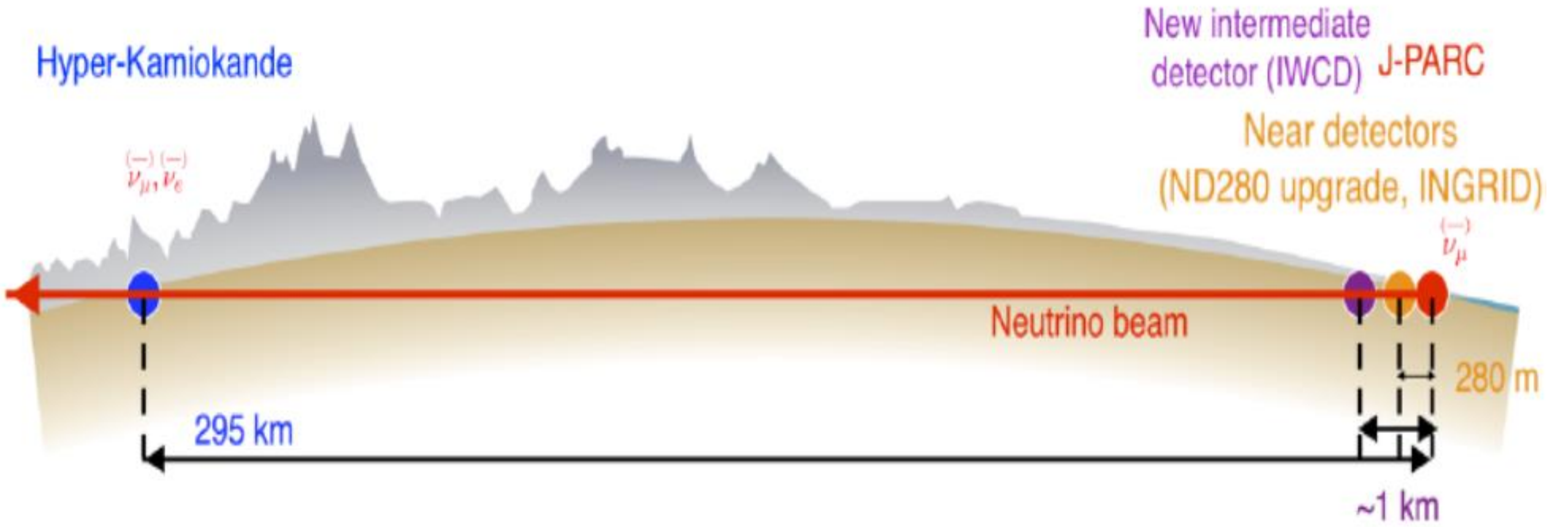
Hyper-Kamiokande

Marcin Ziembicki

Particle Astrophysics Science and Technology Centre, Nicolaus Copernicus Astronomical Center

and Warsaw University of Technology, Institute of Radioelectronics and Multimedia Technology

Hyper-Kamiokande Experiment

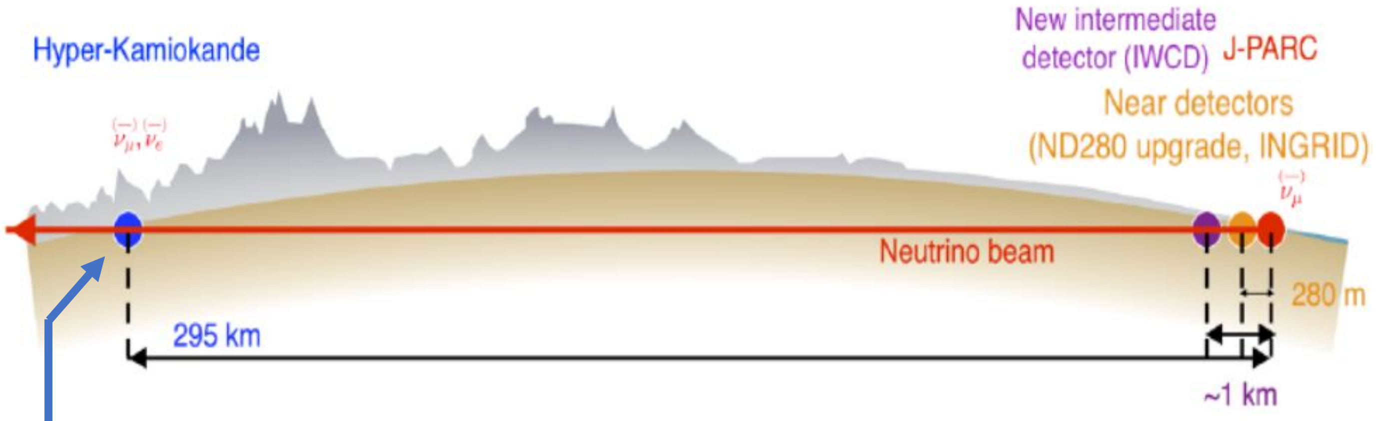


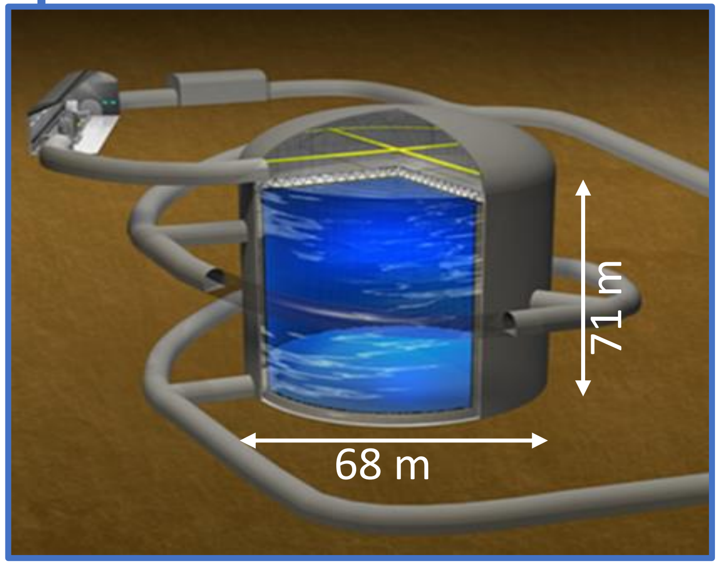
Next generation long-baseline neutrino experiment

Rich physics program that aims to address some of the most significant questions facing particle physicist today

- Neutrino oscillations
  - With beam and atmospheric neutrinos
  - CP violation measurement
  - Precise measurement of θ_{23}
  - Determination of mass hierarchy
- Neutrino astrophysics
  - Precise measurement of solar neutrinos, sensitivity to address solar and reactor neutrinos discrepancy
  - Supernova burst and relic supernova neutrinos
- Search for nucleon decay
  - Sensitivity 10x better than Super-Kamiokande (10^{35} years)
  - All visible modes can be advanced
- Other:
  - Indirect Dark Matter search
  - Geophysics
  - Neutrinos from solar flares
  - etc.

Hyper-Kamiokande Experiment

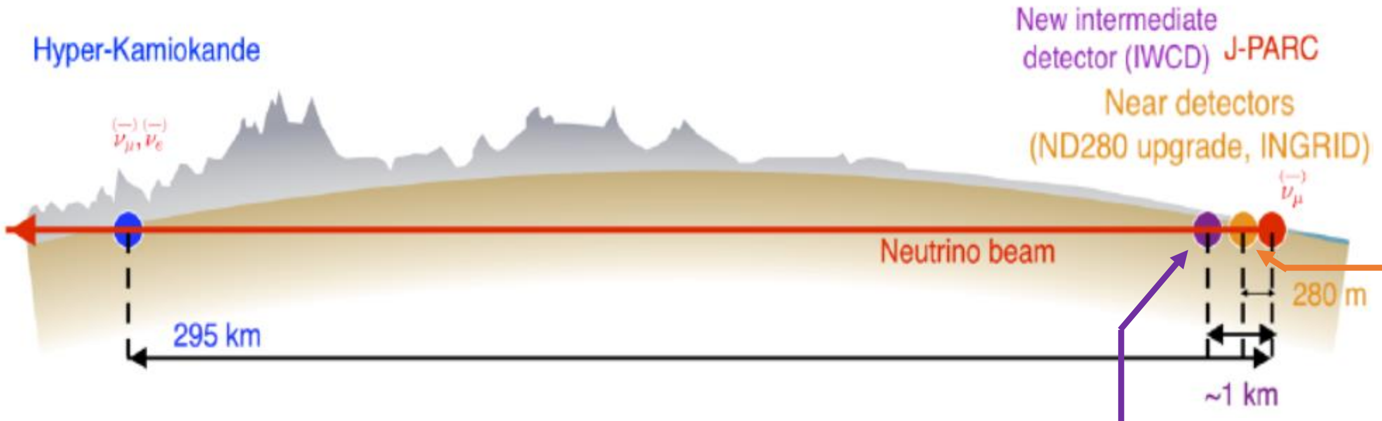




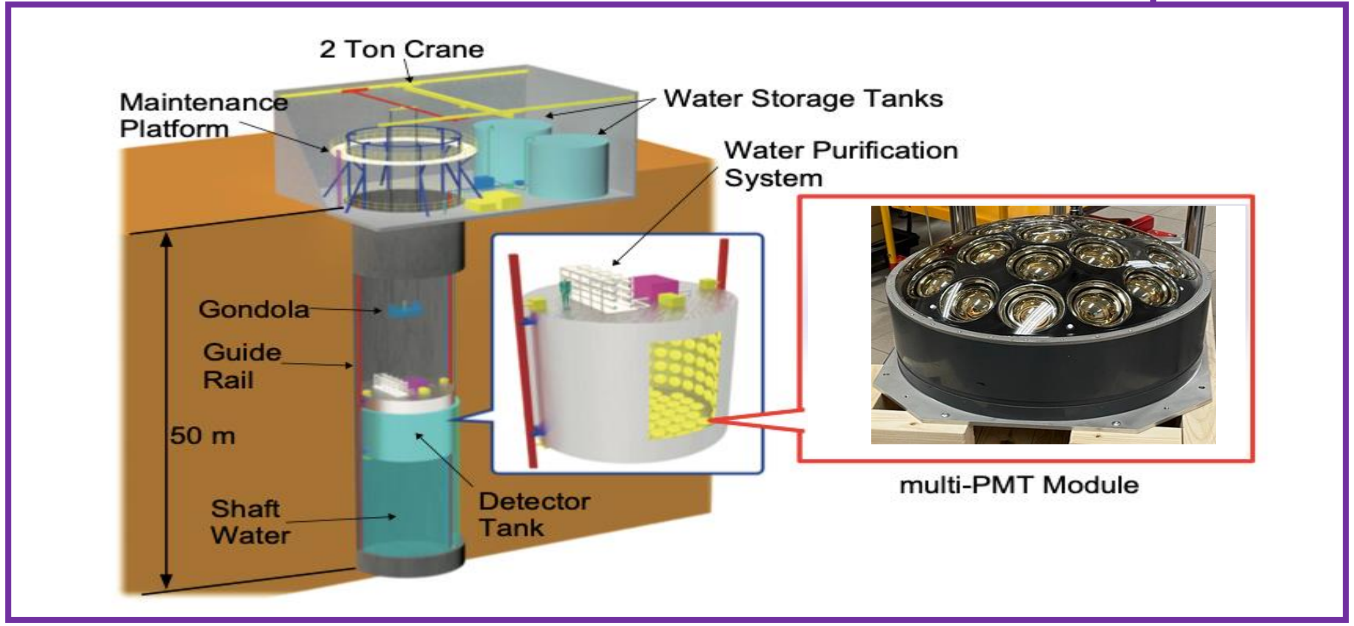
- Hyper-Kamiokande (far) detector
  - Newly built 258 kt underground water Cherenkov detector
  - Inner detector:
    - 20% photocoverage
    - 20000 pcs. of 50 cm Box&Line PMTs (main photosenson)
    - 800 multi-PMT modules (calibration)
  - Outer detector
    - ~3000 3’’ PMTs coupled to Wavelength Shifter (WLS) plates
  - Calibration systems (incl. LiNAC)

ON-GOING CONSTRUCTION (on schedule, starts in 2027)

Hyper-Kamiokande Experiment



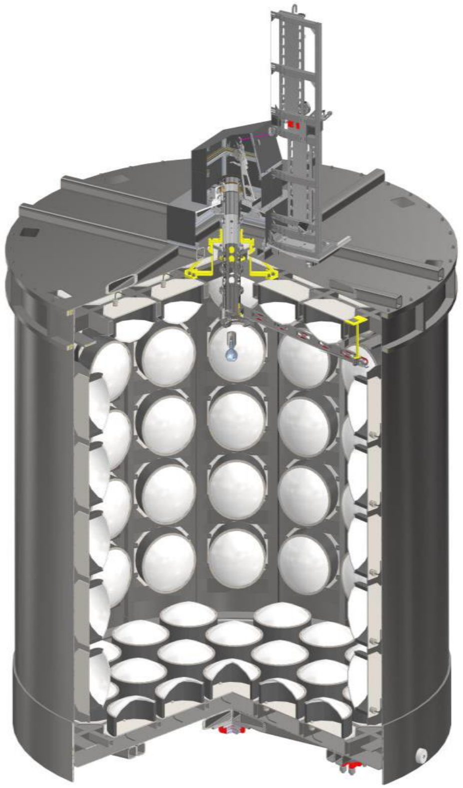
- Other upgrades
  - J-PARC neutrino beam power increase (0.5 MW → 1.3 MW)
    - On-going
  - ND280 (near) detector
    - New Super-FGD (completed)
    - High Angle TPC (completed)



- Intermediate Water Cherenkov Detector
  - Newly built kt-scale water Cherenkov detector, approx. 1 km from neutrino production target
  - Inner (ID) & outer (OD) detector volumes:
    - ID -> approx. 400 multi-PMTs
    - OD -> 3” PMT tubes

PREPARING FOR CONSTRUCTION

Water Cherenkov Test Experiment



- Water Cerenkov Test Experiment @ CERN
  - 50-ton scale detector (~4m×4m cylinder) to study detector calibration and response with known p, e, π, μ fluxes of 0.2-1.1 GeV/c and develop percent level calibration of water Cerenkov detector.
  - Secondary beam of particles produced by target upstream of the detector.
  - Measurements with ultra-pure and 0.2% gadolinium sulphate-doped water (to capture neutrons produced in CCQE antineutrino interaction and in secondary protons/pions interactions).
  - About 100 multi-PMTs.
- Major test bed for Hyper-Kamiokande multi-PMT systems and several calibration strategies
- Several beam tests already done
- Manufacturing parts & modules now
- **Plan to start in 2024 (this year !!!)**
  - Construction starts in June/July 2024 (delayed from April 2024)

Simple pre-amplifiers for beam tests

Activities in Poland (2023)

- Management:
  - Executive Board membership (*prof. Ewa Rondio from NCBJ*)
  - Speakers Board chair
  - Two deputy conveners for far detector working groups (**electronics**, calibration)
  - **Deputy convener** – IWCD and WCTE detectors (photodetectors & electronics)
  - Technical coordinator, working group level (multi-PMTs)
  - **Steering Committee membership** (IWCD, WCTE)

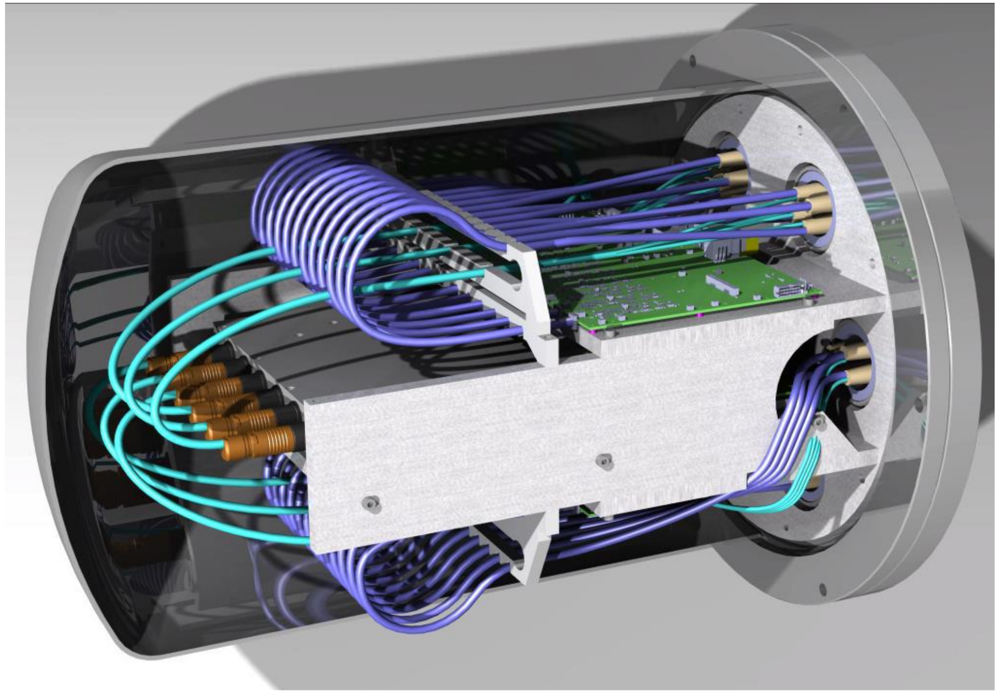
Over 40 people in Poland from 9 institutions;
WUT/CAMK/AGH/UJ -> 17 people, ≈13 FTE

- R&D + production:
  - Linear accelerator (NCBJ)
  - Far detector electronics (CAMK, WUT, UJ)
    - Data processing module (DPB)
    - Data concentrator card for multi-PMTs (MCC)
    - Reliability estimations
    - Ground system design
    - Design reviews
  - IWCD electronics (WUT, UJ, AGH, CAMK)
    - Multi-PMT front-ends
    - High voltage supplies
    - Data concentrator card for multi-PMTs (MCC)
    - Quality asurance (incl. dedicated test hardware)
    - Design reviews
  - multi-PMTs (WUT, CAMK)
    - Photosensor characterization
    - Optimization of assembly strategy
    - Mass production (starting now for WCTE)
    - Quality assurance
  - WCTE (CAMK, WUT)
    - Electronics for beam tests
  - Analysis + simulations + computing

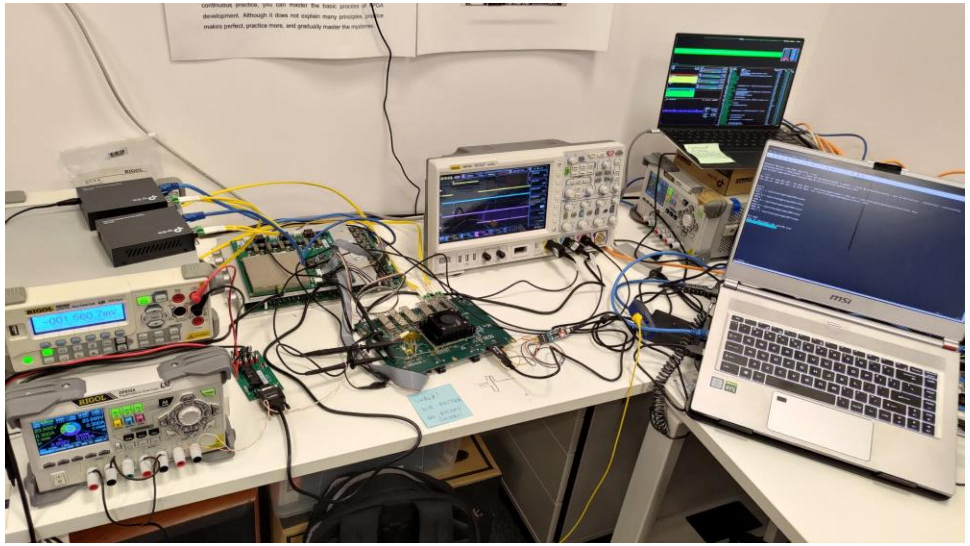
Collaboration with UPV (Valenzia)

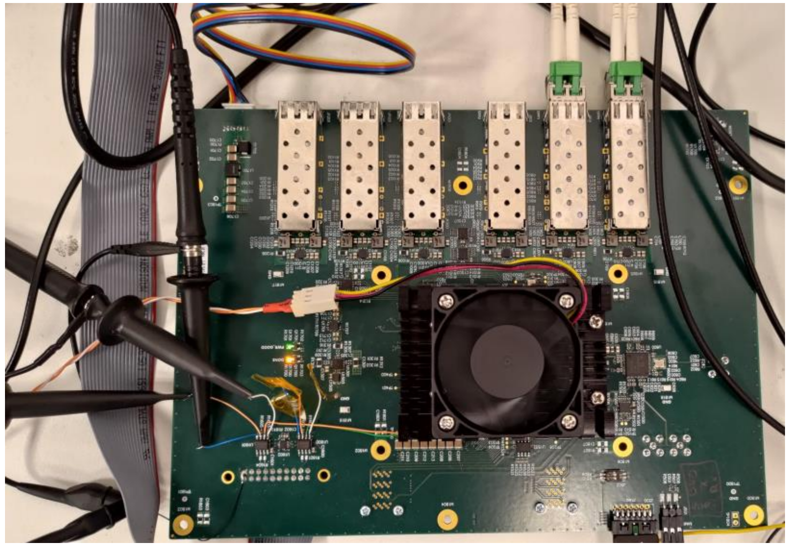
Close collaboration with TRIUMF and INFN Naples

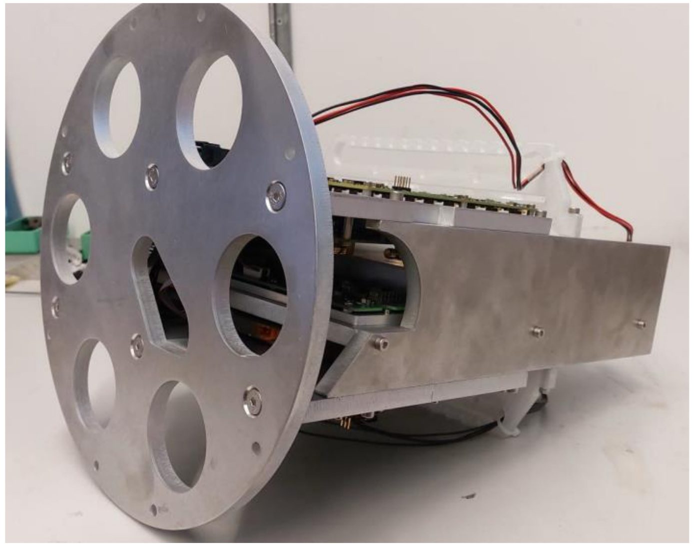
Far detector electronics (DPB)



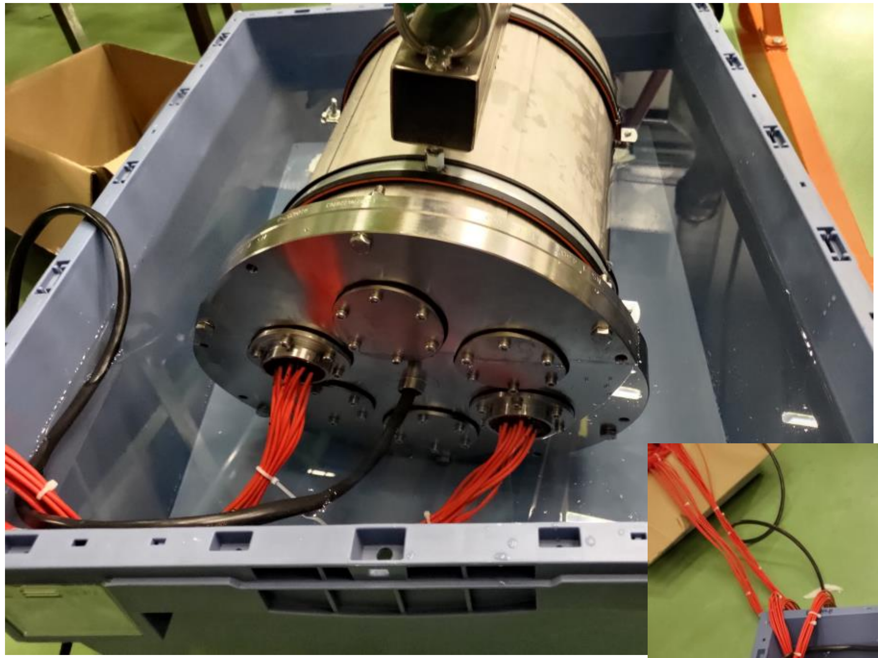
- Design review
  - Actual design done by external company based on specification by HK
- Verification of prototypes
- Development of slow-control
- Reliability estimations (SN29500 standard)



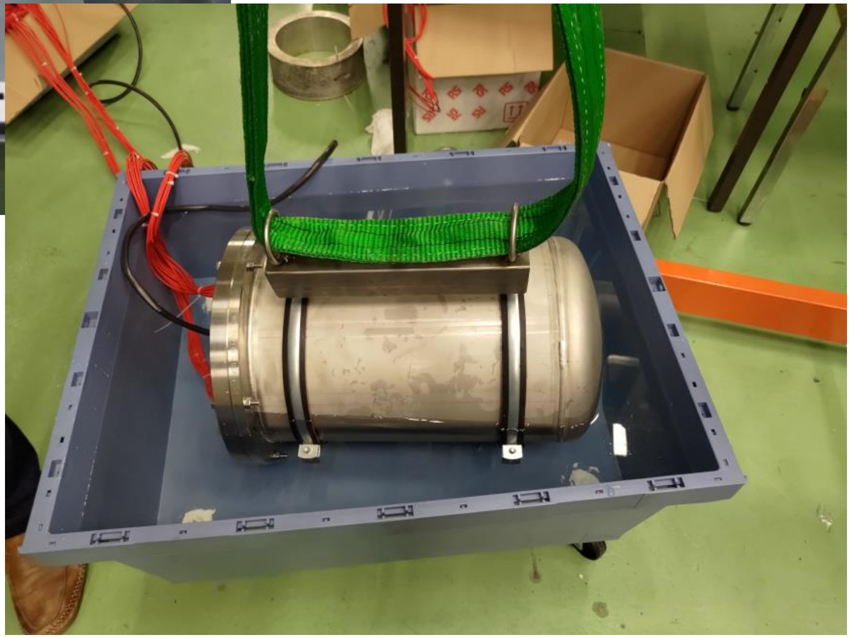


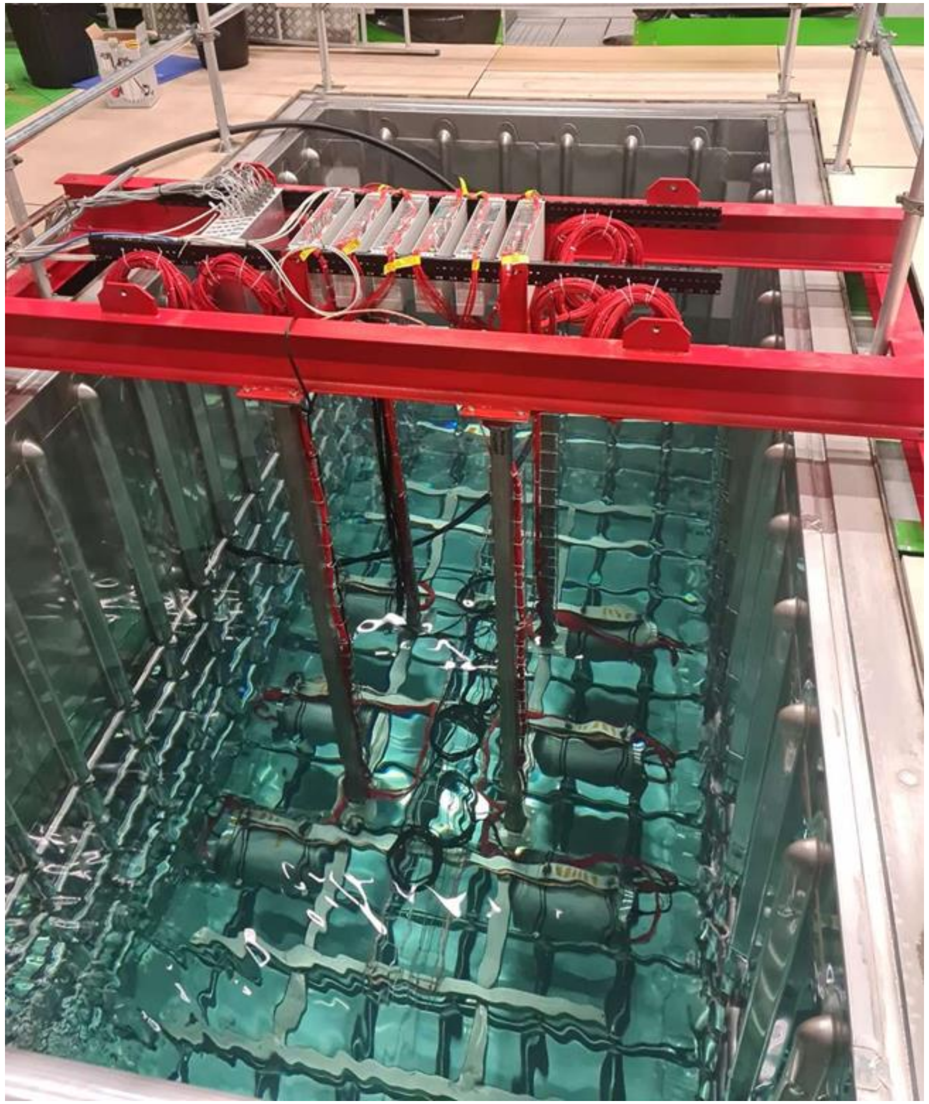


Testing Underwater Electronics @ CERN (ETH group)



Real power supplies (LV & HV), but dummy loads for other electronics modules

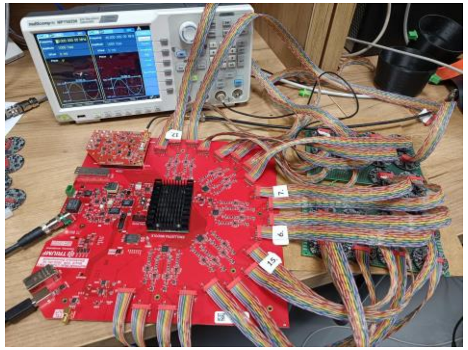


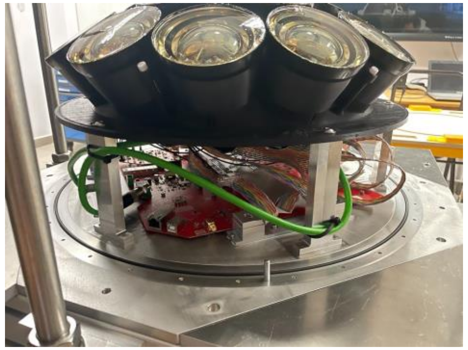


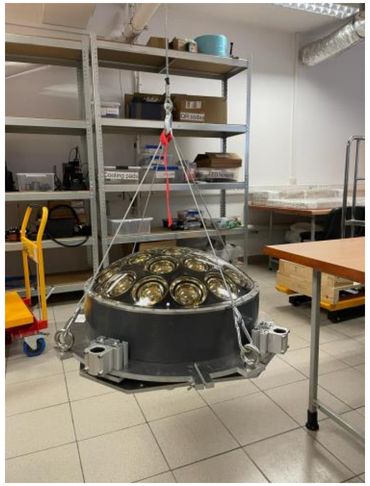
Initial tests of water tightness, thermals, long-term vapor penetration, assembly strategy, etc.

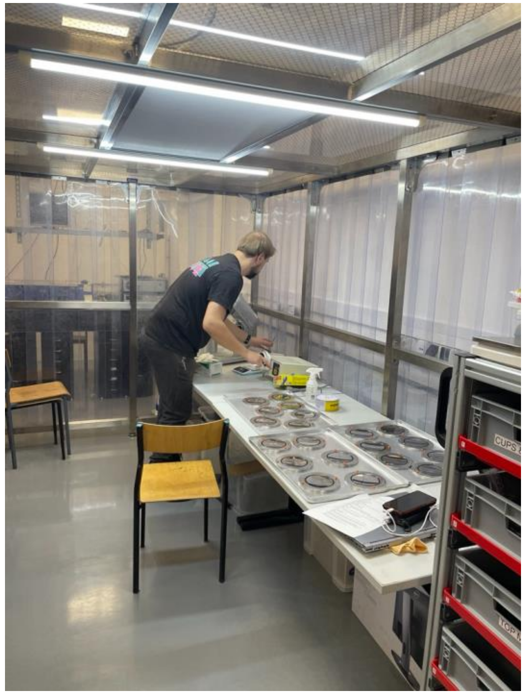
Multi-PMTs

- Optimization of assembly process
- Preparation of assembly line
- Complete redesign of HV
- Custom tools for QA
- Photosensor characterization

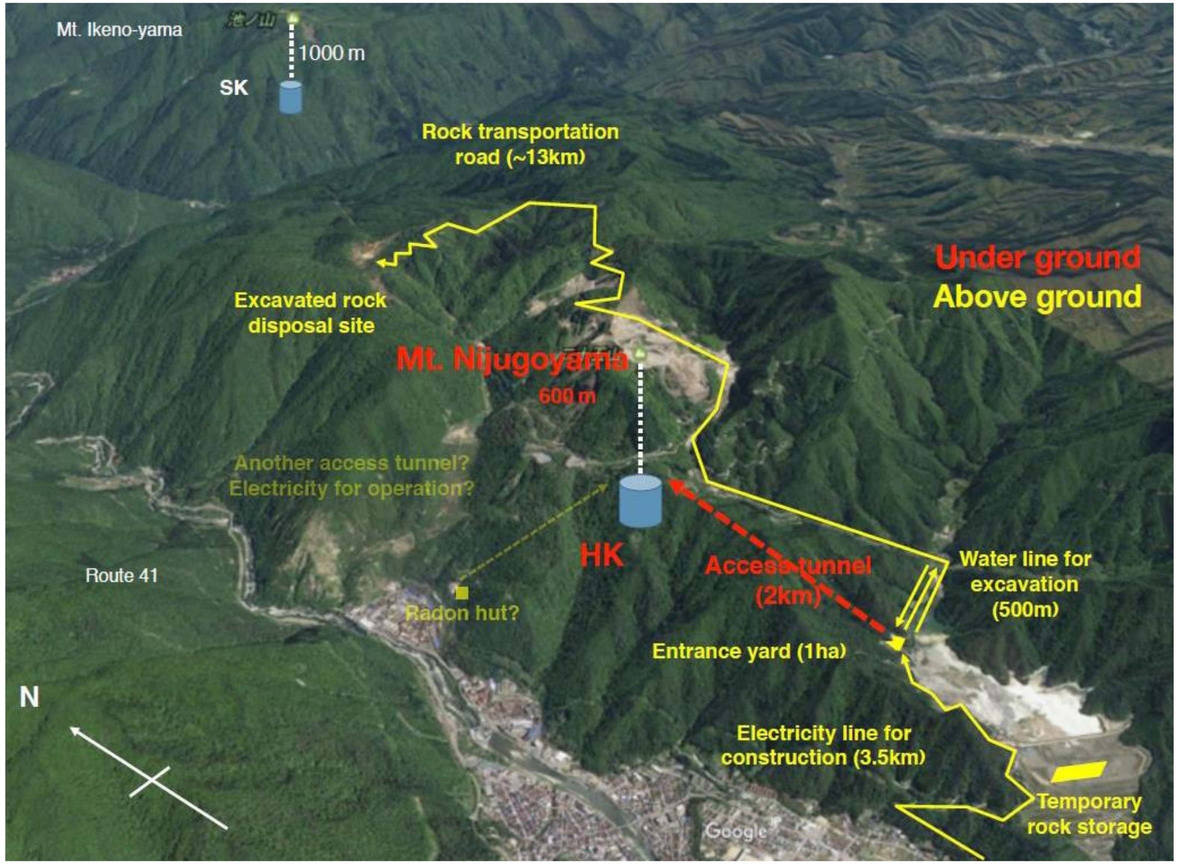








Summary



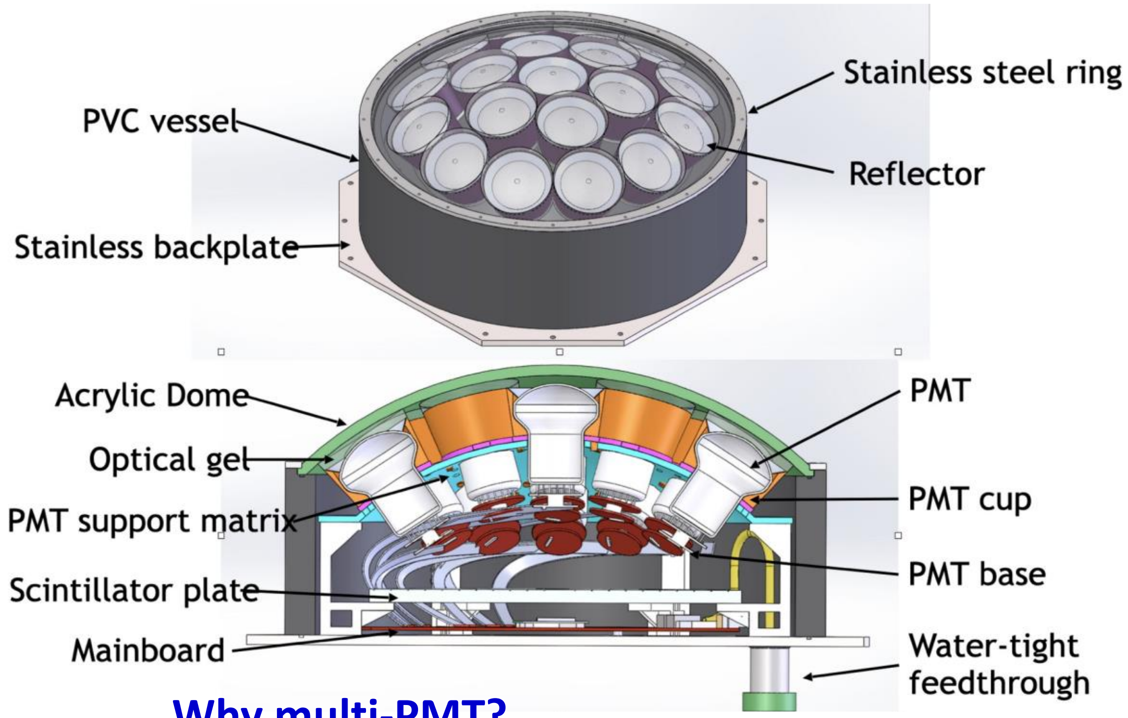
- ✓ Access tunnel (~ 2km) excavation completed
- ✓ Approach and circular tunnels excavations completed
- ✓ Water system cavern excavation completed
- ✓ Dome excavation completed
- ✓ Currently excavating barrel section

- Growing collaboration (>500 people, 20 countries)
- Construction on schedule
- Planned start of operation in 2027
- Budget approvals:
  - Japan – 2020
  - Many other countries
  - **Poland – December 2022 (approx. 68 MPLN)**
- Polish contributions:
  - LINAC, multi-PMTs, Electronics, Computing, Analysis
- **2024 is a critical year for Hyper-Kamiokande**
  - Need to finalize all reviews to start procurements of components for mass production
  - Need to complete WCTE to make large-scale test of multi-PMT systems for IWCD and Hyper-Kamiokande
  - Need to finalize LiNAC design
  - Need to start accelerated aging tests of all underwater system, to verify lifetime
  - Continuing long-term testing

BACKUP

Multi-PMTs for Hyper-Kamiokande

- Multi-PMT $\rightarrow$ 19 3'' PMTs in a pressure vessel.
  - Also includes HV supply (Cockcroft-Walton base), front-ends, digitizers, mechanical components
- Inspired by modules developed for the KM3NeT experiment.
- ~800 will complement 20'' PMTs in far detector.
- ~400 will fully equip IWCD (the only photodetector).
- Optical gel used to couple PMTs to transparent, acrylic dome.
- Single twisted-pair cable to connect power supply and transmit data & clock.
- 2 variants with different front-end electronics
  - Far detector - optimized of pressure resistance and low-power consumption
  - IWCD - higher pulse rates

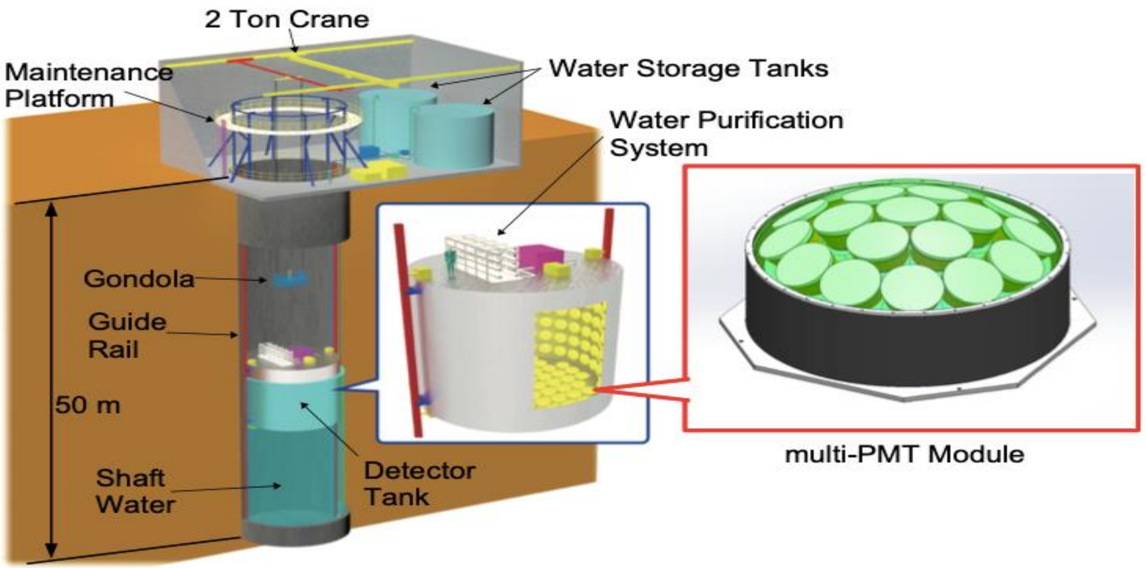


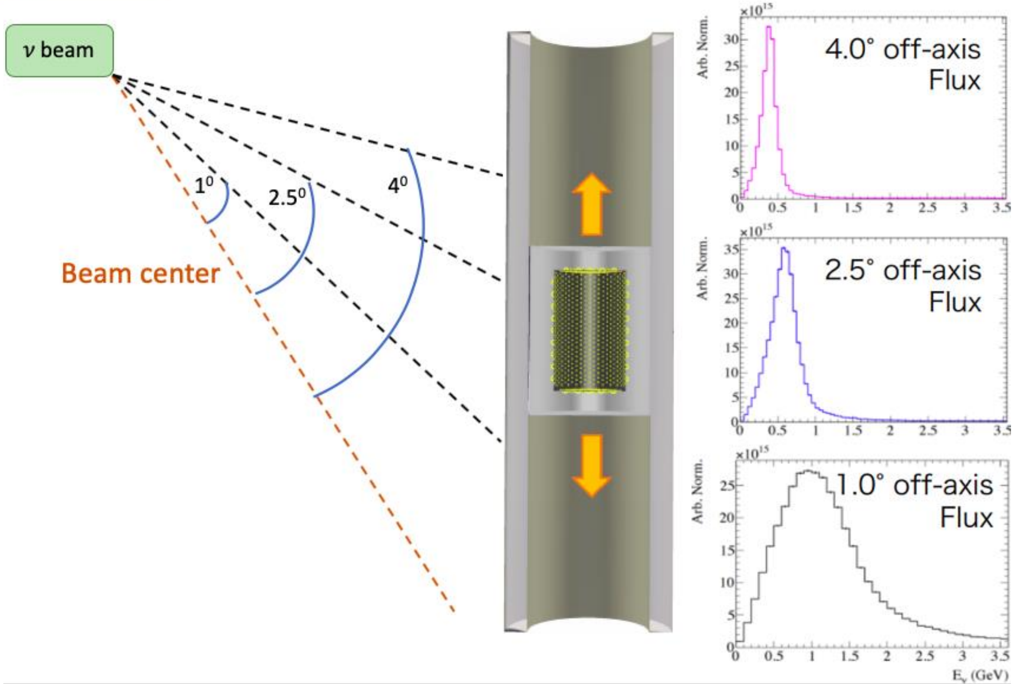
Why multi-PMT?

- IWCD
  - Directionality improves reconstruction (larger FV)
  - Cost optimization
  - Shorter installation time
- Far detector
  - Calibration
  - Better reconstruction of high energy events near walls

Intermediate Water Cherenkov Detector

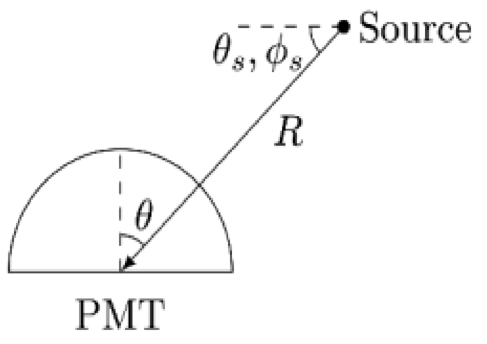
- HK will study the CP violation (CPV) by comparing ν_e and anti-ν_e event rates, i.e. ν_e and anti-ν_e cross section uncertainties will dominate systematic error. For far detector, CPV-relevant region of neutrino energies is 0.3÷0.9 GeV. Due to complicated nuclear effects, uncertainties need to be **constrained by data (not by theory)**.
- Measurements at different neutrino beam off-axis angles (1º–4º) by moving detector filled with ~600 tons of water.
- A linear combination of the results for different off-axis angles will allow the reconstruction of the neutrino energy corresponding to an almost monochromatic neutrino spectrum without using neutrino interaction models.
- Very high event rate (~1km from neutrino source) compared to the event rate at the far detector → different requirements for the electronics.



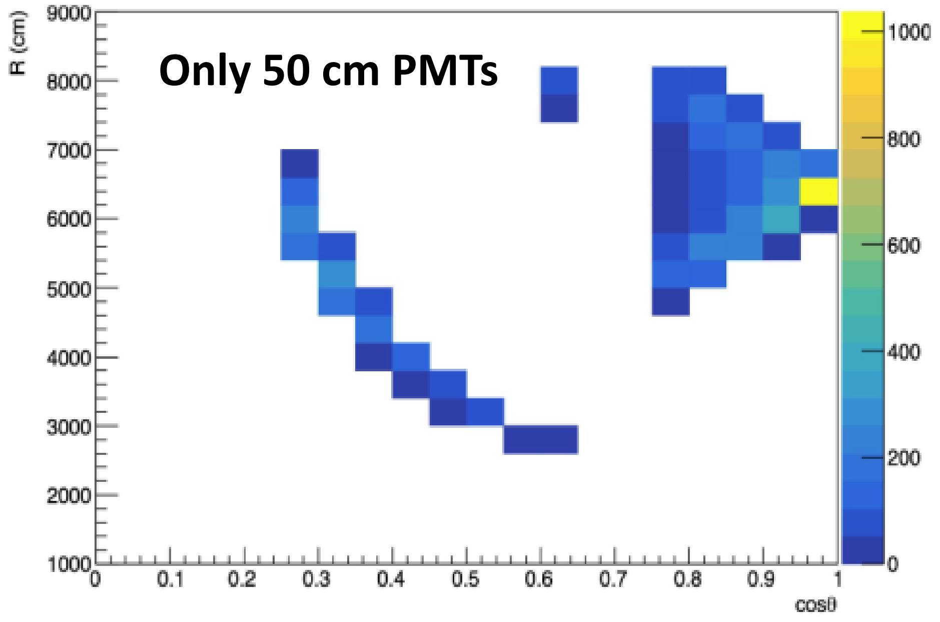


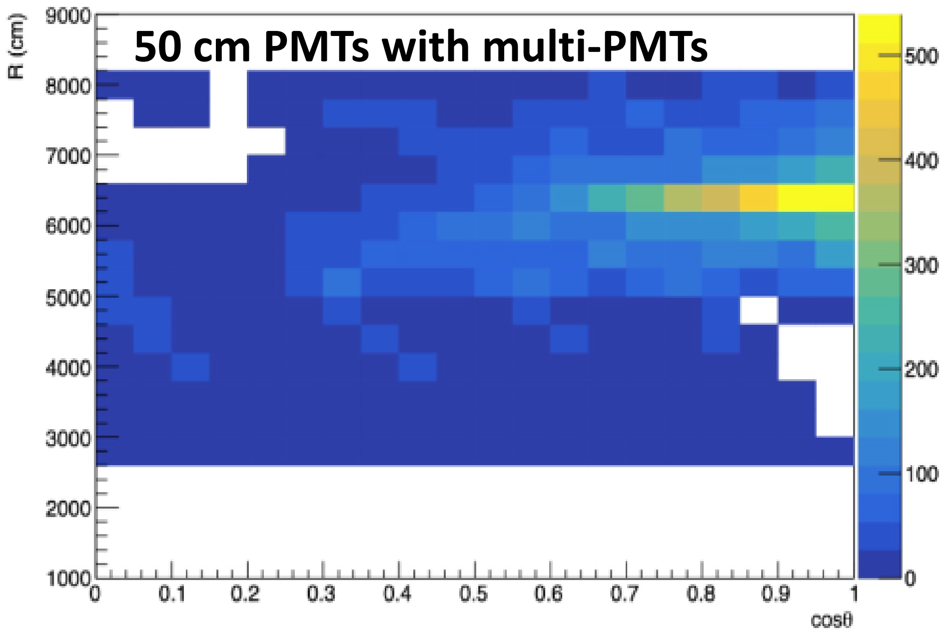
Detector calibration with Multi-PMTs

- Reduction of systematic uncertainties requires precise knowledge of the spatial distribution of light attenuation in water.
- Water attenuation is measured with constant intensity light sources and photomultipliers whose response depends on the incident light direction.
- Multiple measurements for different configurations of angle θ of incident light and distance R have to be performed with detectors determining the light direction → multi-PMTs.



R: water (absorption)
θ: PMT (angular response)





Hyper-Kamiokande – Photosensors, Electronics

Inner Detector

20000 PMTs

New high-QE 20" Box&Line PMT

Pressure tolerance for min. 60 m depth

High detection efficiency, very good time & charge resolutions

800 units

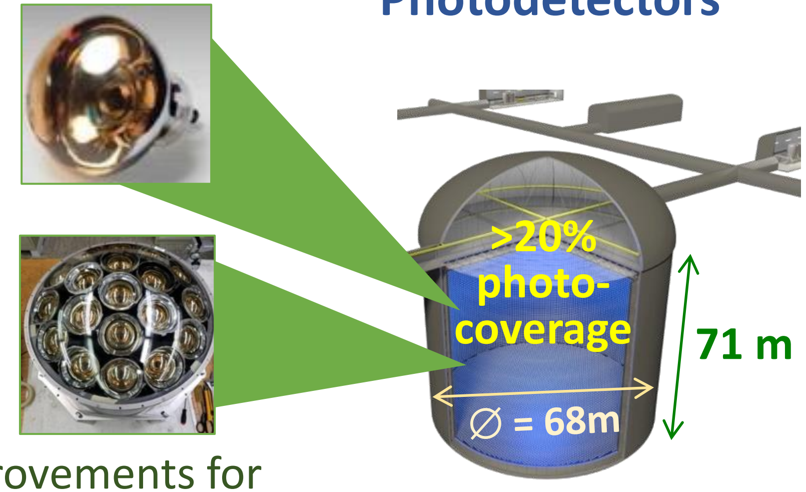
Multi-PMT modules (3" PMTs)

Smaller PMTs → better timing response

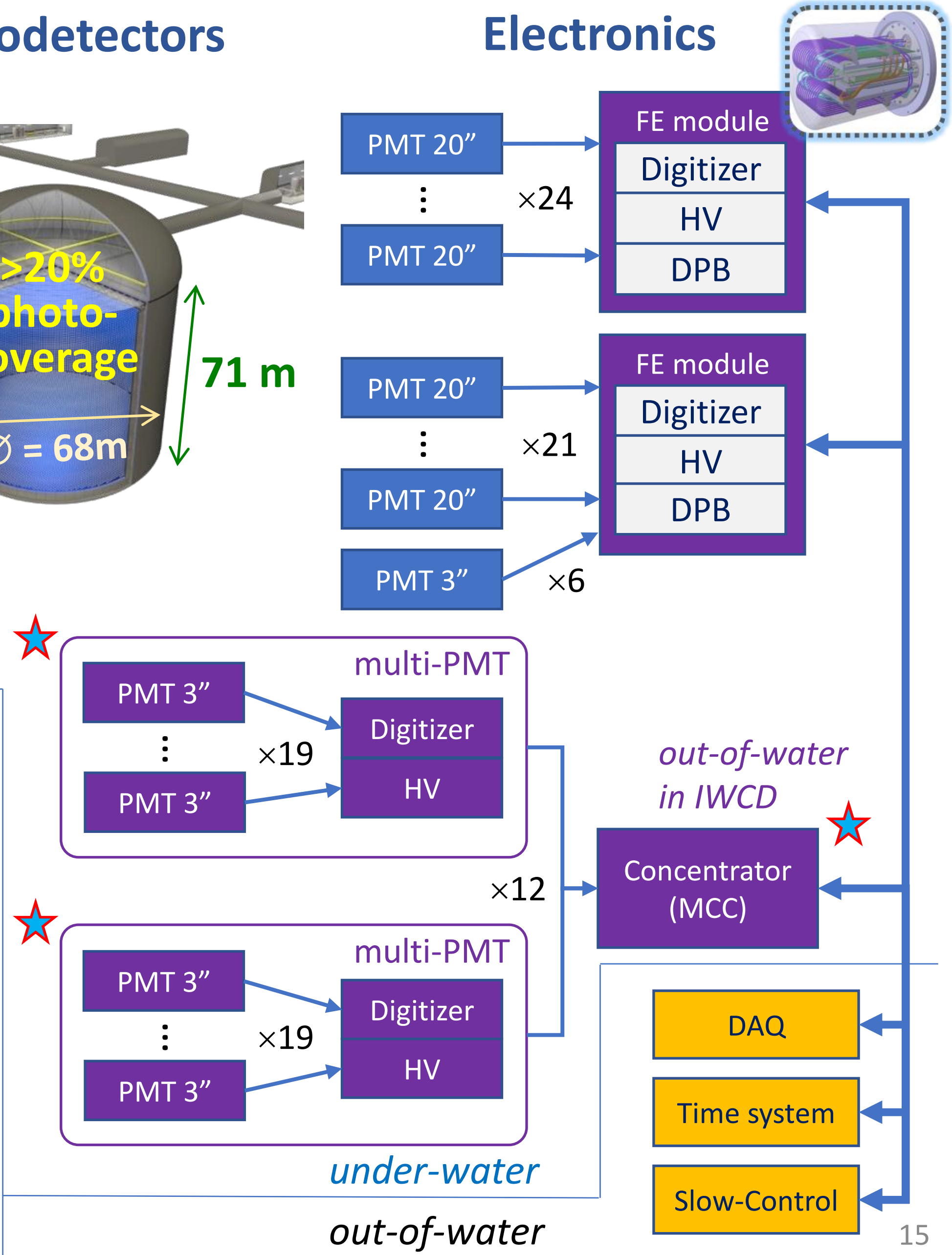
Additional directional information

Far detector – benefits in calibration, improvements for high energy physics; optimized for low power

Main building block of the intermediate detector (IWCD)



Photodetectors **Electronics**

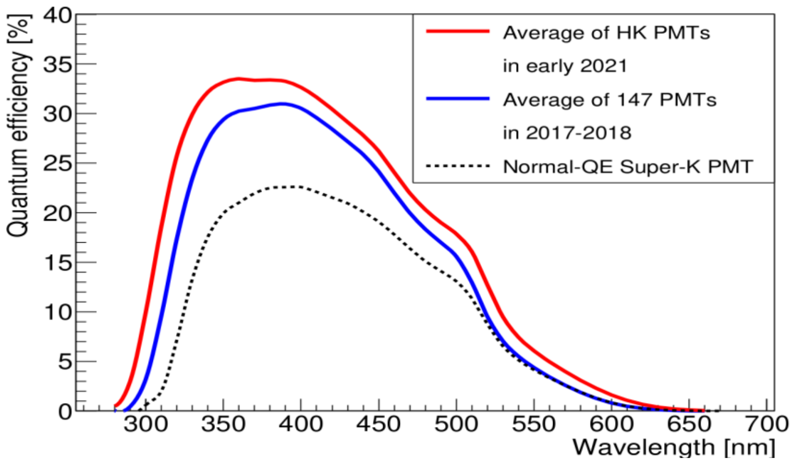


Outer Detector

3" PMTs + WLS (3000 units)

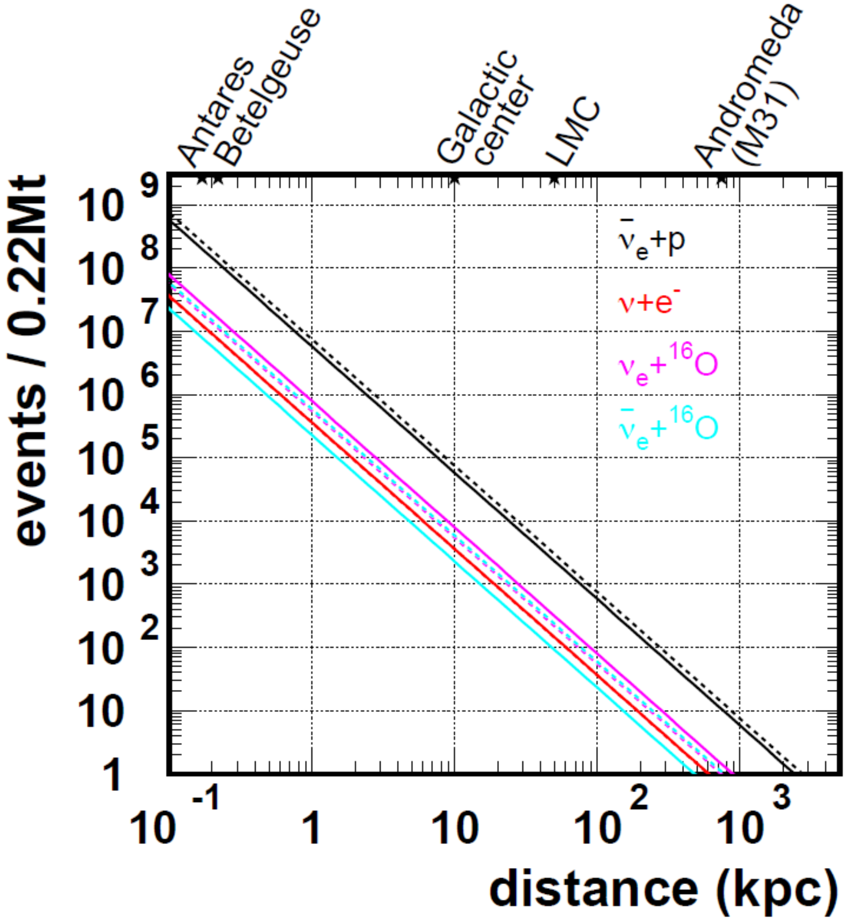
- Reduced radioimpurities in glass (source of scintillations)
- Improved glass transparency
- Reduced radon content in cables: 1.4 mBq/m → <0.1 mBq/m
- Dark noise reduction down to 4 kHz
- ~3772 PMTs (18% of 20k) delivered by April 2022

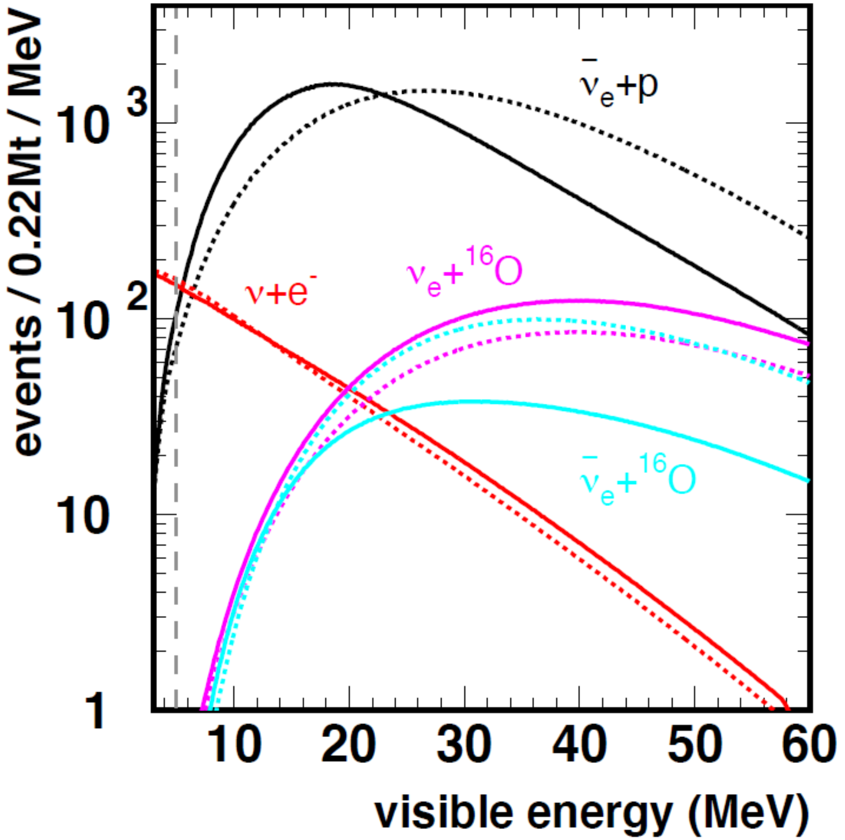
New HPK R12860 PMT



(C. Bonner 22nd Int. Workshop on Neutrinos from Accelerators, 2021)

Expected SN Event Rates (from SN paper)





Plots from: *Supernova Model Discrimination with Hyper-Kamiokande,* K. Abe *et al* 2021 *ApJ* **916** 15