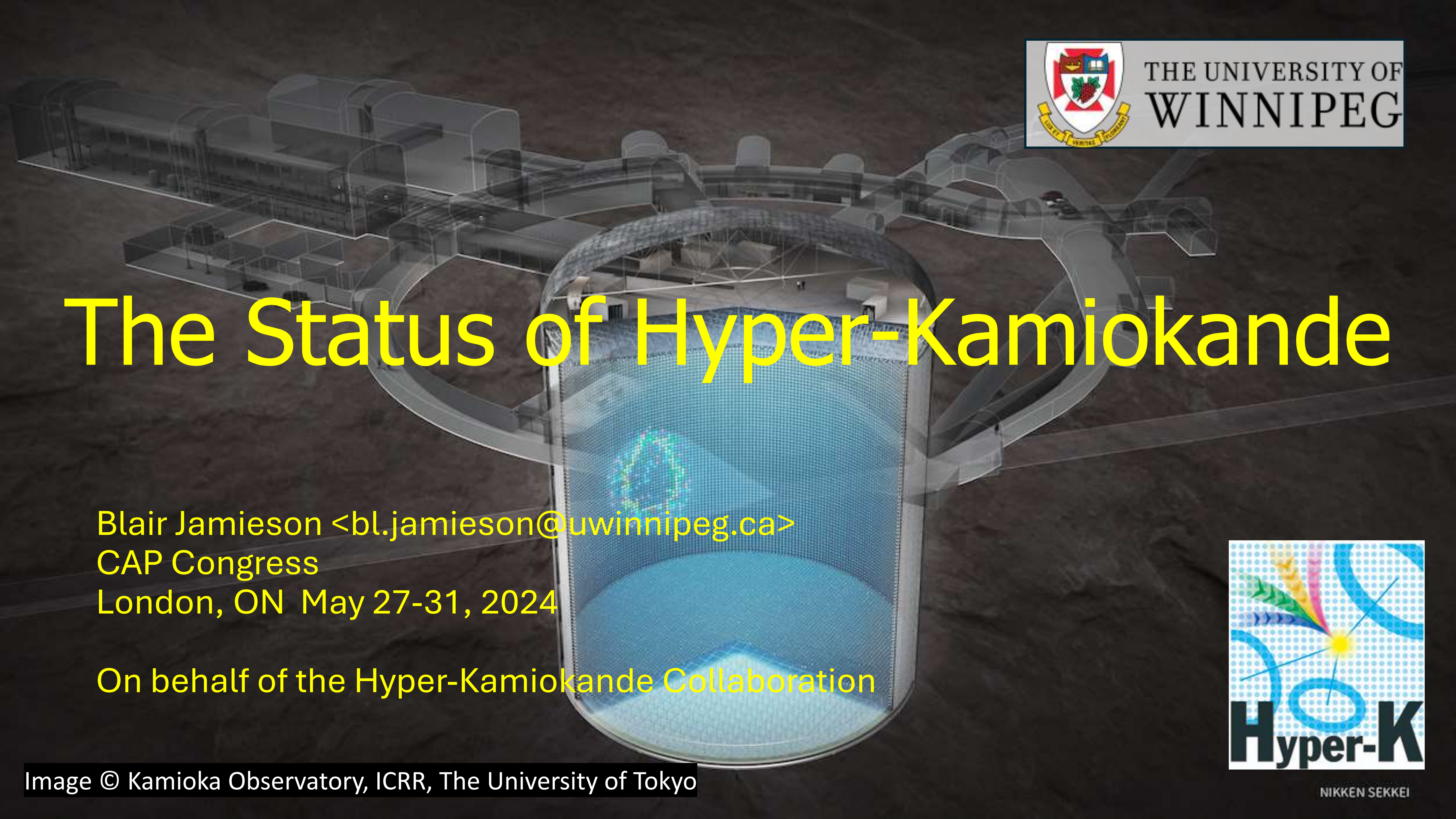


Image © Kamioka Observatory, ICRR, The University of Tokyo

NIKKEN SEKKEI

The Status of Hyper-Kamiokande

Blair Jamieson <bl.jamieson@uwinnipeg.ca>
CAP Congress
London, ON May 27-31, 2024

On behalf of the Hyper-Kamiokande Collaboration

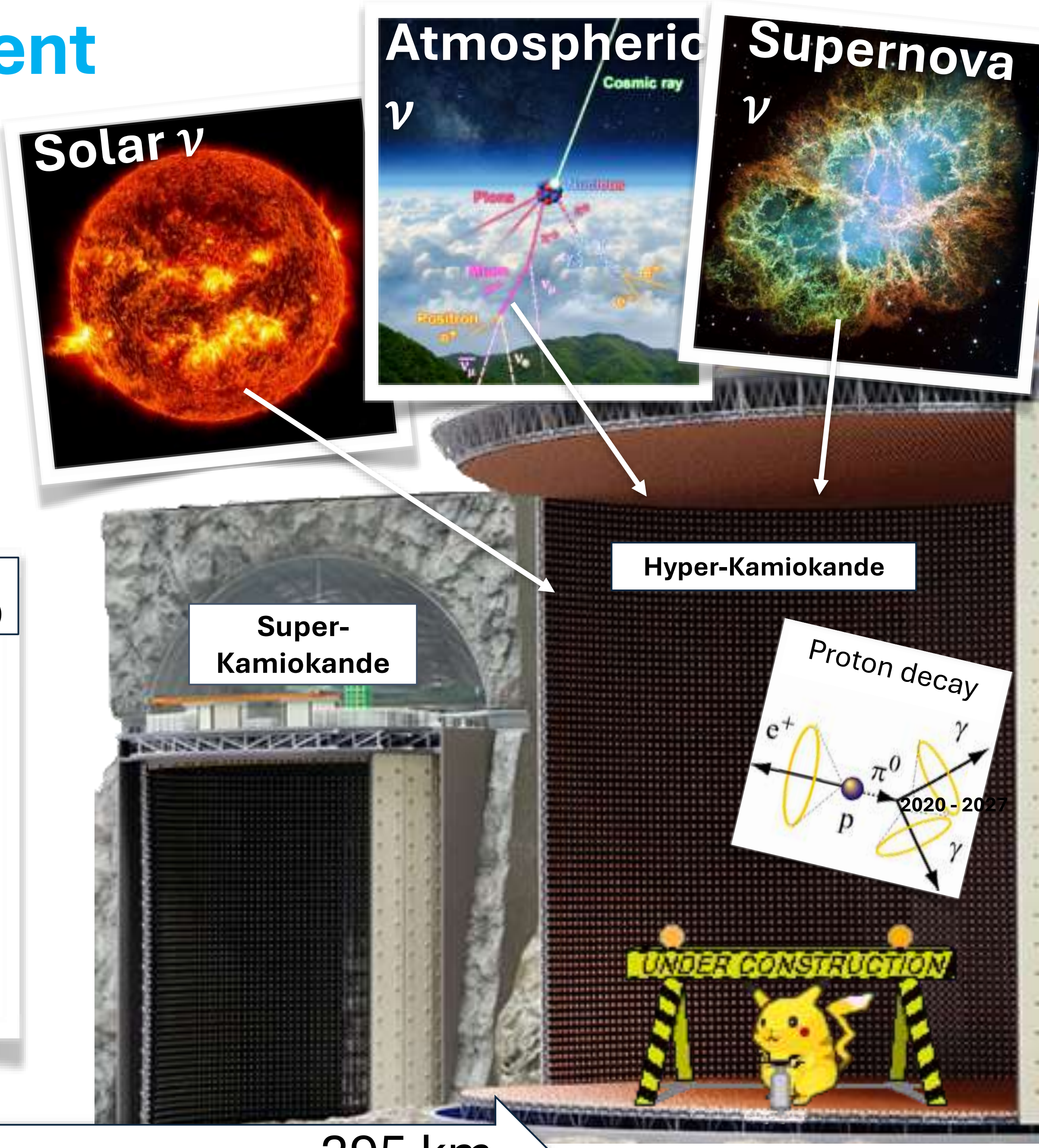
THE UNIVERSITY OF WINNIPEG

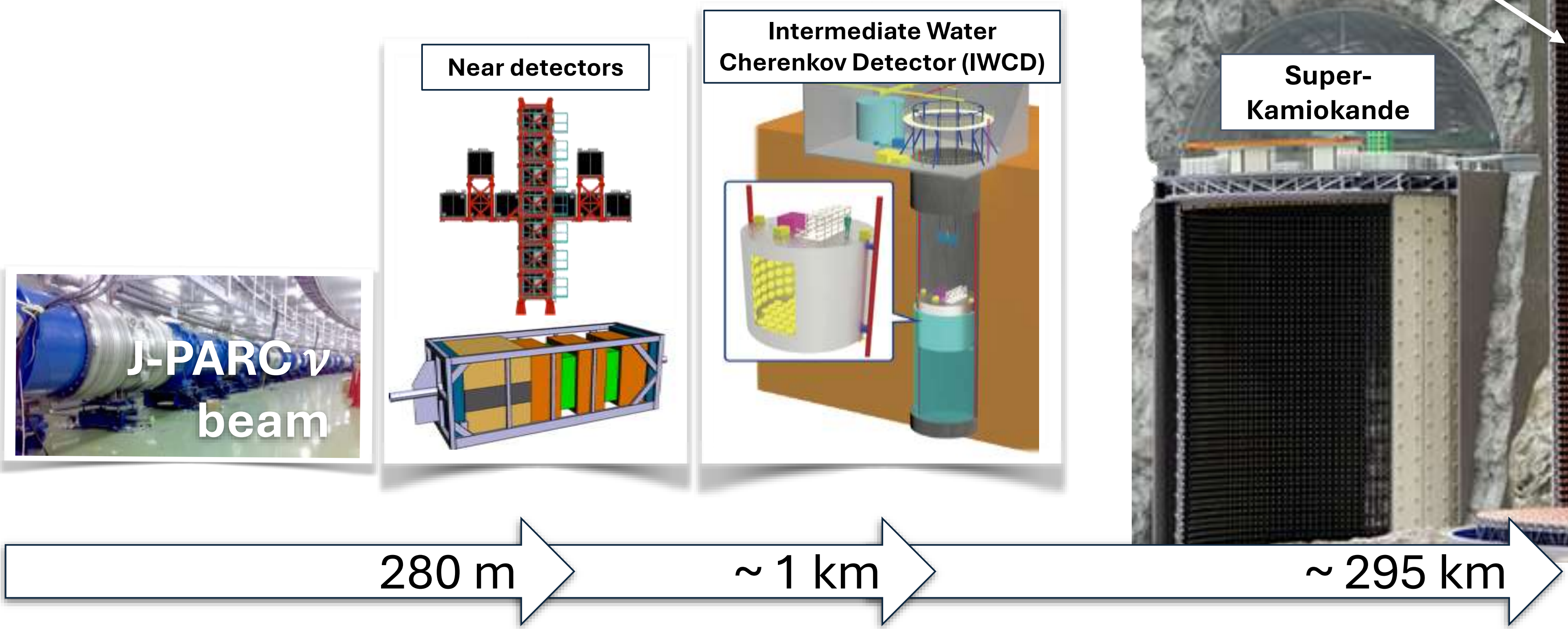
The Hyper-Kamiokande Experiment

Hyper-Kamiokande (Hyper-K) is a world-leading neutrino experiment, building on success of Super-Kamiokande & T2K.

Broad & ambitious physics programmes covering many neutrino sources as well as proton decay measurements.

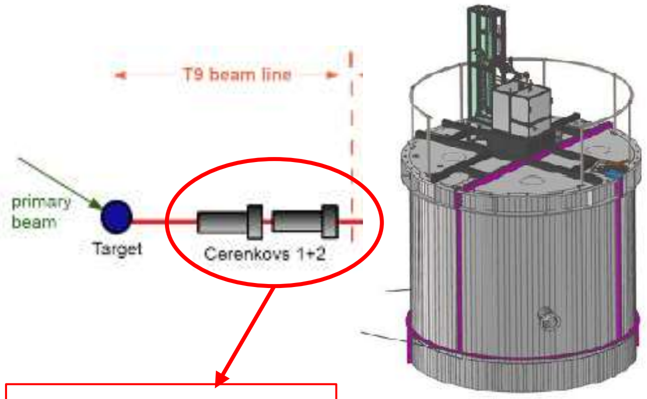
Water Cherenkov detector technology provides huge target mass with excellent particle ID and reconstruction capabilities.





Water Cherenkov detectors for neutrino physics

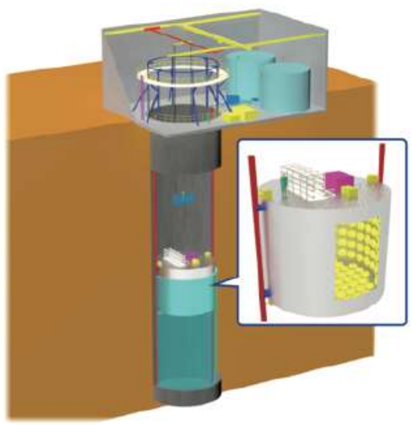
WCTE



Talk by S.Yousefnejad was in Monday PM session

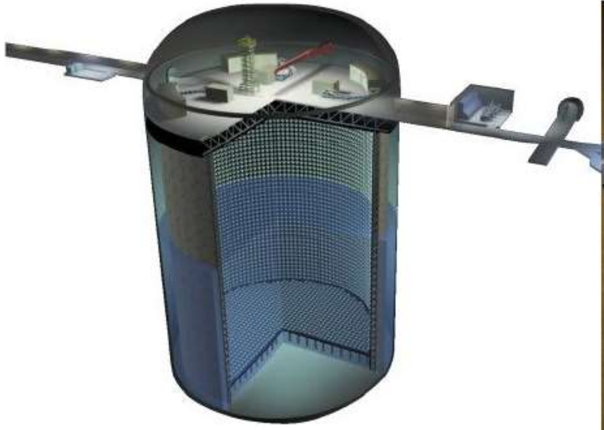
4 m ⌀ x 3.5 m tall
100 mPMTs
Operation in 2024-2025

IWCD



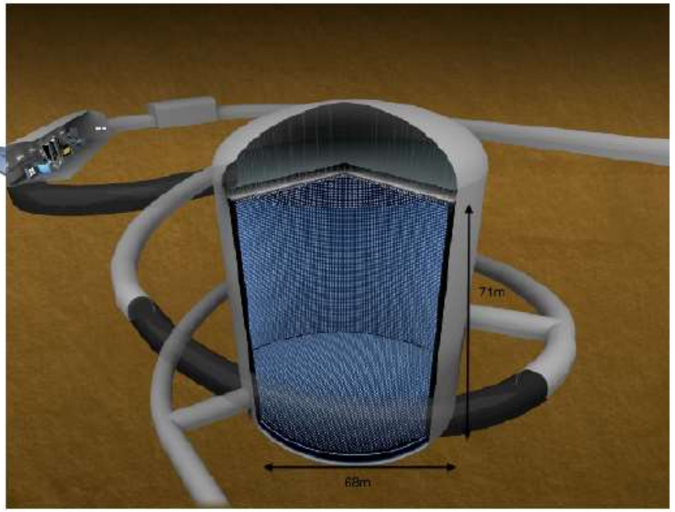
7 m ⌀ x 8 m tall (ID)
370 mPMTs
Operation from 2027

Super-K



39 m ⌀ x 41 m tall
11,000 20-inch PMTs
Operating now, including for T2K

Hyper-K



68 m ⌀ x 71 m tall
20,000 20-inch PMTs
800 mPMTs (200 LED-mPMT)
Operation from 2027

- WCTE and Super-K can be seen as testbeds for detector systems, calibration techniques and event reconstruction to be used in IWCD and Hyper-K
- They can also used to produce interesting physics before the start of Hyper-K
- WCTE measurements can be inputs to Super-K and T2K measurements in the near term

Neutrino oscillations

- For 3 neutrinos → Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"Solar neutrinos" "Reactor neutrinos" "Atmospheric neutrinos"

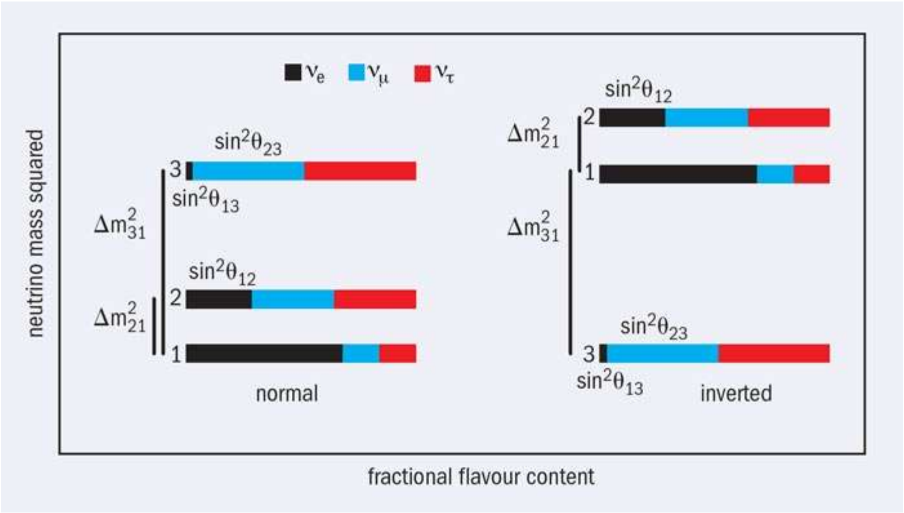
- 3 non zero mixing angles → possible CP violation in the lepton sector

$$P(\nu_\mu \to \nu_e) \neq P(\overline{\nu}_\mu \to \overline{\nu}_e)$$

Param	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.10^{+0.13}_{-0.12}$	$2.75 \to 3.50$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.58^{+0.20}_{-0.33}$	$4.27 \to 6.09$
$\theta_{23}/^\circ$	$48.3^{+1.2}_{-1.9}$	$40.8 \to 51.3$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.241^{+0.066}_{-0.065}$	$2.046 \to 2.440$
$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$
$\delta_{CP}/^\circ$	222^{+38}_{-28}	$141 \to 370$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$	$2.449^{+0.032}_{-0.030}$	$2.358 \to 2.544$

PDG 2019

Open questions:
- CP violation
- Mass hierarchy
- θ_{23} octant



Hyper-K Detector

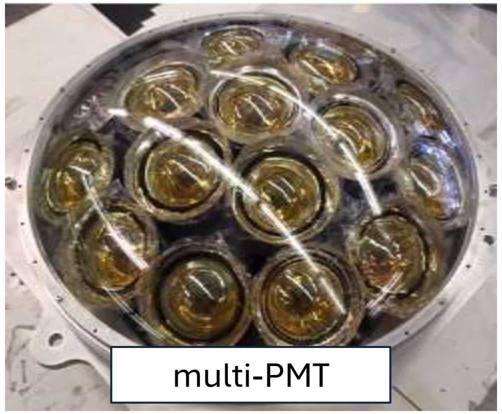
8 x increase in fiducial mass over Super-K

- 71 m tall x 68 m diameter = 258 kt total mass
  188 kt fiducial mass
- Outer detector region for active veto of incoming particles
  - 1 m wide around barrel, 2 m at top & bottom

New photo-detector technology for increased sensitivity

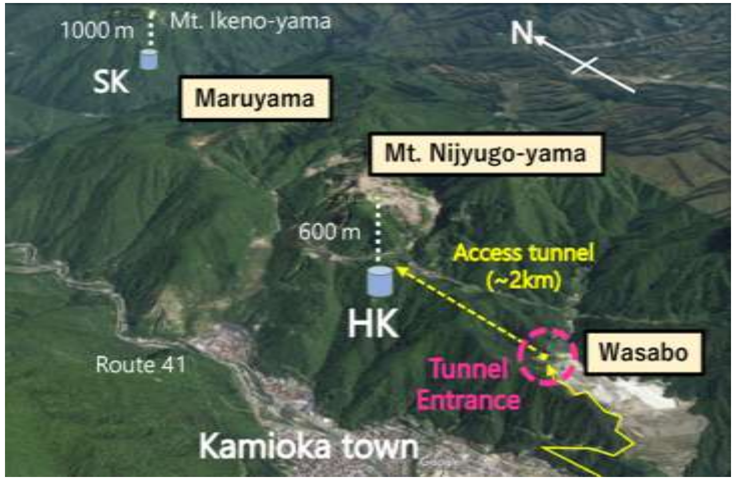
- 20,000 B&L 50 cm PMTs = 20% photo-coverage
  - 1.5 ns timing resolution (half that of SK PMTs)
  - Double quantum efficiency of SK PMTs
- Additional photo-coverage from multi-PMT modules
  - 8 cm PMTs grouped in modules of 19 PMTs
  - Improved position, timing, direction resolution
  - Also used for in-situ calibration of 50cm PMTs


50cm B&L PMT


multi-PMT

Detector Construction

Access tunnel completed, dome competed,
Cavern excavation underway



PMT production on schedule

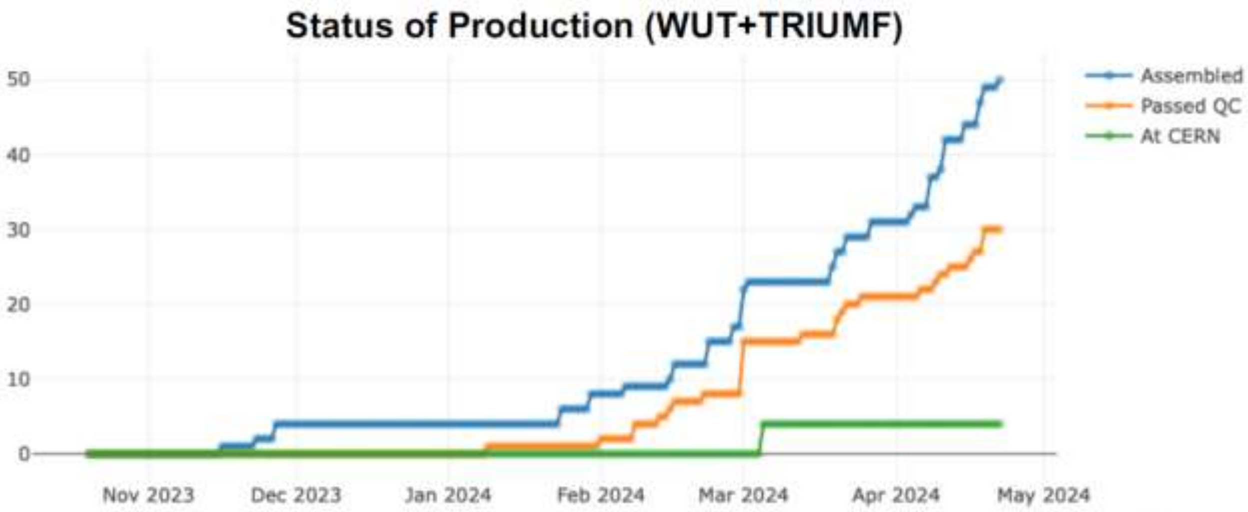
Inspection and testing is ongoing

R&D for 50cm PMT covers is in progress

Front. Phys., 26 March 2024
Sec. High-Energy and Astroparticle Physics
Volume 12 - 2024 | https://doi.org/10.3389/fphy.2024.1378254

Multi-PMTs

- Multi-PMTs are a major part of Canada's contribution to Hyper-K (funded through CFI-IF)
- Significant effort to develop the IWCD-style multi-PMT
  - These are the main photon detection system for IWCD - must work!
- Pilot production of IWCD-style multi-PMTs for initial operation in WCTE now advancing
- Operation in WCTE will be major milestone towards delivery of mPMTs for IWCD!



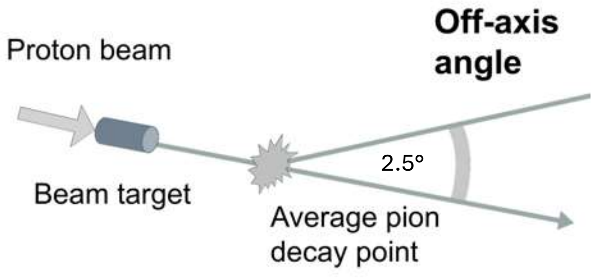
FD mPMT

Modified FD mPMT

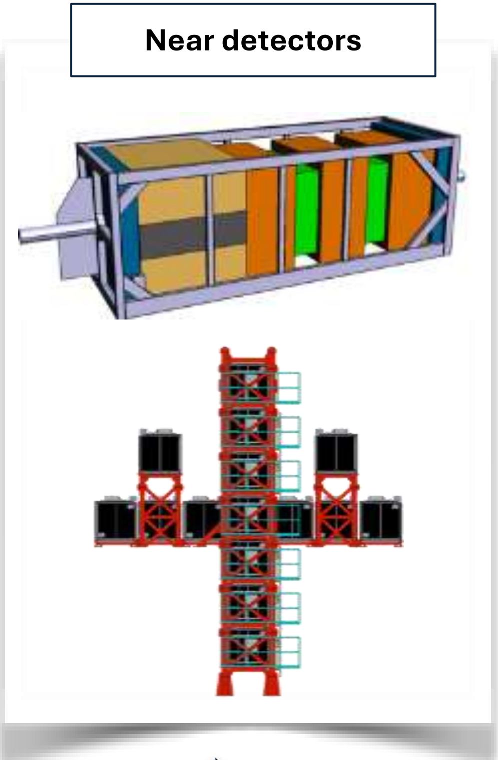
R. Gornea

J-PARC Beam & Detectors

J-PARC beam upgrade 0.75 → 1.3 MW for increased event rate

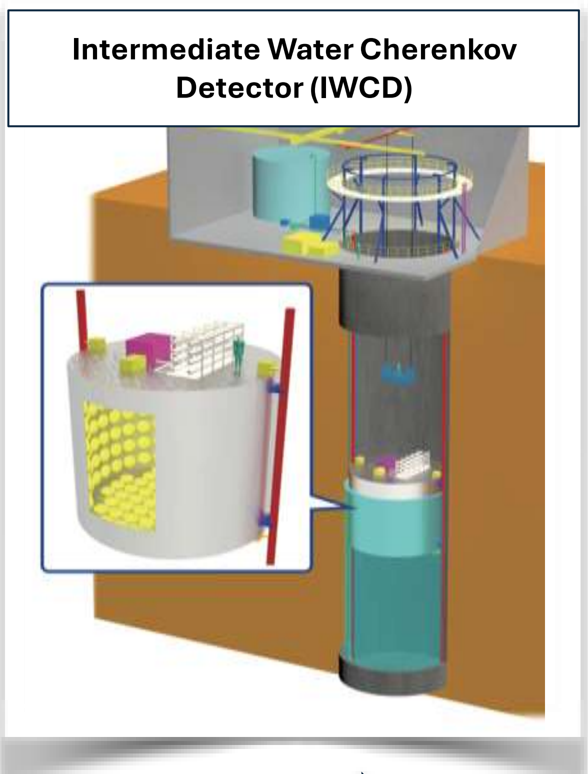


Upgraded T2K near detectors to continue to Hyper-K era



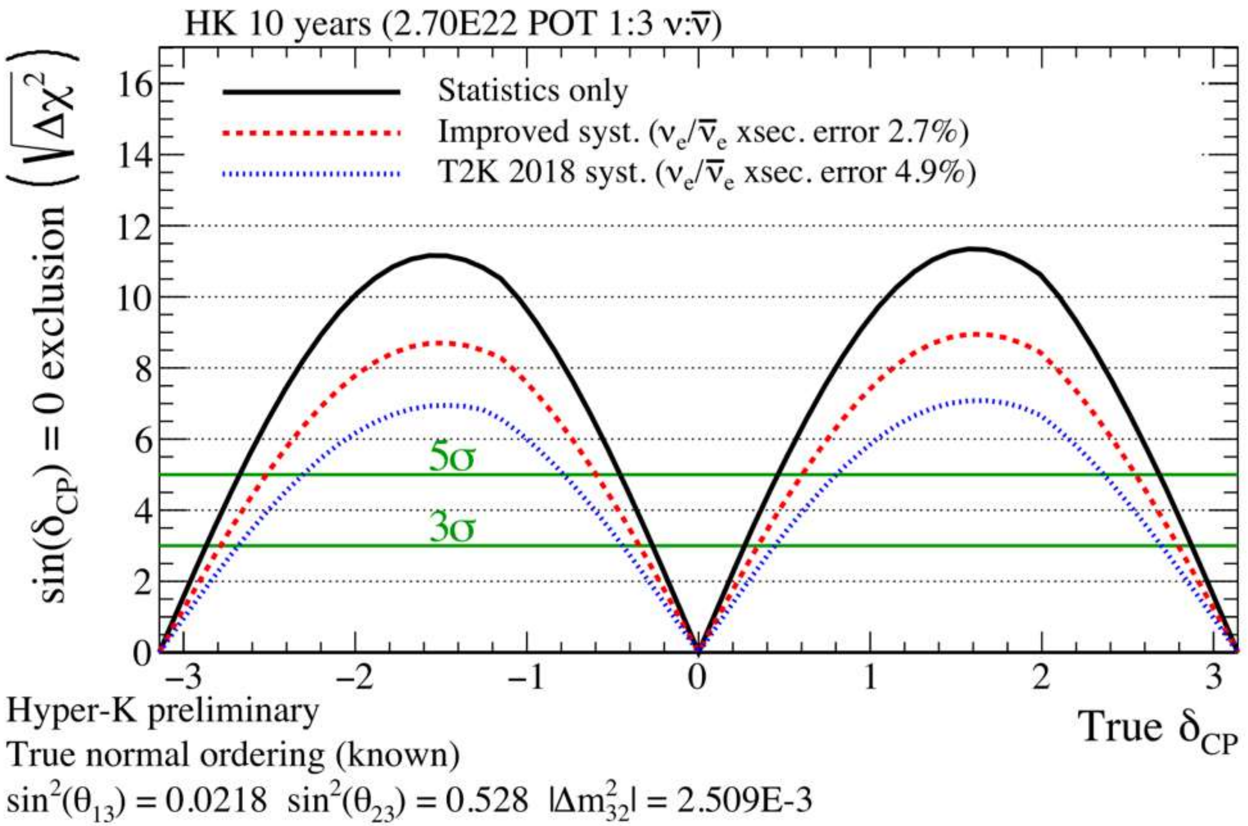
New Intermediate Water Cherenkov Detector

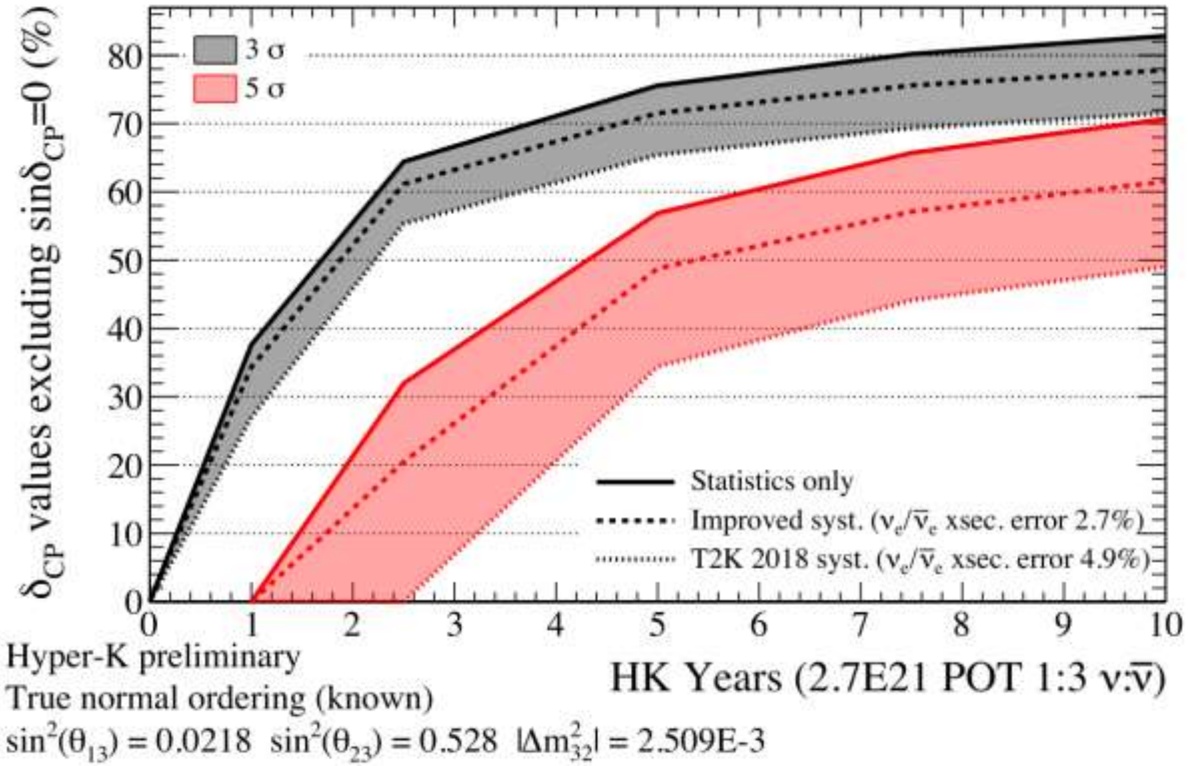
- Measure flux and cross sections of mostly unoscillated beam
  - Reduce systematics at far detector
- Moves vertically in ~50 m tall pit
  - Spans off-axis angles for different ν energy spectra
- 6 m tall x 8 m diameter surrounded with ~ 500 multi-PMT modules
- Gadolinium doped water provides enhanced neutron detection



280 m → ~ 1 km

Oscillation Measurements - Search for CP Violation





- **Reduction of systematic errors has large impact on potential to discover CP violation**
- $>5\sigma$ discovery after 10 years for 60% of δ_{CP} values
- $\sim 8\sigma$ around $\delta_{CP} = -\pi/2$ (favoured by T2K measurements)

DETECTOR CALIBRATION IN HYPER-K

- Individual PMT response
  - Relative gain
  - Absolute SPE gain, relative QE, SPE distribution
  - Charge nonlinearity
  - PMT relative timing
  - TQ map
  - **Angular response**
- **Reflectance** from PMT and black sheet
- Water parameters (Rayleigh scattering, Mie scattering, attenuation, **Raman scattering**)
- Energy scale
- **Geometry (PMTs and calibration sources)**
- **Cherenkov physics**

LEDs

mPMT

NiCf source

Laser diffuser

Light injectors

Control samples

eLINAC

Ex-situ PMT measurement

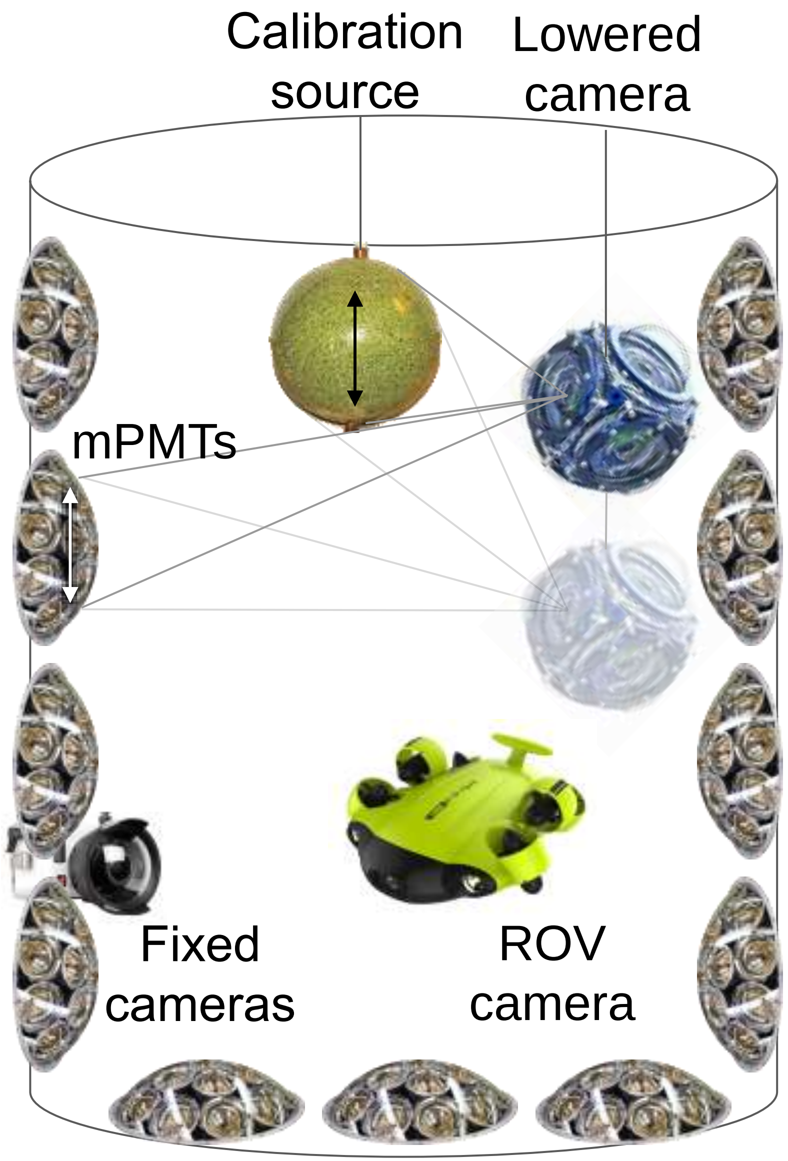
Photogrammetry

Test beam (WCTE)

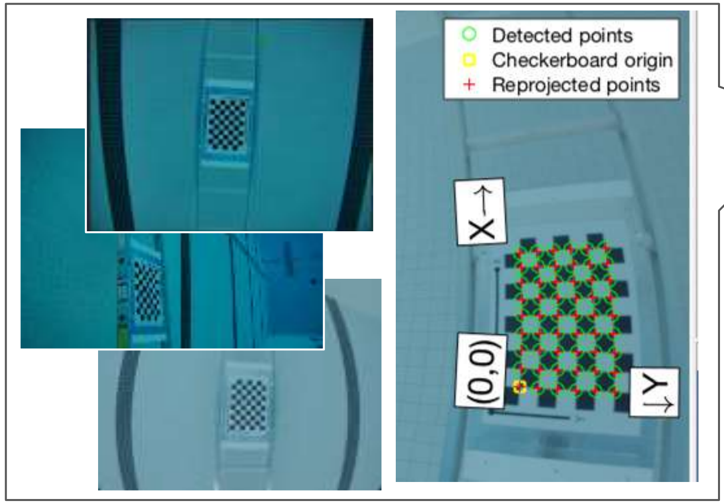
Photogrammetry

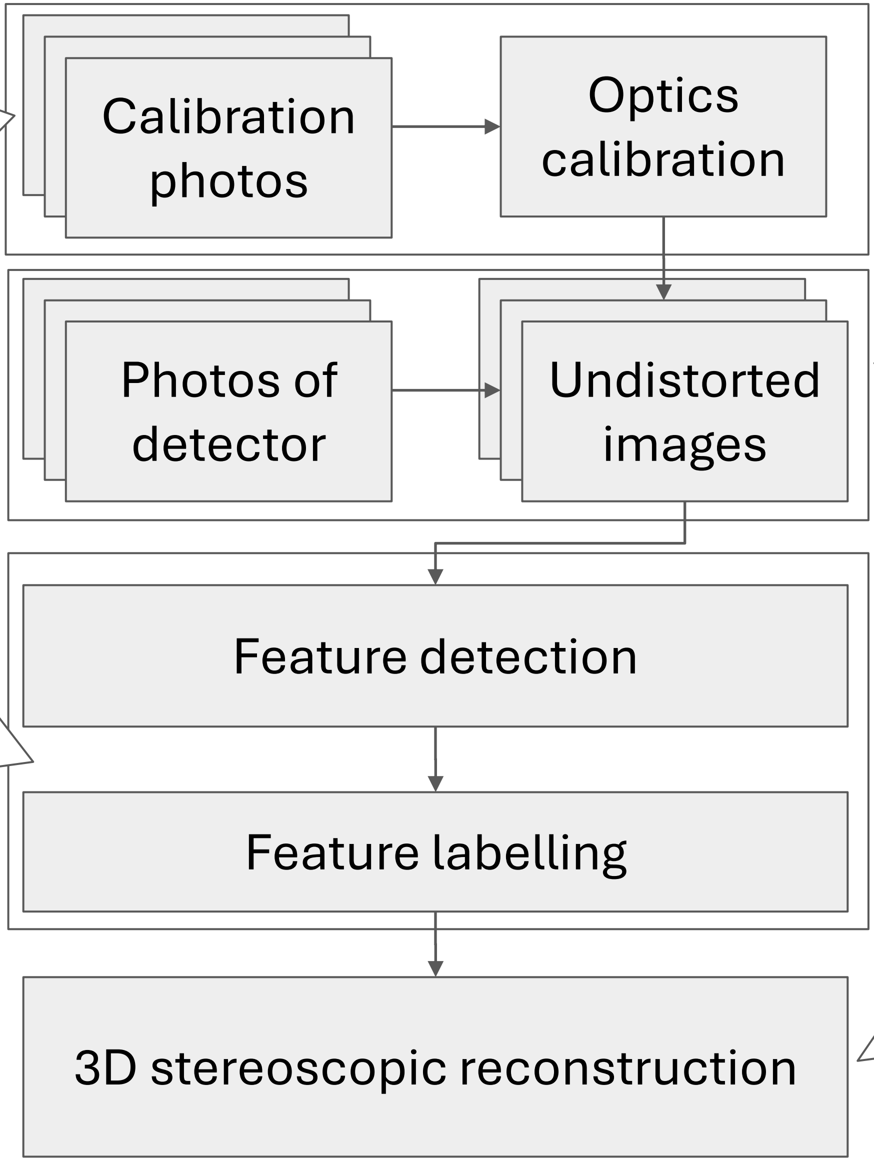
Major contribution of Winnipeg group

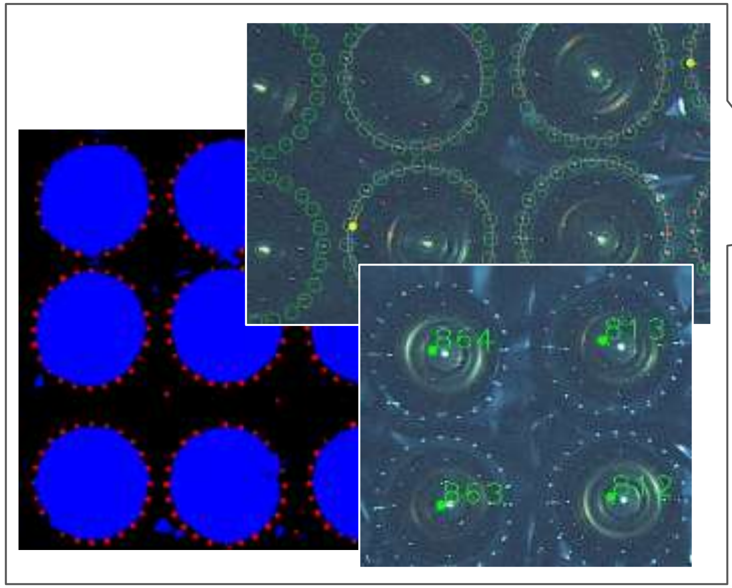
- Detector geometry and source position measurements using stereoscopic reconstruction with photographs
- Mitigate uncertainties due to:
  - Construction tolerances / imperfections
  - Stretching / twisting of support structure due to PMT buoyancy
  - Source deployment positioning

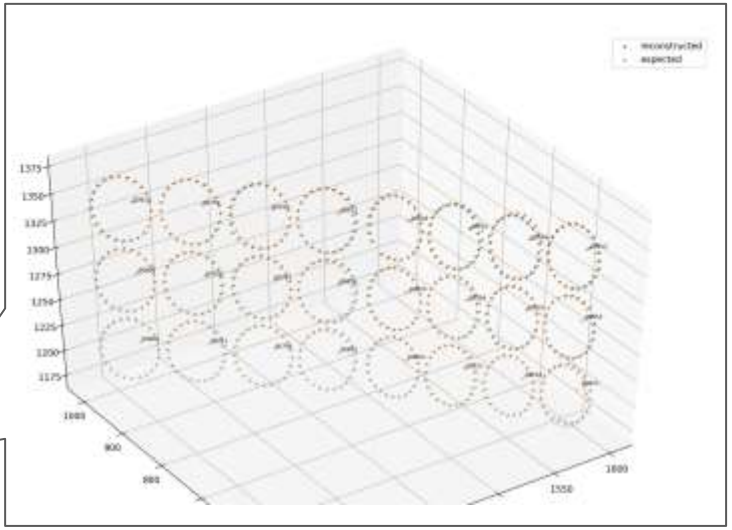


Photogrammetry procedure



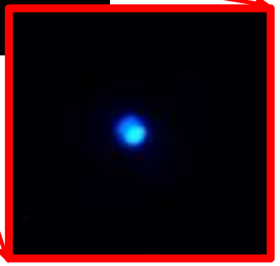






Photogrammetry status

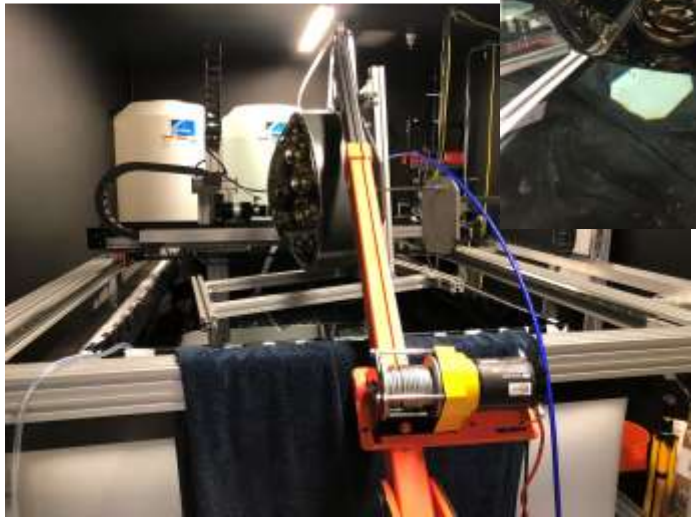
- 7/8 cameras prepared for WCTE experiment
  - Being installed in WCTE in July and Aug 2024
  - to be reused in IWCD
- Calibration obtained both in / out of water
- Imaged two different varieties of mPMT LEDs underwater

In-situ gelled mPMT


Ex-situ gelled mPMT

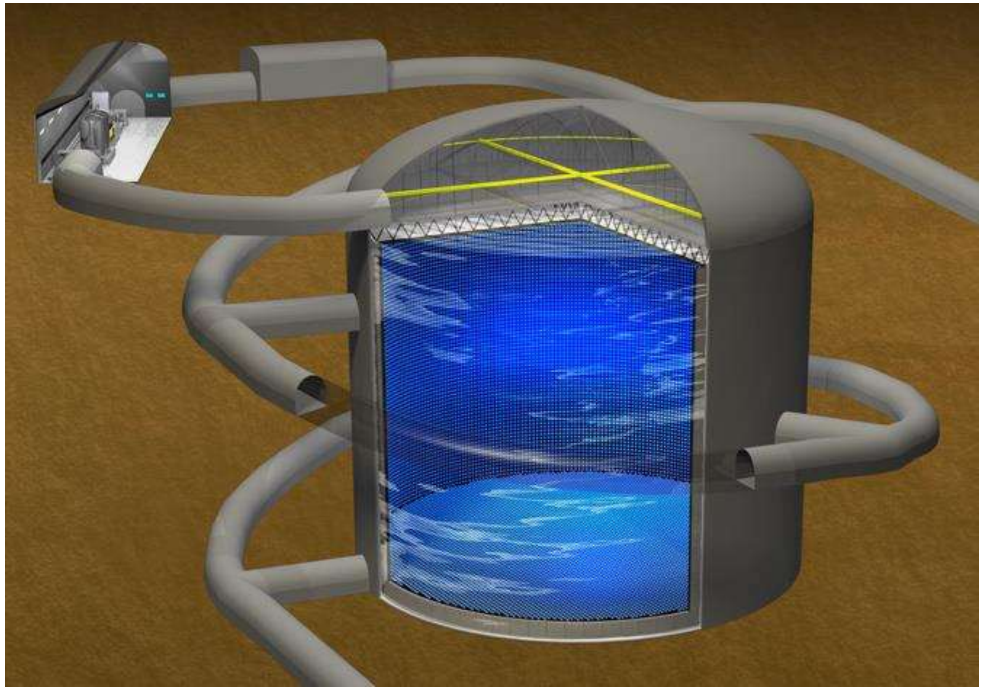




Hyper-K Summary

Hyper-Kamiokande construction has begun, with first data taking planned for 2027!

- Building on the success of Super-K & T2K with a next generation neutrino experiment
  - New far detector with 8 x fiducial mass of Super-K
  - Improved photosensors with 2 x detection efficiency & timing resolution reduced by half
  - Upgraded near detectors and new intermediate detector
  - Beam upgrade from 750 kW to 1.3 MW
- Wide range of physics measurements
  - Search for CP violation with precision oscillation measurements
  - Neutrino astrophysics through solar and supernova neutrinos
  - Searches for proton decay and other new physics



Thanks for your attention

Hyper-K Canada
Collaboration meeting
TRIUMF
Apr. 24-26, 2024

Backup

slides

How do accelerator-based long baseline experiments work?

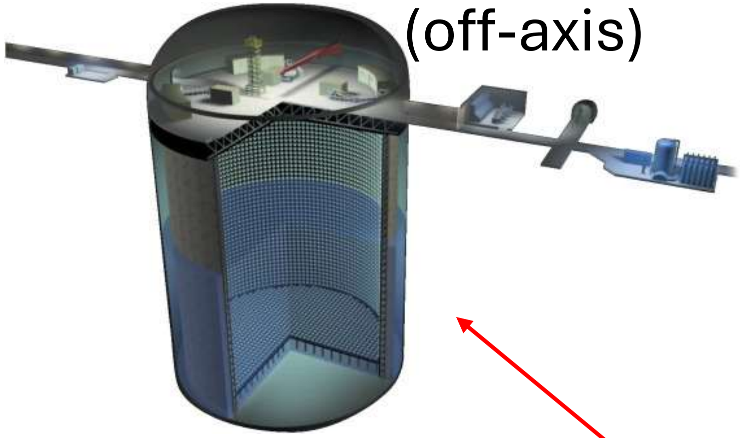
- Example: Tokai to Kamioka (T2K) in Japan

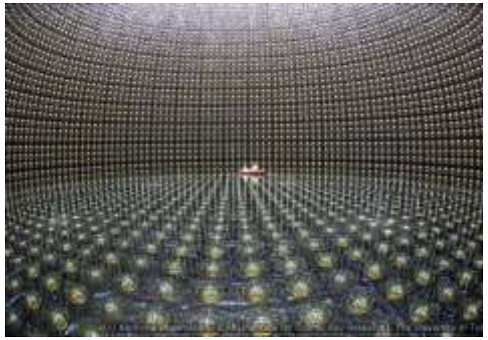
Far detector for measuring neutrinos after oscillations.

Near detectors for measuring neutrinos before oscillations.

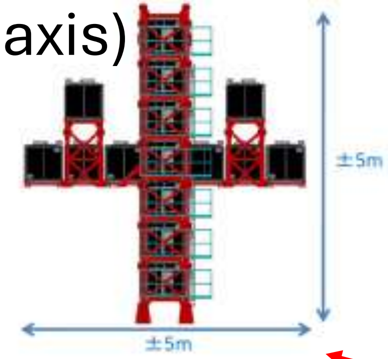
Neutrinos are decay products of pions, kaons and muons created in hadronic interactions.

Super-Kamiokande (off-axis)

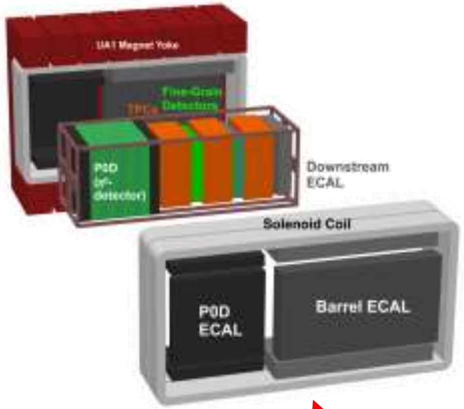




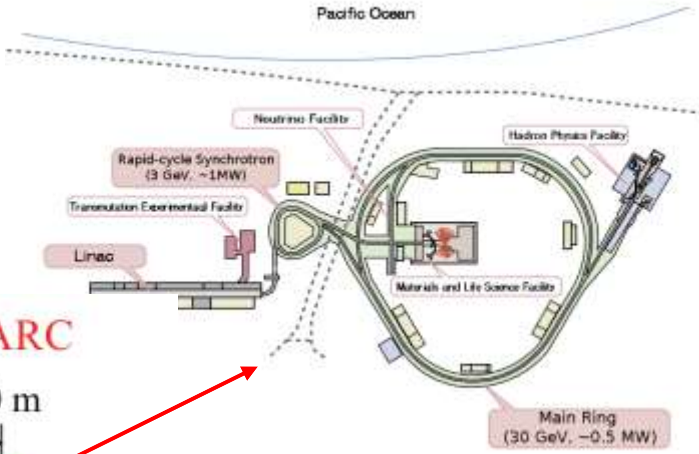
INGRID (on-axis)

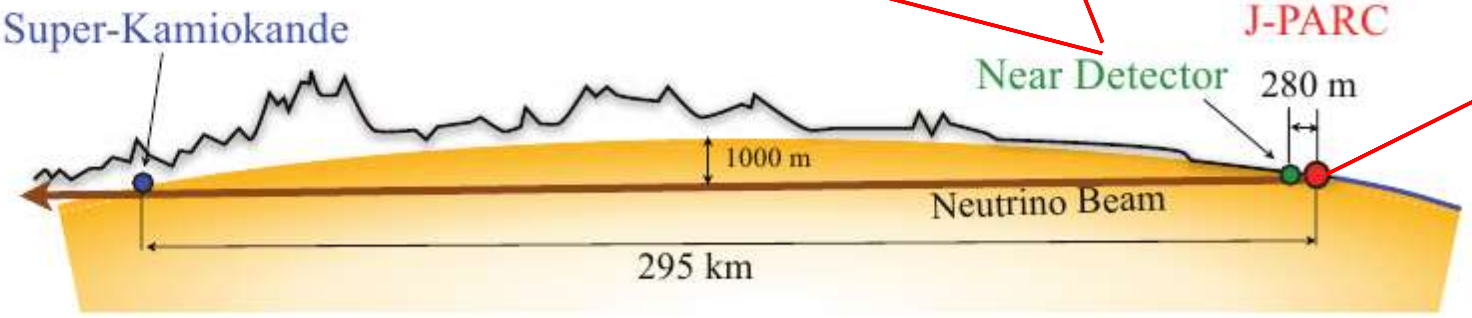


ND280 (off-axis)

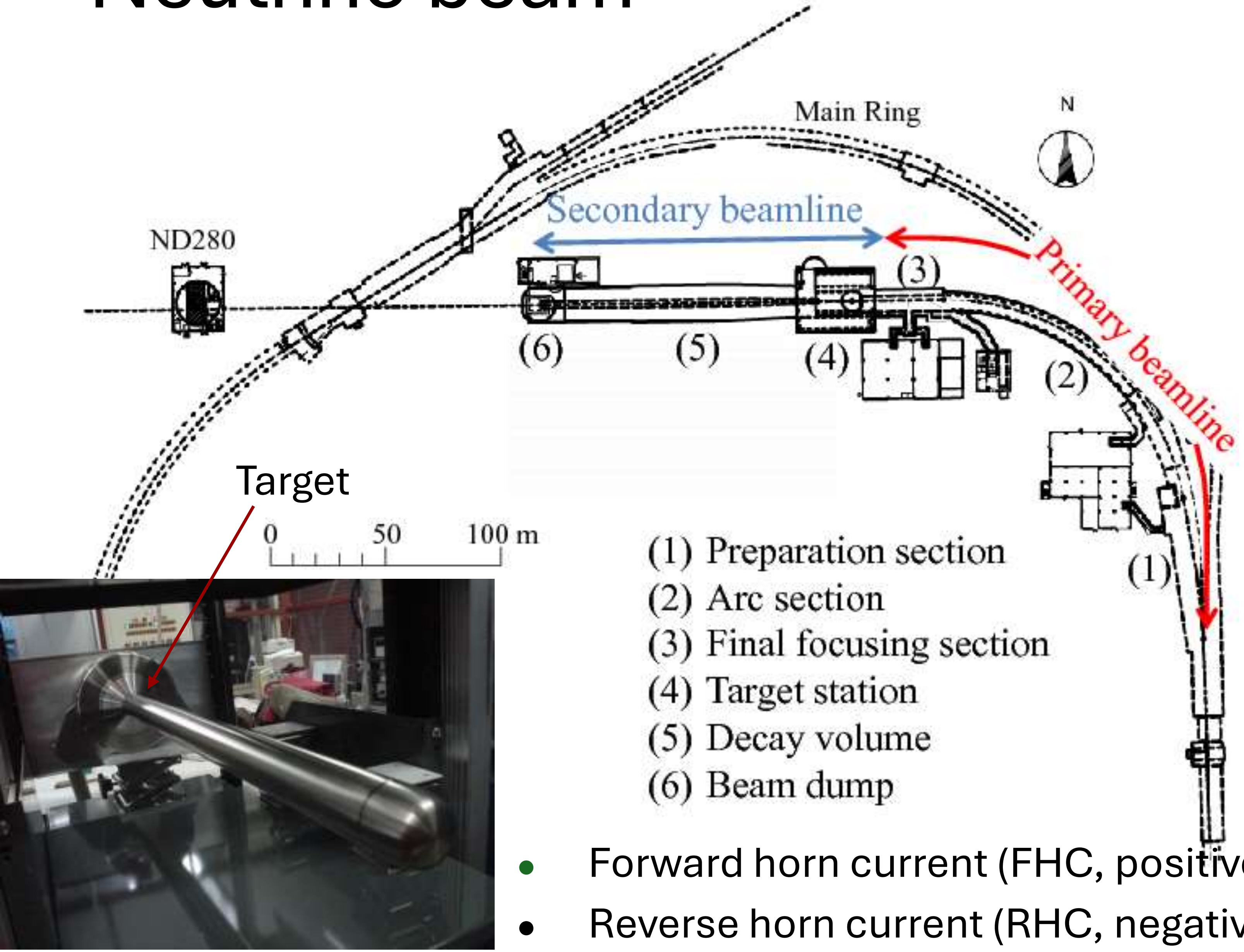


J-PARC

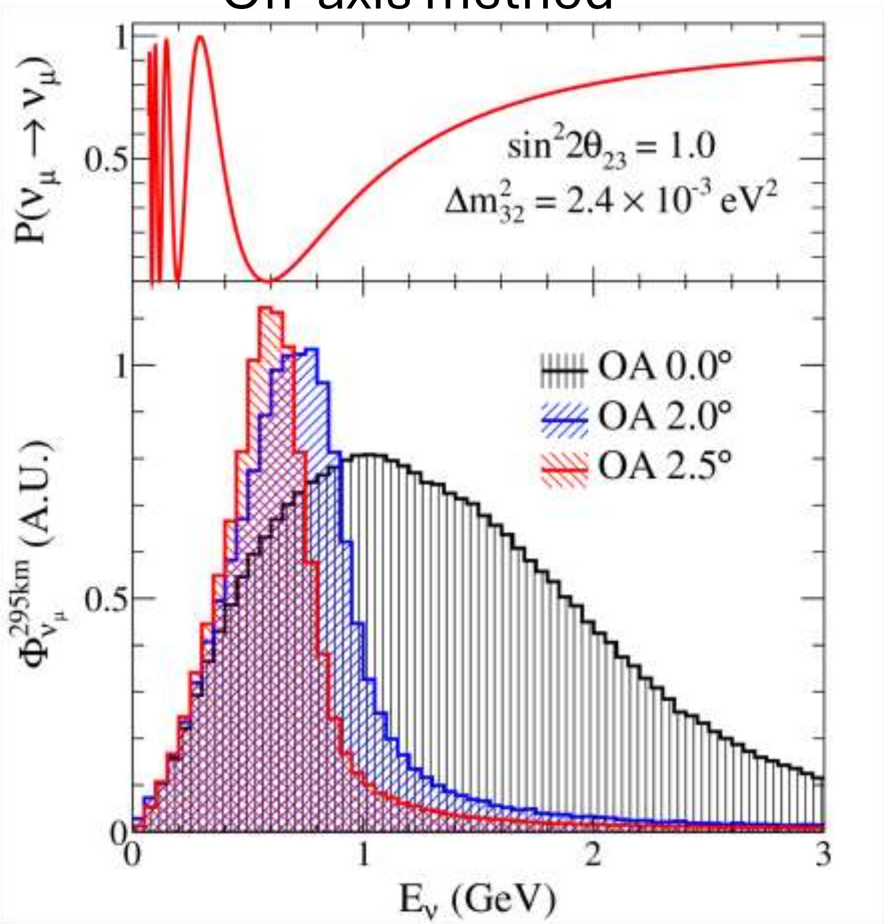




Neutrino beam



Off-axis method



- Forward horn current (FHC, positive focusing) → muon neutrino beam
- Reverse horn current (RHC, negative focusing) → muon antineutrino beam

How accelerator-based long baseline experiments work?

Rate in the near detector

$$N_{ND}(E_\nu) \propto \Phi_{ND} * \sigma_{ND} * \epsilon_{ND}$$

Rate in the far detector

Flux

Neutrino cross-section

Detector response

$$N_{FD}(E_\nu) \propto \Phi_{FD} * \sigma_{FD} * P_{osc} * \epsilon_{FD}$$

Oscillation (survival or appearance) probability

Oscillation measurements:

1. Measure rate in the near detector
2. Extrapolate to the far detector
3. Calculate far/near ratio
4. Fit PMNS model
5. Win Nobel prize

Easy?

Not so easy :(

$$N_{ND}(E_\nu) \propto \Phi_{ND} * \sigma_{ND} * \epsilon_{ND}$$

Near detector sees line neutrino source (target + decay tunnel).
Far detector sees point neutrino source.

Target materials in near and far detectors are not necessarily the same.
Neutrino energy spectra is different in the far detector.
Nuclear effect are biassing neutrino energy reconstruction.

Detector response is different.
Final state interactions, pions re-interacting in the detector.

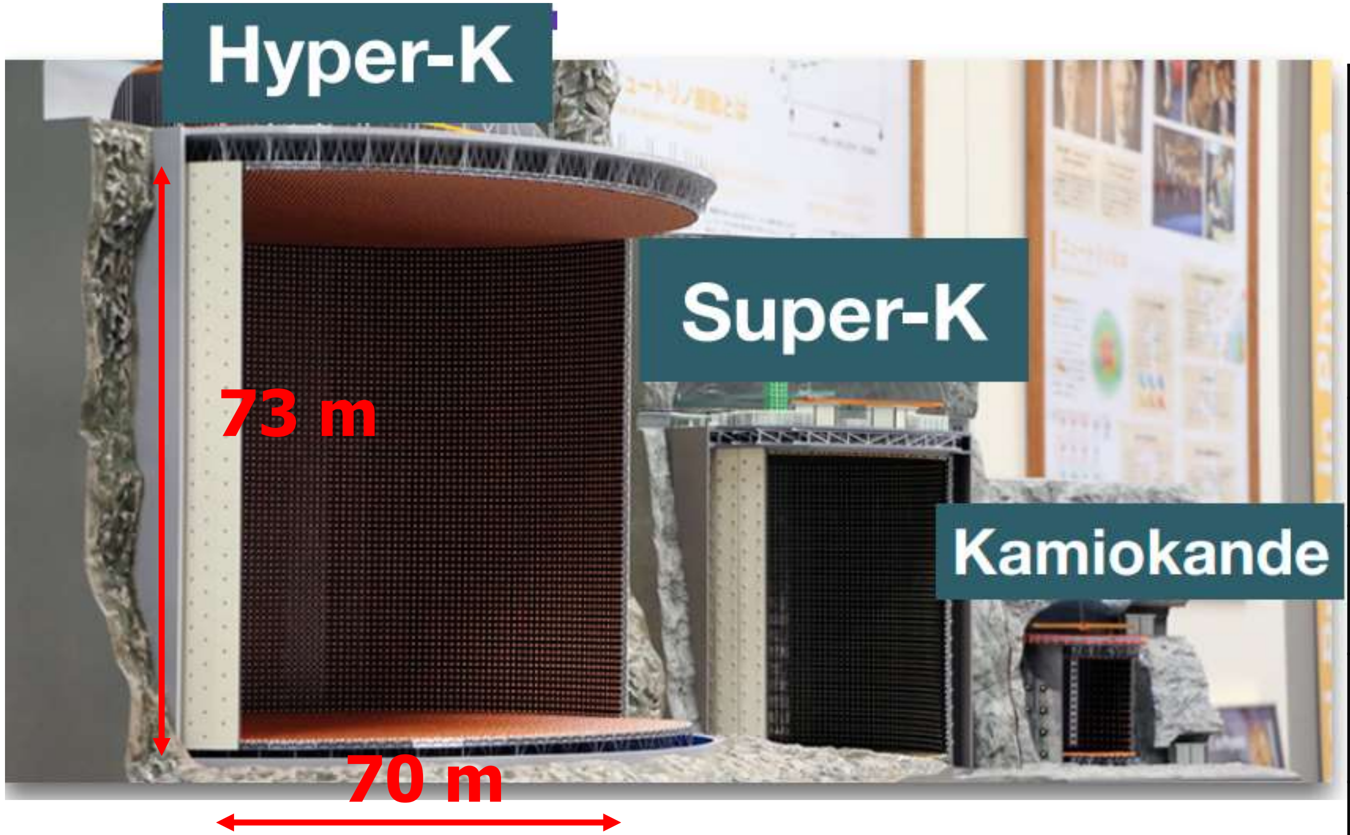
$$N_{FD}(E_\nu) \propto \Phi_{FD} * \sigma_{FD} * P_{osc} * \epsilon_{FD}$$

Current experiments (T2K, NOvA) are limited by statistics!

HyperK-Canada group

- **~40 collaborators (including co-op students)**
- **University of Victoria**
- **TRIUMF**
- **British Columbia Institute of Technology**
- **University of Regina**
- **University of Winnipeg**
- **Carleton University**

Far detector - Water Cherenkov Detector



	SK	HK
Site	Mozumi	Tochibora
# PMTs (ID)	11129	40000*
# PMTs (OD)	1885	15000
Photo-coverage	40%	40%*
Mass [kton]	50	237
Fiducial mass [kton]	22.5	187

8 times larger fiducial mass than SK

*Depends on the international contribution

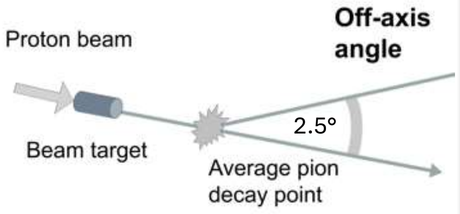
Off-axis Long-Baseline Neutrinos

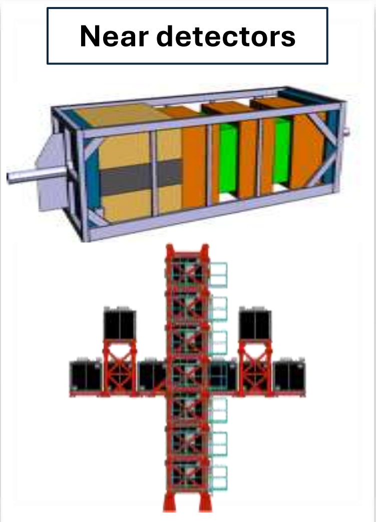
Neutrino beam produced at J-PARC, 295 km baseline from Hyper-K.

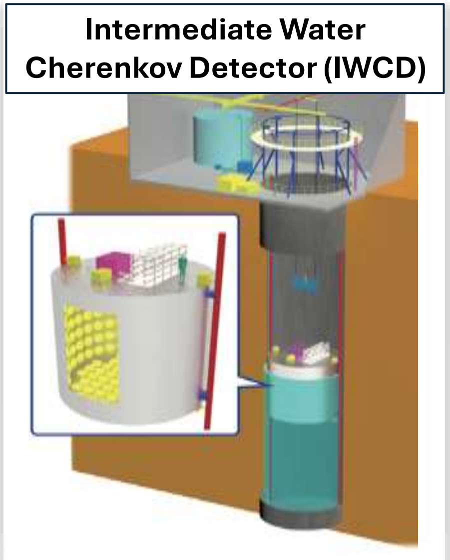
Near and intermediate detectors measure unoscillated flux and cross sections.

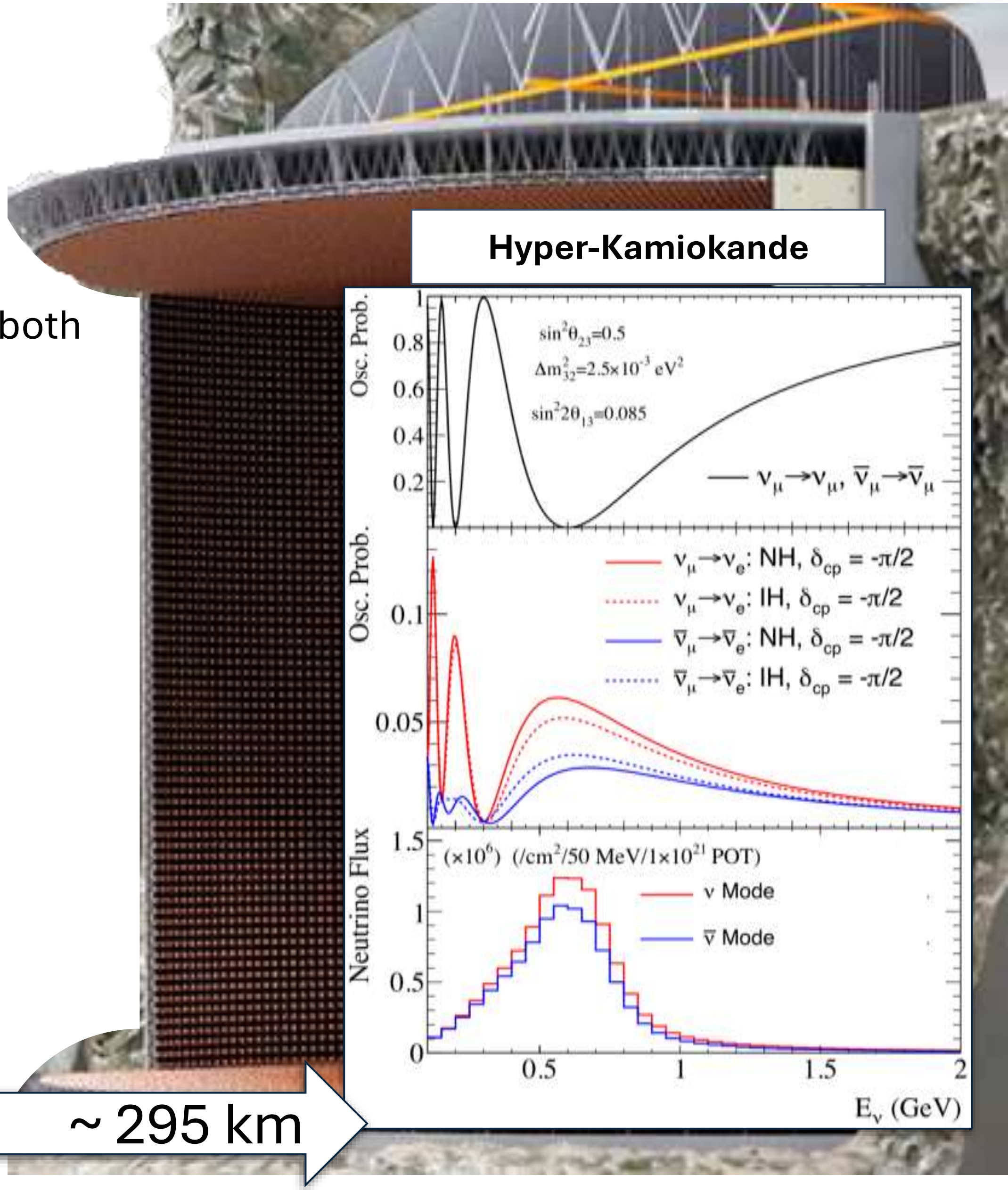
Oscillations observed through ν_μ disappearance and ν_e appearance, for both neutrinos and antineutrinos.

Difference between $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ provides sensitivity to CP violation and δ_{CP} measurement.









280 m → ~ 1 km → ~ 295 km

Hyper-Kamiokande Cavern Design

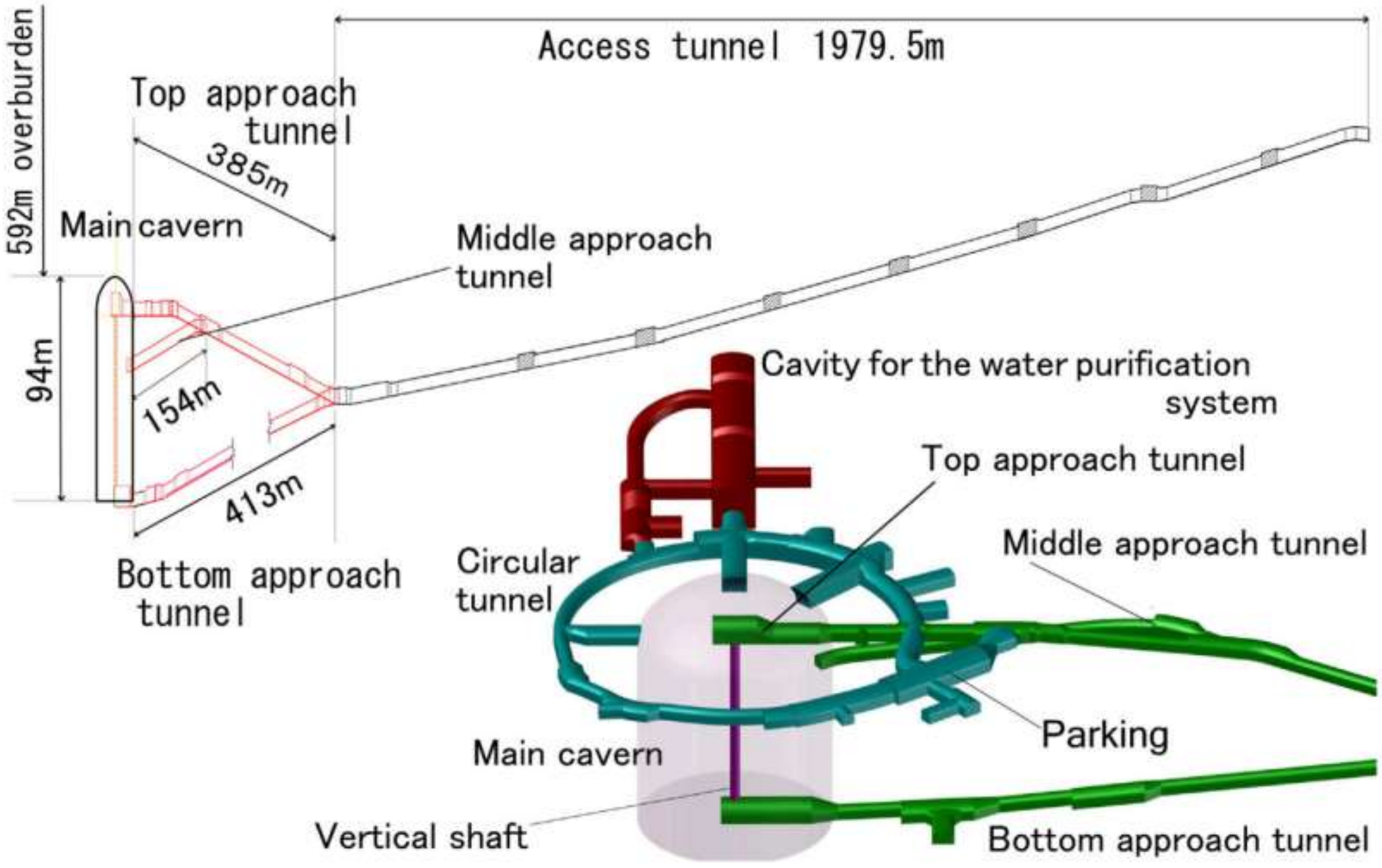


FIGURE 1
The Hyper-K underground facility overview (top) and the schematic view of the detector area (bottom).

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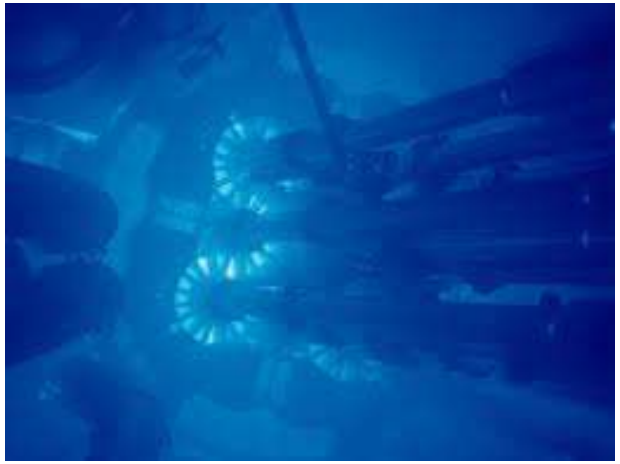
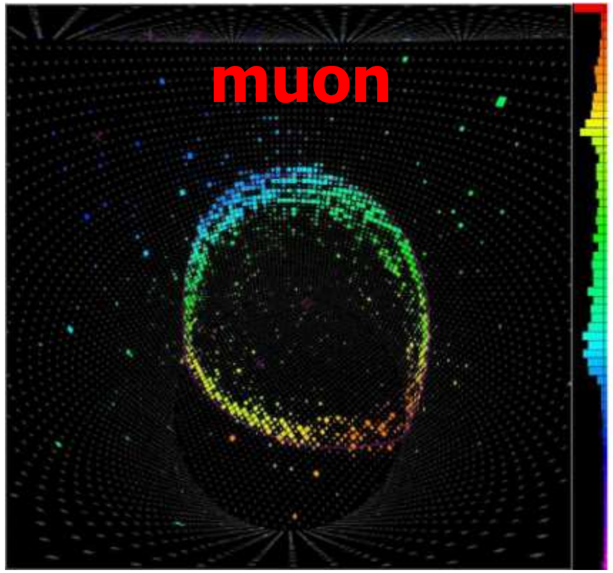
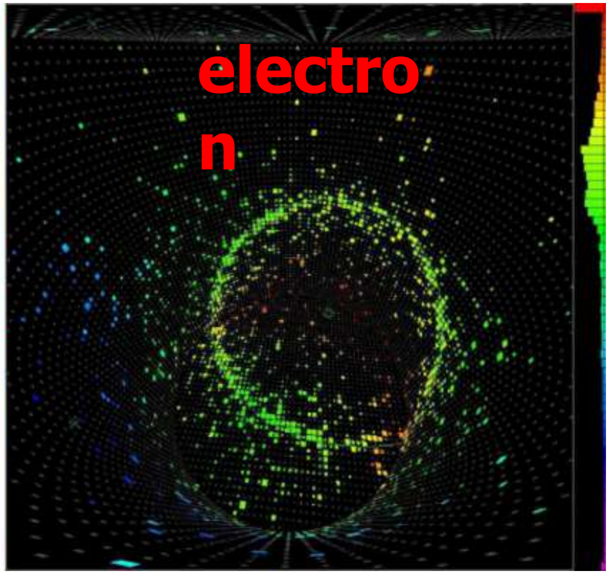
Sec. High-Energy and Astroparticle Physics
Volume 12 - 2024
| https://doi.org/10.3389/fphy.2024.1378254

Water Cherenkov Detectors

- Neutrinos interact and produce leptons (and other particles)
- If produced charged particles travel faster the the speed of light in water → Cherenkov radiation
- Vertex position determined from timing
- Ring size + vertex position → Cherenkov angle → particle momentum
- PID (electron or muon) → “fuzziness” of the ring (electron multiple scattering)

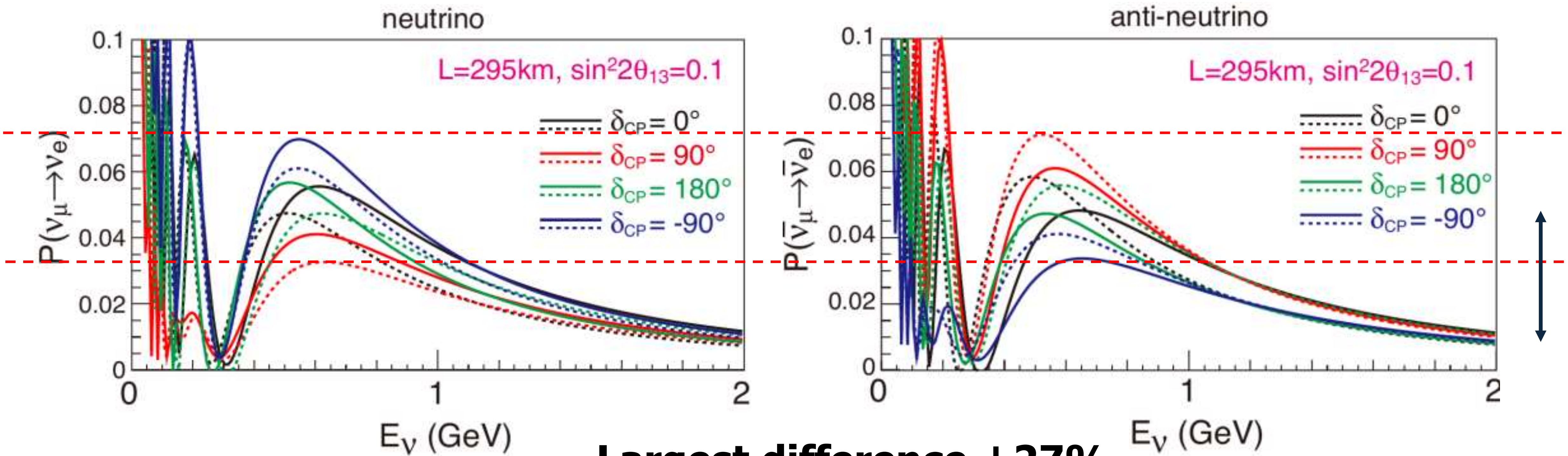






CPV measurement

- CP violation can be measured by observing differences between ν_e and anti- ν_e appearance in the accelerator based long-baseline neutrino beam



Largest difference ±27%

Normal hierarchy = solid
Inverted hierarchy = dashed

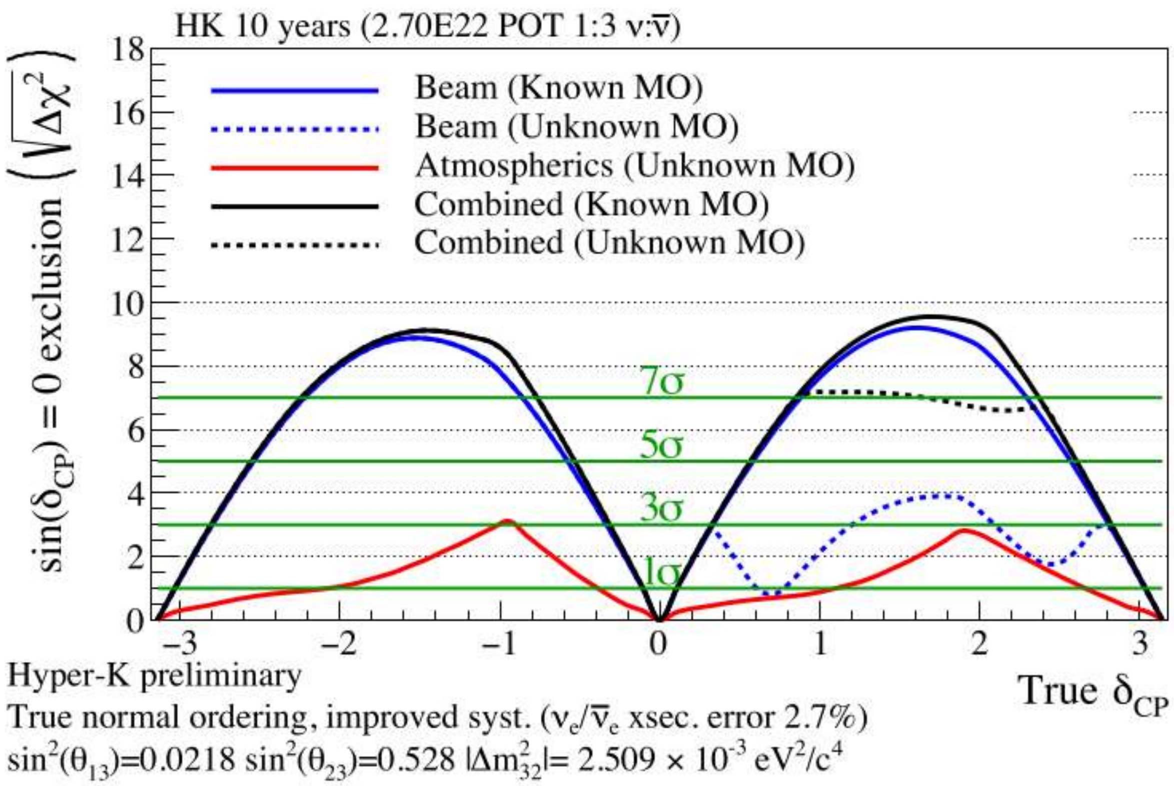
Appearance probability depends on the CP phase

Oscillation Measurements - Atmospheric ν + Beam

	$\sin^2\theta_{23}$	Atmospheric ν	Atmospheric + beam ν
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 1.3 MW, normal mass ordering is assumed

- Atmospheric neutrinos sensitive to mass ordering through Earth's matter effect
- Beam measurements enhance sensitivity to mass ordering and atmospheric mixing angle

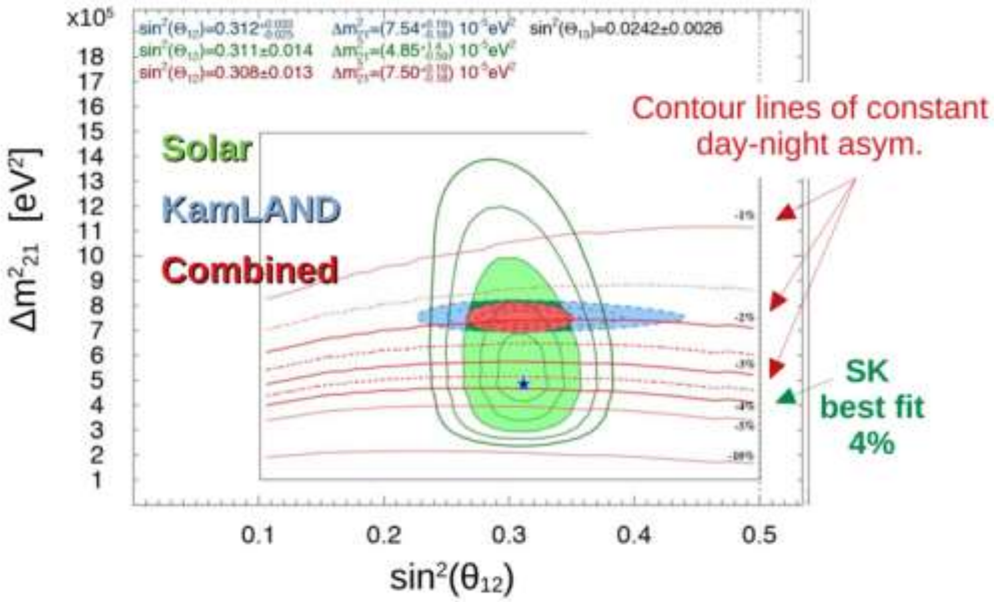


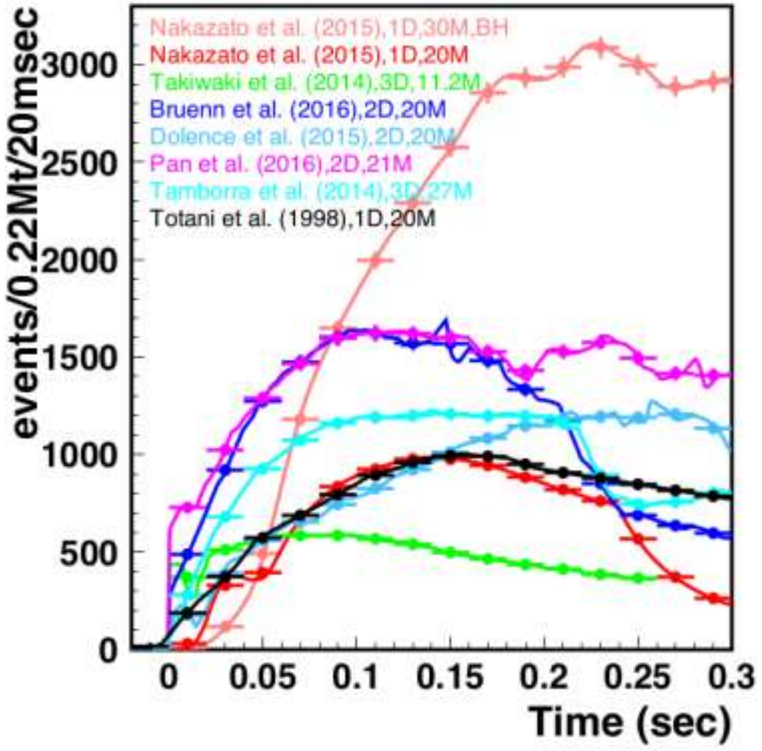
- CP violation and matter effect both create difference between ν and $\bar{\nu}$ oscillations
- Breaking degeneracies also enhances CP violation search

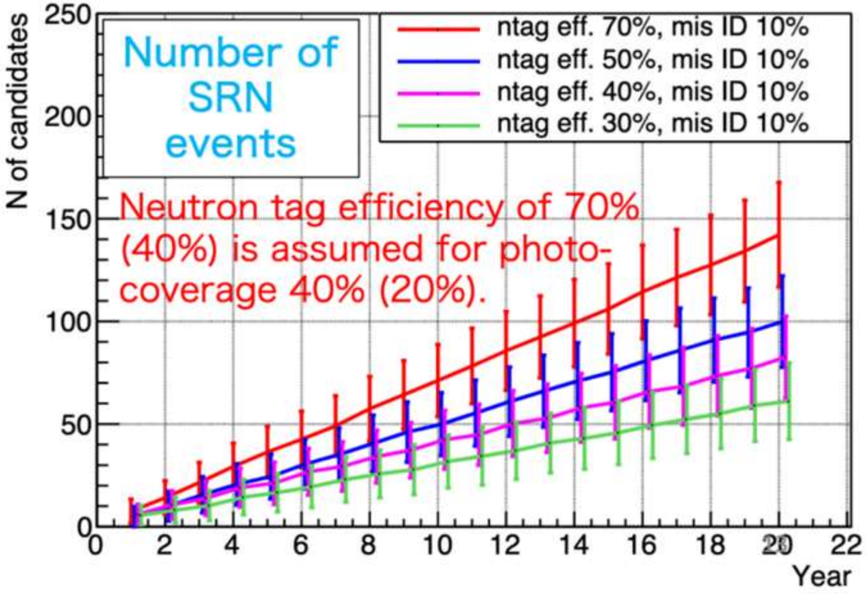
Solar & Supernova Neutrinos

Solar neutrinos

- Measure solar upturn predicted by MSW effect
- Day-night asymmetry (from matter effect through Earth)
  - Study $\sim 2\sigma$ tension in Δm^2_{21} between solar & KamLAND







Supernova neutrinos

- O(100,000) ν events from a supernova in galactic centre
  - Ability to distinguish supernova models
- O(10) events from supernova in Andromeda galaxy
- Observation of supernova relic neutrinos within 10 years