IMPERIAL

Lauren Anthony
(lanthony@imperial.ac.uk)
On behalf of the WCTE collaboration

01/09/2025: Liverpool, NuFACT 2025

Updates on detector technologies for Water Cherenkov detectors

Photo curtesy of the WCTE collaboration

Contents

Part 1

- Concept of Cherenkov radiation and water Cherenkov detectors
- Physics capabilities
- Brief history of detectors
  - Pioneers
  - Current detectors
  - Future detectors
- Upgrades in detector technologies
  - Water enhancing test beds
  - New detection technologies

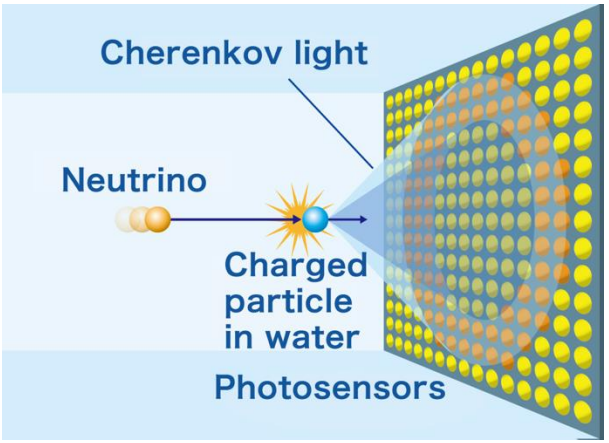
Part 2

- The Water Cherenkov Test Experiment
  - Empowering future neutrino detectors
- Detector
  - Instrumentation
  - Calibration
- Physics measurements
- Impact on future neutrino detectors

Concept of Cherenkov radiation & neutrinos

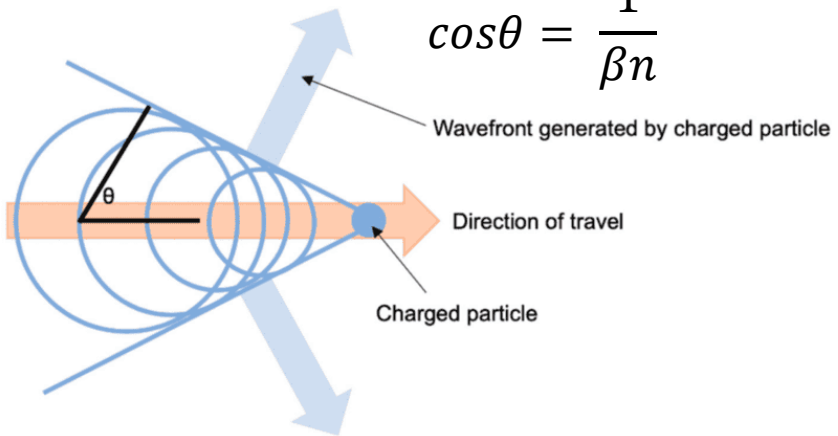
- **Cherenkov radiation**: Electromagnetic radiation produced when a particle travels through a medium at a speed > speed of light
- Charged particles disturb the atoms in the medium they enter, e.g water and release photons produce a shockwave of visible light
- Water is cheap – easily available in large volumes

Use Water Cherenkov detectors for indirect neutrino measurements



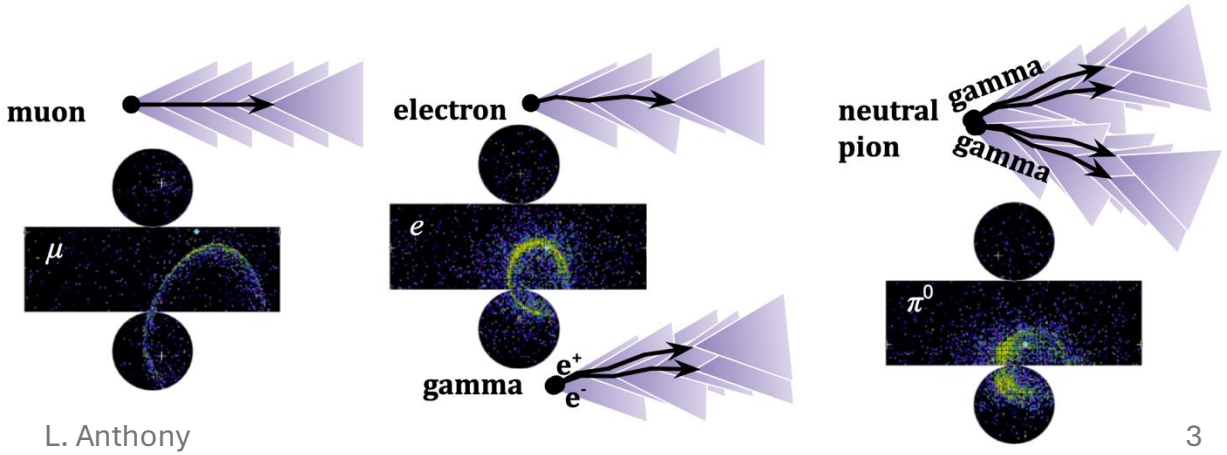
$$\beta = \frac{1}{n} = \frac{1}{1.33} = 0.75 \text{ in water}$$

$$cos\theta = \frac{1}{\beta n}$$



Particle information reconstruction

- Location and time of PMT hits allows for triangulating particle's position and direction
- Amount of charge collected by PMTs gives an estimate of particle's energy



High energy astrophysics

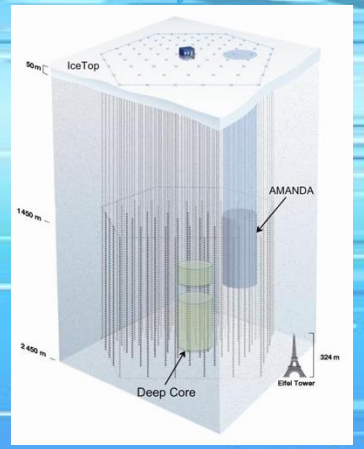
Supernova neutrino

Under water/Embedded detectors
Utilize the sea, ice
Vast detector areas with multi-PMT modules

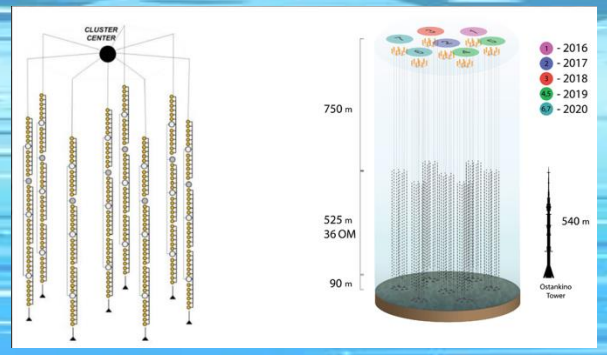
Great for high energy astrophysics, supernova neutrinos – GeV to TeV scale
Multi-messenger astronomy

Future detectors include P-ONE (Canada) and TRIDENT (China)

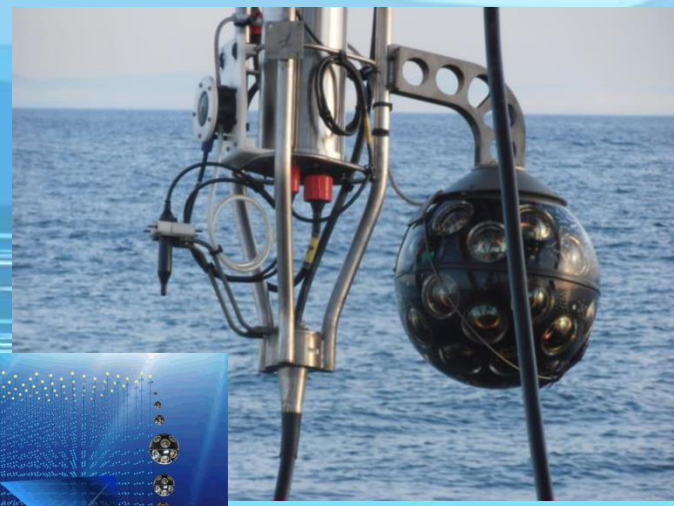
Ice CUBE

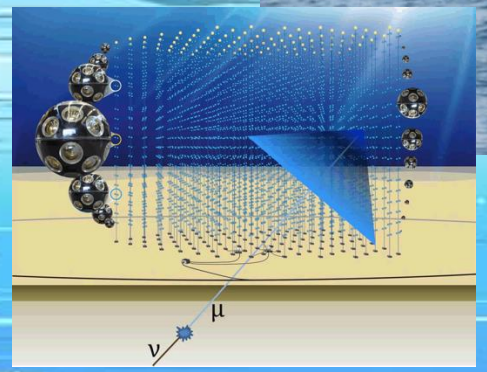


Baikal Deep Underwater Neutrino Telescope



KM3NeT





See Chiara F Lastoria's talk

L. Anthony

Atm neutrino oscillation discovery in 1998 - Super-K

Atmospheric neutrinos

Supernova neutrinos

Solar neutrinos

Solar neutrino oscillation discovery in 2001 – SNO and Super-K

Proton decay

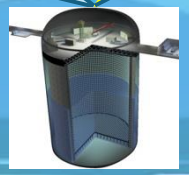
Reactor neutrinos

Neutrino oscillation

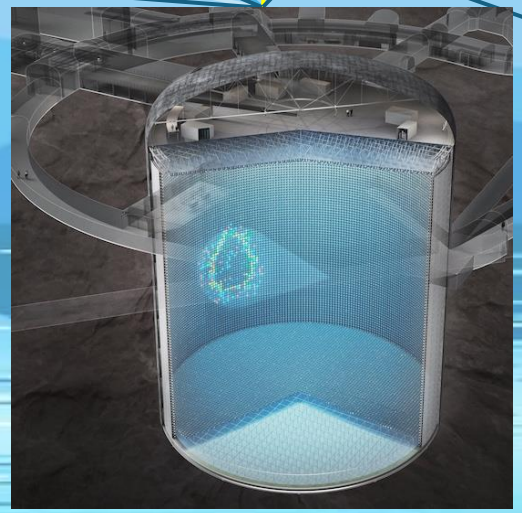
SN neutrino observation in 1987 – Kamiokande & IMB

IMB
Irvine-Michigan-Brookhaven

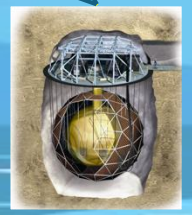
Kamiokande



Super-K



Hyper-K



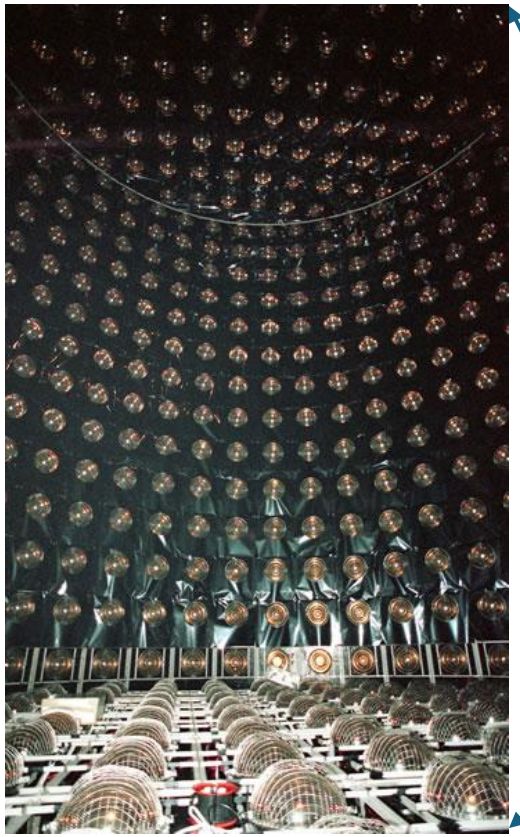
SNO/SNO+

Embedded detectors with shielding
MeV to GeV scale
Wide range of applications including supernova, solar, reactor neutrinos and BSM physics!

Water Cherenkov detectors for neutrino searches and nucleon decay

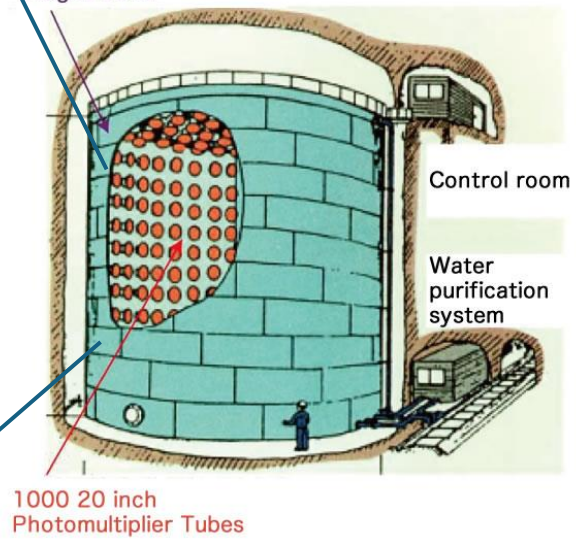
Past: Kamiokande (Japan)

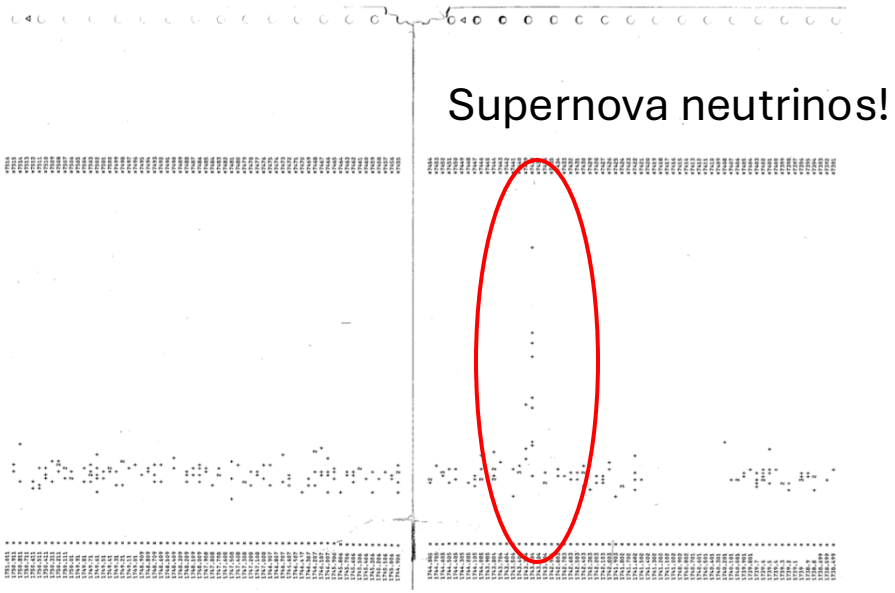
- Originally built as detectors of proton decay
- The technology became popular for neutrino detection
  - Simple detector design
  - Nobel prize for neutrino detection from supernova 1987a



Kamiokande/Kamiokande-II

Cylindrical detector
0.7 kt fiducial mass
1000 PMTs



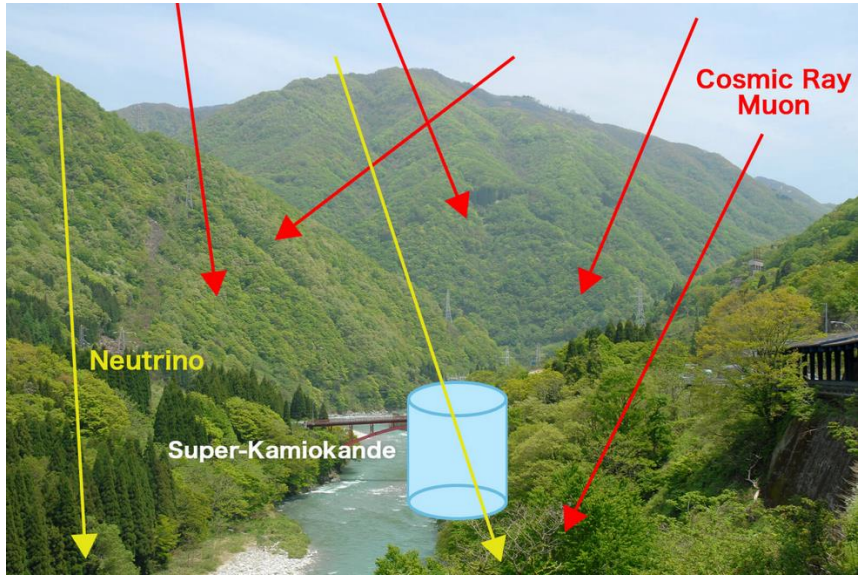


- How to improve?
- More statistics? -> Bigger detector
- Better resolution? -> Higher PMT coverage
- Incoming particles? -> Outer detector

Operating: Super-Kamiokande

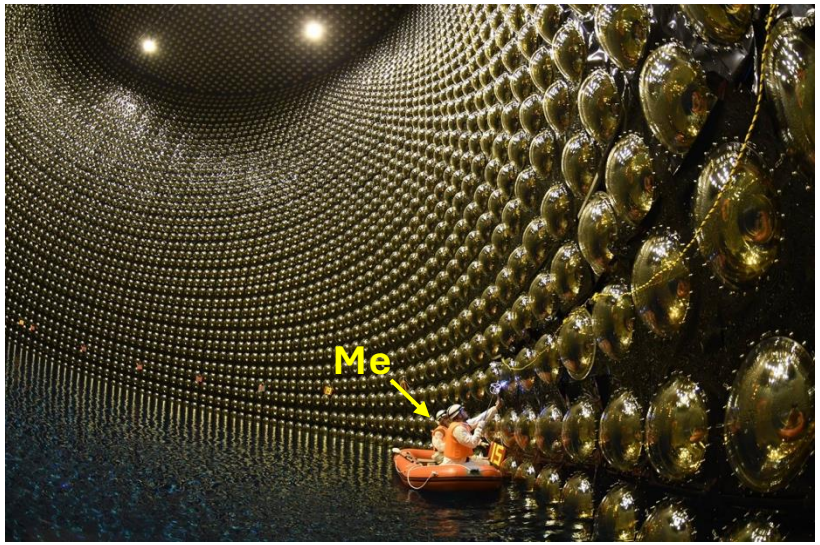
Operation 1996 – 2018

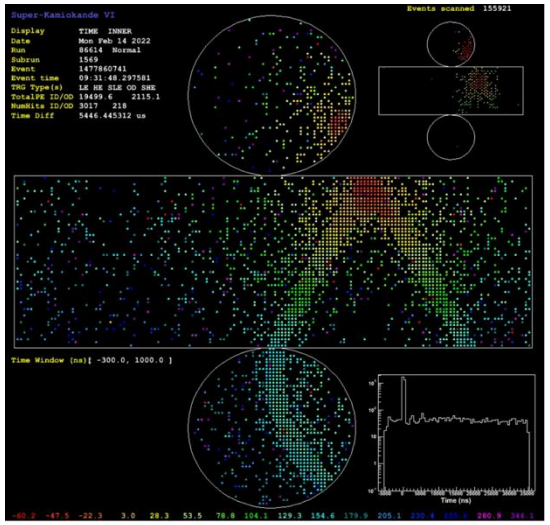
- 22.5 kt fiducial mass
- Ultra pure water
- ~11000 PMTs
- 1000m overburden

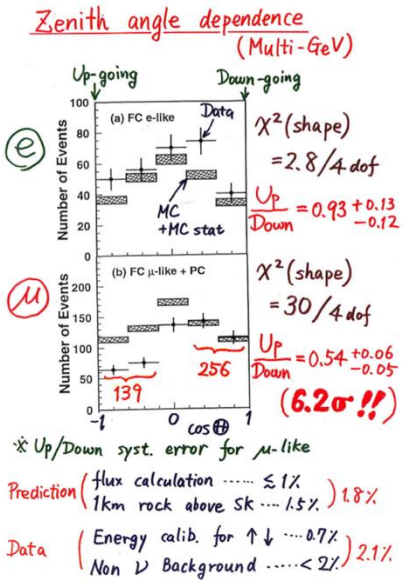


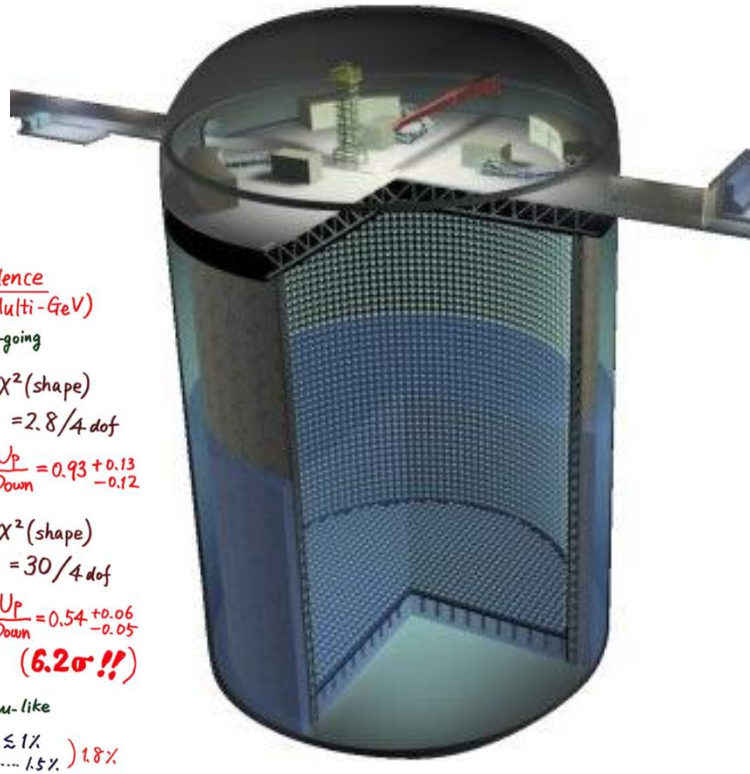
Operation 2018 - present

- Super-Kamiokande-Gd
- New equipment installed, PMT measurements
- Addition of gadolinium sulphate









Discovery of atmospheric neutrino oscillation

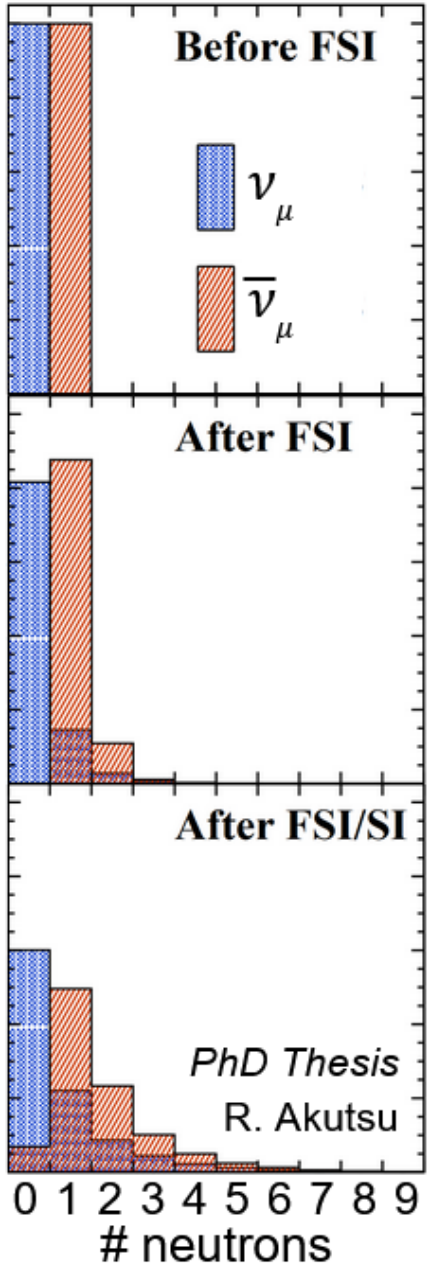
- Excellent performance
  - 99% μ/e separation
  - 2% momentum resolution
  - 1° direction resolution

Towards SK-Gd: Enhancing neutron tagging with Gadolinium

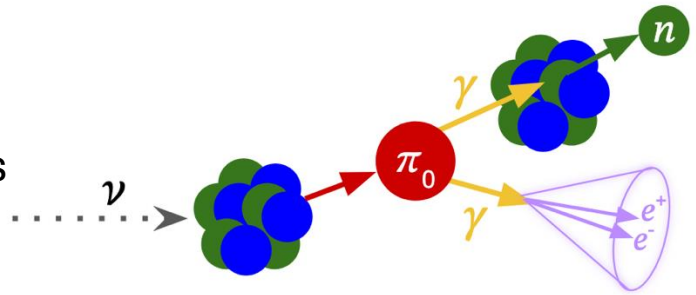
Why Gadolinium?

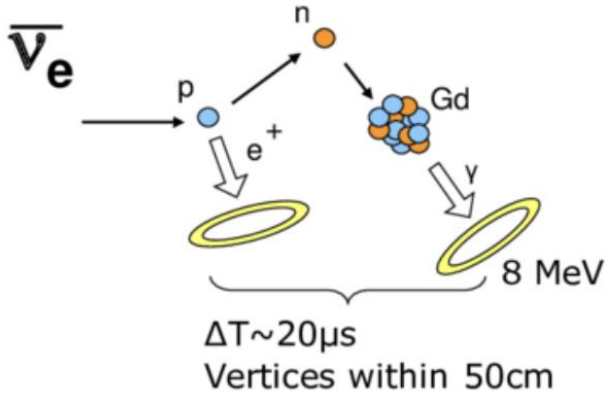
Gd doping: Measuring neutron multiplicities

- Adding gadolinium to ultrapure water increase neutron capture cross section
- CCQE **neutrino interactions produce 1 proton**, while **antineutrino interactions produce 1 neutron**
- **Tagging neutrons** allows statistical ν / $\overline{\nu}$ separation
- **Large model uncertainties** in final state interactions (FSI) and secondary interactions (SI) that modify observed neutron distribution
- **Gadolinium doped water enables neutron detection** via gammas after n-capture
- Improved neutron capture is also important for **supernova and Diffuse Supernova Neutrino Background neutrino** detection



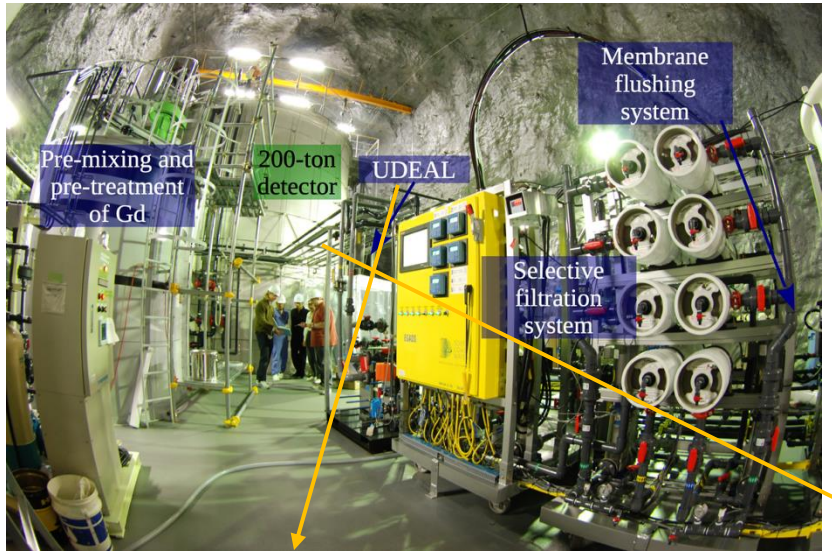
Common NCπ_0 background looks exactly like ν_e signal when one γ interacts with water before producing light

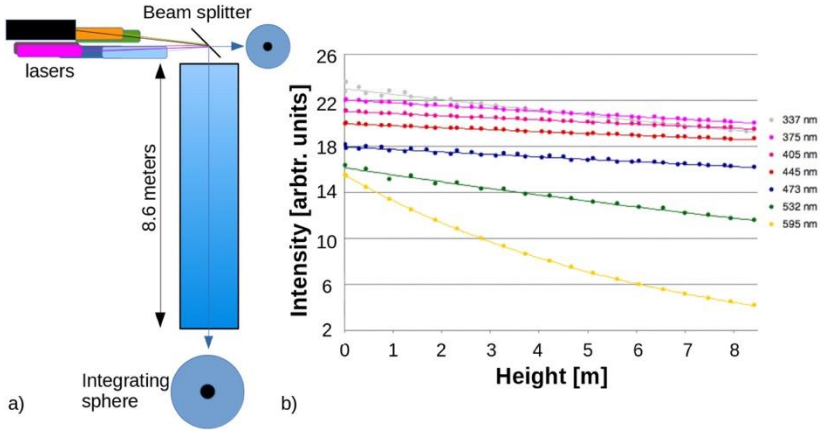




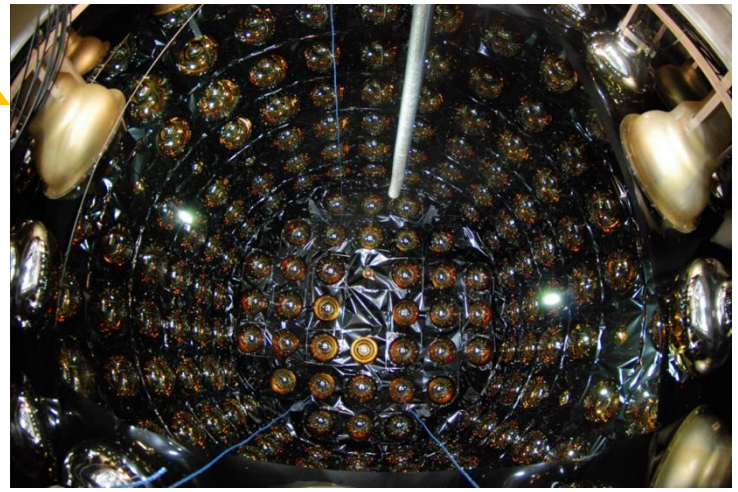
EGADS (Evaluating Gadoliniums Actions on Detector Systems)

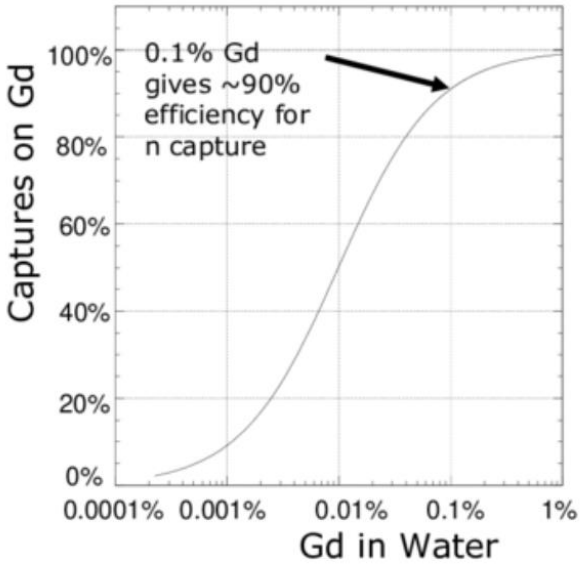
- EGADS is inside the same mine as Super-K - funding approved in 2009



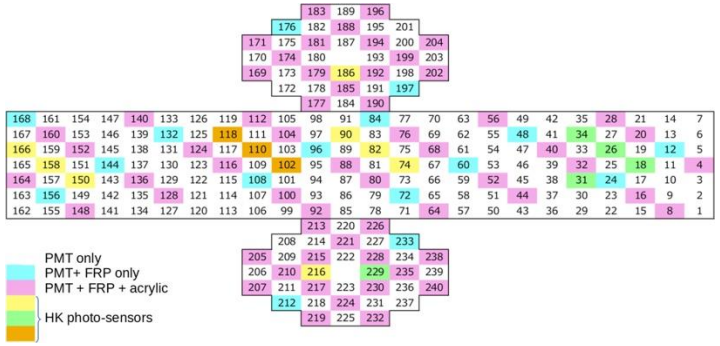


- Demonstrated water purification with constant Gd concentration
- Confirmed no potential negative impact on Super-K
- Tested new water transparency device





Final run with 0.2% Gd sulphate and 90+% neutron tagging efficiency



For SN enthusiasts
https://www-sk.icrr.u-tokyo.ac.jp/egadsSNalarm/
Real time public announcements

Test beds: Combined water enhancement

Gd + WbLS

ANNIE (Accelerator Neutrino Neutron Interaction Experiment)

See Luis Mora-Lepin's talk

- 26-ton water Cherenkov detector (3.8m x 2.3m)
- Installed in Booster Neutrino Beam at Fermilab
  - ANNIE can examine neutrino interactions directly!

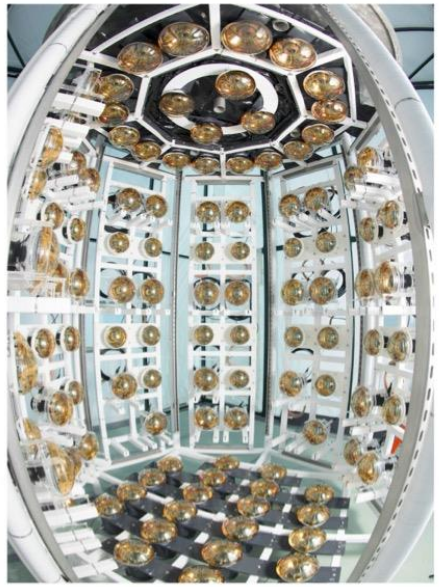
- Phase 1 completed in 2017: Mapping neutron background
- Phase 2 began in 2020: Physics measurements

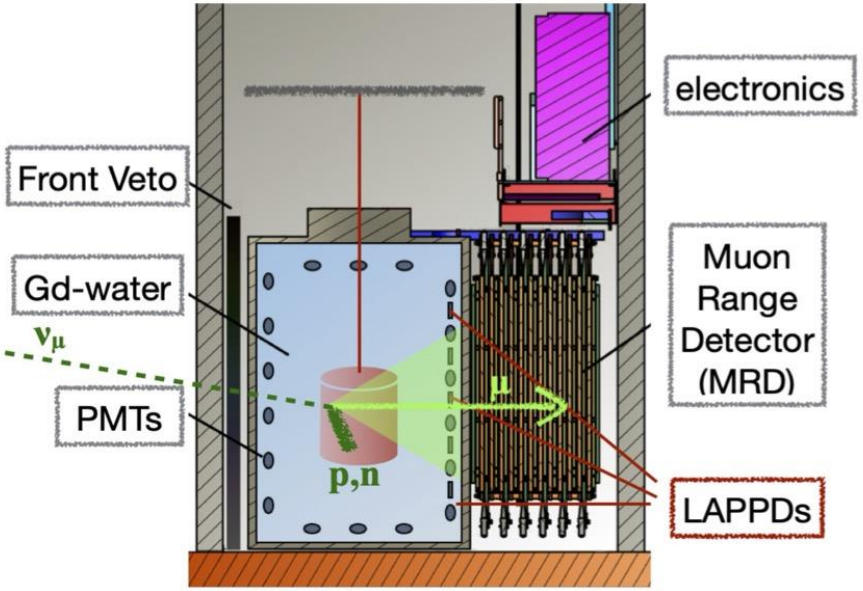
- WbLS upgrade in 2023, second WbLS deployment due to start soon!

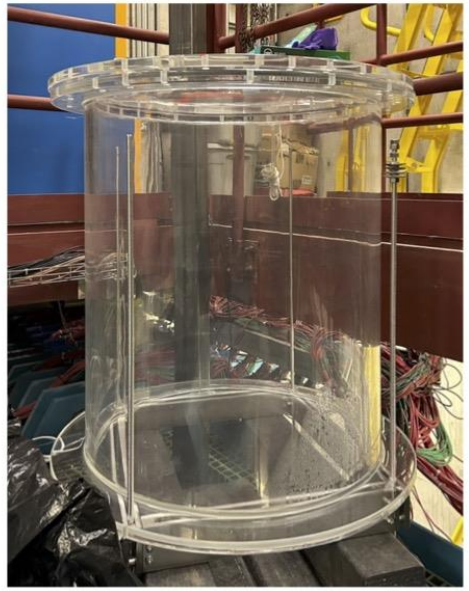
Program

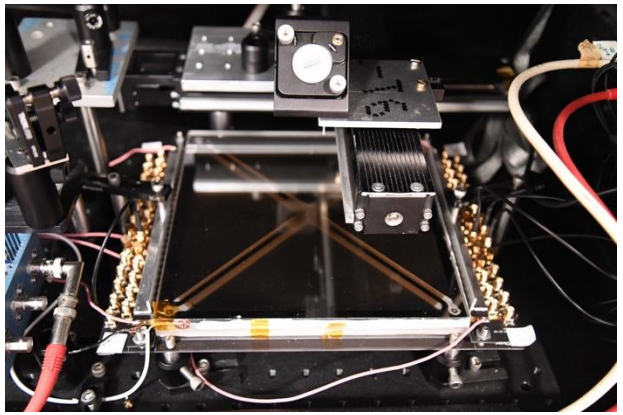
- Neutrino interactions
- Test WbLS
- Gd doped for neutron tagging
- Prototype of LAPPDs
  - Large area Picosecond Photodetectors

- LAPPDs: 50ps, conventional PMT: 250ps
  - Currently 5 deployed







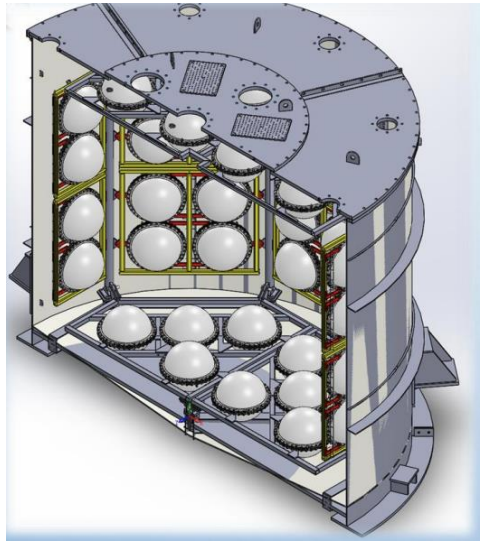


Deployment of 366L WbLS vessel in 2023

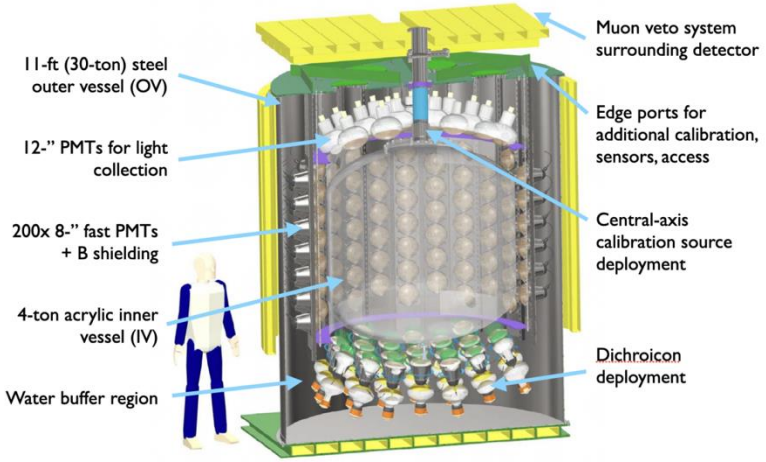
The BUTTON experiment

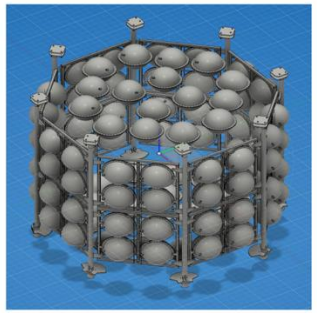
(Boulby Underground Technology Testbed Observing Neutrinos)

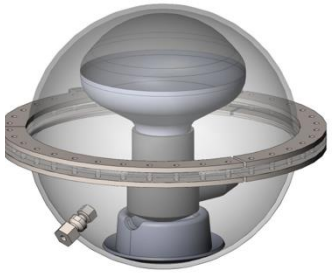
- Measure (anti)neutrinos from fission sources
- 96 8” PMTs within acrylic vessel
  - Vessel ensures no PMT damage due to WbLS
- In conjunction with future EOS and BNL experiments



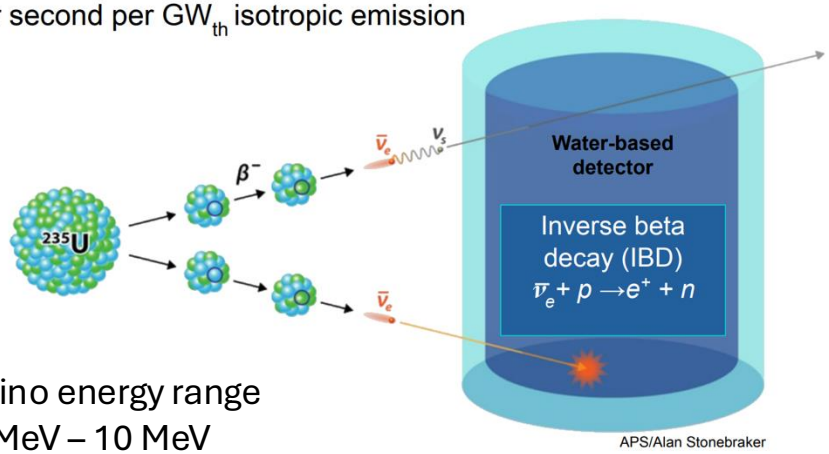
Conceptual EOS design



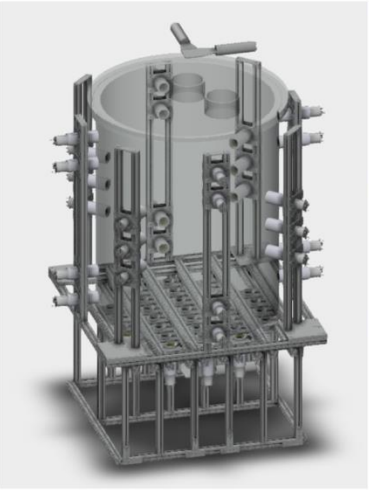




~6 antineutrinos per fission
O(10^{21}) per second per GW_{th} isotropic emission



Antineutrino energy range from 1.8 MeV – 10 MeV



BNL test bed

Towards Hyper-Kamiokande and the future:

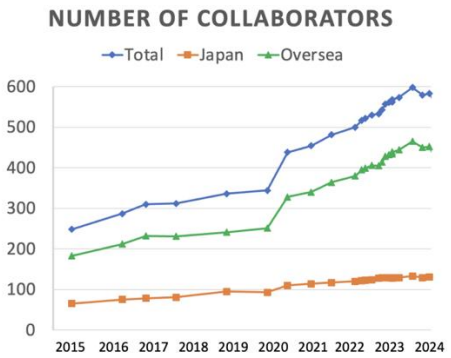
How do we do we reach beyond our systematic uncertainty limits?

Next generation: Hyper-Kamiokande

See Veera Mikolas talk!

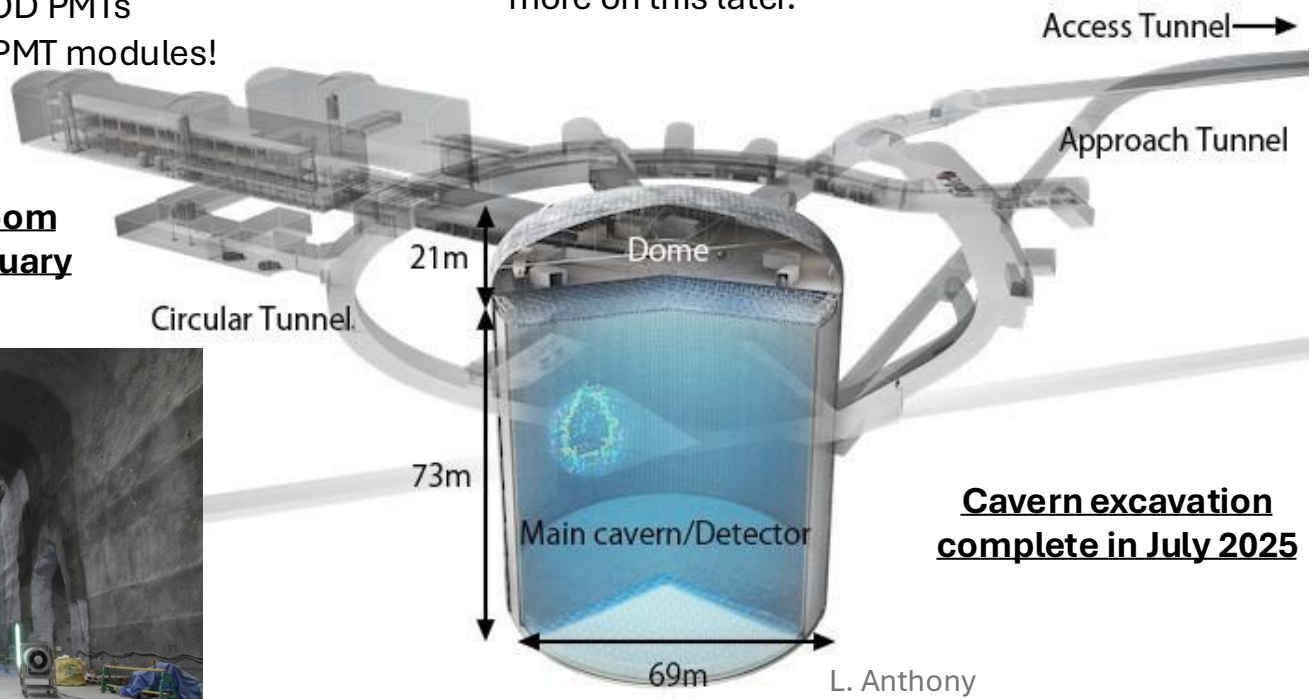
PMT test facility, 15000 PMTs delivered!

Growing number of collaborators.
Detector construction to begin in 2026!



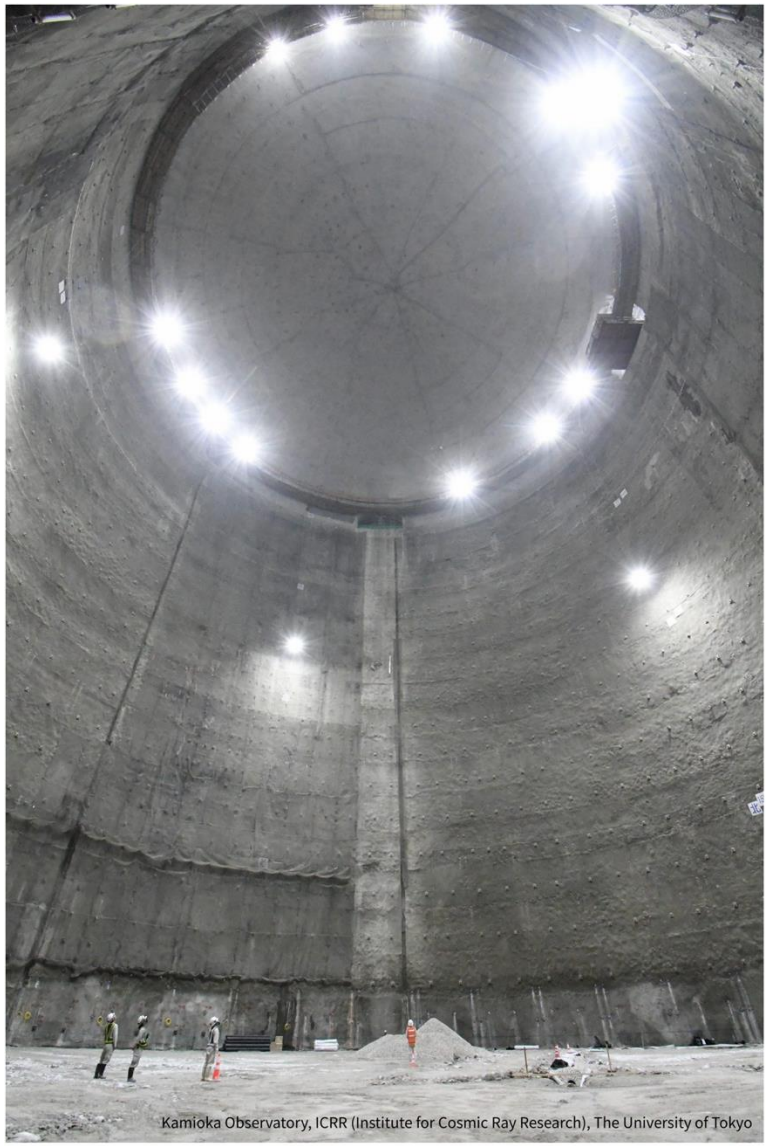
188 kt fiducial mass
20,000 PMTs + 3600 OD PMTs
20” B&L + new multi PMT modules!

Multi-PMTs tested at CERN – more on this later.



Water system room complete in February 2025

Cavern excavation complete in July 2025



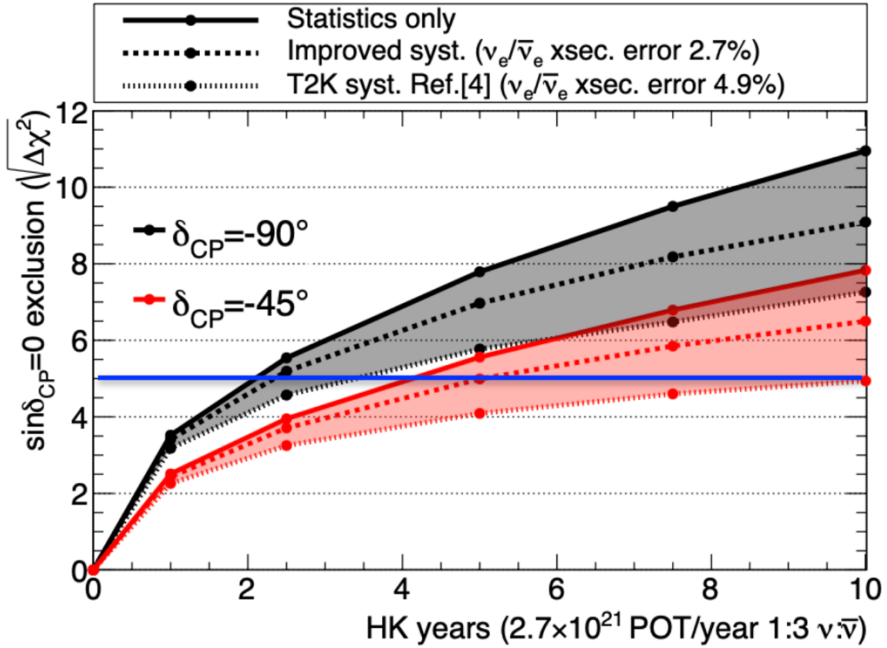
Measurement uncertainties: Hyper-K

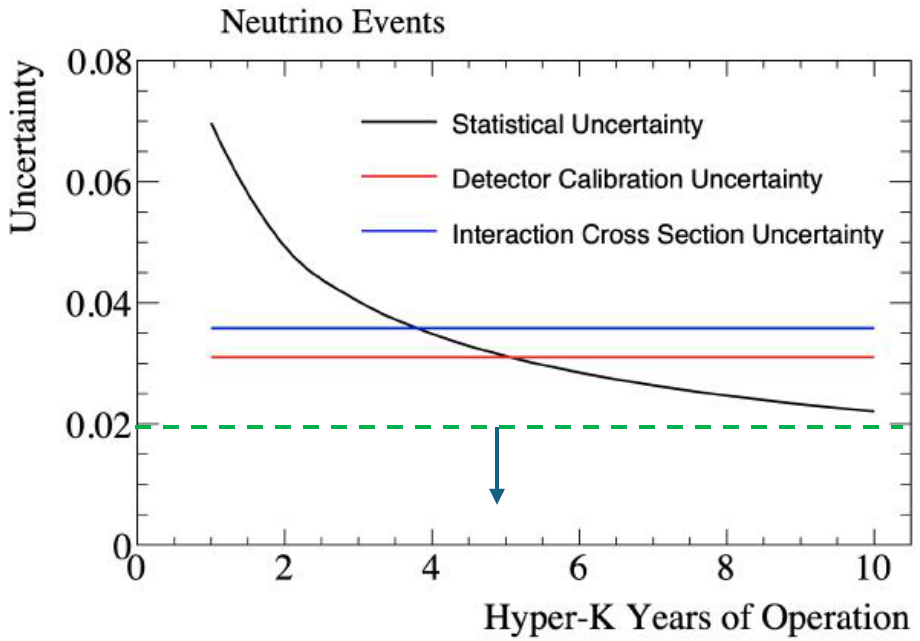
Detector model uncertainties

- **Particle interactions on water**
- **Cherenkov light production**
  - **Propagation of light** through water volume (absorption, scattering)
- **Photosensor response**
- **Reconstruction of complex and challenging event topologies** in both signal and background channels

Interaction model uncertainties

- ν_μ **& $\bar{\nu}_\mu$ production** to understand ν_μ beam flux, ν_e contamination and "wrong sign" background
- ν **interaction cross-sections on water** for CCQE signal, other CC signal channels and wide array of backgrounds

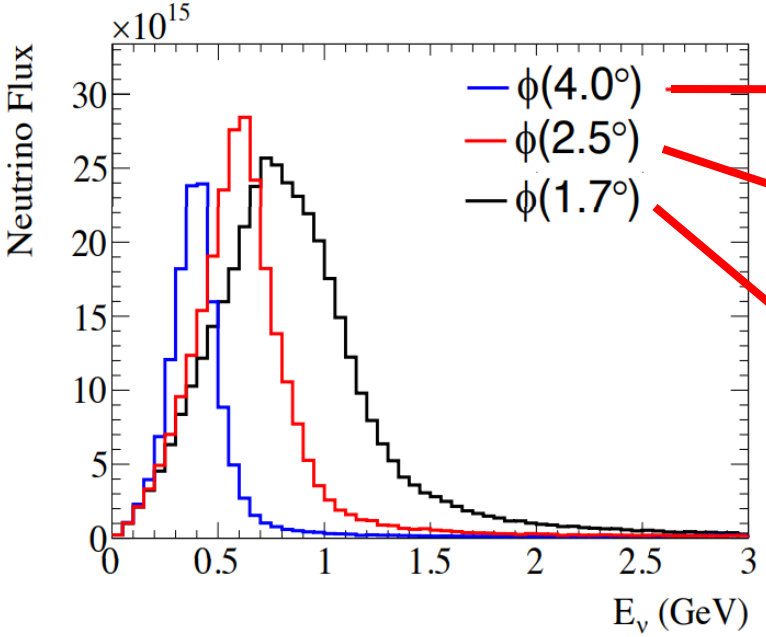


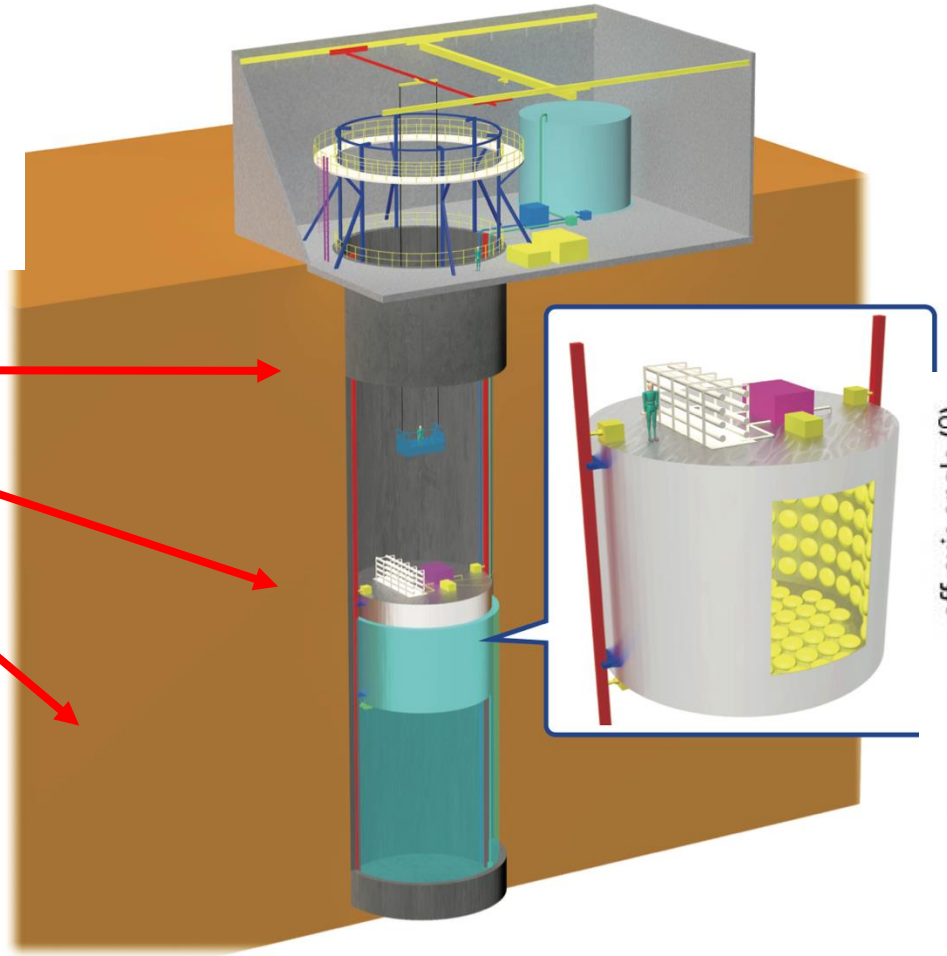


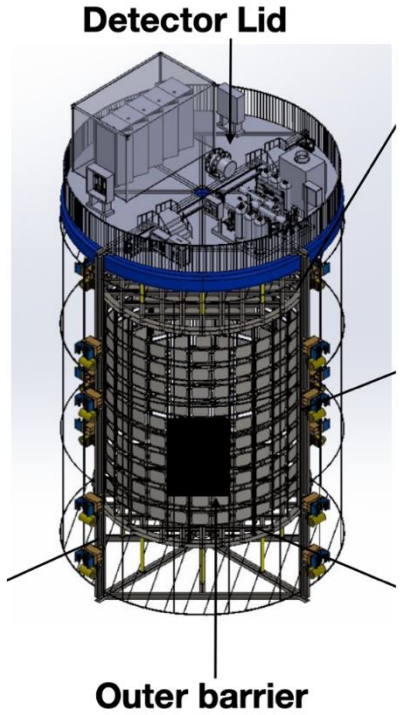
Hyper-Kamiokande detectors: IWCD

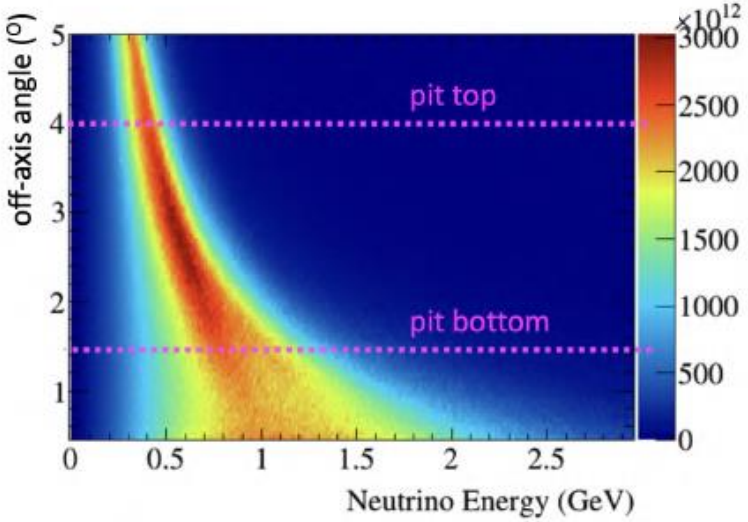
Intermediate Water Ckerenkov Detector designed to directly measure ν flux & cross-section of un-oscillated beam with high event rate across range of energy spectra

- Intermediate water Cherenkov at ~1km from the beam
  - covering 1.7 - 4 degree off-axis neutrino flux: sampling different neutrino energy



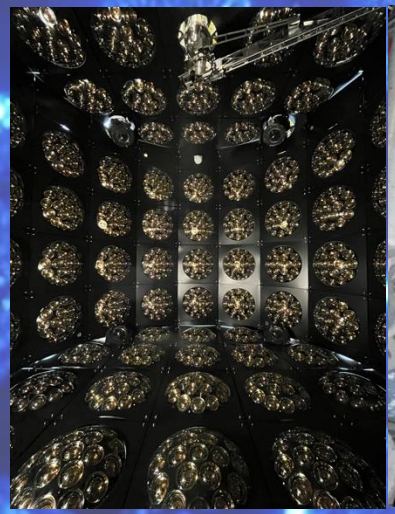


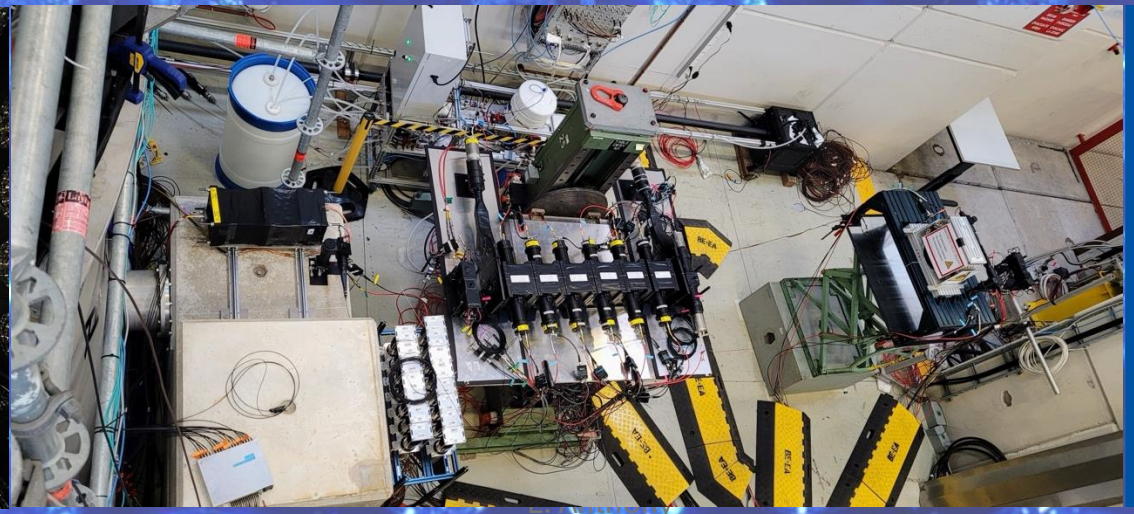




Water Cherenkov detectors: Beam tests and technology test beds

The Water Cherenkov Test Experiment





CERN

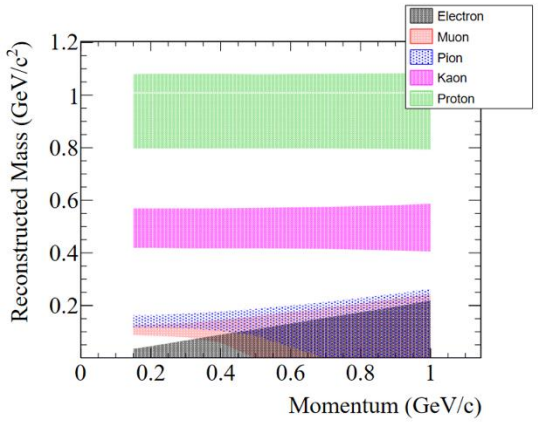
The Water Cherenkov Test Experiment

WCTE is a 40-ton water Cherenkov detector which operated at CERN

- 93 IWCD style mPMTs
- 4 Hyper-K style mPMTs
- 8 cameras use to image the detector

Proof of concept and demonstration of technologies being developed for IWCD and Hyper-K and other future detectors

Access to a well understood and characterized beam of sub-GeV particles



Good mass separation between particles species!

Suite of beamline monitor detectors:

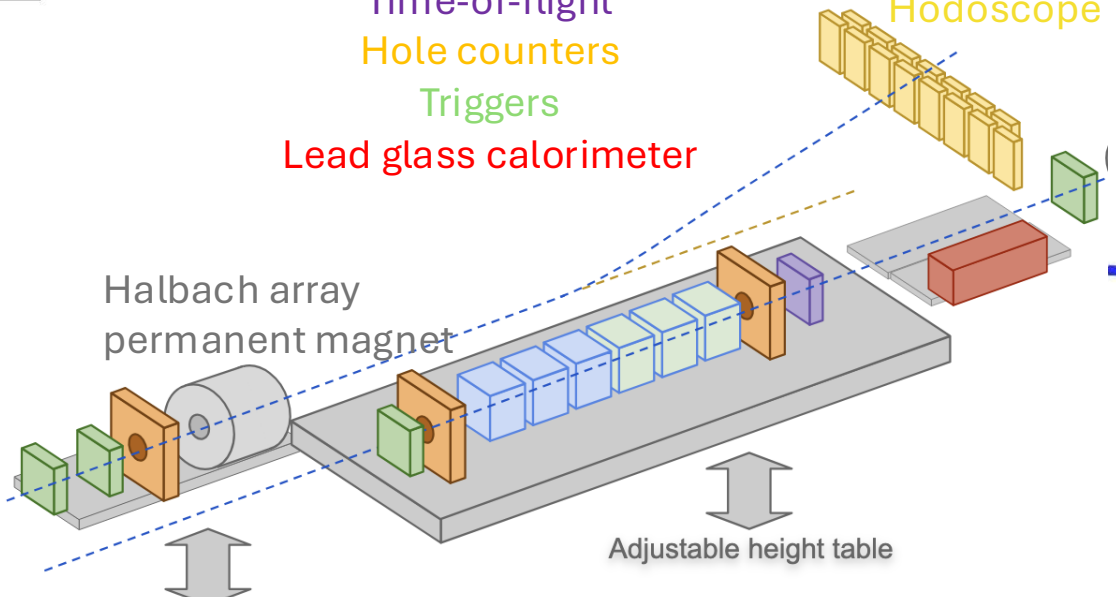
Aerogel Cherenkov

Time-of-flight

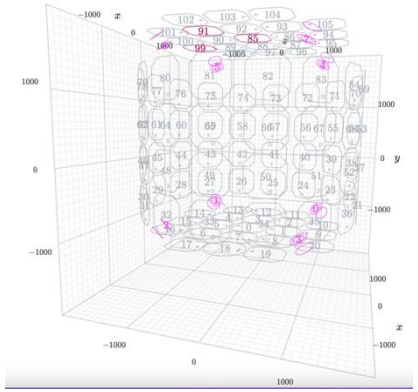
Hole counters

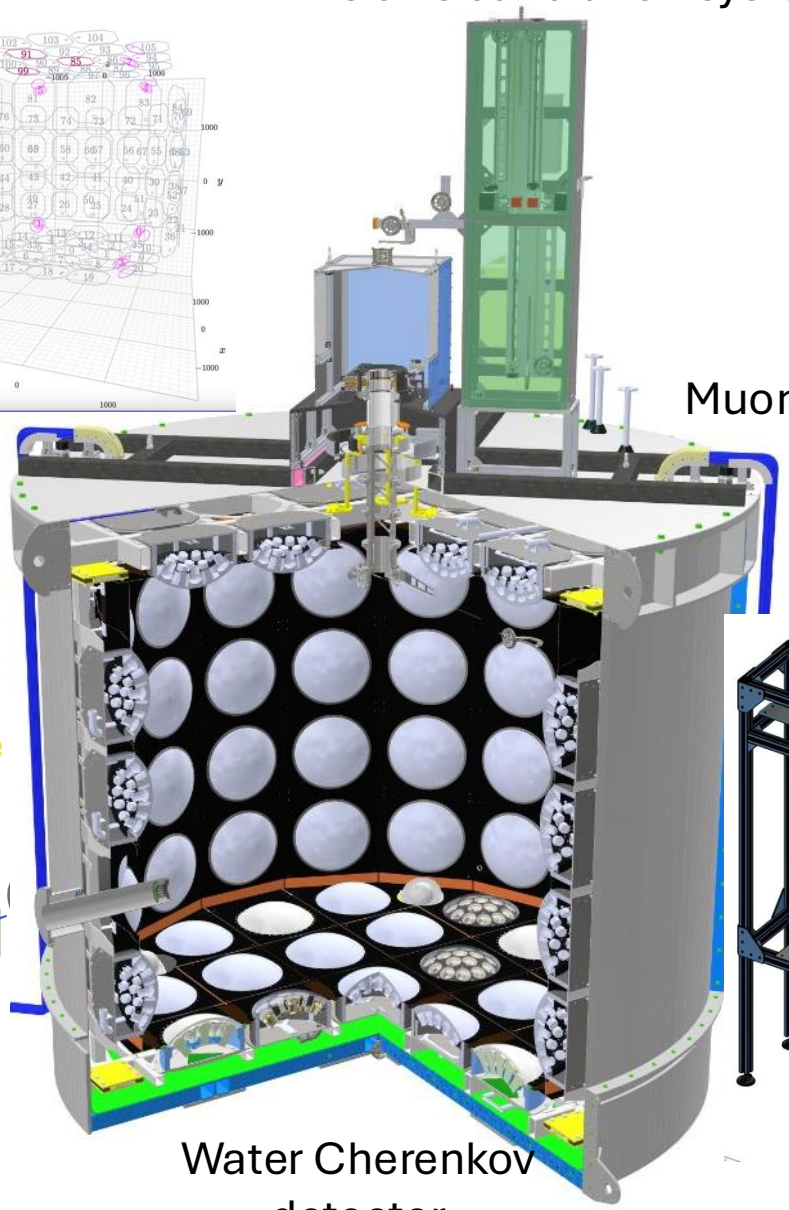
Triggers

Lead glass calorimeter



3 axis calibration system





Muon tagger

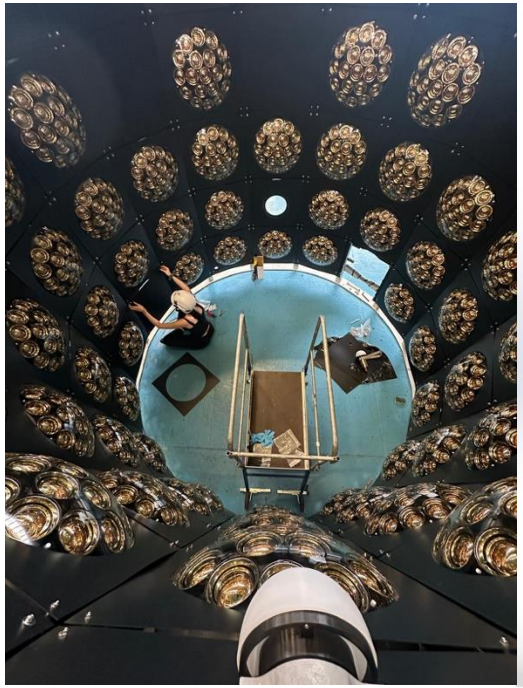
Water Cherenkov detector

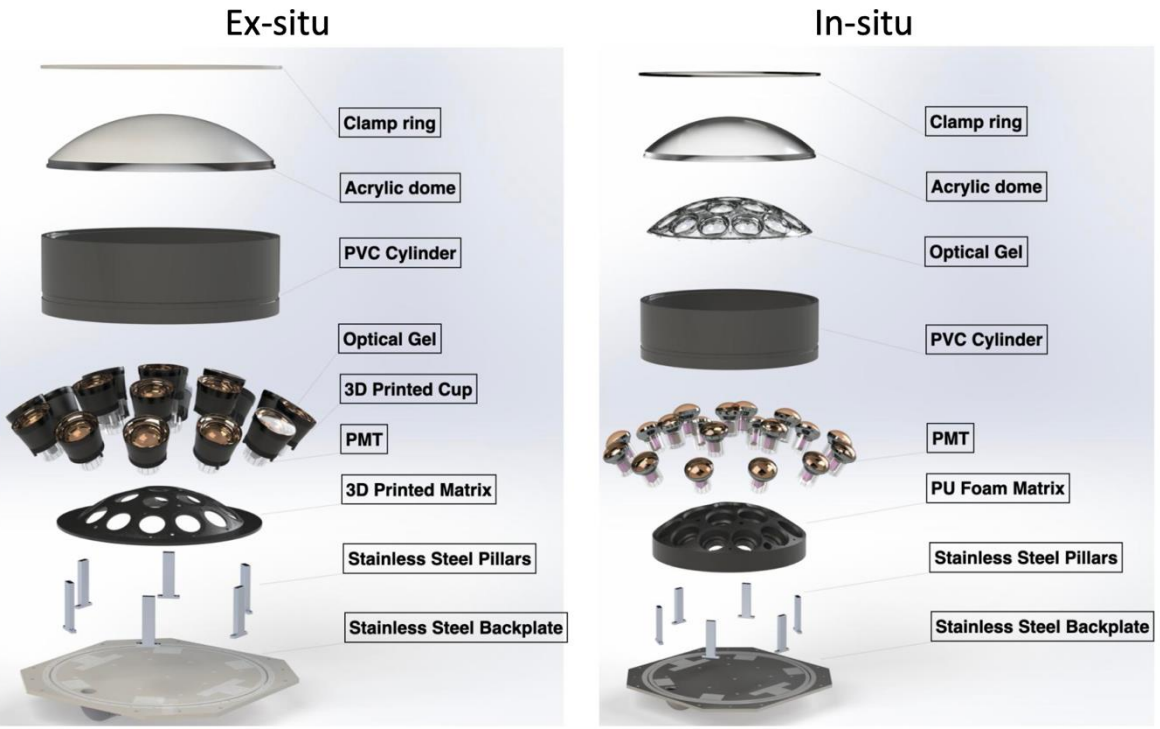
WCTE Detector Instrumentation: mPMTs

Much more information in Krzysztof Dygnarowicz's talk!

19 x 8cm diameter PMTs (Hamamatsu R14374) in each multi-PMT modules (mPMT)

- Improved granularity and timing compared to larger PMTs
- <1 ns timing resolution
- **HV generated at each PMT** base with Cockroft-Walton circuit
- **In-module digitizer mainboard** with power cable and communication over single PoE cable



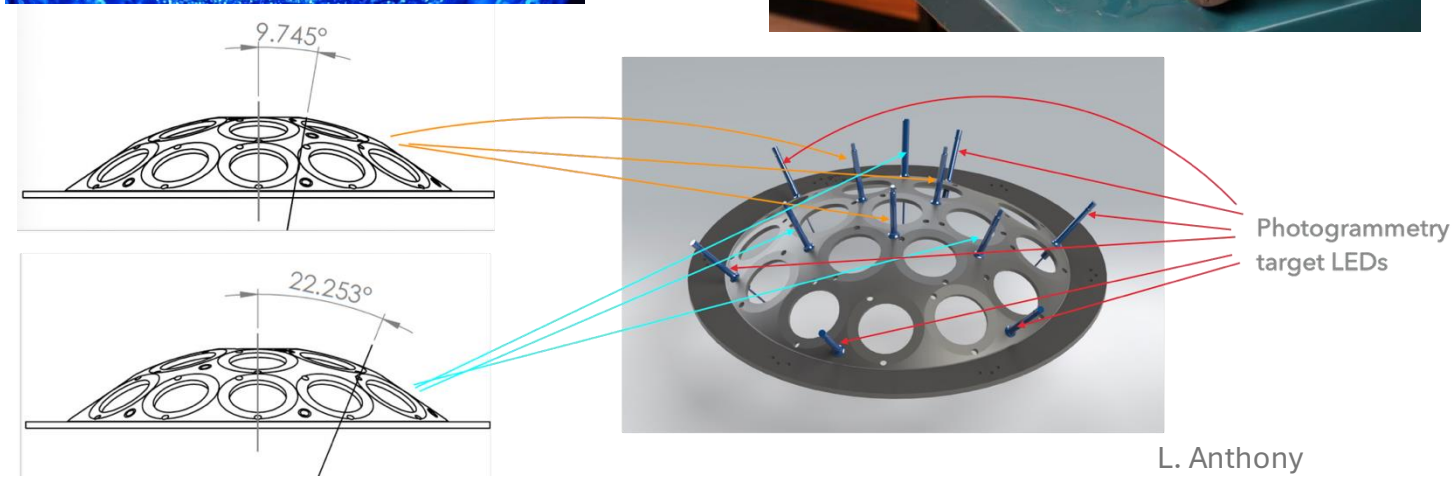


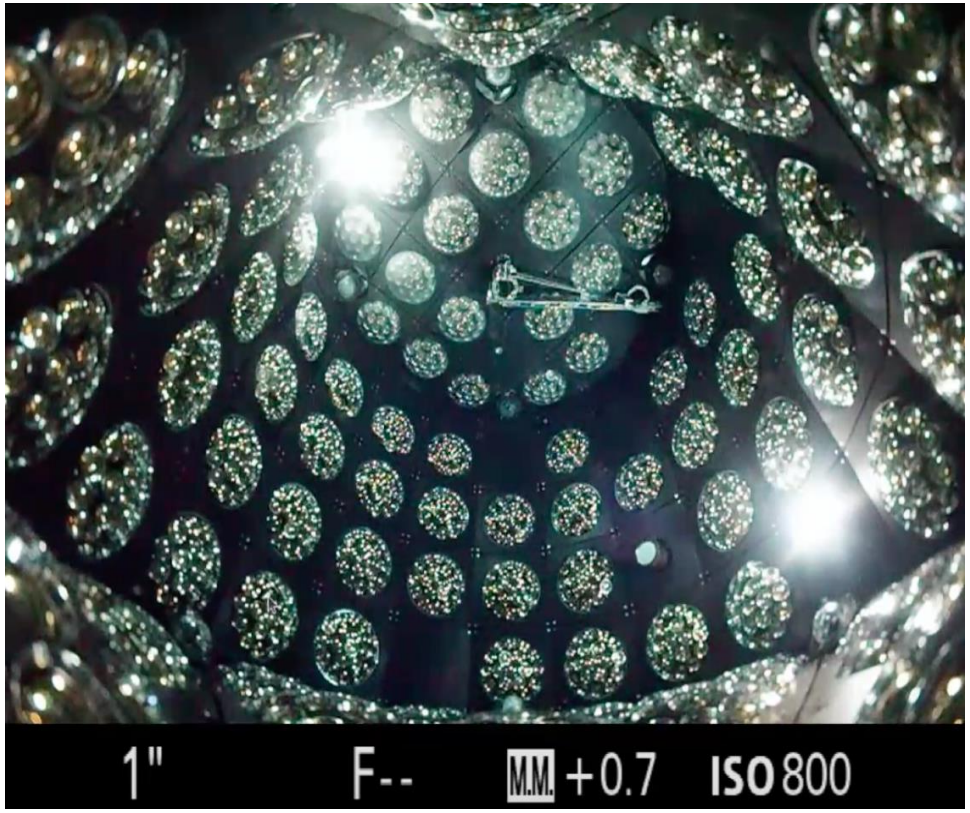
- **Integrated LED calibration systems**
  - 1st Set used for photogrammetry beacons (continous)
  - 2nd set with sub-ns pulse width:
    - Diffuse: are also used to characterize the PMT charge response and HV tuning.
    - Collimated: for calibrating the reflections off mPMTs and black sheet.
    - The LEDs used for monitoring changes in the detectors

Mounted calibration sources

- **8 Photogrammetry Cameras** mounted inside the detector
- **3D detector geometry reconstruction** from each mPMT LEDs visible to multiple cameras
- **< 1cm position resolution** expected to observe any deformation of mPMT support structure after filling

- **Hyper-K diffuser**
- Developed at Warwick
- 16 sets of optics planned for IWCD, 122 for Hyper-K
- Testing in WCTE and using for DAQ testing
- 45 degree diffuse light cone
- See Sam Jenkins' talk tomorrow

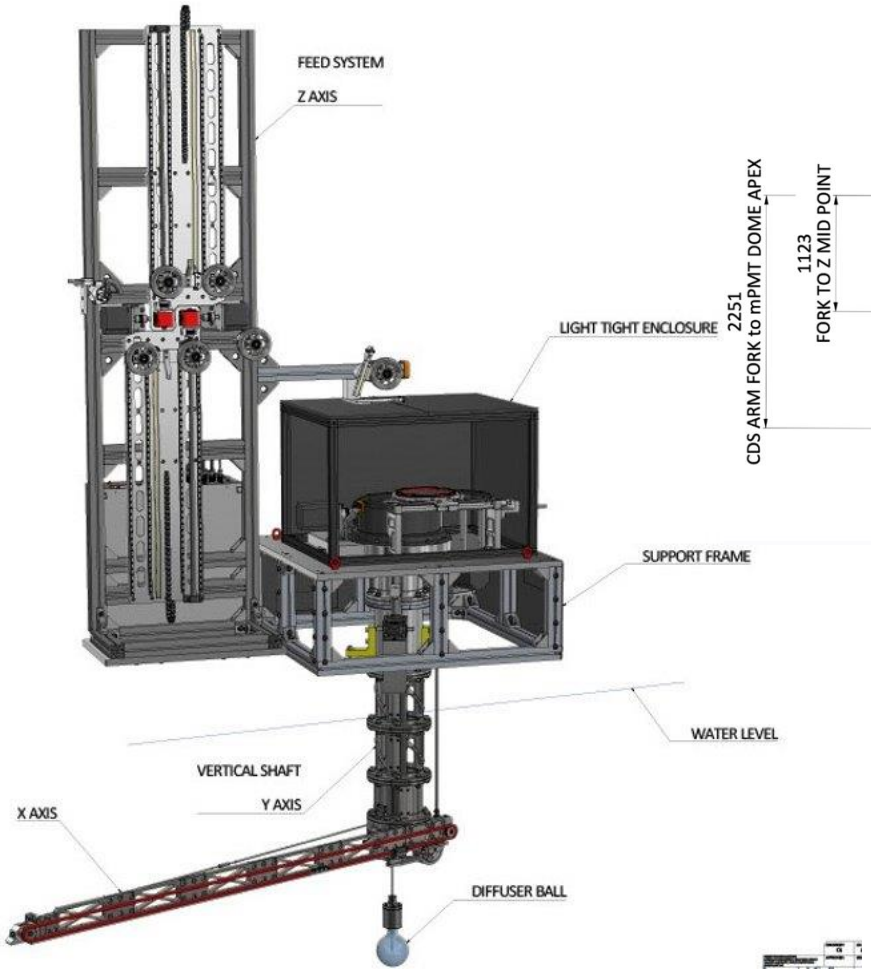


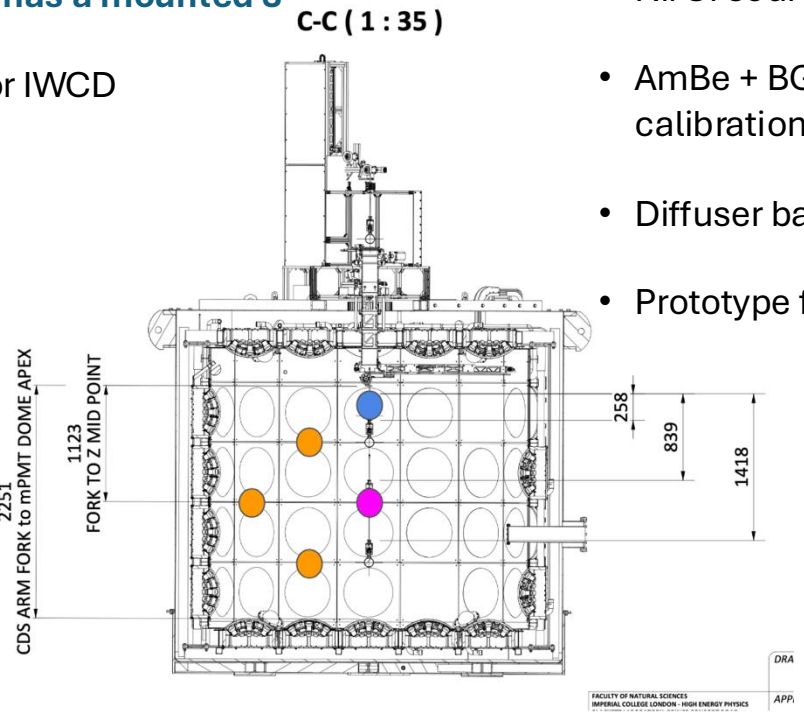


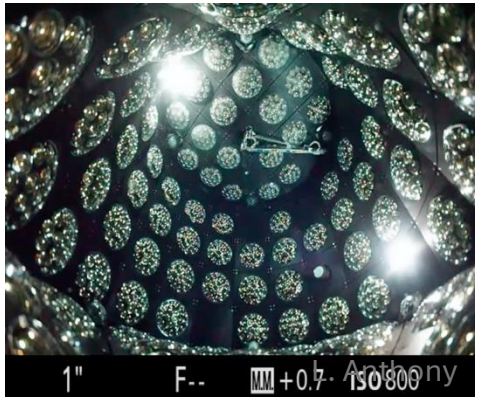
L. Anthony

Custom Calibration Deployment System

- To deploy the calibration sources, **WCTE has a mounted 3 axis central deployment system (CDS)**
  - The CDS for WCTE is a prototype for IWCD

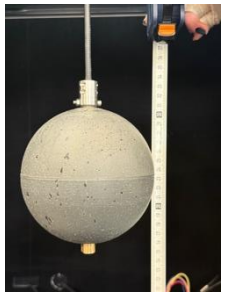


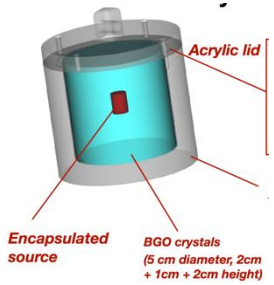


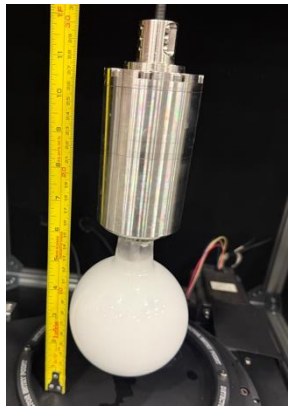


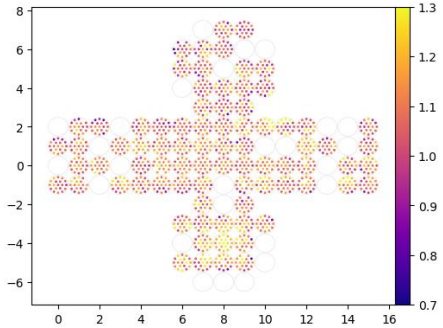
Interchangeable sources

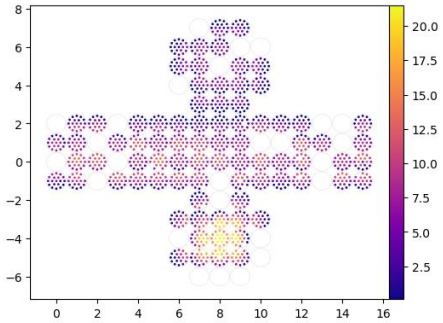
- Ni/Cf source for PMT quantum efficiency calibration
- AmBe + BGO source for neutron detection efficiency calibration
- Diffuser ball for gain and timing calibration
- Prototype for IWCD and Hyper-K

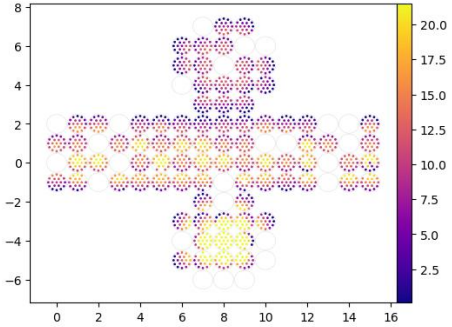








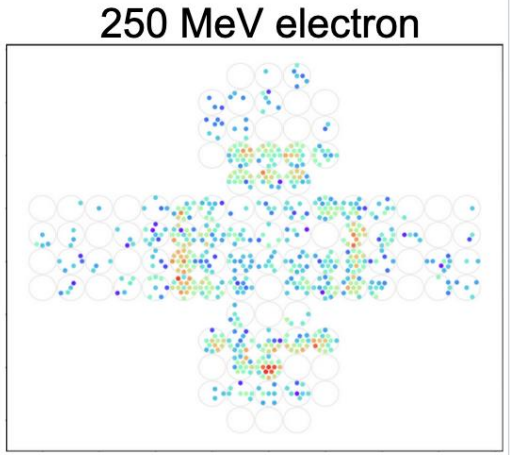


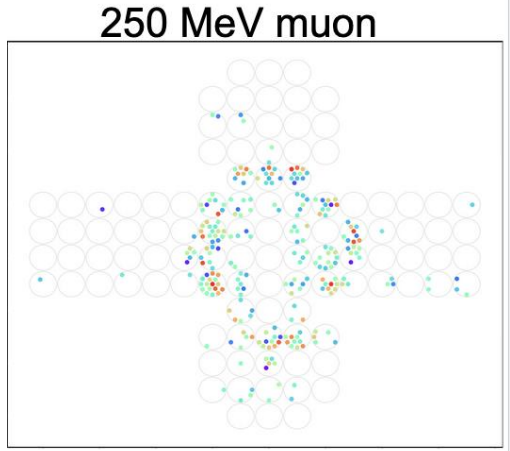


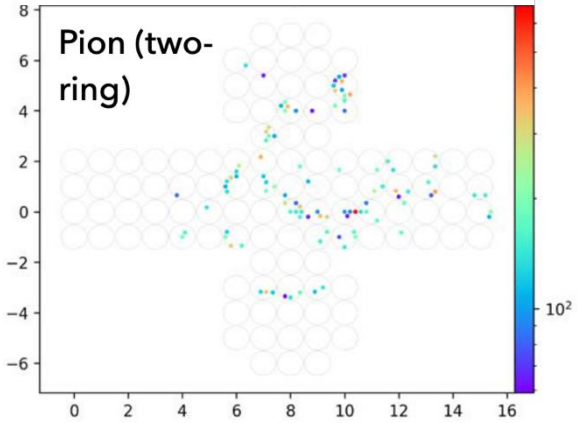
WCTE physics run 2: 2025

- Array of physics measurements to inform Hyper-K physics
- **Directly measure Cherenkov detector response** to charged particles
- **Pure control samples of charged particle and photon interactions**: validation of improvement of models
- Predominantly ran in ultra-pure water mode
- Gd loaded mode for 1.5 weeks

Measurements	Beam Momentum	Water Mode	Beam Mode
Reco. capabilities, pion scattering	200-1200 MeV/c	Pure	Charged Particle
Muon/electron scattering	800 MeV/c	Pure	Charged Particle
Gamma Identification	500-1000 MeV/c	Pure	Tagged Gamma
Neutron Production	200-1200 MeV/c	Gd	Charged Particle
Photonuclear with n tagging	500-1000 MeV/c	Gd	Tagged Gamma

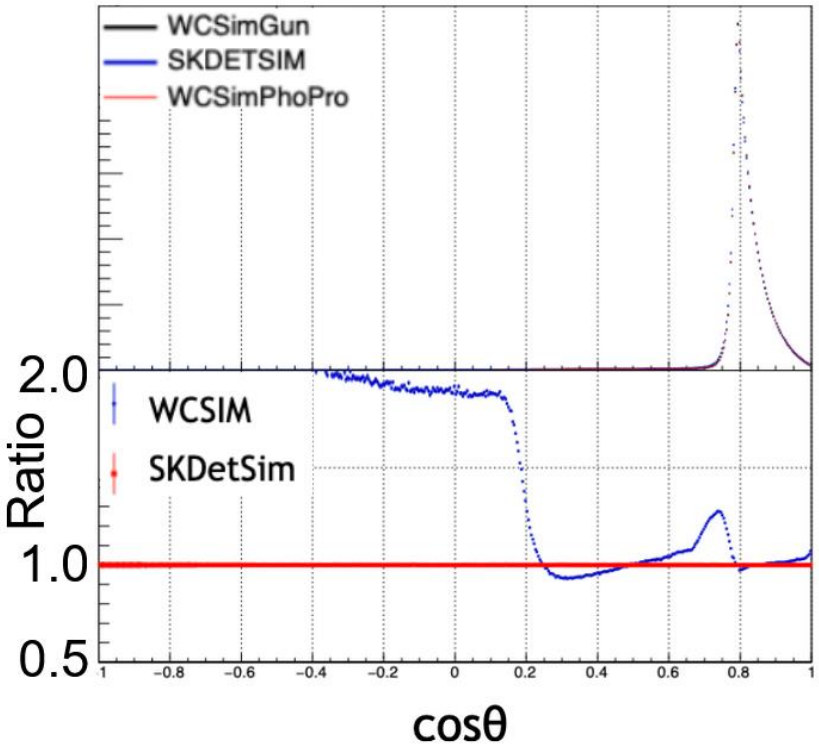


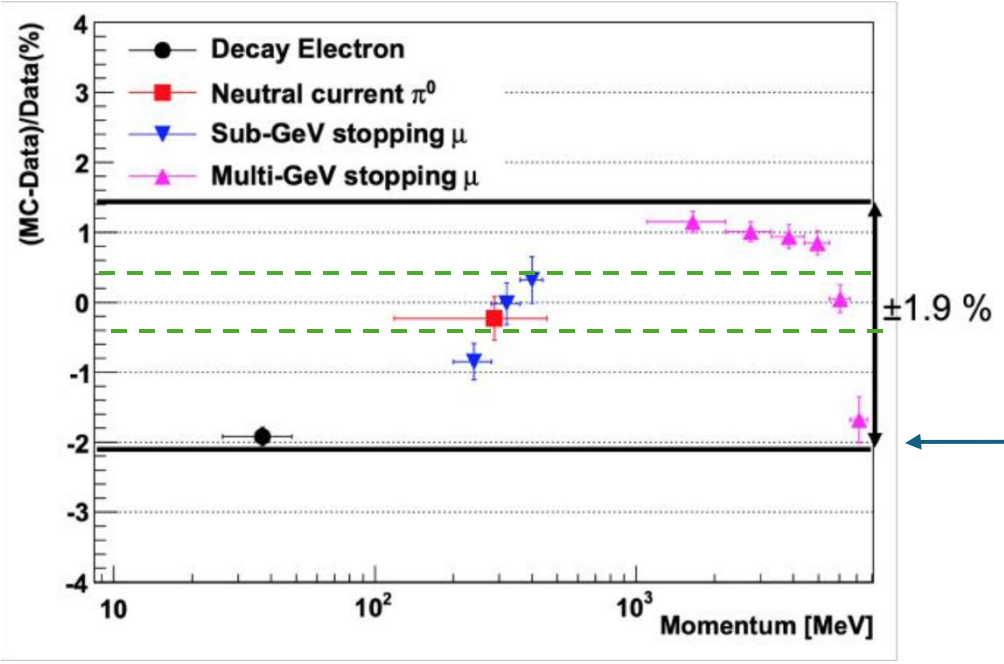




Detector response to charged particles

- **WCTE will help reduce detector uncertainties by directly measuring the detector response to charged particles**
- **WCTE measures e / μ observed PMT charge ratio** at fixed beam momenta
- **Super-K** shows 1.9% discrepancy in energy scale
- **Reduction to < 0.5% uncertainty** is necessary for ν measurements at Hyper-Kamiokande (including δCP measurements)



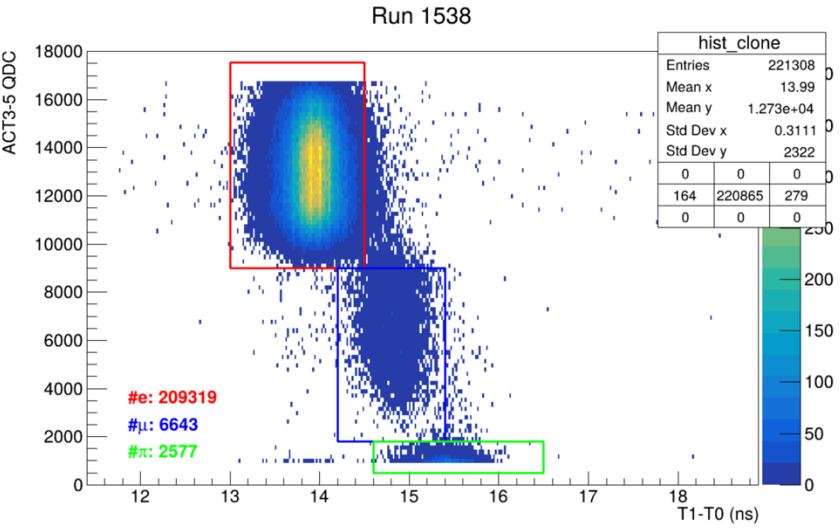


- **PMT angular response modelling and water property uncertainties**
- **Discrepancies in Cherenkov production models** limit ability to use backward-going Cherenkov light to enhance reconstruction
- **WCTE measures emission profile** from e and μ of known momenta

Charged particle configuration

- **Triggers** identify particles in beamline while **hole counters** veto particles that shower before reaching WCTE

- **Aerogel Cherenkov Threshold** detectors use aerogel produced at Chiba university with n = 1.006 to 1.15
  - Low index aerogel used to **identify** e^+ / e^-
  - Higher index aerogels are matched to beam momentum for **π / μ separation**



Suite of beamline monitor detectors:

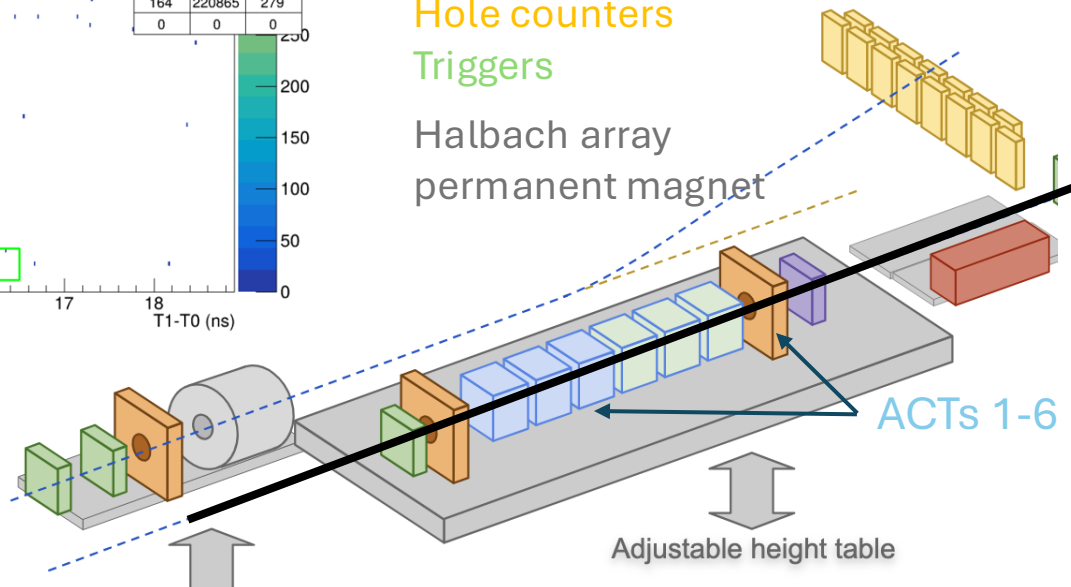
Aerogel Cherenkov

Time-of-flight

Hole counters

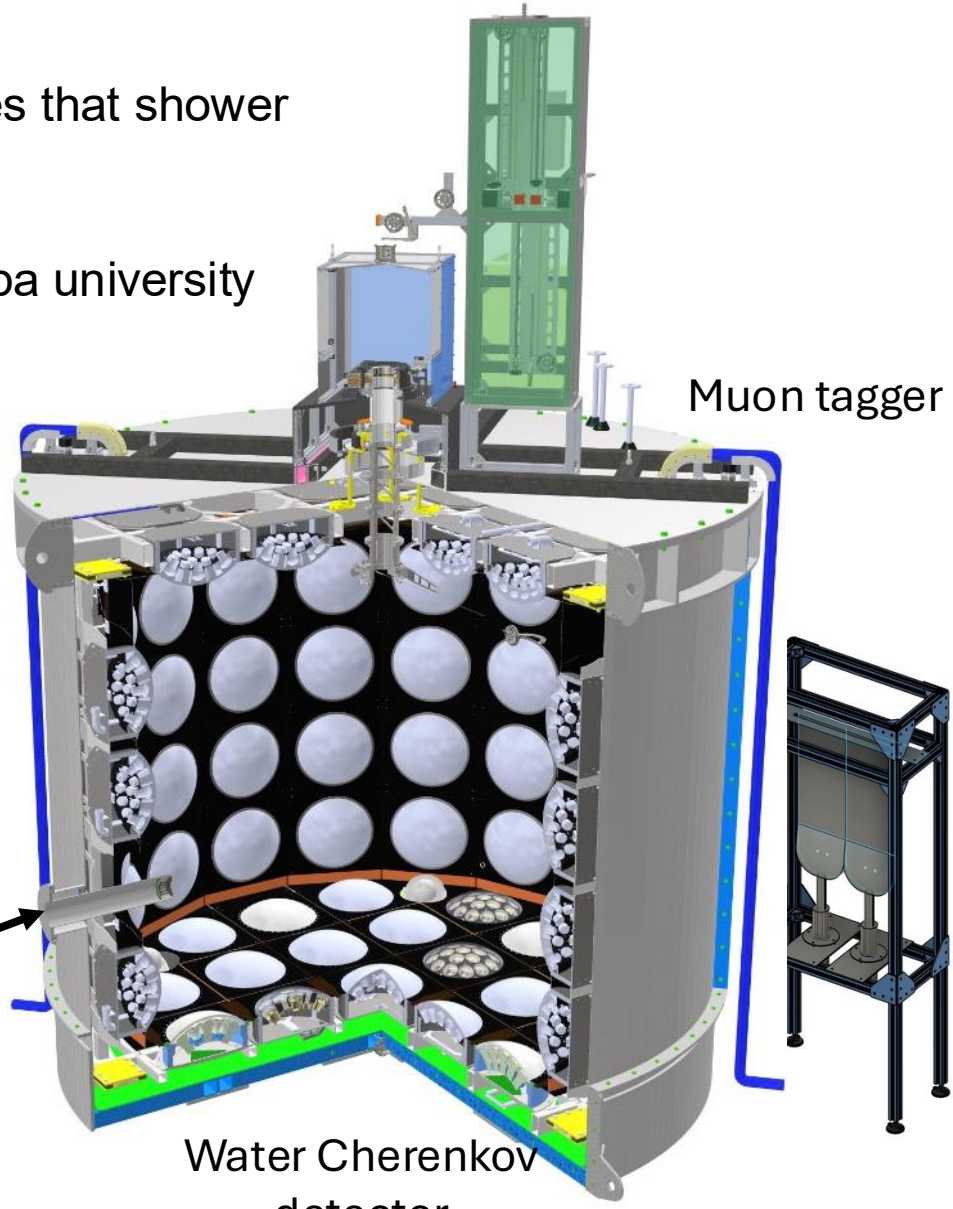
Triggers

Halbach array permanent magnet



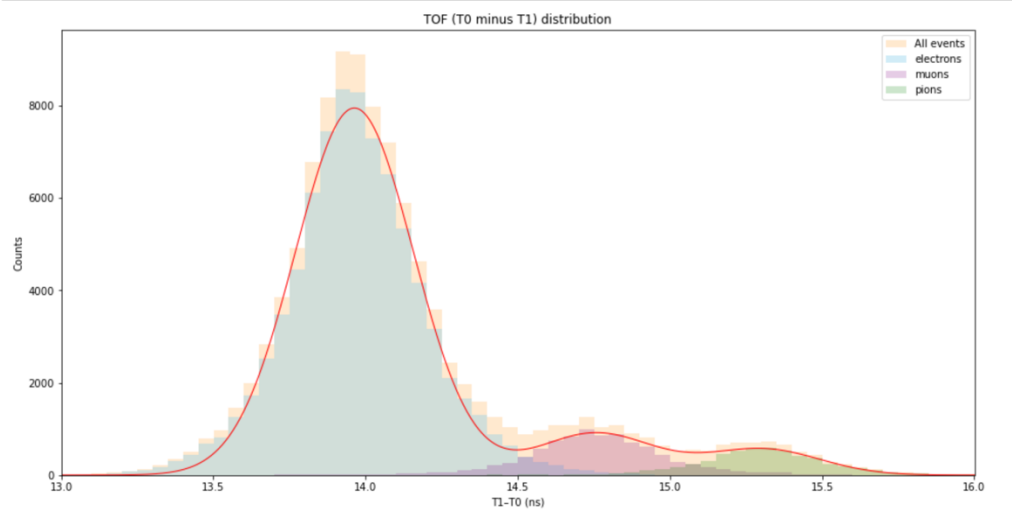
T9 beam

e, μ, π, p

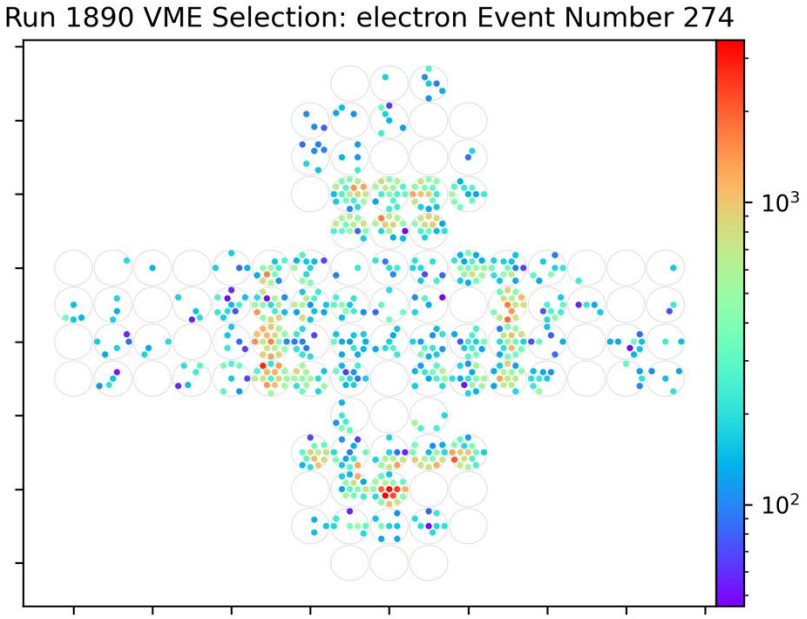


Charged particle detection

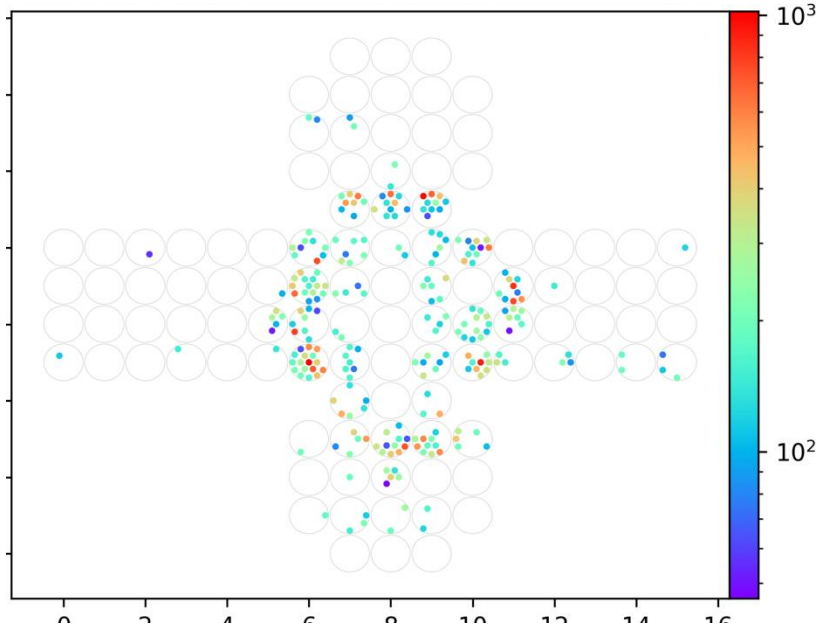
- WCTE successfully observed Cherenkov rings from charged particles!
- With the mPMTs, we achieved great charge and timing resolution
- We can match beam monitor data to water Cherenkov data and tag events
- Example 280 MeV charged particle events



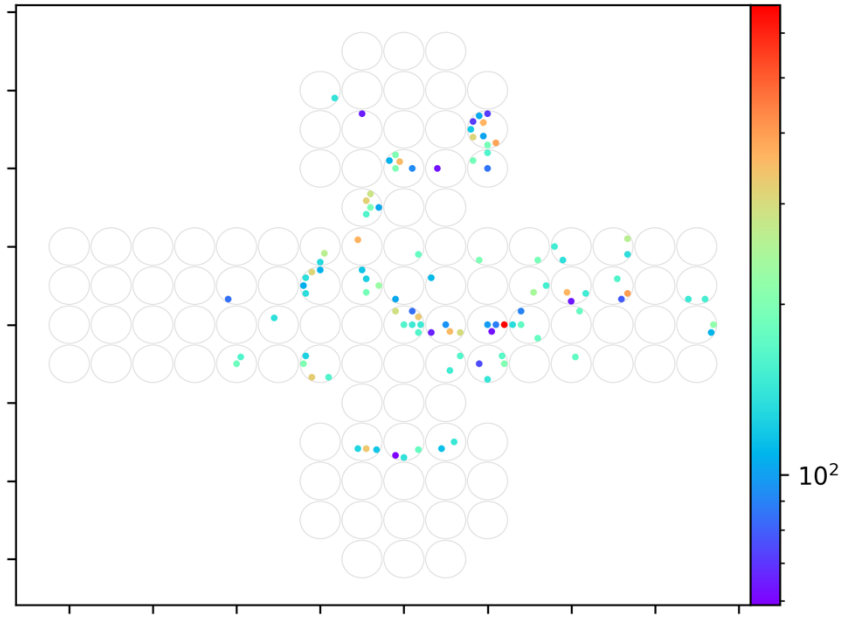
Electron Event



Muon Event

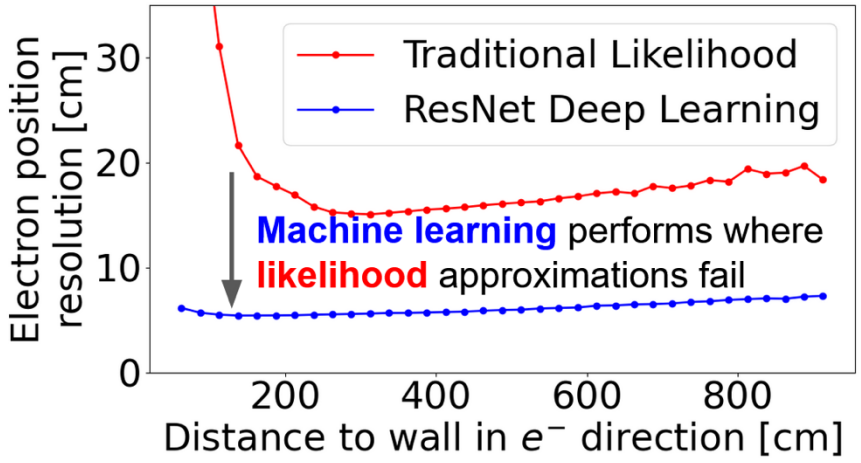


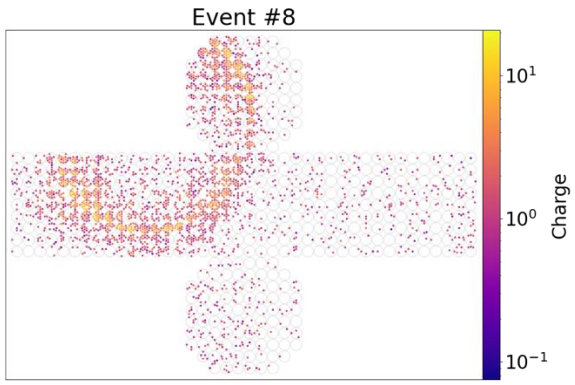
Pion Event



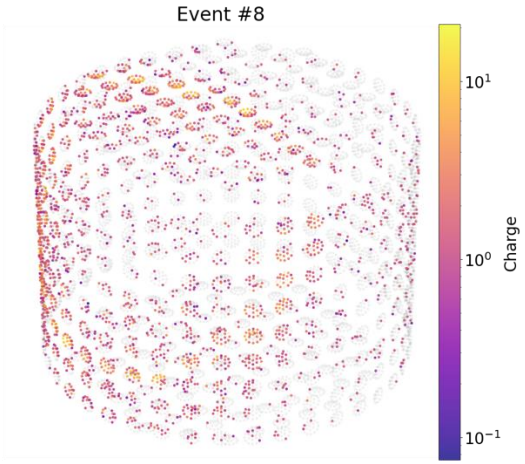
Machine learning in WC detectors (WatChMaL)

- Traditional likelihood reconstruction methods are reaching limits
  - Computational time is a limiting factor – 1M events in fiTQun = 10,000s CPU hours
- ML and deep neural networks can perform significantly better
  - Very fast once network is trained: 1M events with CNN < 100 CPU hours
- WCTE aiding development of a new calibration and reconstruction
- Essential data driven validation of ML based methods

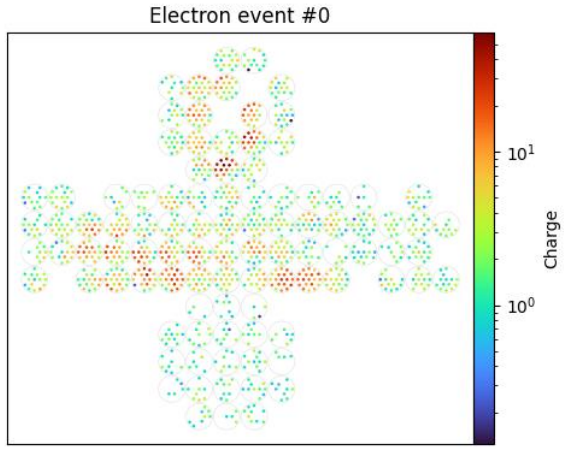




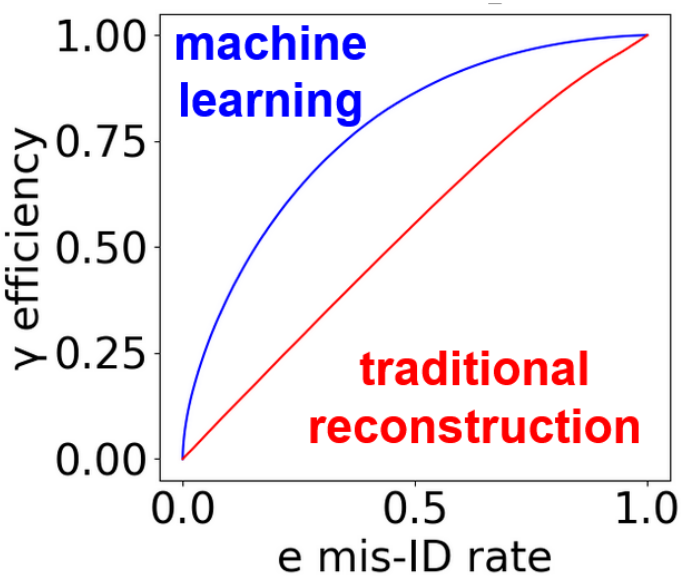
Networks on 2D image like data (IWCD)



Networks on 3D point-clouds or graphs (IWCD)



Networks for WCTE



Summary

- Water Cherenkov detectors have a very rich physics program
- Technology constantly developing, informed by pushing boundaries and detector limits
- The next generation of neutrino detectors are on the way and reducing systematic errors is key for achieving precision measurements
- **WCTE is the first water Cherenkov detector to be placed in a fully characterized beam of sub-GeV tagged e, μ, π, p, γ**
- WCTE Leading development in ML algorithms for water Cherenkov detectors
- BUTTON and ANNIE leading the way for WbLS Cherenkov detectors

<u>WC talks and posters at NuFACT</u>

- Hyper-K
  - Overview: V. Mikola (03/09 plenary)
  - Calibration:
    - S.Jenkins (02/09 WG6)
    - U. Limbu (Poster)
    - B. Bogdan (Poster)
  - mPMTs : K. Dygnarowicz (02/09 WG6)
  - 50” PMT : T. Tashiro (02/09 WG6)
- ANNIE
  - Overview: Luis Mora-Lepin (02/09 WG6)
- KM3NeT/ORCA
  - Overview: Chiara F Lastoria (02/09WG1)
- Supplementary - T2K: 18 talks at NuFACT!

Backup

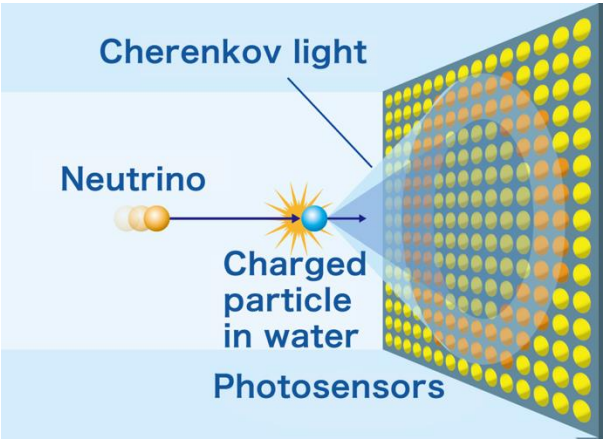
Water Cherenkov detection technique : neutrinos

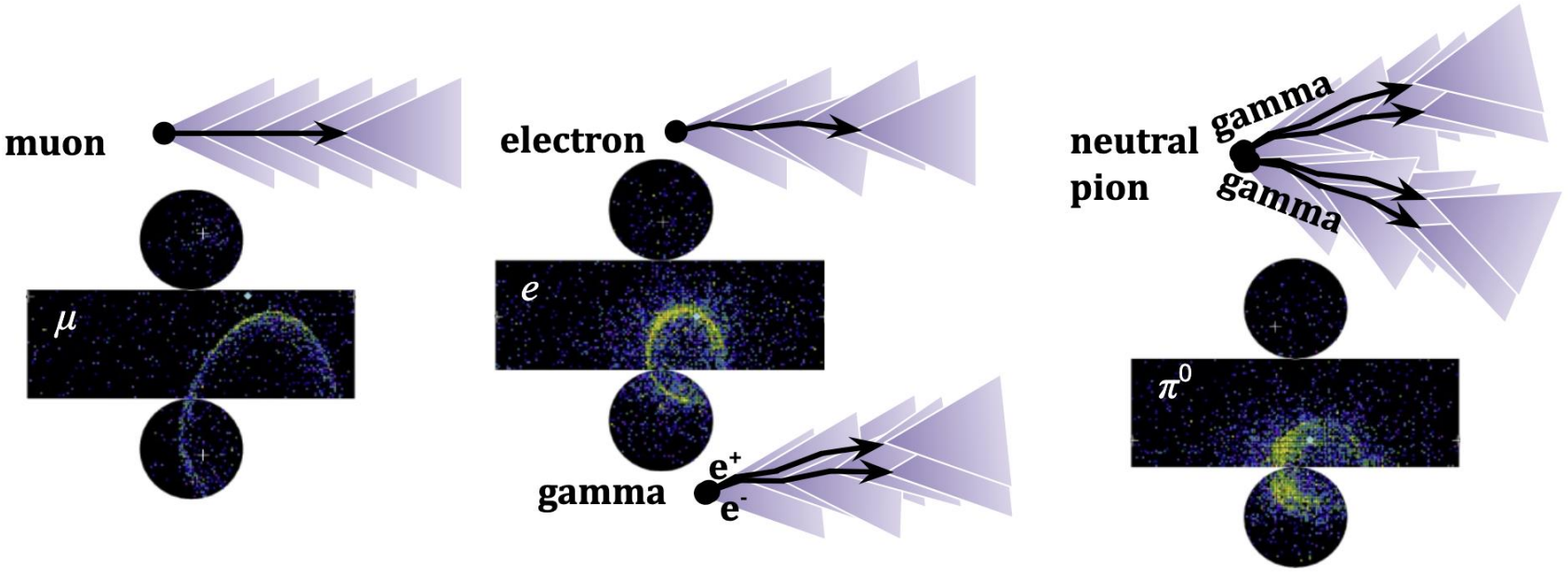
Particle detection

- In Water Cherenkov detectors, we do not measure neutrinos directly but by products from interactions in the water

Particle Classification: Particle type identification (PID)

- Particles produce different types of ring signals due to their interactions in water



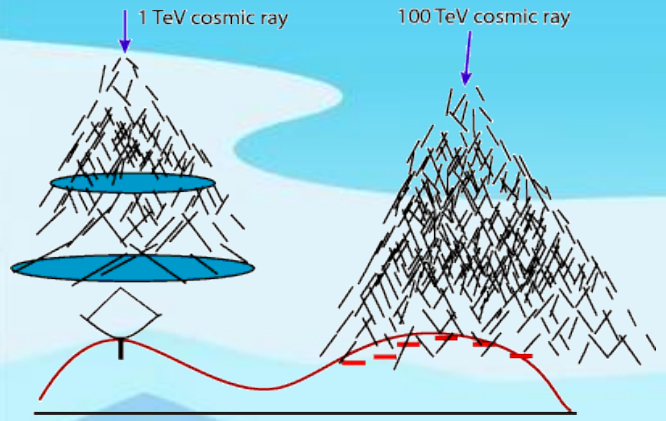


Particle information reconstruction

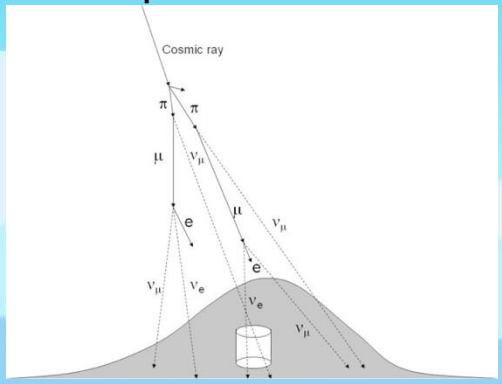
- Location and time of PMT hits allows for triangulating particle's position and direction
- Amount of charge collected by PMTs gives an estimate of particle's energy

High energy astrophysics

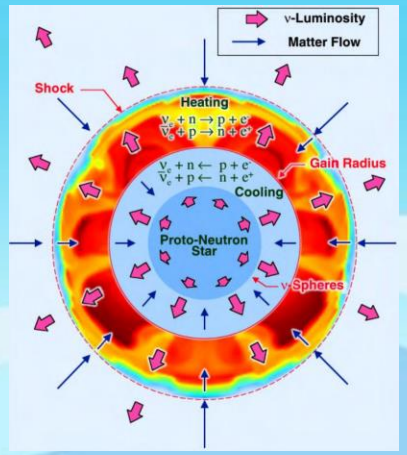
Cosmic rays



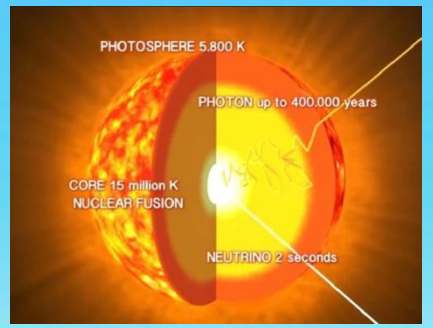
Atmospheric neutrinos

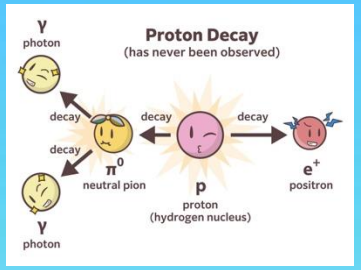


Supernova neutrinos

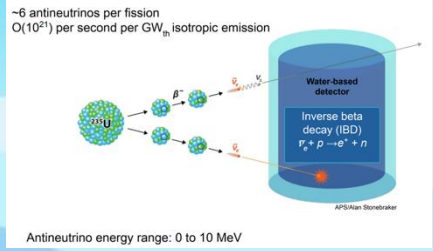


Solar neutrinos





Proton decay



Reactor neutrinos

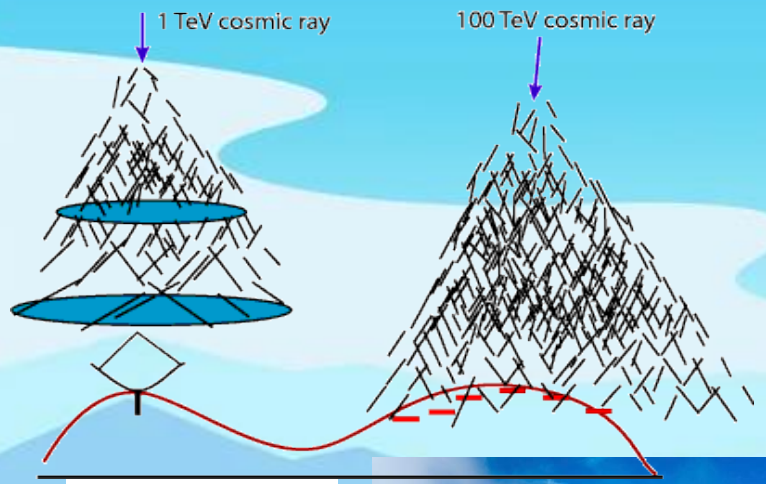
Neutrino oscillation

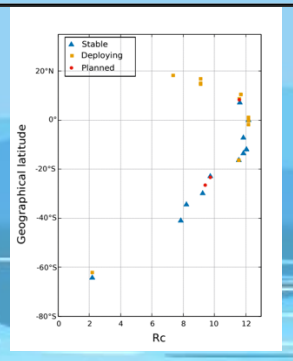
Wide range of target measurements from astrophysics to proton decay to CP violation

- **Cosmic rays**
- **Neutrinos**
- **Proton decay**

High energy astrophysics

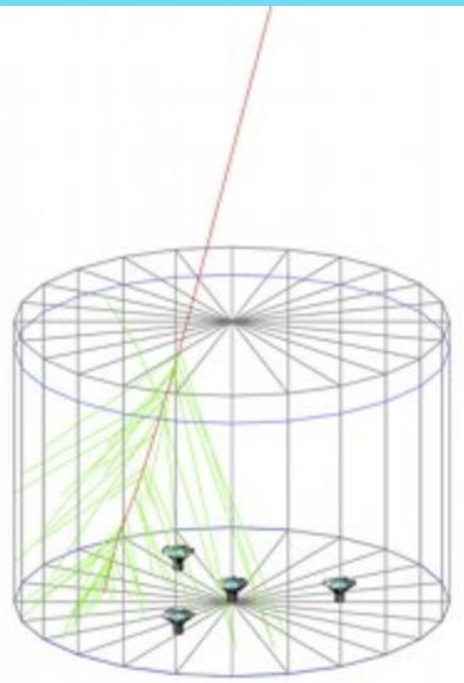
Cosmic rays





LAGO

HAWK



Simulation of a charged particle passing through a tank (red line) and emitting Cherenkov light (green lines). Also shown is the layout of the PMTs.

High altitude detectors
LAGO, HAWK, Pierre Auger observatory
Many small detectors over a large area

Great for high energy astrophysics, cosmic rays, Gamma Ray Bursts, space weather. GeV to TeV scale

Neutrino oscillation observation

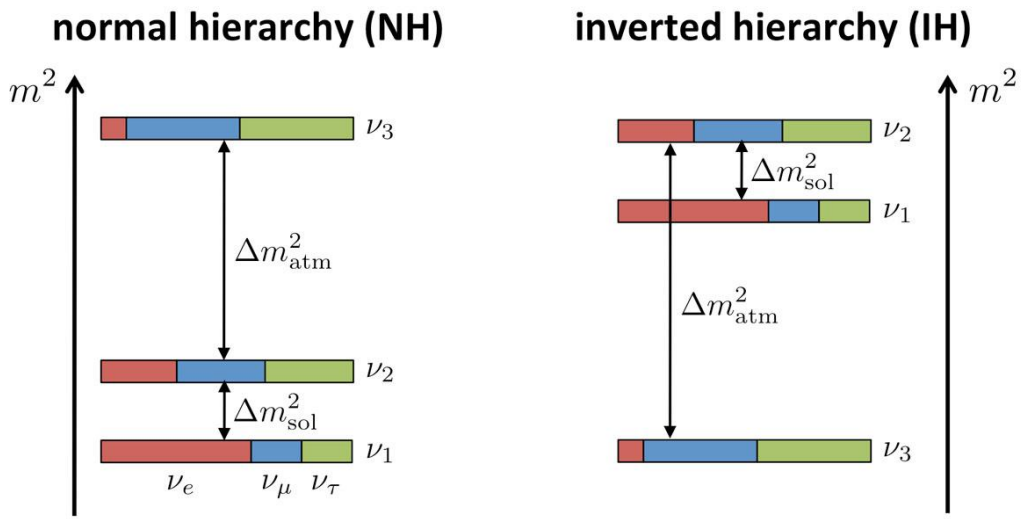
$$P_{\alpha\to\beta}(L) = \left| \sum_{i=1}^{3} U^*_{\alpha i} U_{\beta i} e^{-i\frac{Lm_i^2}{2E_\nu}} \right|^2$$

How can we measure neutrino oscillation?

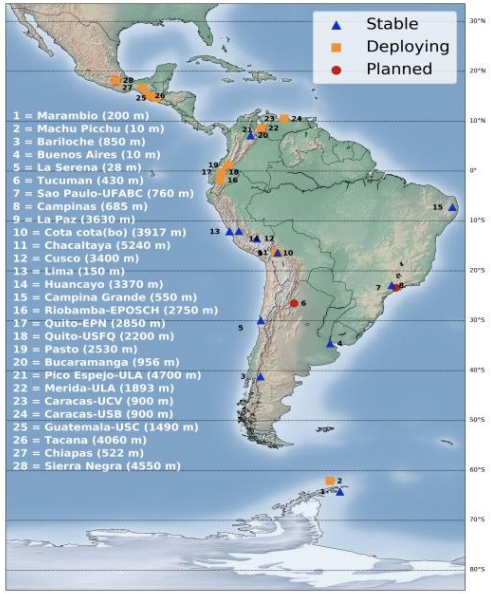
$$U_{\alpha i} = \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}^{(\text{Atmospheric - } \Delta m^2_{23}, \theta_{23})} \overbrace{\begin{pmatrix} c_{13} & 0 & \boxed{e^{-i\delta} s_{13}} \\ 0 & 1 & 0 \\ \boxed{-e^{-i\delta} s_{13}} & 0 & c_{13} \end{pmatrix}}^{(\text{Reactor/Accelerator - } \Delta m^2_{31}, \theta_{13})} \overbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{(\text{Solar - } \Delta m^2_{12}, \theta_{12})}$$

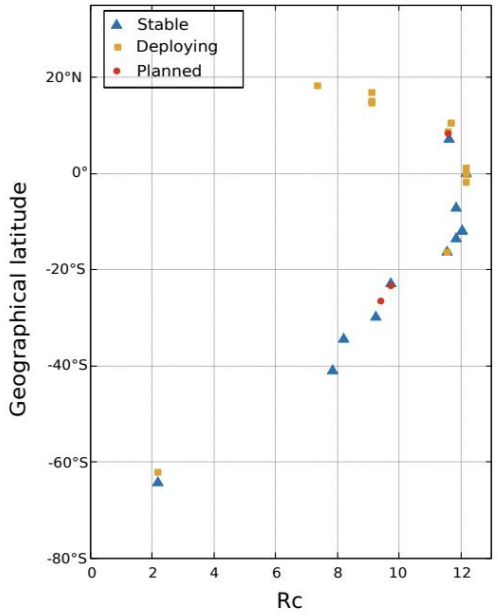
$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \cos\theta_{ij}$$
$$\Delta m^2_{ij} = m^2_i - m^2_j$$

- $\Delta m^2_{12} \approx 0.75 \times 10^{-4}$ eV^2 measured by solar and reactor neutrino experiments
- $|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \approx 0.17 \times 10^{-4}$ eV^2 measured by atmospheric neutrino experiments
- Sign of $|\Delta m^2_{31}|$ (**mass ordering**) is still **unknown**
- **CP violating phase** δ_{CP} introduces difference in neutrino vs antineutrino oscillation probability



LAGO(Latin American Giant Observatory)





The Latin American Giant Observatory (LAGO) is an **extended astroparticle observatory with the goal of studying Gamma Ray Bursts (among other extreme universe phenomena), space weather and atmospheric radiation at ground level.** It consists of a network of several Water Cherenkov Detectors (WCD) located at different sites and different latitudes along the American Continent (from Mexico up to the Antarctic region).

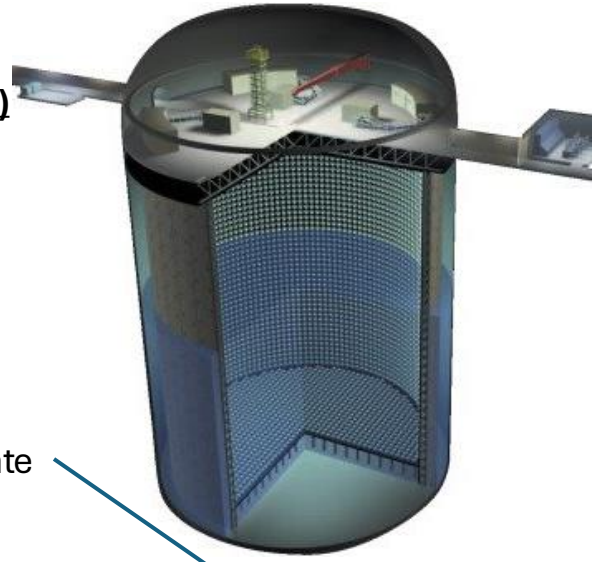
HAWC (High Altitude Water Cherenkov)

HAWC is a facility designed to **observe gamma rays and cosmic rays between 100 GeV and 100 TeV**. TeV gamma rays are the highest energy photons ever observed.

Array of water tanks with 3x 8” Hamamatsu PMTs facing upwards

Simulation of a charged particle passing through a tank (red line) and emitting Cherenkov light (green lines). Also shown is the layout of the PMTs.

Operating: Super-Kamiokande, SNO/SNO+

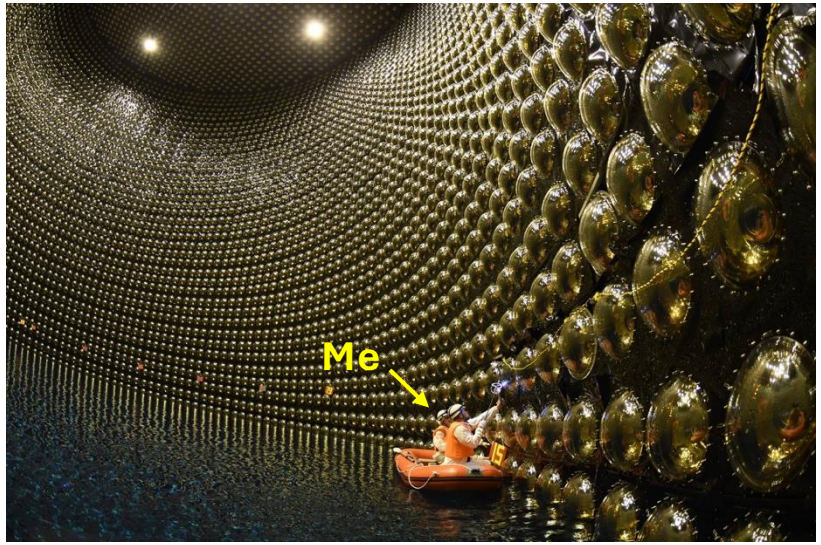


Super-Kamiokande (Japan)

- 22.5 kt fiducial mass
- Ultra pure water
- ~11000 PMTs
- Operating 1996 – 2018

- Super-Kamiokande-Gd
- Addition of gadolinium sulphate
- Operating 2018 -> now!

- Excellent performance
  - 99% μ/e separation
  - 2% momentum resolution
  - 1° direction resolution

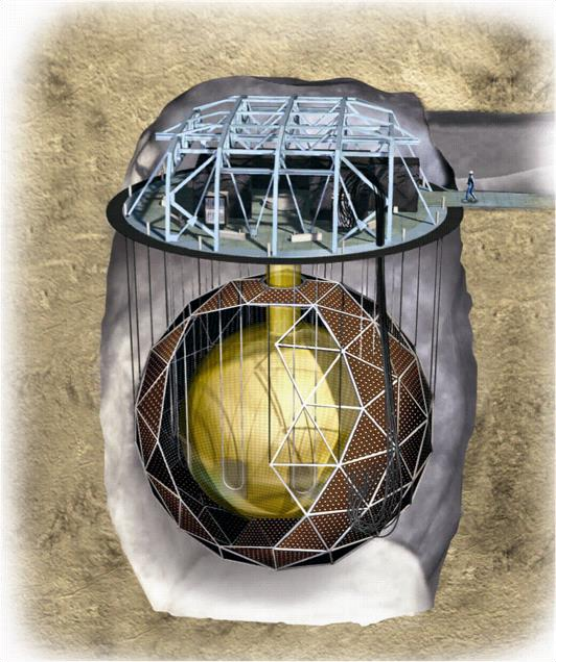


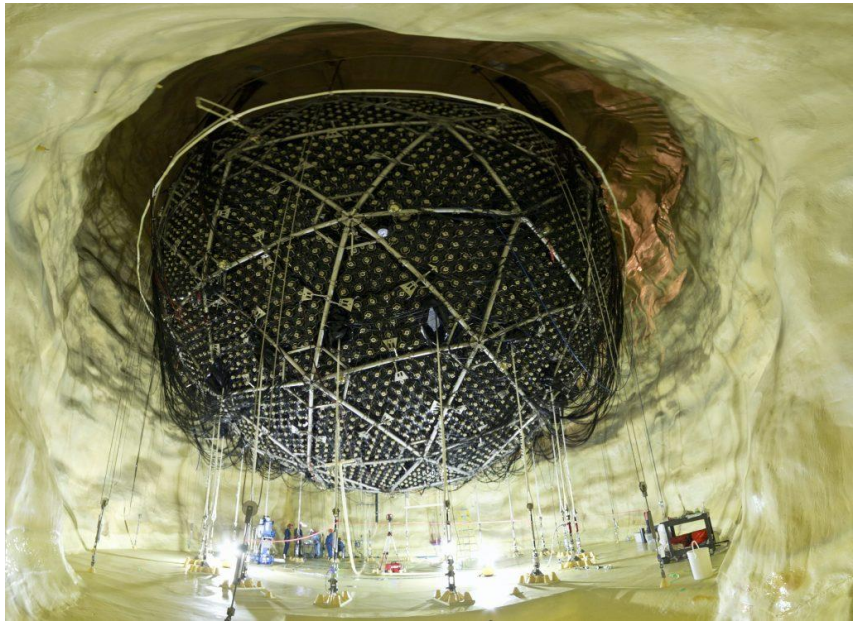
SNO/SNO+ (Canada)

- SNO – 1 kt heavy water + 7 kt water buffer
- Operation 1999 – 2006

- SNO+ - 0.7kton LS + 20kt ultra pure water
- 9000 PMTs
- Operation 2017 – 2026(planned)

- SNO+ future – Tellurium loading!





- Both detectors evolving over time with new technologies!

- Addition of Gd into SK improving neutron tagging (SK-Gd)

- Addition of ^{130}Te into SNO+ for ($0\upsilon\beta\beta$)

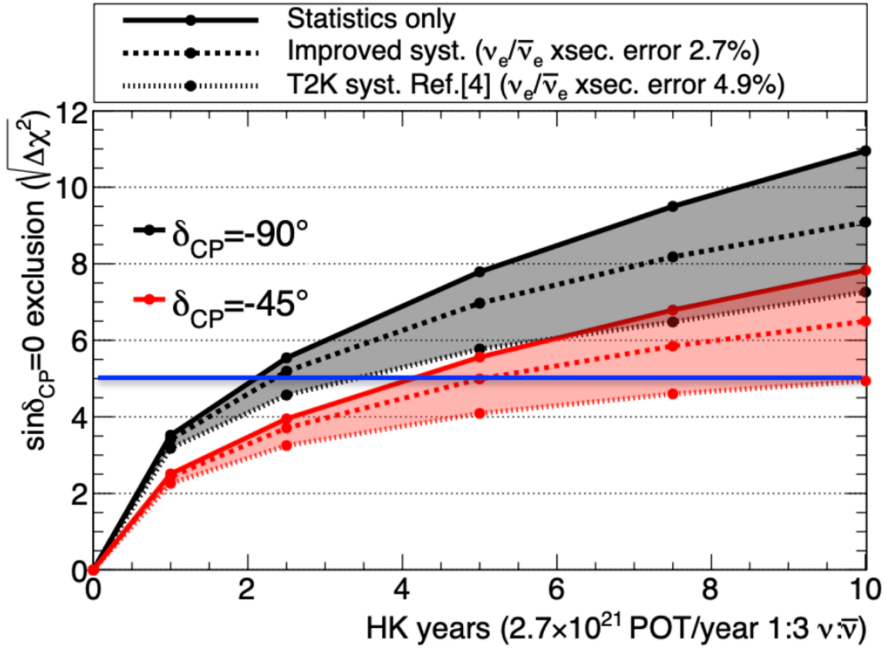
Measurement uncertainties: Hyper-K

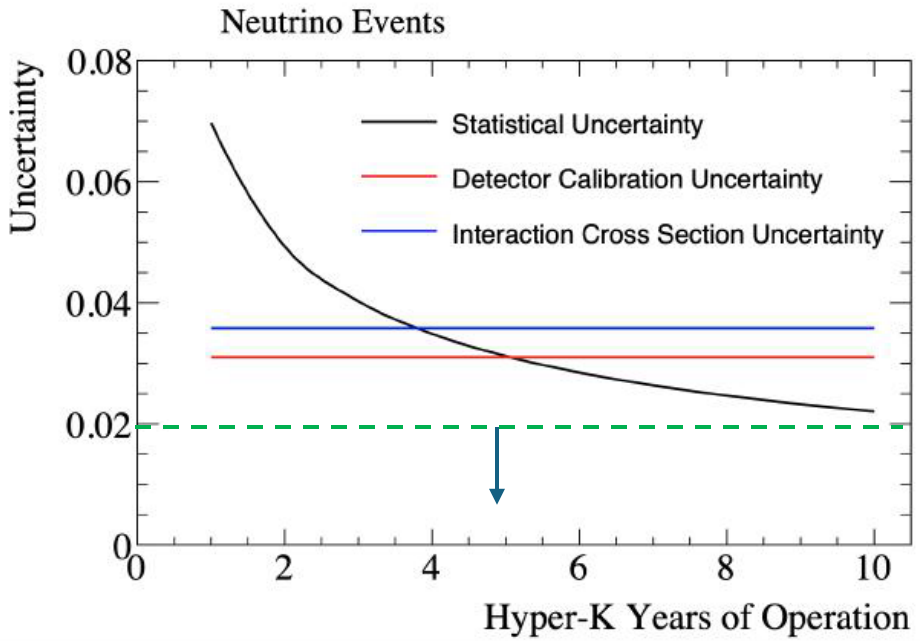
Detector model uncertainties

- Precision understanding required of
  - **Interactions** of particles propagating through water volume
  - **Cherenkov light production** of charged particles in water
  - **Propagation of light** through water volume (absorption, scattering)
  - **Photosensor response** to light including timing, charge and angular response
  - **Reconstruction of complex and challenging event topologies** in both signal and background channels

Interaction model uncertainties

- Critical to CP violation measurement
- ν_μ **&** $\bar{\nu}_\mu$ **production** to understand ν_μ beam flux, ν_e contamination and "wrong sign" background
- ν **interaction cross-sections on water** for CCQE signal, other CC signal channels and wide array of backgrounds





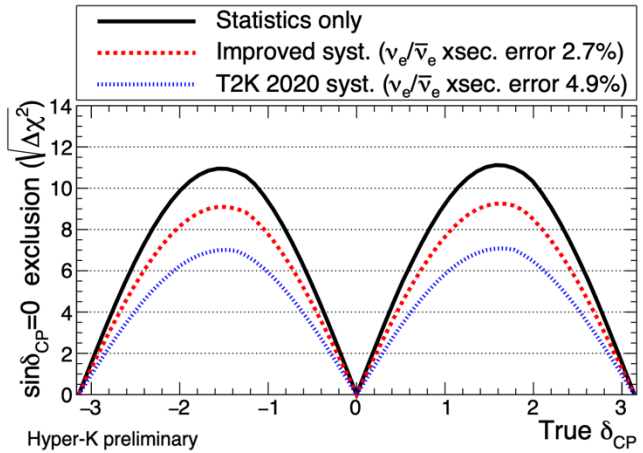
Oscillation measurements: Hyper-K

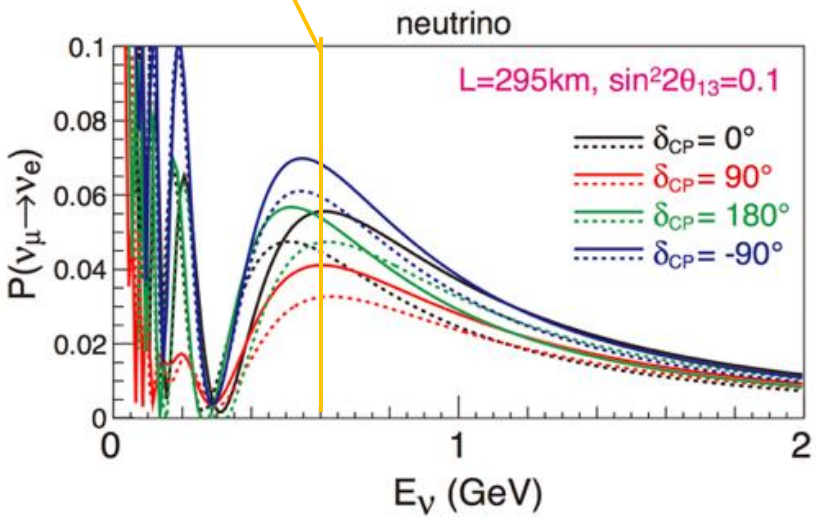
T2K/HyperKamiokande) case:

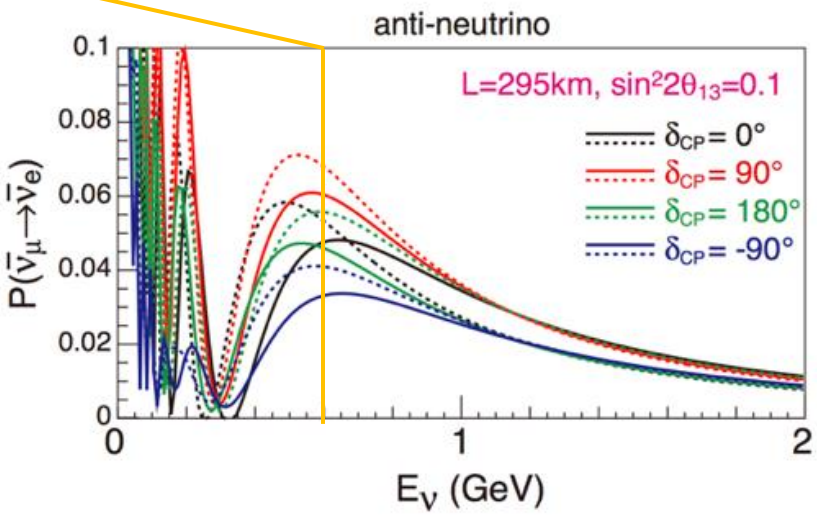
At the peak of E_ν=0.6GeV

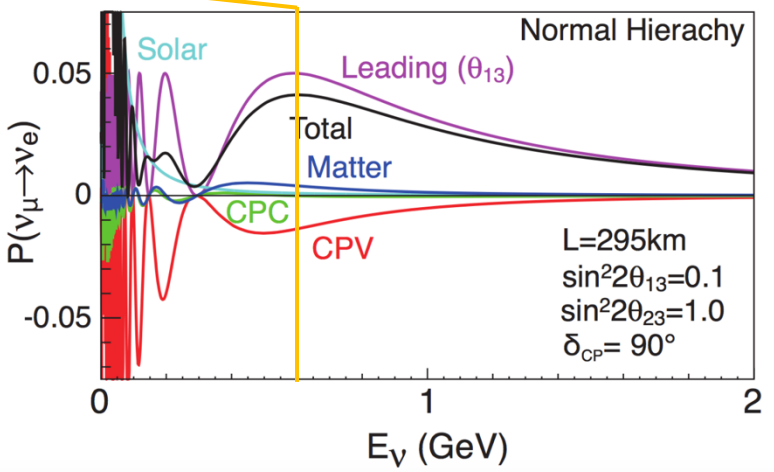
$$\frac{Prob(\nu_\mu \to \nu_e) - Prob(\bar{\nu}_\mu \to \bar{\nu}_e)}{Prob(\nu_\mu \to \nu_e) + Prob(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq -0.28 \sin \delta_{CP} + 0.07$$

matter effect



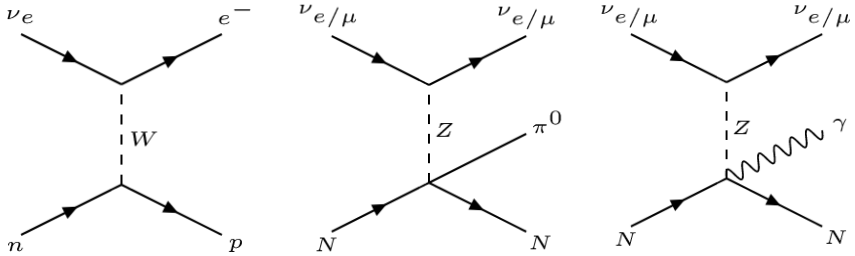






Significant effect of δ_{CP} in oscillations of $\nu_\mu \to \nu_e$ vs $\bar{\nu}_\mu \to \bar{\nu}_e$

- **Charged Current Quasielastic (CCQE)** is dominant signal ν_e interaction
- Significant background sources:
  - **Neutral current interactions** (ν_e or ν_μ) producing neutral pions or gammas mimicking ν_e electrons
  - **Misidentified muons** from ν_μ as electrons from ν_e

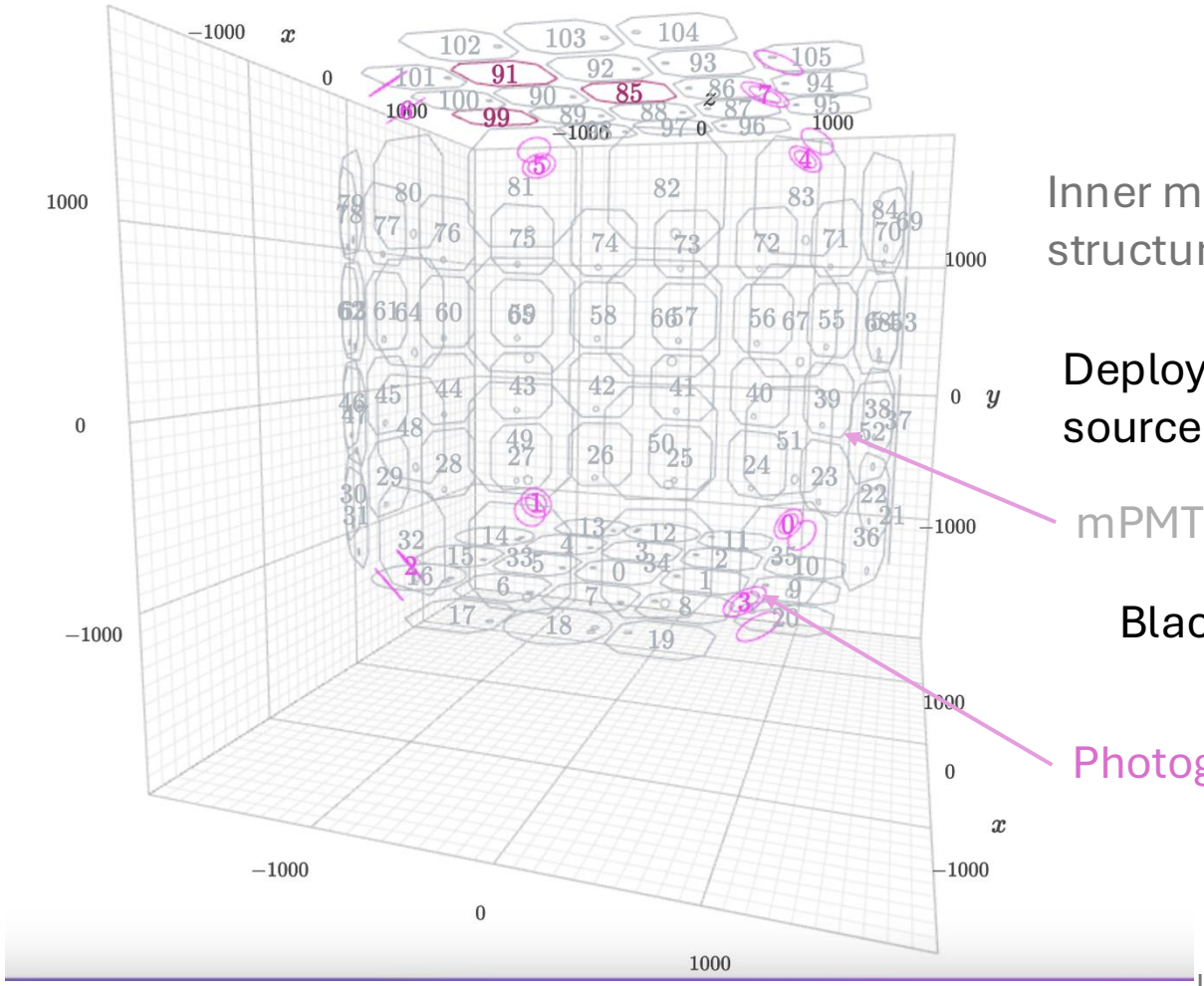


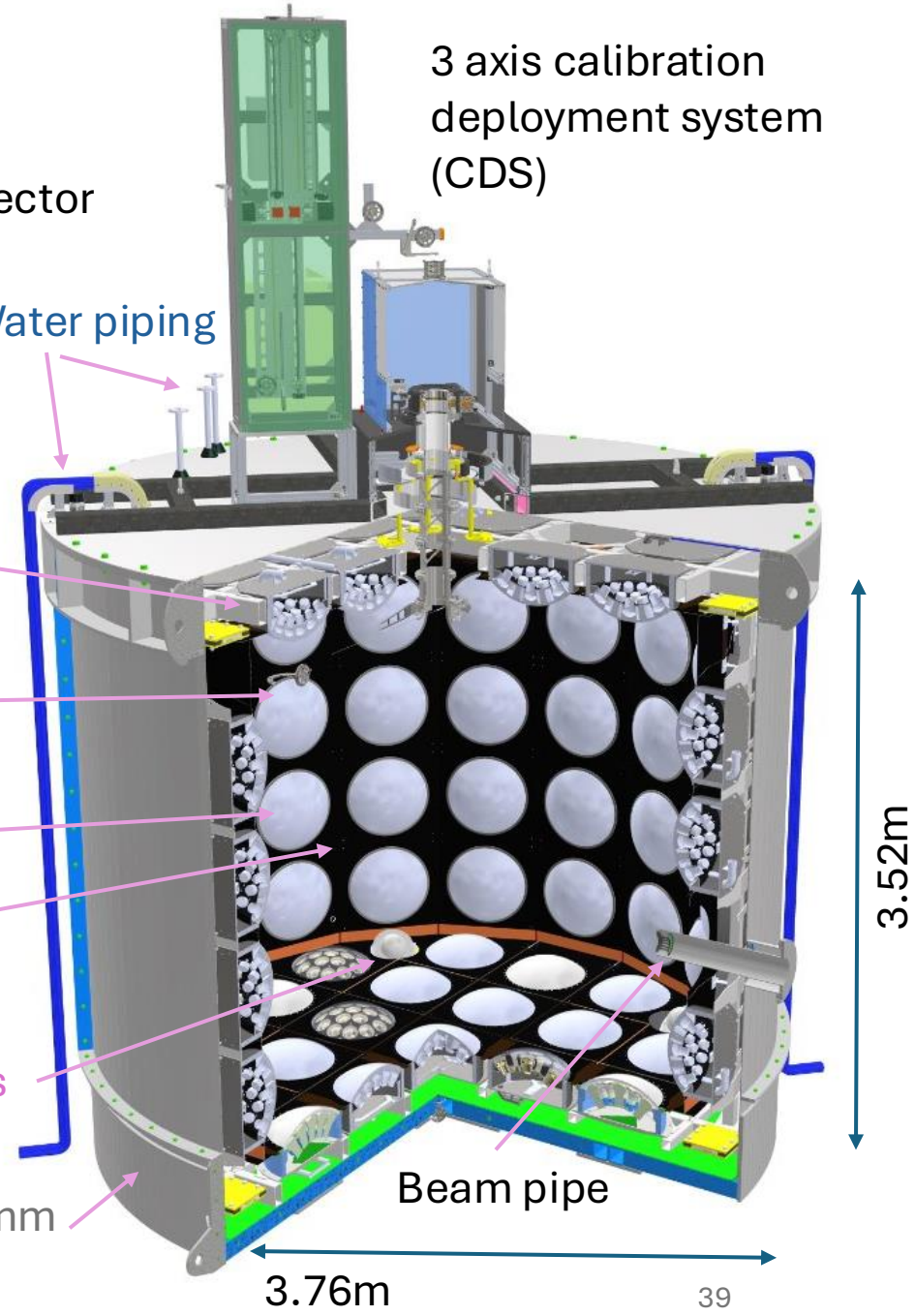
The WCTE detector

WCTE is instrumented with

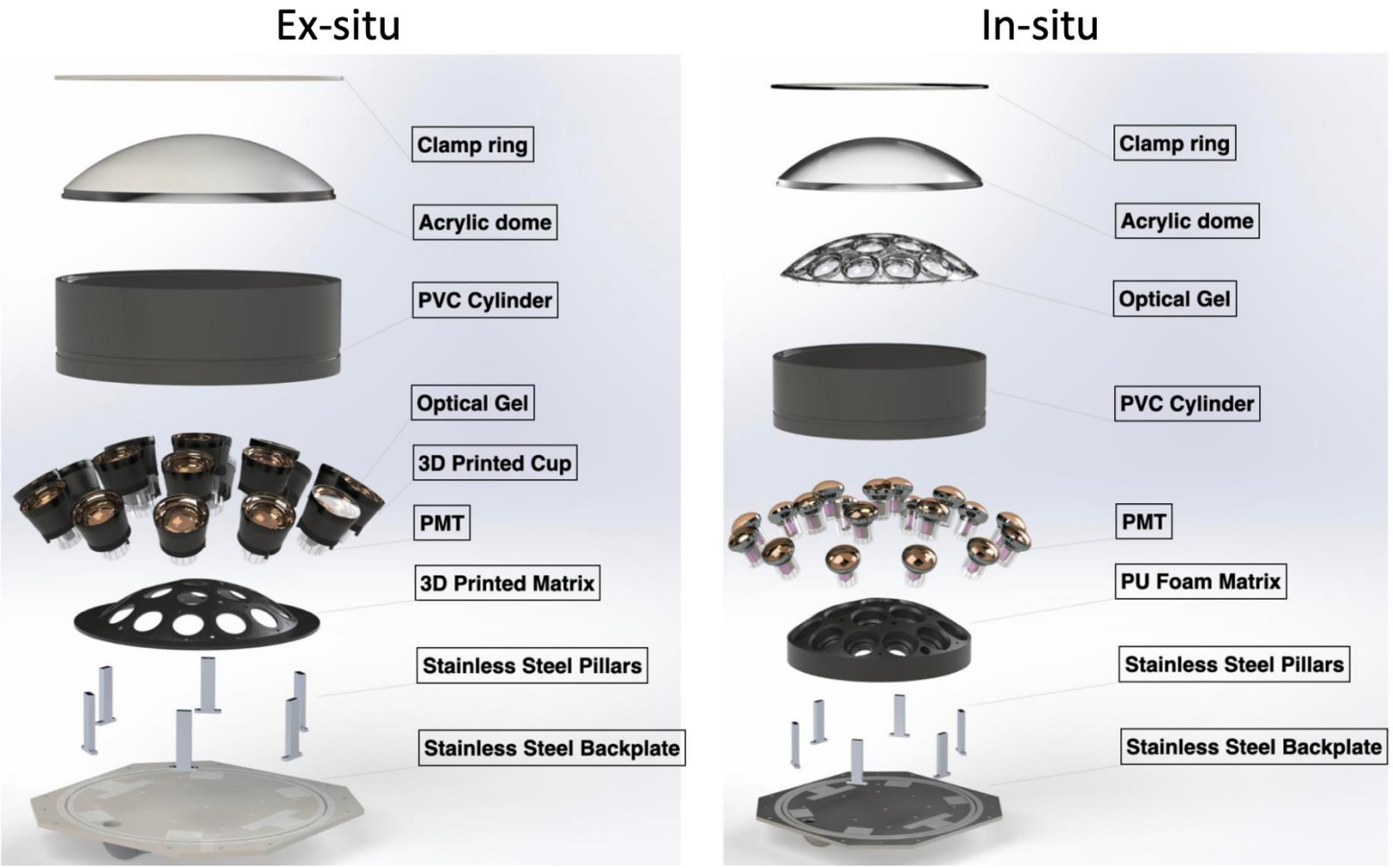
- 93 IWCD style mPMTs
- 4 Hyper-K style mPMTs
- 8 cameras use to image the detector

3D map of mounted detector components





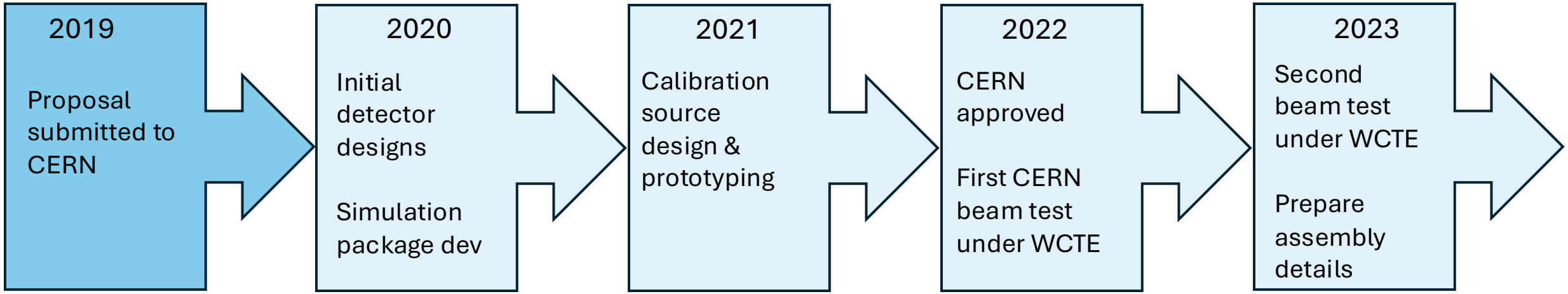
WCTE Detector Instrumentation: mPMTs



Two types of mPMT assembly tested – different gelling procedures

Much more information in Krzysztof's talk!

The WCTE timeline



The WCTE timeline

2019

Proposal submitted to CERN

2020

Initial detector designs

Simulation package dev

2021

Calibration source design & prototyping

2022

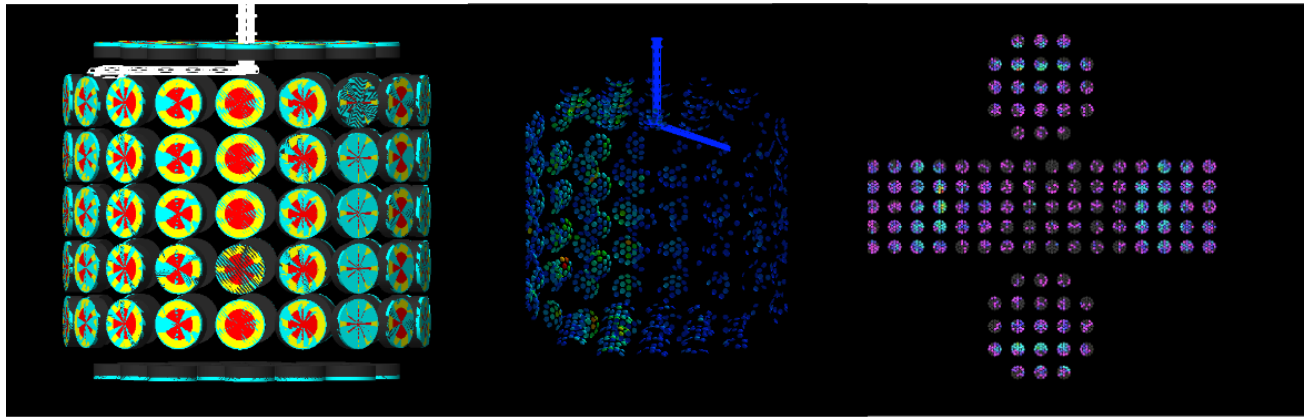
CERN approved

First CERN beam test under WCTE

2023

Second beam test under WCTE

Prepare assembly details



The WCTE timeline

2019

Proposal submitted to CERN

2020

Initial detector designs

Simulation package dev

2021

Calibration source design & prototyping

2022

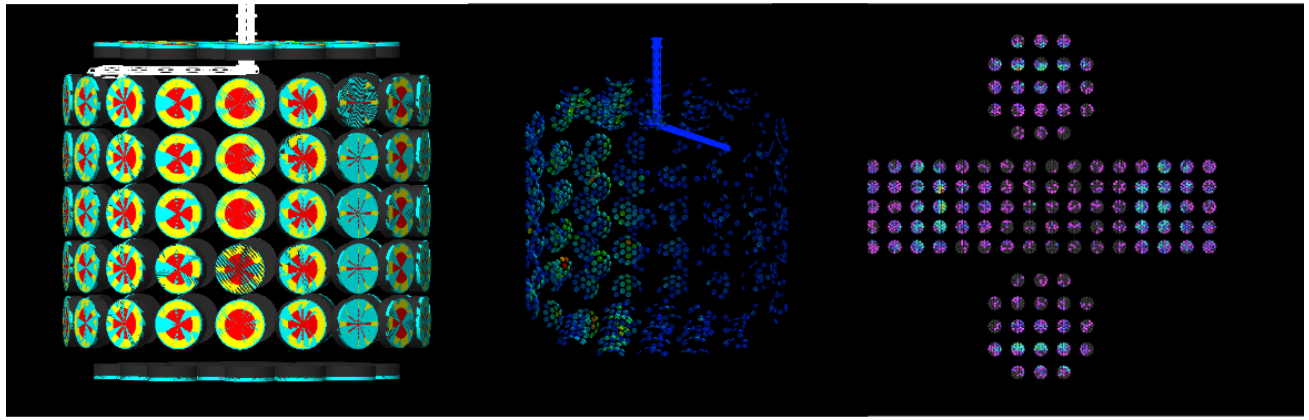
CERN approved

First CERN beam test under WCTE

2023

Second beam test under WCTE

Prepare assembly details



The WCTE timeline

2024

Began mPMT production

Prototype calibration system at CERN

Assembly starts at CERN

First beam data with water Cherenkov

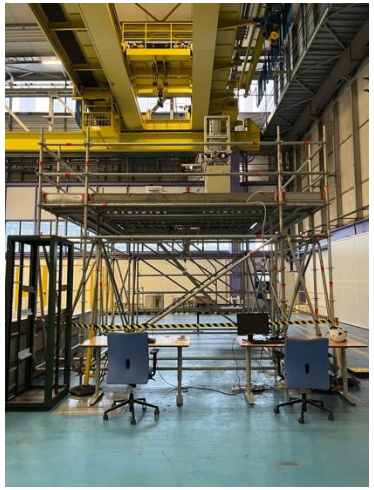
2025

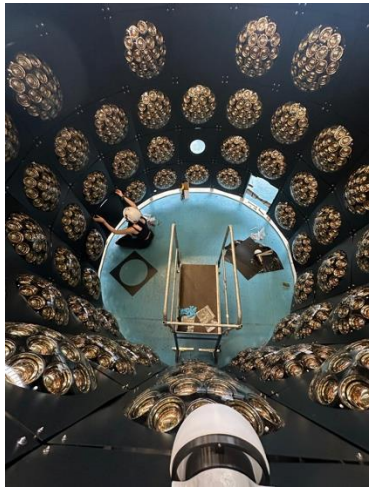
Second beam run

Detector upgrades

Gadolinium doping

Decommission





The WCTE timeline

2024

Began mPMT production

Prototype calibration system at CERN

Assembly starts at CERN

First beam data with water Cherenkov

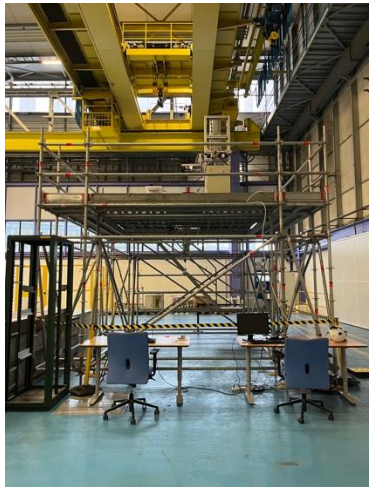
2025

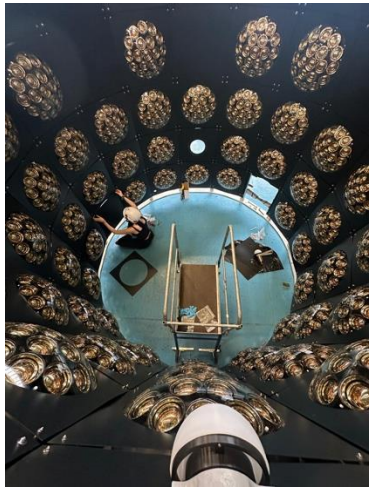
Second beam run

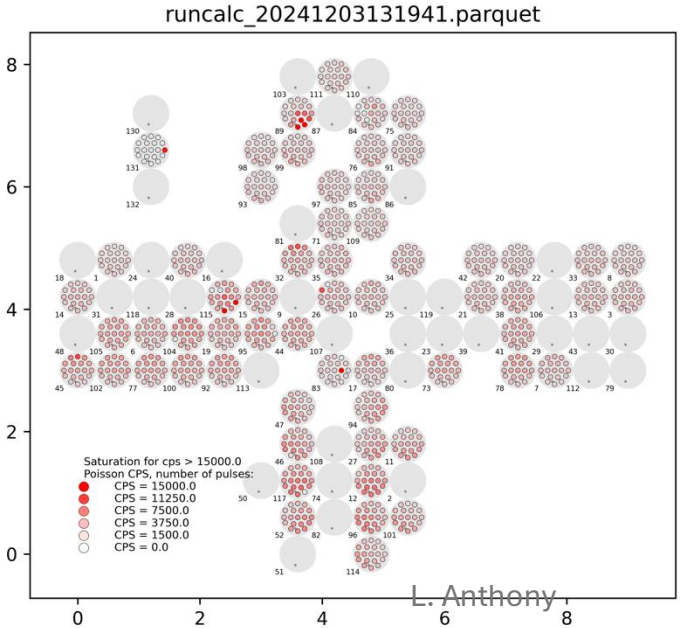
Detector upgrades

Gadolinium doping

Decommission

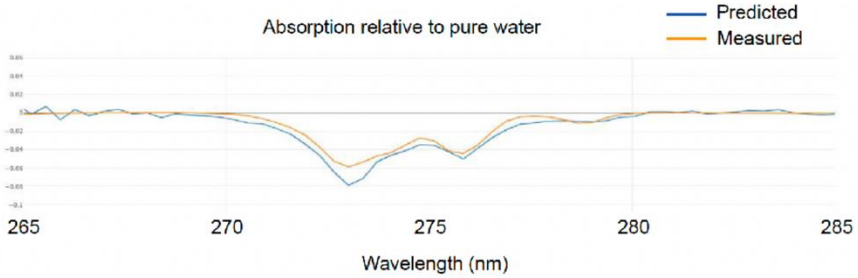






L. Anthony

The WCTE timeline



2024

Began mPMT production

Prototype calibration system at CERN

Assembly starts at CERN

First beam data with water Cherenkov

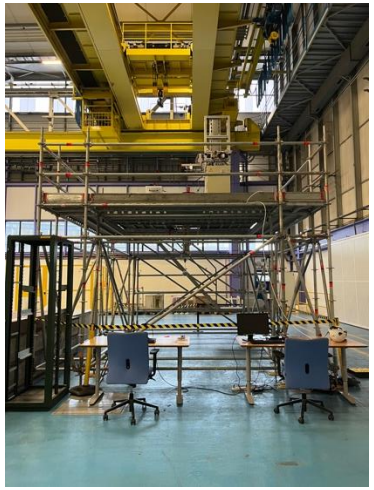
2025

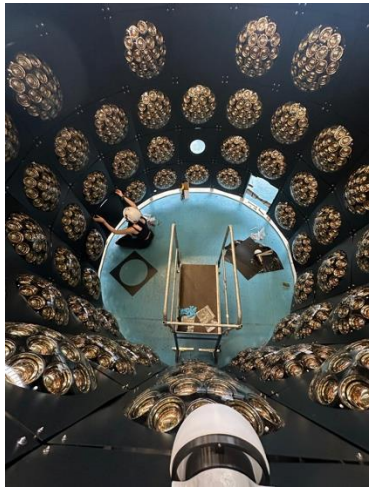
Second beam run

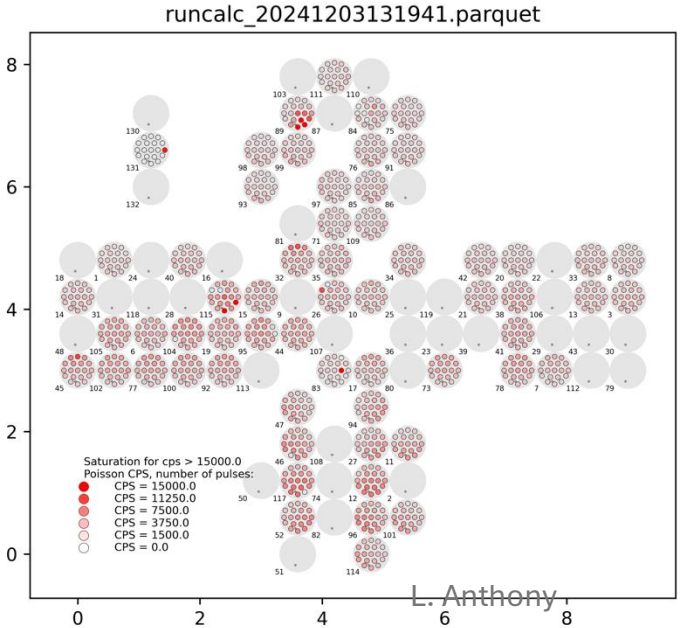
Detector upgrades

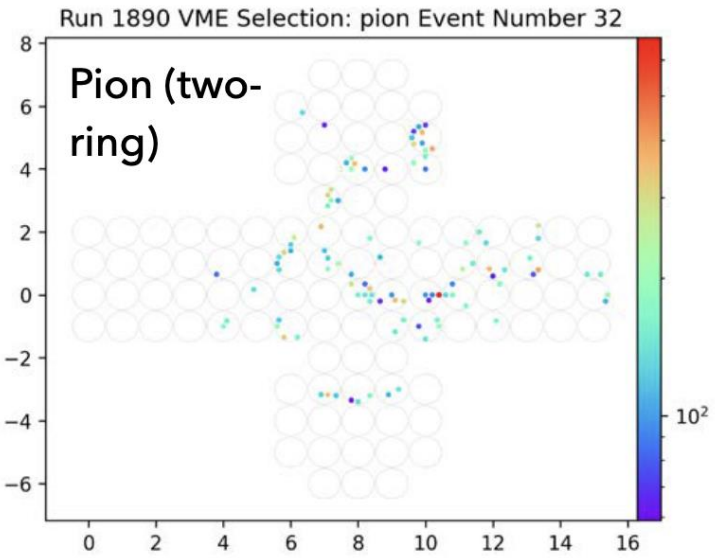
Gadolinium doping

Decommission



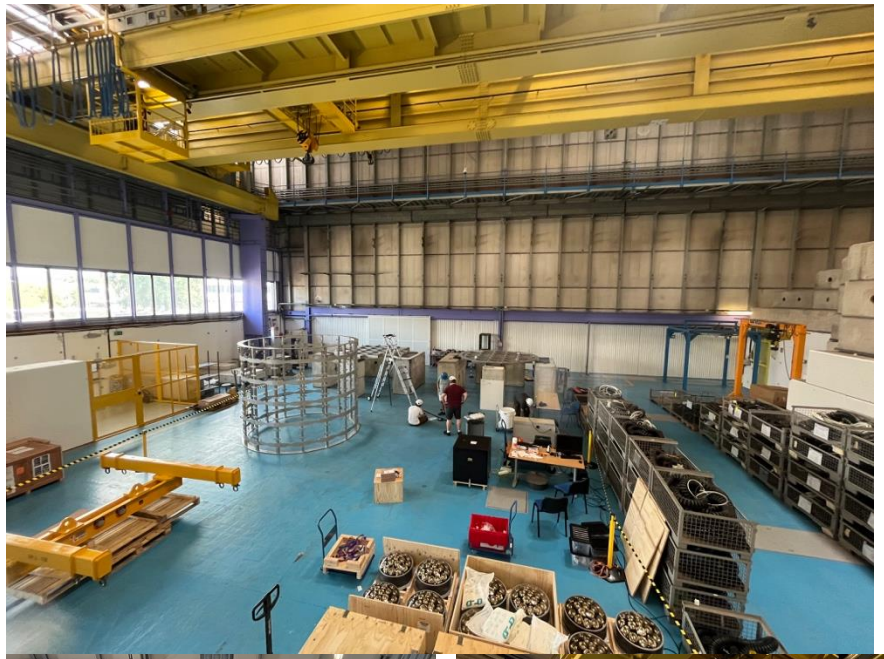


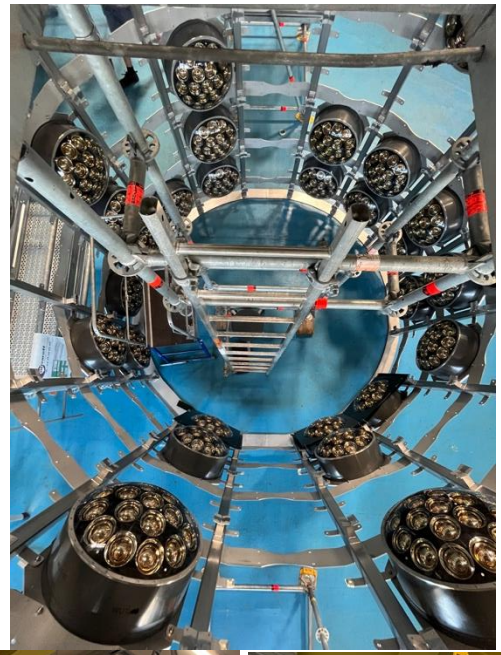


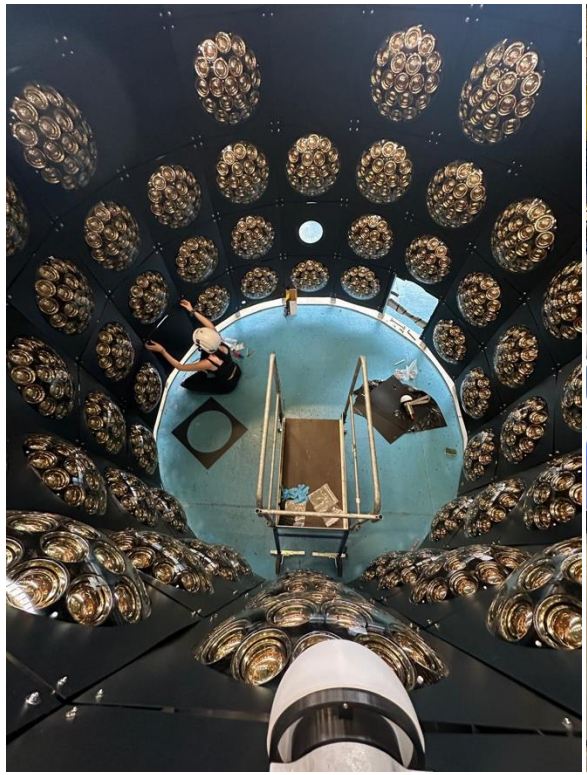


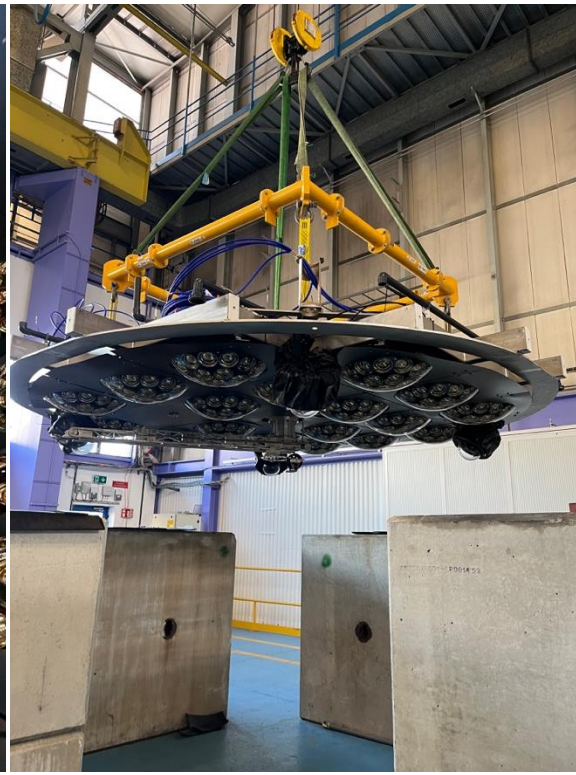
L. Anthony

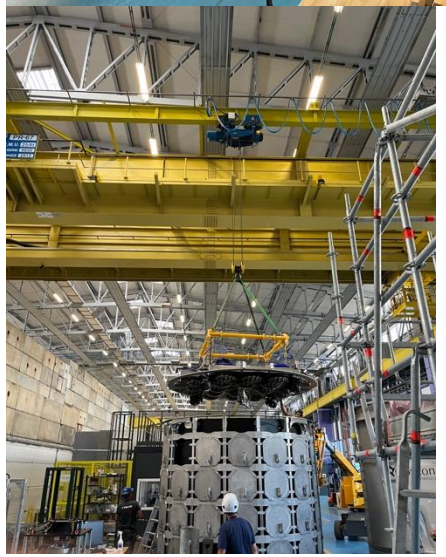
WCTE assembly & commissioning





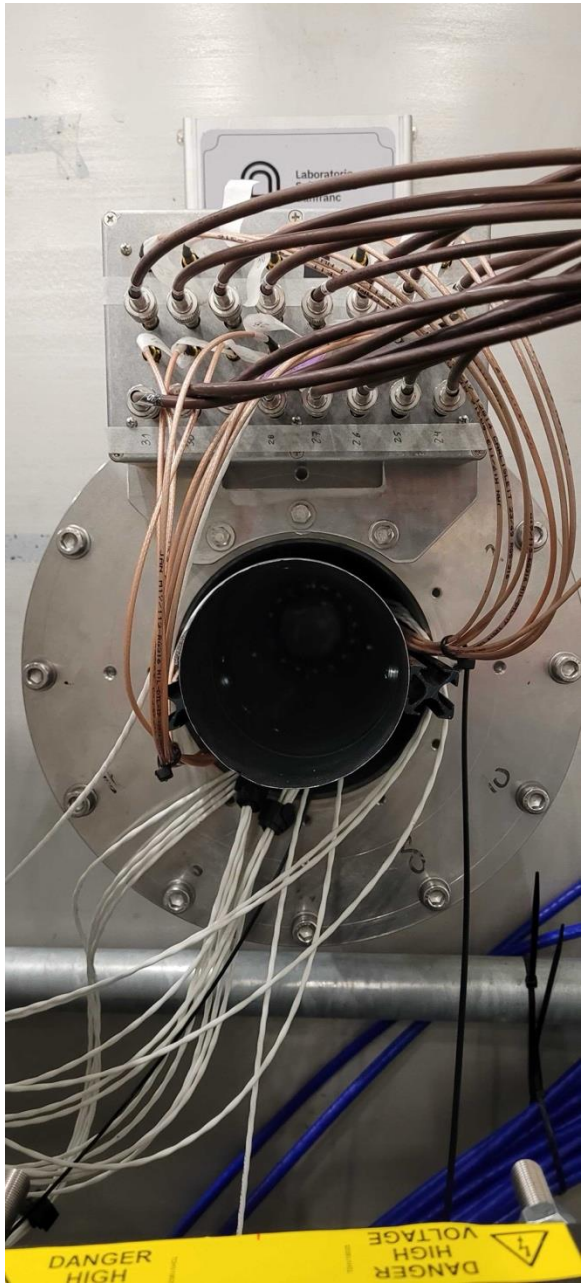






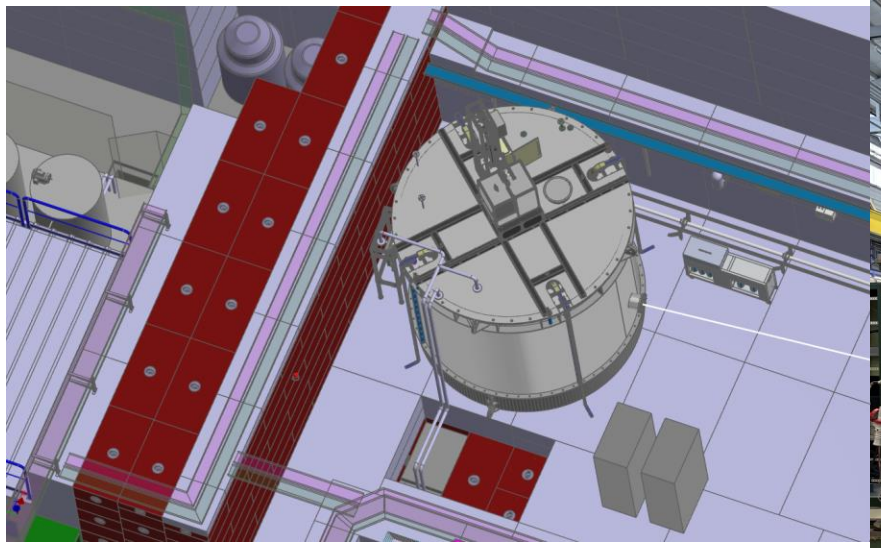
Beam window

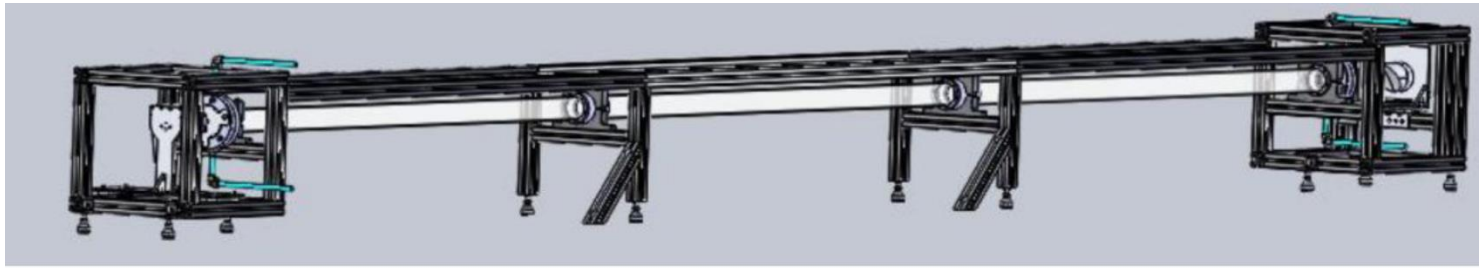
- Beam pipe extends into detector to reduce path length of beam in water
- 150mm beyond mPMT cylinder level (effectively from black sheet)
- 1.2mm thick stainless steel window
- TOF detector installed inside beam pipe

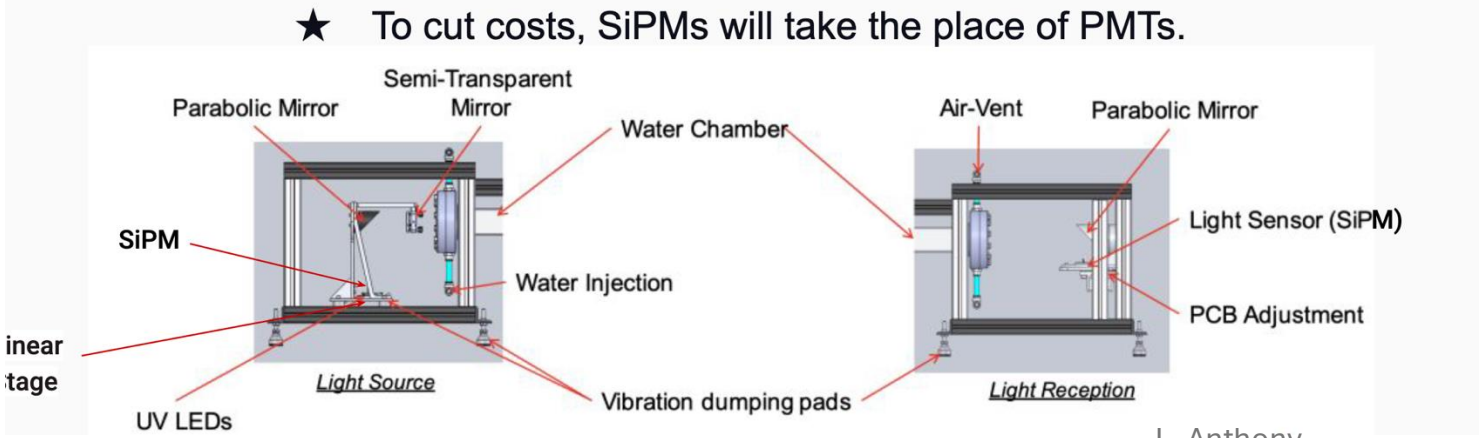


Water monitoring system

- Important for water transparency and long Cherenkov light attenuation length
- For WCTE – horizontal water pipe and measure water quality relative to filtered water by filtering system
- 8 m length pipe with UV-sensitive PMTs and 245 – 470nm LEDs with < 1ns pulse width
- Water filtration system to selectively filter out contaminants





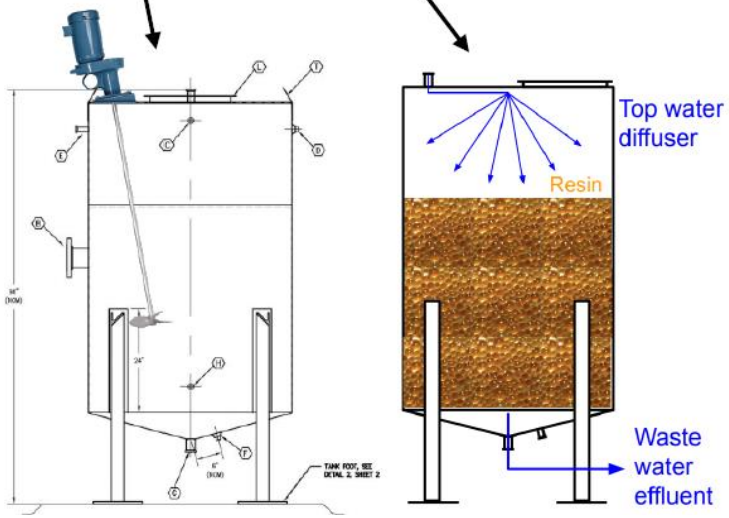


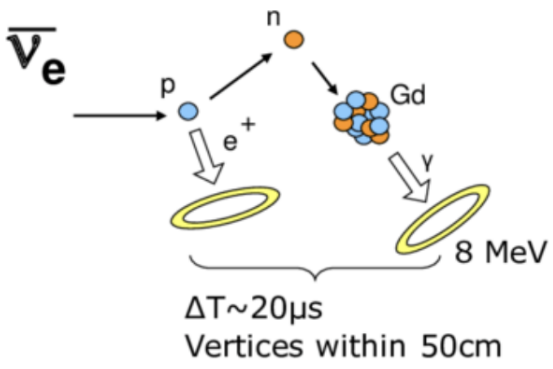
- The WMS is also being developed with drinking water quality in mind
- Gadolinium absorbance detector also installed (GAD)
- **Demonstrated a 1% measurement precision in detecting a change in the water quality, which translates to PPB level of detection sensitivity to Gd.**

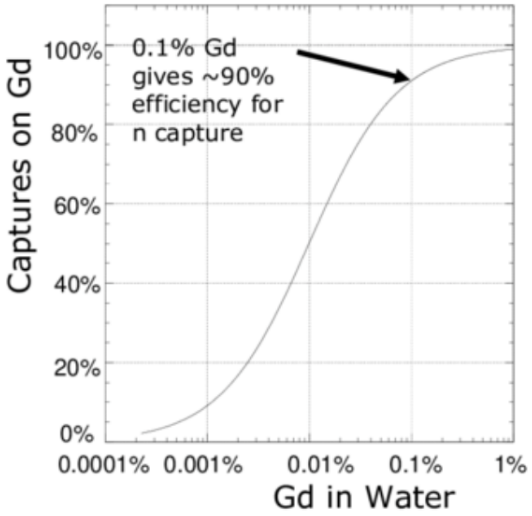
L. Anthony

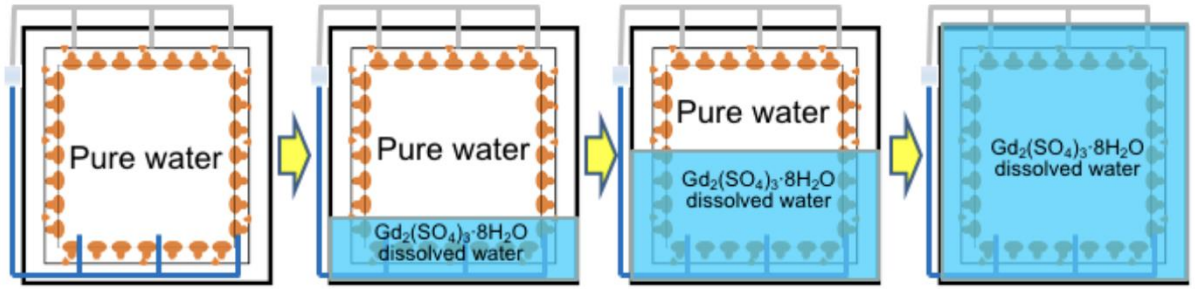
Gadolinium loading WC detectors

- Super-K is currently operating with 0.1% Gd concentration
- Gd has **large neutron capture cross section** and produces delayed energetic gammas of a total ~8 MeV
- Without Gd, capture on Hydrogen produces 2.2 MeV γ
- Neutron tagging can be beneficial for supernova and low energy events
- Loading of with **~0.1% Gd** in detector gives **90% neutron capture efficiency**
- WCTE water system can accommodate Gd loading: we loaded to 0.03%



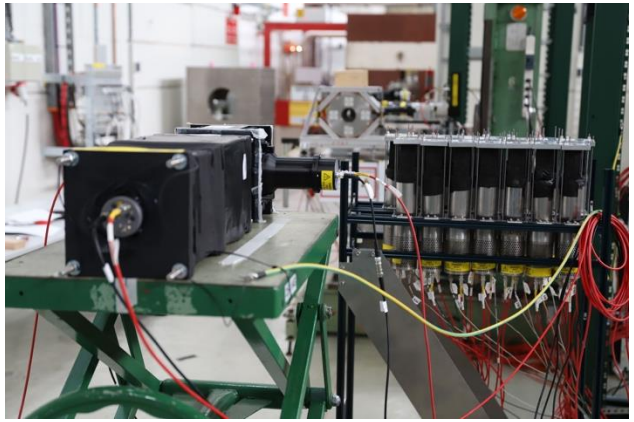




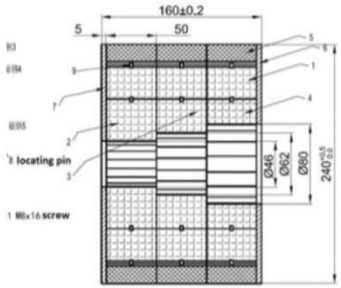


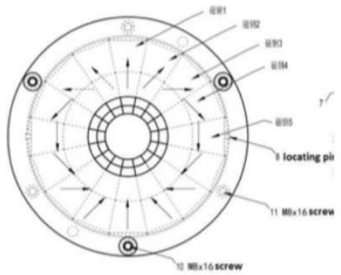
Tagged photon configuration 2024

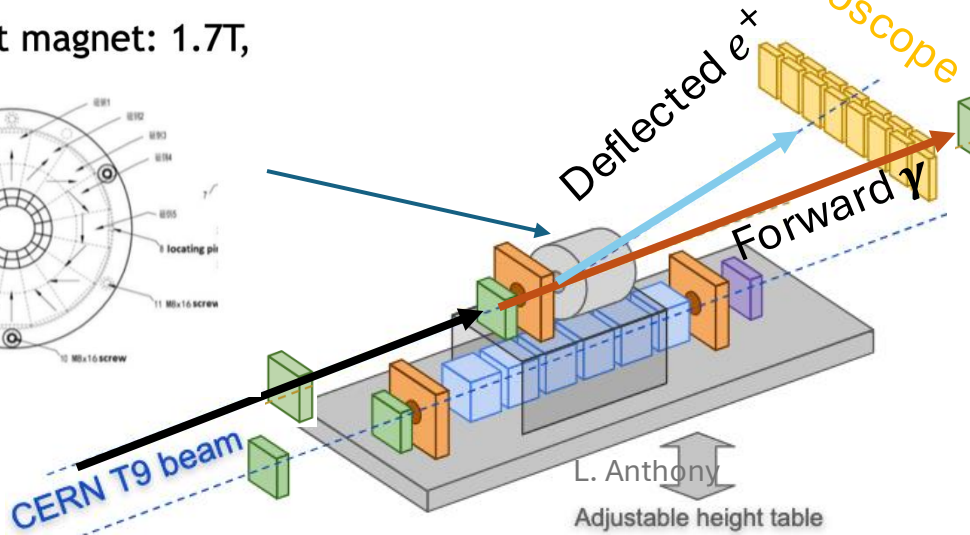
- e^+ produces γ by bremsstrahlung
- **Permanent magnet deflects $e^\pm$**
- **Hodoscope** measures deflection angle to infer γ energy from beam momentum

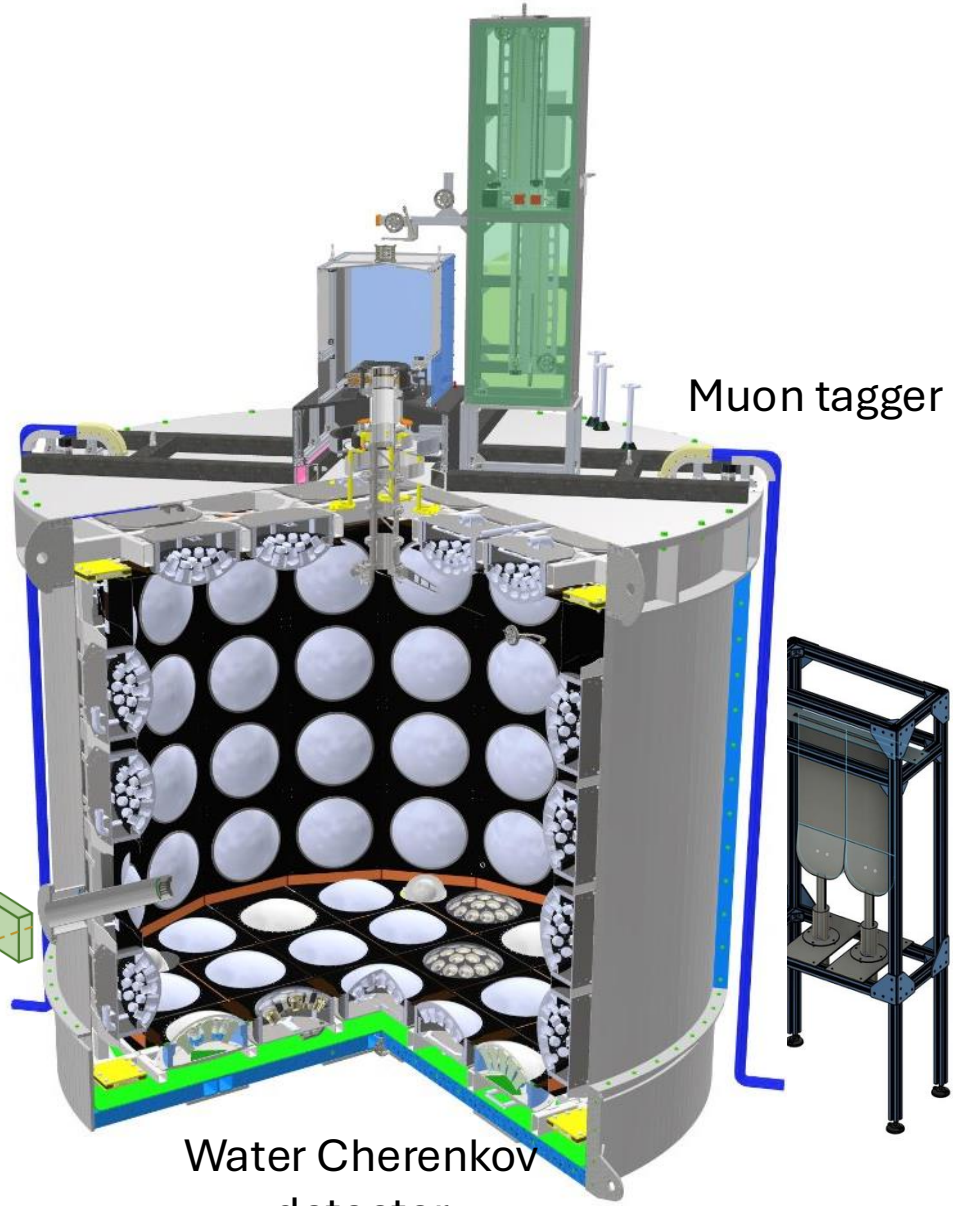


Haalbach array permanent magnet: 1.7T,







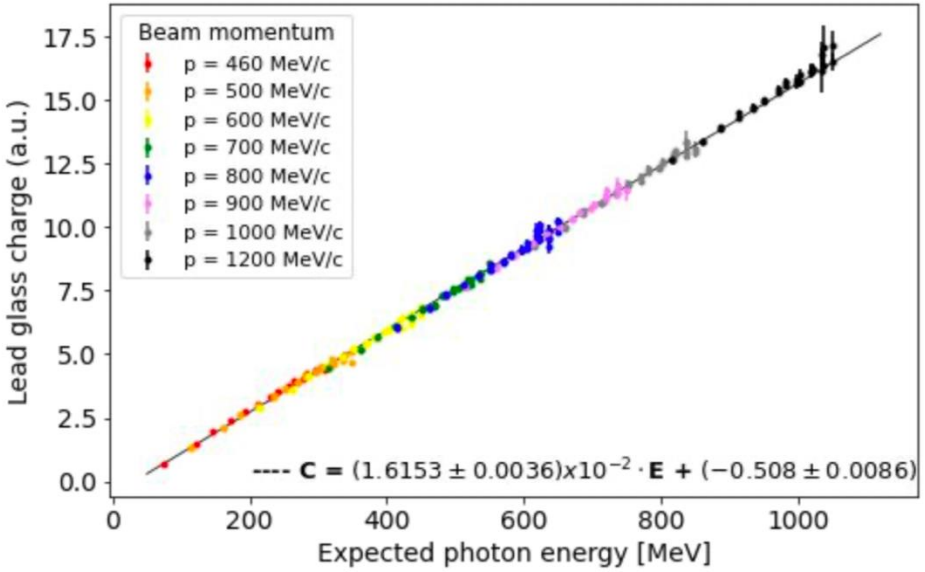


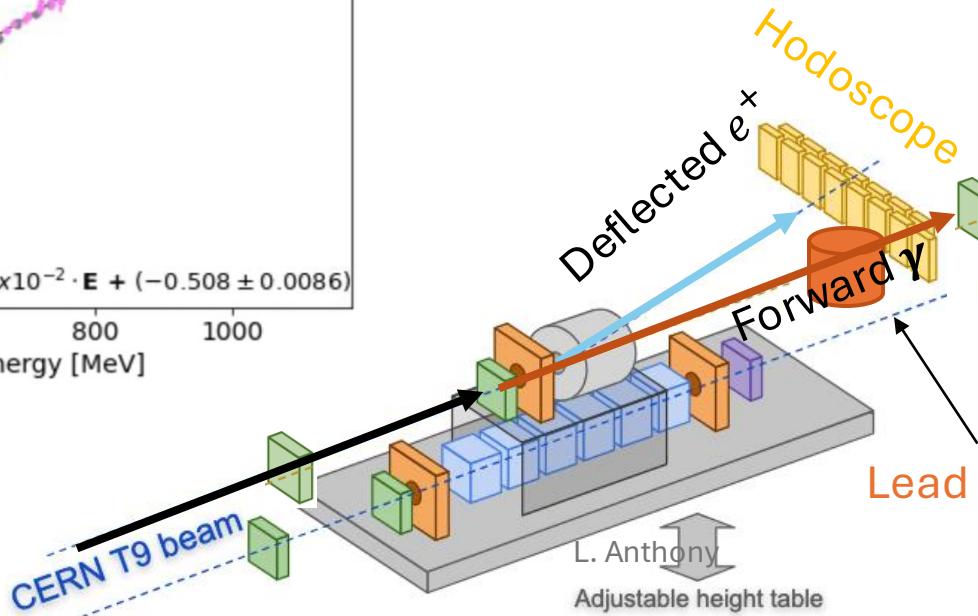
L. Anthony

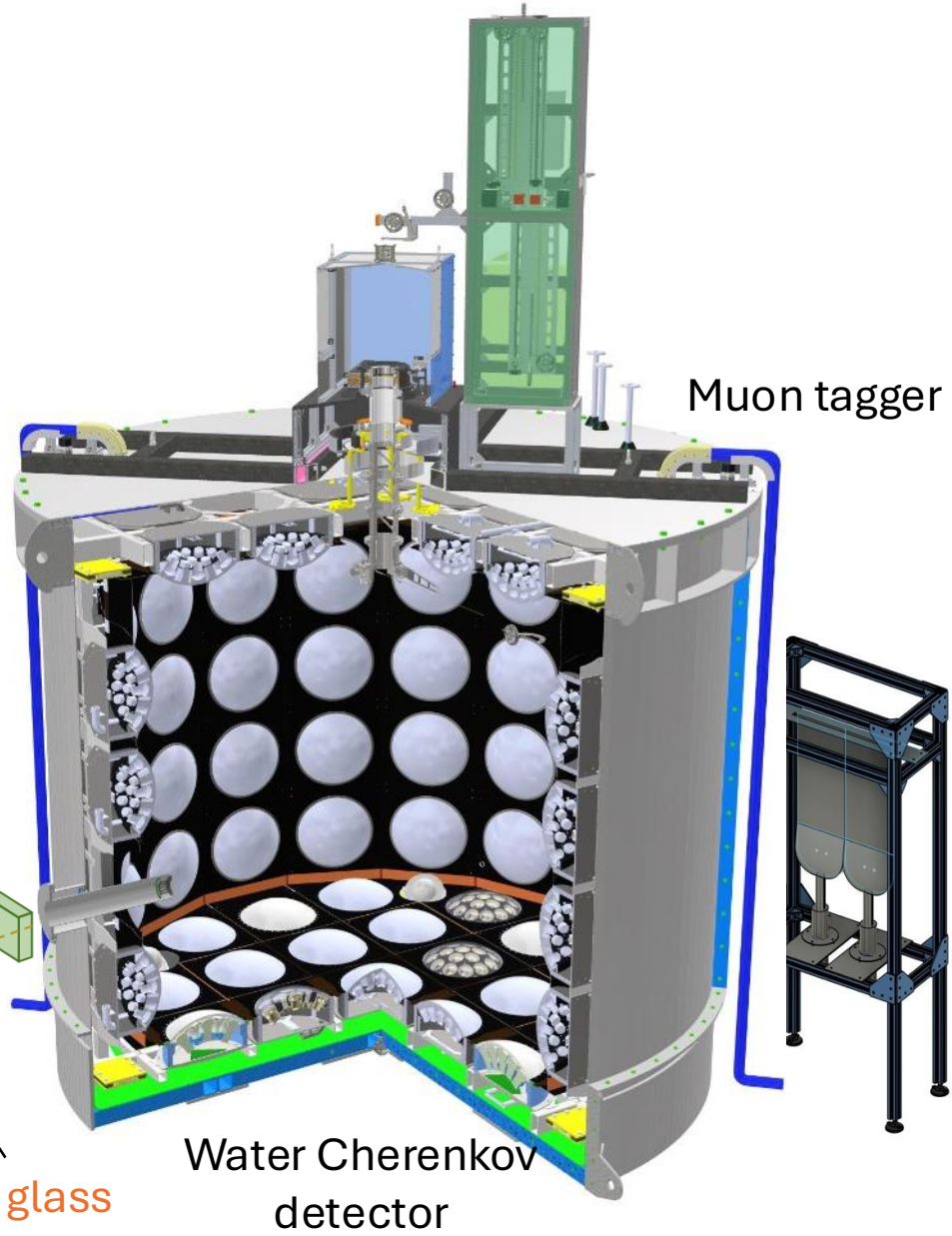
Tagged photon configuration 2024

- e^+ produces γ by bremsstrahlung
- **Permanent magnet deflects $e^{\pm}$**
- **Hodoscope** measures deflection angle to infer γ energy from beam momentum

- **Validated γ energy measurement** using **lead glass calorimeter**



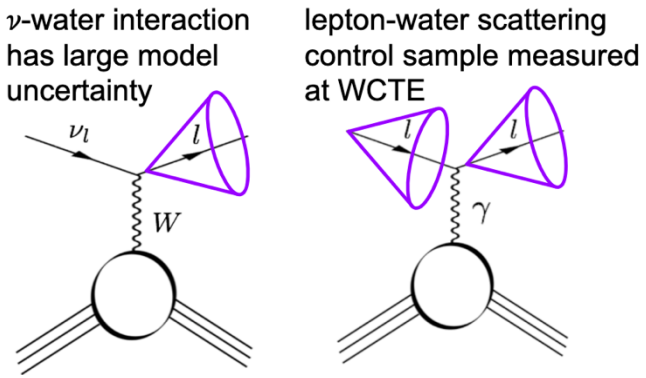


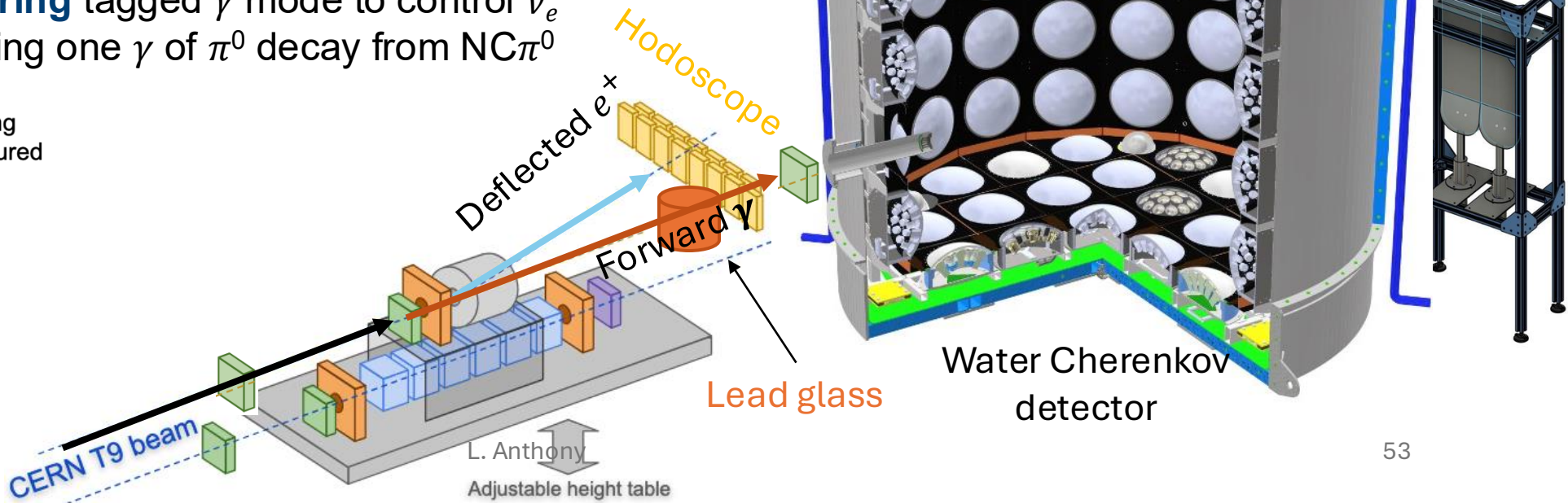


L. Anthony

Tagged photon configuration: Interactions on water

- Controlling ν **cross-section uncertainties** essential for future ν measurements
  - $\boldsymbol{\nu}$ interaction cross-sections contribute **significant uncertainty to neutrino measurements**
- **Pure control samples of WCTE** feed improvement and validation of interaction models
  - **WCTE can measure lepton scattering in water** by searching for two-ring events
  - **Photonuclear scattering** tagged γ mode to control ν_e background when losing one γ of π^0 decay from NCπ^0





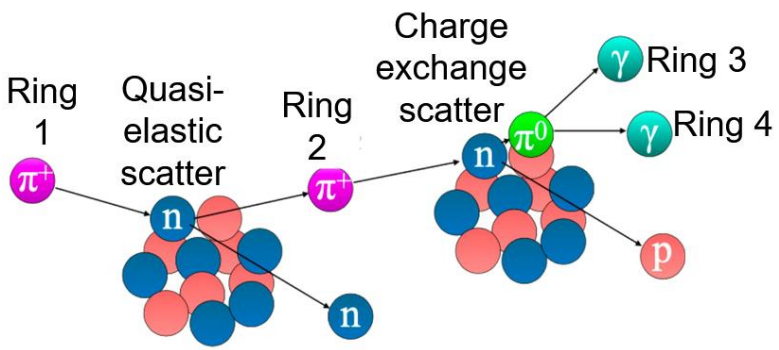
L. Anthony

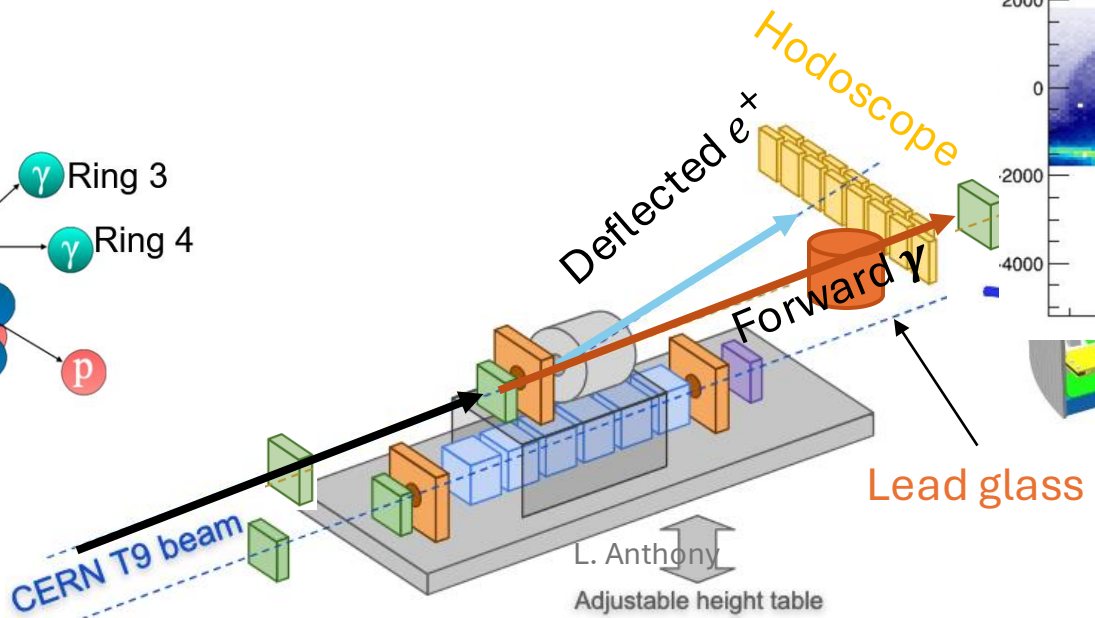
Tagged photon configuration: Pion production

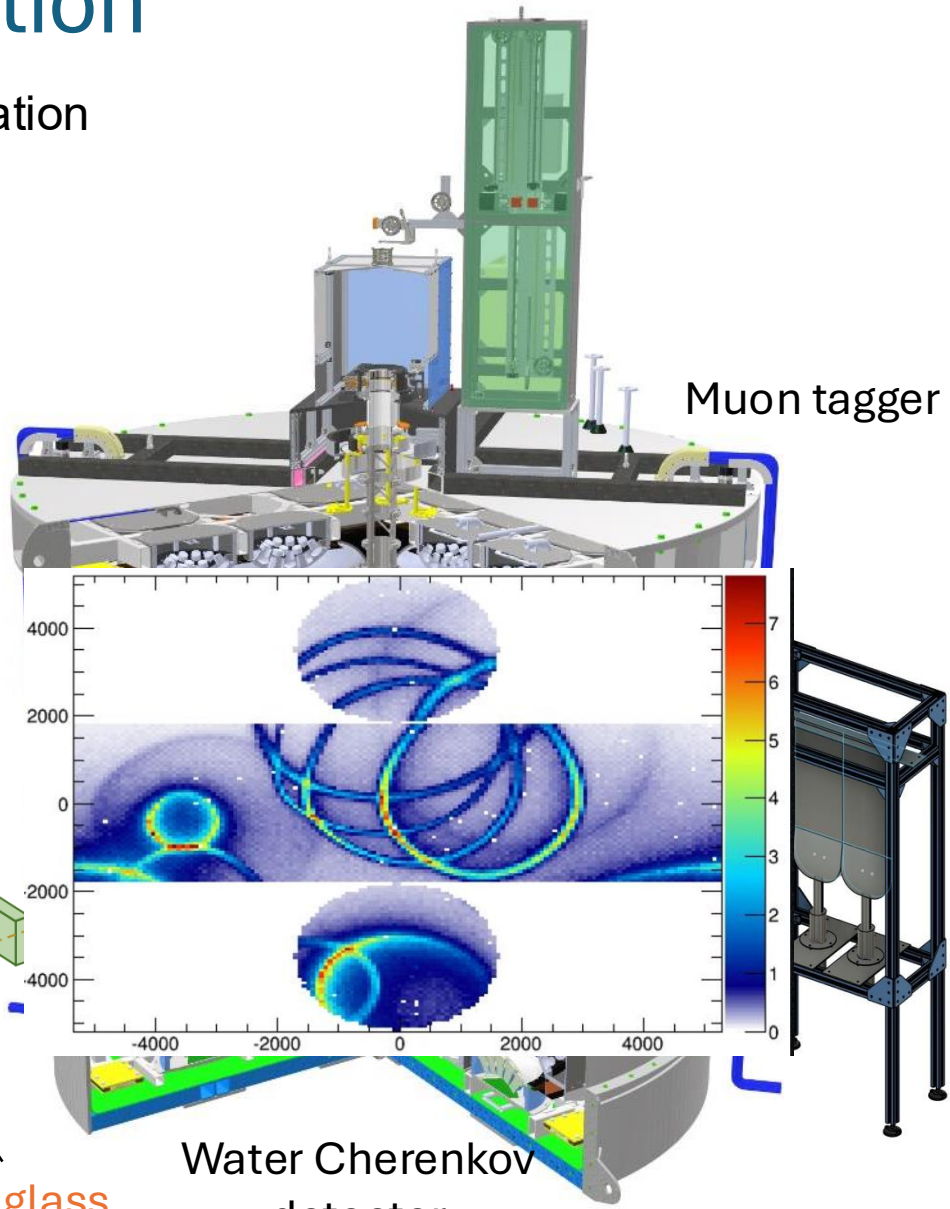
- Potential to also measure **pion photo- production** in tagged γ configuration
  - Control sample for NC$\pi^{\pm}$ ν interactions

- **Pion production in ν interactions** introduces several challenges for ν measurements
- **Multi-ring event topologies are difficult to reconstruct** requiring development of new reconstruction methods to handle pion events

- **WCTE directly measures pions, including all their interactions and detector response**



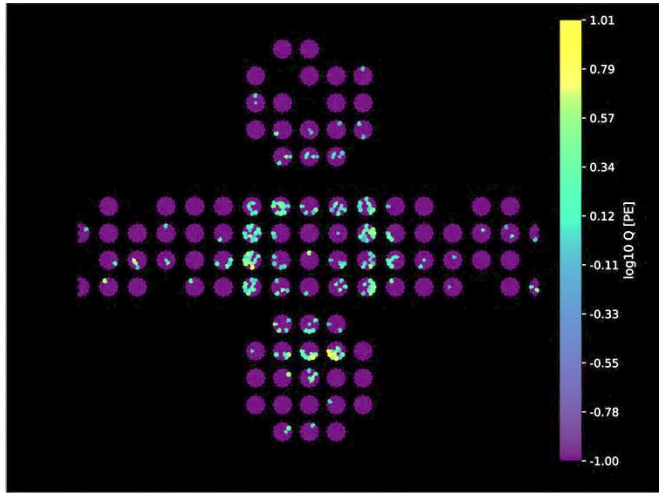




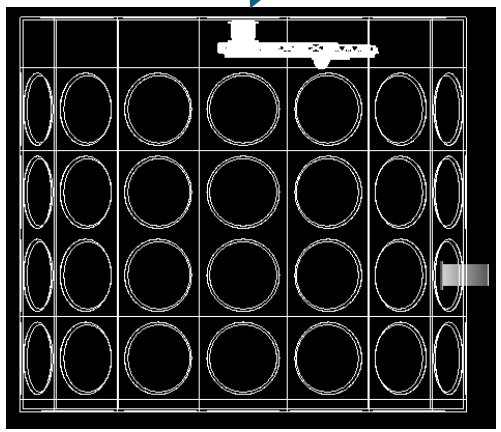
L. Anthony

Monte-Carlo simulation with WCSim

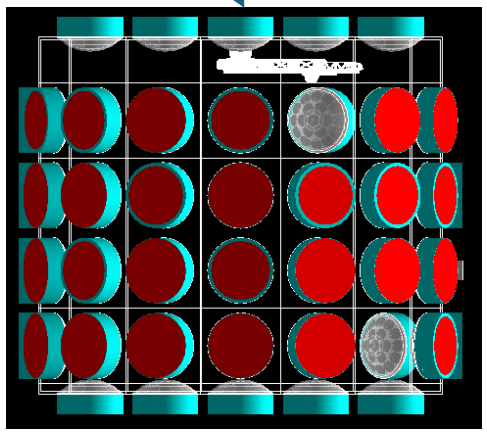
- WCSim (Water Cherenkov Simulation) is an open-source simulation package used for event simulation in Hyper-K, IWCD and WCTE
- Build and place objects like mPMTs using GEANT4
- Implement complex objects like CDS using CAD models



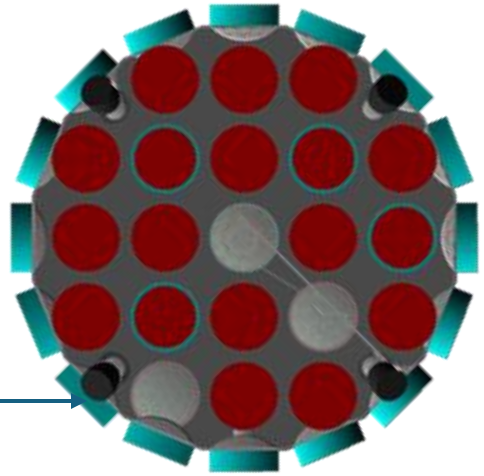
Implement CDS CAD model



Construct detector volume and mPMT slots

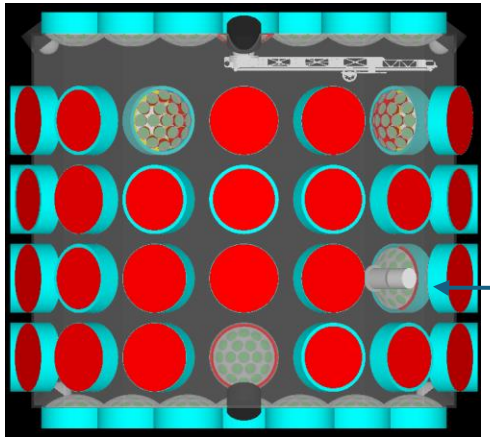


Construct detailed mPMT



Construct basic shape for photogrammetry camera housing

Construct basic shape for beam pipe



Remove mPMTs from unused or dead slots