The Hyper-Kamiokande multi-Photomultiplier Tubes

And the Water Cherenkov Test Experiment

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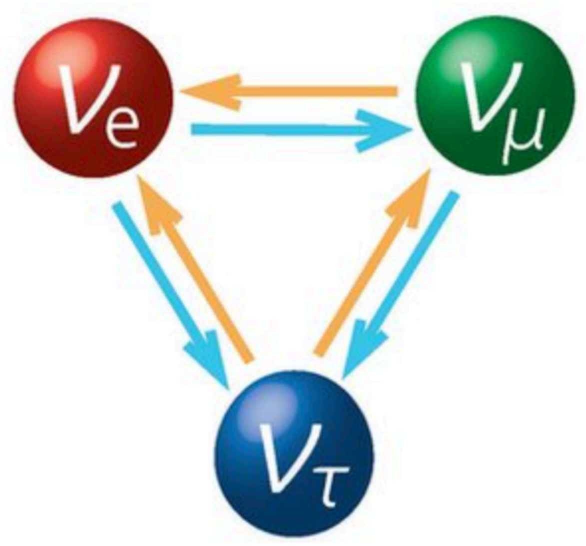
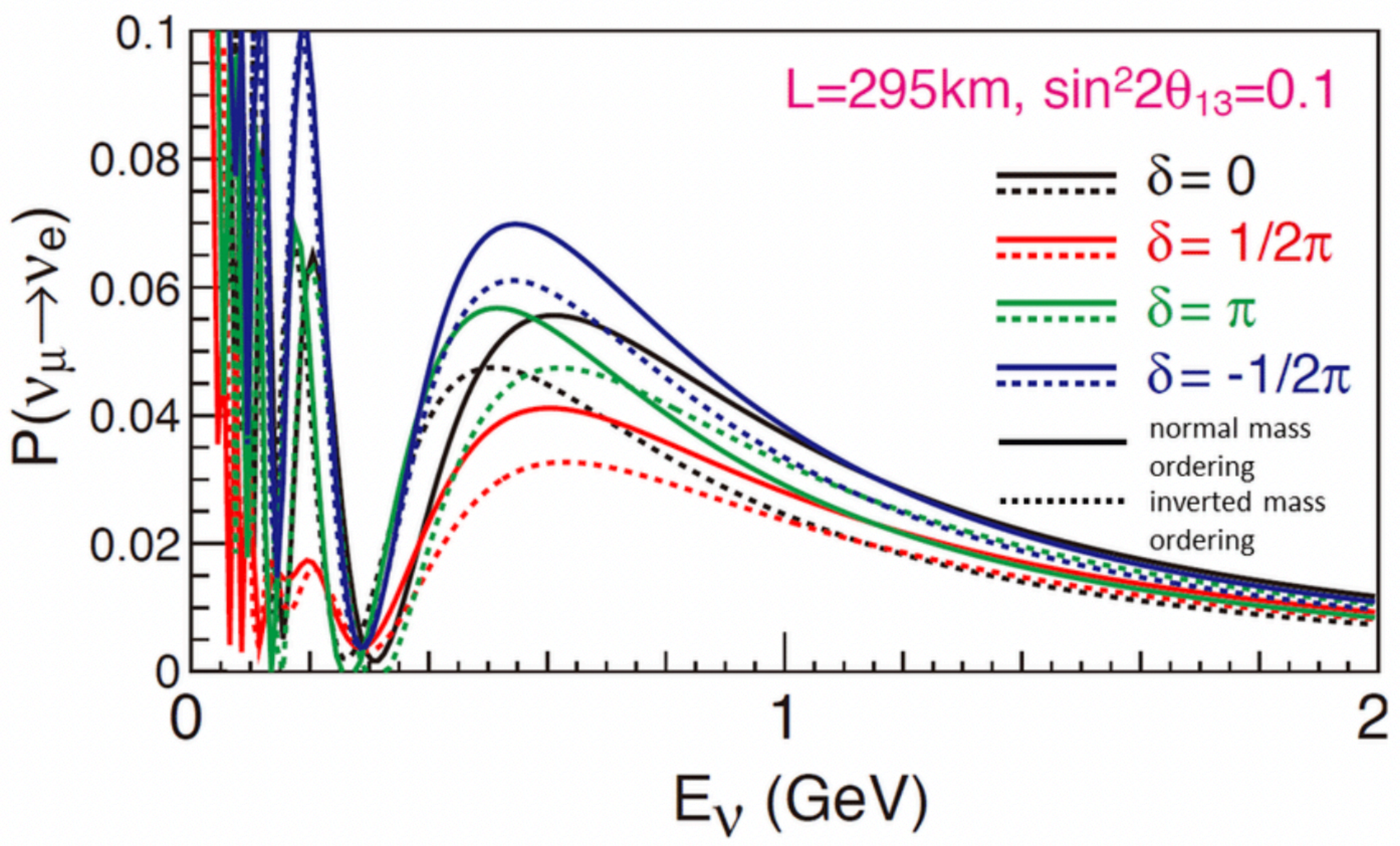
Neutrinos

- Neutrinos are fundamental particles that come in three flavours:
  - Electron neutrinos (**ν**e)
  - Muon neutrinos ($\boldsymbol{\nu}_\mu$)
  - Tau neutrinos ($\boldsymbol{\nu}_\tau$)





- As a neutrino traverses vacuum or matter, it can oscillate from one flavour to another: e.g. $\nu_\mu \rightarrow \nu_e$

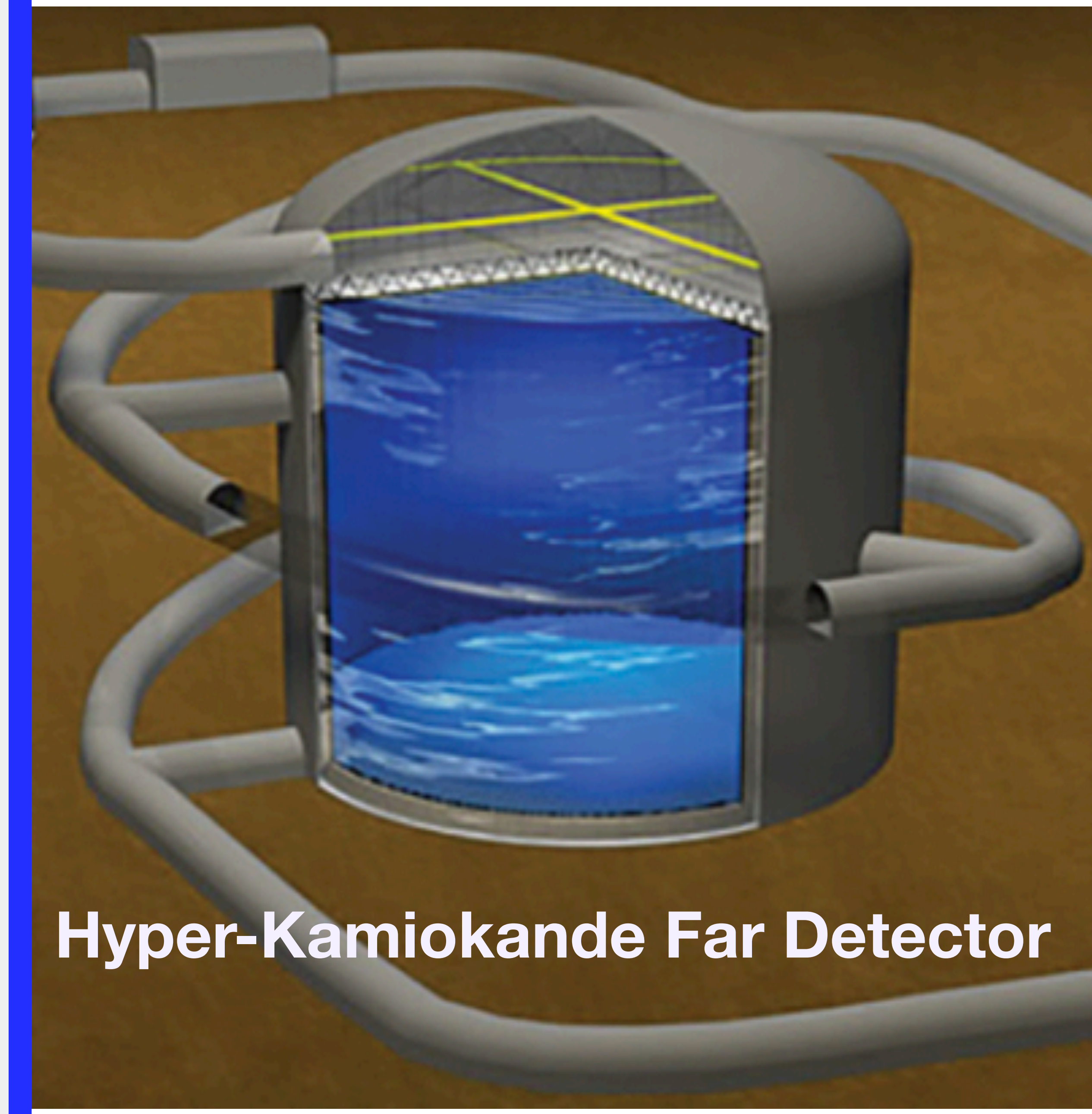
- Probe if the universe treats matter and antimatter differently by comparing the rates of oscillation of neutrinos (ν) and antineutrinos ($\bar{\nu}$)

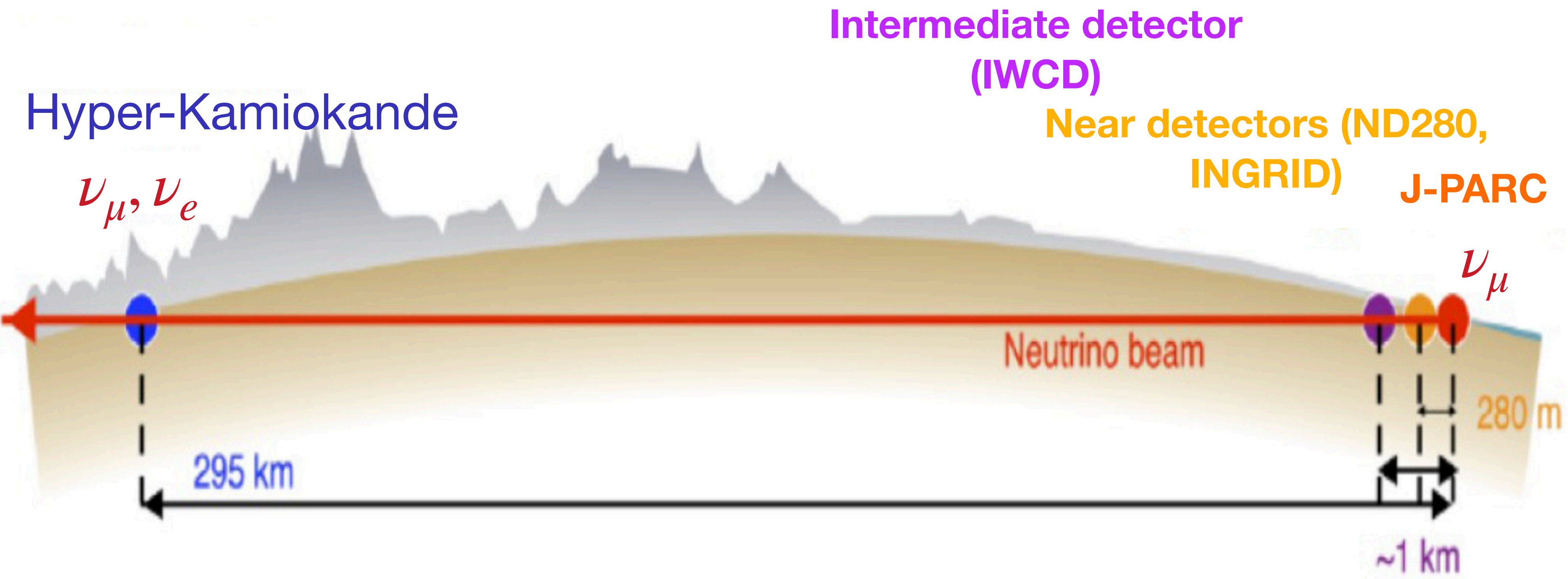
  - If the oscillation probabilities are different for ν and $\bar{\nu}$, it is referred to as **charge-parity violation ($\delta_{CP} \neq 0, \pi$)**

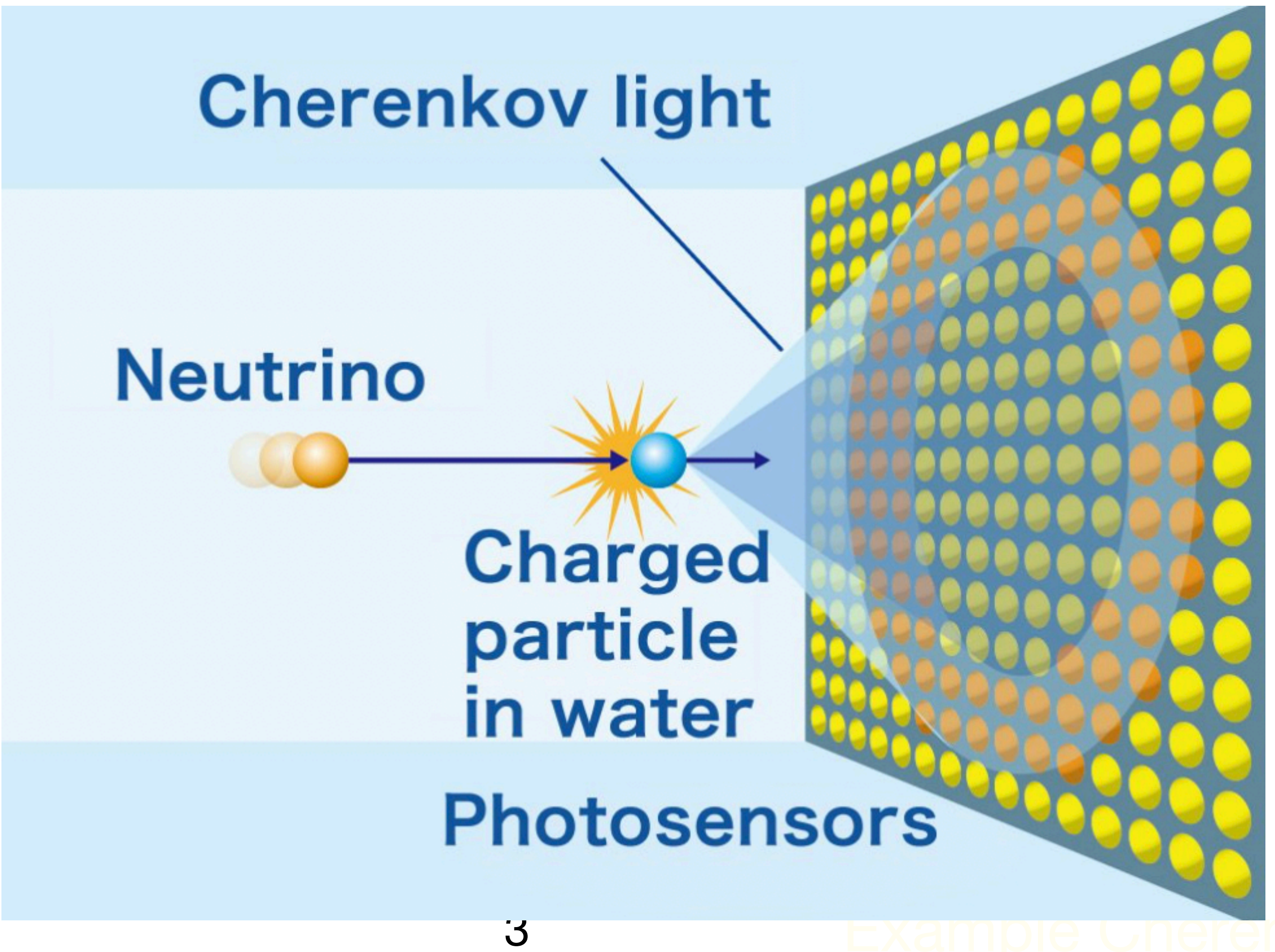
Neutrinos are very abundant in the universe, but have extremely small interaction cross-sections
⟶ To detect them, it is helpful to use large detectors and large neutrino fluxes

Water Cherenkov Detectors and Hyper-Kamiokande

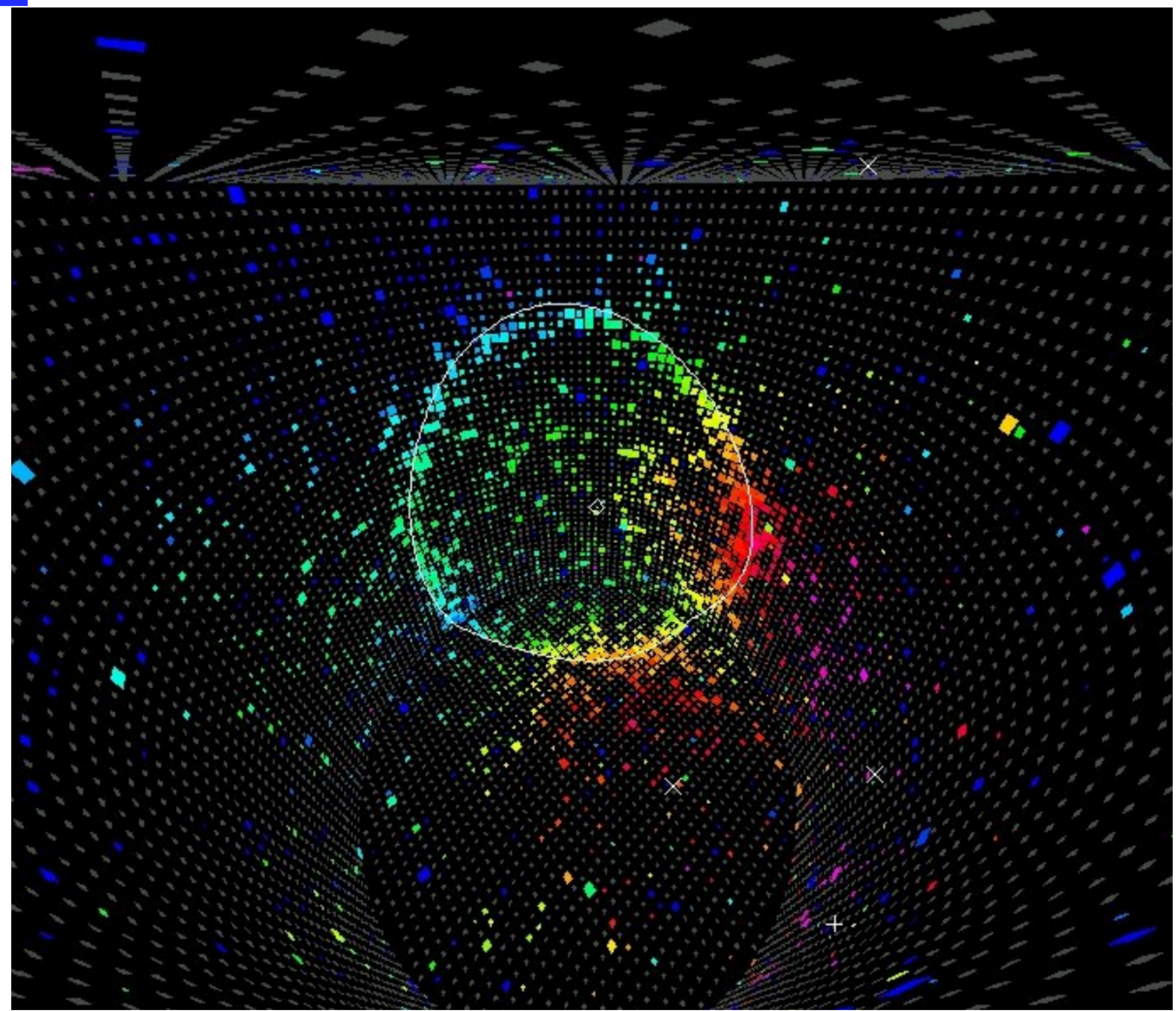
- One way of detecting neutrinos is by means of **Water Cherenkov Detectors**
- Hyper-Kamiokande (Hyper-K) will be one such detector:
  - Cylindrical volume filled with 187 kton of water, with photosensors on the walls of the detector
  - Will use a muon neutrino beam generated 295 km away at the JPARC accelerator complex
  - When a neutrino interacts with a nucleus, it can produce a charged lepton
  - Charged lepton can produce Cherenkov radiation, which will form a ring of light on the wall of the detector
  - Photosensors can detect the Cherenkov ring and use it to infer the neutrino characteristics
    - **Use this to measure neutrino oscillations and ultimately if** $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$





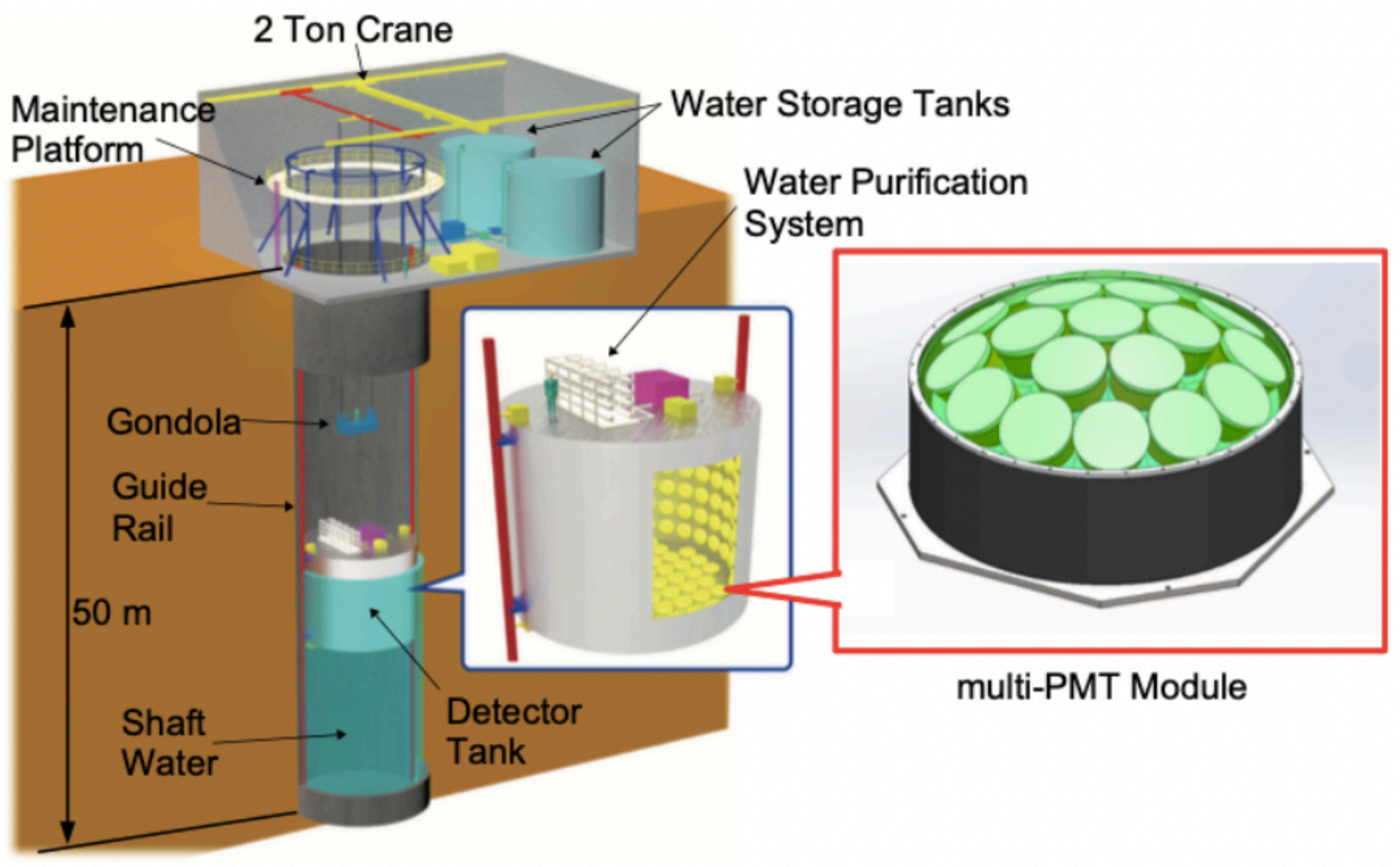


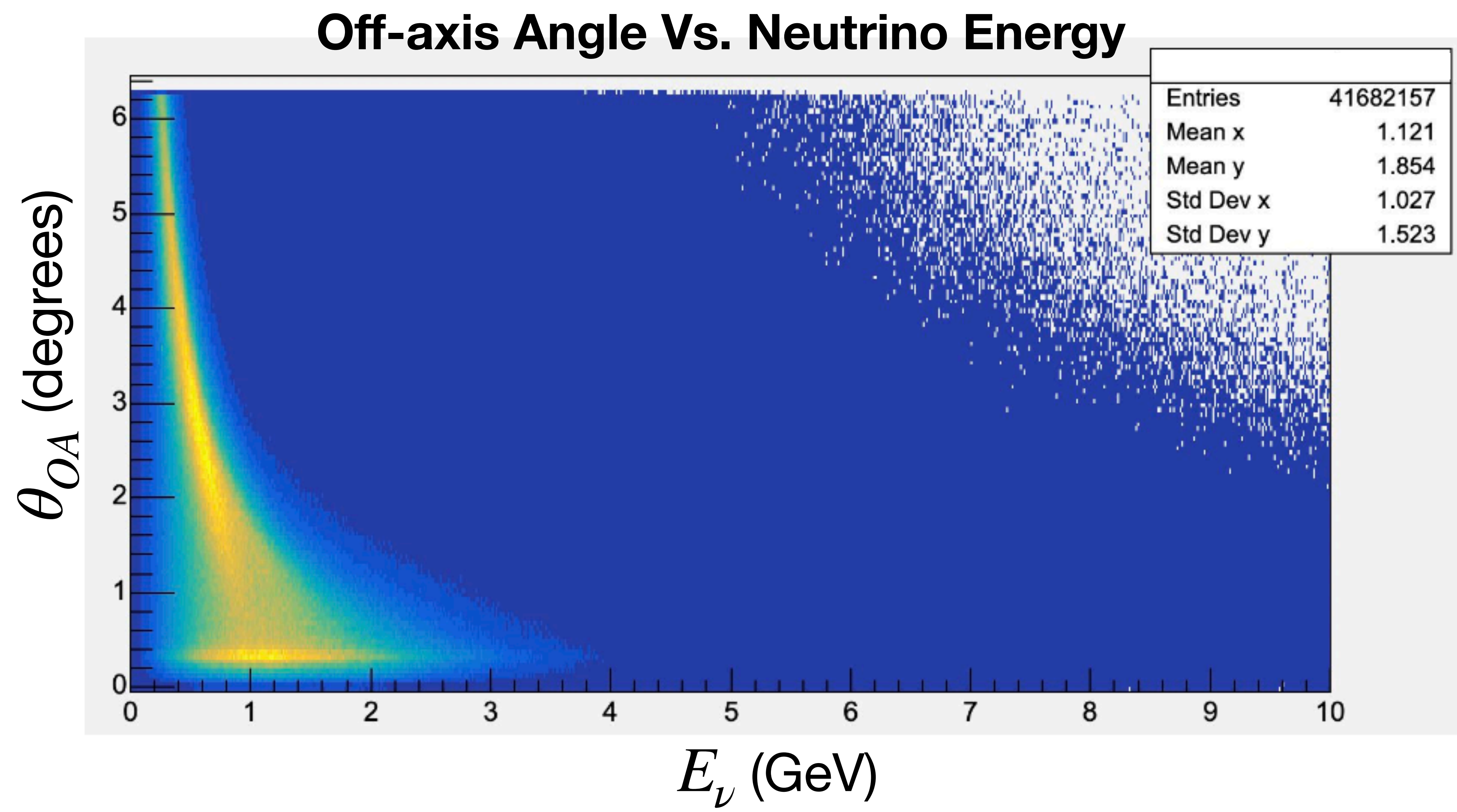
What we observe →



Intermediate Water Cherenkov Detector

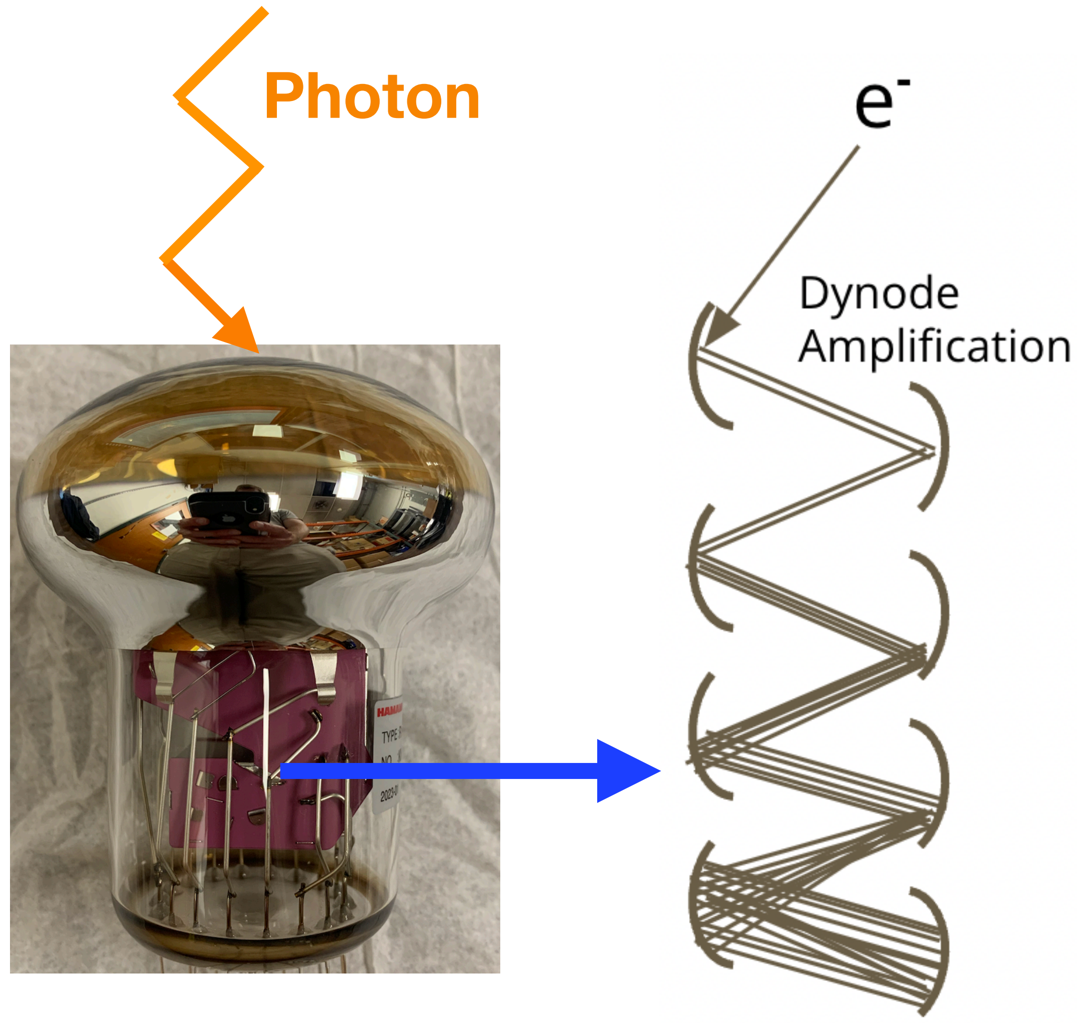
- ~850 m from the beam source, there will be an Intermediate Water Cherenkov Detector (IWCD)
  - IWCD will be 7 m in diameter by 8 m tall
  - Measure the beam prior to oscillation effect becoming dominant
- Capable of moving vertically in a 47 m pit
  - Neutrino energy distribution depends on angle with respect to beam axis
  - Better constrain relationship between true and reconstructed energy
- **IWCD will use a new photosensor technology that has largely been developed in Canada**





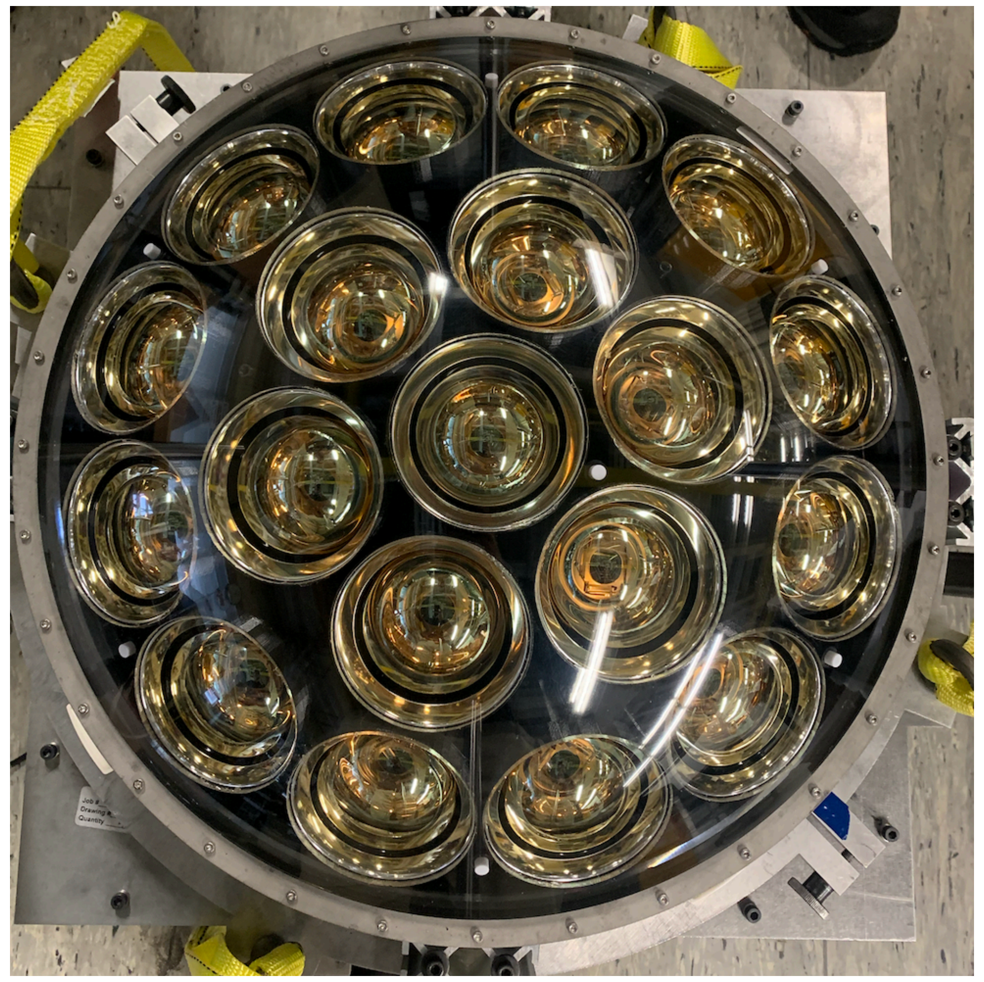
IWCD Photosensors

- We have developed a new photosensor technology for the IWCD called multi-photomultiplier tubes (mPMT)
  - Semi-spherical array of 19 individual 8-cm diameter PMTs
  - Far better spatial resolution and timing resolution (1.5 ns FWHM) than 20-inch PMTs used in Super-K (the predecessor to Hyper-K)
  - Two different versions of mPMTs have been developed



- **50 mPMTs constructed at TRIUMF in ~6 months**
- **Majority of mPMTs constructed are in-situ style**
  - **Faster and easier to produce than ex-situ mPMTs**

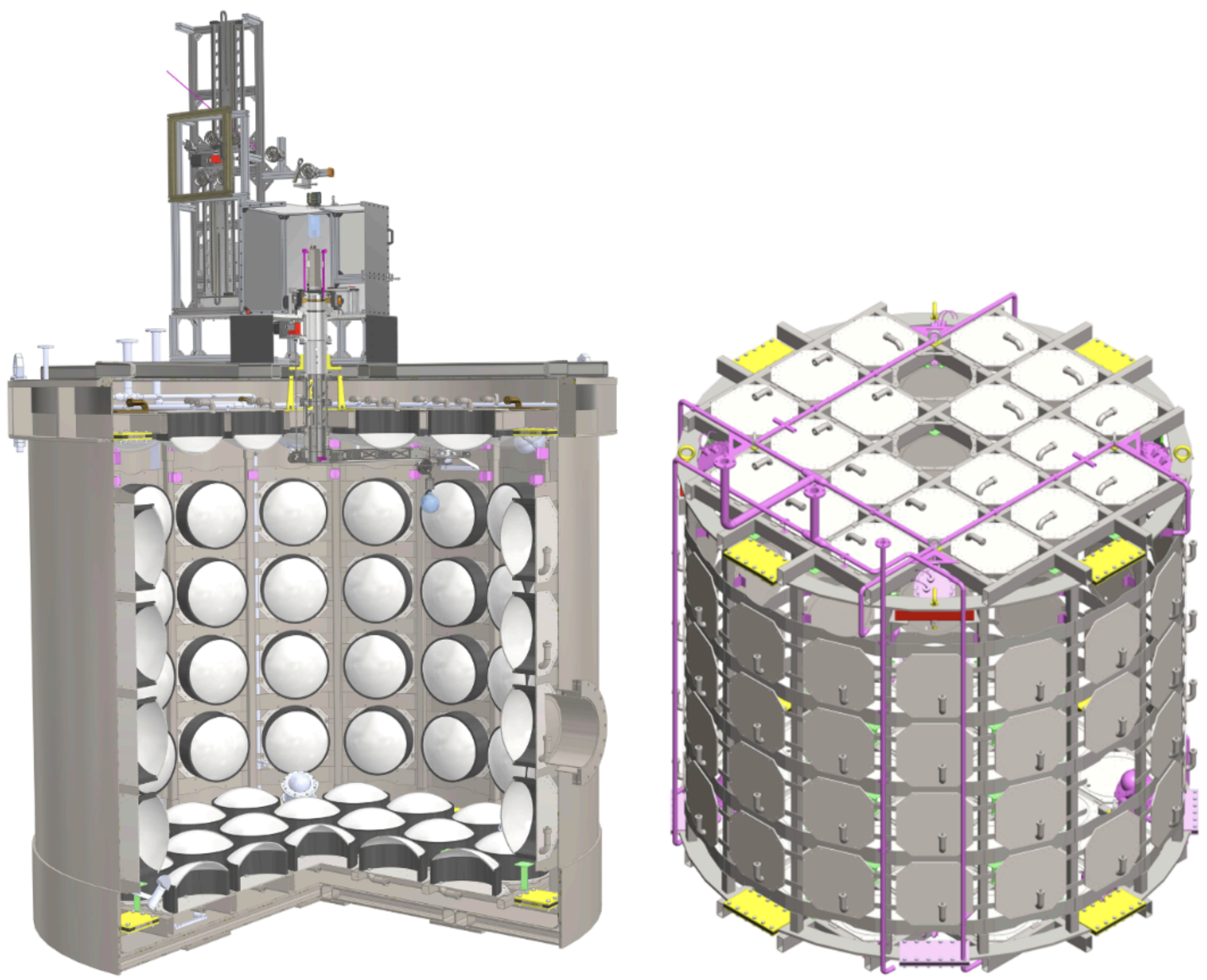
Ex-situ mPMT



In-situ mPMT

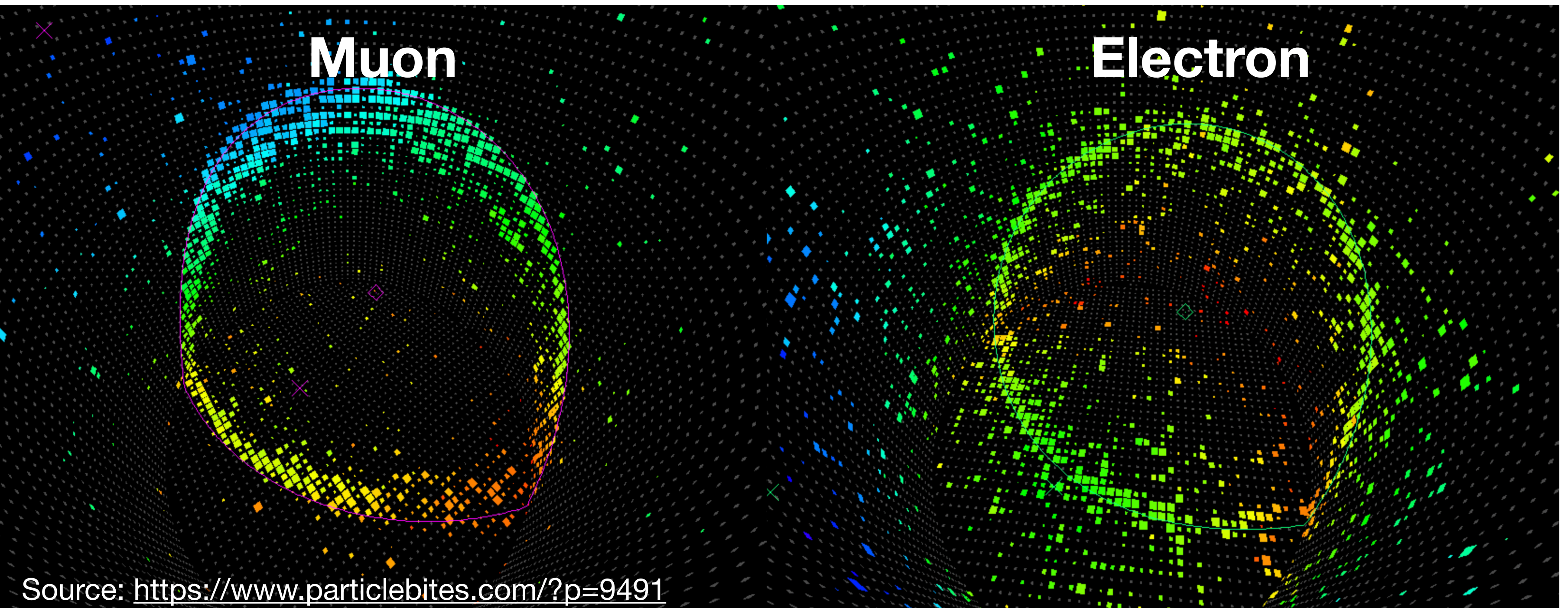
The Water Cherenkov Test Experiment

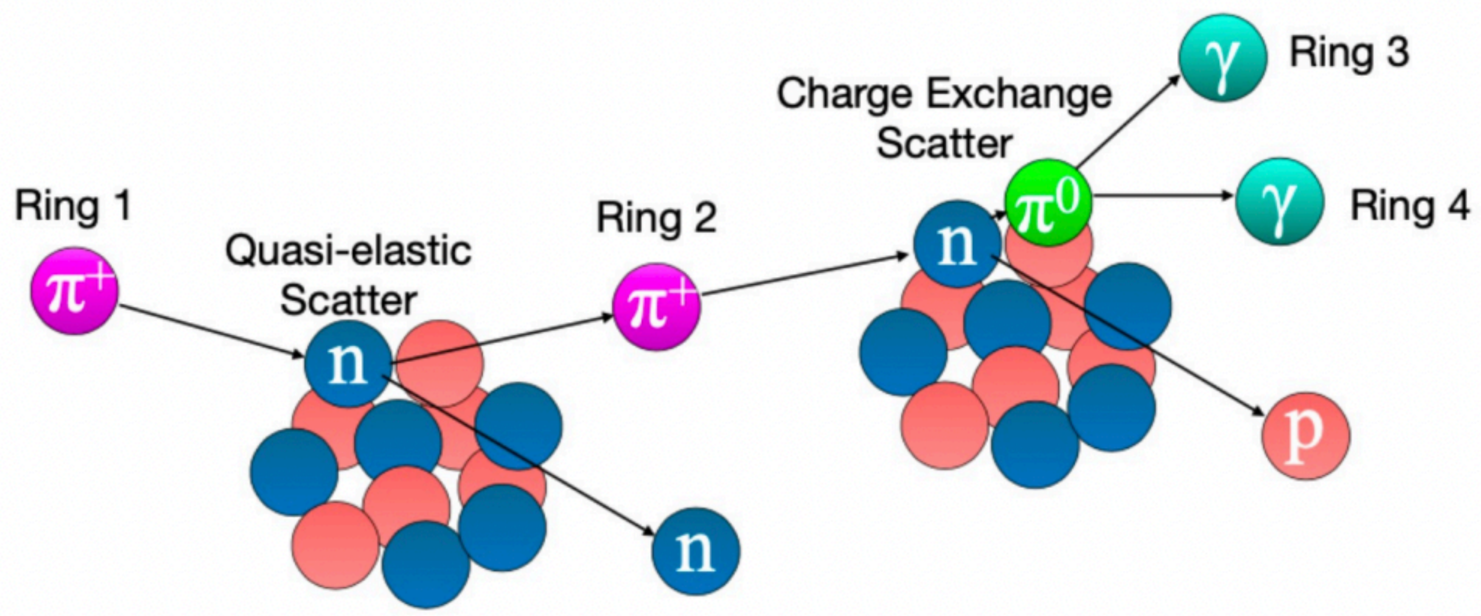
- We have constructed a Water Cherenkov Test Experiment (WCTE) that is currently in the T9 beam line at CERN
  - WCTE is a small prototype of the IWCD
  - 4m diameter by 3.6m tall cylinder containing 97 mPMTs
  - Particles of known energies are injected into the detector:
    - $p^+, e^\pm, \pi^\pm, \mu^\pm, \gamma$
  - Purpose is to test mPMT technology, understand performance, and enhance physics understanding
  - Results will be used to reduce systematic uncertainties in the IWCD and Hyper-K!



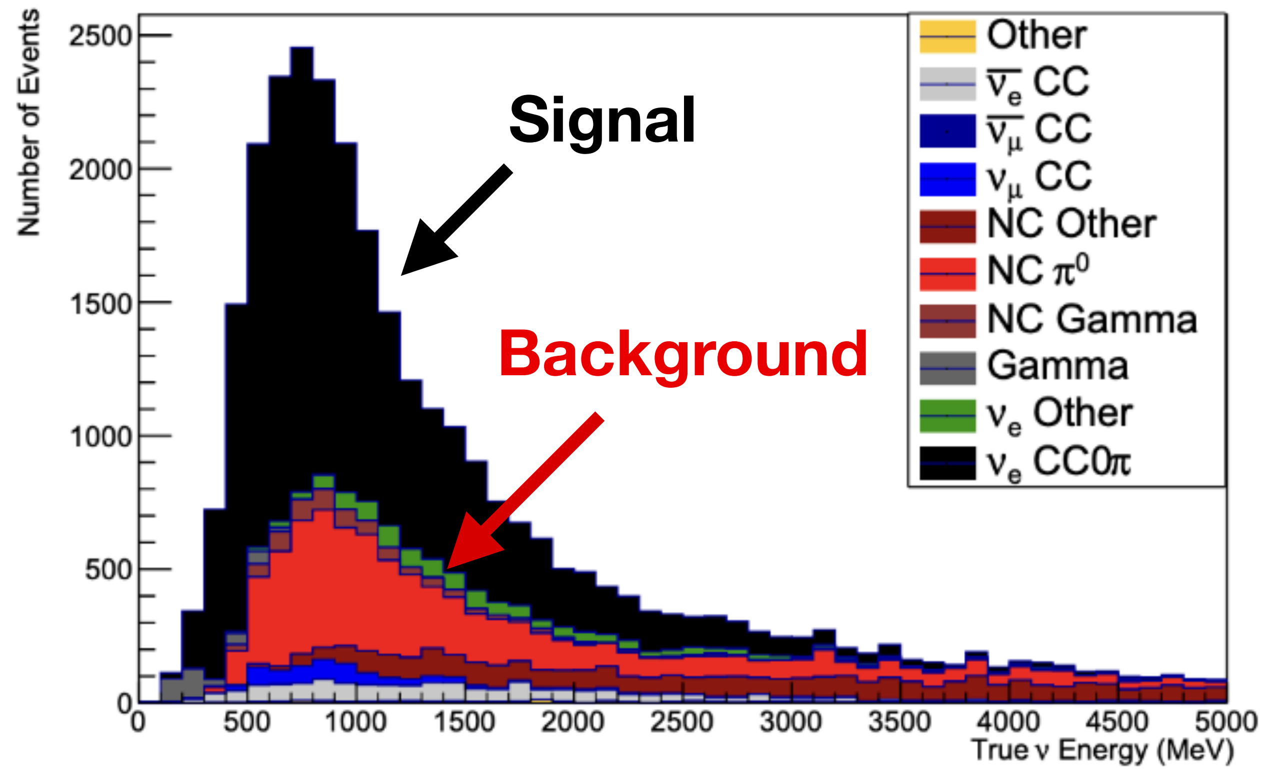
(Some) WCTE Physics Goals

- Understand e/μ separation capabilities with mPMTs
  - $e^{\pm}$ produce electromagnetic showers in water, while $\mu^{\pm}$ do not
- Improve upon understanding of water Cherenkov detector response to $\pi^{\pm}$ scattering and measure cross-section
  - Understanding pion scattering kinematics can help neutrino energy reconstruction
- Improve upon e/γ separation
  - Interactions that produce gammas are largest background for electron events
  - Rings from $e^{\pm}$ and γ are similar due to electromagnetic showering

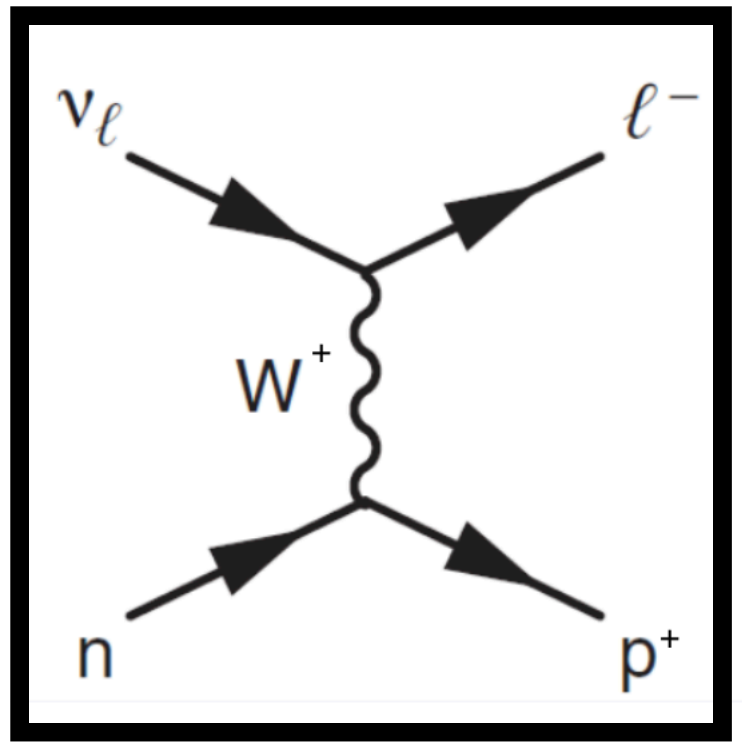




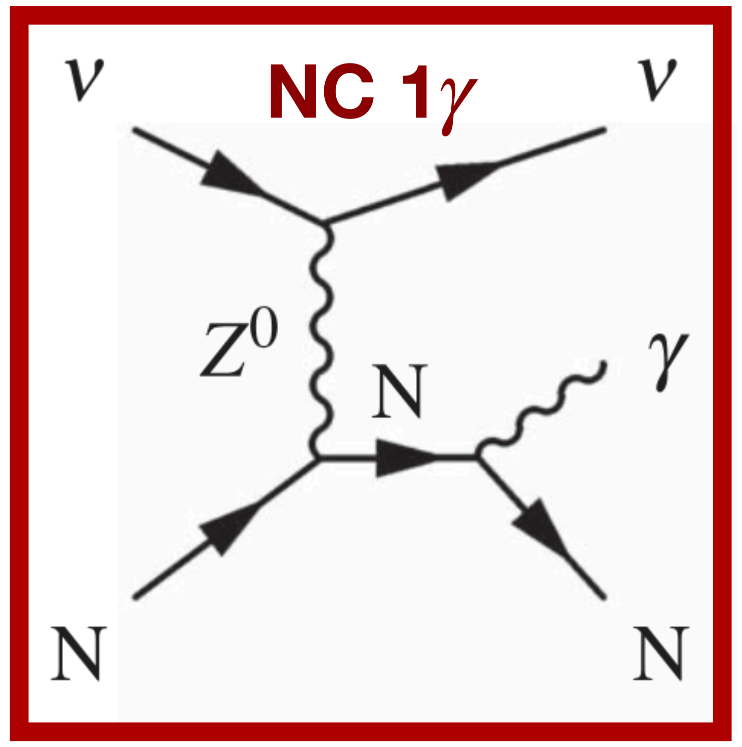
Simulated Events Reconstructed as Electrons

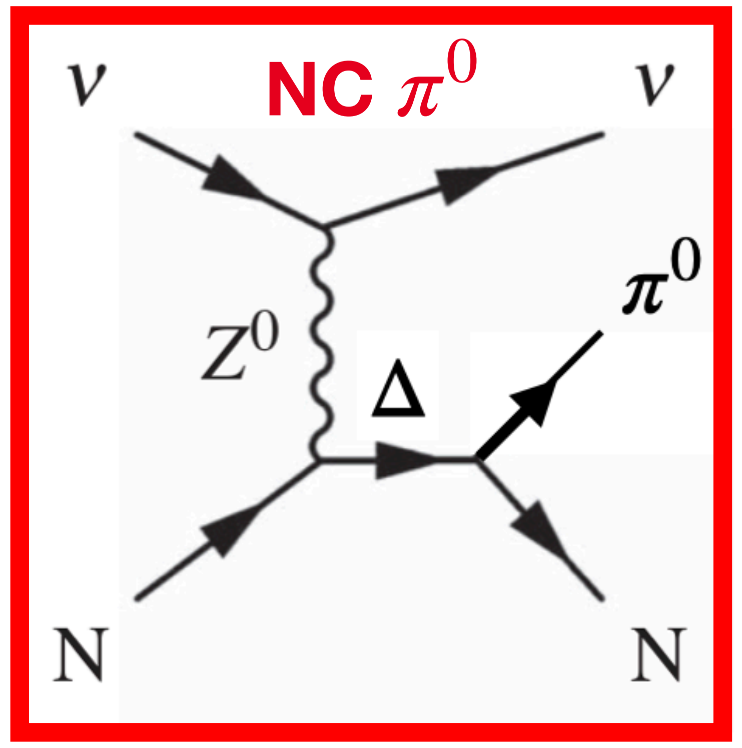


Charged Current (CC)



Neutral Current (NC)



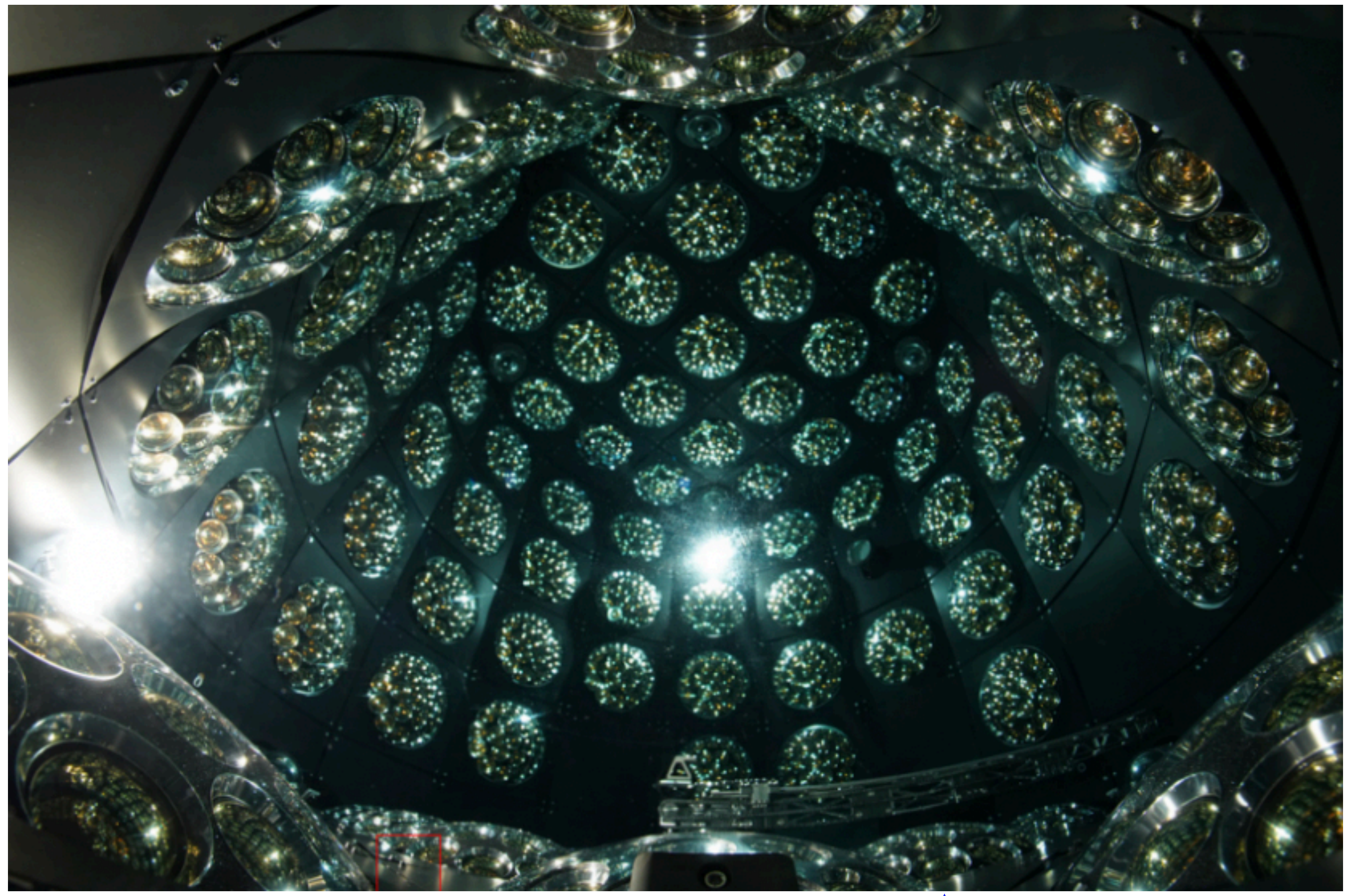


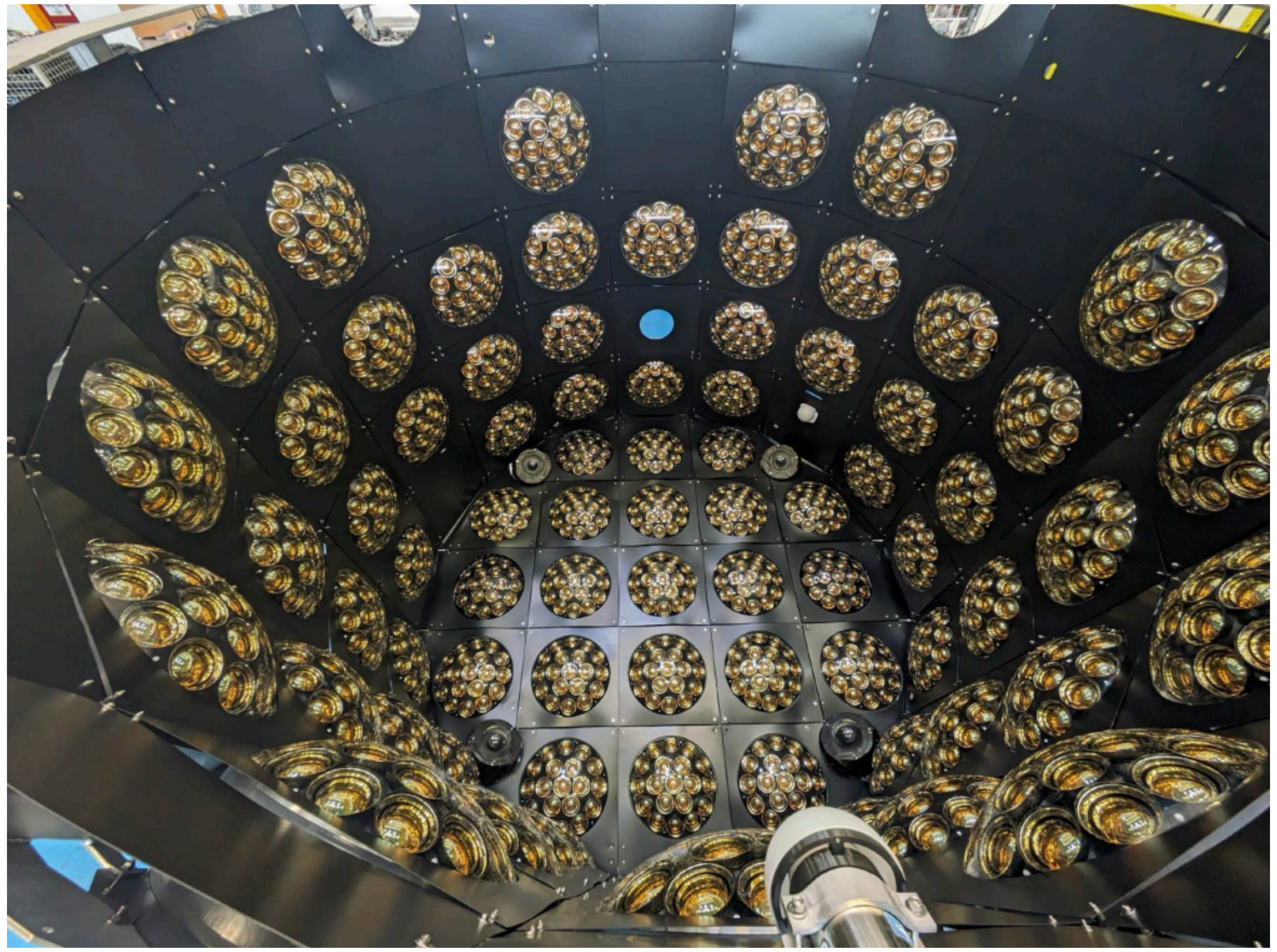
Time

WCTE Construction

- Detector was constructed this past summer at CERN
- Placed in path of T9 beam line in the fall of 2024 and filled with ultra-pure water
- WCTE was operated from October to December of 2024
    - Next beam time for WCTE is in March of this year

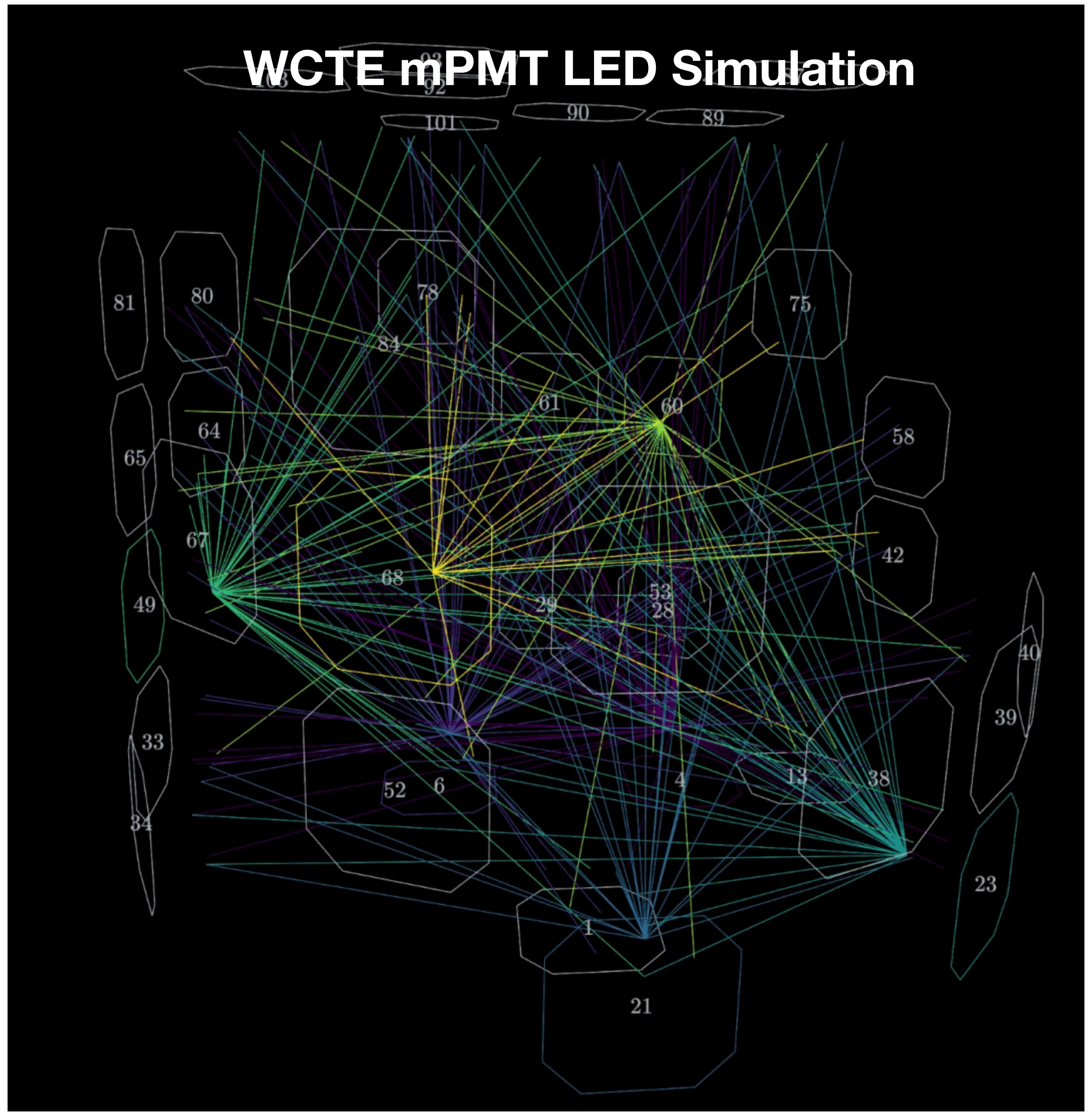
WCTE Filled with Water

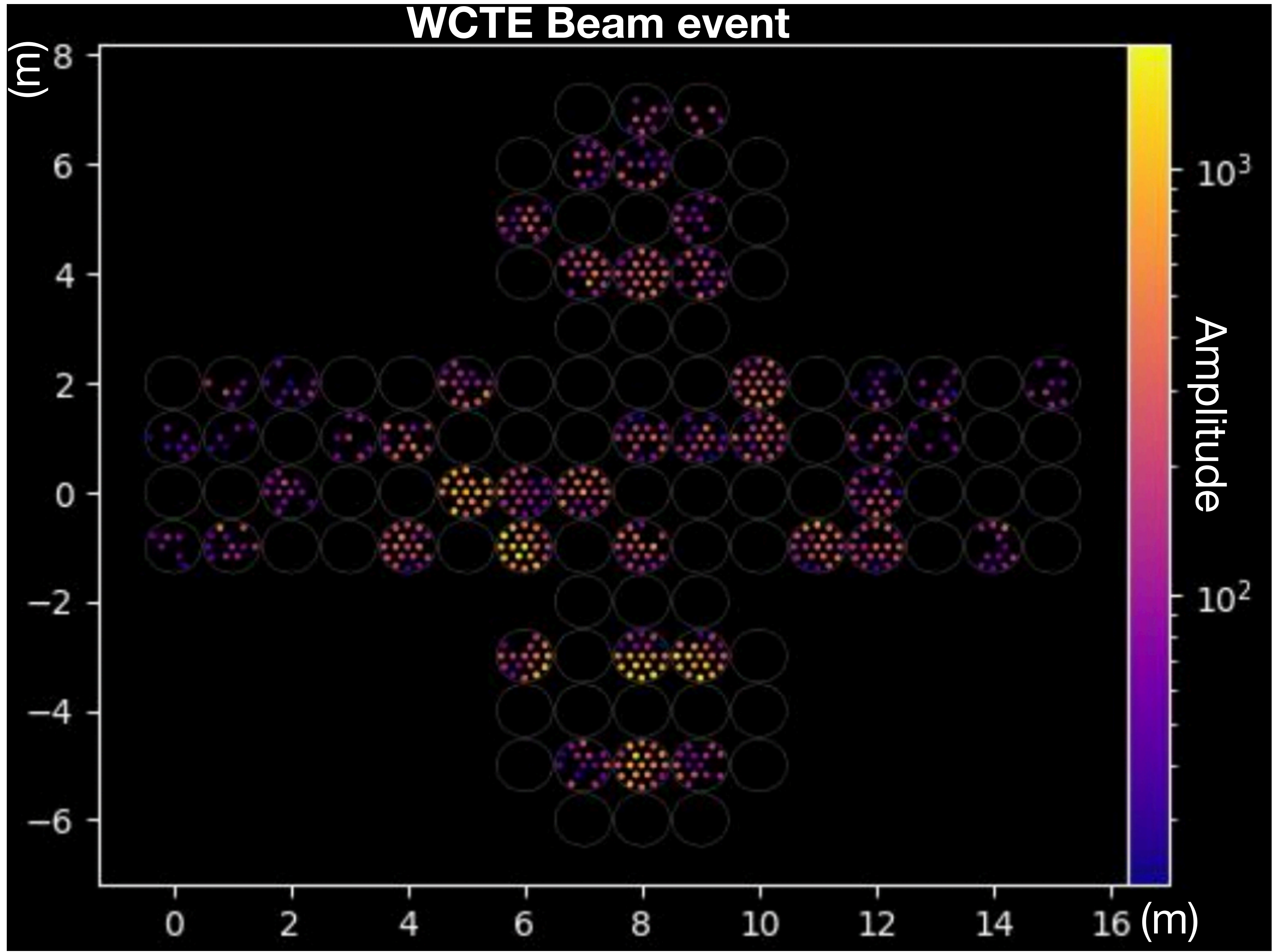




2024 WCTE Operation

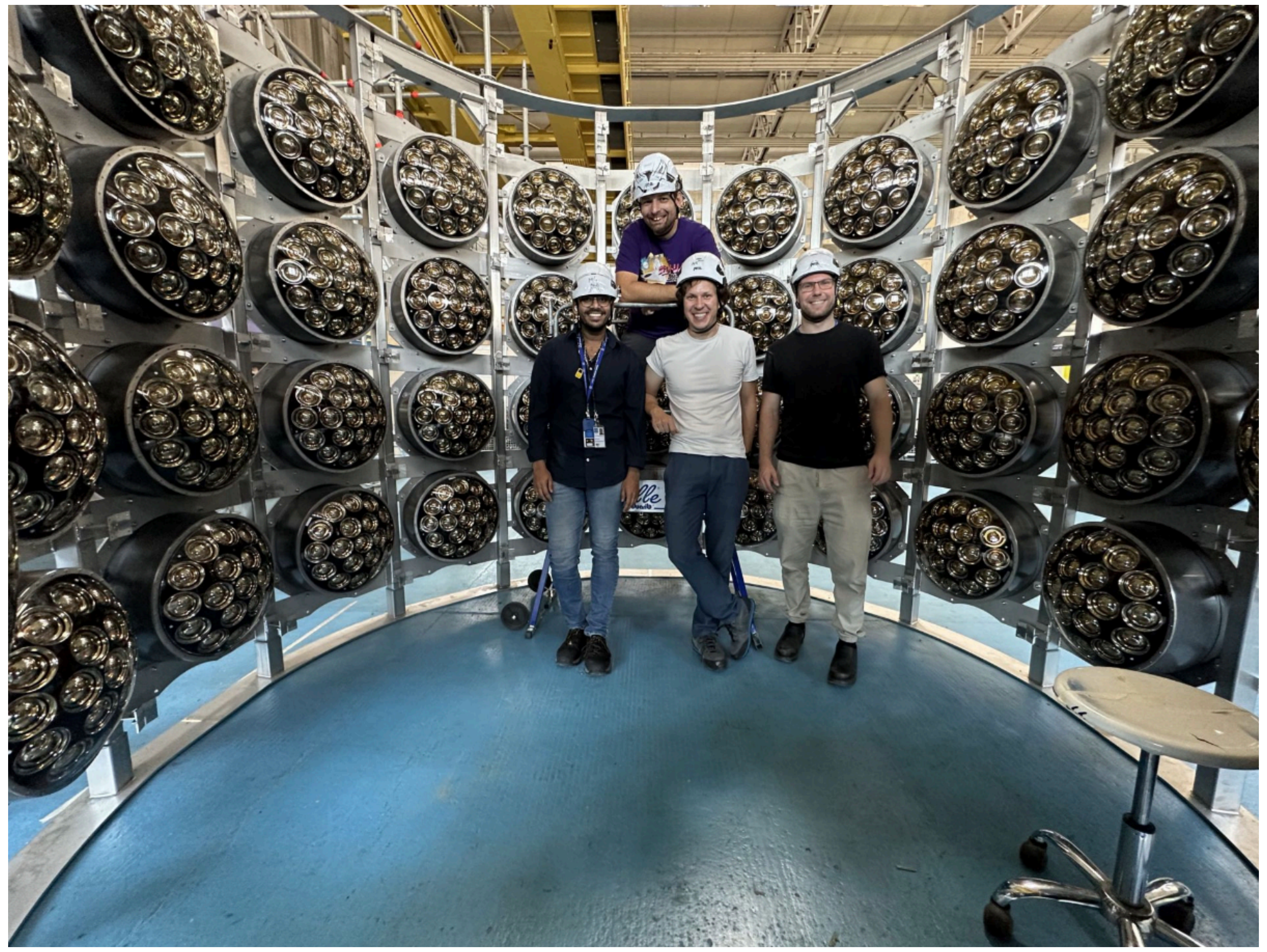
- Achieved stable data-taking with 61 mPMTs simultaneously
- Successful sub-nanosecond-level timing calibration achieved using internal mPMT LEDs
  - Flash many LEDs consecutively in the detector, estimate timing offsets necessary for precise event-reconstruction
- Some beam data collected, clear evidence of particles entering the WCTE seen in PMT signals
- Plan to make most useful physics measurements during 2025 beam time





Hyper-K/WCTE Summary

- Hyper-K looks to measure neutrino oscillations with unprecedented precision
  - Primary goal is to discover CP-violation in the lepton sector
- An intermediate water Cherenkov detector will be used to measure the beam prior to oscillations
  - Multi-photomultiplier tube photosensors used in this detector have largely been developed in Canada
- The Water Cherenkov Test Experiment is underway at CERN
  - Test the mPMT technology in a water Cherenkov detector
  - Make measurements to improve our understanding of neutrino interactions in water Cherenkov detectors



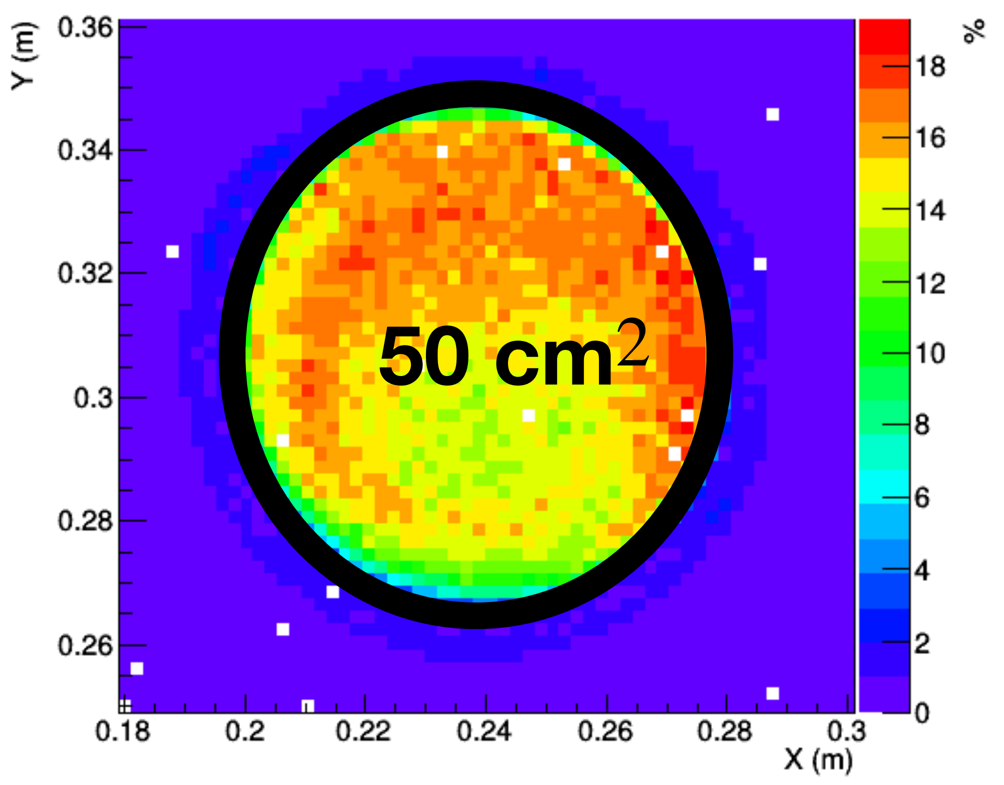
Backup Slides

mPMT Optical Measurements

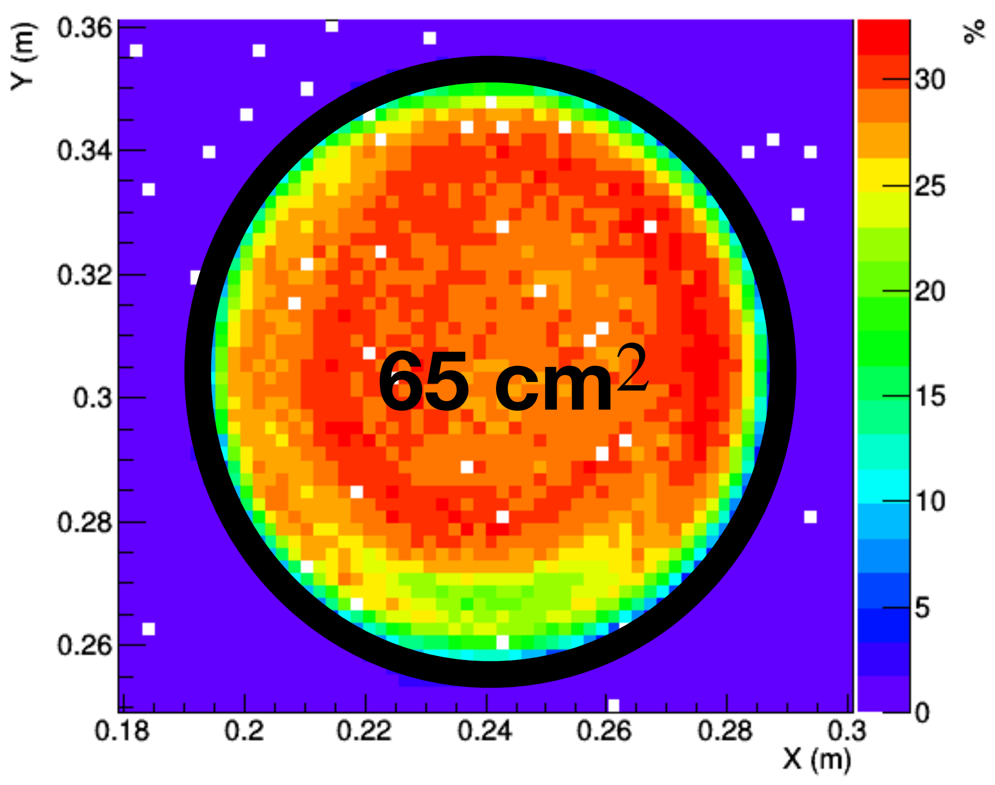
Reflectors

- We have increased the light yield of our mPMTs by using reflective material around the edge of each PMT
  - Up to 30% increase in PMT photosensitive area depending on incident angle of light:

Relative Efficiency: No Reflector



Relative Efficiency: With Reflector



Angular Response

- Light incident on PMT at high angles (>~45 degrees) will result in increased detection efficiency
  - This confirms what one finds when calculating the absorption at the gel-PMT boundary

34 Degrees w.r.t. Light Source