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

Saul Cuen-Rochin (Tecnologico de Monterrey)

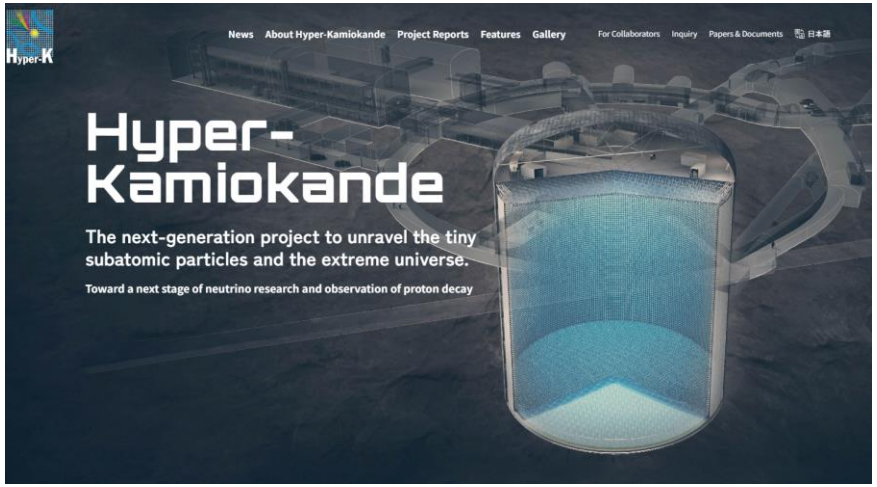
on behalf of the Hyper-K collaboration and Mexican group

SILAFAE 2024

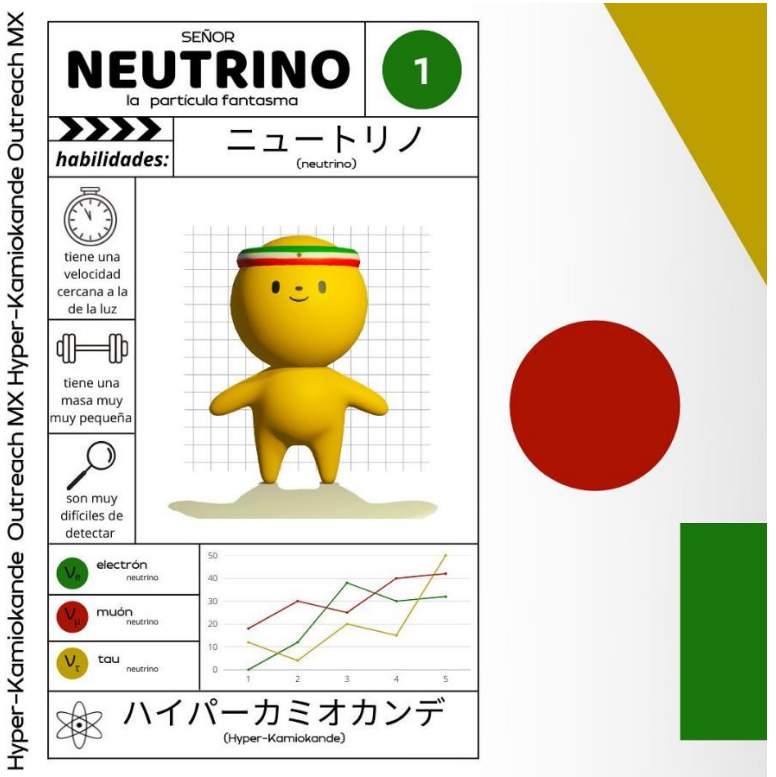
https://www-sk.icrr.u-tokyo.ac.jp/en/hk/

Agenda

- Hyper-K project goals and status
- Work at local national institutions
  - Neutrino classification
  - Multi-PMT detector design and manufacturing

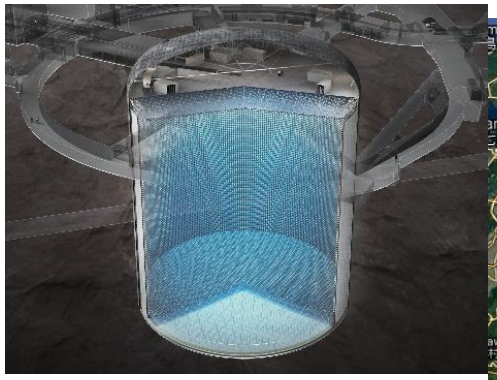


https://bio.site/Outreach_HK_MX

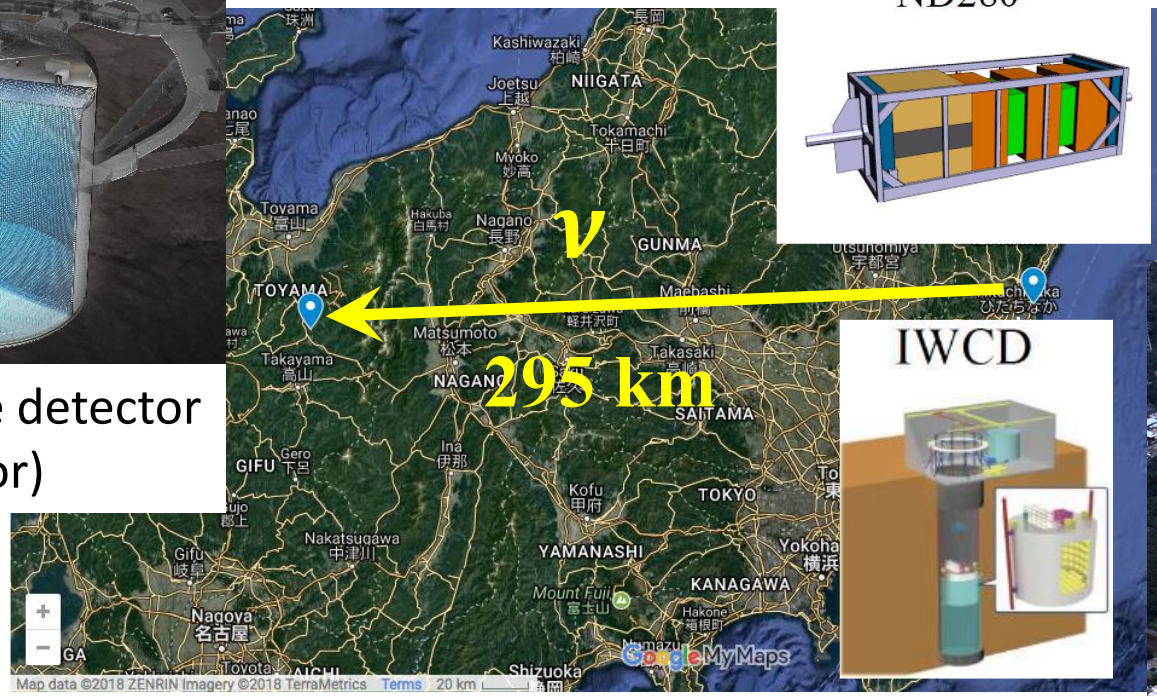


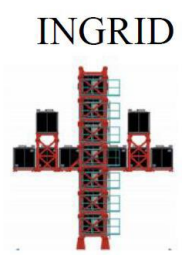
Hyper-Kamiokande Project

- 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

Three Generations of Water Cherenkov Detector in Kamioka

- **Kamiokande (1983 - 1996)**
  - Atmospheric and solar neutrino “anomaly”
  - Supernova 1987A

  Birth of neutrino astrophysics

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

  Discovery of neutrino oscillations

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

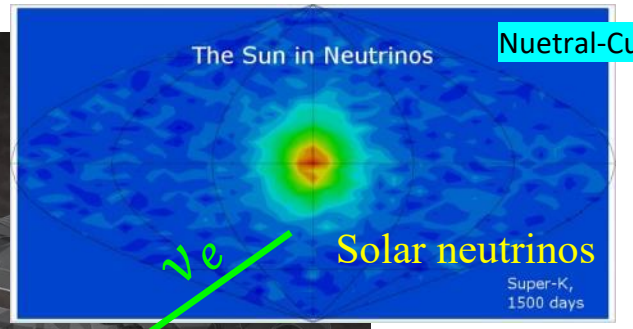
  Explore new physics

Hyper-K Observation Target

$\nu_e + n \to e^- + p$

$\bar{\nu}_e + p \to e^+ + n$

$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$



ν_e

Nuetral-Current Interactions (NC)

$\nu_e + e^- \to \nu_e + e^-$

$\nu + N \to \nu + N'$

$\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$

Charged-Current Interactions (CC

$\nu_e + n \to e^- + p$

$\bar{\nu}_e + p \to e^+ + n$

$\nu_\mu + n \to \mu^- + p$

$\nu_\tau + n \to \tau^- + p$

$\tau^- \to e^- + \bar{\nu}_e + \nu_\tau$

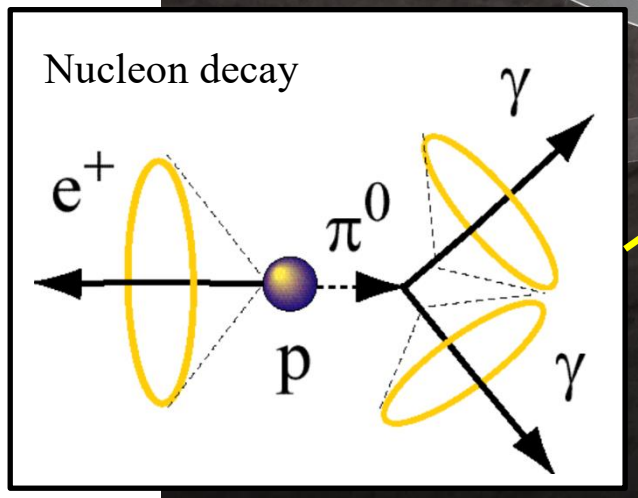
$\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau$

$\tau^- \to \text{hadrons} + \nu_\tau$

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

$p \to \mu^+ + \pi^0$

$\pi^0 \to \gamma + \gamma$



$\nu_\mu, \bar{\nu}_\mu$

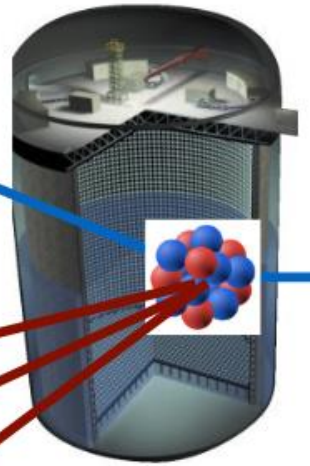
Experiment

l

π

p

n



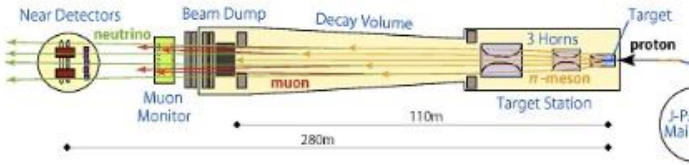
Detection

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



E_ν

Analysis

Cross section model

$\sigma(E_\nu)$

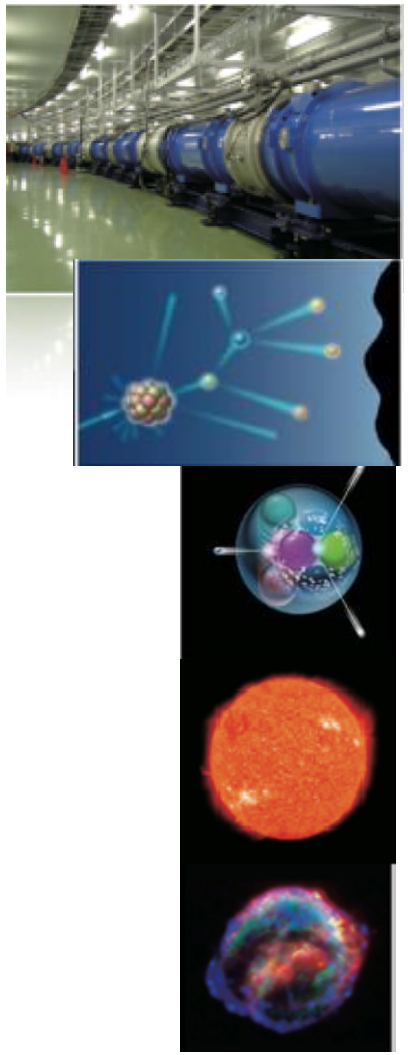
Reconstruct

E_ν

Oscillation Parameters $\theta_e, \theta_\mu, \theta_\tau \quad \delta_{CP}$

$\Delta m_e^2, \Delta m_\mu^2, \Delta m_\tau^2$

Hyper-K Target sensitivity

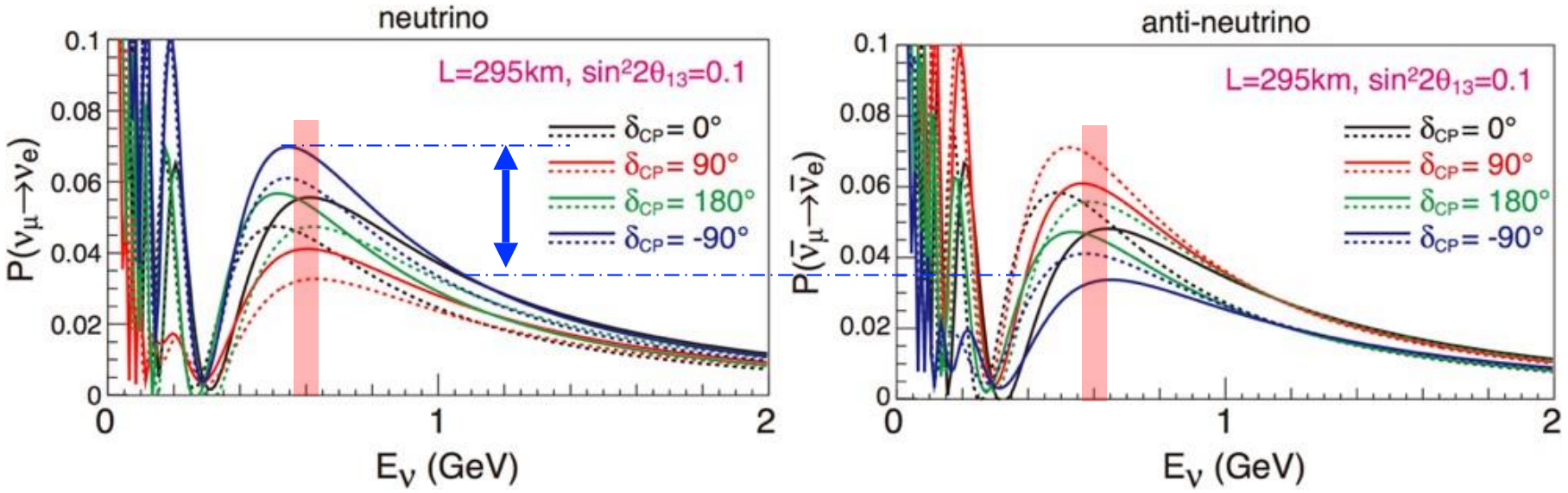


Physics category	Parameters	Sensitivity
LBL (1.3MW×10years)	δ precision	7°-20°
	CPV coverage (3/5σ)	76%/58%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.017
ATM+LBL (10 years)	MO determination	>3.8σ
	Octant determination (3σ)	$\lvert\theta_{23}-45°\rvert>2°$
Proton Decay (20 years)	τ for $e^+\pi^0$ (3σ)	1×10^{35} 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

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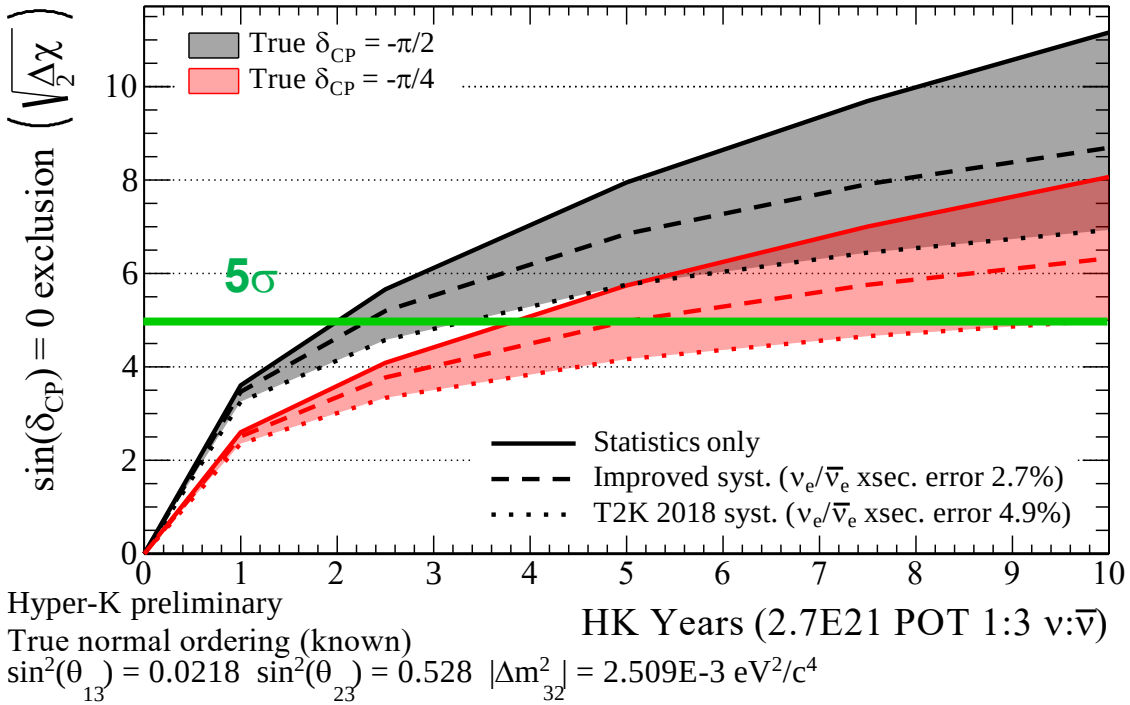
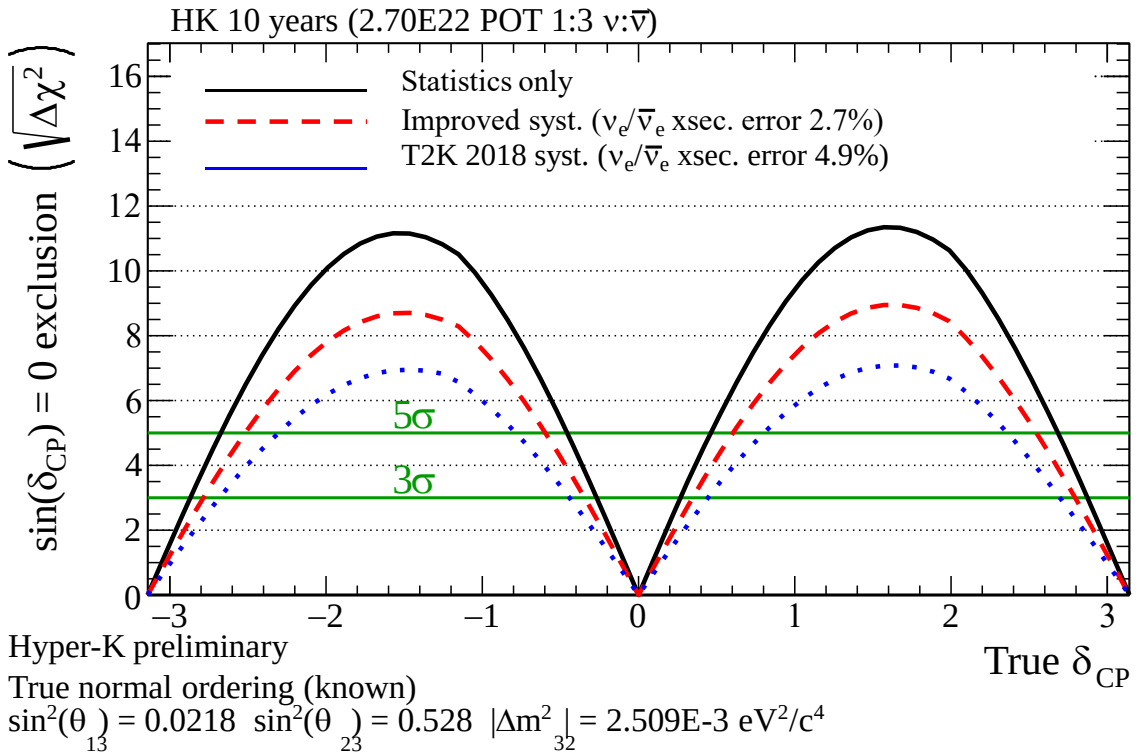
CP violation sensitivity

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





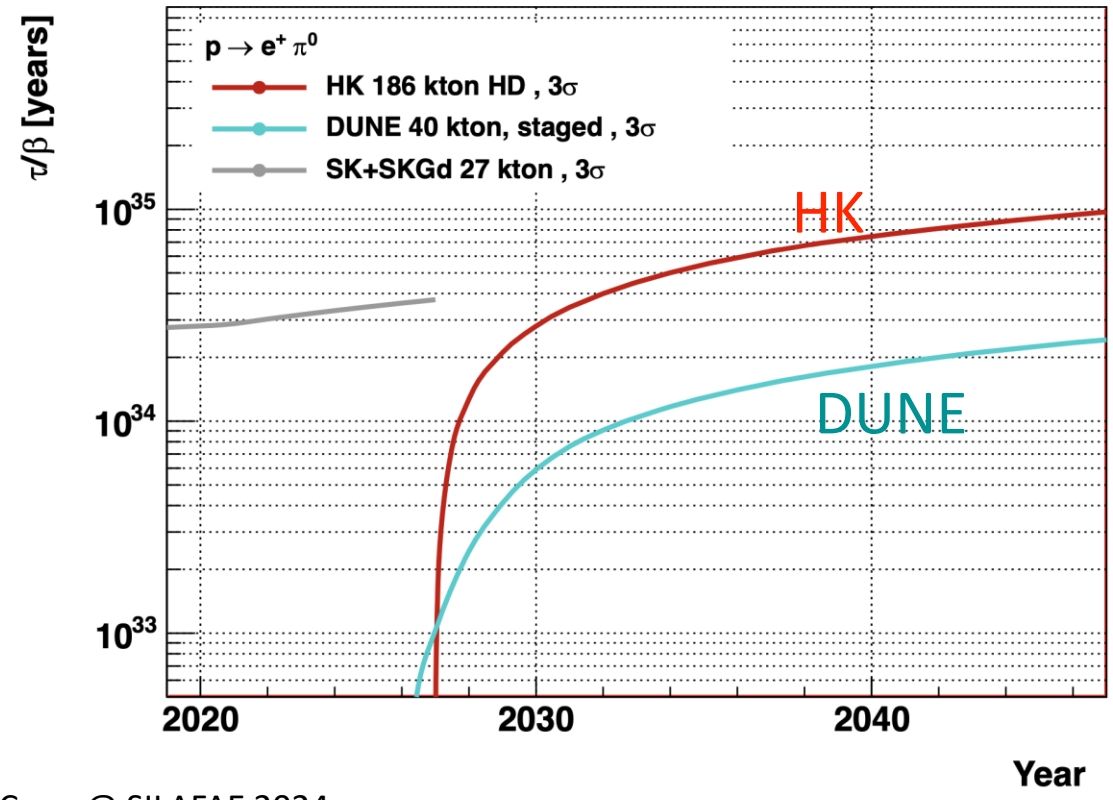
- With systematics and known mass ordering (MO): 2-3 years for 5σ sensitivity to exclude CP conservation for true $\delta\_CP = -\pi/2$.
- After 10 years of operation, 60% of δ_CP values excluded at > 5σ

Nucleon decay search

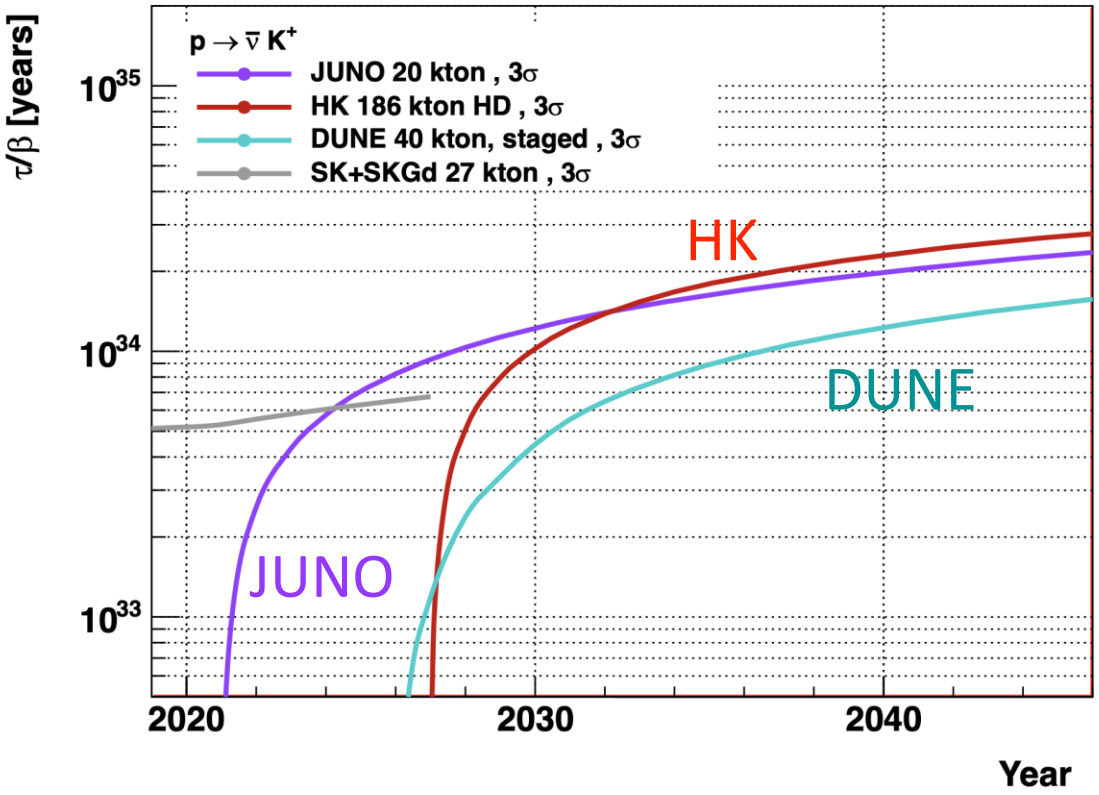
- Nucleon decay is evidence of Beyond Standard Model (BSM) and Grand Unified Theories (GUT)
- Examples of proton decay sensitivity in two modes:

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

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



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



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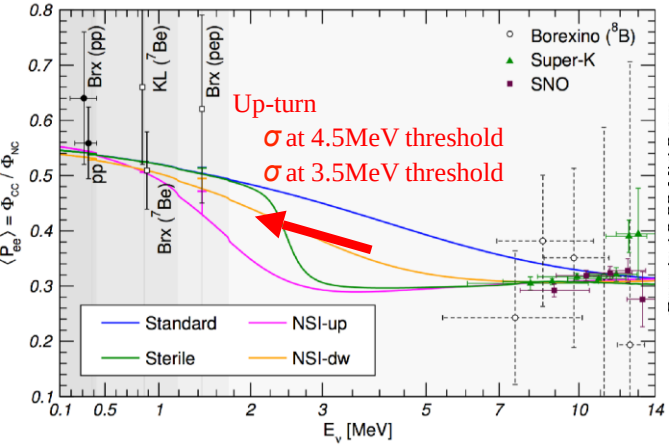
$\tau \sim 10^{35}$ years (3σ)

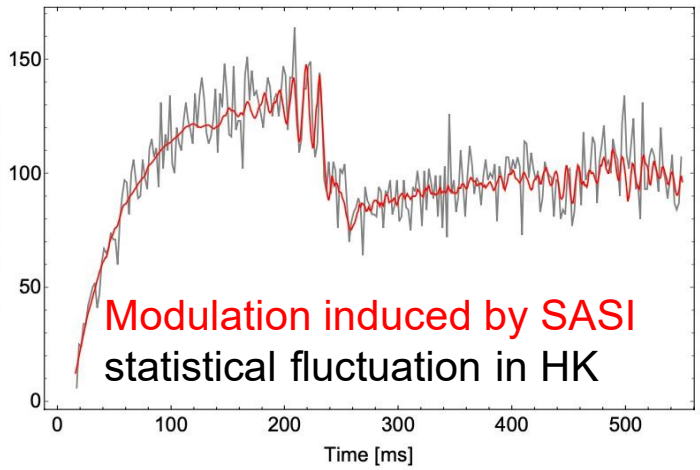
$\tau \sim 3 \times 10^{34}$ years (3σ)

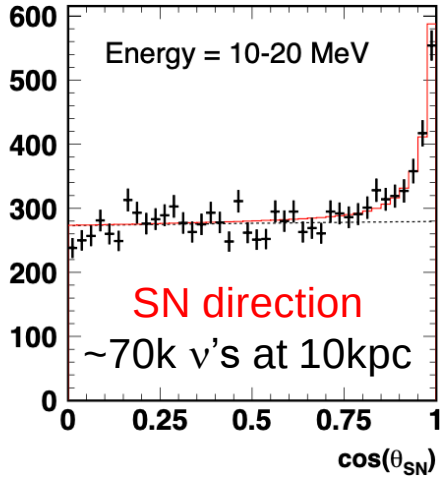
Neutrino astrophysics

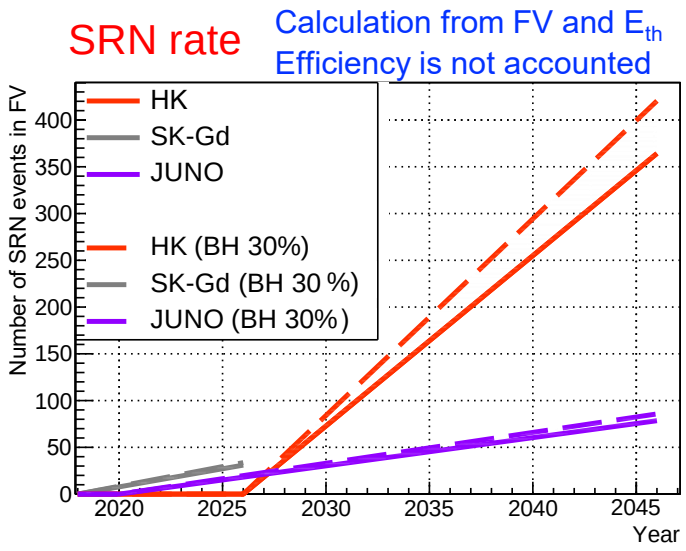
- Hyper-K is designed to be sensitive to neutrinos with energies starting from a few MeV, including time, energy and direction information. Unique role in multi-messenger observation
- **Solar neutrinos:** up-turn at vacuum-MSW transition, Day/Night asymmetry, hep neutrino observation
- **Supernova burst 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)







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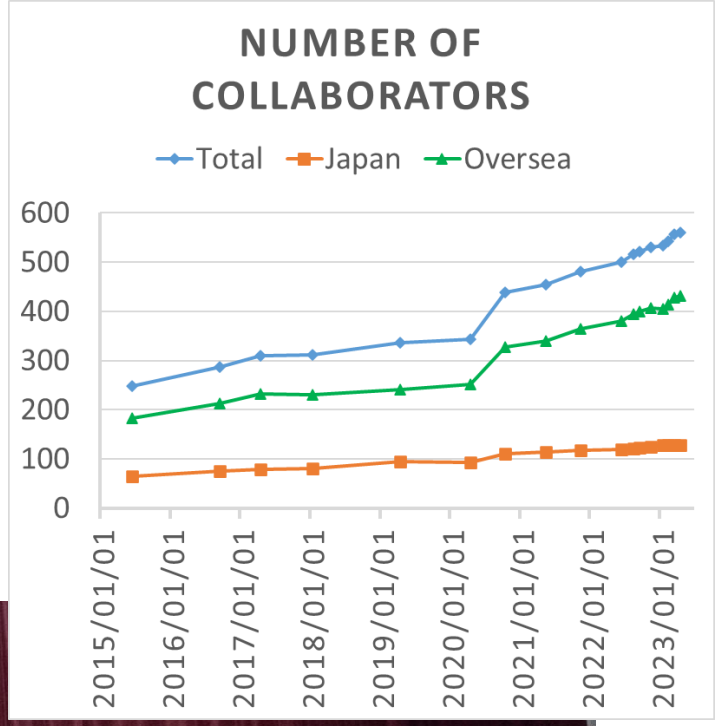
Hyper-Kamiokande Collaboration

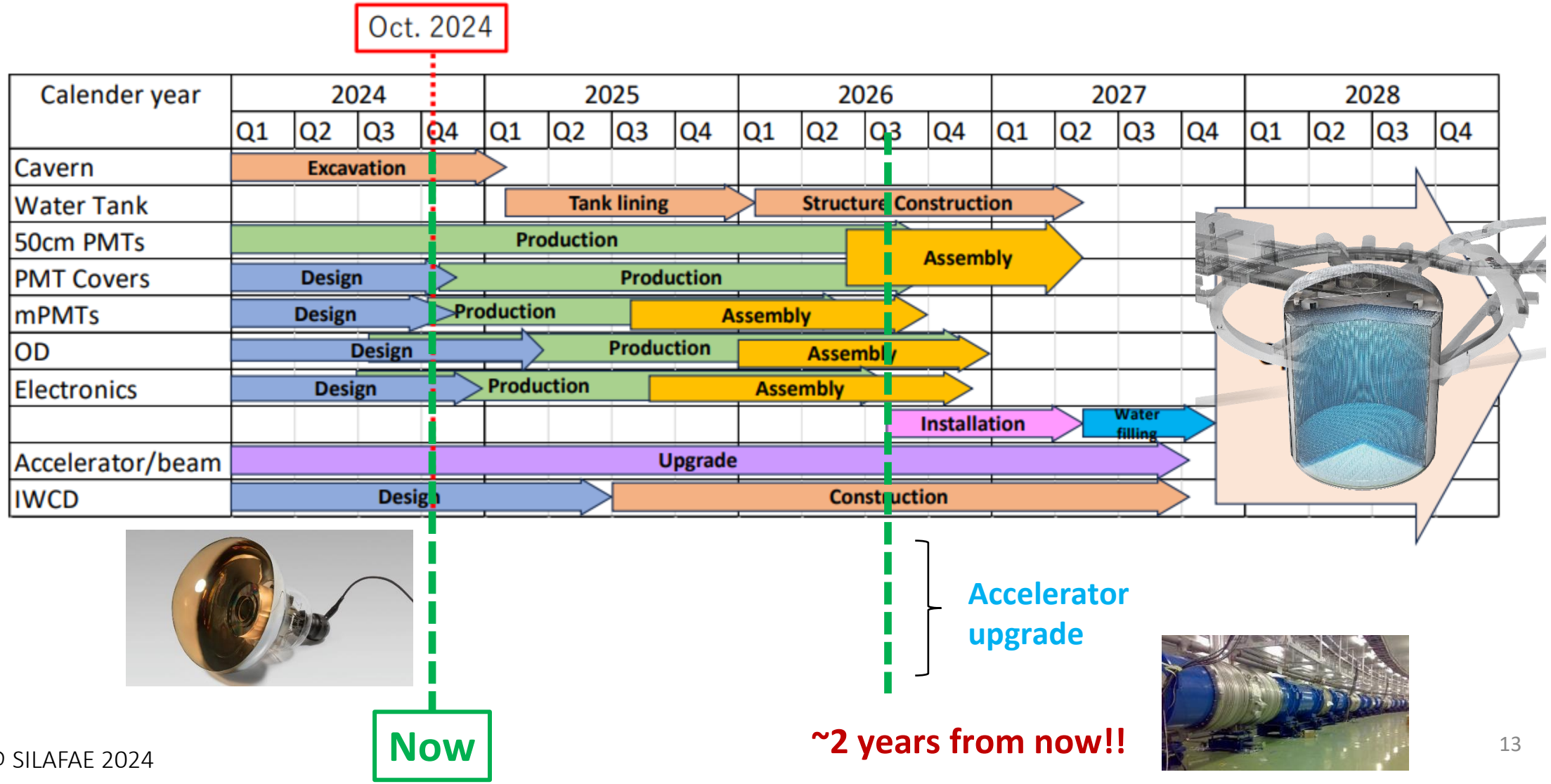


- ~600 members located in 102 institutes from 22 countries
  - 25% Japanese / 75% non-Japanese
- Recently approved as a recognized experiment (RE45) at CERN

- <u>Latest collaboration meeting October 2024 in Toyama:</u>

Hyper-K construction schedule

- The Hyper-K construction started in 2020 and will start operation in 2027.

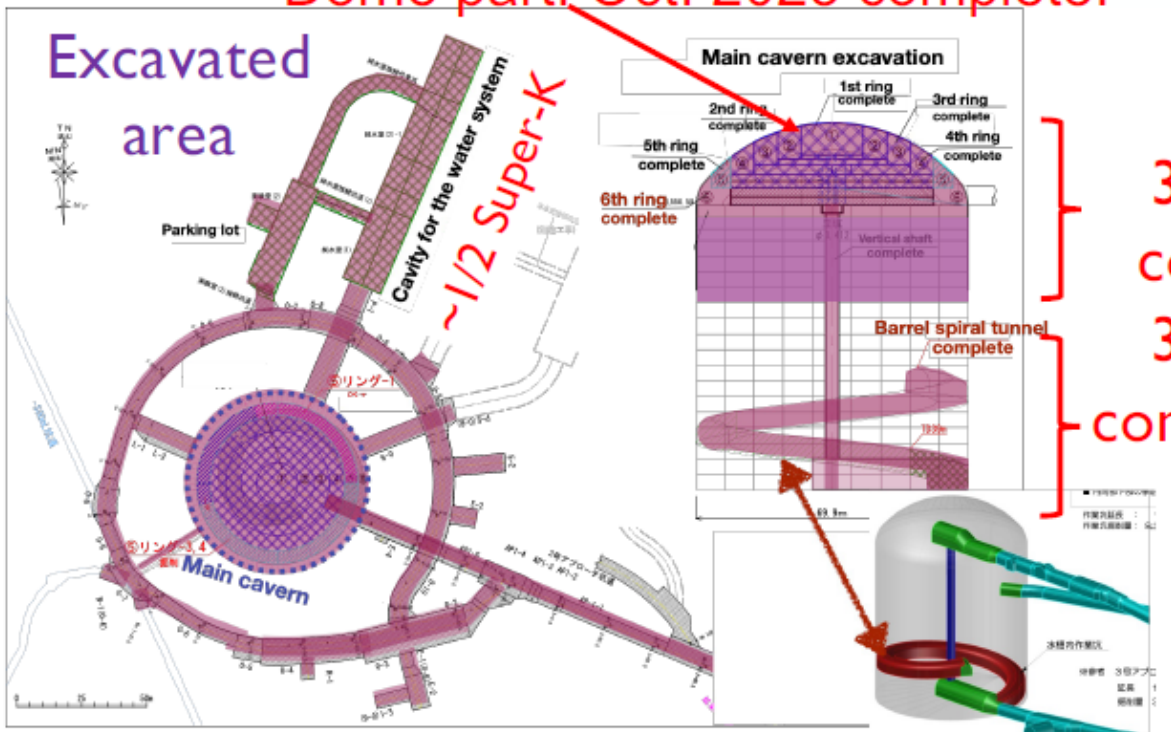


Excavating the world's largest human-made cavern

✓ Approach tunnels:
Aug. 2022 complete.

✓ Access tunnel: Feb. 2022 complete.

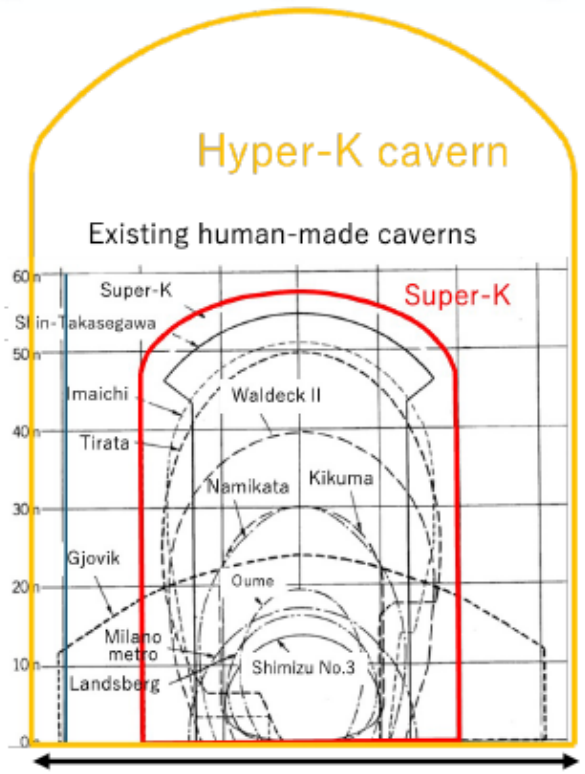
✓ Dome part: Oct. 2023 complete.



3 Super-K completed.

3 Super-K coming ~1/2yr

69.0 m



94.0 m

Hyper-K main cavern excavation

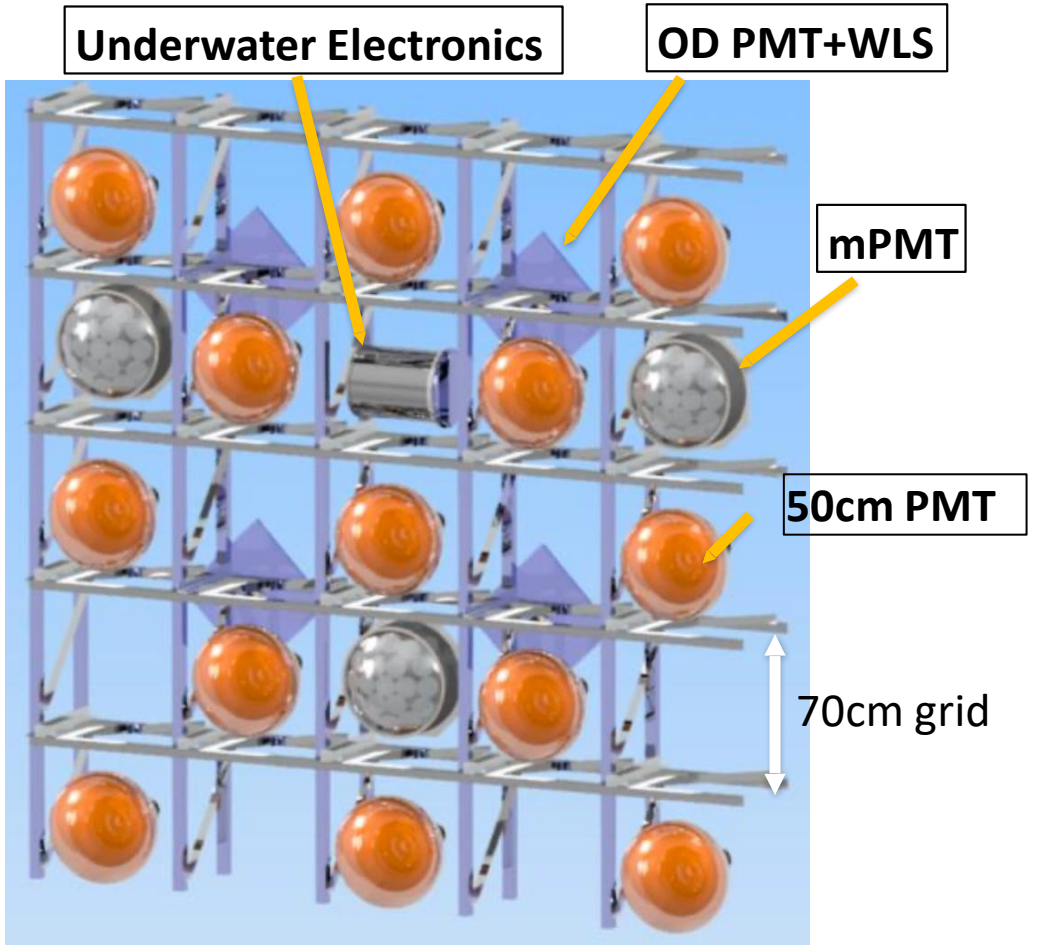
- **<u>October 3, 2023:</u>** Excavation of the dome section completed.
  - 69m diameter, 21m height
  - One of the largest human-made underground space.
- Now, the excavation of the barrel section is ongoing.

Katsuki Hiraide @ NNN23


Excavation of the HK cavern will be completed by the end of this year!

Hyper-K detector configuration

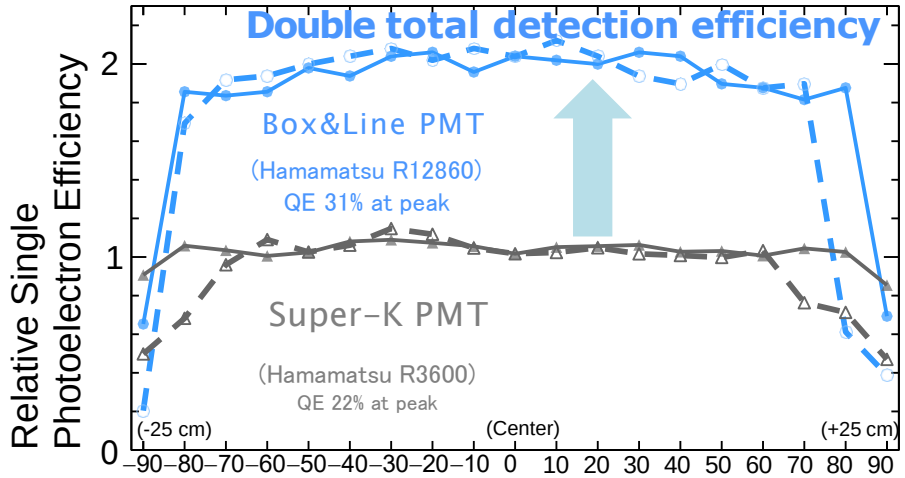
- **Inner Detector (ID)**
  - 20,000 – 20’’ PMT
  - 64.8m diameter, 65.8m height
  - 50cm PMTs will be installed
  - 800 multi-PMT modules (19 3’’ PMT each) will be integrated as hybrid configuration
- **Outer Detector (OD)**
  - 3,600 – 3’’ PMT
  - 1m (barrel) or 2m (top/bottom) thick
  - 3-inch PMT + WLS plate
  - Walls are covered with high-reflectivity Tyvek sheets
- **Under-water electronics**
  - Mitigate disadvantage of long cables



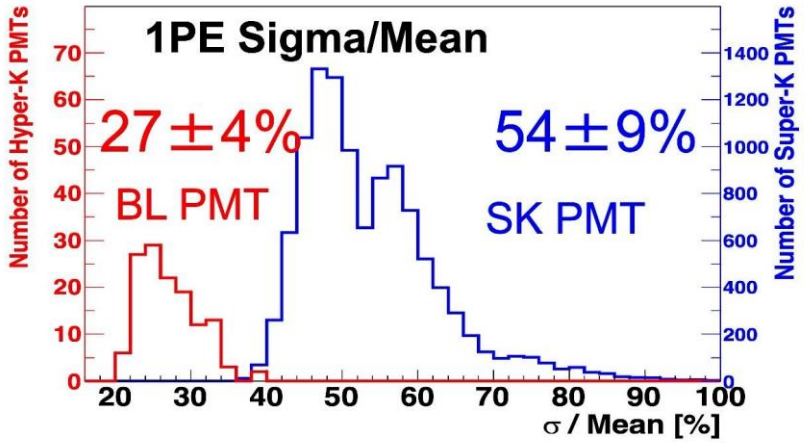
Hyper-K 50cm PMT performance

(Performance in SK tank, 1.7e7 gain)

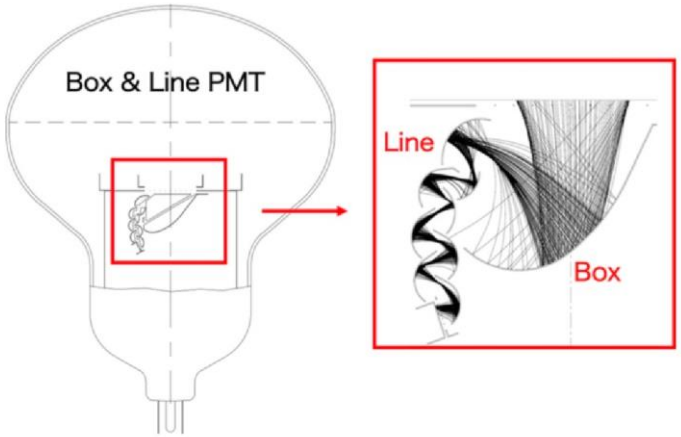
×2 better photodetection efficiency (QE×CE)



×2 better charge resolution



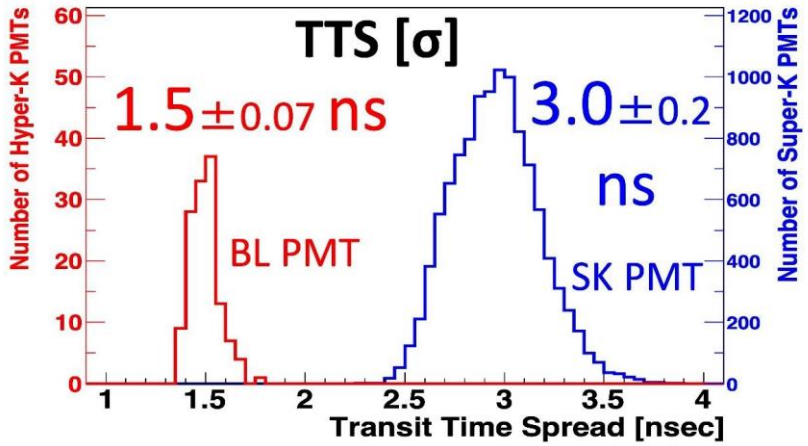
Box&Line dynode



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

Low dark rate (4kHz) and RI

×2 better timing resolution



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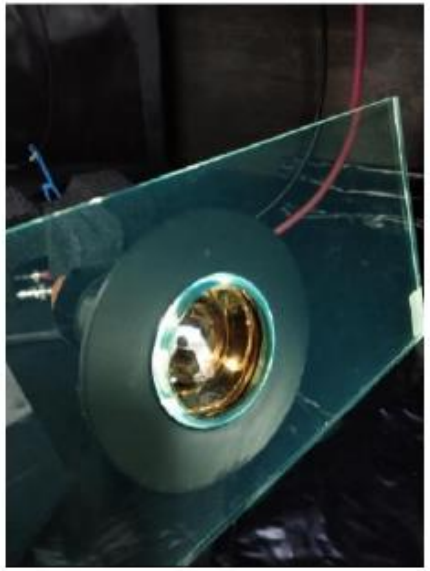
Saul Cuen @ SILAFAE 2024

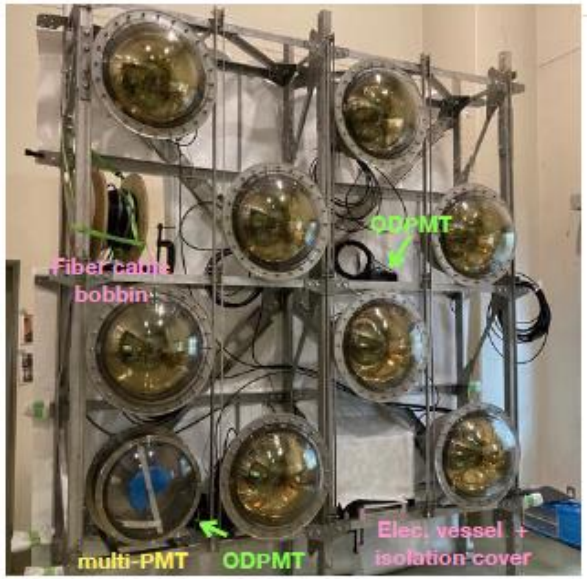
Moriyama@ Neutrino 2024

Photosensors and underwater electronics

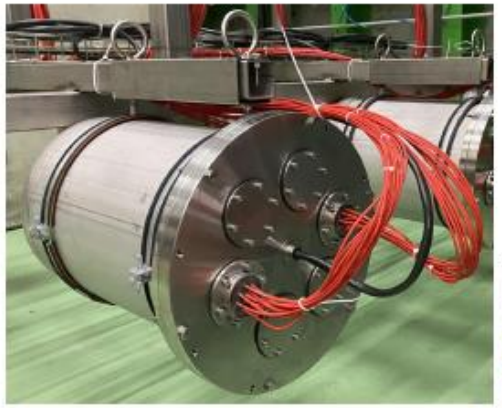
Outer detector: PMT+WLS plate

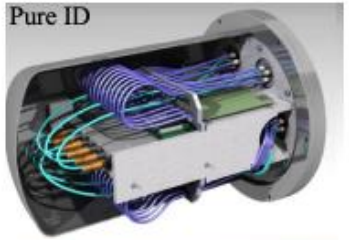


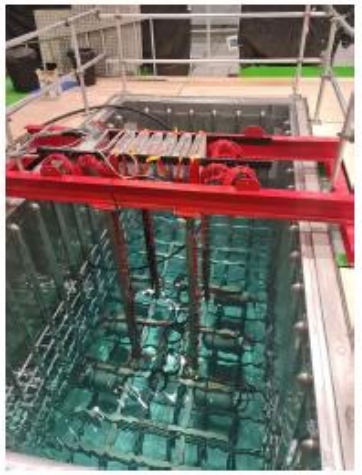
Photosensors/elec. mockup



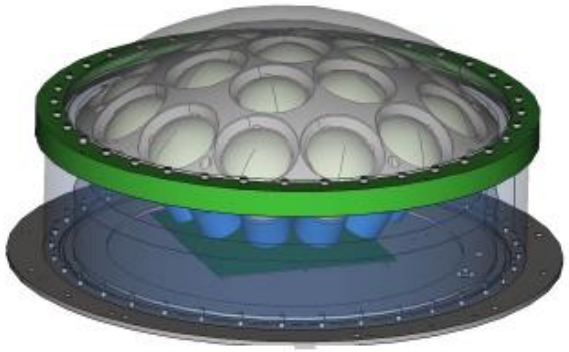
Underwater electronics: Case design and feedthrough



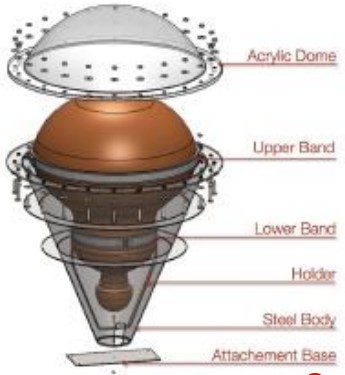


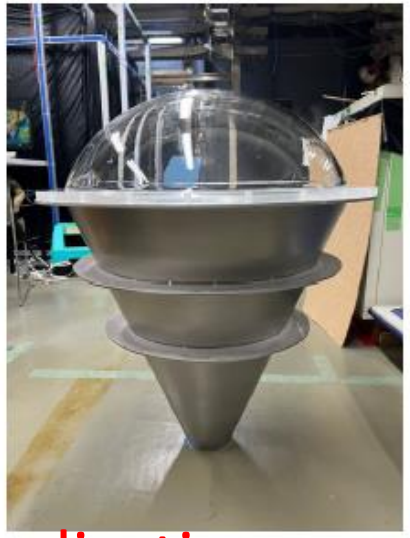


Multi-PMT module:



PMT cover





Design finalization ongoing

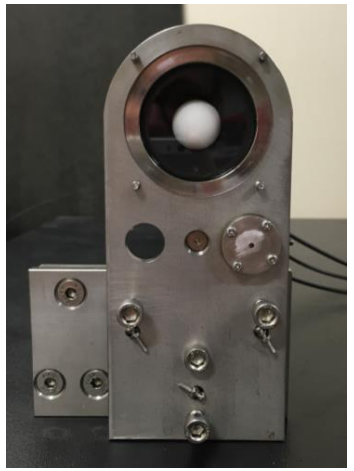
Hyper-K Calibration

- 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 gamma cascade

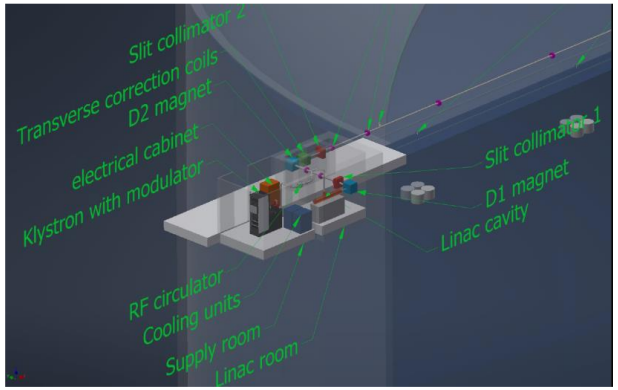
Photosensor Test Facility

Photogrammetry testing

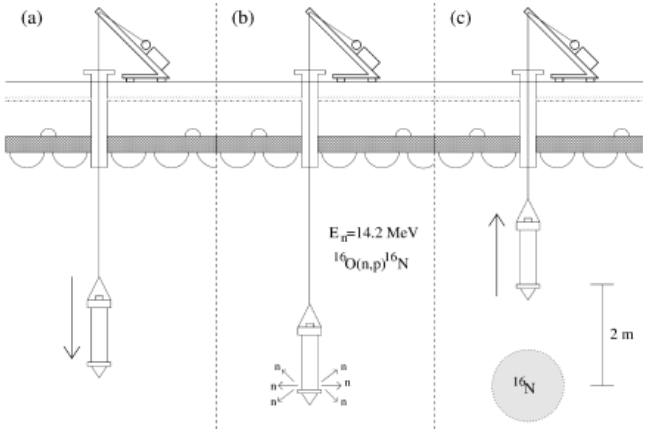


Light injectors

LINAC beam simulation

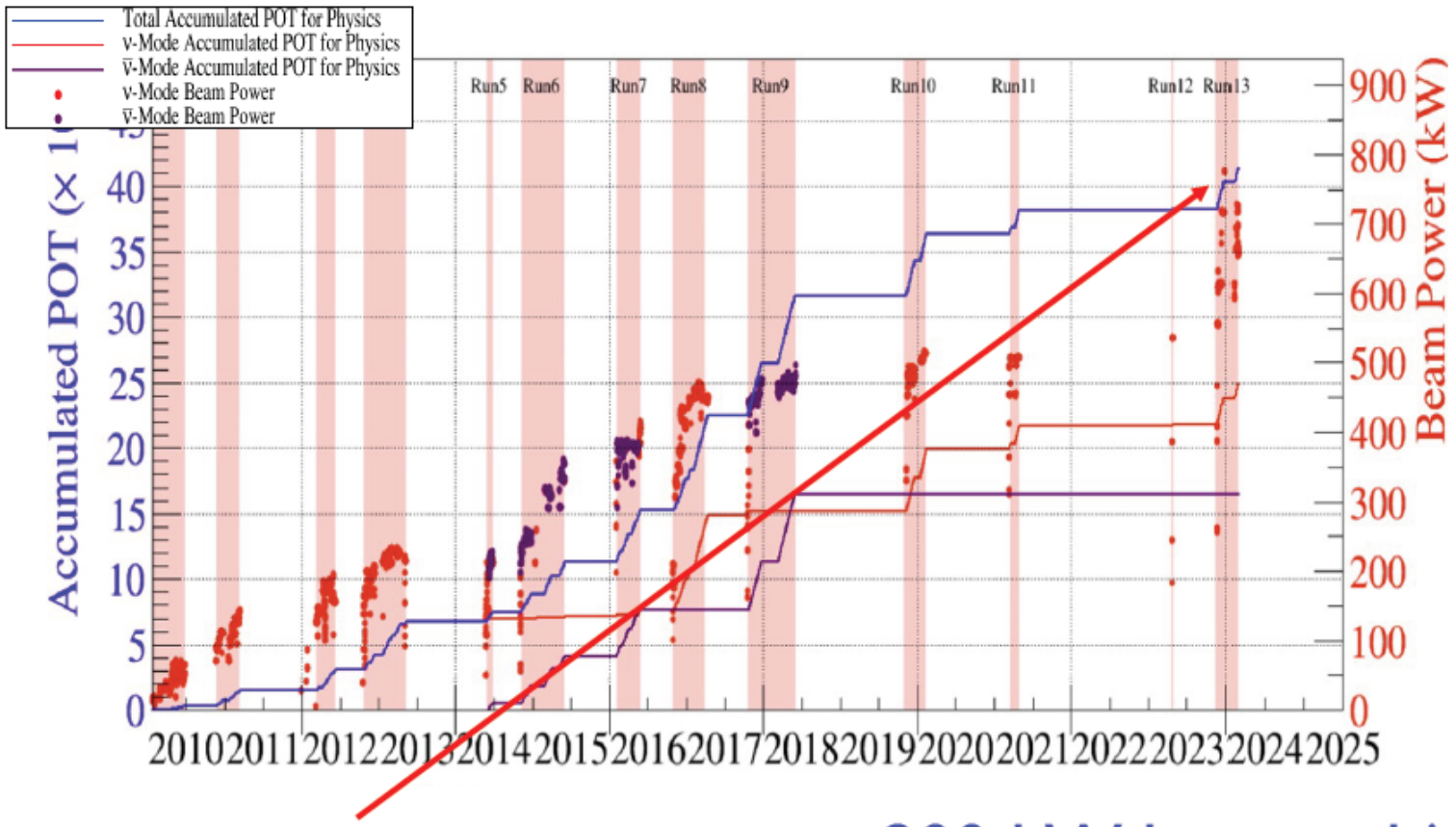


Ni/Cf source



DT operation

Beam: status and plan of power increase

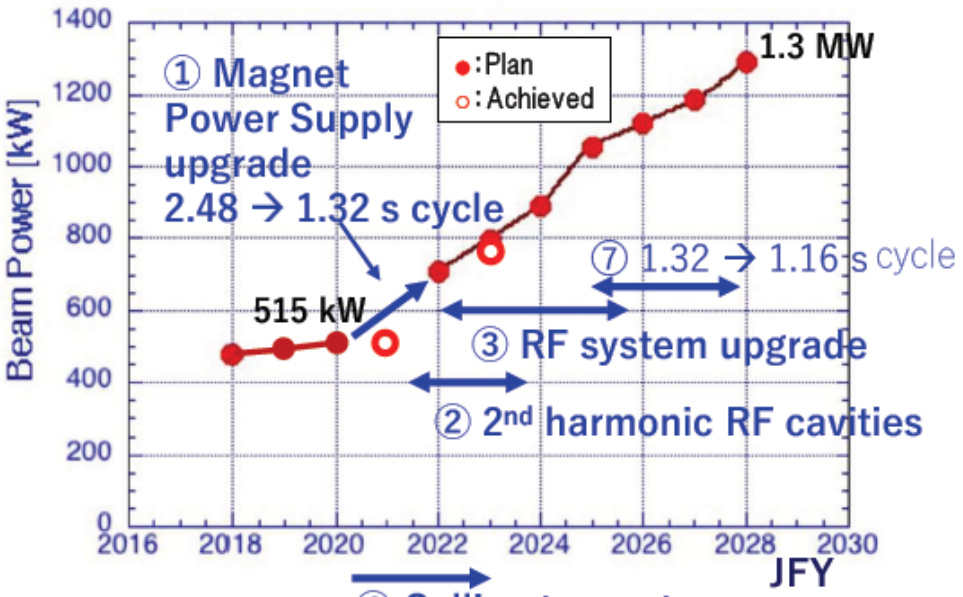


760 kW achieved already and 800 kW last week!

Further beam power increase requires:

- Seeking beam loss with optics improvements
- More protons/pulse by upgrading RF system
- Further beam intensity increase will be done by 1.36 → 1.16 sec cycle

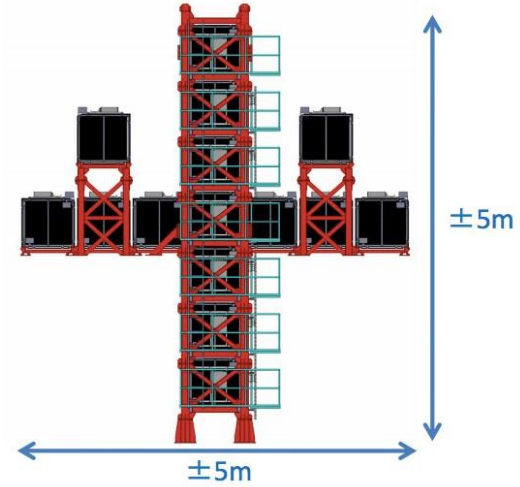
Original power projection in MR Upgrade Plan



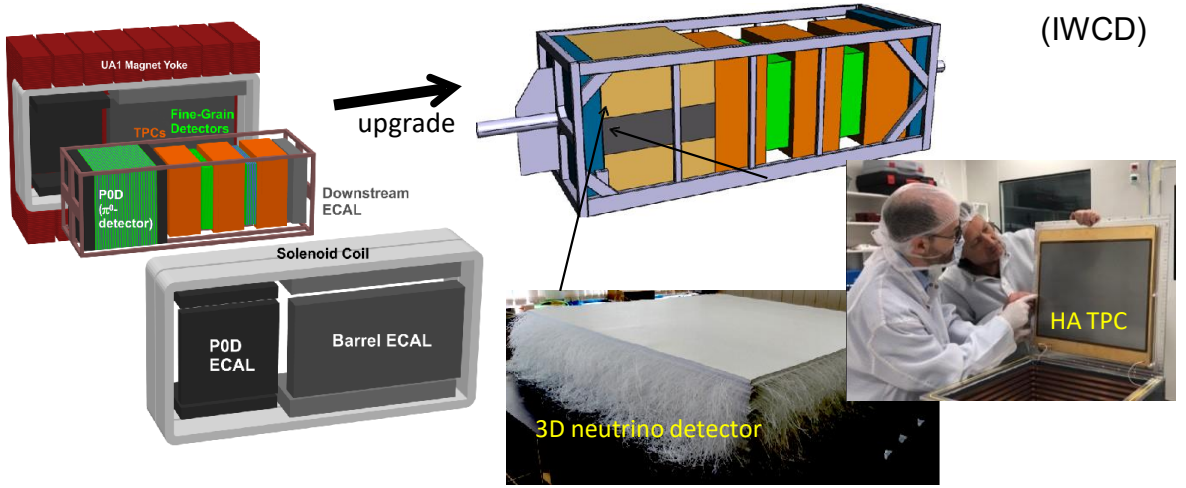
S. Igarashi, *et. al.*, PTEP vol 2021, Issue.3,p33

Neutrino detectors at J-PARC

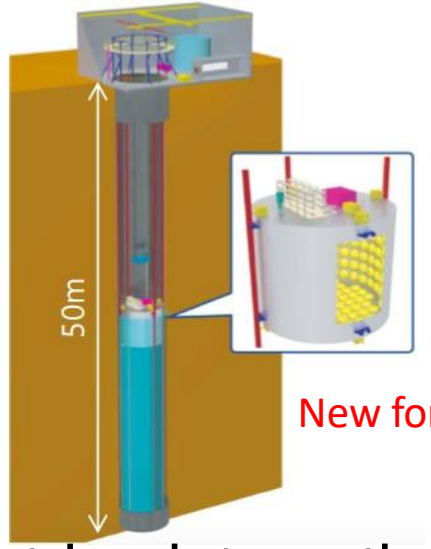
On-axis Detector
(INGRID)



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:

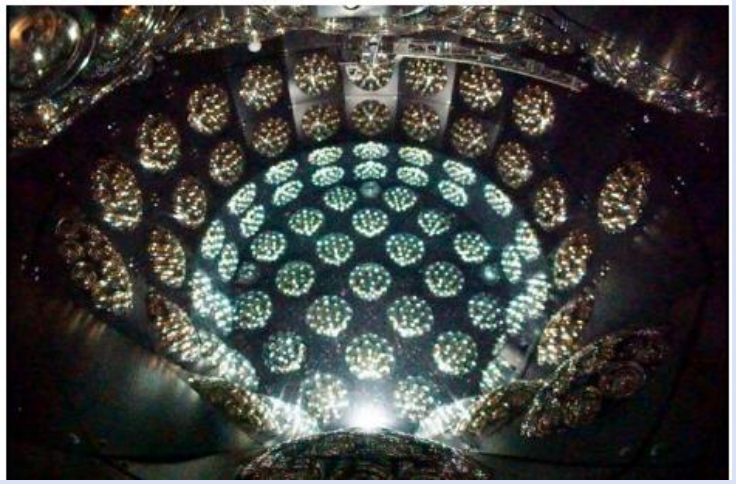
- **On-axis detector:** Measure beam direction and event rate
- **Off-axis magnetized tracker:** Measure primary (anti)neutrino interaction rates, spectrum, and properties. Charge separation to measure wrong-sign background
  → Upgrade by T2K experiment and intensive discussion for further upgrade in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

WCTE EXPERIENCE: MPMT PRODUCTION, LIFTING, AND INSTALLATION

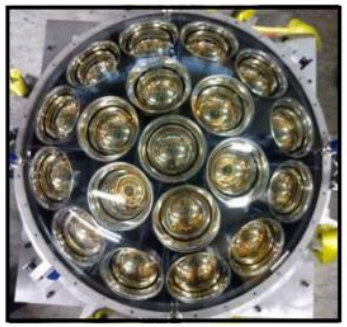
HK/IWCD COLLABORATION MEETING

Mohit Gola, 22/10/2024

TRIUMF



EX-SITU



IN-SITU

Mexican funds awarded for Hyper-K

- 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)
    - Grant holder: Eduardo de la Fuente Acosta (UdeG)
    - Institutions involved:
        - 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)
    - Grant holder : Saul Cuen Rochin (TEC-SIN)
    - Institutions involved :
        - GIANNINA DALLE MESE ZAVALA (UAS)

CONAHCYT
Consejo Nacional de Humanidades Ciencias y Tecnologías

MOU between Mexican Institutions and U.Tokyo/KEK should be ready during 2025.

Mexican involvement in Hyper-K

Master thesis completed (**TEC**):

- Neutrino Classification Through Deep Learning amid the Hyper-Kamiokande Project Development

Student: Maria Fernanda Romo Fuentes
Advisor: 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: Eduardo de la Fuente, Luis Eduardo Falcon, Saul Cuen

Thesis open position (**UAS**):

- Analysis for supernova detection

Advisor: GIANNINA DALLE MESE ZAVALA, Saul Cuen
POSTER session from Sergio Galarza TODAY!

Thesis open position (**UNACH**):

- Analysis for supernova detection

Advisors: KAREN SALOME CABALLERO MORA

Thesis open position:

- Neutrino Classification with AI

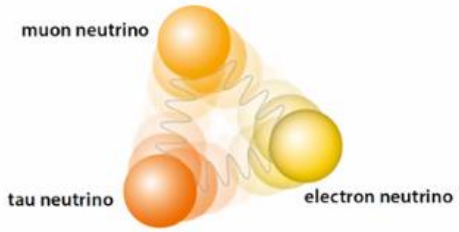
Advisors: Saul Cuen, Kadsumi Tomatani, Rodrigo Gamboa (volunteers?)
POSTER session from E. Avendaño, E. Haces Gil, E. Juárez, G. Rodriguez, N. Castro, R. Guzmán TODAY!

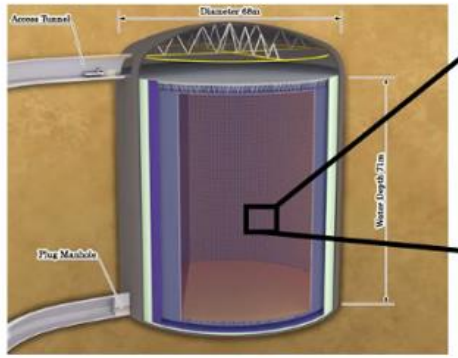
Thesis open position:

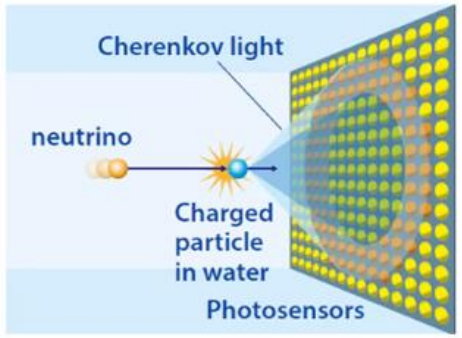
- mPMT design and manufacturing for Hyper-K

Advisors: Saul Cuen, Kadsumi Tomatani, (volunteers?)

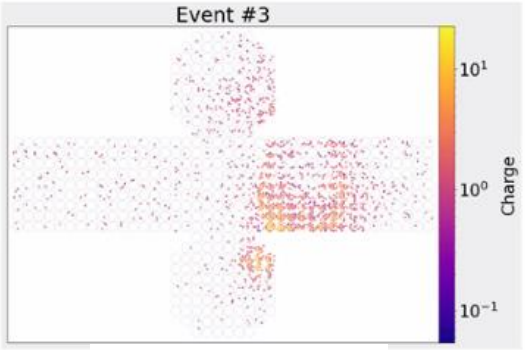
Neutrino classification

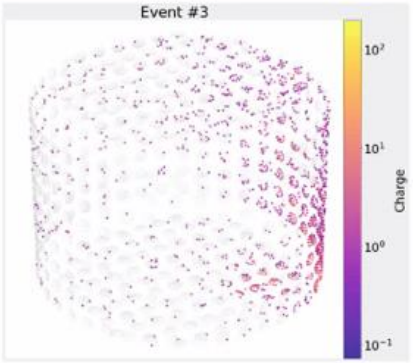






Neutrinos and their oscillation detected by Hyper-Kamiokande, IWCD, FD by mPMTs because of Cherenkov Radiation

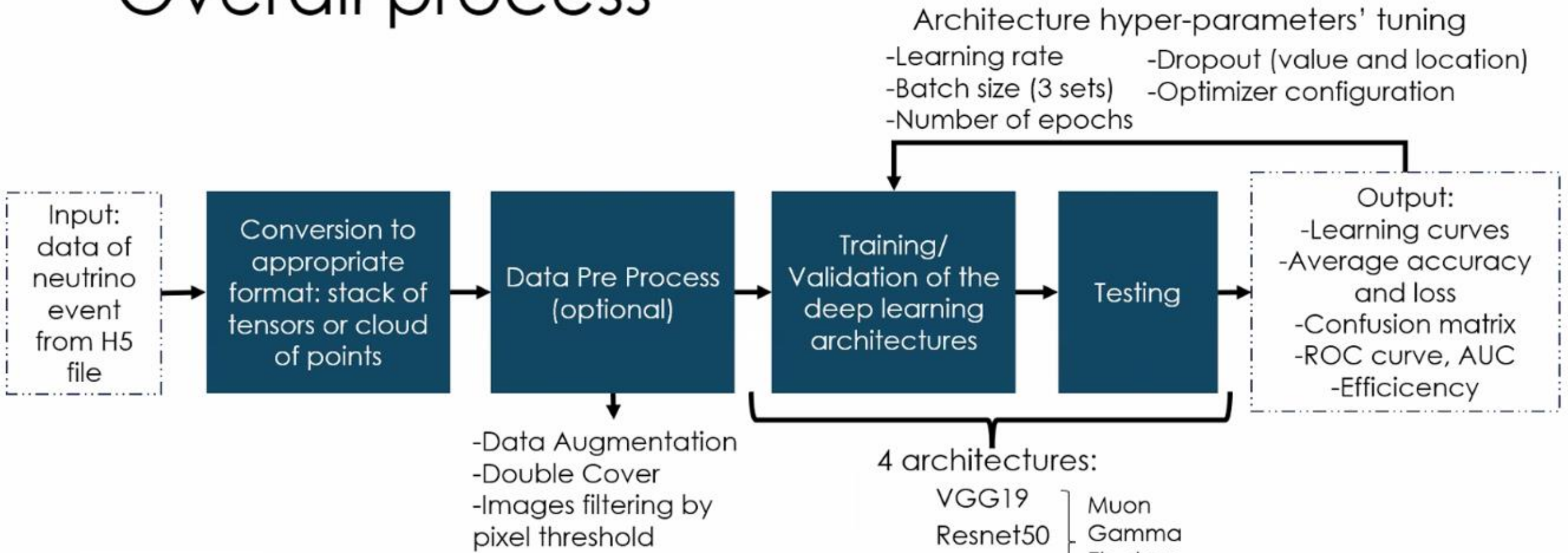




Detected event
has to be
Reconstructed
starts by
Identifying the particles involved in an event

Tecnológico de Monterrey **Maria Fernanda Romo Fuentes**

Overall process

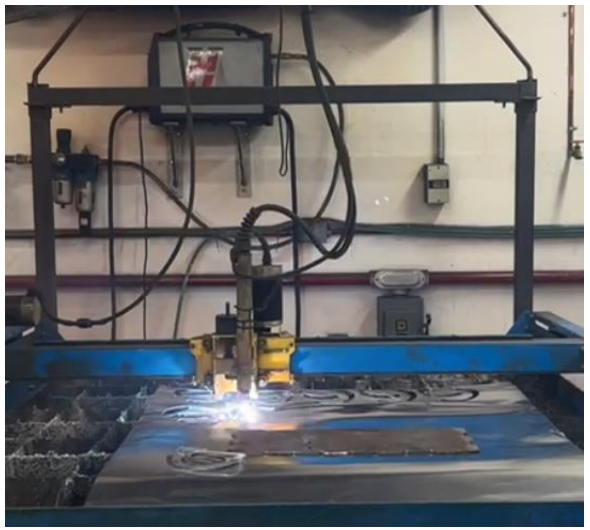


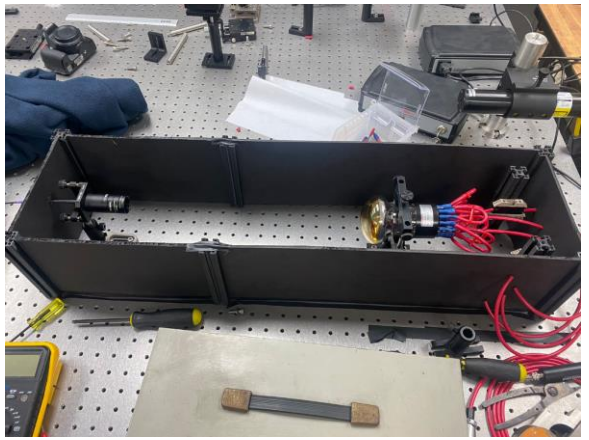
Tecnológico de Monterrey **Maria Fernanda Romo Fuentes**

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

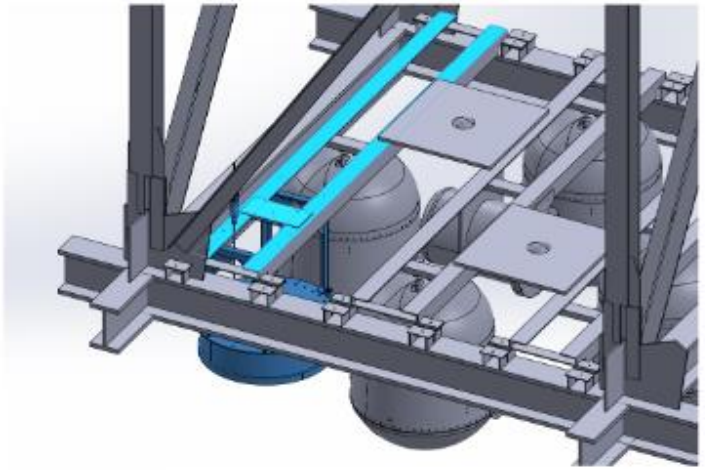
- Mechanical metrology and assembly
- Setting un blackbox and optical testing for PMT check (student Roy Medina)

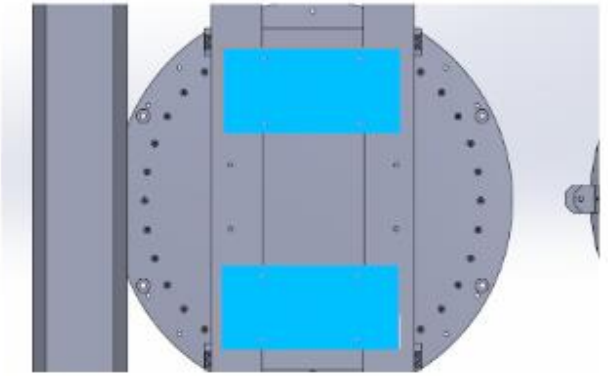


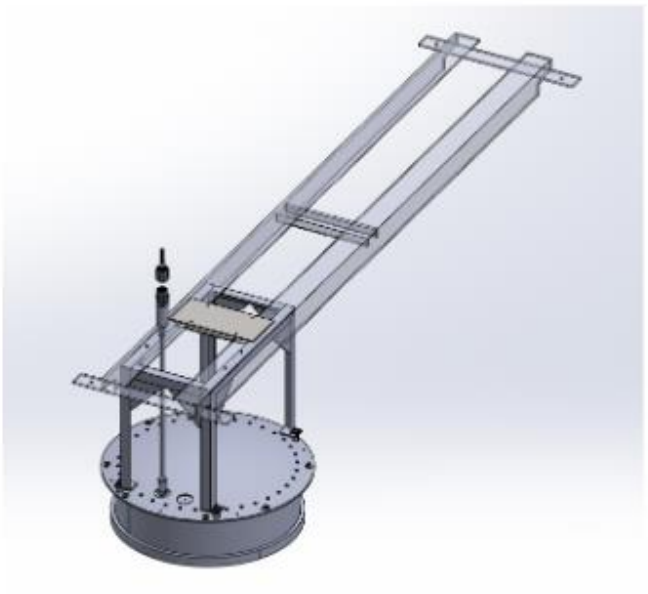


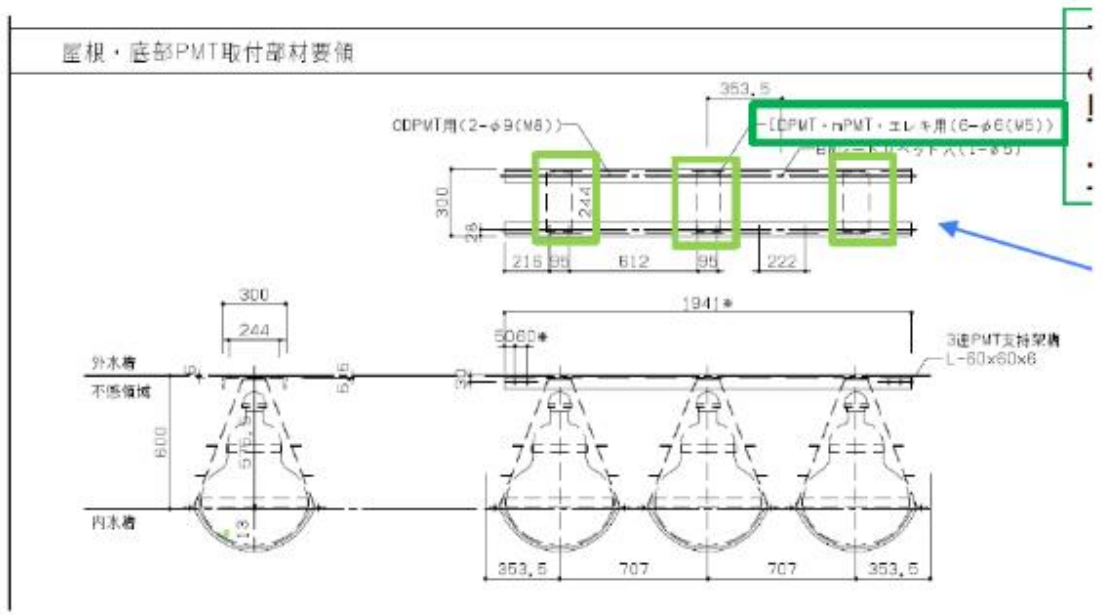
top & bottom mPMT support

Currently working on requirements from the integration group.









mPMT mechanical stress test

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

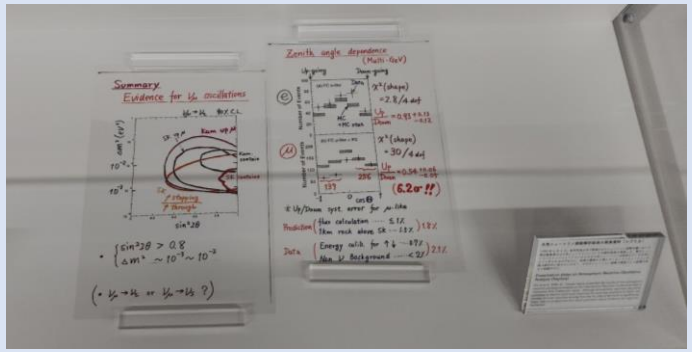
- mPMT lifted by ceiling crane (not the original and final installation procedure) - successful
- Cause by the issues of lifting the 3-PMT module with middle space occupied

Conclusions

- 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.


周辺地図 Area Map
至 富山
To Toyama
宿泊棟
Kamioka Dormitory
茂住バス停
Mozumi Bus Stop
Kavli IPMU サテライトオフィス
Kavli IPMU Satellite Office
東京大学宇宙線研究所
神岡宇宙素粒子研究施設
Kamioka Observatory
計算機棟
KEISANKITO
研究棟
KENKYUTO
現在地
You Are Here
東北大学 カムランドオフィス
Tohoku University, KamLAND Office
茂住郵便局
Mozumi Post Office
神岡総合研究棟
Kamioka Research Complex
(SOGOTO)
高原川
Takahara River
重力波観測研究施設
KAGRA Observatory
茂住パーキング
Mozumi Parking Lot
国道41号
Route 41
至 神岡市街地・高山市
To Center of Kamioka, Takayama
スーパーカミオカンデ
Super-Kamiokande
大型低温重力波望遠鏡 かぐら
KAGRA
カムランド
KamLAND
至 富山
To Toyama
現在地
You Are Here
池ノ山
Mt. Ikeno
1369
新猪谷ダム
Shininotani Dam
地下実験施設
Underground Facilities
高原川
Takahara River
岐阜県
Gifu Prefecture
国道41号
Route 41
富山
Toyama
現在地
You Are Here
東京
Tokyo
大阪
Osaka
名古屋
Nagoya
至 神岡市街地・高山市
To Center of Kamioka, Takayama
ハイパーカミオカンデ
Hyper-Kamiokande
ハイパーカミオカンデ
Hyper-Kamiokande


THE UNIVERSITY OF TOKYO
宇宙線研究所
神岡総合研究棟
INSTITUTE FOR COSMIC RAY RESEARCH
KAMIOKA RESEARCH COMPLEX
NEXT-GENERATION NEUTRINO SCIENCE AND
MULTI-MESSENGER ASTRONOMY ORGANIZATION


Summary
Evidence for ν oscillations
Zenith angle dependence
(6.2σ !!)


宇宙線は
天啓である
吉馬朋人