Hyper-Kamiokande

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THE UNIVERSITY OF WINNIPEG

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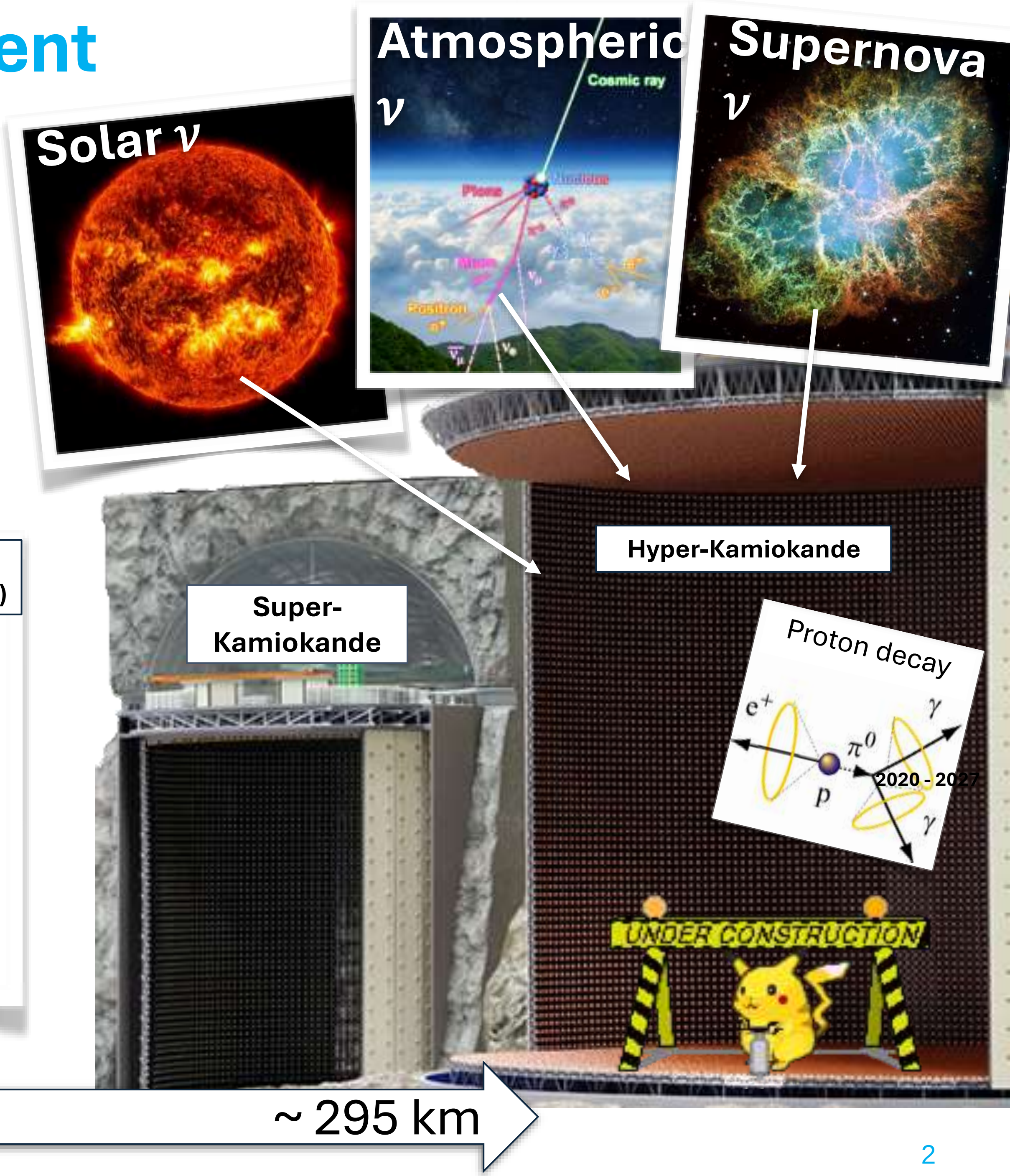
On behalf of the Hyper-Kamiokande Collaboration

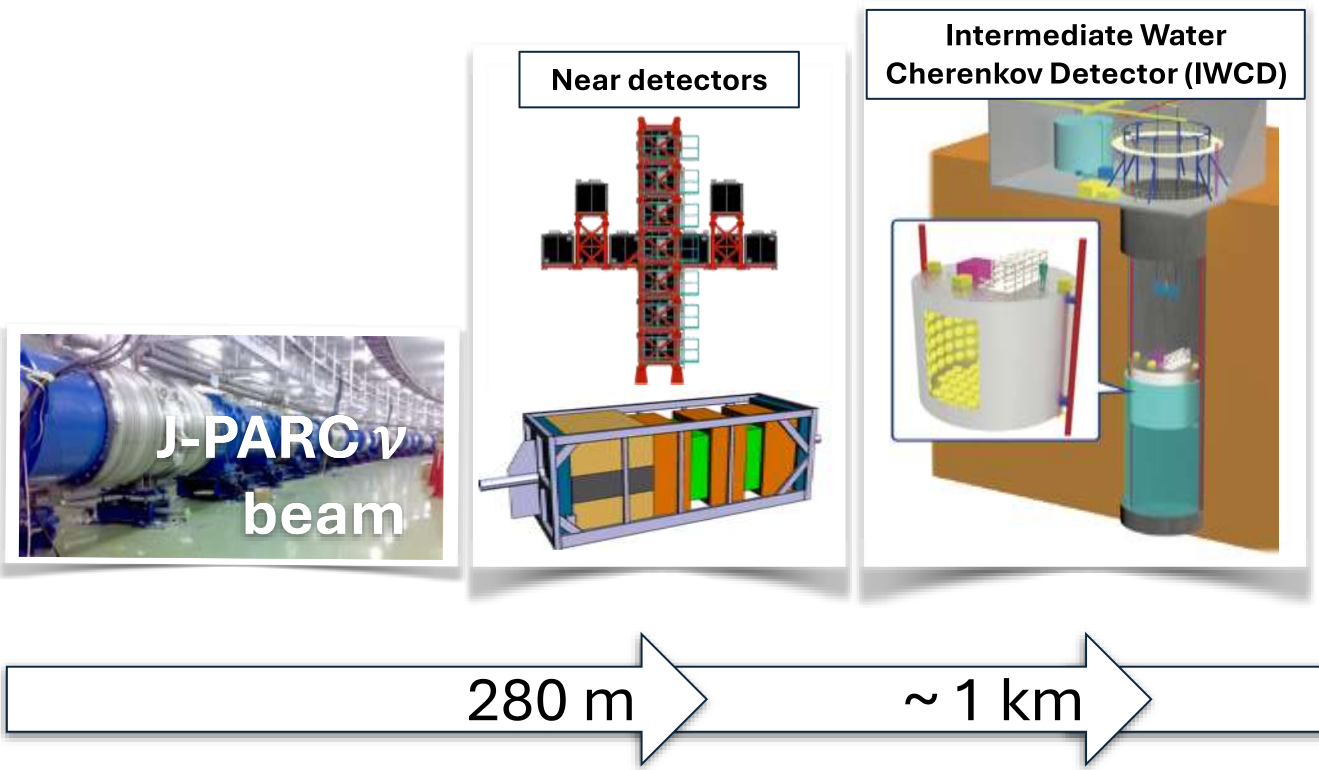
The Hyper-Kamiokande Experiment

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.





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"

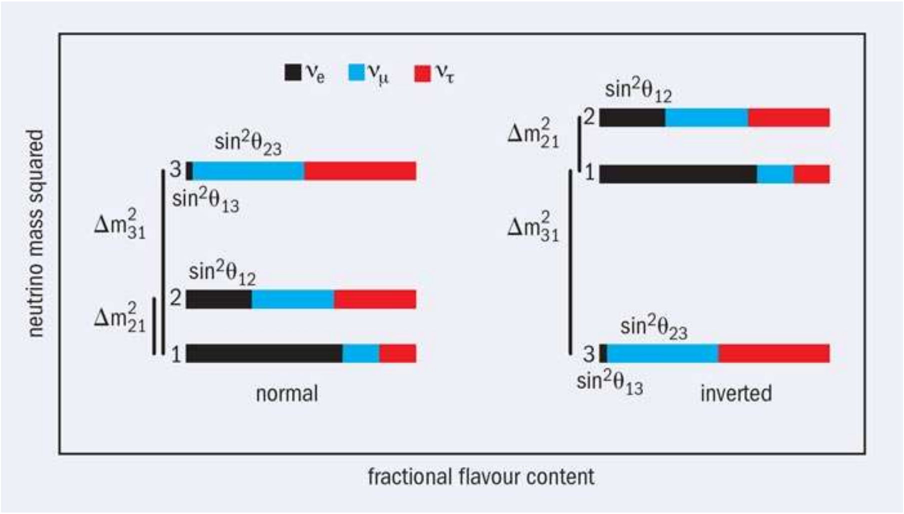
- 3 non zero mixing angles → possible CP violation in the lepton sector

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

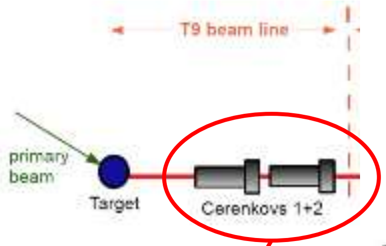
Param	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.10^{+0.13}_{-0.12}$	$2.75 \to 3.50$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.58^{+0.20}_{-0.33}$	$4.27 \to 6.09$
$\theta_{23}/^\circ$	$48.3^{+1.2}_{-1.9}$	$40.8 \to 51.3$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.241^{+0.066}_{-0.065}$	$2.046 \to 2.440$
$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$
$\delta_{CP}/^\circ$	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

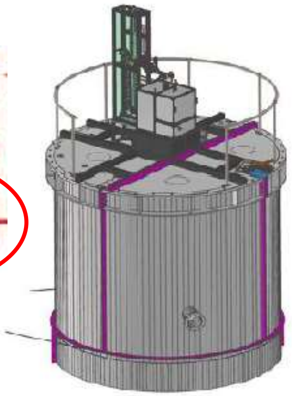


Water Cherenkov detectors for neutrino physics



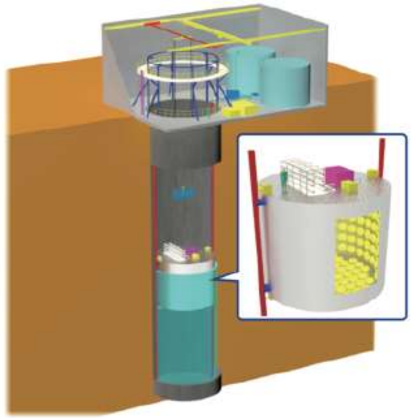
Talk by S.Yousefnejad was in M3-1 session

WCTE



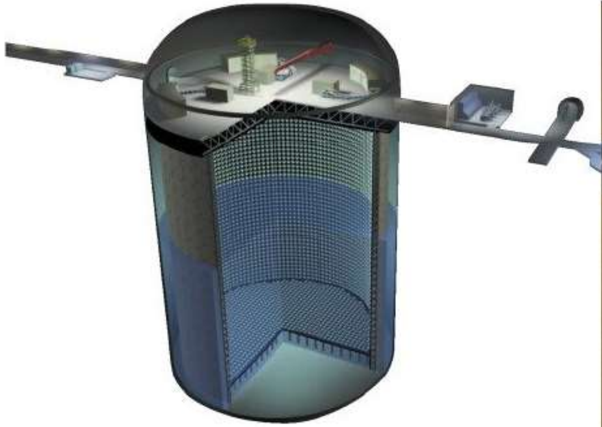
4 m ⌀ x 3.5 m tall
100 mPMTs
Operation in 2024-2025

IWCD



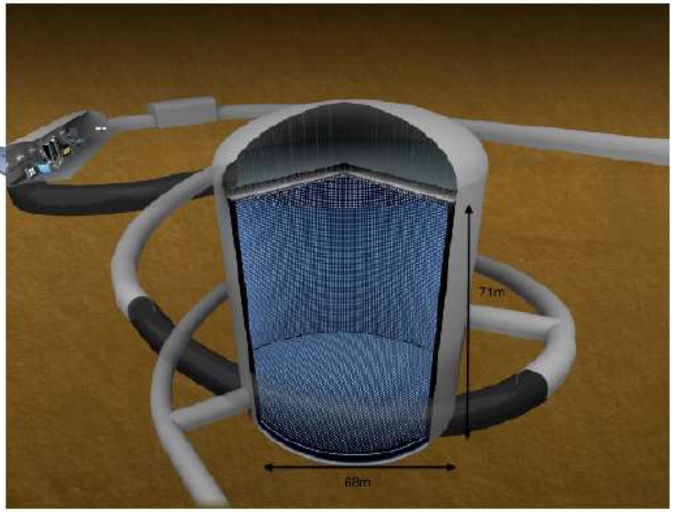
7 m ⌀ x 8 m tall (ID)
370 mPMTs
Operation from 2027

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

Hyper-K Detector

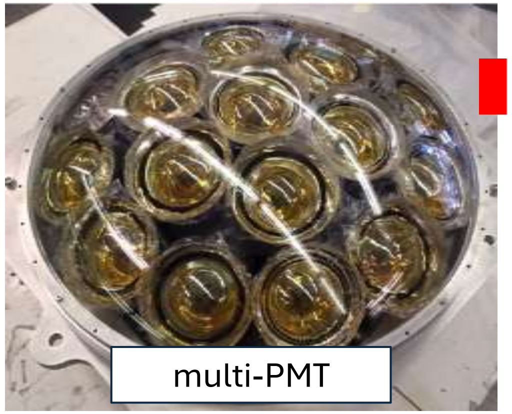
8 x increase in fiducial mass over Super-K

- 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

Long-Baseline Neutrinos

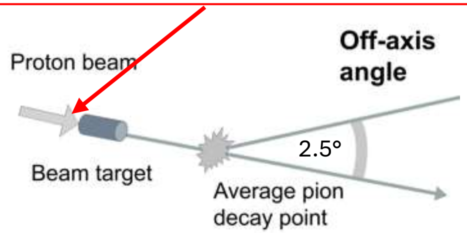
Neutrino beam produced at J-PARC, 295 km baseline from Hyper-K.

Near and intermediate detectors measure unoscillated flux and cross sections.

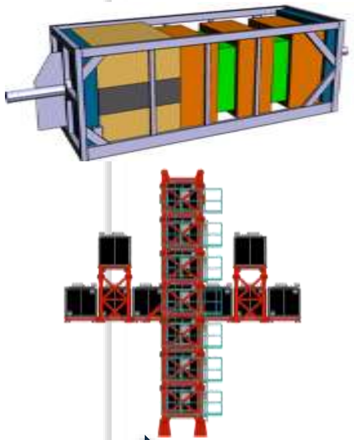
Oscillations observed through ν_μ disappearance and ν_e appearance, for both neutrinos and antineutrinos.

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

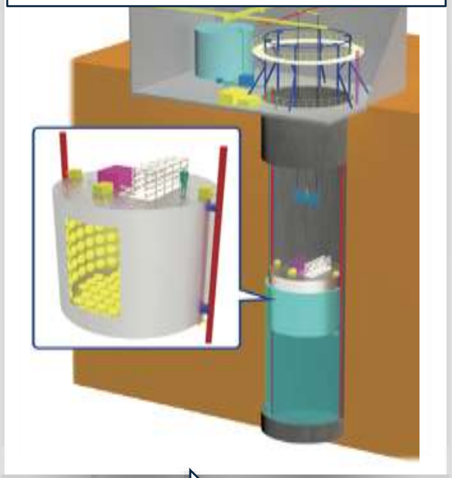
Optical Transition Radiation (OTR)
Talk by J. Zhang given in T2-1 session



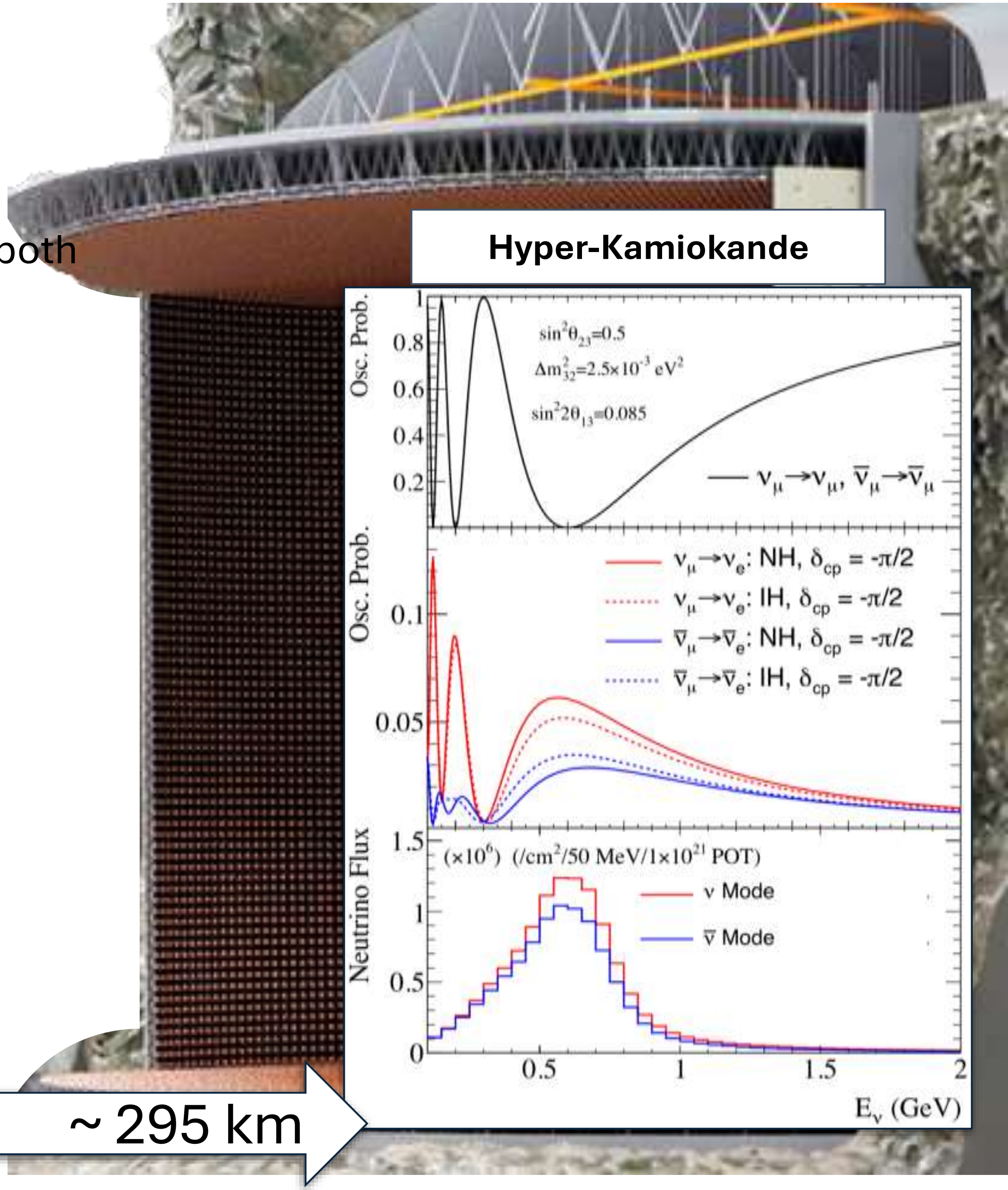
Near detectors



Intermediate Water Cherenkov Detector (IWCD)



Hyper-Kamiokande

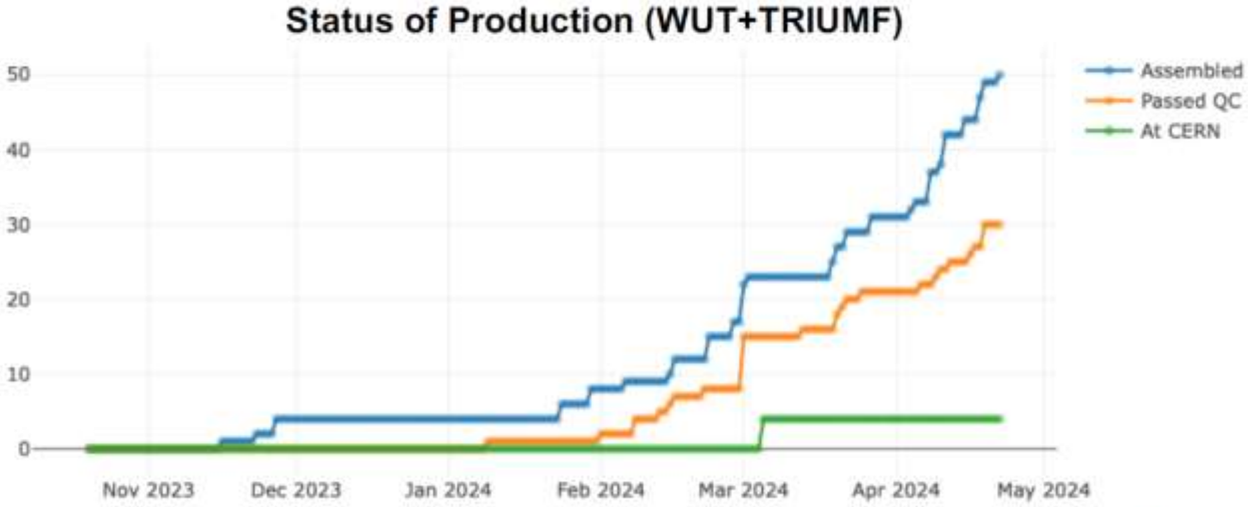


280 m → ~ 1 km → ~ 295 km

Multi-PMTs

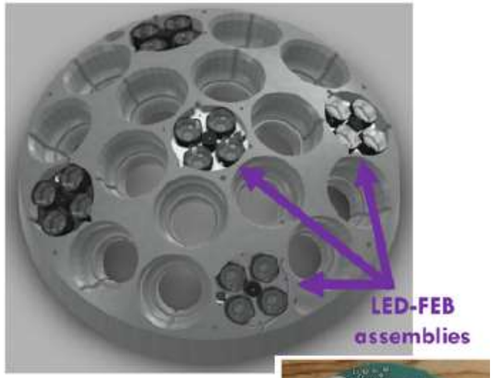
IWCD CFI-IF 2020 Funded for $5.4-million

- 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

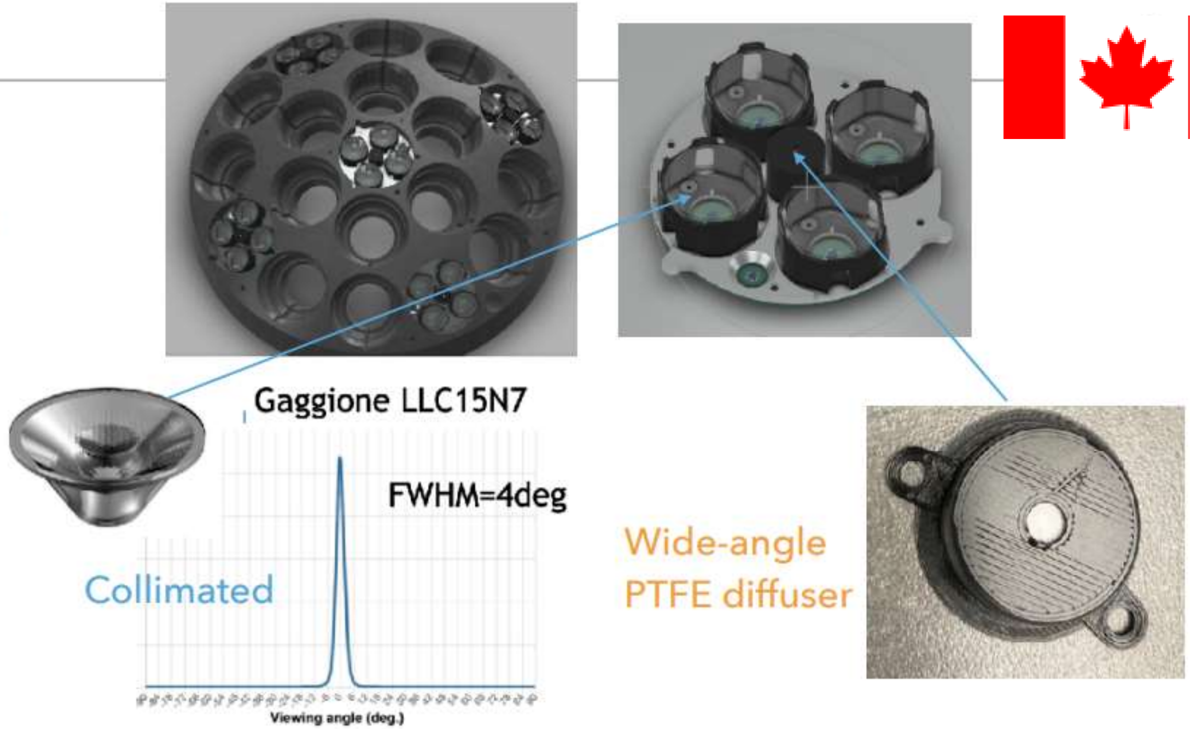


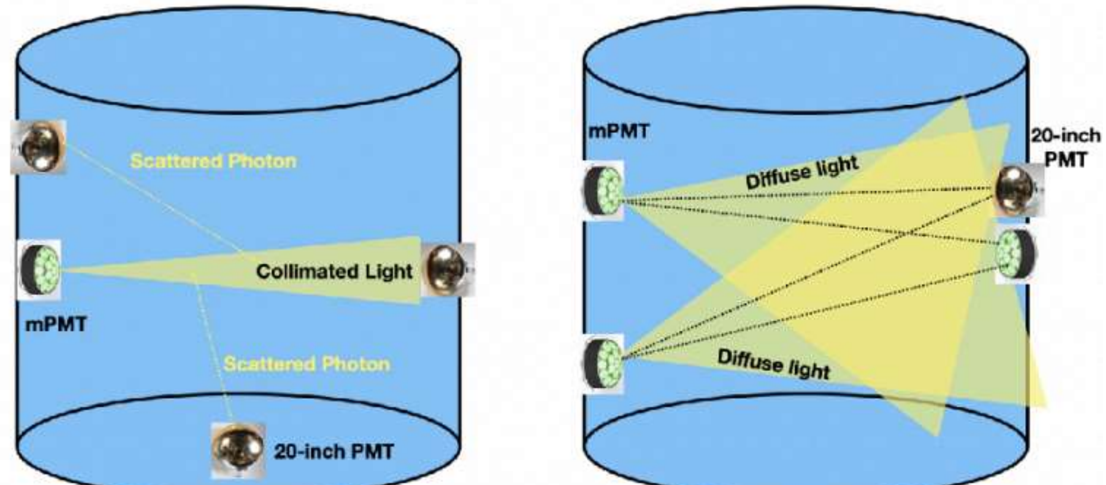
R. Gornea

CFI-IF 2023 mPMTs with LED for Calibration of Hyper-Kamiokande $6.36-million

MULTI-PMT LIGHT SOURCE IN HYPER-K

- For 200 mPMTs in HK we would replace 5 PMTs with LED units
  - Each of the five LED units will have 7 LEDs with LEDs with wavelengths of (295, 365, 405, 475nm) and (305, 330, 440, 550nm) with < 1 ns pulse width
  - A narrow-angle collimator for each wavelength
  - A wide-angle diffuser for three longer wavelengths LEDs
  - No need for long optical fibres
- Collimated light sources can be used for photon scattering, absorption and reflection calibration
- Wide-angle light sources can be used for PMT timing and angular response calibration

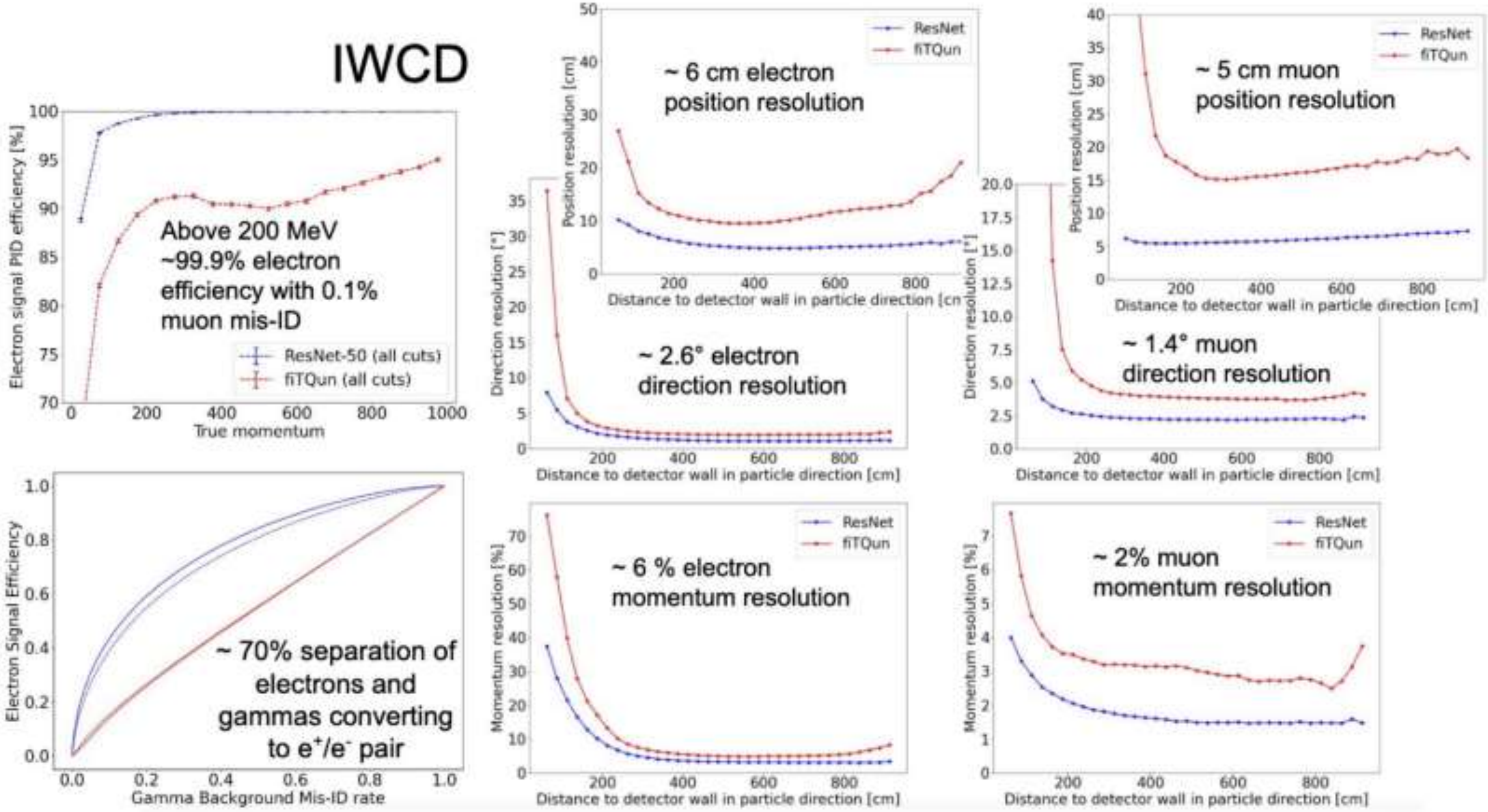




Analysis and Machine Learning

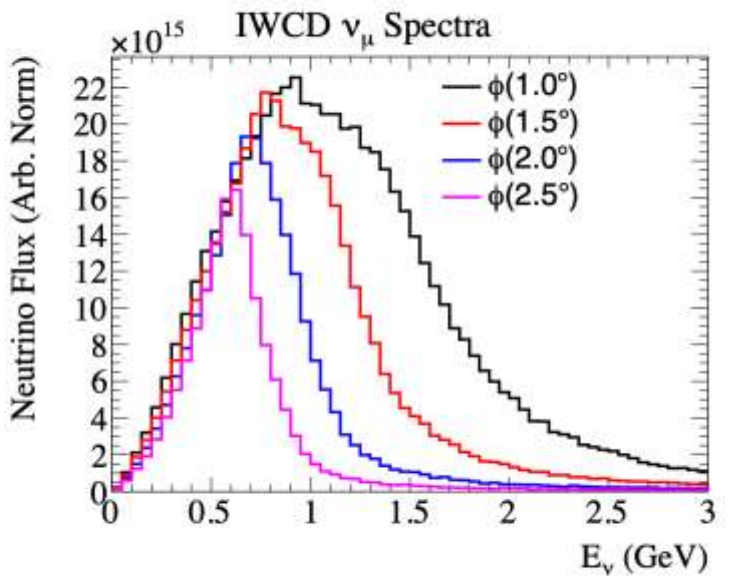
- Significant improvement in Super-K Supernova detection and direction analysis (B. Pointon)
  - Even (especially?) decades old methods can be improved significantly!
- Application of machine learning techniques (using ResNet) to IWCD have shown significant improvements in event reconstruction compared to fiTQun

Talk was given by F. Cormier Tue. May 28 neutrino+dark matter session

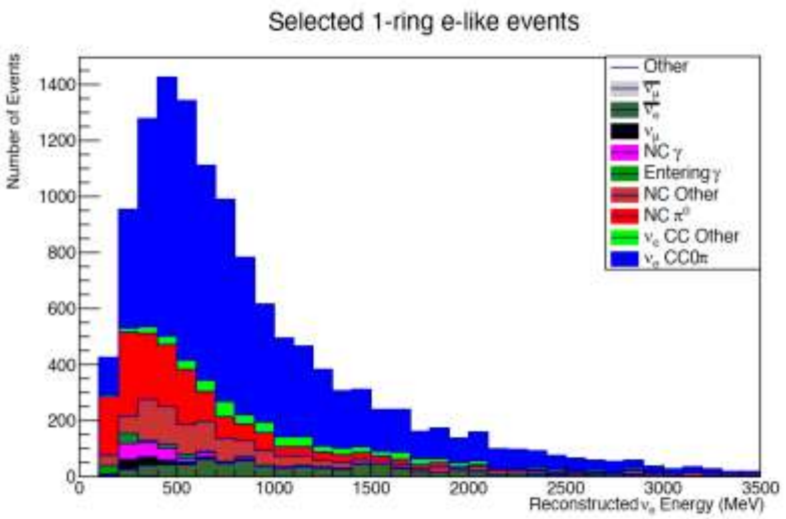


IWCD and HK Physics

- IWCD measurements at different off-axis angles allow us to probe different ranges of neutrino energy (upper right)
- Better understand and constrain the relationship between the true neutrino energy (not observed) and the final state charged lepton (observed)
- Range of energies covered depends on off-axis angle range

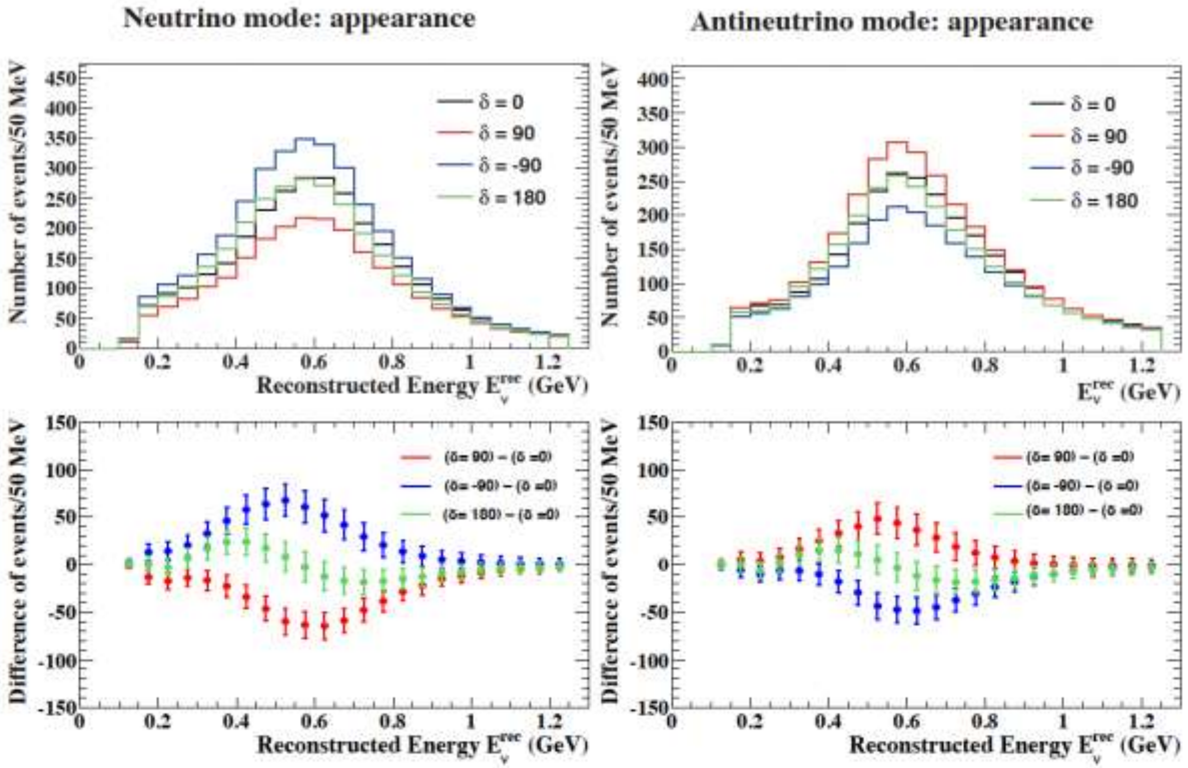


- We can select large samples of relatively pure electron (anti)neutrino interactions in IWCD (lower right)
- Dominant background are NCπ^0 events or NCγ where one or more γ produce a shower that is confused with an electron or positron



Electron (Anti)Neutrinos in HK

Electron (anti)neutrino Candidates at HK



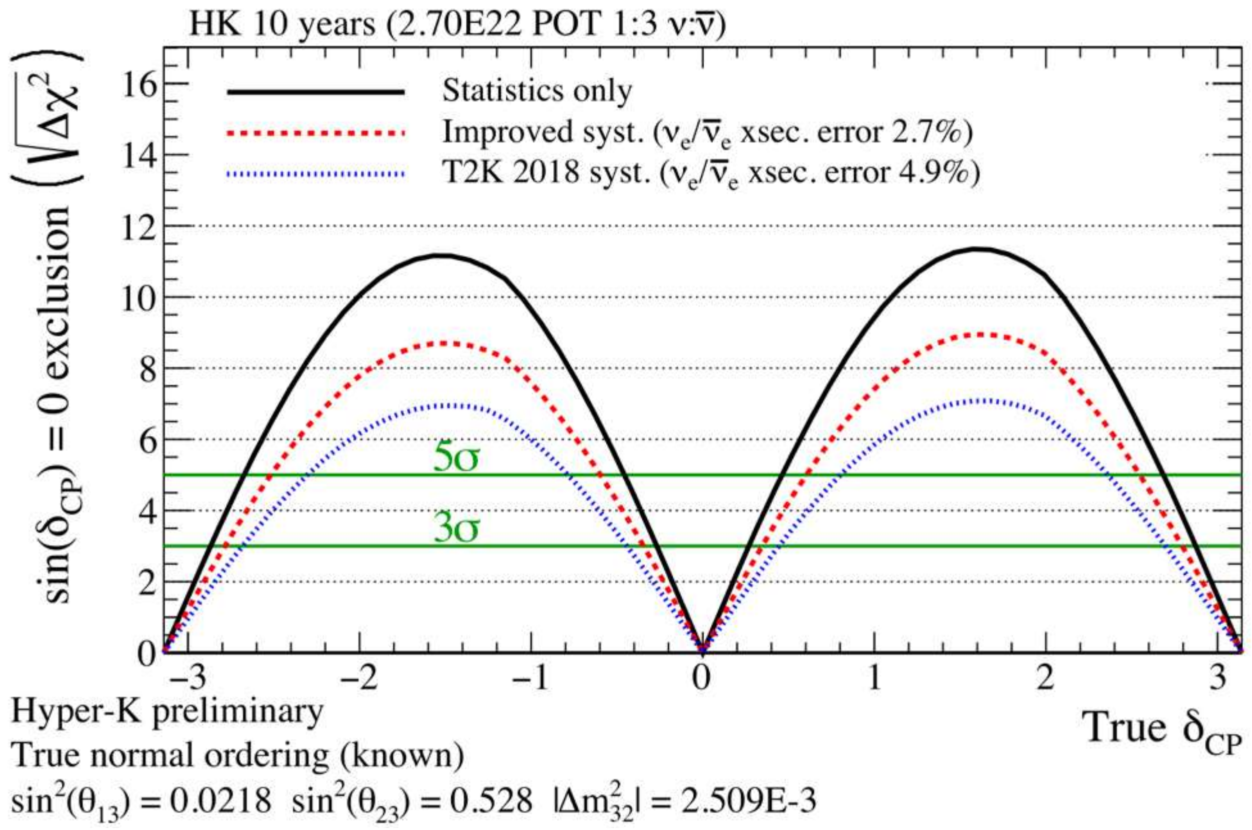
- We search for CP violation in the muon (anti)neutrino to electron (anti)neutrino oscillations
- Beam consists of 99% muon (anti)neutrinos and only 1% electron (anti)neutrinos before oscillations
  - Near detectors have a small fraction of electron (anti)neutrinos to study neutrino oscillations
- Need to measure:

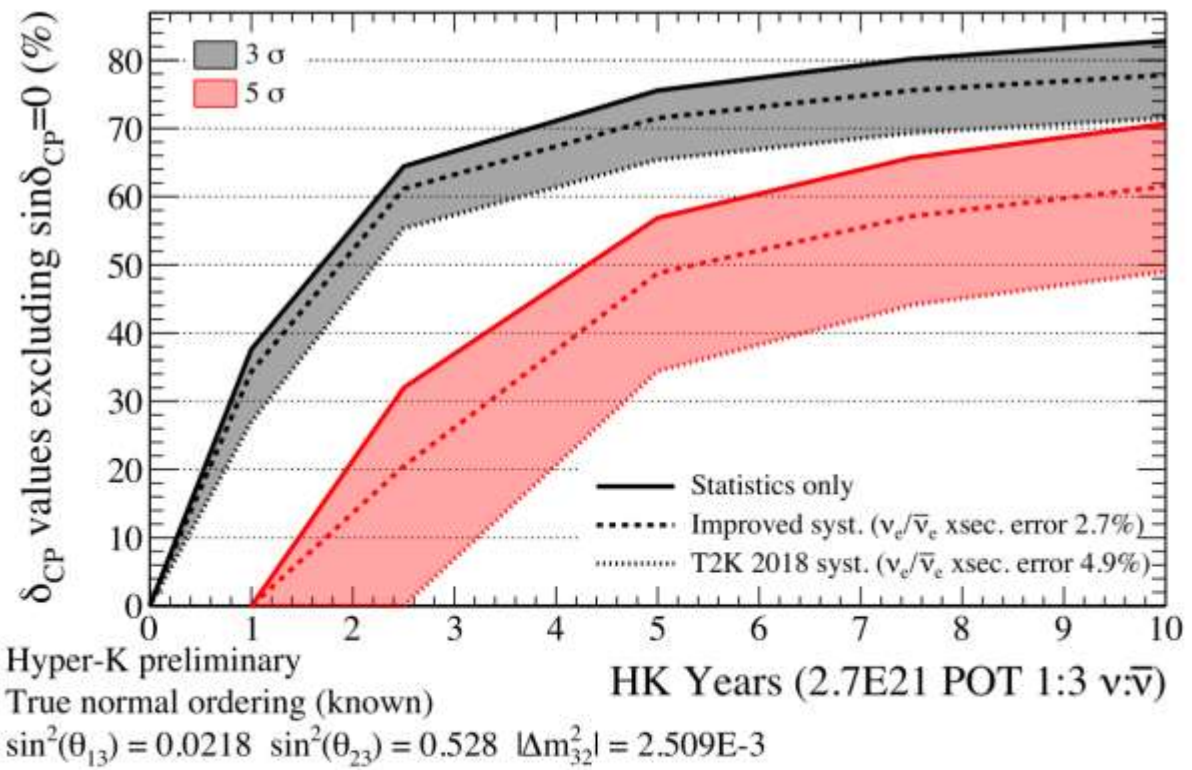
$$\frac{\sigma_{\nu_e}(E_\nu)}{\sigma_{\nu_\mu}(E_\nu)}, \frac{\sigma_{\bar{\nu}_e}(E_{\bar{\nu}})}{\sigma_{\bar{\nu}_\mu}(E_{\bar{\nu}})}$$

$$P_{\mu\to e} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) \mp \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin^2 2\theta_{13}\sin\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)\sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)\sin\delta_{CP} + \ldots$$

sign flips for antineutrinos

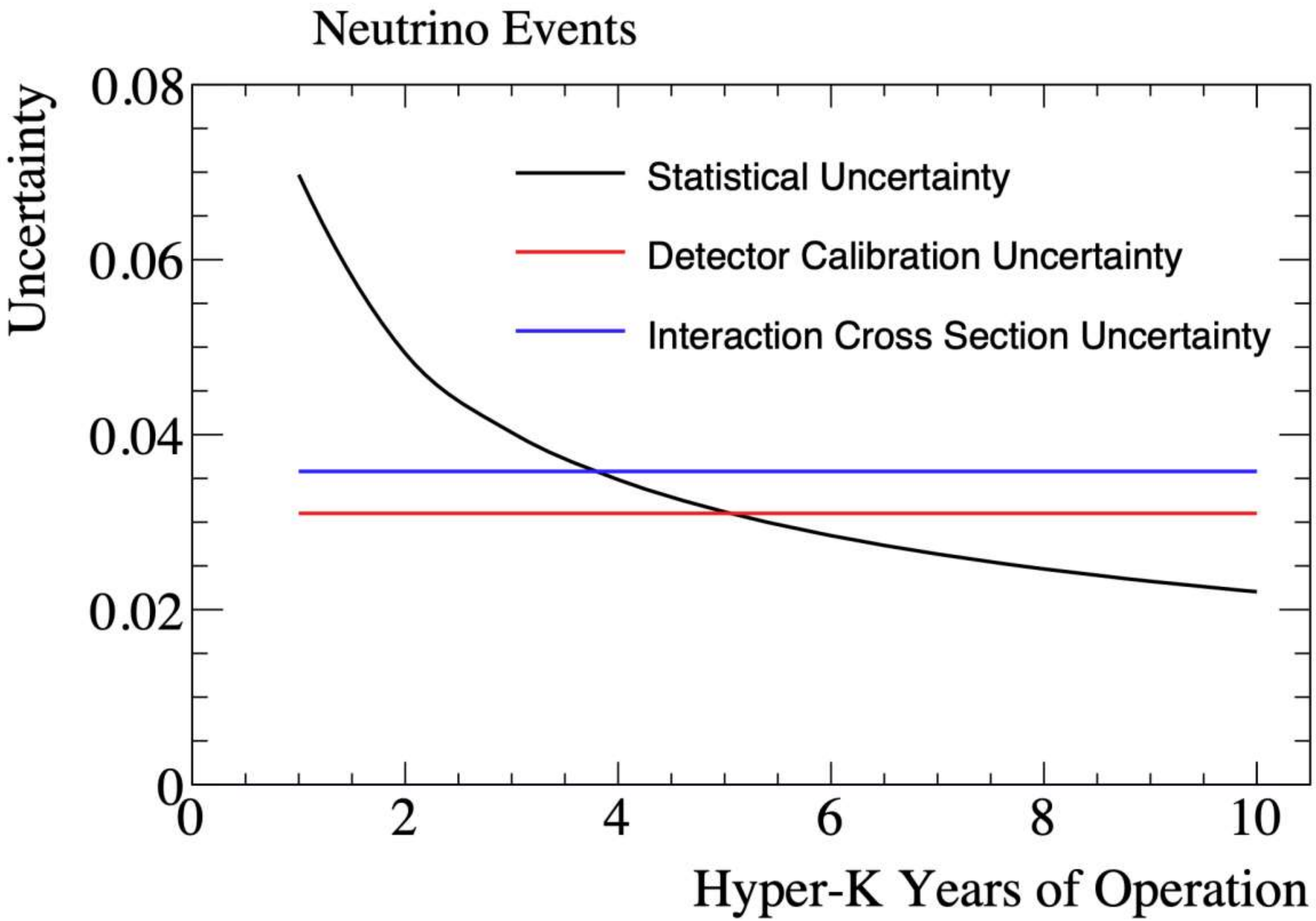
Oscillation Measurements - Search for CP Violation





- **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)

HyperK Systematics in $\nu_\mu \to \nu_e$ vs. $\bar{\nu}_\mu \to \bar{\nu}_e$ event rate



$\nu_\mu \to \nu_e$ measurement sensitivity is limited by the systematic uncertainties

- Detector
- Cross section

We rely on the double ratio to cancel the systematics in the CP measurement

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

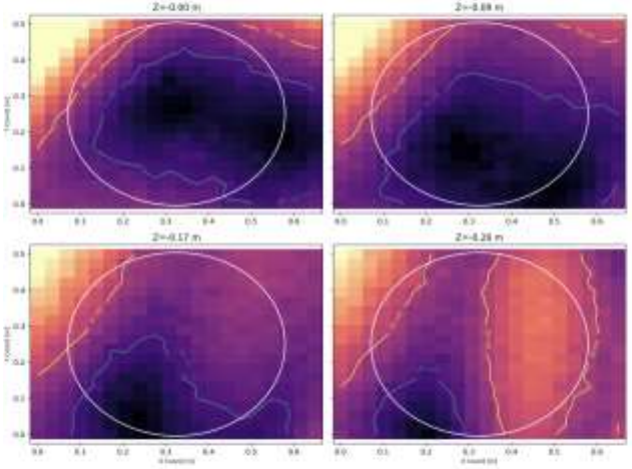
Photogrammetry

Test beam (WCTE)

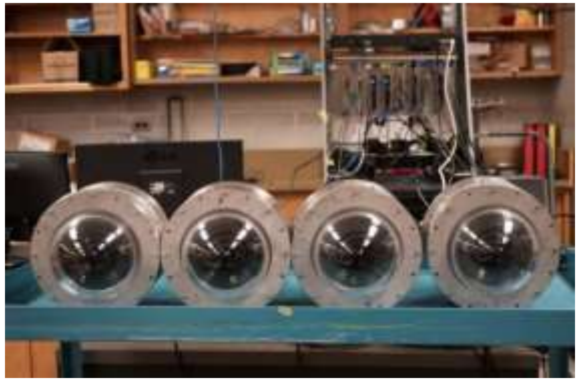
Calibration

- B. Smithers has taken over the PTF operation and making progress towards measurements of 20-inch PMTs in different magnetic field settings
  - Important to establish PTF as a stabling operating facility for future measurements
- Photogrammetry cameras are nearly ready for WCTE
  - Important to proceed with WCTE calibration analysis (R. Banerjee)
- Good progress on the water quality monitor system
- LED light injection analysis by A. Fiorentini is important for confirming the LED-mPMT design, but also establishing tools for integration of simulation, calibration sources and analysis

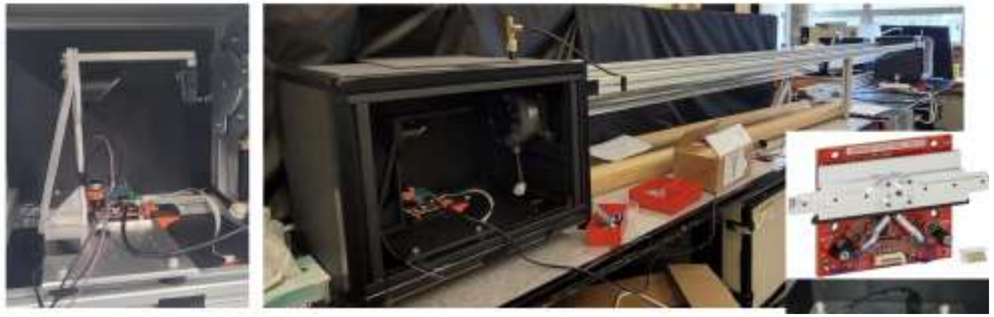
B. Smithers



B. Jamieson

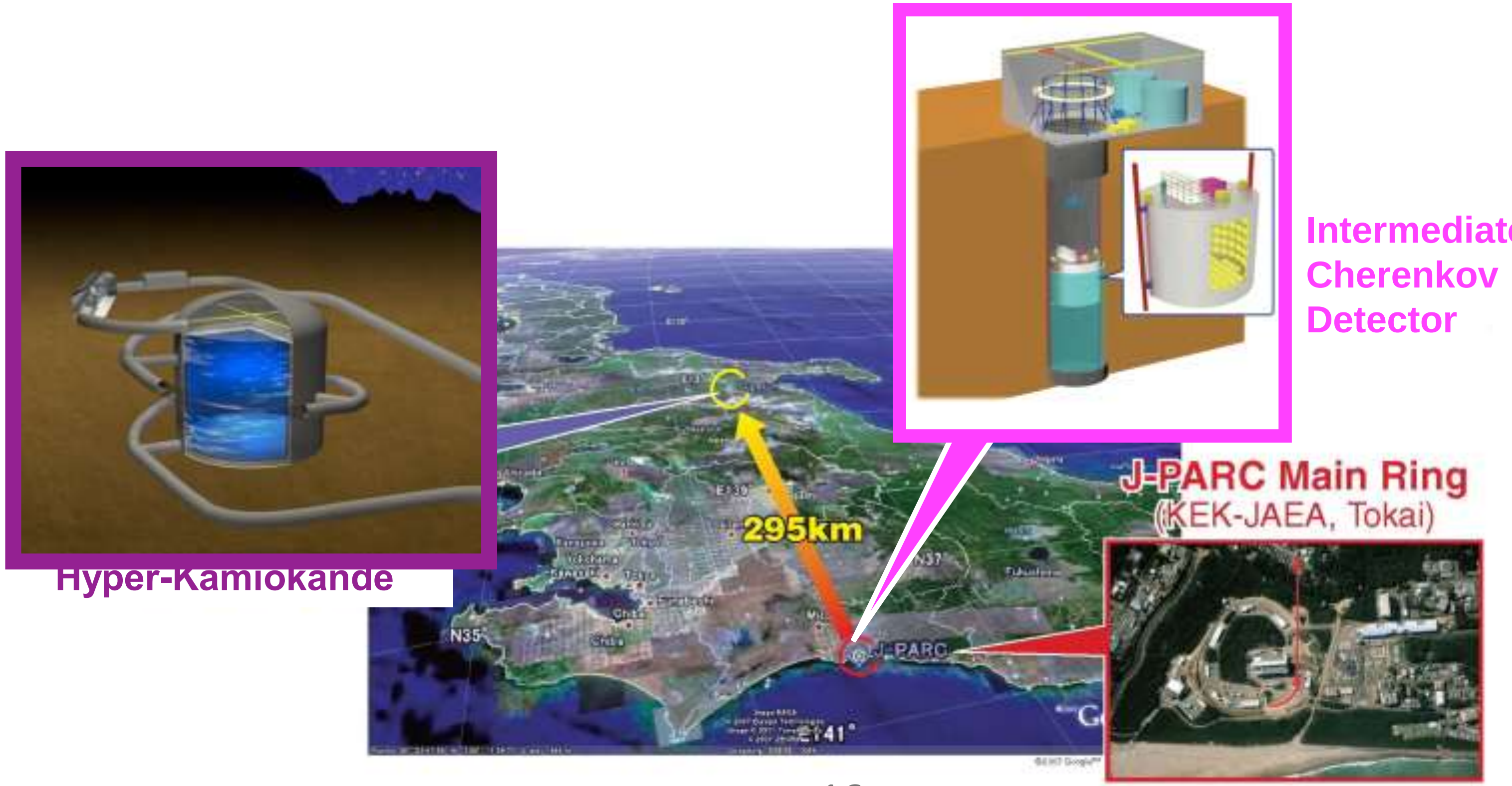


S. Taghayor



Why WCTE?

- Hyper-K (including IWCD), T2K and Super-K require well calibrated detectors with high performance event reconstruction
  - Precision measurements of 0.1-1.0 GeV particles in detector size of IWCD is not well established yet
- Developing high resolution photon detection systems, calibration techniques and improved event reconstruction with machine learning to test in WCTE

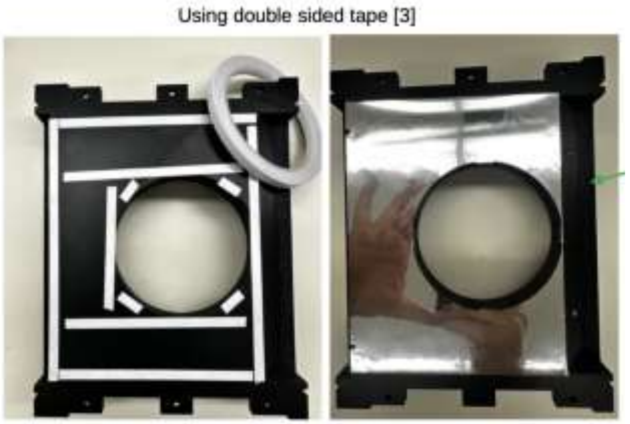


WCTE CERN T9 Beam Monitors

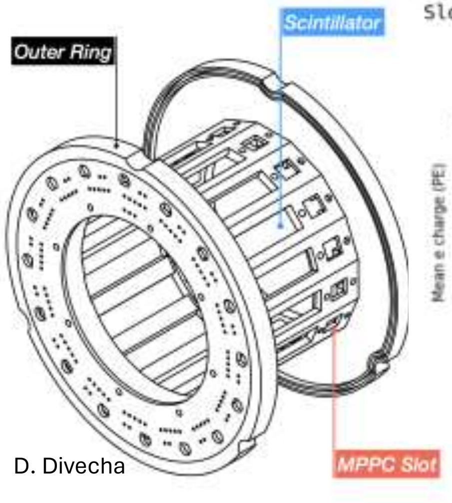
- HK-Canada collaborators have played a huge role in the development of beam monitors and analysis of their data for WCTE
- Especially students and postdocs!
- The beam monitors are the foundation of WCTE measurements that feed into IWCD, Super-K and Hyper-K programs
- Reminder that this significant work replaced a very challenging and risky approach to move WCTE between secondary and tertiary beams

2023

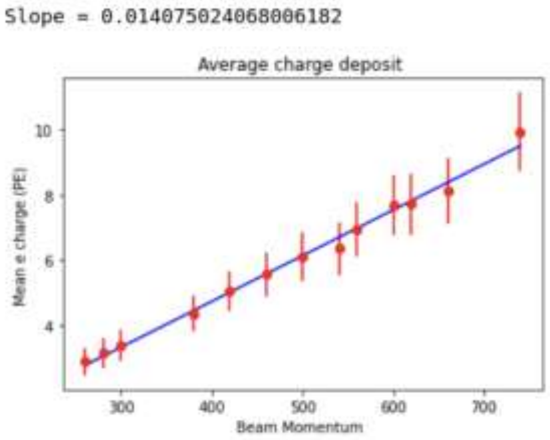
2024



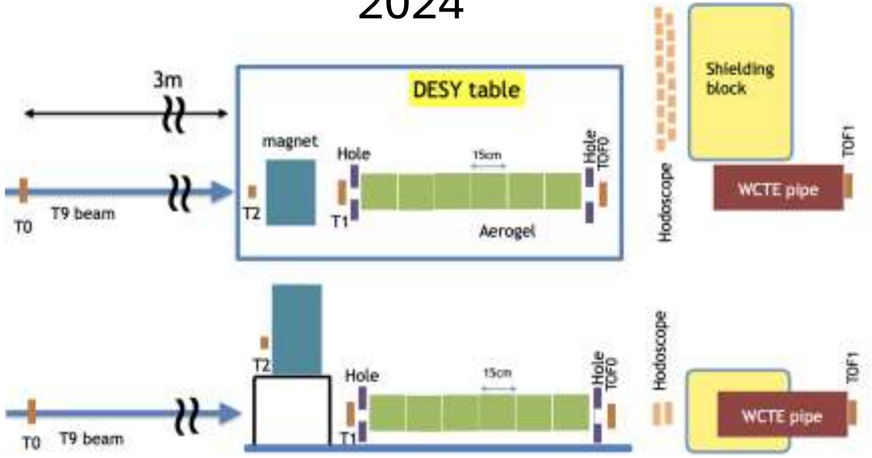
S. Yousefnejad



D. Divecha



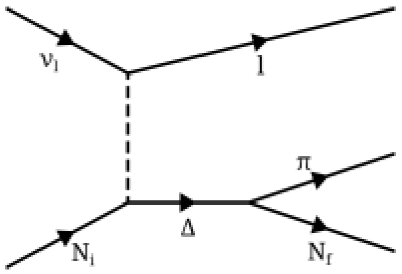
M. Mansoor



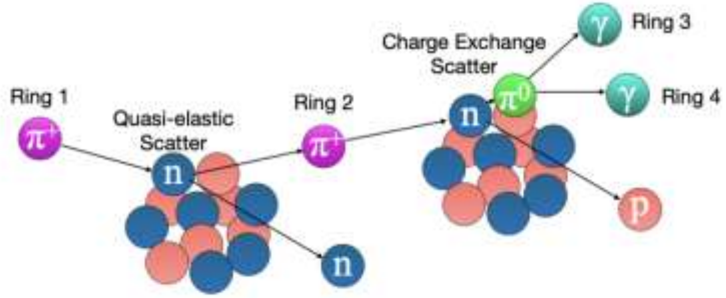
WCTE Physics

- Pions of ~500 MeV/c or less are produced in neutrino interactions
- Modeling of their hadronic interactions in water and their reconstruction is challenging
- WCTE data will be used to study pion reconstruction in water Cherenkov detectors and measure interaction cross sections
- Impact on T2K and Super-K analyses

Pion production in neutrino interaction

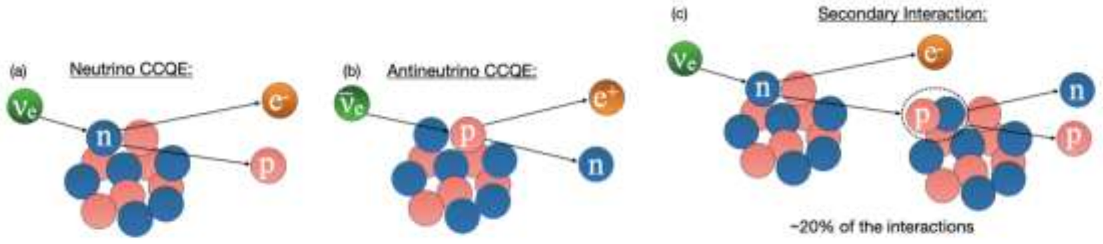


Pion scattering in water



- Antineutrino interactions tend to produce neutrons, while neutrinos tend to produce protons
- Capability to tag antineutrinos vs. neutrinos with neutron detection is limited by secondary production of neutrons (right)
- WCTE will measure secondary neutron production
- Important for using neutrons to ID antineutrino events in Super-K

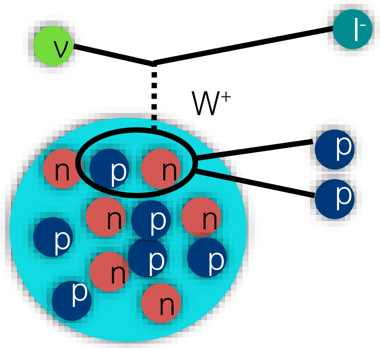
Neutron production in neutrino interactions



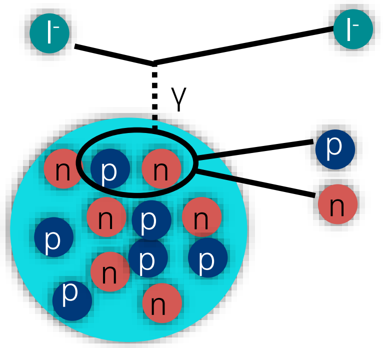
WCTE Physics

- Neutrino-nucleus scattering involves difficult to model effects such as multi-nucleon scattering (right)
- We can study the related processes of electron and muon scattering on nuclei in WCTE in order to constrain nuclear models
- Alternative approach to experiments with thin targets

Neutrino-nucleus scattering

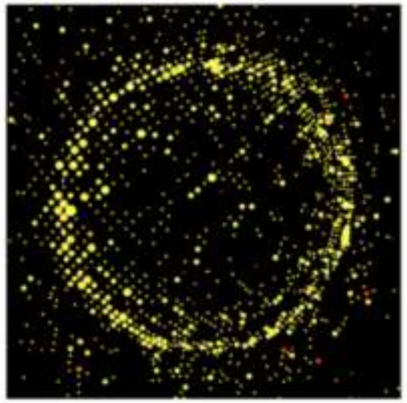


Electron/muon-nucleus scattering

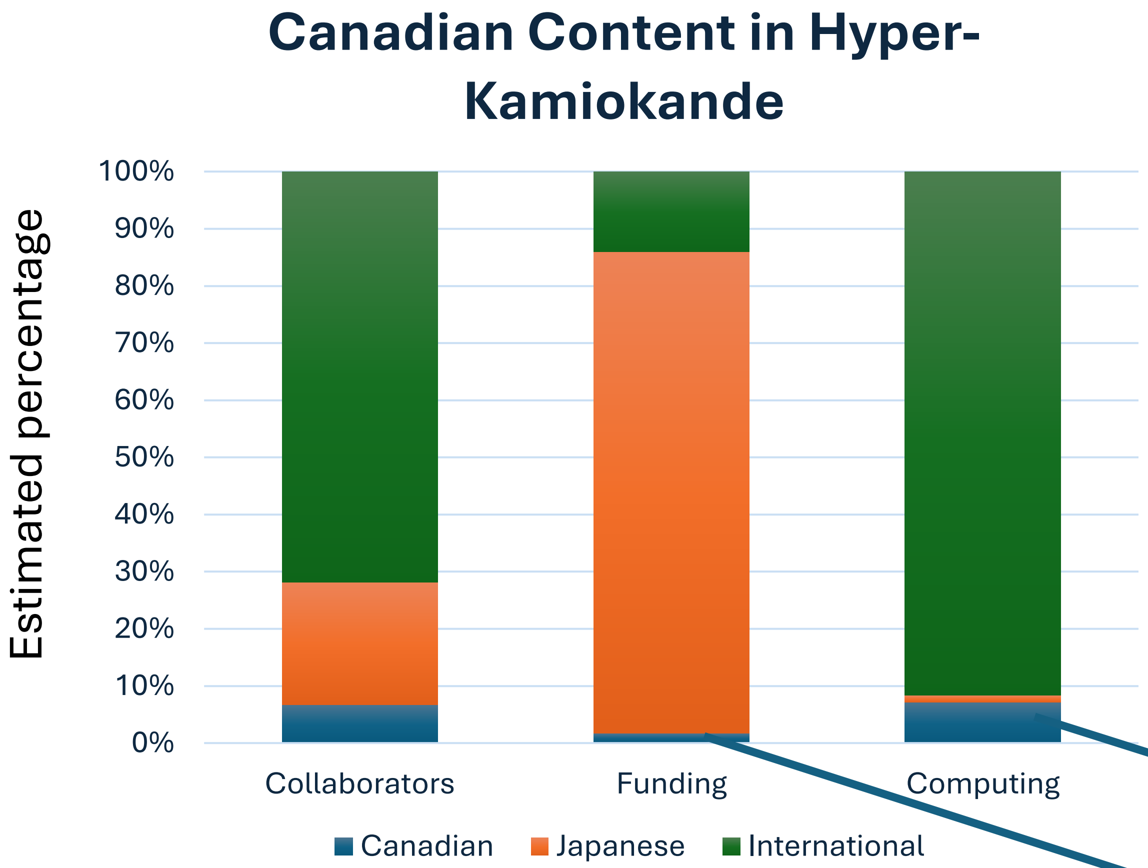


- Electrons are identified as “fuzzy” rings in WC detectors due to EM shower
- High energy gammas can fake electron
- WCTE will study capability to tag gammas by additional light produced by e+e- pair at beginning of shower
- Gammas can also be used to study pion photoproduction, which is important for understanding gamma production through pion production in neutrino interactions
- Requires tagged photon beam (detector developed by UWinnipeg and URegina)

Example electron ring in Super-K



Hyper-K Canadian Contributions



- Candadians in Hyper-K leadership
  - A. Konaka (Executive Board Member)
  - M. Hartz (Steering / Resource Board Member)
  - M. Hartz (IWCD Technical Board Member)
  - X. Li (IWCD Calibration leader)
  - R. Gornea (Safety Committee)
  - T. Lindner (mPMT Electronics)
  - B. Jamieson (Photogrammetry)

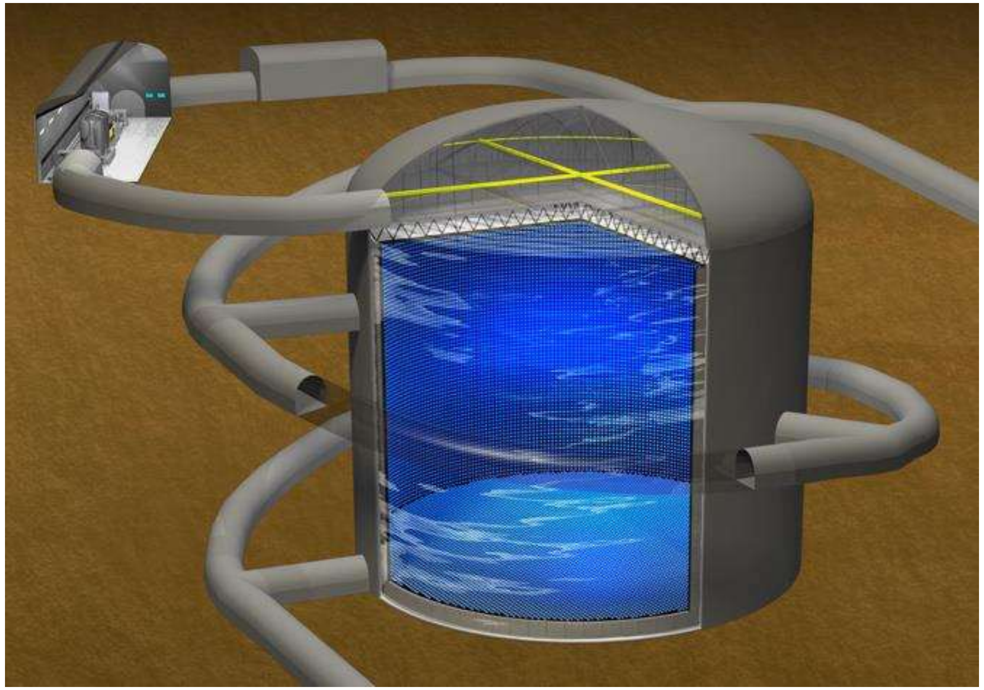
DRAC Research Projects and Portal support for T2K and Hyper-K

IWCD CFI-IF 2020 Funded for $5.4-million
CFI-IF 2023 LED mPMTs for calibration of Hyper-K $6.36-million

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

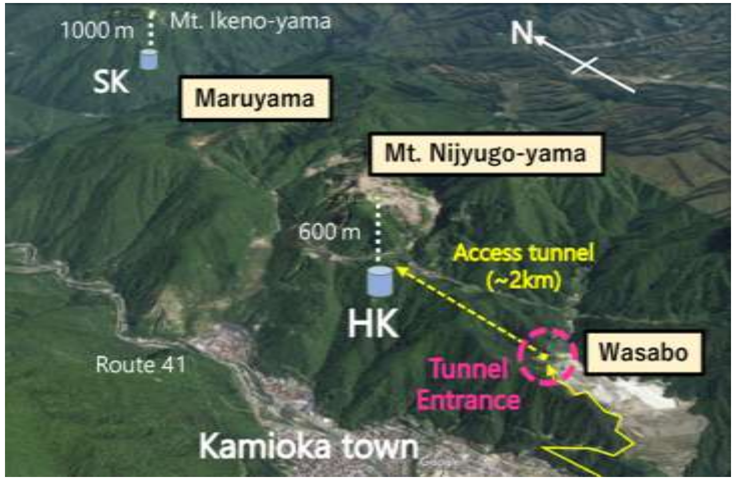
Backup

slides

HK 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

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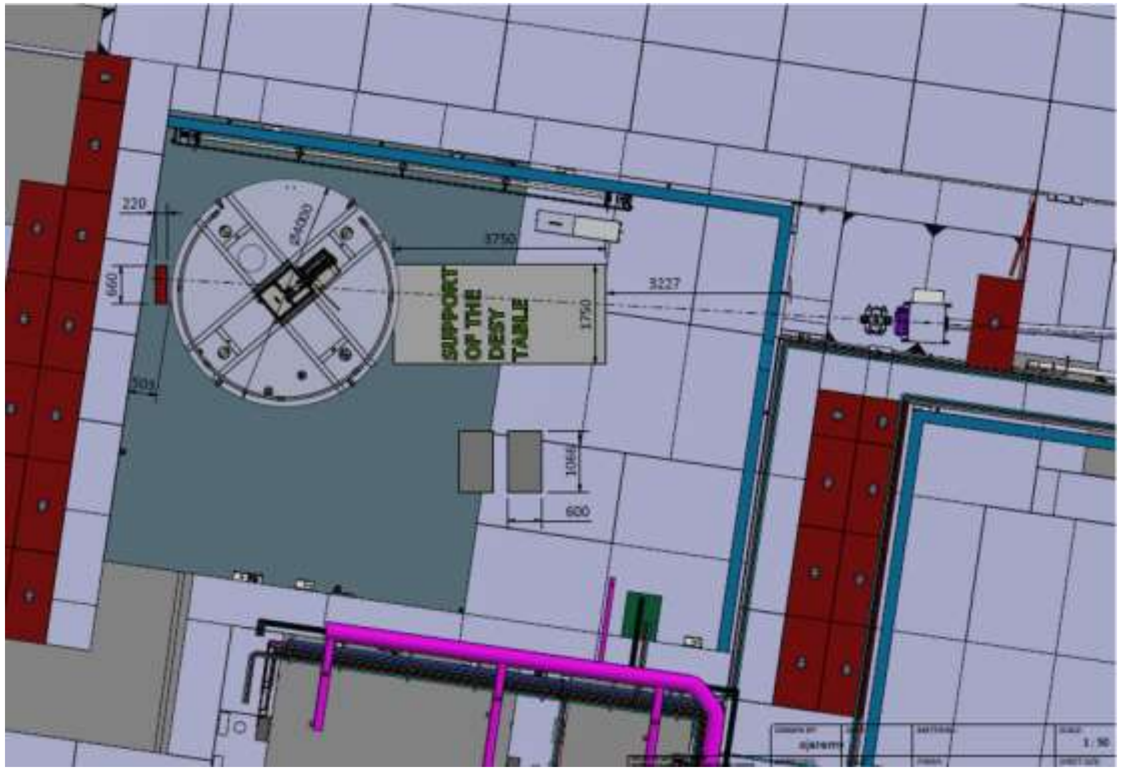
HyperK-Canada group

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

WCTE Layout

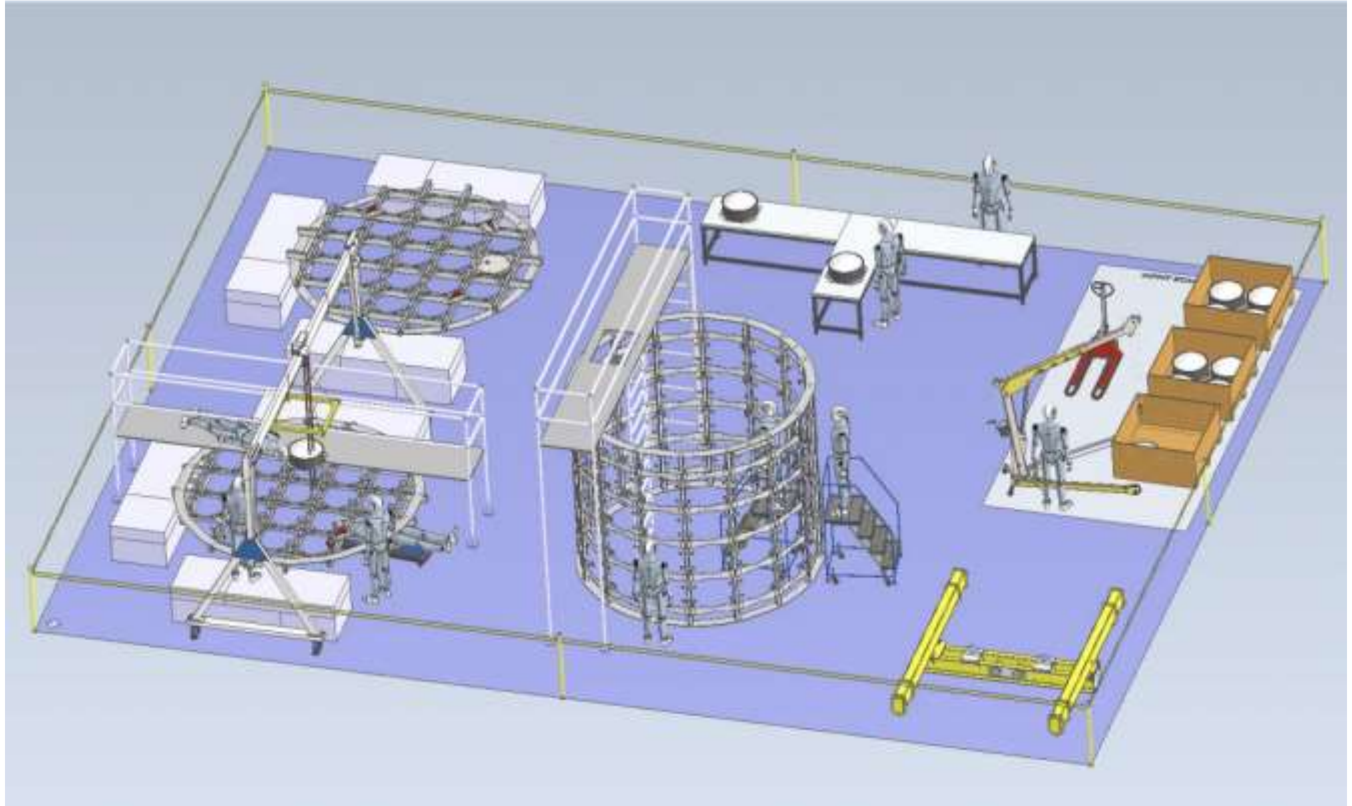
Water system located downstream of T9 beam area



- Planning to install WCTE as far back as possible in WCTE beam line
- Water system to be installed in the staging area downstream of the T9 beam line
- Beam monitors for particle tagging are install upstream of WCTE

Layout in East Hall for Installation

O. Jeremy



- WCTE will be assembled in the East Hall
- This layout shows manual A-frame crane, but we now plan to use overhead crane in East Hall
- We will still have a manual crane for moving around mPMTs as they are removed from boxes, tested and prepared for installation
- We expect that we need 4 people working together for the mPMT installations

How do accelerator-based long baseline experiments work?

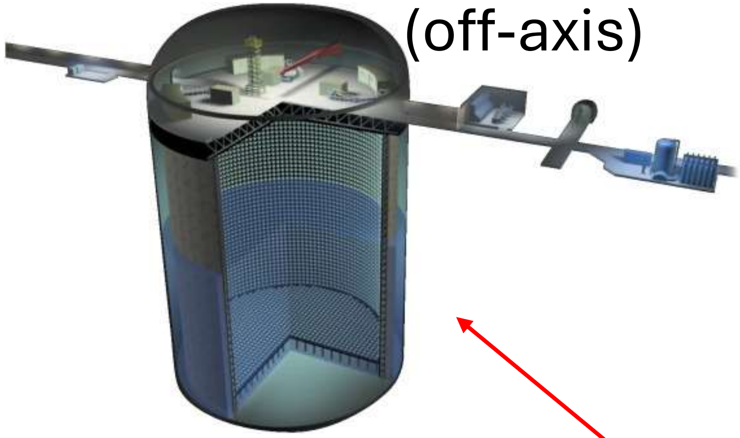
- Example: Tokai to Kamioka (T2K) in Japan

Far detector for measuring neutrinos after oscillations.

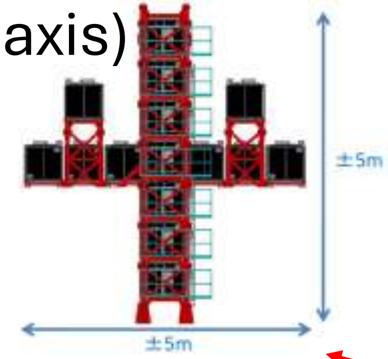
Near detectors for measuring neutrinos before oscillations.

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

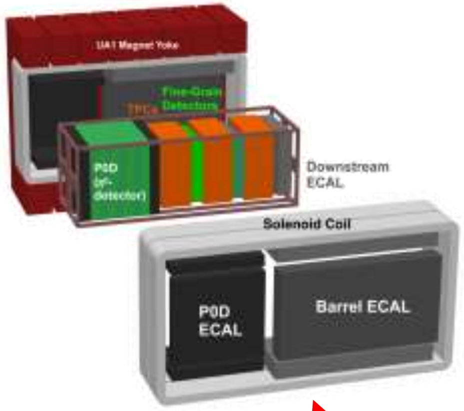
Super-Kamiokande (off-axis)



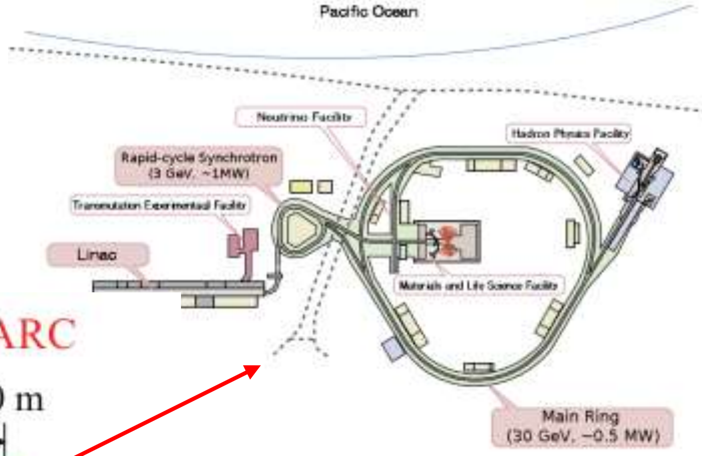
INGRID (on-axis)

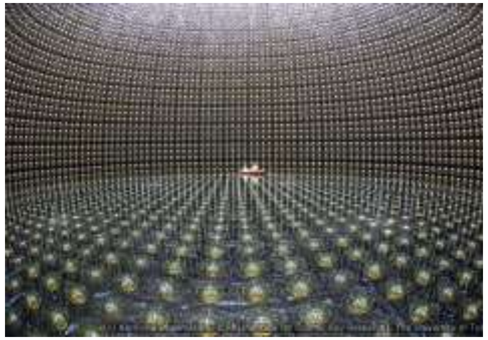


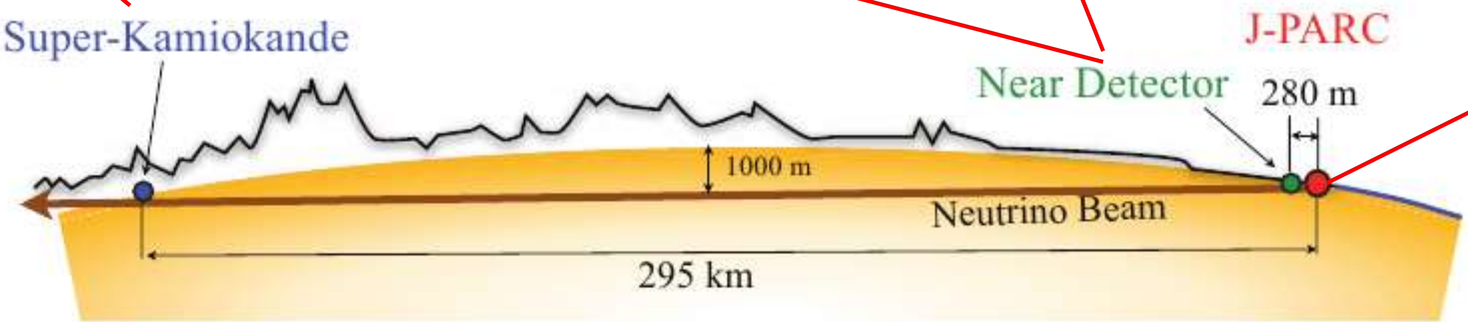
ND280 (off-axis)



J-PARC

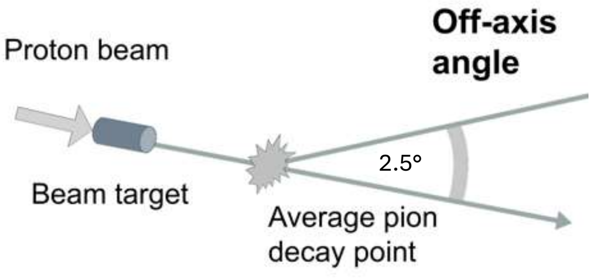




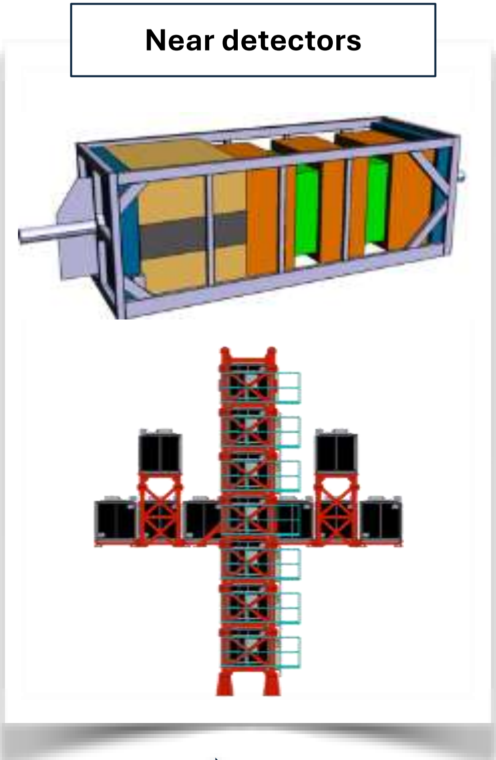


J-PARC Beam & Detectors

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

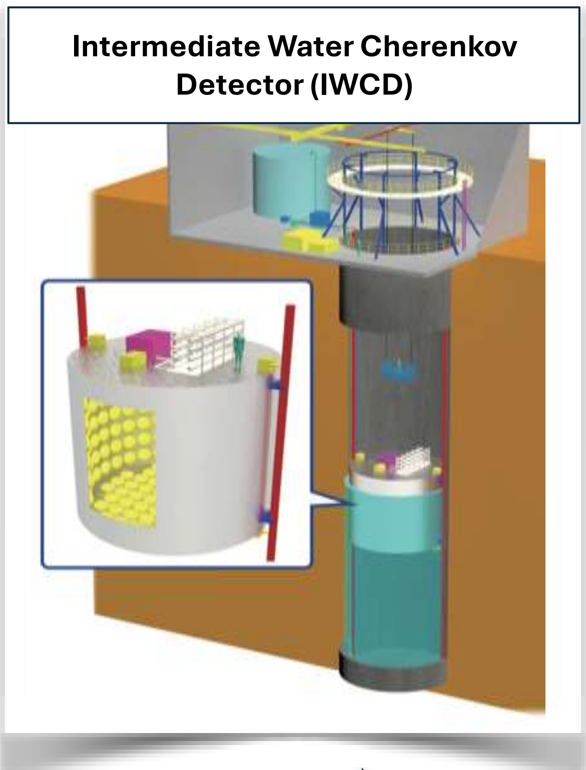


Upgraded T2K near detectors to continue to Hyper-K era



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



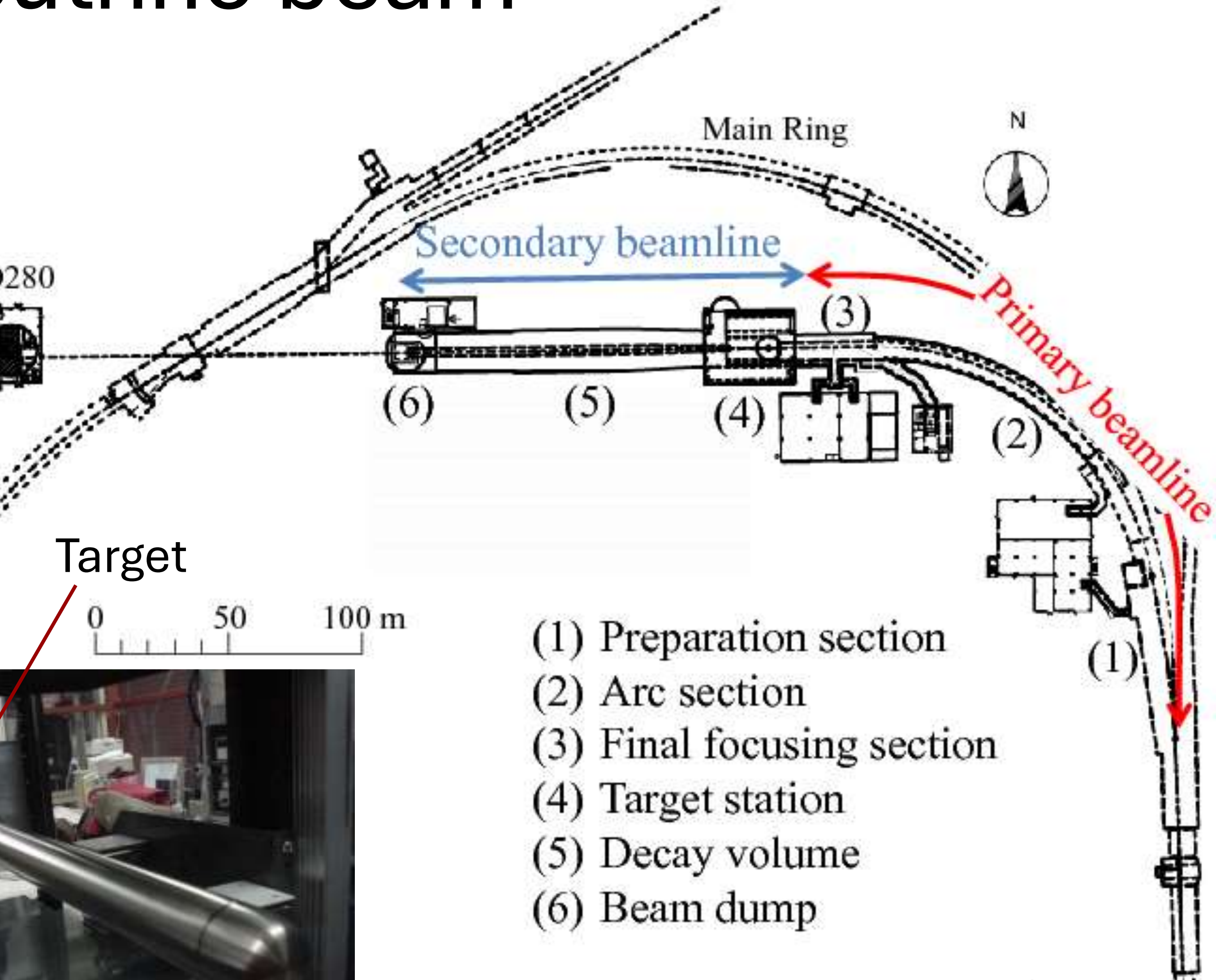
280 m → ~ 1 km

CP double ratio [Detector systematics]

$$\frac{\Phi_{far}(\nu_e)/\Phi_{near}(\nu_\mu) - \Phi_{far}(\bar{\nu}_e)/\Phi_{near}(\bar{\nu}_\mu)}{\Phi_{far}(\nu_e)/\Phi_{near}(\nu_\mu) + \Phi_{far}(\bar{\nu}_e)/\Phi_{near}(\bar{\nu}_\mu)} \simeq \frac{-16 J_{CP} \sin\Delta_{21} + 16 c_{13}^2 s_{13}^2 s_{23}^2 a/\Delta m_{31}^2}{8 c_{13}^2 s_{13}^2 s_{23}^2}$$

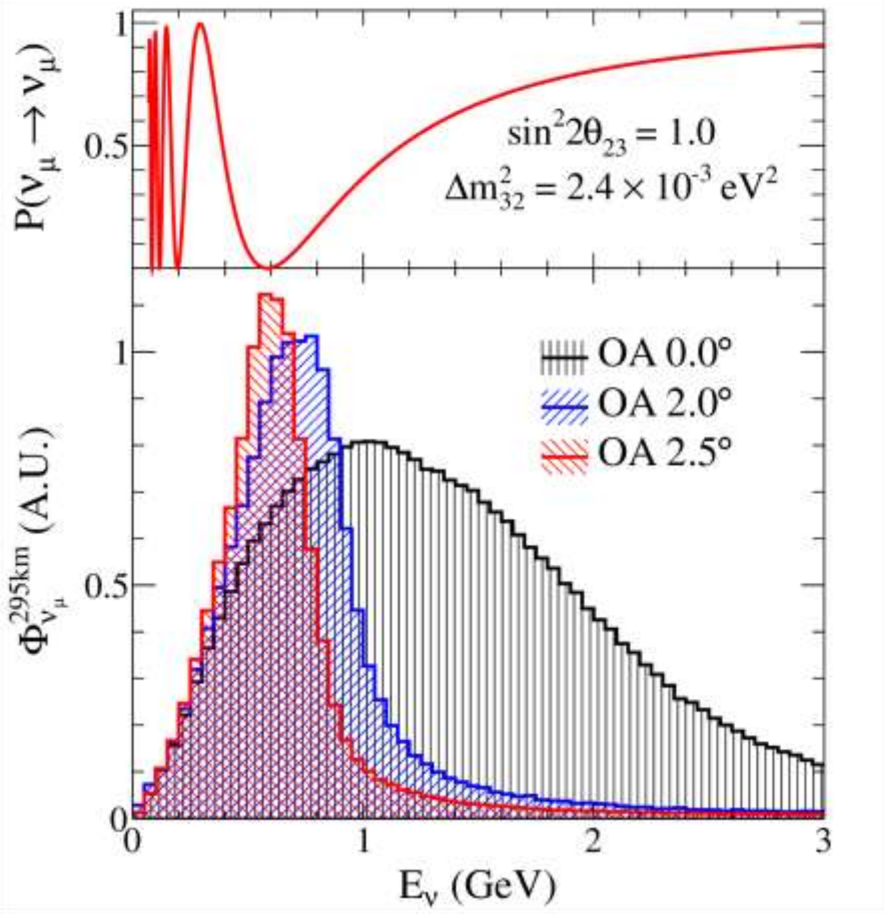
- Far/Near detector responses
  - the same water Cherenkov technology for good cancellation (IWCD), but there are differences
    - μ (Near) and e (Far) responses are different
    - kinematics of e/μ from ν and $\bar{\nu}$ kinematics (energy and direction) are different
  - these systematics that prevent cancellation are not properly taken into account
    - WCTE will provide control data for calibration
    - Photogrammetry for IWCD geometry challenge
    - LED mPMT for HyperK position and energy-dependent responses

Neutrino beam



Target

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.

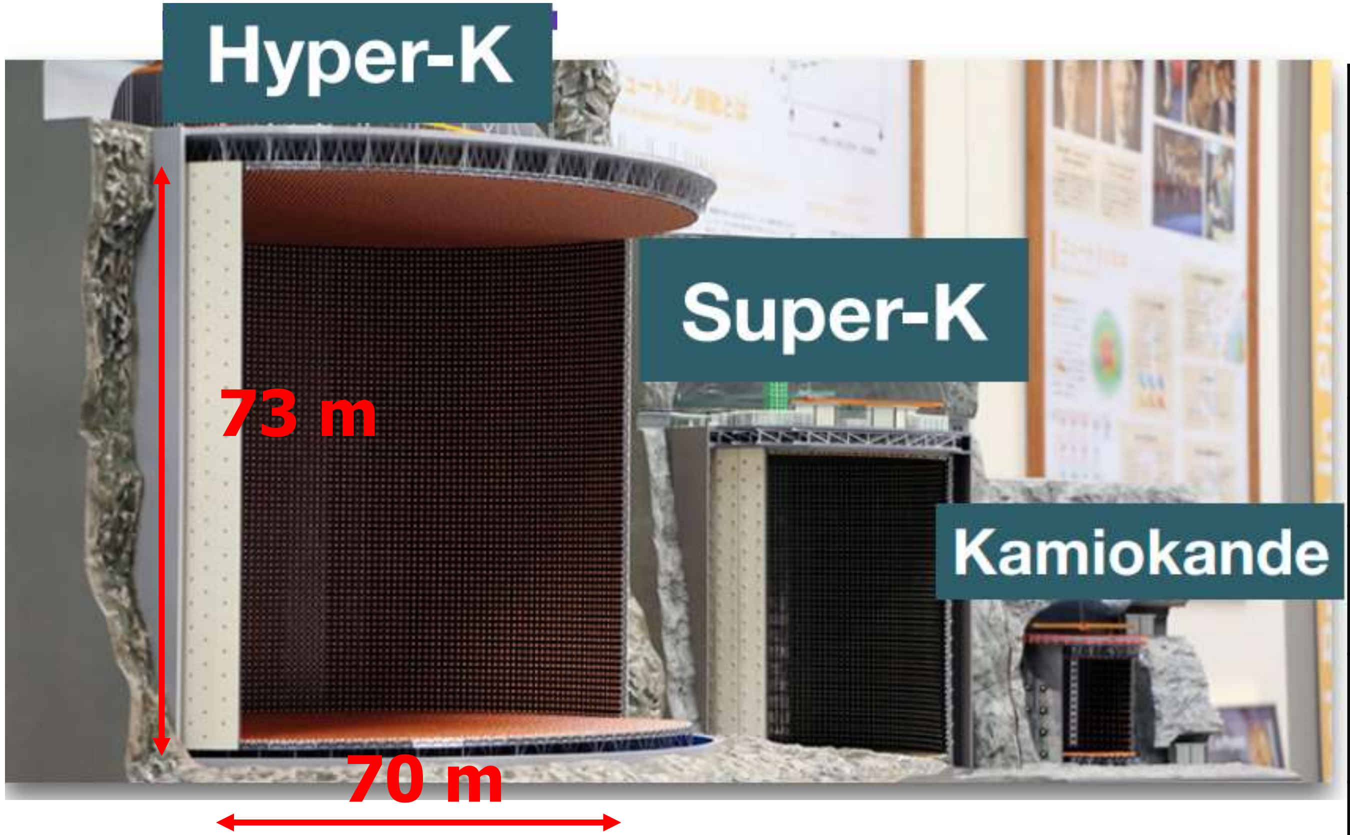
Target materials in near and far detectors are not necessarily the same.
Neutrino energy spectra is different in the far detector.
Nuclear effect are biassing neutrino energy reconstruction.

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!

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

Hyper-Kamiokande Cavern Design

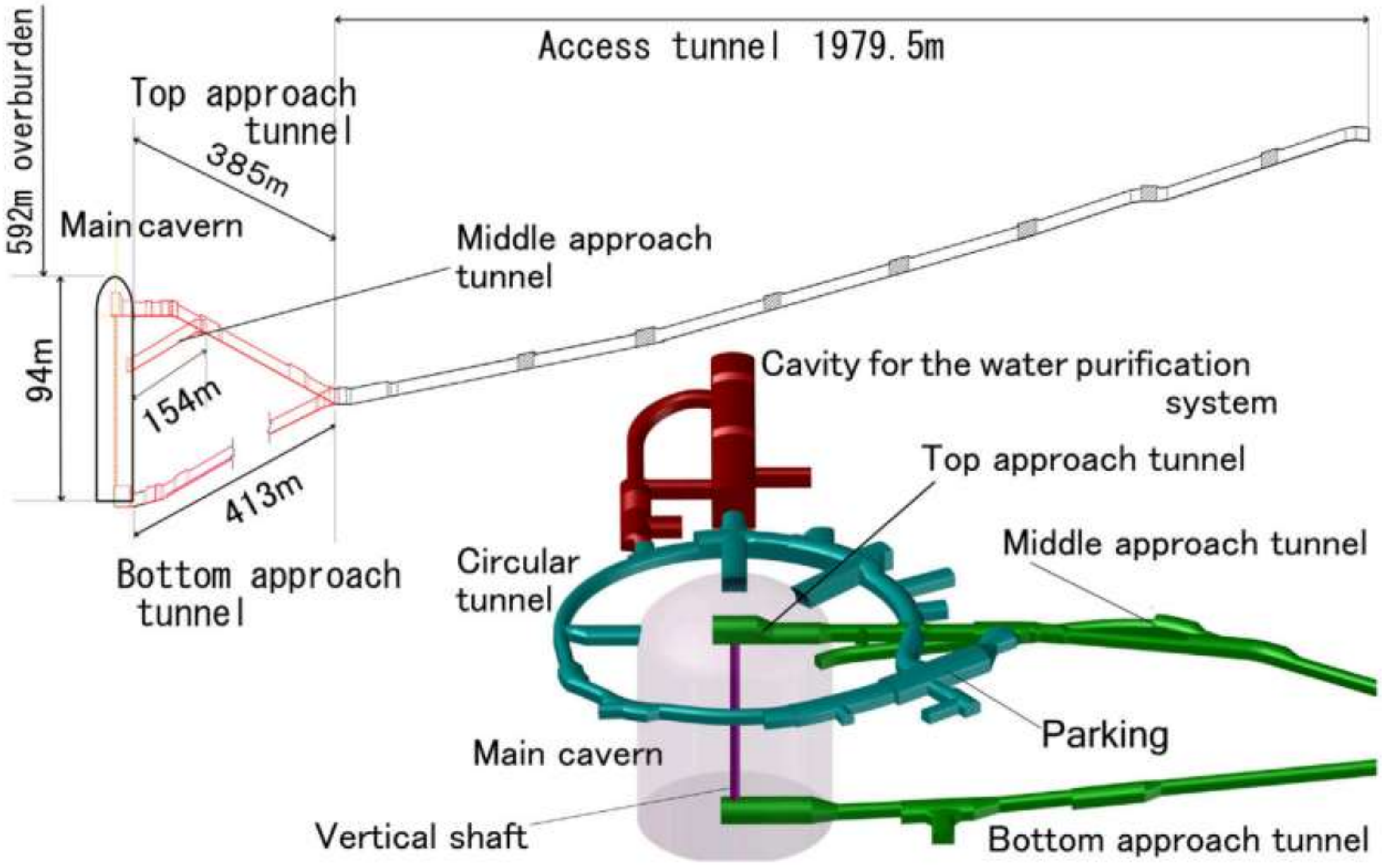


FIGURE 1
The Hyper-K underground facility overview (top) and the schematic view of the detector area (bottom).

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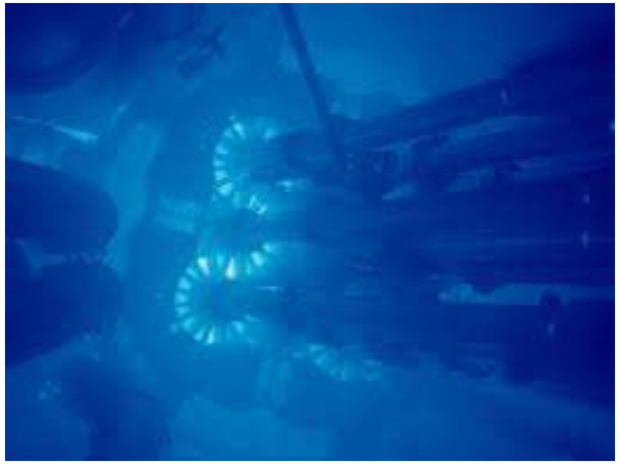
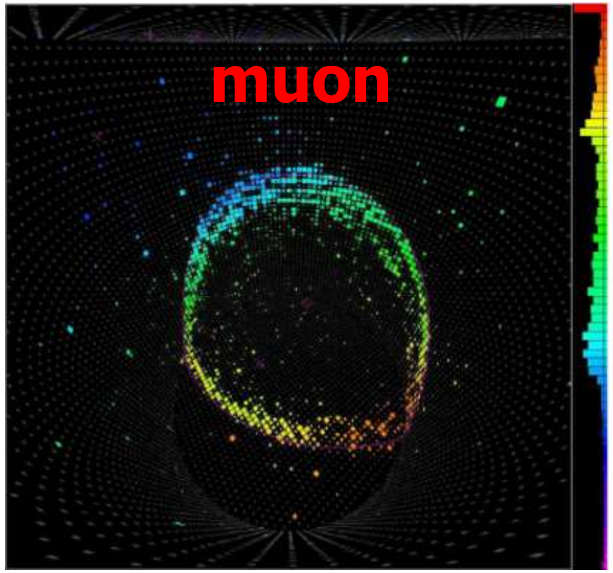
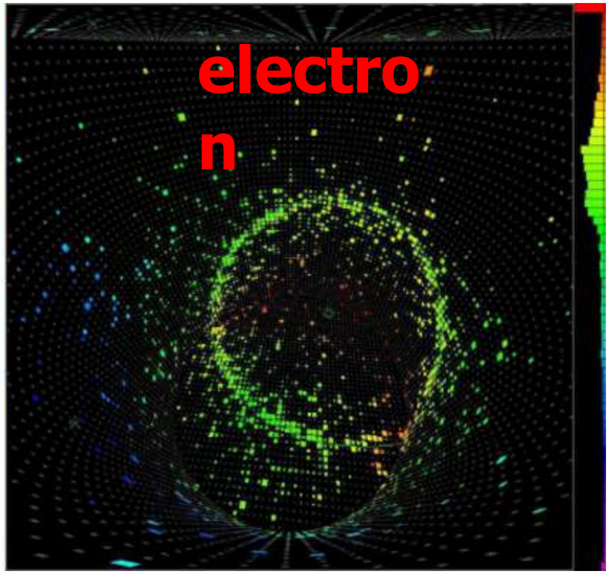
Water Cherenkov Detectors

- 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)

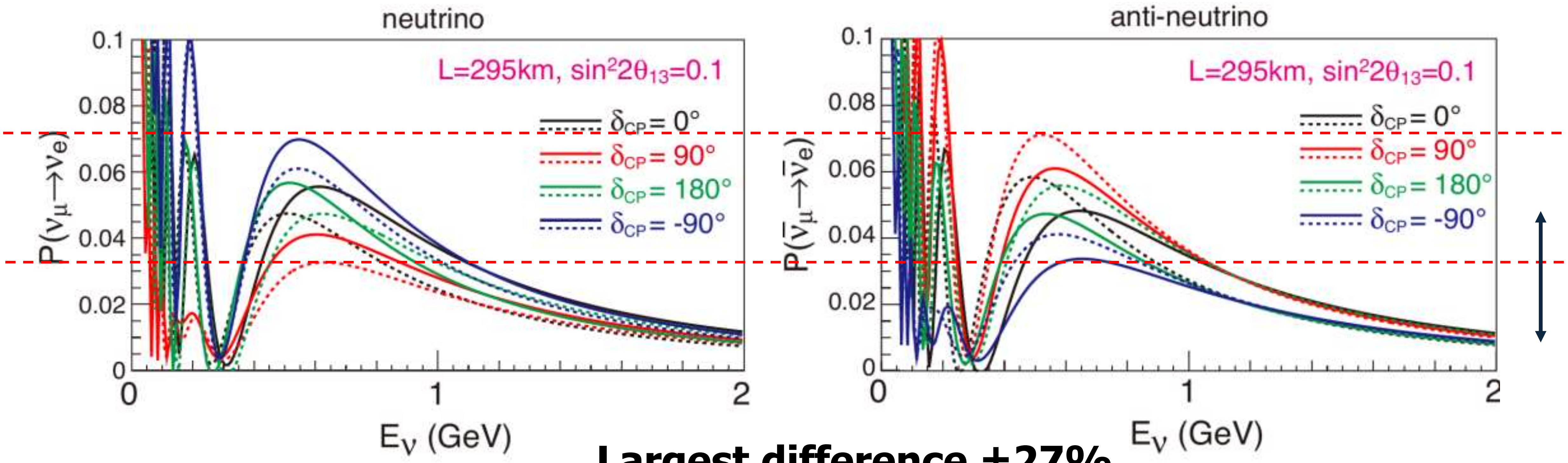






CPV measurement

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

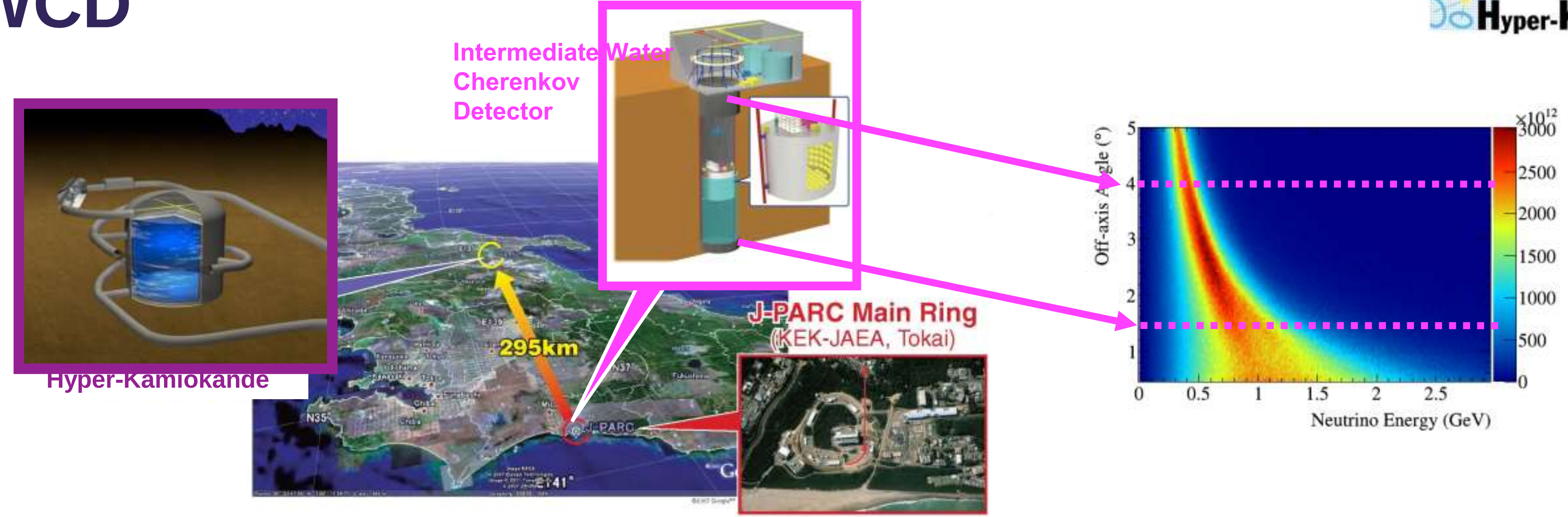


Largest difference ±27%

Normal hierarchy = solid
Inverted hierarchy = dashed

Appearance probability depends on the CP phase

IWCD



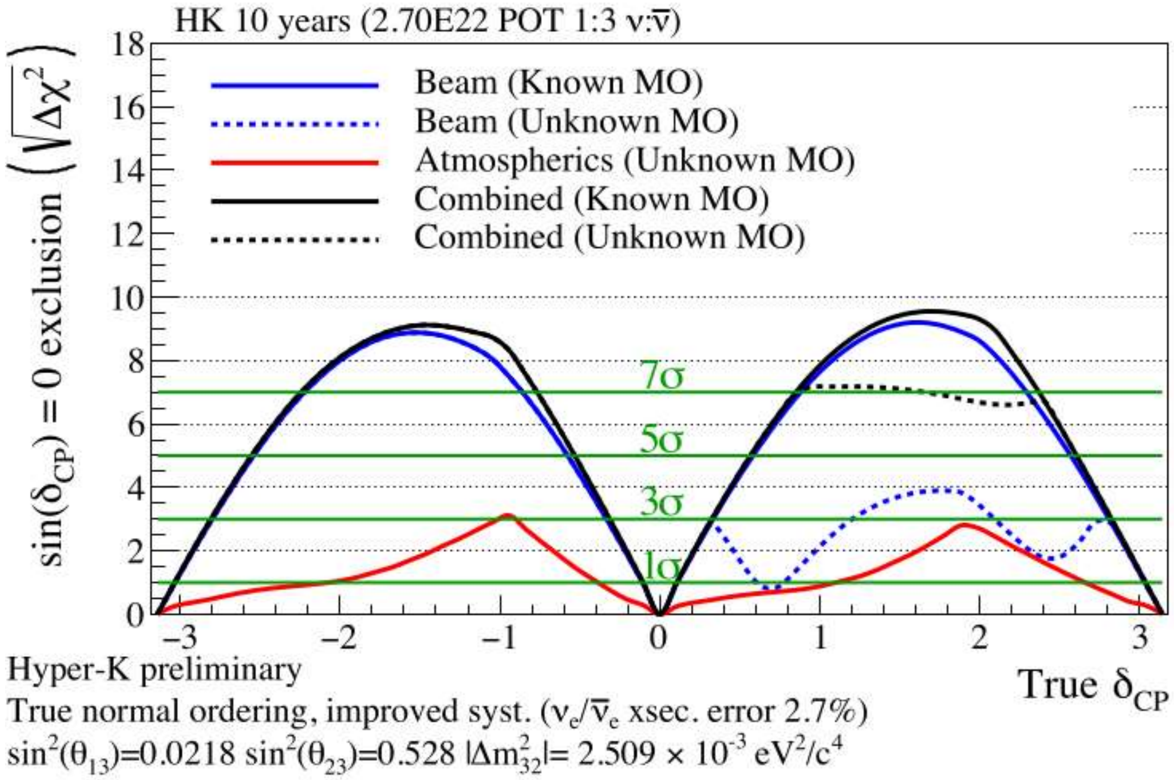
- Intermediate Water Cherenkov Detector located ~850 m downstream of the neutrino production point
- Detector moves in a vertical shaft in order to make measurements at different off-axis angles
  - Average energy varies due to kinematics of the pion decays that produce the muon (anti)neutrinos

Oscillation Measurements - Atmospheric ν + Beam

	$\sin^2\theta_{23}$	Atmospheric ν	Atmospheric + beam ν
Mass ordering	0.40	$2.2\,\sigma$	$3.8\,\sigma$
	0.60	$4.9\,\sigma$	$6.2\,\sigma$
θ_{23} octant	0.45	$2.2\,\sigma$	$6.2\,\sigma$
	0.55	$1.6\,\sigma$	$3.6\,\sigma$

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

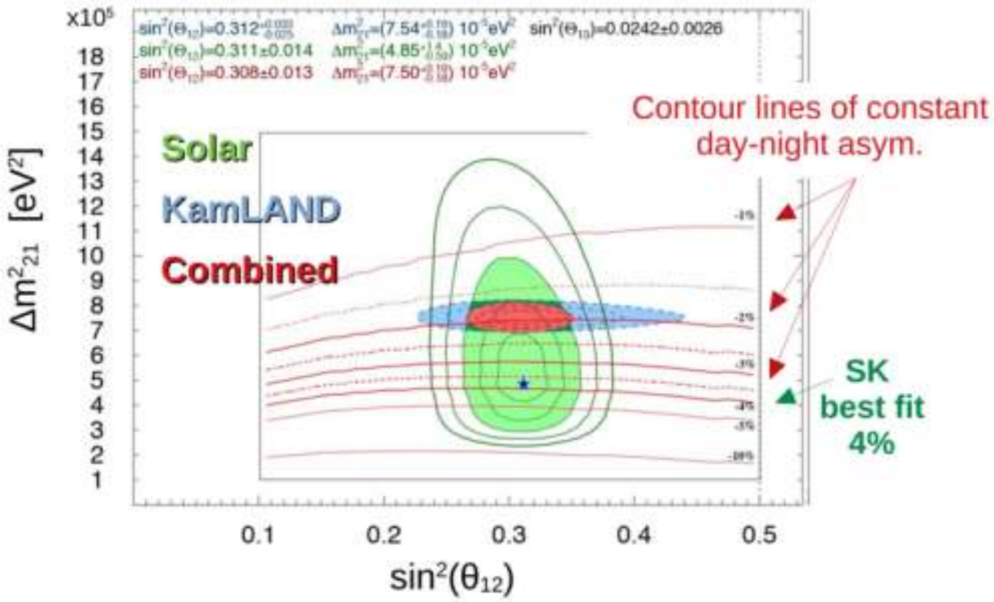


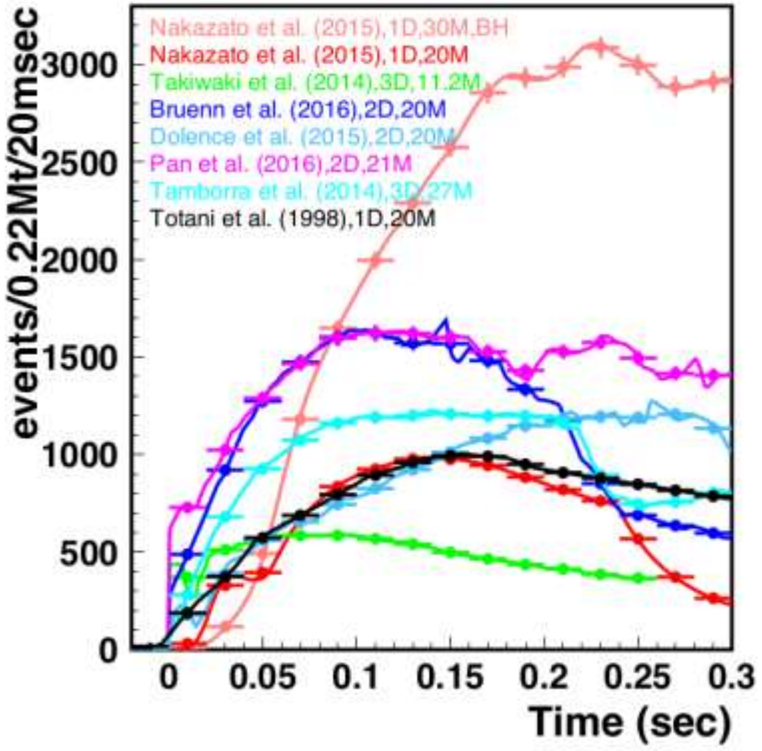
- CP violation and matter effect both create difference between ν and $\bar{\nu}$ oscillations
- Breaking degeneracies also enhances CP violation search

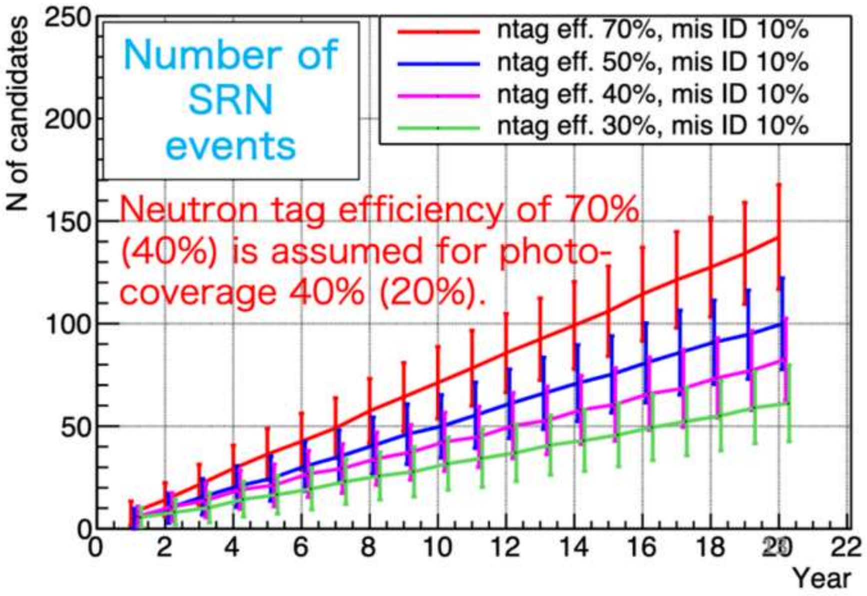
Solar & Supernova Neutrinos

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