Status of the Hyper-K Experiment, and Mexican contributions so far

Saul Cuen-Rochin (Tecnologico de Monterrey)

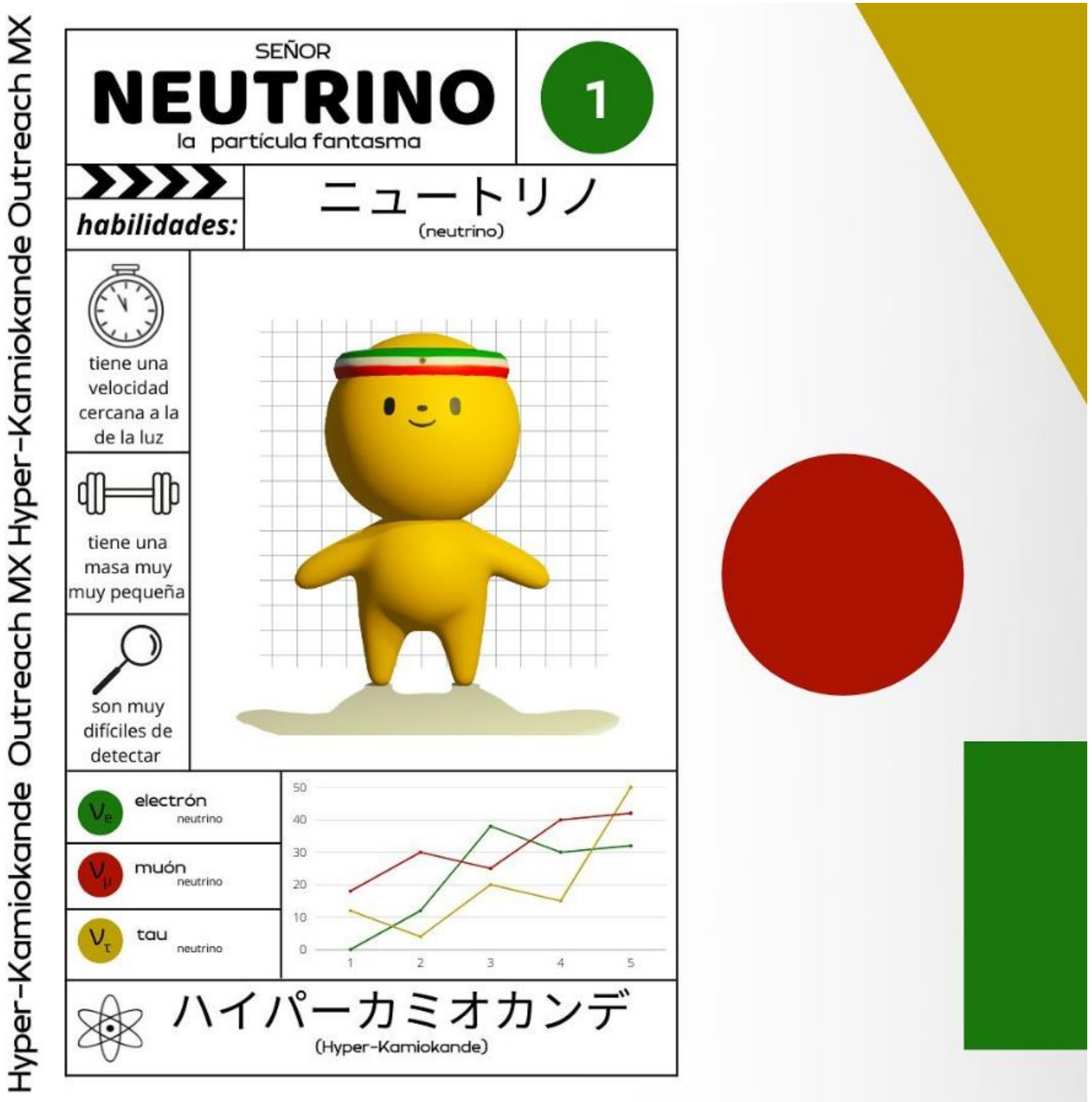
on behalf of the Hyper-K collaboration and Mexican group

2024/06/07

Annual Meeting (RADPyC)
Division of Particles and Fields of the Mexican Physical Society (DPyC-SMF)
Unidad de Seminarios "Dr. Ignacio Chávez", Mexico City, Mexico

Agenda

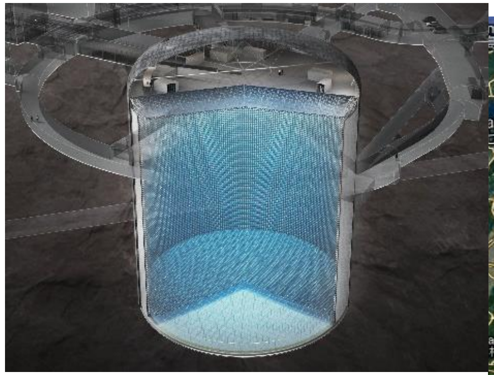
- Hyper-K project goals and status
- mPMT detector design and manufacturing
- Work at local national institutions



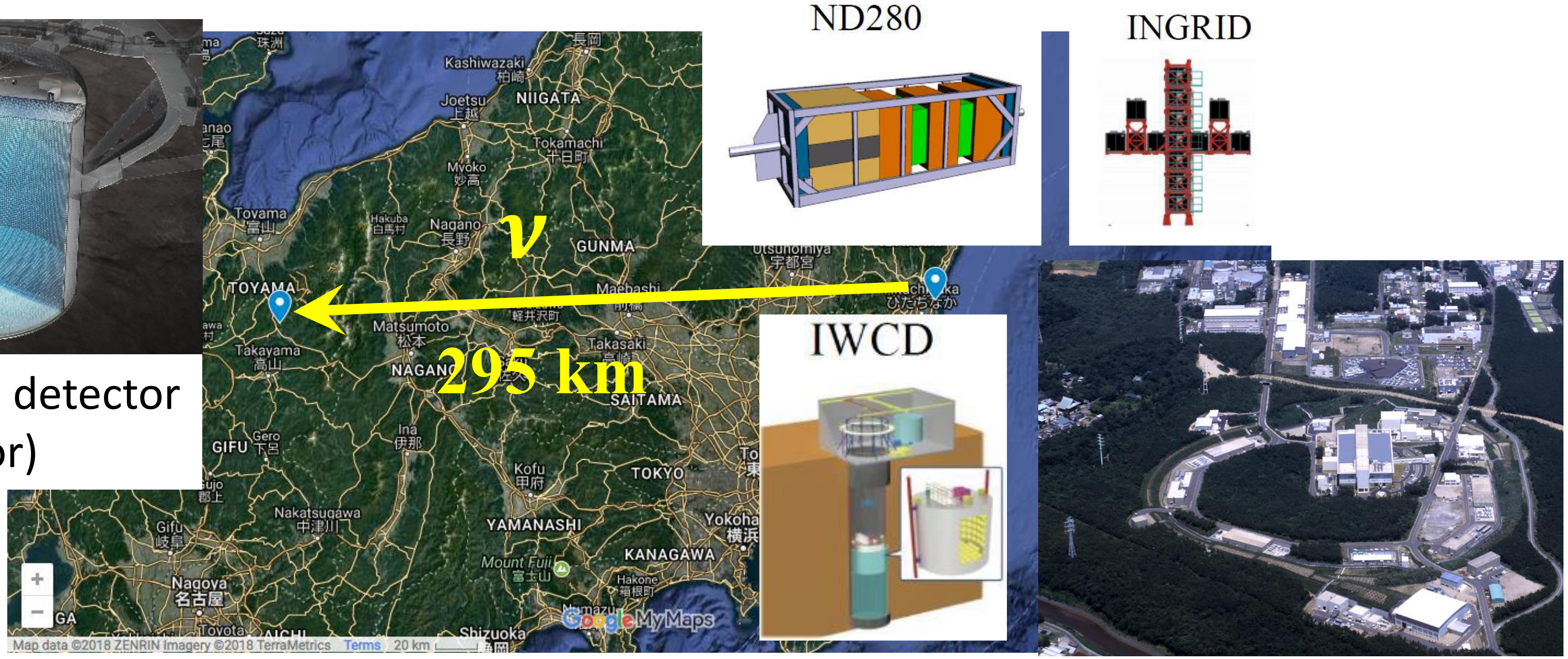
https://bio.site/Outreach_HK_MX

Hyper-Kamiokande Project

- The Hyper-Kamiokande project includes a far detector, a neutrino beam, and a neutrino near detector complex
  - Construct the Hyper-Kamiokande detector at Kamioka
  - Upgrade the J-PARC neutrino beam
  - Construct the Intermediate Water Cherenkov Detector (IWCD) at Tokai



Hyper-Kamiokande detector
(Far detector)



J-PARC

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Katsuki Hiraide @ NNN23

Three Generations of Water Cherenkov Detector in Kamioka

- **<u>Kamiokande (1983 - 1996)</u>**
  - Atmospheric and solar neutrino "anomaly"
  - Supernova 1987A

  Birth of neutrino astrophysics

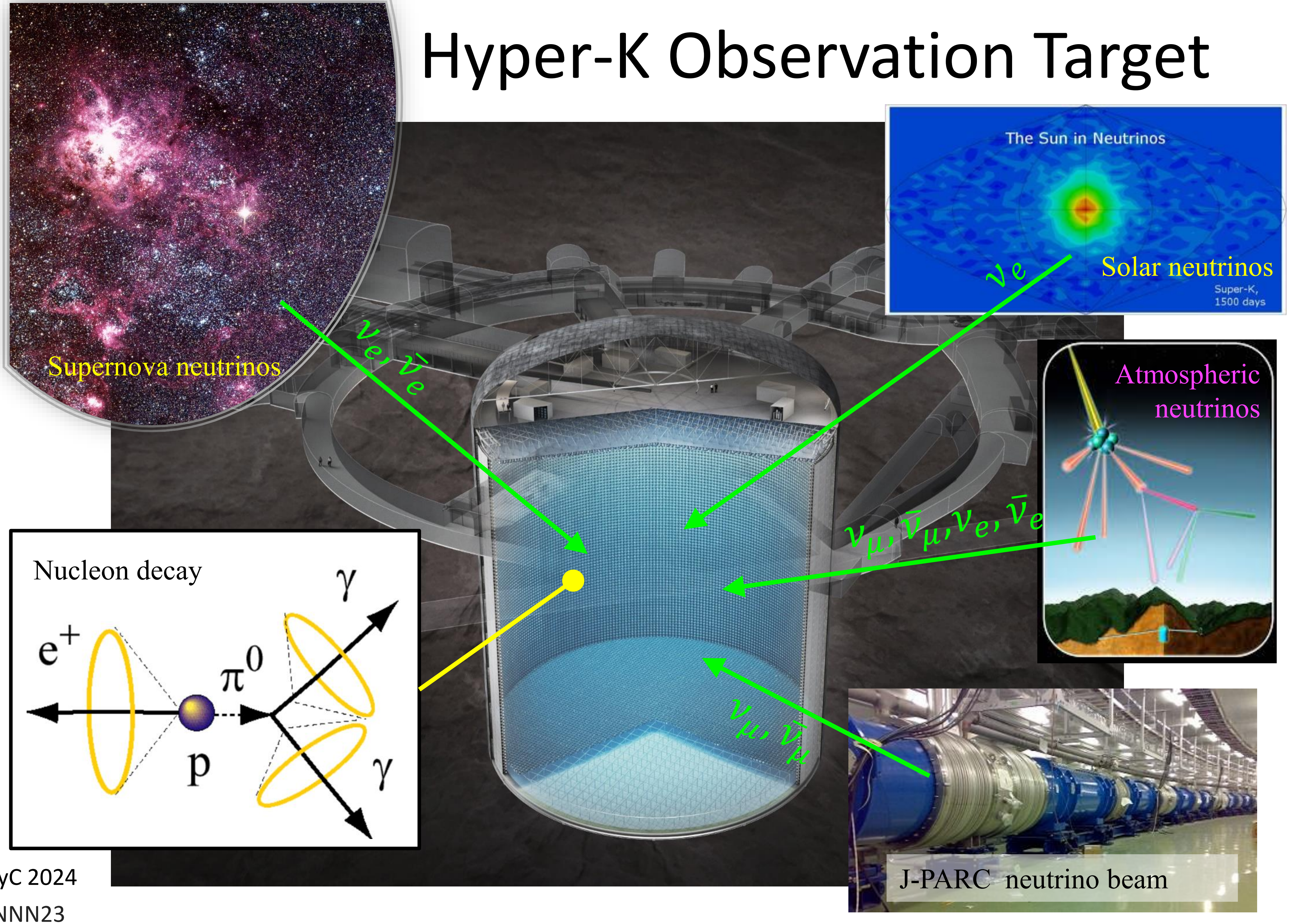
- **<u>Super-Kamiokande (1996 - ongoing)</u>**
  - Proton decay: world best-limit
  - Neutrino oscillation (atm/solar/LBL)
    - All mixing angles and Δm^2s

  Discovery of neutrino oscillations

- **<u>Hyper-Kamiokande (2027 -)</u>**
  - Extended search for proton decay
  - Precision measurement of neutrino oscillation including CPV and MO
  - Neutrino astrophysics

  Explore new physics

Hyper-K Observation Target



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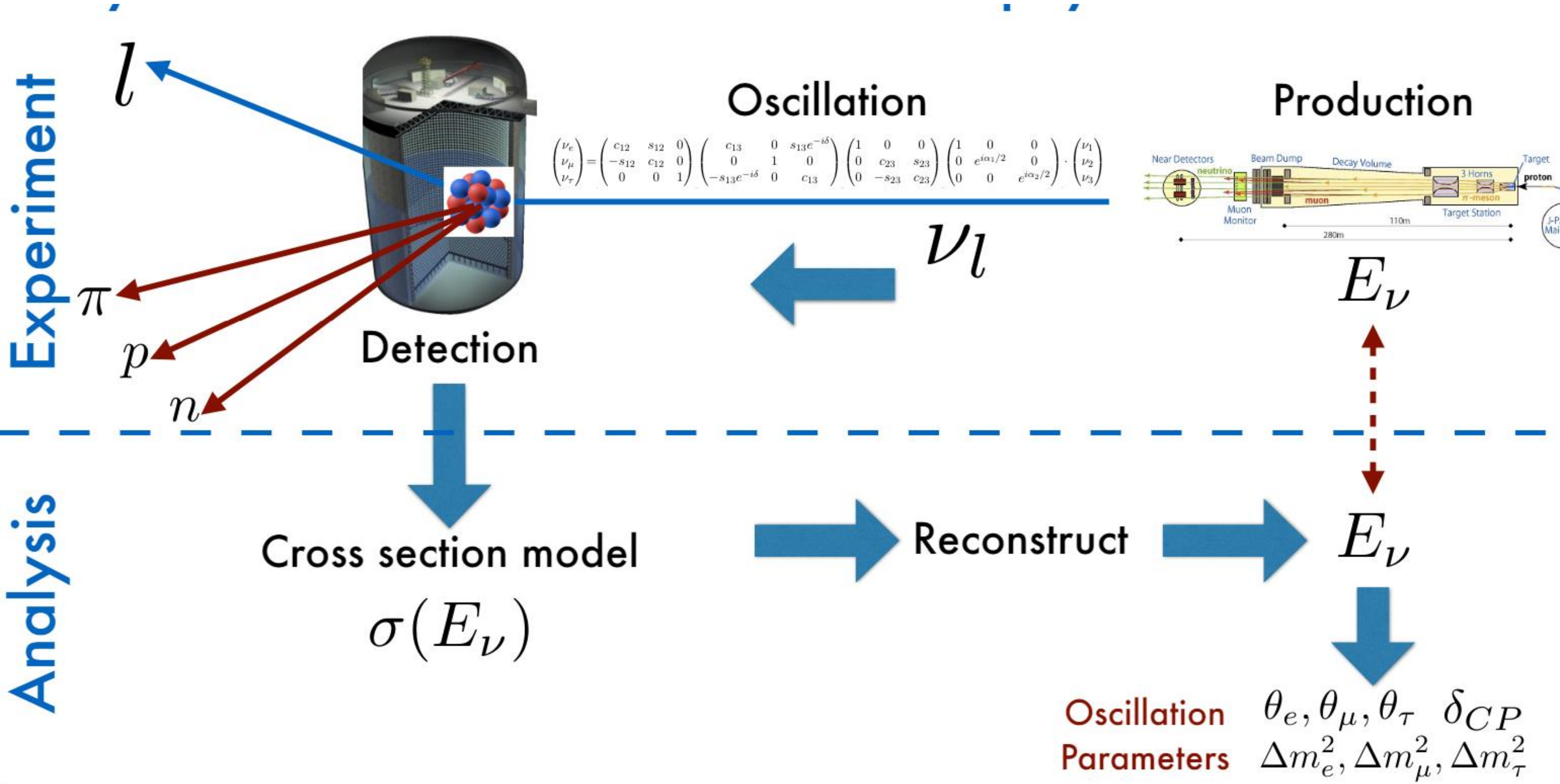
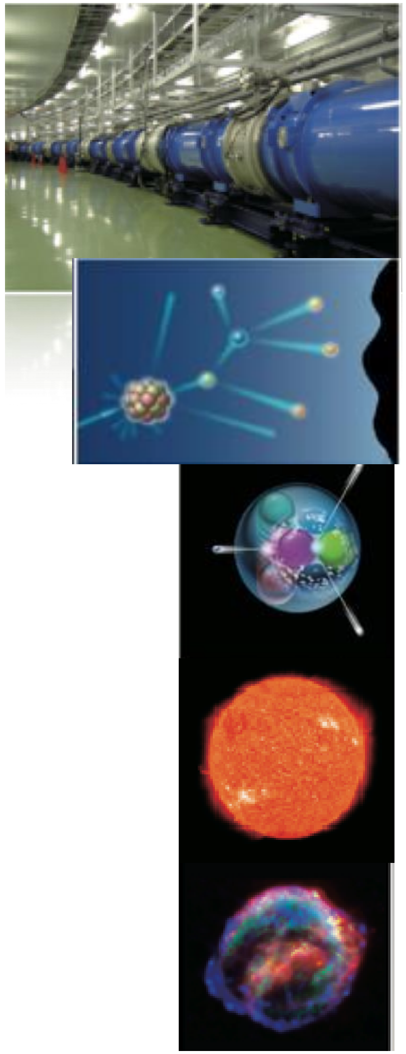


Experiment
Analysis
l
π
p
n
Detection
Oscillation
$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}c_{12}&s_{12}&0\\ -s_{12}&c_{12}&0\\ 0&0&1\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\ 0&1&0\\ -s_{13}e^{-i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}1&0&0\\ 0&c_{23}&s_{23}\\ 0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}1&0&0\\ 0&e^{i\alpha_1/2}&0\\ 0&0&e^{i\alpha_2/2}\end{pmatrix}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$
ν_l
Production
Near Detectors
neutrino
Beam Dump
Decay Volume
Target
proton
3 Horns
π-meson
muon
Muon Monitor
Target Station
110m
280m
E_ν
Cross section model
$\sigma(E_\nu)$
Reconstruct
E_ν
Oscillation Parameters
$\theta_e, \theta_\mu, \theta_\tau \quad \delta_{CP}$
$\Delta m_e^2, \Delta m_\mu^2, \Delta m_\tau^2$

Target sensitivity

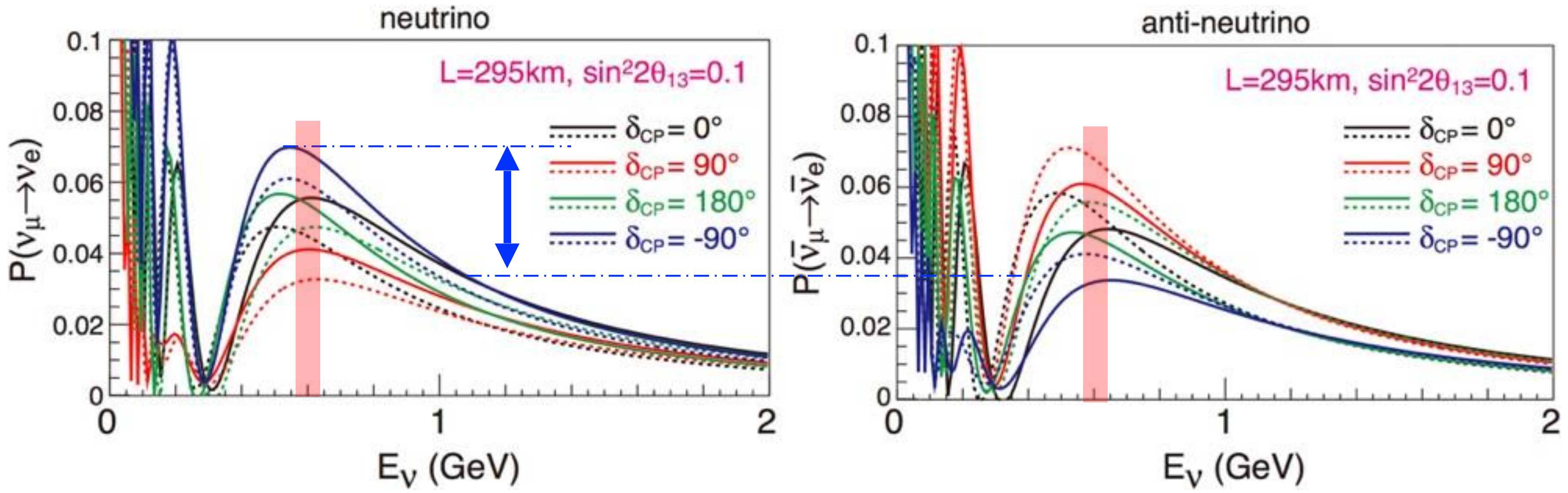


Physics category	Parameters	Sensitivity
LBL (1.3MW×10years)	δ precision	7°-20°
	CPV coverage (3/5σ)	76% / 58%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.017
ATM+LBL (10 years)	MO determination	>3.8σ
	Octant determination (3σ)	$\lvert\theta_{23}$-45°$\rvert$>2°
Proton Decay (20 years)	τ for $e^+\pi^0$ (3σ)	1×10^{35} years
	τ for νK (3σ)	3×10^{34} years
Solar (10 years)	Day/Night (from 0/from KL)	8σ/4σ
	Upturn	>3σ
Supernova	Burst (10kpc)	54k-90k
	Relic	70ν's / 10 years

Long-baseline program with the J-PARC neutrino beam

Experimental setup

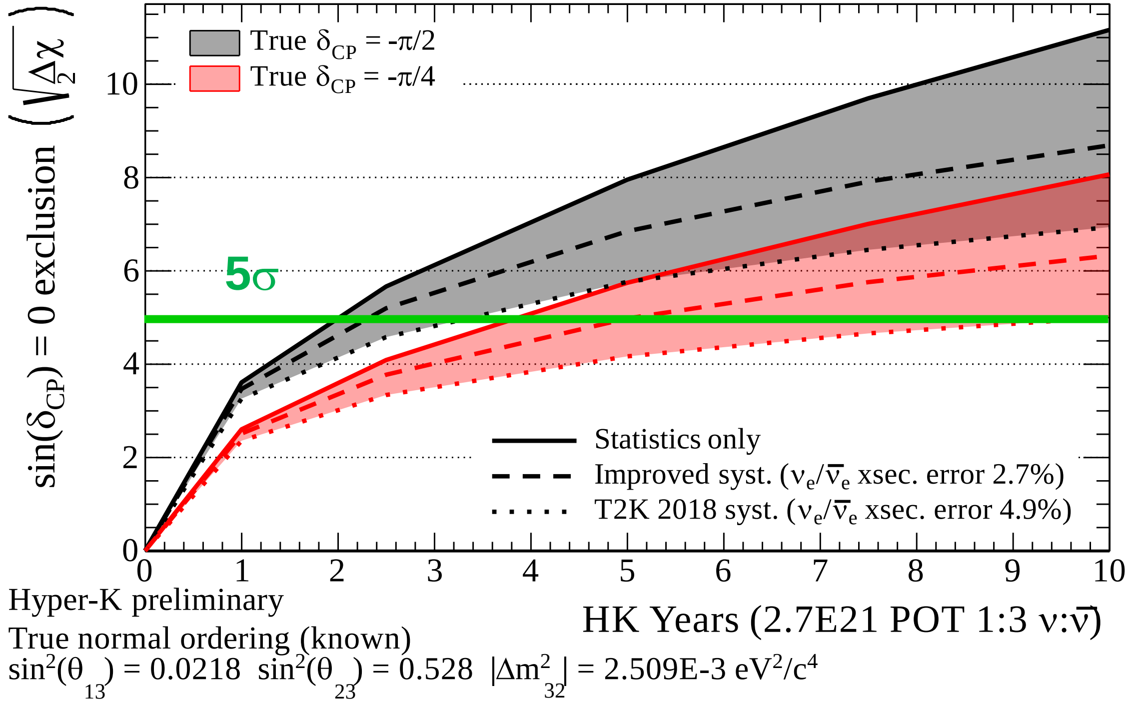
- 2.5° off-axis ν_μ and $\bar{\nu}_\mu$ beam peaked at 0.6 GeV (oscillation maximum at 295km)
  - Major interaction is QE: E_ν determined from (p, θ) of charged lepton
- Measures CP violation in neutrinos by comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

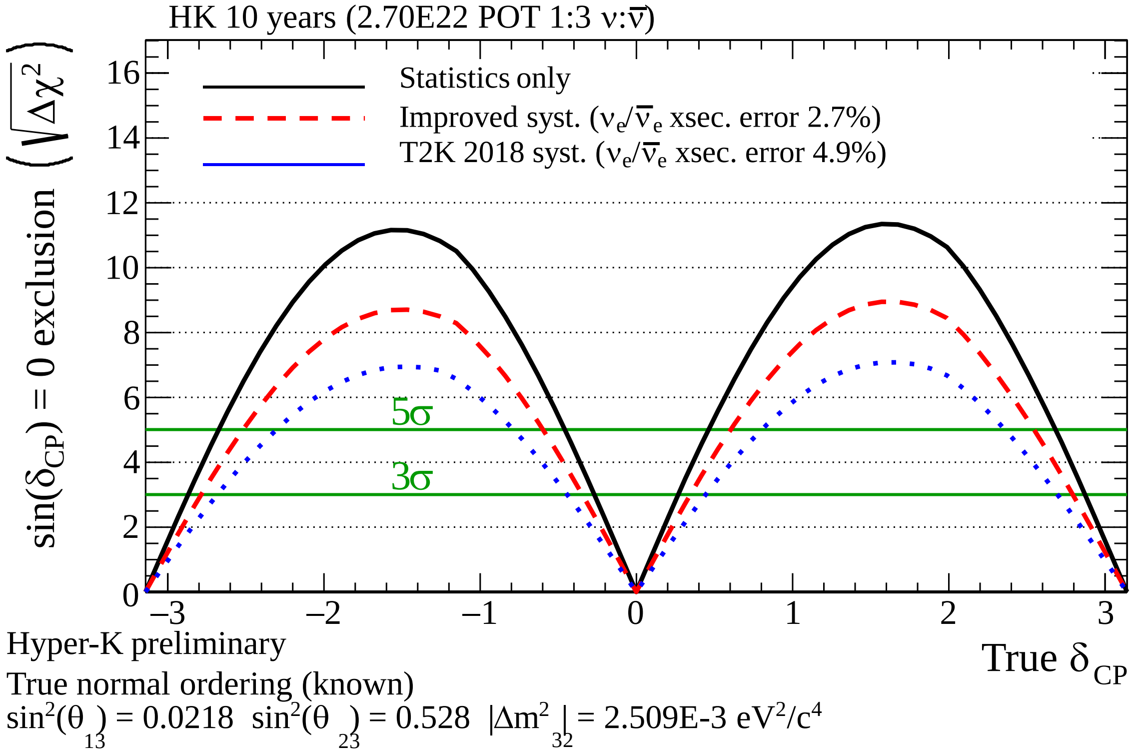


- A few % statistical uncertainties after 10 years operation with >1000 ν_e and $\bar{\nu}_e$ signals

CP violation sensitivity

- Sensitivity CP violation with 1:3 $\nu:\bar{\nu}$ beam





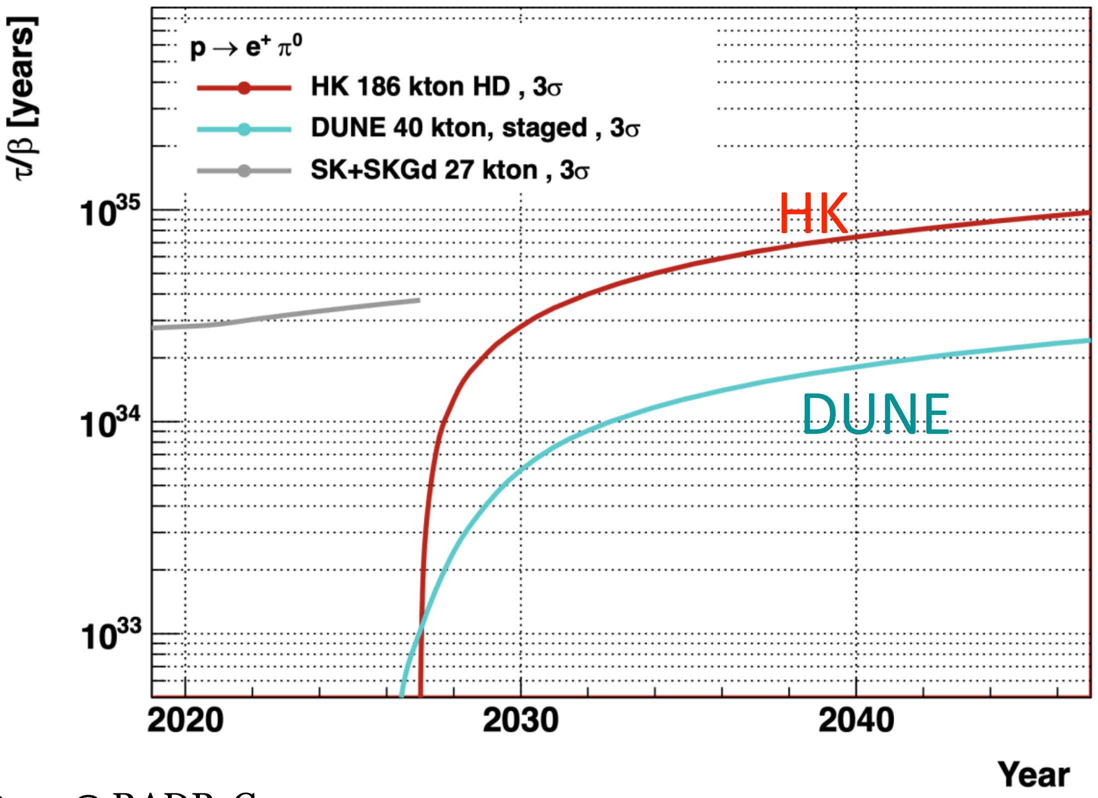
- With optimistic systematics and known mass ordering (MO): 2-3 years for 5σ sensitivity to exclude CP conservation for true $\delta CP = -\pi/2$.
- After 10 years of operation, 60% of δCP values excluded at > 5σ

Nucleon decay search

- Nucleon decay is evidence of Beyond Standard Model (BSM) and Grand Unified Theories (GUT)
- Examples of proton decay sensitivity in two modes:

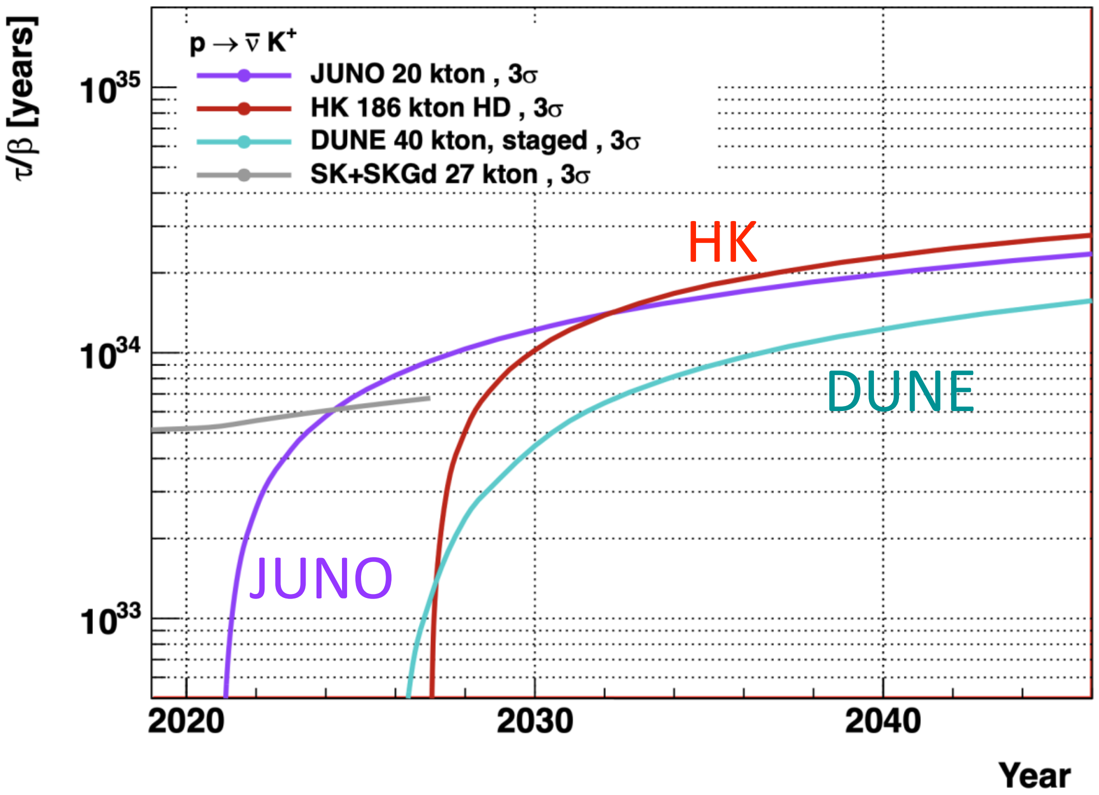
[HK] arXiv:1805 04163
[DUNE] arXiv:2002.03005
[JUNO] arXiv:1508.07166

$p \rightarrow e^+\pi^0$



$\tau \sim 10^{35}$ years (3σ)

$p \rightarrow \bar{\nu} K^+$



$\tau \sim 3 \times 10^{34}$ years (3σ)

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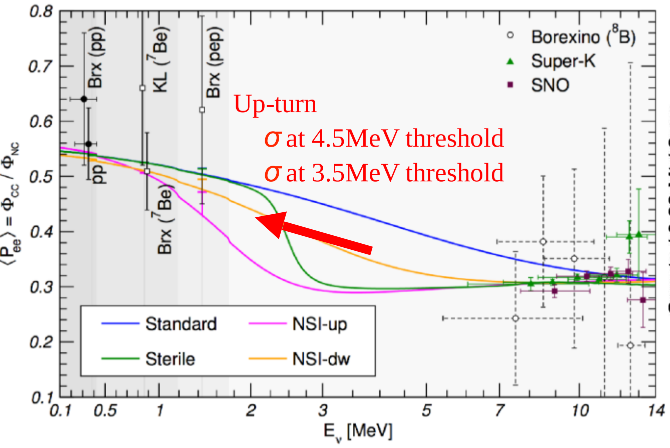
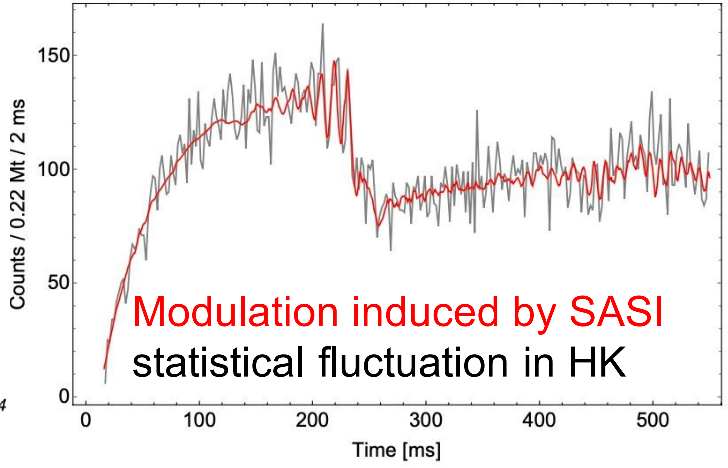
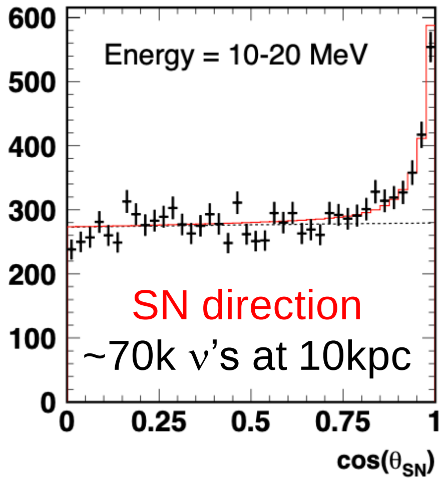
Neutrino astrophysics

- Observation of a few~10MeV neutrinos with time, energy and direction information
  - Unique role in multi-messenger observation
- **Solar neutrinos:** up-turn at vacuum-MSW transition, Day/Night asymmetry, hep neutrino observation
- **Supernova burst neutrinos:** explosion mechanism, BH/NS formation, alert with ~1° pointing
- **Supernova Relic Neutrinos (SRN):** stellar collapse, nucleosynthesis and history of the universe



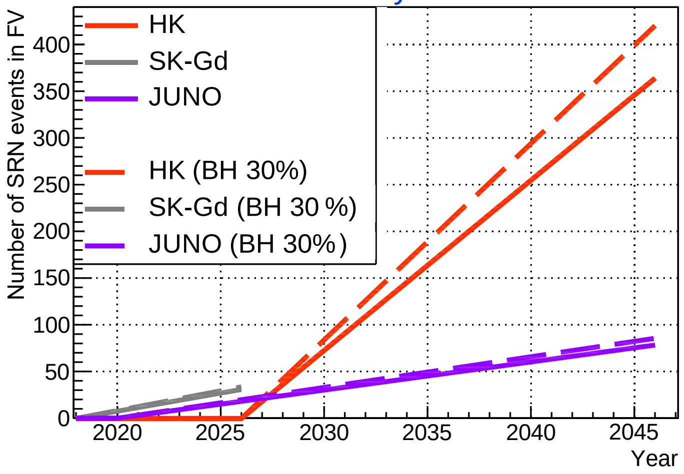
M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)





SRN rate

Calculation from FV and E_{th}
Efficiency is not accounted



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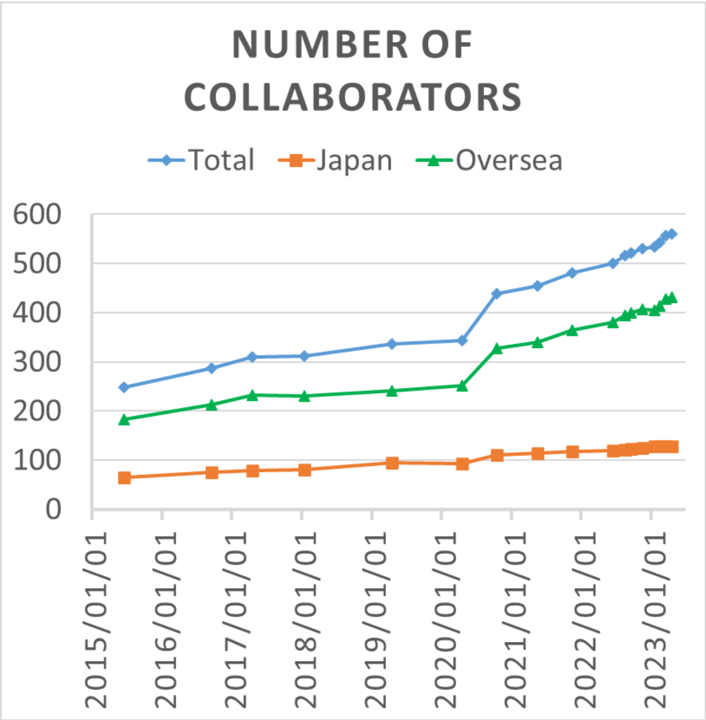
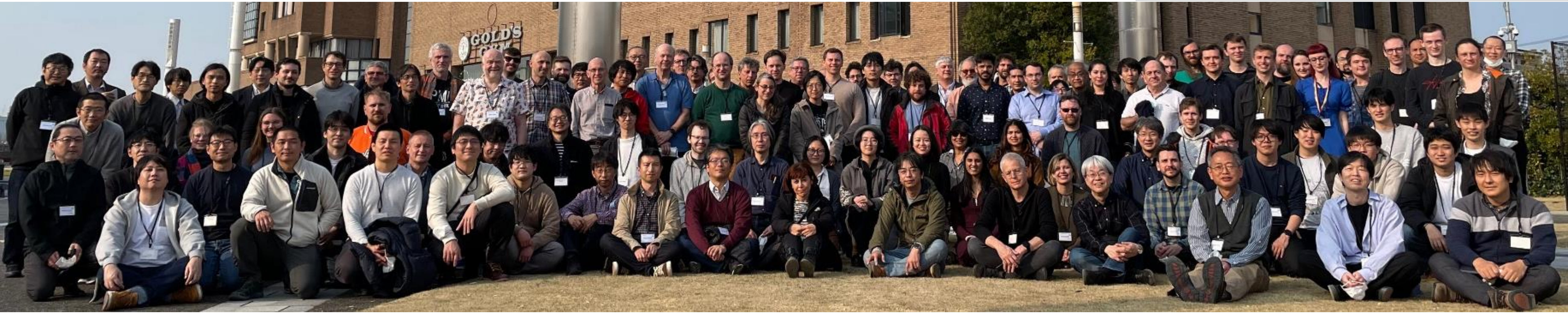
Hyper-Kamiokande Collaboration

- ~600 members located in 102 institutes from 22 countries
  - 25% Japanese / 75% non-Japanese
- Recently approved as a recognized experiment (RE45) at CERN

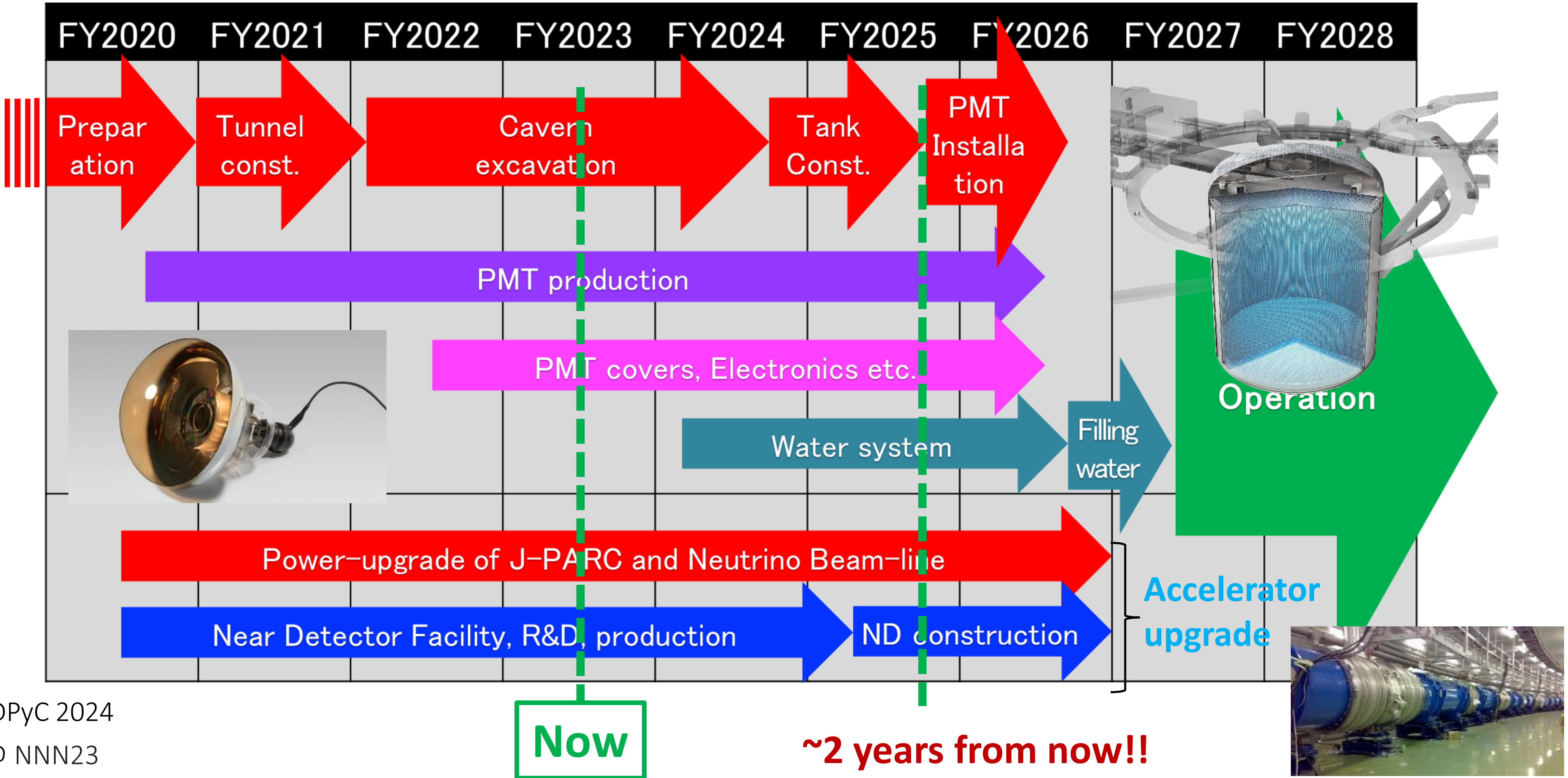
- March 2023:
  our very 1st Collaboration meeting in person after COVID!





Hyper-K construction schedule

- The Hyper-K construction started in 2020 and will start operation in 2027.
- We are in the middle of the civil construction and starting to produce detector components.



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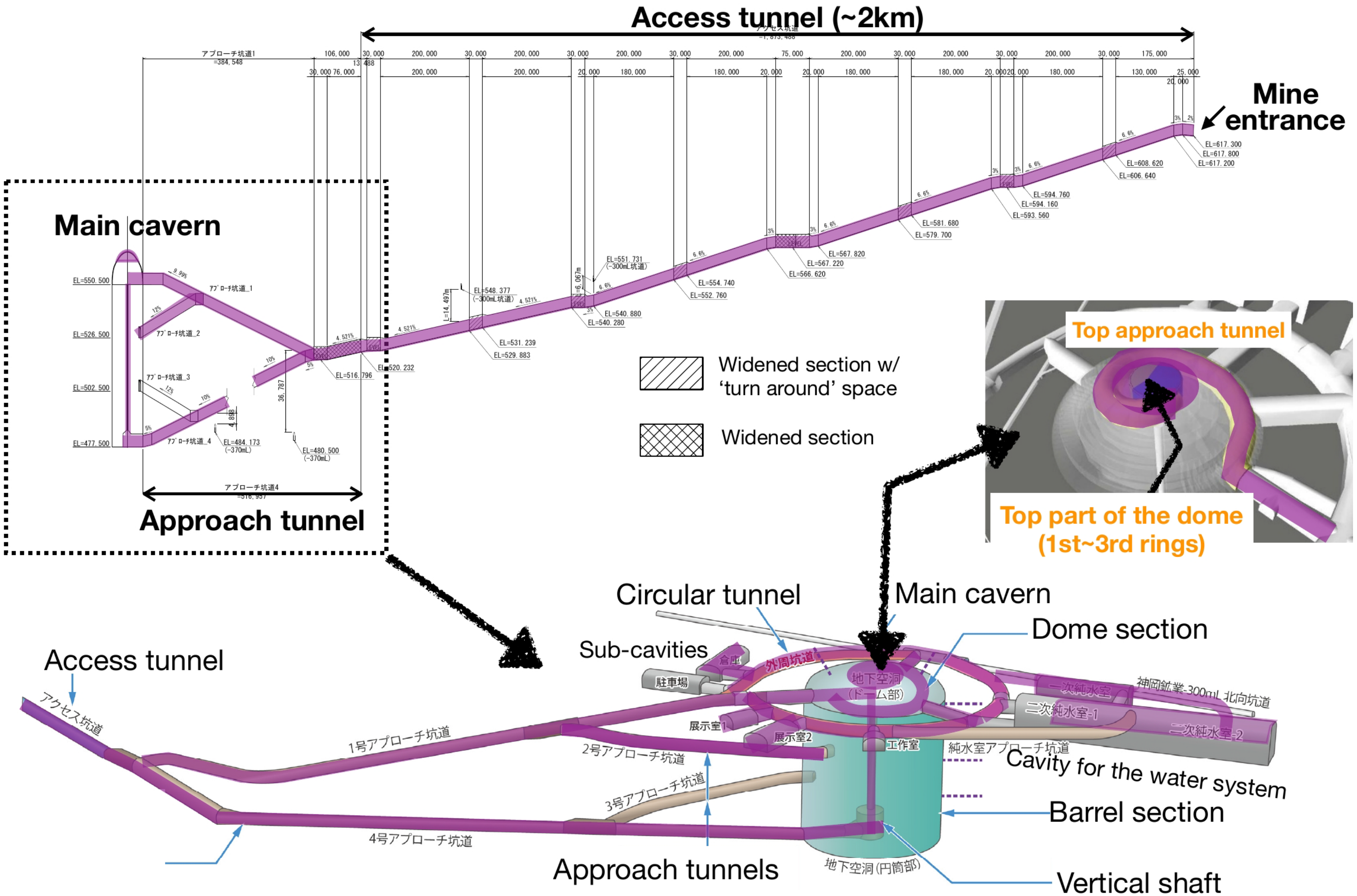
Hyper-K caverns excavation



- Access tunnel excavation completed.
- Approach & circular tunnel excavation completed.
- Main cavern excavation has started ! → On-time !

Access tunnel excavation

Access tunnel excavation completed on schedule.

Center of the future Hyper-K Main Cavern's Dome reached in June 2022

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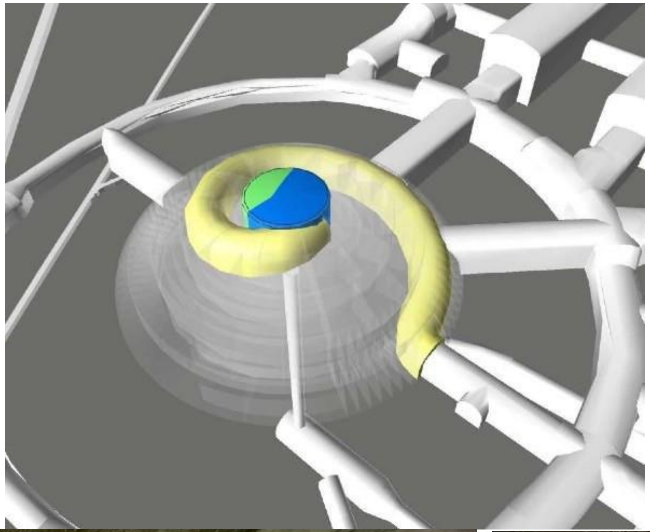
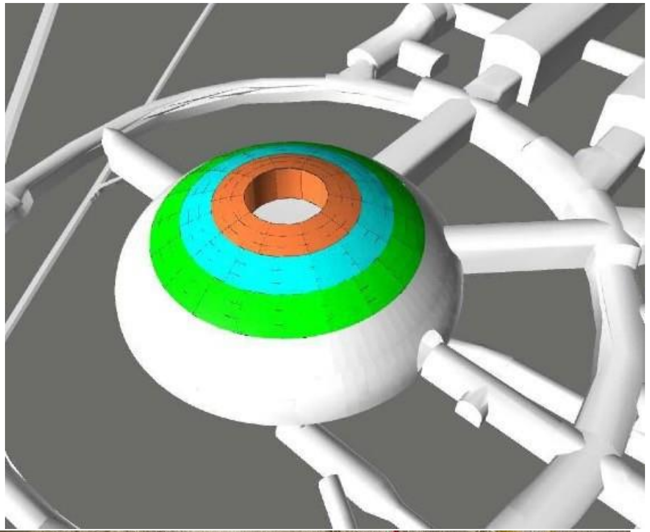
Hyper-K main cavern excavation

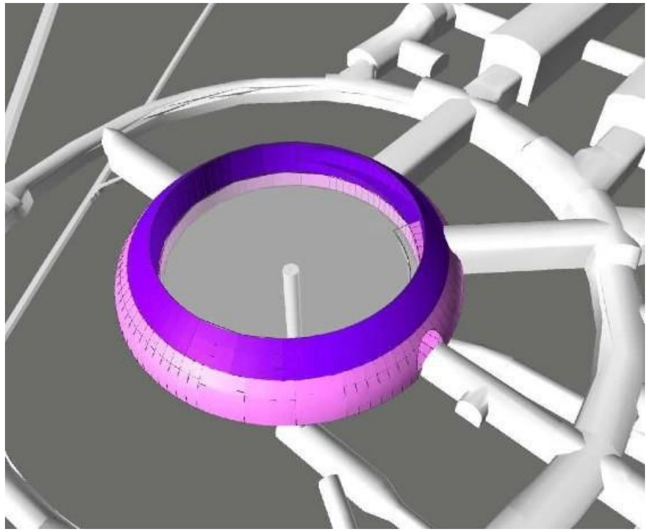
First ring

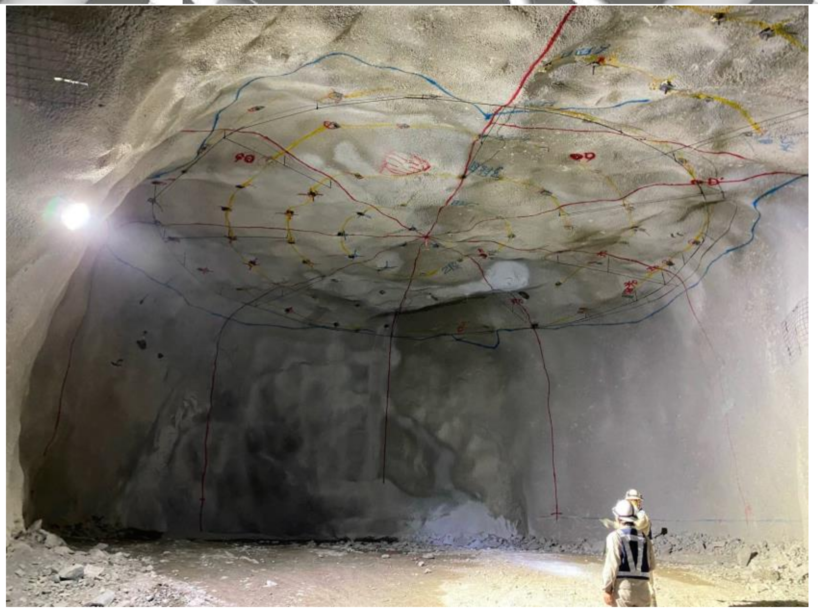


2nd - 4th rings



5th - 6th rings





Cavern dome constructed in consecutive rings

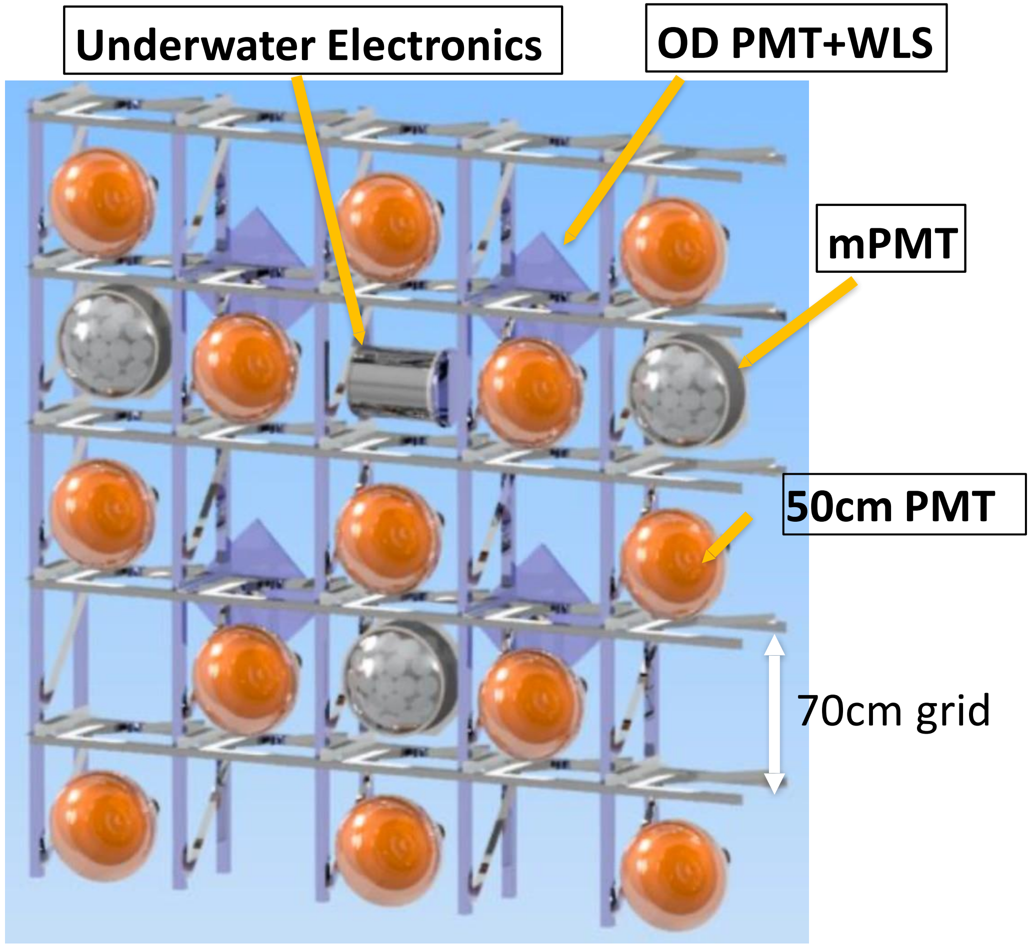
Hyper-K main cavern excavation

- **<u>October 3, 2023:</u>** Excavation of the dome section completed.
  - 69m diameter, 21m height
  - One of the largest human-made underground space.
- Now, the excavation of the barrel section is ongoing.

Katsuki Hiraide @ NNN23

Hyper-K detector configuration

- **Inner Detector (ID)**
  - 64.8m diameter, 65.8m height
  - 50cm PMTs will be installed
  - Multi-PMT (mPMT) modules will be integrated as hybrid configuration
- **Outer Detector (OD)**
  - 1m (barrel) or 2m (top/bottom) thick
  - 3-inch PMT + WLS plate
  - Walls are covered with high-reflectivity Tyvek sheets
- **Under-water electronics**
  - Mitigate disadvantage of long cables



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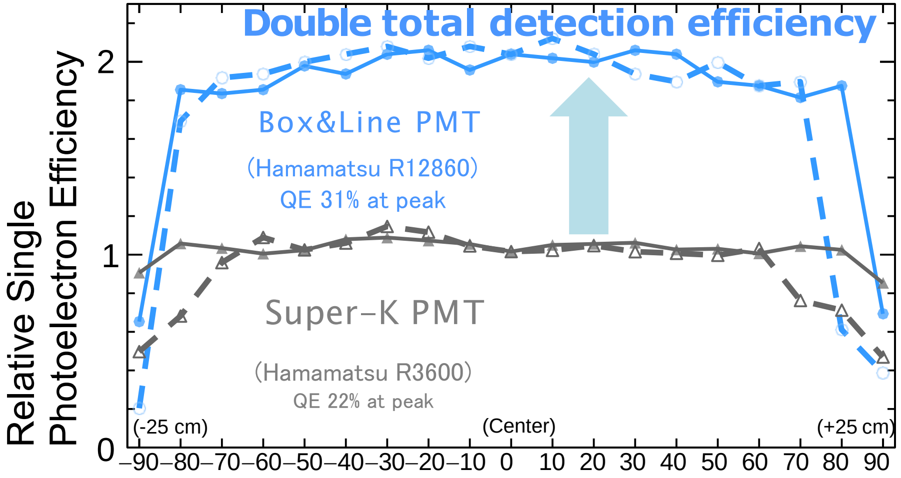
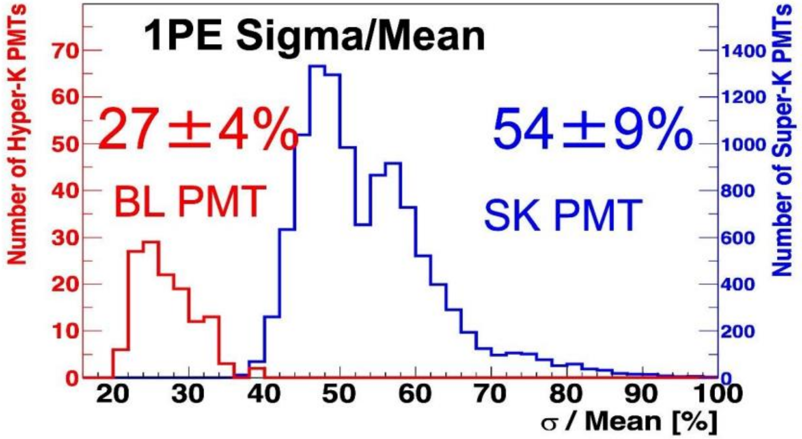
Hyper-K 50cm PMT performance

(Performance in SK tank, 1.7e7 gain)

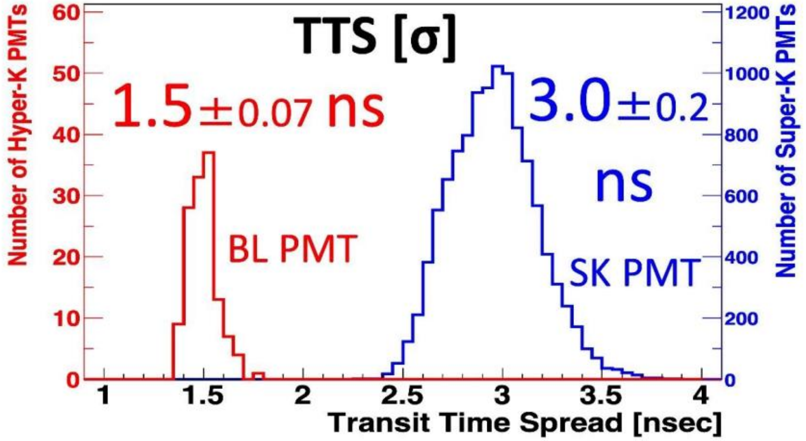
×2 better photodetection efficiency (QE×CE)



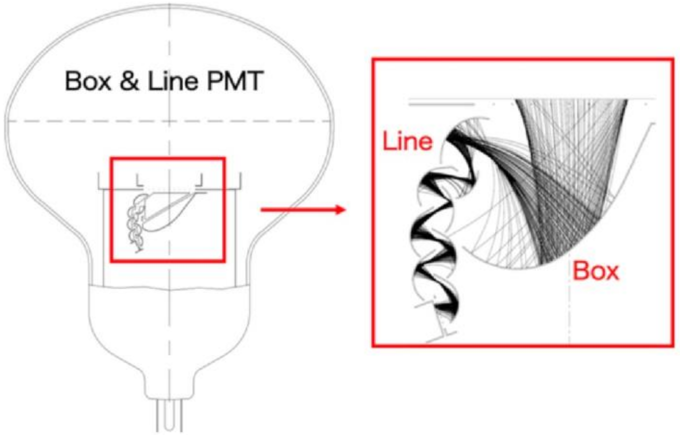
×2 better charge resolution



×2 better timing resolution



Box&Line dynode



×2 better pressure tolerance
→ enable deeper tank design, project cost reduction

All PMTs will be tested >0.85MPa

Low dark rate (4kHz) and RI

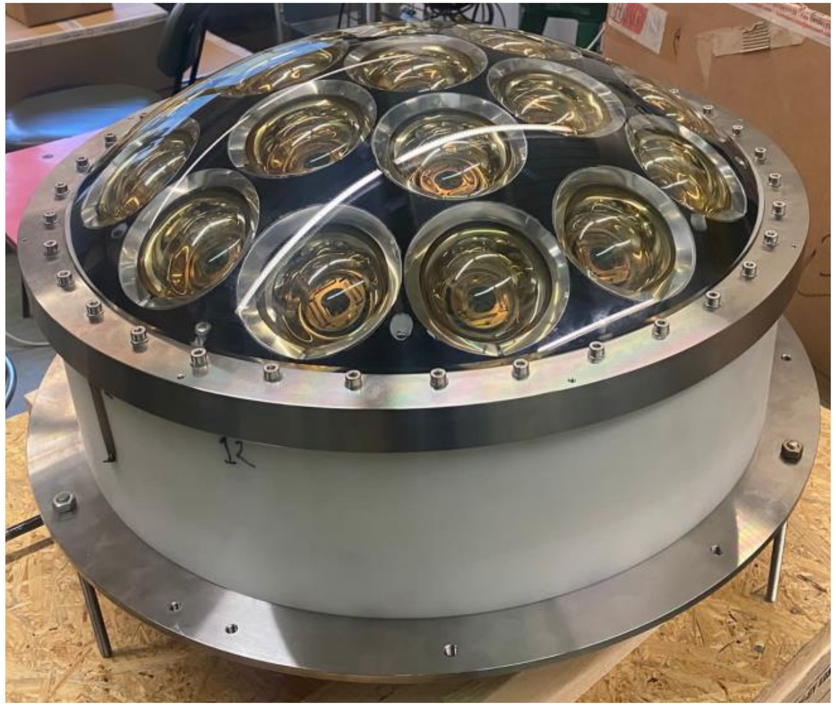
Hyper-K 50cm PMT production

- Mass production started in Dec. 2020.
- Production was suspended to investigate their defect rate in April 2022.
- From May 2023, production resumed after improvement and screening by manufacturer.
- Delivery completion remains unchanged as originally scheduled.
- Constant quality inspections at Kamioka are ongoing.

Hyper-K Photosensors

Multi-PMT (mPMT) modules

- 19 3-inch PMTs and electronics arranged inside a pressure resistant vessel
- Improvements for Cherenkov ring reconstruction and reference for detector calibration



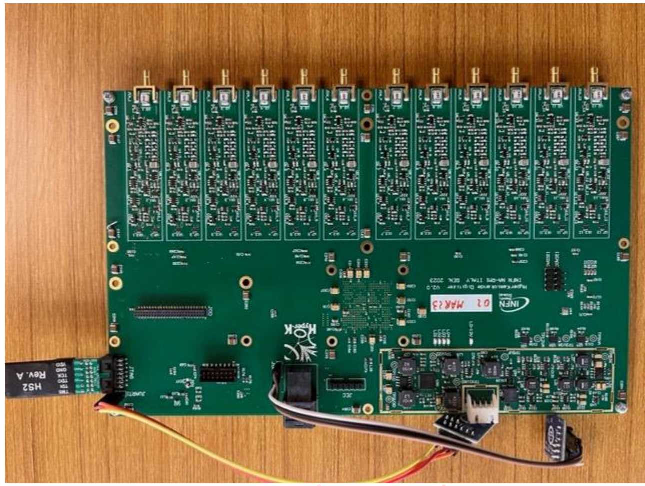
OD PMT+WLS units

- 3-inch PMT attached to wavelength shifting plate
- To veto cosmic-ray muons

Design finalization ongoing

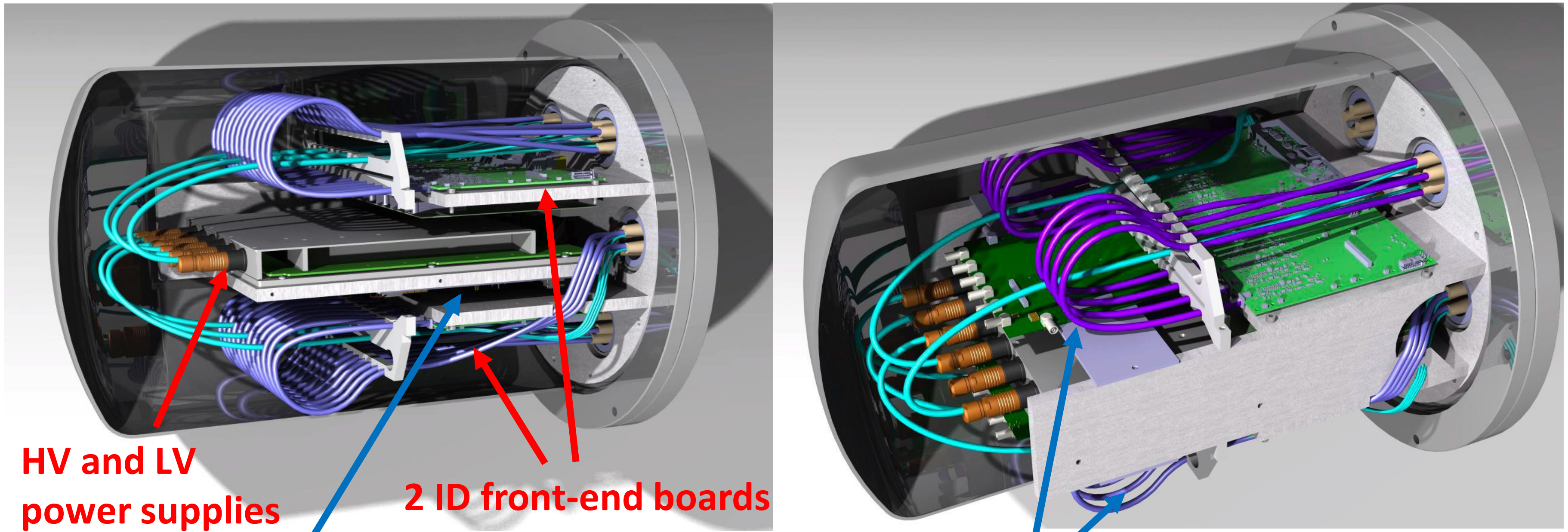
Hyper-K Electronics

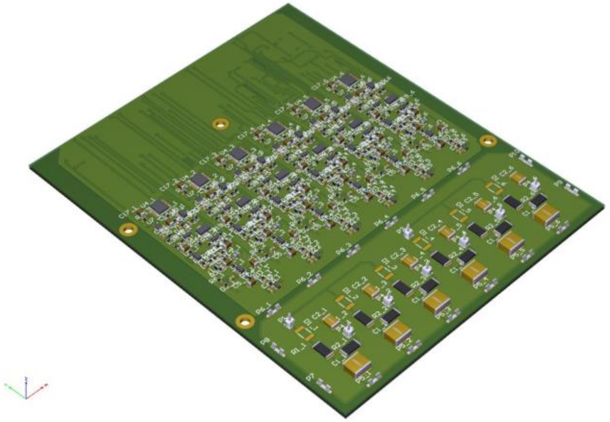
- Front-end electronics placed in underwater vessels
- Two types of underwater electronics vessels
  - Inner detector vessels: 24 ID channels read out by two PCBs
  - Hybrid outer + inner detector vessels: 20 ID + 12 OD channels



ID 12-channel
front-end board

Preliminary





OD 6-channel FE board

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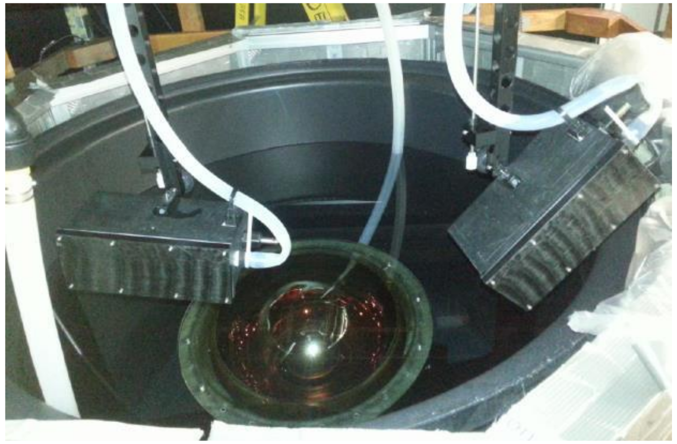
Hyper-K Calibration

- Various programs to determine detector parameters and measure systematics

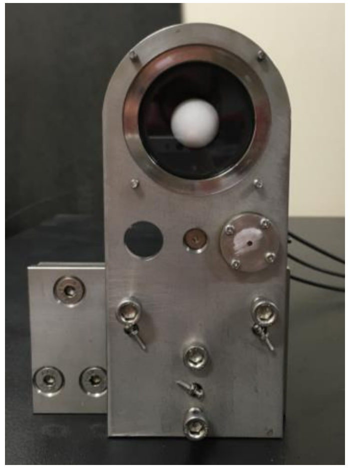
- Pre-calibration of photosensors
- Photogrammetry
- Light Injection
  - Diffusers and collimators
  - mPMT system
  - OD injectors
- Electron LINAC
  - 3-24 MeV electrons
- Radioactive Sources
  - DT Source - 16N
  - AmBe + BGO – tagged neutrons
  - Ni/Cf - 9 MeV g cascade

Photosensor Test Facility

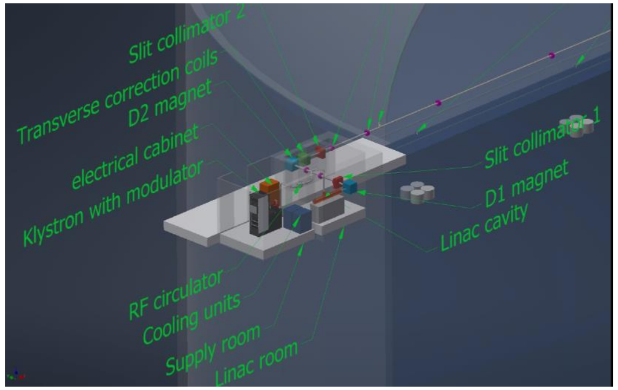


Photogrammetry testing

Light injectors

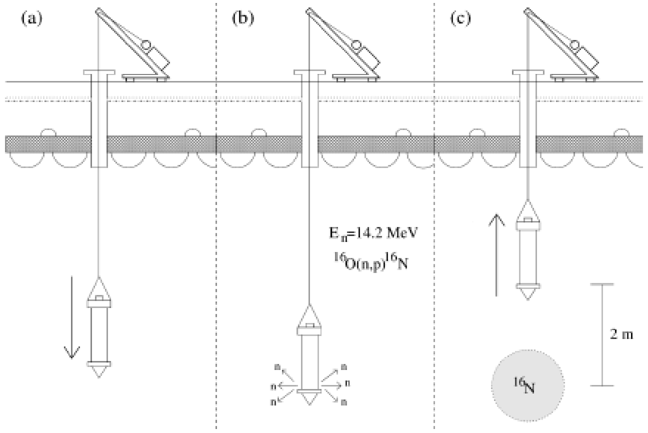


LINAC beam simulation



Ni/Cf source

DT operation



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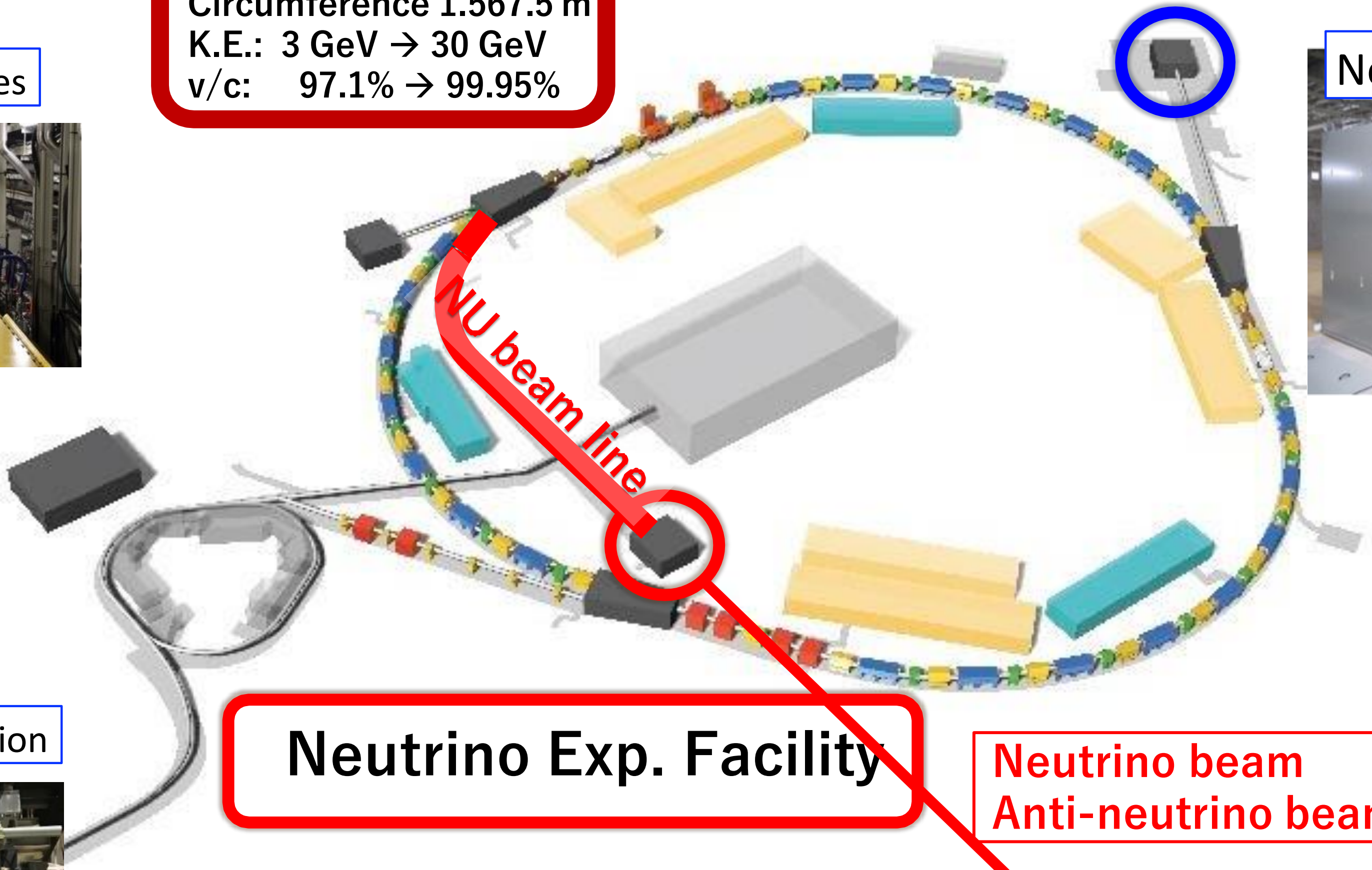
J-PARC Upgrade

MR-RF cavities

Main Ring
Circumference 1.567.5 m
K.E.: 3 GeV → 30 GeV
v/c: 97.1% → 99.95%

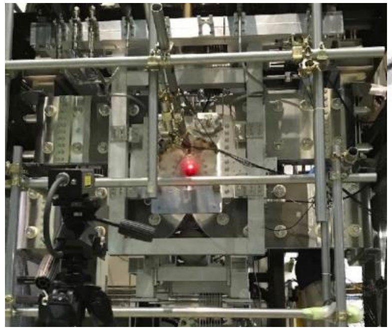


Neutrino Exp. Facility

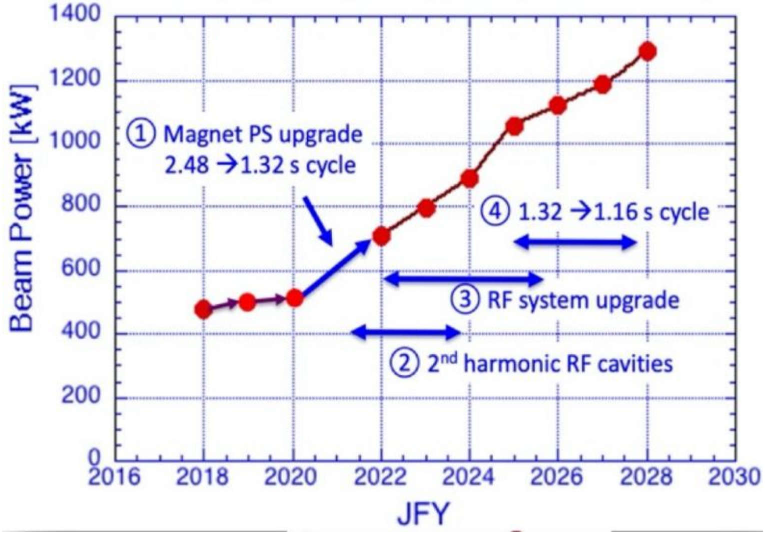
Neutrino beam
Anti-neutrino beam

New main magnet PS for high rep. rate

320kA horn operation

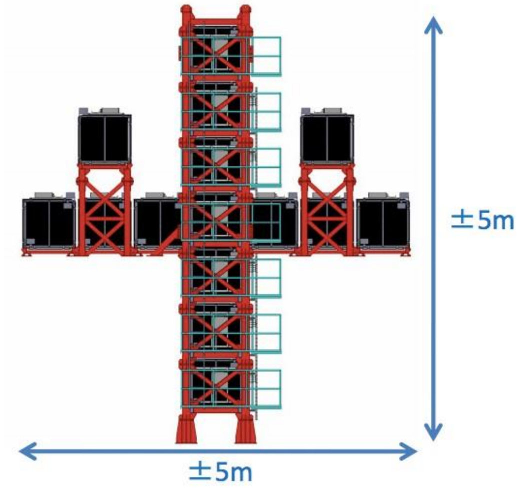


Achieved 515 kW in JFY2020
Aiming 1.3 MW by JFY2028

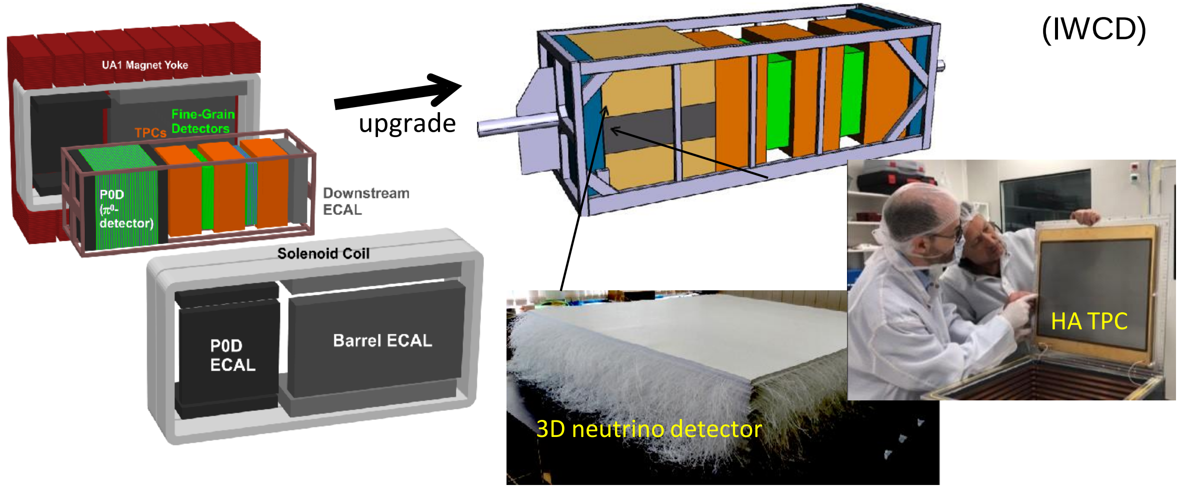


Neutrino detectors at J-PARC

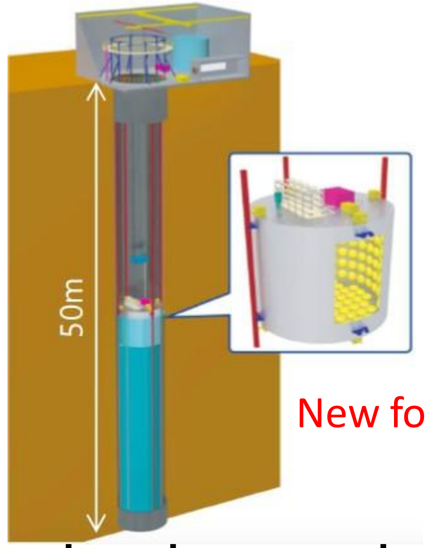
On-axis Detector
(INGRID)



Off-axis Magnetized Tracker
(ND280→Upgrade for T2K →Upgrade for HK)



Off-axis spanning Intermediate water Cherenkov detector
(IWCD)



New for HK

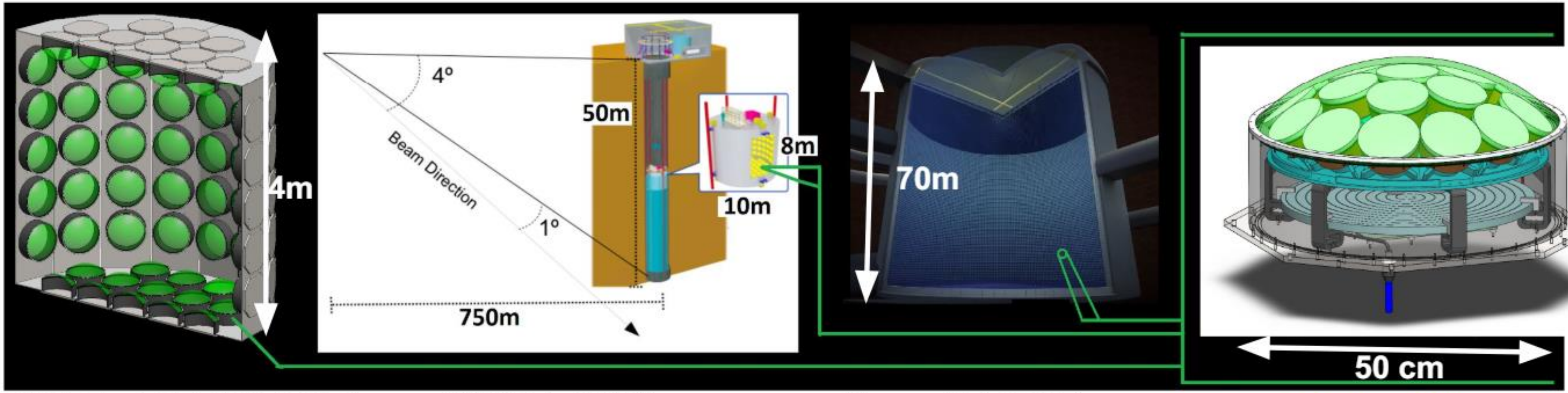
Critical components to precisely understand J-PARC beam and neutrino interactions:

- **On-axis detector:** Measure beam direction and event rate
- **Off-axis magnetized tracker:** Measure primary (anti)neutrino interaction rates, spectrum, and properties. Charge separation to measure wrong-sign background
  → Upgrade by T2K experiment and Intensive discussion for further upgrade in HK-era is on-going.
- **Intermediate WC detector:** H_2O target with off-axis angle spanning orientation.
  → Detector site investigation and conceptual facility design are on-going.

Conclusions (fist part)

- Hyper-Kamiokande is 3rd generation water Cherenkov detector in Kamioka
- Important physics targets
  - Neutrino CP violation: Discovery with 5 σ for ~60% parameter regions
  - Nucleon Decay Search for testing GUT: $\tau > 10^{35}$ years for $p \rightarrow e^{+}\pi^{0}$
  - Neutrino Astrophysics: Supernova neutrinos
- Hyper-Kamiokande construction on schedule
  - World's largest underground facility: 260 kton water Cherenkov detector
  - Access tunnel and cavern construction on track
  - 50cm PMT production underway
  - Other detector component designs being finalized
  - Neutrino beam upgrade to 1.3 MW
  - Near detector upgrade and design of intermediate detector being finalized
- Hyper-Kamiokande will start operation in 2027.

mPMT for detector suite



WCTE at CERN (~2021) **IWCD** (~2026) **Hyper-K** (~2027)

mPMT module
19 forward looking 7.7-cm PMTs

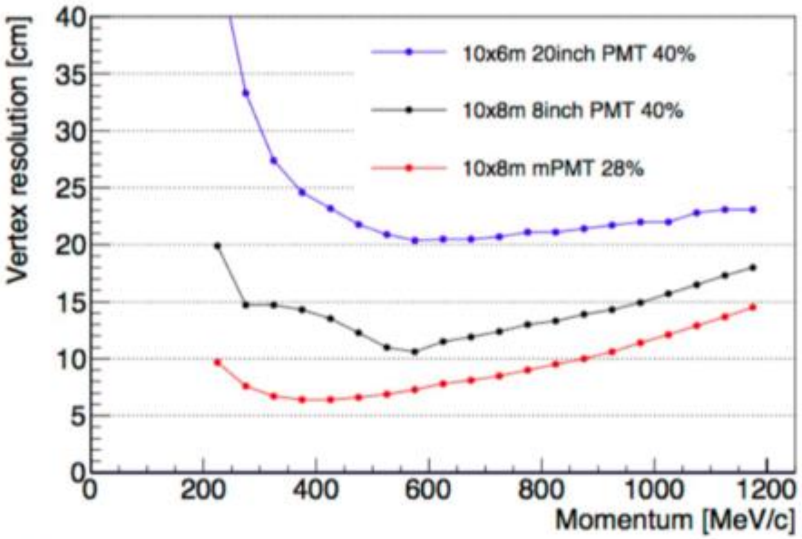
Hyper-K host 40k nominal 50-cm Inner Detector (ID) PMTs.
International contribution ~5k mPMT modules

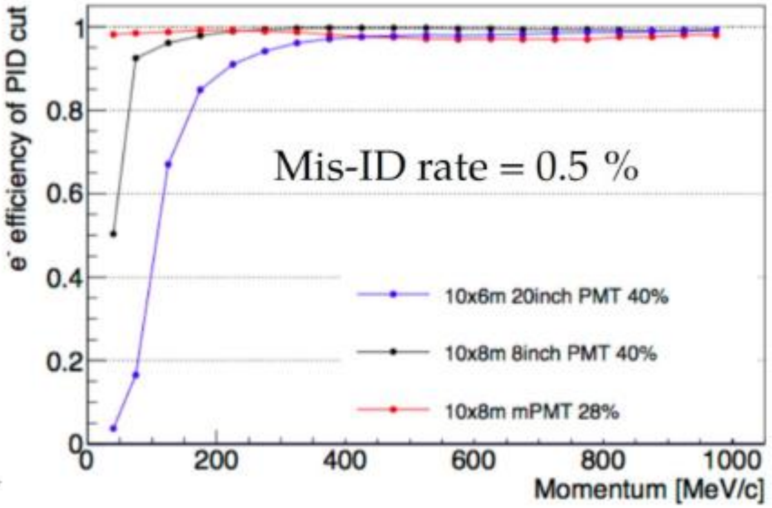
IWCD requires ~500 mPMT
Water Cherenkov Test Experiment (WCTE) at CERN ~120 mPMT
From LOI CERN-SPSC-2019-042 ; SPSC-I-254

Concept from KM3NeT

Why mPMT?

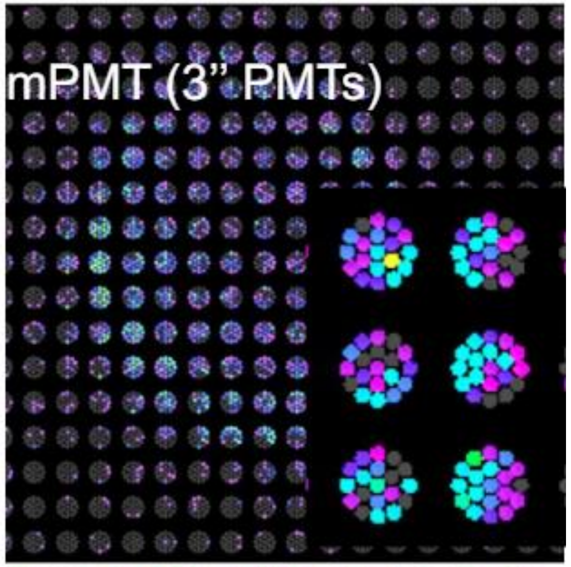
IWCD simulation and reconstruction with mPMTs.

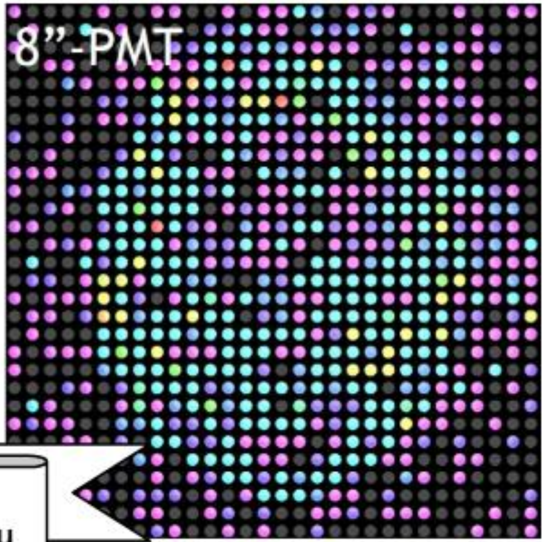




- -Improve vertex resolution, Improved PID
- -essential for smaller water cherenkov detectors
- -Finer granularity, good timing resolution
- -each of 19 3'' PMTs have different orientations
- -information on the direction of each detected photon
- -improve dark hit discrimination and event reconstruction.
- -vessel houses digitization electronics and calibration sources.
- -Finer Granularity also helps reconstruction for Hyper-K
- -Currently developing ML analysis

See **ML** talk:
N. Prouse, 2:30pm Thu





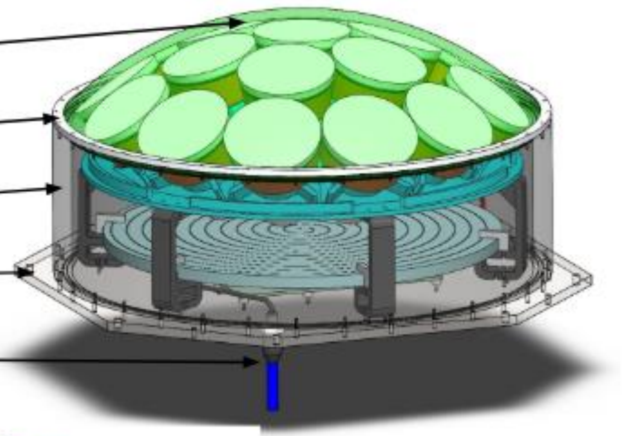
Hyper-Kamiokande

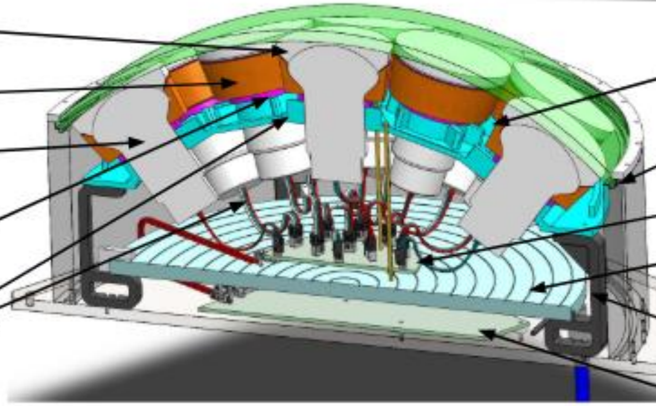
Requirements and components

TRIUMF

pressure tolerant to 20m-80m

compatible with ultrapure water





Prototype mechanically ready for IWCD. We are going through an optimization phase of the vessel to have the same design/assembly for both IWCD and Hyper-K.

mPMT cup and PMT support matrix

Currently 3D printing cups at TRIUMF.

New spherical and thin matrix model with extra holes for orientation with cup with pins.

3D printing at ForgeLabs in Canada.

-we are trying to make a version with less material

→ looking into mass production options:

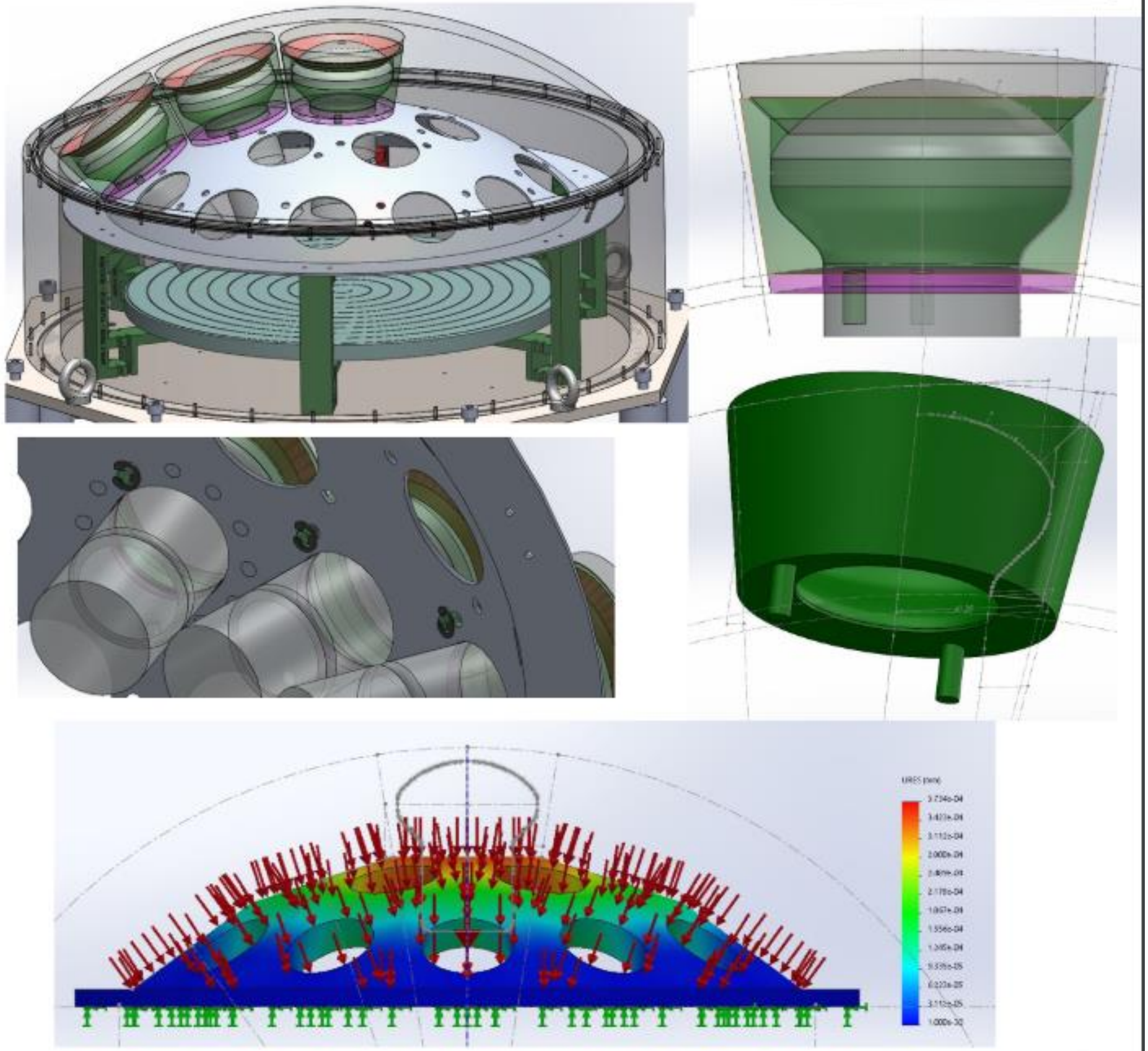
Ensinger

-*Reaction mold* (casting) in Europe

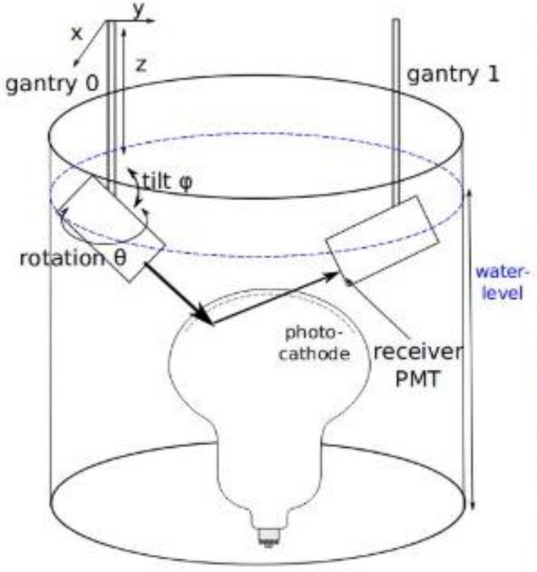
-*Thermoforming and 5-axis CNN machining* in USA

ZenZen: *injection molding* in Mexico

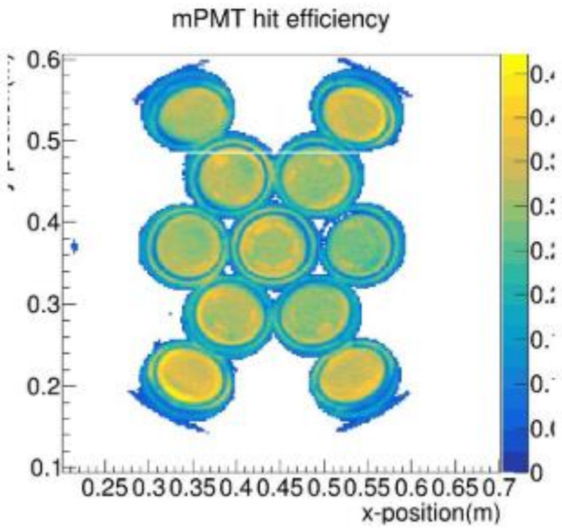
Deformation, Strain, Stress, and FOS simulations in SolidWorks and ANSYS

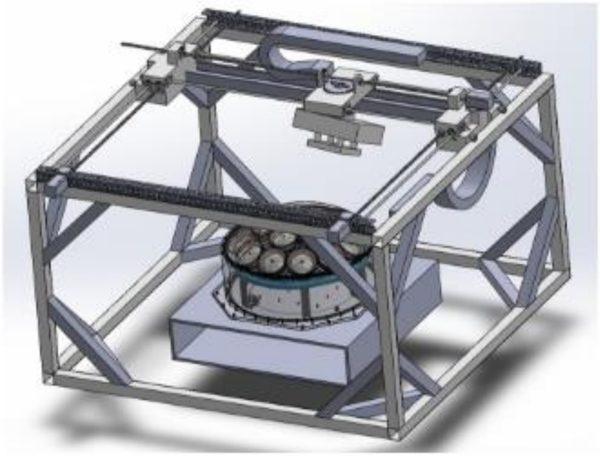


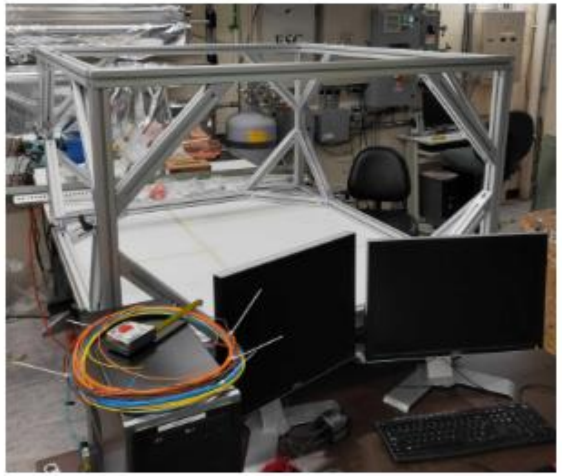
Test stand

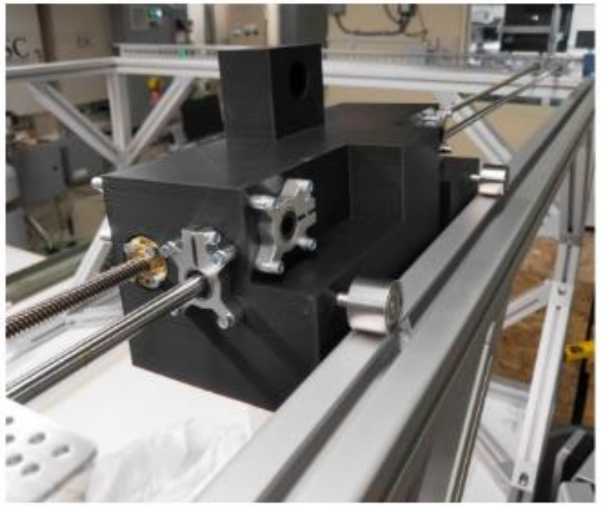


- Used Photosensor Testing Facility (PTF) at TRIUMF to get hit efficiency from old mPMT prototype.
- Developing a **NEW mPMT test stand** as a simplified PTF version for mass production testing.
  - shoot photons (laser) at different wavelengths (325, 400, and 500 nm) from all angles.









(Dis)assembly test [VIDEO]

-**<u>Good contact</u>** between **acrylic dome** and **gels**

https://docs.google.com/file/d/1ketHoMZkY_D-a2U4ZP5TKWbrSPwUp1r5/preview

Work at local national institutions

- CF-2023-G-643 "Construcción y comisionado de sensores de ciencia frontera para la detección de supernovas, materia oscura, y medición de la asimetría bariónica en el Universo, en experimentos de Neutrinos de nueva generación" (2023)
  - Responsable técnico: Eduardo de la Fuente Acosta (UdeG)
  - Instituciones participantes:
    - KAREN SALOME CABALLERO MORA (UNACH)
    - GIANNINA DALLE MESE ZAVALA (UAS)
    - ALEJANDRO KADSUMI TOMATANI SANCHEZ (TEC-GDL)
    - Saul Cuen Rochin (TEC-SIN)
- CBF2023-2024-427 "Deep Learning y Fabricación de Sensores de Ciencia de Frontera para Experimentos de Neutrinos de Próxima Generación" (2024)
  - Responsable técnico: Saul Cuen Rochin (TEC-SIN)
  - Institución colaboradora:
    - GIANNINA DALLE MESE ZAVALA (UAS)

CONAHCYT
Consejo Nacional de Humanidades Ciencias y Tecnologías

Ongoing work…

Master thesis in progress (**TEC**):
- Neutrino Classification Through Deep Learning amid the Hyper-Kamiokande Project Development

Student: Maria Fernanda Romo Fuentes
Advisor: Dr. Luis Eduardo Falcon Morales

Doctoral thesis in progress (**UdeG**):
- Use of Machine Learning and Deep Learning in the reconstruction of high energy events for the Hyper Kamiokande

Student: Felipe Orozco Luna
Advisors: Dr. Eduardo de la Fuente, Dr. Luis Eduardo Falcon, Dr. Saul Cuen

Thesis open position (**UAS**):
- Analysis for supernova detection

Advisor: Dra. GIANNINA DALLE MESE ZAVALA

Thesis open position (**UNACH**):
- Analysis for supernova detection

Advisors: Dra. KAREN SALOME CABALLERO MORA

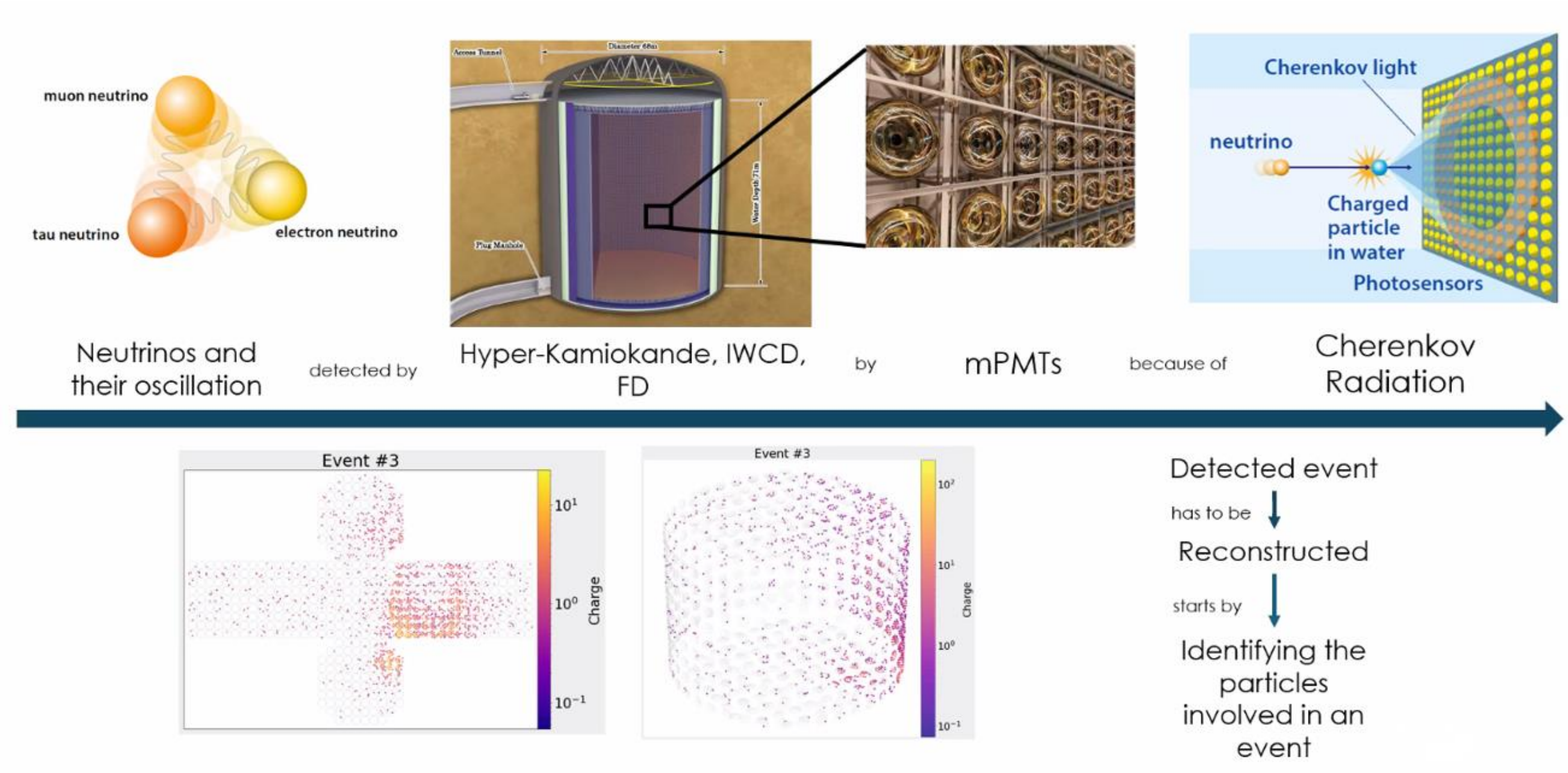
Thesis open position:
- Neutrino Classification with AI

Advisors: Dr. Saul Cuen, (volunteers?)

Thesis open position:
- mPMT design and manufacturing for Hyper-K

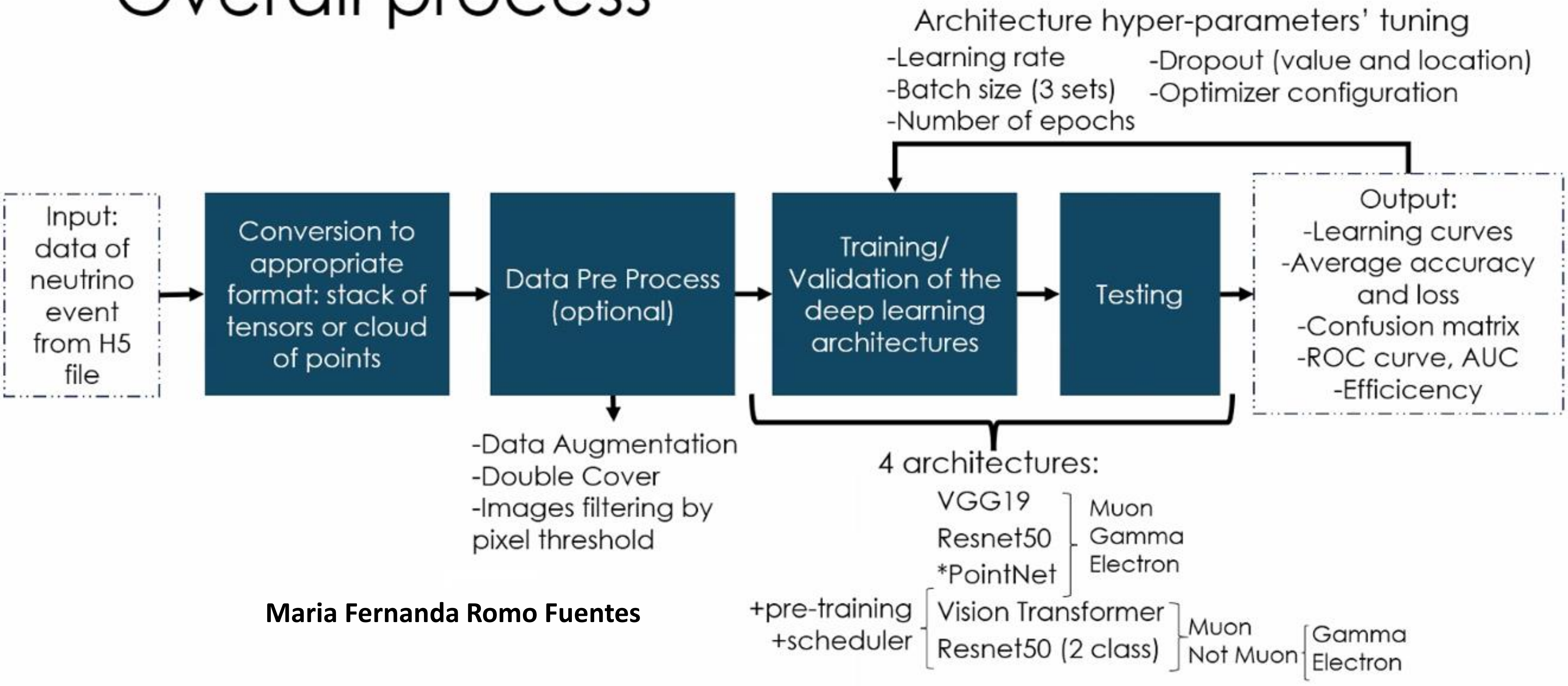
Advisors: Dr. Saul Cuen, (volunteers?)

Neutrino classification



Maria Fernanda Romo Fuentes

Overall process

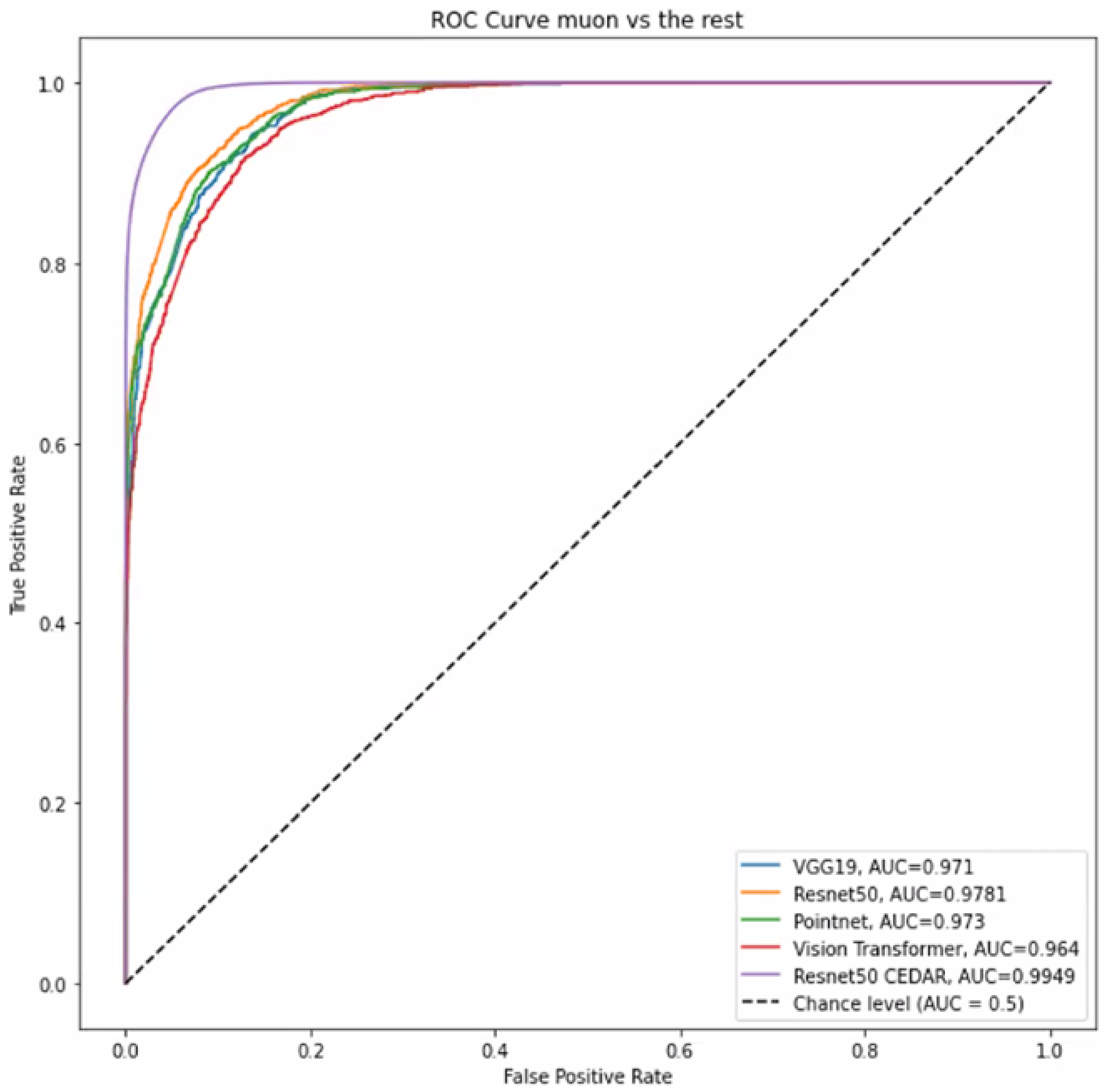


Maria Fernanda Romo Fuentes

Muon

Model	Background	Efficiency
VGG19	gamma+electron	68.88%
ResNet50	gamma+electron	70.96%
PointNet	gamma+electron	66.29%
Vision Transformer	not muon	60.59%
ResNet50 Cedar Dataset	gamma+electron	79.39%

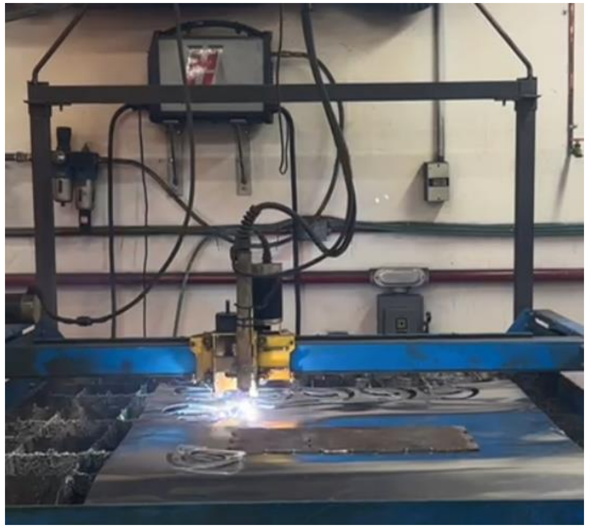
Maria Fernanda Romo Fuentes

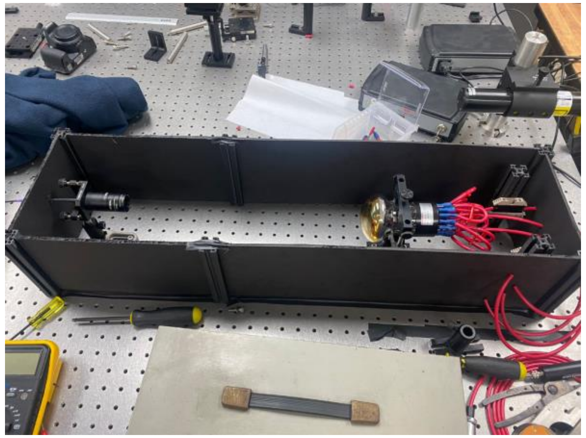


mPMT prototype in Mexico

mPMT assembly and testing at TEC in collaboration with Professors Rodrigo Salmon, Kadsumi Tomatani, Raul Aranda, Christoper Falcon, Eduardo de la Fuente and Saul Cuen

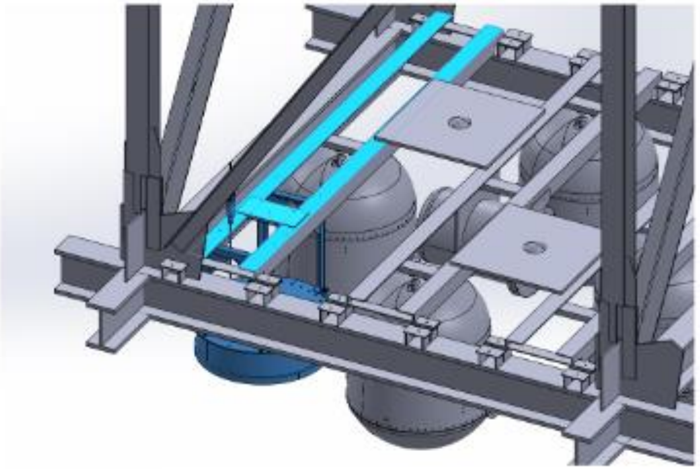
- Mechanical metrology and assembly
- Setting un blackbox and optical testing for PMT check (student Roy Medina)

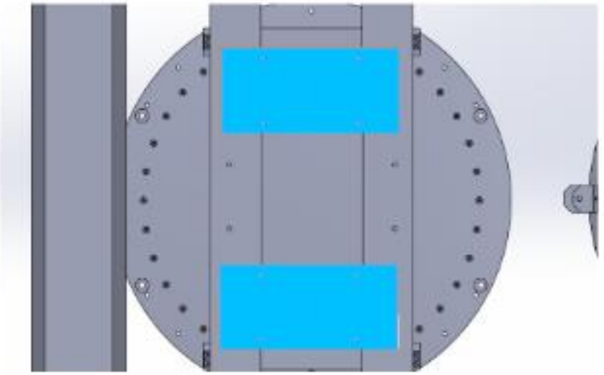


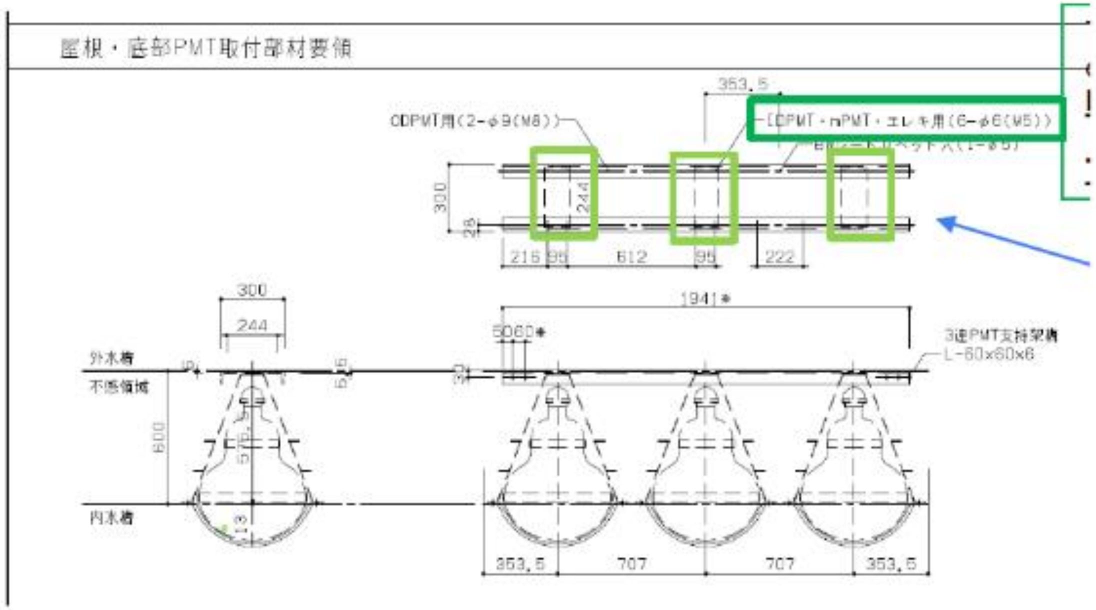


top & bottom mPMT support

Currently working on requirements from the integration group.







mPMT mechanical stress test

Top/bottom configuration
Barrel configuration
Transportation studies, and box design
- Compression
- Temperute
- Vibrations

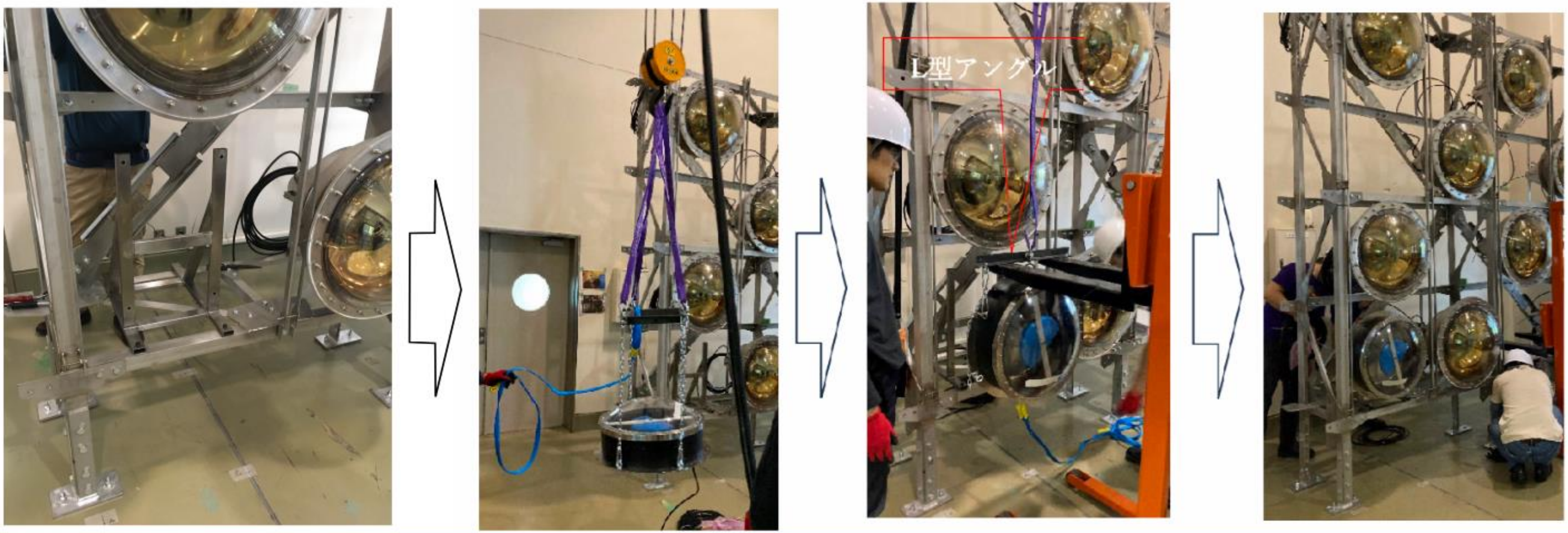
(Kadsumi Tomatani, Christoper Falcon, Saul Cuen)






Barrel Installation Overview

- mPMT installed successfully - procedure itself ok (possible change after talking to the inst. company)
- The main issue was the interference of the with the main frame due to
  - Enlarged gusset plate (cannot by modified)
  - Shifted front mounting holes (can/should be modified)



Top Installation Overview

- mPMT lifted by ceiling crane (not the original and final installation procedure) - successful
- Cause by the issues of lifting the 3-PMT module with middle space occupied

Thanks…