Hyper-Kamiokande: From Construction to Discovery Physics

Jeanne Wilson

Contents

- Why long baseline ν experiments?
- The Hyper-K project
- Physics design considerations
- IWCD
- Far Detector
  - Cavern
  - Tank
  - Instrumentation: 50cm PMTs, mPMTs
  - Outer Detector
  - Electronics
  - Water Systems
  - Calibrations
- Status

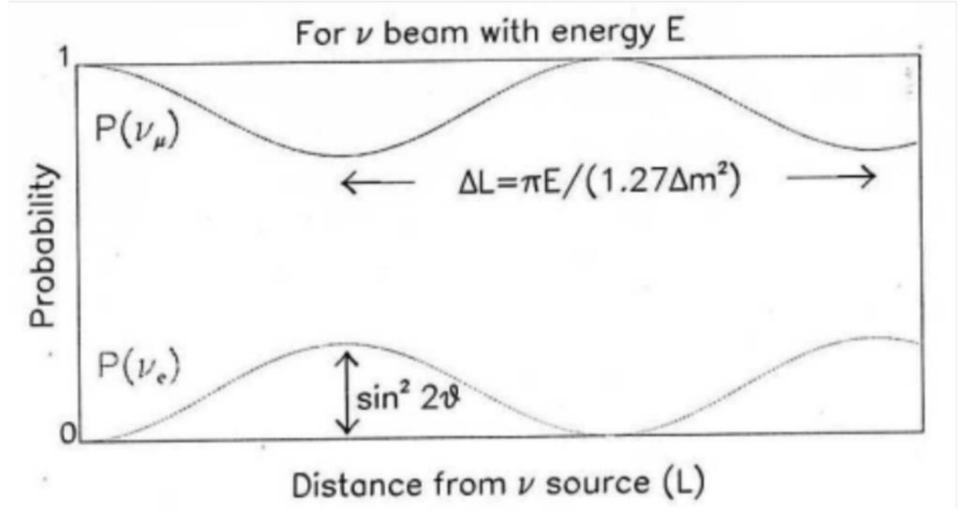
Neutrinos Oscillate

ν_e, ν_μ, ν_τ

Amplitude

Frequency

$$P(\nu_a \to \nu_b) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$



Disappearance

Appearance

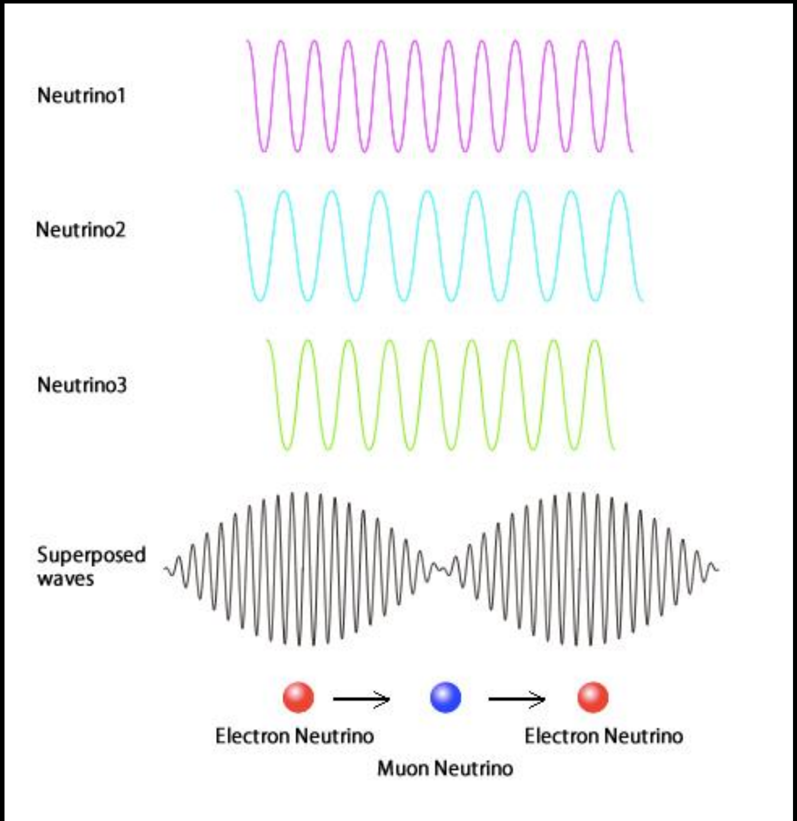
Start with a know source (flavour, flux) of neutrinos

Measure or calculate the flux before oscillations

Does the initial flavour disappear? Does a different flavour appear?

3 flavour oscillations

- 3 mixing angles
- 2 mass splittings
- + CP violating phase

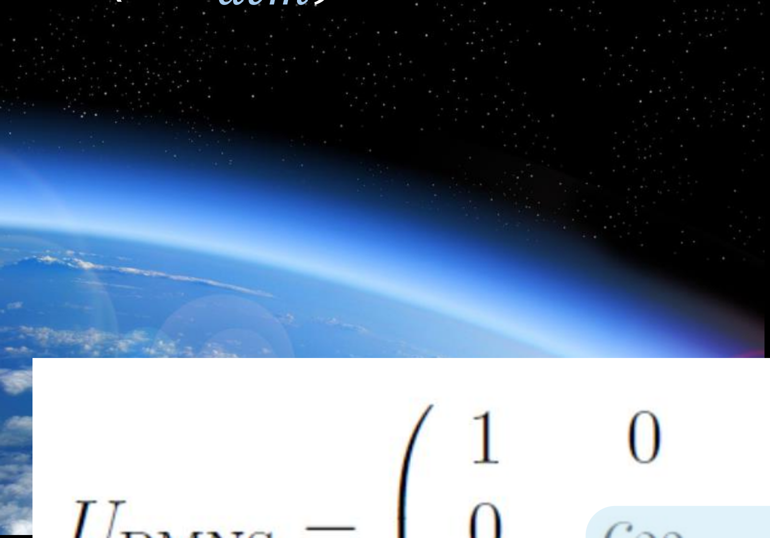


$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

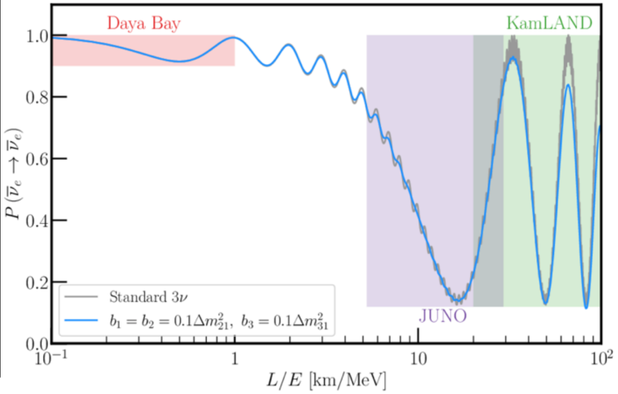
$s_{ab} = \sin\theta_{ab}$, $c_{ab} = \cos\theta_{ab}$

The story without beams

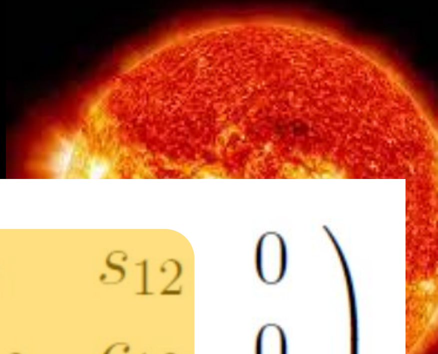
- Atmospheric neutrinos (Super-K)
- ν_μ disappearance
- θ_{23} and Δm^2_{23} (Δm^2_{atm})



- Reactor neutrinos, short baseline (Daya Bay, Double Chooz, RENO)
- $\overline{\nu_e}$ disappearance
- θ_{13} and Δm^2_{23}.



- Solar neutrinos (SNO Super-K)
- ν_e disappearance
- KamLAND 180km reactor baseline
- $\overline{\nu_e}$ disappearance
- θ_{12} and Δm^2_{21} (Δm^2_{solar})



$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

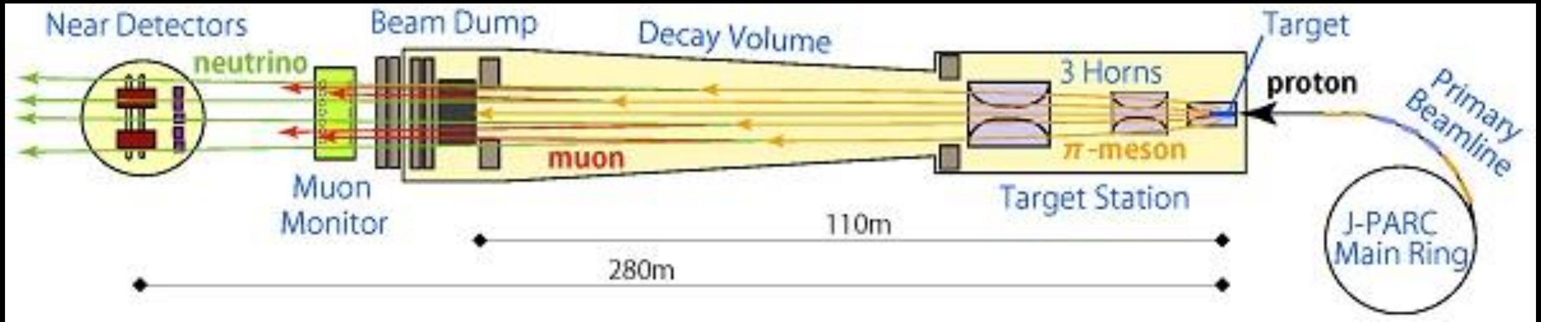
$s_{ab} = \sin\theta_{ab}\,,\; c_{ab} = \cos\theta_{ab}$

$\Delta m^2_{solar} \ll \Delta m^2_{atm}$

+ Beam neutrinos

$$\pi^+ \to \mu^+ + \nu_\mu \ , \quad \pi^- \to \mu^- + \overline{\nu_\mu}$$

- Control your source
- Measure your source



ν_μ disappearance → θ_{23} and Δm^2_{23}

ν_e appearance → θ_{13}, θ_{23} and Δm^2_{23}

Compare $\overline{\nu_e}$ and ν_e appearance → δ_{CP}

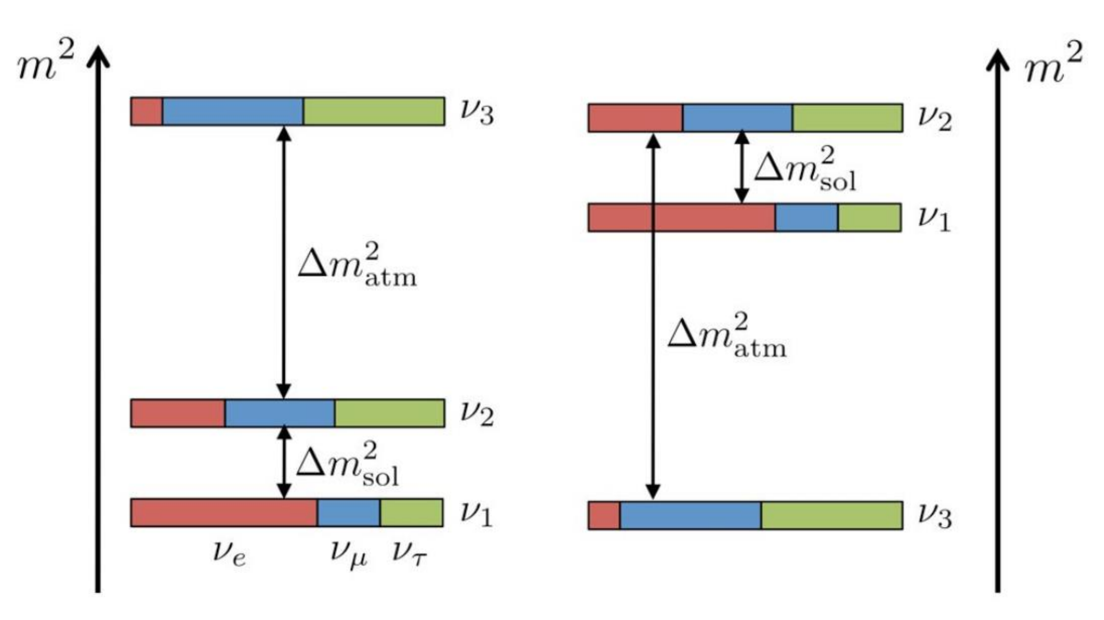
MINOS, K2K
T2K, NoνA

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Oscillations measure Δm^2 - how do we know the sign of Δm?

Normal Ordering

- $\nu_\mu \rightarrow \nu_e$ oscillations enhanced in matter
- $\overline{\nu_\mu} \rightarrow \bar{\nu}_e$ oscillations suppressed in matter



Inverted Ordering

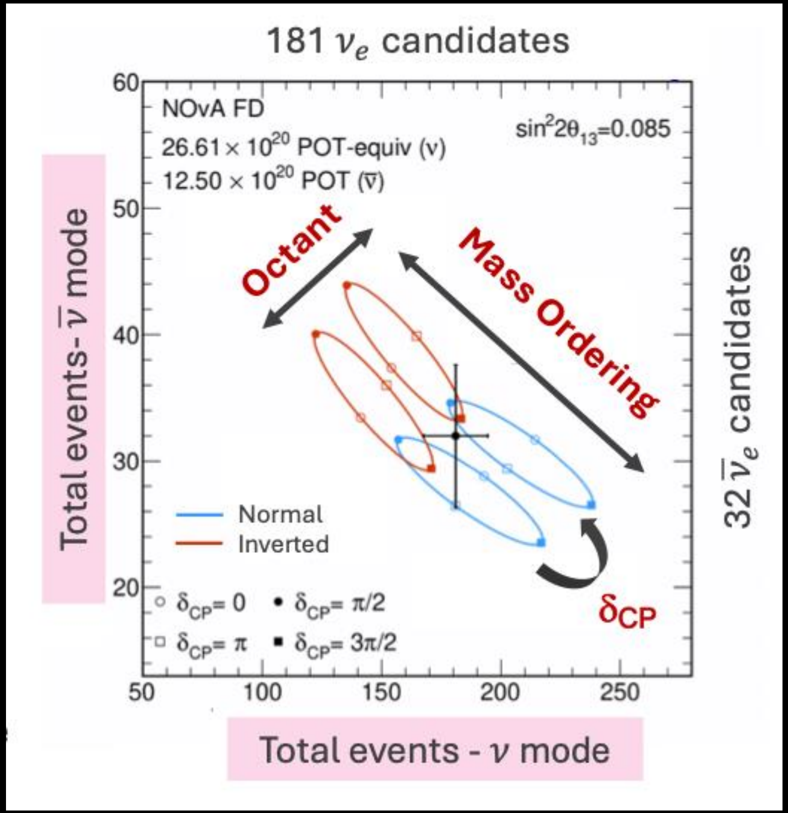
- $\nu_\mu \rightarrow \nu_e$ oscillations suppressed in matter
- $\overline{\nu_\mu} \rightarrow \bar{\nu}_e$ oscillations enhanced in matter

Matter effects alter the effective Δm^2 and mixing angles in matter compared to a vacuum

- ν_e - additional potential due to ambient electrons
- Effect larger in denser medium, longer baseline, higher energy

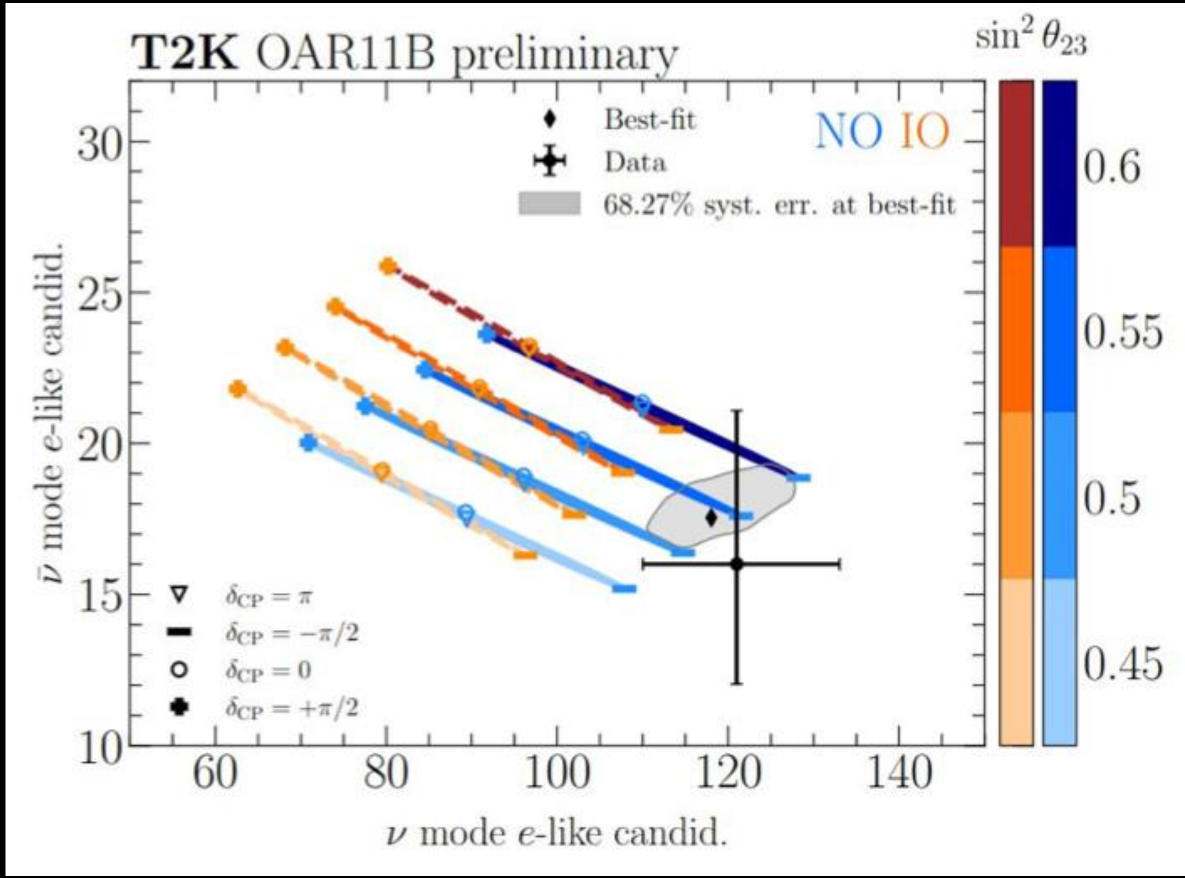
Current Status

- δ_{CP} and matter effects are degenerate



NovA – Nu2026 talk

Baseline = 810km



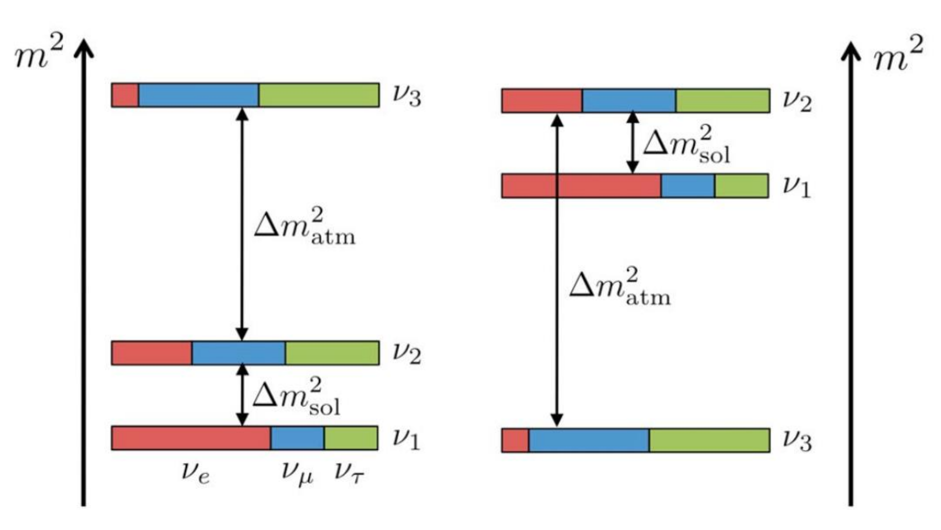
T2K– Nu2026 talk

Baseline = 295km

Why we need Long Baseline Neutrino Experiments

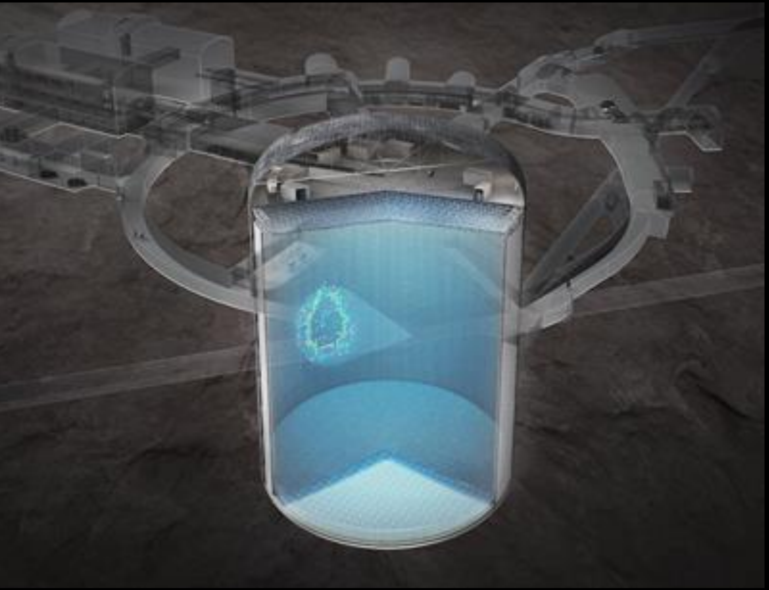
Next Generation of Experiments should:

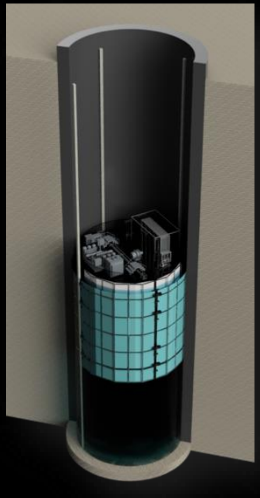
- Determine the mass ordering
  - Through matter effect
  - Long baseline (or atmospheric ν)
- Determine if neutrinos violate CP
  - Compare ν_e and $\bar{\nu}_e$ appearance to probe δ_{CP}
- Determine if this model is correct – precise parameter measurements



$$U_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\rm CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\rm CP}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Overview of the Hyper-Kamiokande project





Far Detector (FD)
- Water Cherenkov
- 187kton fiducial mass
- 1750 m.w.e. overburden
- Oscillated ν_μ , $\overline{\nu_\mu}$ and $\nu_e, \bar{\nu}_e$ measurement

Statistics!
Excellent μ: e separation

Intermediate Water Cherenkov Detector (IWCD)
- 870m downstream
- Vertically moving Water Cherenkov spans 1.5°-4° off-axis angles
- 110t fiducial mass
- $\nu_e, \bar{\nu}_e$ cross sections
- Neutral current

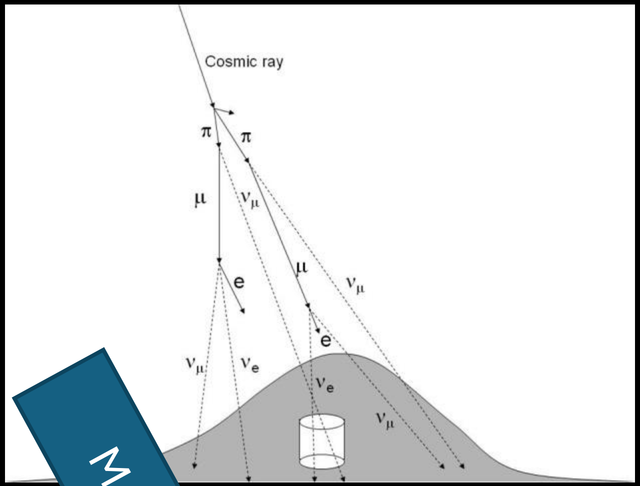
Near Detectors (ND280)
- 280m downstream
- Magnetised tracking detector
- ν_μ , $\overline{\nu_\mu}$ flux measurement (including wrong sign)
- Final state hadrons and interaction cross-sections
- Since beginning of T2K, upgraded 2024

JPARC neutrino beam
- Provide ν_μ or $\overline{\nu_\mu}$ beam
- 2.5° Off-axis narrow energy peak 0.6GeV

Upgrading to 1.3MW beam operation in 2028

Hyper-Kamiokande Physics

See Nataly Ospina's talk this afternoon for more details



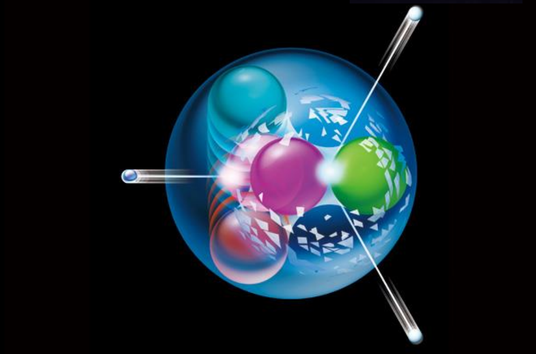
Atmospheric neutrinos: $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$

High Energy Neutrinos

Solar neutrinos, ν_e

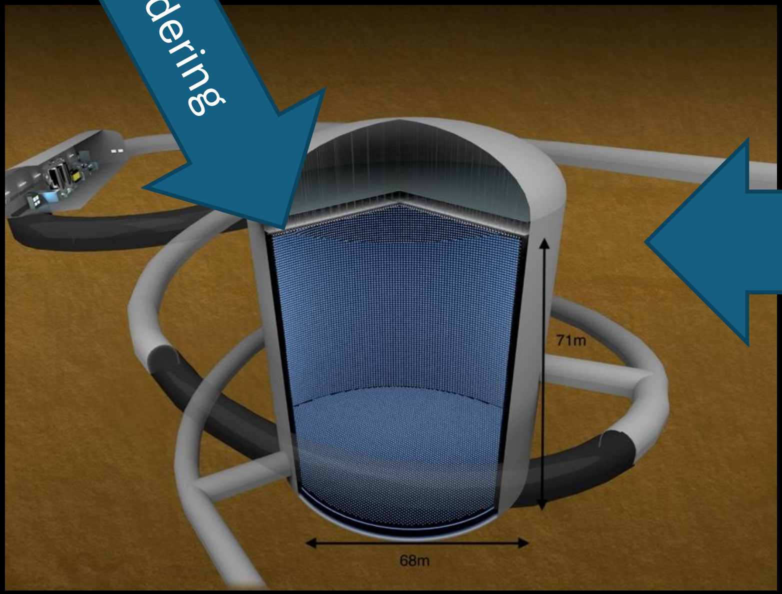
Supernova bursts

Diffuse Supernova Background Neutrinos



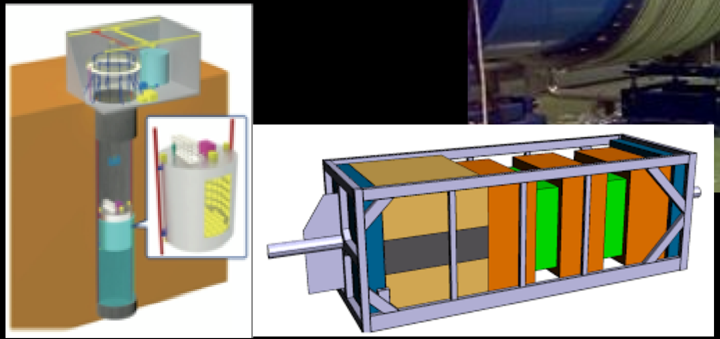
Proton Decay Search

Mass Ordering



CP violation, oscillation parameters

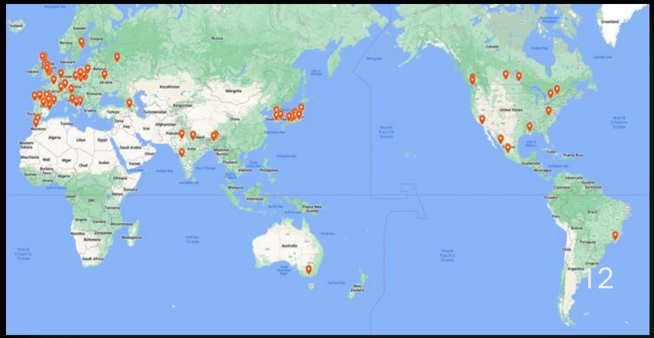
J-PARC neutrino beam: $\nu_\mu, \bar{\nu}_\mu$



Near Detectors

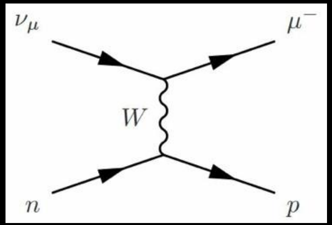
Hyper-Kamiokande Collaboration

- ~660 members from 23 countries and ～100 institutes

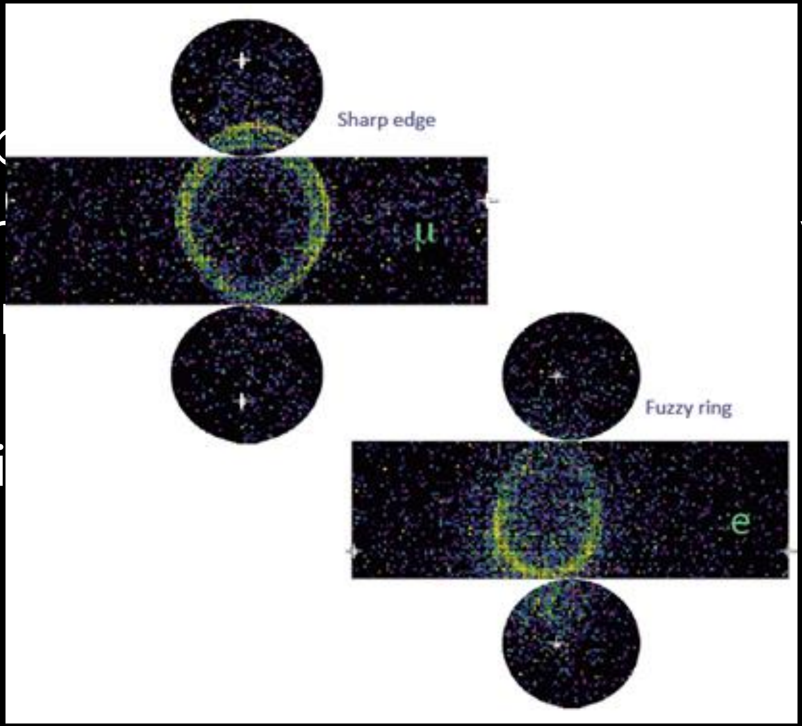


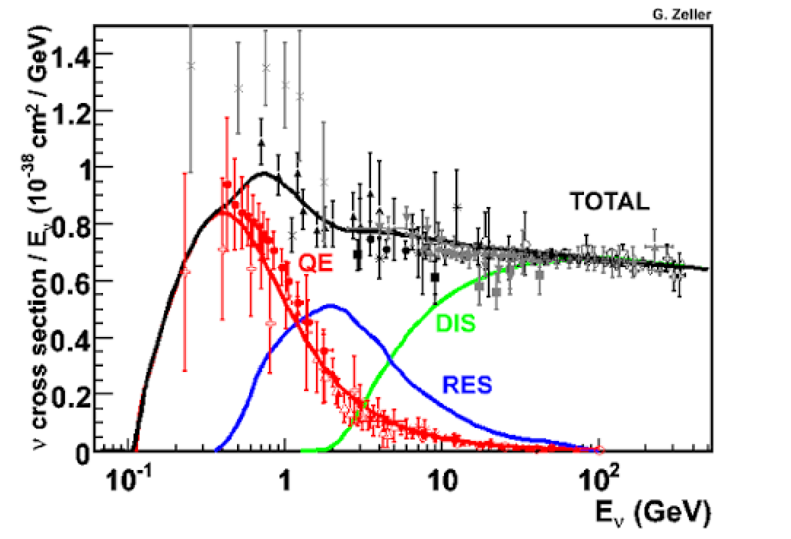
Hyper-K long baseline strategy

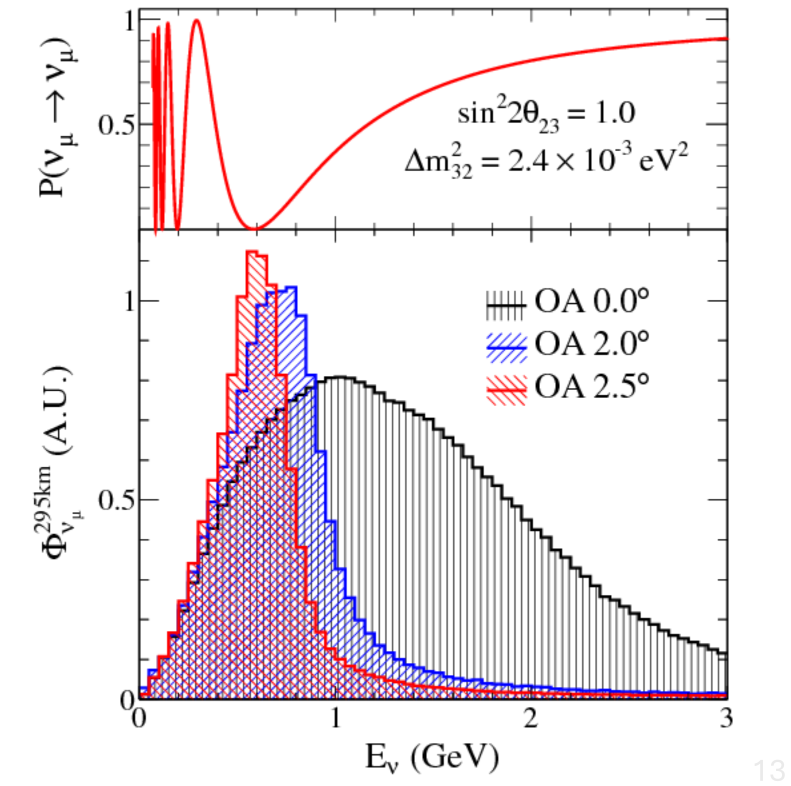
- At a 295km baseline, ν_μ disappearance oscillation maximum corresponds to 600MeV
  - Matter effects are sub-dominant (<10%)
  - Quasi-elastic interactions dominate at low energy
    - Select 1-ring e-like or μ-like samples in Water Cherenkov
    - Reconstruct neutrino energy from basic kinematics



- Off-axis b
  - Use kir y
  - Near a give neutrino energy
  - Intrinsi off-axis



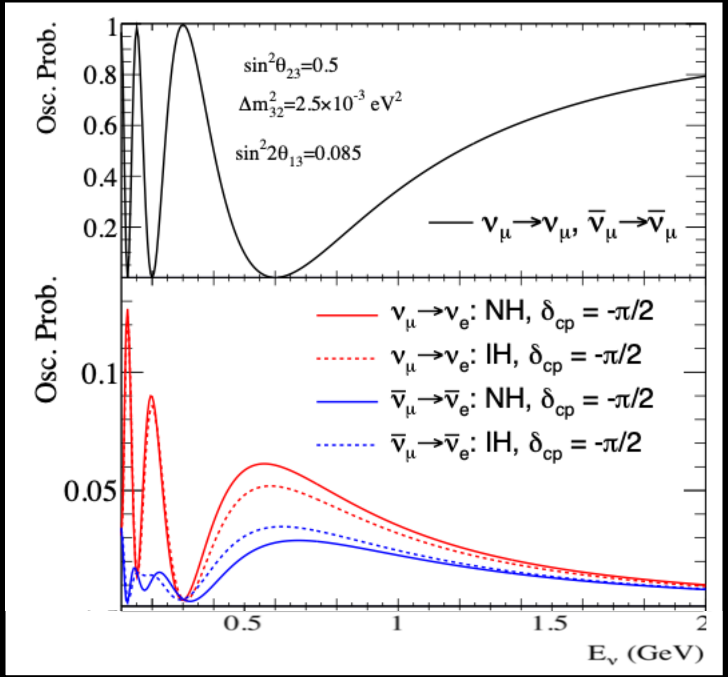


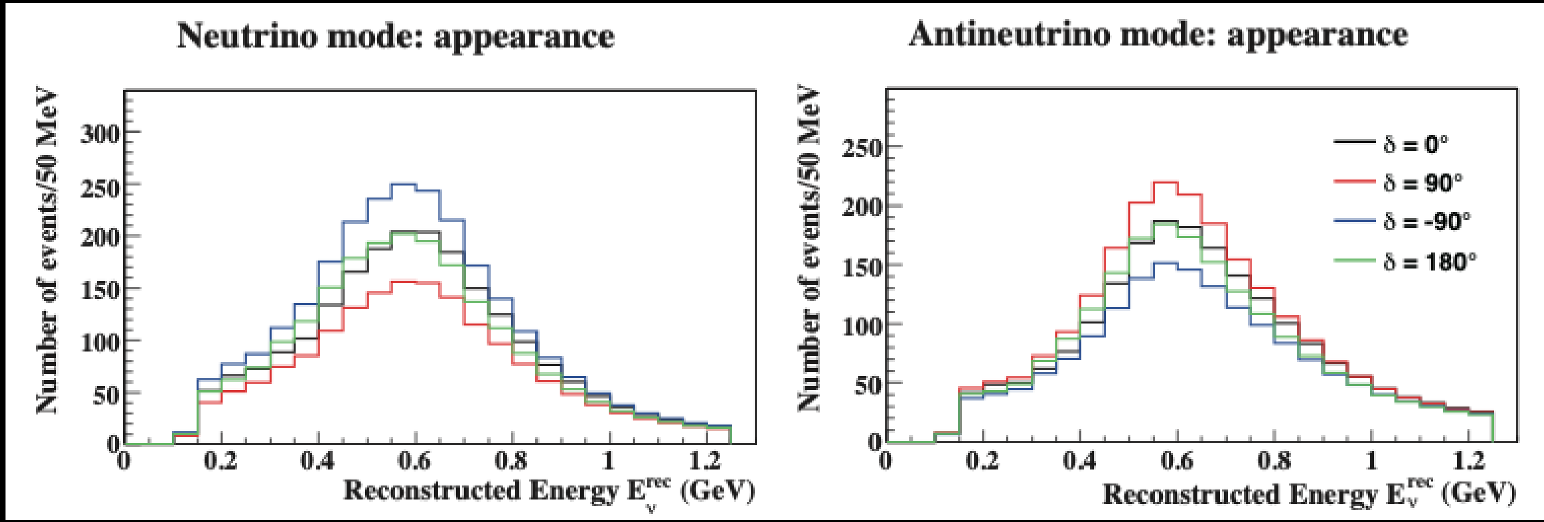


Long Baseline Oscillation Measurements

- $\nu_\mu, \overline{\nu_\mu}$ survival $\rightarrow$ sensitive to $\sin^2(2\theta_{23})$ and Δm^2_{32}

- $\nu_e, \overline{\nu_e}$ appearance $\rightarrow$ sensitive to $\sin^2(2\theta_{23})$, $\sin^2(2\theta_{13})$ and Δm^2_{32} in leading terms
  $\rightarrow$ sensitive to δ_{CP} in sub-leading terms (different signs)

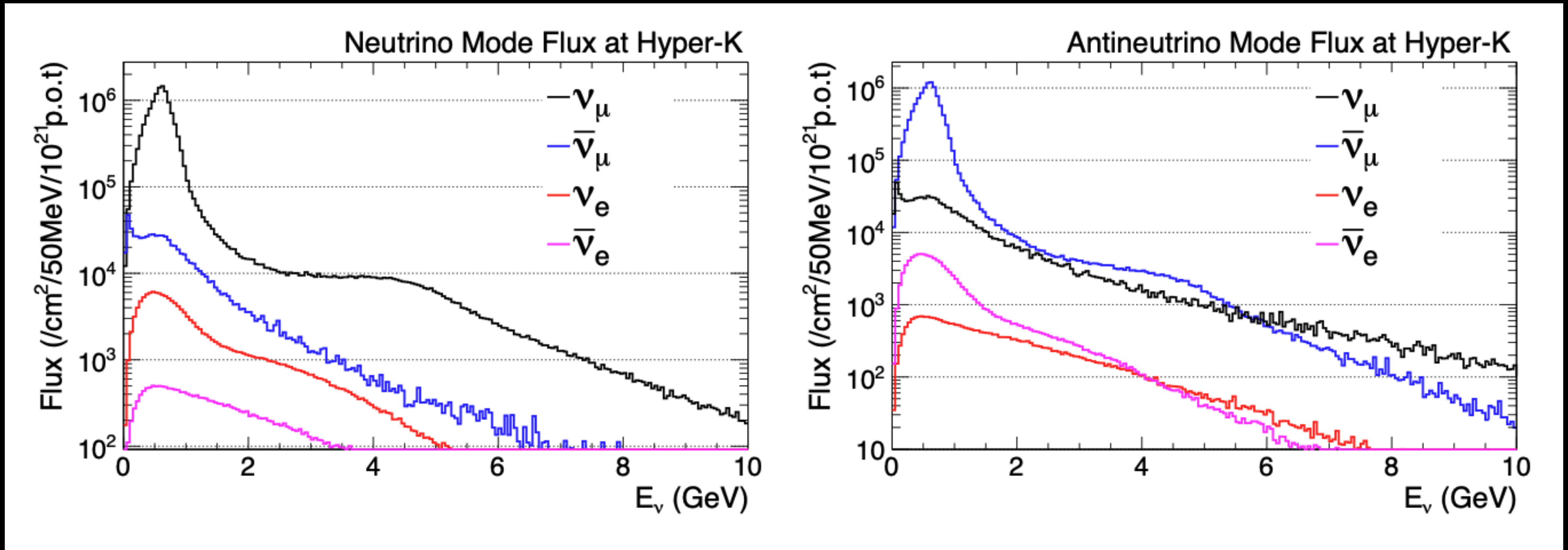




1) Need to accumulate of order 10^3 ν_e and $\overline{\nu_e}$ signal events at FD to measure CP violation with few % accuracy
$\rightarrow$ 3% statistical error
2) Need to control systematic uncertainties

Plots from HK design report: https://arxiv.org/pdf/1805.04163

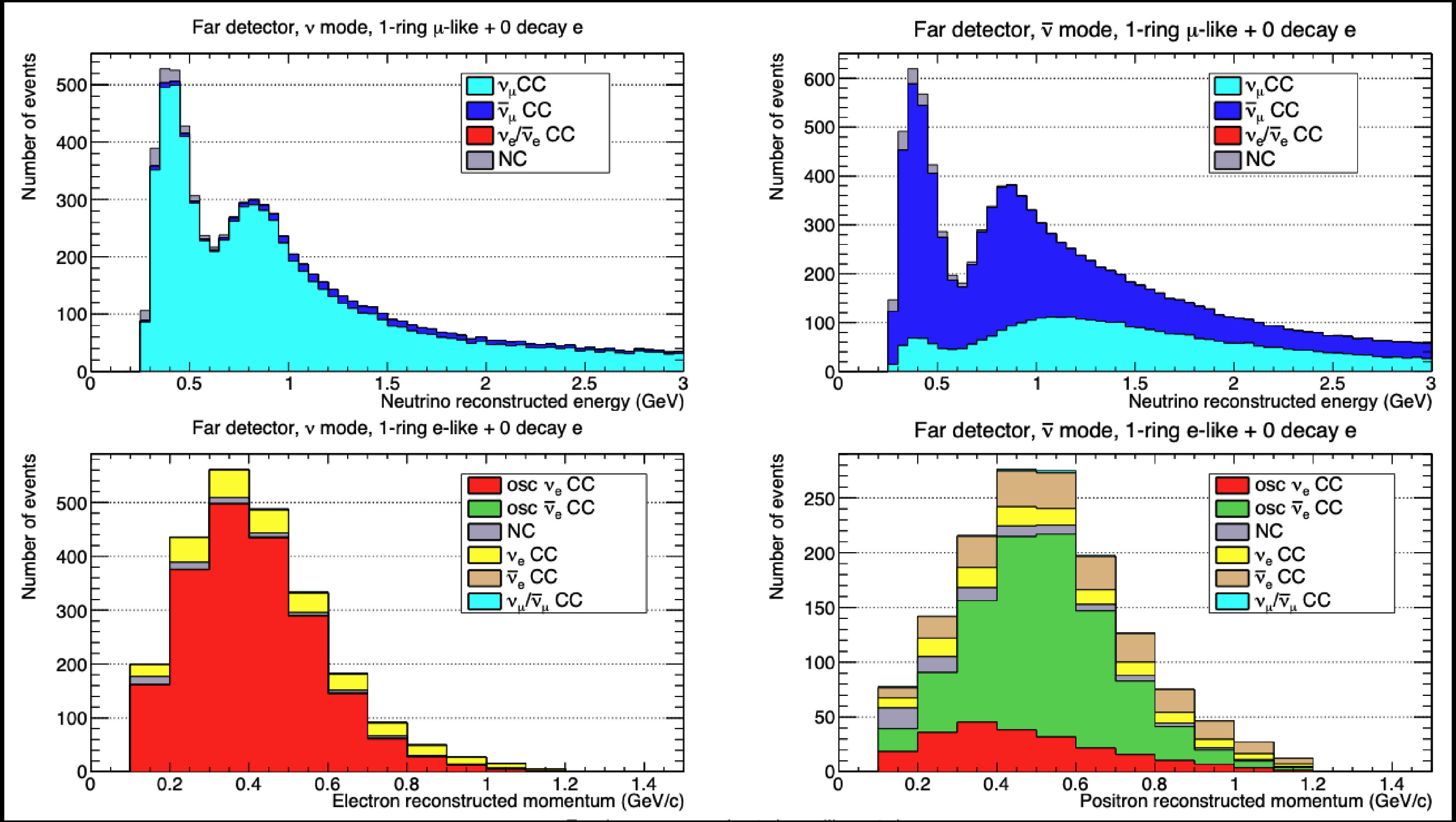
Beam Event Rates



Expect 2.7×10^{21} Protons on Target (POT) per Calendar year

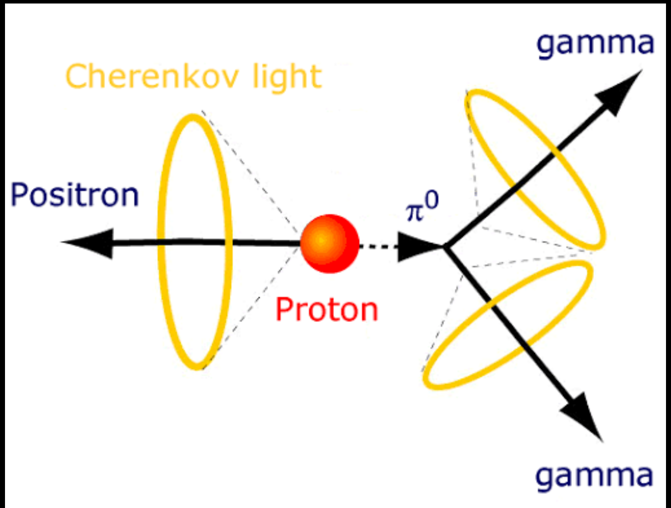
- 6 cycles of 22 days Beam / year with 87% efficiency at 1.3MW
- 1:3 FHC to RHC ratio
  - Comparable numbers of electron-like events at far detector for CP conservation scenario
  - Optimal to break CPV degeneracy with $\sin^2\theta_{23}$ and $\sin^2\theta_{13}$

Far Detector Event Selections



Other Measurement Key Requirements

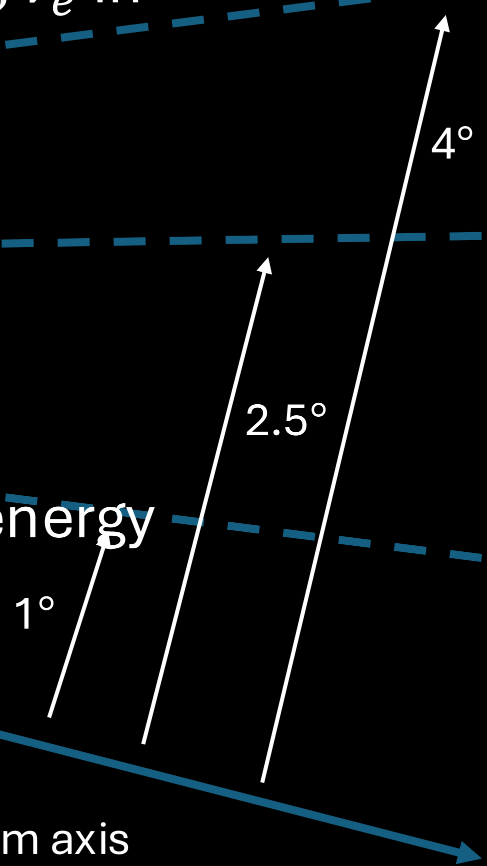
- Proton Decay
  - 187kton FV contains order 10^{35} nucleons to give sensitivity to nucleon lifetime at the level of 10^{35} years
  - Fiducial volume = statistics
  - Reconstruction and π^0 PID



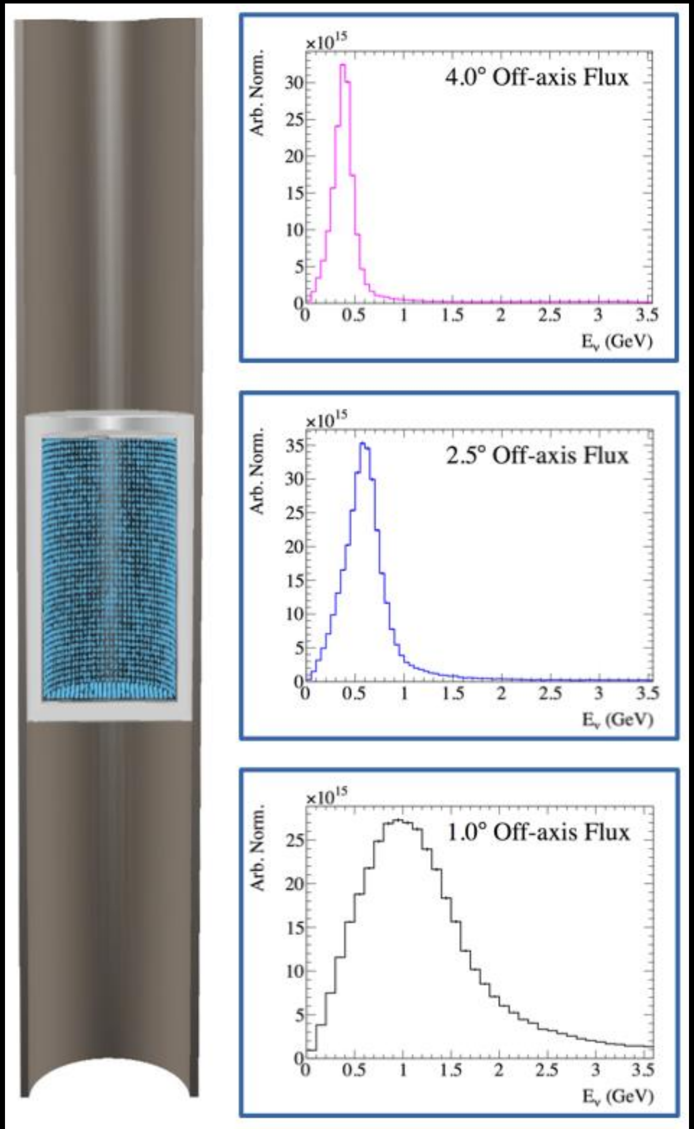
- Atmospheric neutrinos
  - Separation of ν_e and ν_μ interactions
- Solar neutrinos
  - Low energy threshold (<5MeV), low radioactive backgrounds

Intermediate Water Cherenkov Detector

- Additional detector 870m from neutrino production point, same target medium as Far Detector
  - Increased cancellation of systematics
  - Measure cross-sections from intrinsic $\nu_e, \overline{\nu_e}$ in beam
  - >10k signal events for each in 10 years
  - >4% accuracy on $\frac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\overline{\nu_e})/(\overline{\nu_\mu})}$
  - Detector moves 1.5°-4° off axis
  - Neutrino energy varies with position
  - Measure relationship between neutrino energy and lepton kinematics

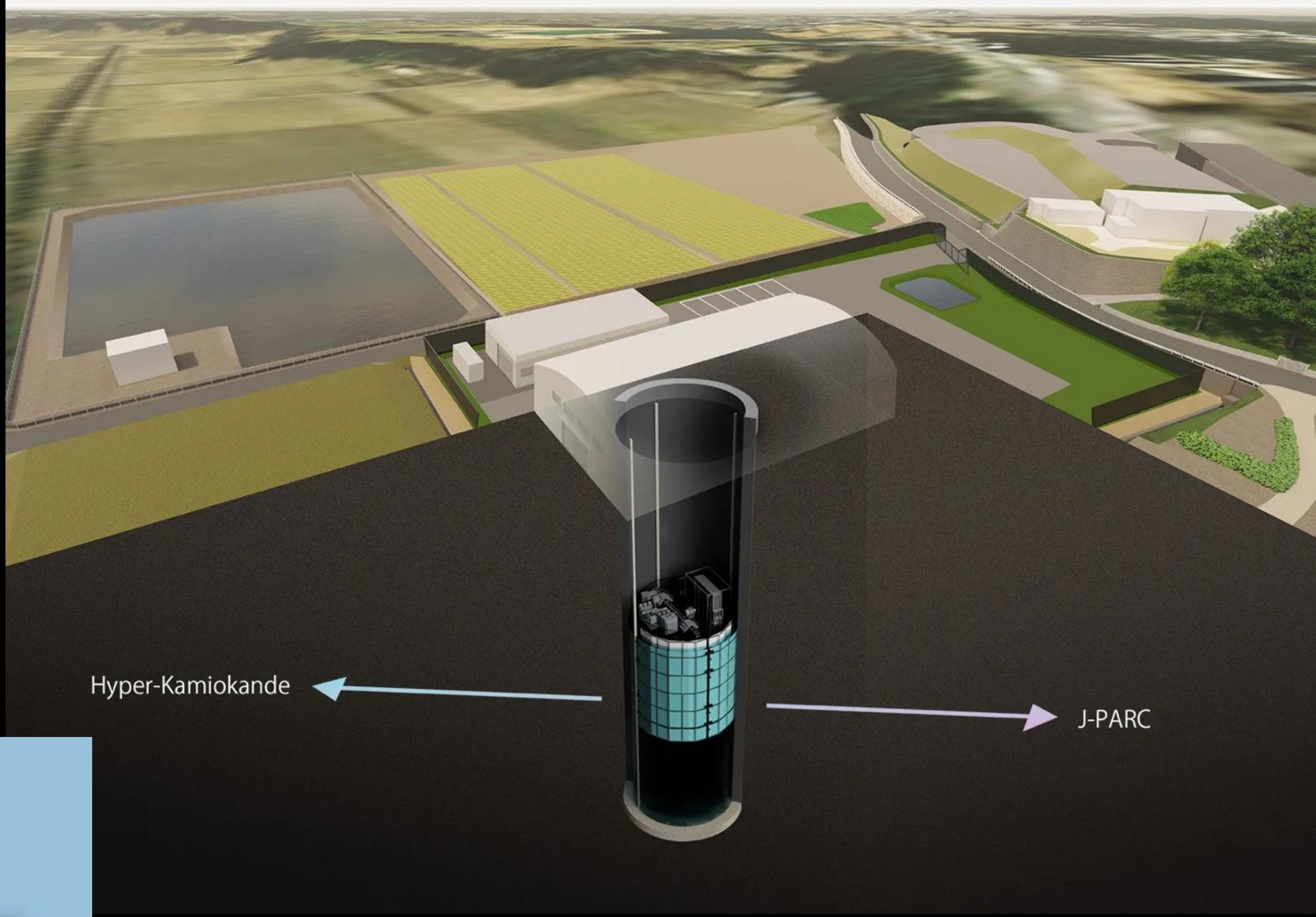


Beam axis



IWCD

- Inner diameter 9m, high 12m
- Construction of the 50m deep shaft has begun
- Water Cherenkov Test Experiment (WCTE) performed @CERN

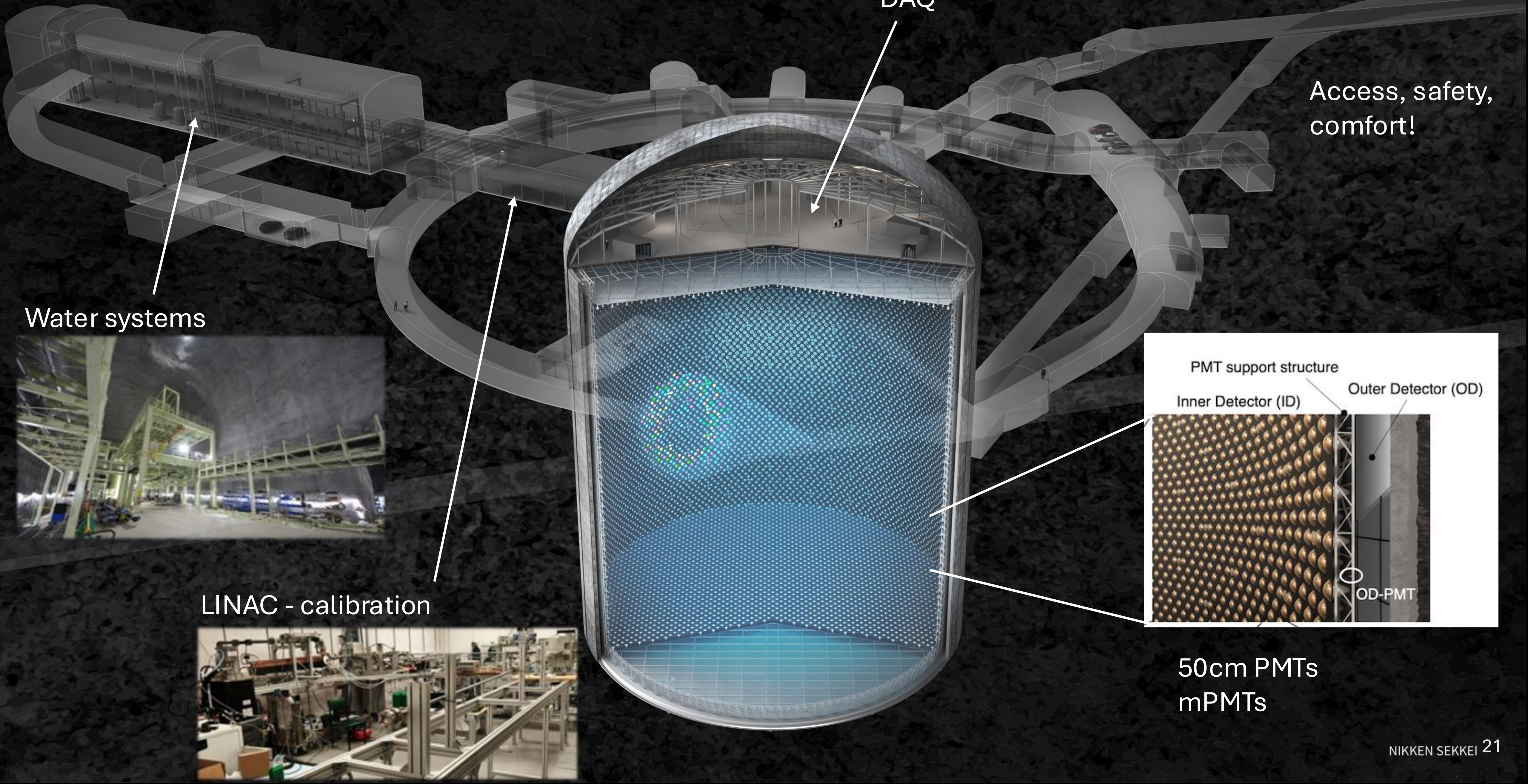


mPMTs

- IWCD will be instrumented with ~400 mPMT modules
- Each consists of 19 8cm PMTs in a pressure vessel
  - Improved timing (lower TTS)
  - Improved granularity
- Better event reconstruction

- Path lengths ~8m vs ~80m in FD
- Considerable event pile-up

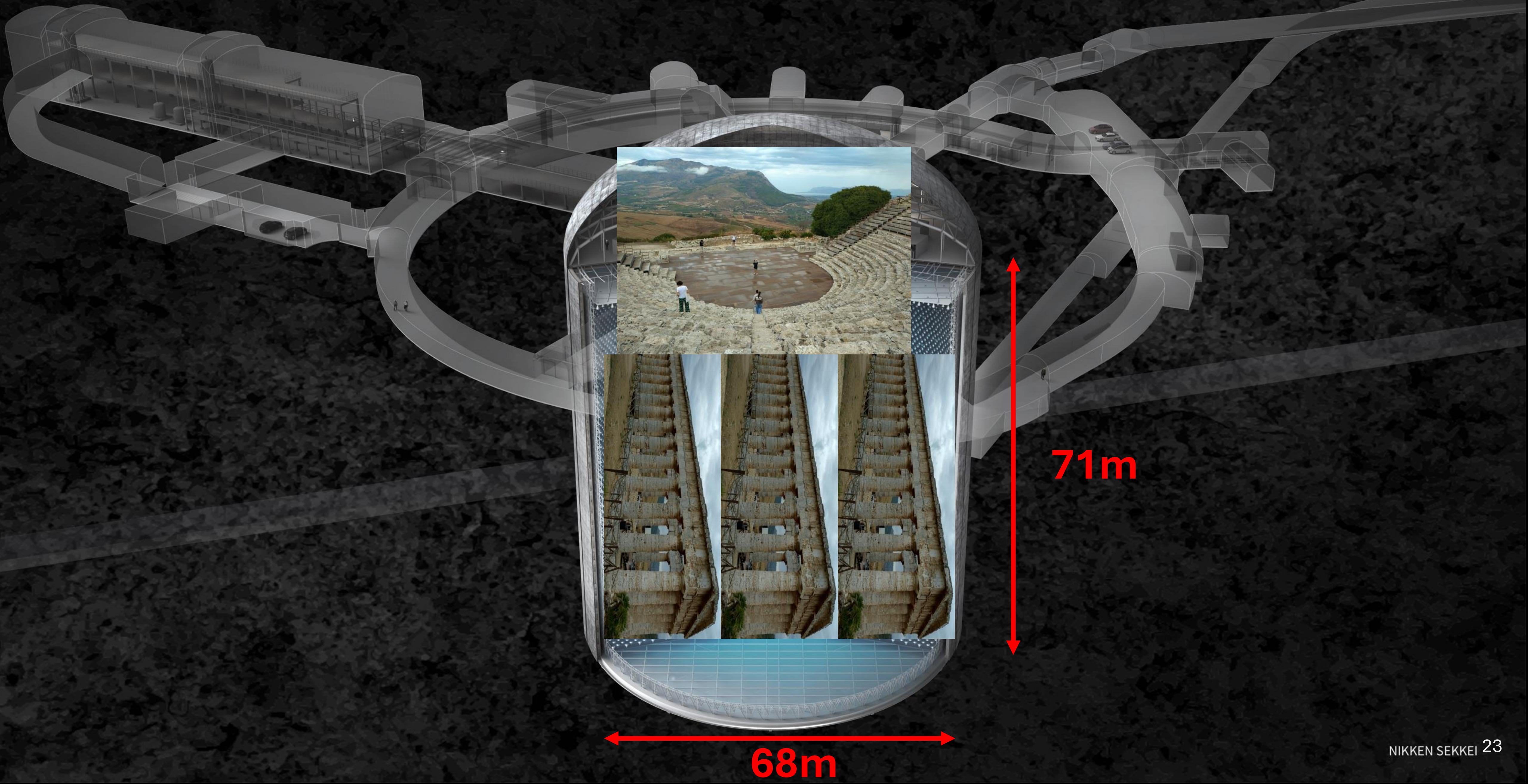
Far Detector Overview



Segesta Acropolis and Amphitheater

63m

Far Detector Overview



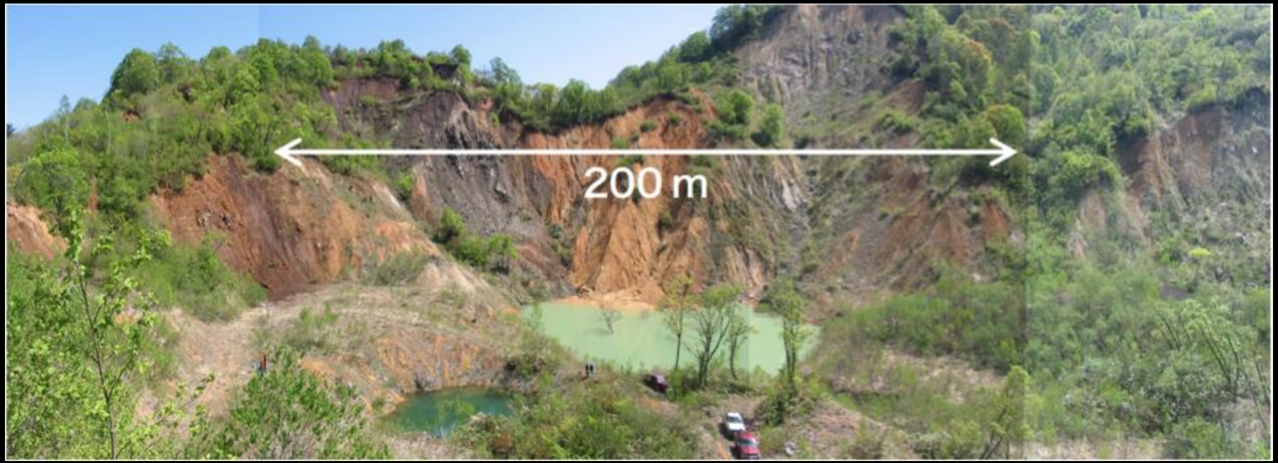
Cavern

- Excavation of world’s largest human-made cavern was completed in 2025

Y. Asaoka et al., Prog. Theor. Exp. Phys *2026, ptag91*

Infrastructure

- Access tunnels
- Rock disposal



- Side cavern for water purification systems

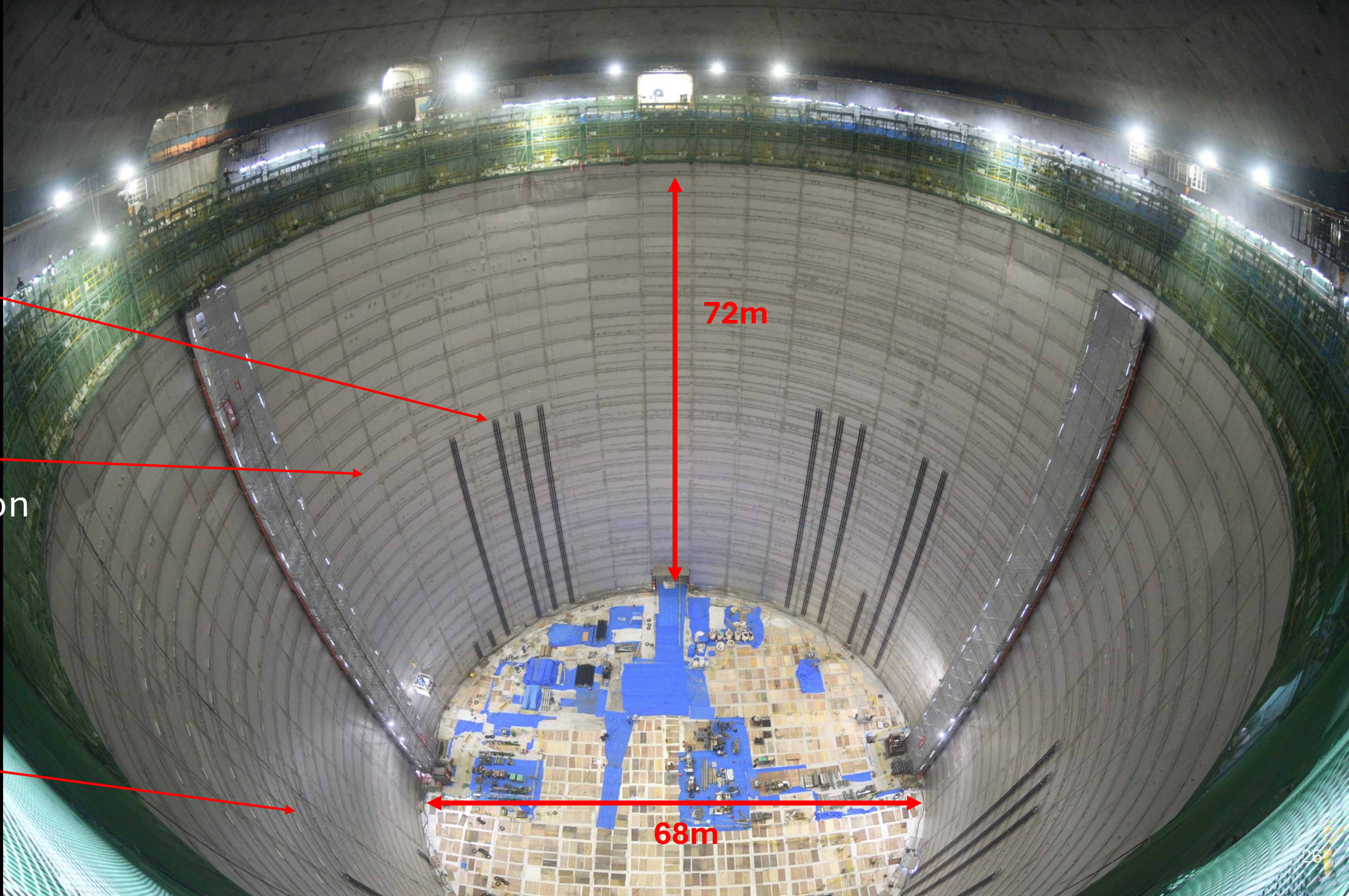
- Air-flow, power, water, wifi, transport, safety, toilets, cleanliness ....

Tank

Start of Water Piping

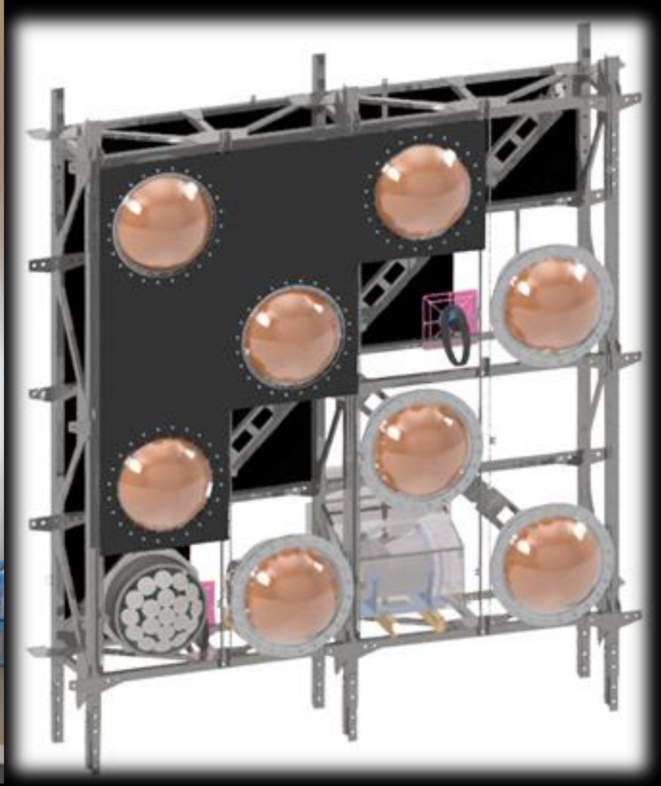
Magnetic compensation coils

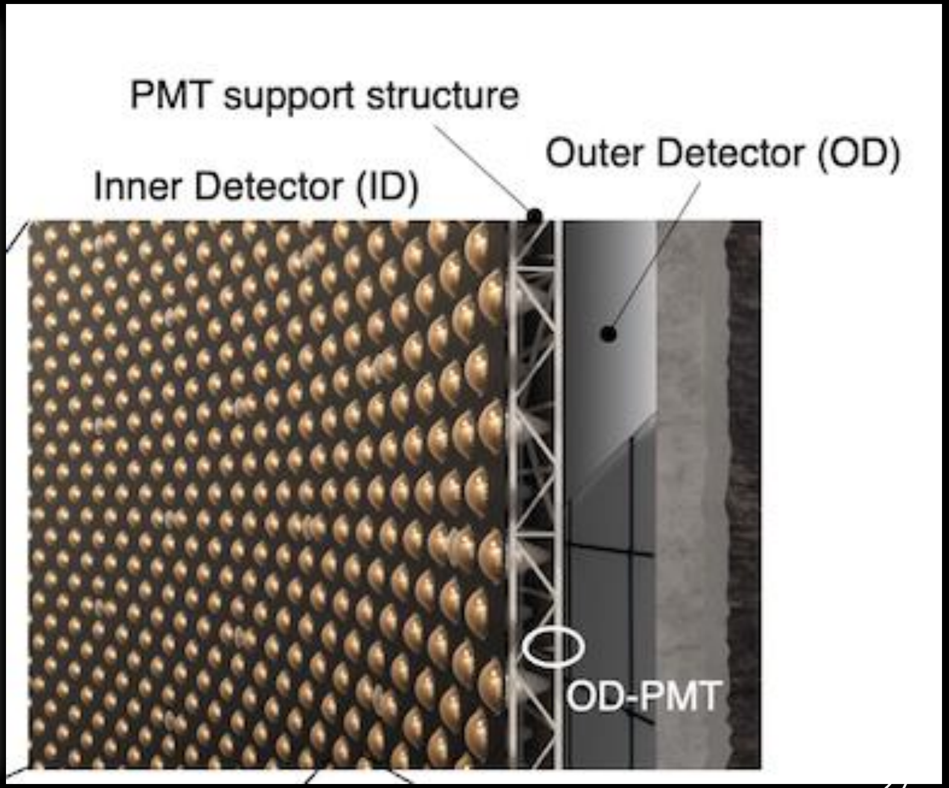
Stainless Steel Lining



Support Structure

- Capacity for 40,000 50cm diameter PMTs, each cell is 70×70 cm^2
- Structure built and instrumented at base of cavern and raised into place
- Barrel is 93 cells high, 288 cells in circumference.
- Aim to install a 4-cell high ring in 3 days



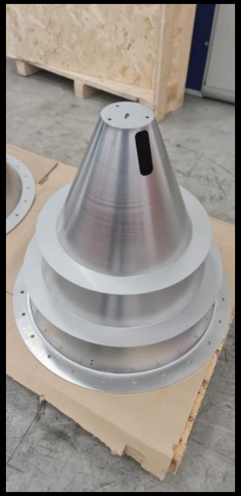


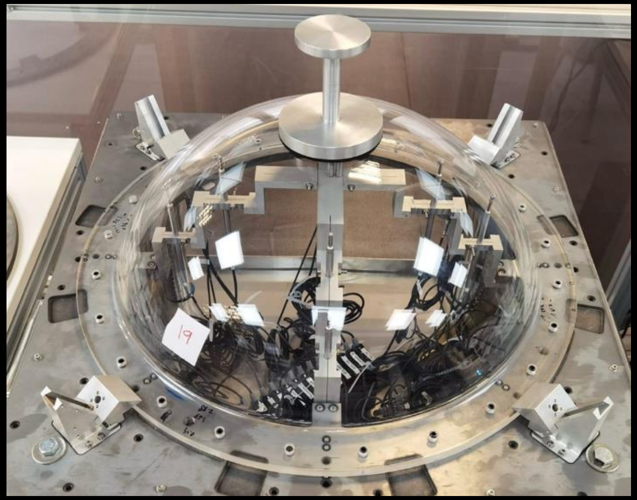
50cm PMTs

- 20,000 Hamamatsu PMTs
- Improved efficiency, timing, and pressure tolerance
  - R&D on shape, manufacturing process
  - Box-and-line dynode design
- Purchase complete
- Quality Assurance performed

Pressure Tolerance

- Bottom of the detector will be under 70m of water = 7 bar of pressure
- Stainless steel covers with acrylic faces designed to protect 50cm PMTs from implosion
- Implosion tests conducted in the Mediterranean sea.
- Production of the covers is underway

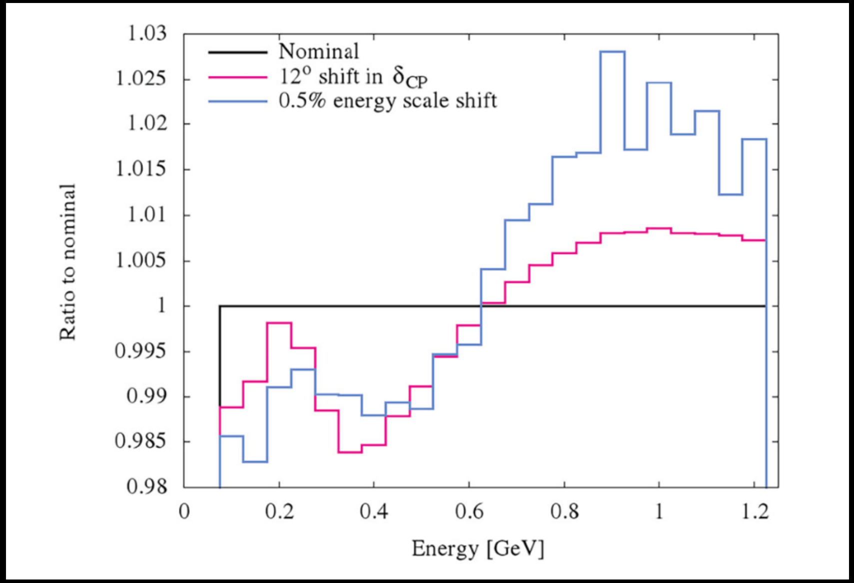


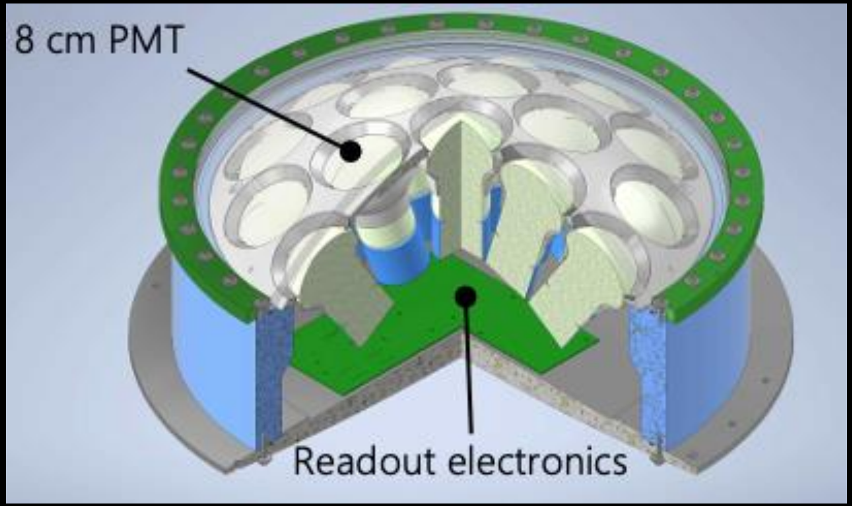


mPMTs

https://doi.org/10.22323/1.402.0056

- Production of 800 mPMTs for installation into the far detector underway
  - Multiple production sites
  - Some fitted with units with LEDs for calibration
- Help to constrain particle dependent energy scale errors
- Improve detector calibration by breaking correlations
  - Extra directionality and granularity helps separate direct and indirect light
  - resolve degeneracies between eg. absorption length and angular response of PMTs
- Improve event reconstruction close to the detector wall
  - Extend fiducial volume and increase statistics for all physics analyses



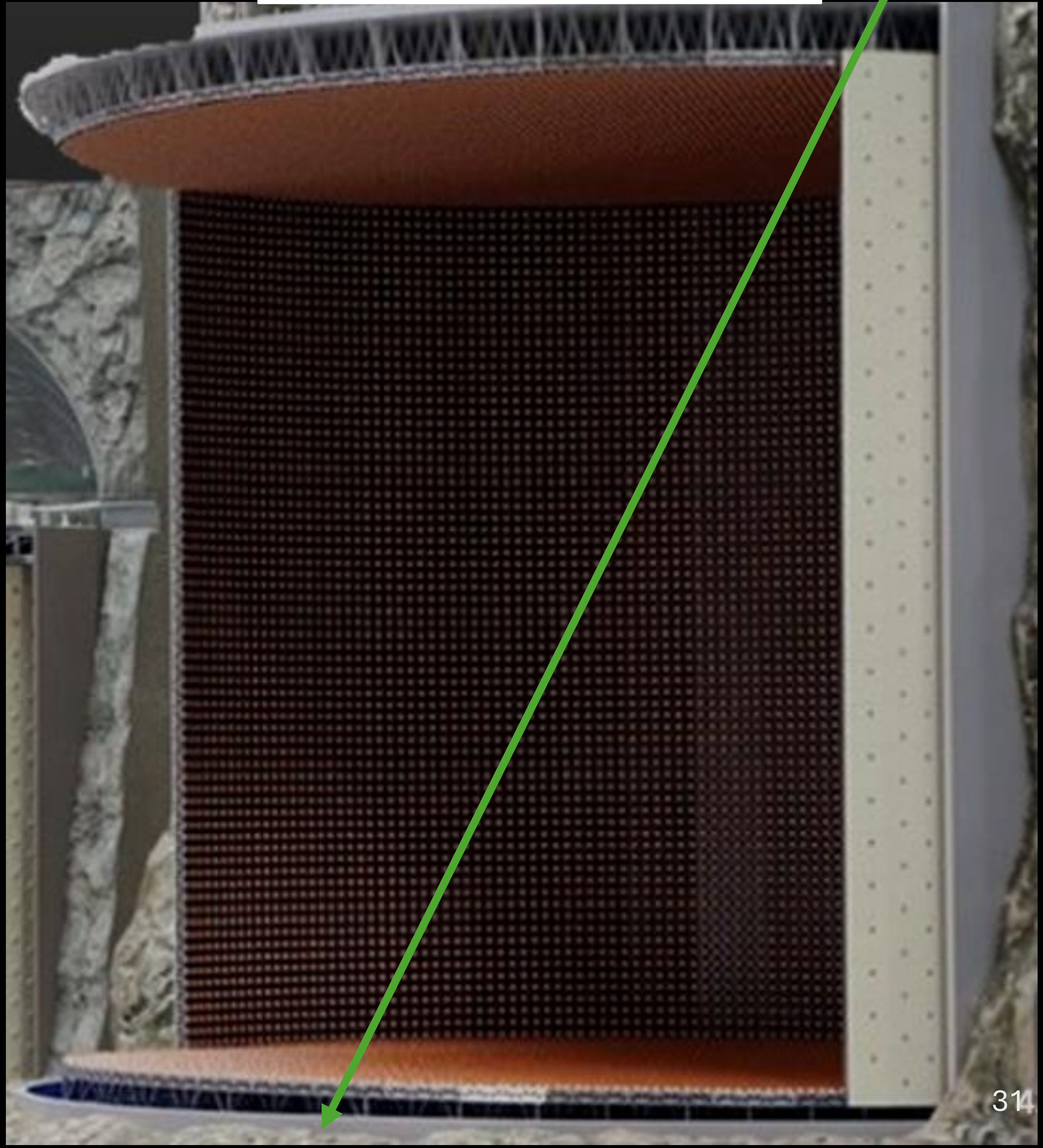


Hyper-K Outer Detector

- The OD is 2m deep in the end-caps and a 1m wide shell in the barrel region.
- Maximise the collection of Cherenkov light generated by cosmic muons in this volume

Cosmic muons, 45Hz = ~4 million/day

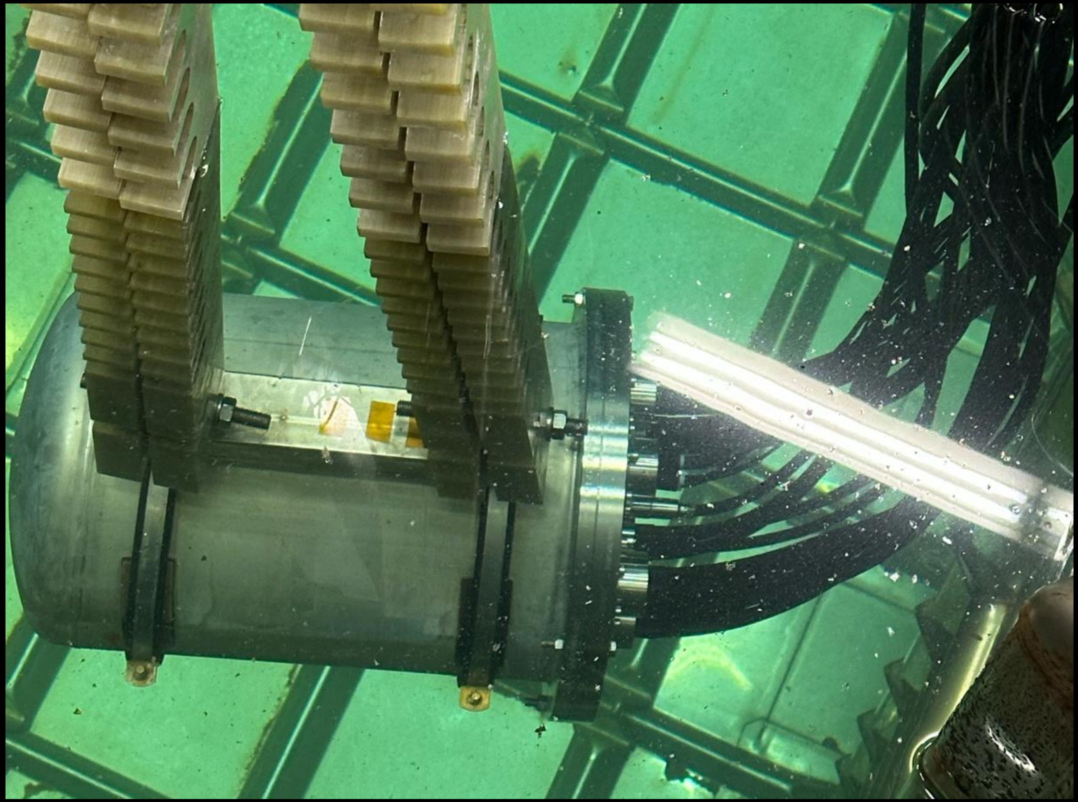
- Background to all physics measurements



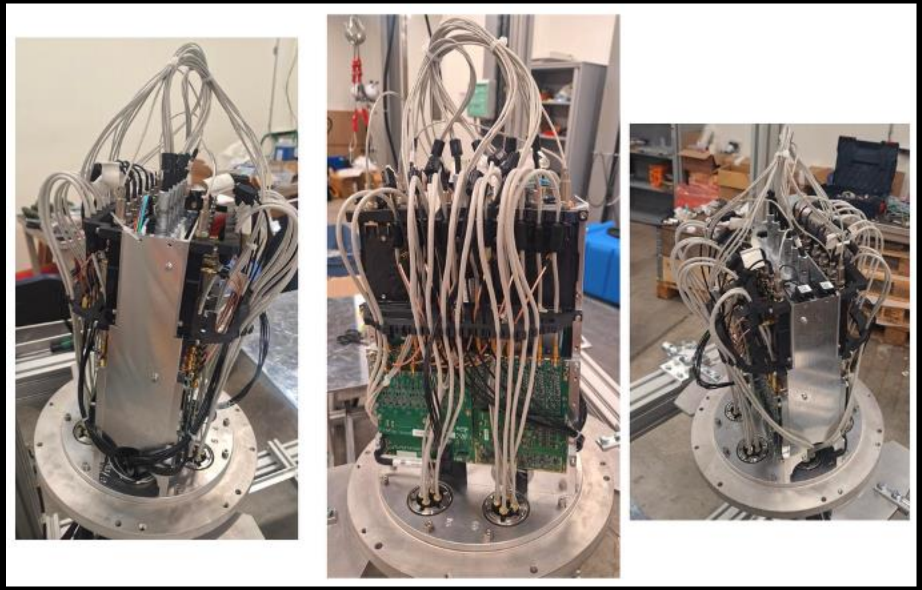
3600 photo-sensing modules (8cm PMT + WLS plate)

6 football pitches worth of Tyvek

Underwater Electronics



- Readout electronics encapsulated in a waterproof vessel
  - Up to 10bar pressure
  - No access once water filled – 10s years stable operation
  - Underwater cable connections
- Route communication fibers to the deck after installation



Water Systems

- Attenuation lengths > 100m required
- Radon concentration < 1mBq/m^3
  - To control radioactive background rate in solar and other low -E measurements
- Potential to add Gd (for n-detection) in the future

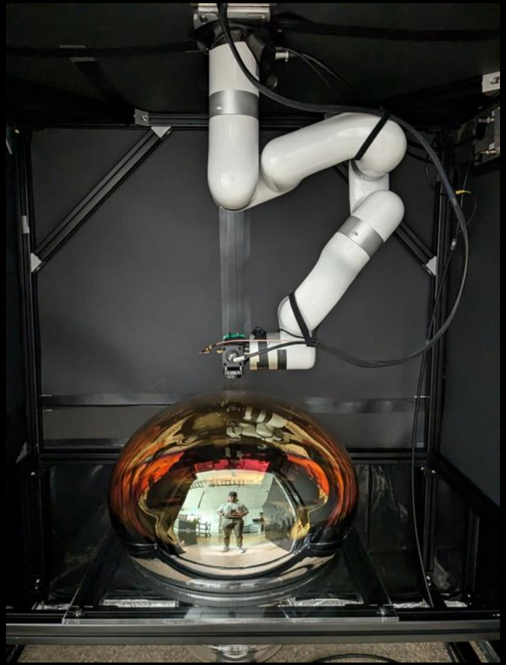
- The FD will hold 250 kilotonnes of water
  - equivalent to 100 Olympic swimming pools!
- It will take nearly 6 months to fill

Calibrations

- Low level calibration with:
  - Light injection
  - B-field mapping
  - PMT pre-calibration
- High level calibration with sources a d control samples
  - LINAC
  - DT
  - AmBe
  - Stopping muo
  - Michel electr
  - $\pi^0 s$
- Photogrammetry
  - Fixed cameras
  - Drone option
- Many components tested in the WCTE

See Menai Lamers James's talk this afternoon for more details

UK groups



Melbourne, Australia

NCBJ, Poland

Status

- Hyper-K cavern is excavated and the tank is constructed
- Component production and testing is underway
  - 50cm PMTs, PMT covers, mPMTs, OD units, electronics, DAQ, Calibration systems
- Instrumentation installation in the tank next year
- Water filling and start of operation planned for 2028

Backup

The story so far

- Atmospheric neutrinos: ν_μ disappearance (Super-K): θ_{23} and Δm^2_{23}
- Solar neutrinos: ν_e disappearance (SNO, Super-K): θ_{12} and Δm^2_{21} Δm^2_{solar}
- Reactor neutrinos (180km baseline): $\bar{\nu}_e$ disappearance (KamLAND): θ_{12} and Δm^2_{21}
- Reactor neutrinos (short baseline): $\bar{\nu}_e$ disappearance θ_{13} and Δm^2_{23}. (Daya Bay, Double Chooz, RENO):
- Beam neutrinos: ν_μ disappearance (MINOS, K2K): θ_{23} and Δm^2_{23}
- Beam neutrinos: $\nu_e, \bar{\nu}_e$ appearance (T2K, NovA): θ_{13}, θ_{23} and Δm^2_{21}

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$s_{ab} = \sin\theta_{ab}\,,\ c_{ab} = \cos\theta_{ab}$