Status of the Hyper-Kamiokande experiment

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(on behalf of the Hyper-Kamiokande Collaboration)

Outline

- **Hyper-Kamiokande project:**
  (1) far detector,
  (2) near detectors,
  (3) J-PARC neutrino beam,
  (4) Intermediate Water Cherenkov Detector (IWCD)

- **Hyper-Kamiokande sensitivity to long-baseline neutrino oscillation parameters with beam:**
  (1) CP violation,
  (2) wrong θ_{23} octant exclusion,
  (3) $sin^2\theta_{23}$ and Δm^2_{32}

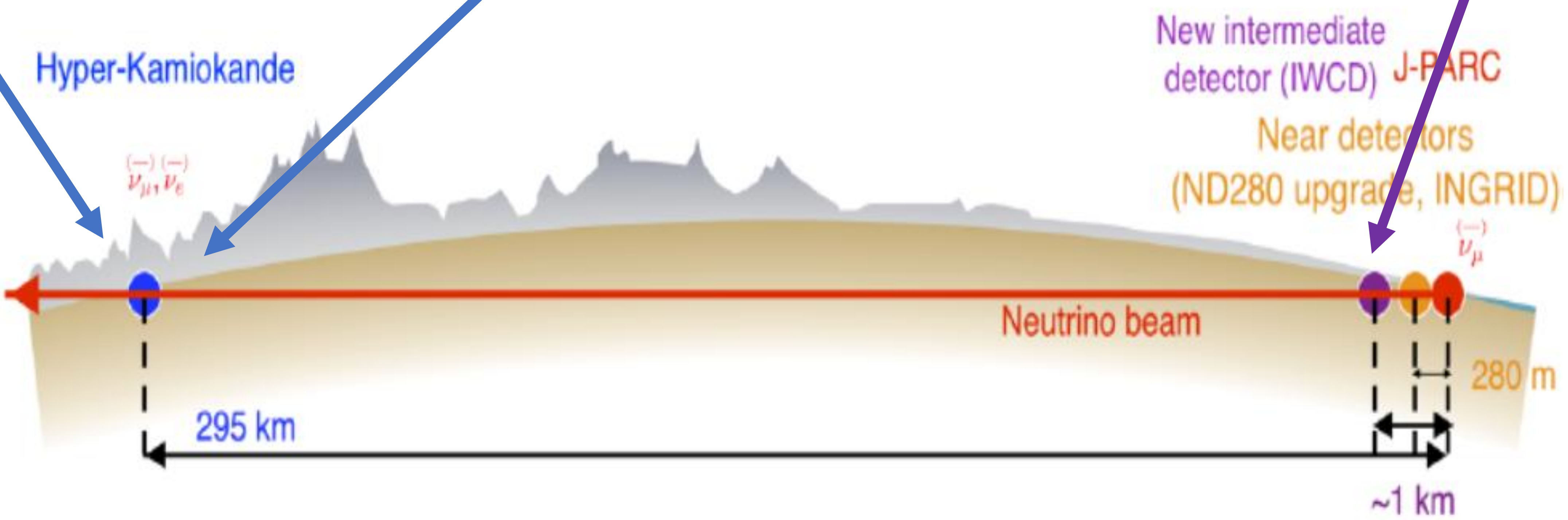
- **Outlook**

Hyper-Kamiokande

HK Inner Detector (ID)
- 20% photocoverage
- ~20000 20” PMTs and
- ~800 multi-PMTs

HK Outer Detector (OD)
- ~3600 3” PMTs
- mounted on Wave Length Shifter (WLS) plates

Intermediate Water Cherenkov Detector (IWCD)
- ~400 multi-PMTs



HK-project:
1) new far water Cherenkov detector (8.4 x Super-Kamiokande fiducial volume)
2) upgraded J-PARC neutrino beam : 0.8 MW (now) → 1.3 MW
3) upgraded ND280 detector (new Super-FGD and High Angle TPCs)
4) new Intermediate Water Cherenkov Detector (IWCD)

Based on Japan’s successes with water Cherenkov exp.

Water Cherenkov detector development (in Japan)

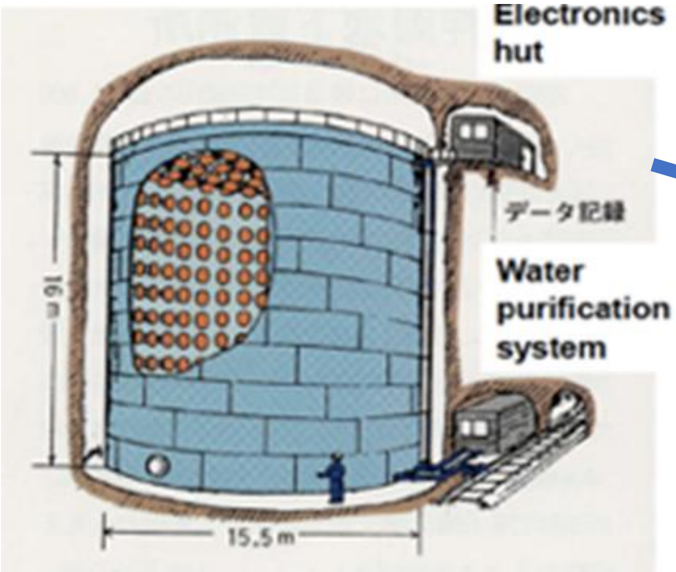
- **Kamiokande (1983-1996), 3 kton, 20% PMT coverage:**
  - SN1987A neutrinos,
  - ν_{atm} deficit,
  - …

M.Koshiba
(for the detection
of cosmic neutrinos)

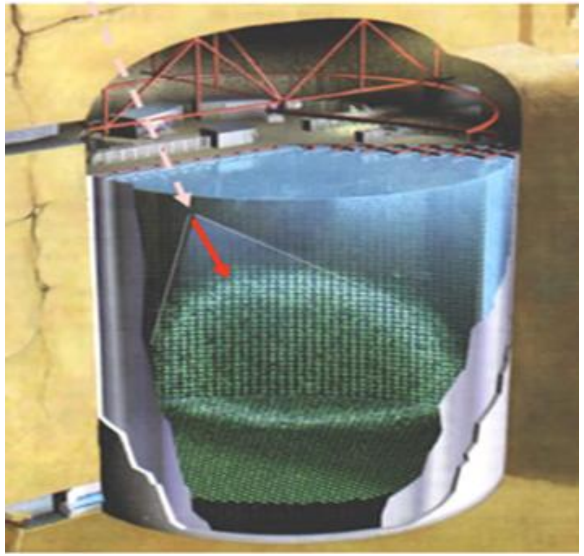
- **Super-Kamiokande (1996-…), 50 kton (22.5 kton FV), 40% PMT coverage:**
  - ν_{atm} and ν_{solar} oscillations,
  - best limits on proton decay,
  - far detector for T2K exp.,
  - …

T. Kajita
(for the discovery
of neutrino oscillations)

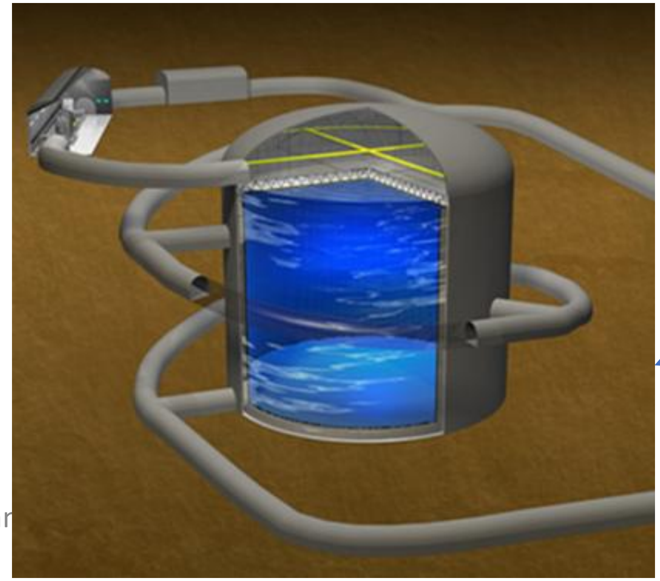
- **Hyper-Kamiokande (2027-…), 258 kton (188 kton FV), 20% PMT coverage:**
  - CP violation: elucidation of the matter dominance in the Universe
  - proton decay (most sensitive channel: $p \rightarrow e^{+} + \pi^{0}$):
  - neutrino oscillation (beam, atmospheric, solar)
  - neutrino mass hierarchy (combined fit of the beam and atmospheric data),
  - neutrino astrophysics (supernova, …),
  - …



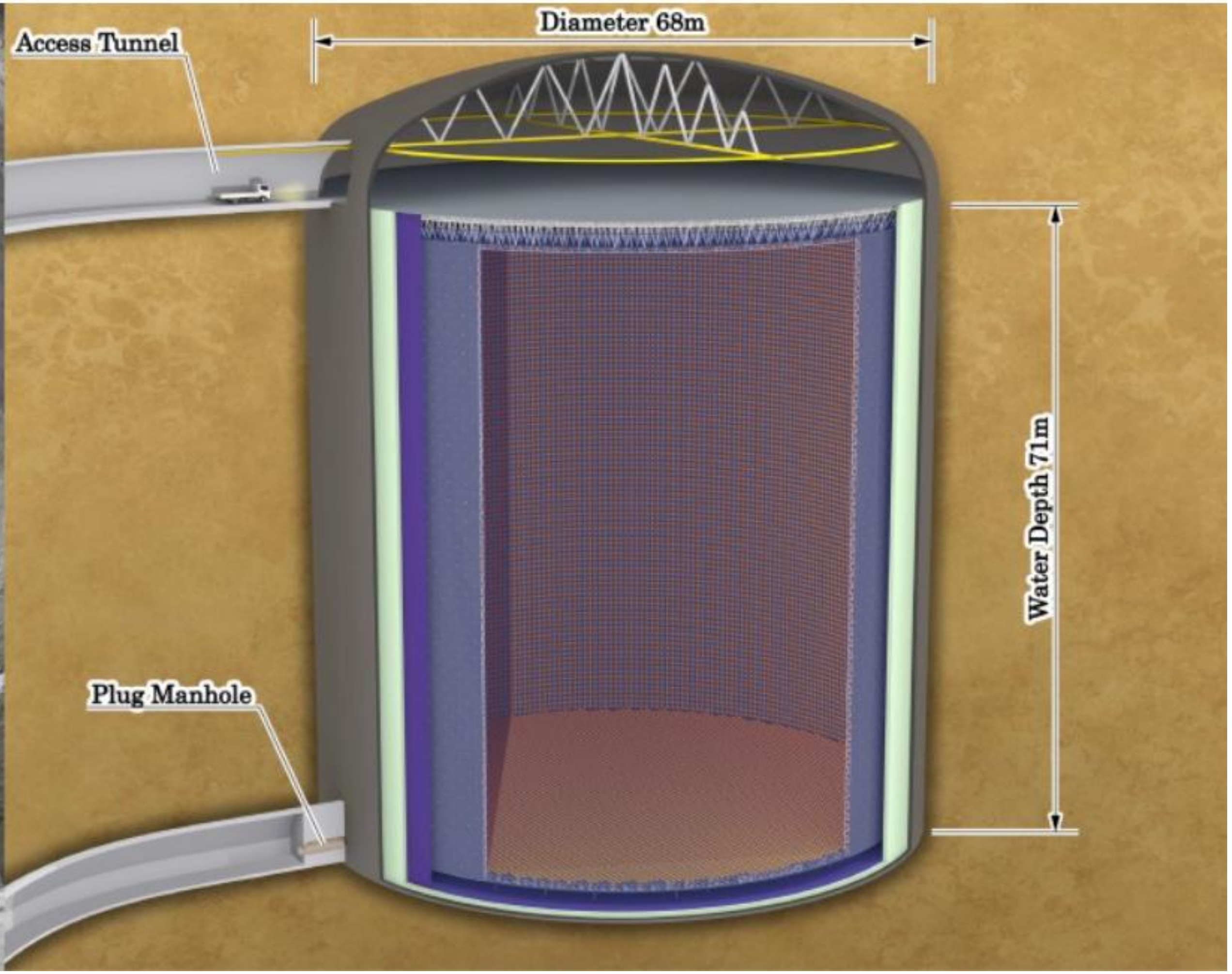
20x

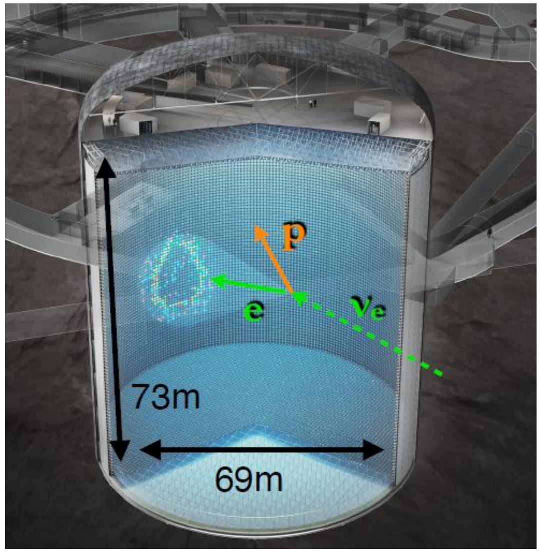


8.4x



Hyper-Kamiokande: far detector site

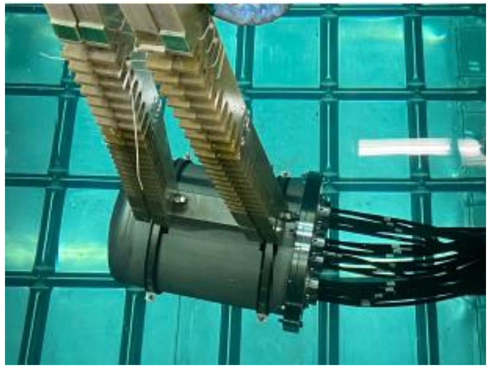




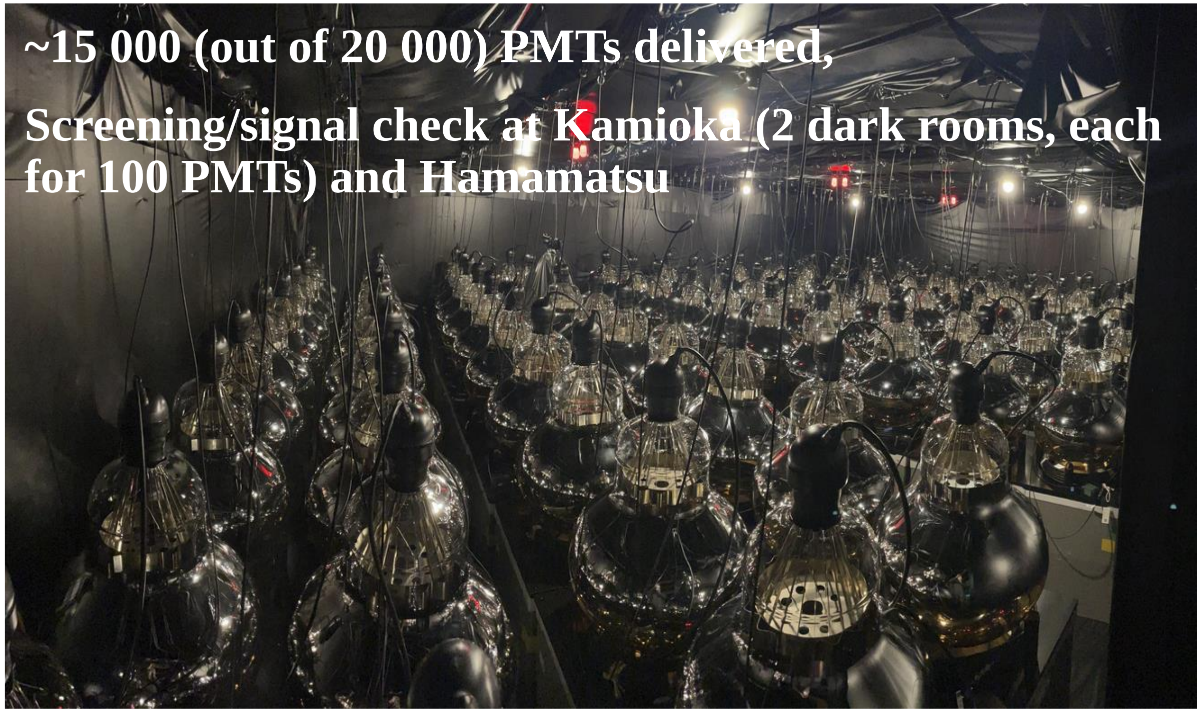
- **Far detector: fiducial volume: ~188 kton (~8.4 Super-K); tank bottom: ~8 bars of water pressure.**
- **Main cavern: one of the largest ever human-built caverns,**

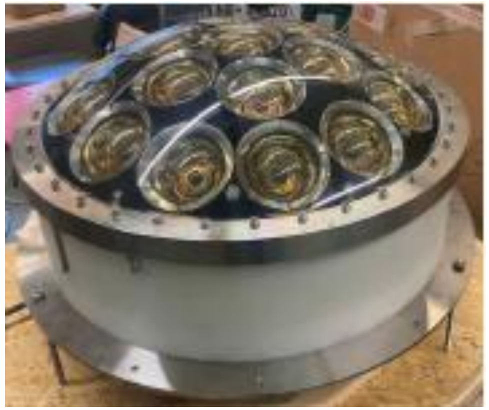
Hyper-Kamiokande far detector

Measurement of interaction vertex, particle direction and energy; e/μ PID with 20k 20" improved PMTs + 800 mPMTs (inner detector) and 3600 3" PMTs mounted at WLS plates (outer detector).



900 electronic modules in underwater pressure vessels (~600 for 20" PMTs only; ~300 hybrid (20" and 3" PMTs)), unlike in SK to avoid signal deterioration by long cables.





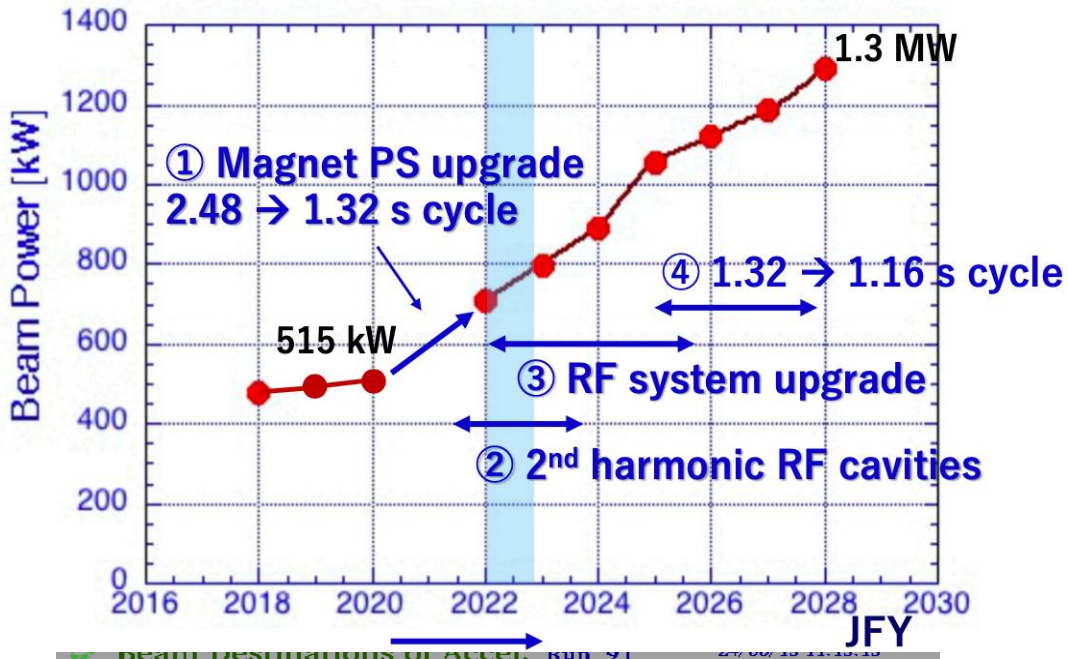
Multi-PMT (mPMT) modules: 19x3" PMTs with electronics inside a pressure resistant vessel to improve the Cherenkov rings reconstructions in the detector corners.

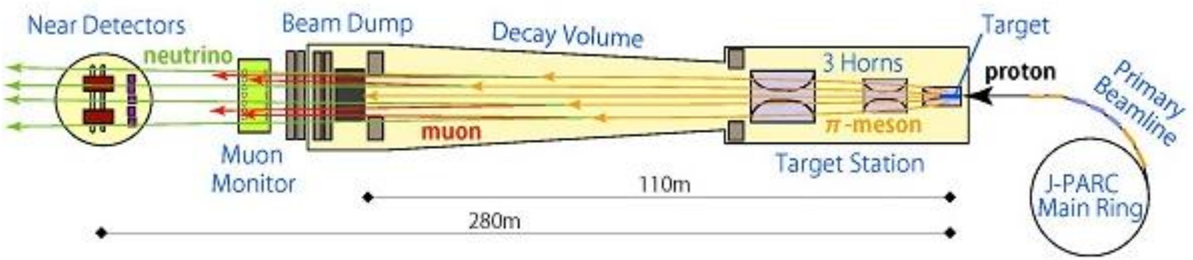
Outer detector: 3" PMT attached to wavelength shifting plate to veto cosmic-ray muons.

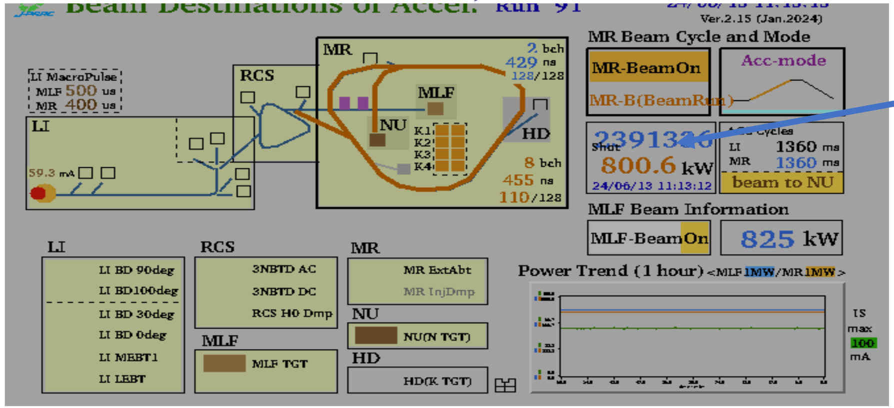
HK 20" PMTs: twice better performance (photodetection efficiency, charge and time resolutions) than SK PMTs; confirmed with 136 installed in the SK during 2018 refurbishment; data for long term stability tests in real HK conditions.

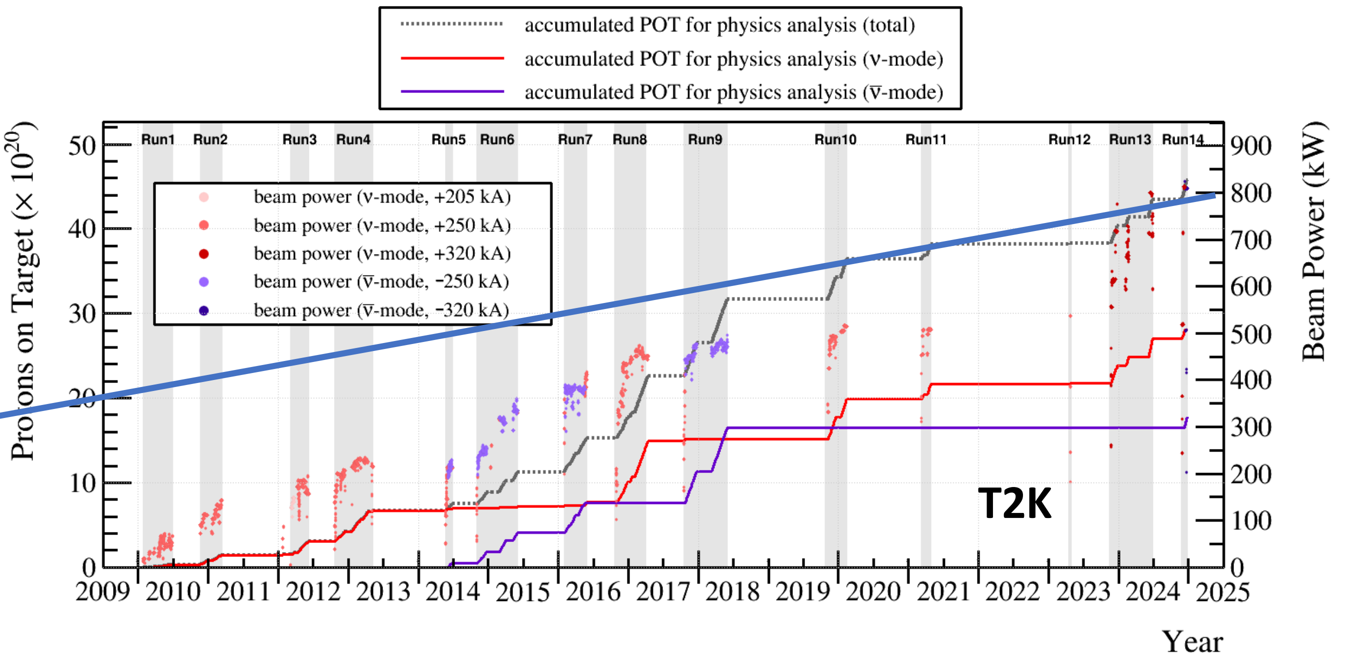
Upgrade of J-PARC proton beam intensity

- **Continuous increase: from 0.5 MW (2019) to 1.3 MW (2028); already above 0.8 MW.**
- **Cycle time: 2.48 s → 1.16 s; protons per pulse: $2.6\times10^{14} \rightarrow 3.3\times10^{14}$; beam optics improvement.**
- **J-PARC neutrino beam will be used by T2K until the start of HK.**





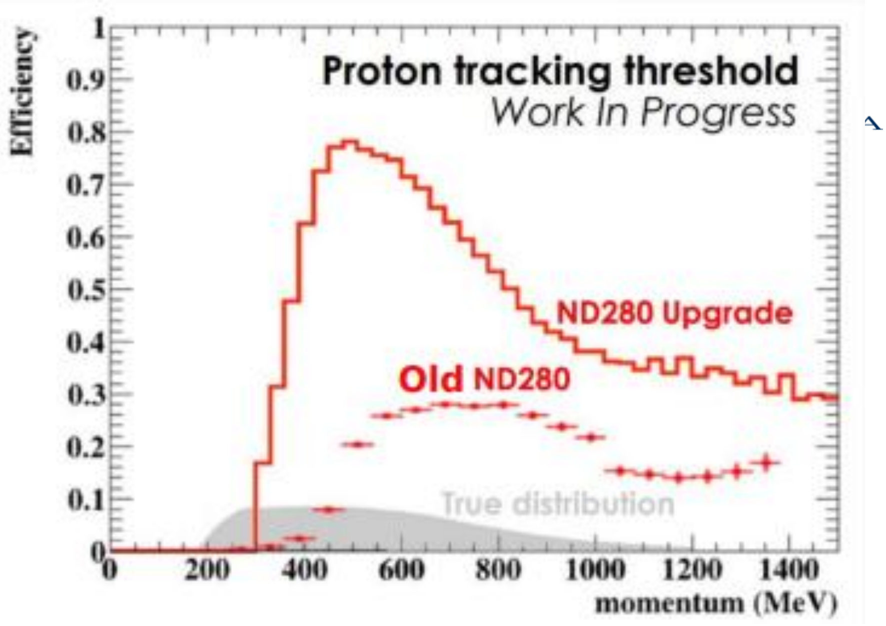




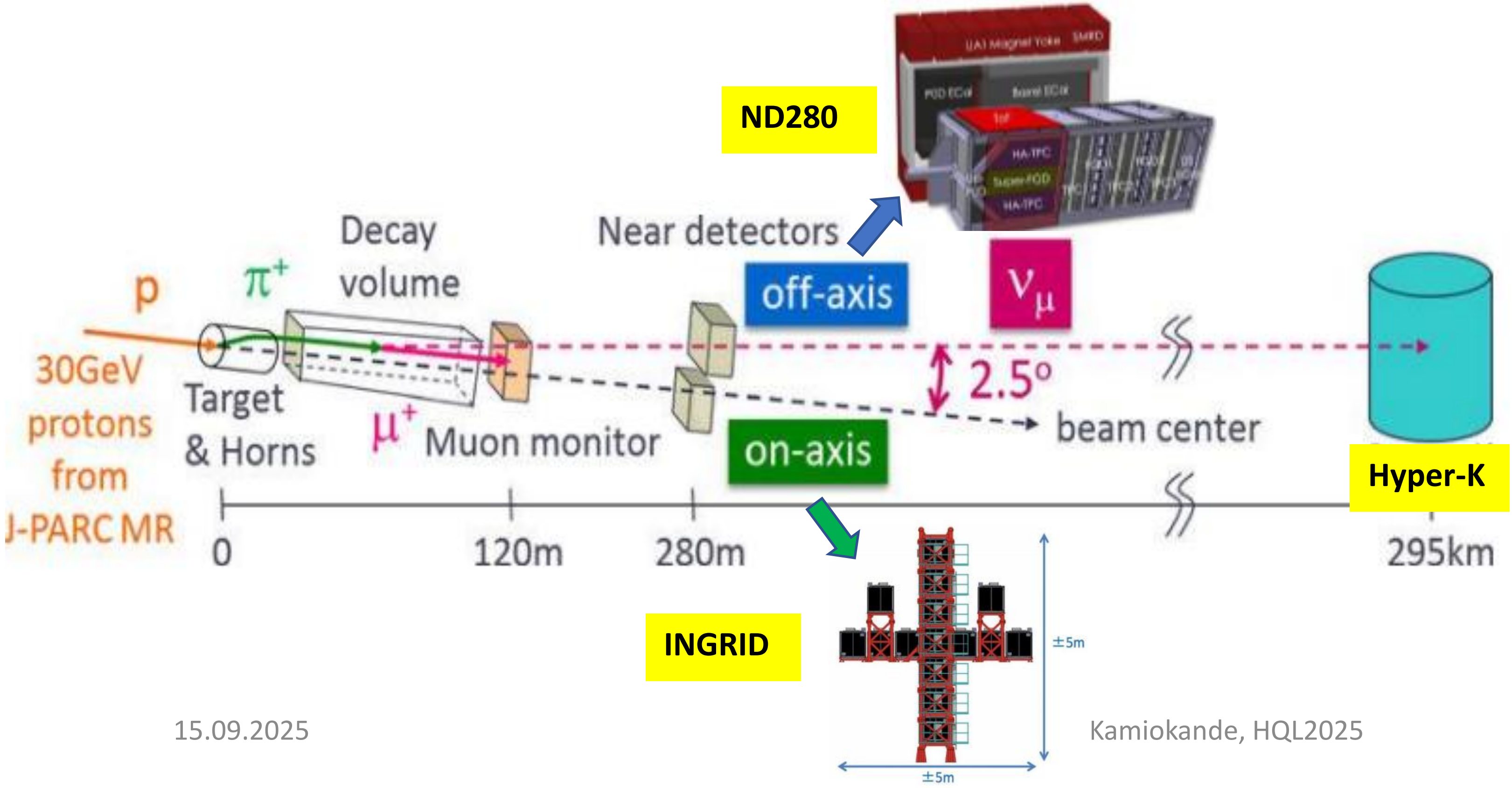
The near detectors at 280m

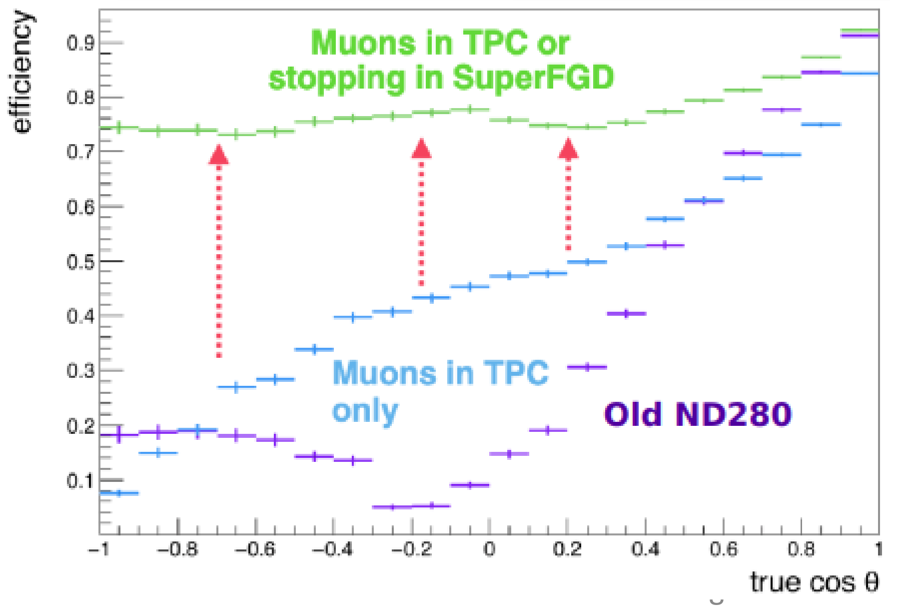
Near detectors: used to understand neutrino beam/interactions (before oscillations) and control systematics.

- **INGRID: on-axis detector to monitor neutrino beam stability and profile.**
- **ND280: 2.5° off-axis magnetized tracker to measure neutrino interactions (cross-sections) and energy spectrum before oscillations occur. Recently upgraded with: SuperFGD – 2M 1cm^3 optically isolated plastic scintillator cubes for 3D track reconstruction – significant improvement in backward angles, also 2 tons target; 2 horizontal gaseous Ar TPCs with central cathode with 1m drift distance; ToF with 6 scintillator planes with 150 ps timing resolution for PID.**



Proton tagging threshold: lowered

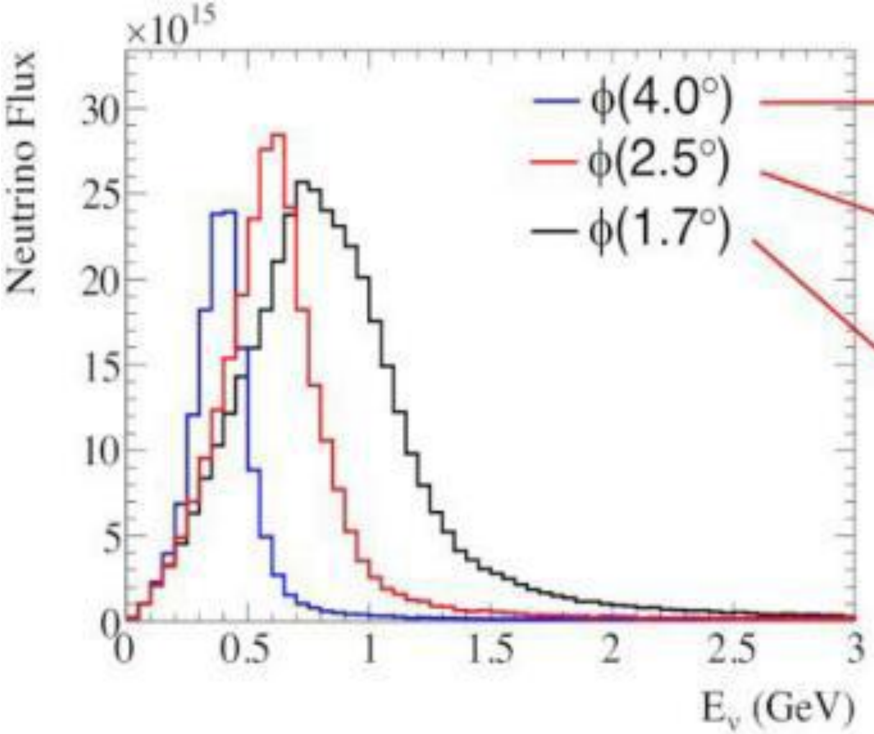


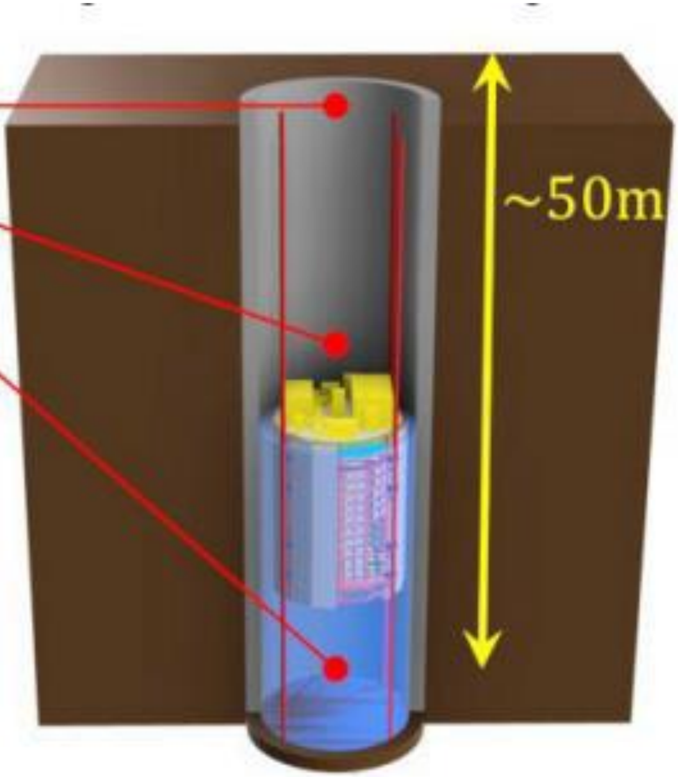


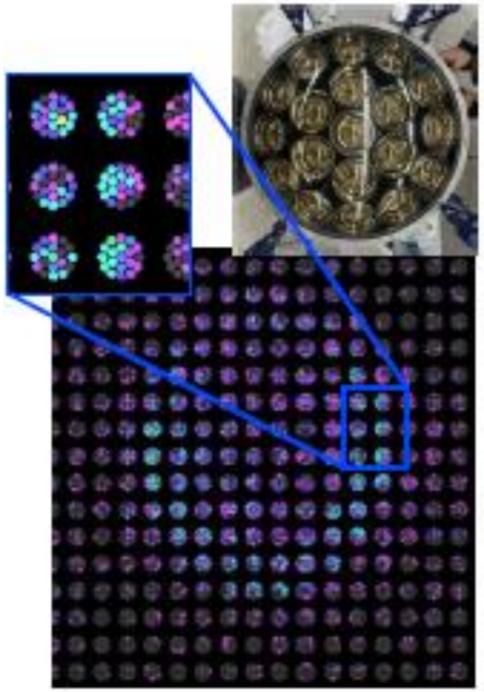
Muon angular acceptance: improved

Intermediate Water Cherenkov Detector

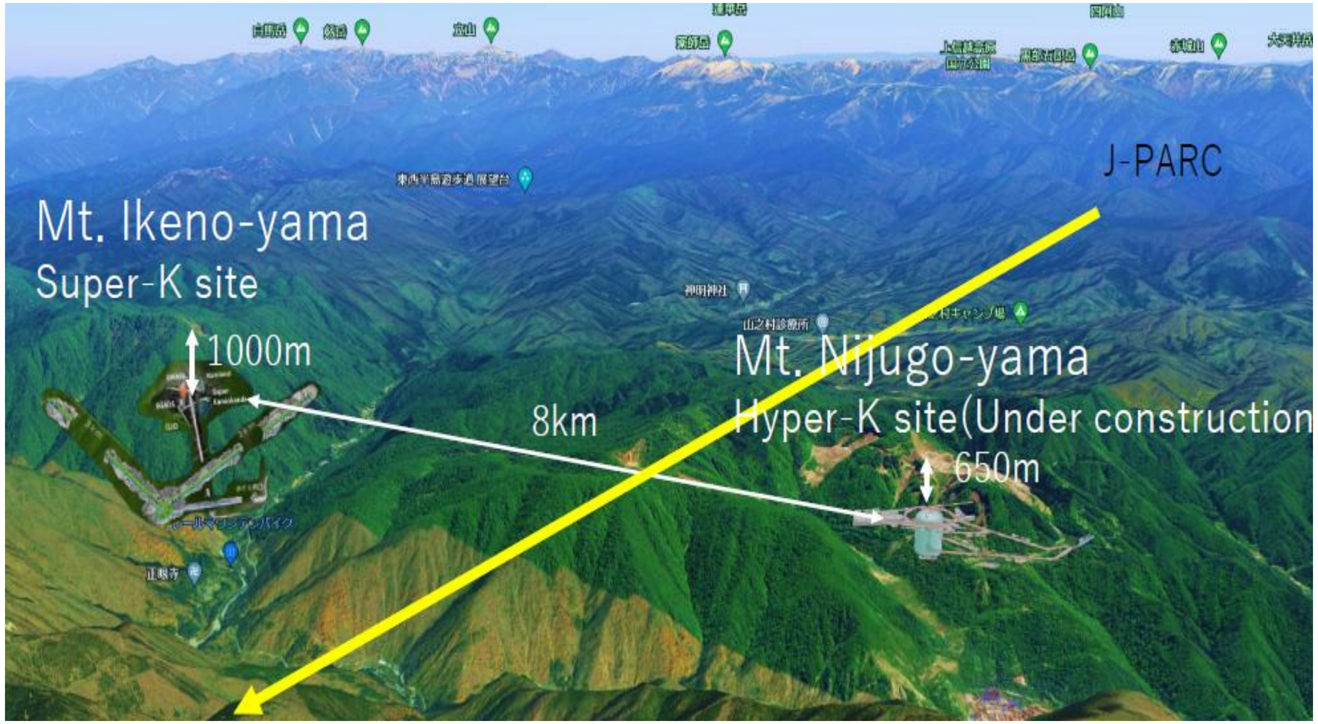
- Measurement of $\frac{\sigma(\nu_e)}{\sigma(\nu_\mu)} / \frac{\sigma(\overline{\nu_e})}{\sigma(\overline{\nu_\mu})}$ with ~3% accuracy at 600 MeV to improve δ_{CP} sensitivity significantly. Oscillated neutrino energy spectrum at HK will differ from that at IWCD.
- A linear combination of the results for different off-axis angles will allow to reconstruct the neutrino energy corresponding to an almost monochromatic neutrino spectrum without neutrino interaction models.
- New, vertically movable detector with 400 mPMTs inside 50m (height) x 10m (diameter) water tank, 850m away from the beam source. Facility construction already started.



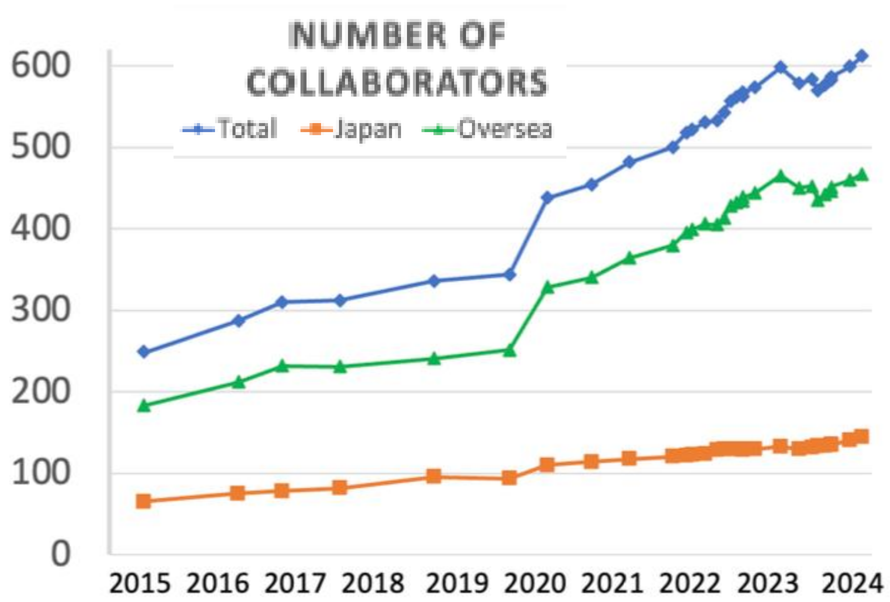




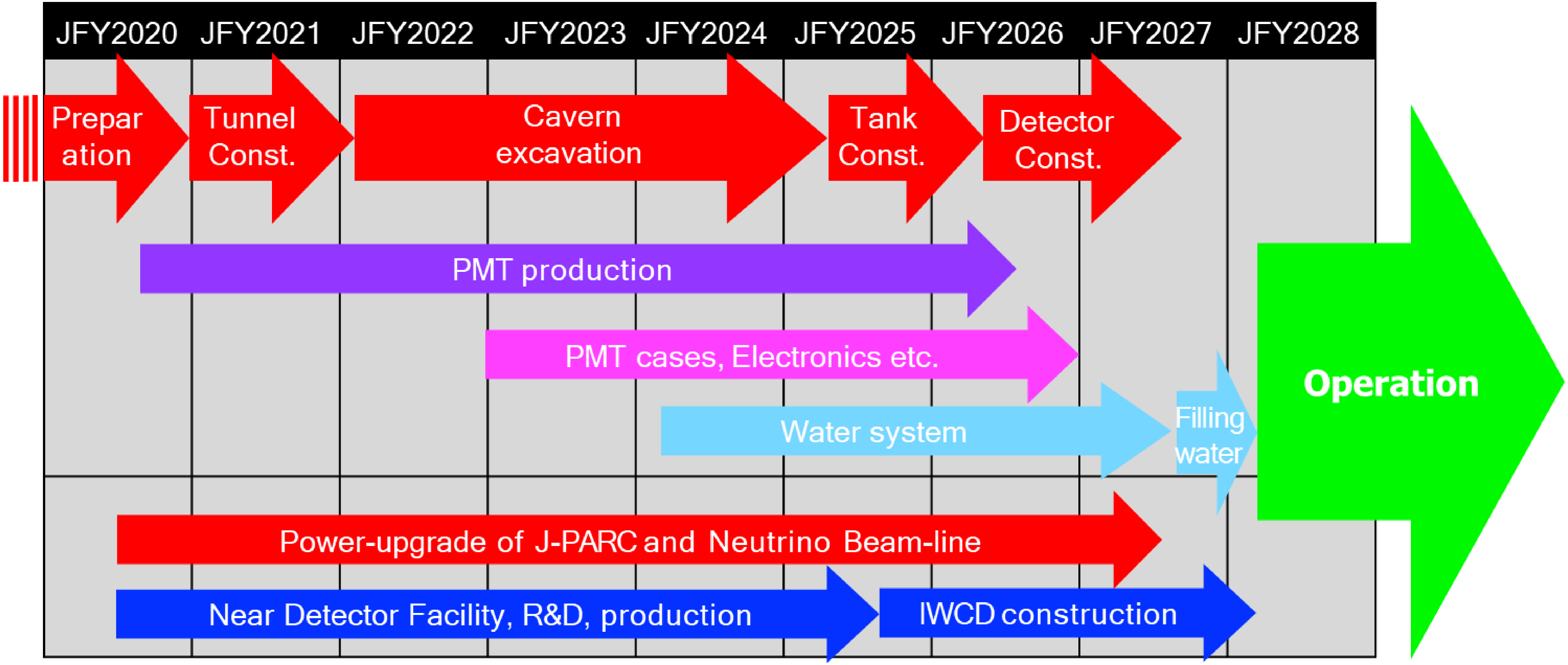
Hyper-Kamiokande collaboration



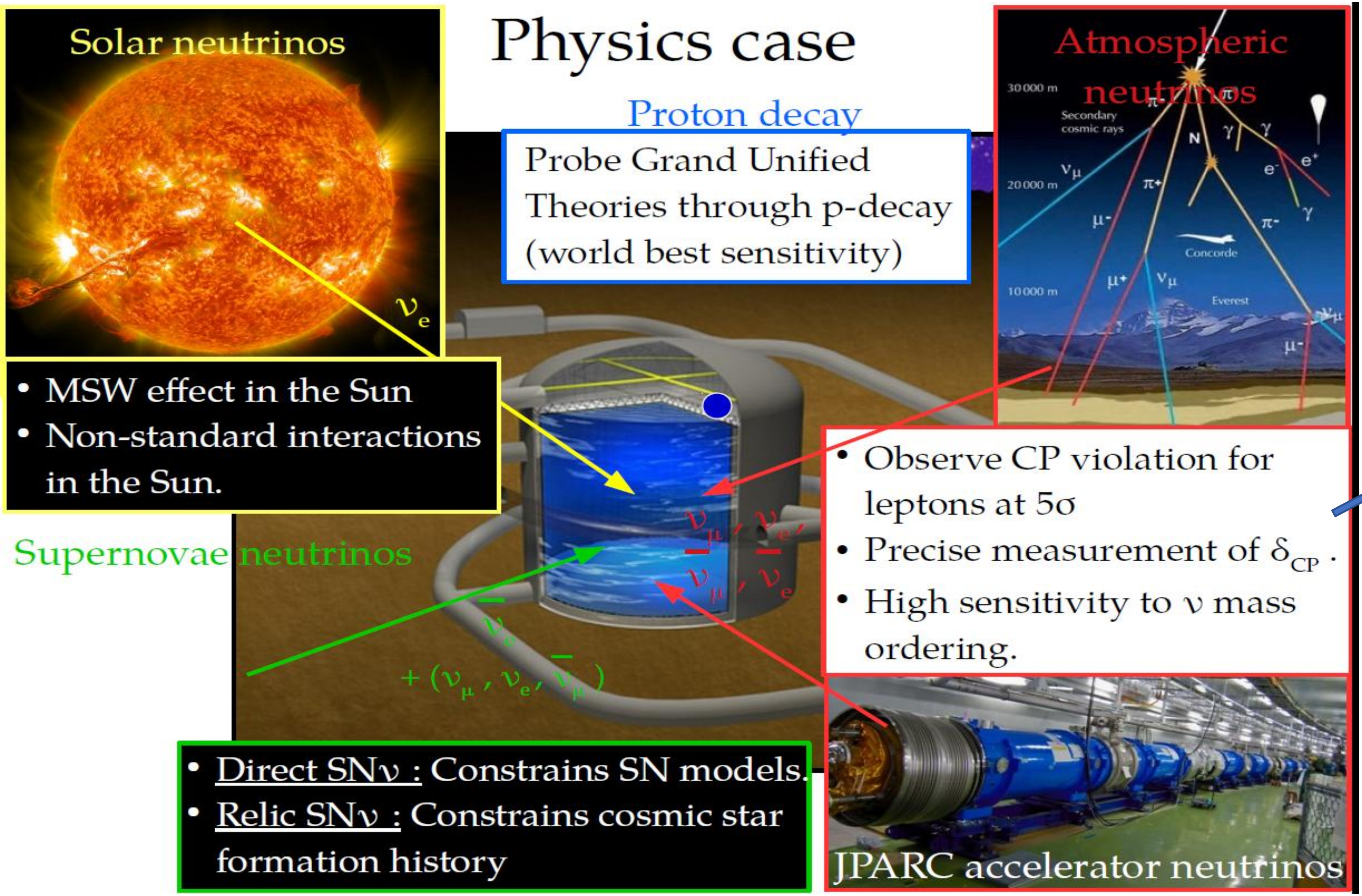
- 6 continents, 22 countries, 106 institutions, ~650 people as of December 2024; ~75% non-Japanese; continuously growing.
- Far detector: Univ. of Tokyo.
- Beam and near detectors: KEK/J-PARC.



Hyper-Kamiokande: timeline



Hyper-Kamiokande: physics program



(this talk)

B. Quilain, Conf. of the 2 infinities, Kyoto, 2023

Hyper-Kamiokande

Oscillation of 3ν flavors: known & unknown

UNIVERSITY OF SILESIA IN KATOWICE

Unitary, Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix describes the mixing between neutrino flavor and mass eigenstates:

atmospheric/accelerator — accelerator/reactor — solar/reactor

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&C_{23}&S_{23}\\0&-S_{23}&C_{23}\end{pmatrix}\begin{pmatrix}C_{13}&0&S_{13}e^{-i\delta}\\0&1&0\\-S_{13}e^{-i\delta}&0&C_{13}\end{pmatrix}\begin{pmatrix}C_{12}&S_{12}&0\\-S_{12}&C_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

flavor — mass

$$S_{ij}=\sin(\theta_{ij})$$
$$C_{ij}=\cos(\theta_{ij})$$

In the three flavor model there are 6 parameters to be measured:

2 differences of mass in quadrature, 3 mixing angles and 1 CP phase (for Dirac neutrinos)

Current values, PDG2024

$sin^2\theta_{13} = 0.0219 \pm 0.007$

$sin^2\theta_{12} = 0.307^{+0.013}_{-0.012}$

$\Delta m^2_{21} = 7.53 \pm 0.18 \times 10^{-5} eV^2$

Normal mass ordering

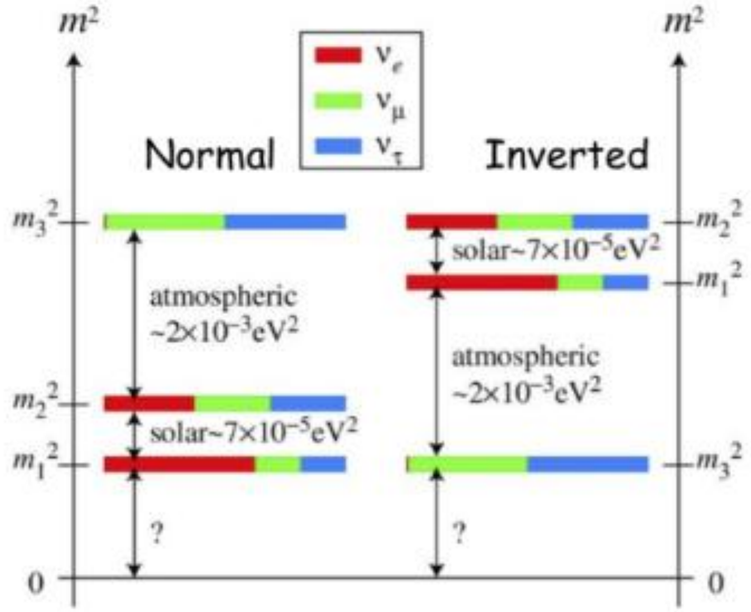
$\Delta m^2_{32} = 2.455 \pm 0.028 \times 10^{-3} eV^2$

$sin^2\theta_{23} = 0.558^{+0.015}_{-0.021}$

Inverted mass ordering

$\Delta m^2_{32} = -2.529 \pm 0.029 \times 10^{-3} eV^2$

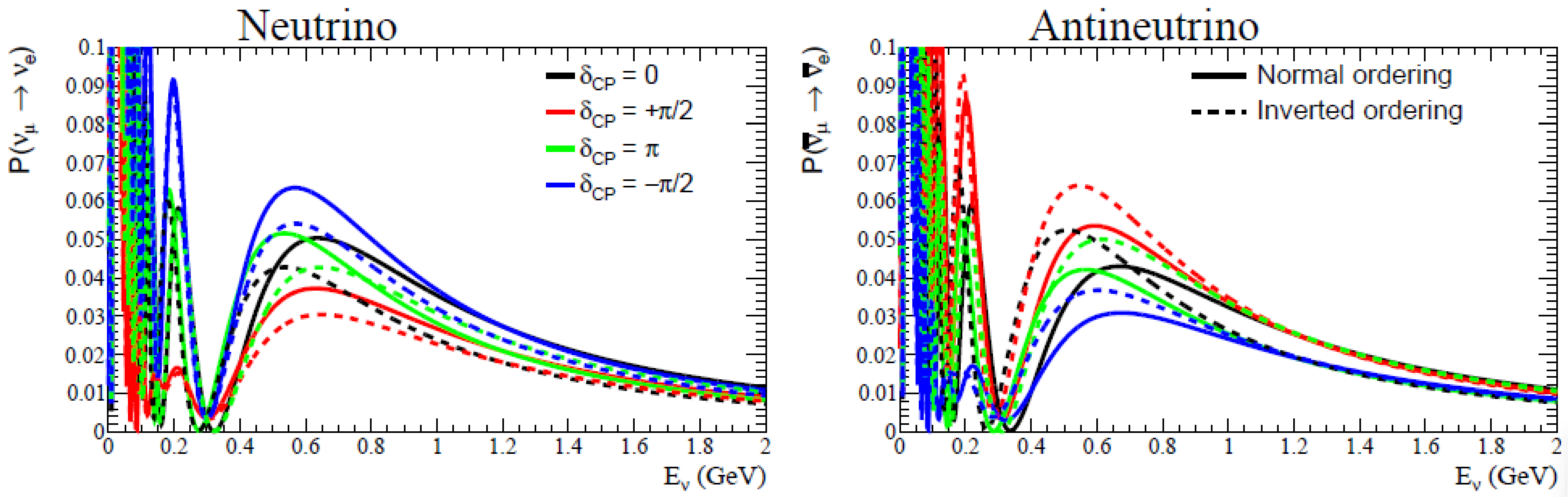
$sin^2\theta_{23} = 0.553^{+0.016}_{-0.024}$



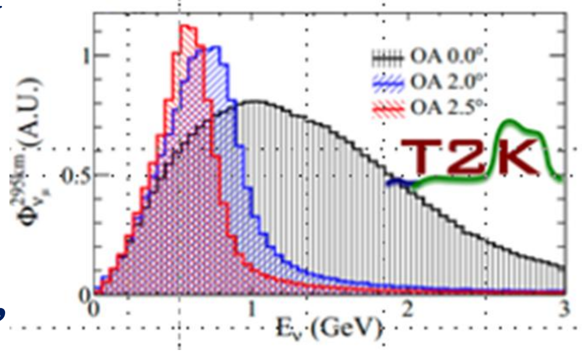
Open questions:

- **CPV (δ_{CP} phase, difference in $\nu_\mu \to \nu_e$, $\overline{\nu_\mu} \to \overline{\nu_e}$ oscillations)**
- **mass ordering**
- **$\Theta_{23} > 45^o$ or $\Theta_{23} < 45^o$ or $\Theta_{23} = 45^o$**

HK: $\nu_e(\overline{\nu_e})$ appearance probabilities, 295 km



- **J-PARC neutrino and antineutrino off-axis beam fluxes peaks at ~ 0.6 GeV, currently used by T2K, from 2028 by HK**
- **For $\delta_{CP} = -\pi/2$: $\nu_e(\overline{\nu_e})$ appearance enhanced (suppressed)**
- **Unknown neutrino mass ordering makes δ_{CP} measurement more complicated, but …**
- **Neutrino mass ordering may be resolved with HK atmospheric neutrino data (not in this talk, detailed beam-atmospheric neutrino joint HK fit will come)**
- **First hint for CPV from T2K exp.** (Nature 580 (2020) 339, https://doi.org/10.1038/s41586-020-2177-0)



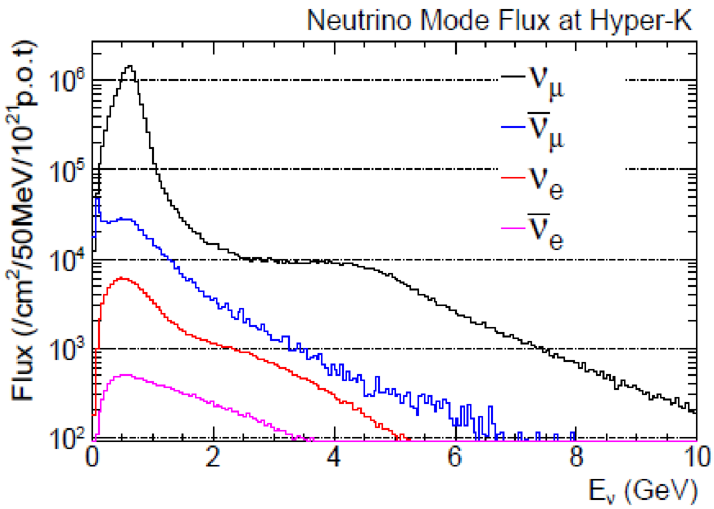
HK sensitivities: assumptions

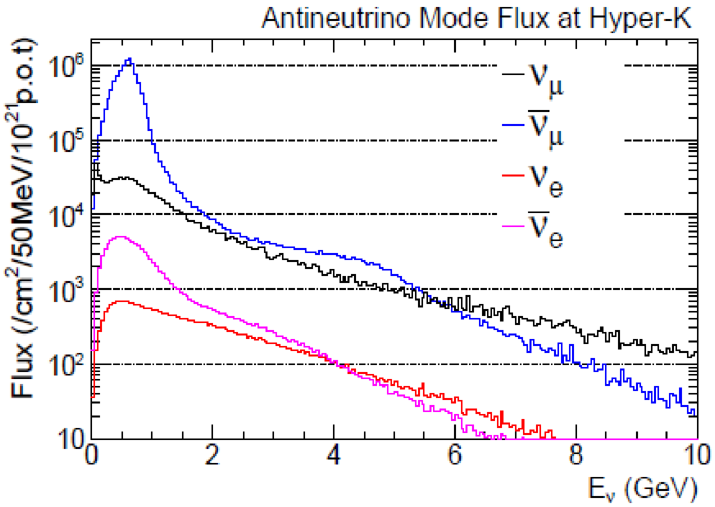
- **Expected number of events for 10 years, 27×10^{21} protons on target (1.3 MW) and ratio of 1:3 in neutrino to antineutrino beam mode:**

CCQE-like muon neutrino	**~10 000**
CCQE-like muon antineutrino	**~10 000**
CCQE-like electron neutrino (assuming $\delta_{CP} = -1.6$)	**~2 000**
CCQE-like electron antineutrino (assuming $\delta_{CP} = -1.6$)	**~ 800**

- **T2K neutrino flux model (increase in horn current and position of far detector included).**
- **T2K analysis (details in EPJ C83, 782, 2024 DOI 10.1140/epjc/s10052-023-11819-x, ref.[4] in figures) method used with new beam and new far detector.**
- **Central values of the oscillation parameters used:**

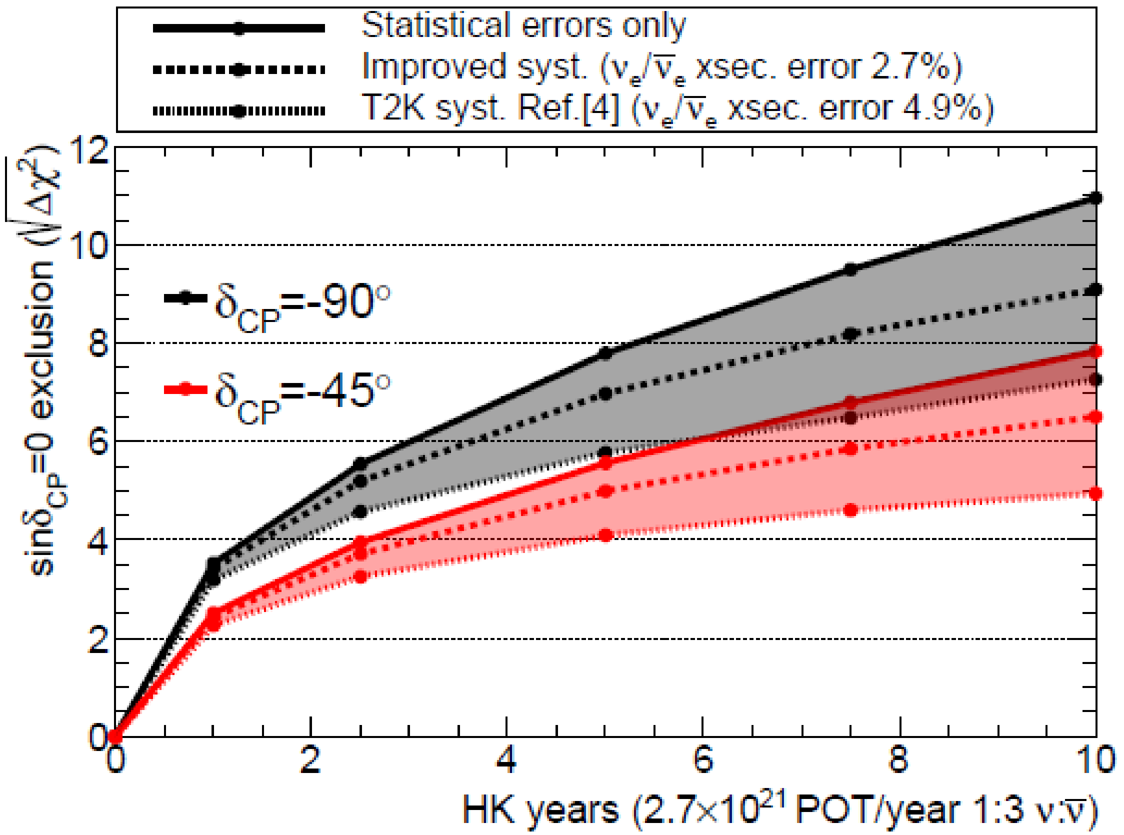
$sin^2\theta_{12}$	Δm^2_{21}	$sin^2\theta_{23}$	Δm^2_{32}	$sin^2\theta_{13}$	δ_{CP}	*mass ordering*
0.307	$7.53 \times 10^{-5} eV^2$	0.528	$2.509 \times 10^{-3} eV^2$	0.0218	$-1.601\ rad$	*normal*

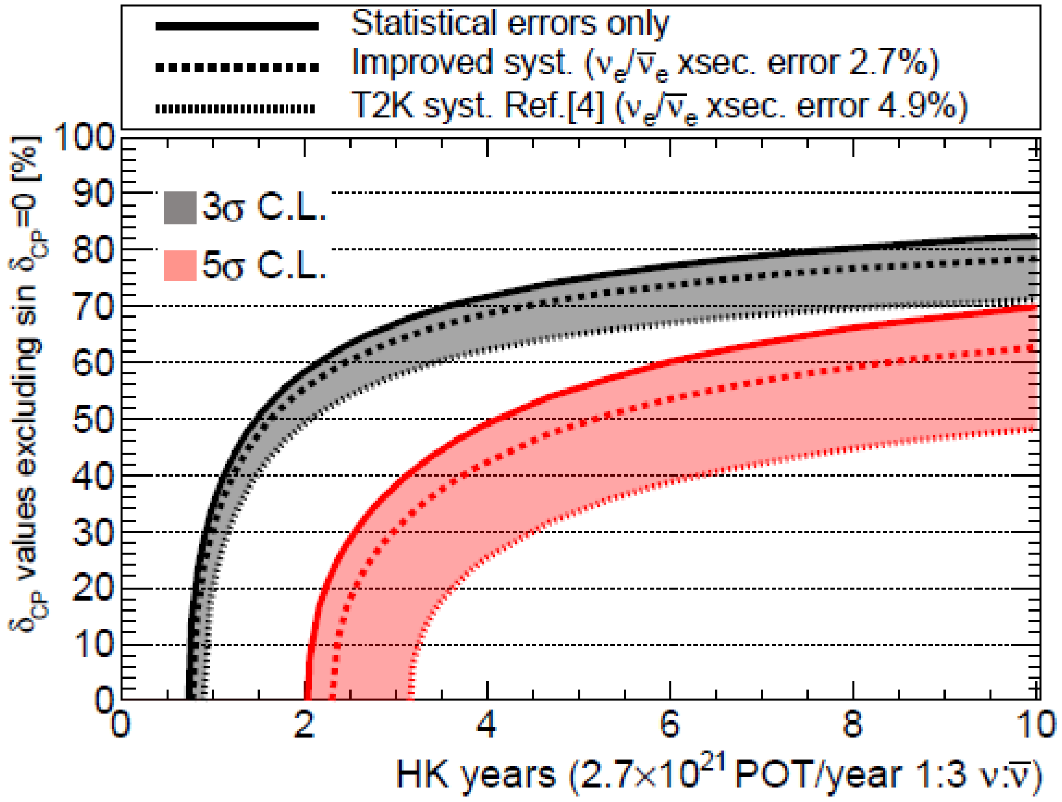




Details in arXiv:2505.15019v1, submitted to EPJ C

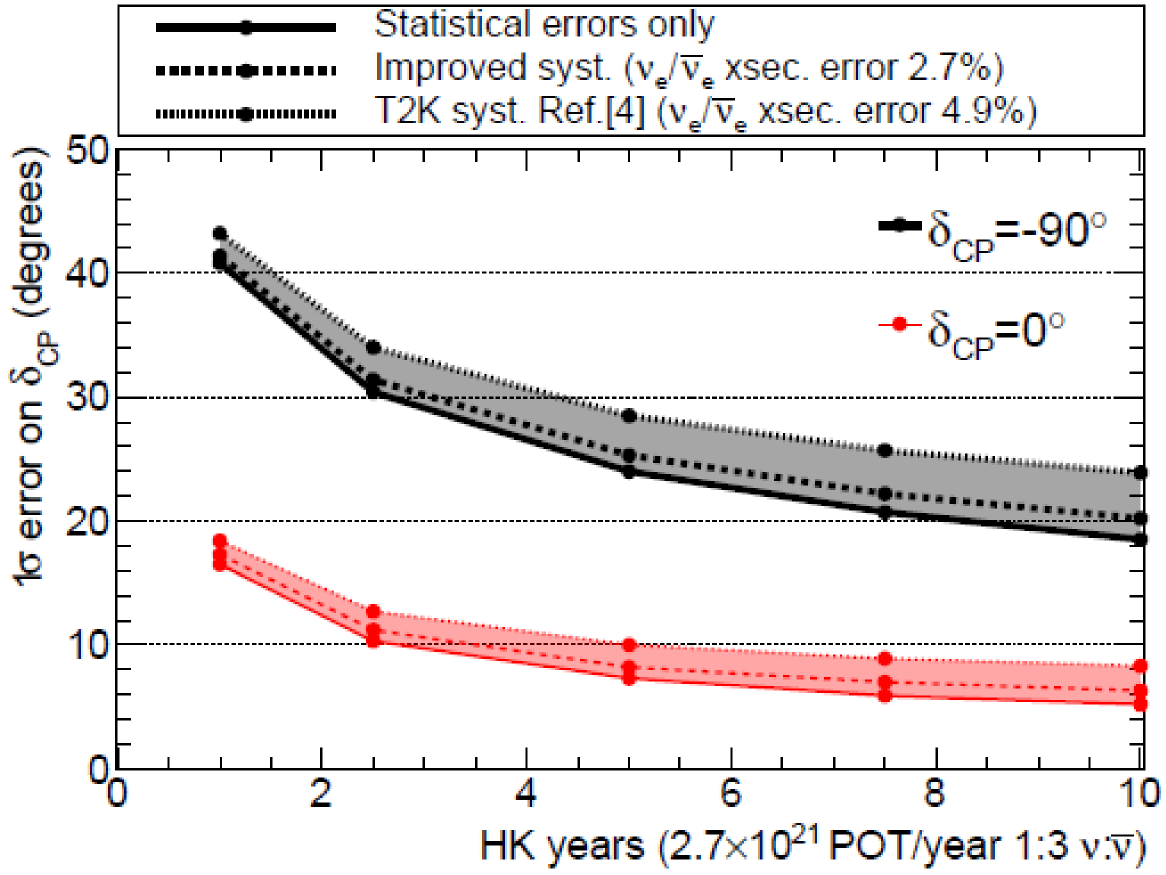
HK: CP violation phase sensitivity

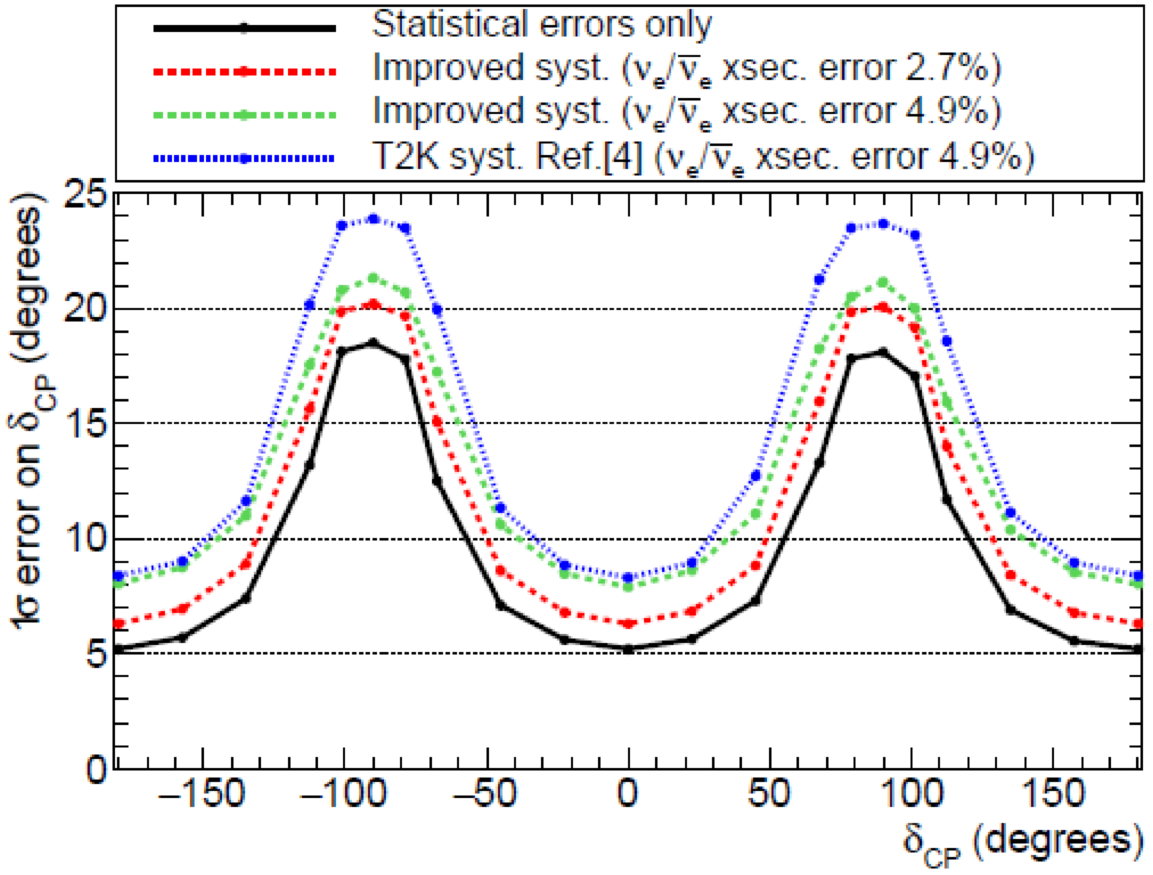




- **For maximal CPV ($\delta_{CP} = -\pi/2$) and improved systematics, 5σ discovery in $<$ 3 years.**
- **For maximal CPV ($\delta_{CP} = -\pi/2$) and T2K-like, conservative systematics, 5σ discovery in $<$ 6 years.**

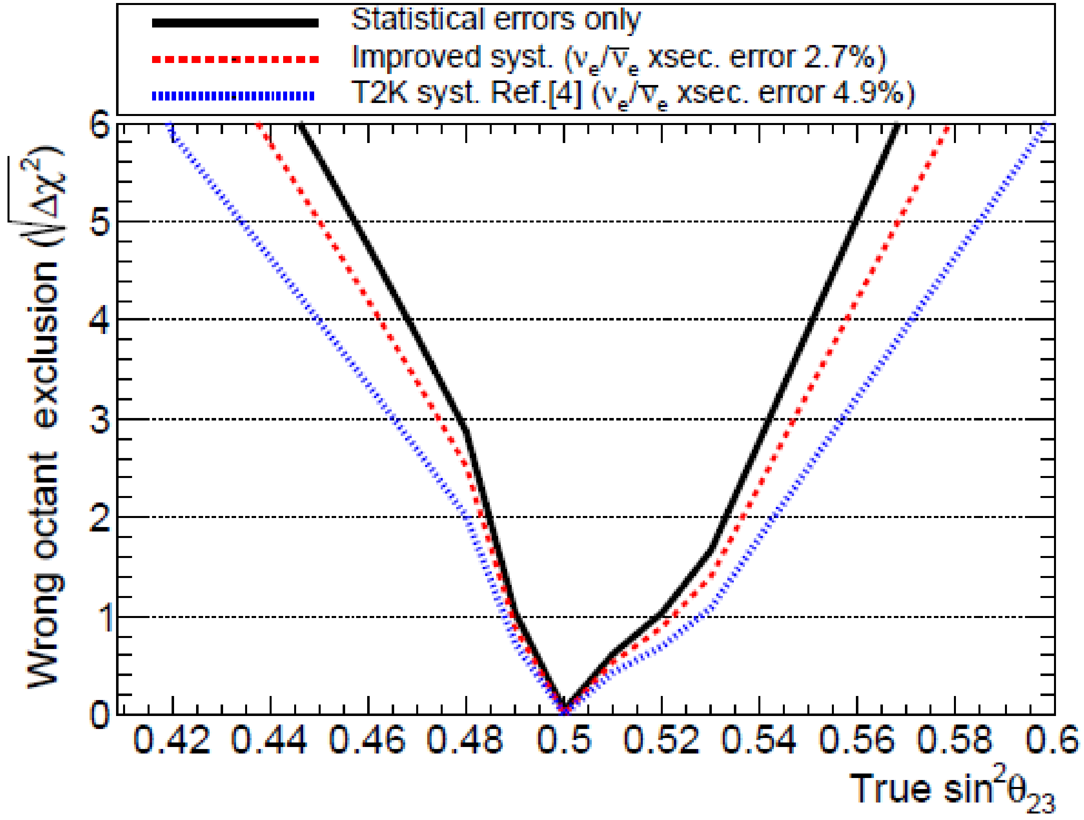
HK: precision measurement of CP phase

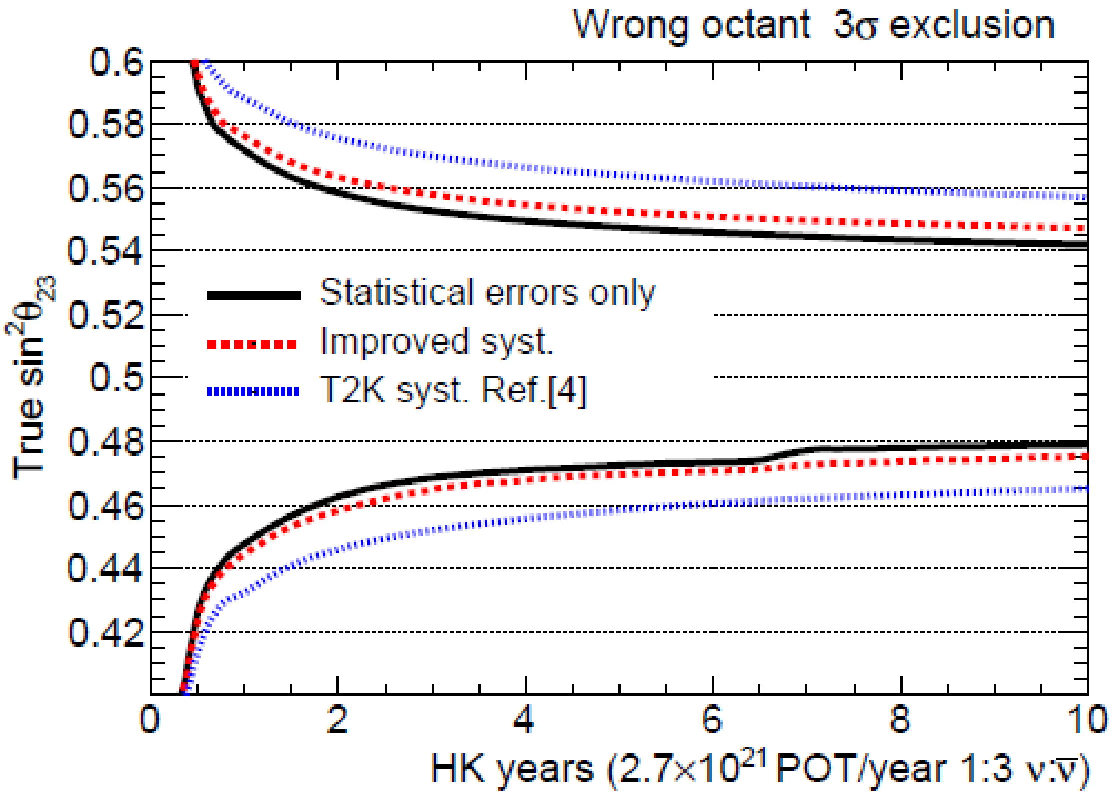




- δ_{CP} **measurement expected precision of ~6° (~20°) for CP conservation (maximal CPV).**

HK: sensitivity to wrong θ_{23} octant exclusion

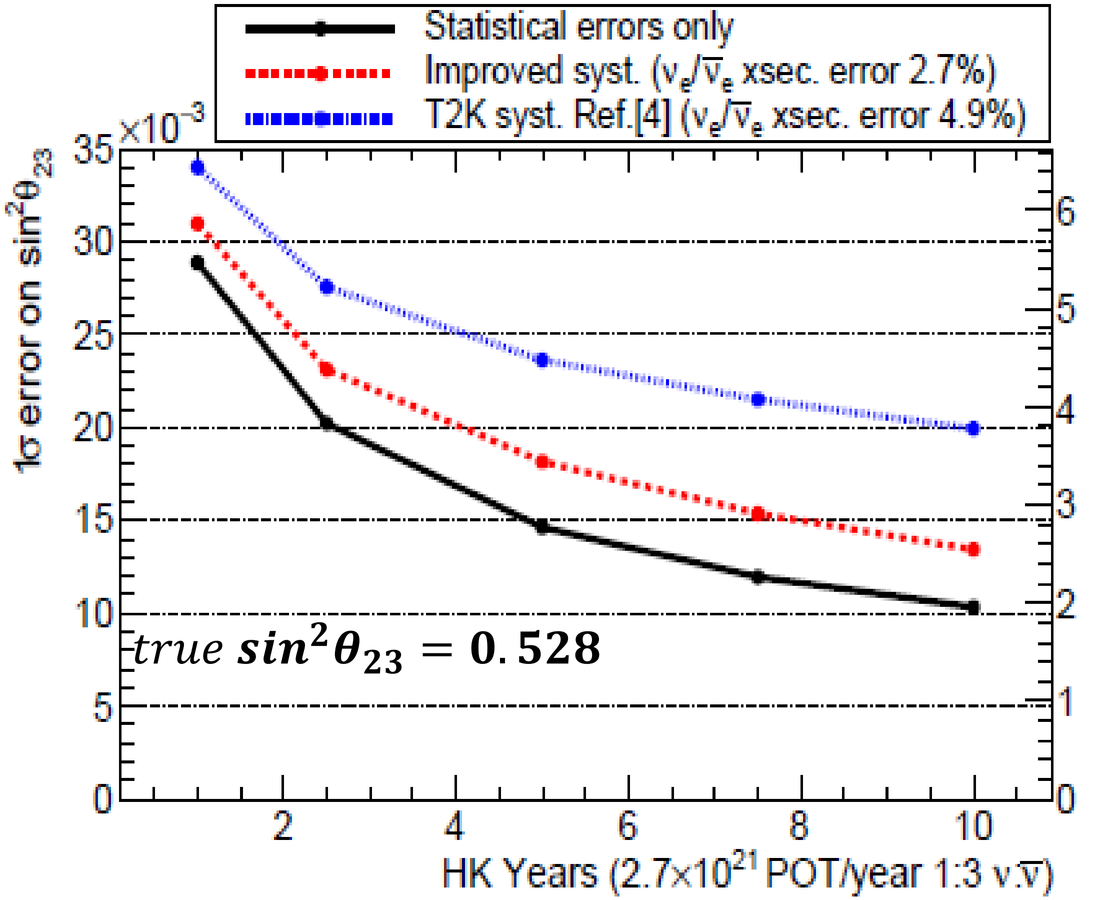


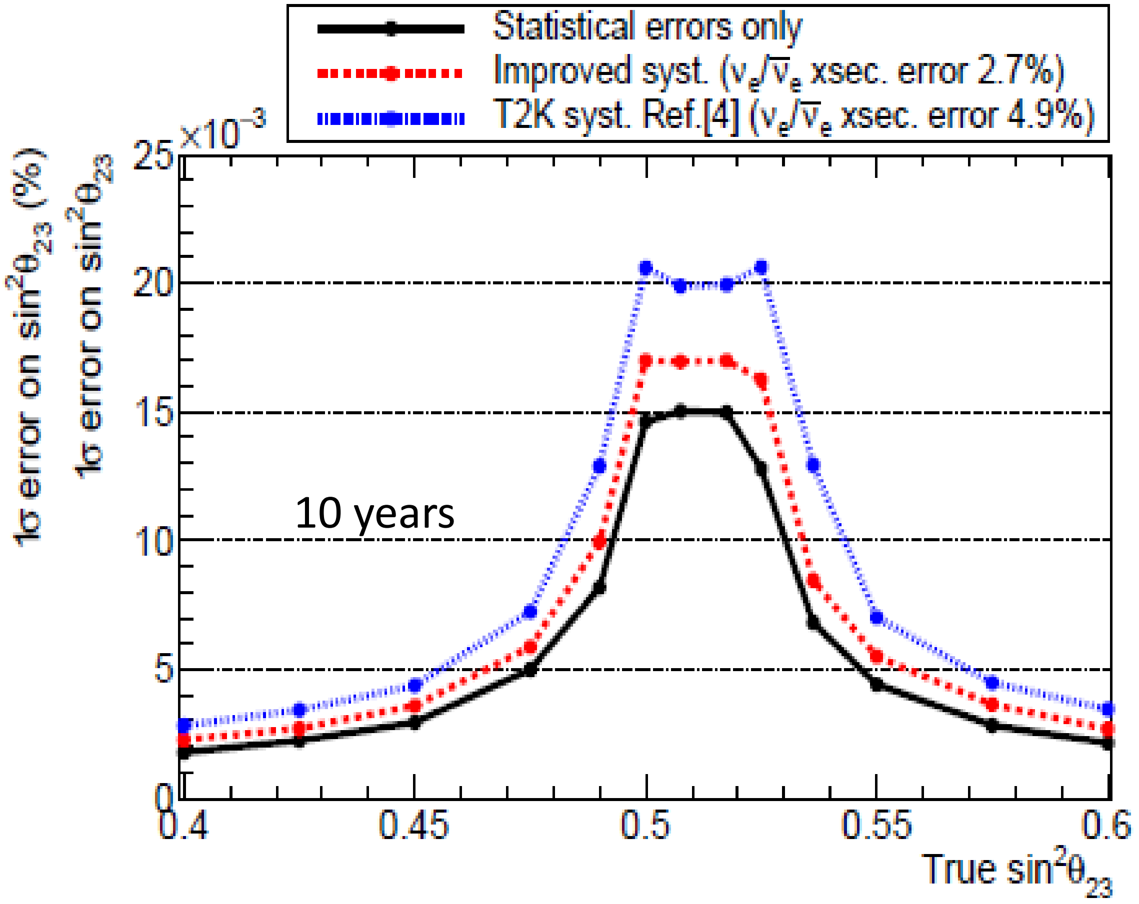


For improved systematics:

- **Above 3σ wrong $sin^2\theta_{23}$ octant exclusion for $sin^2\theta_{23} < 0.47$ and $sin^2\theta_{23} > 0.55$**
- **Above 5σ wrong $sin^2\theta_{23}$ octant exclusion for $sin^2\theta_{23} < 0.45$ and $sin^2\theta_{23} > 0.57$**

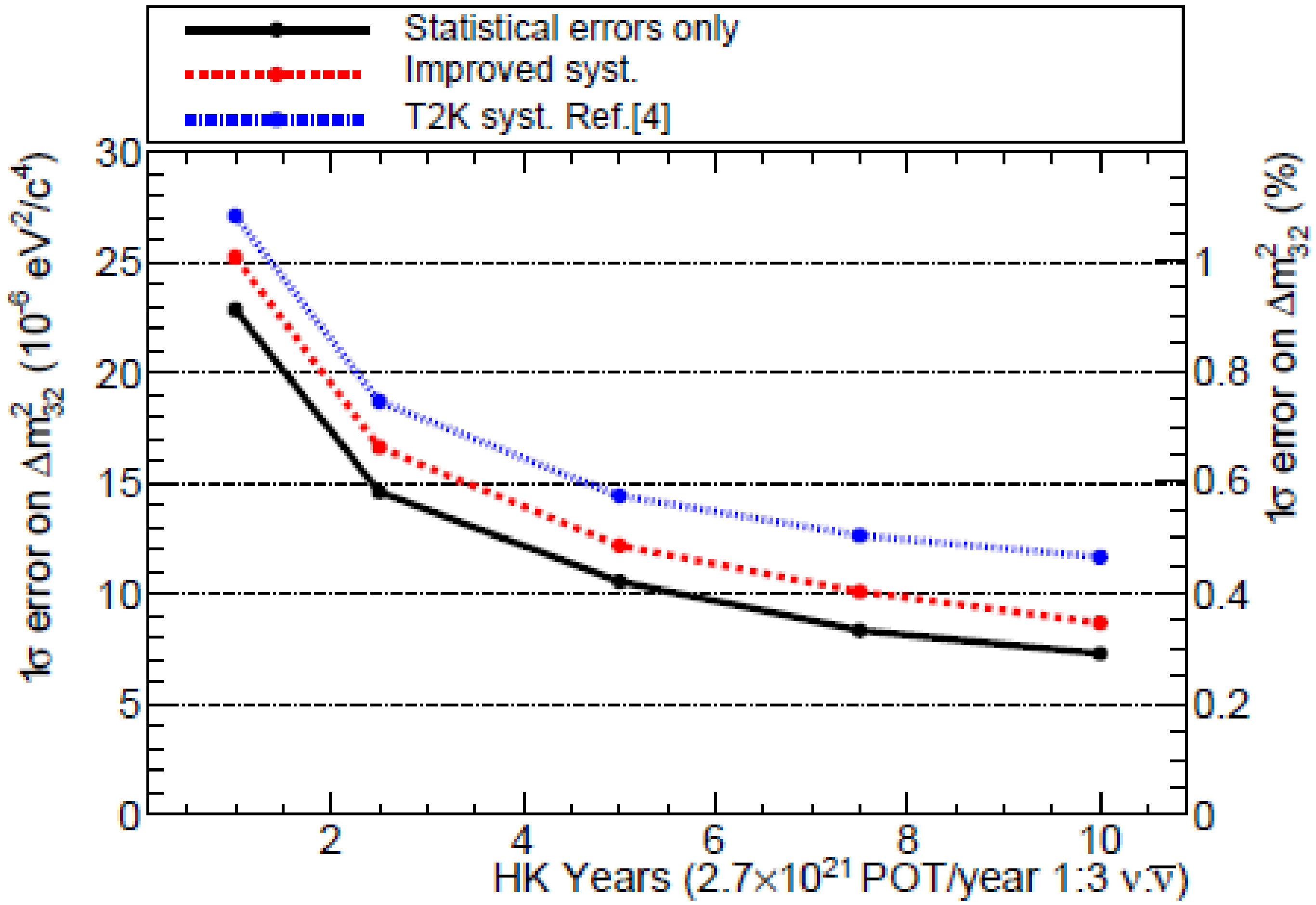
HK: sensitivity to $sin^2\theta_{23}$





- $\sim 3\%$ precision of $sin^2\theta_{23}$ measurement in the region of maximal disappearance.
- $\sim 0.5\%$ or better precision of $sin^2\theta_{23}$ measurement otherwise.

HK: sensitivity to Δm^2_{32}



- Δm^2_{32} **measurement expected precision better than** 0.5%.

Outlook

- Hyper-Kamiokande is the next generation neutrino experiment in Japan:
  - New, huge, ~260 kton water Cherenkov far detector,
  - Upgraded to 1.3 MW J-PARC neutrino beam,
  - Upgraded near detectors,
  - New Intermediate Water Cherenkov detector.

- Wide and ambitious Hyper-Kamiokande physics program is based on detection of neutrinos from various sources (J-PARC beam, Sun, Earth's atmosphere, supernova, relic, …), and proton decay searches.

- Construction started in 2020, is ongoing; beginning of operation in 2028.