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The Intermediate Water Cherenkov Detector for the Hyper-Kamiokande experiment

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Hyper-Kamiokande

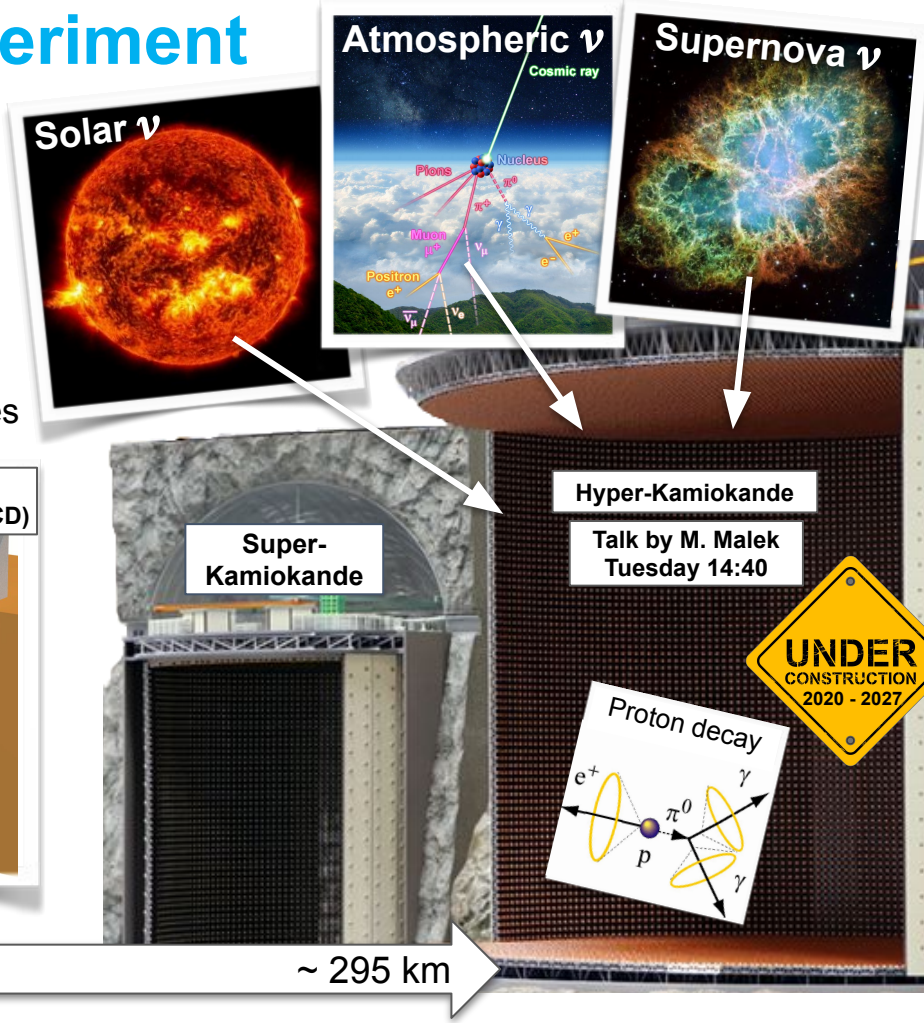
LEPTON PHOTON 2021 MAN

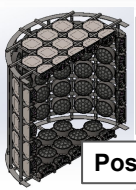
The Hyper-Kamiokande Experiment

Hyper-Kamiokande (Hyper-K) is a world-leading neutrino experiment building on the success of Super-Kamiokande

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

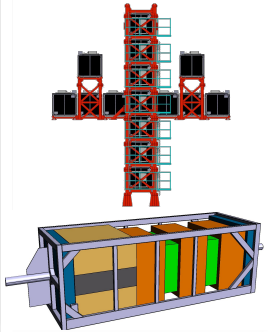




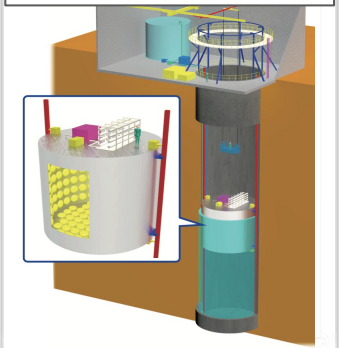
Water Cherenkov Test-beam Experiment (WCTE) at CERN

Poster by L. Anthony

Near detectors



Intermediate Water Cherenkov Detector (IWCD)



280 m → ~ 1 km → ~ 295 km

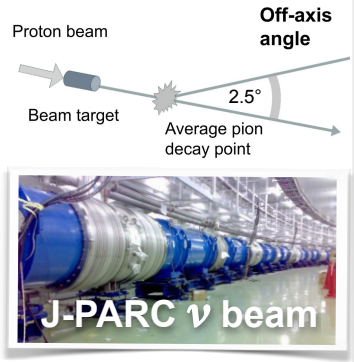
Long-Baseline Neutrinos

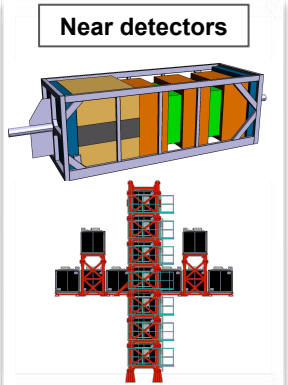
Neutrino beam produced at 295 km baseline from Hyper-K

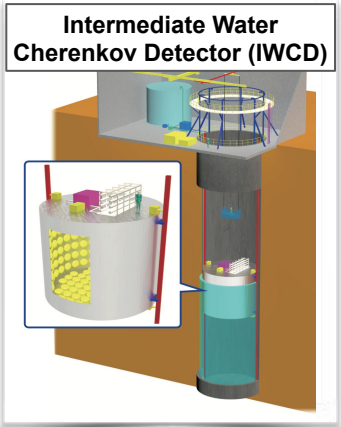
Near and intermediate detectors measure unoscillated flux and cross sections

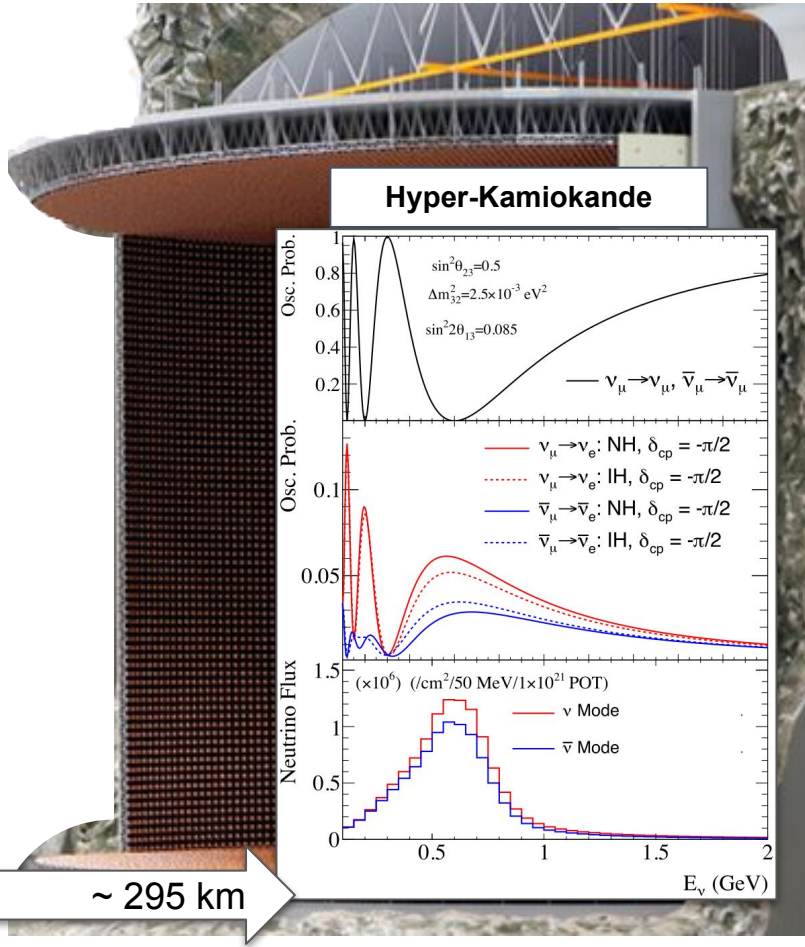
Oscillations observed through ν_μ disappearance and ν_e appearance, for both neutrinos and antineutrinos

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









280 m → ~ 1 km → ~ 295 km

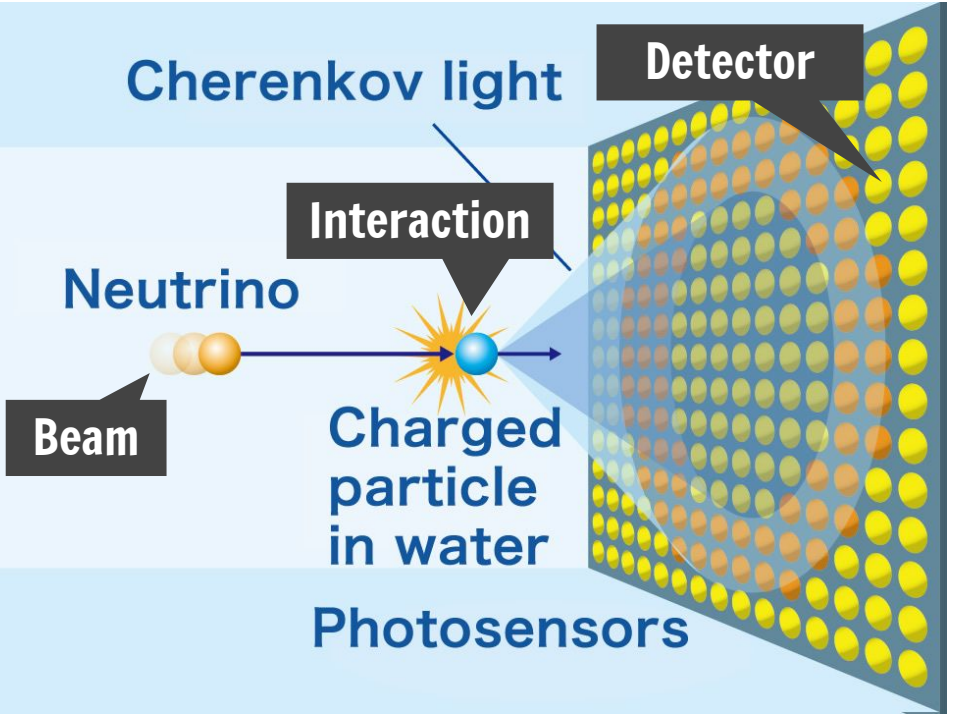
Systematic Uncertainties

1.3 MW beam (2.5x T2K) and 260 kton fiducial mass far detector (8x Super-K) gives 20x event rate

Systematic uncertainties must be reduced to exploit Hyper-K's increased statistical power

Current T2K uncertainty for CPV	Error (%)
Super-K detector	1.5
Super-K FSI + SI + PN	1.6
Flux and cross section (near detector constrained)	2.7
Flux and cross section (near detector unconstrained)	1.2
Nucleon removal energy	3.6
ν_e / $\bar{\nu}_e$ cross section ratio	3.0
NCγ + other interactions	1.5
Total	6.0

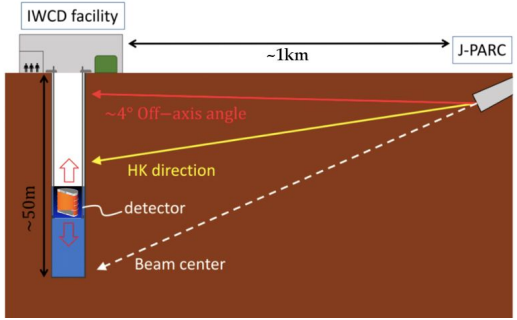
arXiv:2101.03779

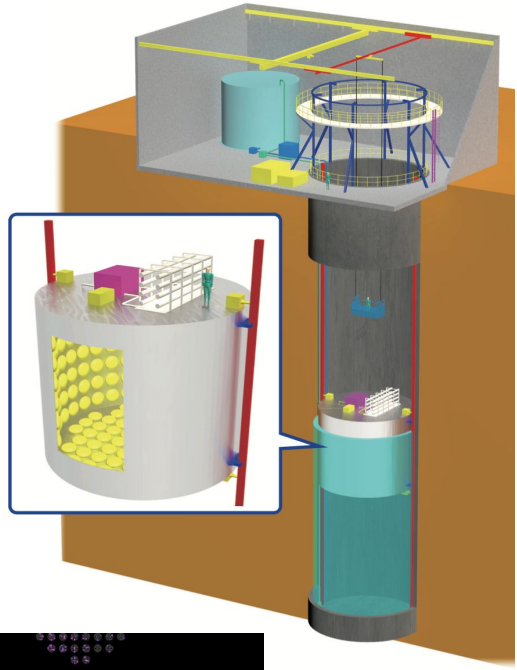


Total systematic error at Hyper-K should be reduced to less than 3 %

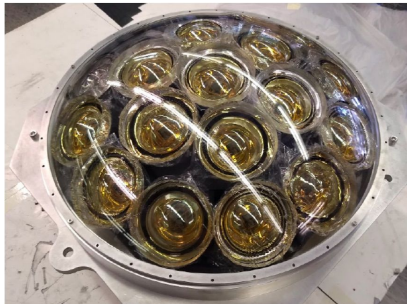
The Intermediate Water Cherenkov Detector

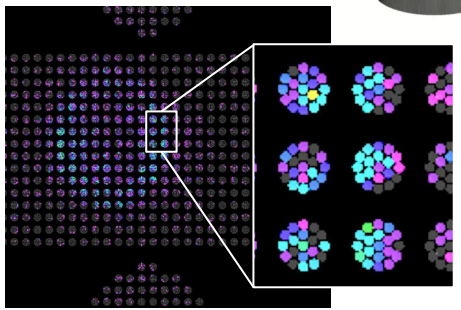
- Measure flux and cross sections of mostly unoscillated beam to reduce systematics at far detector
- Located ~ 1 km from ν beam source
- Moves vertically in ~50 m tall pit
  - Spans range of angles off axis from ν beam for different ν energy spectra



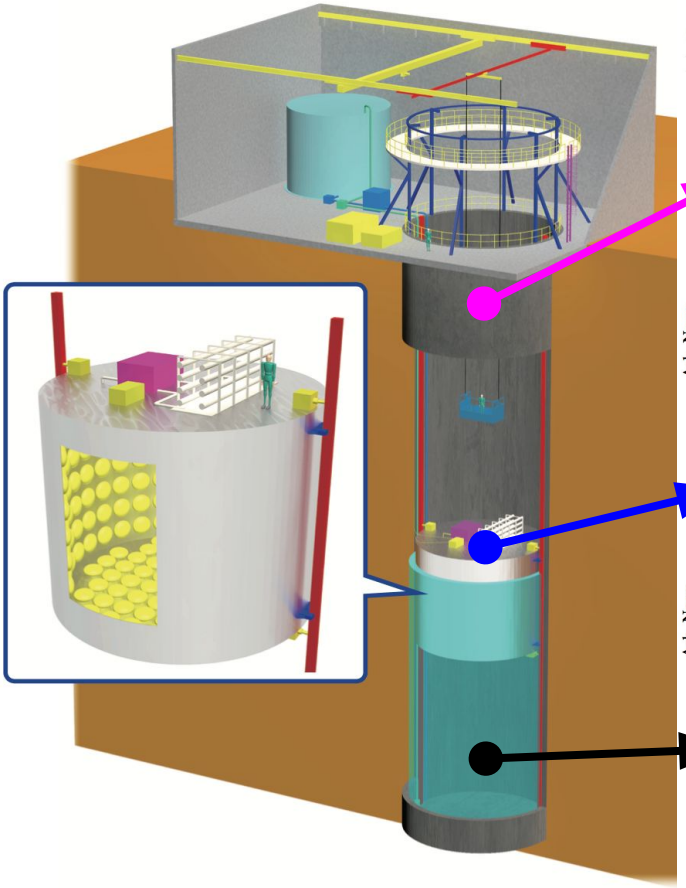


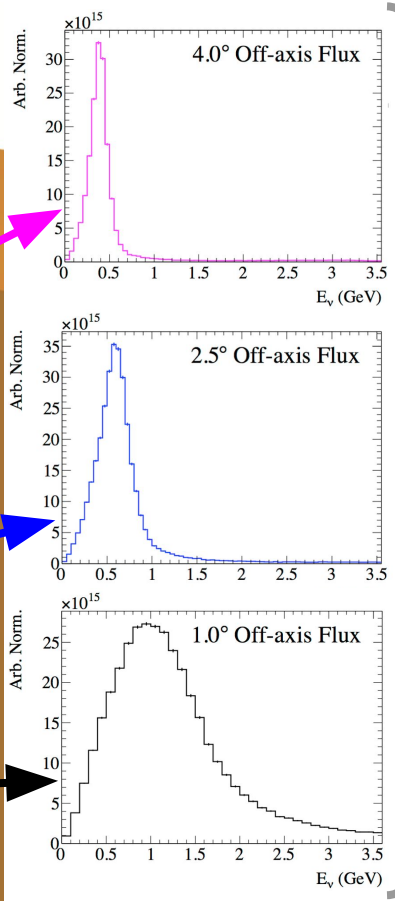
- 6 m tall x 8 m diameter surrounded with ~ 500 multi-PMT modules
- Gadolinium doped water provides enhanced neutron detection
- Small detector with high event rate introduces challenges for hardware, calibration and event reconstruction



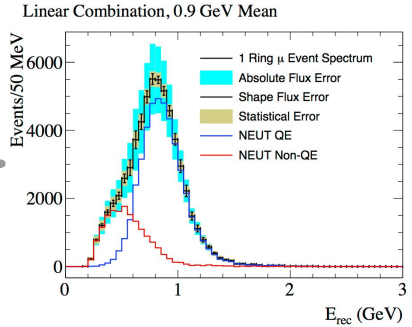


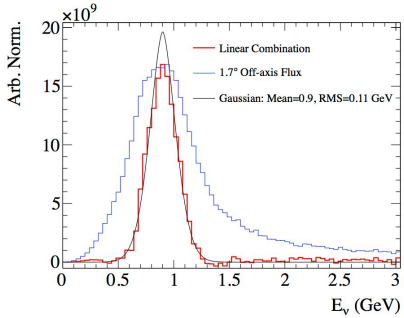
Spanning Off-Axis Angles





- ν energy spectrum depends on angle off-axis to the neutrino beam
- Far detector @ 2.5° for peak at ~600 MeV, but oscillated ν_e spectrum is different to unoscillated spectrum at near detectors
- Moving IWCD varies angle, allowing measurements at different energies
- Linear combinations allows mimicking far-detector spectrum or monochromatic beams





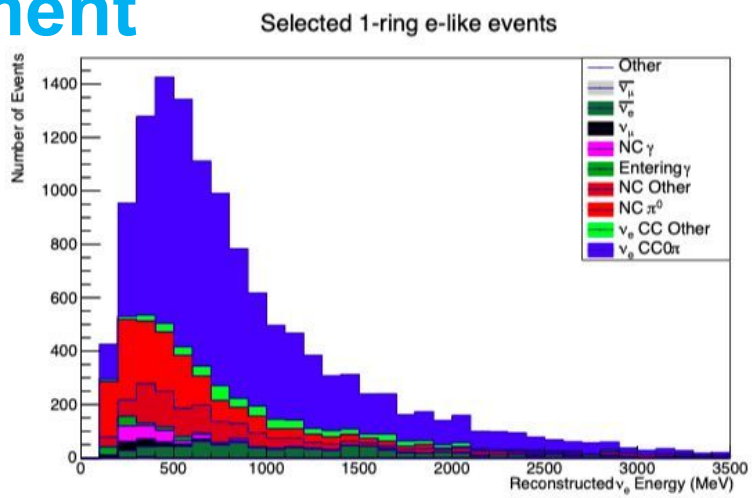
ν_e / $\bar{\nu}_e$ Cross Section Measurement

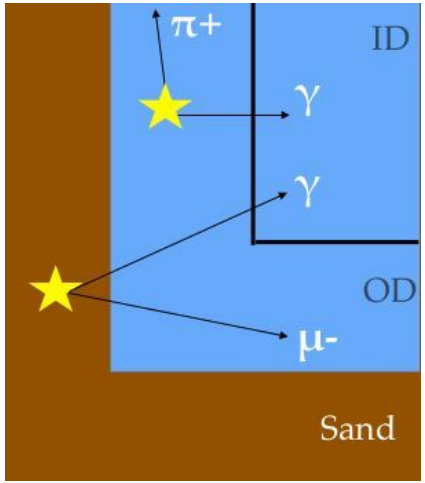
- 1% contamination of ν_μ / $\bar{\nu}_\mu$ beam with ν_e / $\bar{\nu}_e$ allows measurement of ν_e / $\bar{\nu}_e$ cross-sections
- Larger off-axis angle positions have more ν_e contamination
- CP-violation search depends on double-ratio

$$\frac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)}$$

  - Existing T2K systematic errors on $\sigma(\nu_e)$ and $\sigma(\bar{\nu}_e)$ come from theoretical uncertainties
  - IWCD can measure these cross-sections directly
- Large background from entering γ removed using outer-detector (OD) as active shield

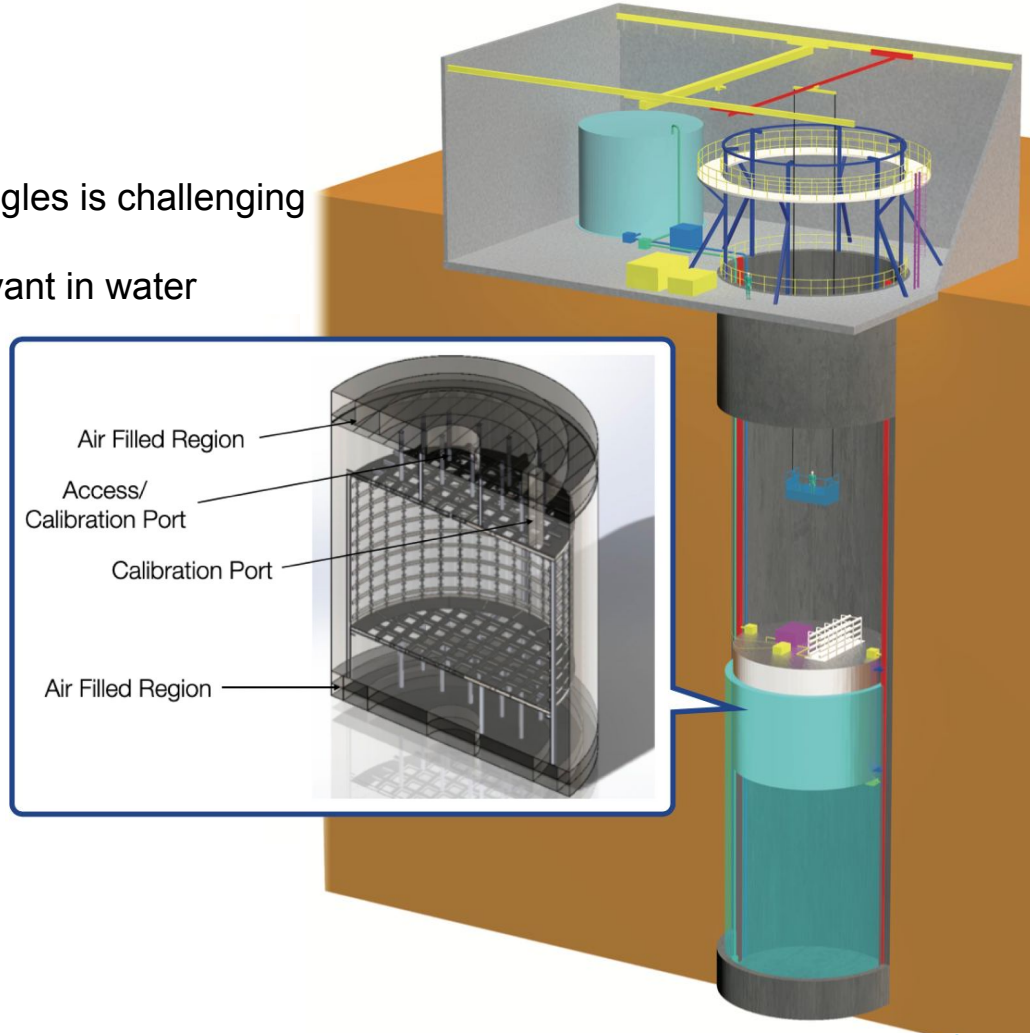
See also poster by C. Naseby





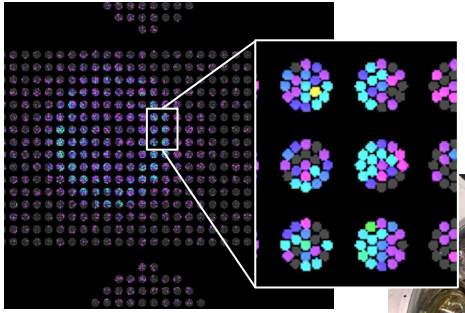
Moving detector

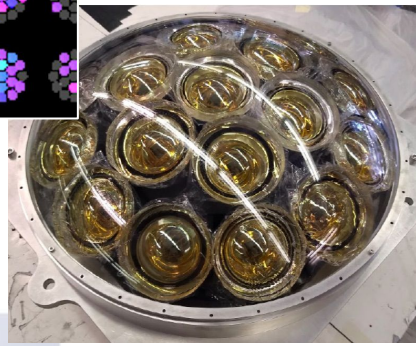
- Moving detector vertically to span off-axis angles is challenging
- Air-filled regions used to make detector buoyant in water
- Water is filled below the detector, raising it to the desired level
- Rail system guides detector as it moves
- Parts of water system, readout electronics and calibration system located on top of the moving tank

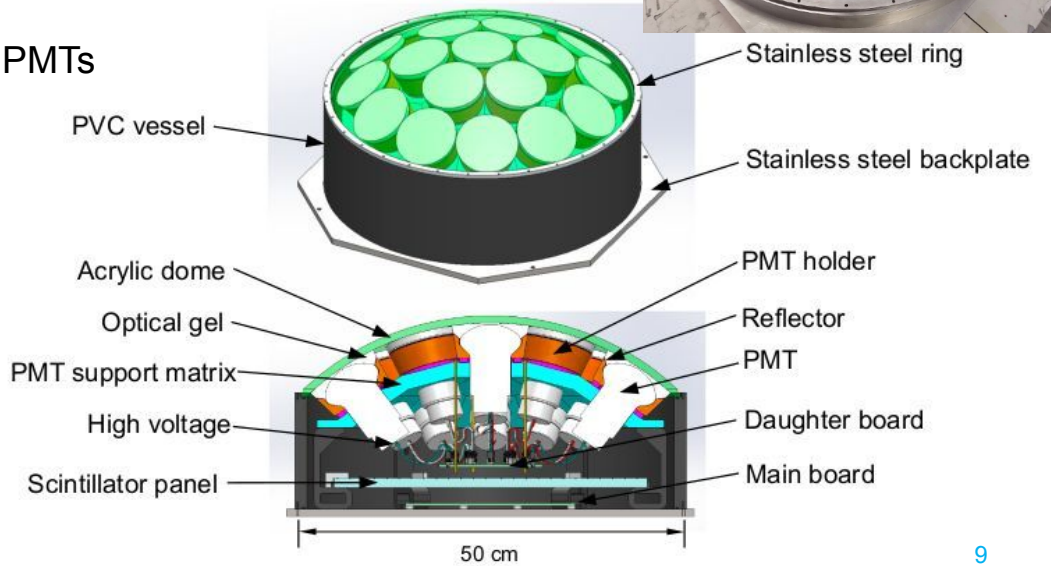


Multi-PMT modules

- IWCD is much smaller detector compared to far detector
- Improved photosensor resolutions and increase granularity required for equivalent event reconstruction performance
- 19 x 8 cm PMTs integrated into water-tight mPMT module
  - High voltage and readout electronics inside mPMT
  - Scintillator panel for OD veto
- 8cm PMTs compared to far detector's 50cm PMTs
  - Better position resolution
  - 1.6 ns (FWHM) timing resolution
  - Additional directionality information
- Also under investigation: Combining 50 cm PMTs + multi-PMT modules in far detector



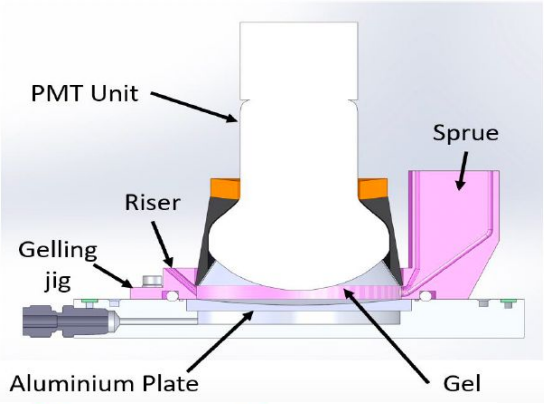


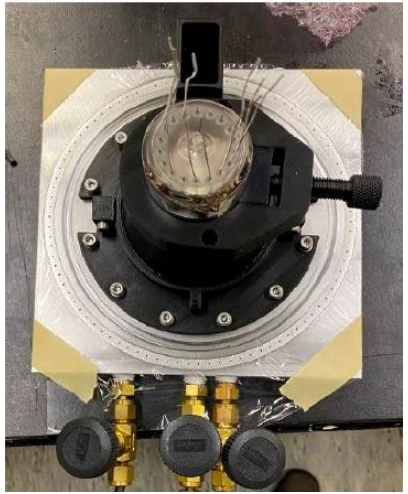


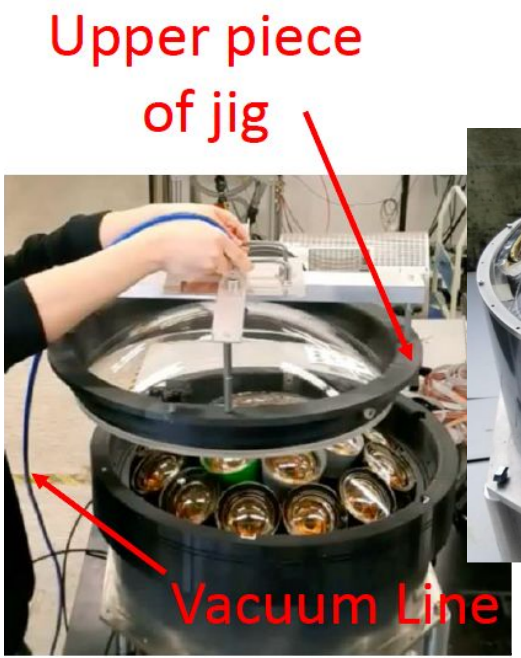
mPMT Assembly

mPMT components designed for mass production

- Assembly starts from stainless steel backplate
- Components added inside PCV cylinder
- 3D support matrix holds PMTs in place
- Optical gel added to PMTs before assembly
  - Provides good optical contact with transparent dome
- Acrylic dome lowered into place with jig
- Attached with stainless steel ring







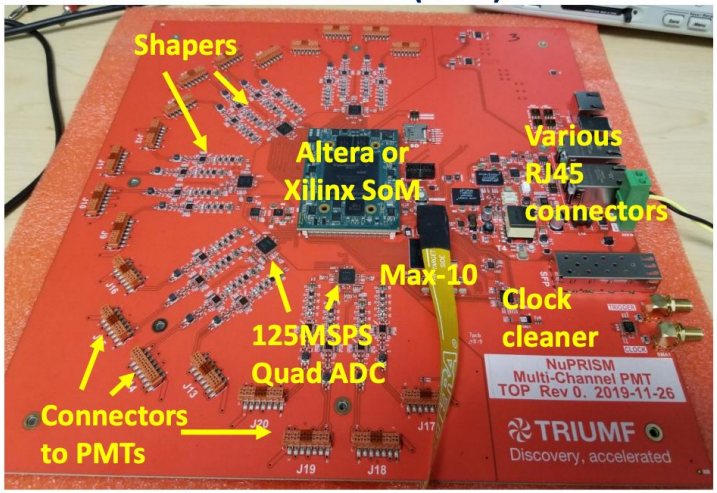
mPMT Electronics and HV

- IWCD close to beam source
  - High event rate can cause pile-up of multiple neutrino interactions
  - Full PMT waveform can allow better identification and reconstruction of pile-up events

- 20-channel 125 MSPS FADC electronics board developed
  - Full waveform can be read-out
  - On-board waveform processing in FPGA to reduce readout size

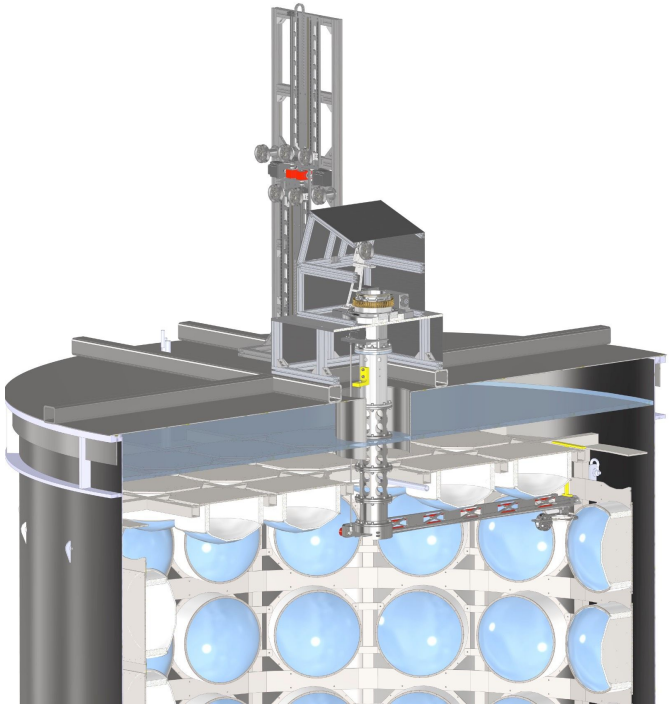
- Cockroft-Walton HV base for each PMT
  - Reduced power consumption compared to resistive base

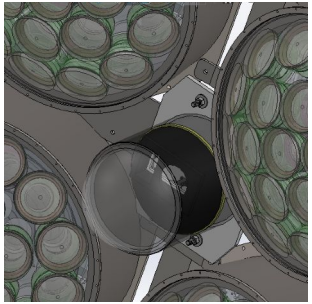
1st PROTOTYPE (rev. 0)

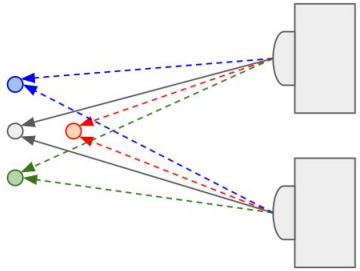


Calibration

- Calibration is critical for precision measurements at IWCD
  - Precise calibration needed at each vertical position
- Calibration source deployment system with full 3D movement to place source at any location in tank
  - Arm rotates around axis
  - Cart moves radially along arm
  - Source hangs from vertically from cable
- Photogrammetry position calibration system
  - Small shifts in detector components possible after moving
  - Cameras placed inside detector volume
  - Calibration LEDs mounted in mPMTs
  - Stereoscopic reconstruction measures geometry to precision of a few mm

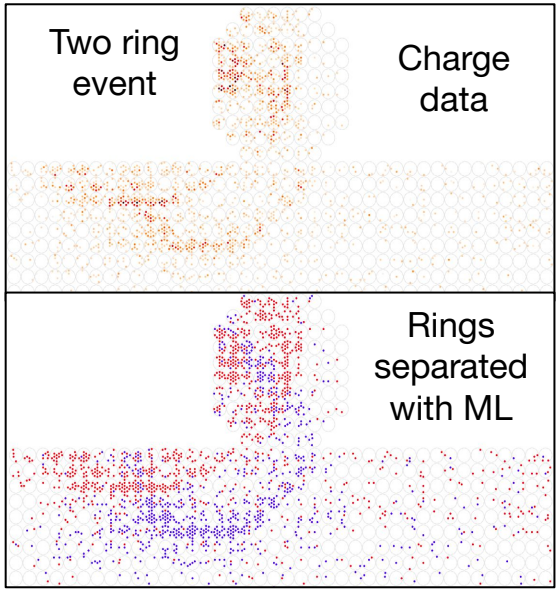


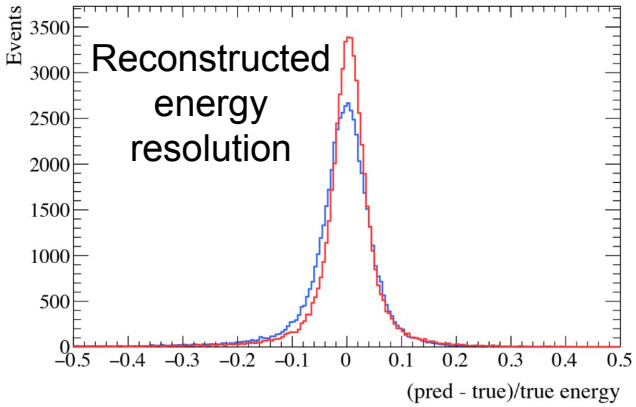


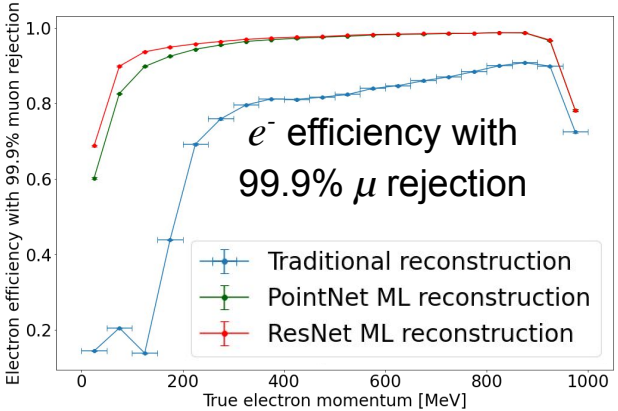


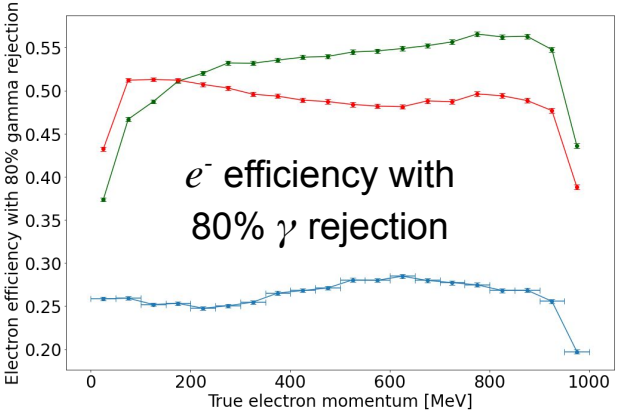
Machine Learning

- Machine learning methods being developed to exploit all information from mPMTs
- Improved reconstruction and PID performance over likelihood-based reconstruction
  - Statistical separation of e^- and γ not previously possible
  - Better handle on entering γ and NCγ backgrounds
- Identification and reconstruction of multi-vertex and multi-ring events from beam pile-up









Summary

- Hyper-Kamiokande is currently under construction with first data taking planned for 2027
- IWCD will provide critical measurements to control systematic uncertainties in Hyper-K's search for CP violation
- Vertically moving detector spans off-axis angles to measure cross sections at varying energy spectra
- New multi-PMT photosensor hardware and calibration systems enable precision measurements in small water Cherenkov detector
- Machine learning reconstruction techniques will maximise potential of IWCD
- IWCD is now moving towards design completion and construction phase!