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

Saul Cuen-Rochin (Tecnologico de Monterrey)

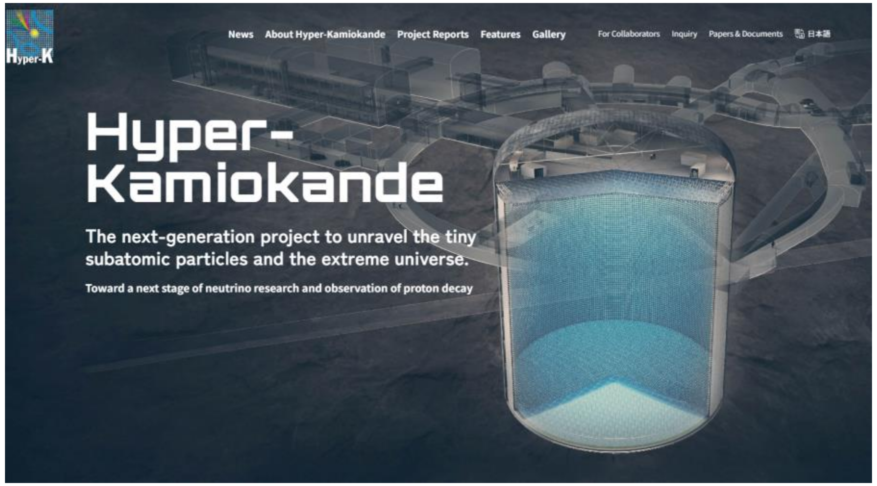
on behalf of the Hyper-K collaboration and Mexican group

The International Symposium on Very High Energy Cosmic Ray Interactions (ISVHECRI) 2024
Puerto Vallarta, Mexico
8 – 12 July 2024

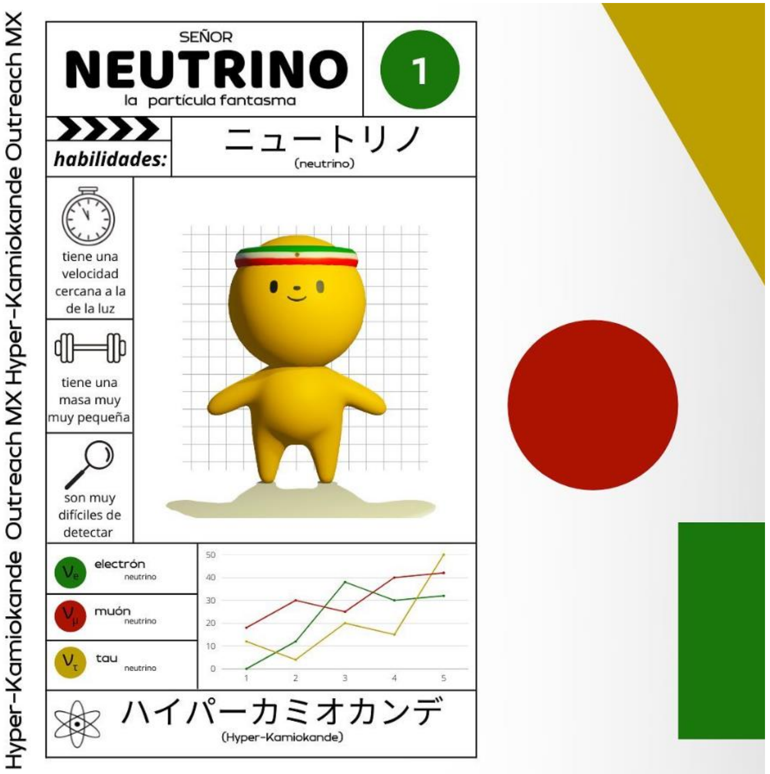
https://www-sk.icrr.u-tokyo.ac.jp/en/hk/

Agenda

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

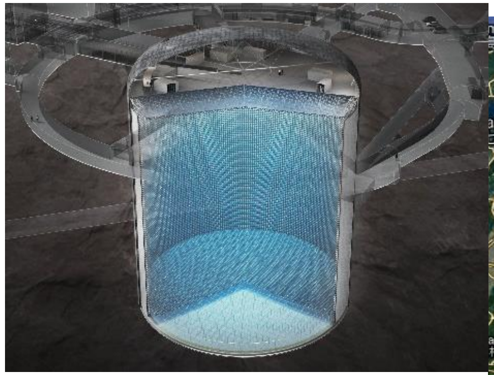


https://bio.site/Outreach_HK_MX

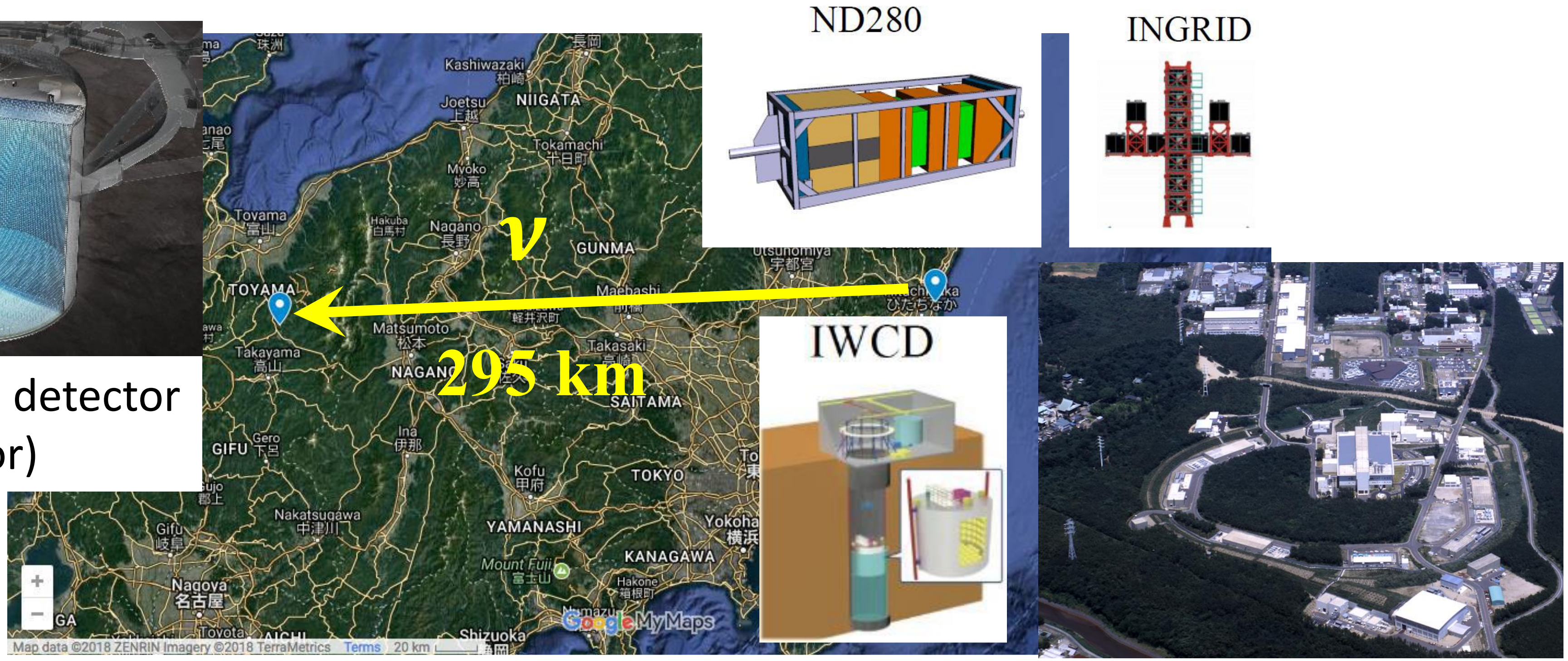


Hyper-Kamiokande Project

- 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

- **<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

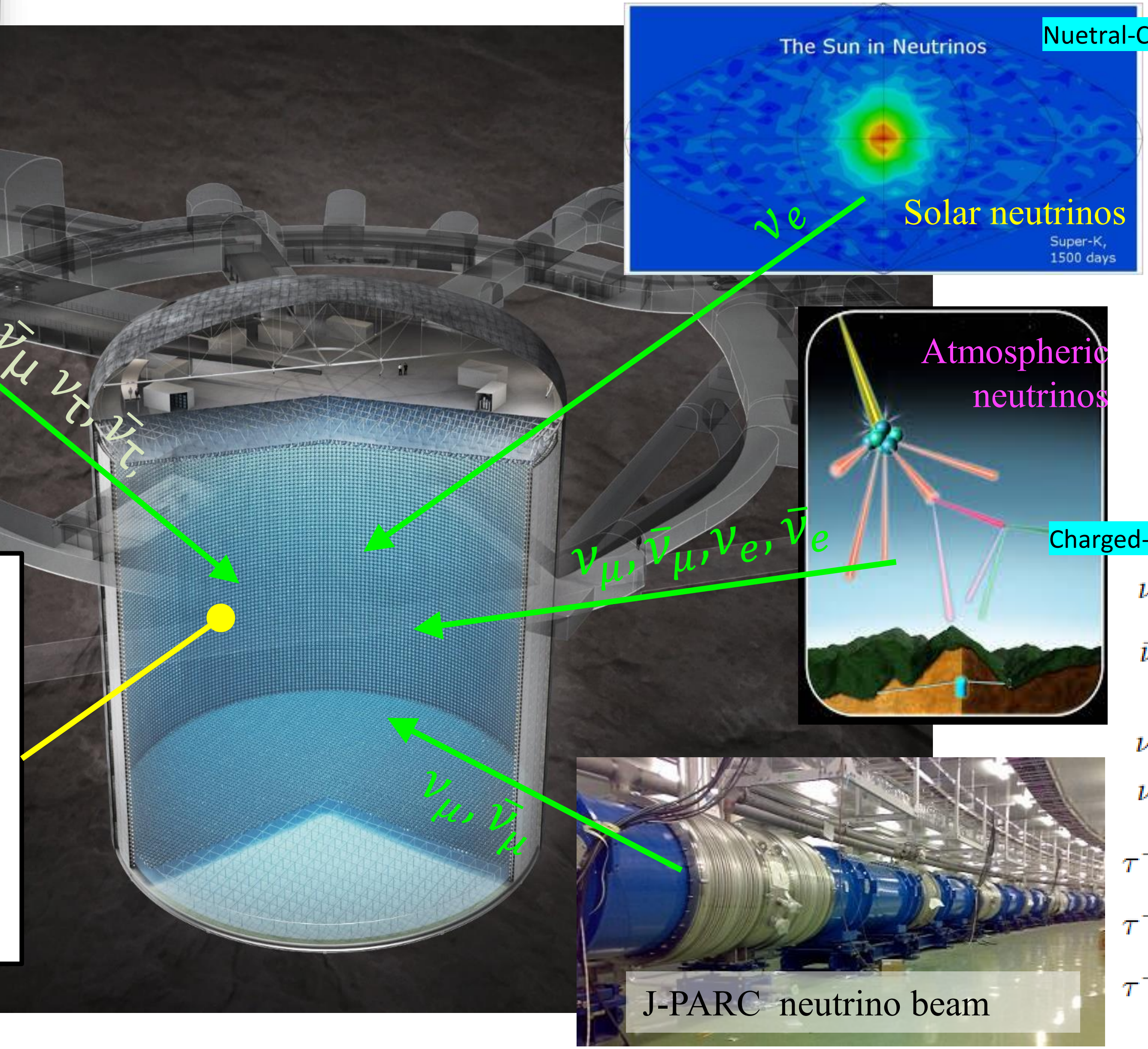
- **<u>Hyper-Kamiokande (2027 -)</u>**
  - Extended search for proton decay
  - Precision measurement of neutrino oscillation including CPV and MO
  - Neutrino astrophysics

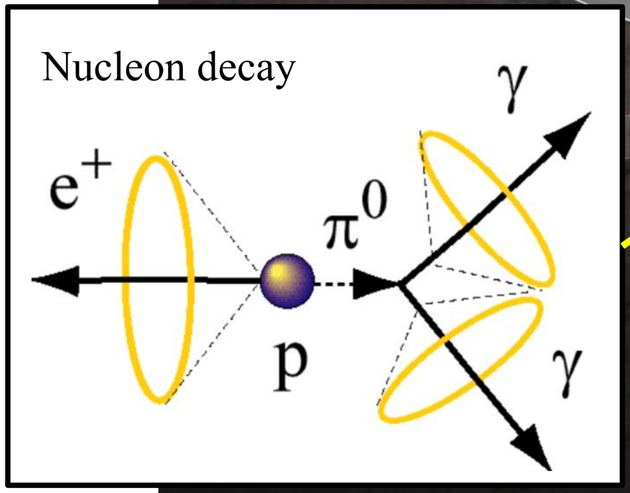
  Explore new physics

Hyper-K Observation Target

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

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





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

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

$\pi^0 \rightarrow \gamma + \gamma$

Nuetral-Current Interactions (NC)

$\nu_e + e^- \rightarrow \nu_e + e^-$

$\nu + N \rightarrow \nu + N'$

Charged-Current Interactions (CC)

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

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

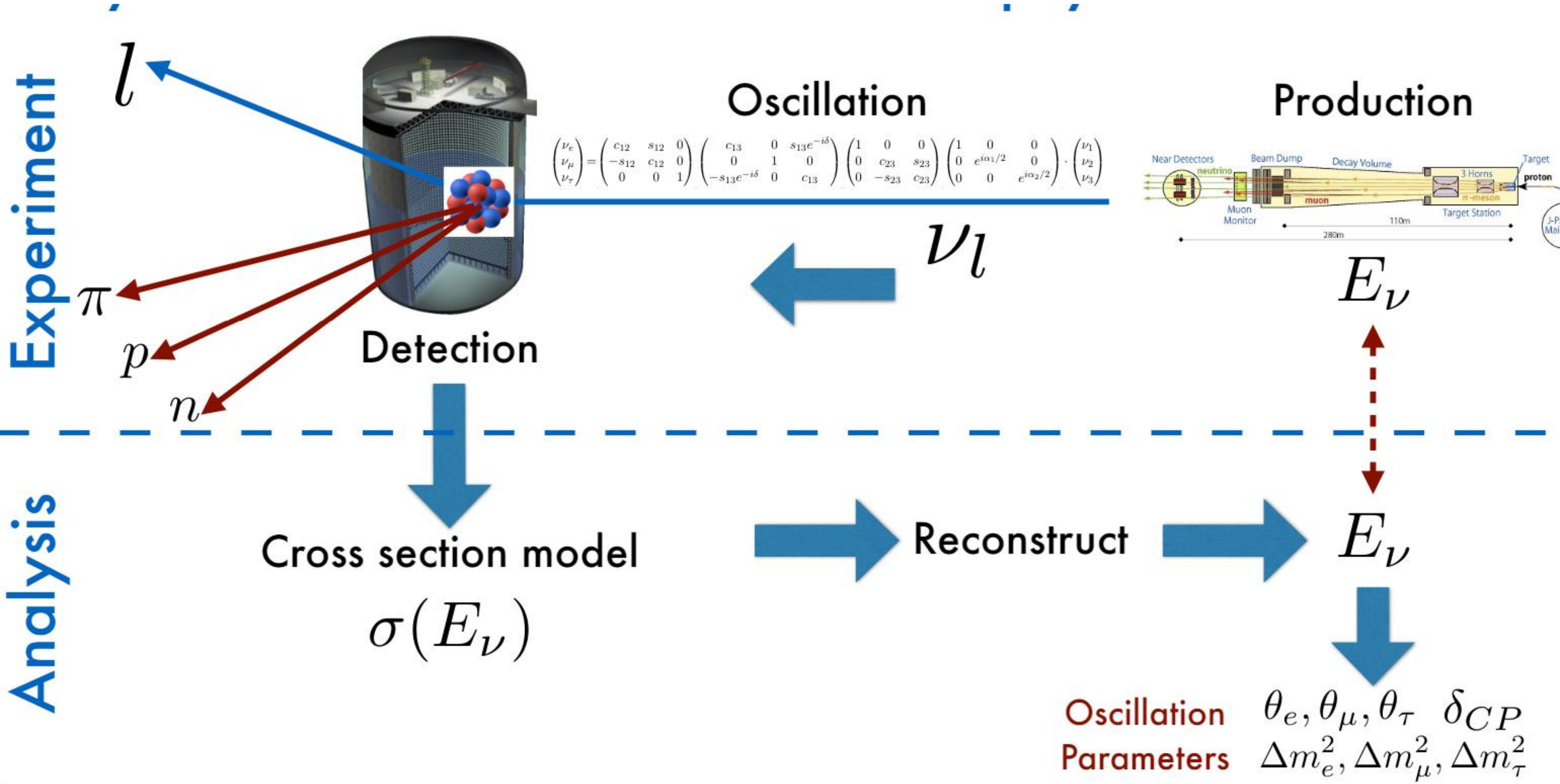
$\nu_\mu + n \rightarrow \mu^- + p$

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

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

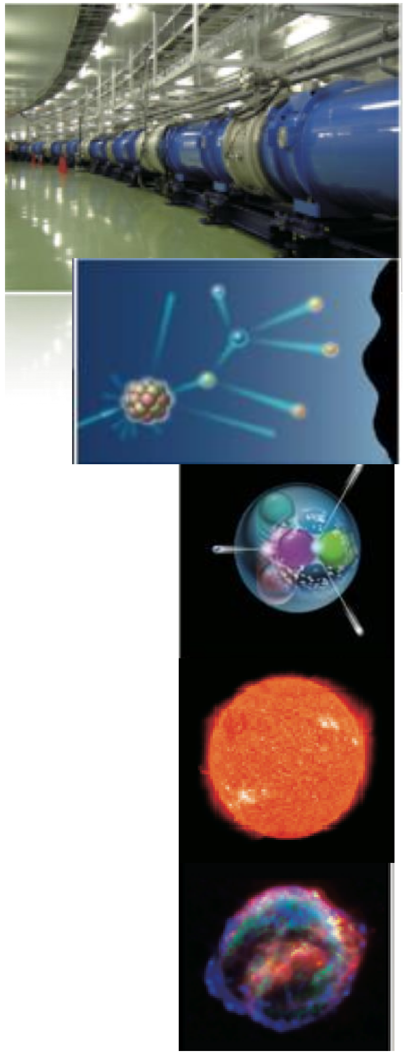
$\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau$

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



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
muon
π-meson
Muon Monitor
Target Station
110m
280m
E_ν
Cross section model
$\sigma(E_\nu)$
Reconstruct
E_ν
Oscillation Parameters
$\theta_e, \theta_\mu, \theta_\tau \quad \delta_{CP}$
$\Delta m^2_e, \Delta m^2_\mu, \Delta m^2_\tau$

Hyper-K Target sensitivity



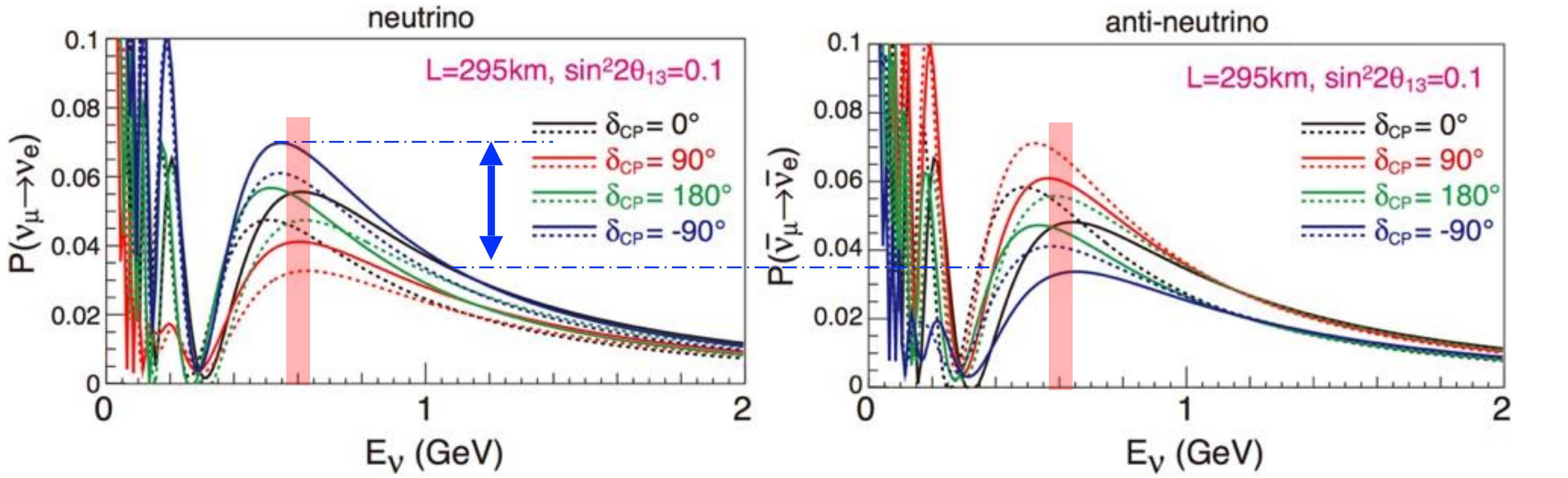
Physics category	Parameters	Sensitivity
LBL (1.3MW×10years)	δ precision	7°-20°
	CPV coverage (3/5σ)	76% / 58%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.017
ATM+LBL (10 years)	MO determination	>3.8σ
	Octant determination (3σ)	$\lvert\theta_{23}$-45°$\rvert$>2°
Proton Decay (20 years)	τ for $e^+\pi^0$ (3σ)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

Saul Cuen @ ISVHECRI 2024 Katsuki Hiraide @ NNN23

Long-baseline program with the J-PARC neutrino beam

Experimental setup

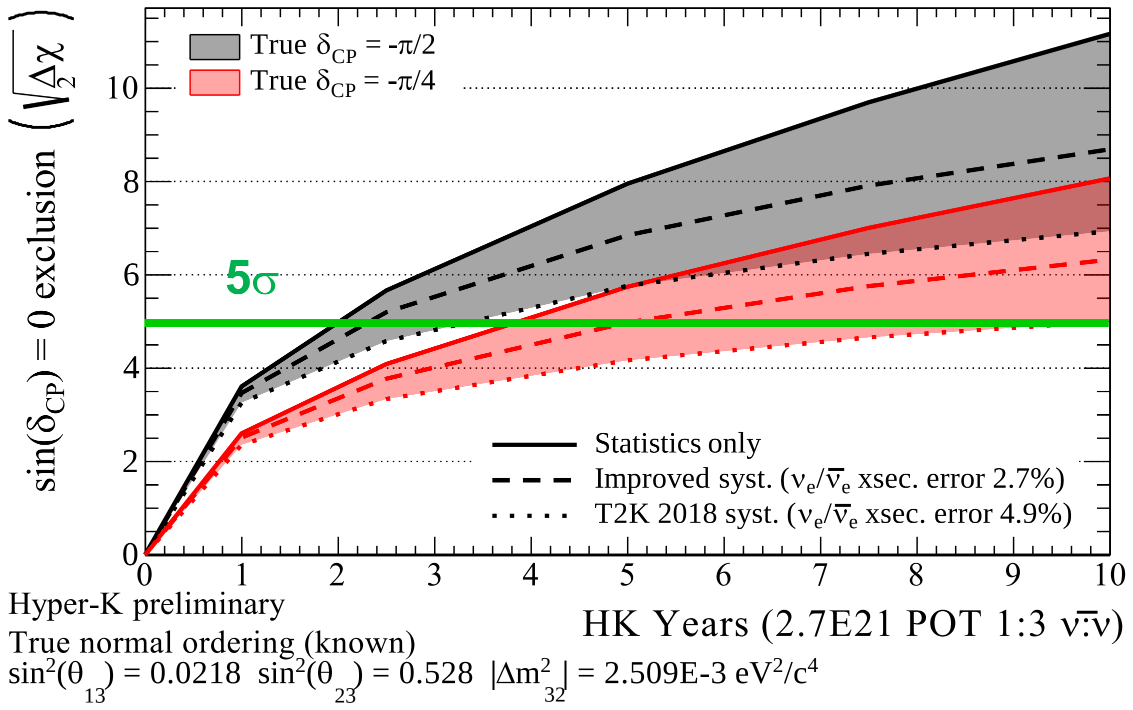
- 2.5° off-axis ν_μ and $\bar{\nu}_\mu$ beam peaked at 0.6 GeV (oscillation maximum at 295km)
  - Major interaction is QE: E_ν determined from (p, θ) of charged lepton
- Measures CP violation in neutrinos by comparing $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

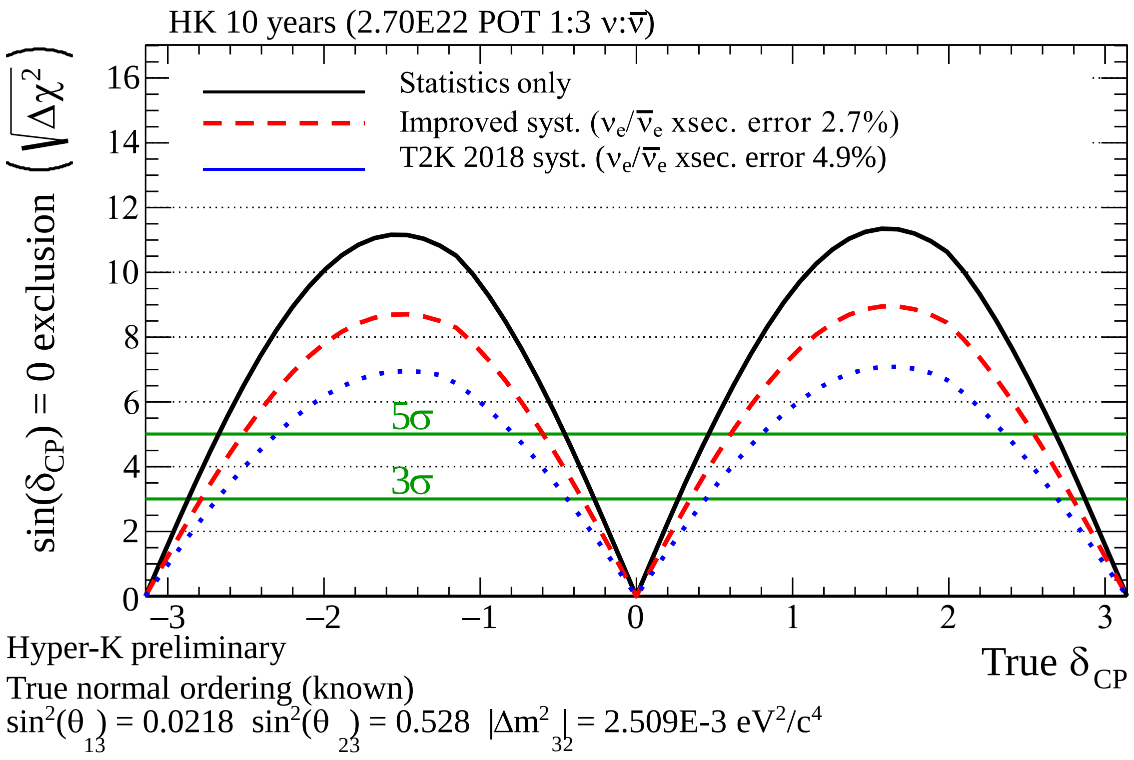


- A few % statistical uncertainties after 10 years operation with >1000 ν_e and $\bar{\nu}_e$ signals

CP violation sensitivity

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





- With 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

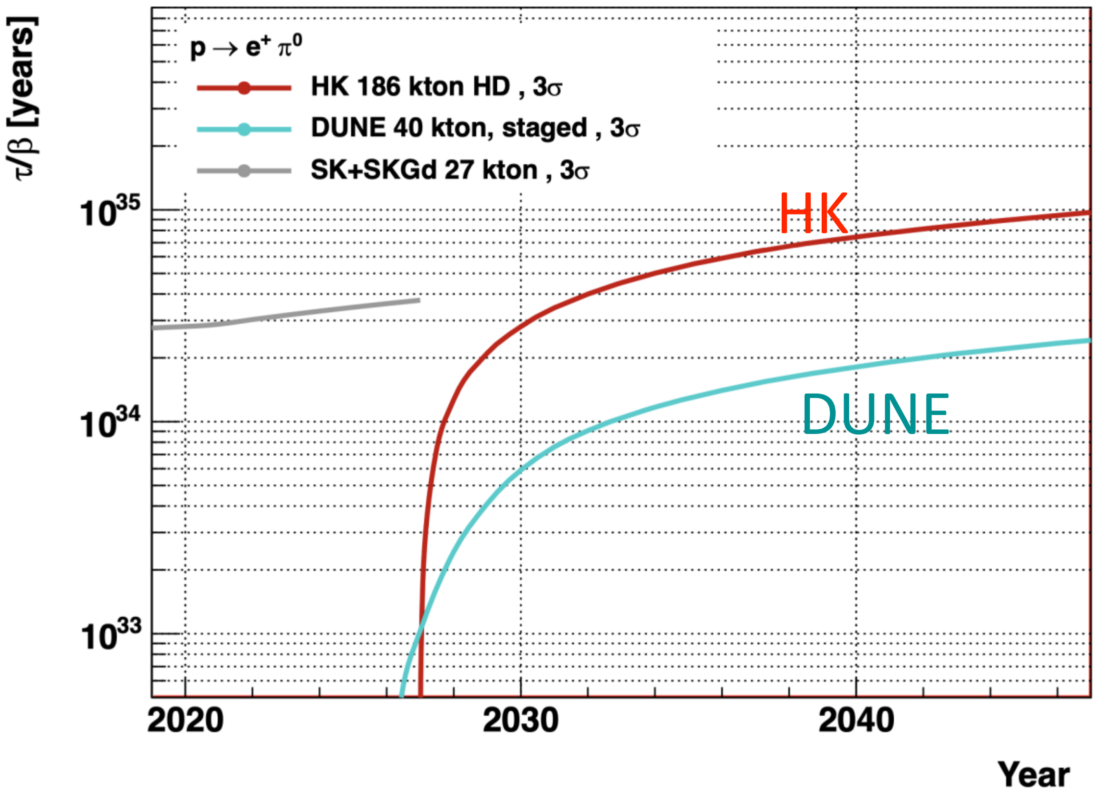
Katsuki Hiraide @ NNN23

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:

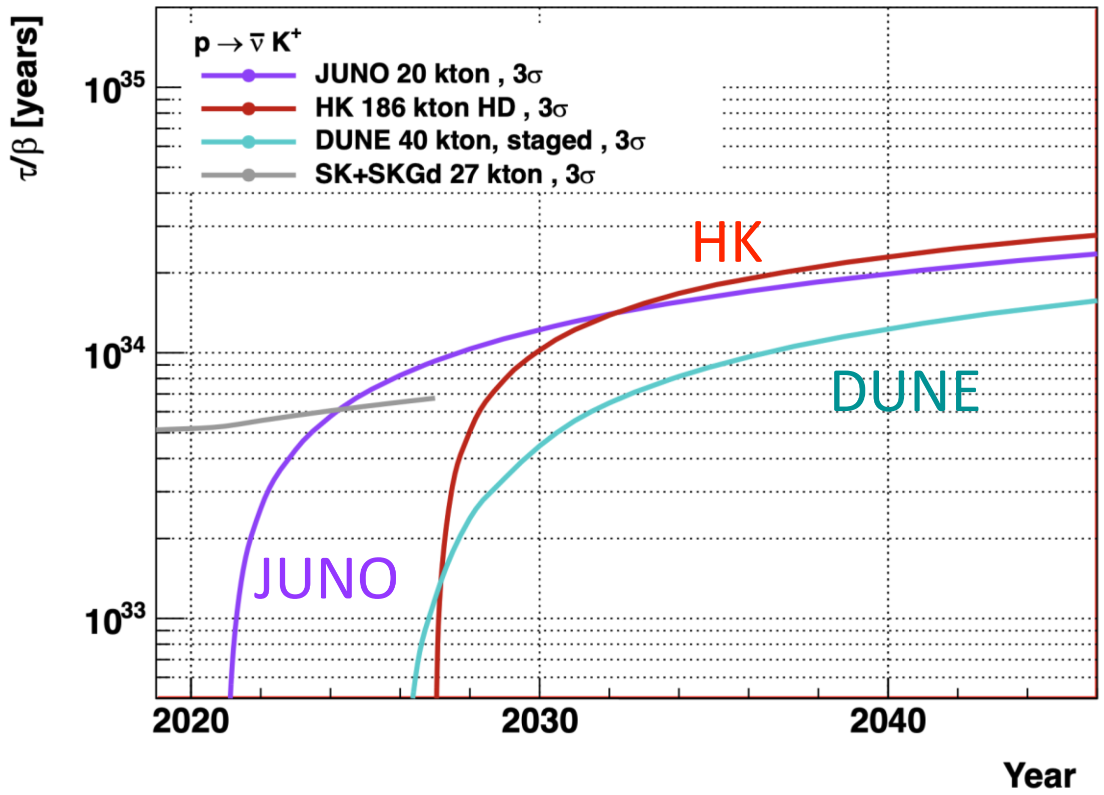
[HK] arXiv:1805 04163
[DUNE] arXiv:2002.03005
[JUNO] arXiv:1508.07166

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



τ~10^{35} years (3σ)

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



τ~$3\text{x}10^{34}$ years (3σ)

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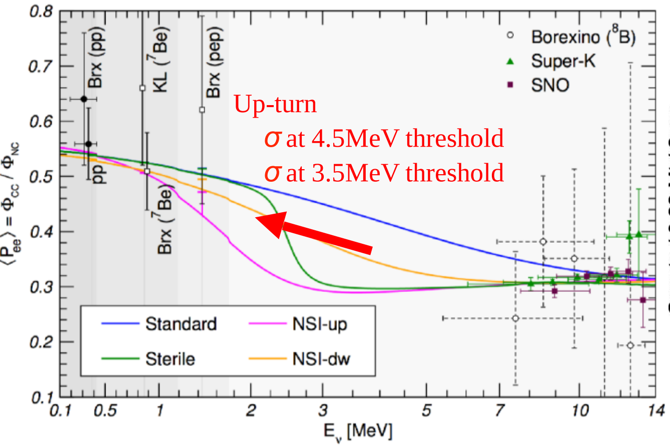
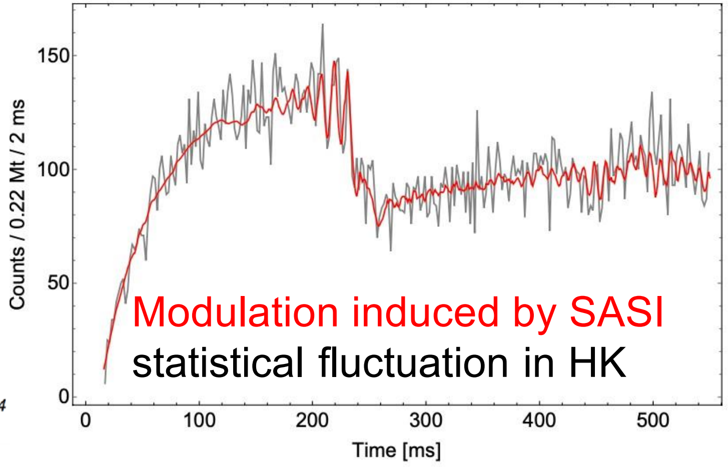
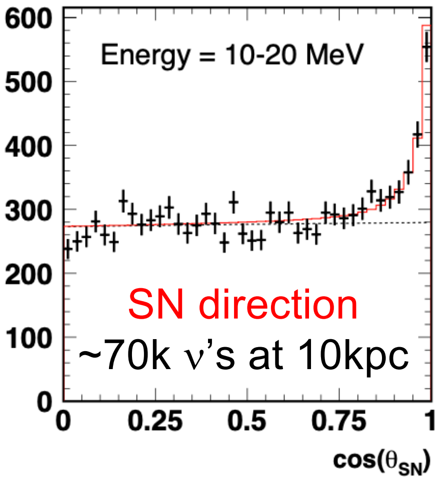
Neutrino astrophysics

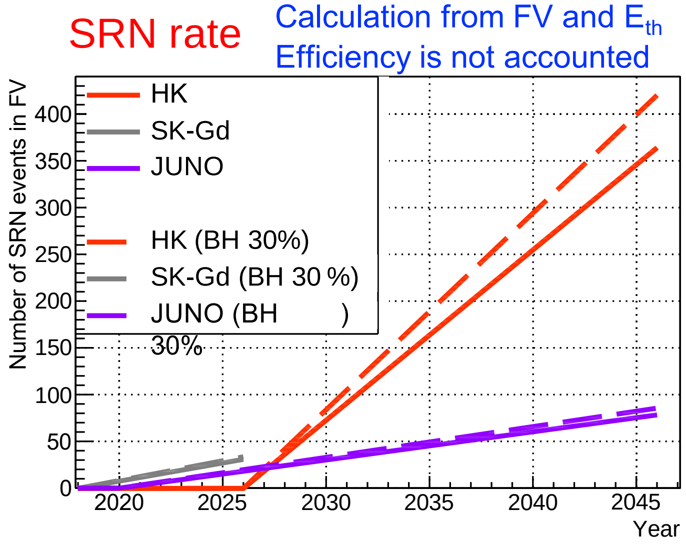
- Hyper-K is designed to be sensitive to neutrinos with energies starting from a few MeV, including time, energy and direction information. Unique role in multi-messenger observation
- **Solar neutrinos:** up-turn at vacuum-MSW transition, Day/Night asymmetry, hep neutrino observation
- **Supernova burst neutrinos:** explosion mechanism, BH/NS formation, alert with ~1^{o} 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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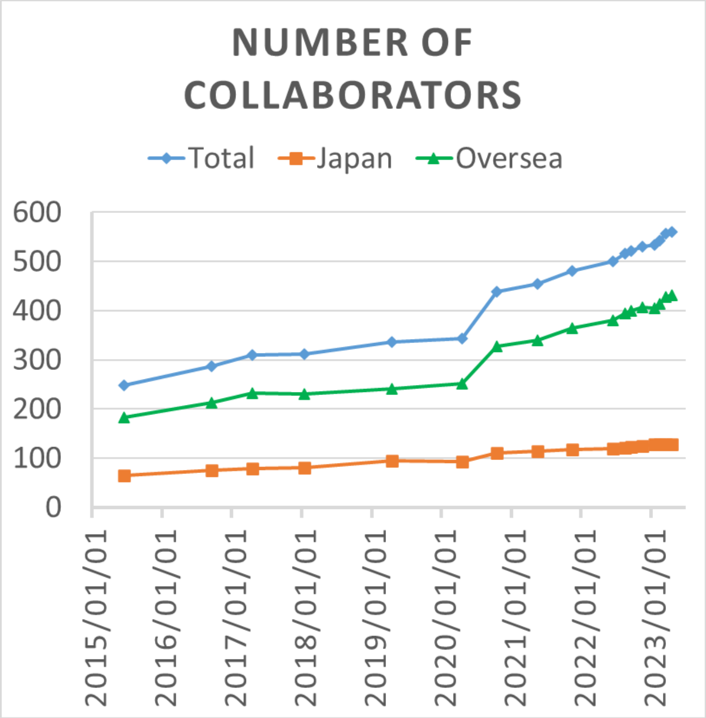
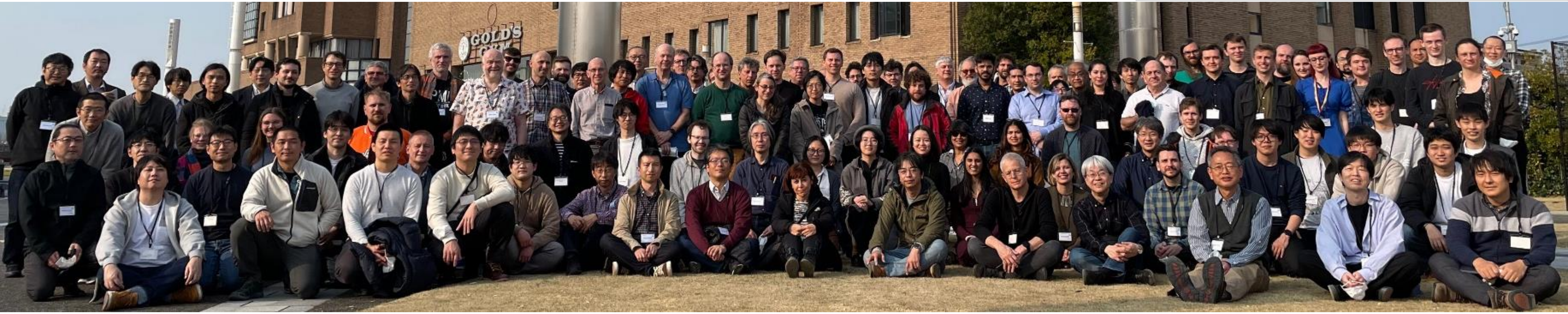
Hyper-Kamiokande Collaboration

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

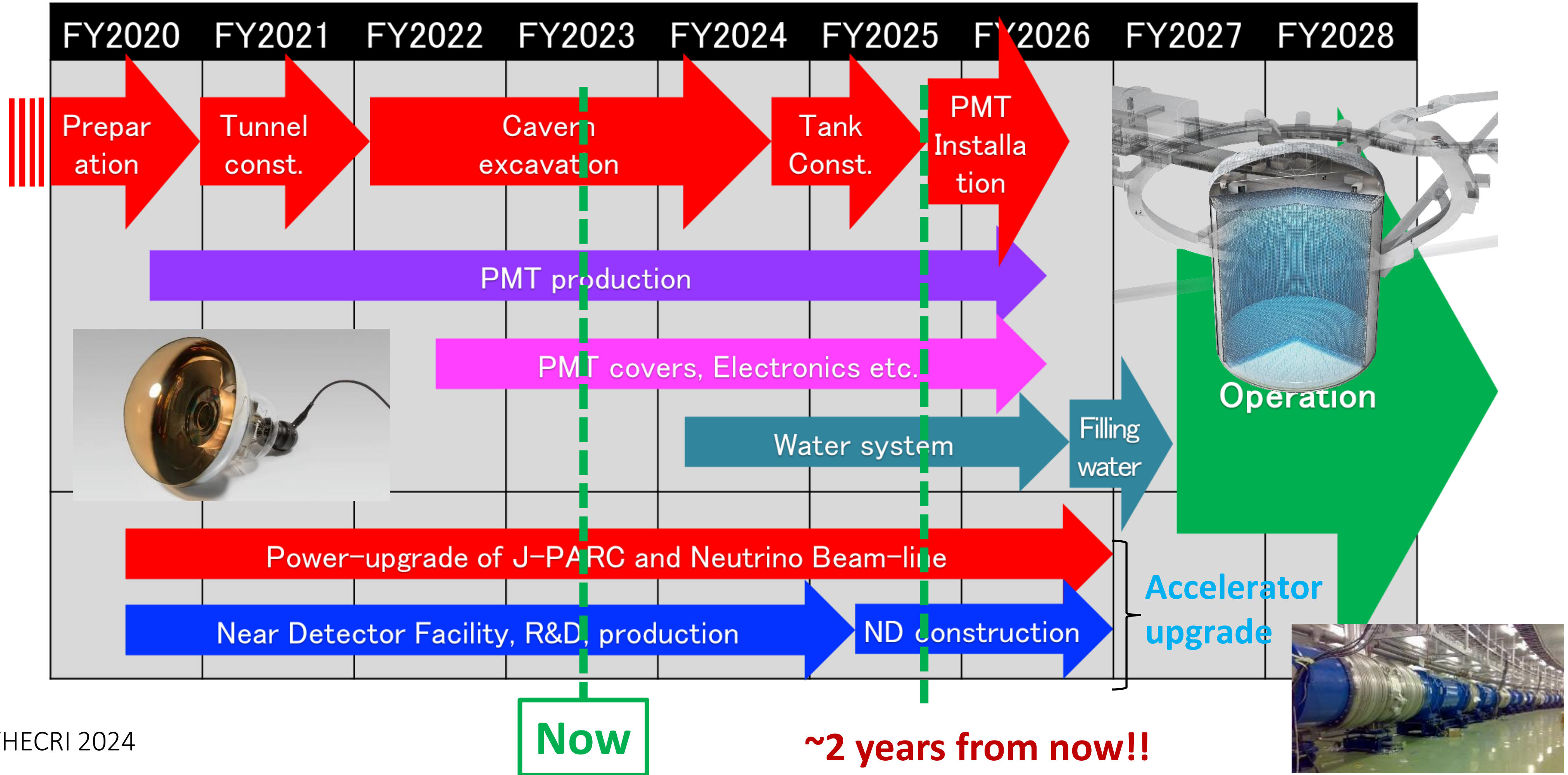
- <u>March 2023:</u>
  our very 1st Collaboration meeting in person after COVID!



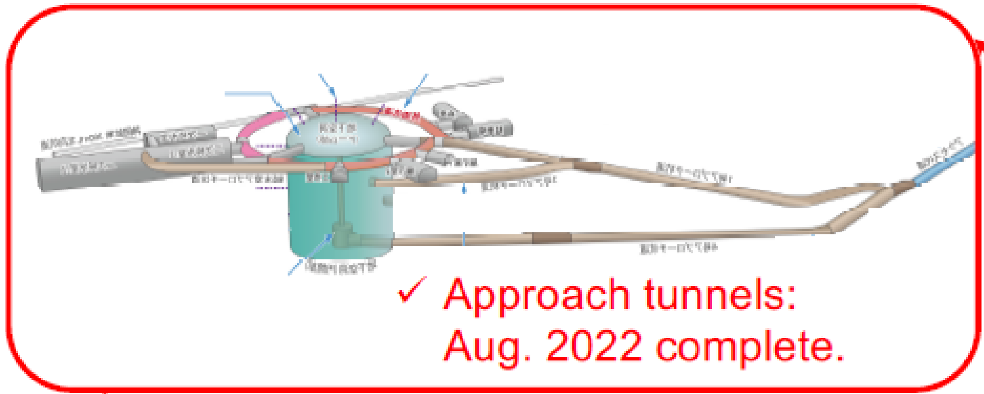


Hyper-K construction schedule

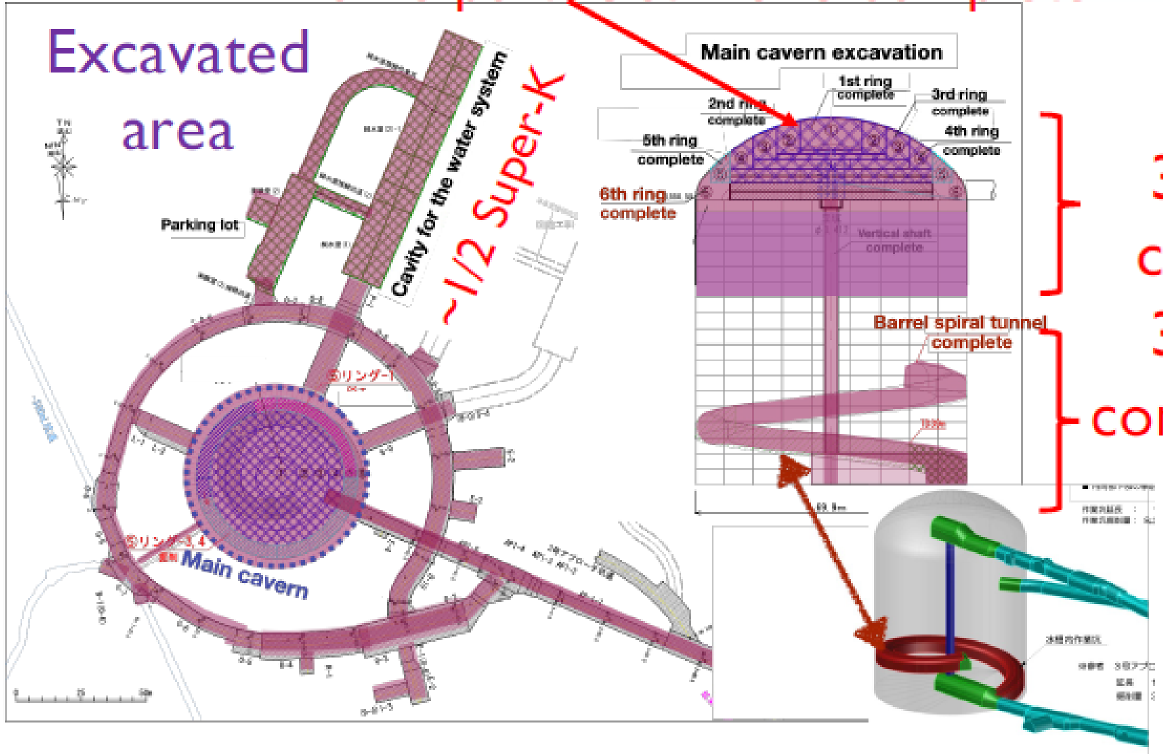
- The Hyper-K construction started in 2020 and will start operation in 2027.



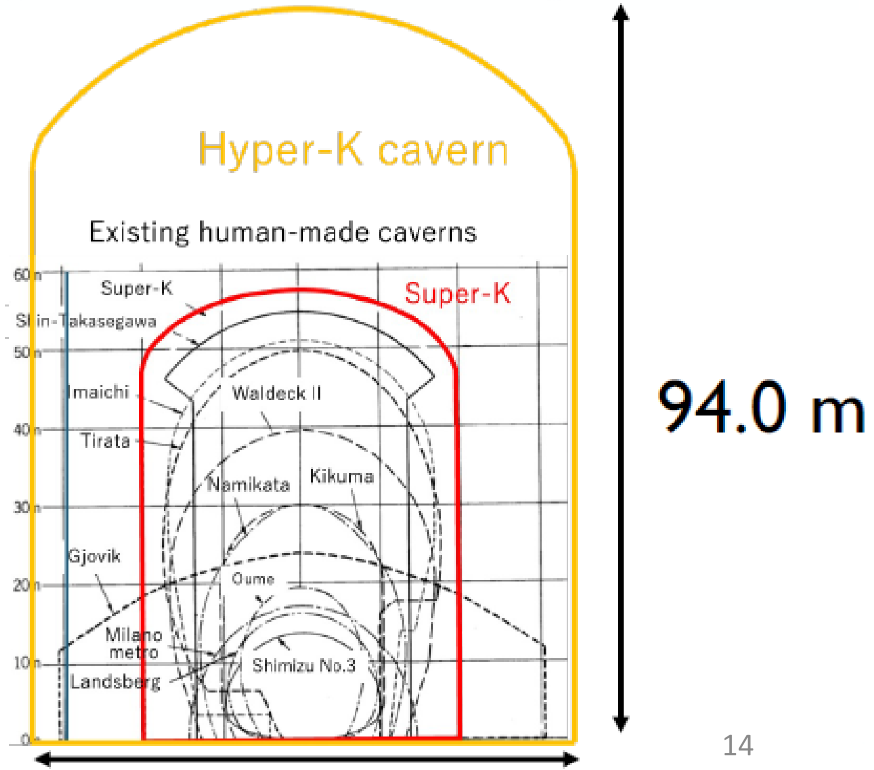
Excavating the world's largest human-made cavern



✓ Dome part: Oct. 2023 complete.



3 Super-K completed.
3 Super-K coming ~1/2yr



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Hyper-K main cavern excavation

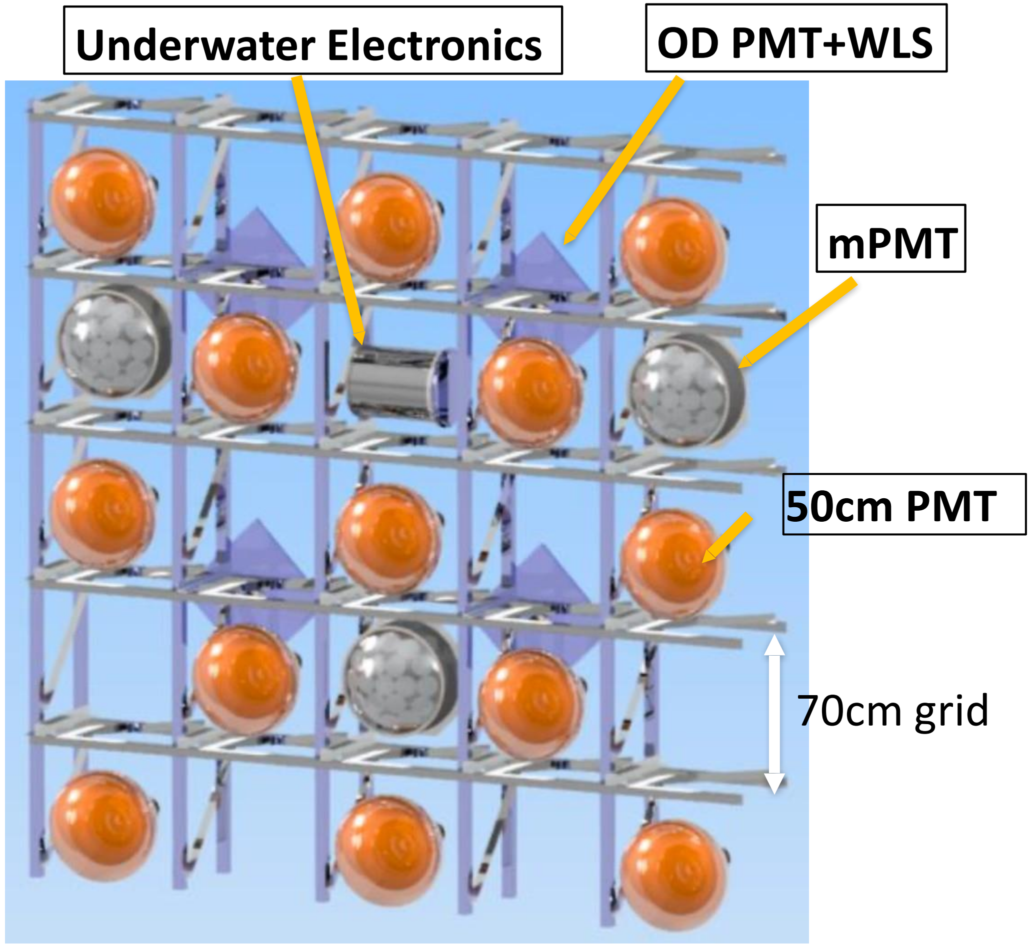
Katsuki Hiraide @ NNN23

- **October 3, 2023:** 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.


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



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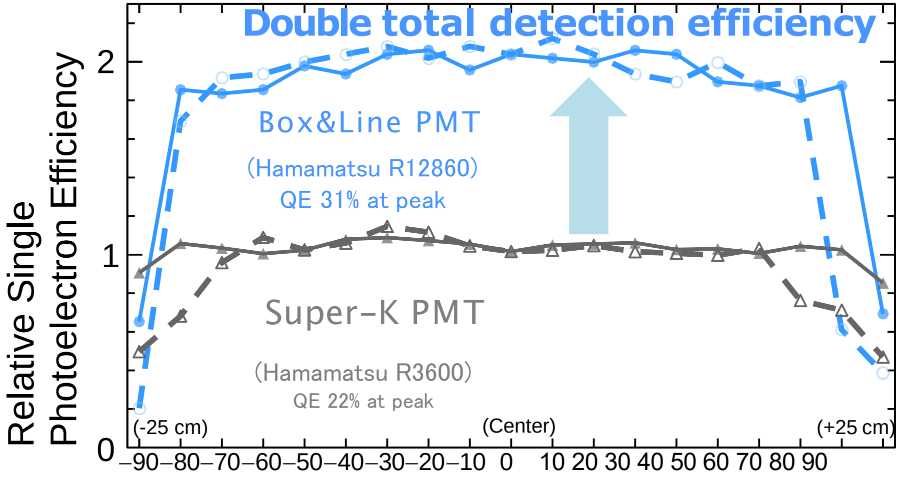
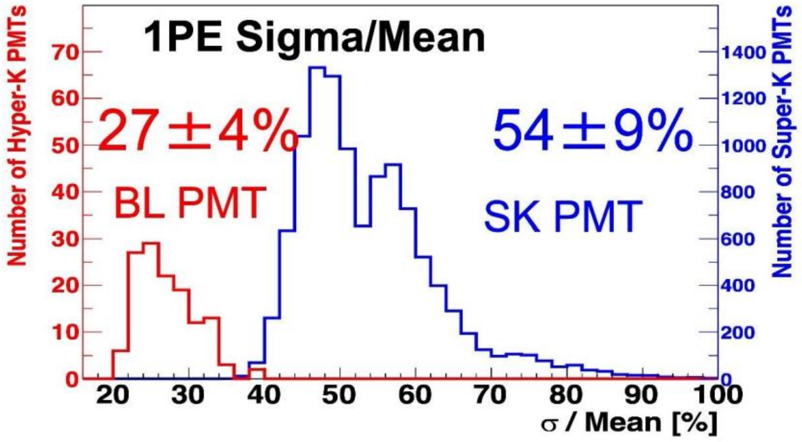
Hyper-K 50cm PMT performance

(Performance in SK tank, 1.7e7 gain)

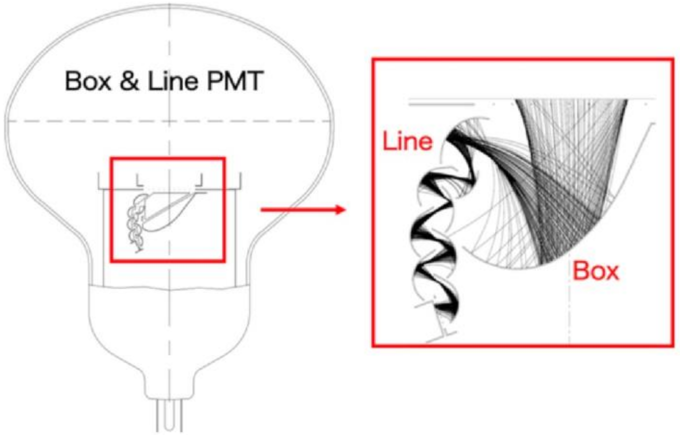
×2 better photodetection efficiency (QE×CE)



×2 better charge resolution



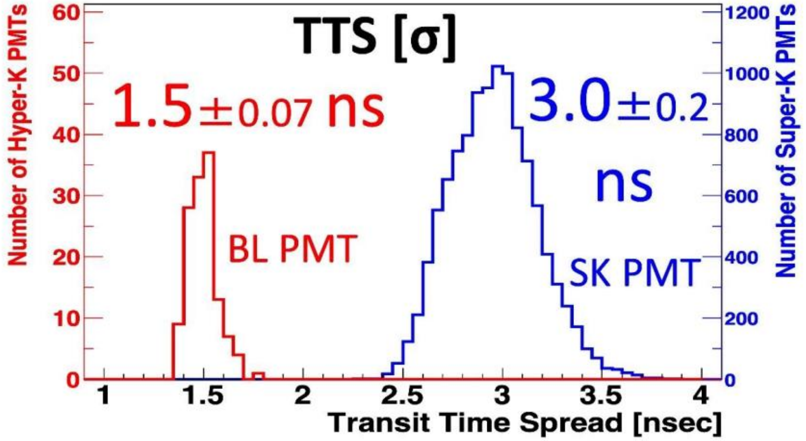
Box&Line dynode



×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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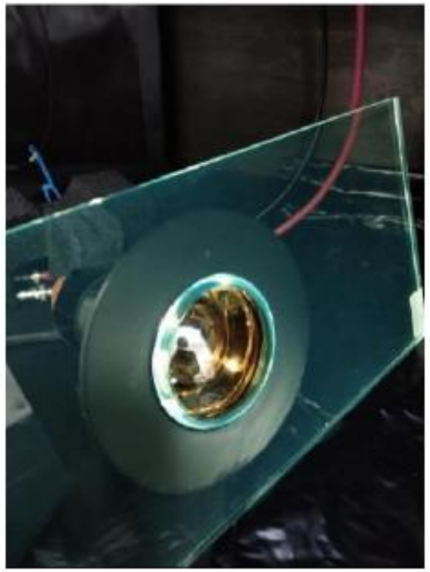
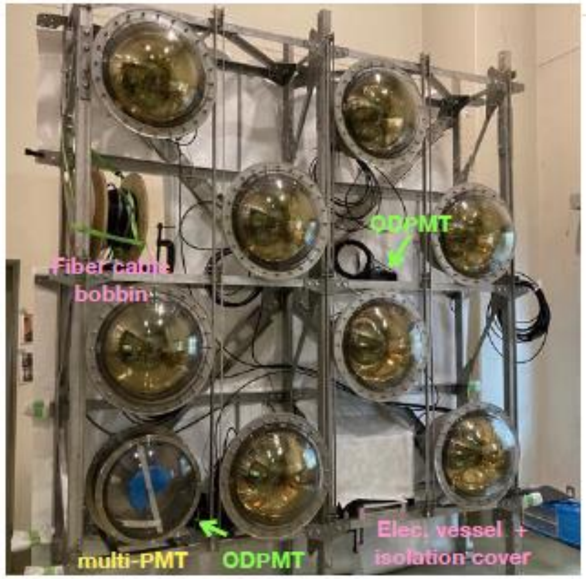
PMT production ongoing, >10,000 delivered.
Screening both at Hamamatsu and Kamioka

Photosensors and underwater electronics

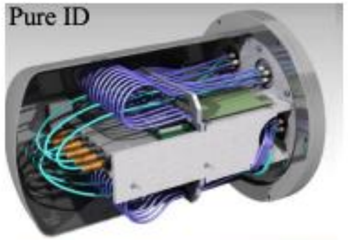
Outer detector: PMT+WLS plate

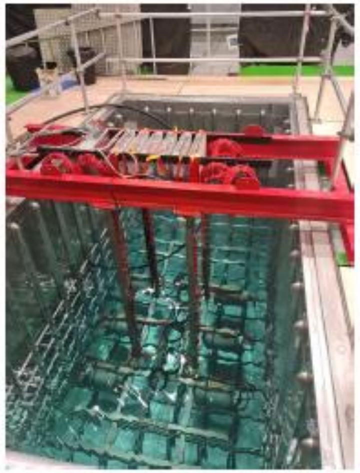


Photosensors/elec. mockup

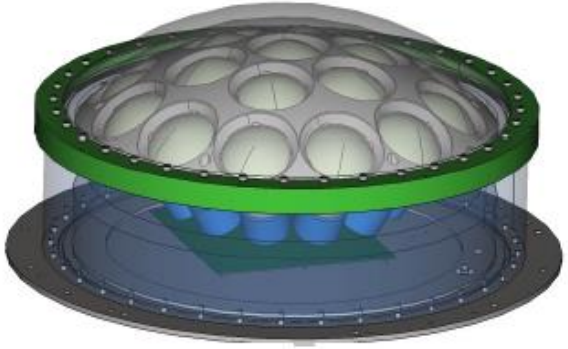


Underwater electronics: Case design and feedthrough

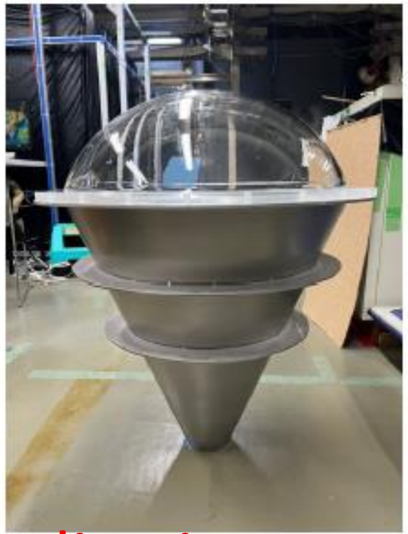




Multi-PMT module:



PMT cover



Design finalization ongoing

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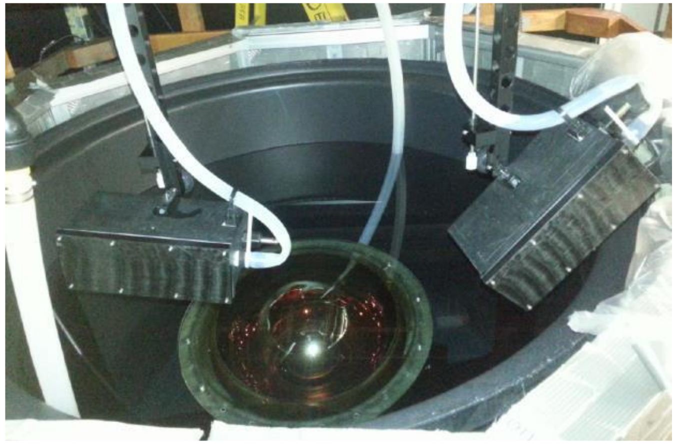
Hyper-K Calibration

- Various programs to determine detector parameters and measure systematics

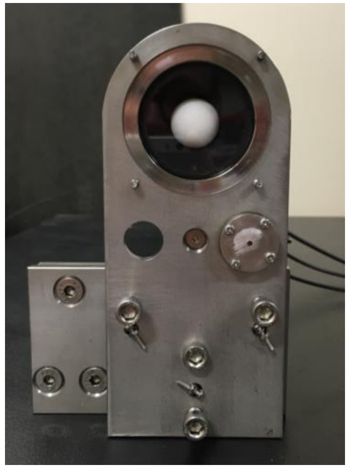
- Pre-calibration of photosensors
- Photogrammetry
- Light Injection
  - Diffusers and collimators
  - mPMT system
  - OD injectors
- Electron LINAC
  - 3-24 MeV electrons
- Radioactive Sources
  - DT Source - 16N
  - AmBe + BGO – tagged neutrons
  - Ni/Cf - 9 MeV gamma cascade

Photosensor Test Facility

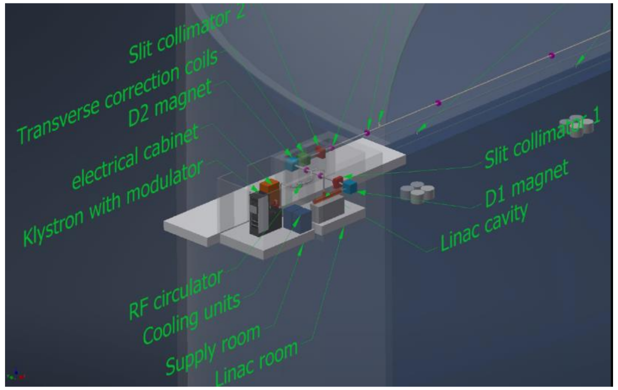


Photogrammetry testing

Light injectors

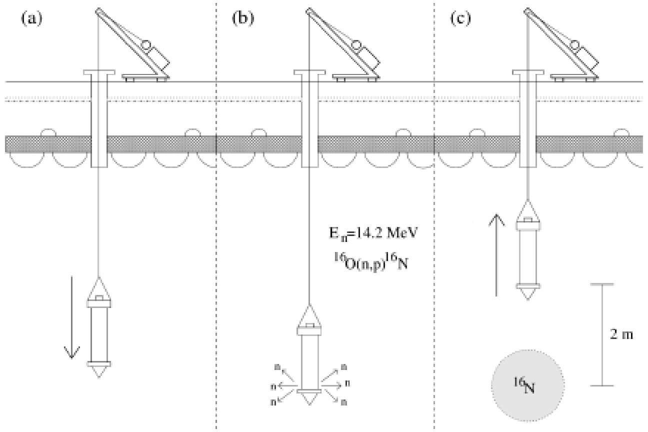


LINAC beam simulation



Ni/Cf source

DT operation



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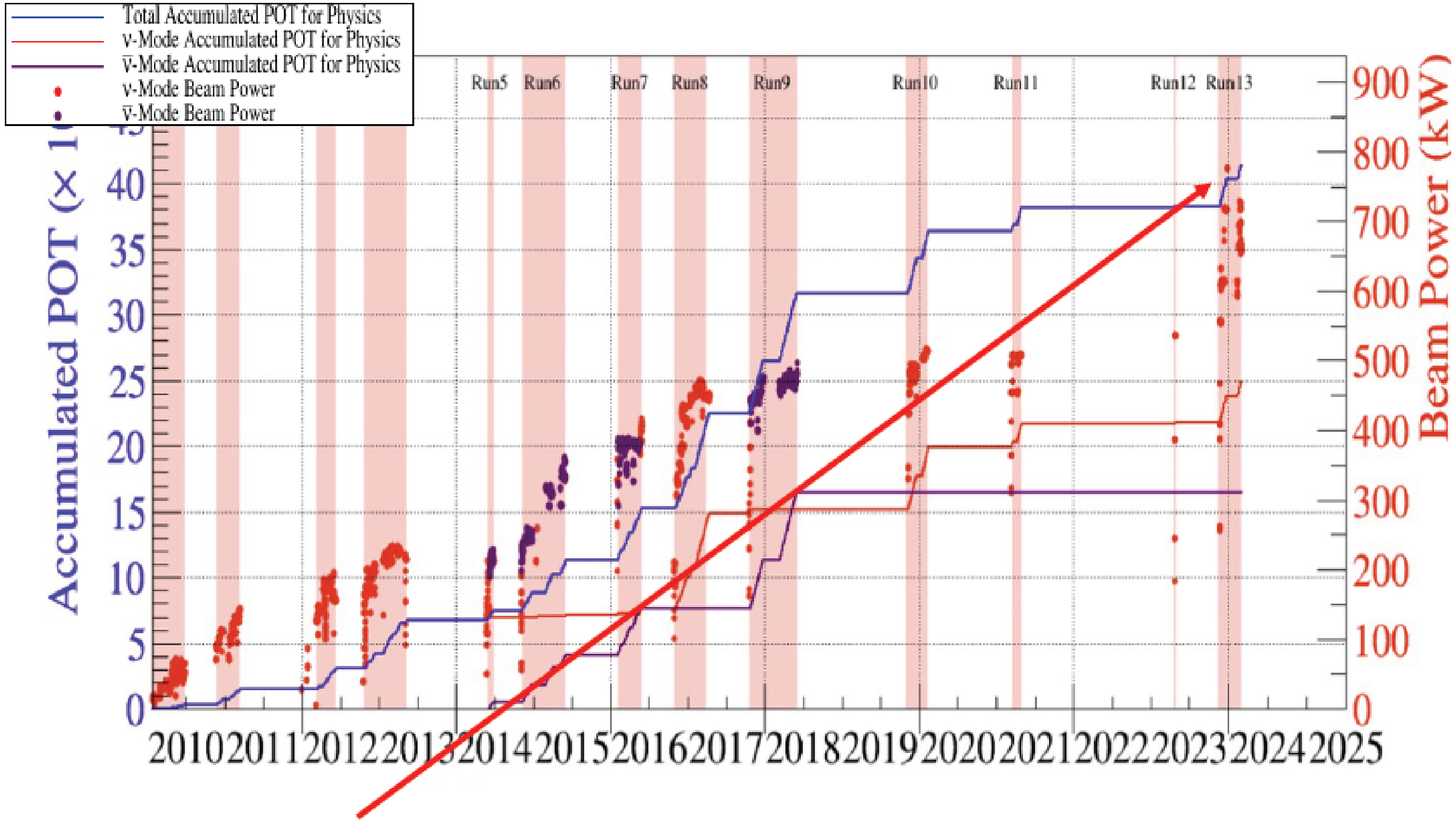
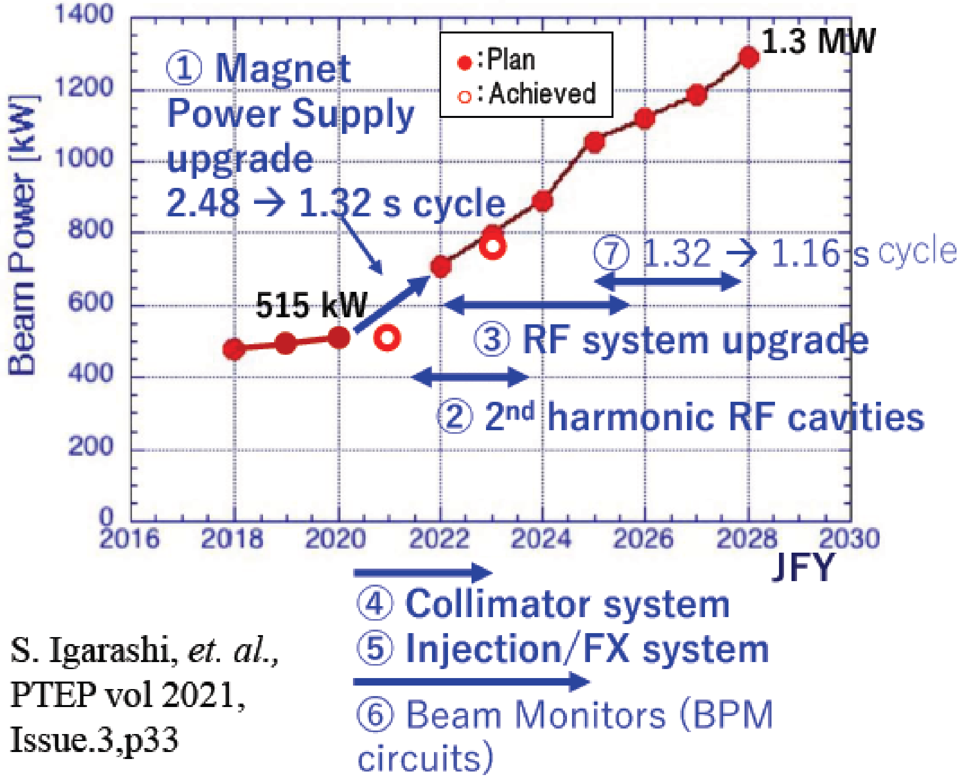
Beam: status and plan of power increase



Original power projection in MR Upgrade Plan



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

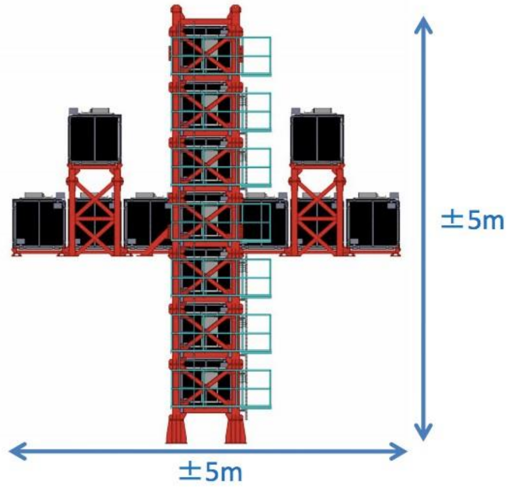
760 kW achieved already and 800 kW last week!

Further beam power increase requires:

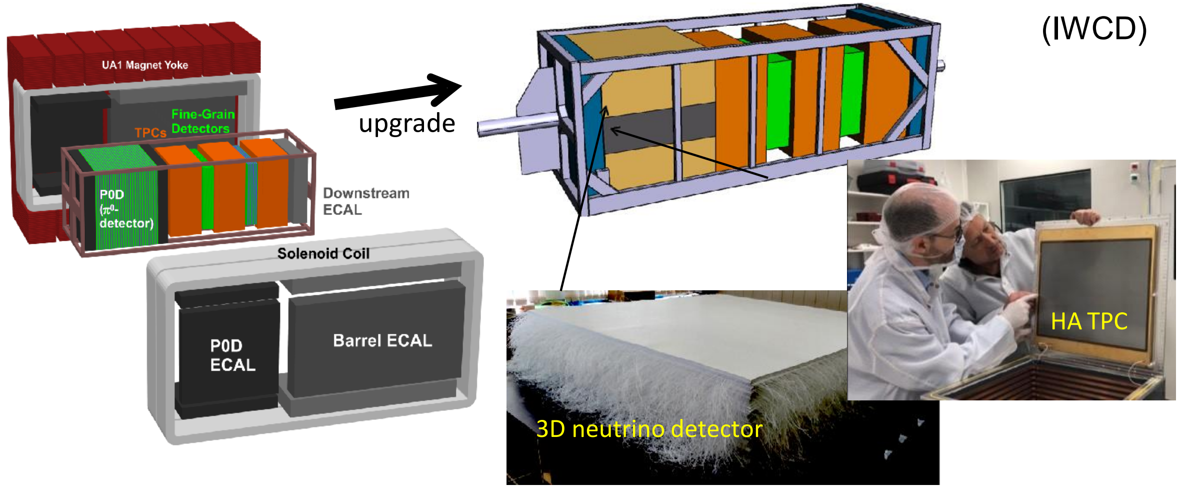
- Seeking beam loss with optics improvements
- More protons/pulse by upgrading RF system
- Further beam intensity increase will be done by 1.36 → 1.16 sec cycle

Neutrino detectors at J-PARC

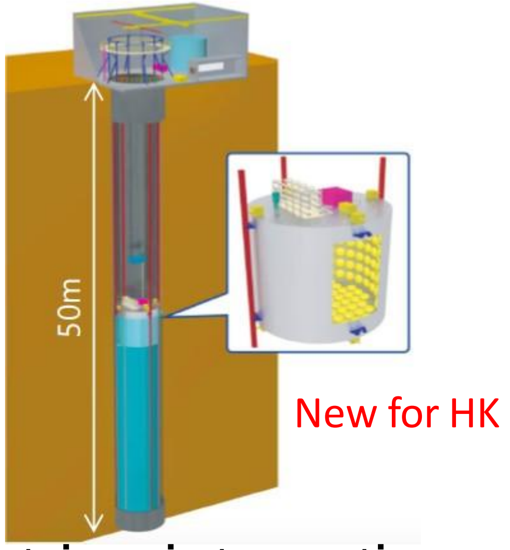
On-axis Detector
(INGRID)



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



Off-axis spanning Intermediate water Cherenkov detector
(IWCD)



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.

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 by the end of 2024.

Mexican involvement in Hyper-K

Master thesis in progress (**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

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

Advisors: KAREN SALOME CABALLERO MORA

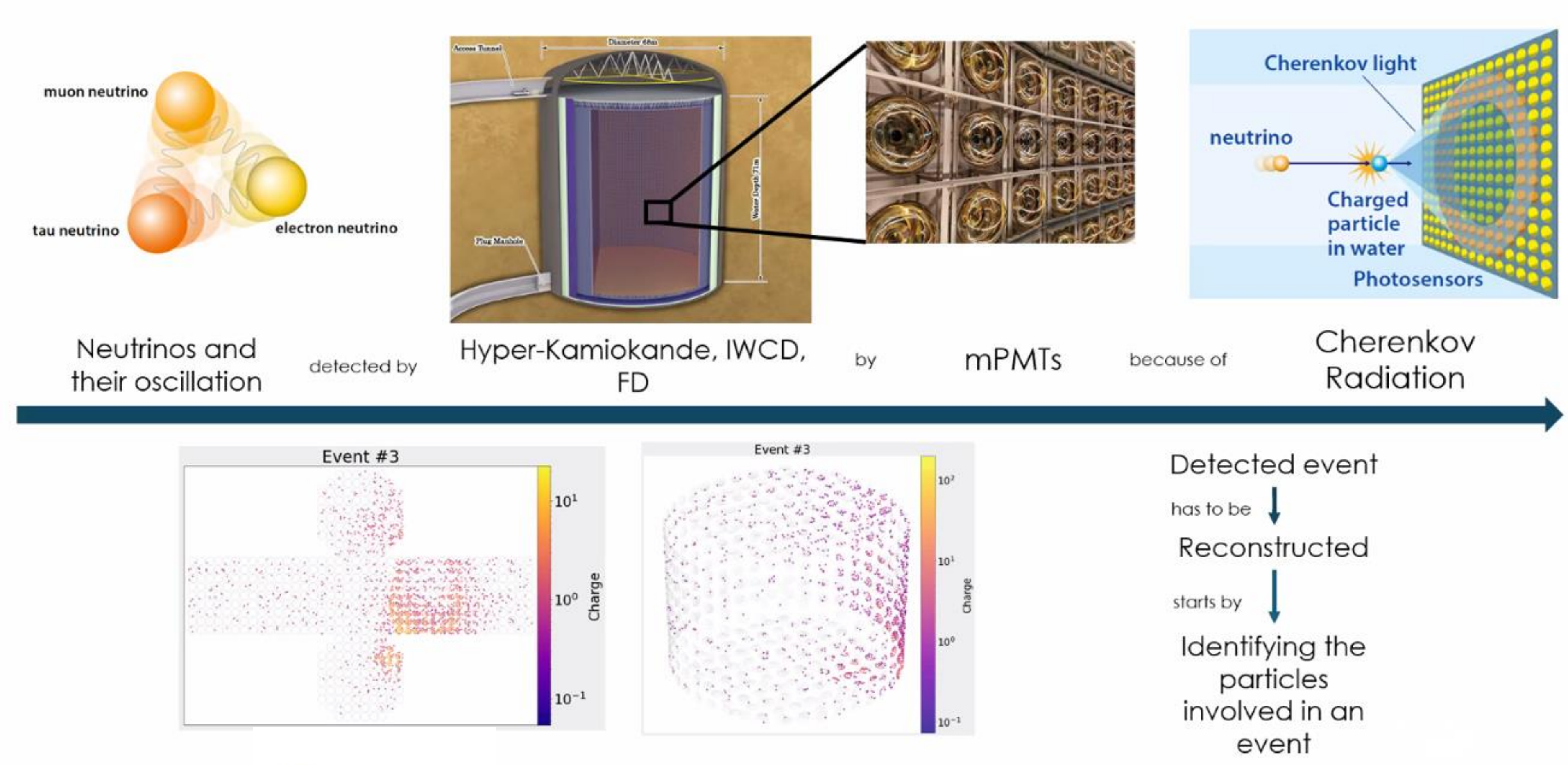
Thesis open position:
- Neutrino Classification with AI

Advisors: Saul Cuen, Rajesh Biswal, Rodrigo Gamboa (volunteers?)

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

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

Neutrino classification



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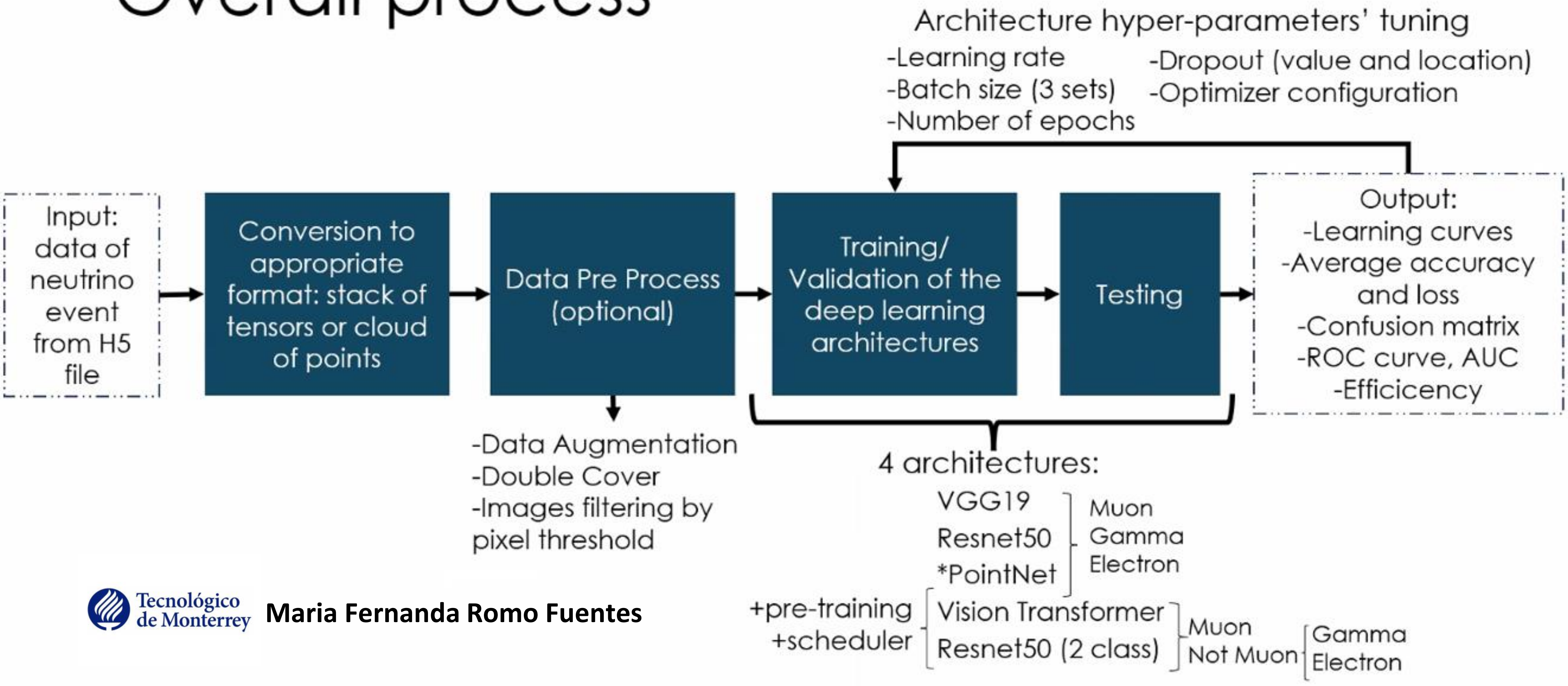
Overall process



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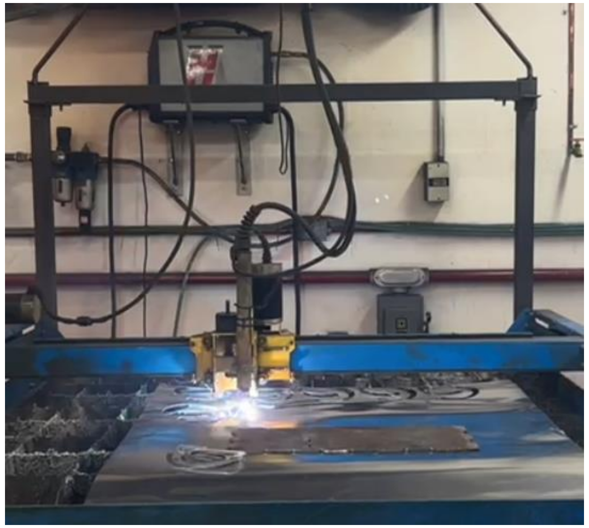
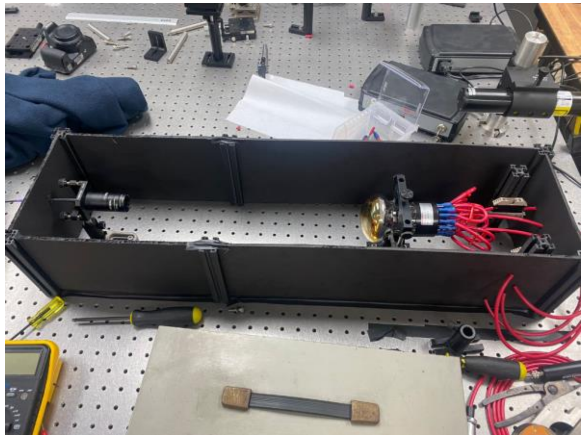
mPMT prototype in Mexico

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

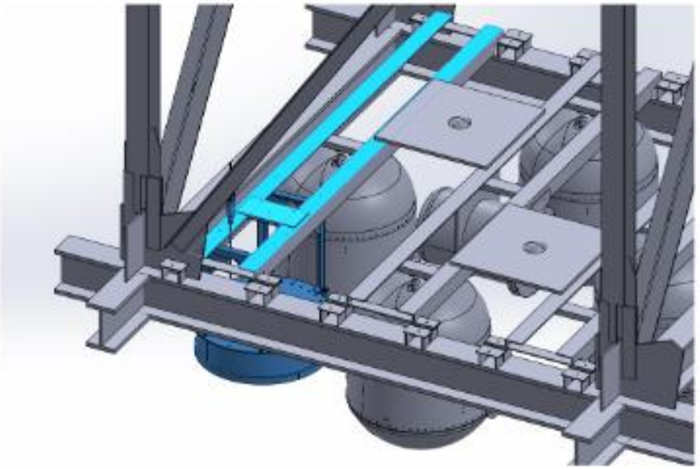
- Mechanical metrology and assembly
- Setting un blackbox and optical testing for PMT check (student Roy Medina)

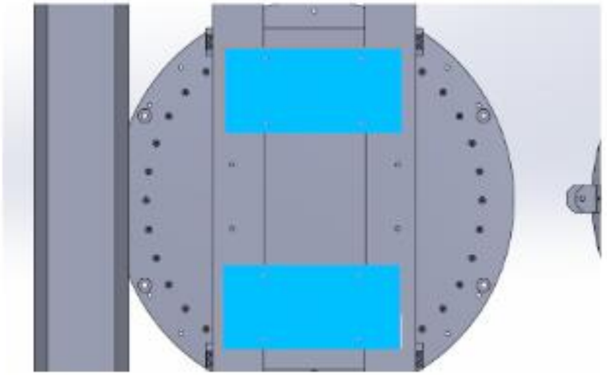


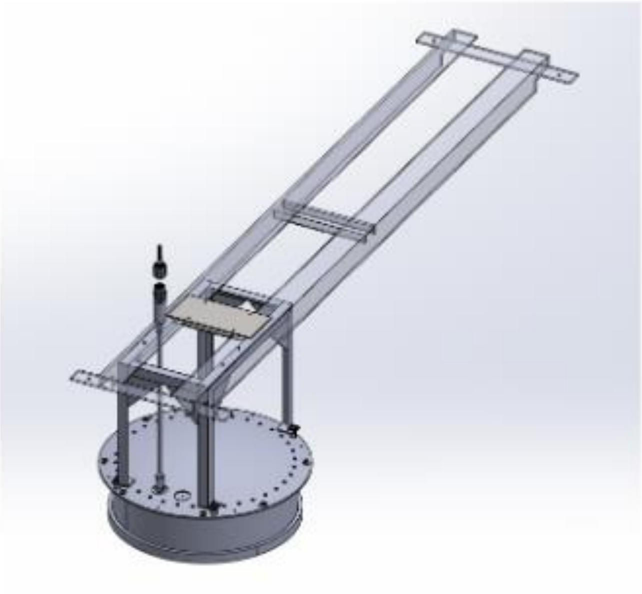


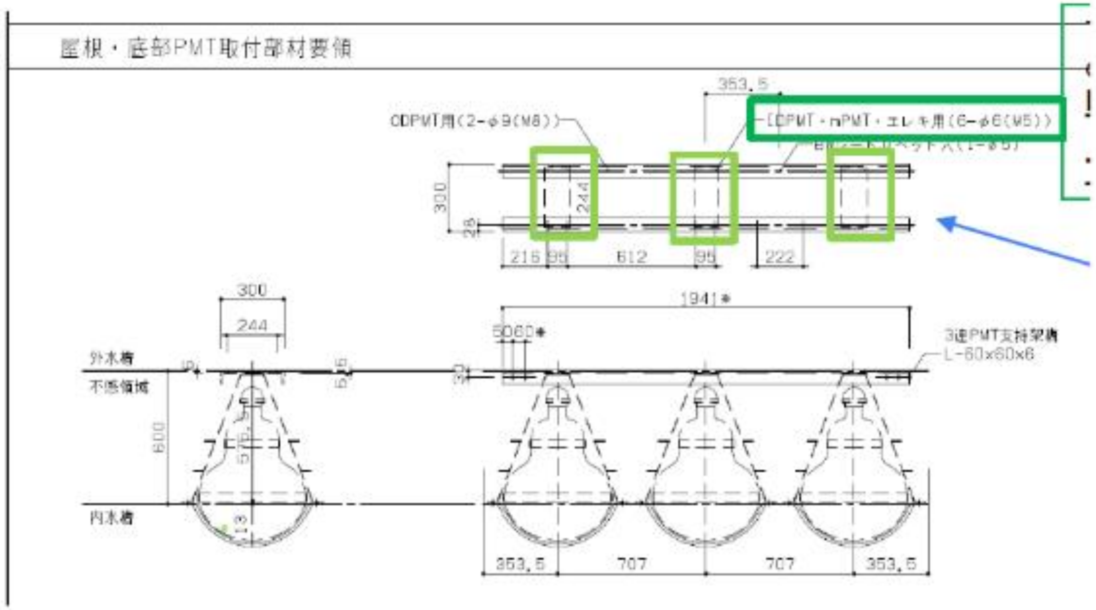
top & bottom mPMT support

Currently working on requirements from the integration group.









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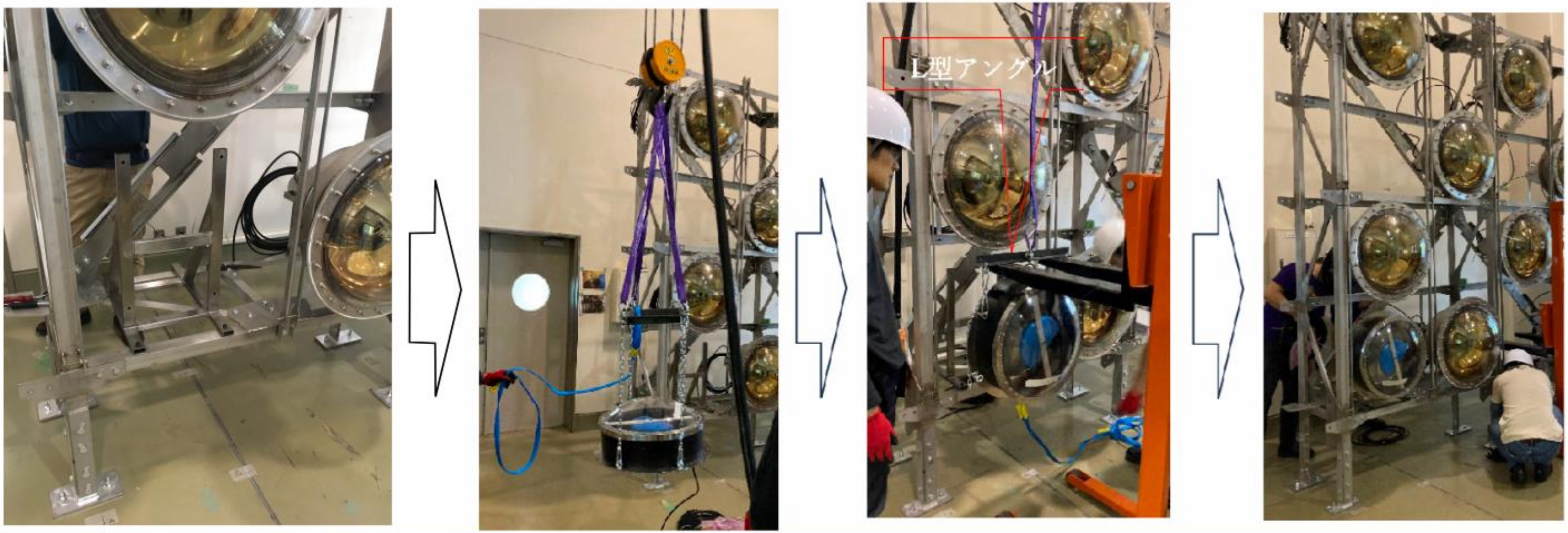
mPMT mechanical stress test

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.