The Hyper-Kamiokande experiment

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Outline

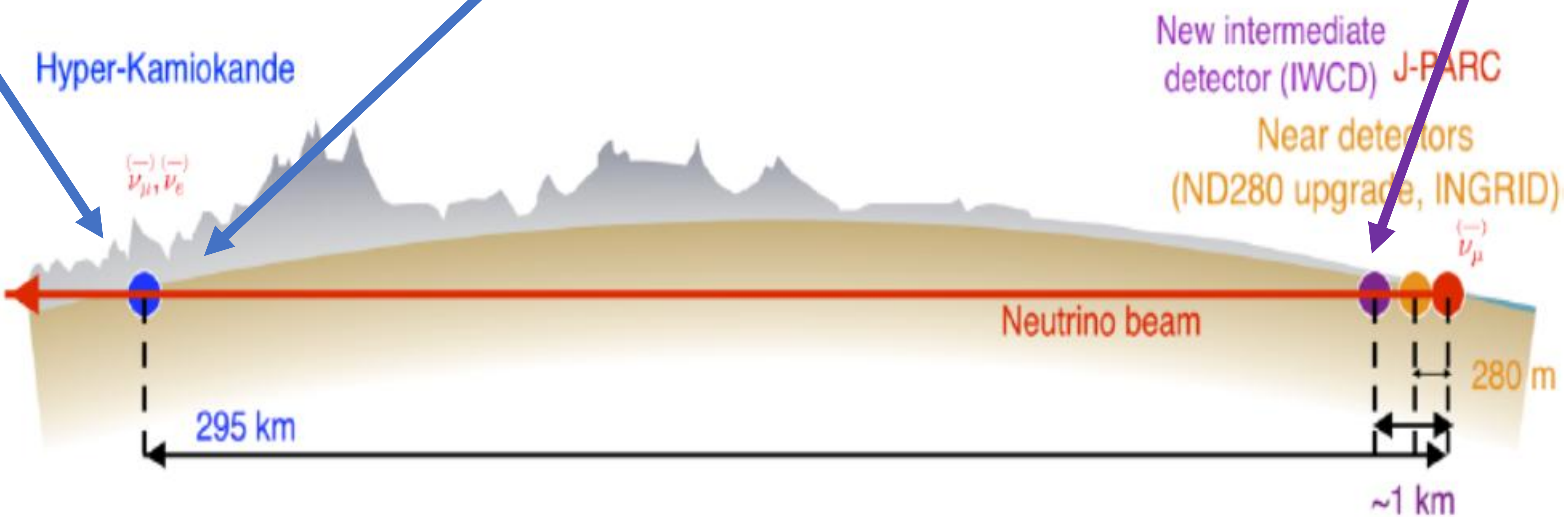
- Hyper-Kamiokande project:
  (1) far detector,
  (2) near detectors,
  (3) J-PARC neutrino beam,
  (4) Intermediate Water Cherenkov Detector (IWCD)
- Hyper-Kamiokande: physics program
- Hyper-Kamiokande: timeline
- Polish contribution to Hyper-Kamiokande experiment
- Outlook

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)
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)

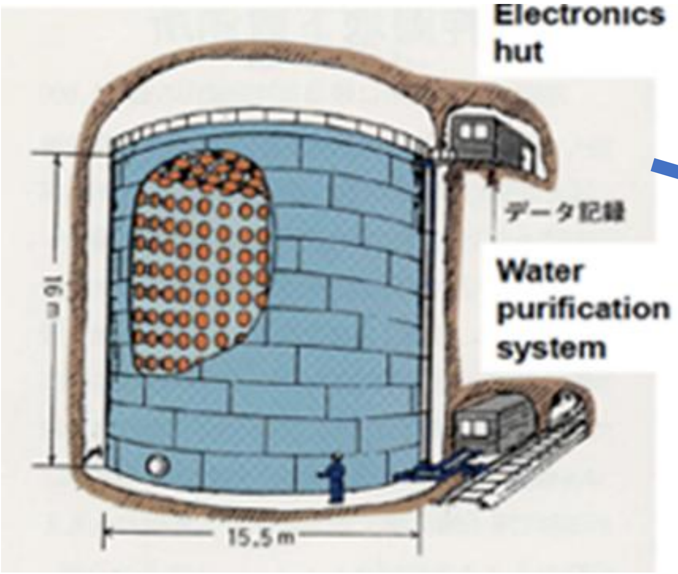
- **Kamiokande (1983-1996), 3 kton, 20% PMT coverage:**
  - SN1987a neutrinos,
  - ν_{atm} deficit,
  - …

M.Koshiba
(for the detection
of cosmic neutrinos)

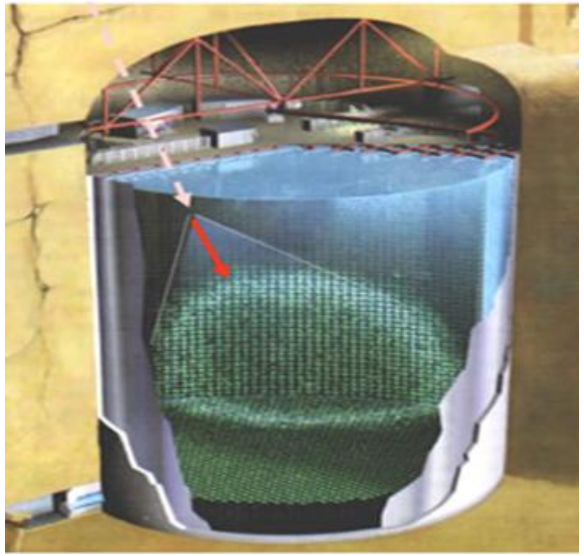
- **Super-Kamiokande (1996-…), 50 (22.5 FV) kton, 40% PMT coverage:**
  - ν_{atm} and ν_{solar} oscillations,
  - proton decay,
  - far detector for T2K exp.,
  - …

T. Kajita
(for the discovery
of neutrino oscillations)

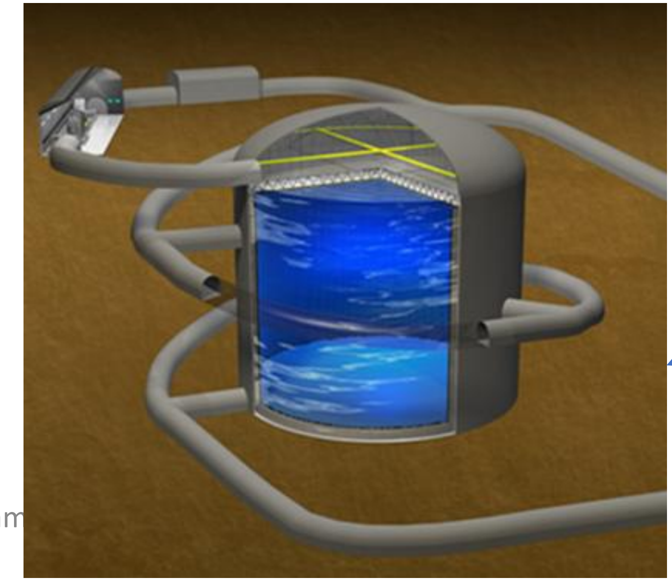
- **Hyper-Kamiokande (2027-…), 258 (188 FV) kton, 20% PMT coverage:**
  - CP violation: elucidation of the matter dominance in the Universe
  - proton decay (most sensitive channel: $p \rightarrow e^{+} + \pi^{0}$):
  - neutrino oscillation (beam, atmospheric, solar)
  - neutrino mass hierarchy (combined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



20x

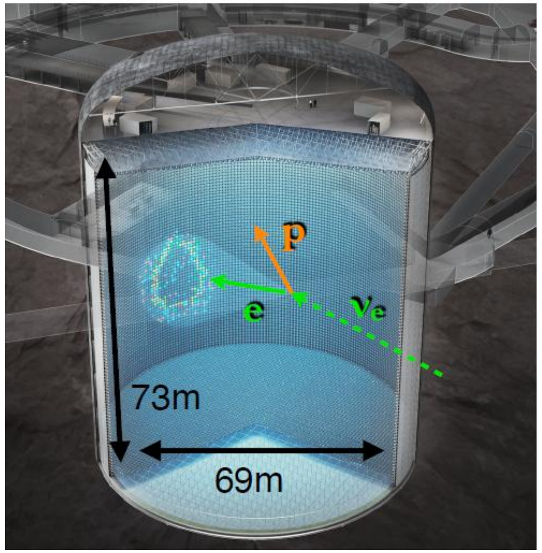


8.4x



Hyper-Kamiokande: far detector site

- Water Cherenkov far detector:
  - fiducial volume: ~188 kton, ~8.4 Super-K;
  - the tank bottom: ~8 bars of water pressure.
- Main cavern: the largest ever human-built cavern,

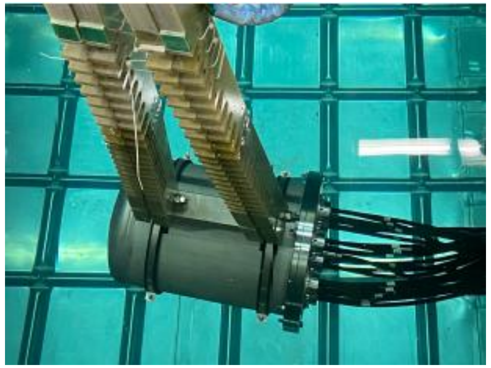


Hyper-Kamiokande

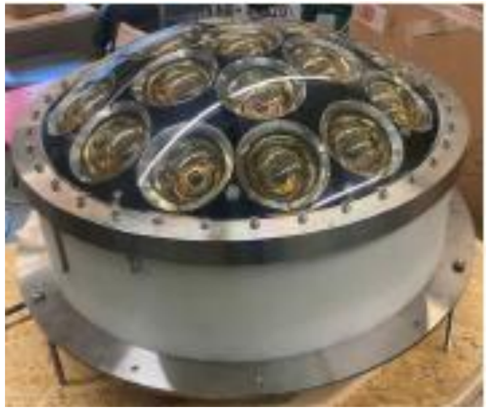
Hyper-Kamiokande far detector

UNIVERSITY OF SILESIA IN KATOWICE

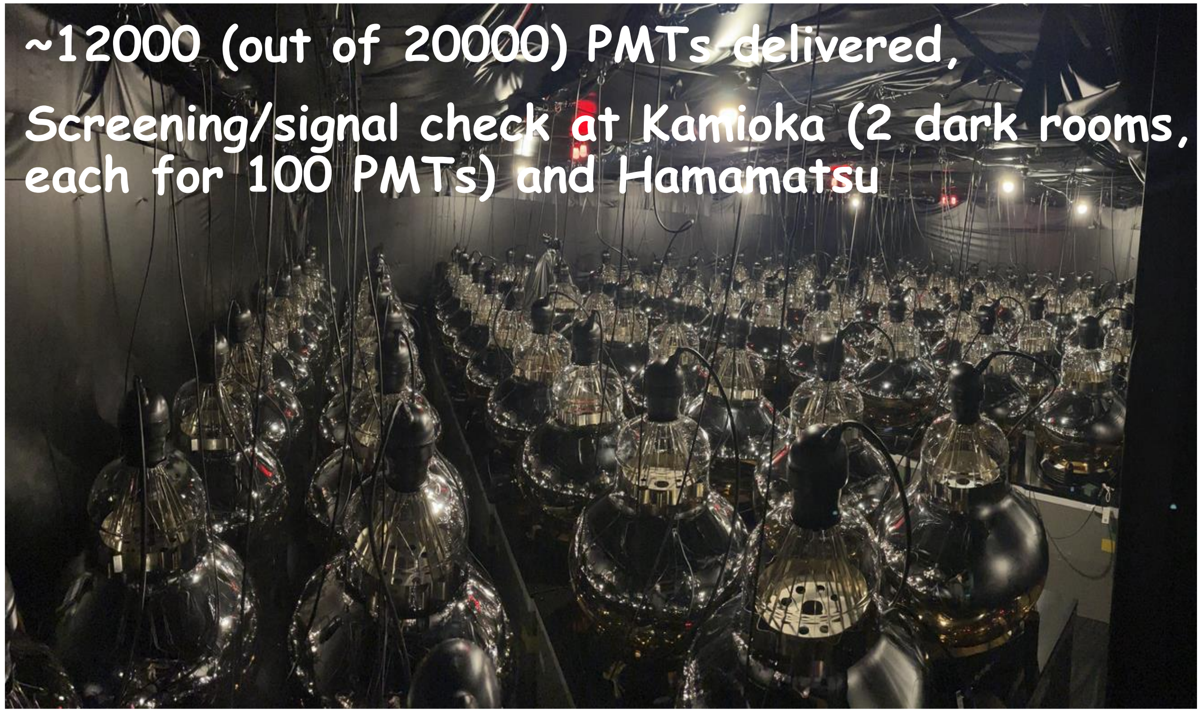
Measurement of interaction vertex, particle direction and energy; e/μ PID with 20k 20" improved PMTs + 800 mPMTs (inner detector) and 3600 3" PMTs mounted at WLS plates (outer detector).



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.

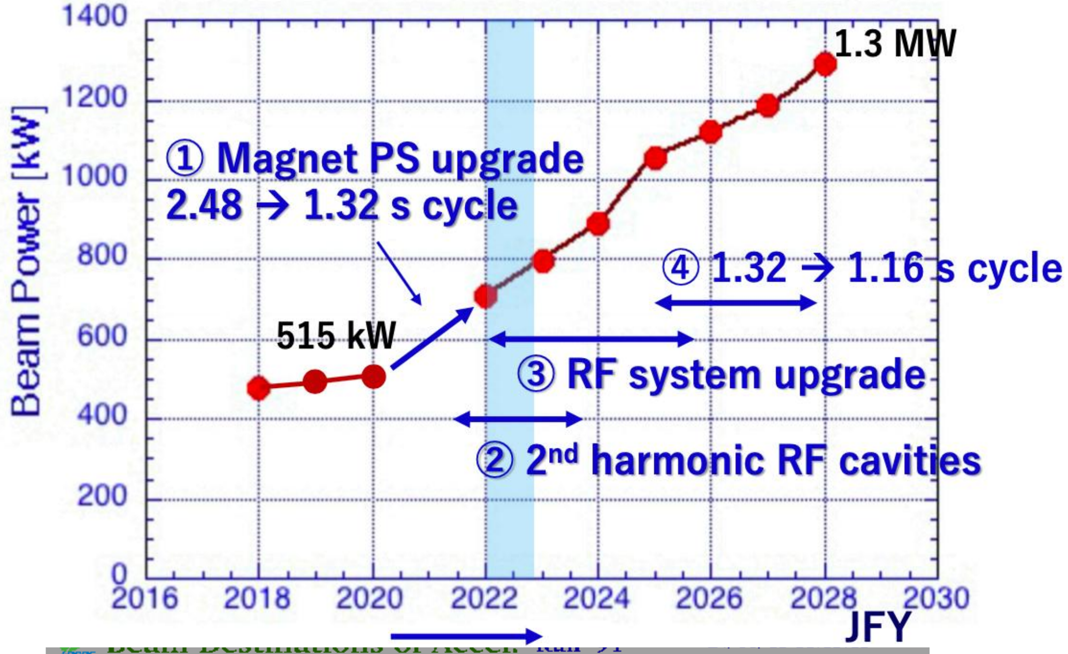


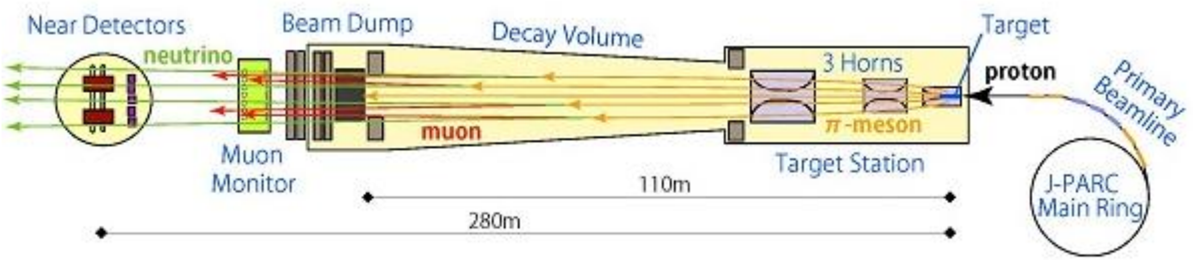
Outer detector: 3" PMT attached to wavelength shifting plate to veto cosmic-ray muons.

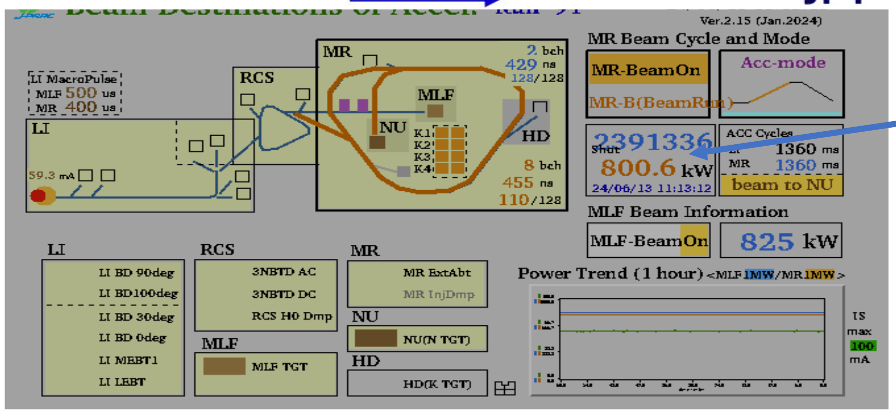
HK 20" PMTs: twice better performance (photodetection efficiency, charge and time resolutions) than SK PMTs; confirmed with 136 installed in the SK during 2018 refurbishment; data for long term stability tests in real HK conditions.

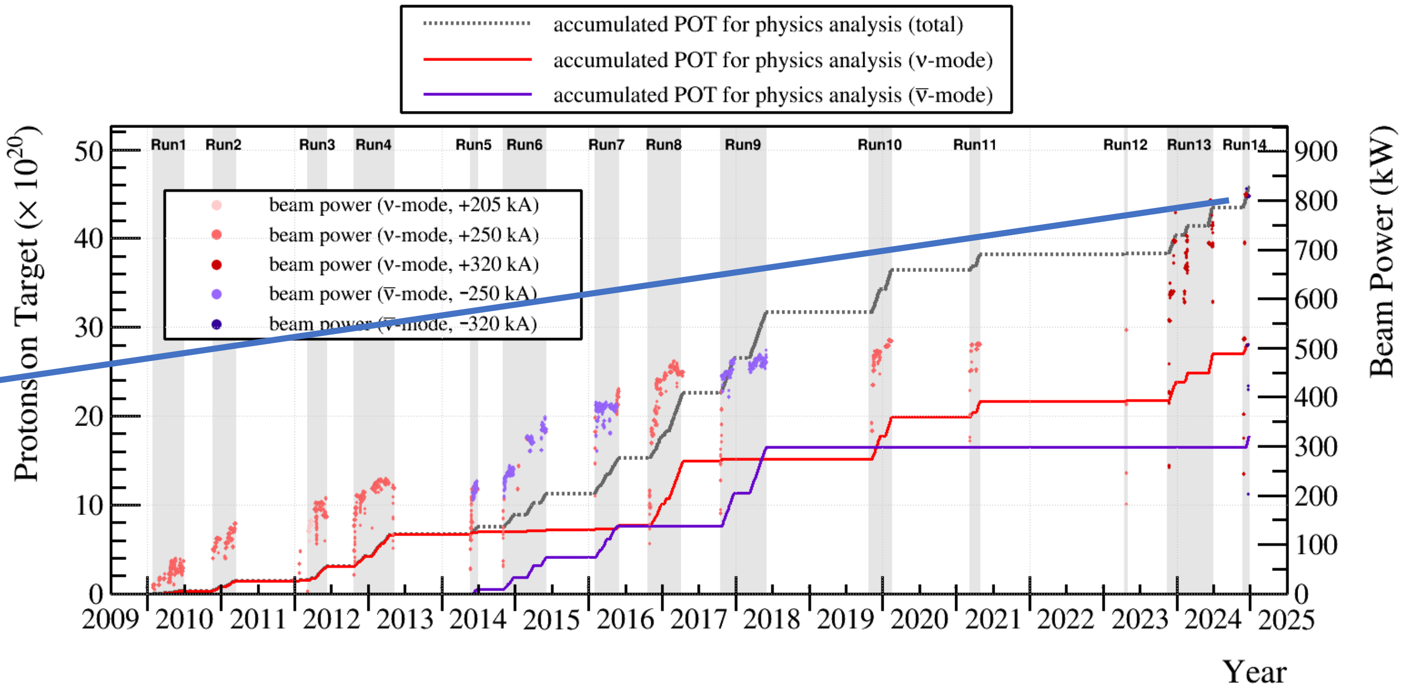
Upgrade of J-PARC proton beam intensity

- Continuous increase: from 0.5 MW (2019) to 1.3 MW (2028); already 0.8 MW in 2024.
- Cycle time: 2.48 s → 1.16 s; protons per pulse: $2.6 \times 10^{14} \rightarrow 3.3 \times 10^{14}$; beam optics improvement.
- J-PARC neutrino beam will be used by T2K until the start of HK.





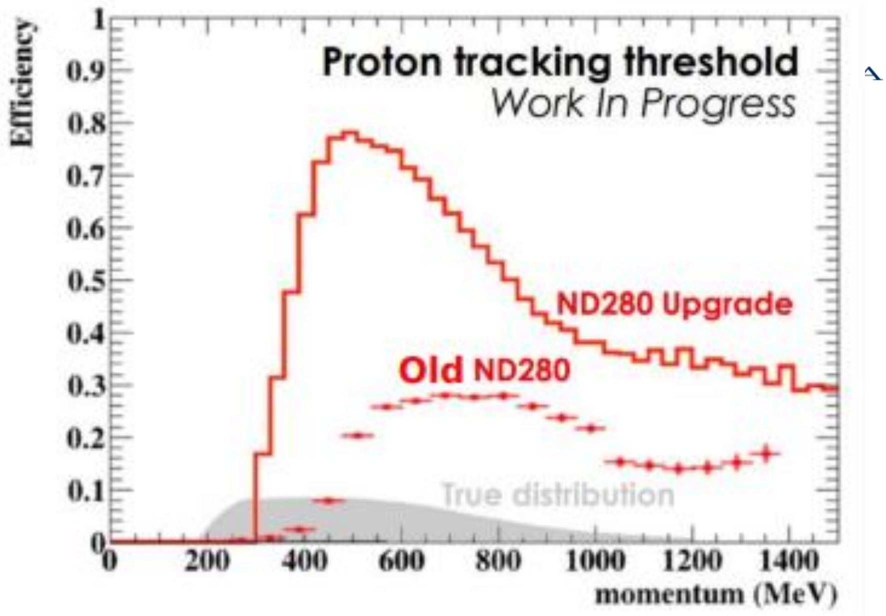




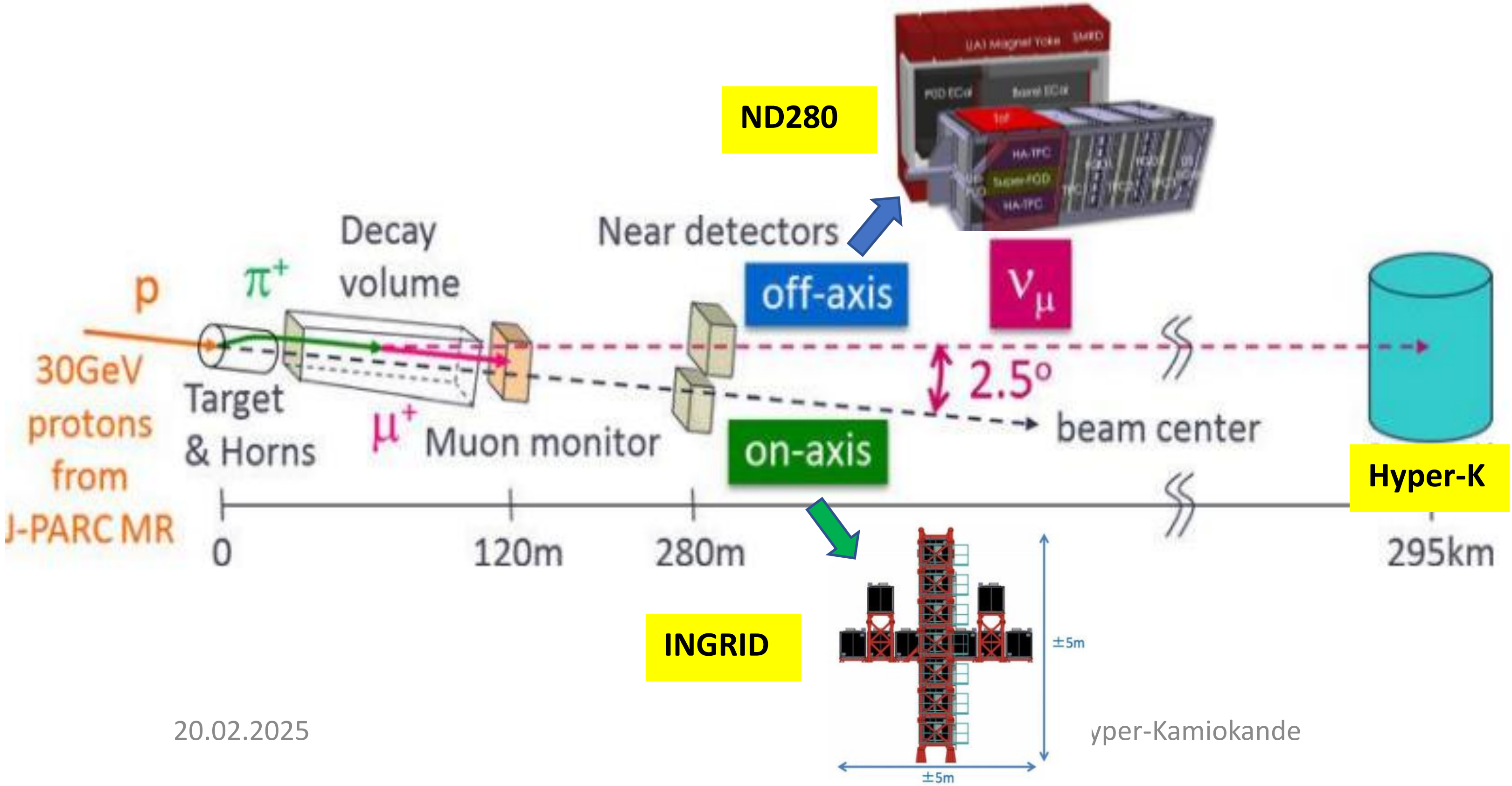
The near detectors at 280m

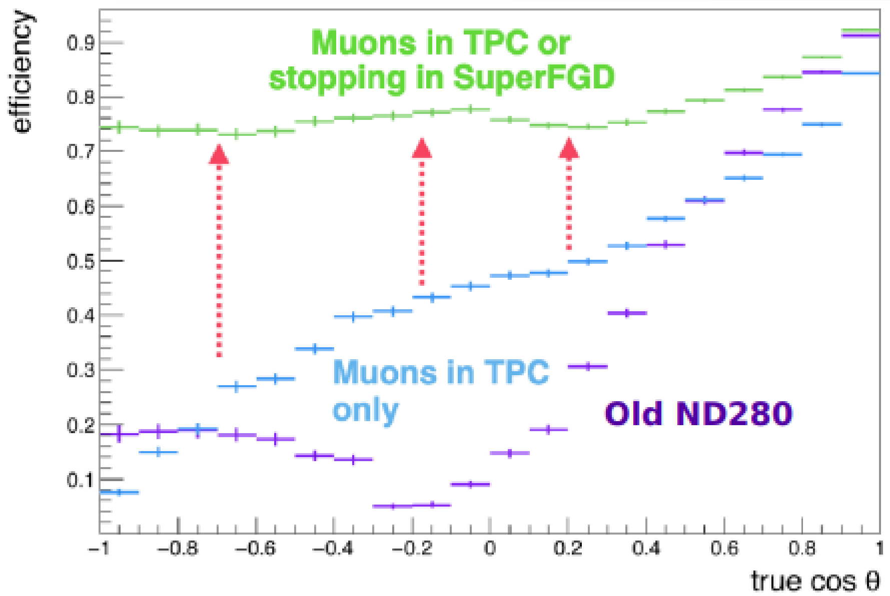
Near detectors: used to understand neutrino beam/interactions (before oscillations) and control systematics.

- 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

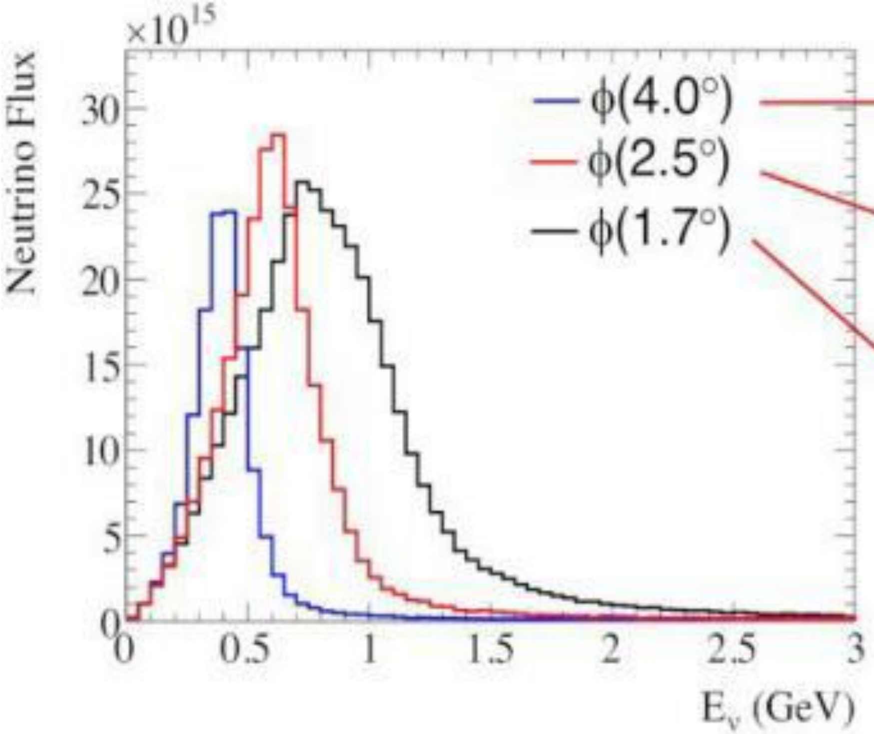


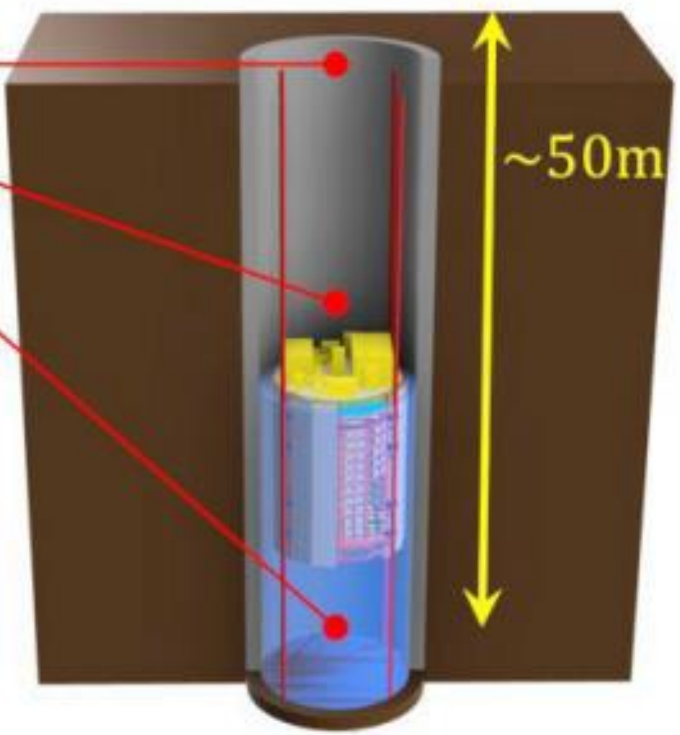


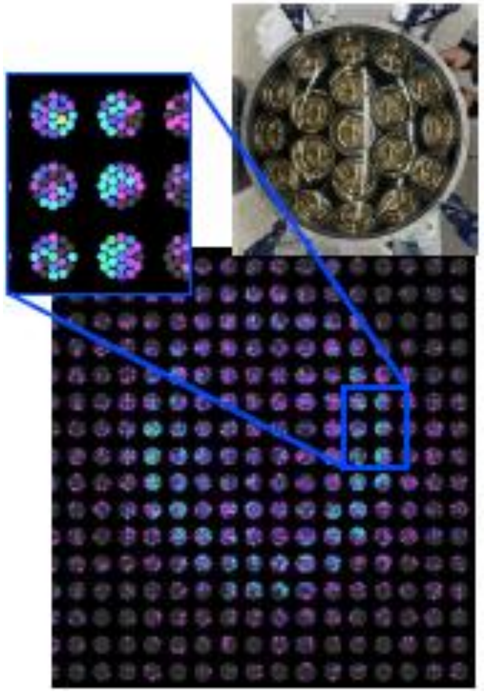
Muon angular acceptance: improved

Intermediate Water Cherenkov Detector

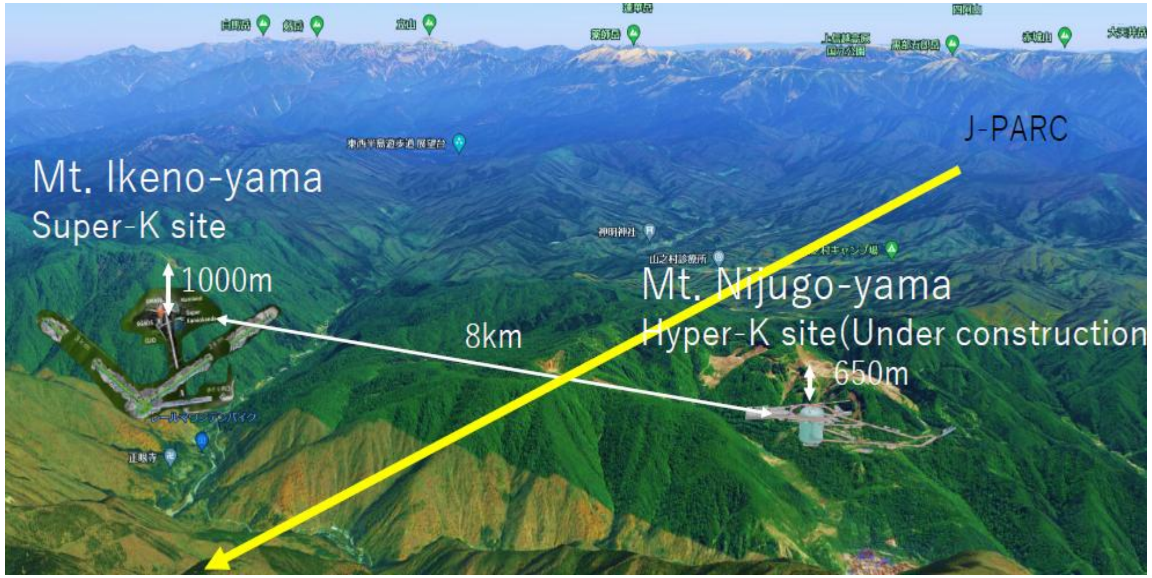
- Measurement of $\frac{\sigma(\nu_e)}{\sigma(\nu_\mu)} / \frac{\sigma(\overline{\nu_e})}{\sigma(\overline{\nu_\mu})}$ with ~3% accuracy at 600 MeV to improve δ_{CP} sensitivity significantly. Oscillated neutrino energy spectrum at HK will differ from that at IWCD.
- A linear combination of the results 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, 830m away from the beam source. Facility construction (pit excavation) starts summer 2025.

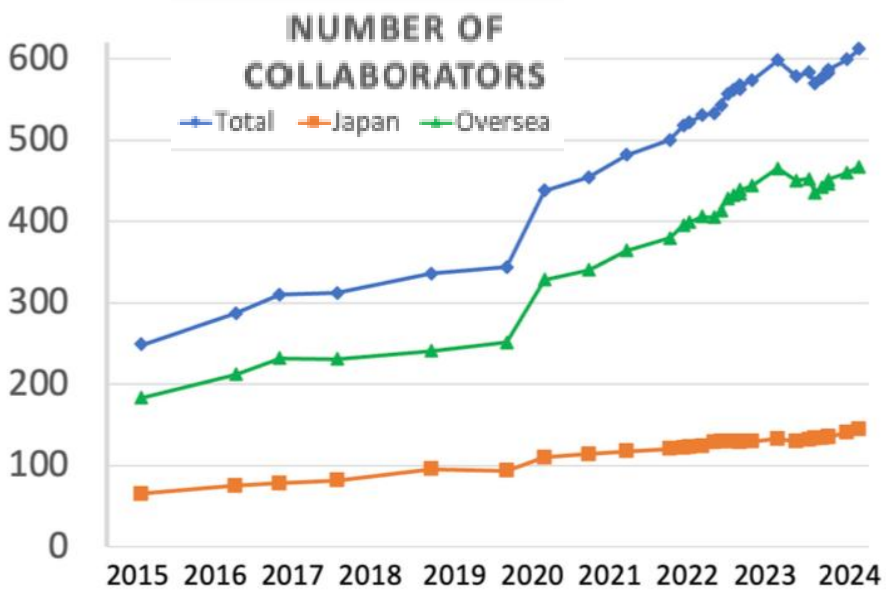






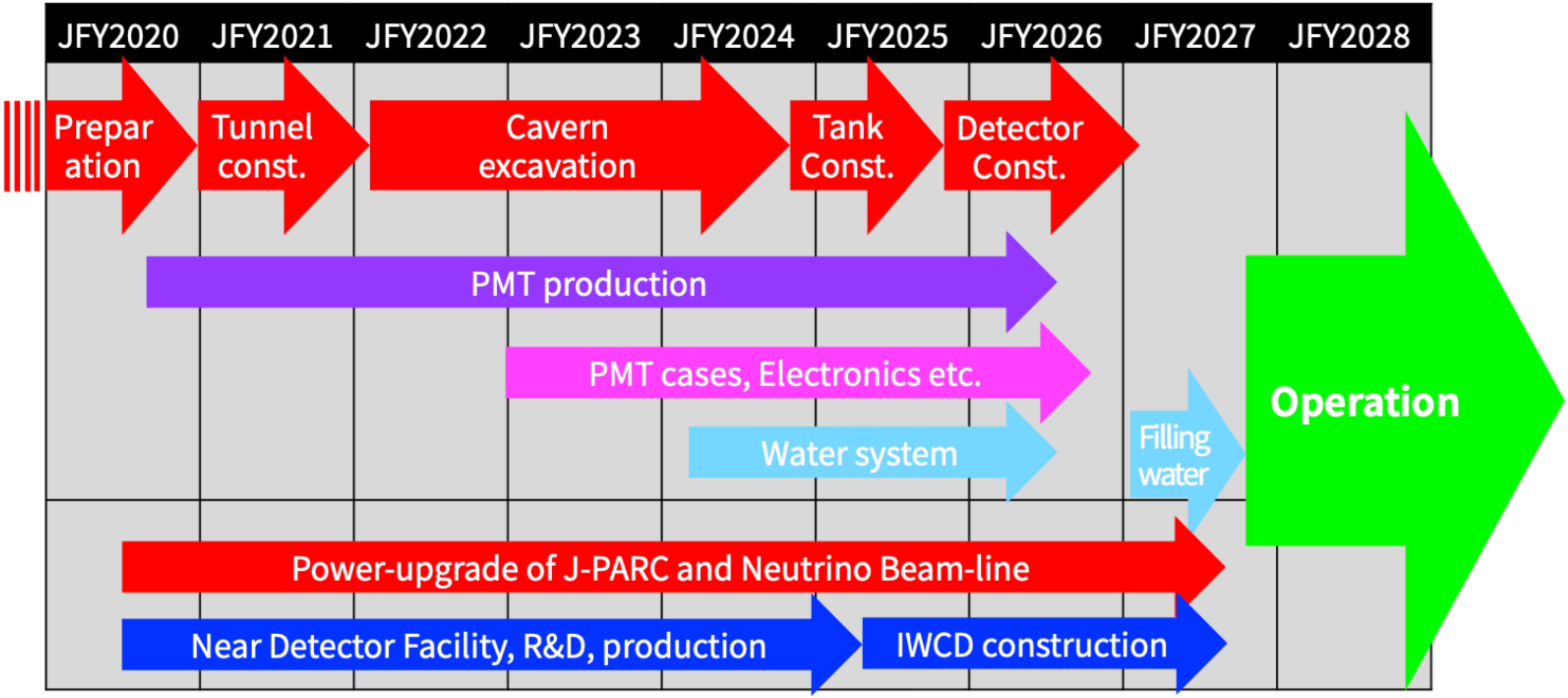
Hyper-Kamiokande collaboration





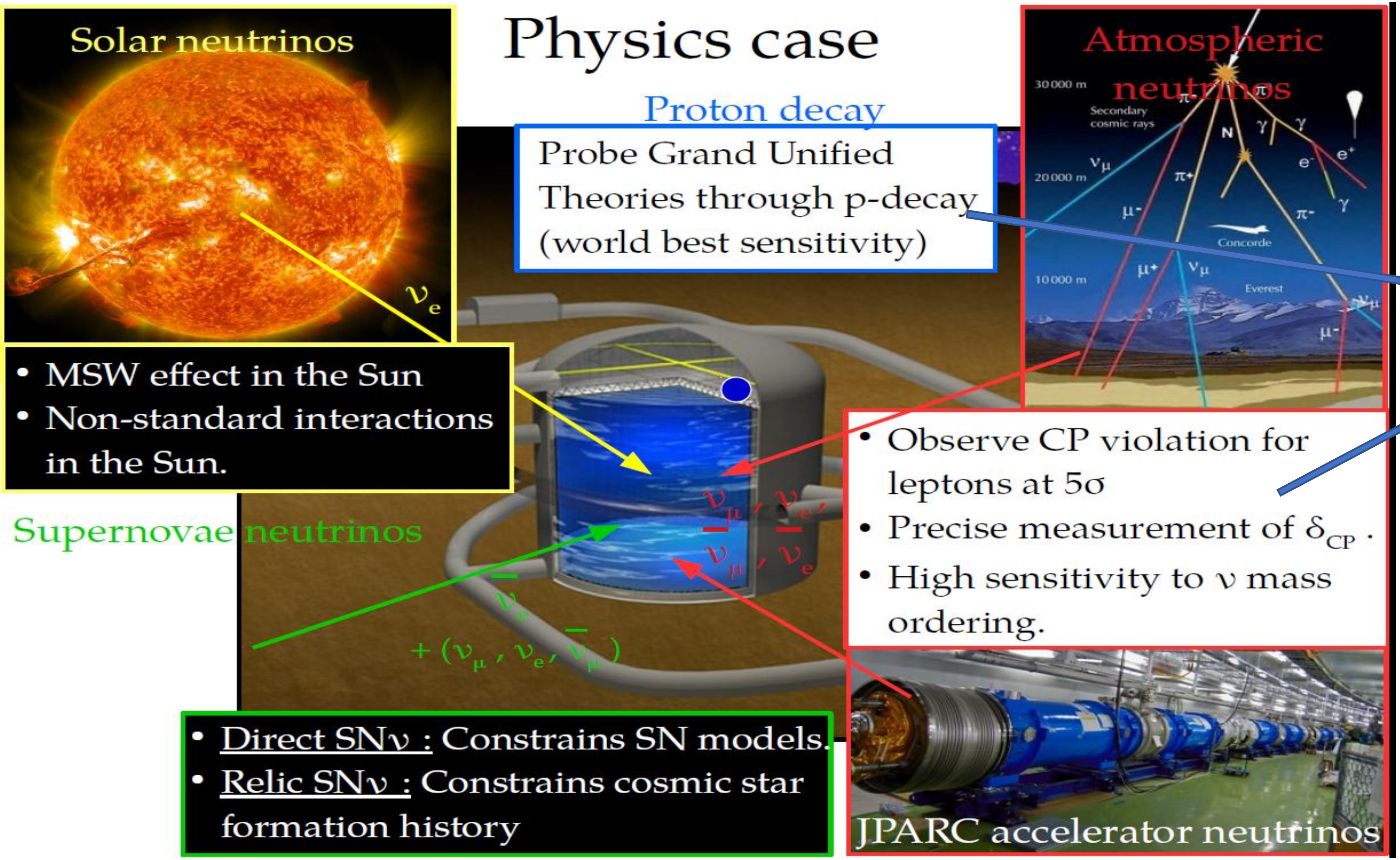
- 6 continents, 22 countries, 106 institutions, ~650 people as of December 2024; ~75% non-Japanese; continuously growing.
- Far detector: Univ. of Tokyo.
- Beam and near detectors: KEK/J-PARC.
- Strong Polish contribution, >30 members;
  - NCBJ,
  - UW,
  - WUT,
  - CAMK,
  - UWr,
  - AGH,
  - UJ,
  - IFJ PAN,
  - UŚ.

Hyper-Kamiokande: schedule



- Construction phase extended (6 months) due to the changes of the structure of the detector top.
- May 2027: start of the water filling.
- December 2027: start of the detector operation.

Hyper-Kamiokande: physics program



(this talk)

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

Oscillation of 3ν flavors: known & unknown

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

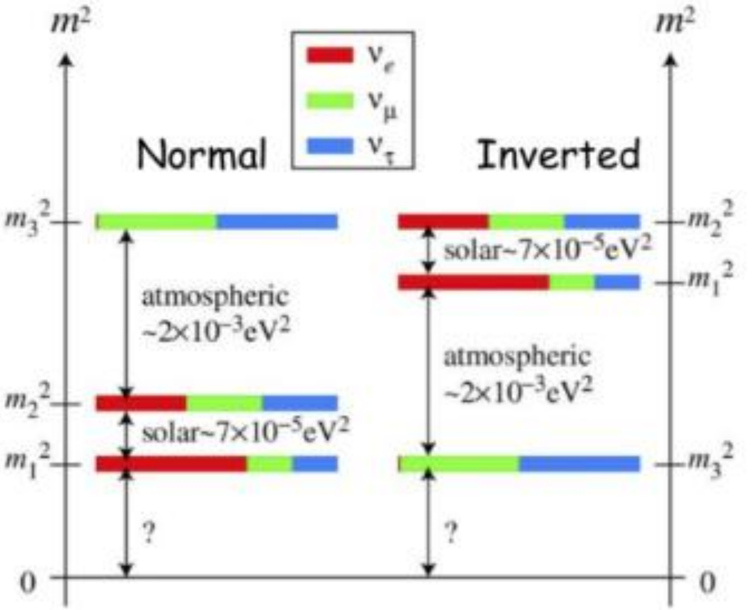
$\Delta m^2_{32} = 2.455 \pm 0.028 \times 10^{-3} eV^2$

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

Inverted mass ordering

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

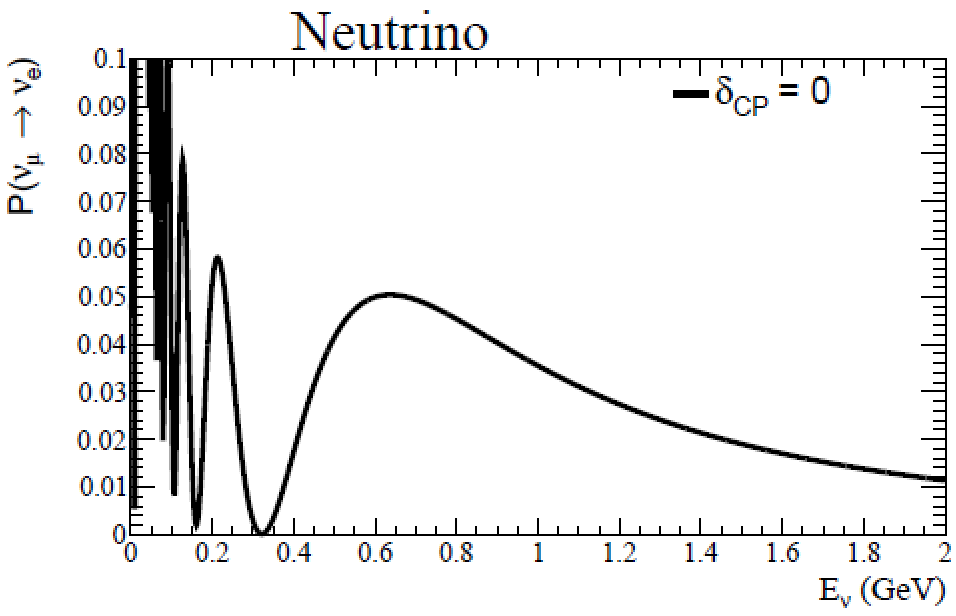
$sin^2\theta_{23} = 0.553^{+0.016}_{-0.024}$

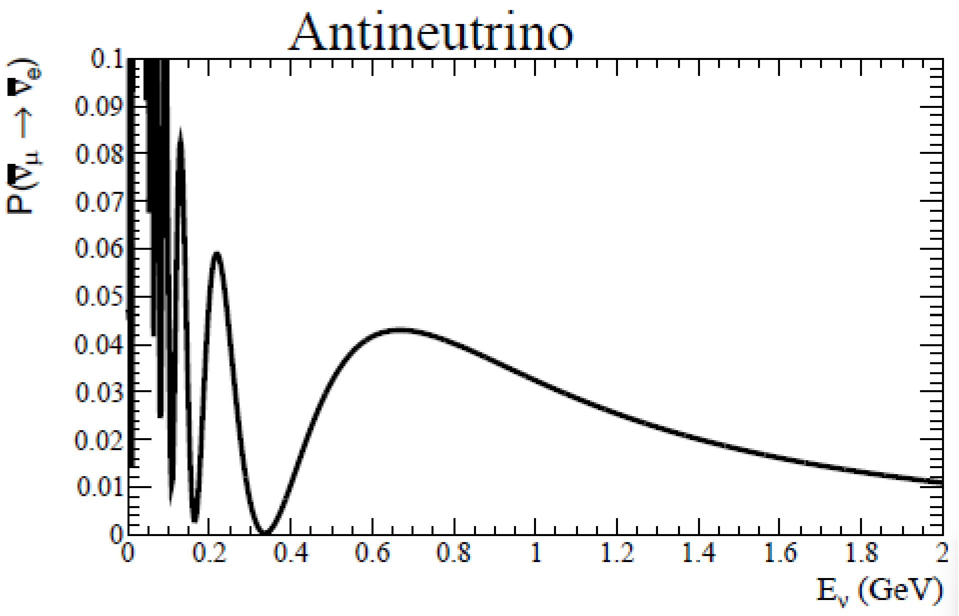


Open questions:

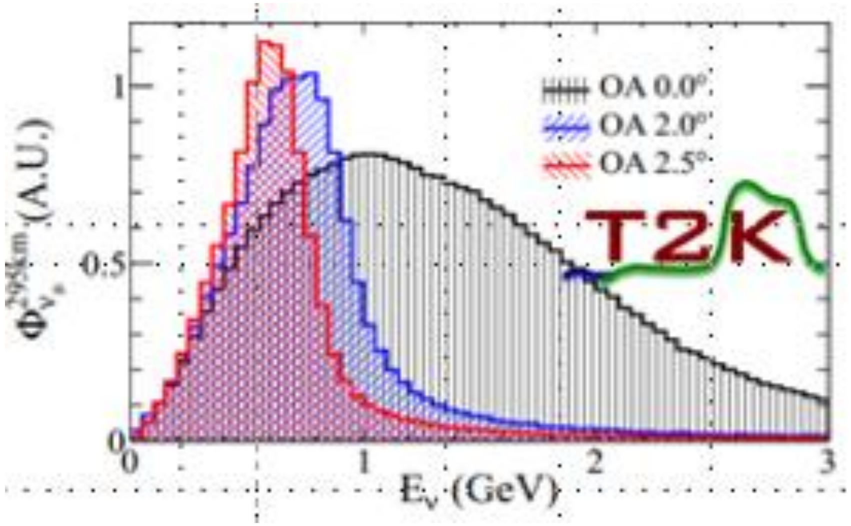
- **CPV (δ_{CP} phase, difference in $\nu_\mu/\overline{\nu_\mu}$ oscillations)**
- **mass ordering**
- **Θ_{23} > 45° or Θ_{23} < 45° or Θ_{23} = 45°**

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

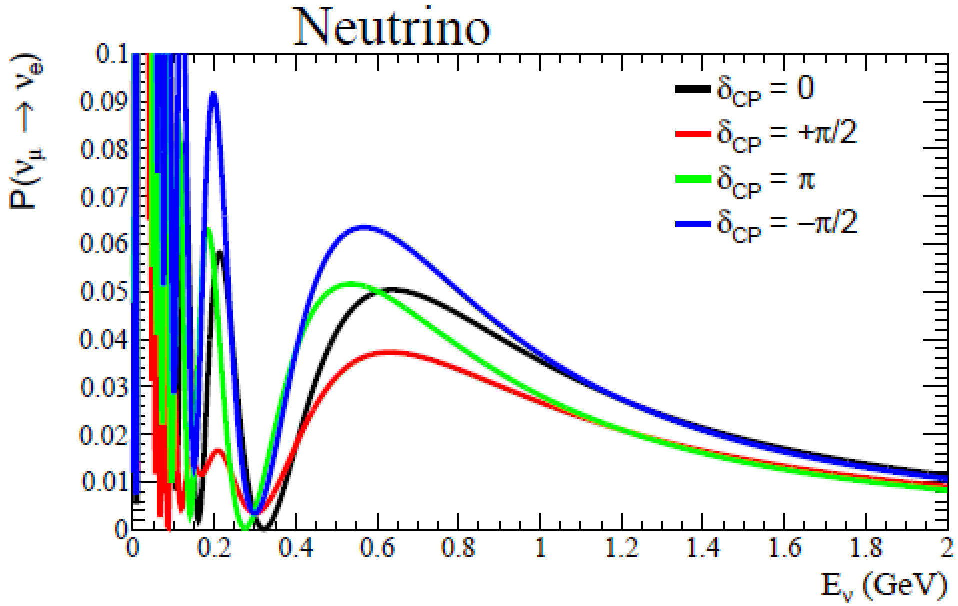


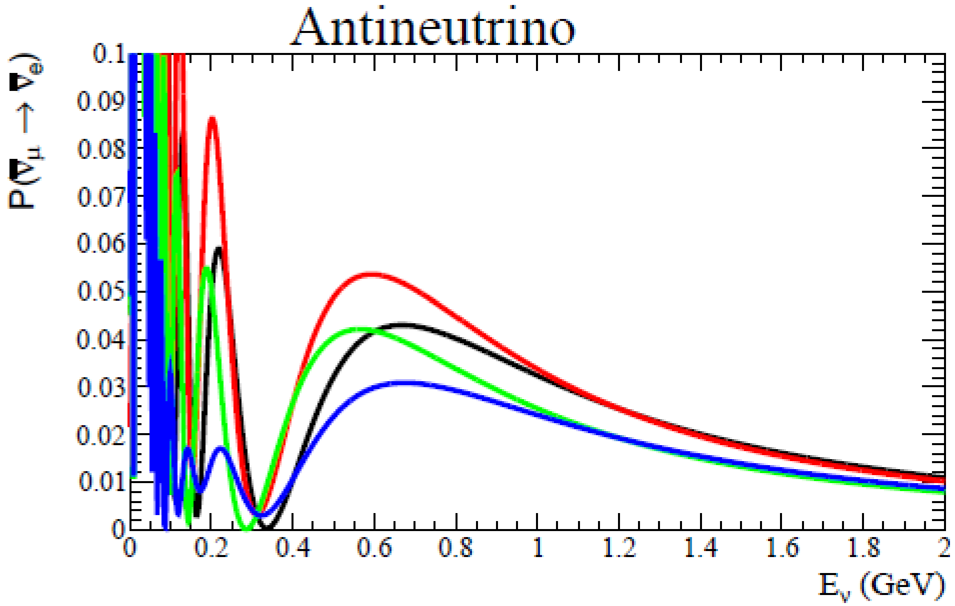


- J-PARC neutrino and antineutrino off-axis beam fluxes peak at ~ 0.6 GeV, currently used by T2K; from 2027 by Hyper-K.



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

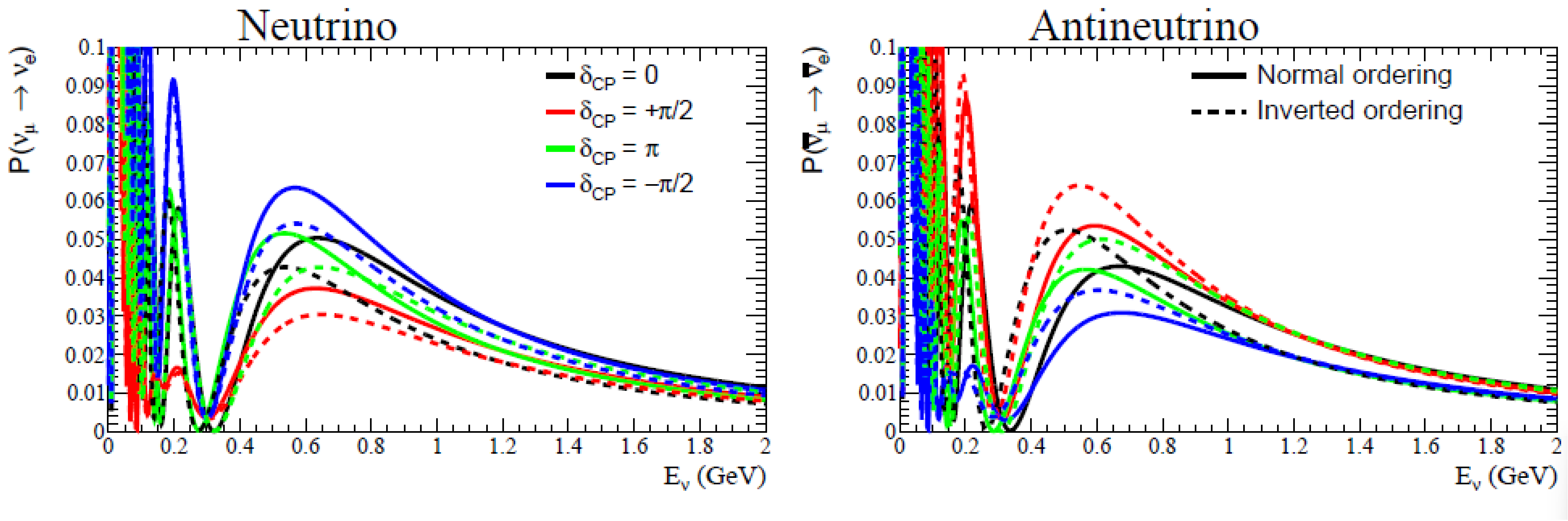




- J-PARC neutrino and antineutrino beam fluxes peak at ~ 0.6 GeV
- For $\delta_{CP} = -\pi/2$: $\nu_e(\overline{\nu_e})$ appearance enhanced (suppressed)
- Expected number of events (10 years, $\delta_{CP} = 0^\circ, \nu : \overline{\nu} = 1{:}3;\ 2.7 \times 10^{22} POT$):

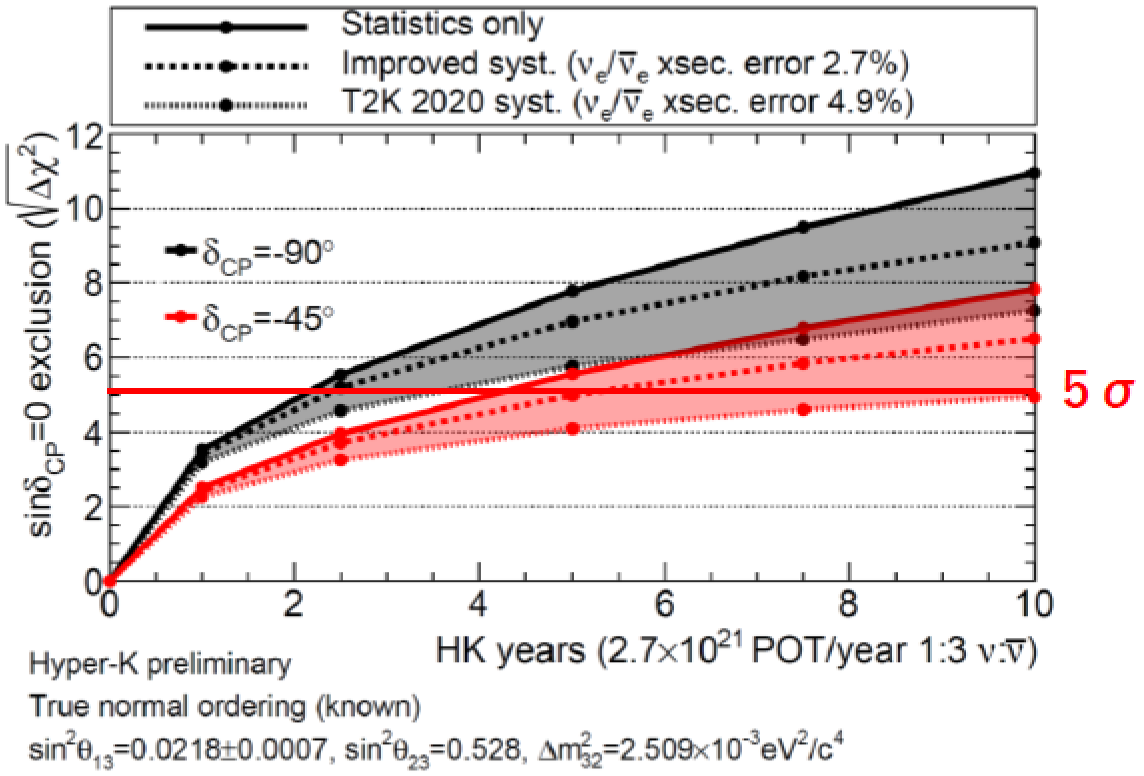
Neutrino beam; μ-like ring	~8800
Antineutrino beam; μ-like ring	~12000
Neutrino beam; e-like ring	~2100
Antineutrino beam; e-like ring	~1800

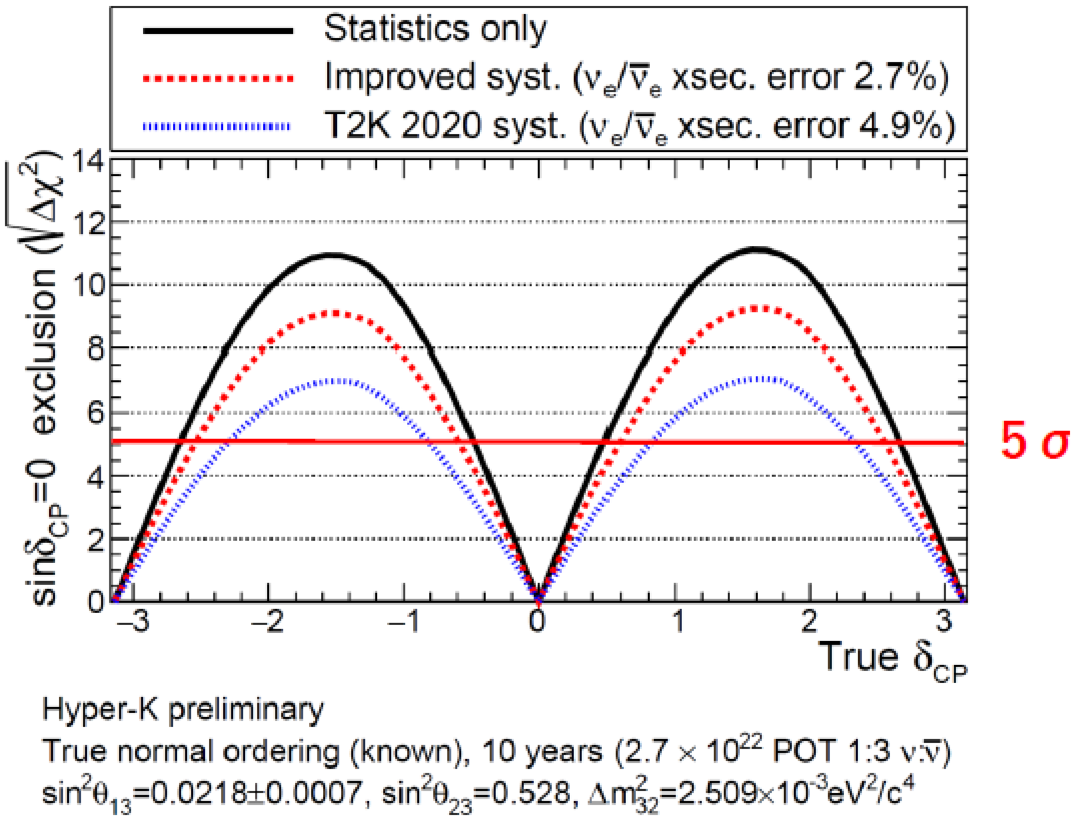
HK: $\nu_e(\overline{\nu_e})$ appearance probabilities, 295 km



- J-PARC neutrino and antineutrino beam fluxes peaks at ~ 0.6 GeV
- 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 (later in this talk)
- First hint for CPV from T2K exp. (Nature 580 (2020) 339, https://doi.org/10.1038/s41586-020-2177-0)

HK: CP violation phase sensitivity





- CPV discovery (5σ) in 10 years, with known MO for ~60% depending of the δ_{CP} true value.
- δ_{CP} resolutions: $20°\ if\ \delta_{CP} = -\frac{\pi}{2}; 6°\ if\ \delta_{CP} = 0°$
- If NO and $\delta_{CP} = -\frac{\pi}{2}$: exclusion of CP conservation in 3-5 years, depending on systematics.

So far, known mass ordering assumed. If unknown – degeneracies degrade δ_{CP} sensitivity, which can be resolved with atmospheric neutrinos (next slide).

Atmospheric/beam neutrino oscillations

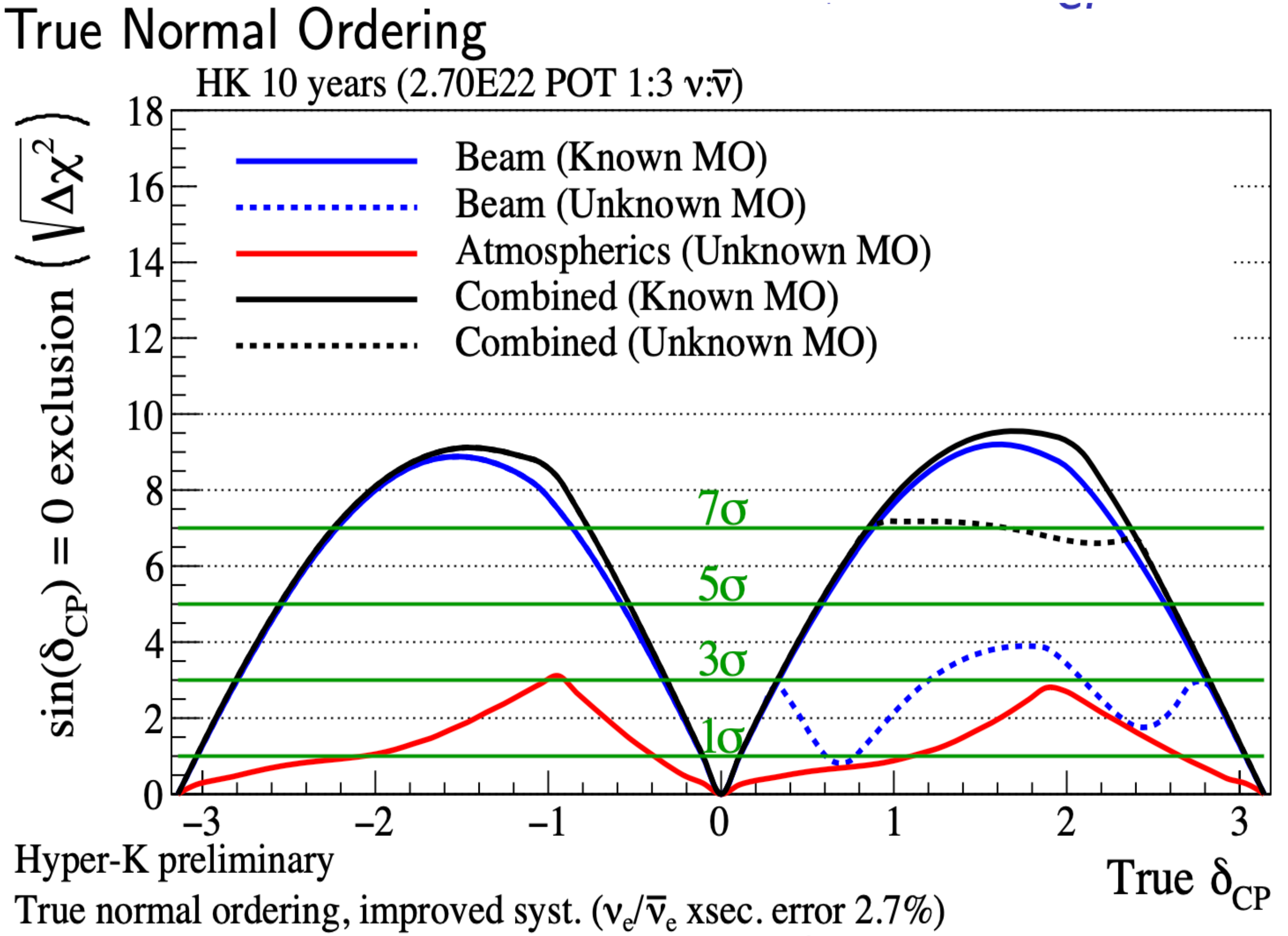
- Atmospheric neutrinos: wide energy range (0.1-10^3 GeV) & long baseline (10-13000 km) → sensitivity to matter ordering
- Atmospheric neutrinos while penetrating Earth are affected by the mass effect which is sensitive to the neutrino mass ordering:

  Normal ordering: $\nu_\mu \rightarrow \nu_e$ is enhanced

  Inverted ordering: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ is enhanced
- Comparison between neutrino and anti-neutrino oscillation can help to resolve neutrino mass hierarchy.

	$\sin^2\theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	2.2 σ →	3.8 σ
	0.60	4.9 σ →	6.2 σ
θ_{23} octant	0.45	2.2 σ →	6.2 σ
	0.55	1.6 σ →	3.6 σ

10 years with 1.3MW, normal mass ordering is assumed



Hyper-K preliminary

True normal ordering, improved syst. ($\nu_e/\bar{\nu}_e$ xsec. error 2.7%)

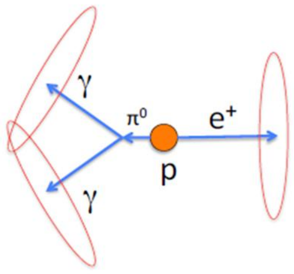
$\sin^2(\theta_{13})=0.0218$ $\sin^2(\theta_{23})=0.528$ $|\Delta m^2_{32}|= 2.509 \times 10^{-3}$ eV^2/c^4

Mass ordering and octant: 4 – 6σ (10 years)

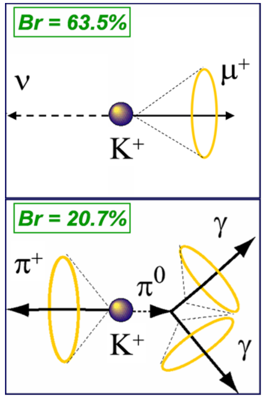
More about atm/beam joint fit in M. Posiadała-Zezula talk.

HK: search for proton decay

Proton (nucleon) decay is predicted by many Grand Unified Theories.

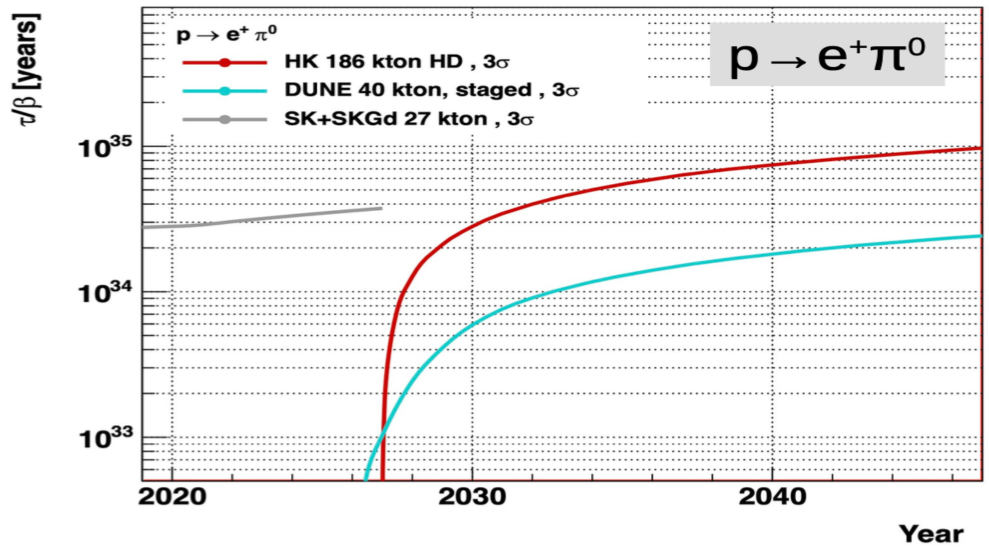


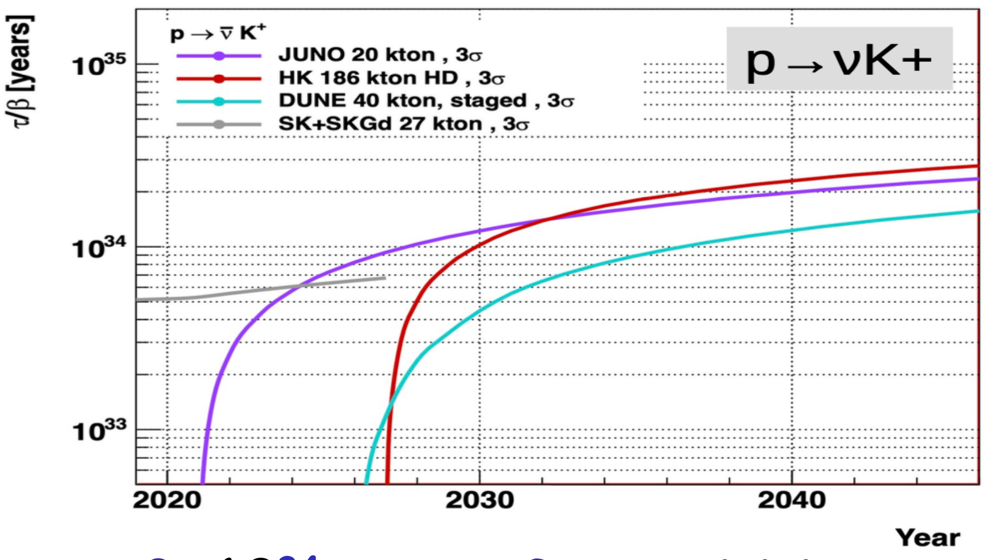
- Back-to-back EM showers, final state fully reconstructed.
- Compelling evidence: invariant proton mass.
- Efficiency of ~45%, dominated by nuclear absorption of π^0.



K^+ is below Cherenkov threshold (not visible)
K^+ identified/reconstructed via its decays:

- $K^+ \rightarrow \mu^+ + \nu$ (BR=64%): monochromatic (236 MeV) muon.
- or search for $K^+ \rightarrow \pi^0\pi^+$ decay (BR=21%): π^0 momentum ~ 205 MeV/c and opposite to π^+.





~6×10^{34} years: 3σ sensitivity, 10 years

~2×10^{34} years: 3σ sensitivity, 10 years

HK: Polish involvement

- NCBJ, CAMK, WUT, UW, IFJ PAN, UJ, AGH, UWr, UŚ
- Design and construction of multi-PMT for the far (HK) and intermediate detector (IWCD)
- Design of data concentration modules and low-voltage power supply modules for underwater electronics
- Design, production and installation of electron linear accelerator, with the deployment and beam steering systems
- WCTE (Water Cherenkov Test Experiment at CERN) – 40 ton detector as a test for HK technologies: construction, tests, installation of multiPMTs, DAQ, front-end electronics, participation in the detector installation, calibration, data taking and analysis
- Work on neutrino interaction models with implementation in the NuWro event generator
- Cosmic and beam-related backgrounds simulation
- Participation in large-scale Monte Carlo samples production
- Participation in 20" PMT quality checks
- Development of analysis/software tools for oscillation/cross section studies with HK data
- Project management: EB membership, chairs of Electronic group and Speakers Board, Publication Board membership

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, atmospheric, supernova, relic, …), including proton decay searches.
- Construction started 2020 is ongoing; beginning of operation in 2027.

HK: sensitivities at a glance

Physics	Parameter	Sensitivity
J-PARC beam neutrinos (1.3 MW; 10 years)	δ_{CP}	7º - 20º
	CPV coverage: 3σ (5σ)	76% (58%)
	$sin^2\theta_{23}$ (uncertainty for 0.5)	± 0.017
J-PARC beam neutrinos + atmospheric (10 years)	Mass ordering	>3.8σ
	Octant determination, 3σ	$\lvert\theta_{23} - 45°\rvert > 2°$
Solar neutrinos (10 years)	Day/Night: from 0 (from KL)	$8\sigma\ (4\sigma)$
	Upturn	$> 3\sigma$
Supernova neutrinos	10 kpc burst	54k – 90k events
	Relic neutrinos	$\sim$70 in 10 years
Proton decay (20 years)	Lifetime (3σ): $e^+\pi^0$	$1 \times 10^{35}\ years$
	Lifetime (3σ): νK^+	$3 \times 10^{34}\ years$