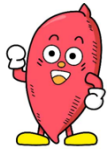
Lauren Anthony (lanthony@imperial.ac.uk)
On behalf of the Hyper-K and WCTE collaborations

17/09/2024: Kraków, WCD II 2025

Intermediate Water Cherenkov Detector
&
Water Cherenkov Test experiment prototype

Photo curtesy of the WCTE collaboration

Hyper-Kamiokande



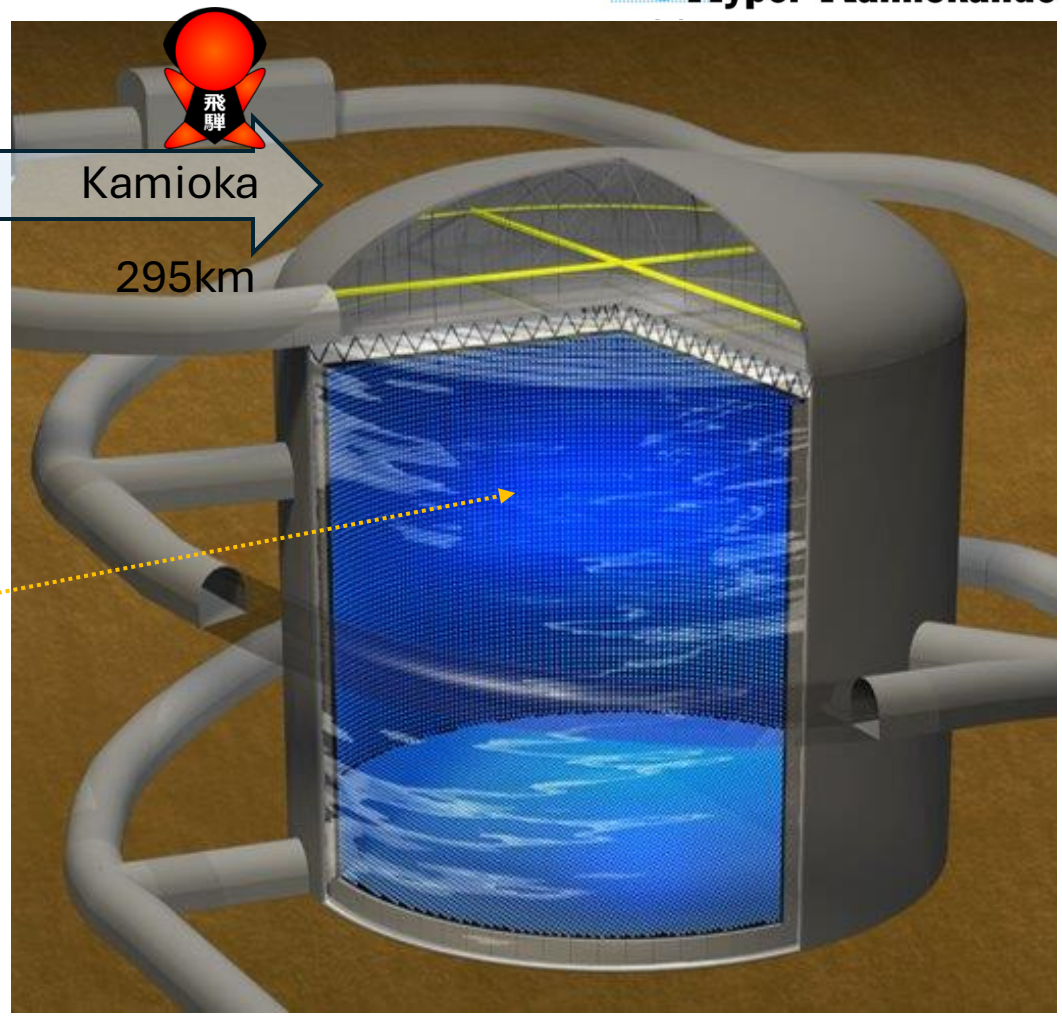
280m

Tokai

1km

Kamioka

295km

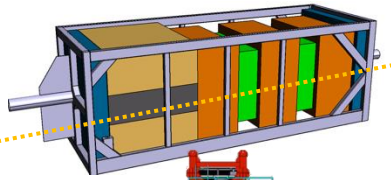


1.3MW upgraded beam power

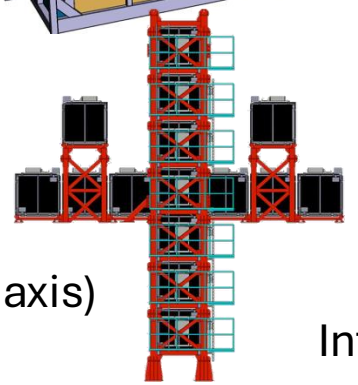
J- PARC υ beam

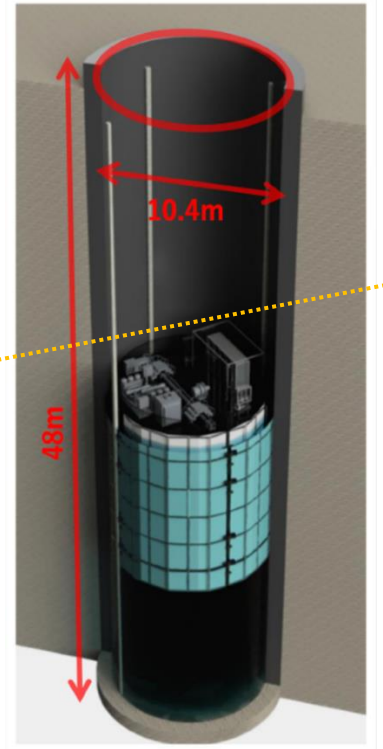
Near Detectors

ND280 (off axis)



INGRID(on axis)

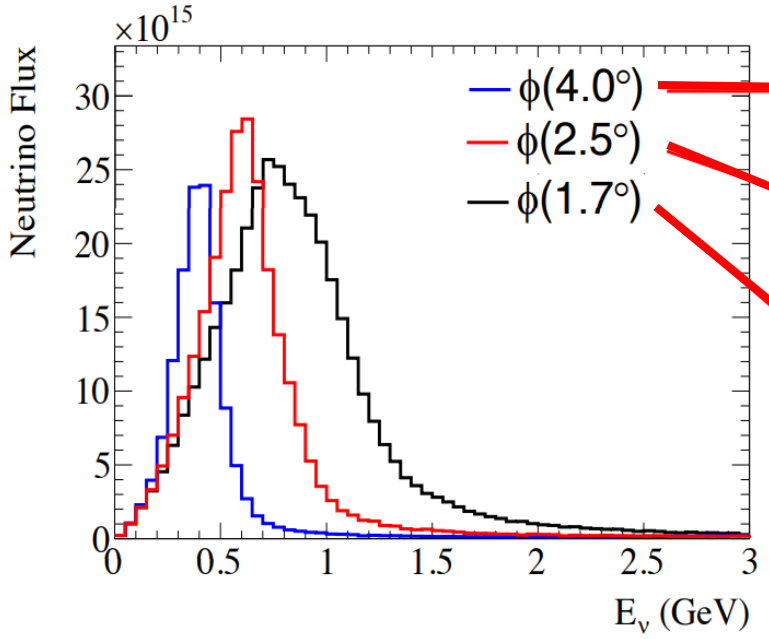


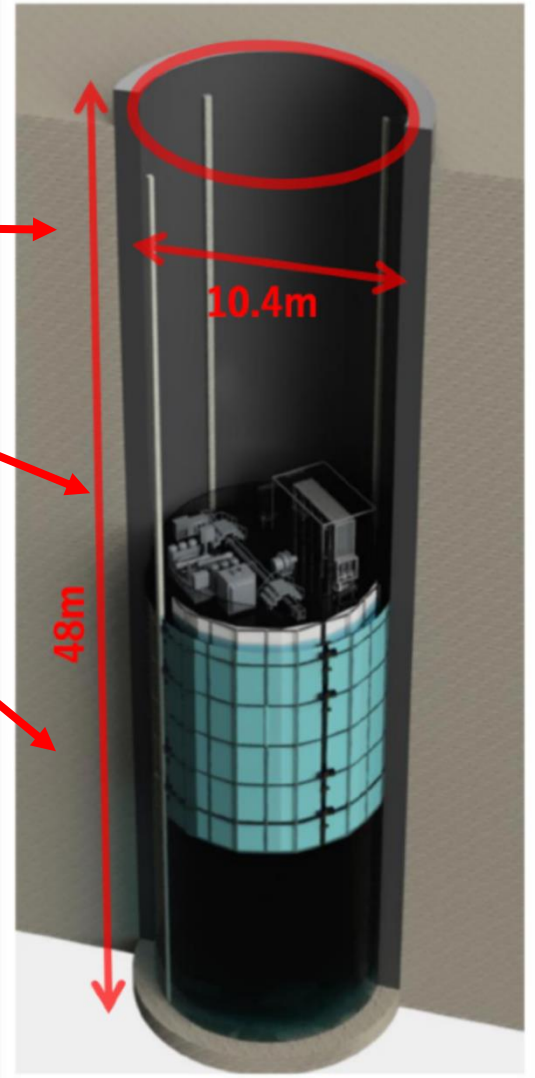


Intermediate Water Cherenkov Detector

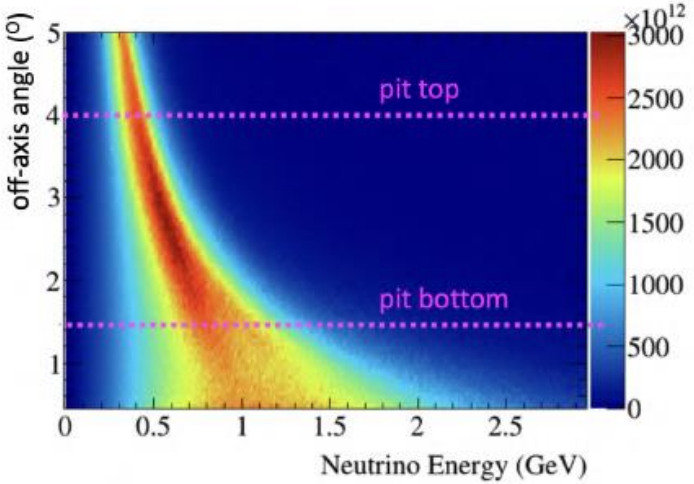
Intermediate Water Cherenkov Detector Capabilities (IWCD)

Intermediate Water Cherenkov Detector designed to directly measure ν flux & cross-section of un-oscillated beam with high event rate across range of energy spectra, 1km from JPARC site

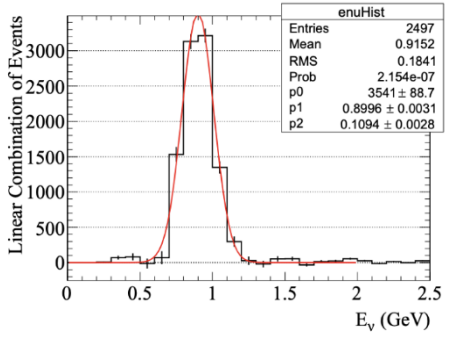


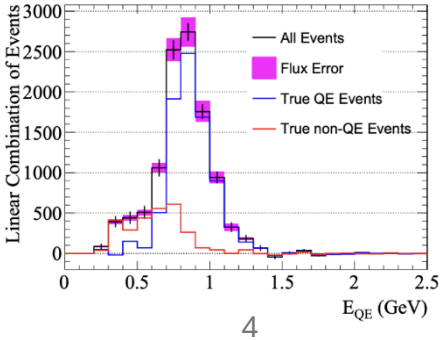


Pit spans 1.7 - 4 degree off-axis neutrino flux: sampling different neutrino energy



- Measurements with PRISM method at different off axis angles
- Predict spectra after oscillations at HK





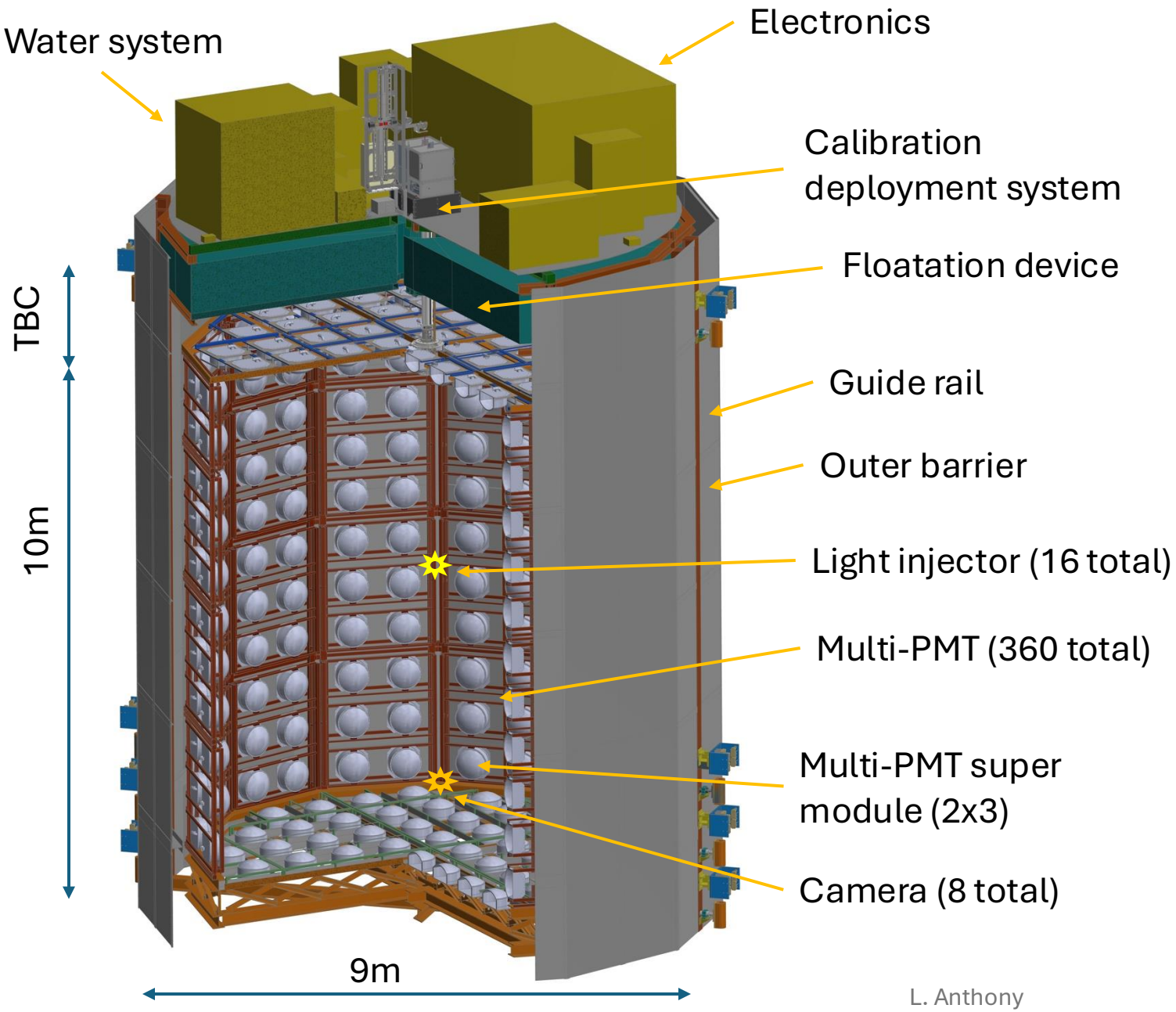
Key oscillation probabilities for HK

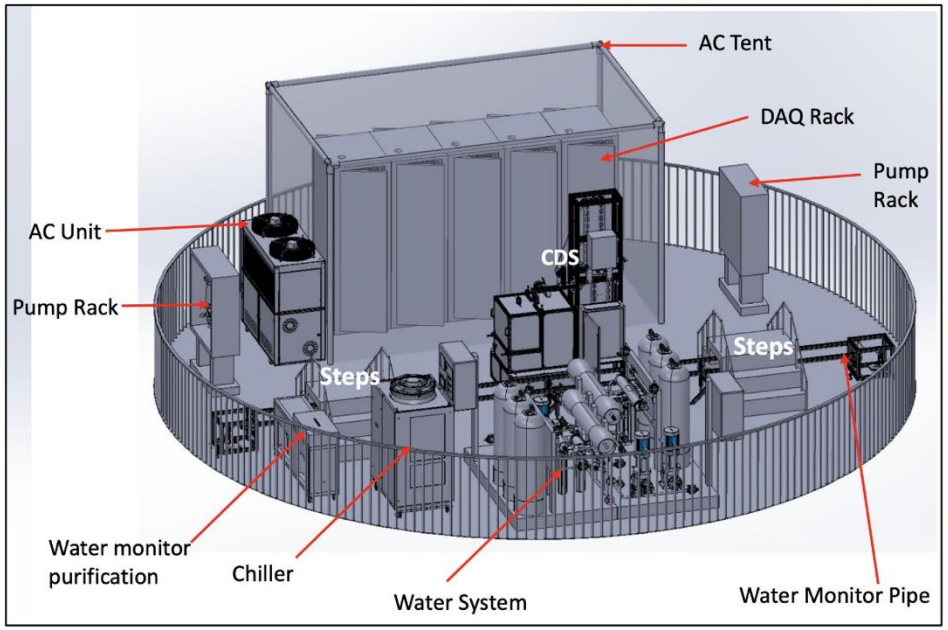
$$P_{\nu_\mu \to \nu_e}(E_\nu), P_{\overline{\nu}_\mu \to \overline{\nu}_e}(E_{\overline{\nu}})$$

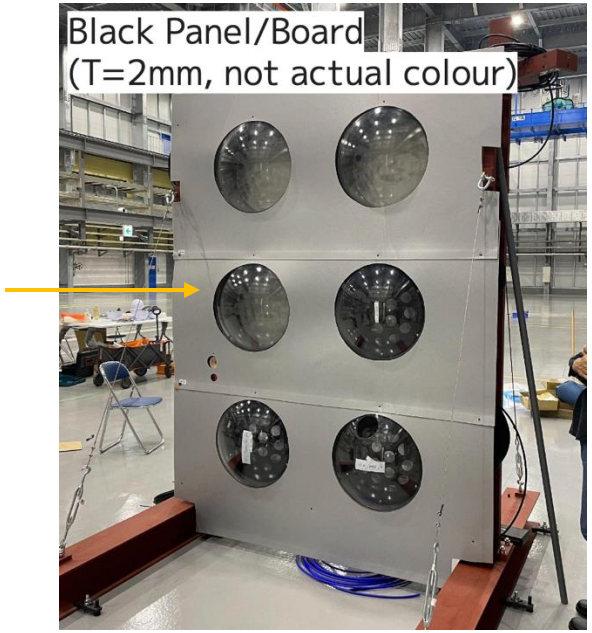
IWCD will measure neutrino-nucleus cross section ratios

$$\frac{\sigma_{\nu_e(E_\nu)}}{\sigma_{\nu_\mu(E_\nu)}}, \frac{\sigma_{\overline{\nu}_e\,(E_{\overline{\nu}})}}{\sigma_{\overline{\nu}_\mu\,(E_{\overline{\nu}})}}$$

IWCD design







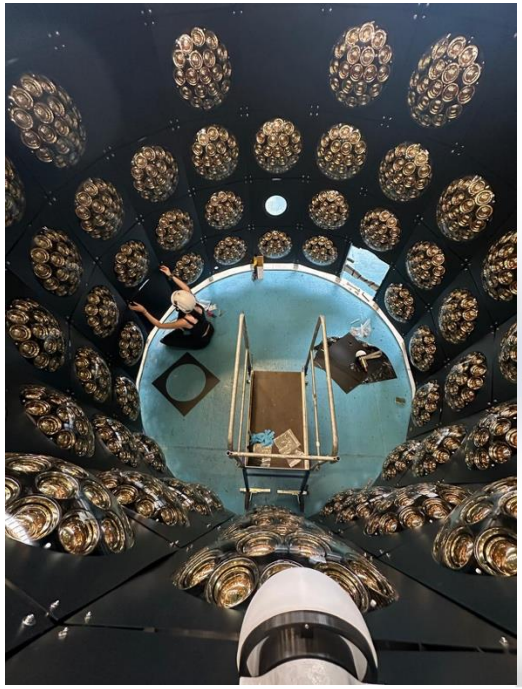
Mock-up of super module in Japan earlier this year

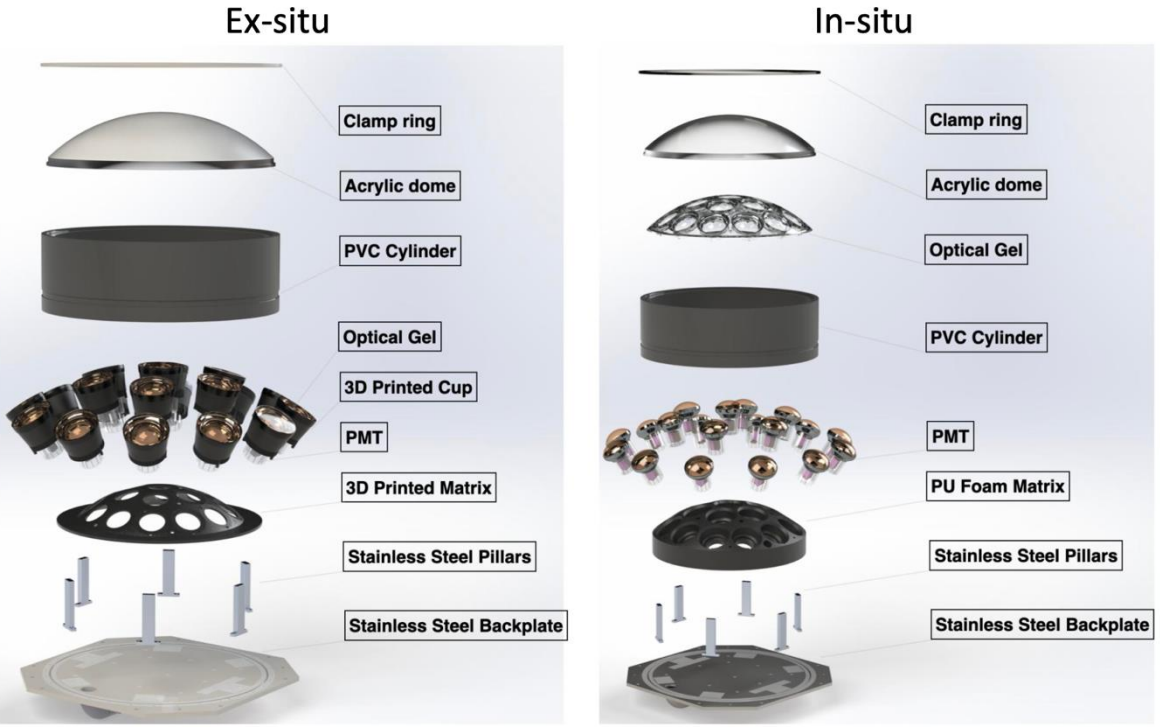
IWCD Detector Instrumentation: mPMTs

19 x 8cm diameter PMTs (Hamamatsu R14374) in each multi-PMT modules (mPMT)

- Improved granularity and timing compared to larger PMTs
- <1 ns timing resolution
- **HV generated at each PMT** base with Cockroft-Walton circuit
- **In-module digitizer mainboard** with power cable and communication over single PoE cable

mPMTs being installed in WCTE





- **Integrated LED calibration systems**
  - 1st Set used for photogrammetry beacons (continous)
  - 2nd set with sub-ns pulse width:
    - Diffuse: used to characterize the PMT charge response and HV tuning.
    - Collimated: for calibrating the reflections off mPMTs and black sheet.
    - The LEDs used for monitoring changes in the detectors

IWCD Detector Instrumentation: mPMTs

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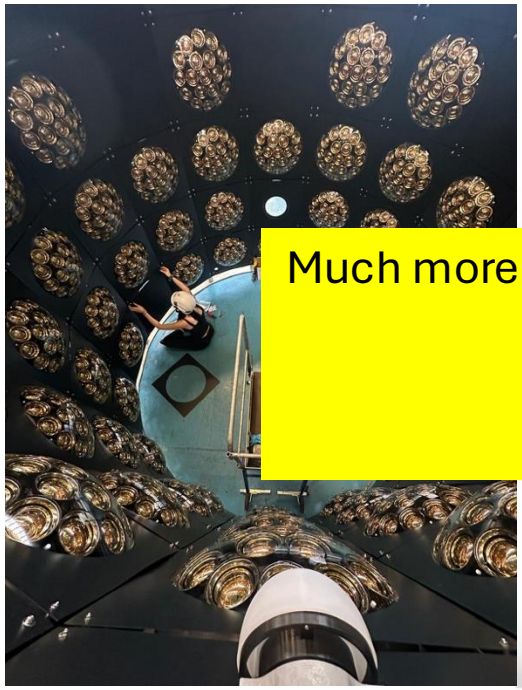

Much more information in Krzysztof Dygnarowicz, and Monika Marek's poster!

Including show mPMT!

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IWCD calibration

Absolute energy scale

- Cosmic muons

Neutron tagging efficiency

Only used for HK

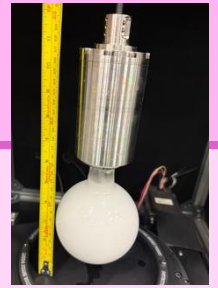
AmBe + BGO source

Detector geometry

Photogrammetry cameras

PMT response

PMT gain & charge distribution
PMT relative timing



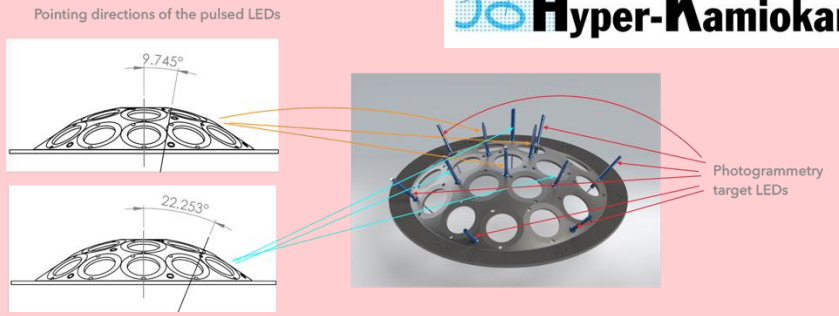
Laser diffuser

Timing vs. charge
Charge linearity

Angular response
Relative QE

NiCf source

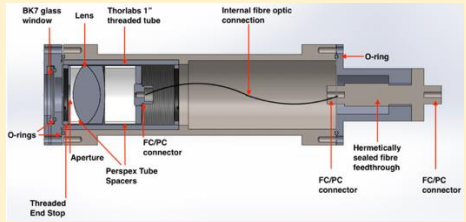
Hyper-Kamiokande

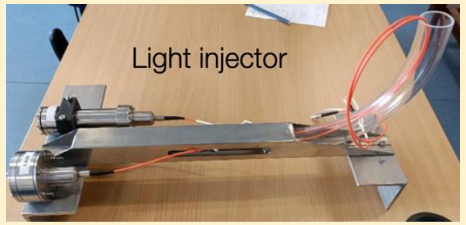


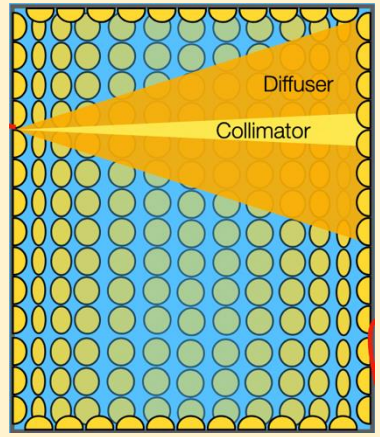
Embedded mPMT LEDs

Water properties

Transparency
Light scattering and attenuation







Collimated and diffuse light sources

Prototyping:

The Water Cherenkov Test Experiment @ CERN

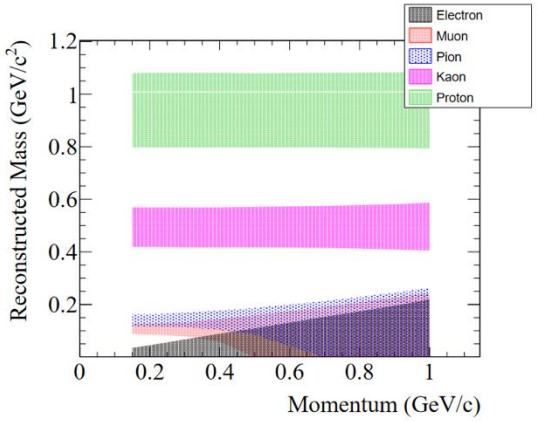
The Water Cherenkov Test Experiment

WCTE is a 40-ton water Cherenkov detector which operated at CERN

- ***October 9th 2024 → 8 weeks, March 14th 2025 → 12 weeks***
- 93 IWCD style mPMTs
- 4 Hyper-K style mPMTs
- 8 cameras use to image the detector

Proof of concept and demonstration of technologies being developed for IWCD and Hyper-K and other future detectors

Access to a well understood and characterized beam of sub-GeV particles



Good mass separation between particles species!

Suite of beamline monitor detectors:

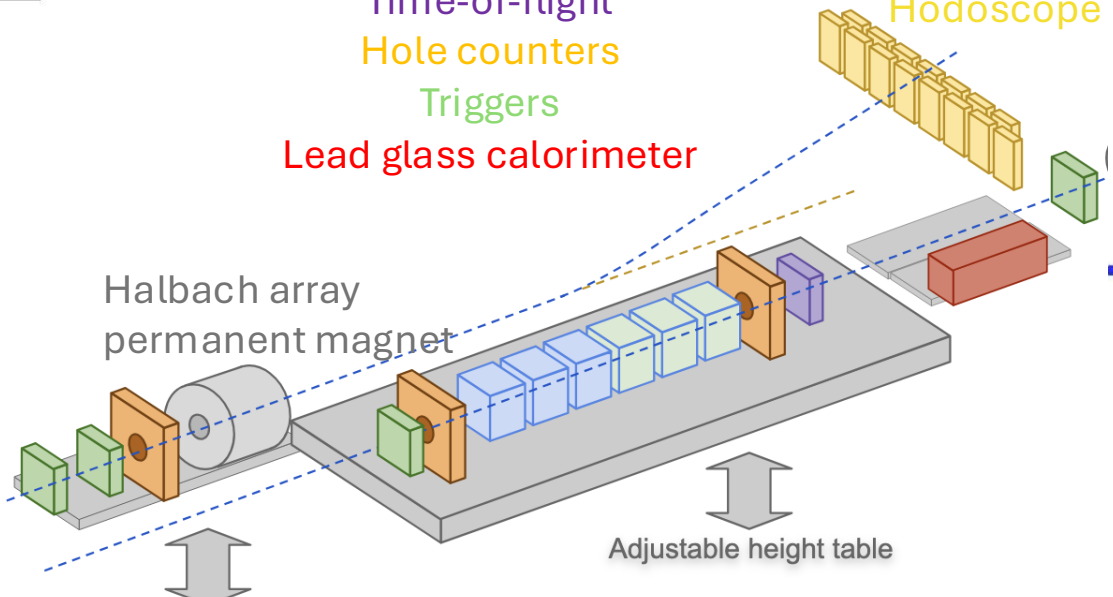
Aerogel Cherenkov

Time-of-flight

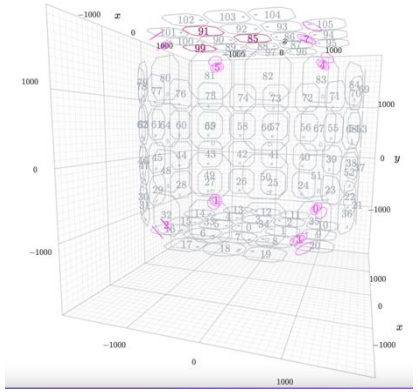
Hole counters

Triggers

Lead glass calorimeter



3 axis calibration system

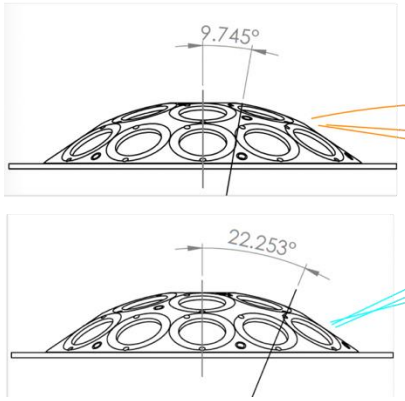


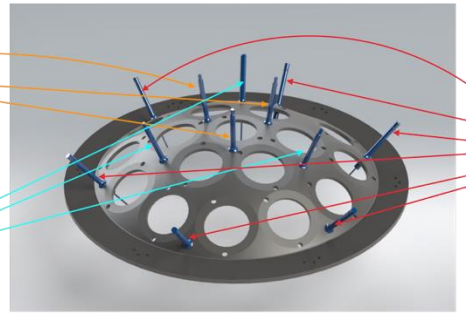
Muon tagger

Water Cherenkov detector

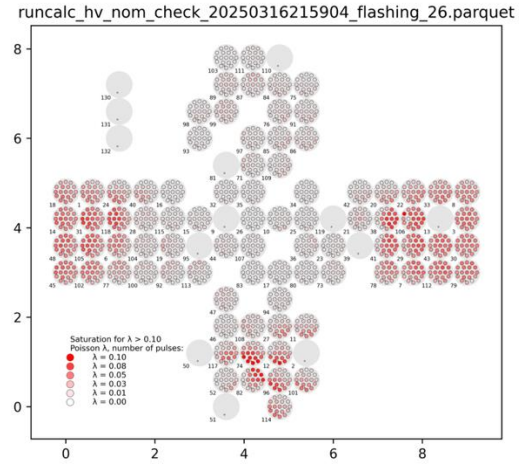
Demonstrating calibration techniques

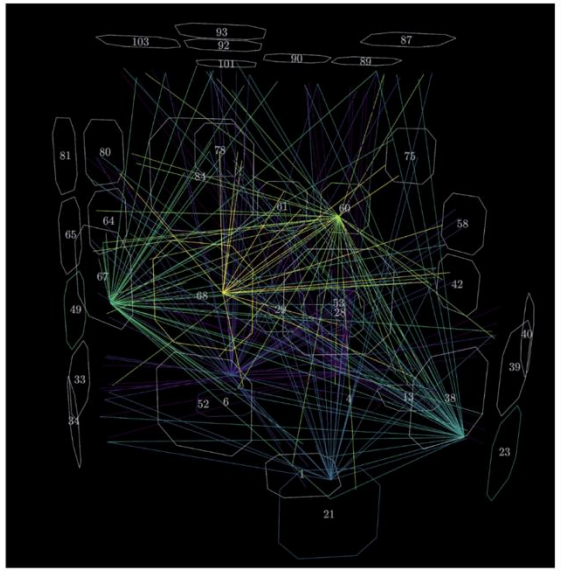
- **8 Photogrammetry Cameras** mounted inside the detector
- **3D detector geometry reconstruction** from each mPMT LEDs visible to multiple cameras
- **< 1cm position resolution** expected to observe any deformation of mPMT support structure after filling

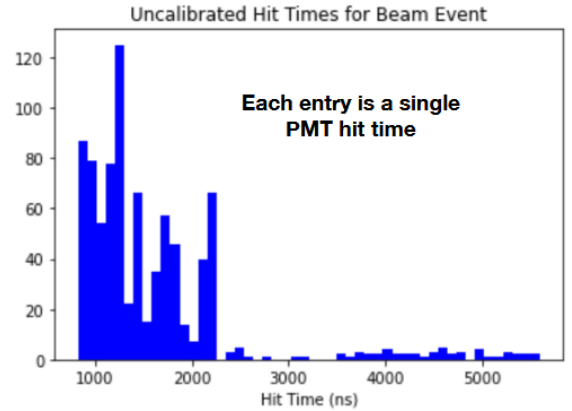


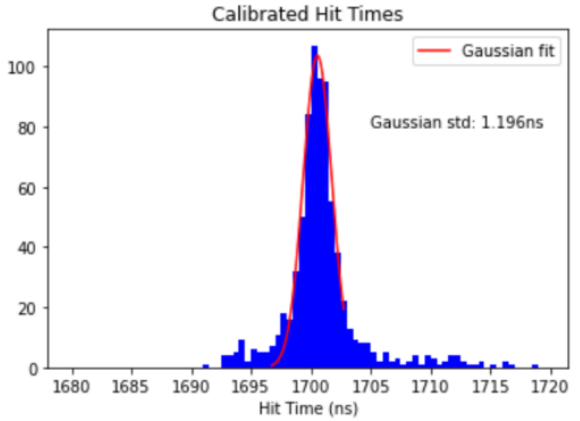


- **Demonstrated timing calibration with mPMT LEDs**
- Example of LED 26 flashing



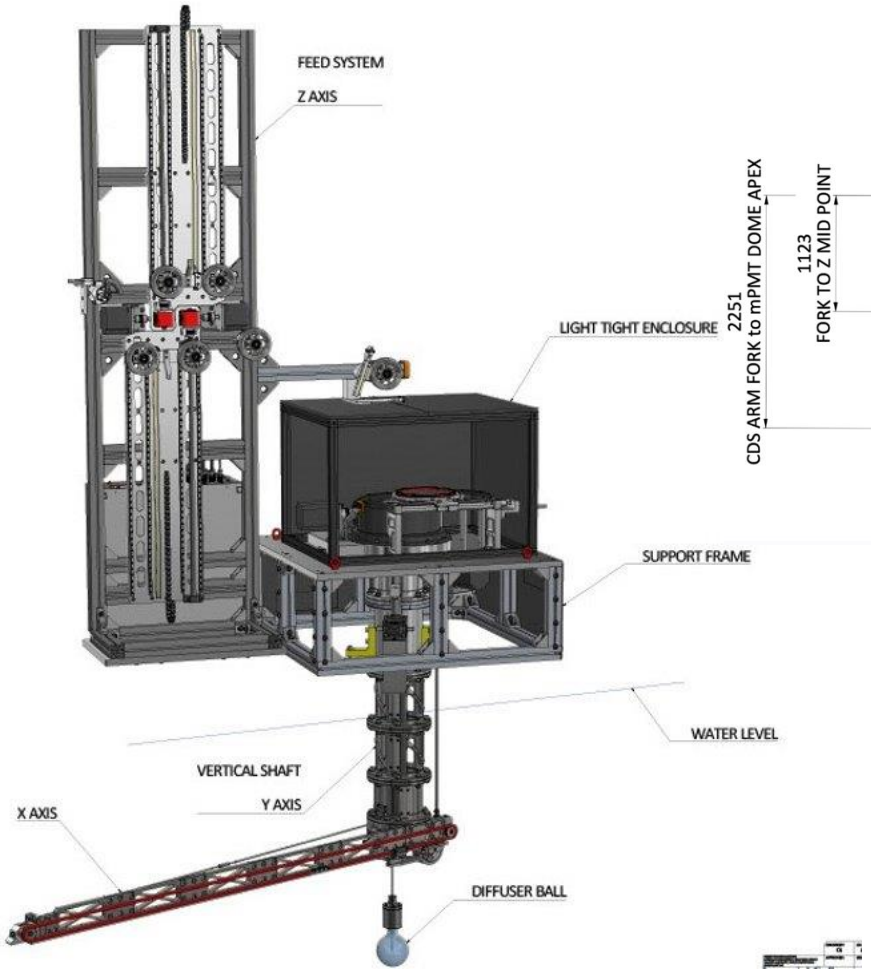


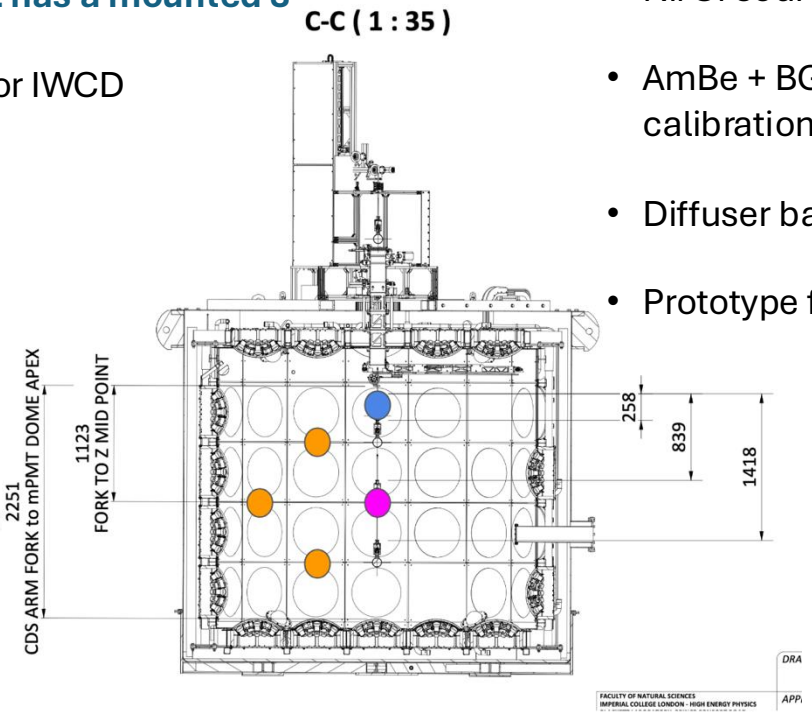


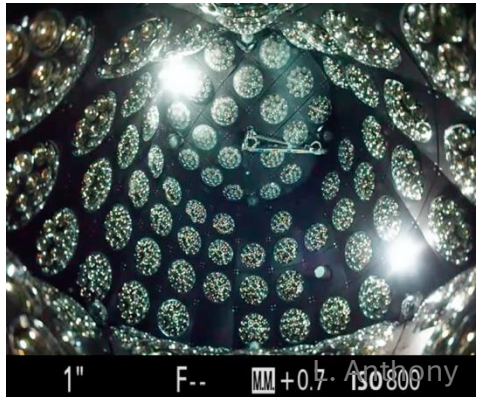


Calibration Deployment System

- To deploy the calibration sources, **WCTE has a mounted 3 axis central deployment system (CDS)**
  - The CDS for WCTE is a prototype for IWCD

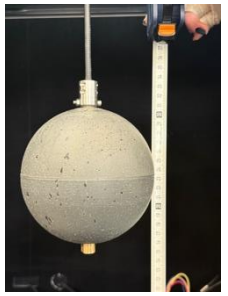


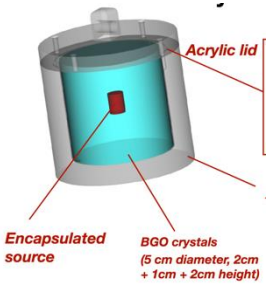


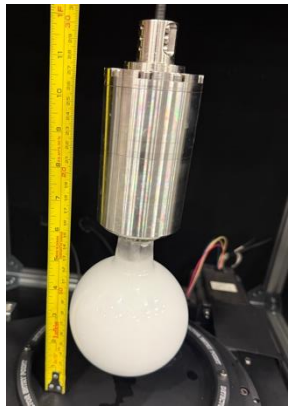


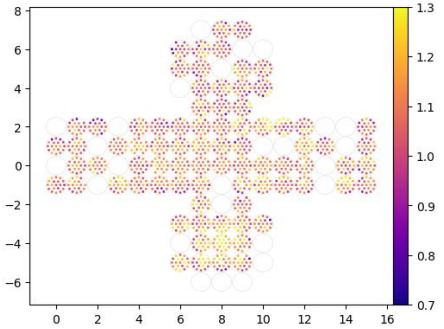
Interchangeable sources

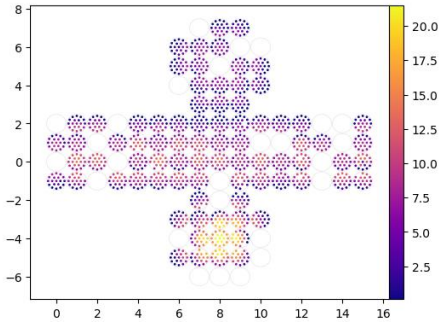
- Ni/Cf source for PMT quantum efficiency calibration
- AmBe + BGO source for neutron detection efficiency calibration
- Diffuser ball for gain and timing calibration
- Prototype for IWCD and Hyper-K

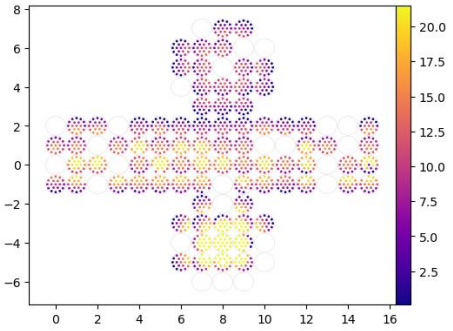








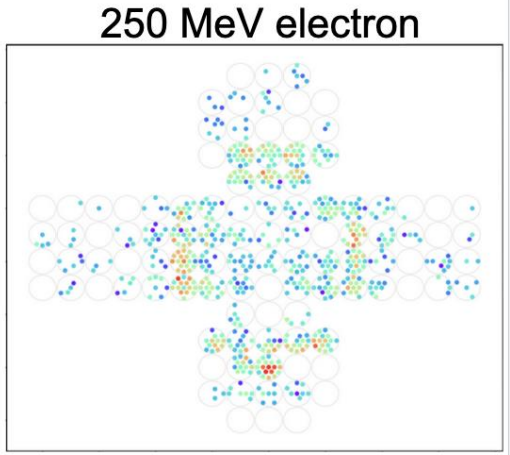


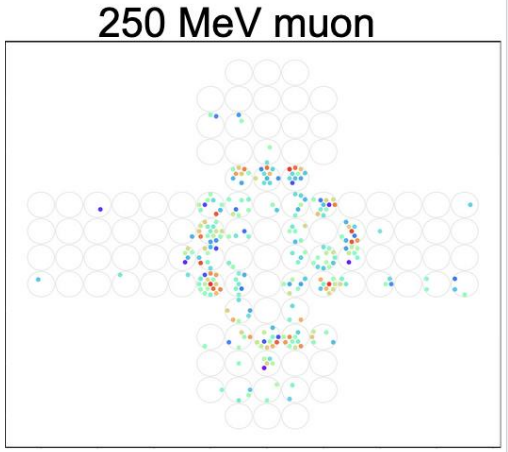


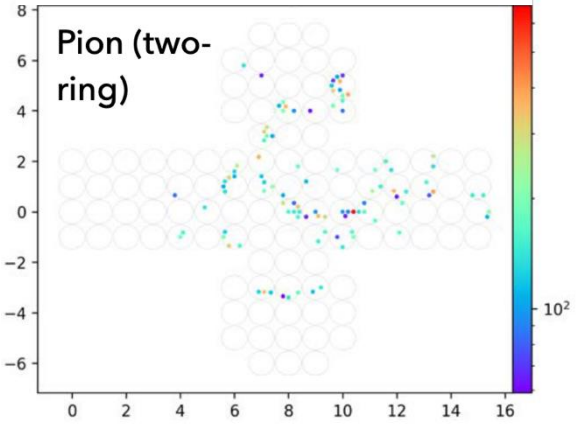
WCTE physics run 2: 14/03 – 06/06/2025

- Array of physics measurements to inform Hyper-K physics
- **Directly measure Cherenkov detector response** to charged particles
- **Pure control samples of charged particle and photon interactions**: validation of improvement of models
- Predominantly ran in ultra-pure water mode
- Gd loaded mode for 1.5 weeks

Measurements	Beam Momentum	Water Mode	Beam Mode
Reco. capabilities, pion scattering	200-1200 MeV/c	Pure	Charged Particle
Muon/electron scattering	800 MeV/c	Pure	Charged Particle
Gamma Identification	500-1000 MeV/c	Pure	Tagged Gamma
Neutron Production	200-1200 MeV/c	Gd	Charged Particle
Photonuclear with n tagging	500-1000 MeV/c	Gd	Tagged Gamma

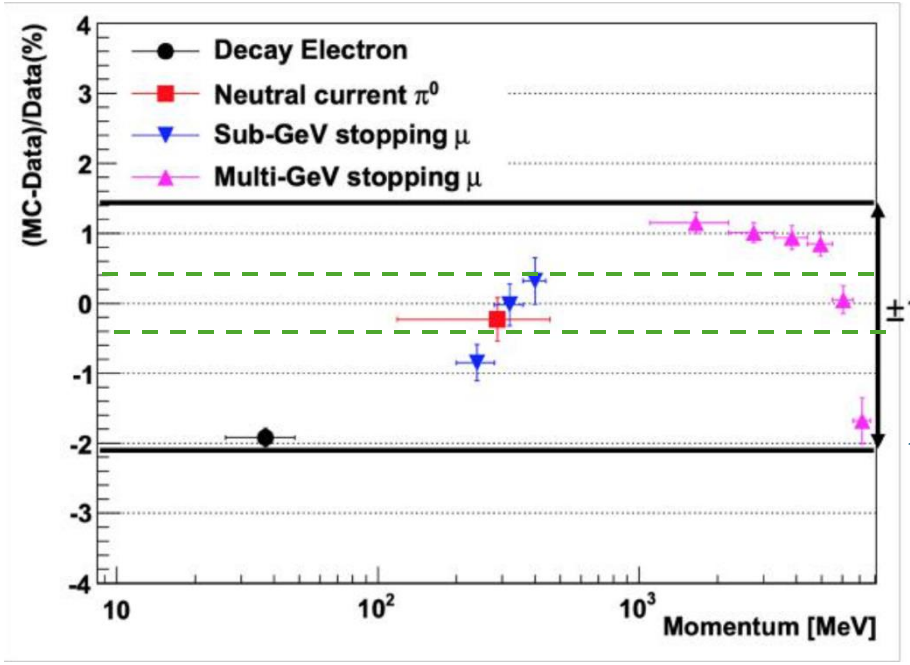


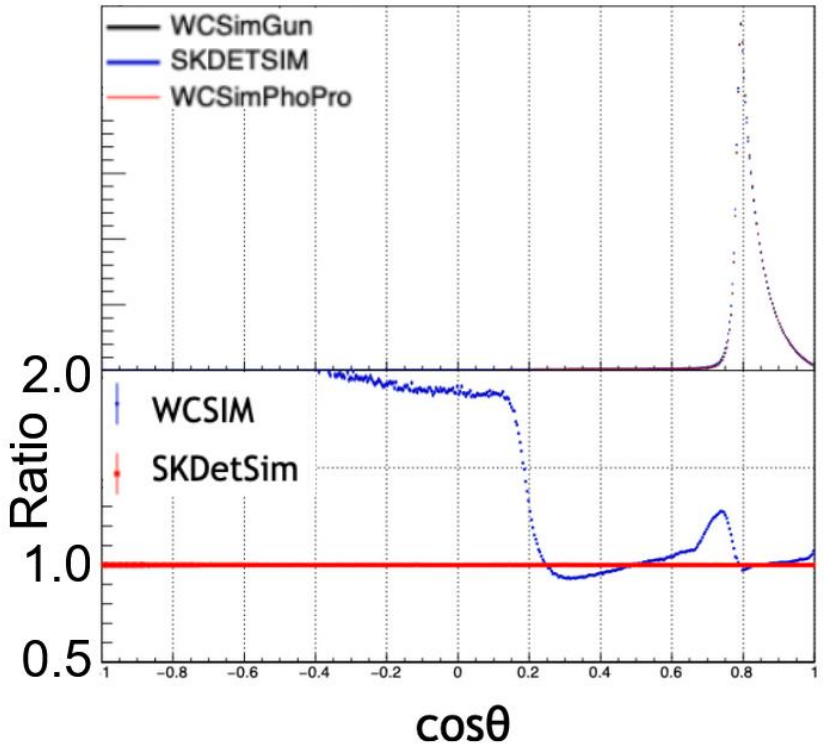




Detector response to charged particles

- **WCTE will help reduce detector uncertainties by directly measuring the detector response to charged particles**
- **WCTE measures e / μ observed PMT charge ratio** at fixed beam momenta
- **Super-K** shows 1.9% discrepancy in energy scale
- **Reduction to < 0.5% uncertainty** is necessary for ν measurements at Hyper-Kamiokande (including δCP measurements)



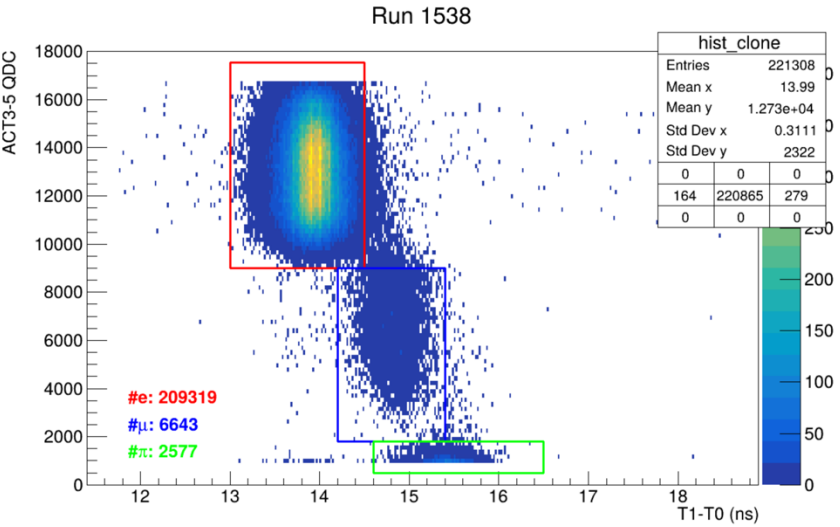


- **PMT angular response modelling and water property uncertainties**
- **Discrepancies in Cherenkov production models** limit ability to use backward-going Cherenkov light to enhance reconstruction
- **WCTE measures emission profile** from e and μ of known momenta

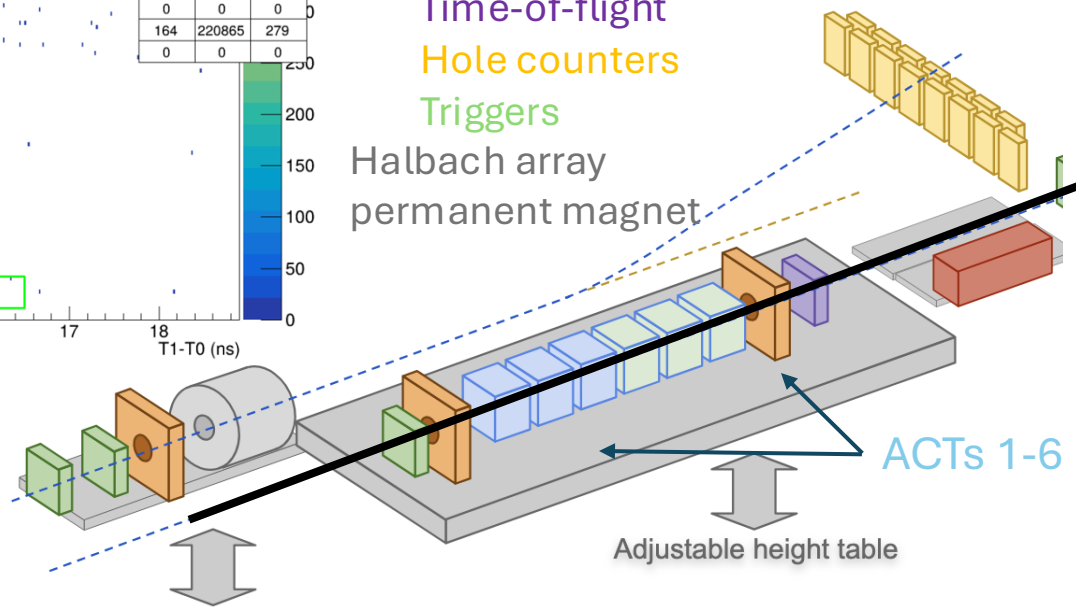
Charged particle configuration

- **Triggers** identify particles in beamline while **hole counters** veto particles that shower before reaching WCTE

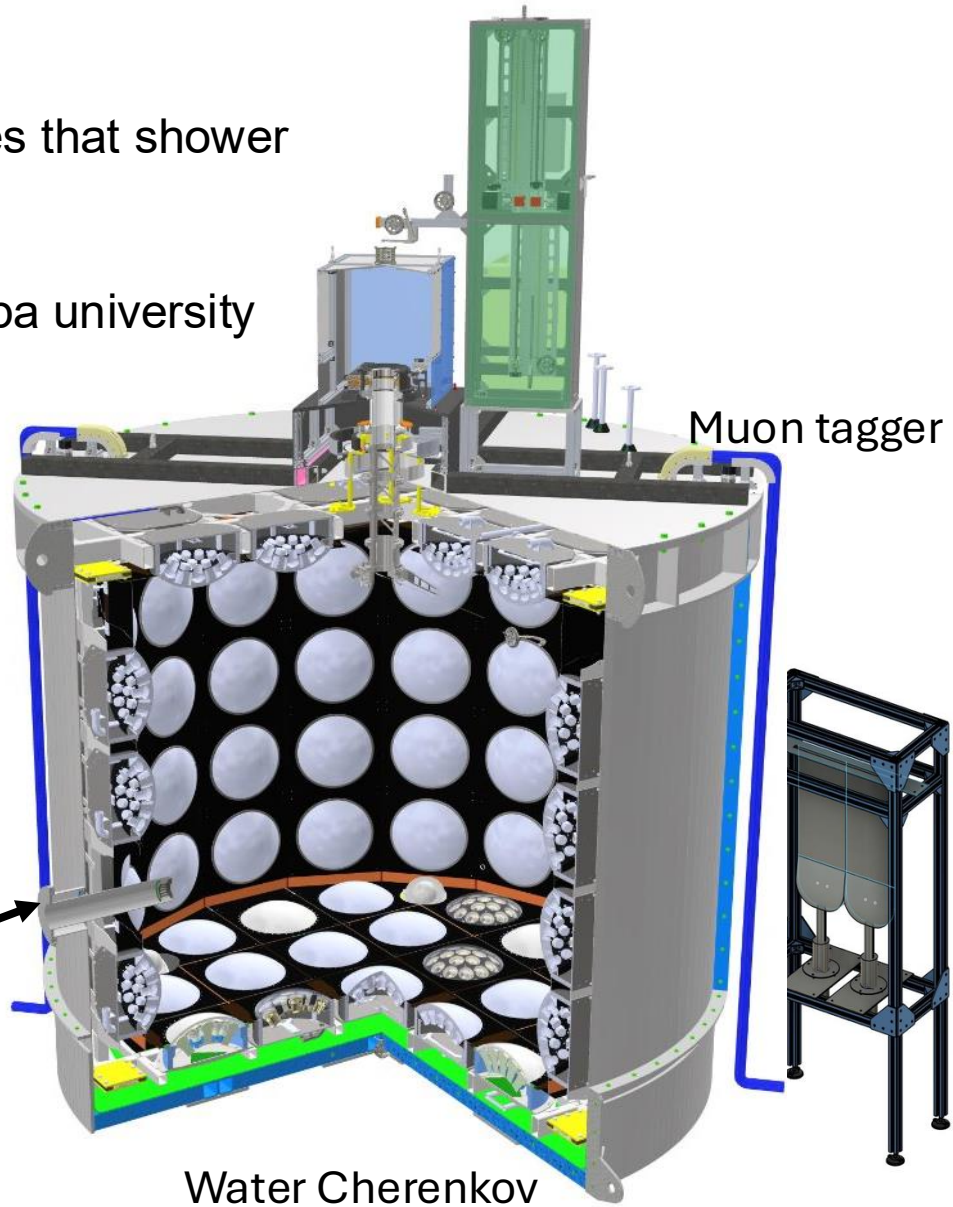
- **Aerogel Cherenkov Threshold** detectors use aerogel produced at Chiba university with n = 1.006 to 1.15
  - Low index aerogel used to **identify** e^+ / e^-
  - Higher index aerogels are matched to beam momentum for π / μ **separation**



Suite of beamline monitor detectors:
Aerogel Cherenkov
Time-of-flight
Hole counters
Triggers

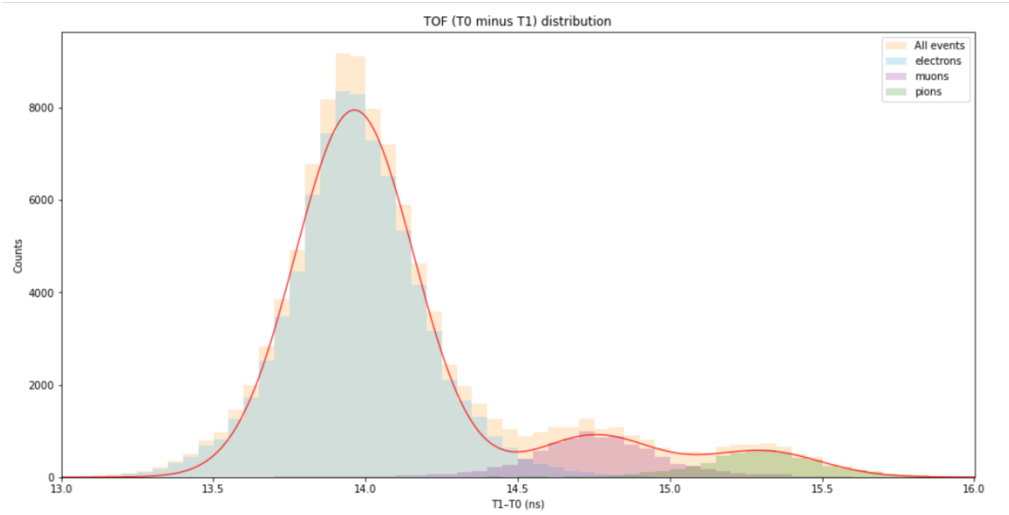


T9 beam
e, μ, π, p

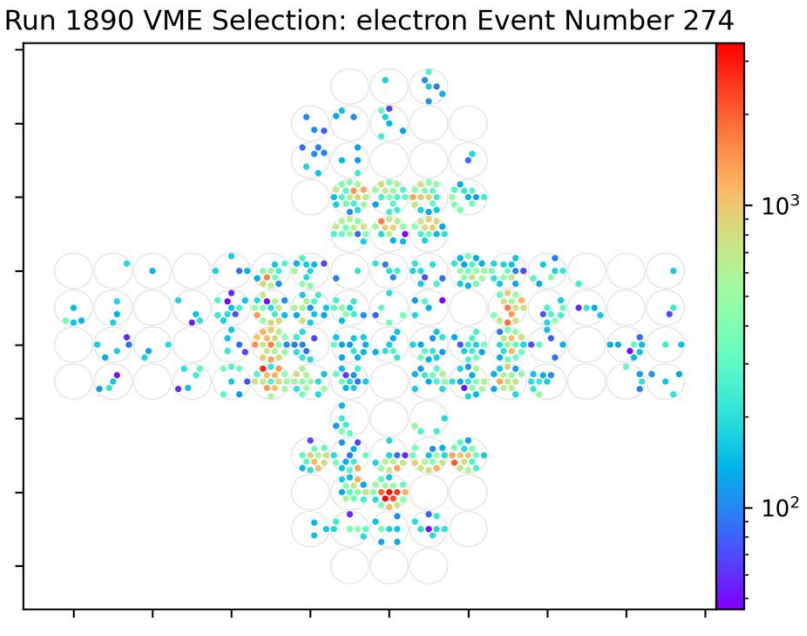


Charged particle detection

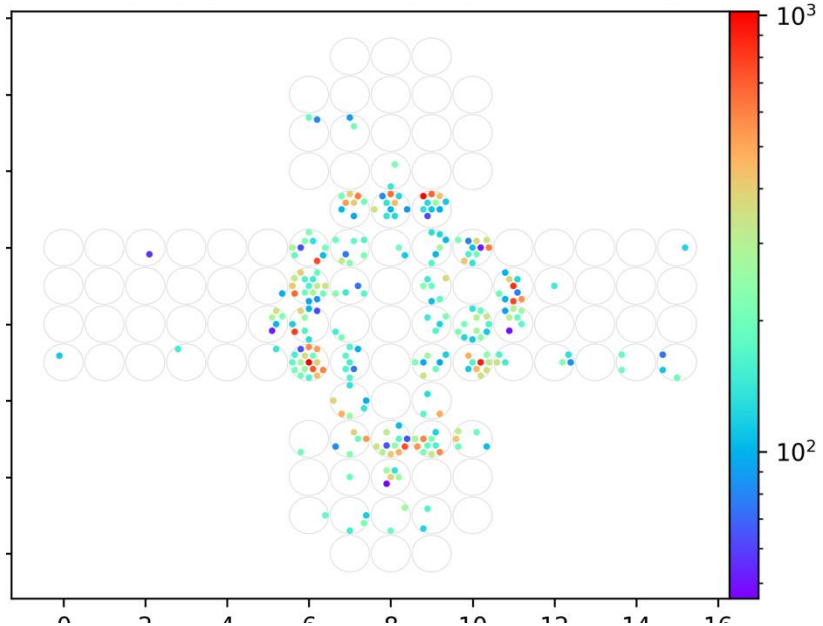
- WCTE successfully observed Cherenkov rings from charged particles!
- With the mPMTs, we achieved great charge and timing resolution
- We can match beam monitor data to water Cherenkov data and tag events
- Example 280 MeV charged particle events



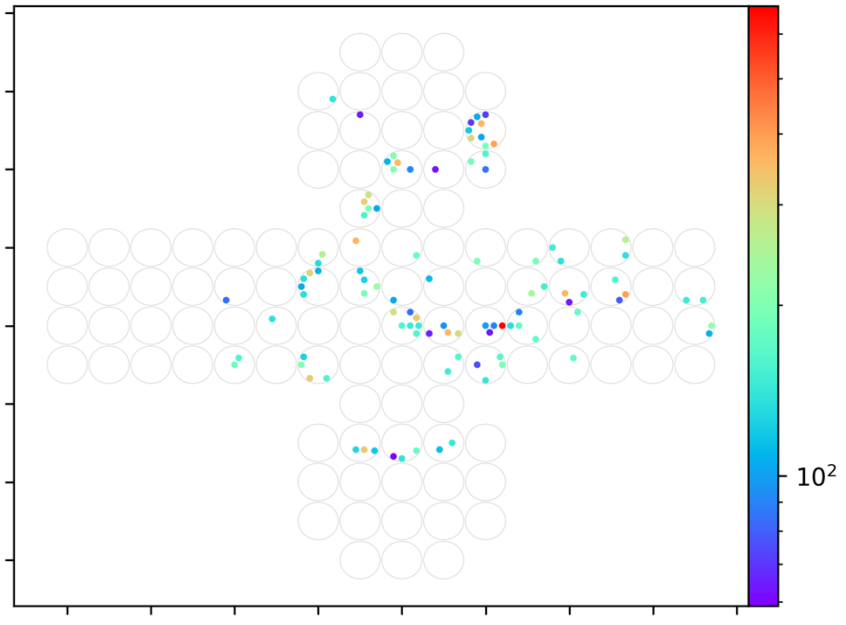
Electron Event



Muon Event



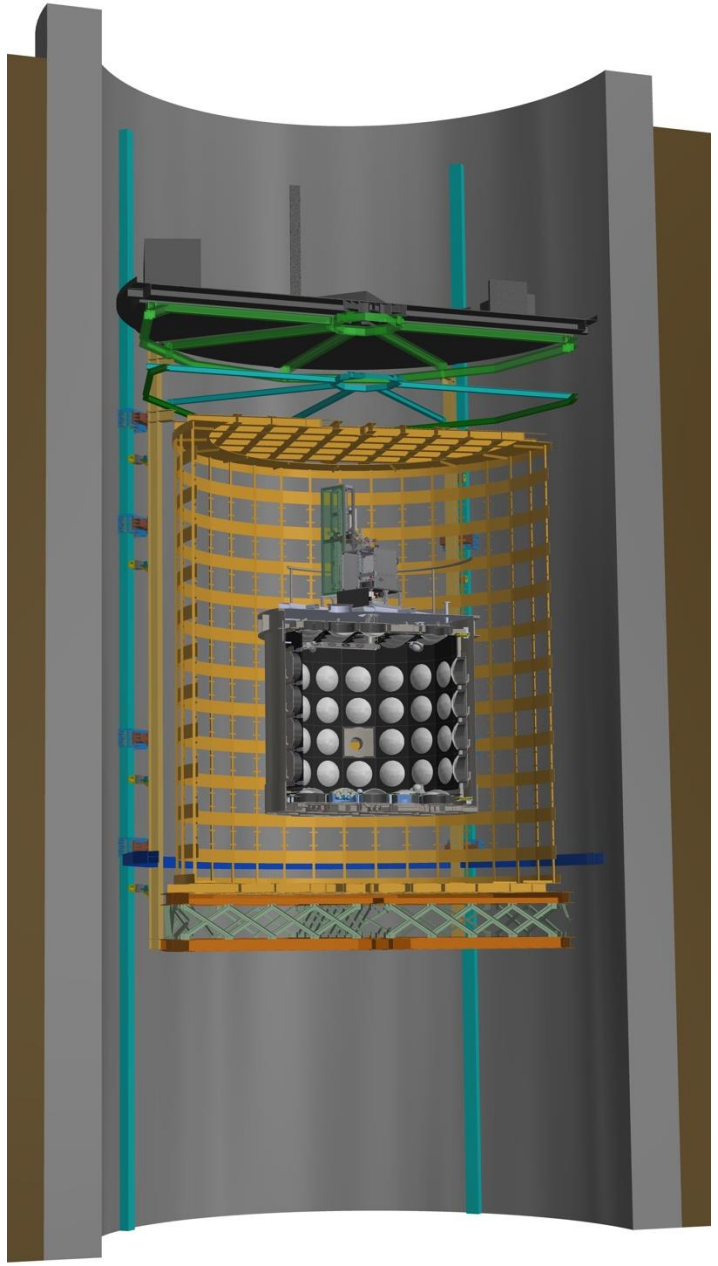
Pion Event

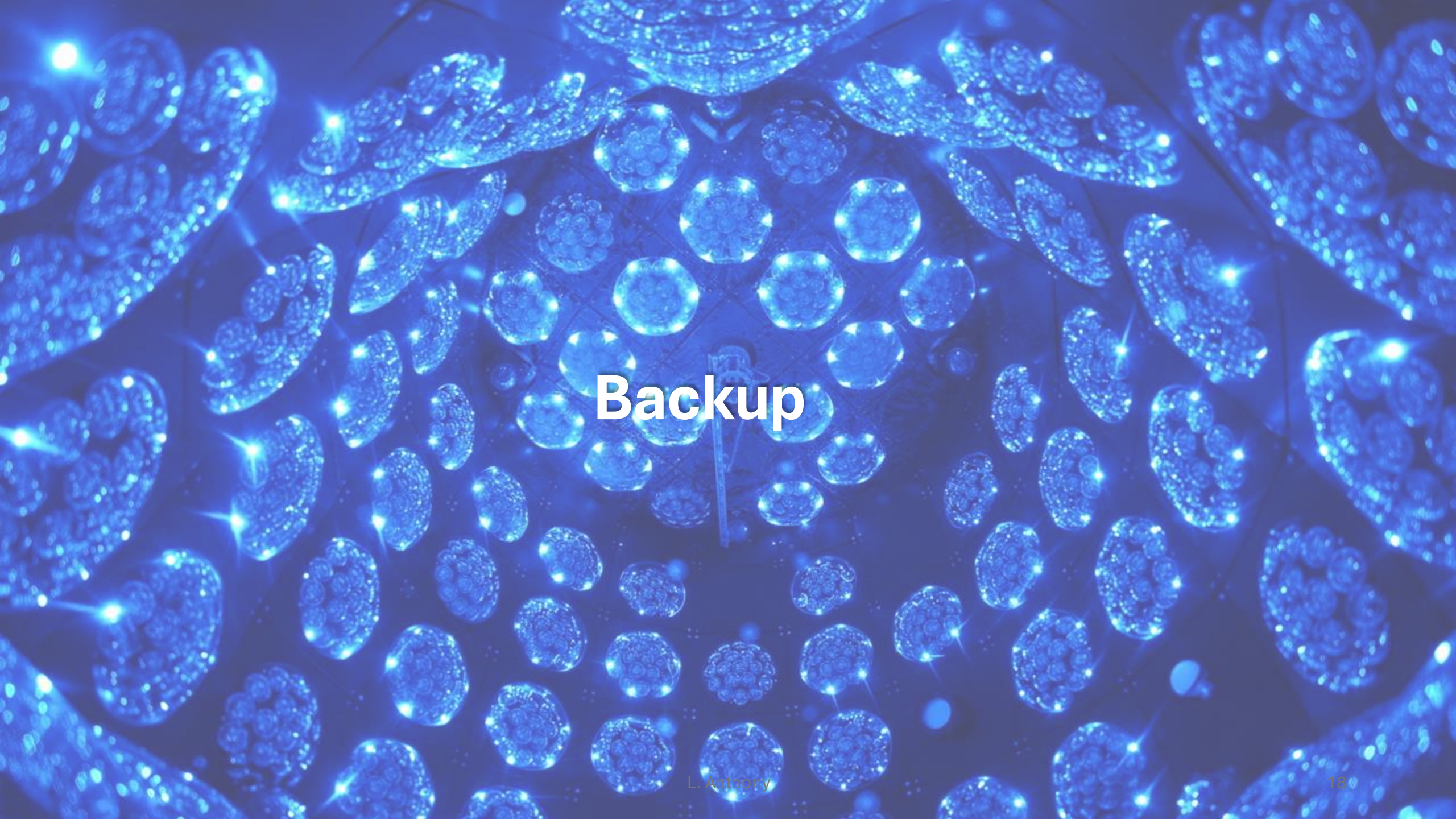


Summary

- The IWCD will measure the neutrino beam from JPARC at a range of off-axis angles
  - Better understanding of beam at production with same technology as far detector
  - Measure neutrino-nucleus cross section ratios
  - Predict neutrino spectra after oscillations at HK

- Many components tested at WCTE: Operated at CERN from 09/10/2024 – 06/06/2025
  - mPMT operation and readout
  - DAQ using toolDAQ
  - Calibration sources & techniques
  - Machine learning and fiTQun reconstruction for small detectors
  - Water system & Water monitoring system
  - Charged particle beam data for particle interactions




Backup

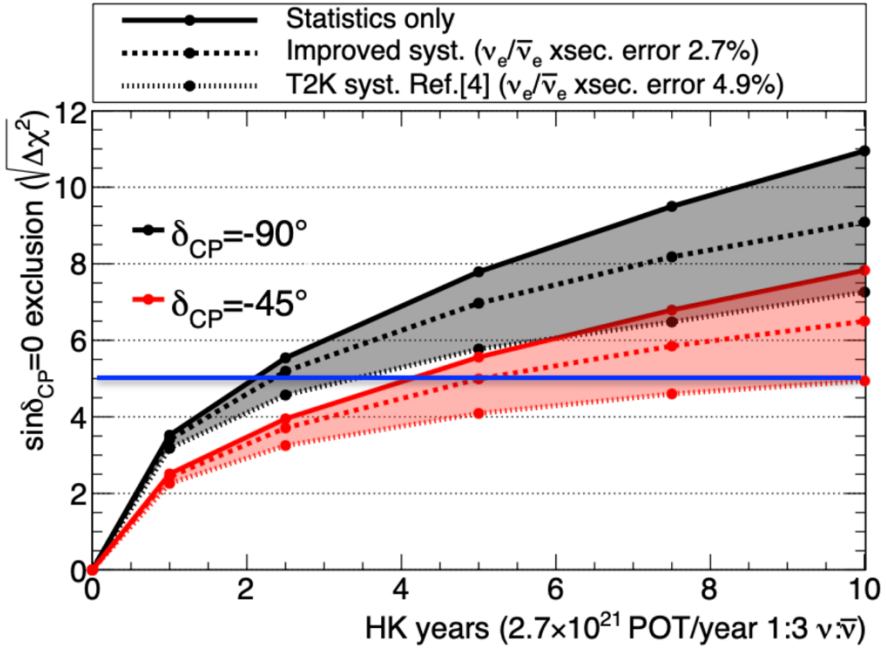
Measurement uncertainties: Hyper-K

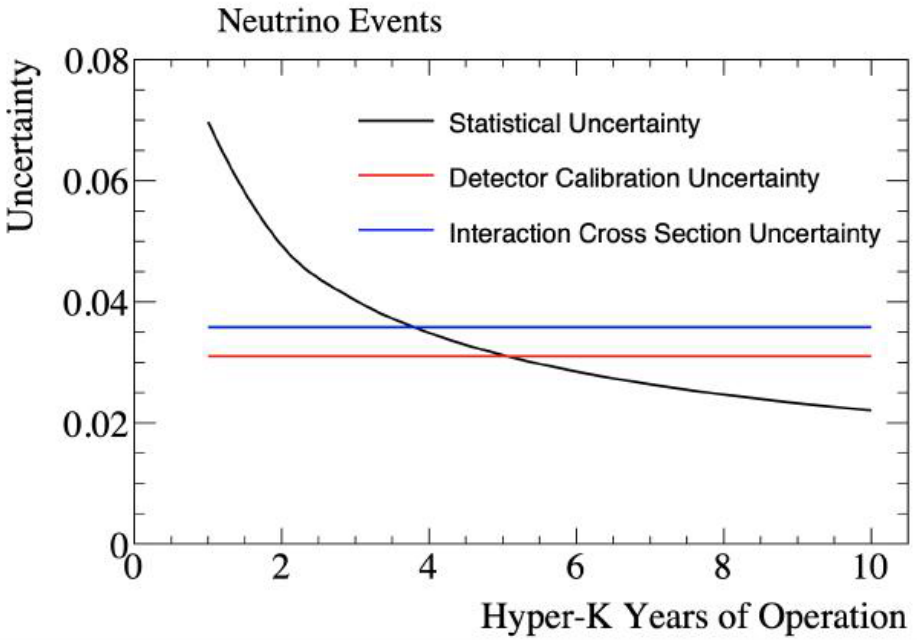
Detector model uncertainties

- Precision understanding required of
- **Interactions** of particles propagating through water volume
- **Cherenkov light production** of charged particles in water
- **Propagation of light** through water volume (absorption, scattering)
- **Photosensor response** to light including timing, charge and angular response
- **Reconstruction of complex and challenging event topologies** in both signal and background channels

Interaction model uncertainties

- Critical to CP violation measurement
- ν_μ **&** $\overline{\nu}_\mu$ **production** to understand ν_μ beam flux, ν_e contamination and “wrong sign” background
- ν **interaction cross-sections on water** for CCQE signal, other CC signal channels and wide array of backgrounds





Measurement uncertainties: Hyper-K

Detector model uncertainties

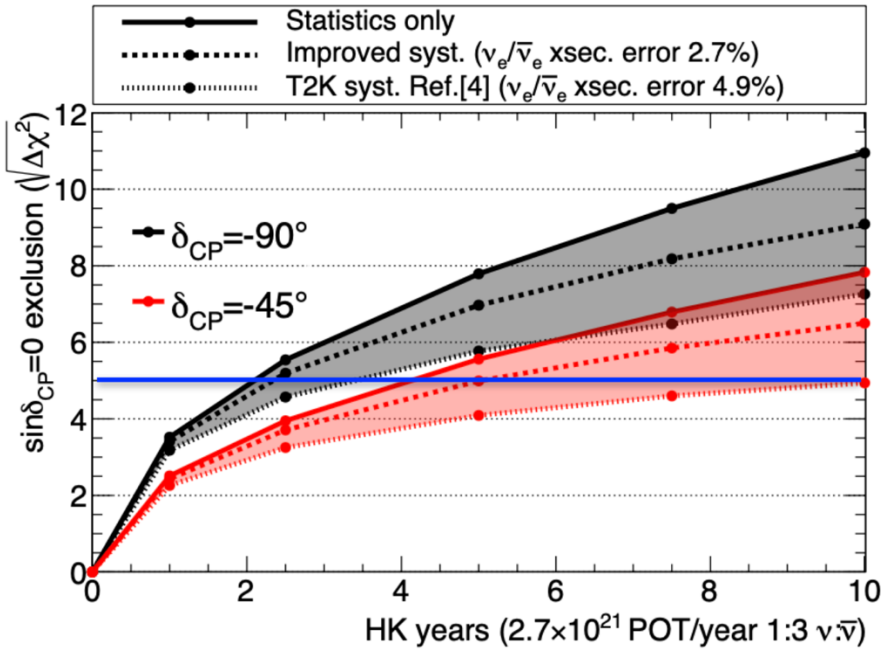
- Precision understanding required of
- **Interactions** of particles propagating through water volume
- **Cherenkov light production** of charged particles in water
- **Pro** tion, sca
- **Photosensor response** to light including timing, charge and angular response
- **Reconstruction of complex and challenging event topologies** in both signal and background channels

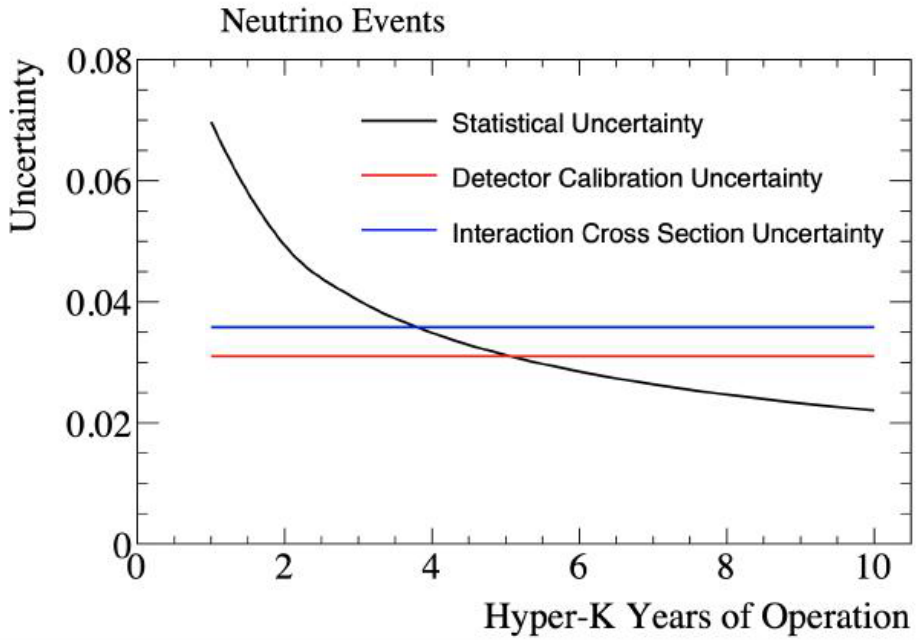
Detector calibration techniques

Interaction model uncertainties

- Critical to CP violation measurement
- ν_μ **&** con
- ν **interaction cross-sections on water** for CCQE signal, other CC signal channels and wide array of backgrounds

Near detector beam measurements

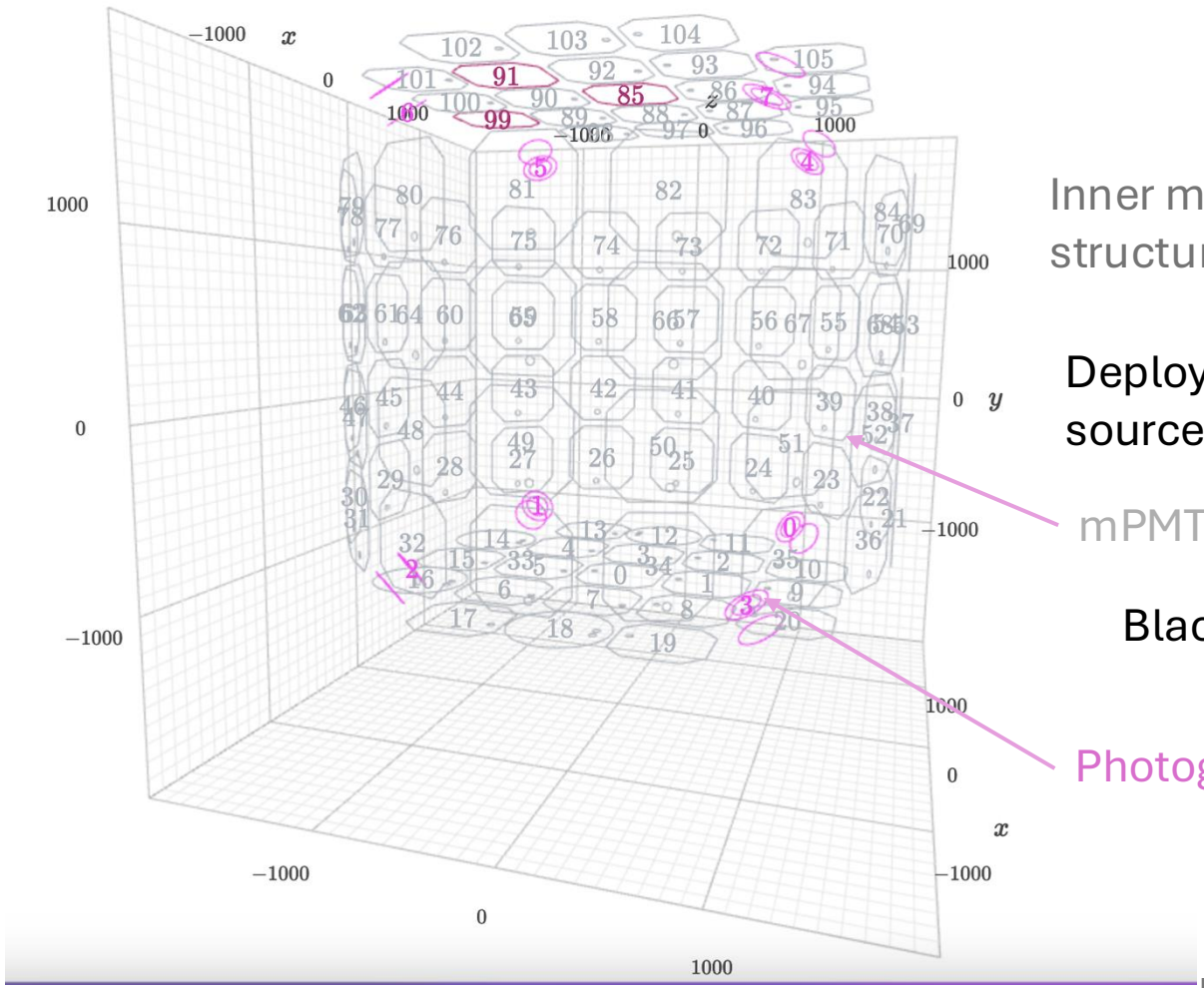


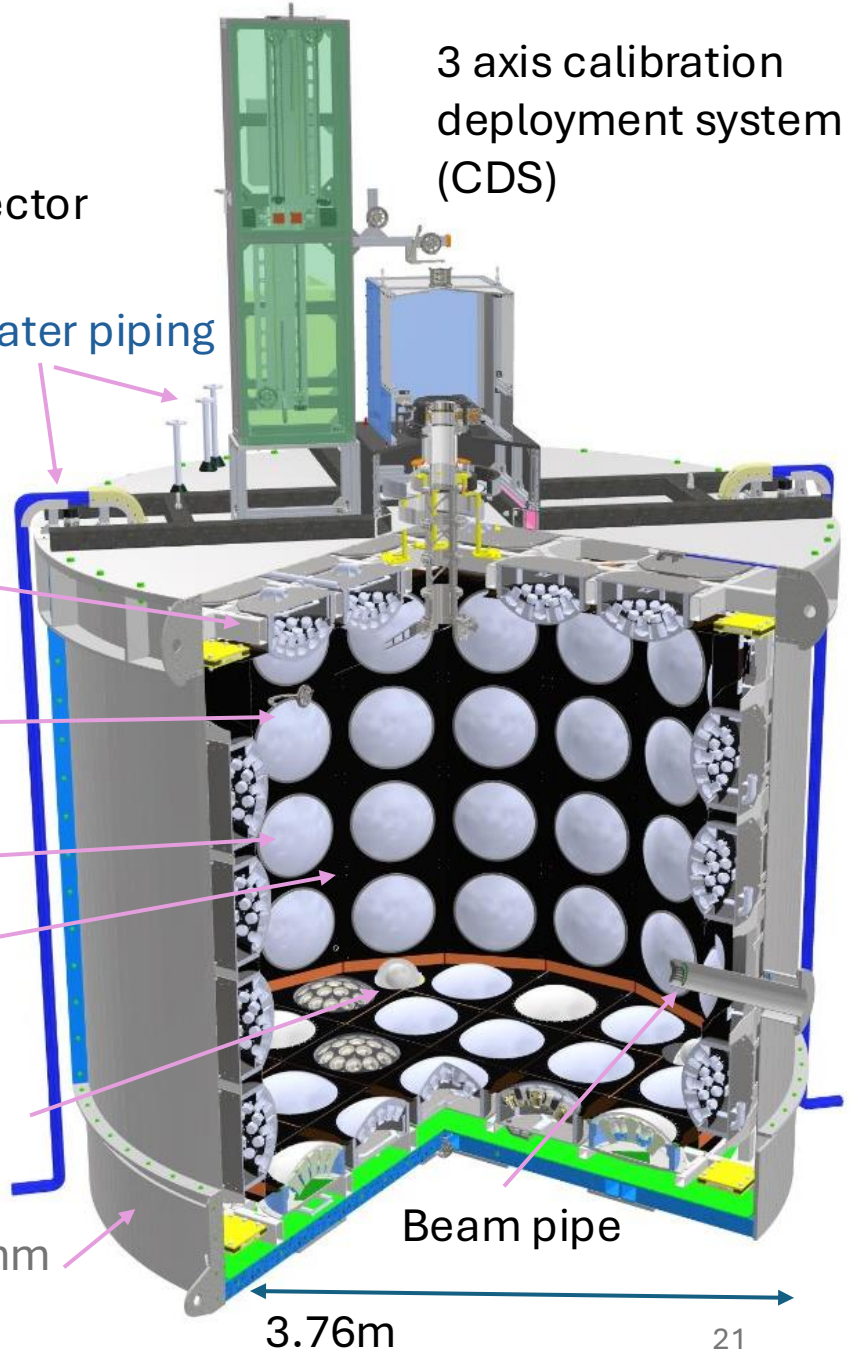


The WCTE detector

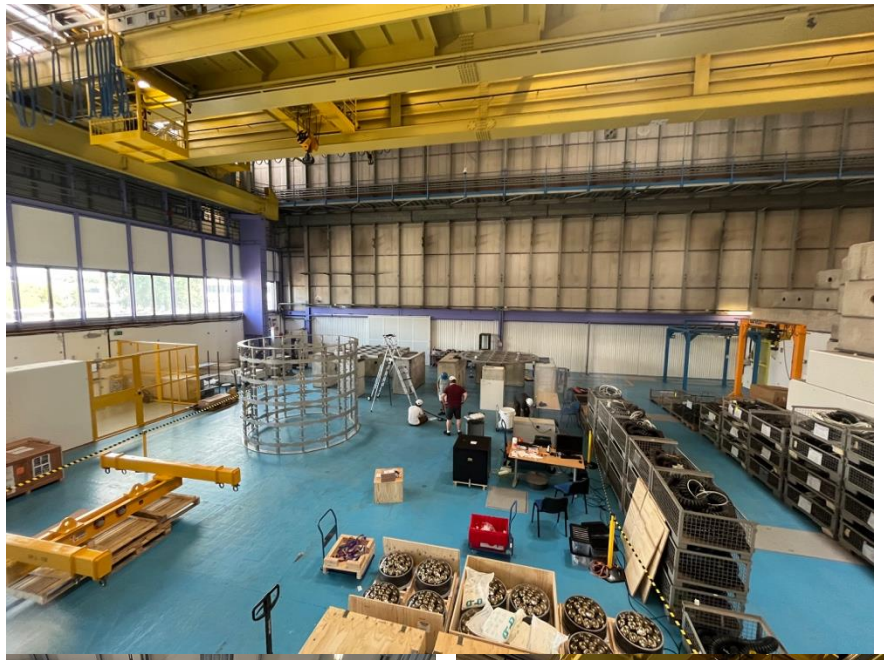
WCTE is instrumented with
- 93 IWCD style mPMTs
- 4 Hyper-K style mPMTs
- 8 cameras use to image the detector

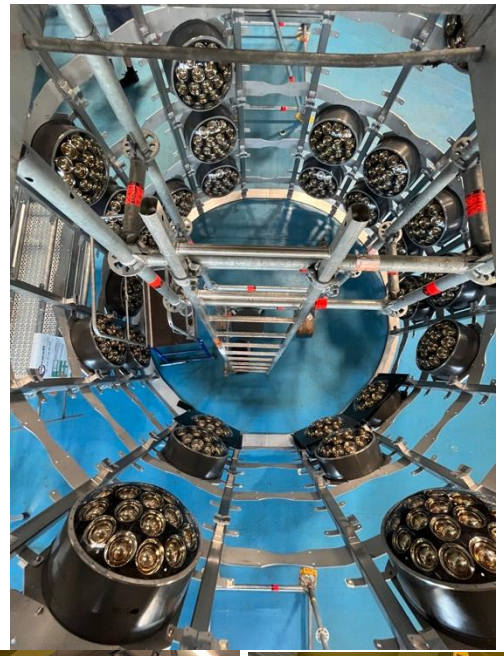
3D map of mounted detector components

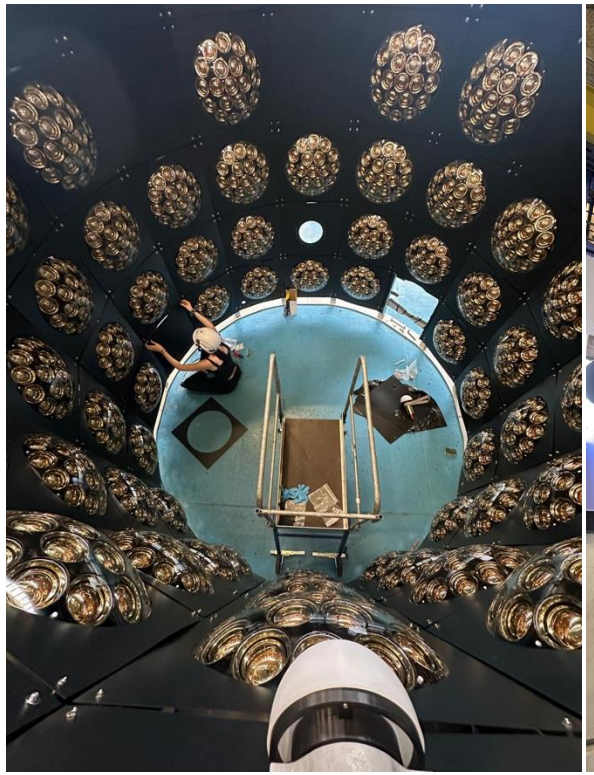


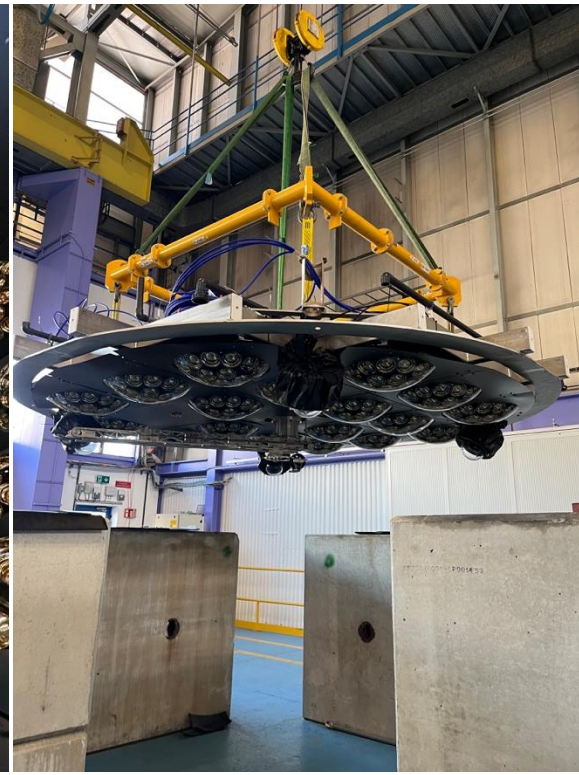


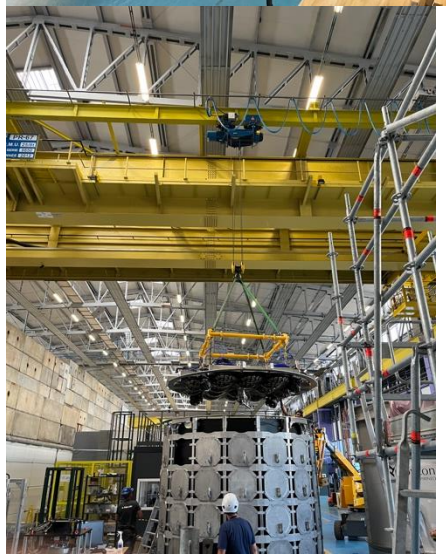
WCTE assembly & commissioning





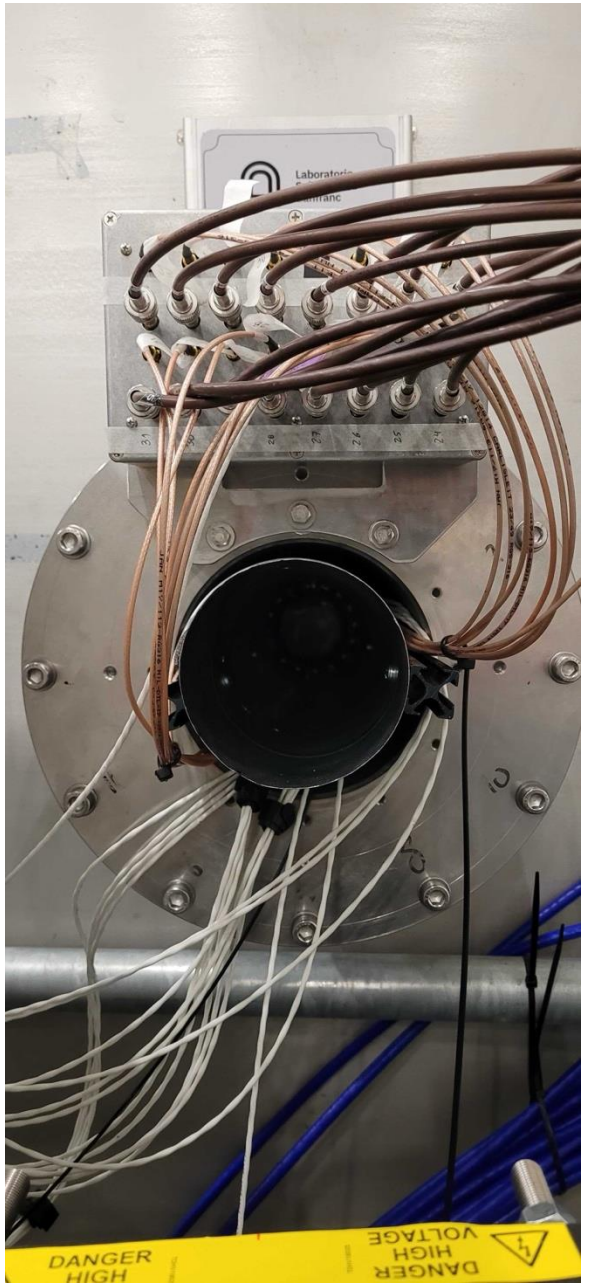






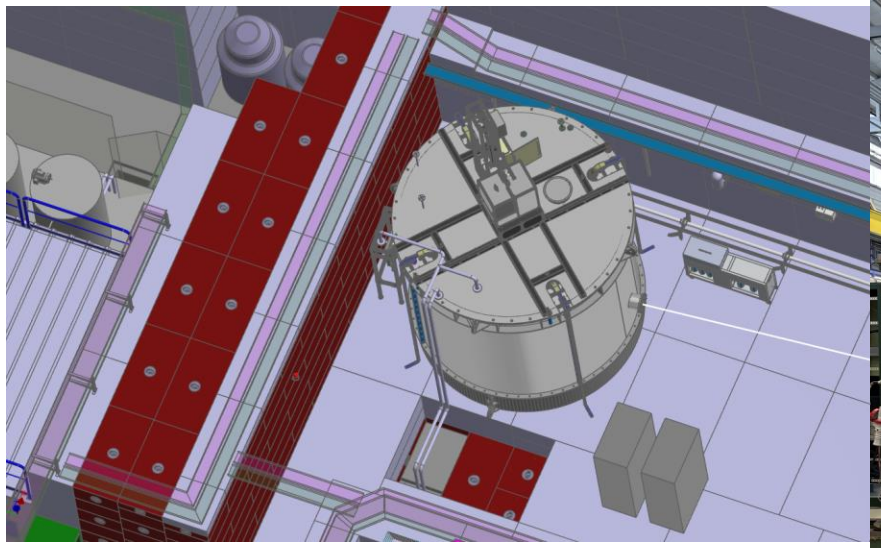
Beam window

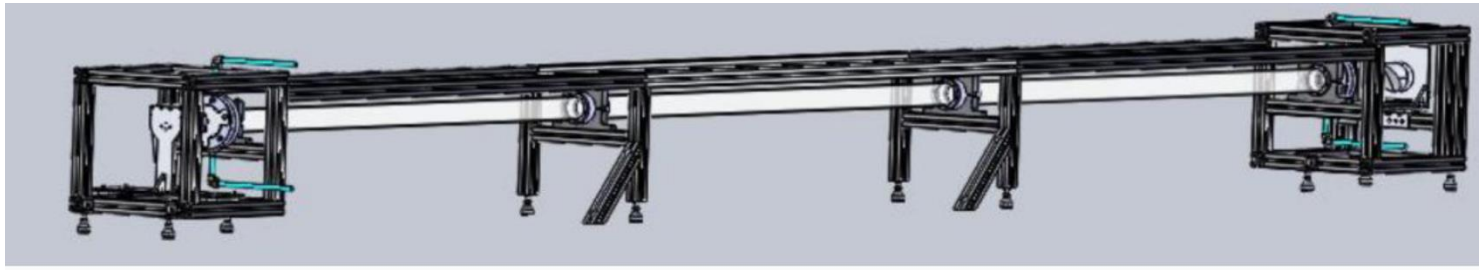
- Beam pipe extends into detector to reduce path length of beam in water
- 150mm beyond mPMT cylinder level (effectively from black sheet)
- 1.2mm thick stainless steel window
- TOF detector installed inside beam pipe



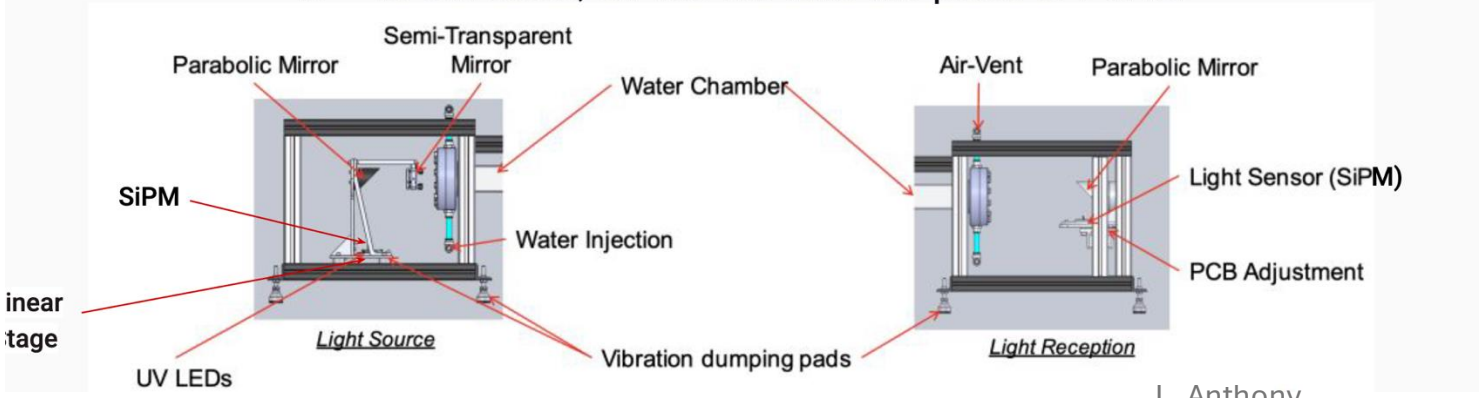
Water monitoring system

- Important for water transparency and long Cherenkov light attenuation length
- For WCTE – horizontal water pipe and measure water quality relative to filtered water by filtering system
- 8 m length pipe with UV-sensitive PMTs and 245 – 470nm LEDs with < 1ns pulse width
- Water filtration system to selectively filter out contaminants





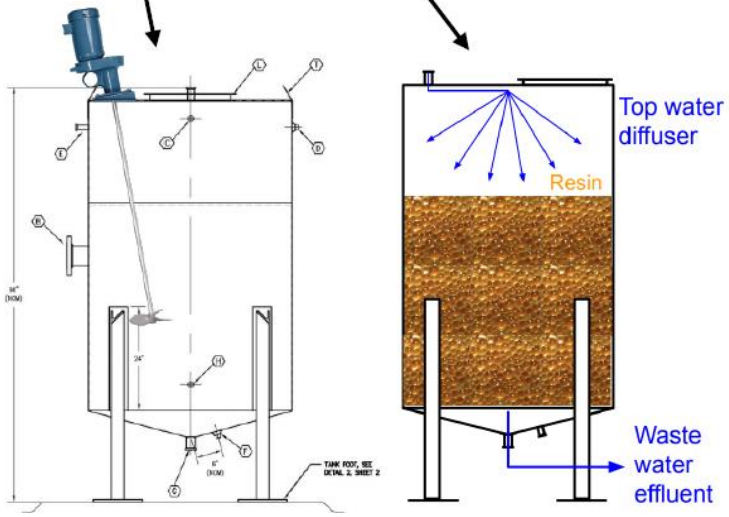
★ To cut costs, SiPMs will take the place of PMTs.

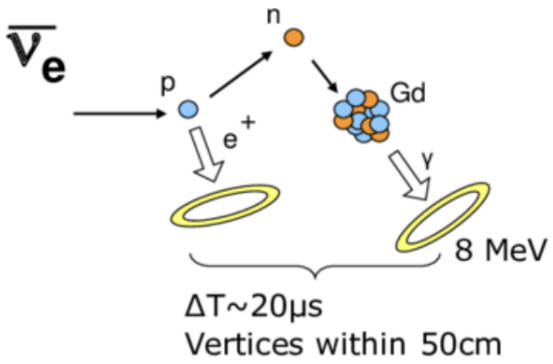


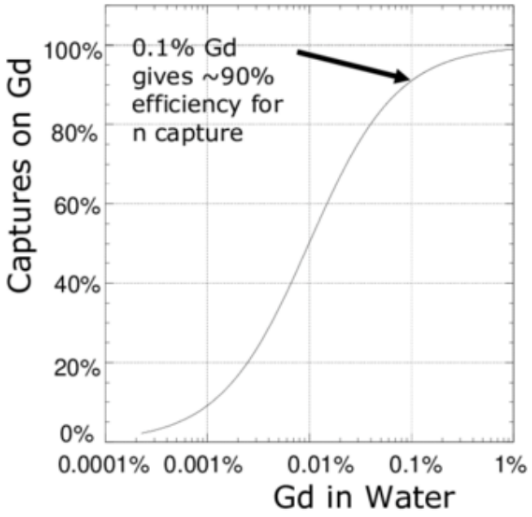
- The WMS is also being developed with drinking water quality in mind
- Gadolinium absorbance detector also installed (GAD)
- **Demonstrated a 1% measurement precision in detecting a change in the water quality, which translates to PPB level of detection sensitivity to Gd.**

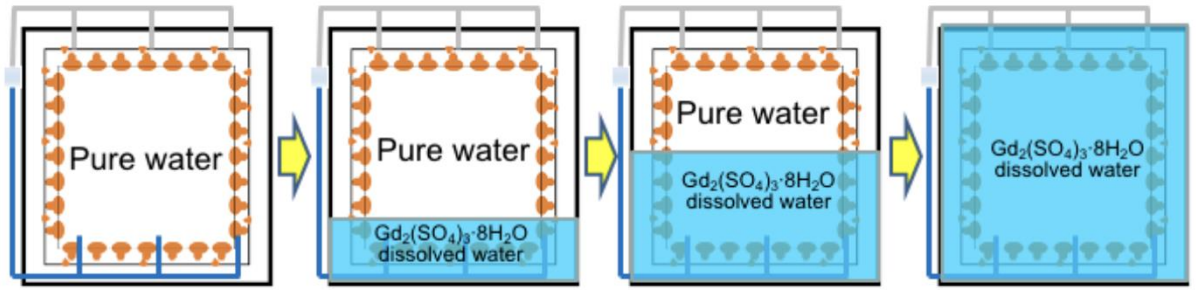
Gadolinium loading WC detectors

- Super-K is currently operating with 0.1% Gd concentration
- Gd has **large neutron capture cross section** and produces delayed energetic gammas of a total ~8 MeV
- Without Gd, capture on Hydrogen produces 2.2 MeV γ
- Neutron tagging can be beneficial for supernova and low energy events
- Loading of with **~0.1% Gd** in detector gives **90% neutron capture efficiency**
- WCTE water system can accommodate Gd loading: we loaded to 0.03%



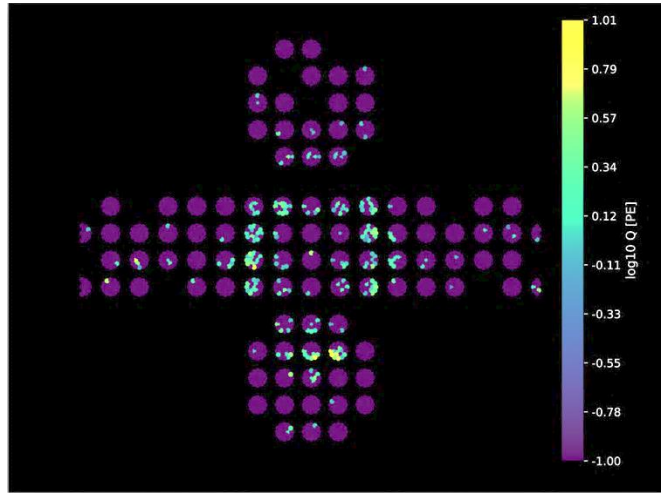




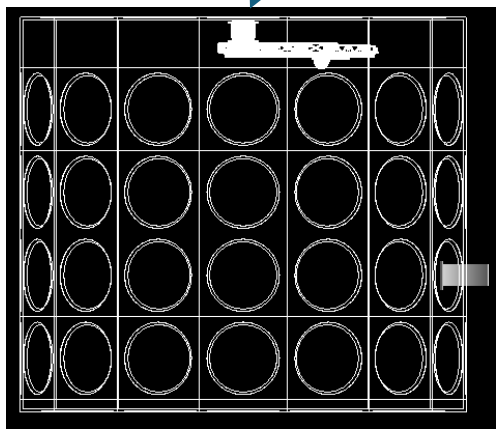


Monte-Carlo simulation with WCSim

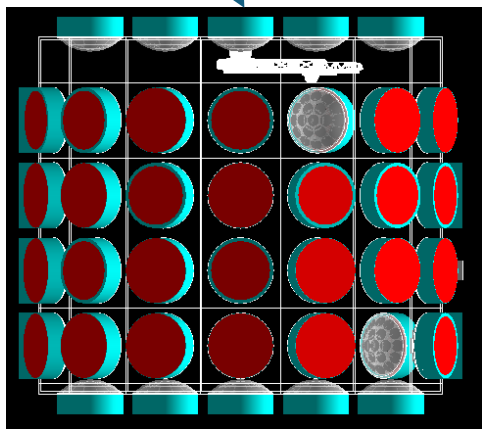
- WCSim (Water Cherenkov Simulation) is an open-source simulation package used for event simulation in Hyper-K, IWCD and WCTE
- Build and place objects like mPMTs using GEANT4
- Implement complex objects like CDS using CAD models



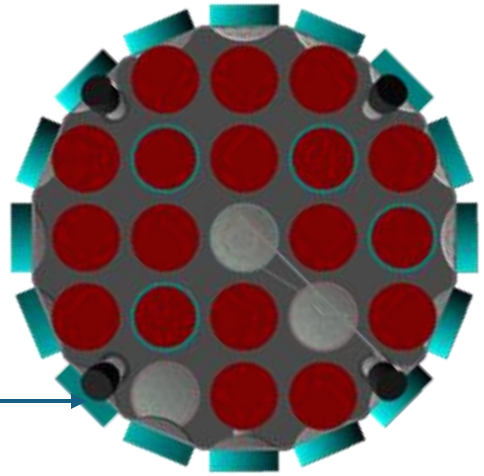
Implement CDS CAD model



Construct detector volume and mPMT slots

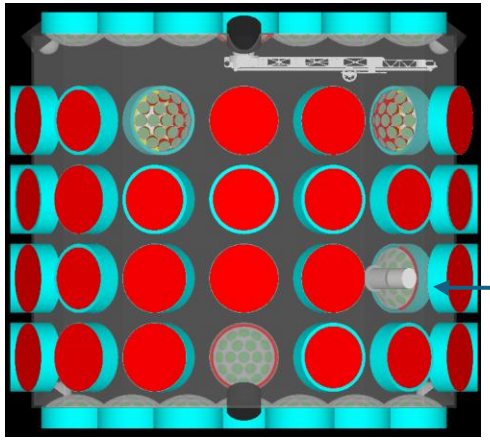


Construct detailed mPMT



Construct basic shape for photogrammetry camera housing

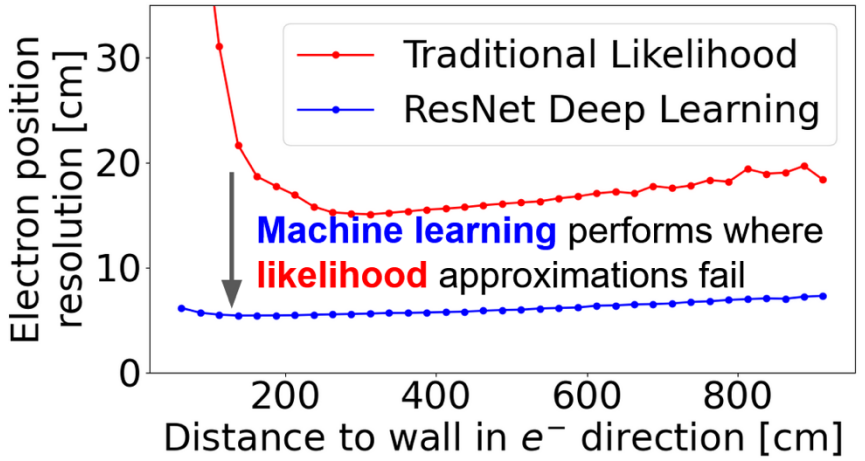
Construct basic shape for beam pipe

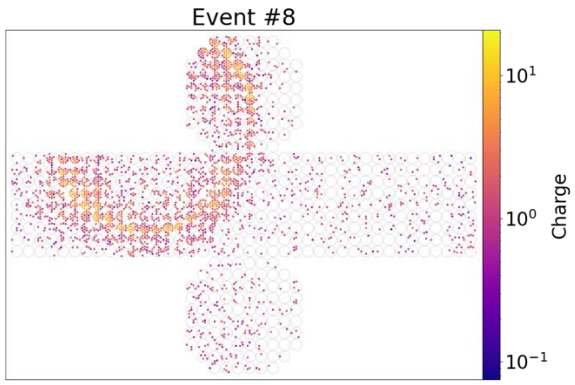


Remove mPMTs from unused or dead slots

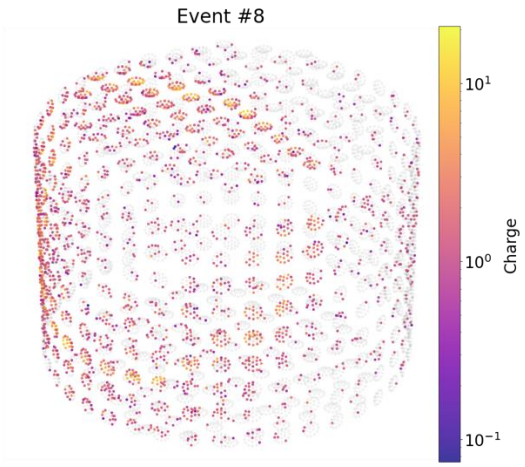
Machine learning in WC detectors (WatChMaL)

- Traditional likelihood reconstruction methods are reaching limits
  - Computational time is a limiting factor – 1M events in fiTQun = 10,000s CPU hours
- ML and deep neural networks can perform significantly better
  - Very fast once network is trained: 1M events with CNN < 100 CPU hours
- WCTE aiding development of a new calibration and reconstruction
- Essential data driven validation of ML based methods

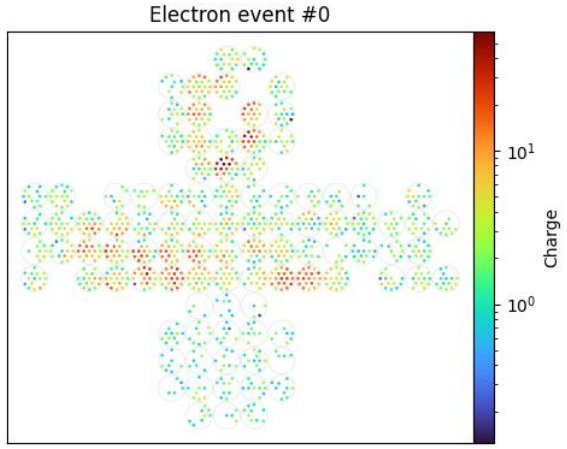




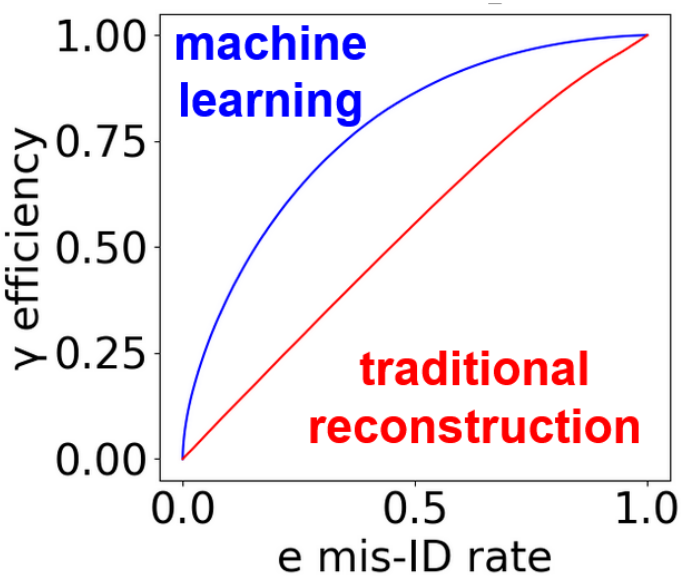
Networks on 2D image like data (IWCD)



Networks on 3D point-clouds or graphs (IWCD)

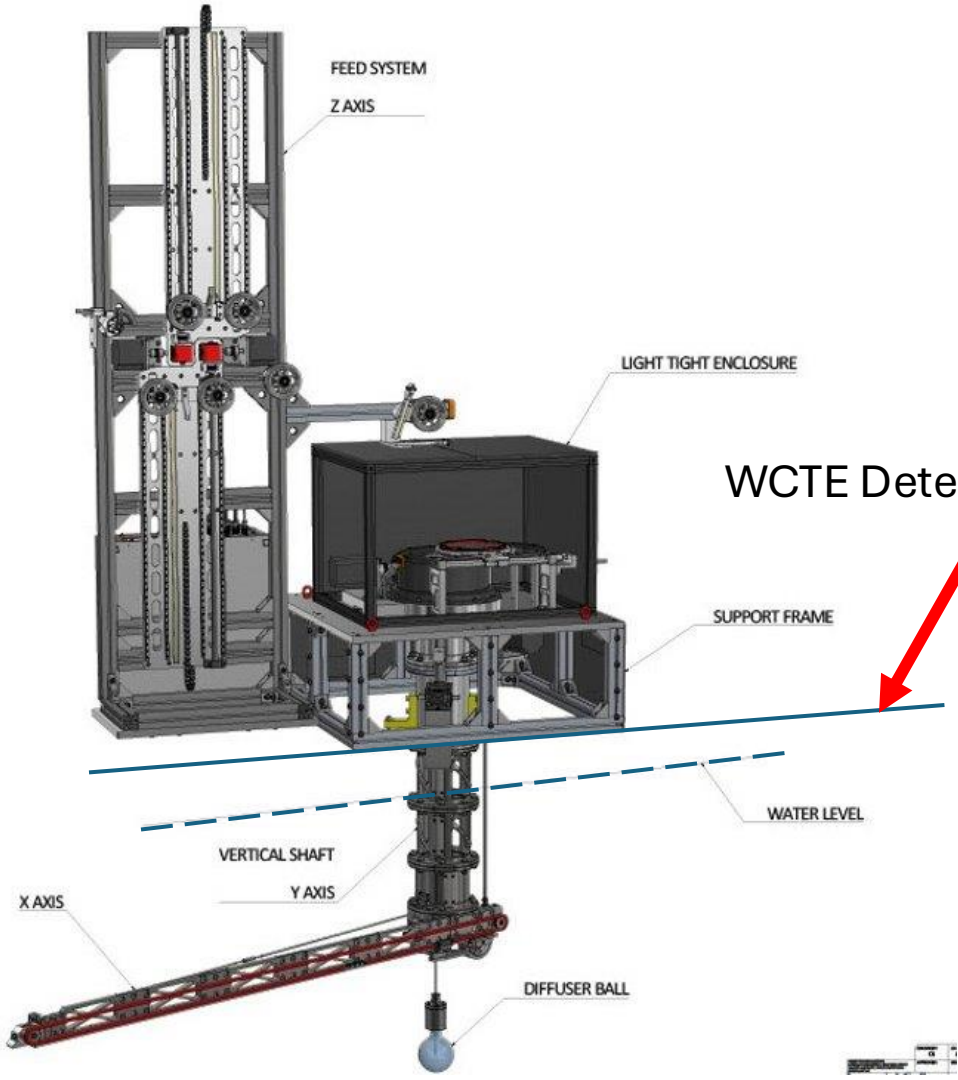


Networks for WCTE

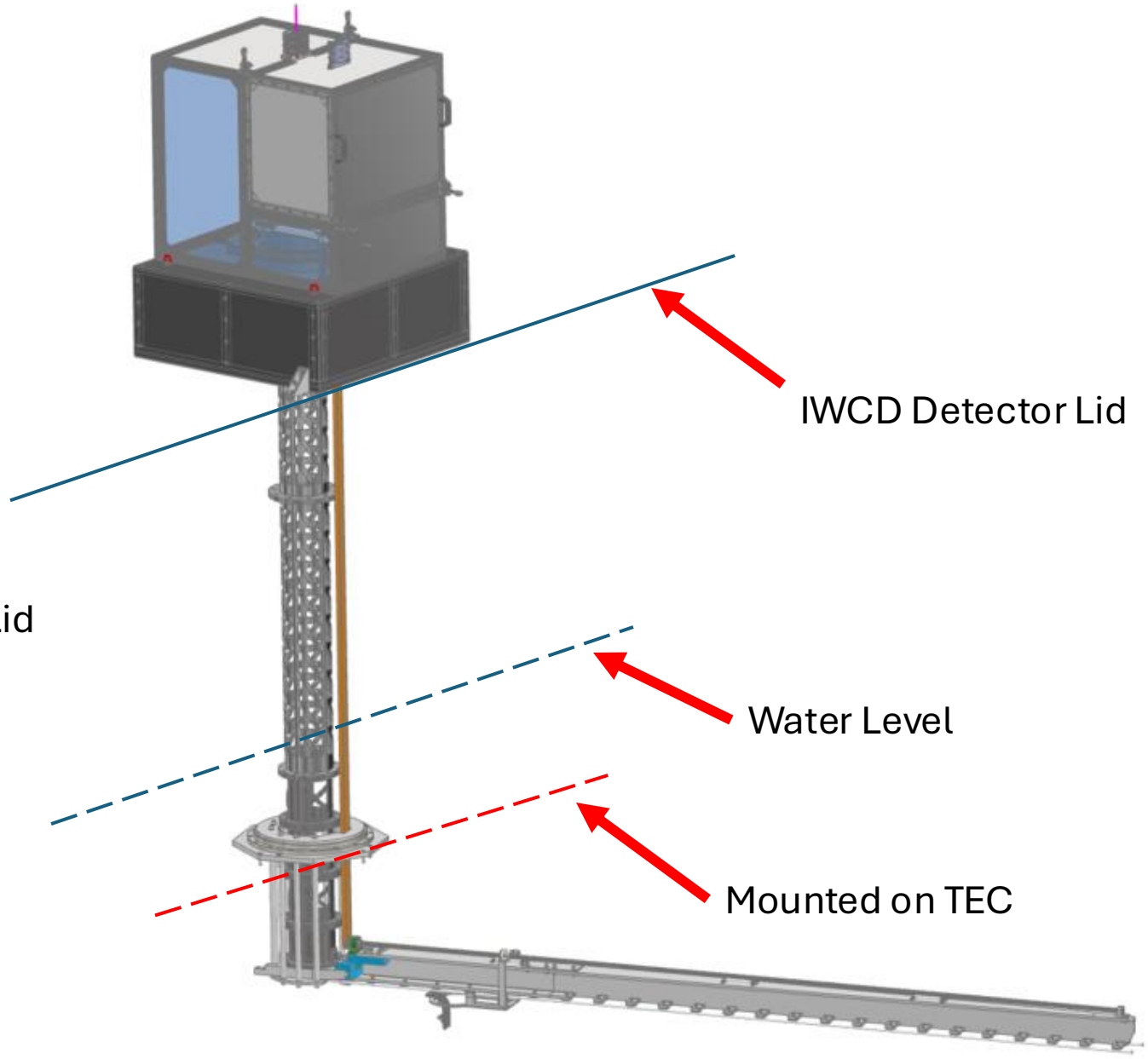


WCTE & IWCD CDS

Comparing the WCTE CDS to the IWCD design



WCTE Detector Lid



IWCD Detector Lid

Water Level

Mounted on TEC