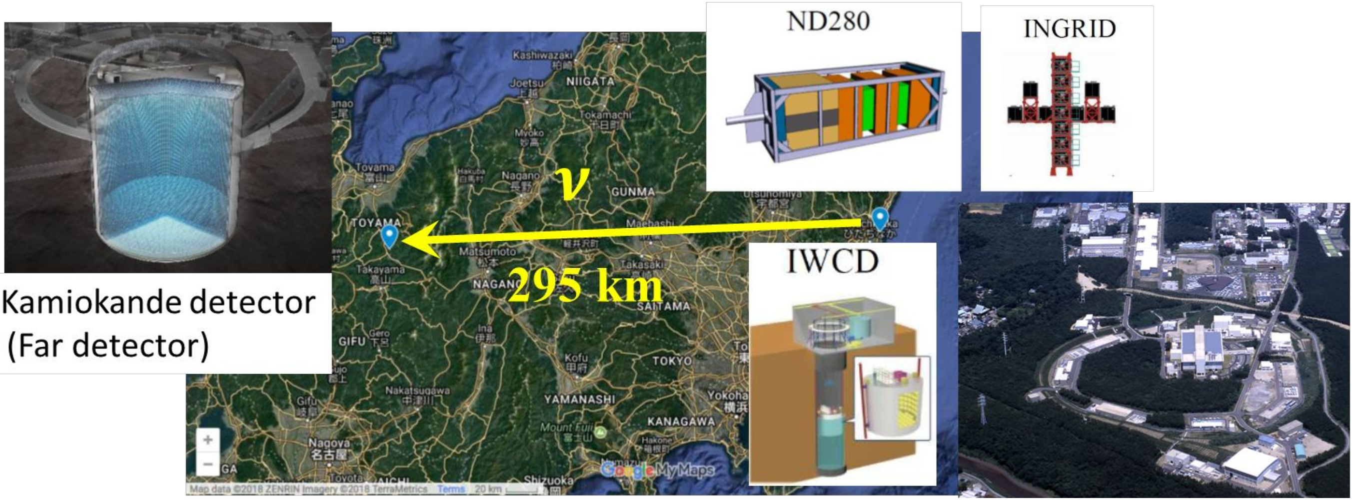
Status Hyper-K

Saul Cuen-Rochin (Tecnologico de Monterrey)

22 Oct
MWPF2025

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

- **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

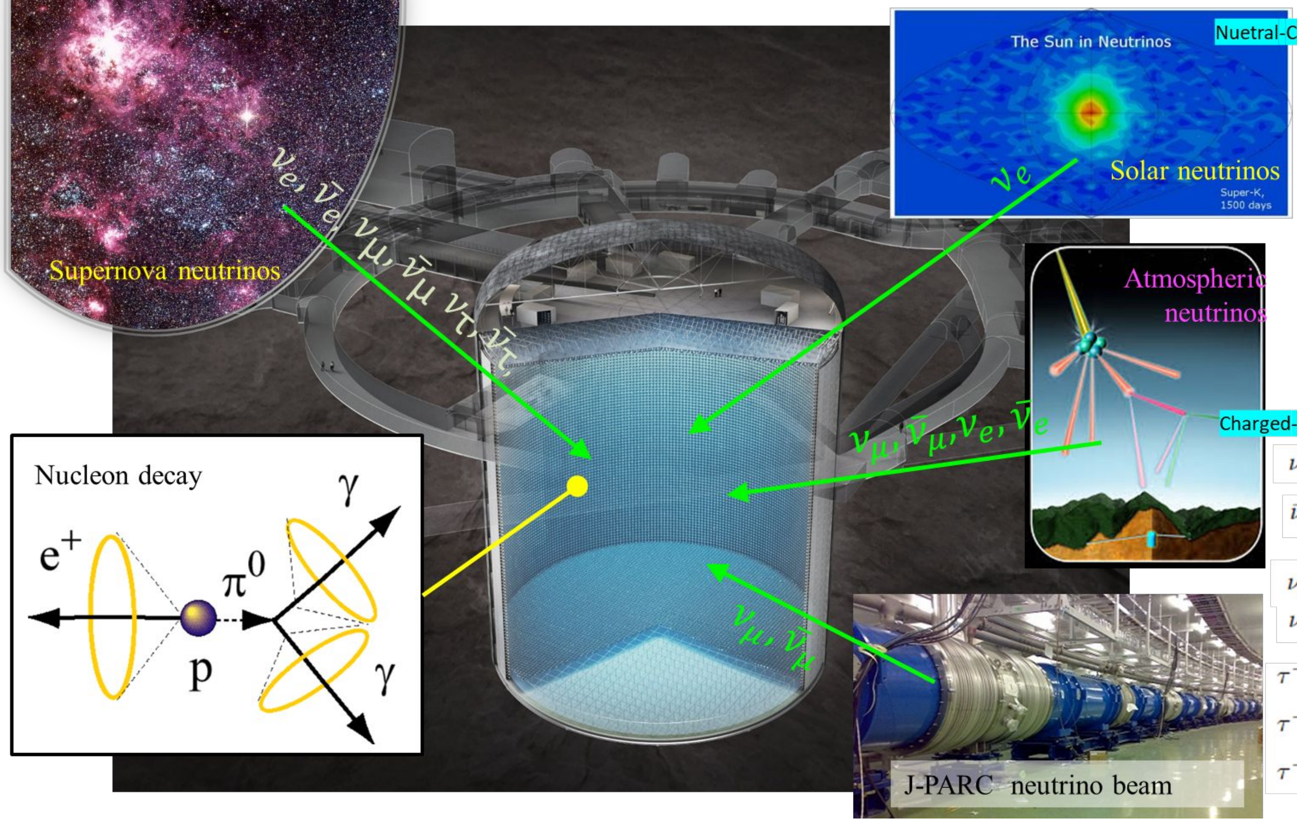
- **Hyper-Kamiokande (2027 -)**
  - Extended search for proton decay
  - Precision measurement of neutrino oscillation including CPV and MO
  - Neutrino astrophysics

  Explore new physics

Hyper-K Observation Target

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

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



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

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

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

Nuetral-Current Interactions (NC)

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

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

Charged-Current Interactions (CC)

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

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

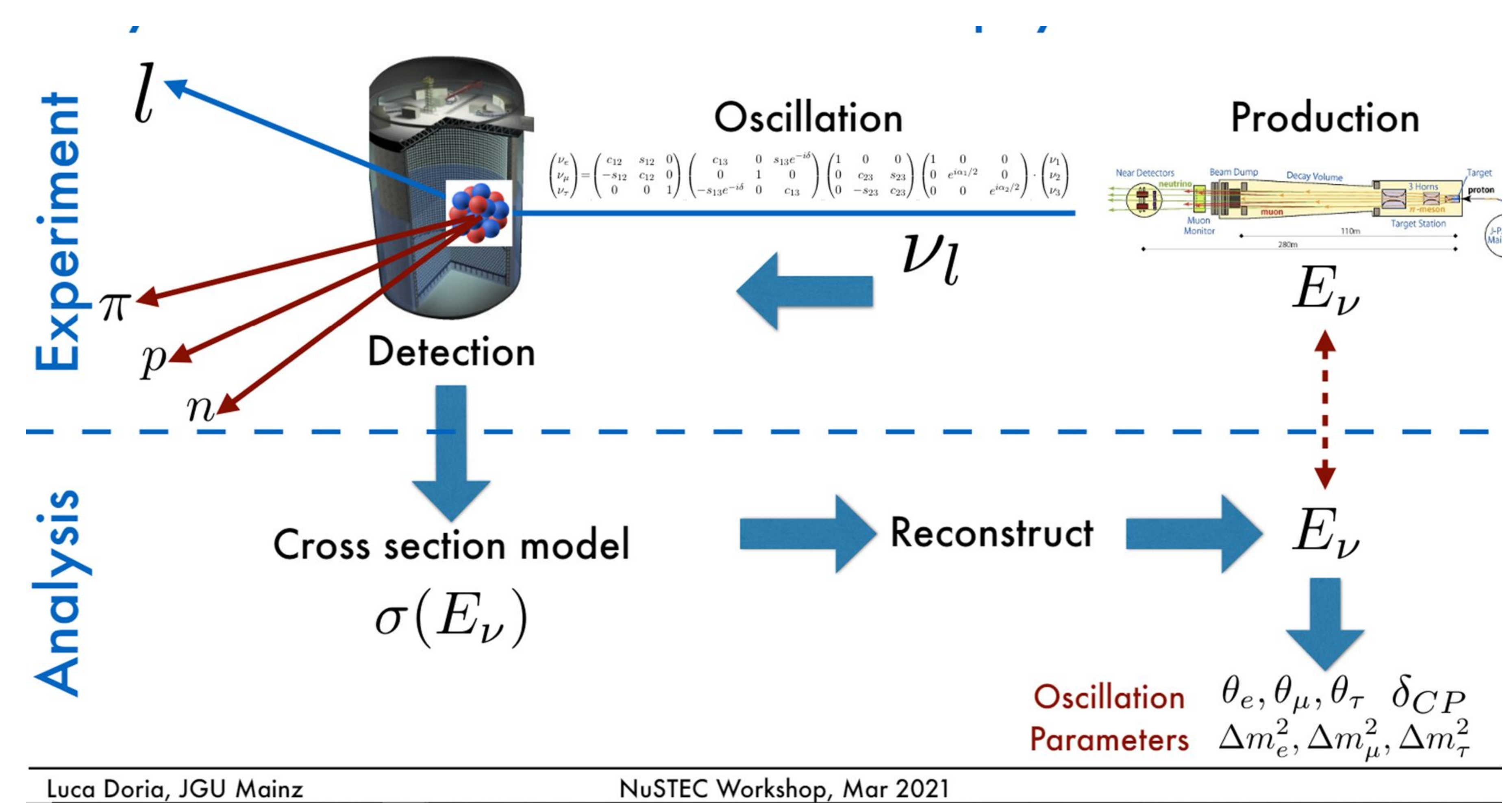
$\nu_\mu + n \rightarrow \mu^- + p$

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

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

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

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


Experiment
Analysis
l
π
p
n
Detection
Oscillation
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\alpha_1/2} & 0\\ 0 & 0 & e^{i\alpha_2/2}\end{pmatrix}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$
Production
Near Detectors
neutrino
Beam Dump
Decay Volume
Target
proton
3 Horns
π-meson
muon
Muon Monitor
Target Station
110m
280m
ν_l
E_ν
Cross section model
$\sigma(E_\nu)$
Reconstruct
E_ν
Oscillation Parameters
$\theta_e, \theta_\mu, \theta_\tau \quad \delta_{CP}$
$\Delta m^2_e, \Delta m^2_\mu, \Delta m^2_\tau$
Luca Doria, JGU Mainz
NuSTEC Workshop, Mar 2021

New paper just accepted to Eur. Phys. J. C!

https://arxiv.org/pdf/2505.15019

Eur. Phys. J. C manuscript No.
(will be inserted by the editor)

Sensitivity of the Hyper-Kamiokande experiment to neutrino oscillation parameters using accelerator neutrinos

K. Abe[1], R. Ahl Laamara[2], H. Aihara[3], A. Ajmi[4], R. Akutsu[5,114], H. Alarakia-Charles[6], I. Alekseev, Y. Alj Hakim[7], S. Alonso Monsalve[8], E. Amato[9], F. Ameli[10], L. Anthony[11], A. Araya[12], S. Arimoto[13], Y. Asaoka[1], V. Aushev[14], F. Ballester Merelo[15], M. Barbi[16], G. Barr[17], M. Batkiewicz-Kwasniak[18], A. Beauchêne[19], D. Benchekroun[20], V. Berardi[9,21], E. Bernardini[22,23], L. Berns[24], S. Bhadra[25], N. Bhuiyan[26], J. Bian[27], D. Bianco[28], A. Blanchet[29], A. Blondel[30], P. M. M. Boistier[31], S. Bolognesi[31], L. Bonavera[32], S. Bordoni[29], D. Bose[33], S. Boyd[34], C. Bozza[35,36], A. Bravar[29], C. Bronner[37], A. Bubak[38], A. Buchowicz[39], M. Buizza Avanzini[19], G. Burton[26,40], F. S. Cafagna[9], N. F. Calabria[9,21], J. M. Calvo Mozota[41], S. Cao[5,114], D. Carabadjac[19,115], S. Cartwright[7], M. P. Casado Lechuga[42,116], M. G. Catanesi[9], S. Cebrián[43], E. M. Chakir[44], S. Chakrabarty[45], J. H. Choi[46], S. Choubey[47], E. A. Chucuan Martinez[48], L. Chytka[49], M. Cicerchia[113], L. Cid Barrio[41], M. Cieślar[a] [50], J. Coleman[51], G. Collazuol[22,23], L. Cook[52], F. Cormier[52], D. Costas-Rodríguez[53], A. Craplet[11], S. Cuen-Rochin[48], C. Dalmazzone[30], M. Danilov, T. Daret[31], F. J. De Cos[32], E. de la Fuente[54,55], A. De Lorenzis[42,117], G. De Rosa[28,56], T. Dealtry[6], Della Valle, M.[28], C. Densham[40], A. Dergacheva, M. M. Devi[57], F. Di Lodovico[26], A. Di Nitto[28,56], A. Di Nola[28,56], G. Díaz López[30], T. C. Dieminger[8], D. Divecha[16], M. Dobrzynska[58], T. Dohnal[59], E. Drakopoulou[60], O. Drapier[19], J. Dumarchez[30], K. Dygnarowicz[39], S. Earle[61], A. Eguchi[3], Abderrazaq El Abassi[44], A. El Kaftaoui[44], J. Ellis[26], S. Emery[31], R. Er-Rabit[44], A. Ershova[19], A. Esmaili[62], R. Esteve Bosch[15], C. E. Falcon Anaya[48], L. E. Falcon Morales[63], J. Fannon[7], S. Fedotov, J. Feng[13], D. Ferlewicz[3], P. Fernández-Menéndez[64], E. Fernández-Martinez[65], P. Ferrario[64], B. Ferrazzi[16], A. Finch[6], C. Finley[66], G. A. Fiorentini Aguirre[67], M. Fitton[40], M. Franks[8], M. Friend[5,114,118], Y. Fujii[5,114], Y. Fukuda[68], L. Fusco[36,35], G. Galiński[39], R. Gamboa Goñi[63], J. Gao[26], F. Garcia Riesgo[32], C. Garde[69], R. Gaur[52], L. Gialanella[28,70], C. Giganti[30], V. Gligorov[30], O. Gogota[14], M. Gola[52], A. Goldsack[26], A. Gomez-Gambin[15], J. J. Gomez-Cadenas[64], M. Gonin[1,71], J. González-Nuevo[32], A. Gorin, R. Gornea[67], S. Goto[3], M. Gouighri[44],

$$
\begin{aligned}
P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq\ & 4c_{13}^2 s_{13}^2 s_{23}^2 \cdot \sin^2 \Delta_{31} \\
& + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos \delta_{CP} - s_{12} s_{13} s_{23}) \\
& \qquad \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
& - (+) 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin \delta_{CP} \cdot \sin \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
& + 4c_{13}^2 s_{12}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{13}^2 s_{23}^2 - 2c_{12} c_{23} s_{12} s_{13} s_{23} \cos \delta_{CP}) \\
& \qquad \cdot \sin^2 \Delta_{21}, \quad (2)
\end{aligned}
$$

https://arxiv.org/pdf/2505.15019

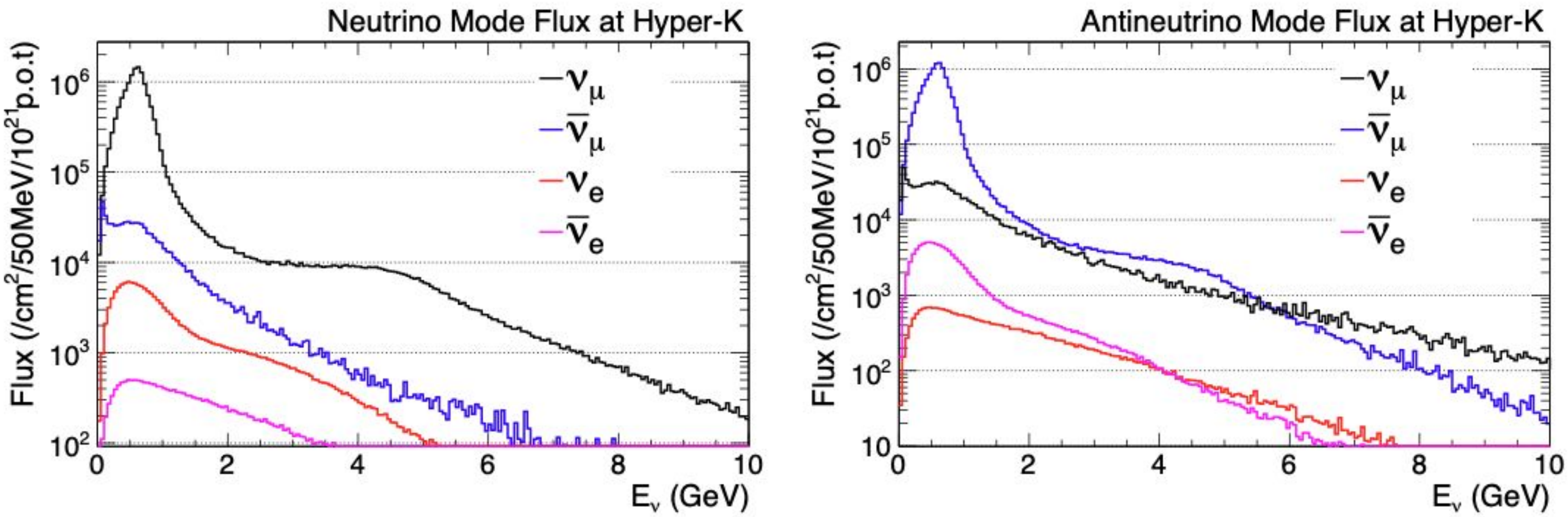


Fig. 1: Simulated flux at the far detector in neutrino mode (left) and antineutrino mode (right).

https://arxiv.org/pdf/2505.15019

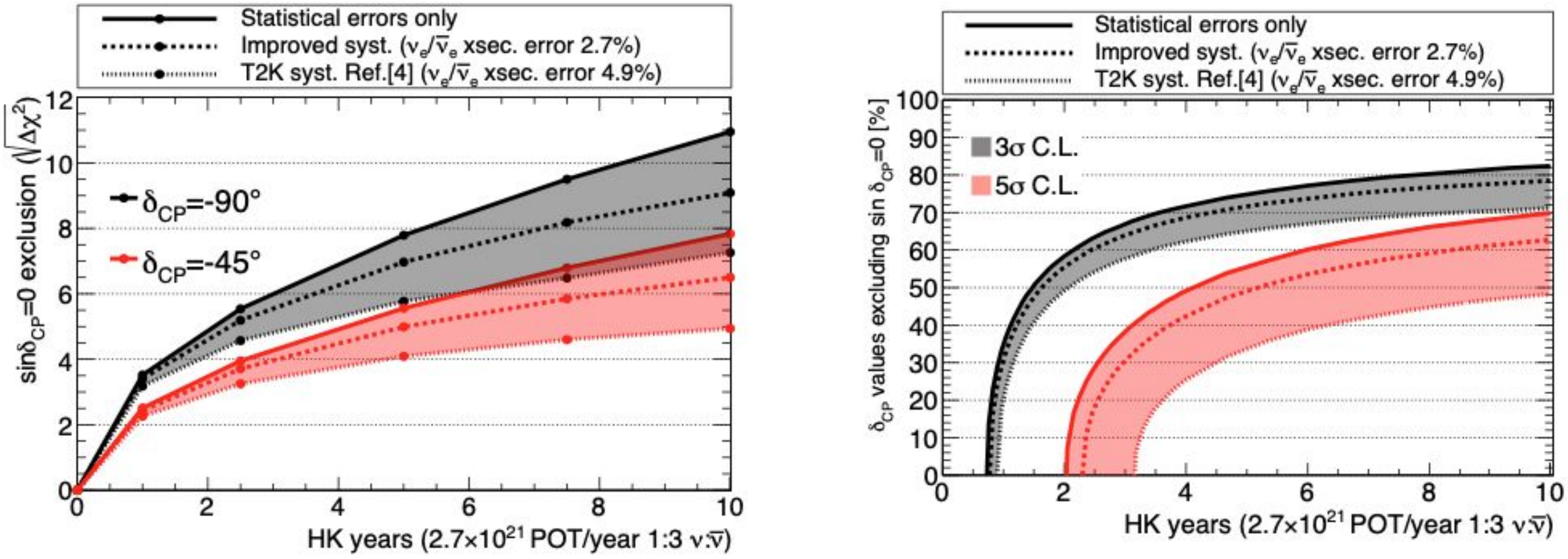


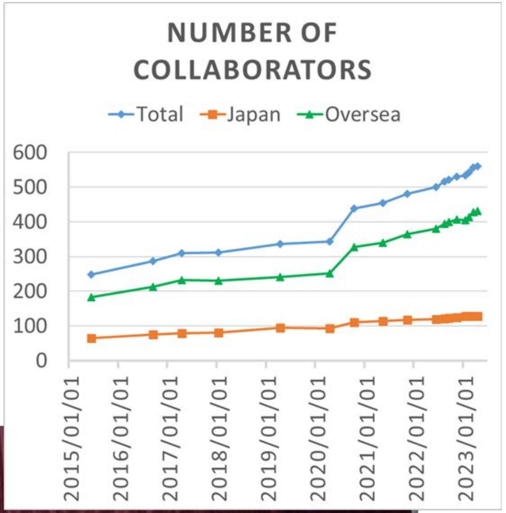
Fig. 4: Sensitivity to CPV as a function of data-taking time: $\sin\delta_{CP} = 0$ exclusion for $\delta_{CP} = -90^\circ$ or -45° (left) and percentage of δ_{CP} values for which $\sin\delta_{CP} = 0$ can be excluded at 3σ and at 5σ (right). The shaded regions in these and following figures, show the span of possible sensitivities when varying the assumed systematic errors.

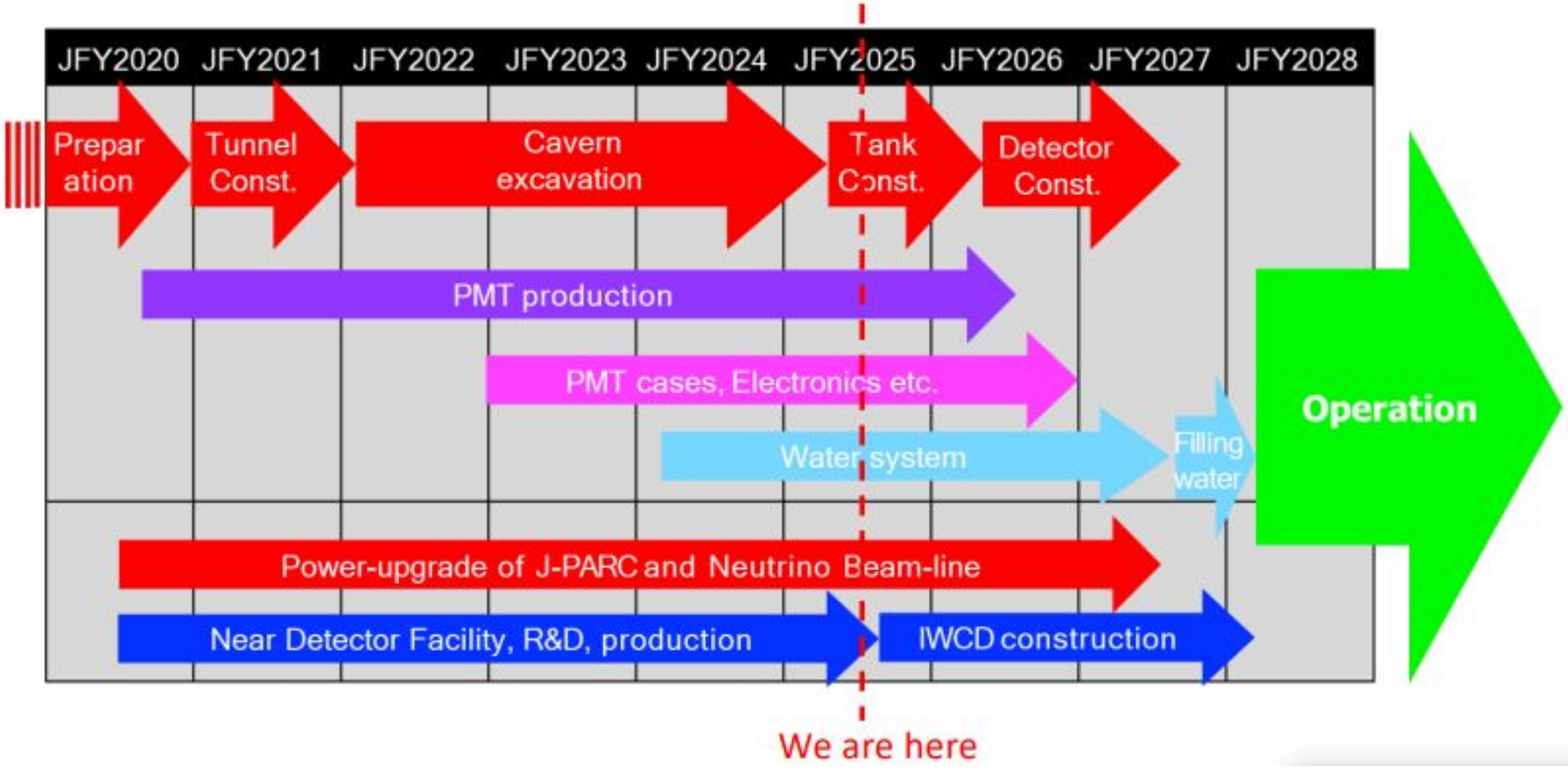
https://arxiv.org/pdf/2505.15019

- Check the paper for more…
- Check talk of Sergio Galarza on Supernova Sensitivity
- And talk of Gilberto Rodriguez on IWCD ML analysis

Hyper-Kamiokande Collaboration

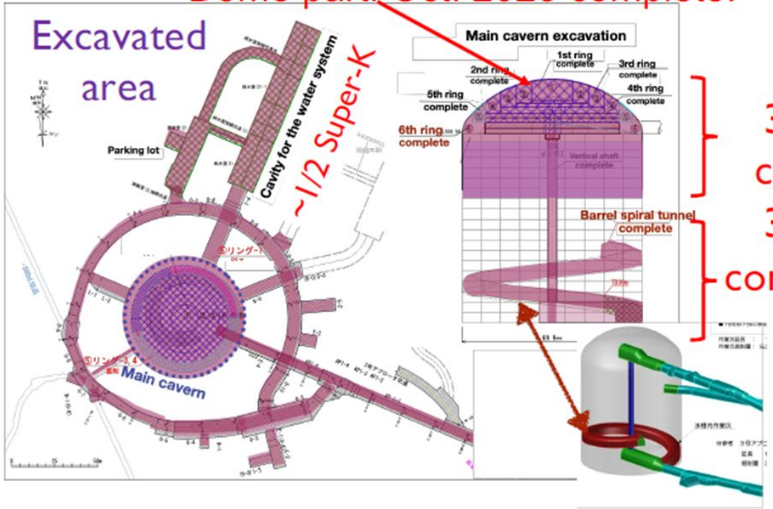
- ~600 members located in 102 institutes from 22 countries
  - 25% Japanese / 75% non-Japanese
- Recently approved as a recognized experiment (RE45) at CERN



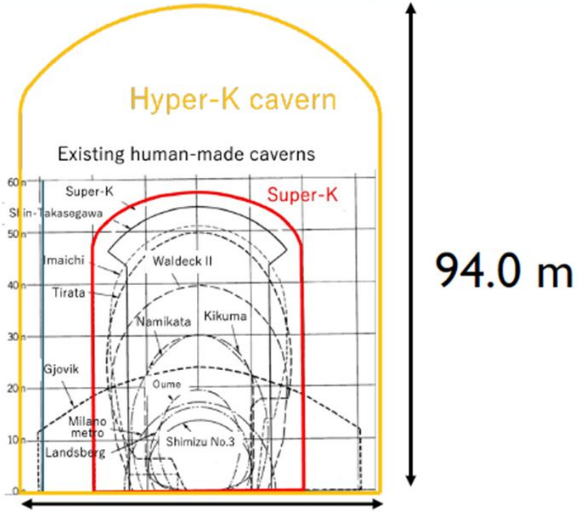

JFY2020
JFY2021
JFY2022
JFY2023
JFY2024
JFY2025
JFY2026
JFY2027
JFY2028
Prepar ation
Tunnel Const.
Cavern excavation
Tank Const.
Detector Const.
PMT production
PMT cases, Electronics etc.
Water system
Filling water
Operation
Power-upgrade of J-PARC and Neutrino Beam-line
Near Detector Facility, R&D, production
IWCD construction
We are here

Excavating the world's largest human-made cavern

✓ Dome part: Oct. 2023 complete.



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



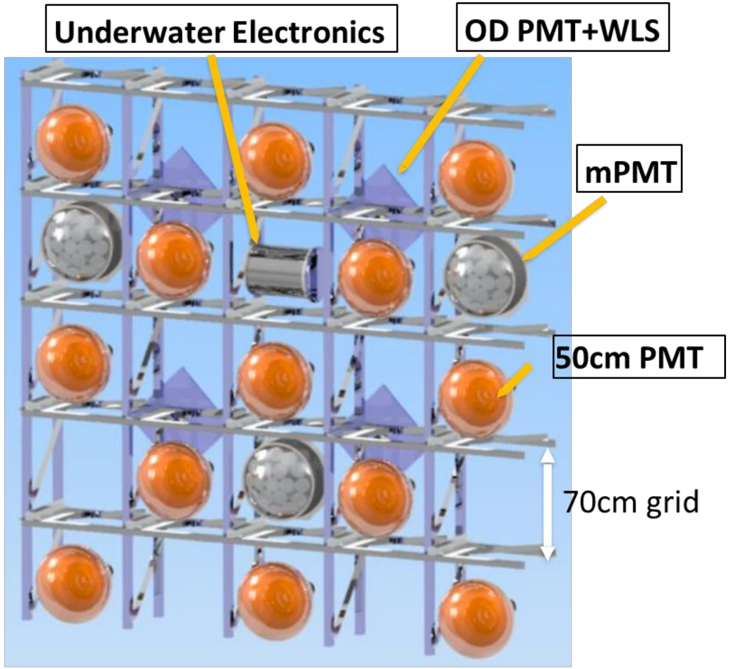
Hyper-K main cavern excavation

- **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!

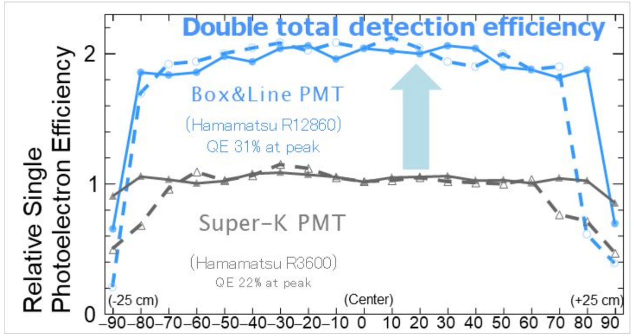
Hyper-K detector configuration

- **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



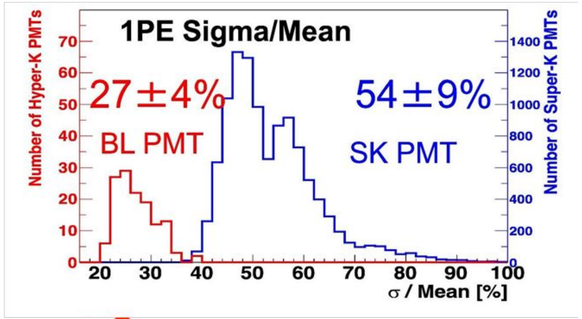
Hyper-K 50cm PMT performance

×2 better photodetection efficiency (QE×CE)

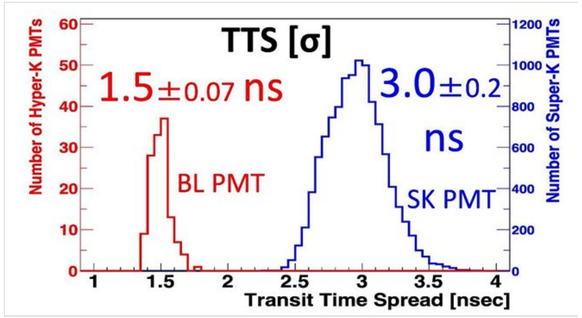


(Performance in SK tank, 1.7e7 gain)

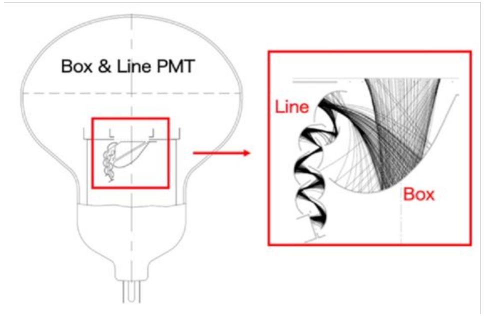
×2 better charge resolution



×2 better timing resolution



Box&Line dynode



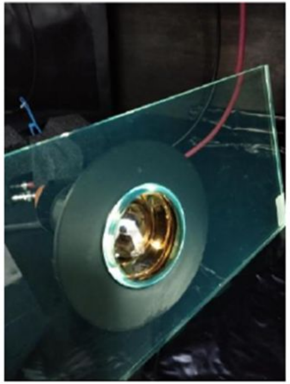
×2 better pressure tolerance
→ enable deeper tank design, project cost reduction

Low dark rate (4kHz) and RI

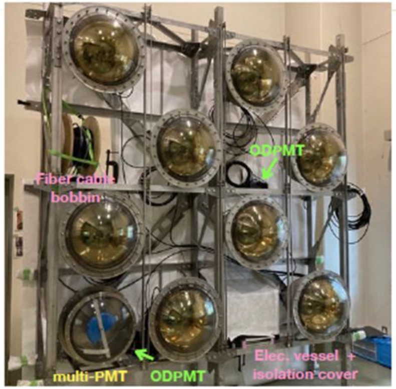

PMT production ongoing, >10,000 delivered.
Screening both at Hamamatsu and Kamioka

Photosensors and underwater electronics

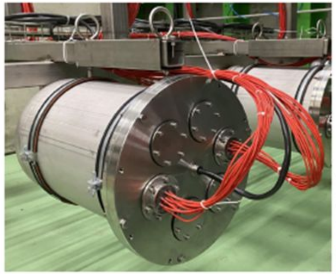
Outer detector: PMT+WLS plate

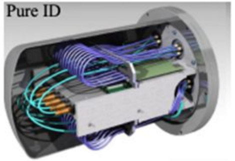


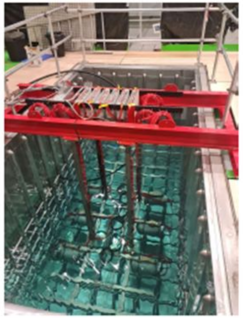
Photosensors/elec. mockup



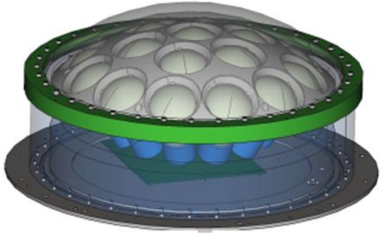
Underwater electronics: Case design and feedthrough



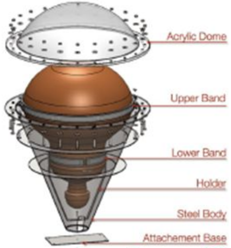


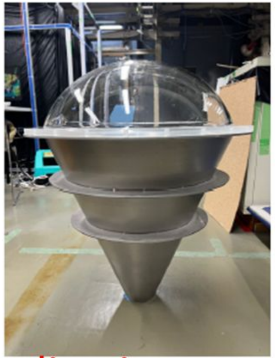


Multi-PMT module:



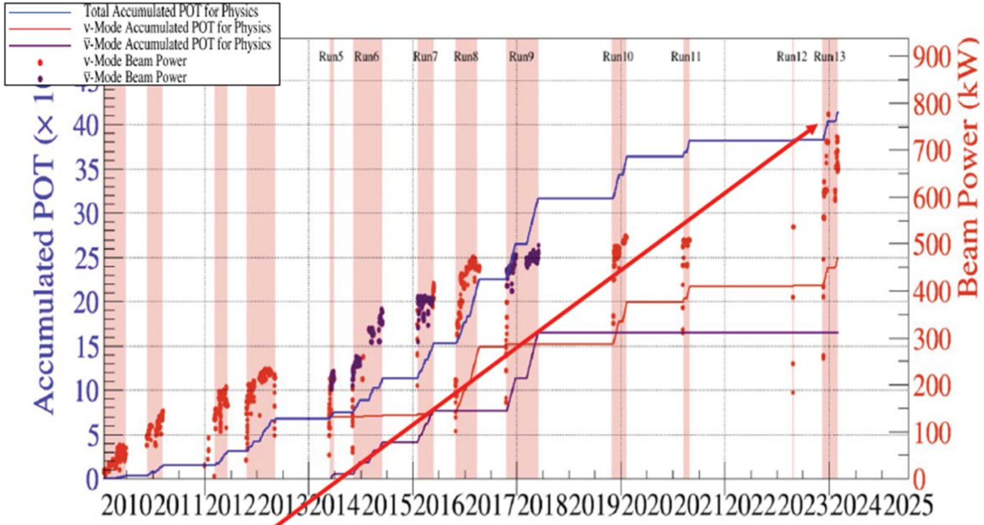
PMT cover



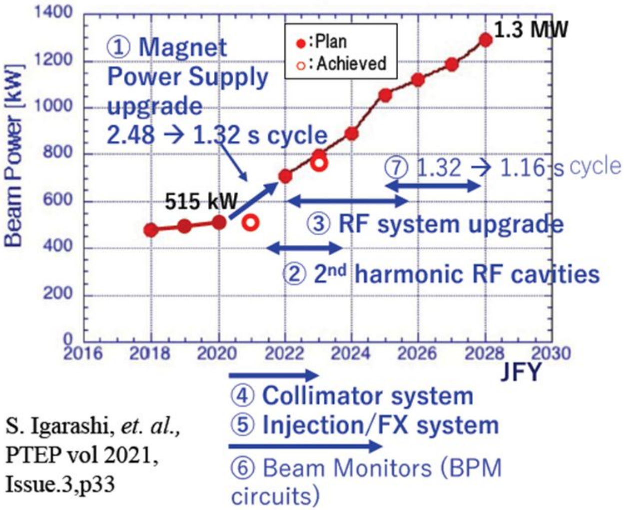


Design finalization ongoing

Beam: status and plan of power increase



Original power projection in MR Upgrade Plan



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

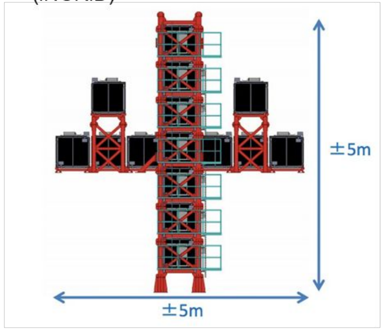
760 kW achieved already and 800 kW last week!

Further beam power increase requires:

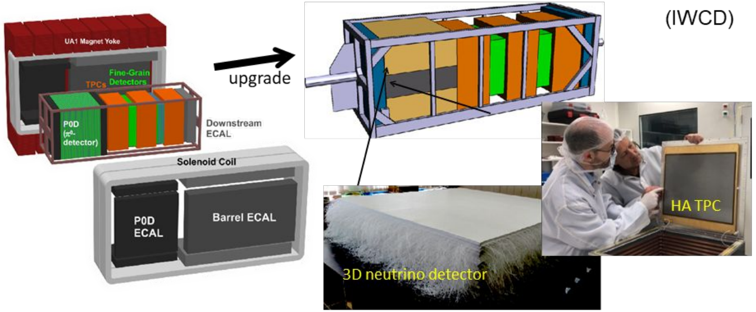
- Seeking beam loss with optics improvements
- More protons/pulse by upgrading RF system
- Further beam intensity increase will be done by 1.36 → 1.16 sec cycle

Neutrino detectors at J-PARC

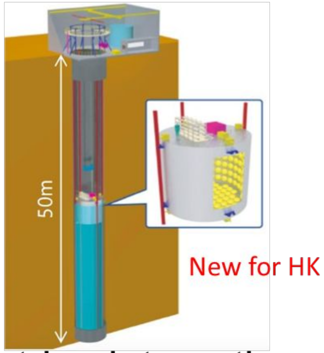
On-axis Detector
(INGRID)



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.

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 1081, January 2026, 170903

https://arxiv.org/pdf/2504.07216
https://doi.org/10.1016/j.nima.2025.170903

Full Length Article

Assembly, testing, and installation of mPMT photosensor for the Water Cherenkov Test Experiment

M. Gola [a], M. Barbi [d], V. Berardi [h], A. Buchowicz [e], N. Buril [c], L. Cook [a], S. Cuen-Rochin [i], G. DeRosa [h], P. de Perio [k], K. Dygnarowicz [e], B. Ferrazzi [d], A. Fiorentini [c], C.S. Garde [j], G. Galiński [e], K. Graham [c], R. Gornea [c], M. Hartz [a], J. Holeczek [f], S. Jagtap [j], M. Kala [c]...M. Ziembicki [e]

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https://doi.org/10.1016/j.nima.2025.170903

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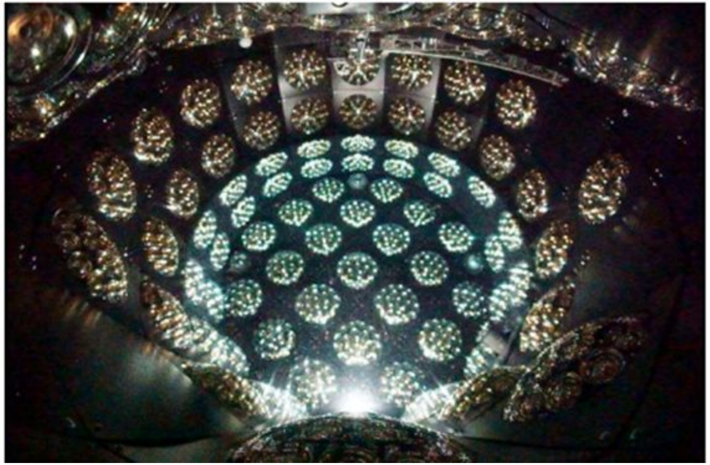
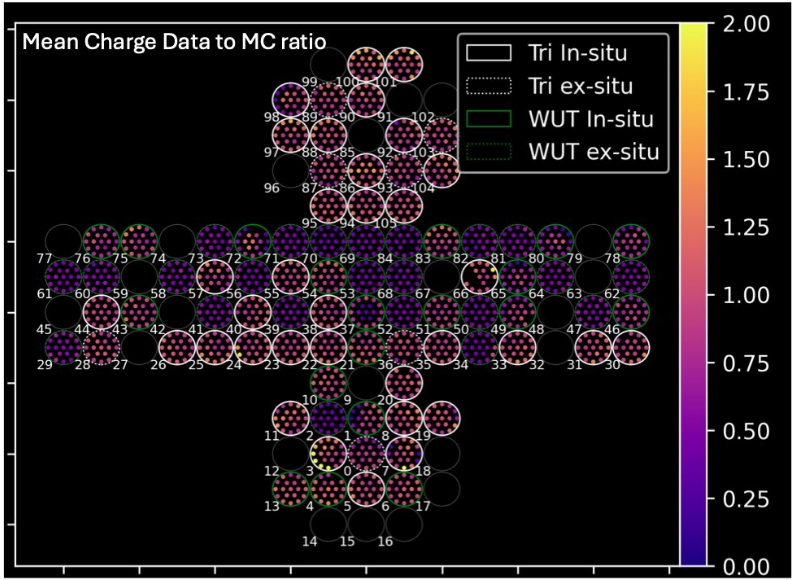
WCTE at CERN



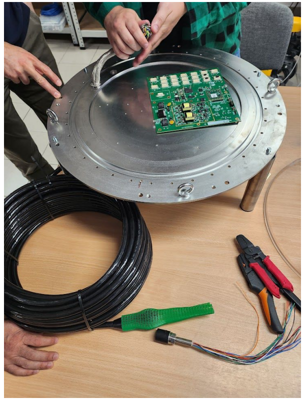

Clamp ring
Acrylic dome
Optical Gel
PVC Cylinder
PMT
PU Foam Matrix
Stainless Steel Pillars
Stainless Steel Backplate

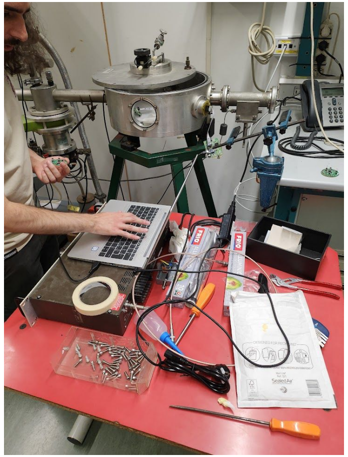
WCTE Tour

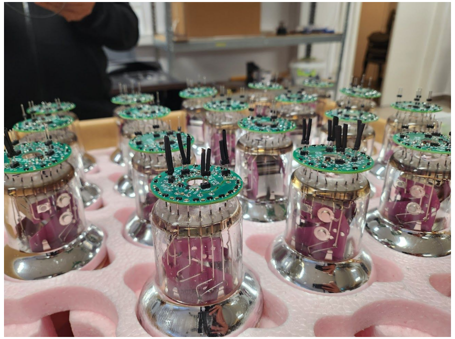
Link to video tour [here]()



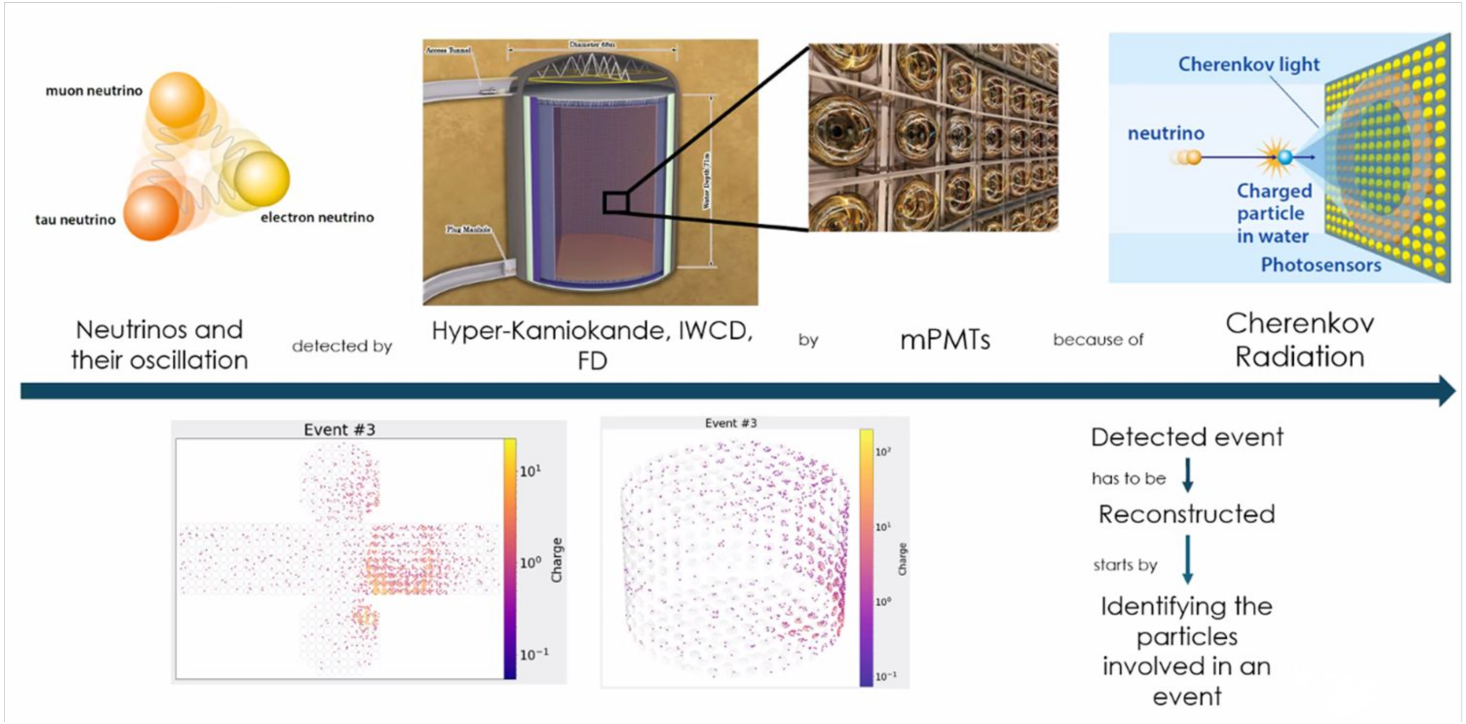
mPMT assembly



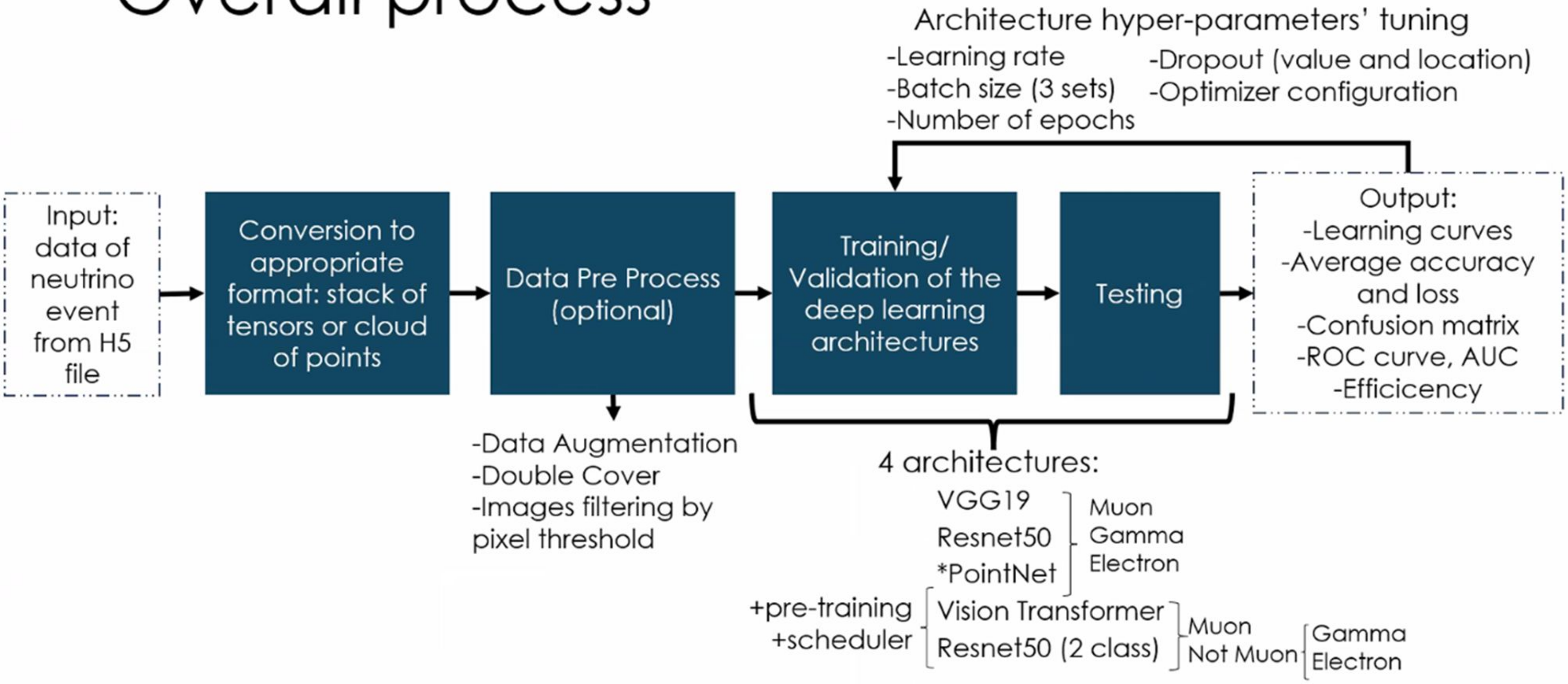




Neutrino classification

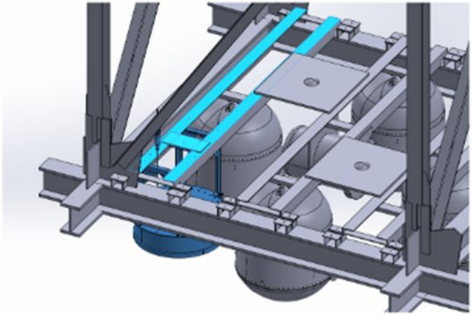


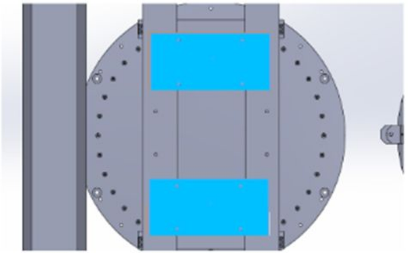
Overall process

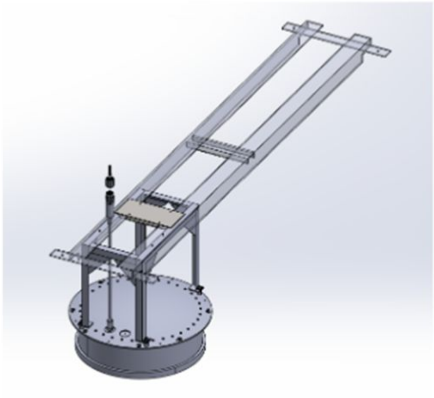


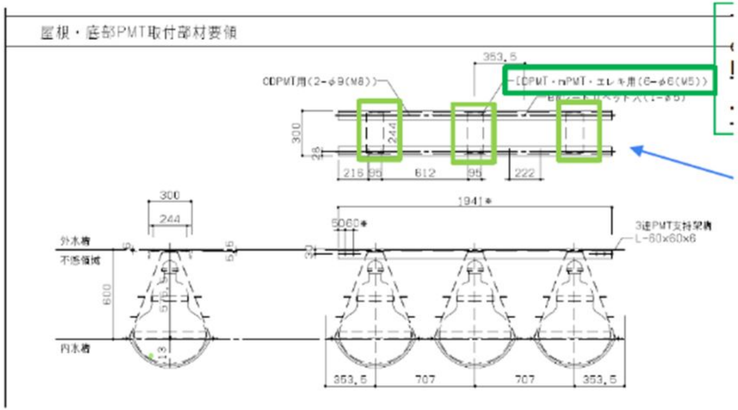
top & bottom mPMT support

Currently working on requirements from the integration group.





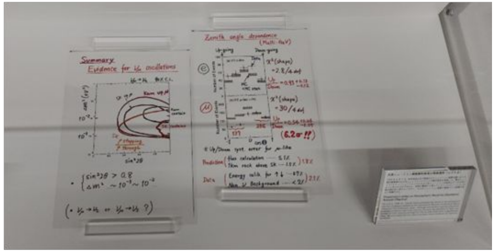


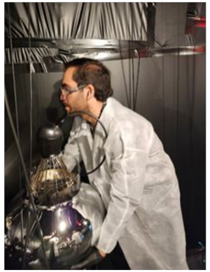


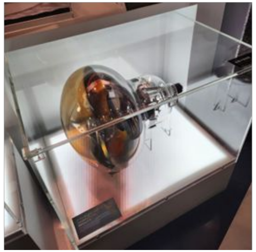
mPMT mechanical stress test

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

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)
重力波観測研究施設
KAGRA Observatory
高原川
Takahara River
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
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
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







Conclusions

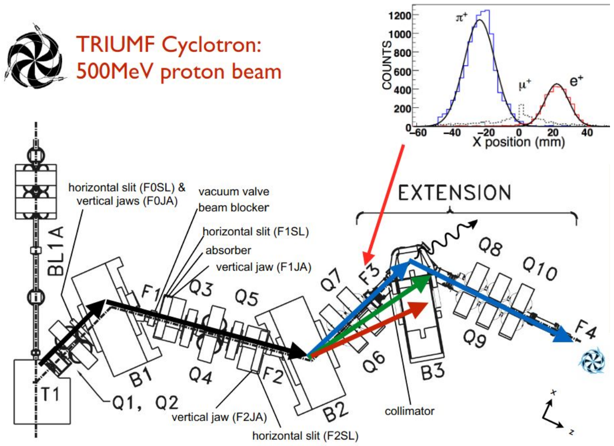
- Hyper-Kamiokande is 3rd generation water Cherenkov detector in Kamioka
- Important physics targets
  - Neutrino CP violation: Discovery with 5 σ for ~60% parameter regions
  - Nucleon Decay Search for testing GUT: $\tau > 10^{35}$ years for $p \rightarrow e^{+}\pi^{0}$
  - Neutrino Astrophysics: Supernova 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.

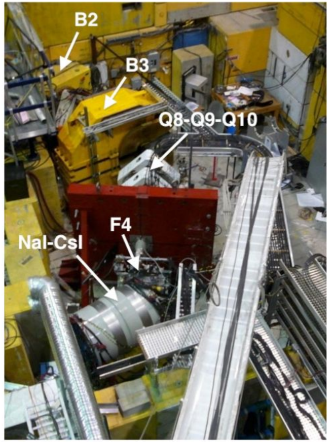
Thanks to SECIHTI (CONAHCyT) for supporting the national projects CBF2023-2024-427, and CF-2023-G-643

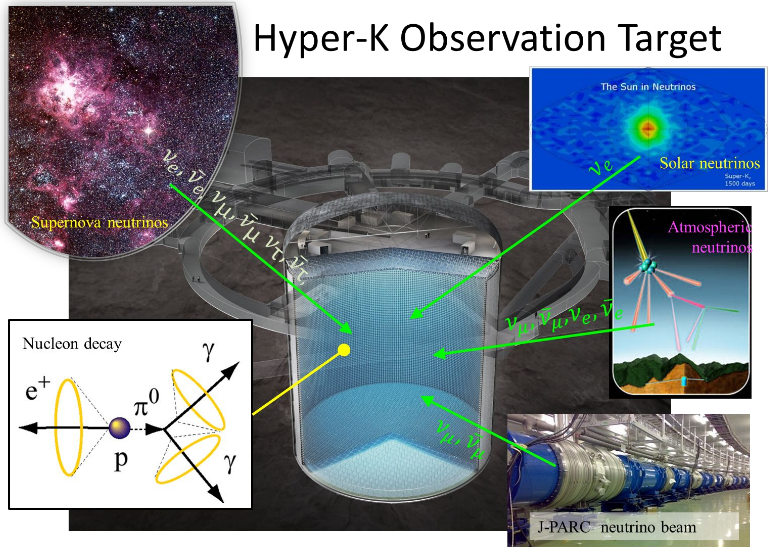
- We plan to build about 4 mPMT in Mexico and will install them in the FD!
- Undergraduate, master, phd thesis, and available for PIONEER and Hyper-K… Get in contact :)
- Thesis for PIONEER:
  - Cinvestav with Pablo Roig
  - Tec de Mty with Saul Cuen <saulcuen@tec.mx>
- Thesis for Hyper-K:
  - UAS with Giannina Dalle Mese
  - UNACH with Karen Caballero
  - UdeG with Eduardo de la Fuente
  - UNAM with Eric Vazquez
  - Tec de Mty with Saul Cuen <saulcuen@tec.mx>

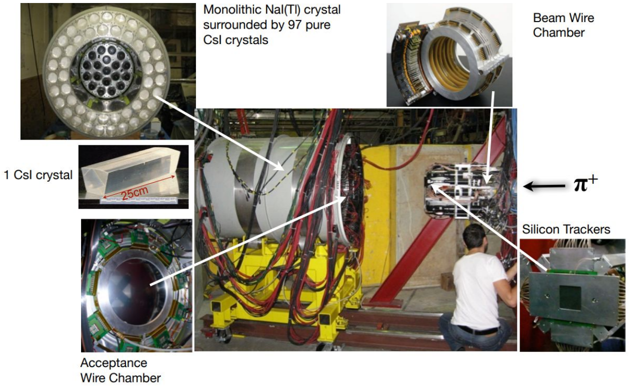
Probing the Foundations of the Standard Model

- One big question: Where will the Standard Model crack again…?
- Two complementary approaches: precision pion decays & gigaton-scale neutrino detection.







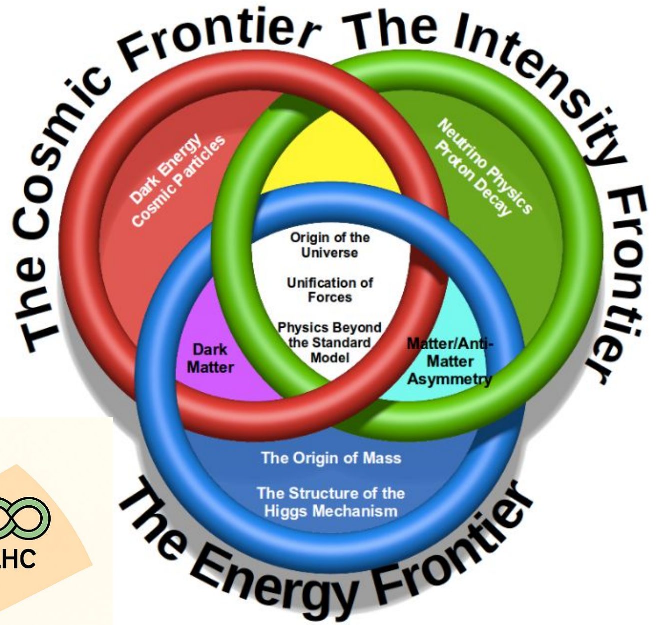


Why Look Beyond the Standard Model?

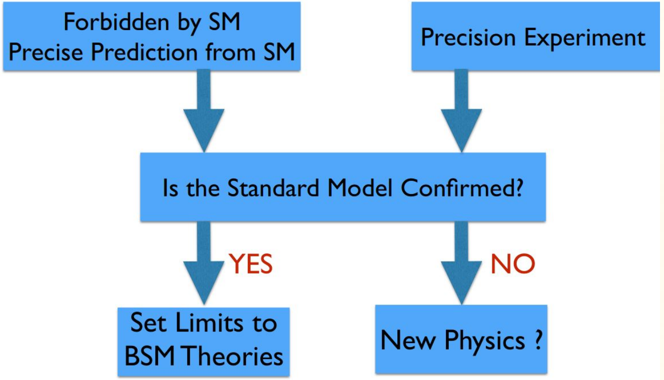
- Neutrino mass, dark matter, matter-antimatter asymmetry → SM incomplete.

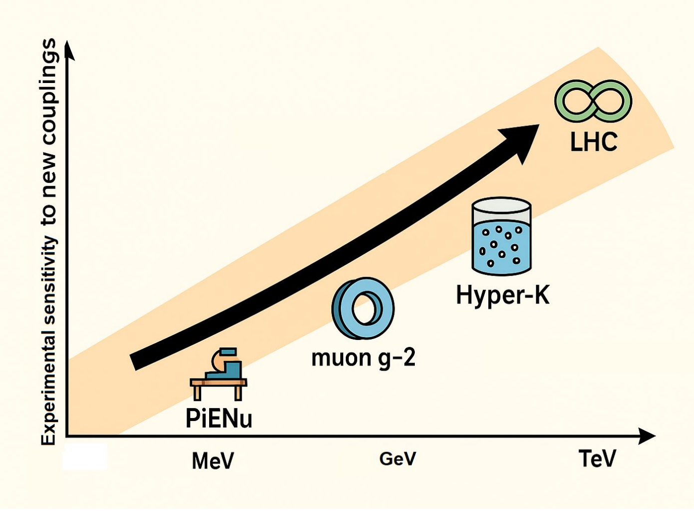
- Need both high precision and high mass experiments (Hyper-K).

- Experimental sensitivity to new couplings rises with accessible energy scale, while pinpointing where PiENu (and Pioneer), muon g-2, Hyper-K, and the LHC sit along that frontier



Precision Frontier



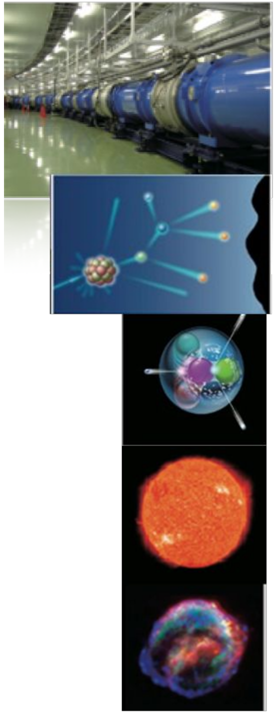


Experimental Dialectic

- Tabletop precision ⇄ monumental scale.
- Each tests different couplings & energy regimes.
- Combined, they constrain a wider slice of parameter space.

Experiment	Physical Scale	Typical Detector Mass / Footprint	Sensitivity Lever	Flagship Observables	Example New-Physics Handles
PiENu and PIONEER	Bench-top spectrometer (≈ 3 m long, 1 m³)	~1 t of scintillator + NaI/CsI calorimetry	**Fractional-percent precision** ΔR_e/μ ≈ 0.1 % for PIENU and 0.01 % for PIONEER (theory level)	π → e ν vs π → μ ν branching ratio	Scalar / tensor couplings, charged-Higgs or leptoquarks that violate lepton universality
Hyper-Kamiokande	Mountain-scale cavern (71 m × 68 m)	260 kt ultrapure water, 40 k PMTs	**Rare-event reach** ($p \rightarrow e^+\pi^0 > 10^{35}$ y; δ_CP at 5 σ)	ν_μ→ν_e oscillations, proton decay, super-nova ν burst	Leptonic CP violation, baryon-number violation, minimal SUSY-GUT, sterile-ν models

Hyper-K Target sensitivity

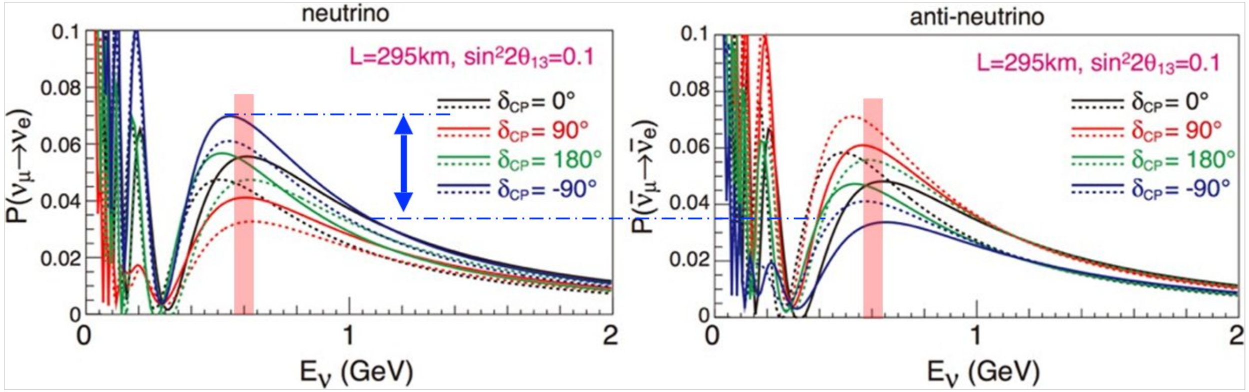


Physics category	Parameters	Sensitivity
LBL (1.3MW×10years)	δ precision	7°-20°
	CPV coverage (3/5σ)	76% / 58%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.017
ATM+LBL (10 years)	MO determination	>3.8σ
	Octant determination (3σ)	$\lvert\theta_{23}$-45°$\rvert$>2°
Proton Decay (20 years)	τ for $e^+\pi^0$ (3σ)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

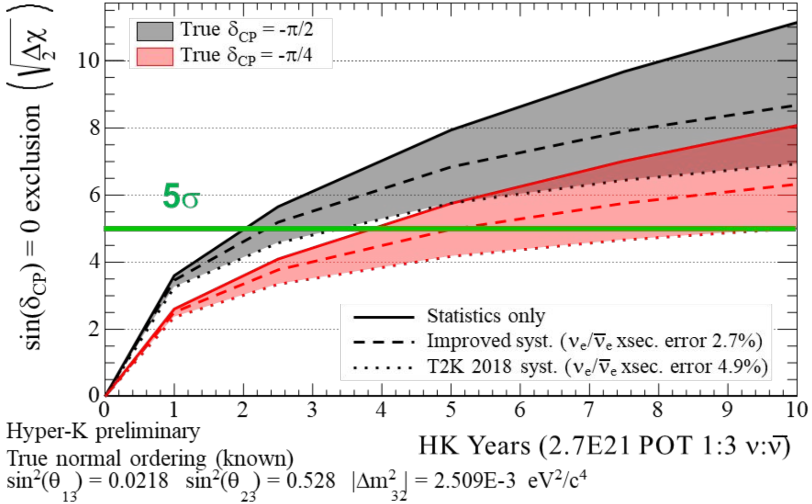
- 2.5° off-axis ν_μ and $\bar{\nu}_\mu$ beam peaked at 0.6 GeV (oscillation maximum at 295km)
  - Major interaction is QE: E_ν determined from (p, θ) of charged lepton
- Measures CP violation in neutrinos by comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

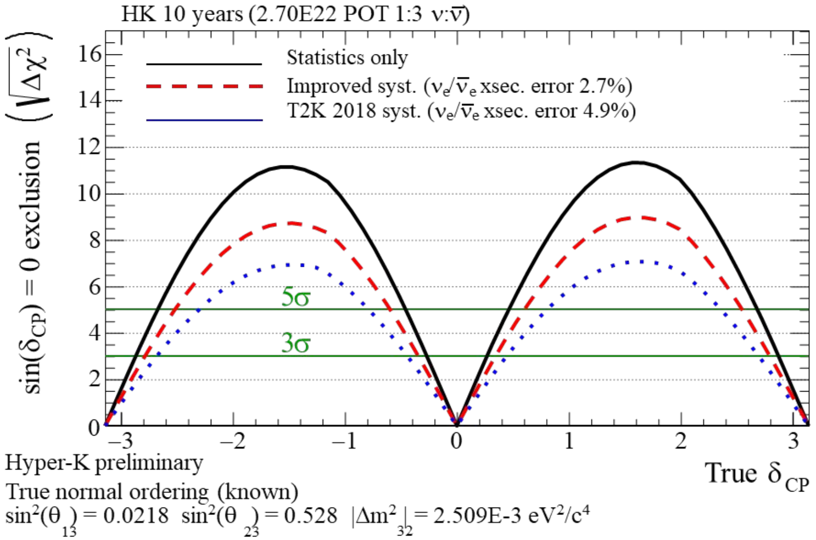


- A few % statistical uncertainties after 10 years operation with >1000 ν_e and $\bar{\nu}_e$ signals

CP violation sensitivity

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





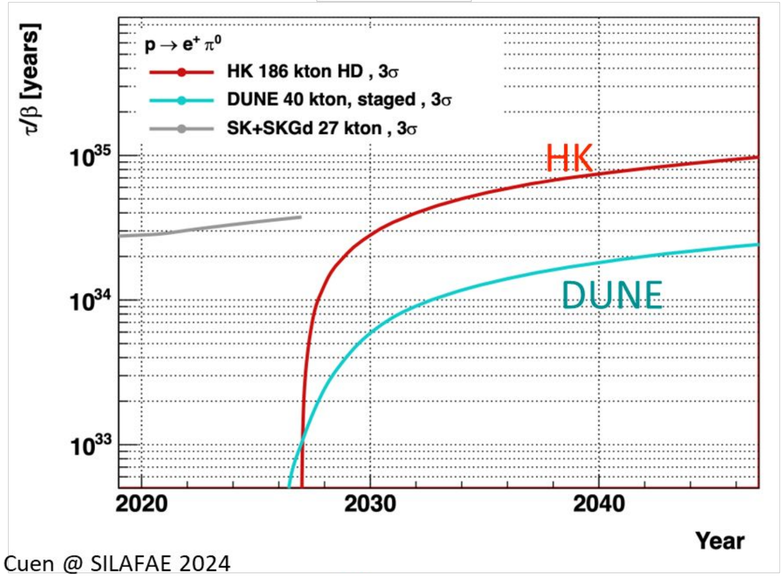
- With systematics and known mass ordering (MO): 2-3 years for 5σ sensitivity to exclude CP conservation for true $\delta\_CP = -\pi/2$.
- After 10 years of operation, 60% of δ_CP values excluded at > 5σ

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

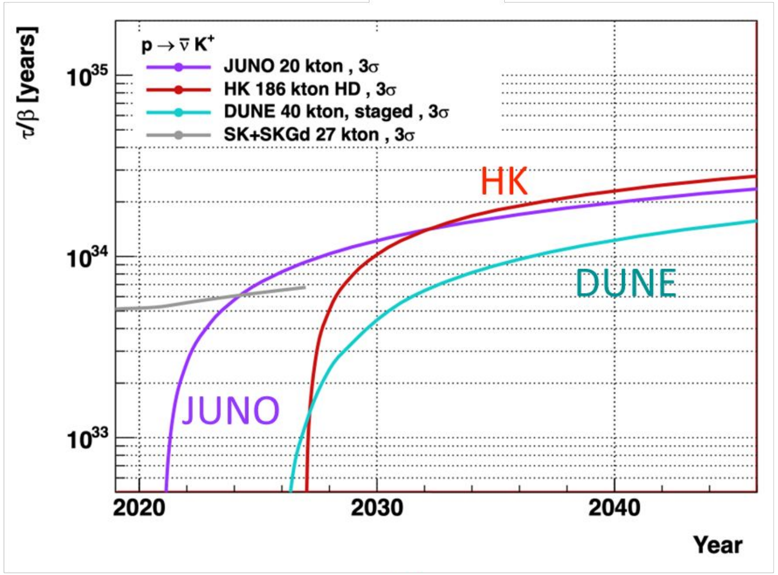
$p \to e^+\pi^0$



Saul Cuen @ SILAFAE 2024

$\tau \sim 10^{35}$ years (3σ)

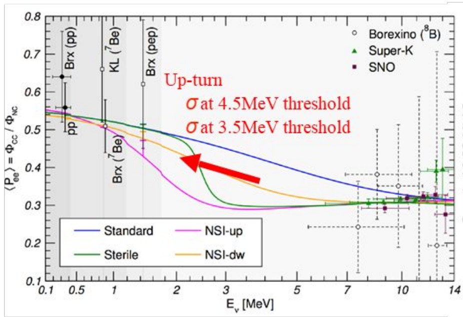
$p \to \bar{\nu} K^+$



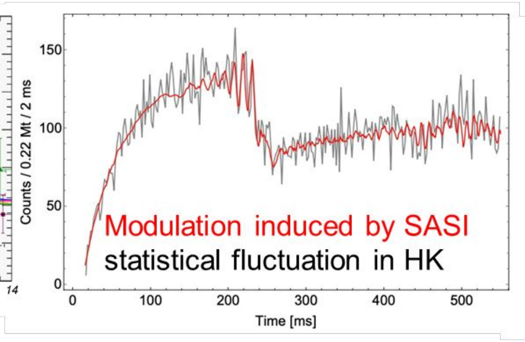
$\tau \sim 3\text{x}10^{34}$ years (3σ)

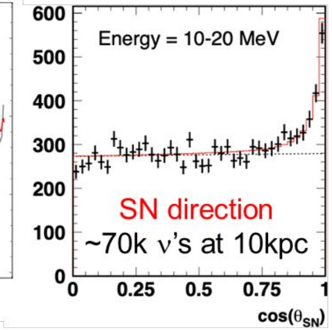
Neutrino astrophysics

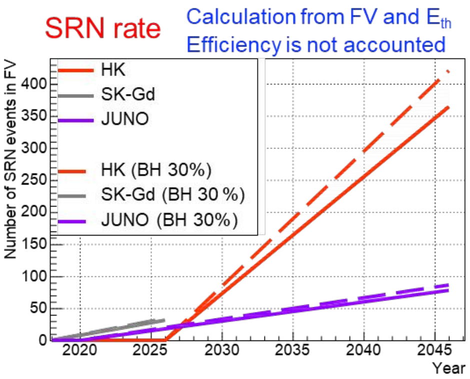
- Hyper-K is designed to be sensitive to neutrinos with energies starting from a few MeV, including time, energy and direction information. Unique role in multi-messenger observation
- **Solar neutrinos:** up-turn at vacuum-MSW transition, Day/Night asymmetry, hep neutrino observation
- **Supernova burst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







Katsuki Hiraide @ NNN23

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