ICRR Inter-University Research Program FY2024

Neutrino and Astroparticle Research Division

1) New Photogrammetry Calibration for Super-Kamiokande and Hyper-Kamiokande

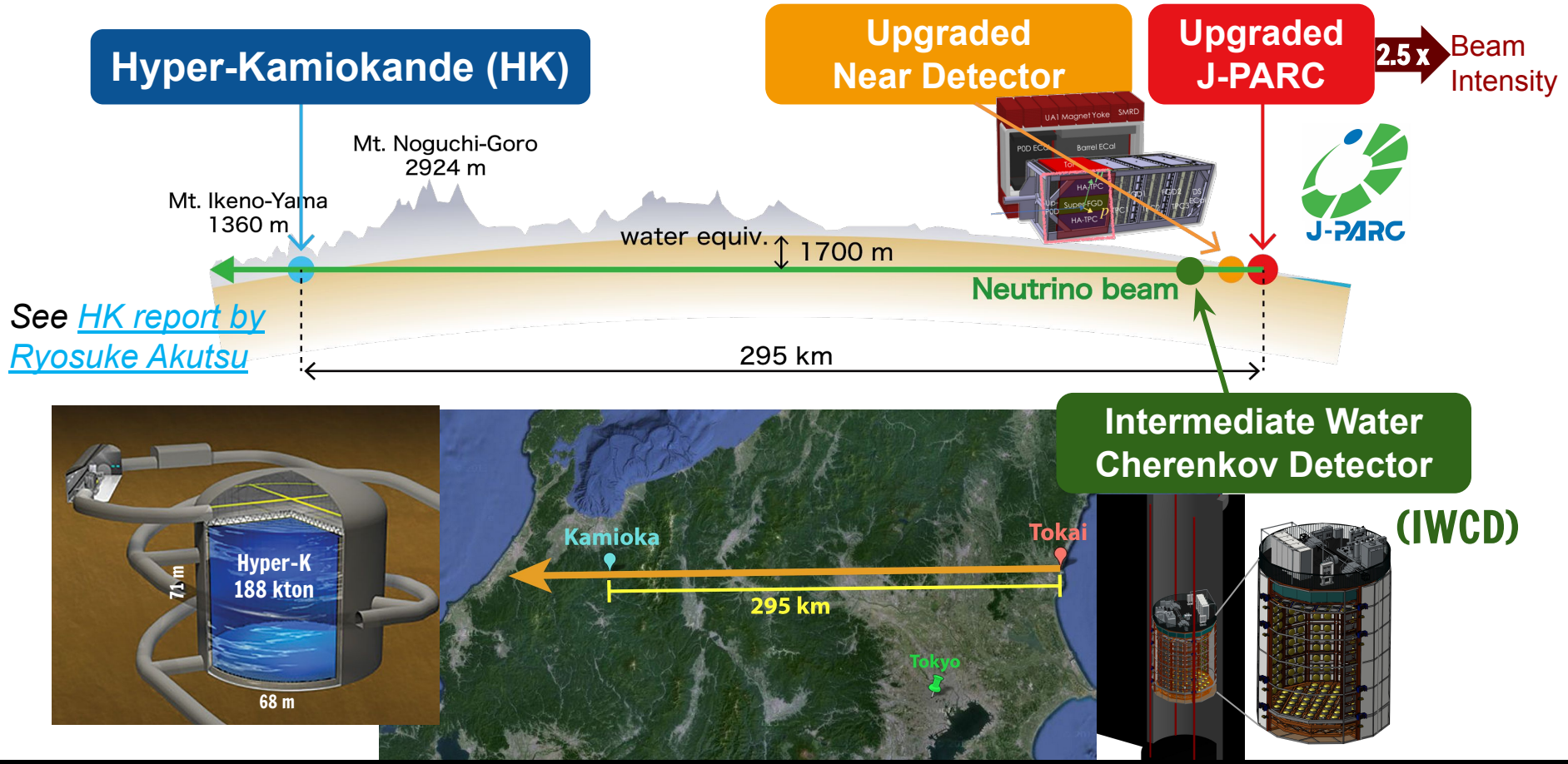
2) Water Purification System R&D for Precision Neutrino Detectors

Patrick de Perio

January 29, 2025

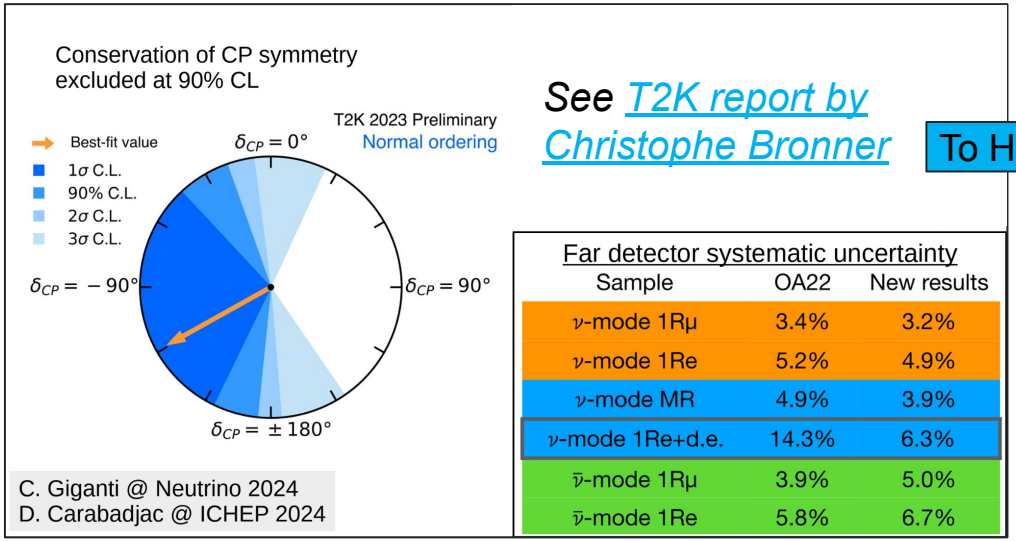
KAVLI IPMU TRIUMF

Hyper-Kamiokande: Long-Baseline Neutrino Experiment



Motivation

- CP violation discovery in neutrino oscillation will become systematics limited in HK
- 10 years to reach 5σ discovery potential with our current (T2K) systematic errors
- 5 years if we can improve our understanding substantially
  - Also giving more robust and trustable result

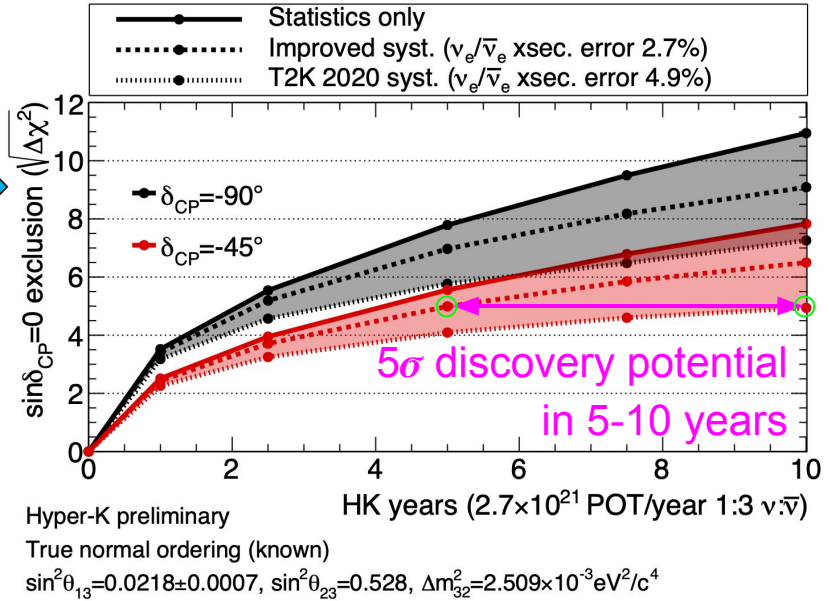


See [T2K report by Christophe Bronner]

Far detector systematic uncertainty

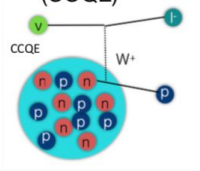
Sample	OA22	New results
ν-mode 1Rμ	3.4%	3.2%
ν-mode 1Re	5.2%	4.9%
ν-mode MR	4.9%	3.9%
ν-mode 1Re+d.e.	14.3%	6.3%
$\bar{\nu}$-mode 1Rμ	3.9%	5.0%
$\bar{\nu}$-mode 1Re	5.8%	6.7%

To HK

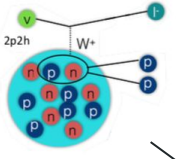


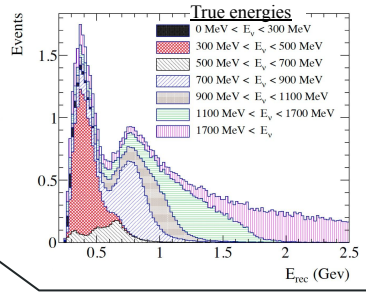
Neutrino Oscillation Systematic Error Breakdown

Charged current (CC) quasi-elastic (CCQE)

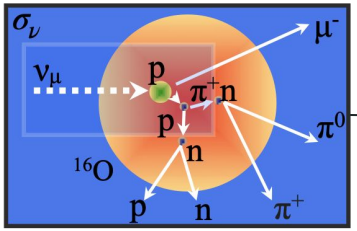


CC multi-nucleon knockout (2p2h)

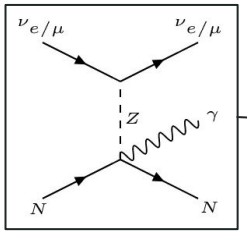




Hadronic re-interactions



Large energy reconstruction errors and event migrations



Geometry

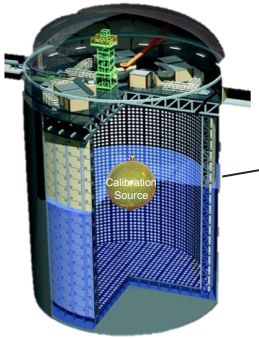
Cherenkov physics

Water properties (light scattering, absorption)

PMT and wall reflectivity

Residual magnetic fields

PMT+electronics response

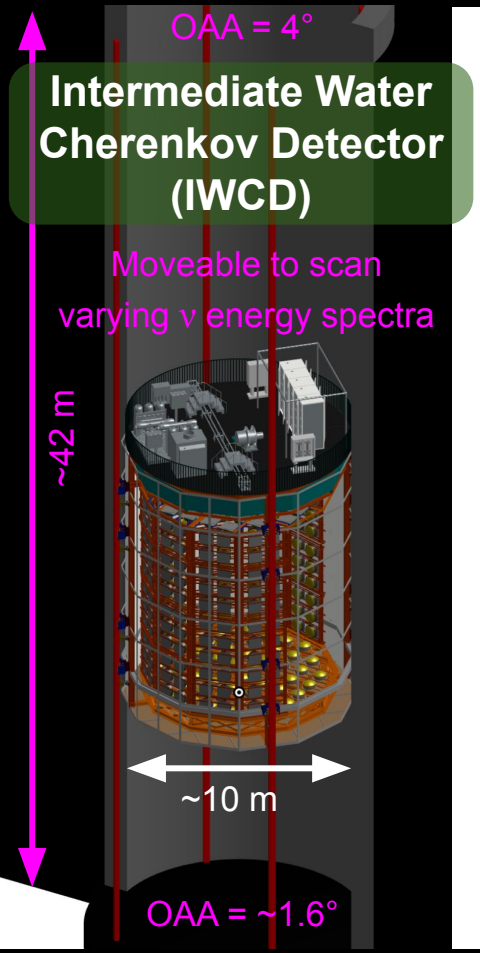


"T2K 2021 syst.": Phys. Rev. D 103, 112008

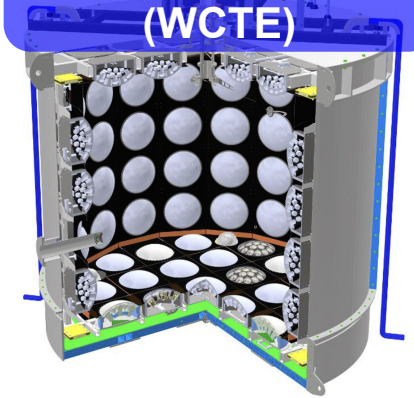
Error Source	% Error for CPV search
φ + σ (ND constrained)	2.7
φ + σ (ND unconstrained)	1.2
Nucleon removal energy	3.6
SK π re-interactions	1.6
Currently theoretical $\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$	3.0
NC γ + other	1.5
SK detector	1.5
Total	**6.0**

Need to reduce to <3% for Hyper-K

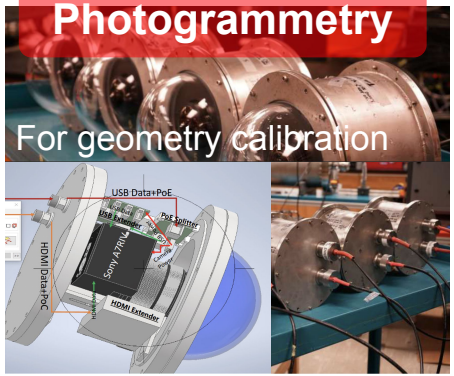
Systematic Error Mitigation Strategies



Water Cherenkov Test Experiment (WCTE)



Photogrammetry



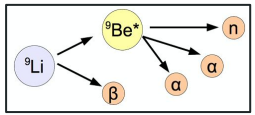
Error Source	Mitigation
φ + σ (ND constrained)	IWCD
φ + σ (ND unconstrained)	IWCD
Nucleon removal energy	IWCD
SK π re-interactions	WCTE
$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$	IWCD
NC γ + other	IWCD, WCTE
SK detector	Photogrammetry

Also for IWCD, WCTE and HK FD

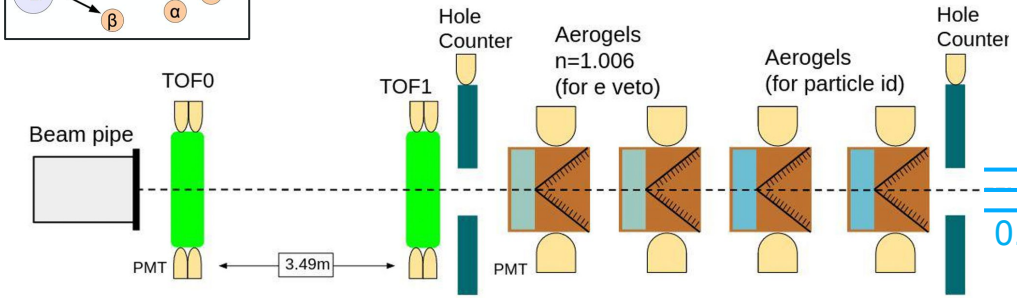
ICRR IURP contributes to improving all errors sources!

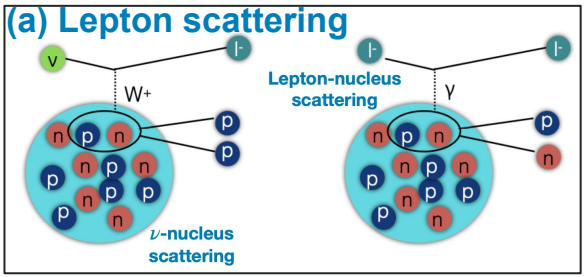
The Water Cherenkov Test Experiment (WCTE)

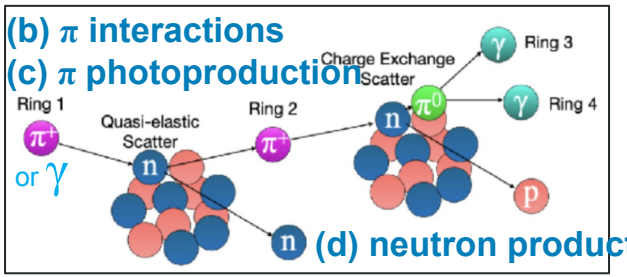
- Prototype of IWCD @ CERN, demonstrator for:
  - New mPMT photosensors (including FD's)
  - Calibration: source deployment, photogrammetry, laser light injector
  - AI/ML technology: e/γ discrimination for potential NCγ measurement in IWCD **(e)**
- Constrain neutrino experiment modeling for SK and HK **(below)**

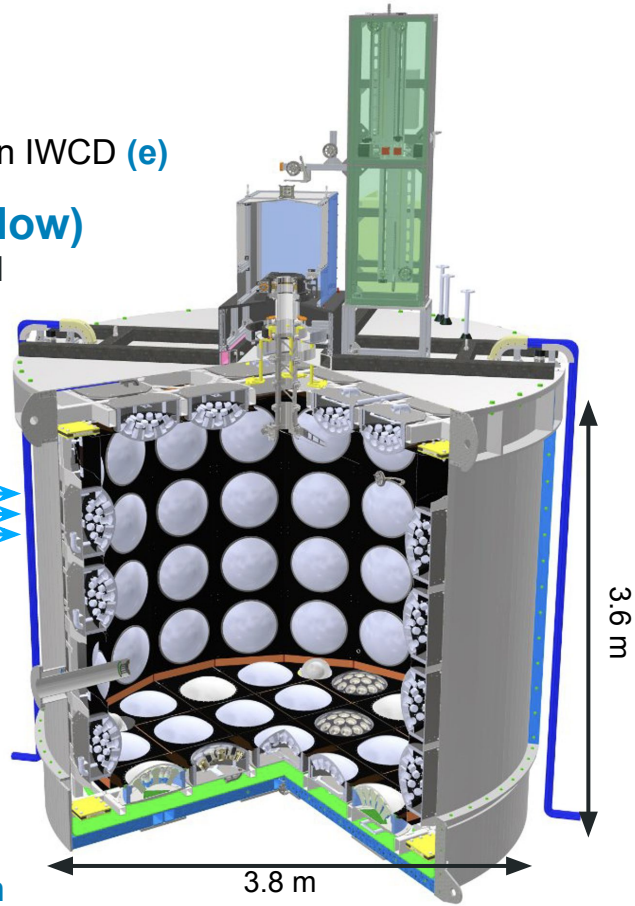


Also, potential measurement of ^{9}Li to constrain DSNB background









1) Photogrammetry Funding Details

- 2019 Goods: Drone, cameras and lamps, deployment hardware
- 2019 Travel: Detector survey and reporting at collaboration meetings
- 2020 Travel: Shipping to Canada to continue calibrations
- 2021 Goods: Underwater red LED lamp
- 2022 Goods: Pressure testing equipment
- 2022 Travel: Pressure testing camera vessels at Kamioka Lab-F
- 2023: Underwater acoustic locator, rental of pool facility for testing

- 2024 Goods: Shipping of computer, lamps, and water system components
  - Remainder to be spent on cable reels for underwater acoustic positioning system

Actual spending (¥):

*Carried over

Year	Goods	Travel	Total	Remainder
2019	832,236	653,170	1,485,406	14,594
2020	0	127,739	127,339	372,261*
2021	872,234	0	872,234	0
2022	124,309	156,940	281,249	168,751*
2023	518,751	0	518,751	0
2024	310,860	0	310,860	39,140

2) Water System Funding Details

- 2022 Goods: Lab materials and infrastructure:
  - Cleaning supplies, computer accessories, networking, chemistry supplies, plumbing, cuvettes for spectrophotometer, network camera
- 2022 Travel: Helped support PG pressure tests, consultation with SK Water Team, obtaining resin and Gd samples
- 2023 Goods: More lab materials to support PMT temperature dependence measurements and materials soak testing:
  - Tank insulation, dehumidifier, power supplies, depth sensors, plumbing and valves, fuses

- 2023 Goods: All-in-one conductivity, depth, temperature sensor
- 2024 Goods: Ultrasonic level sensor, cables, weight scale, (toilet) plunger

Actual spending (¥):

*Carried over

Year	Goods	Travel	Total	Remainder
2022	~333,785	~112,319	~446,104	306,152*
2023	516,048	0	516,048	40,104
2024	173,512	0	173,512	6,488

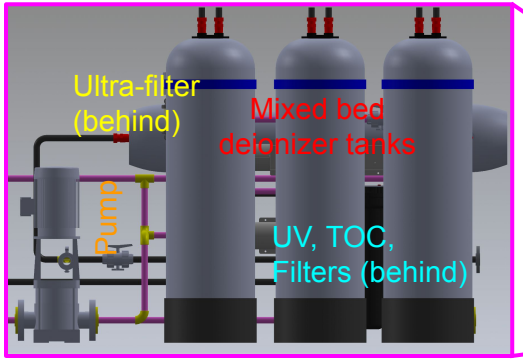
Contributions to WCTE (and IWCD)

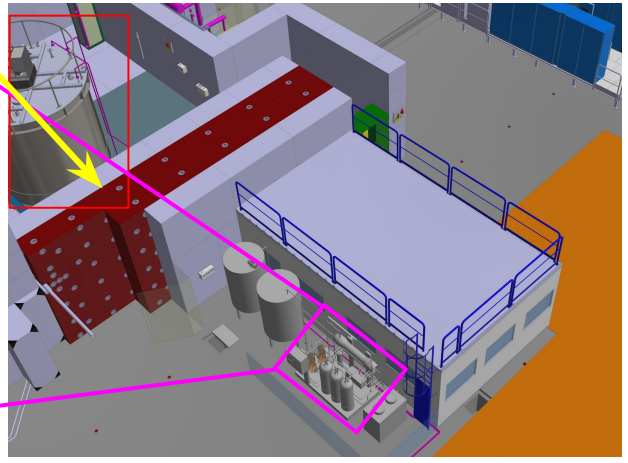
- R&D and components for:

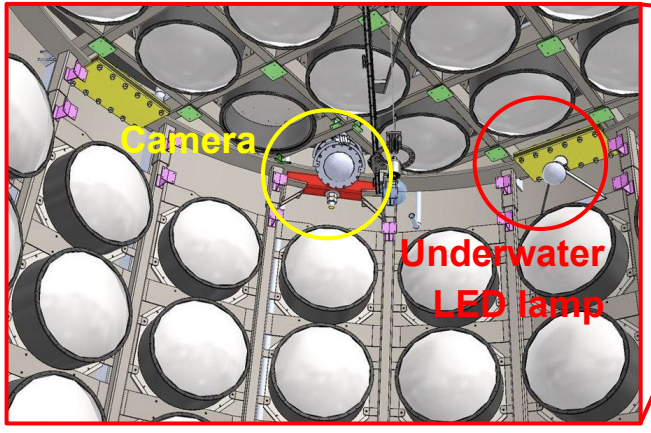
  2) Water purification and gadolinium system
     - Especially experience from SK/EGADS & ICRR/IPMU system

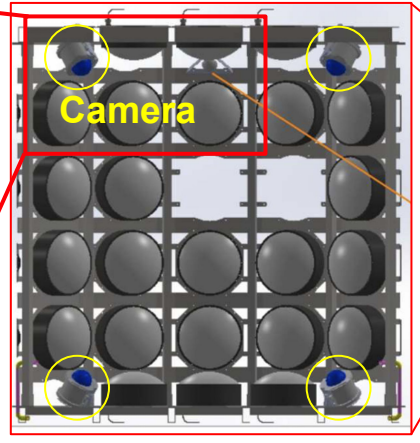
  1) Photogrammetry fixed camera and lighting system

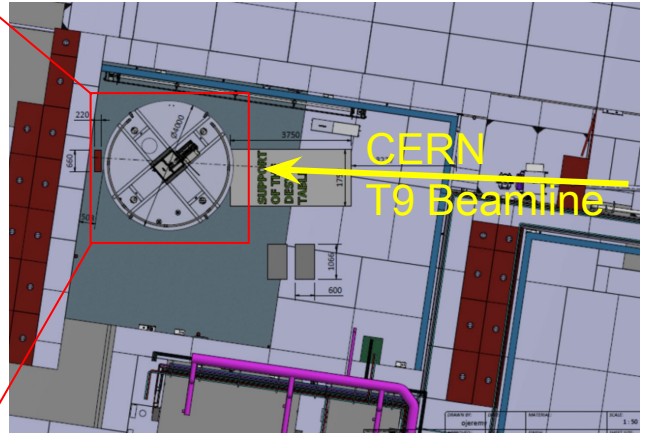
- Both systems will be (partially) re-used in HK's IWCD





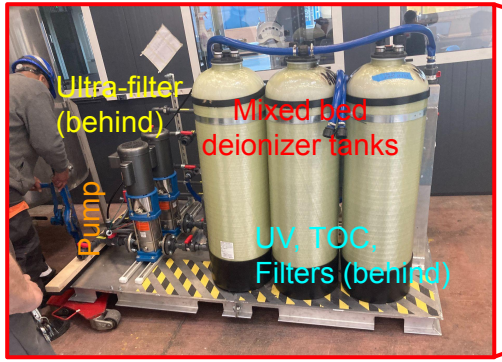


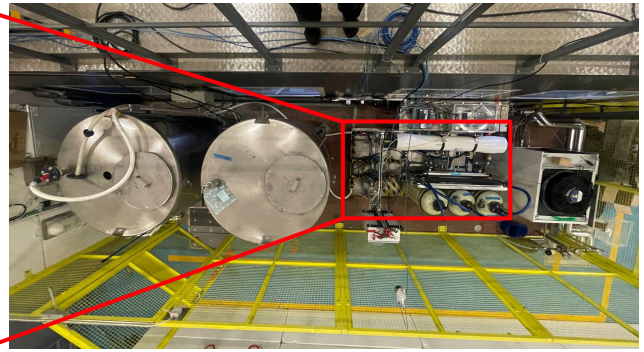


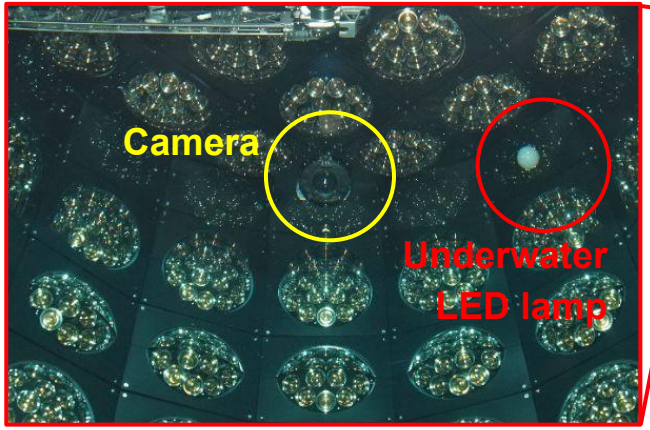


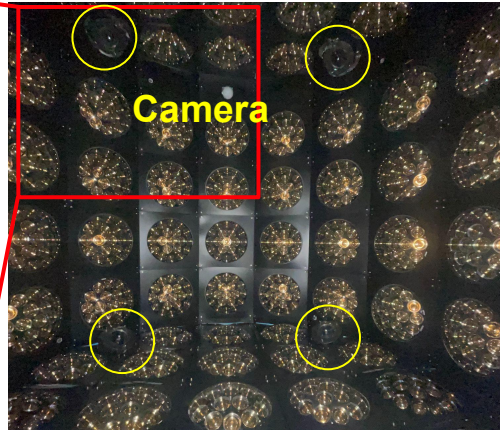
Realizing WCTE

- ICRR IURP helped make WCTE a reality!
- Photogrammetry and water systems delivered, commissioned, and operational by Oct. 2024



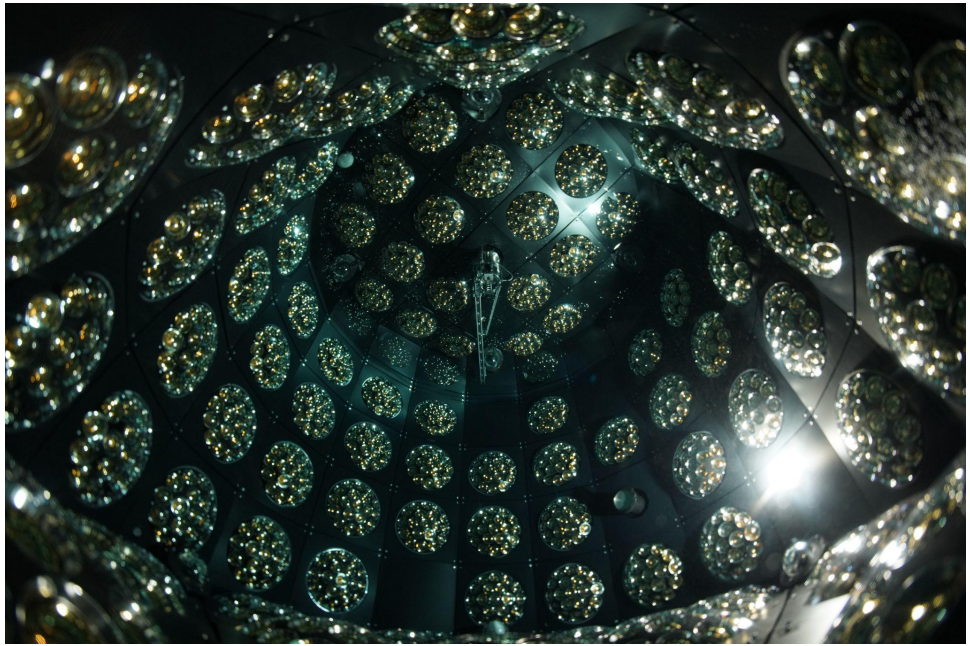


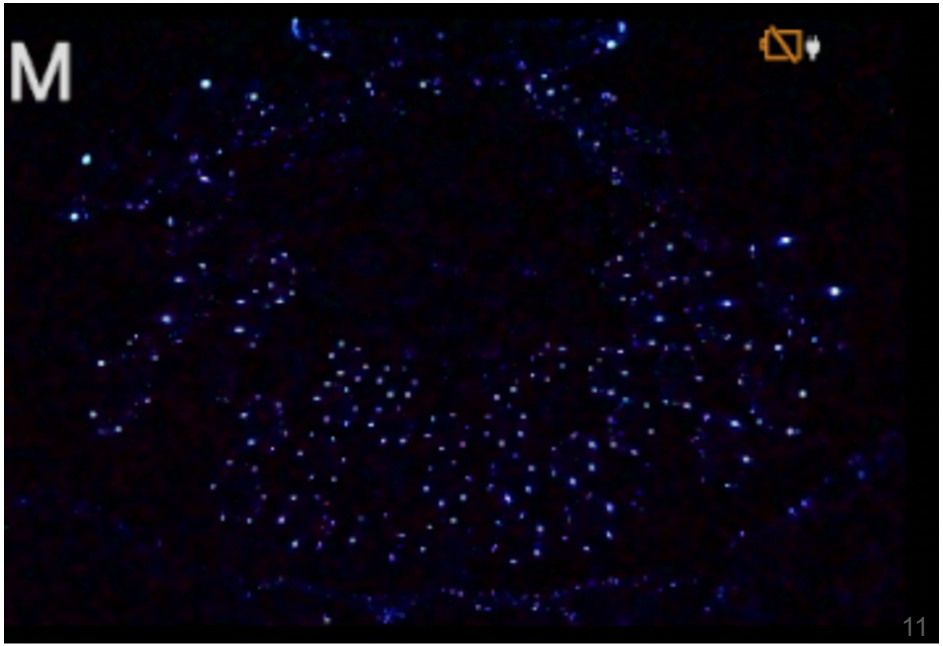




Photogrammetry Data

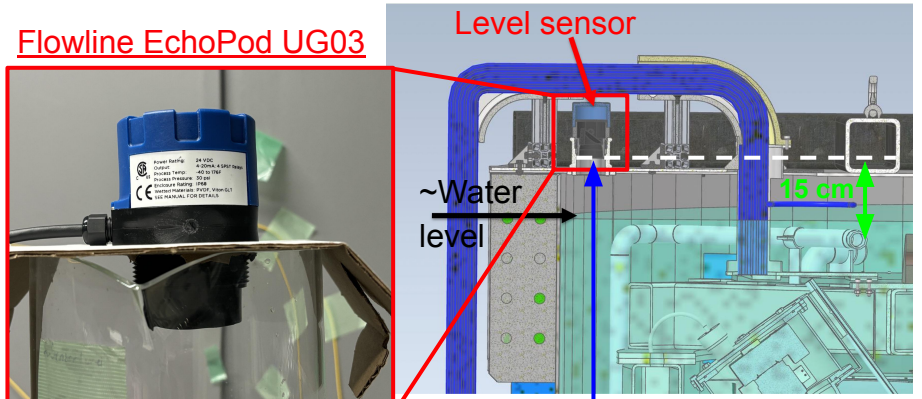
- Took photos from 7 cameras with ambient lighting and mPMT continuous LEDs
- Analysis ongoing to measure geometry
  - Based on software framework developed for SK
- Demonstration and design experience for HK's IWCD

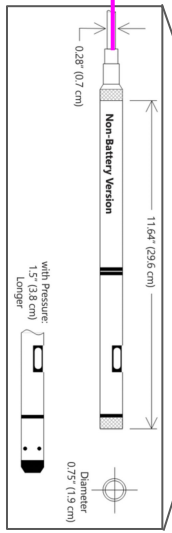


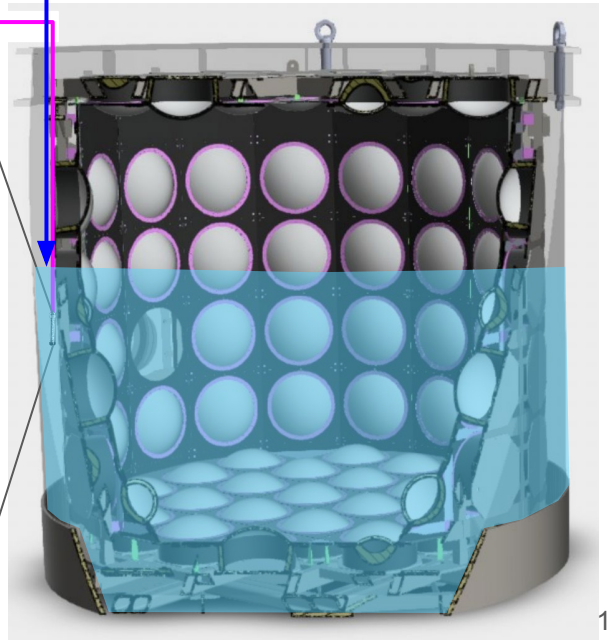


Water Sensors

- Purchased level sensor and all-in-one sensor
- Both monitor detector water level for filling and to detect any leaks
- All-in-one also measures conductivity and temperature for water quality
- Both sensors may be re-used in IWCD

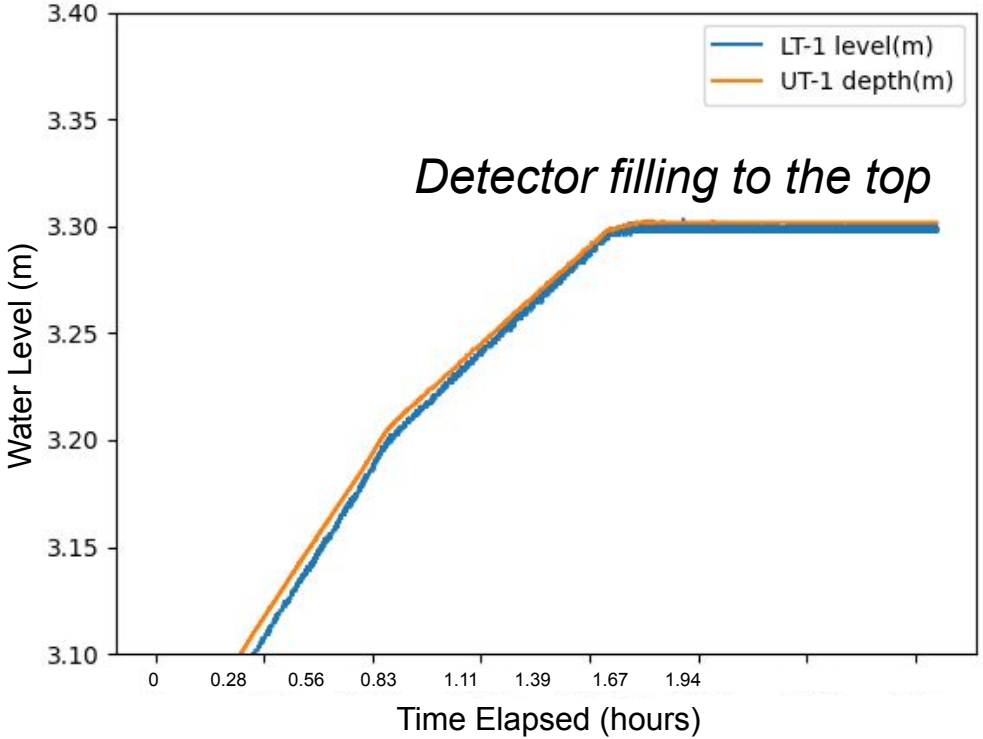




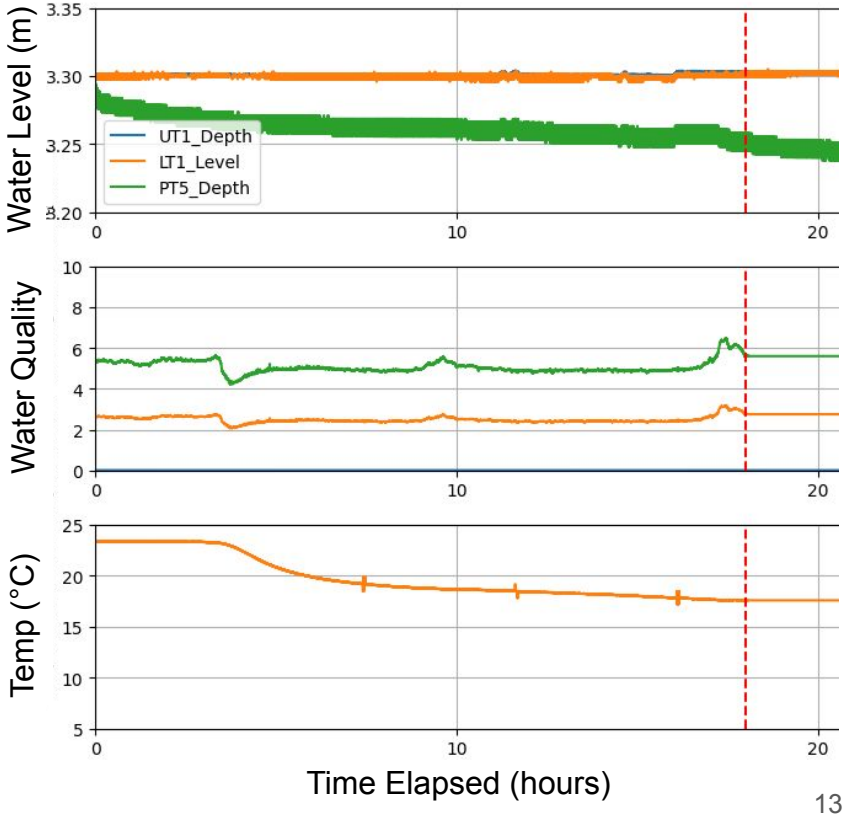


Water Sensor Measurements

Both sensors demonstrated mm resolution

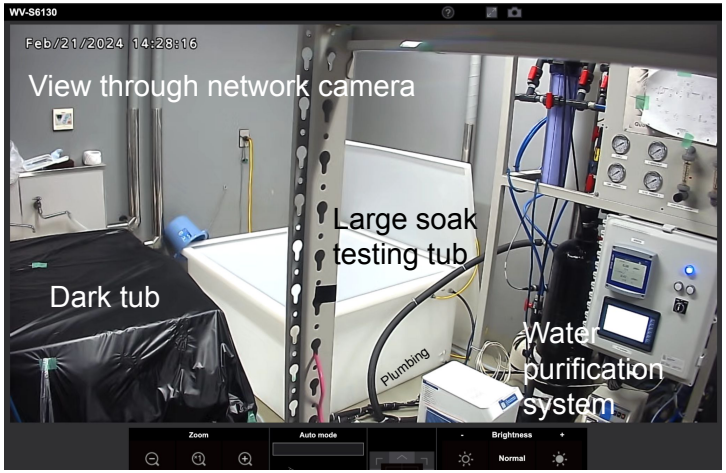


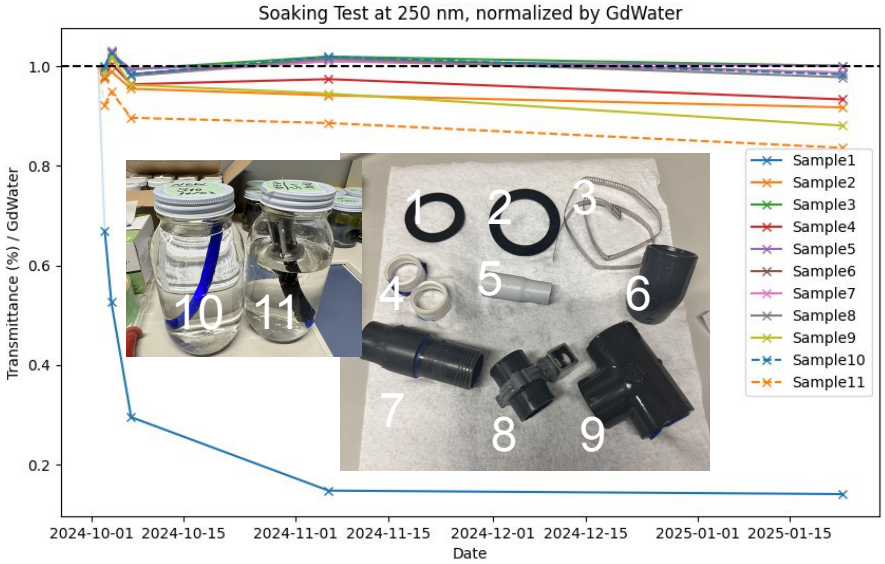
All-in-one monitoring working well:

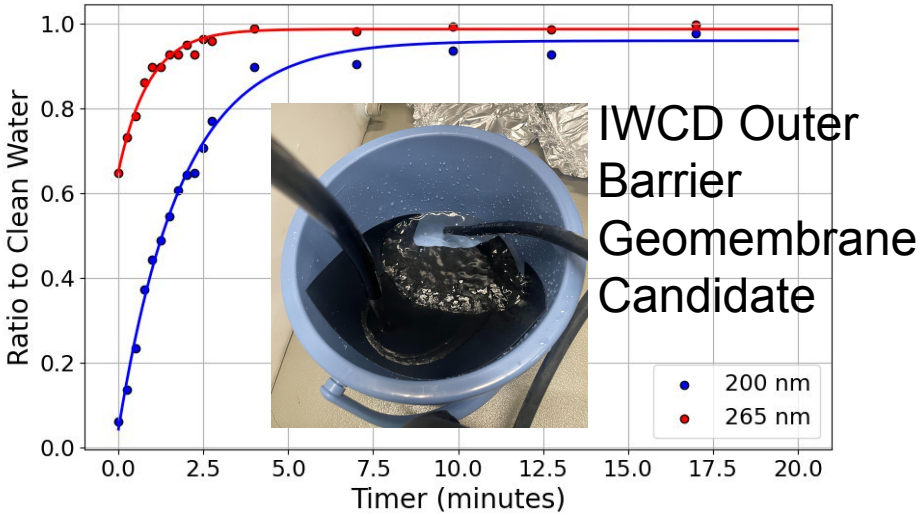


ICRR/IPMU Water System

- Continuing soak tests of WCTE and IWCD materials (also some cable-feedthrough mastic sealing used in FD)
- Also measured purification timescales
- No significant problems found





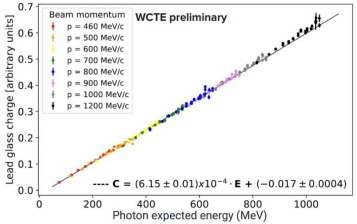


WCTE Highlights

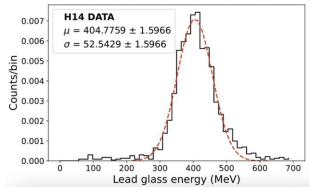
- WCTE analysis started
  - More details featured at last week's [Neutrinos@CERN workshop]
  - Already many lessons learned towards HK-IWCD
- Final run starting this March

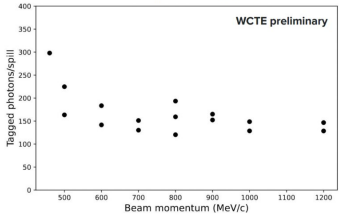
Tagged Gamma Performance

- Tagged gamma data from 2024 is still being analyzed, 2023 test data shown here
- Gamma energy inference confirmed with lead glass calorimeter (right)
- We are able to collect 100-300 tagged gammas per spill
- Tagged gamma configuration is ready for collection of gamma data in WCTE in 2025



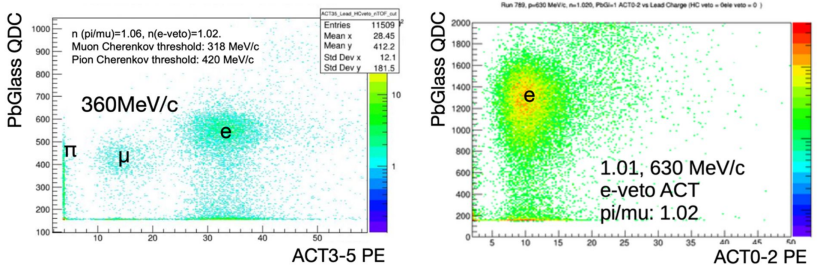
Gamme energy spread of ~50 MeV





ACT Performance

Work-in-progress

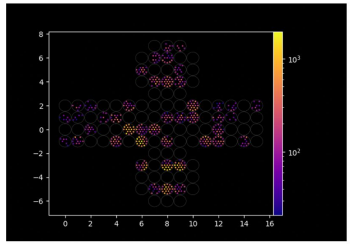


- ACT3-5 used for muon and pion separation, ACT0-2 used for electron/positron tagging
- ACT monitors are able to provide good separation between pions, muons and electrons
- Work is still in progress to establish target timing resolution for TOF monitors

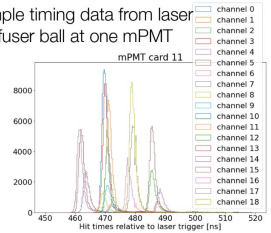
2024 WCTE Data

- Some challenges were met to collect quality WCTE data in 2024
- First instance of operating ~100 multi-PMTs together → issues in firmware, readout and DAQ
  - Firmware and readout work is ongoing to ensure good operation in 2025
- We were able to collect data with about 1/2 of the multi-PMTs operating (see event display to right) and data processing is ongoing
- Major ongoing effort for the calibration of the detector

Example Event Display



Example timing data from laser diffuser ball at one mPMT



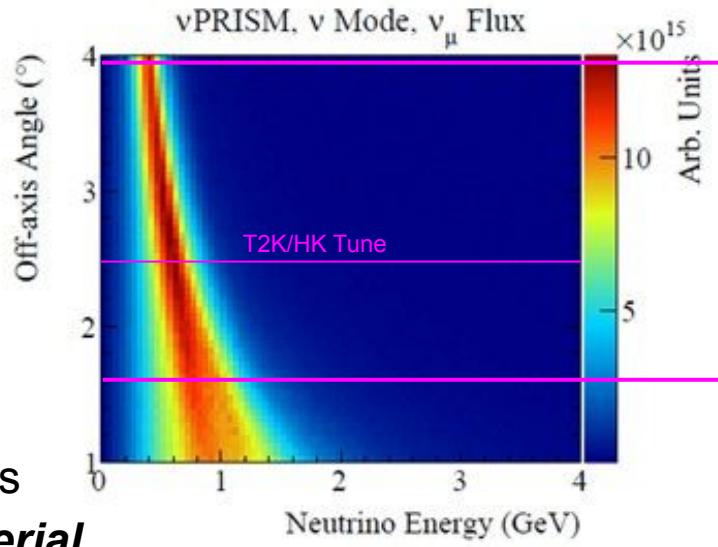
Summary

- WCTE photogrammetry and water purification systems successfully operational
  - Informed by R&D and experience from ICRR/Kamioka
- New WCTE experience and components will be transferred to HK (IWCD)
- Final WCTE beam run starting soon, to provide physics control samples for SK/HK
  - Analysis development is ongoing
- *Thanks to ICRR-IURP for supporting this work!*

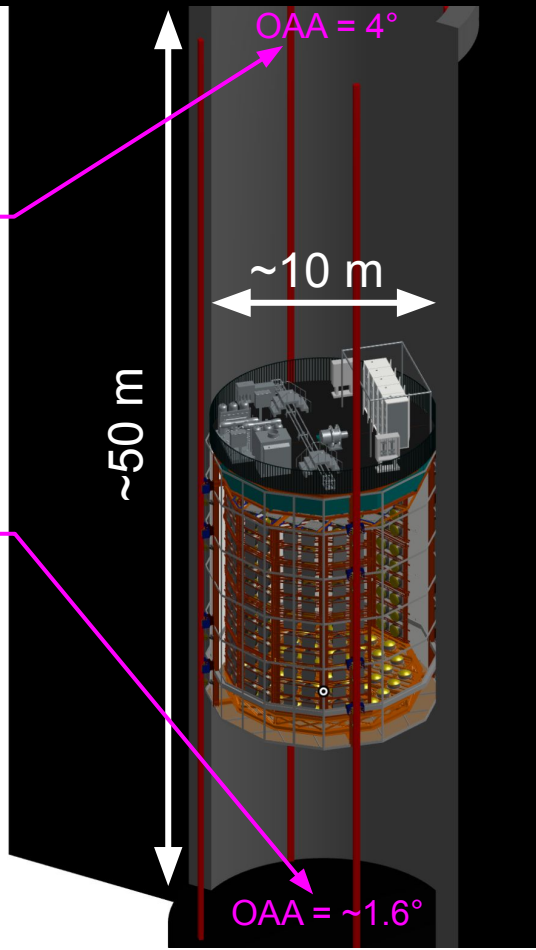
Appendix

The Intermediate Water Cherenkov Detector (IWCD)

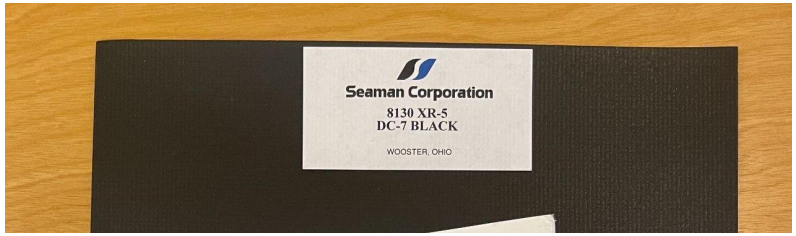
- New detector at ~830 m away from the beam source
- Measure $\frac{\sigma(\nu_e)}{\sigma(\nu_\mu)} / \frac{\sigma(\overline{\nu_e})}{\sigma(\overline{\nu_\mu})}$ a significant systematic for the CPV measurement
- Oscillated energy spectrum very different from unoscillated spectrum
  - ➢ Measure neutrino beam at different energies with ***same detector material***



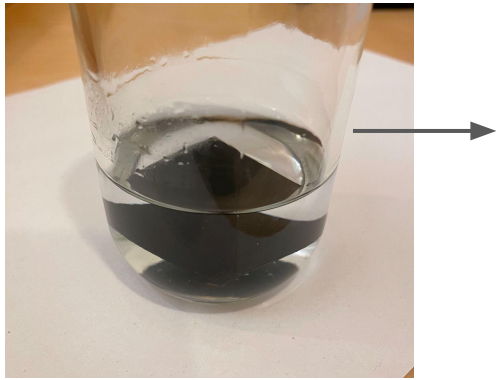
- **nuPRISM concept: Move IWCD vertically** → vary OOA → different neutrino energy spectra → improved neutrino interaction measurements

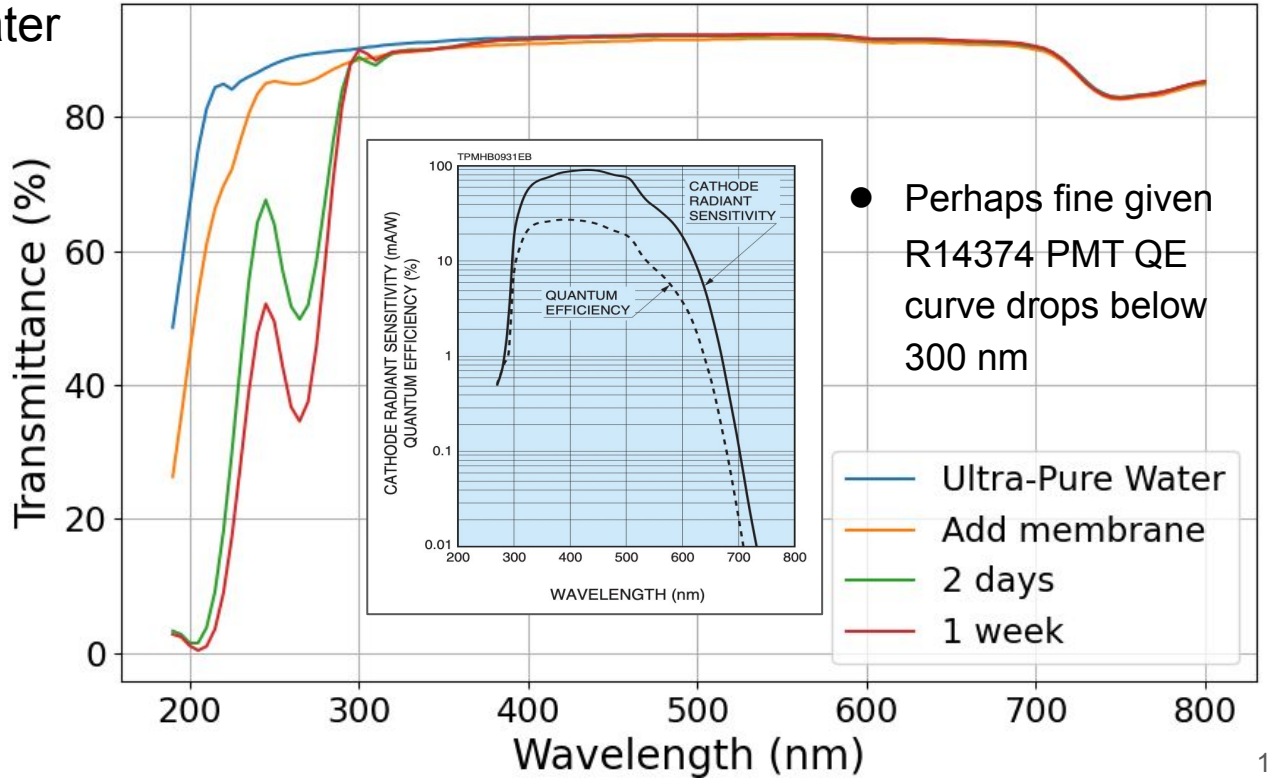


IWCD Outer Barrier Candidate



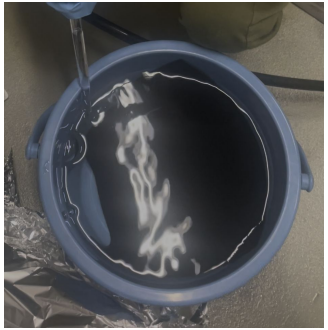
- Geomembrane sample
- Soak test of 16 cm^2 (SA = 32 cm^2) sample in 100 mL of ultra-pure water
- Immediately showed degradation of water quality (transmittance) in the UV region
  -





- Perhaps fine given R14374 PMT QE curve drops below 300 nm

Larger Sample Soak

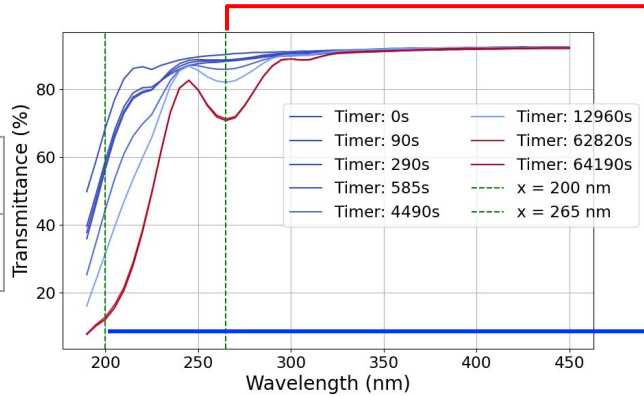


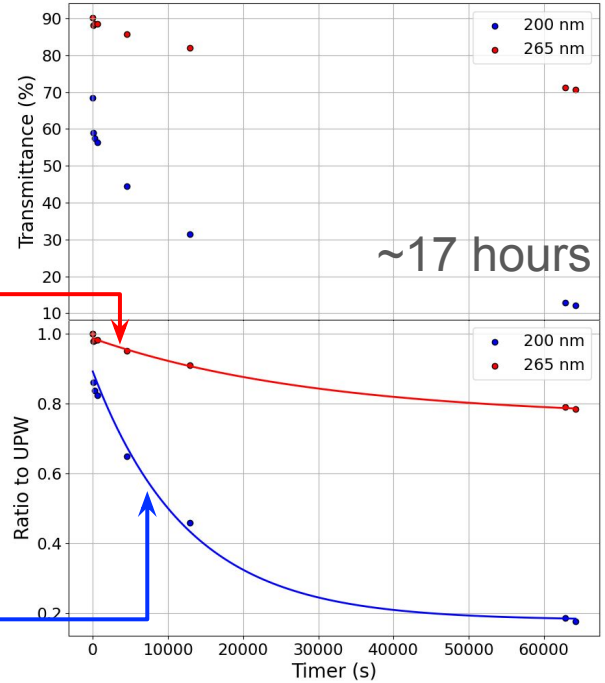
- Bucket of water circulated to purify
- Larger membrane sample immersed and covered
  - But not air tight seal
- Table of quantities to get an idea of scaling factors to IWCD, e.g. elution time scale should be (25/0.65) = 38 times slower in IWCD?

	Water Mass, V (tonne)	Surface Area, SA (m^3)	SA/V Ratio
IPMU	0.004	0.1	25
IWCD	608	398	0.65

Exponential fits indicating rate of elution of impurities into the UPW

Wavelength (nm)	200	265
Exp. τ_{soak} (hour)	3.5 ± 0.8	8.4 ±1.7





Cleaning / Circulation

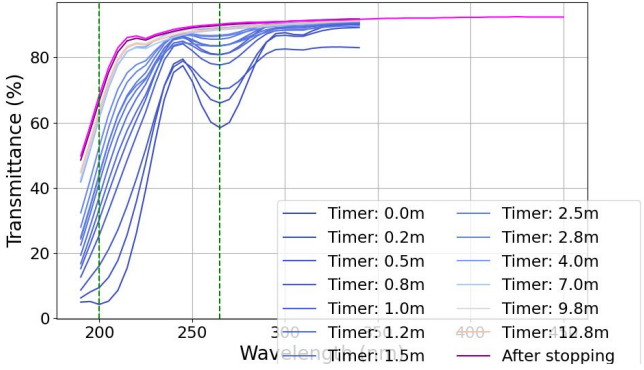
- Bucket circulated with membrane
- Impurities can be removed by purification system

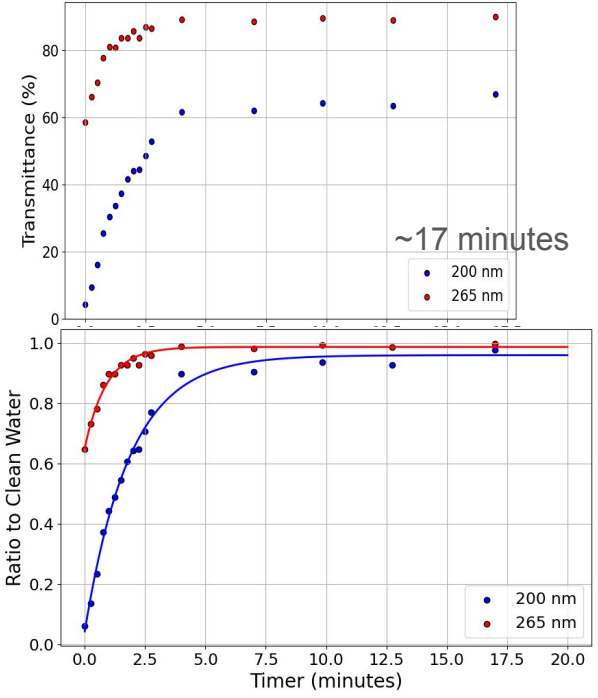
Video online (link)

	Water Mass, V (tonne)	Surface Area, SA (m^3)	SA/V Ratio	Flow (t/hr)	Turnover Time
IPMU	0.004	0.1	25	0.3	49 sec
IWCD	608	398	0.65	4.0	6.3 days

Exponential fits indicating rate of removal of impurities from water

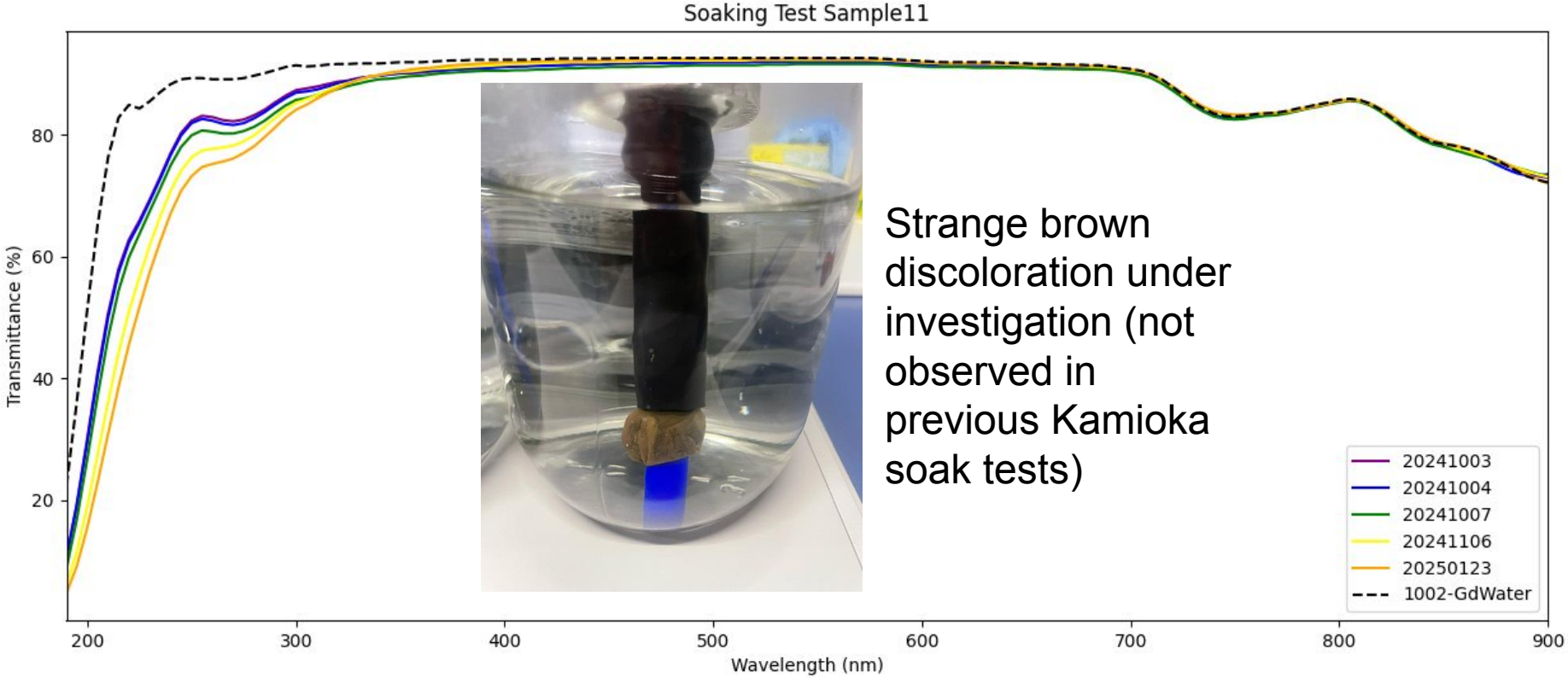
Wavelength (nm)	200	265
Exp. τ_{clean} (min)	1.9 ± 0.1	0.9 ± 0.1
Exp. scale (-ve)	0.9	0.3





Soak Test of Cable Feedthrough Mastic Seal

Degradation very slow (~4 months) and mostly outside PMT QE sensitivity



Strange brown discoloration under investigation (not observed in previous Kamioka soak tests)

1) Photogrammetry Funding Overview

Approved amounts (¥):

Year	Goods	Travel	Total (inc. topup)
2019	700,000	300,000	1,500,000
2020	200,000	300,000	500,000
2021	300,000	200,000	500,000
2022	150,000	300,000	450,000
2023	50,000	300,000	350,000
2024	50,000	300,000	350,000

Reported this time

Actual spending (¥):

*Carried over

Year	Goods	Travel	Total	Remainder
2019	832,236	653,170	1,485,406	14,594
2020	0	127,739	127,339	372,261*
2021	872,234	0	872,234	0
2022	124,309	156,940	281,249	168,751*
2023	518,751	0	518,751	0
2024	310,860	0	310,860	39,140

2) Water System Funding Overview

Approved amounts:

Year	Goods	Travel	Total
2022	760,000	0	760,000
2023	200,000	50,000	250,000
2024	180,000	0	180,000

Reported this time

Actual spending:

*Carried over

Year	Goods	Travel	Total	Remainder
2022	~333,785	~112,319	~446,104	306,152*
2023	516,048	0	516,048	40,104
2024	173,512	0	173,512	6,488