Hyper-Kamiokande Physics goals, status and plans

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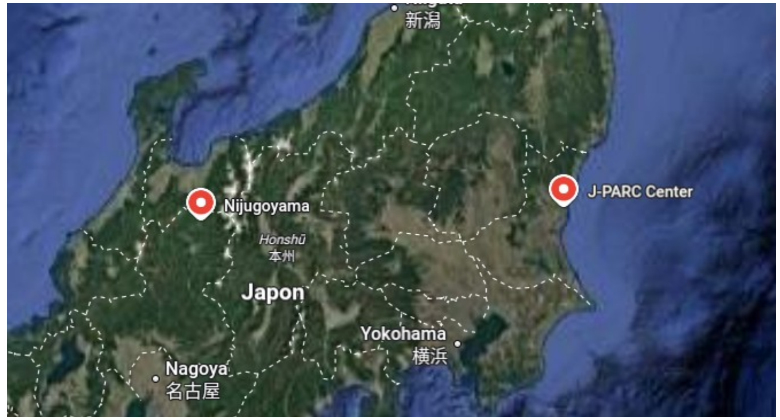
May 19th, 2026

Hyper-Kamiokande Project

The Hyper-Kamiokande experiment Overview

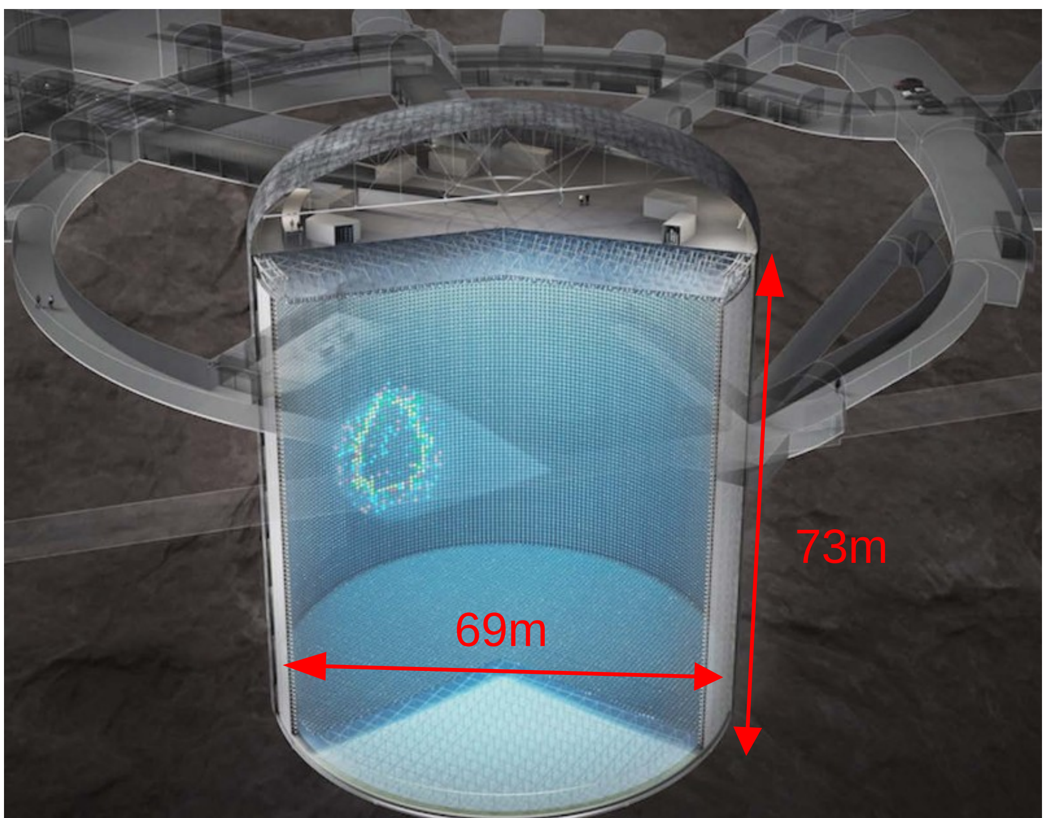
Kamioka

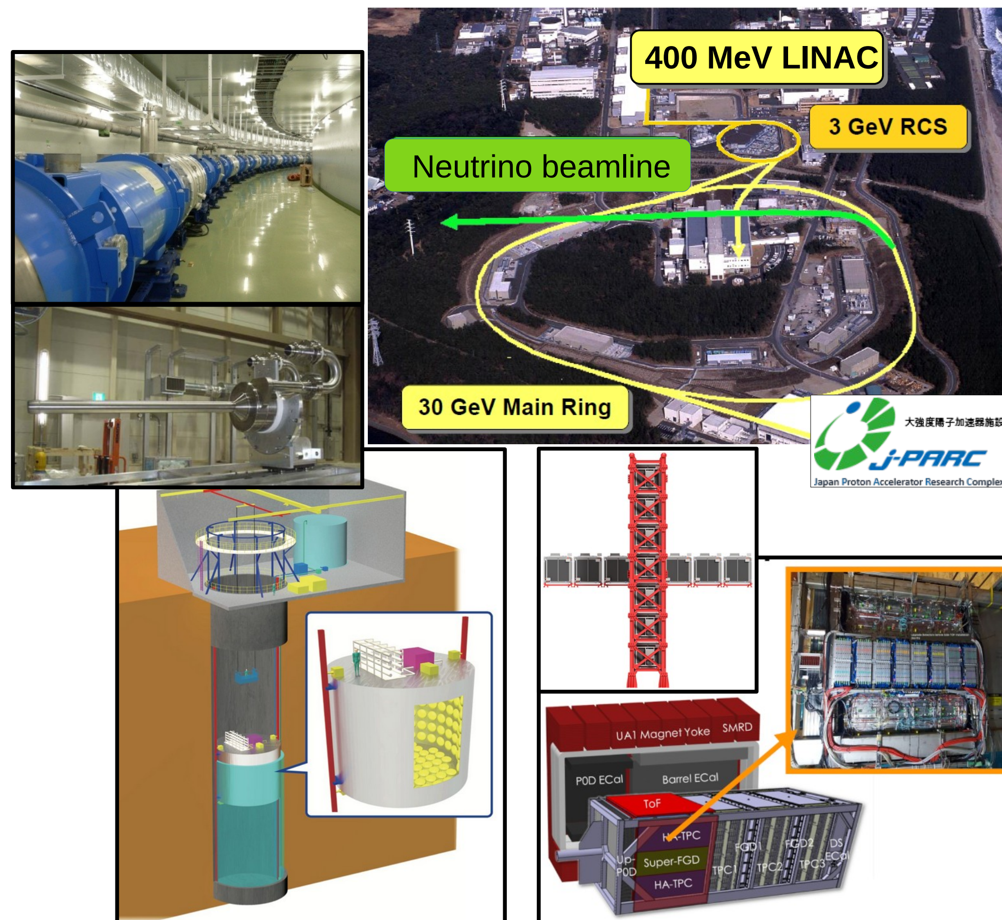
- Massive (258 kton) water Cherenkov detector
- 600m underground below mount Nijugo



J-PARC (Tokai-mura)

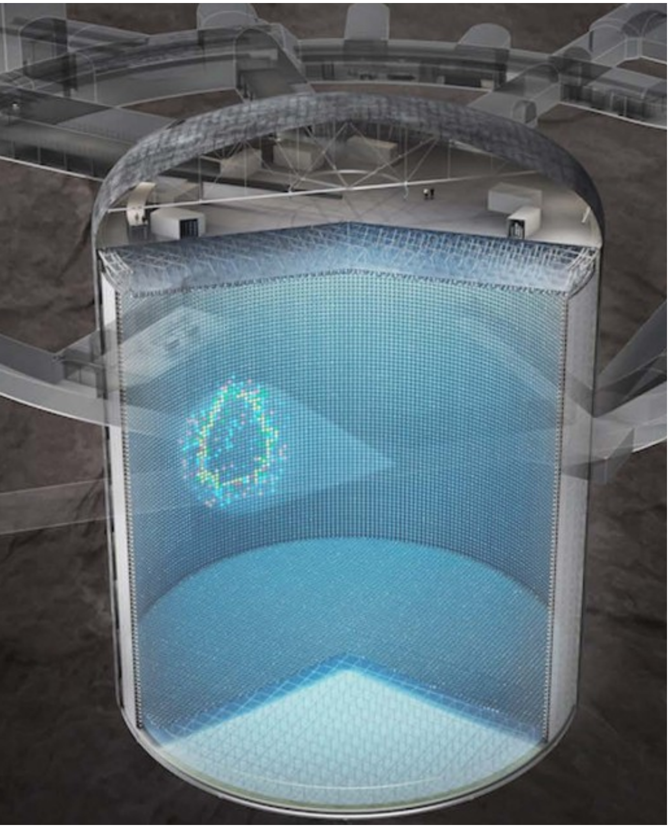
- Beam line for production of neutrino beam from accelerated protons
- Set of (near) detectors to monitor beam and study neutrino interactions



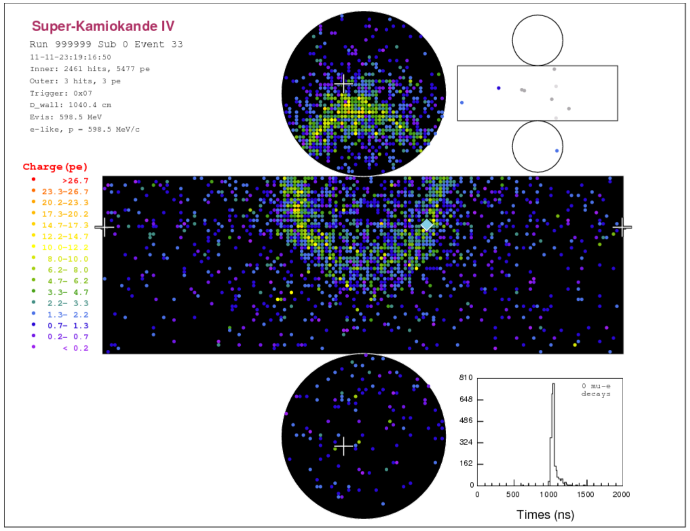


The Hyper-Kamiokande (Far) Detector

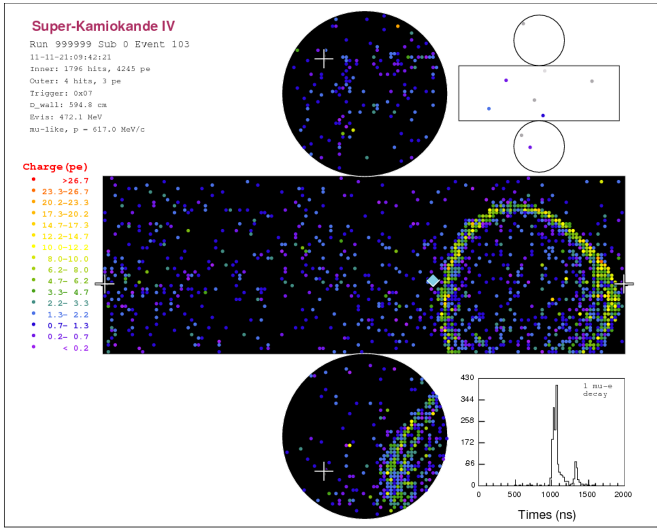
- Optically separated between inner and outer detector
- Charged particles appear as ring patterns on walls of the inner detector
- Instrumented with high performance photon detectors (PMTs)
- Good separation between showering ($e^{\pm}$,γ) and non-showering ($\mu^{\pm}$,$\pi^{\pm}$) particles
- Large water mass allows to study rare phenomena and particles with low interaction probabilities



Showering

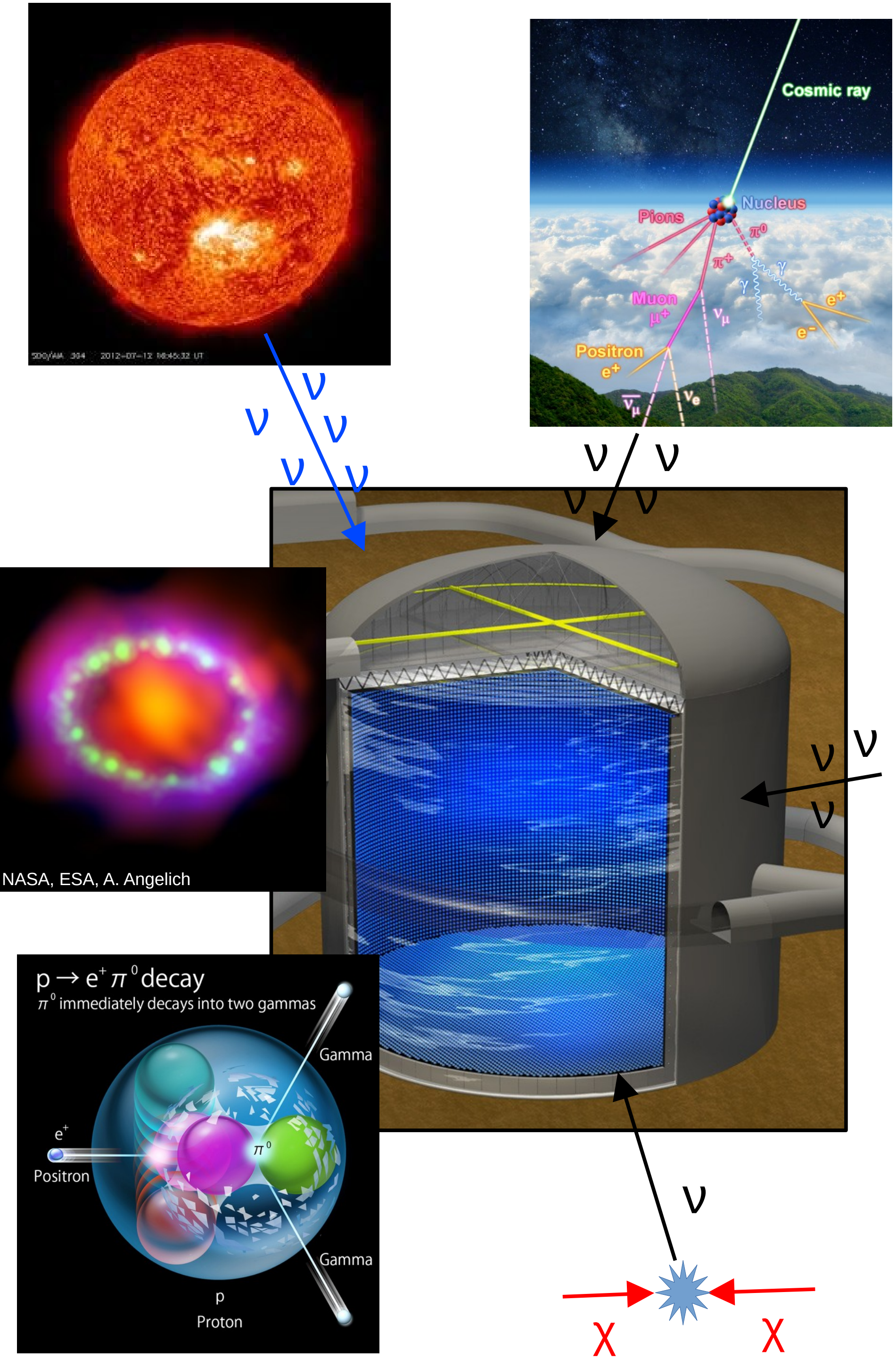


Non-showering



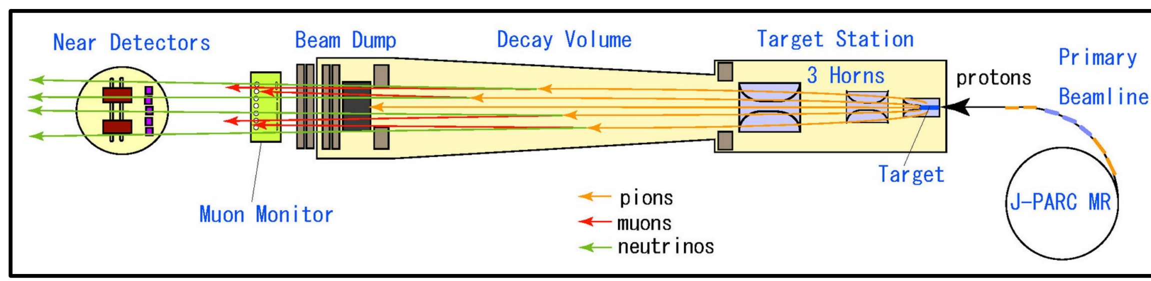
Examples from Super-K simulation

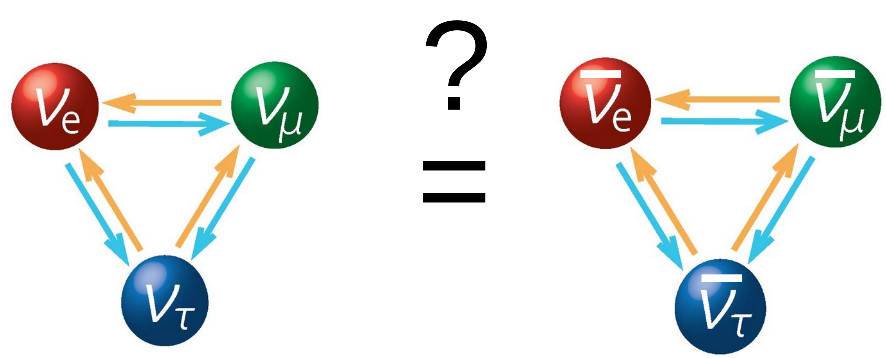
Physics goals



Broad physics program:

- Oscillations of atmospheric, accelerator and solar neutrinos
- Neutrino astronomy and astrophysics
- Supernova neutrinos
- Search for proton decay
- Dark matter indirect detection
- Other searches for new physics (monopoles, Q-Balls, ...)

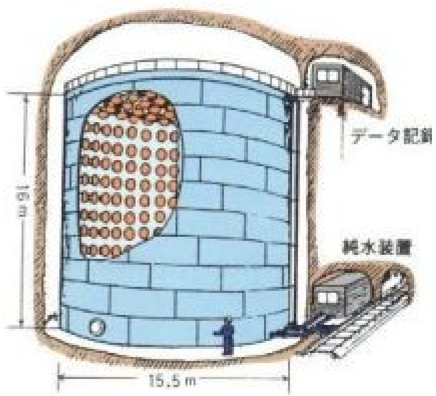




A new chapter in a successful series

Kamiokande experiment

- 1983-1996
- 3kt ultra-pure water
- 1k 20” PMTs



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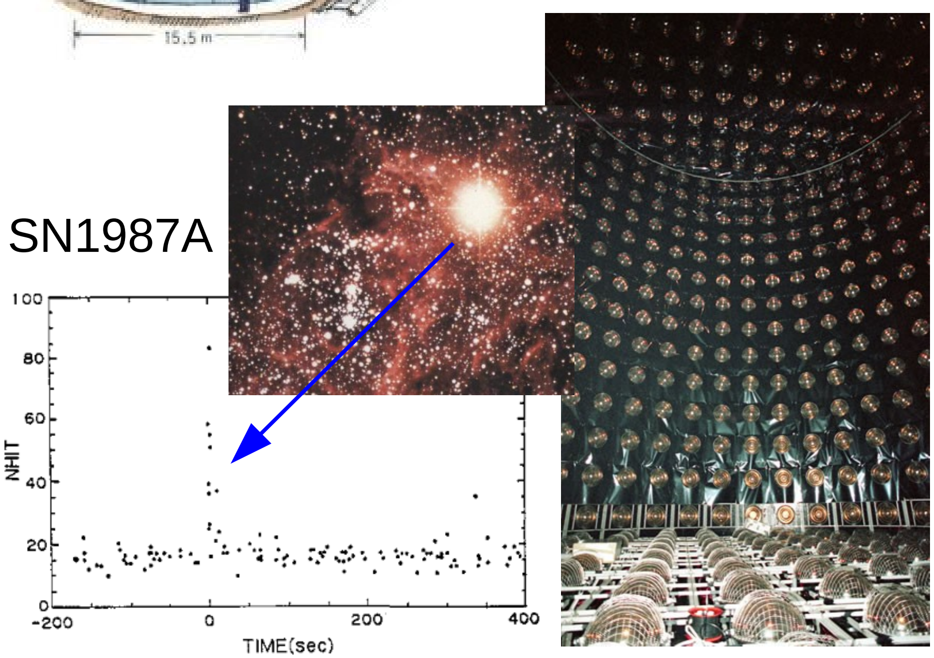
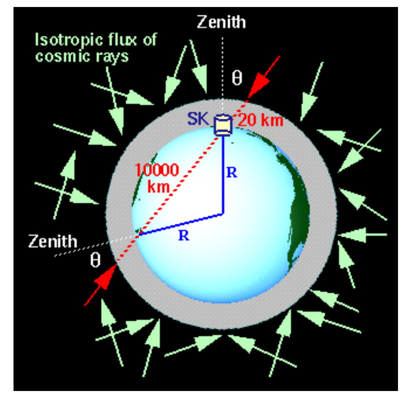
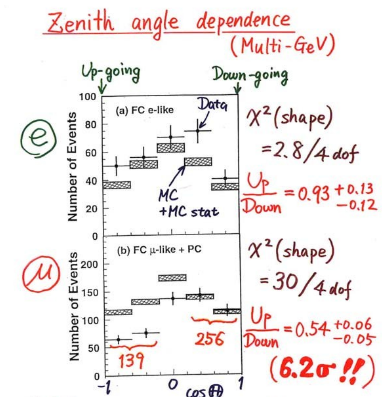
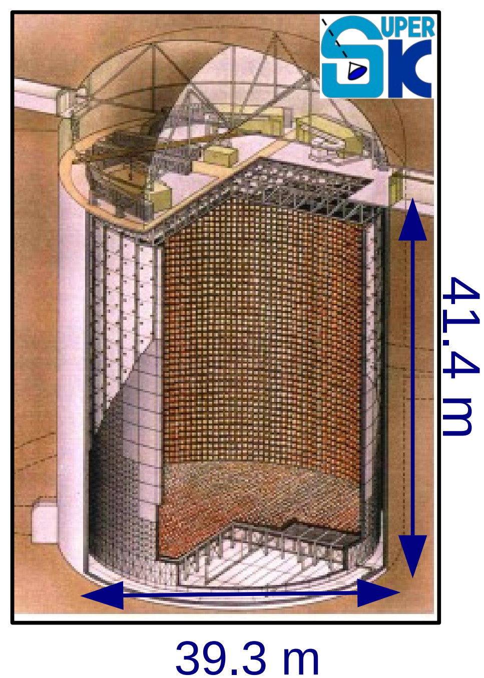


Super-Kamiokande experiment

- 1996~
- 50kt ultra-pure water
- 11.1k 20” PMTs



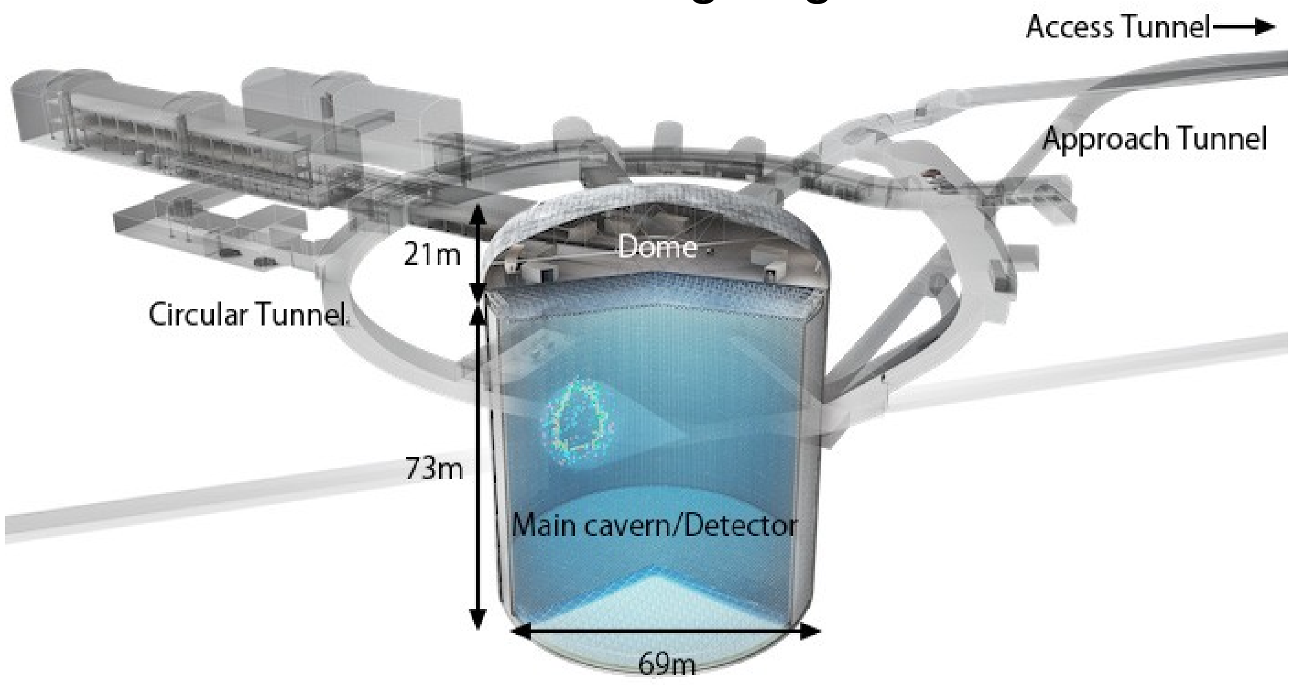


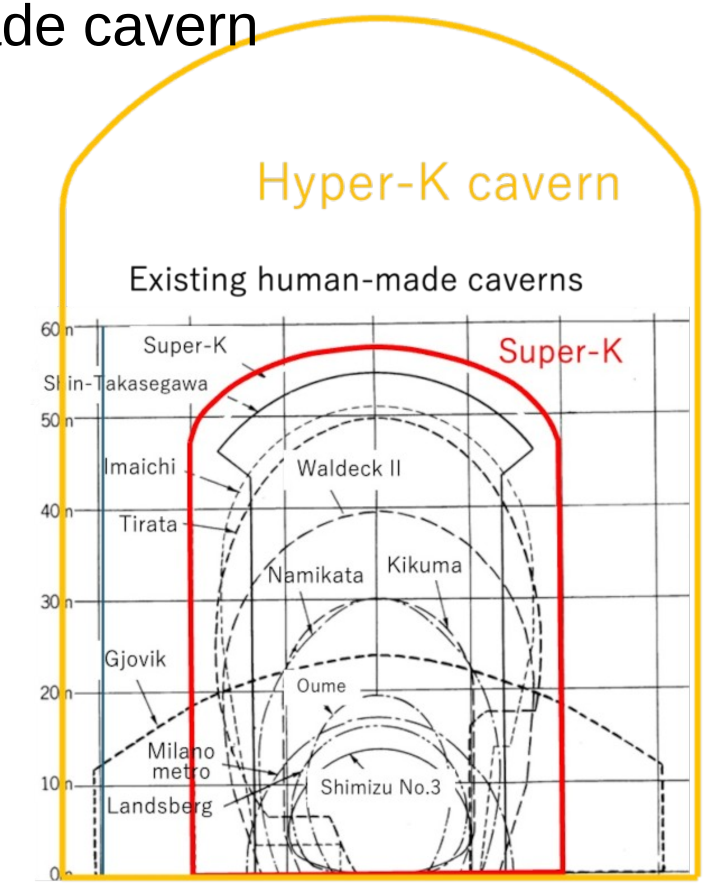


The Hyper-Kamiokande experiment
Far detector

- For most of the physics goals, main limitation in current experiments is statistics: need larger detector to accumulate statistics faster
- Water Cherenkov detector:
  - ✓ Well established technology
  - ✓ "Easy" to scale up
  - ✓ Lot of experience from Super-K and T2K

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

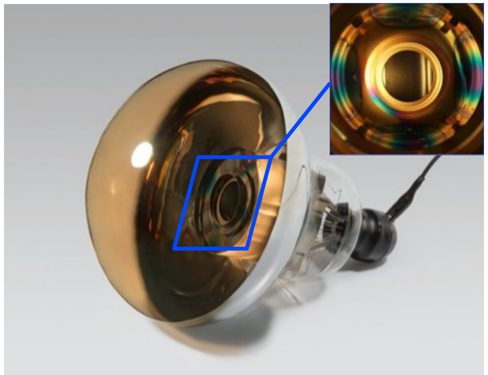


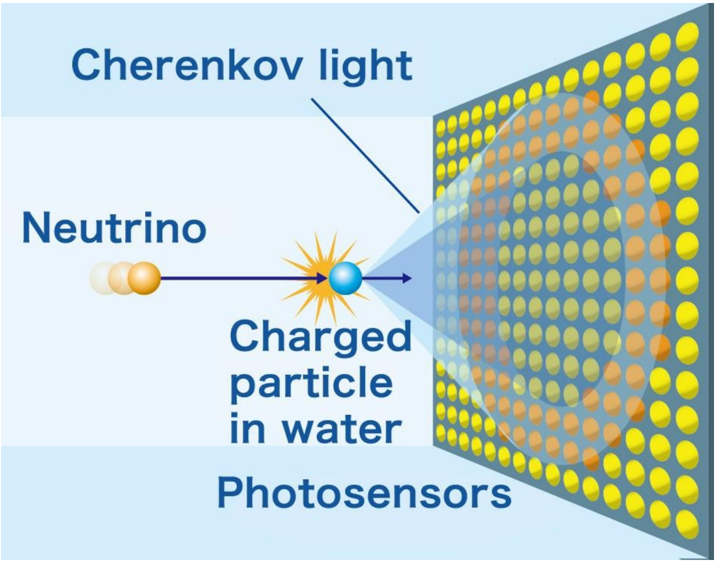


73 m height x 69 m diameter tank
188.4 kton fiducial volume (~8.4x SK)

The Hyper-Kamiokande Far Detector
Improved photo detector system

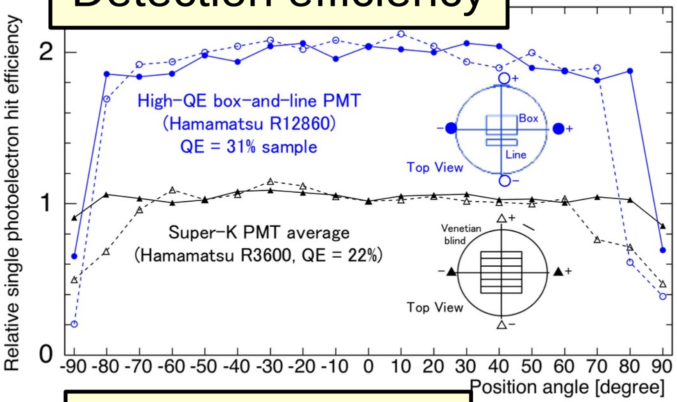
- Performance of Inner Detector (ID) light detectors critical
- HK will use 20k 50cm PMTs to instrument ID
- Improved model compared to SK: R12860 by Hamamatsu Photonics
  - 2x charge resolution and detection efficiencies
  - >2x timing resolution



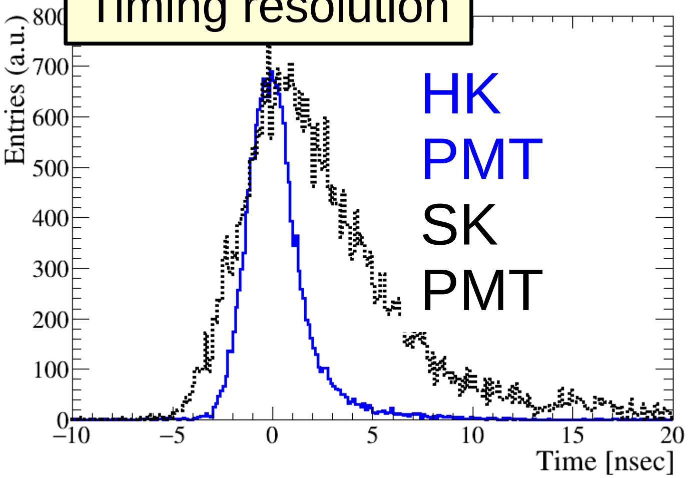


Impact of PMT performance:
- Vertex <-> timing resolution
- Momentum <-> charge resolution, detection eff.

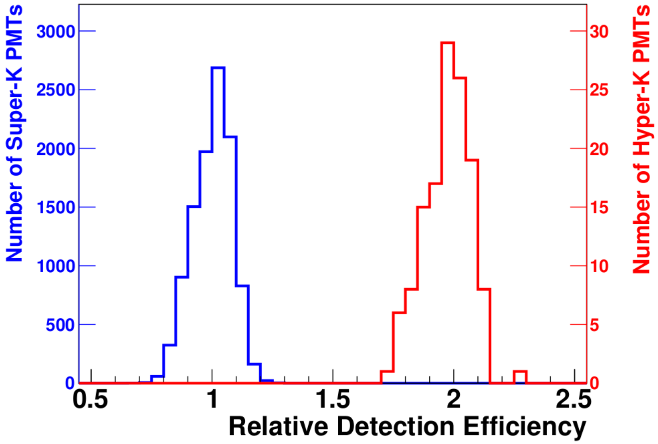
Detection efficiency



Timing resolution



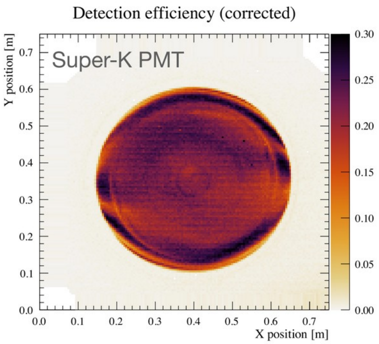
Improved performance confirmed in SK (136 PMTs)

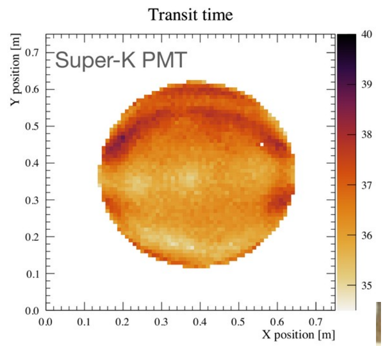


The Hyper-Kamiokande experiment
New calibration methods

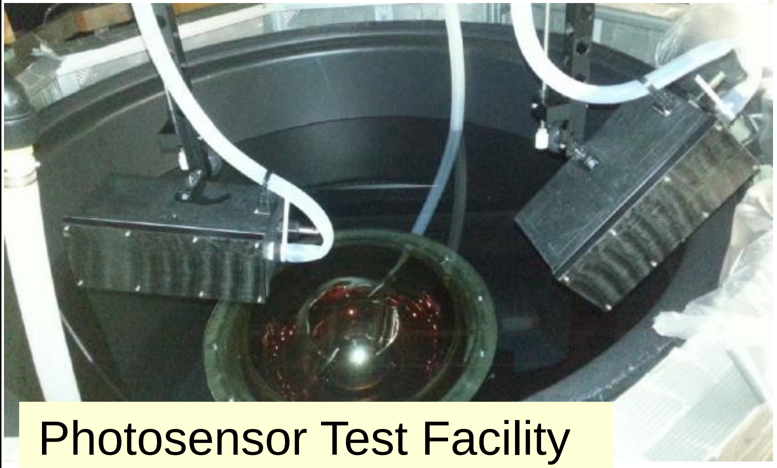
- Use of water Cherenkov detector (PID, momentum, ...) well established in SK
- HK: high statistics, need good control of systematics, including detector response
- Detector will need to be understood with higher precision than SK
- A number of new calibration approaches, both in-situ and pre-measurements

Precise characterization of 50 cm PMTs





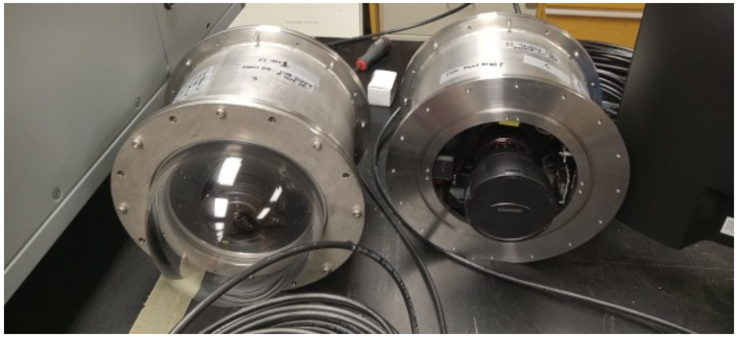
PMT pre-calibration



Photosensor Test Facility (TRIUMF)

Photogrammetry

Cameras in walls for precise PMT positions



~800 Multi-PMTs (19 3” PMTs) in FD

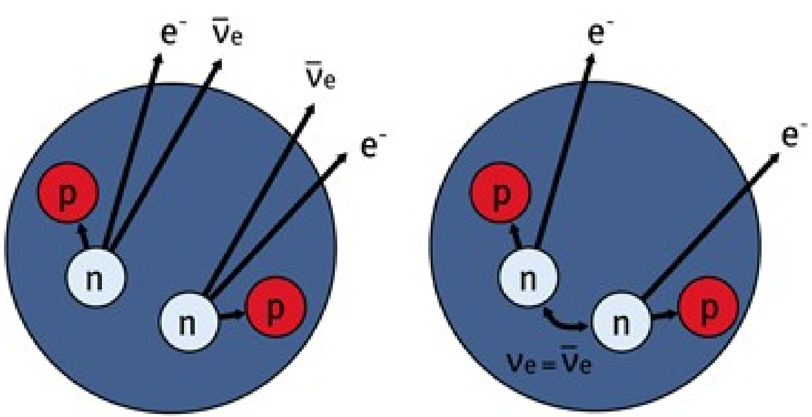
200 equipped with LEDs (including 295 and 305 nm for Raman scattering)

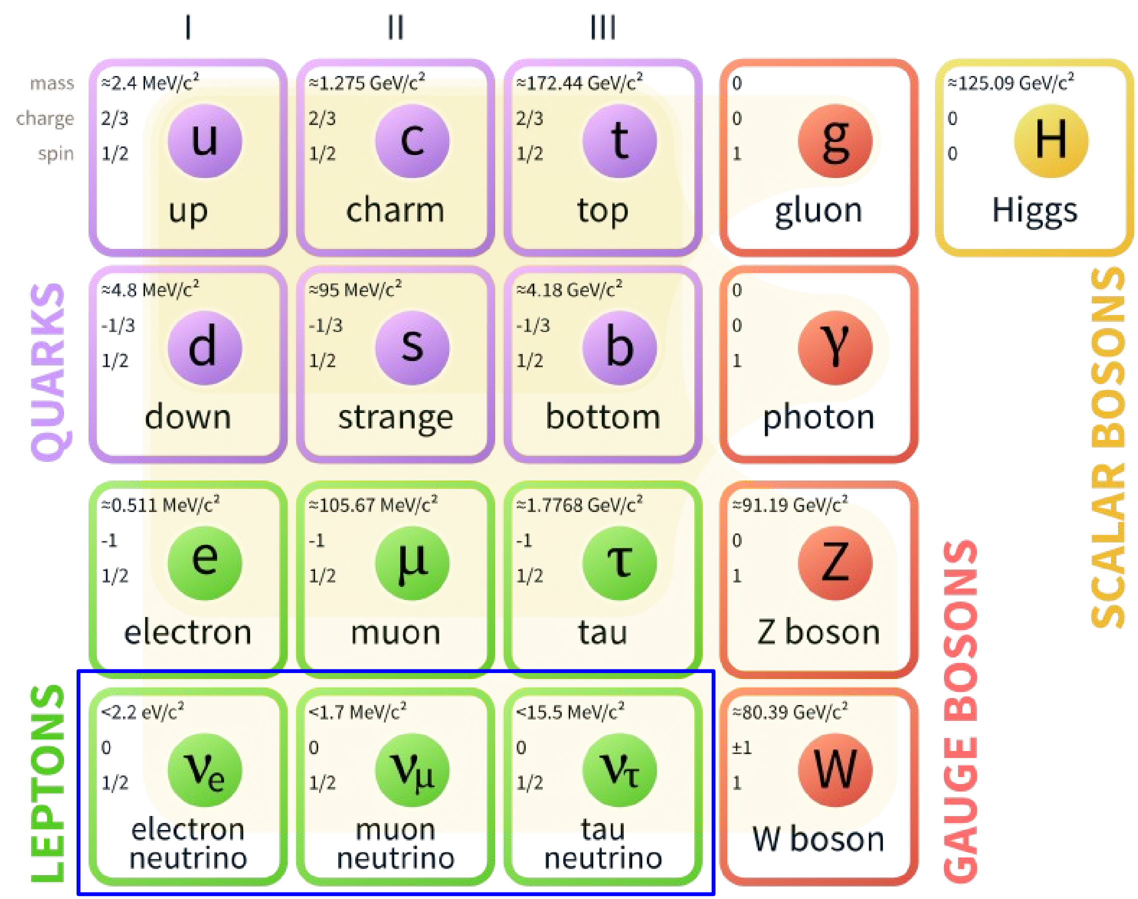
Physics goals and sensitivity

Neutrinos

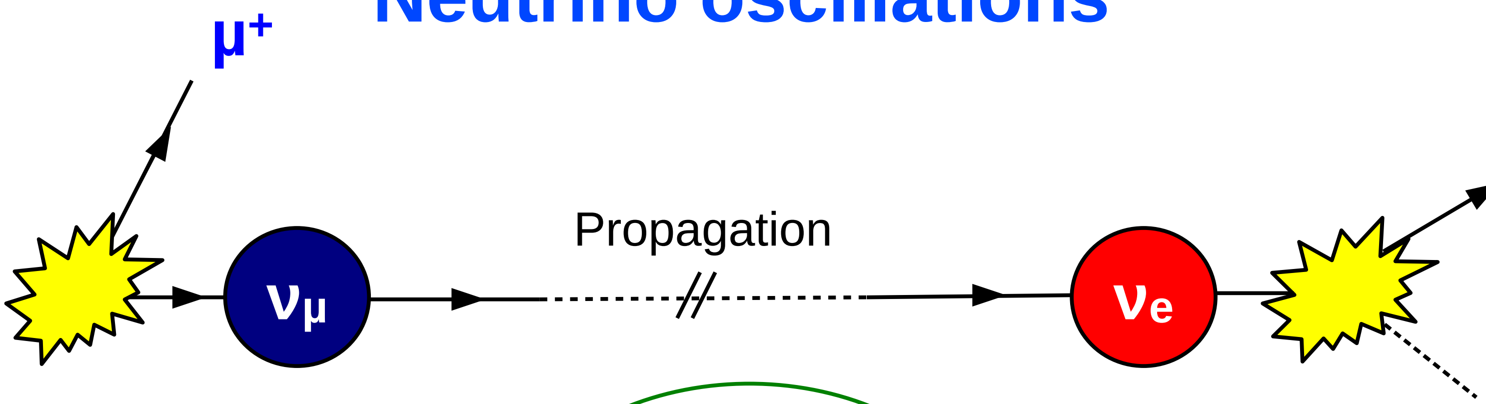
In the standard model, fundamental particle that comes in 3 flavors
- Interact only through weak force: hard to detect
- Not very well known despite its abundance

Many open research topics:
- Low but non-zero mass
  - Origin of its mass ?
  - Determination of absolute mass
- Could be its own anti-particle (Majorana particle)
- **Neutrino oscillations**
- **Astrophysics observations through ν**





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 $\nu/\bar{\nu}$

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

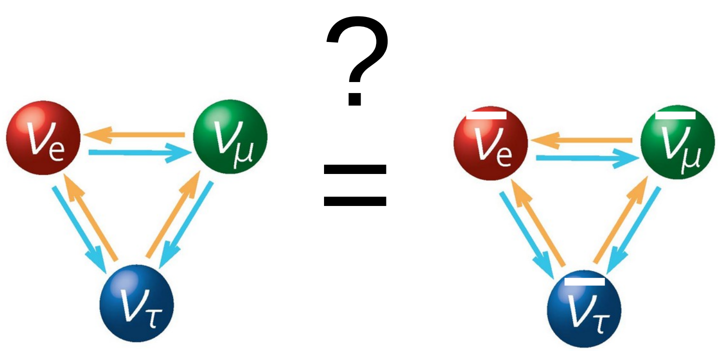
Neutrino oscillations
Current physics goals

- Existence of the phenomenon well established
- Parameters of the 3 flavor oscillation model measured to a certain precision
- 3 open questions in standard oscillations
- Precise measurements to test standard framework, in search of physics beyond the standard model

CP symmetry

- difference matter/anti-matter

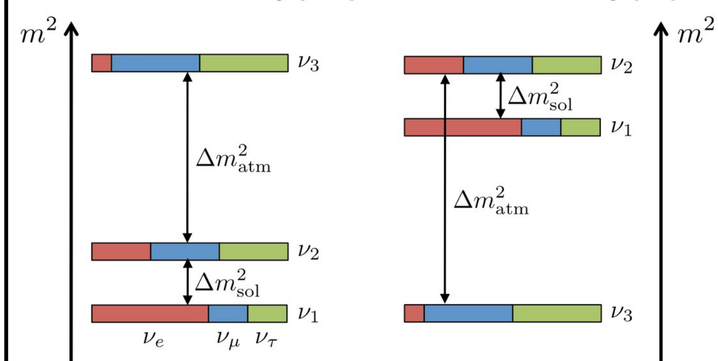
~~CP~~ ⇔ **sin(δ) ≠ 0**



Mass ordering

- Neutrino mass models
- input for other experiments (0νββ, supernova)

normal hierarchy (NH) inverted hierarchy (IH)



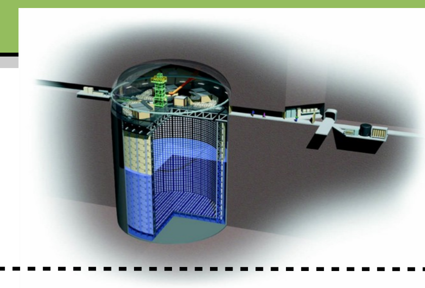
Octant of θ_{23}

- symmetries in lepton sector

$\theta_{23}>\pi/4$?
$\theta_{23}=\pi/4$?
$\theta_{23}<\pi/4$?

Long Baseline oscillations: T2K

- Accelerator neutrinos allow for precise neutrino oscillation measurements:
  - Good L/E resolution and knowledge of initial neutrino content
  - "Near detectors" to constrain uncertainties
  - either (mostly) neutrino or (mostly) anti-neutrino beam
- Successfully used in T2K since 2009



ν production

J-PARC beamline

ν_μ 2.5°

Near detectors

On-axis

Off-axis

ν_μ

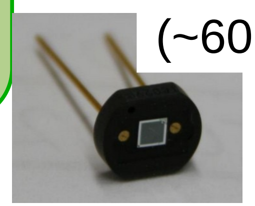
Far detector

Super-Kamiokande

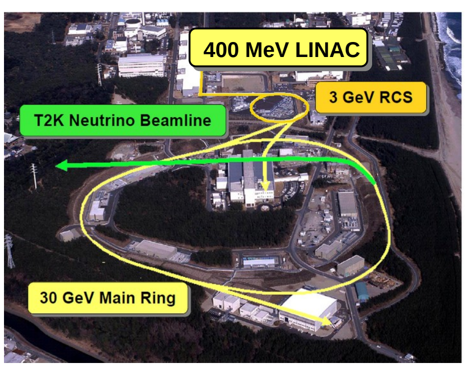
0

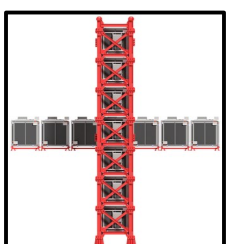
280m

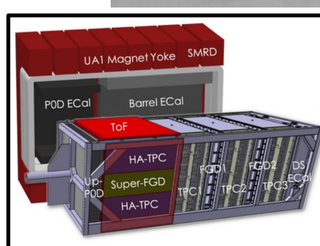
295 km



(~60k)







Study neutrino before oscillations

$\nu_\mu \rightarrow \nu_e$ appearance
$\nu_\mu \rightarrow \nu_x$ disappearance

- Baseline: 295 km
- Off-axis beam

Sensitivity to open questions

Golden channel: $\nu_\mu \rightarrow \nu_e$ "appearance" channel

- CP phase and mass ordering modify $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ differently
- Comparing them allows to measure sin(δ) and the mass ordering
- Also sensitivity to θ_{23} octant if θ_{13} well known:

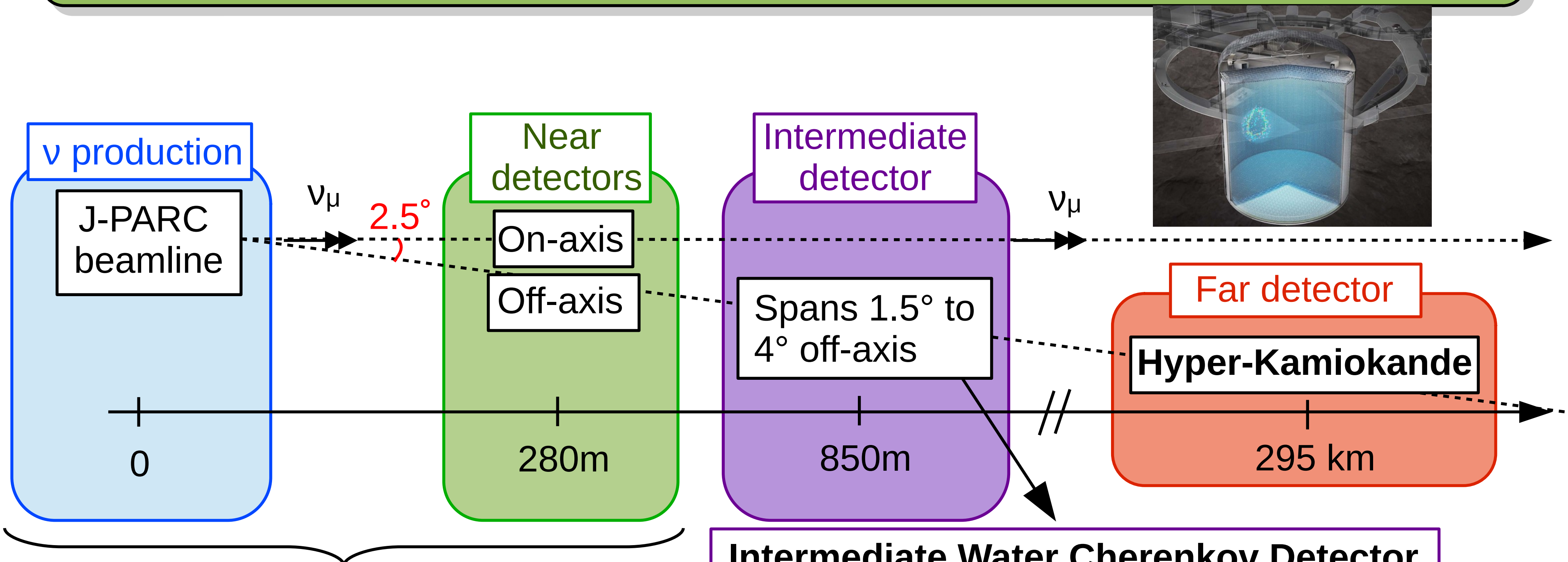
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2\left(1.27 \frac{\Delta m^2 L}{E}\right)$$

Channel	sin(δ) > 0	sin(δ) < 0	Normal ordering	Inverted ordering
$\nu_\mu \rightarrow \nu_e$	Suppressed	Enhanced	Enhanced	Suppressed
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Enhanced	Suppressed	Suppressed	Enhanced

- Degeneracies between δ and mass ordering
- T2K baseline "not very long": effect of δ dominates (~<27% vs ~10%)

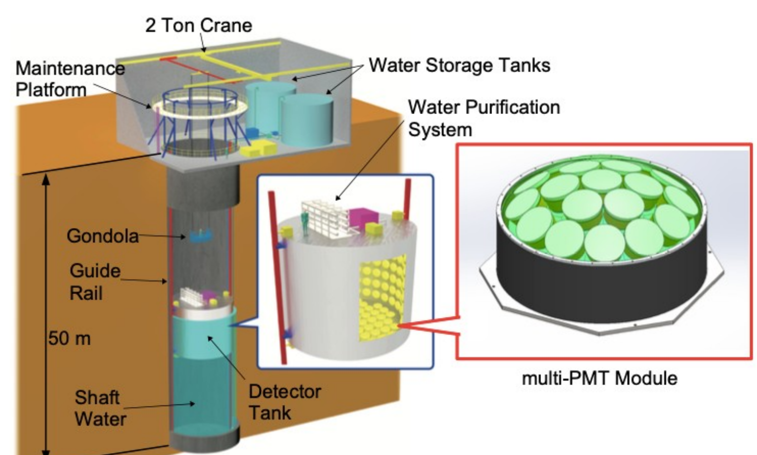
Long Baseline oscillations: Hyper-K

- 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



- Inherited from T2K
- Beam intensity will continue to increase to reach 1.3 MW
- Possibility of further upgrade of the off-axis near detector (see presentation by T. Kikawa)

Intermediate Water Cherenkov Detector

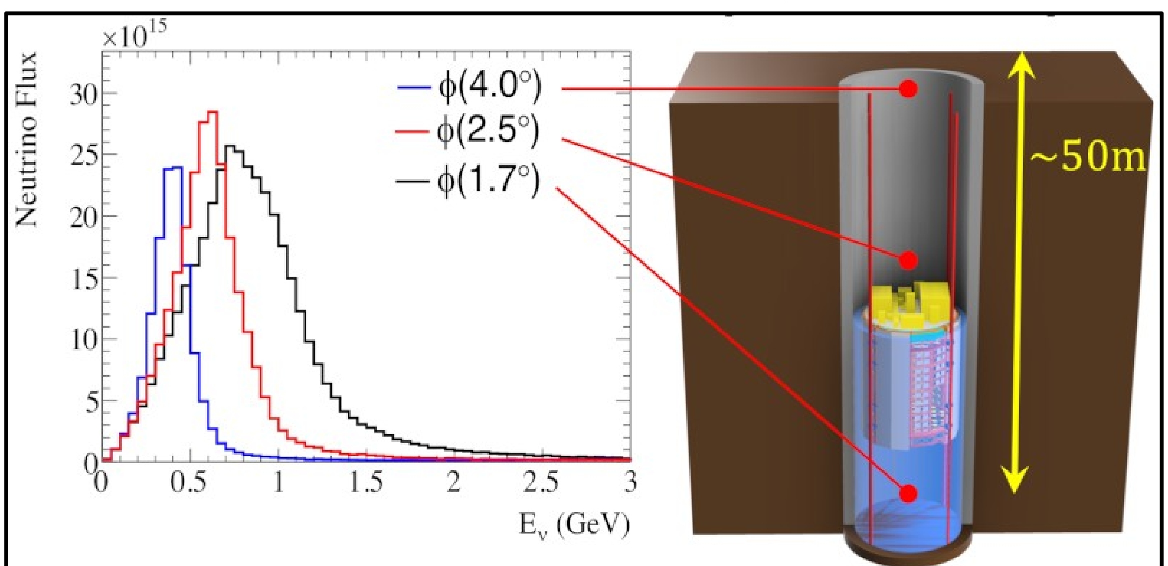


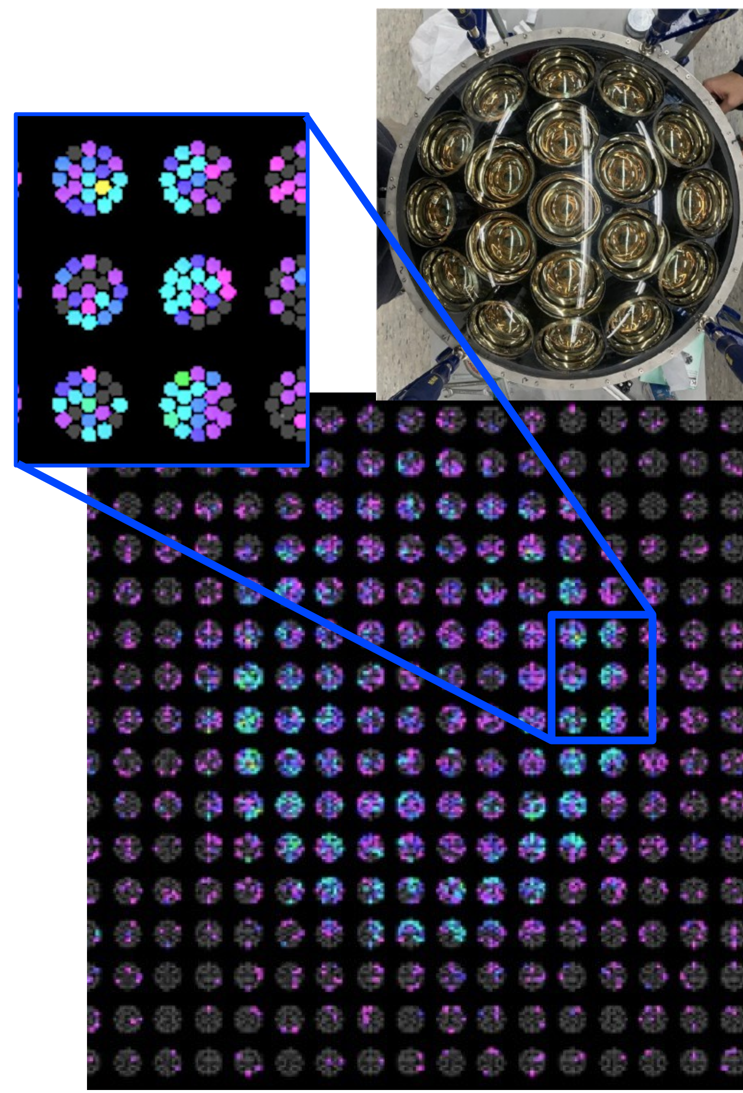
The Hyper-Kamiokande experiment
Intermediate Water Cherenkov Detector

- Additional “near” detector located ~850m from target
- 600 ton Water Cherenkov detector instrumented with mPMTs

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

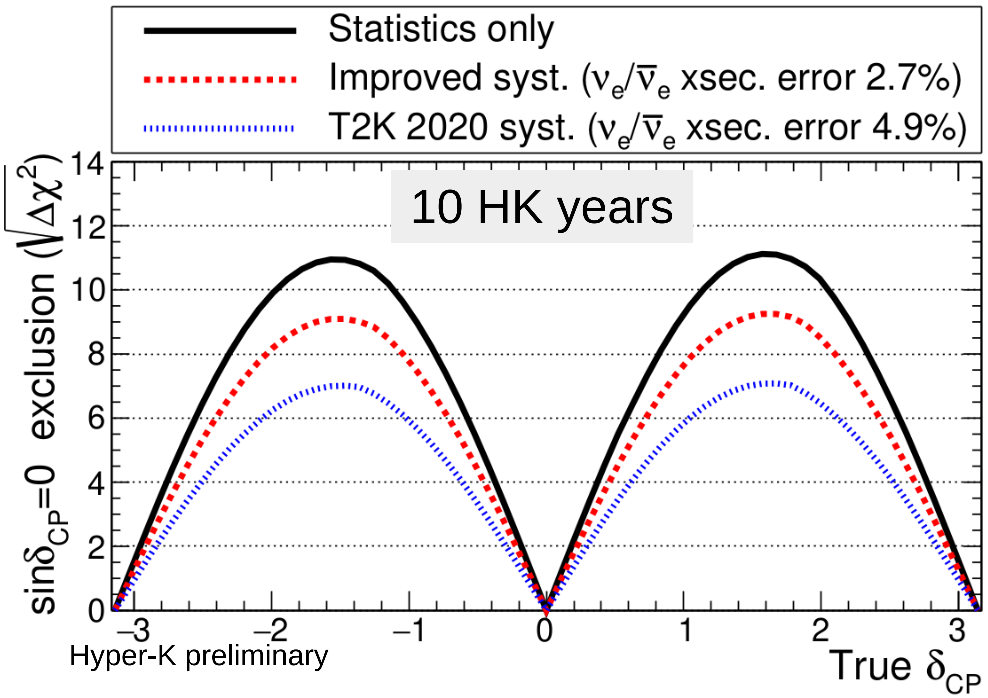


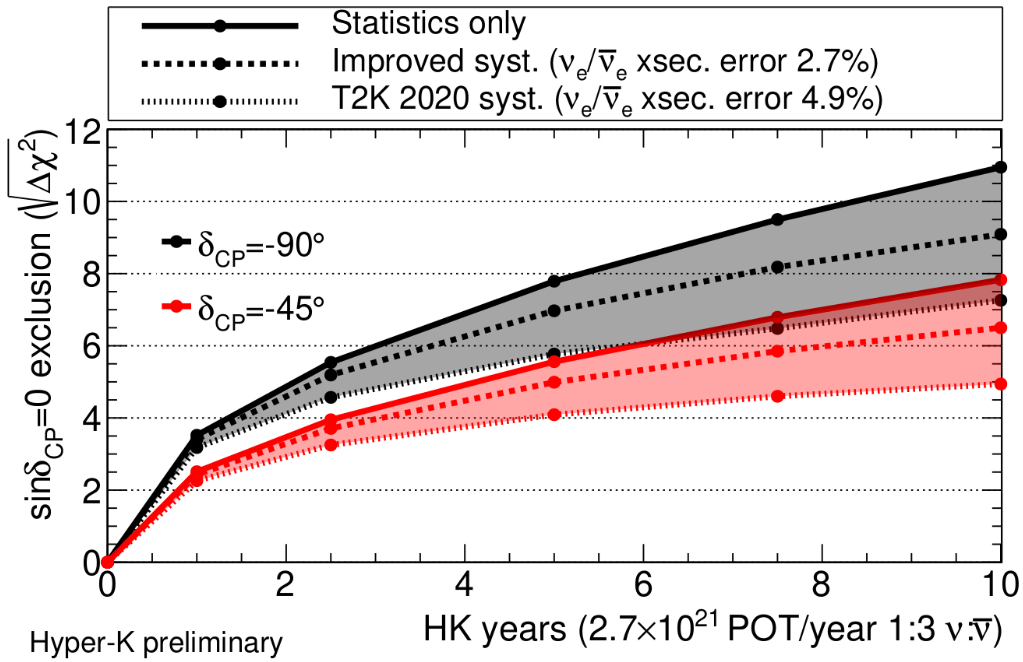


Long Baseline oscillations
Sensitivity - CP symmetry

- Based on T2K analysis (Eur. Phys. J. C 83, 782 (2023)) scaled to HK statistics
- "Improved systematics" to represent improved systematics constraints from IWCD and upgraded near detector 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



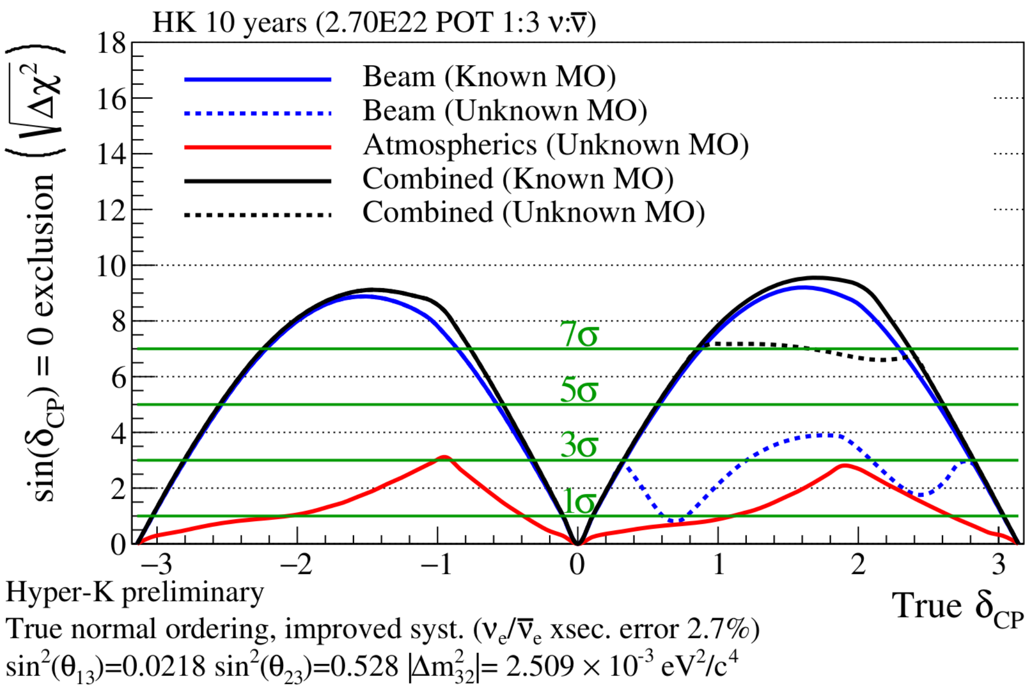


Eur. Phys. J. C 86, 170 (2026)

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
- Rigorous combined analysis established by T2K and Super-K (Phys. Rev. Lett. 134, 011801 (2025))

Ability to reject CP conservation



	$\sin^2\theta_{23}$	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

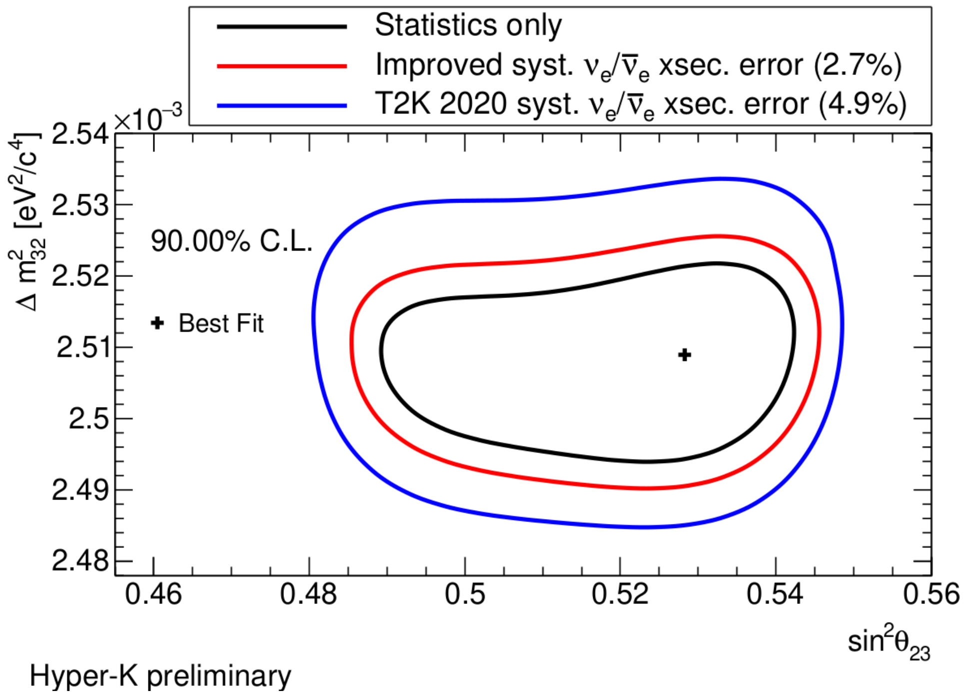
10 years with 1.3MW, normal mass ordering is assumed

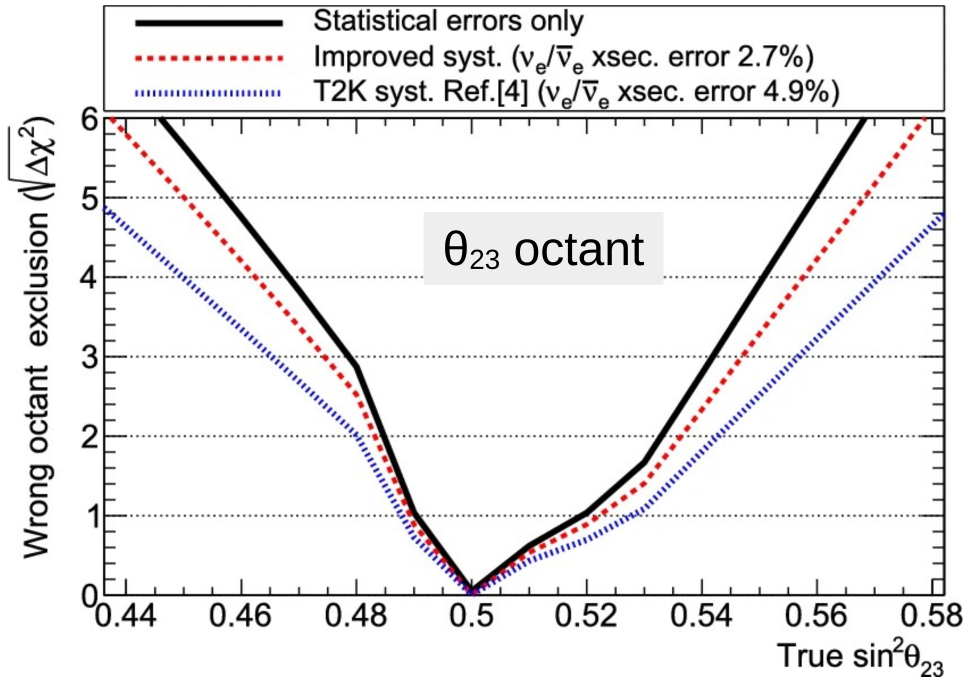
Based on older version of T2K analysis. Updates based on T2K+SK joint analysis in preparation

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**



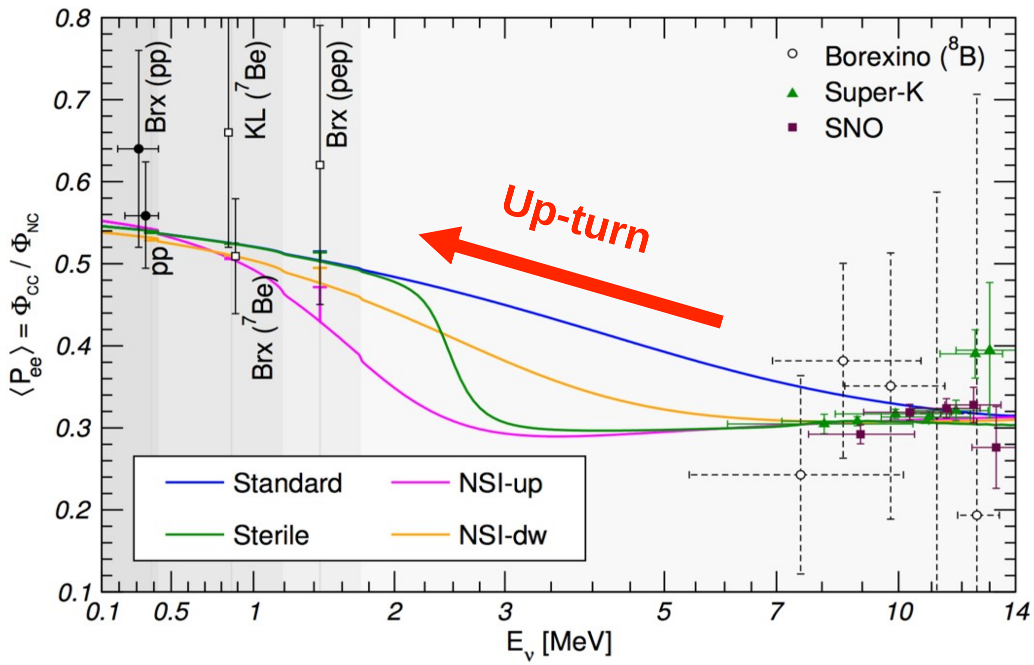


True values of parameters: Normal ordering, $\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}$eV^2/c^4

Low energy neutrinos oscillations
Solar neutrinos

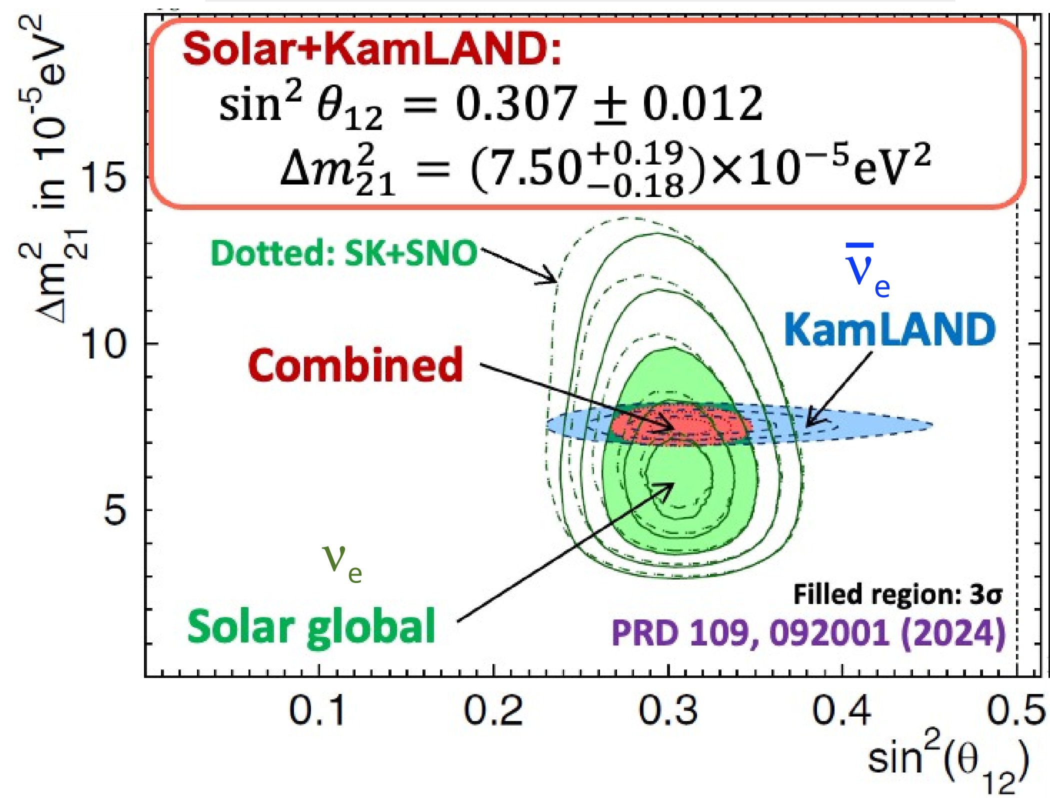
- At low energy, Hyper-K will study remaining questions on solar neutrino oscillations
- ~130 solar neutrino events per day
- > 3σ sensitivity for the spectrum up-turn in 10 yrs (E_{th}=4.5 MeV).
- ~2σ day/night sensitivity expected for the difference in $\nu_e/\bar{\nu}_e$ osc. in 20 yrs.

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



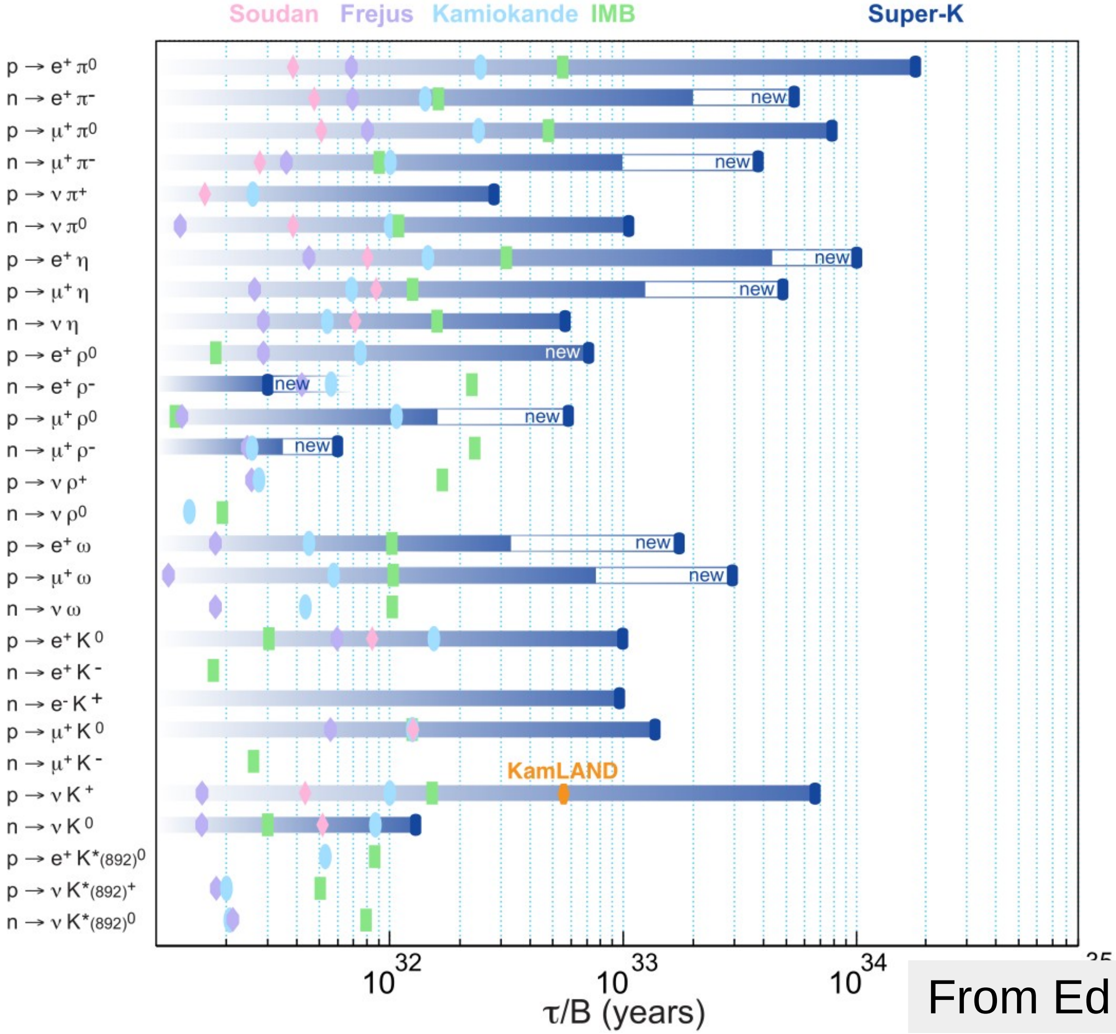
M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)

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



Nucleon decay

- GUTs attempt to unify strong and electroweak interactions
- As a result of proposed unification, baryon number no longer conserved and proton can decay: experimental tests of GUTs
- Predicted lifetimes very large, typically 10^{29}~10^{36} years
- Experimental searches conducted through many channels, no observations so far



From Ed Kearns, BLV2017

Low energy neutrinos
Supernova neutrinos

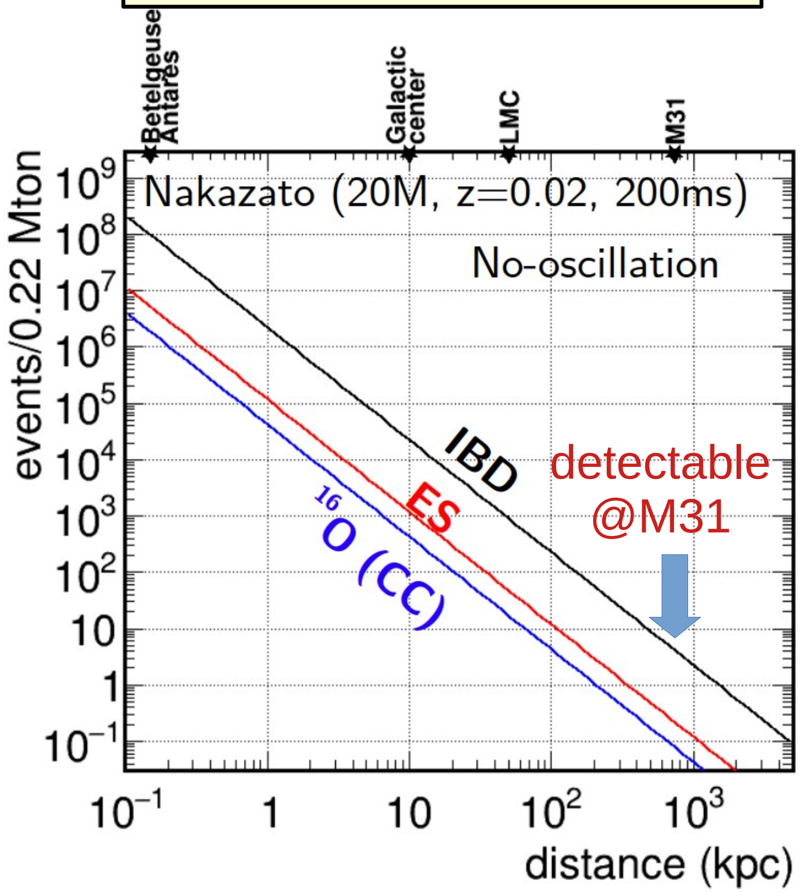
Large size of HK allows it to be sensitive to supernova burst in the Andromeda galaxy, as well as observe more DSNB neutrinos than other experiments

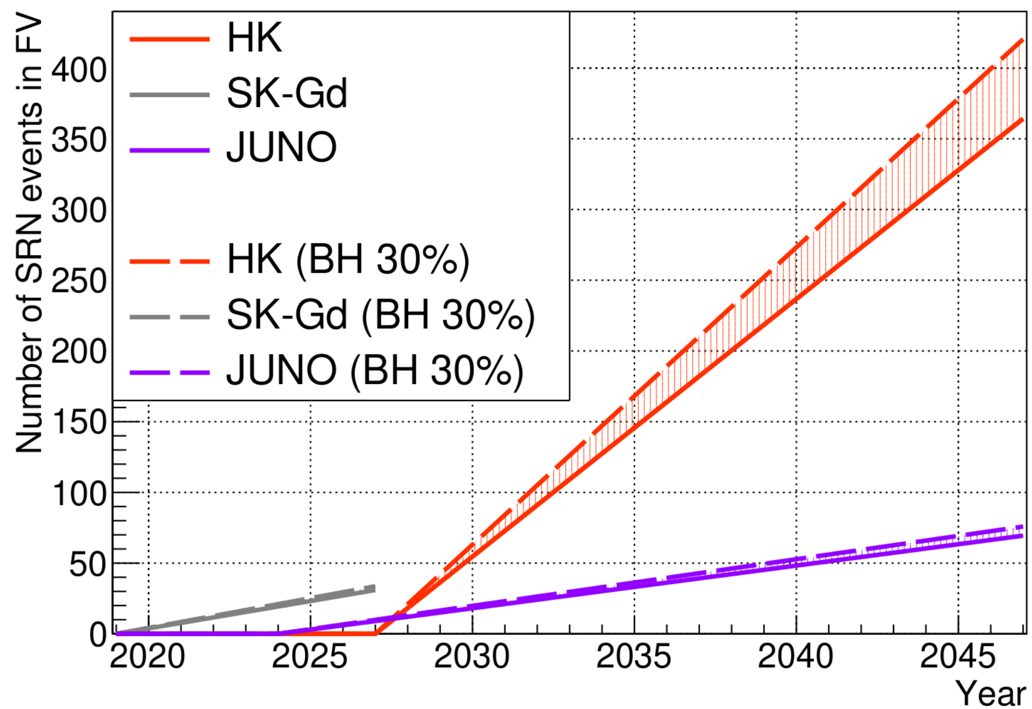
<u>Supernova burst</u>

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

<u>Diffuse Supernova Neutrino Background</u>

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

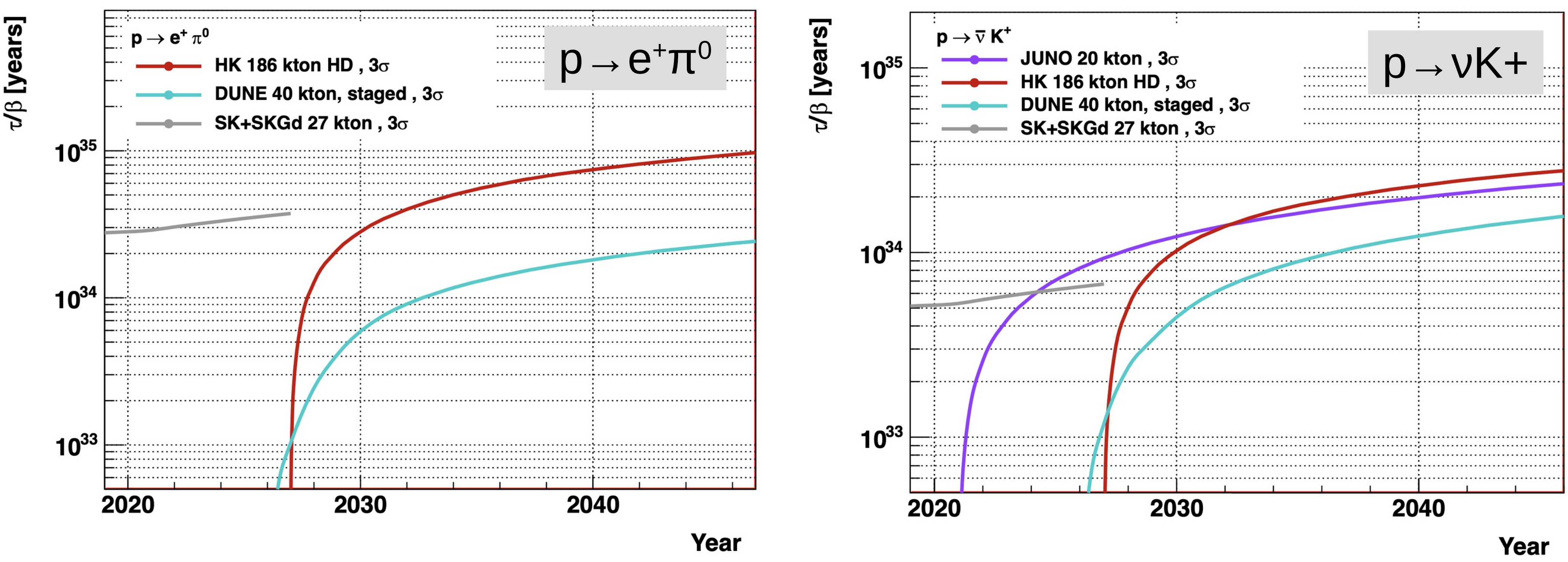




Search for nucleon decay

- 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 $3x10^{34}$ years for $p \rightarrow \nu K^+$ after 20 years

<u>3σ discovery potential as a function of time</u>



Status

Hyper-Kamiokande status
Collaboration

- Hyper-K officially approved in 2020
- Collaboration has been growing since, and continuing
- 23 countries, 110 institutes, ~650 people as of July 2025

Feb. 2026 collaboration meeting

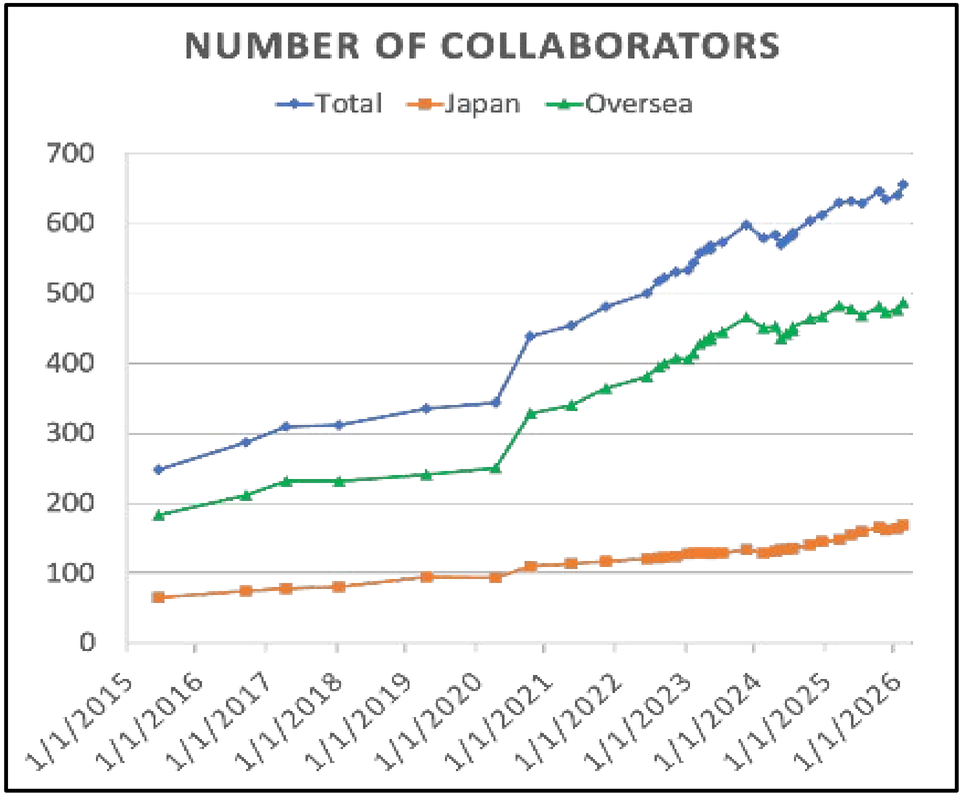
Europe	363 members
Armenia	3
Czech	10
France	52
Germany	1
Greece	3
Italy	58
Poland	54
Russia	27
Spain	50
Sweden	4
Switzerland	10
Ukraine	2
UK	89

Asia	209 members
India	10
Korea	22
Japan	169
Vietnam	8

Oceania	10 members
Australia	10

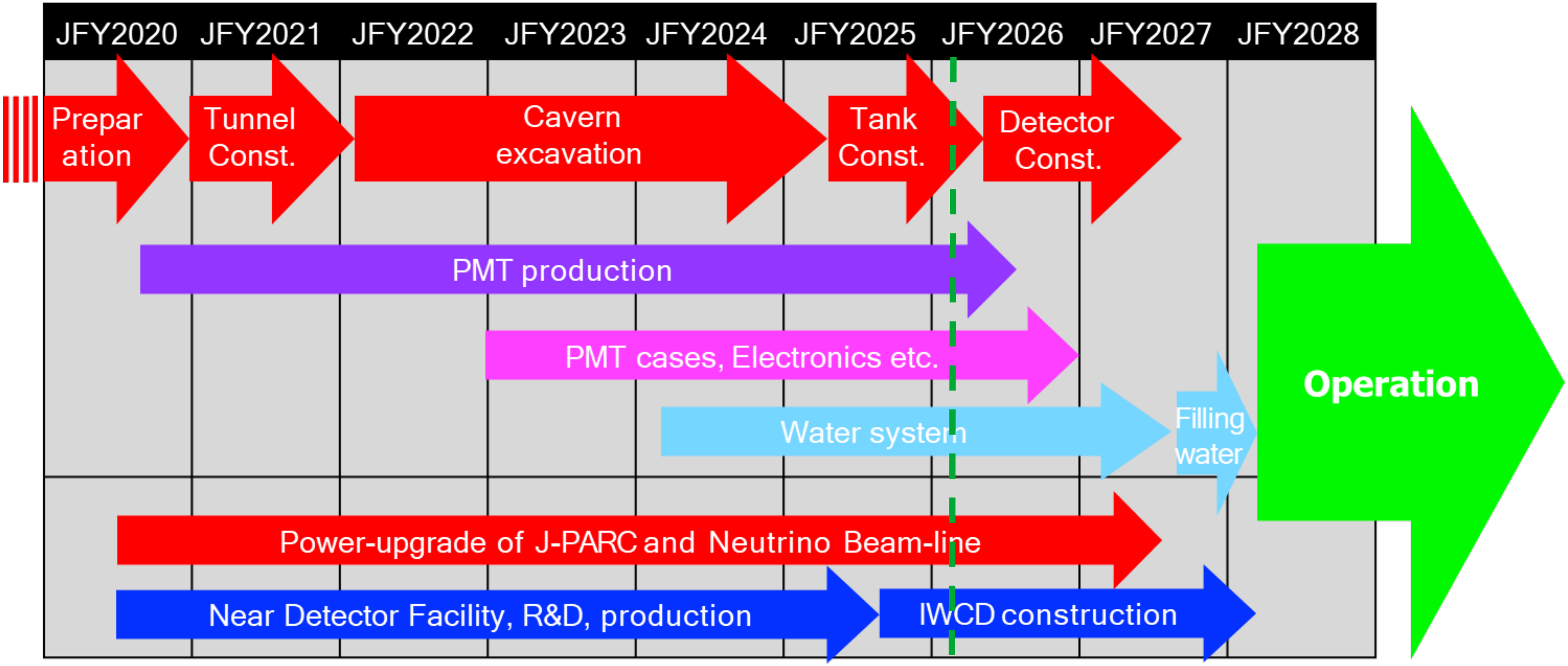
Americas	65 members
Brazil	3
Canada	45
Mexico	6
USA	11

Africa	9 members
Morocco	9



Hyper-Kamiokande status
Schedule

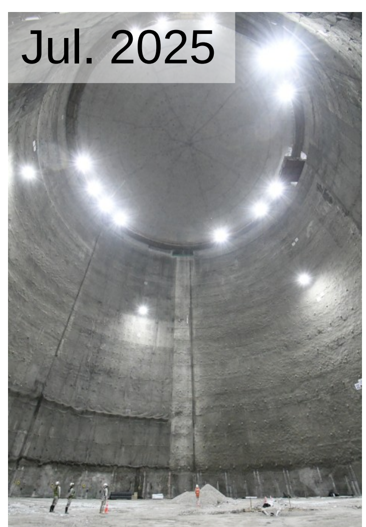
- Significant construction project, spanning several years
- Project started in 2020
- End of detector construction and start of water filling in Nov. 2027
- **Start of physics operation in June 2028**

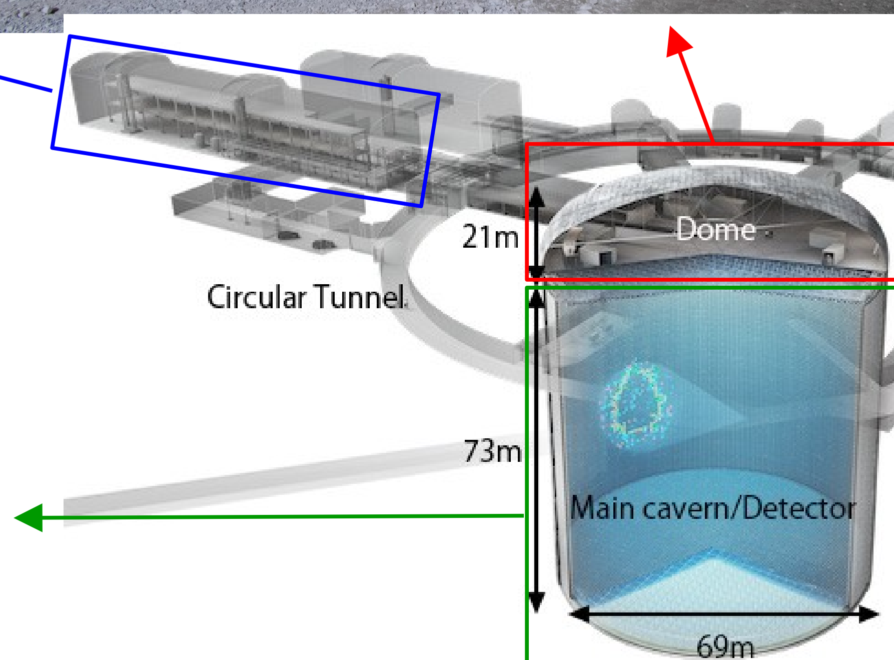


Note: Japanese Fiscal Year starts April 1st

Hyper-Kamiokande status
Excavation

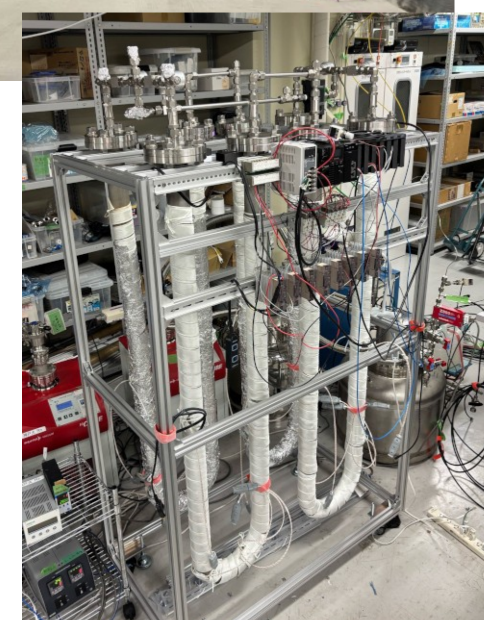
- Excavation of approach tunnels started in May 2021 and completed in 2022
- Excavation of dome part (main technical challenge) and cavity for water system completed in 2023
- Excavation of detector cavern completed in July 2025





Hyper-Kamiokande status
Facility construction

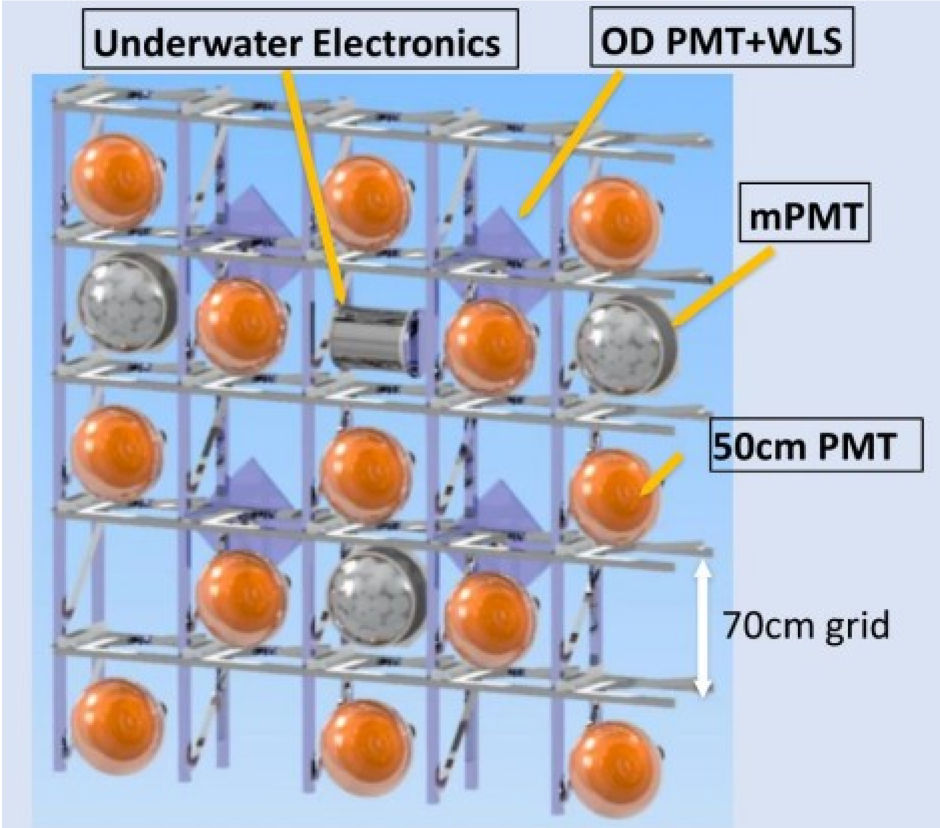
- Construction of tank started end of summer 2025, expected to complete this summer
- Will be followed by construction of top structure
- Keeping such a large amount of water ultra-pure requires massive water system (will process 155m^3/h)
- Construction started in July 2025 and progressing smoothly
- Additional development on-going for a new radon removal system

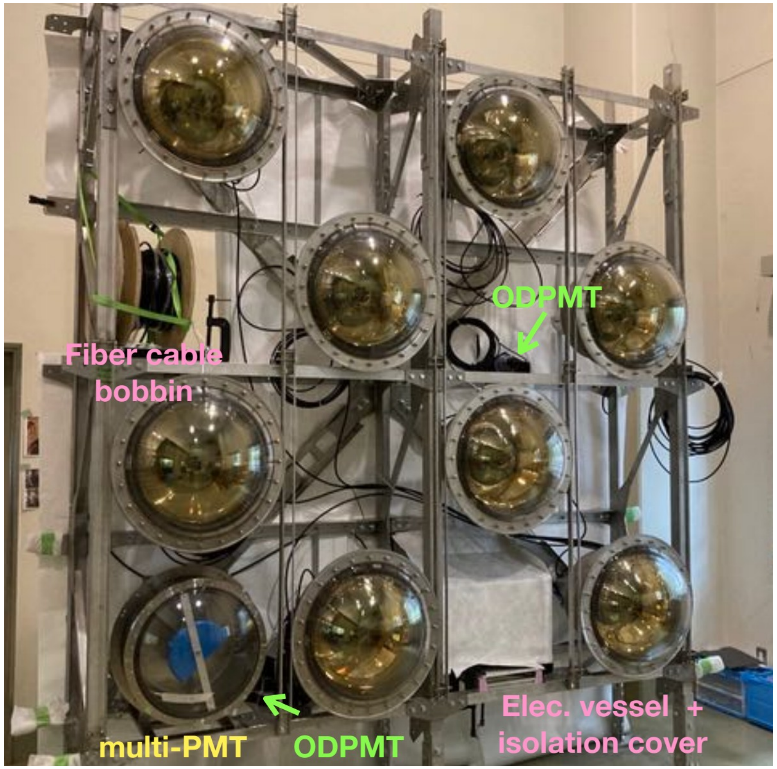


Hyper-Kamiokande status
Underwater components

- PMTs and electronics will be attached on a stainless steel support structure
- Design of the different elements completed, now in or moving to mass production
- Detailed plans for installation being finalized, with tests using mockups
- Start of detector installation scheduled in January 2027

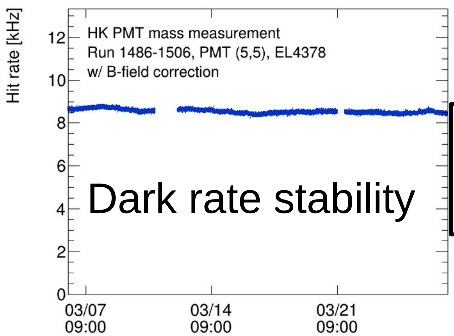
Mock-ups in Japan (ID and OD) and UK (mostly for OD) for tests and validation of the design and installation procedures





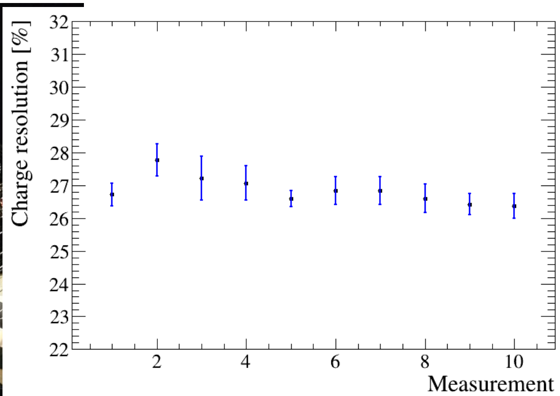
Hyper-Kamiokande status
50cm PMTs

- Mass production of 50cm PMTs started in 2020, QA tests on a fraction of delivered PMTs
- Production suspended in 2022 due to higher than expected failure of tests criteria
- 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
- >18k 50cm PMTs delivered so far, in line to complete delivery of 20.5k by Sep. 2026



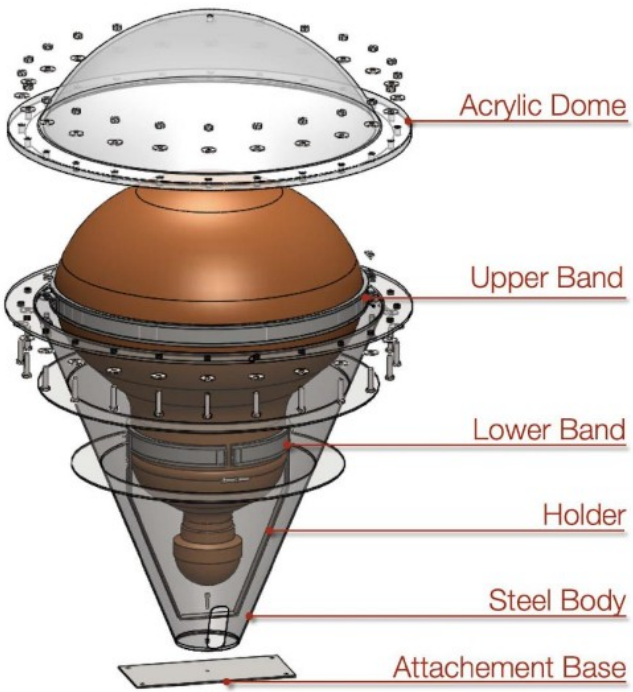
"Mass measurement"
2x 100 PMTs

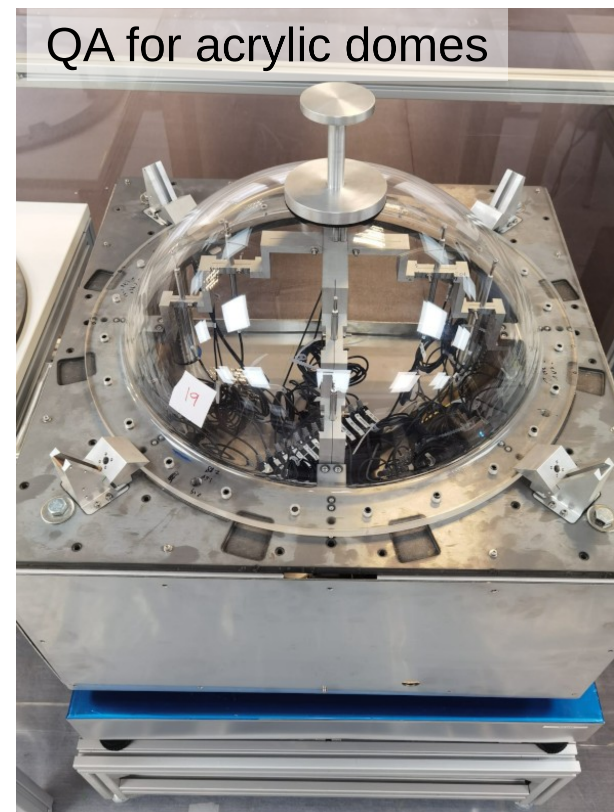
- 2nd system: light injection and B field shielding
- Measure stability of performance between deliveries



Hyper-Kamiokande status
Anti-implosion covers

- Protective covers for 50cm PMTs to prevent chain implosion
- Developed new covers producing less background than Super-K ones
- Validated using hydrostatic and underwater implosion tests
- Design complete, now moving to mass production + QA phase

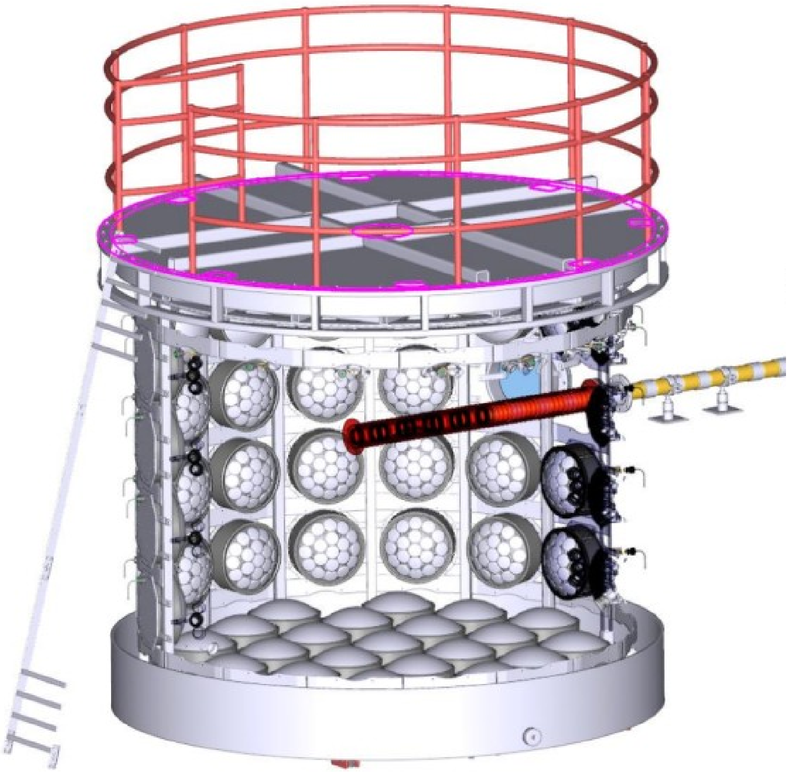



QA for acrylic domes

Hyper-Kamiokande status
Multi-PMTs

- Different types: FD, FD with LED and IWCD, with common basis
- Design complete, mass production of parts started
- First test for assembly and operation in real detector conditions with WCTE

Water Cherenkov Test Experiment

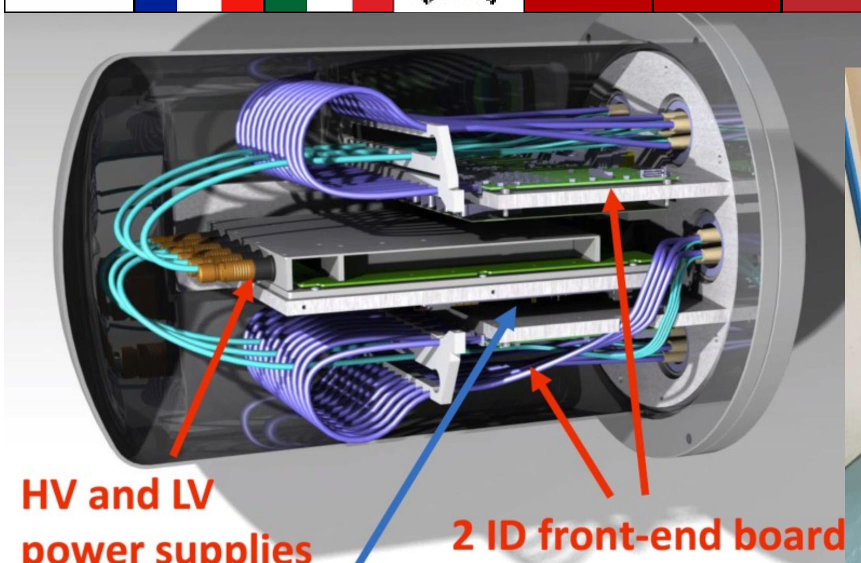


- WCTE measured charged particle scattering at CERN between fall 2024 and summer 2025
- Prototype for IWCD and FD mPMT assembly
- Assembled 100 IWCD style and 5 FD style mPMTs, validating procedure and assembly speed estimates

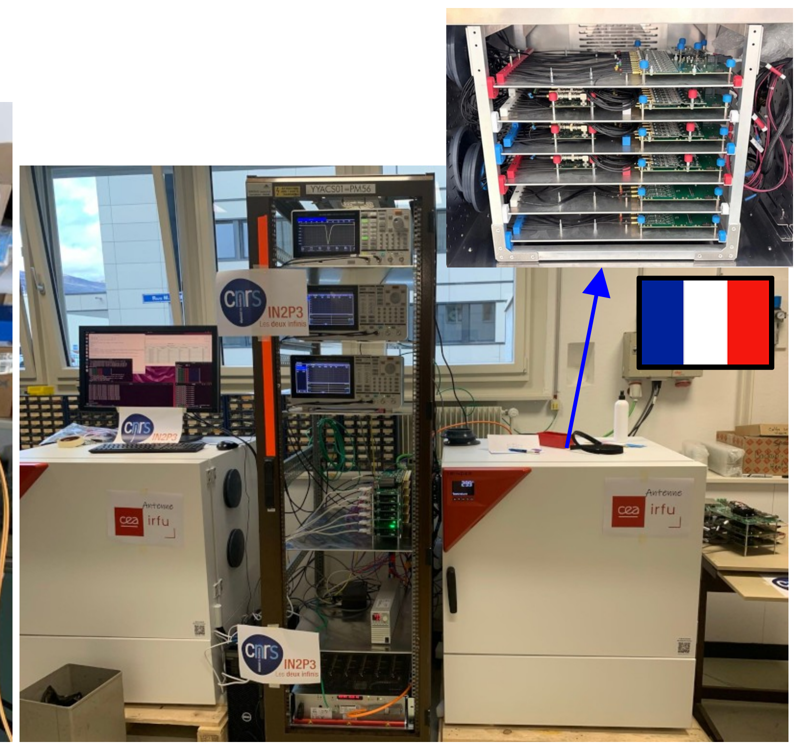
Note: WCTE is an independent collaboration from Hyper-Kamiokande

Hyper-Kamiokande status
Electronics

- Electronics will be underwater, in pressure vessels
- Multiple components with contributions from several countries
- Prototypes of all the components have been produced and tested at CERN and in Kamioka. Now moving to mass production.
- Calibration and assembly of mass produced components will be carried out at CERN and assembled modules shipped to Japan for installation

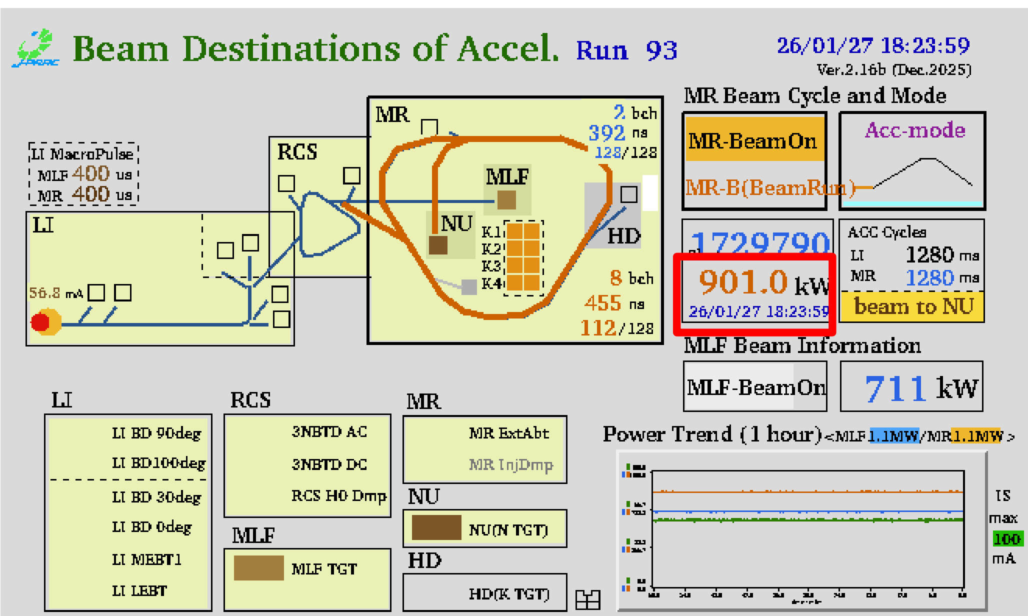


Data processing and timing boards

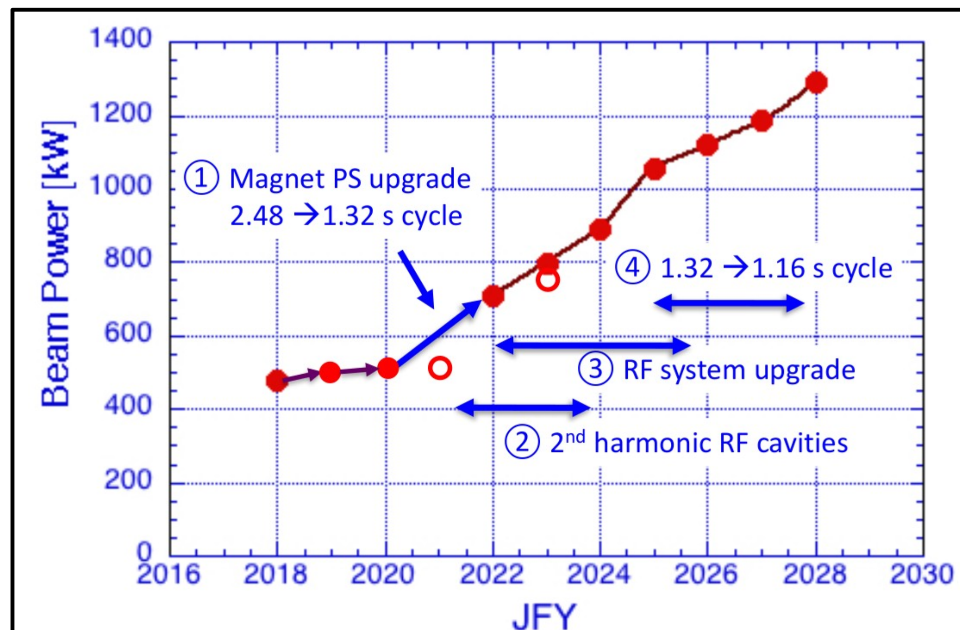


Hyper-Kamiokande status
J-PARC beam

- J-PARC neutrino beamline being operated as part of T2K since 2009
- Operation at progressively increased beam intensity (reached ~900 kW this year)
- Major upgrade will start this summer to prepare for 1.3 MW operation: new target, improved cooling, remote maintenance capability



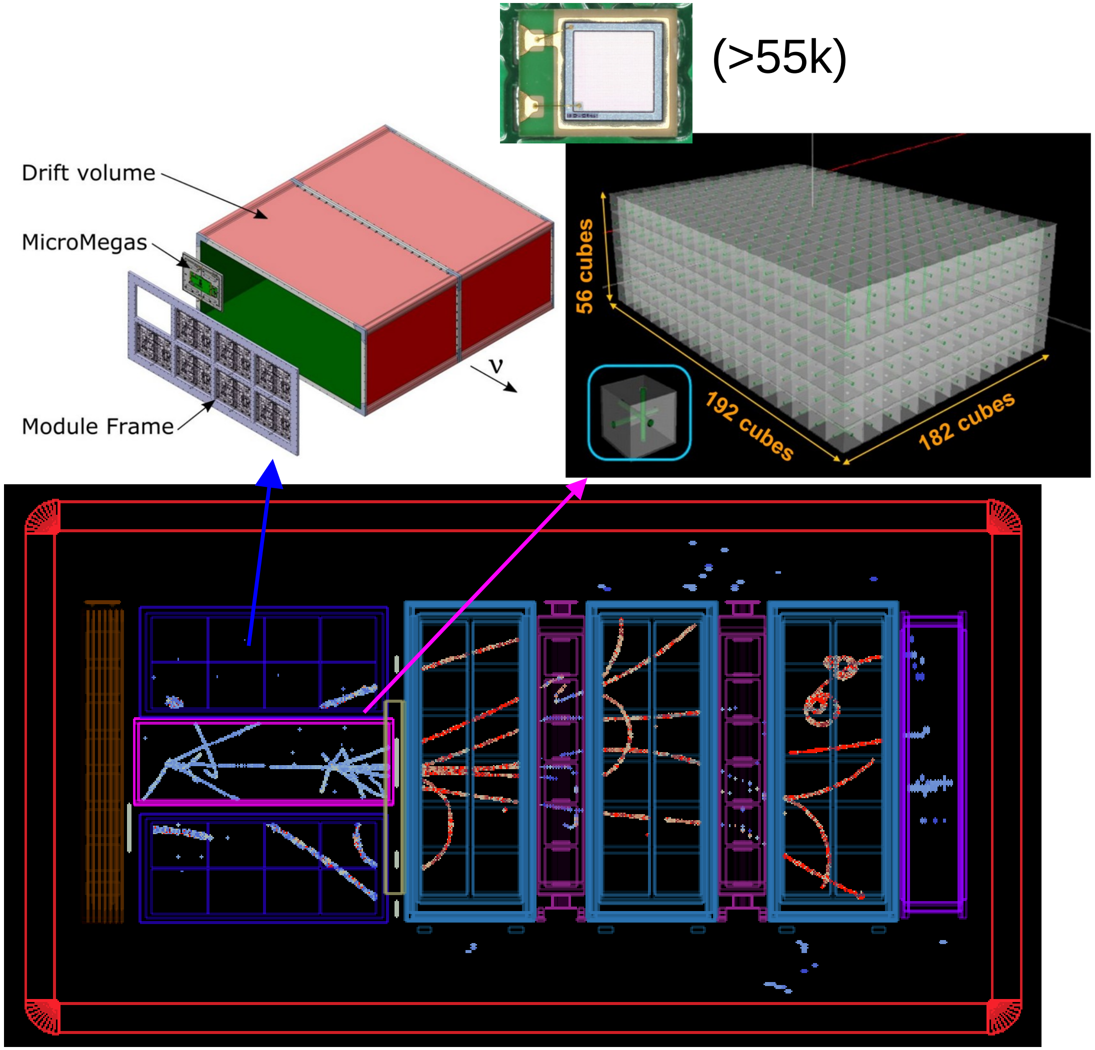
Continuous beam power increase to 1.3MW by the start of HK



From Y. Sato @ J-PARC PAC

Hyper-Kamiokande status
J-PARC Near/Intermediate Detectors

- Off-axis near detector ND280 completed significant upgrade in May 2024, with major contribution from France, and has been taking data in T2K after.
- MOU signed for the transfer of the detector to Hyper-K at the end of T2K
- Work started at IWCD site, target completion of detector installation in the summer of 2028



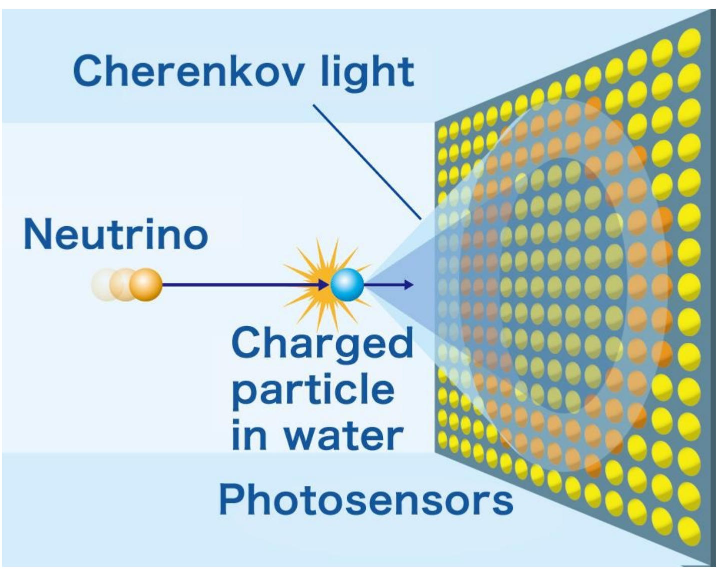
Summary

- 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
- Construction started in 2020, excavation completed in 2025 and construction of the underground facility (tank, water system) on-going
- Design and validation of the different parts of detector complete, now in mass production phase towards installation in 2027
- Start of operation planned for 2028
- Neutrino oscillation experiments in Japan have been supported by a number of contributions from France and Korea over the years, including TYL-FJPPN projects. Some of the current ones will be presented at this workshop:
  - Characterization of the upgraded J-PARC neutrino beam for T2K-II and HK experiments
  - Neutrino cross section measurements with the current and upgraded T2K near detectors
  - Upgrade of the reconstruction algorithms from Super-Kamiokande era towards Hyper-Kamiokande
  - R&D towards ND280++ a new Near Detector for the Hyper-K precision phase era

BACKUP

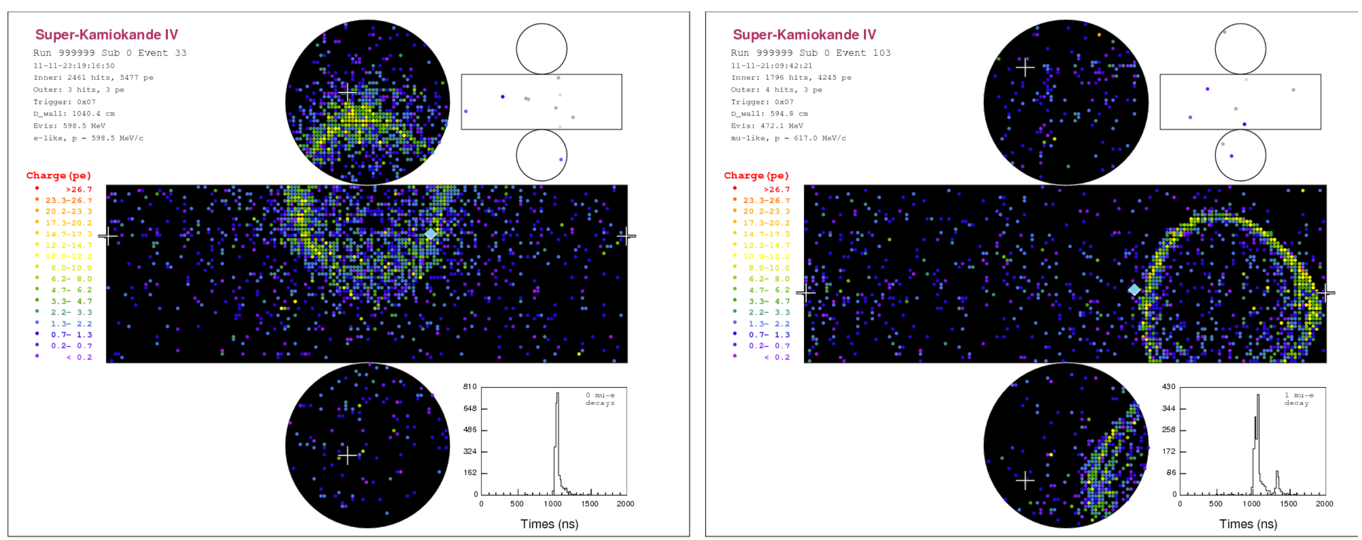
Events in water Cerenkov detector

- Charged particles above Cerenkov threshold appear as ring patterns on walls of the inner detector
- PID from sharpness of ring edges, separate between showering ($e^{\pm}$,γ) and non-showering ($\mu^{\pm}$,$\pi^{\pm}$)
- Interaction vertex position by minimizing spread of (photon arrival time)-(time of flight)
- Momentum from charge deposited in a certain region around ring direction
- Reject entering background using outer detector



Showering

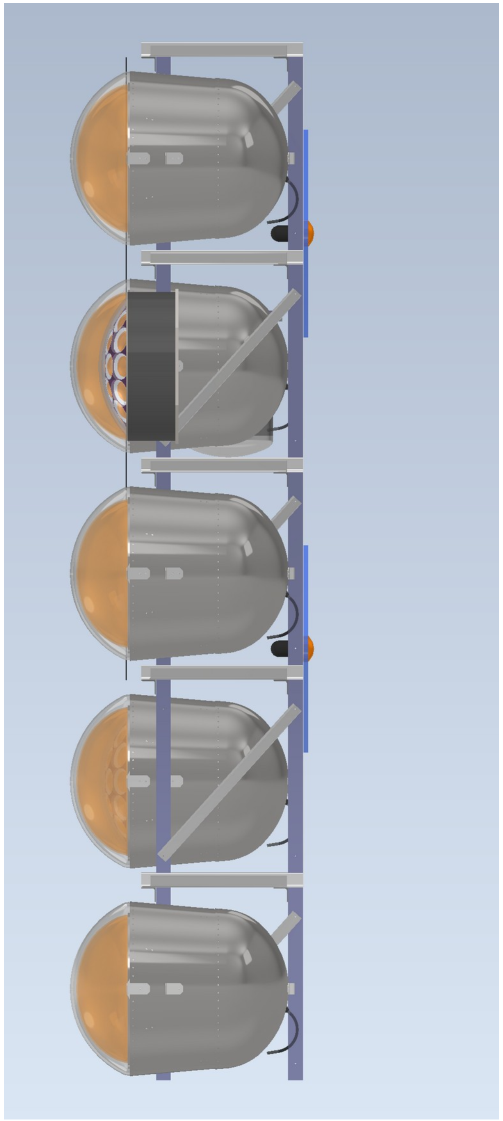
Non-showering



Examples from Super-K simulation

PMTs in the far detector

Photo-detection systems have different goals in inner and outer detectors: important characteristics differ



Inner detector

Event reconstruction

- Timing resolution for vertex reconstruction
- Charge resolution, coverage and detection efficiency for momentum
- Granularity for PID
- Photo-coverage and detection efficiency for low energy events
- Low dark rate for neutron tagging from hydrogen capture

Optimized high QE 20” PMTs + multi-PMTs

Outer detector

Reject entering background

Veto based on cluster of hits above threshold:

- Large number of PMTs to increase information entropy of signal
- Good light collection efficiency
- Low dark rate to be able to use low threshold

3” PMTs in WLS plates with high reflectivity Tyvek

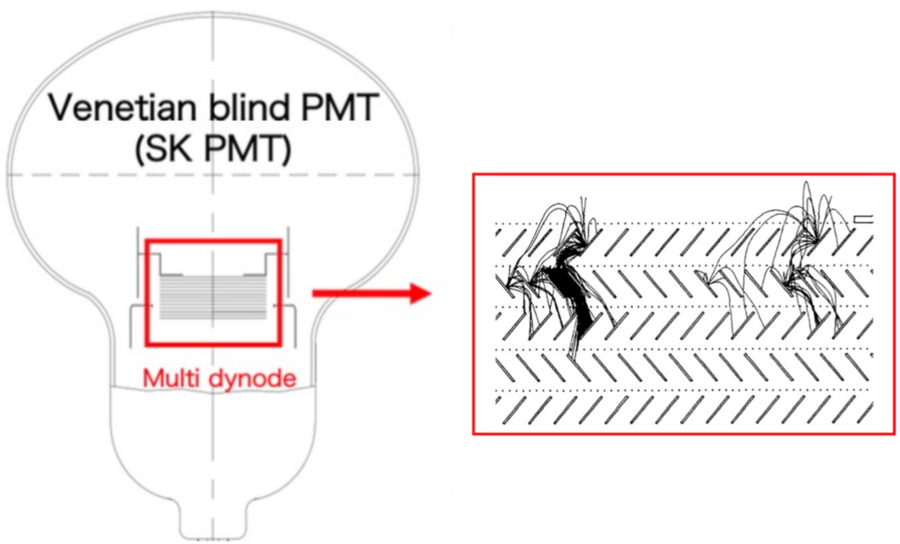
Hamamatsu R12860

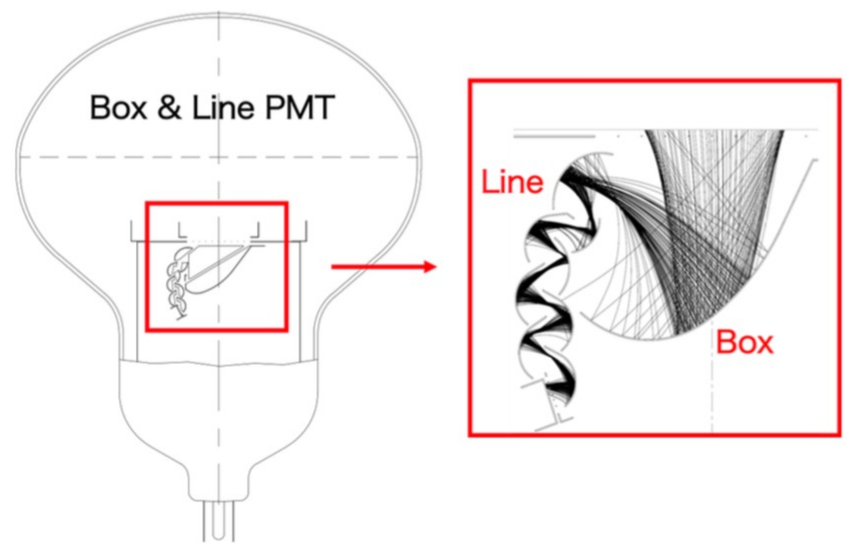
A number of improvement compared to R3600 used in Super-Kamiokande:
- Higher QE and electrons less likely to miss first dynode => higher detection efficiency
- More uniform electron drift path => better timing and charge resolution

Super-K PMT
Hamamatsu R3600

Venetian blind dynode

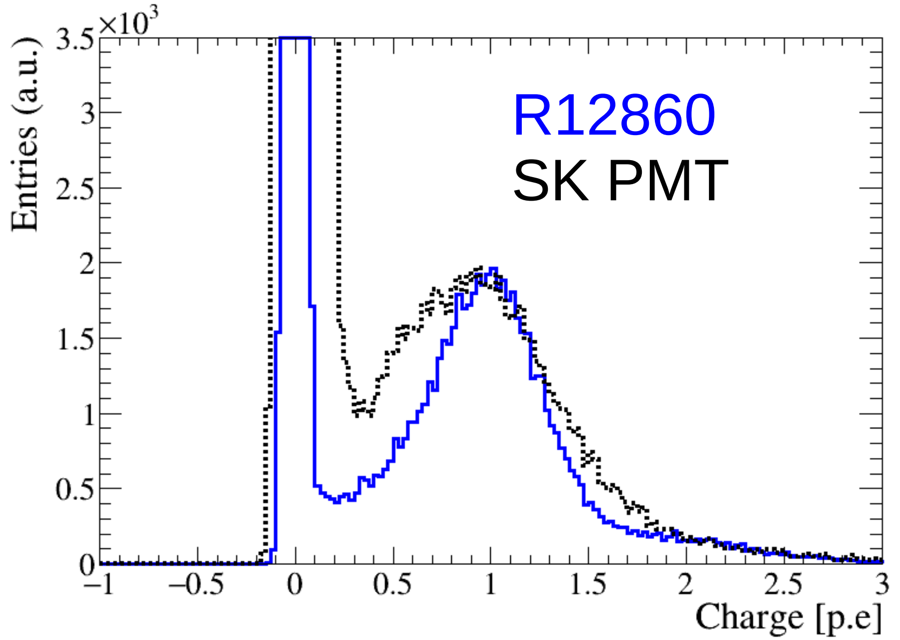
Hamamatsu R12860
Box and line dynode
+ high QE

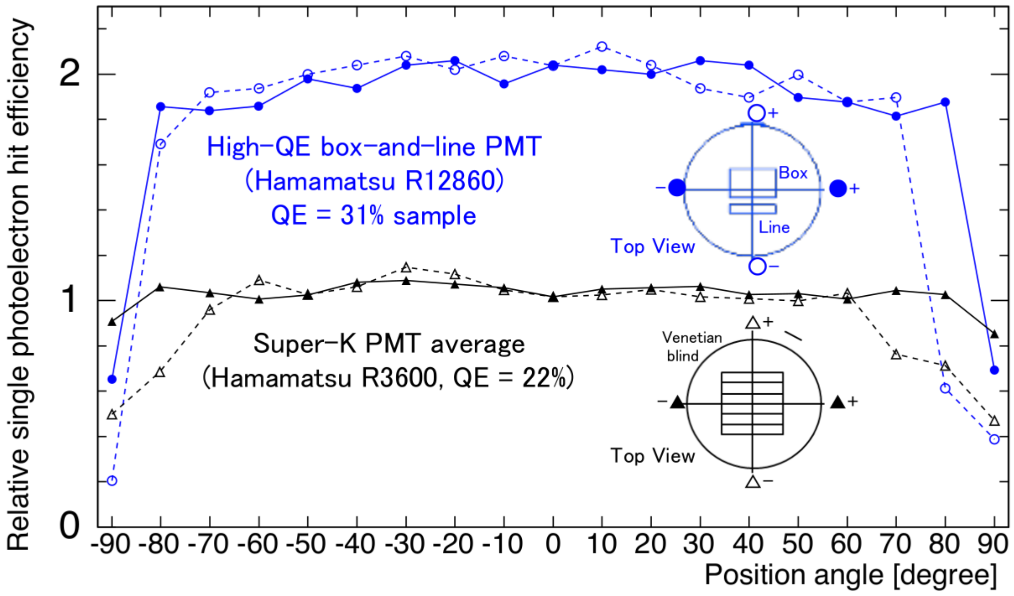


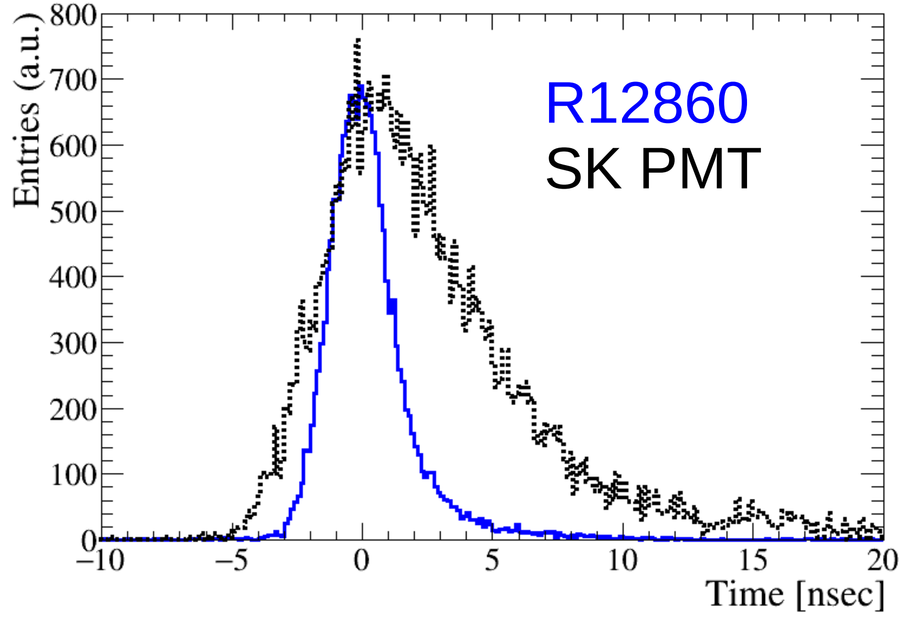


Hamamatsu R12860

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

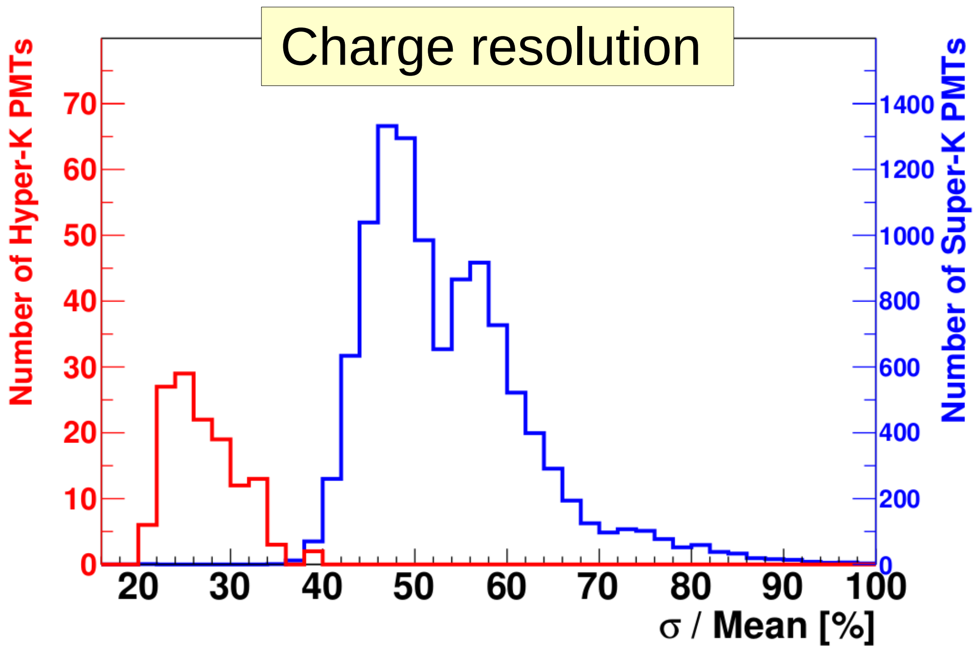


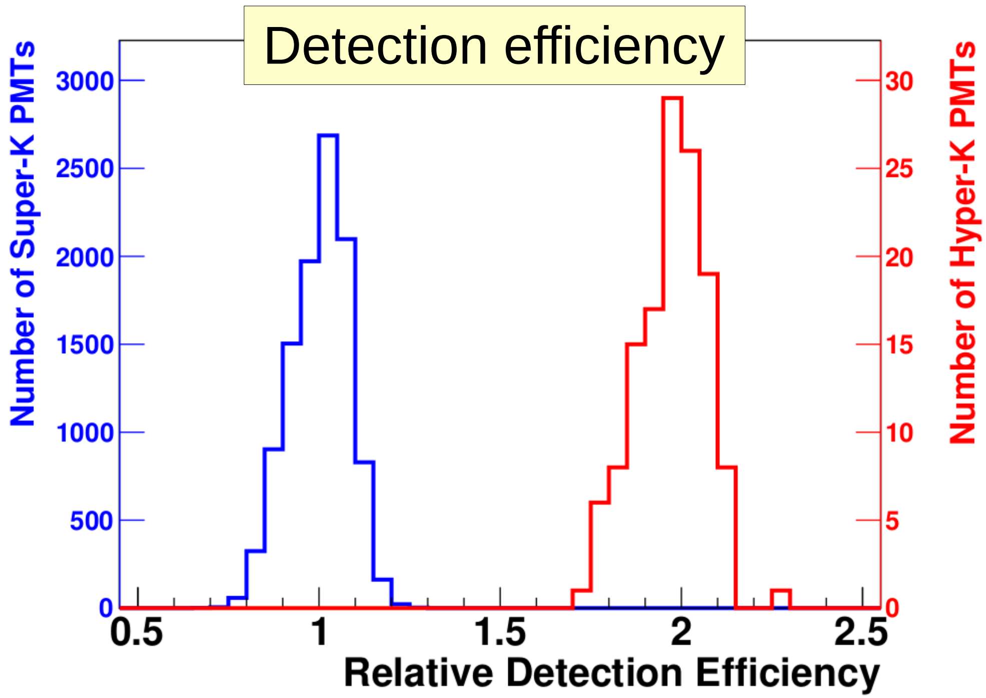


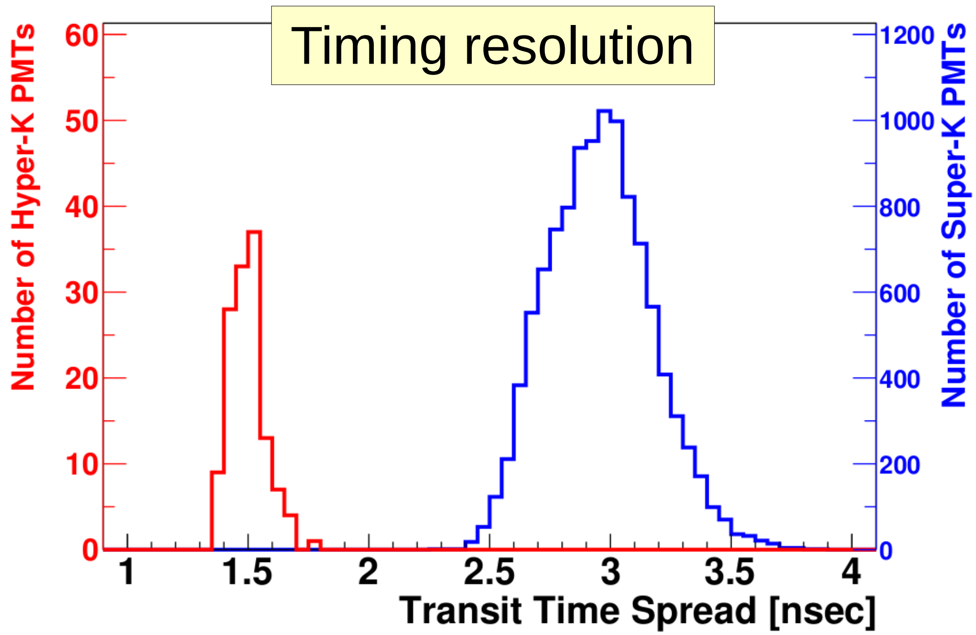


Hamamatsu R12860 Performance in Super-Kamiokande

- 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

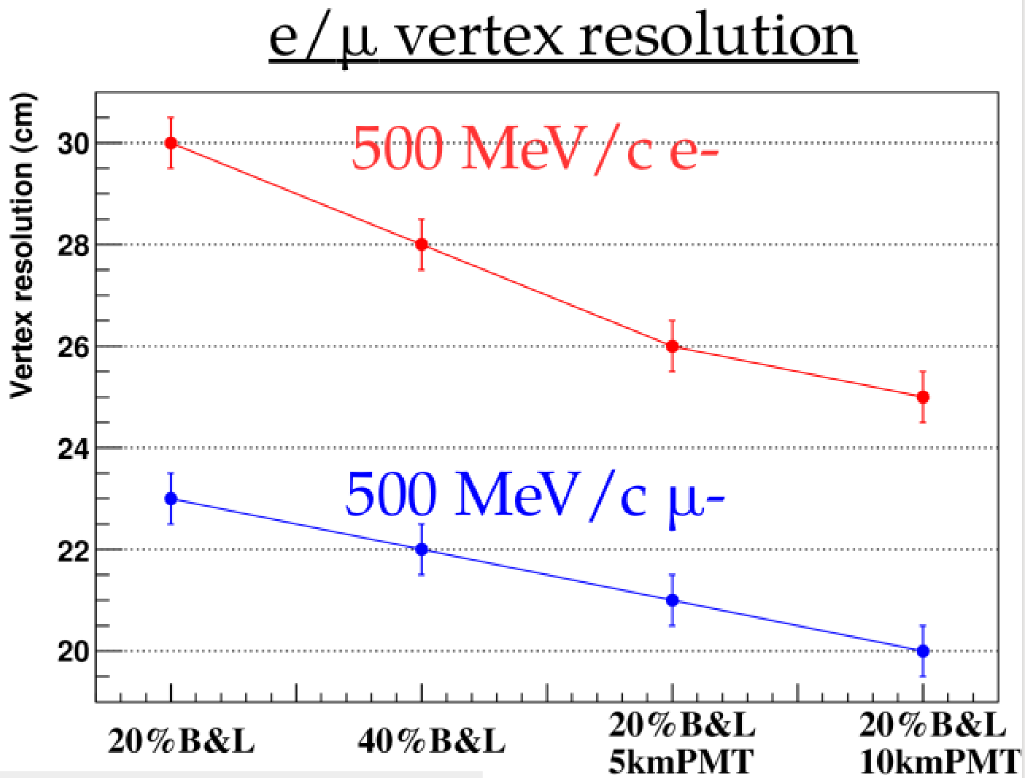


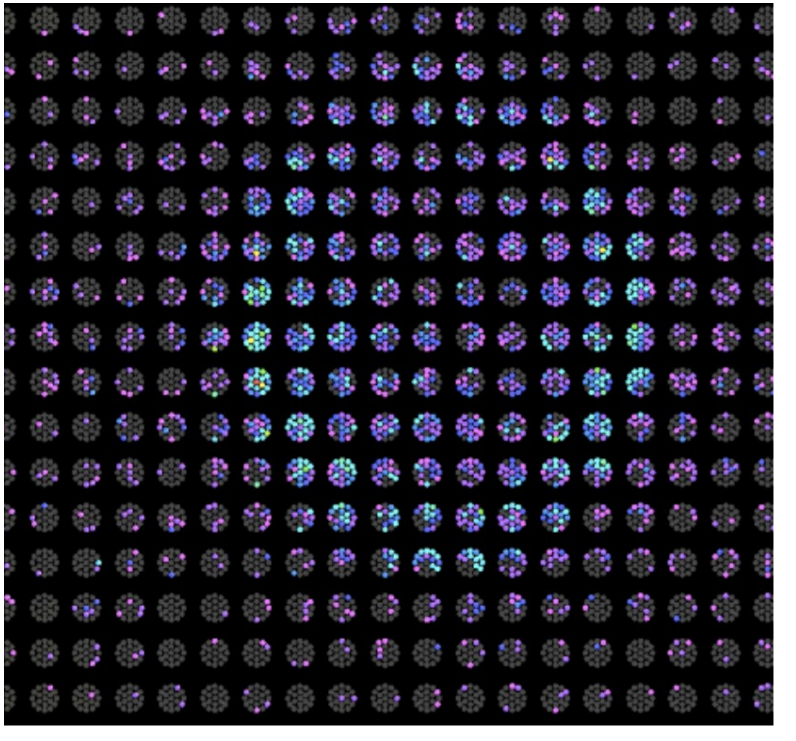




Multi-PMT
Concept and interest

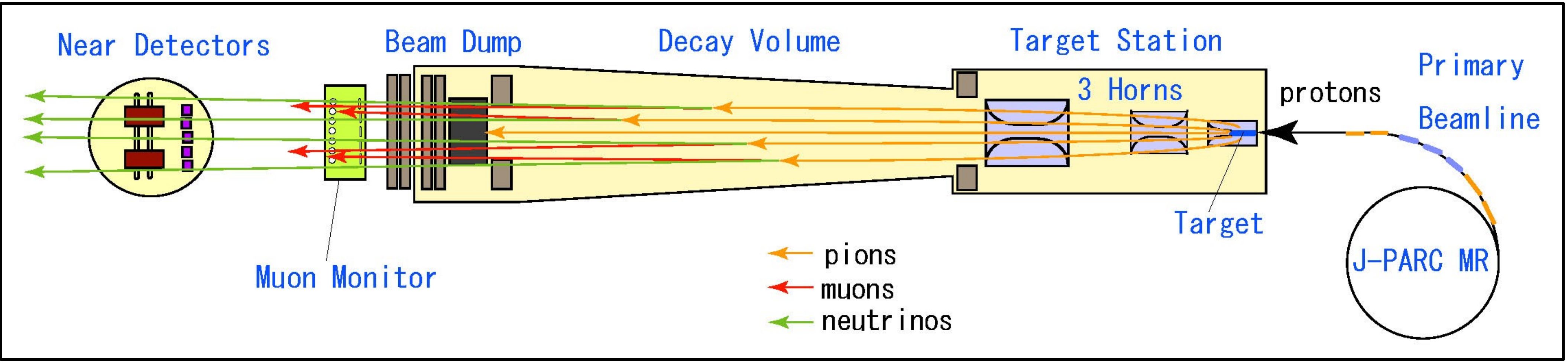
- 19 3” PMTs in a pressure vessel.
- Will be used in complement of 20” PMTs at far detector, and fully equip IWCD
- High granularity, photon directional information improves reconstruction near the walls and potentially ring separation for multi-ring events
- Better timing resolution than 20” PMTs, improves vertex resolution and PID near the walls
- Improves calibration: reference photo-sensor with good charge/timing characteristics, and LED light sources for photogrammetry and various calibrations





B.Quilain @ TAUP 2019

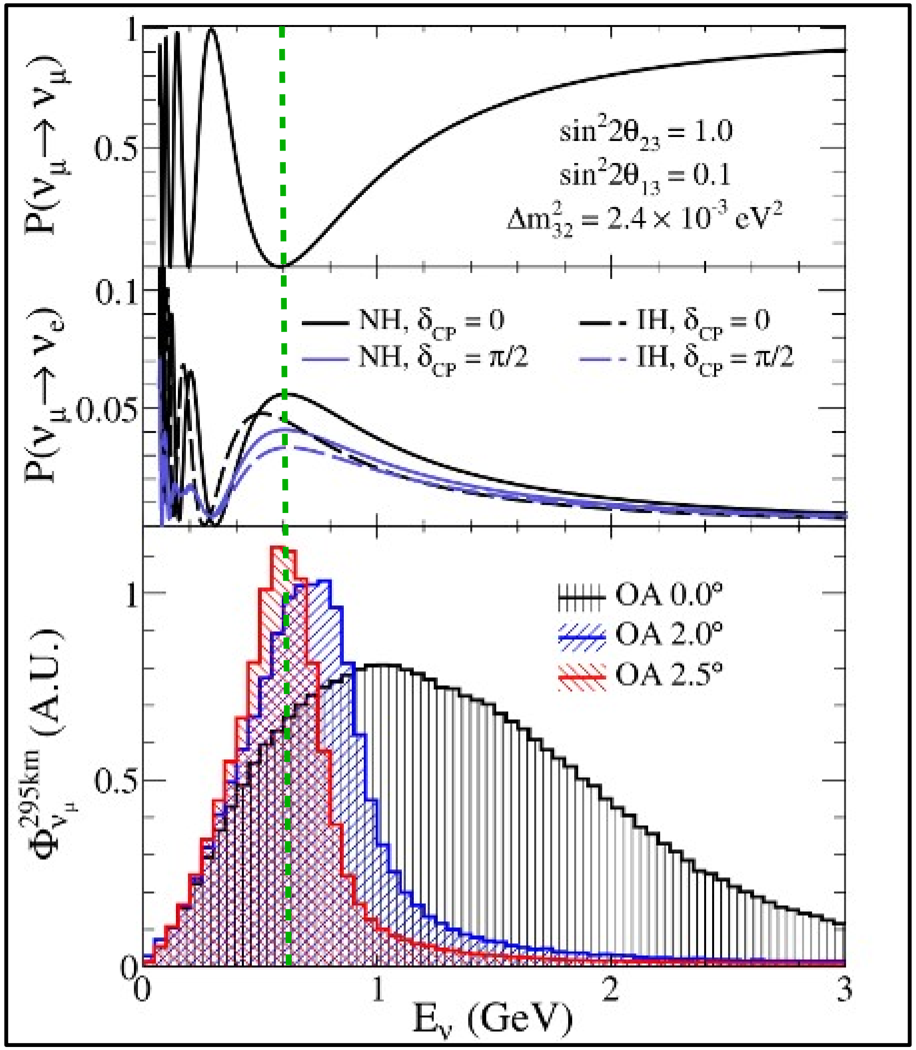
Neutrino production
Conventional neutrino beam

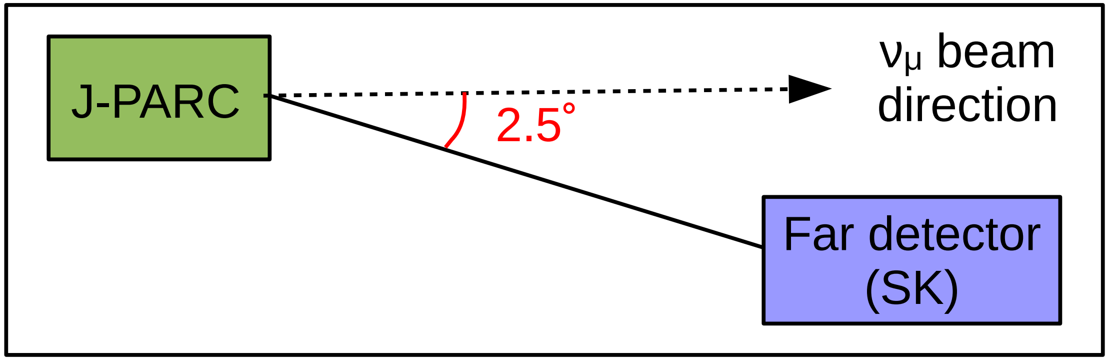


Almost pure $\nu_\mu/\bar{\nu}_\mu$ beam, with an intrinsic $\nu_e/\bar{\nu}_e$ component (<1% at peak)

Can switch from ν_μ beam to $\bar{\nu}_\mu$ beam by inverting the horn polarities

The T2K experiment
Off-axis beam





- Narrow band neutrino beam, peaked at oscillation maximum (0.6 GeV)
- Reduces high energy tail
- Reduces intrinsic ν_e contamination of the beam at peak energy
- Interactions dominated by CCQE mode

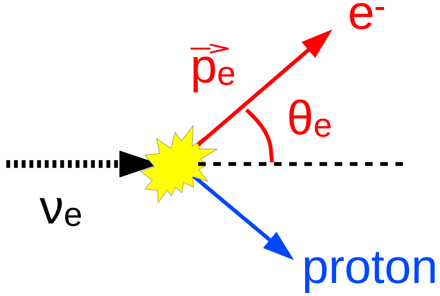
Precise study of oscillations

- Accelerator neutrino beam expensive to produce, and lower statistics than atmospheric neutrinos
- However, allows for precise measurement of oscillations through good L/E resolution and control/knowledge of incoming neutrinos

- ✓ L known exactly
- ✓ Good ν energy estimator for main interaction at T2K/HK energies

$\nu + n \rightarrow p + l^-$

$\bar{\nu} + p \rightarrow n + l^+$



Almost exclusive samples to study different oscillation channels:

- Original neutrino (ν_μ/ $\bar{\nu}_\mu$) from horn polarity
- Final neutrino (ν_e/$\bar{\nu}_e$/ν_μ/ $\bar{\nu}_\mu$) from horn polarity and lepton identified at SK

Water Cherenkov detector:

- Only sees charged particles
- Has a momentum threshold

Long-baseline experiments
First measurements

In first approximation LBL experiments can measure some of the PMNS parameters through exclusive channels:

Far detector ν_μ events

$\nu_\mu \rightarrow \nu_X$ disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2(1.27 \frac{\Delta m^2 \times L}{E})$$

Precise measurement of θ_{23} and $|\Delta m^2|$

Far detector ν_e events

$\nu_\mu \rightarrow \nu_e$ appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27 \frac{\Delta m^2 \times L}{E})$$

- Observation of ν_e appearance
- Measurement of θ_{13}

And similar measurements for anti-neutrinos

CP symmetry

Universe mainly made of matter
Sakharov's conditions: **requires violation of CP symmetry**

3 possible sources in the Standard Model:
- Strong interaction
- Quark mixing matrix
- **Neutrino mixing matrix**

C : Charge conjugation
P : Parity (x → -x)
CP : $\nu_L \rightarrow \nu_R$

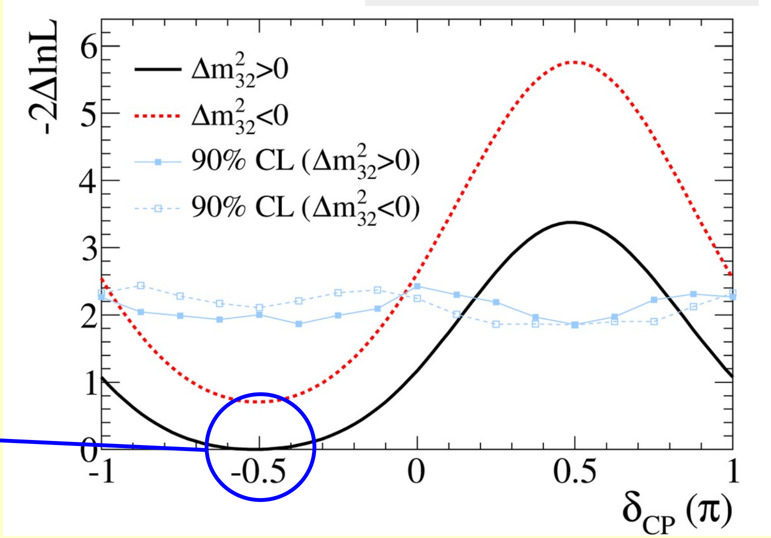
Neutrino oscillations

$\not{CP} \Leftrightarrow \sin(\delta) \neq 0$

$$\text{Amplitude} \propto |\sin(\delta)|$$

First results : δ ~ -π/2 favored
(|sin(δ)|~1 : maximal)

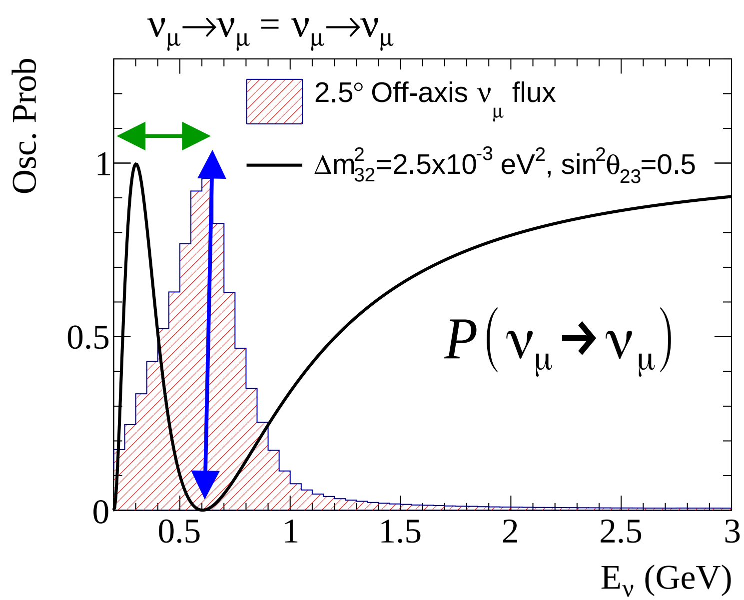
PRL 112, 061802 (2014)

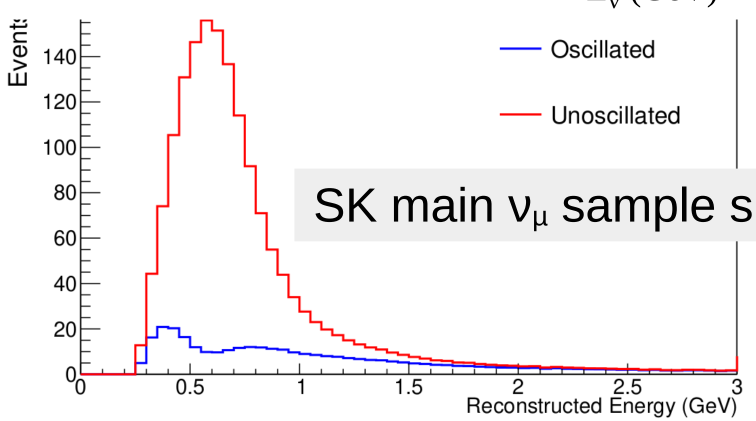


Sensitivity to oscillations
Atmospheric parameters

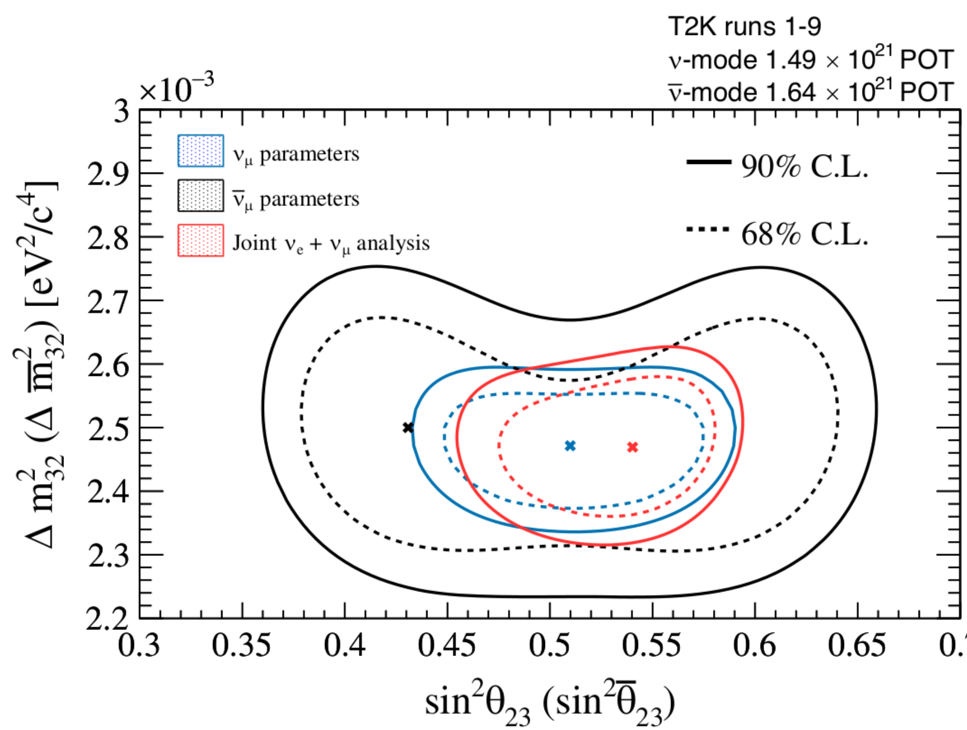
- Muon (anti-)neutrino disappearance gives sensitivity to $\sin^2(2\theta_{23})$ and $|\Delta m^2_{32}|$
- θ_{23} octant sensitivity from appearance channel

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(1.27 \frac{\Delta m^2 L}{E}\right)$$





$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2\left(1.27 \frac{\Delta m^2 L}{E}\right)$$



Phys. Rev. D 103, L011101 (2021)

Sensitivity to open questions

δ and the mass ordering modify the electron to muon flavor oscillation probability in different ways for neutrinos and anti-neutrinos

Full probability in vacuum:

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}$$
$$+ 8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$
$$- 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$
$$+ 4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Delta_{21}$$

$\sin^2\Delta_{ij} = \sin^2(1.27\,\Delta m_{ij}^2 \times L/E),\ s_{ij} = \sin(\theta_{ij}),\ c_{ij} = \cos(\theta_{ij})$

$\nu \to \bar{\nu}$

$\delta \to -\delta$

$x \to -x$

In matter leading term

$$P(\nu_\mu \to \nu_e) \approx \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2\left(1.27\frac{\Delta m^2}{E}\right)$$

Multiplied by $\dfrac{\sin^2(\Delta(1-x))}{(1-x)^2}$

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

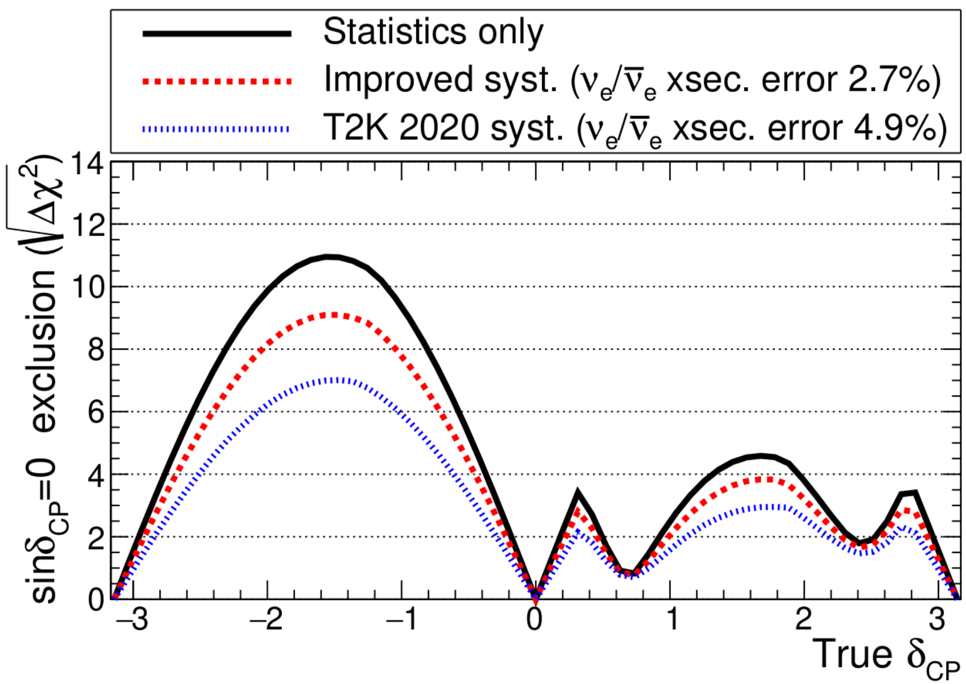
1sigma resolution of oscillation parameters for 10 HK years, accelerator neutrinos only

Parameter & true value	δ_{CP}=0°	δ_{CP}=-90°	$\sin^2\theta_{23}$=0.528	Δm^2_{32}=2.509 x 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 x 10^{-6} eV^2/c^4 0.29%	4.73 x 10^{-4} 2.17%
Improved Systematics	6.3°	20.2°	0.0134 2.54%	8.69 x 10^{-6} eV^2/c^4 0.35%	5.39 x 10^{-4} 2.47%
T2K 2020 systematics	8.3°	23.9°	0.0199 3.77%	11.62 x 10^{-6} eV^2/c^4 0.46%	6.04 x 10^{-4} 2.77%

Long Baseline oscillations
Sensitivity with unknown Mass Ordering

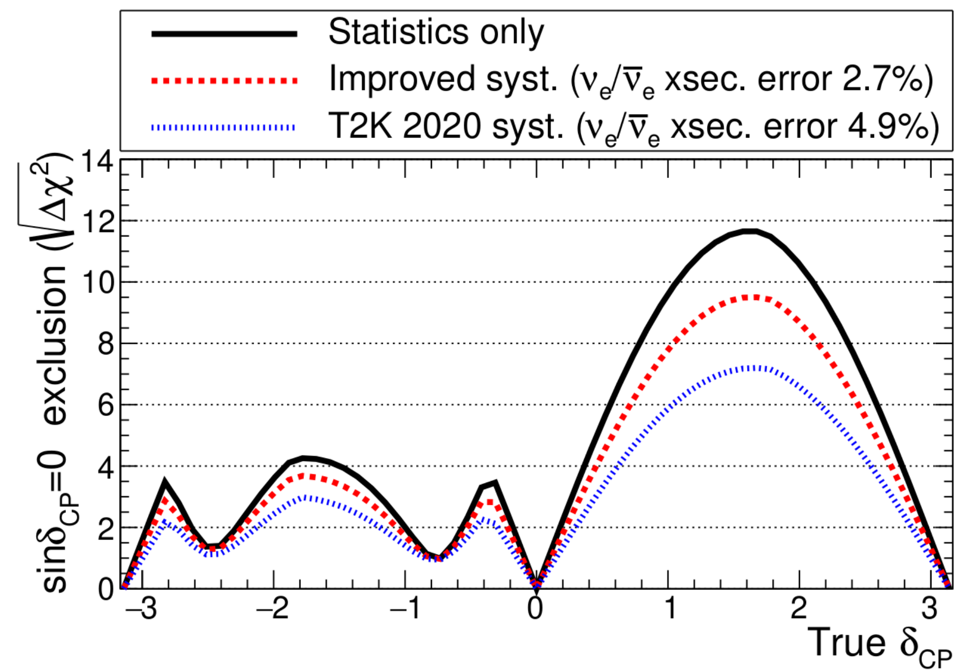
Ability to exclude conservation of CP symmetry for 10 HK years, accelerator neutrinos only, **Unknown Mass Ordering**

<u>True Normal Ordering</u>



Hyper-K preliminary

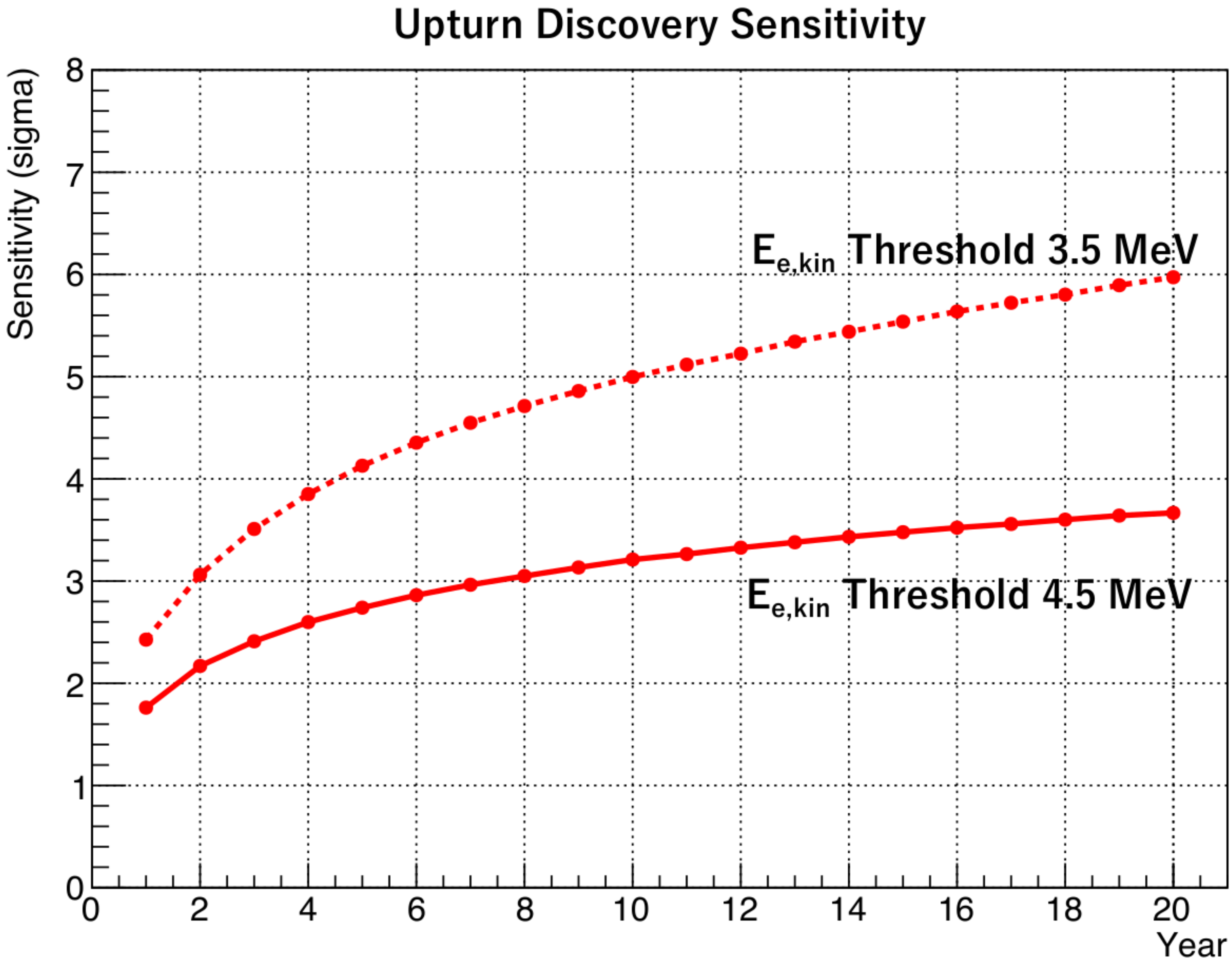
<u>True Inverted Ordering</u>



Hyper-K preliminary

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

Low energy neutrinos
Sensitivity to spectrum upturn

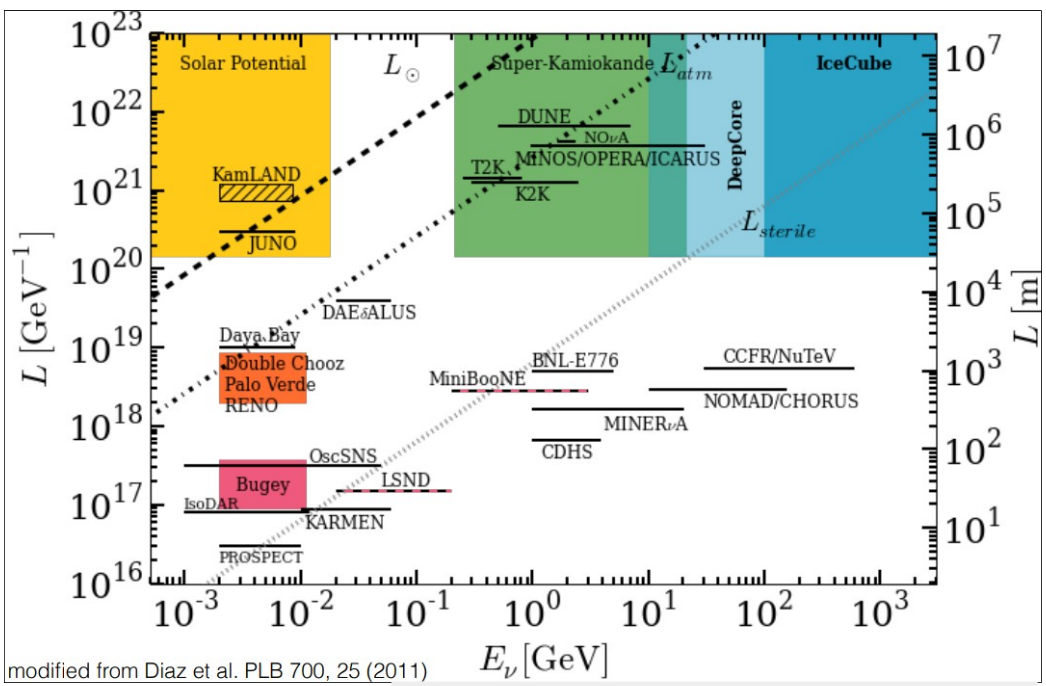


Testing the 3 flavor model

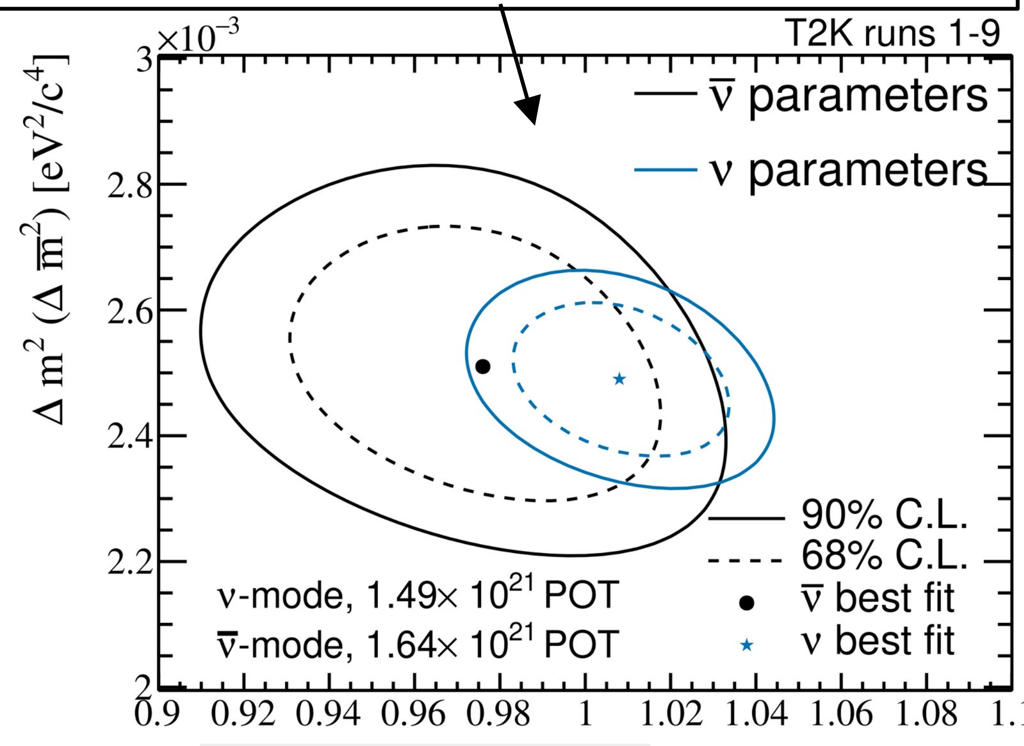
- In the long term, test unitarity of neutrino mixing matrix
- Limited degrees of freedom and maximum possible amplitude of oscillations:
  - parameters should be same when measured at same L/E, through different oscillation channels, or from ν and $\bar{\nu}$
  - parameters cannot exceed certain values ($0<\sin^2(\theta_{ij})<1$)

$$P_{\nu_\mu\to\nu_\mu}\left(P_{\bar{\nu}_\mu\to\bar{\nu}_\mu}\right) \approx 1-\alpha(\bar{\alpha})\sin^2\left(1.267\frac{\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

Effective mixing angle α (= $\sin^2(2\theta)$ for α≤1) can take values larger than 1



J. Hignight @ NuFACT 2019



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