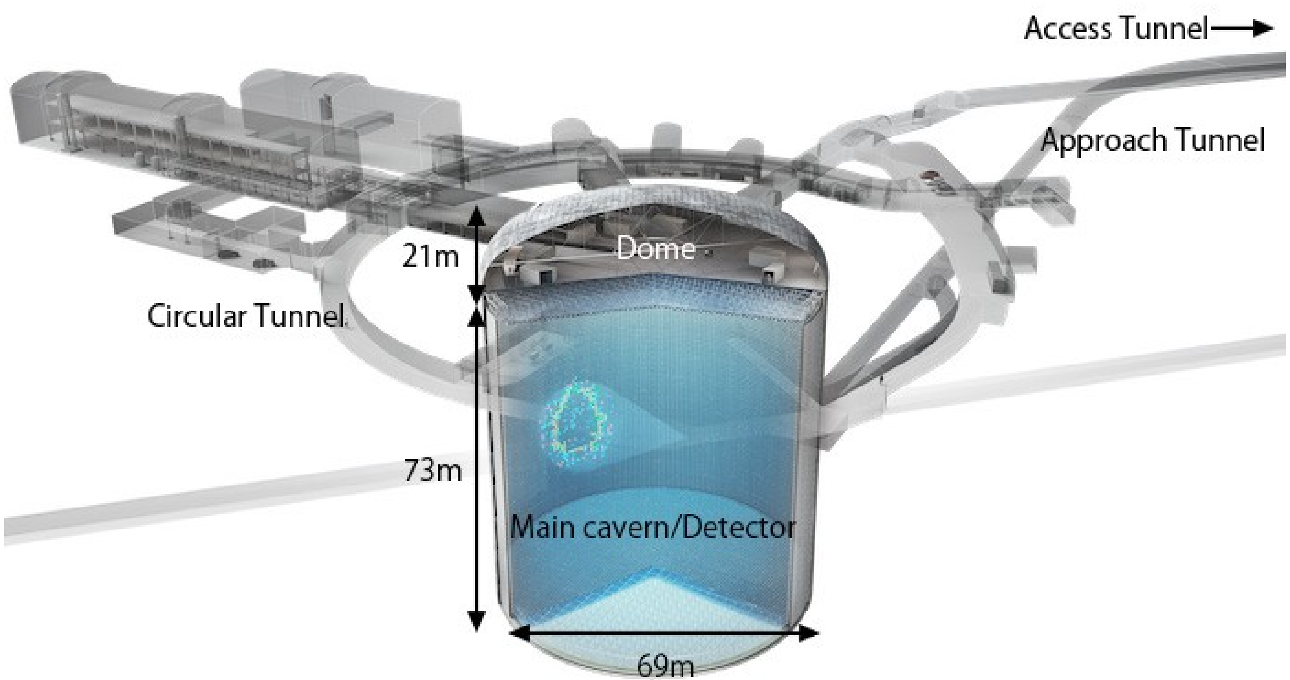


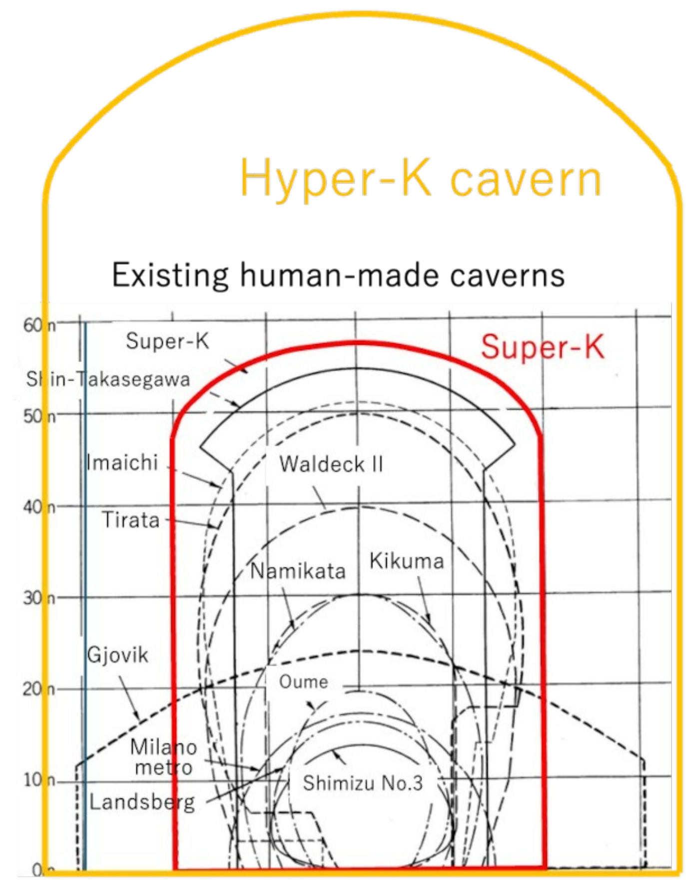
- CP symmetry
  - difference matter/anti-matter
- Mass ordering
  - neutrino mass models
  - input for other experiments ($0\nu\beta\beta$, supernova)
- Octant of θ_{23}
  - symmetries in lepton sector

The Hyper-Kamiokande experiment
Far detector

- A number of these analysis limited by statistics in current experiments
- Larger Water Cherenkov detector:
  - Accumulate statistics faster
  - Well established technology

Building a large new underground complex, including largest ever human-made cavern

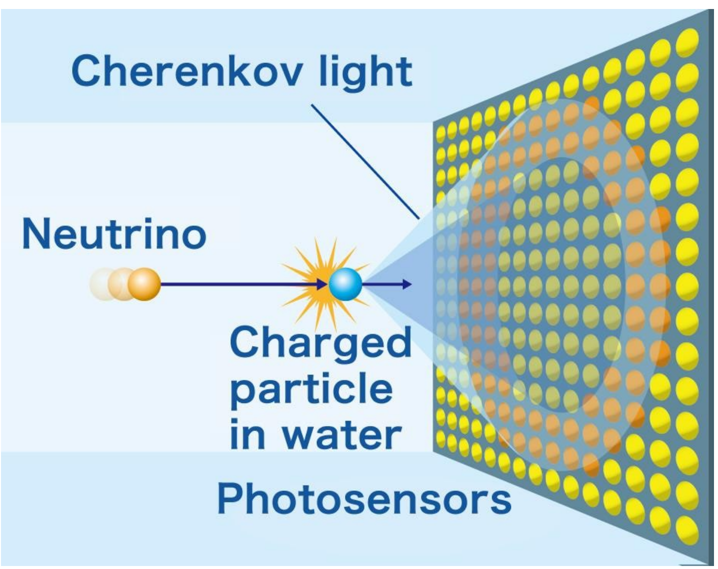




73 m height x 69 m diameter tank
188.4 kton fiducial volume (~8.4x SK)

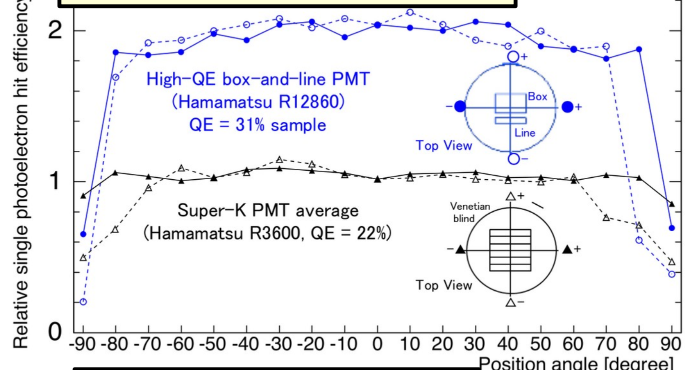
The Hyper-Kamiokande experiment
Improved photo detector system

- Charged particles and photons appear as rings of light on walls
- Performance of Inner Detector (ID) light detectors critical
- HK will use 20k 50cm PMTs to instrument ID
- Improved model compared to SK: R12860 by Hamamatsu Photonics
  - 2x charge resolution and detection efficiencies
  - >2x timing resolution

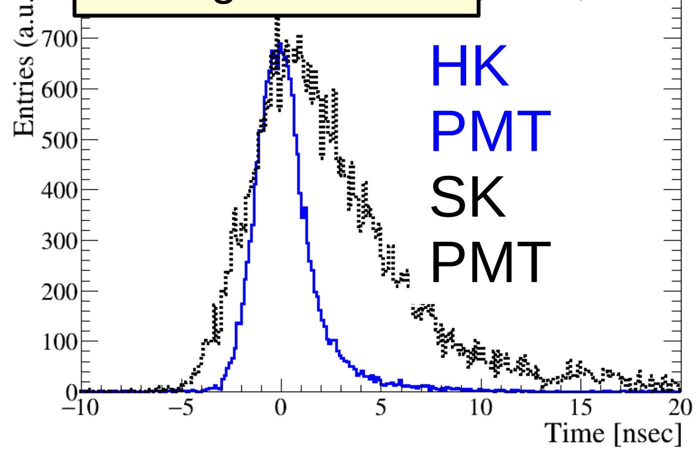


Impact of PMT performance:
- Vertex <-> timing resolution
- Momentum <-> charge resolution, detection eff.

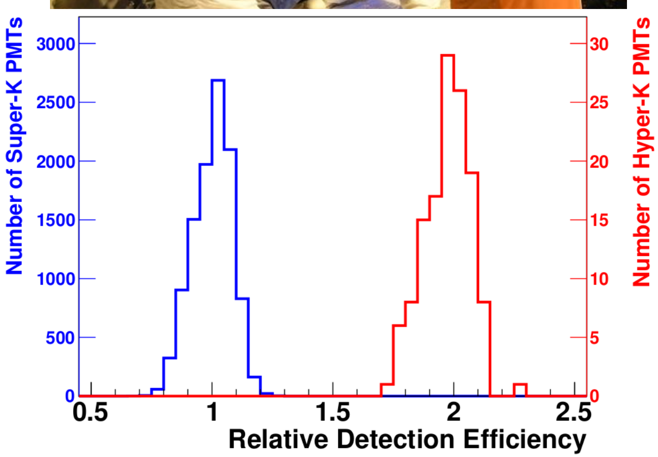
Detection efficiency



Timing resolution



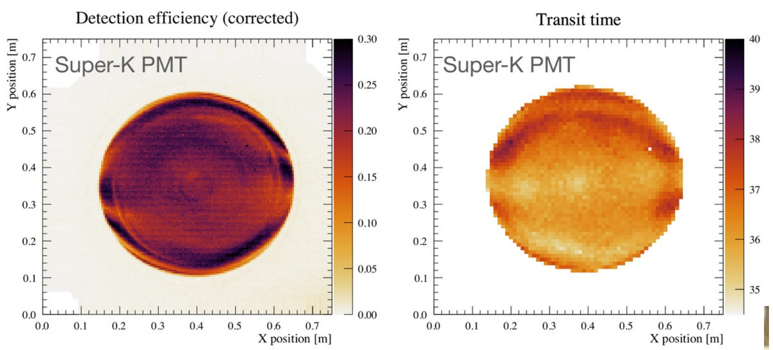
Improved performance confirmed in SK (136 PMTs)

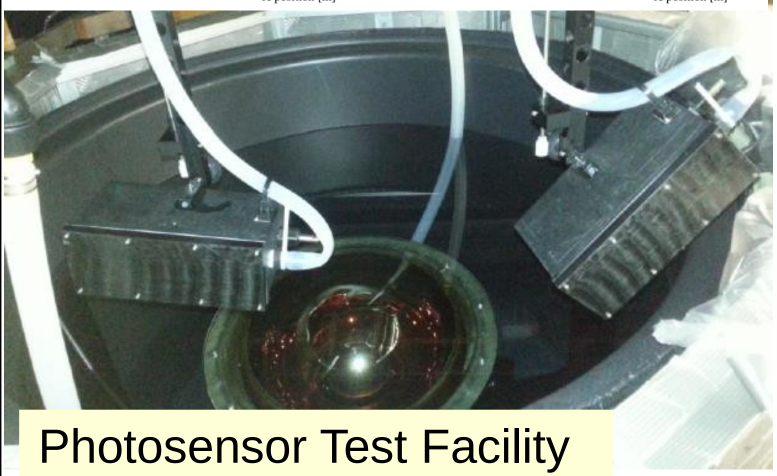


The Hyper-Kamiokande experiment
New calibration methods

- Use of water Cherenkov detector (PID, momentum, ...) well established in SK
- HK: high statistics, need good control of systematics, including detector response
- Detector will need to be understood with higher precision than SK
- A number of new calibration approaches, both in-situ and pre-measurements

Precise characterization of 50 cm PMTs



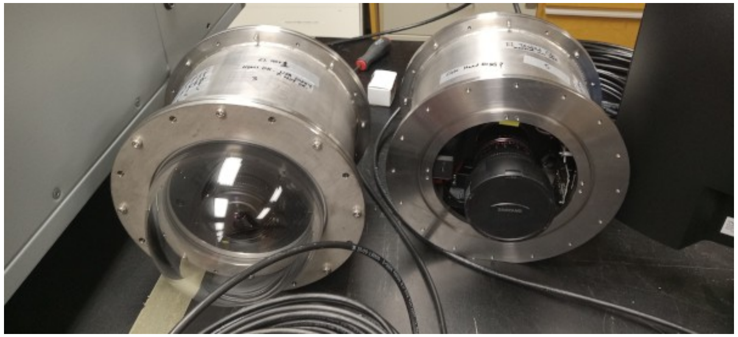


Photosensor Test Facility
(TRIUMF)

PMT pre-calibration
(prototype)

Photogrammetry

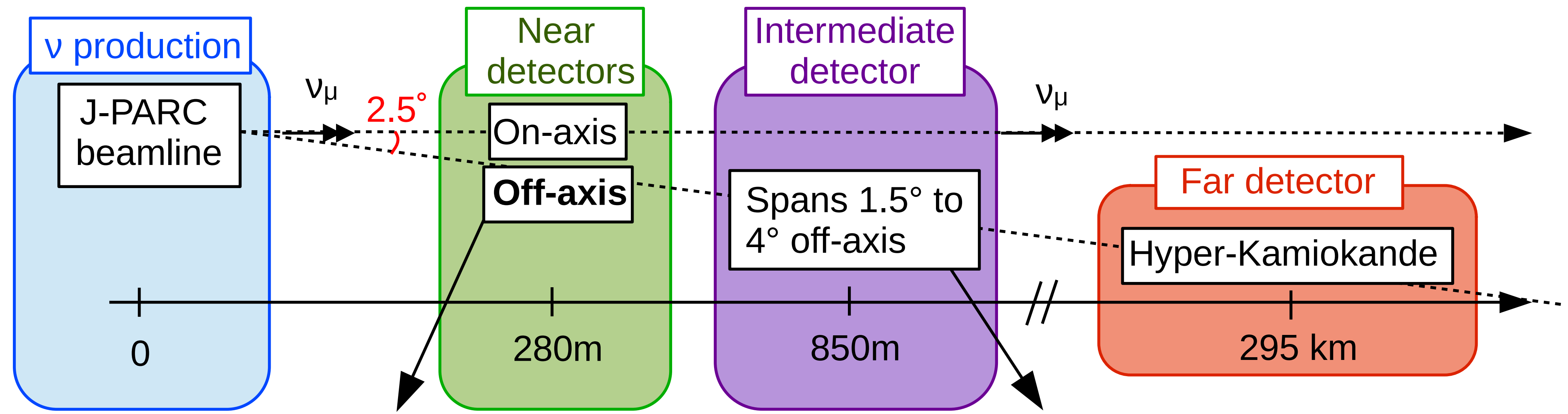
Cameras in walls for precise PMT positions

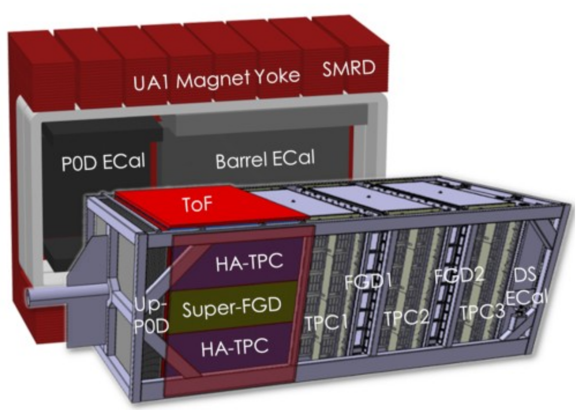


~800 Multi-PMTs (19 3” PMTs) in FD
200 equipped with LEDs (including 295 and 305 nm for Raman scattering)

Long Baseline oscillations Overview

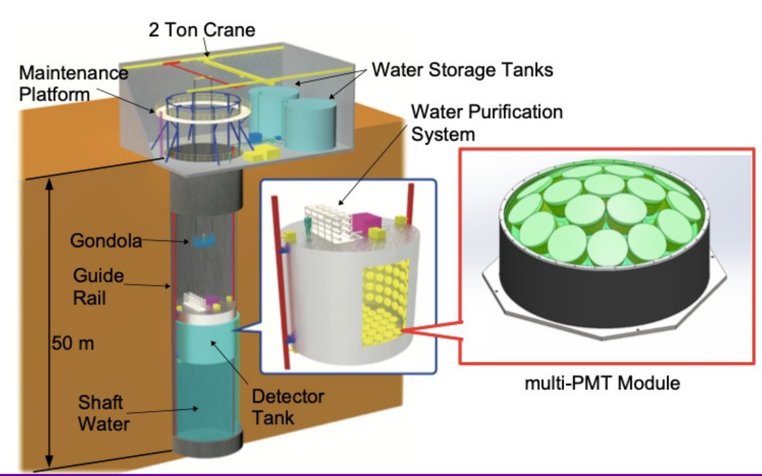
- HK far detector 8 km south of Super-K: looks very similar seen from J-PARC
- Same baseline (295 km) and off-axis angle (2.5°) as T2K
- Main differences: increased beam power (1.3 MW) and intermediate detector





Upgraded ND280: very capable ND from T2K
Ideas for further upgrade later in HK

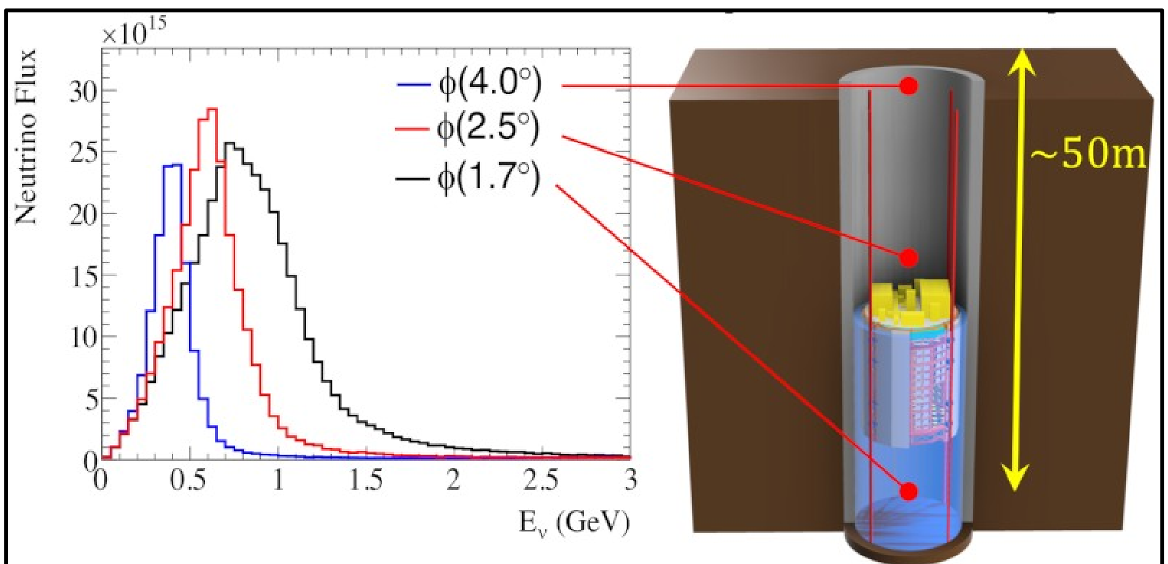
Intermediate Water Cherenkov Detector

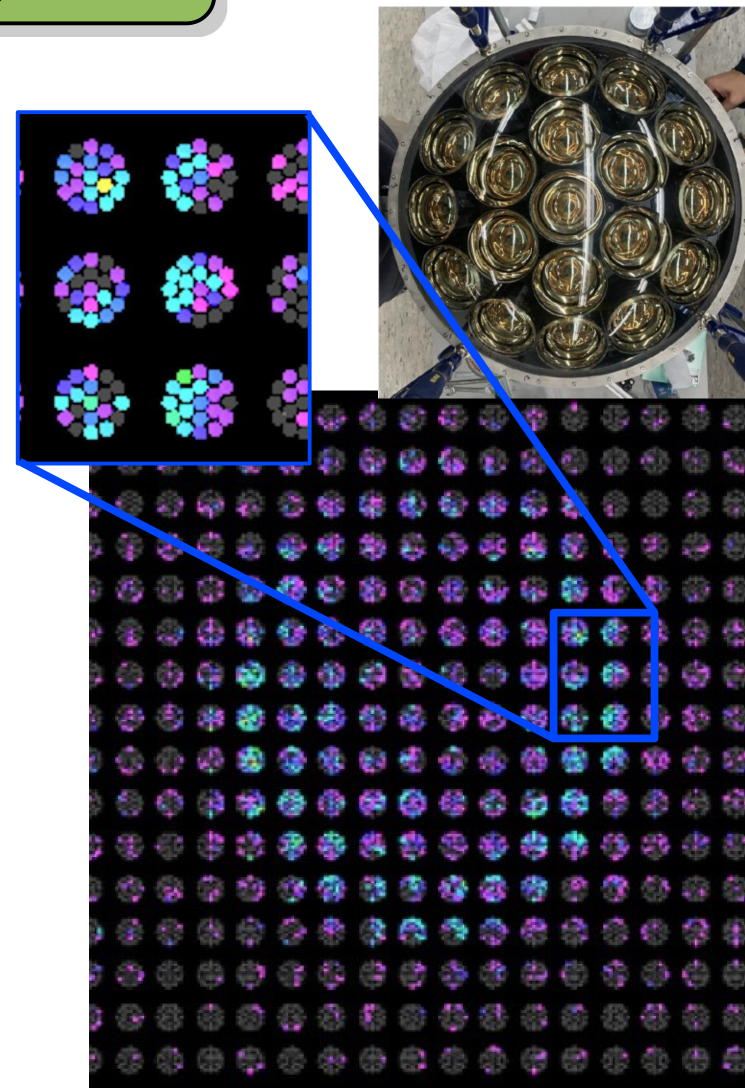


The Hyper-Kamiokande experiment
Intermediate Water Cherenkov Detector

- Additional “near” detector located ~850m from target
- 600 ton Water Cherenkov detector instrumented with mPMTs
- Design on-going, international contributions welcome

Key element to control systematic uncertainties
- Same target material and 4π acceptance as FD
- Measure $\sigma(\nu_e)/\sigma(\nu_\mu)$, NC and beam ν_e bckg
- Movable detector: use of PRISM technique

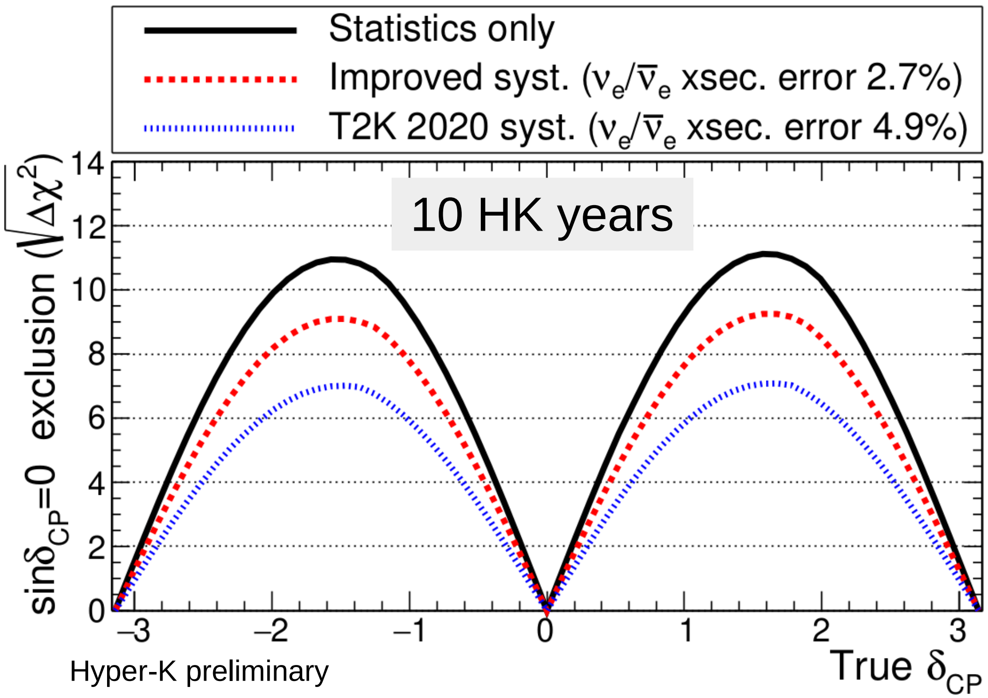


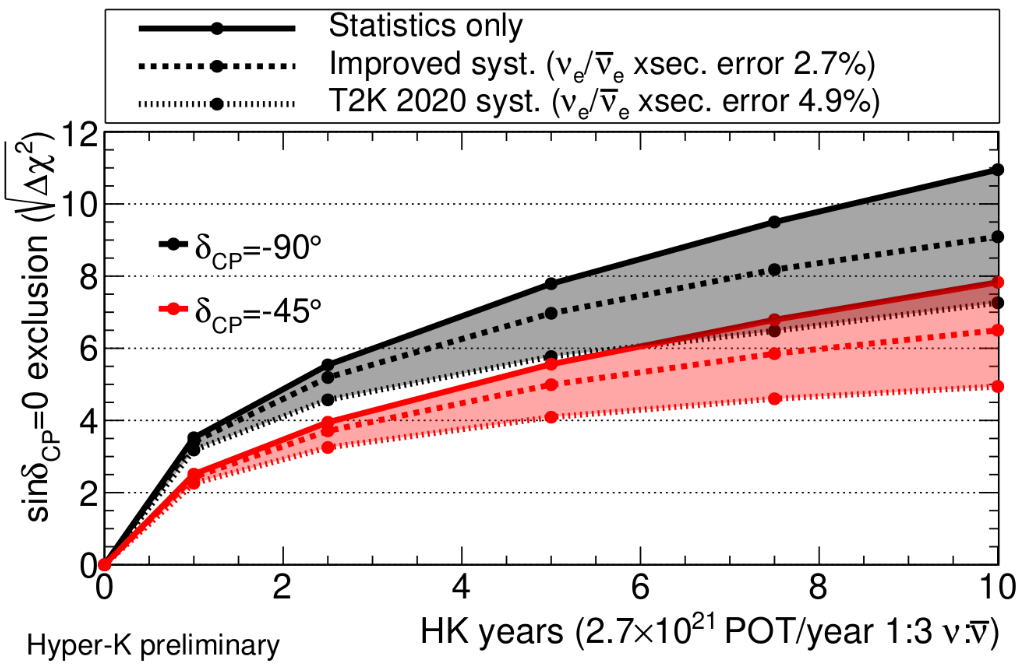


Long Baseline oscillations
Sensitivity - CP symmetry

- Sensitivity of LBL part updated last year
- Based on T2K analysis (neutrino 2020 version) scaled to HK statistics
- “Improved systematics” to represent improved systematics constraints from IWCD and upgraded ND280 measurements

- With **known MO** and improved syst., 5σ sensitivity for 62% of true δ_{CP} values in 10 years
- In most favorable case (NO, $\delta_{CP}=-\pi/2$), can exclude CP conservation in 3-5 years depending on systematics





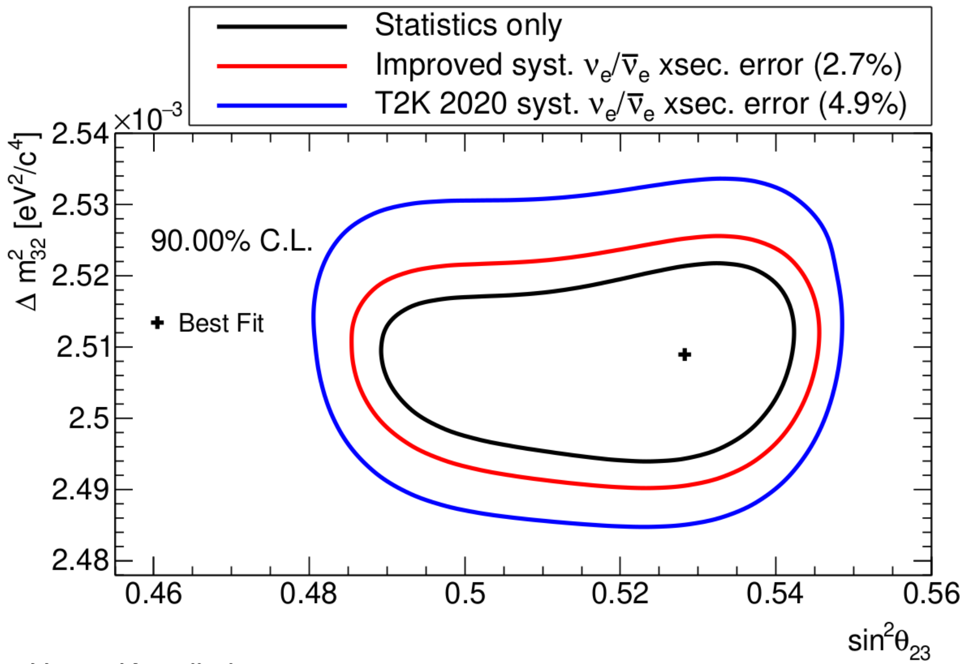
True values of parameters: Normal ordering, $\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\text{eV}^2/c^4$

Long Baseline oscillations
Sensitivity – Atmospheric parameters

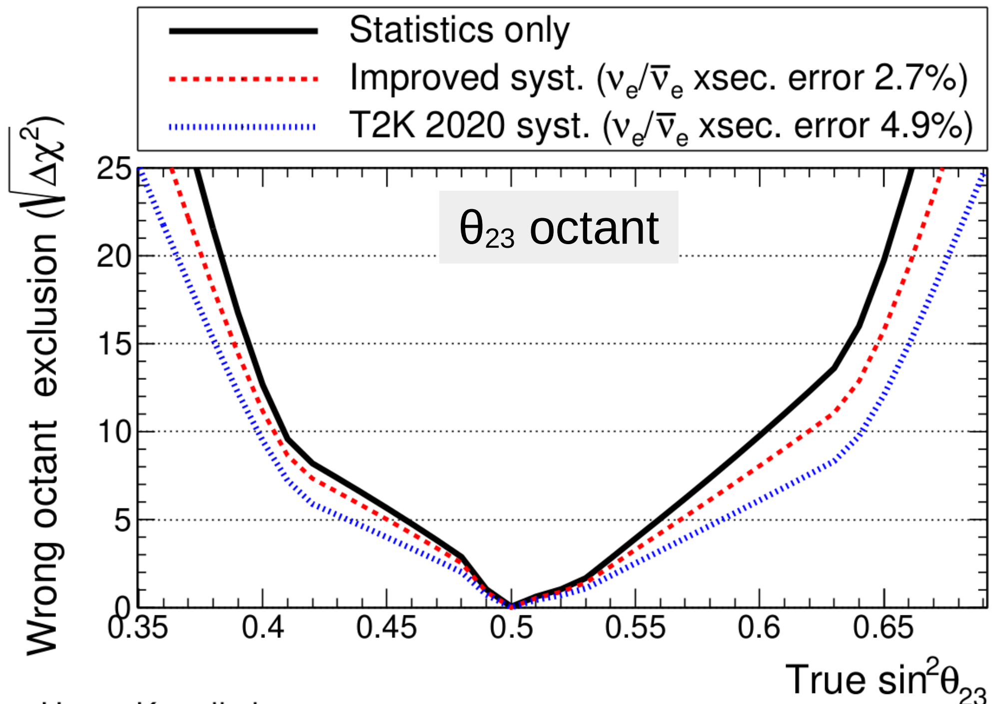
Using 10 years of HK data and improved systematics:

- Precise measurements of Δm^2_{32} (0.35% error) and $\sin^2\theta_{23}$ (2.47% error)
- Can determine octant if true $\sin^2\theta_{23}<0.45$ or true $\sin^2\theta_{23}>0.57$

Sensitivities for 10 HK-years (2.7×10^{22} POT 1:3 $\nu:\bar{\nu}$) with **known MO**



Hyper-K preliminary



Hyper-K preliminary

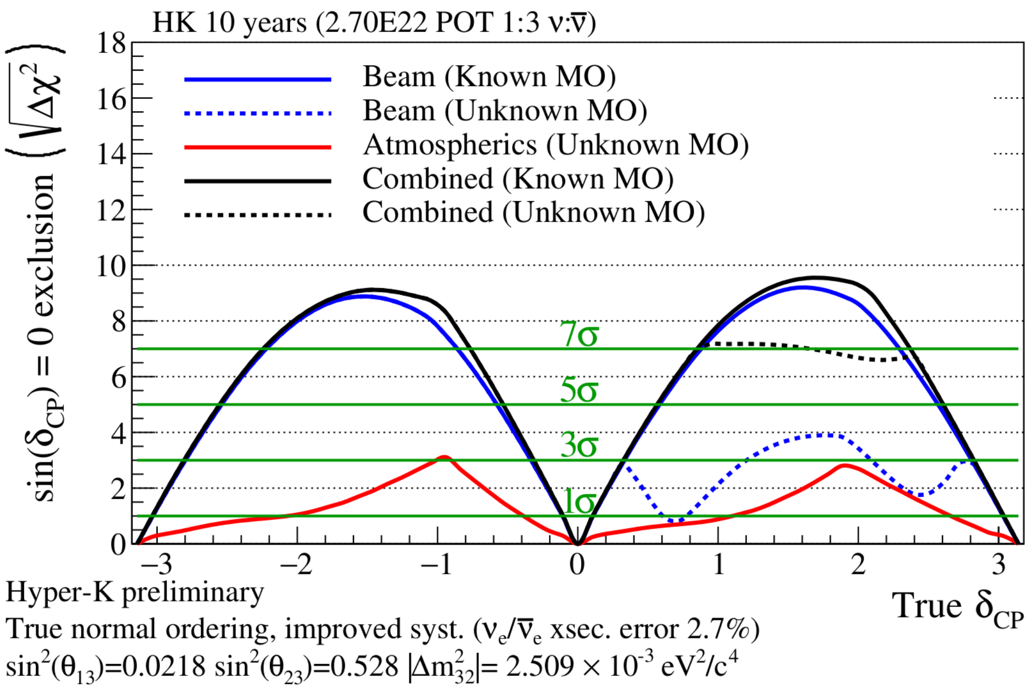
True values of parameters: Normal ordering, $\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}$eV^2/c^4

Long Baseline oscillations
Combination with atmospheric neutrinos

- Previous slides assumed known mass ordering
- If unknown, degeneracies can degrade sensitivity to δ_{CP} and octant
- Combination with atmospheric neutrinos can resolve degeneracies
- Additionally gives improved sensitivity to the mass ordering

Ability to reject CP conservation

See talk by T. Dealtry (WG1 parallel) for details on HK oscillation physics



	$\sin^2\theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	2.2 σ	→ 3.8 σ
	0.60	4.9 σ	→ 6.2 σ
θ_{23} octant	0.45	2.2 σ	→ 6.2 σ
	0.55	1.6 σ	→ 3.6 σ

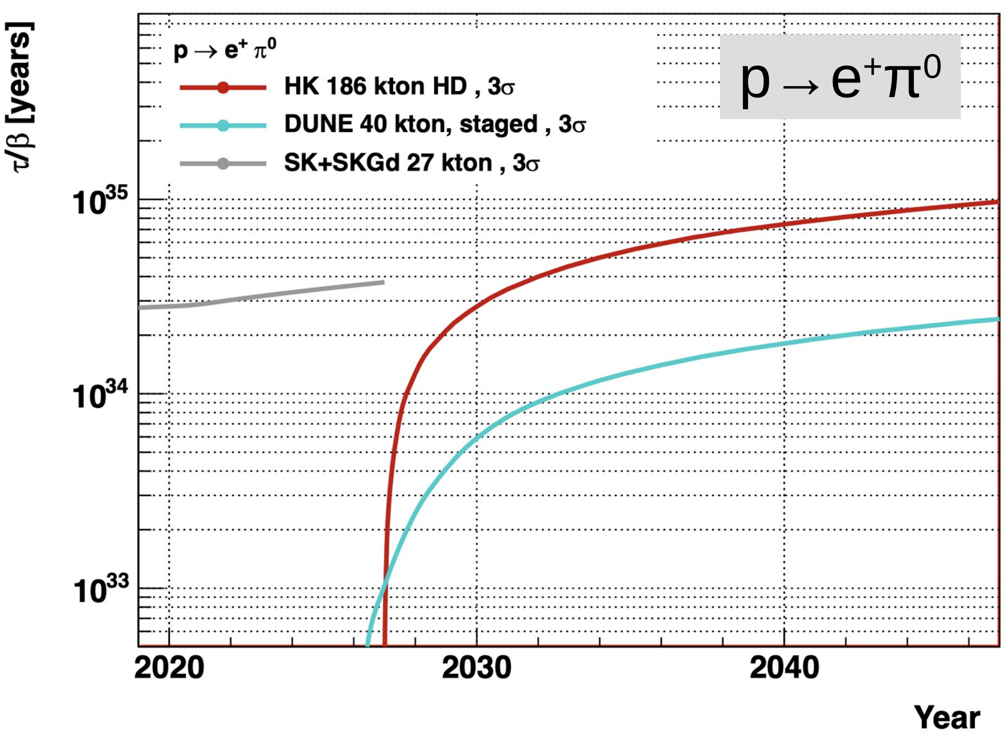
10 years with 1.3MW, normal mass ordering is assumed

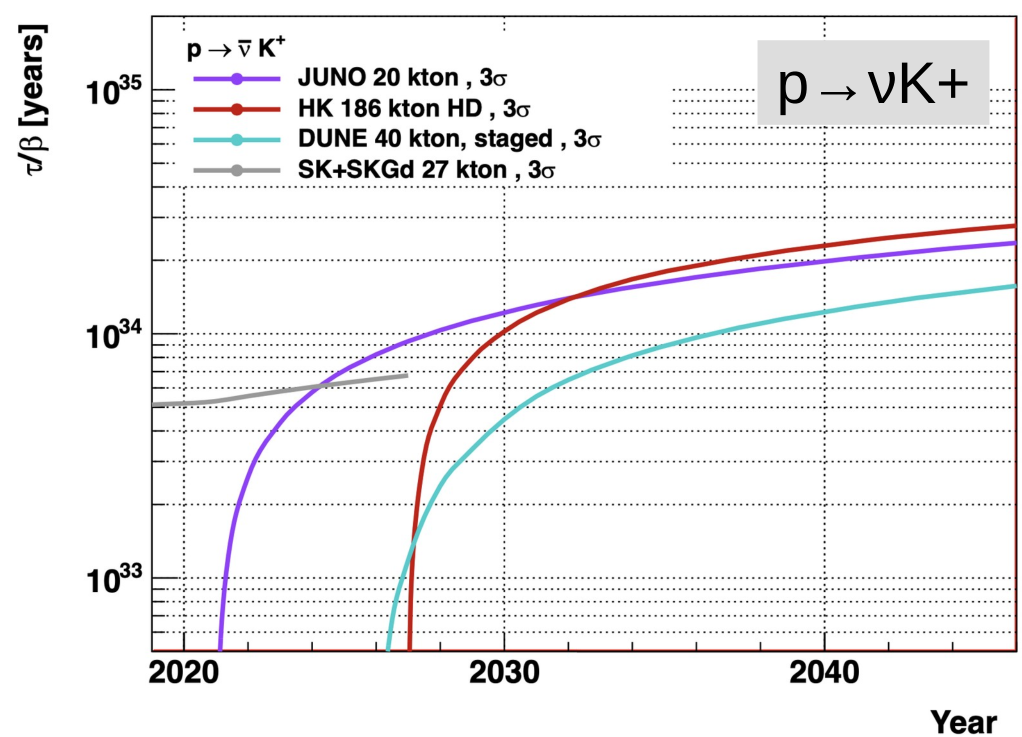
Based on older version of T2K analysis. Updates based on T2K+SK joint analysis in preparation

Search for nucleon decay

- One of the main physics goals of Hyper-K is to search for nucleon decay predicted by a number of grand unifying theories
- World leading sensitivity for proton decay searches: large mass and can use free protons to avoid problems of nuclear effects
- 3σ discovery potential reaches half-life of 10^{35} years for $p \rightarrow e^+\pi^0$ and $3\text{x}10^{34}$ years for $p \rightarrow \nu K^+$ after 20 years

3σ discovery potential as a function of time

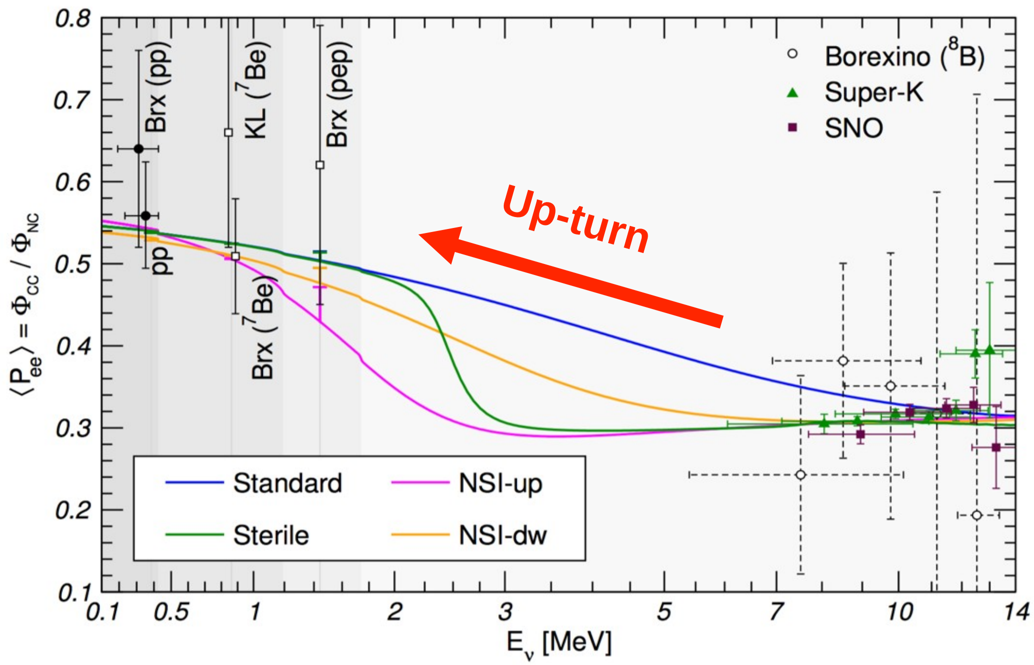




Low energy neutrinos
Solar neutrinos

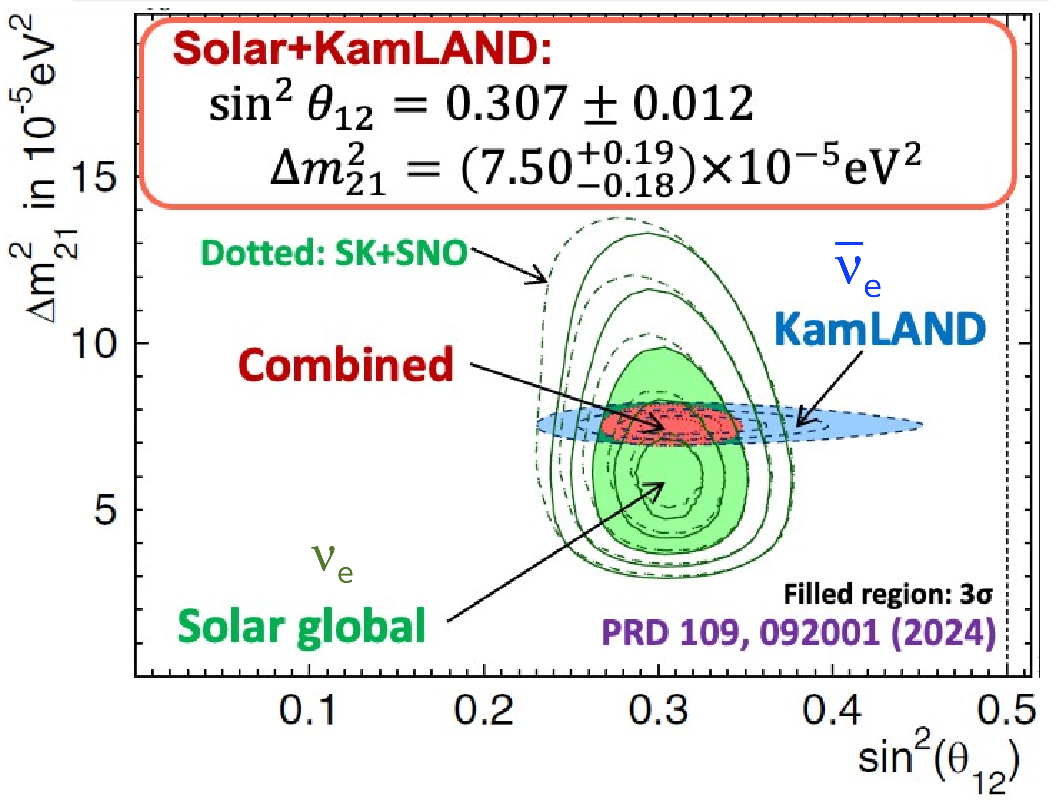
- At low energy, Hyper-K will study remaining questions on solar neutrino oscillations
- > 3σ sensitivity for the spectrum up-turn in 10 yrs (E_{th}=4.5 MeV).
- ~2σ day/night sensitivity expected for the difference in $\nu_e/\bar{\nu}_e$ osc. in 20 yrs.

Upturn from transition from matter dominated to vacuum dominated oscillations in the sun



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

~1.5σ tension between solar and KamLAND Δm^2_{21} measurements



Hyper-Kamiokande status Collaboration

- Hyper-K officially approved in 2020
- Collaboration has been growing since, and continuing
- 22 countries, 106 institutes, ~590 people as of Aug. 2024

June 2024 Collaboration Meeting at J-PARC

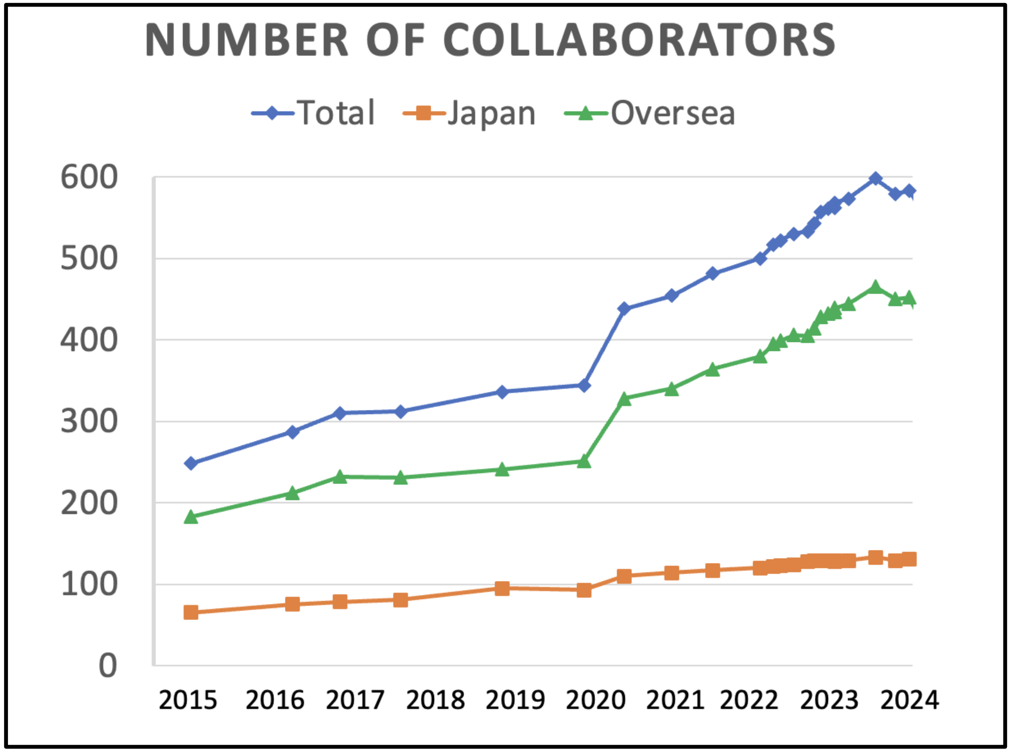
Europe	335 members
Armenia	3
Czech	8
France	50
Germany	1
Greece	4
Italy	46
Poland	45
Russia	21
Spain	45
Sweden	5
Switzerland	14
Ukraine	2
UK	91

Asia	164 members
India	9
Korea	19
Japan	136

Oceania	9 members
Australia	9

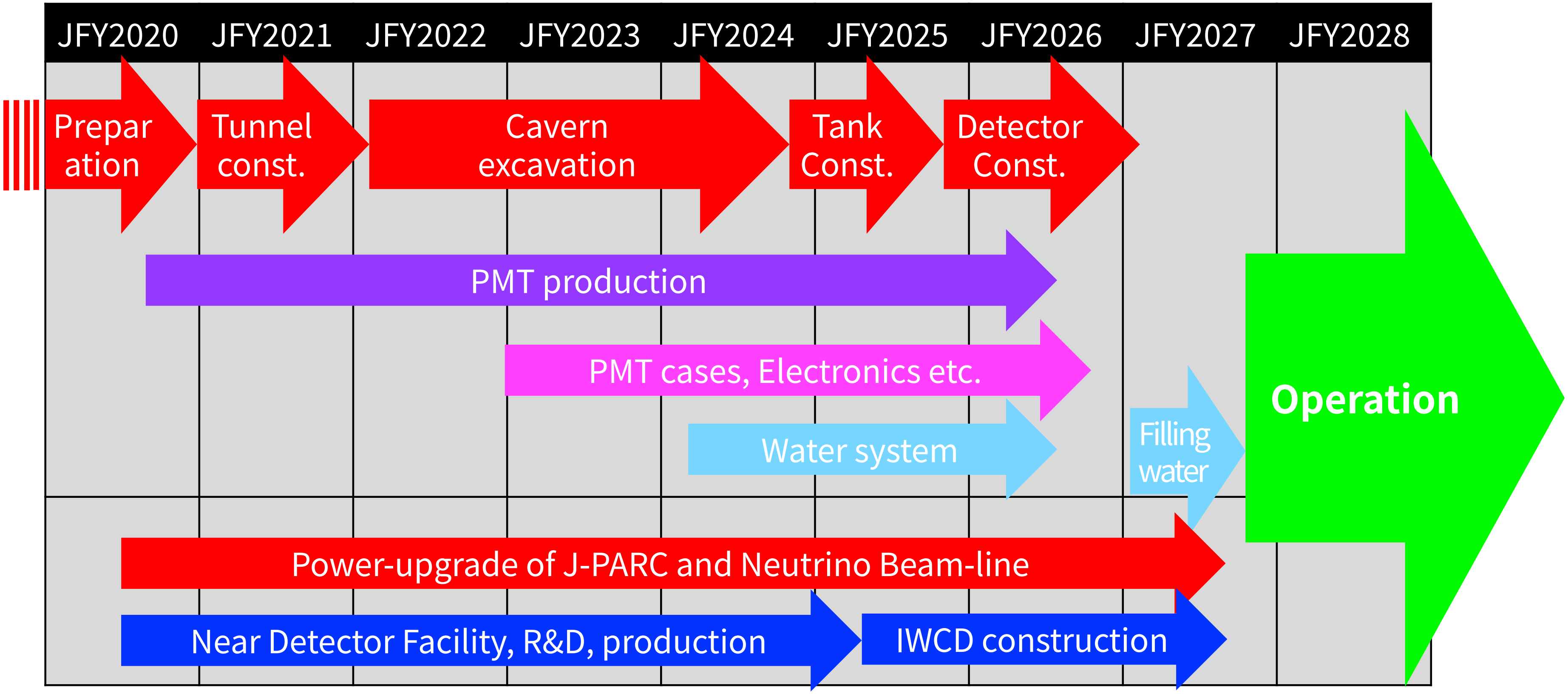
Americas	67 members
Brazil	3
Canada	43
Mexico	11
USA	10

Africa	11 members
Morocco	11



Hyper-Kamiokande status
Schedule

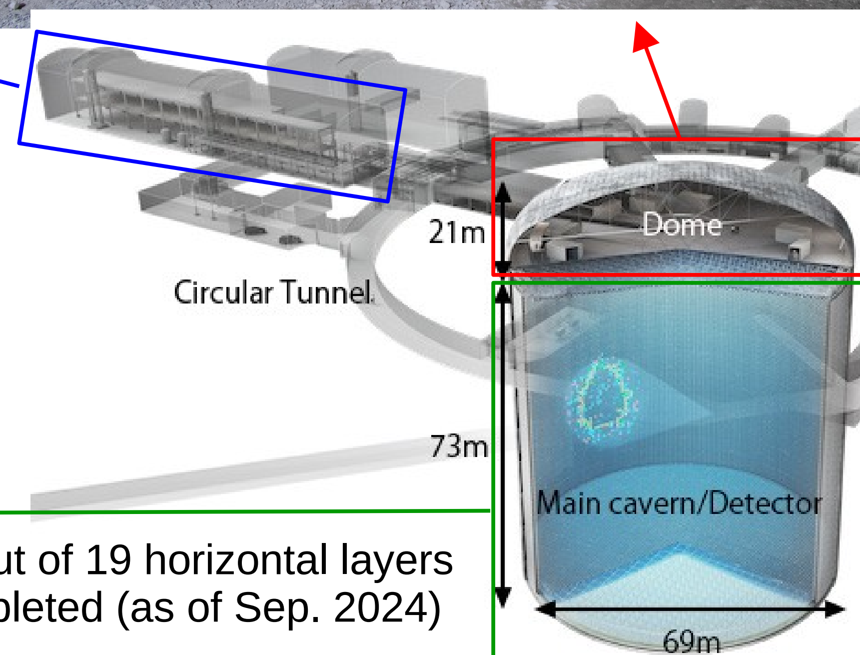
- Construction phase extended by 6 months, mainly due to changes to the top structure of the detector
- End of detector construction and start water filling May 2027
- **Start of operations Dec. 2027**



Note: Japanese Fiscal Year starts April 1st

Hyper-Kamiokande status
Excavation

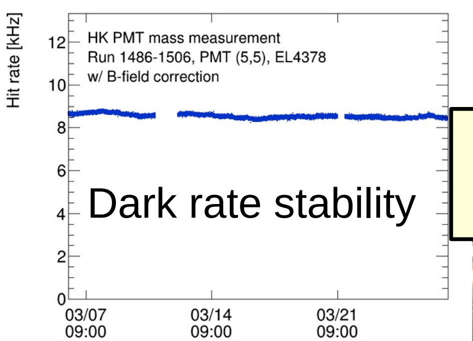
- Excavation progressing smoothly
- Approach tunnels completed in 2022
- Excavation of dome part (main technical challenge and schedule risk) and cavity for water system completed in 2023
- Barrel excavation on-going, on track to finish by the end of the year



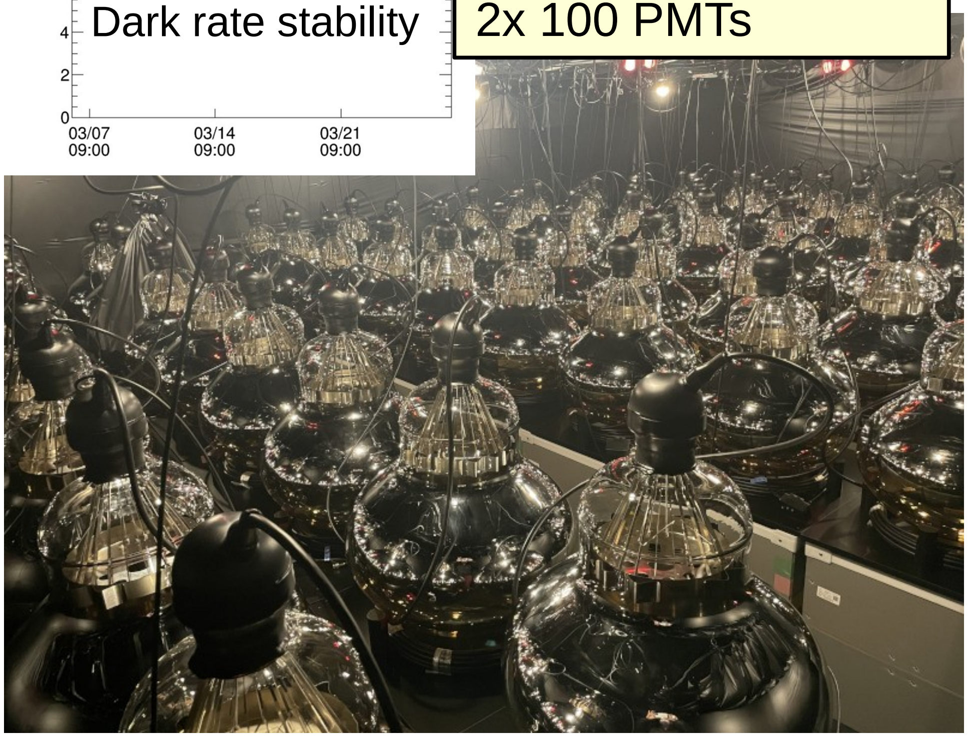
12 out of 19 horizontal layers completed (as of Sep. 2024)

Hyper-Kamiokande status
50cm PMTs

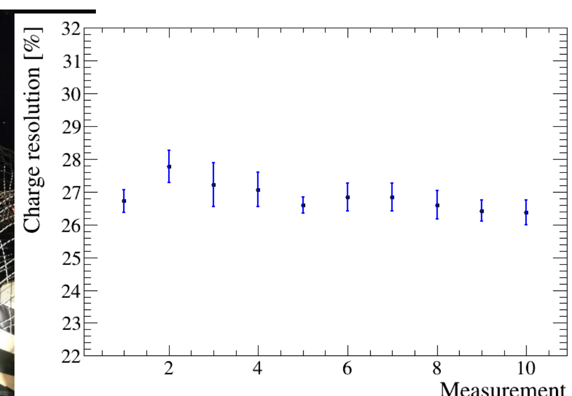
- Mass production of 50cm PMTs started in 2020
- Production suspended in 2022 due to higher than expected failure rate
- New large scale test facility at Kamioka allowed to validate improved PMT design and QC by Hamamatsu Photonics
- PMT delivery restarted in May 2023, with sampling test of delivered PMTs at Kamioka
- >10k 50cm PMTs delivered so far, in line to complete delivery of 20.5k by Sep. 2026



"Mass measurement"
2x 100 PMTs



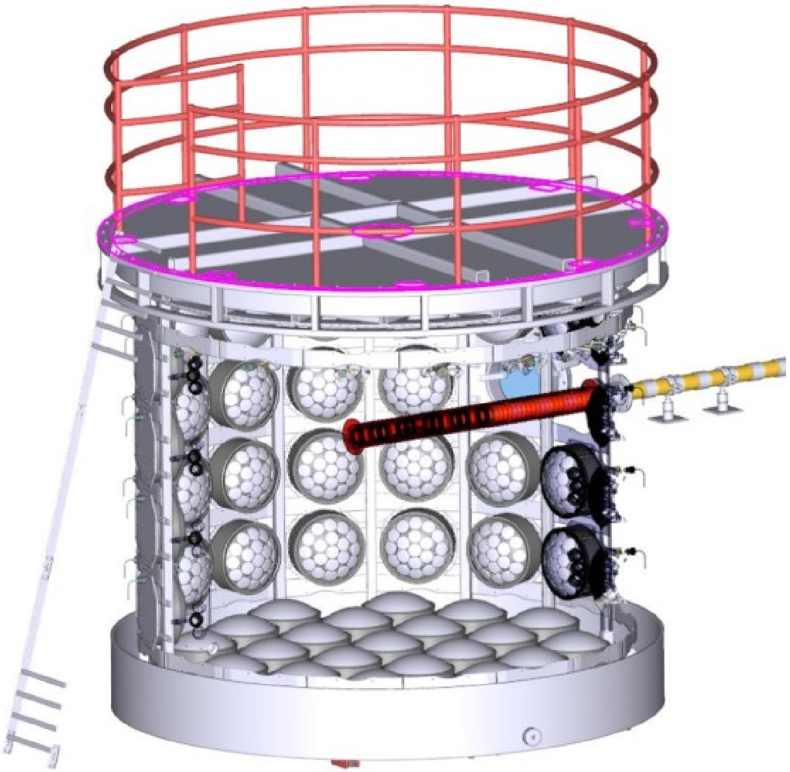
- 2^{nd} system: light injection and B field shielding
- Measure stability of performance between deliveries



Hyper-Kamiokande status
Multi-PMTs

- Different types: FD, FD with LED, IWCD with common basis
- Design complete outside of LED part
- Prototypes built and on-going various tests before mass production next year

Water Cherenkov Test Experiment

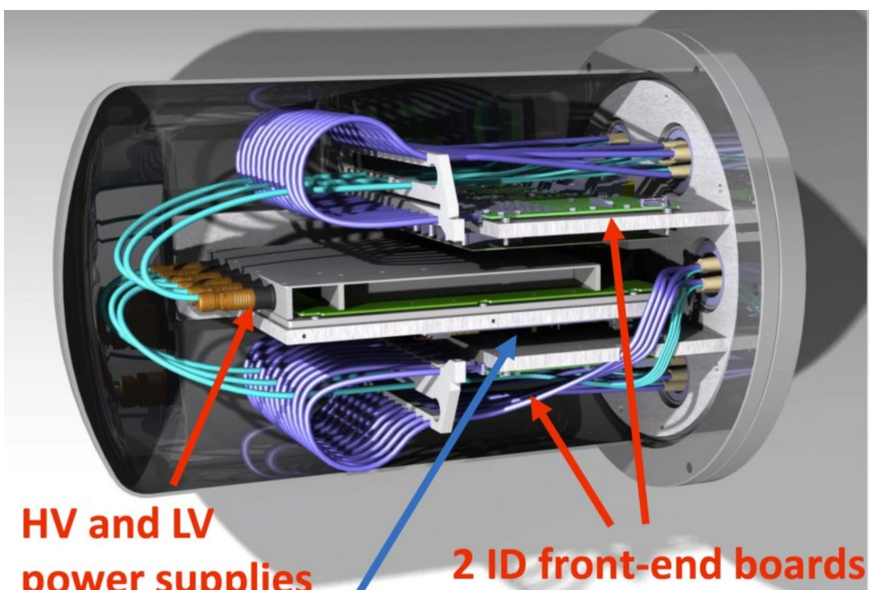


- WCTE will measure charged particle scattering at CERN from this fall
- Prototype for IWCD and FD mPMT assembly
- Assembled 100 IWCD style and 5 FD style mPMTs, validating procedure and assembly speed estimates

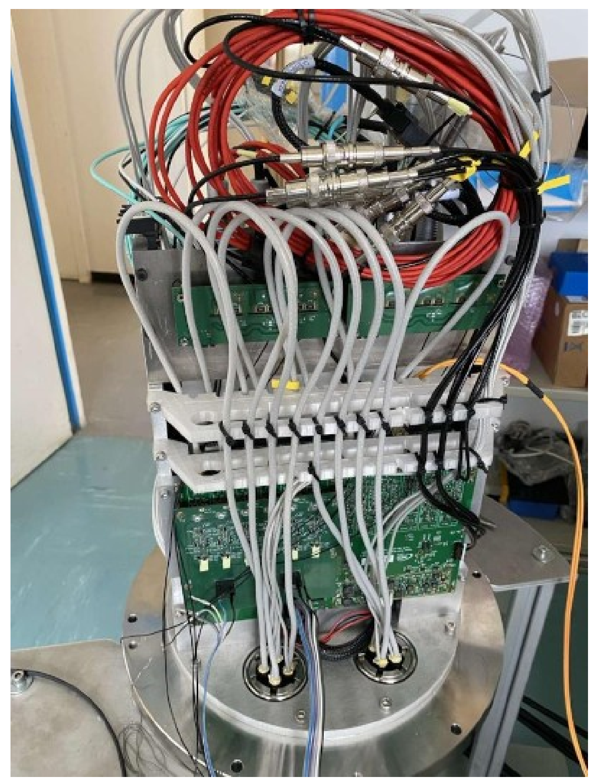
Note: WCTE is an independent collaboration from Hyper-Kamiokande

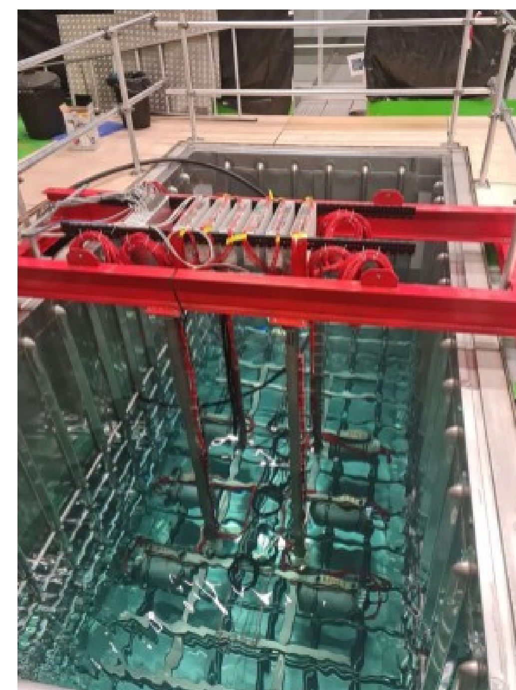
Hyper-Kamiokande status
Electronics

- Electronics will be underwater, in pressure vessels
- Two types: Inner detector PMTs only, and hybrid inner/outer detector PMTs
- Vessel design was fixed and production started
- Prototypes of all the components are produced and assembled, evaluation on-going at CERN and in Kamioka
- Calibration and assembly of mass produced components from summer 2025



Data processing and timing boards

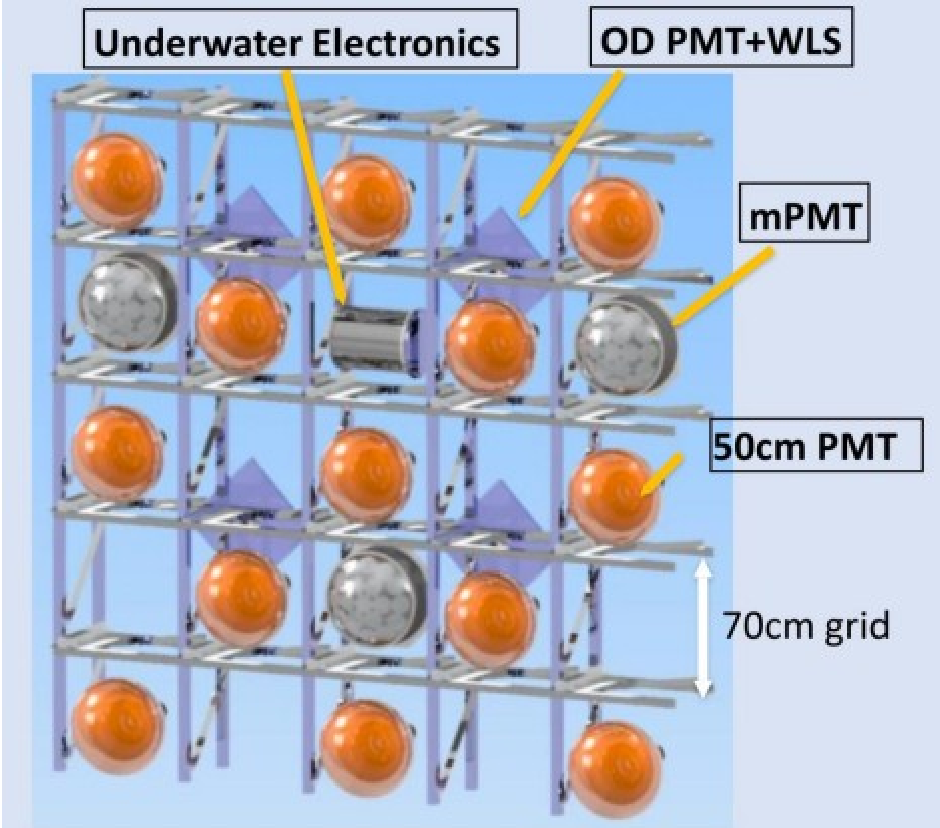


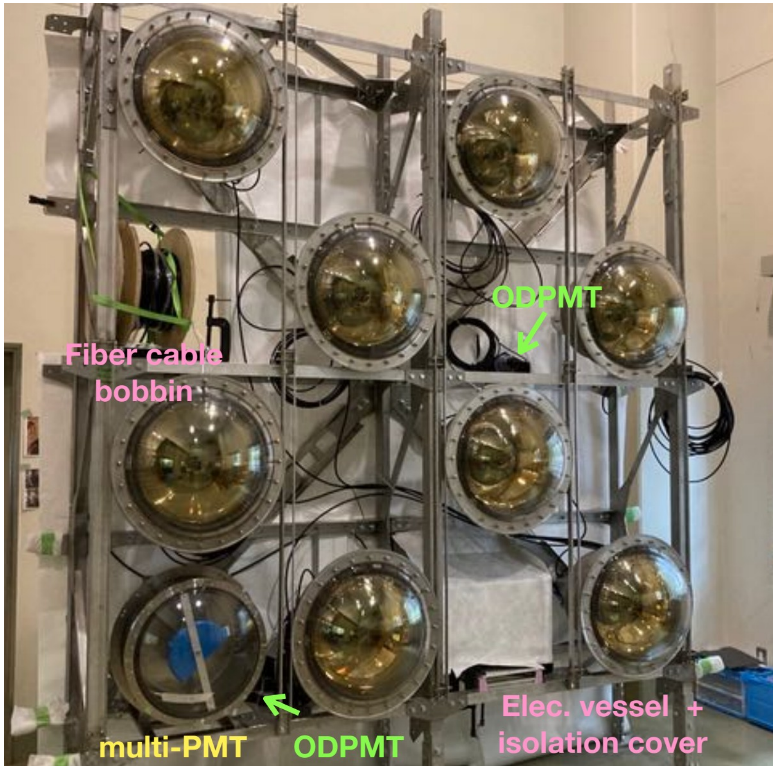


Hyper-Kamiokande status
Detector construction

- Construction company for tank and detector selected in Aug. 2024
- Will follow schedule made during design phase (no delays due to difference between design and construction companies)
- Detailed design of tank lining and PMT support structure completed
- Tank construction will start beginning 2025 and detector installation in Summer 2026

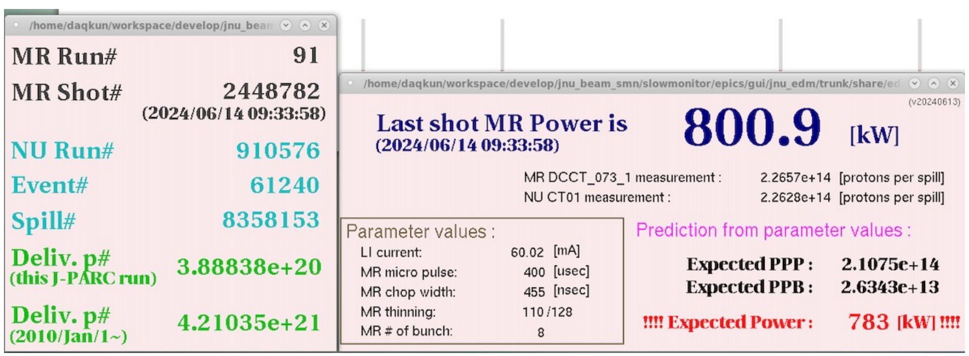
Mock-ups in Japan (ID and OD) and UK (mostly for OD) for tests and validation of the design and installation procedures

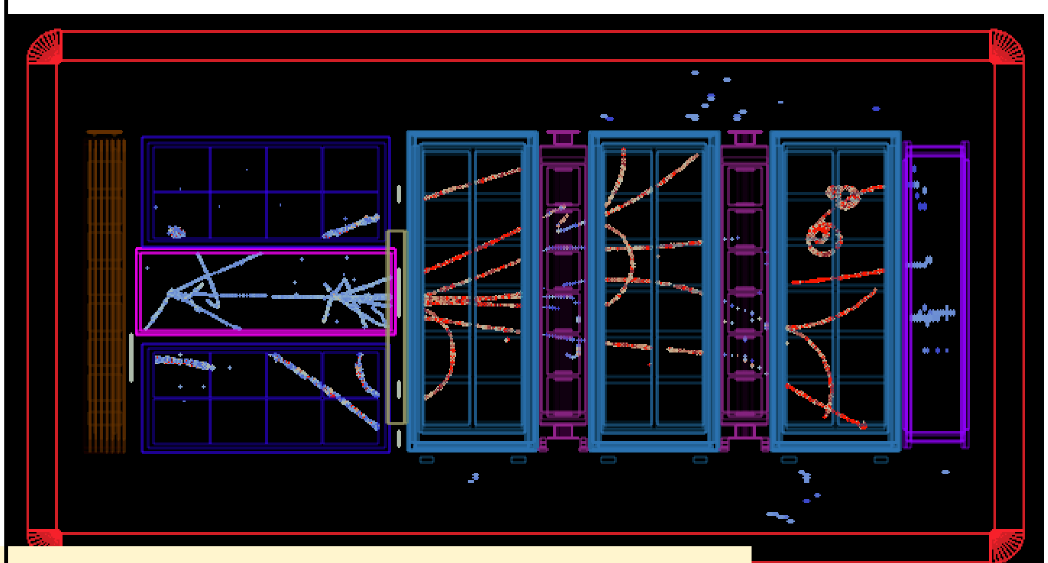




Hyper-Kamiokande status
Beam and near detector

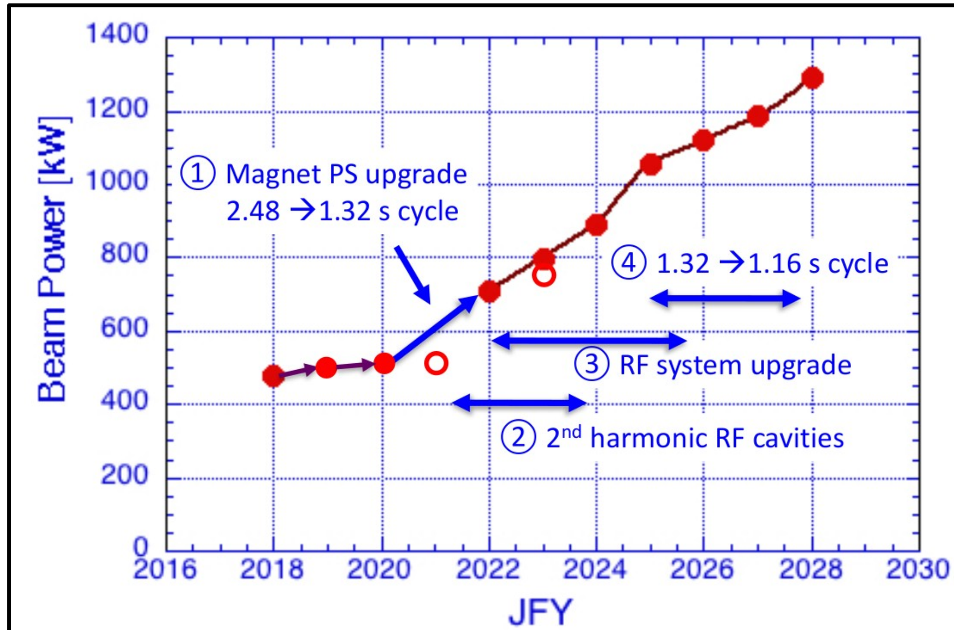
- J-PARC neutrino beamline and near detector currently part of T2K
- Significant milestones over the last year:
  - Operation at increased beam intensity (>800 kW) and horn current following beamline upgrade
  - Installation and first events observed in upgraded near detector ND280





From C. Giganti @ Neutrino 2024

Continuous beam power increase to 1.3MW by the start of HK



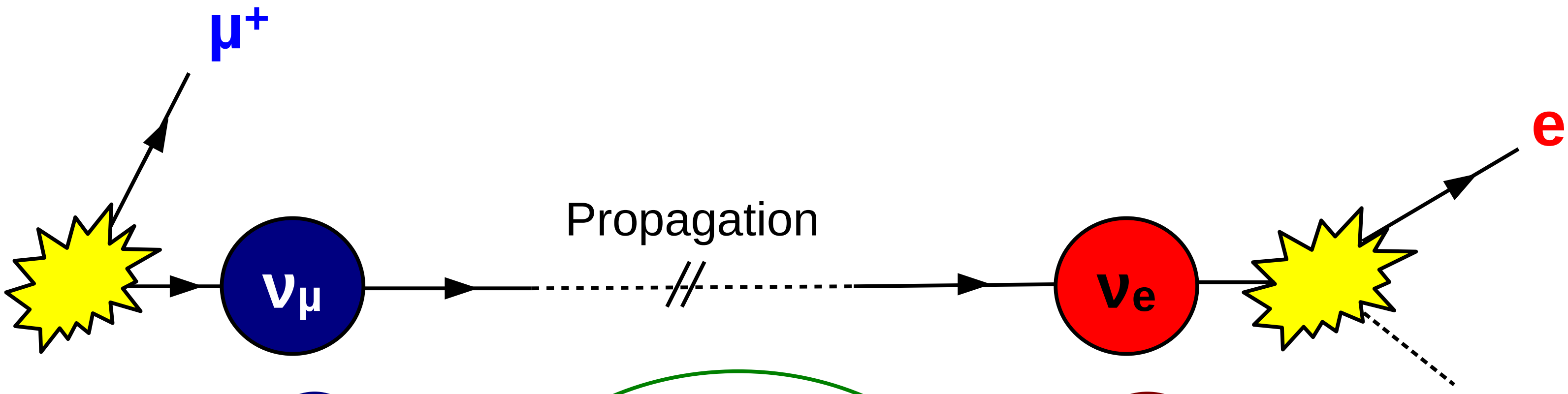
From Y. Sato @ J-PARC PAC

Summary

- Hyper-Kamiokande is the next generation Water Cherenkov experiment in Japan
- Large statistics will allow high precisions studies of the oscillation of atmospheric, accelerator and solar neutrinos, as well as searches for new physics (proton decay in particular)
- Long baseline part will use the J-PARC beamline together with the upgraded T2K near detector and a new intermediate water Cerenkov detector
- Can exclude CP conservation in neutrino oscillations for 62% of true δ_{CP} values in 10 years if mass ordering is known
- Combination between accelerator and atmospheric neutrinos can be used to deal with degeneracies if mass ordering not known
- Detector construction on-going, excavation of the far detector cavern will be completed by the end of 2024
- Start of operation planned for December 2027

Additional slides

Neutrino oscillations



Flavor eigenstates
(interaction)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates
(propagation)

Mixing (or Pontecorvo-Maki-Nagawa-Sakata) matrix
link between the two sets of eigenstates

P($\nu_\alpha \rightarrow \nu_\beta$) oscillates as a function of distance L traveled by the neutrino with periodicity **$\Delta m^2_{ij} L/E$**

($\Delta m^2_{ij} = m^2_i - m^2_j$)

Neutrino oscillations
Parameters

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

($c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$)

$P(\nu_\alpha \rightarrow \nu_\beta)$ depends on 6 parameters:

- 3 **mixing angles** : **θ_{12}, θ_{23}, θ_{13}** → Amplitude
- 2 **mass splittings** : **Δm^2_{ij}** → Periodicity
- 1 (complex) phase : The **CP phase δ** → Difference in oscillations $\nu/\bar{\nu}$

$$P(\nu_\alpha \rightarrow \nu_\beta, U) = P(\overline{\nu_\alpha} \rightarrow \overline{\nu_\beta}, U^*)$$

Hamamatsu R12860

A number of improvement compared to R3600 used in Super-Kamiokande:

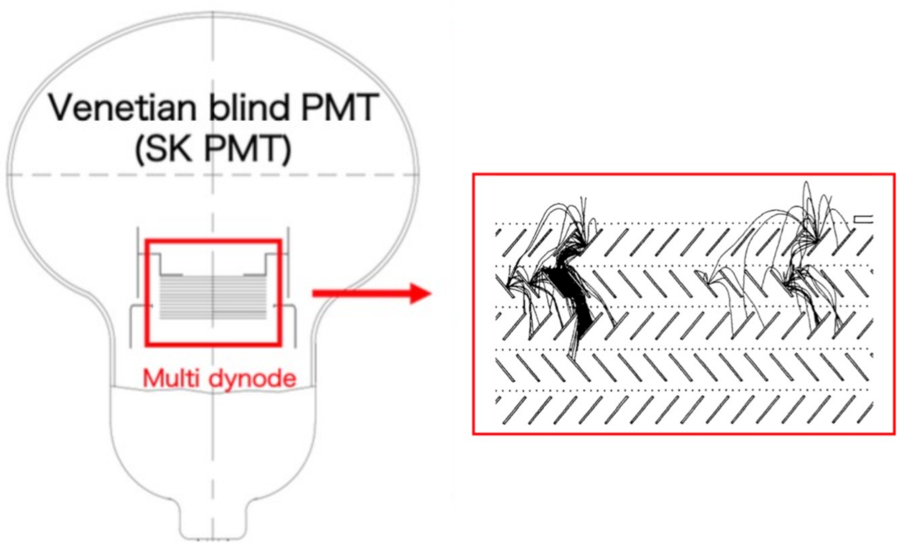
- Higher QE and electrons less likely to miss first dynode => higher detection efficiency
- More uniform electron drift path => better timing and charge resolution

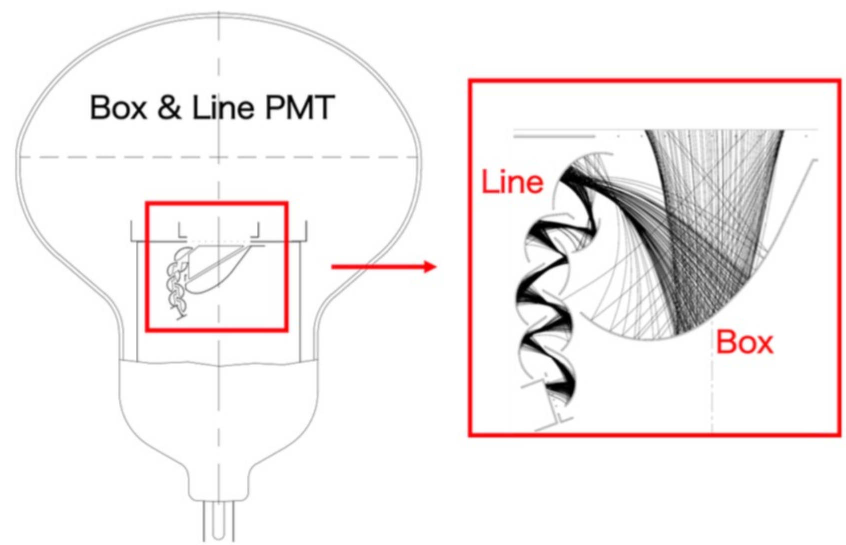
Super-K PMT
Hamamatsu R3600

Venetian blind dynode

Hamamatsu R12860

Box and line dynode
+ high QE

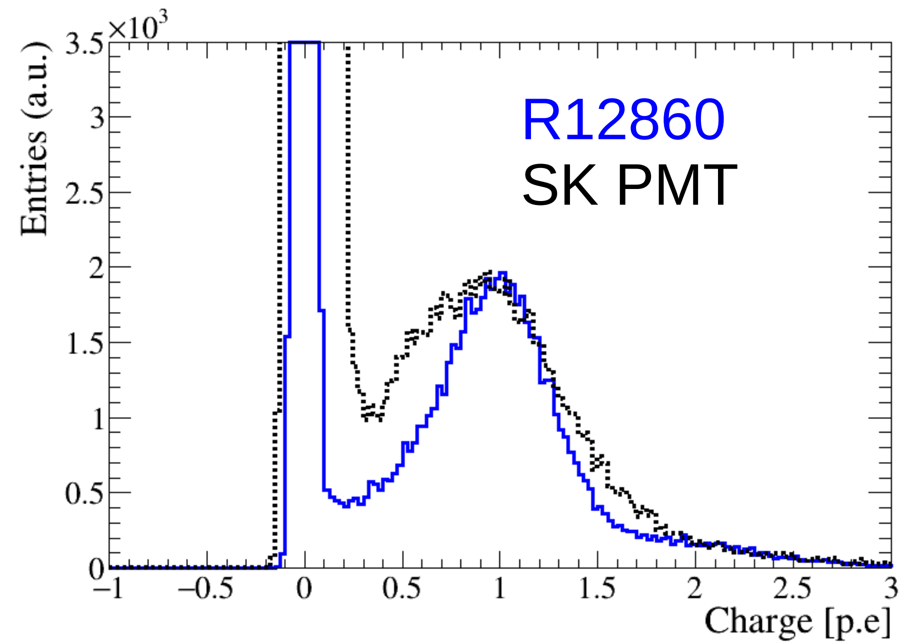


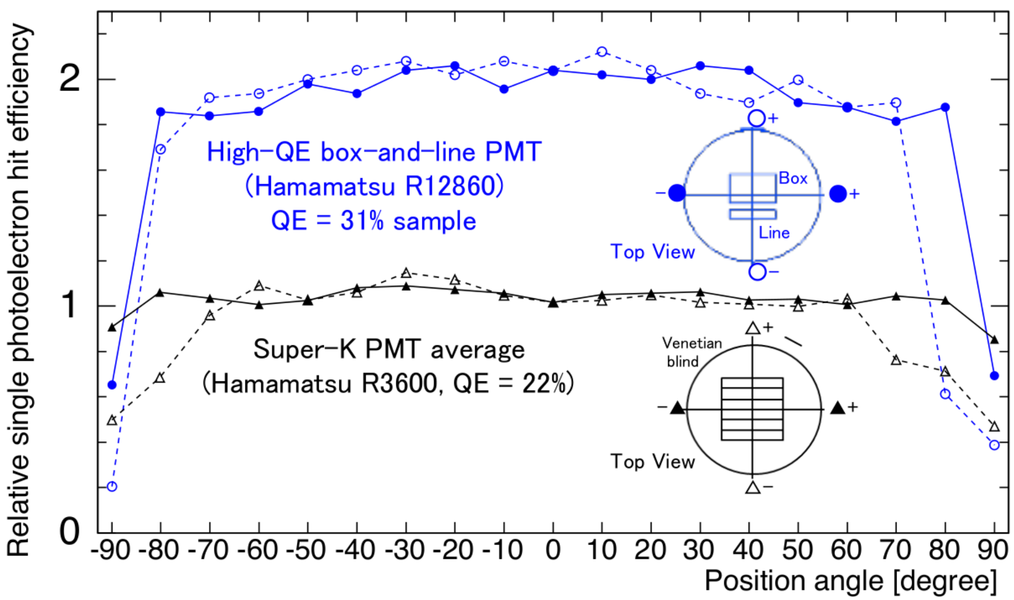


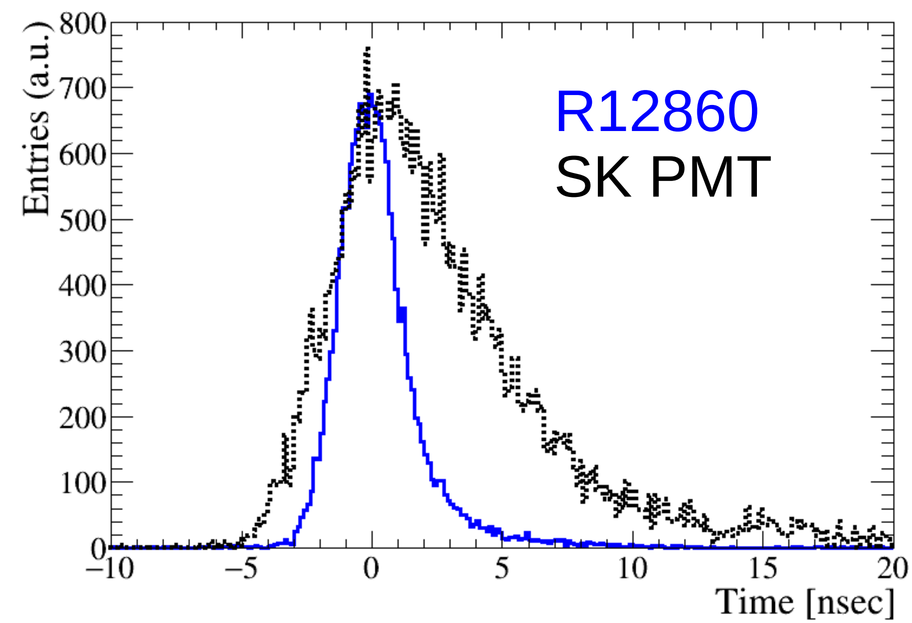
Hamamatsu R12860

Clear improvement seen in tests:

- ~2x photo-detection efficiency
- TTS: 6.73 ns → 2.59 ns (FWHM)
- Charge resolution: 60.1% → 30.8%

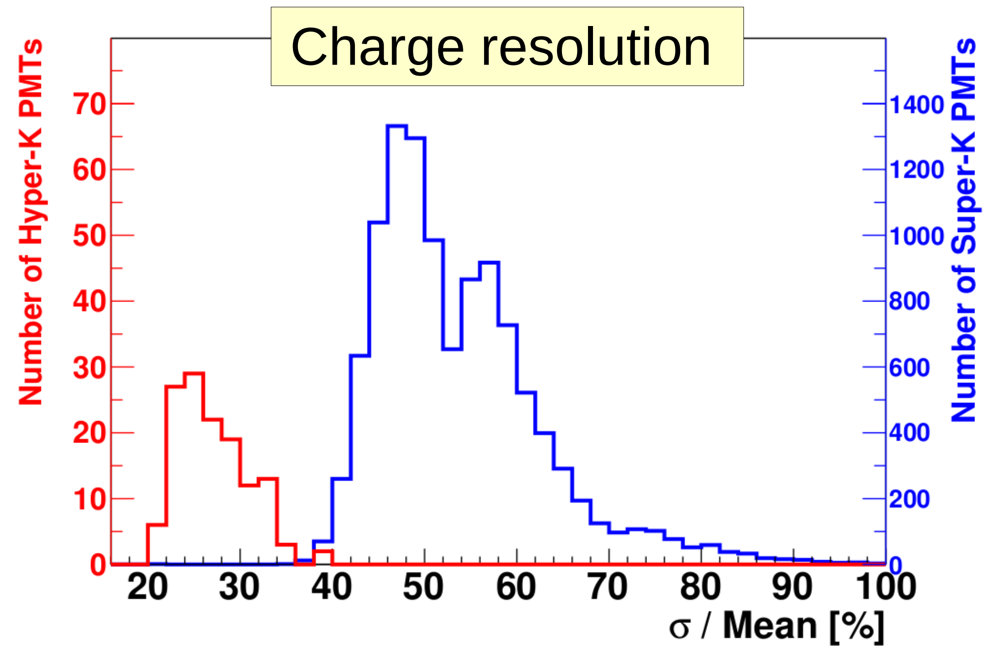


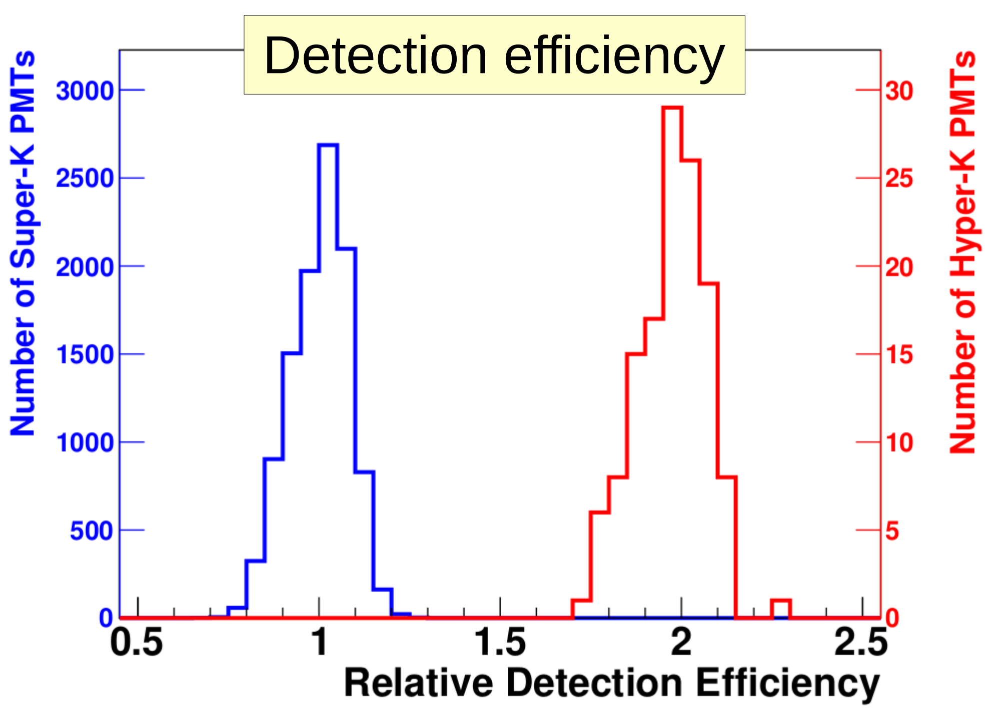


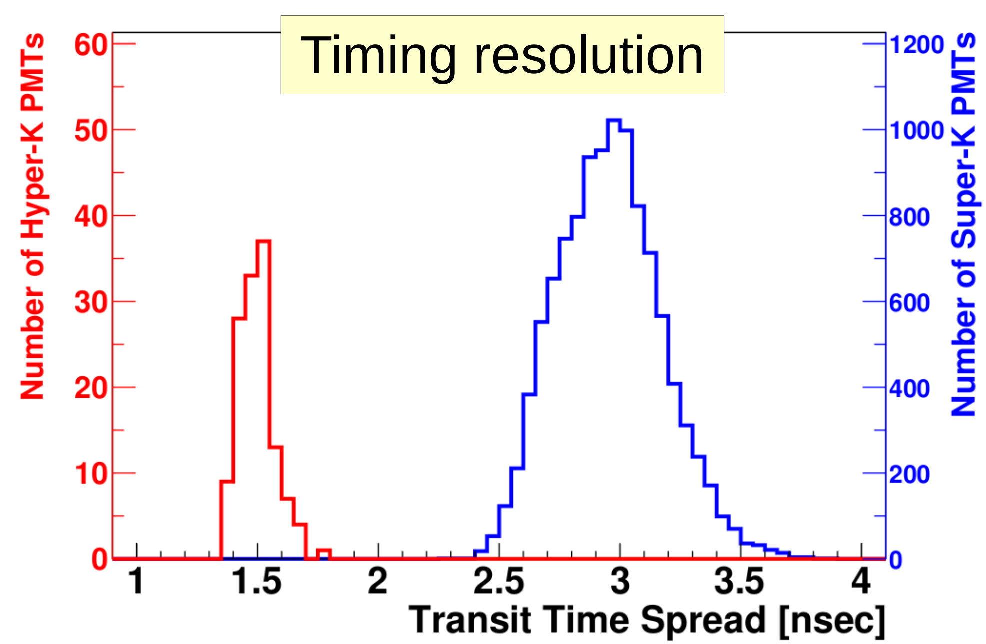


Hamamatsu R12860 Performance in Super-Kamiokande

- Measurement inside Super-K confirmed improved detection efficiency, and charge and timing resolution in real detector conditions
- Measured timing resolution (σ=1.5 ns) worse than pre-installation tests (σ=1.1 ns), believed to be due to unidentified element in Super-K measurement and not change of PMT performance







Long Baseline oscillations
Sensitivity – Uncertainty model

Uncertainties assumed for the "T2K 2020" case

T2K 2020	1 ring μ-like		1 ring e-like			
Error source	ν-mode	$\bar{\nu}$-mode	ν-mode + 0 decay	$\bar{\nu}$-mode + 0 decay	ν-mode + 1 decay	$\nu/\bar{\nu}$-mode + 0 decay
ND constrained Flux + Cross section	2,1 %	3,4 %	3.6 %	4.3 %	4,9 %	4,4 %
Not ND constrained Cross-section	0,5 %	2,6 %	3.0 %	3.7 %	2,7 %	4,1 %
Detector	2,1 %	1,9 %	3.1 %	3.9 %	13,2 %	1,1 %
All systematics	3,0 %	4,0 %	4.7 %	5.9 %s	14,1 %	4,6 %

Long Baseline oscillations Sensitivity – Uncertainty model

Uncertainties assumed for the "Improved systematics" case

Improved	1 ring μ-like		1 ring e-like			
Error source	ν -mode	$\bar{\nu}$ -mode	ν -mode + 0 decay	$\bar{\nu}$ -mode + 0 decay	ν -mode + 1 decay	$\nu/\bar{\nu}$ -mode + 0 decay
ND constrained Flux + Cross section	0,9 %	0.9 %	1.8 %	1,6 %	1,8 %	1,9 %
Not ND constrained Cross-section	0,4 %	0.4 %	1.6 %	1,4 %	1,6 %	1,9 %
Detector	0,8 %	0.7 %	1.1 %	1,5 %	4,9 %	0,4 %
All systematics	1,2 %	1.1 %	2.1 %	2,2 %	5,2 %	2,0 %

Long Baseline oscillations
Sensitivity – Uncertainty model

Construction of the "Improved systematics" model

The Improved systematics model was produced by scaling the post-ND280 T2K-2020 error model by:

- Scaling uncertainty on flux, cross-section and SK detector systematics by 1/sqrt(N), where N = 7.5 is the relative increase in neutrino beam exposure from T2K to Hyper-K
- Studies from ND280 Upgrade group and the IWCD group were used to apply a further constraint to the cross-section model uncertainties:
  - A factor of 3 reduction on all non-quasi-elastic uncertainties
  - A factor of 2.5 reduction on all quasi-elastic uncertainties
  - A factor 2 reduction on all anti-neutrino uncertainties
  - A reduction in neutral current uncertainties to the ~10% level
- The ν_e / $\bar{\nu}_e$ cross-section ratio error was fixed to 2.7%

Long Baseline oscillations Resolutions

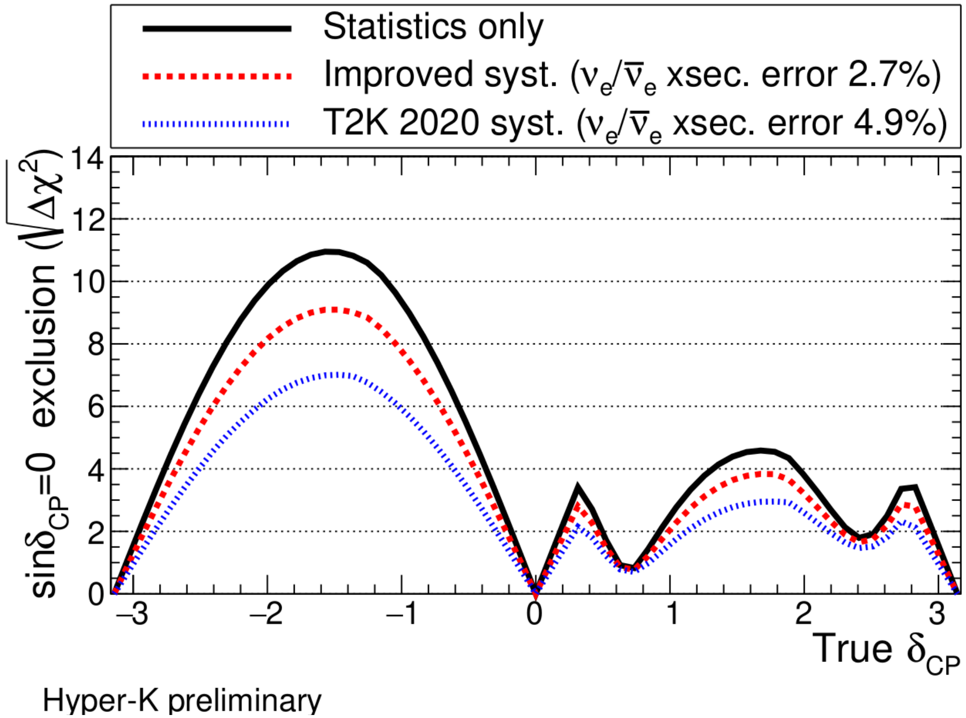
1sigma resolution of oscillation parameters for 10 HK years, accelerator neutrinos only

Parameter & true value	$\delta_{CP}=0°$	$\delta_{CP}=-90°$	$\sin^2\theta_{23}=0.528$	$\Delta m^2_{32}=2.509 \times 10^{-3}$ eV^2/c^4	$\sin^2\theta_{13}=0.0218$ with RC
Statistics only	5.2°	18.5°	0.0103 1.95%	7.30×10^{-6} eV^2/c^4 0.29%	4.73×10^{-4} 2.17%
Improved Systematics	6.3°	20.2°	0.0134 2.54%	8.69×10^{-6} eV^2/c^4 0.35%	5.39×10^{-4} 2.47%
T2K 2020 systematics	8.3°	23.9°	0.0199 3.77%	11.62×10^{-6} eV^2/c^4 0.46%	6.04×10^{-4} 2.77%

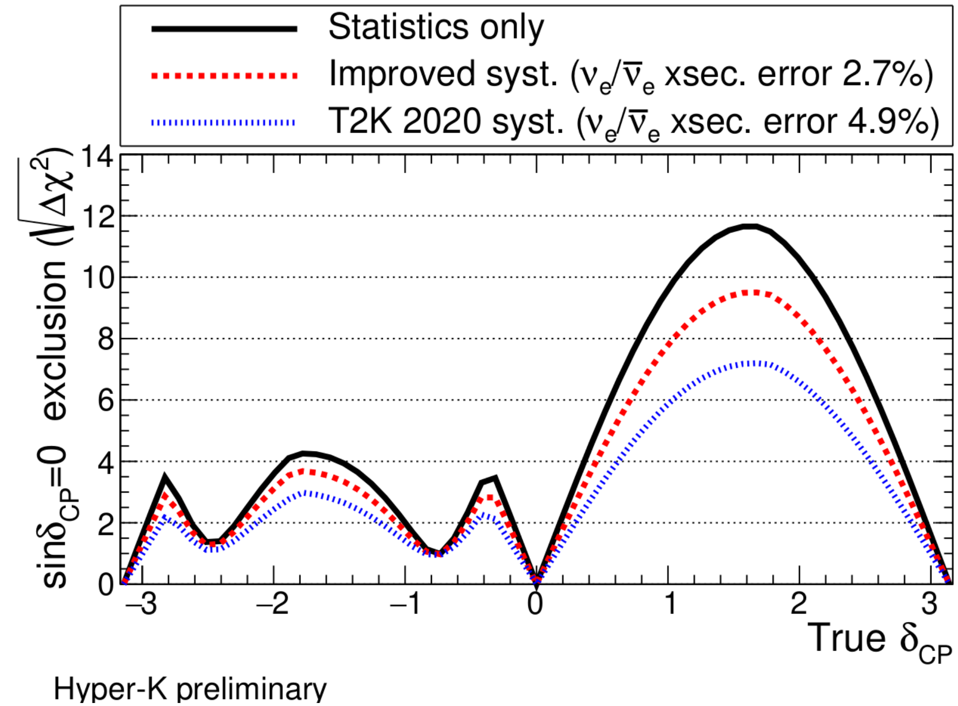
Long Baseline oscillations
Sensitivity with unknown Mass Ordering

Ability to exclude conservation of CP symmetry for 10 HK years, accelerator neutrinos only,
Unknown Mass Ordering

<u>True Normal Ordering</u>

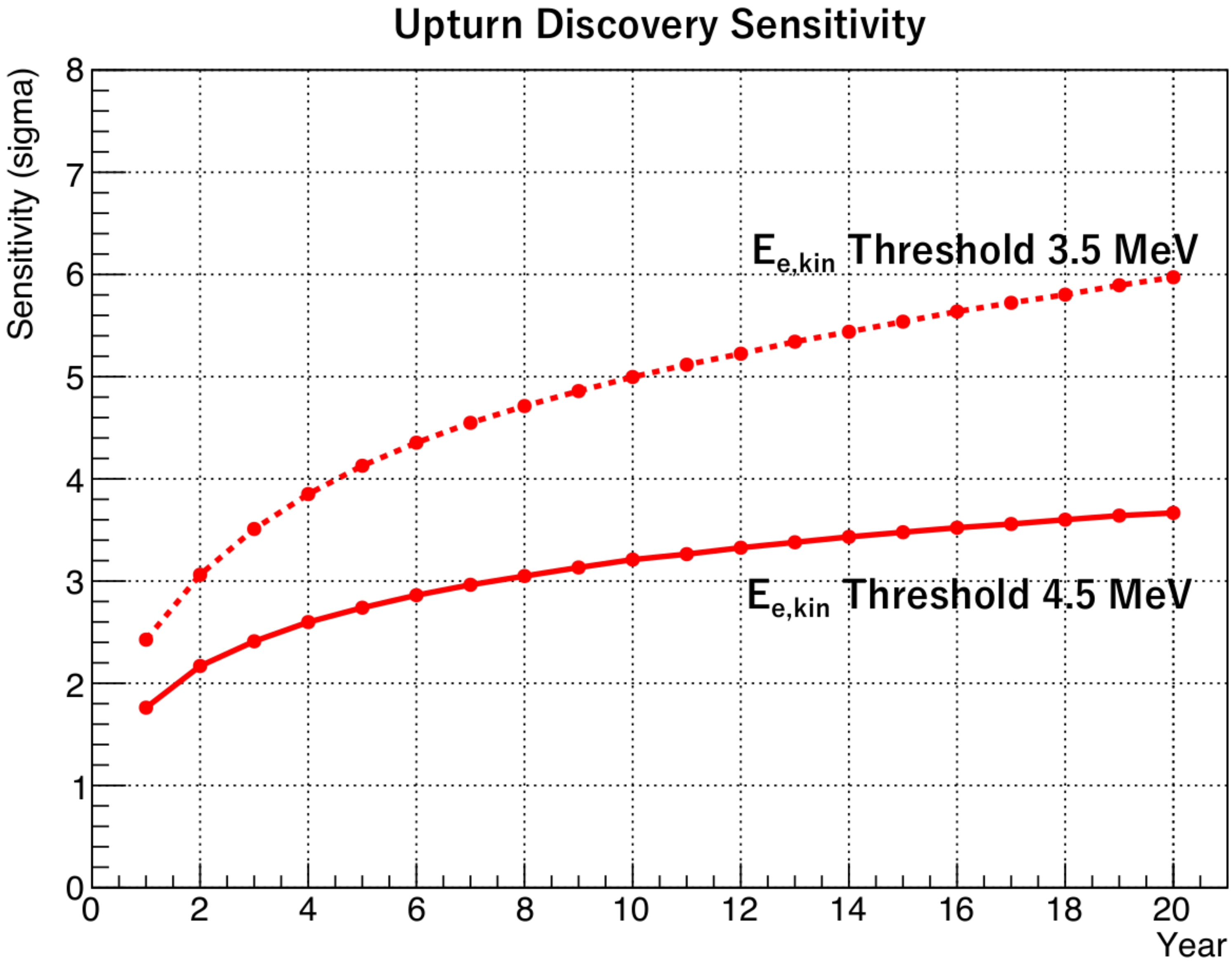


<u>True Inverted Ordering</u>



True values of parameters: Normal ordering, $\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}eV^2/c^4$

Low energy neutrinos
Sensitivity to spectrum upturn



Low energy neutrinos
Supernova neutrinos

Large size of HK allows it to be sensitive to supernova burst in the Andromeda galaxy, as well as observe more DSNB neutrinos than other experiments

Supernova burst

- explosion mechanism,
- BH/NS formation,
- alert with 1° pointing

Diffuse Supernova Neutrino Background

- Stellar collapse model
- Star formation rate
- Heavy element synthesis