The Hyper-Kamiokande Experiment Status and Prospect

Umut KOSE
On behalf of the Hyper-Kamiokande Collaboration

The 17th International Workshop on Tau Lepton Physics
TAU2023, 04-08 December 2023

Evolution of Kamiokande

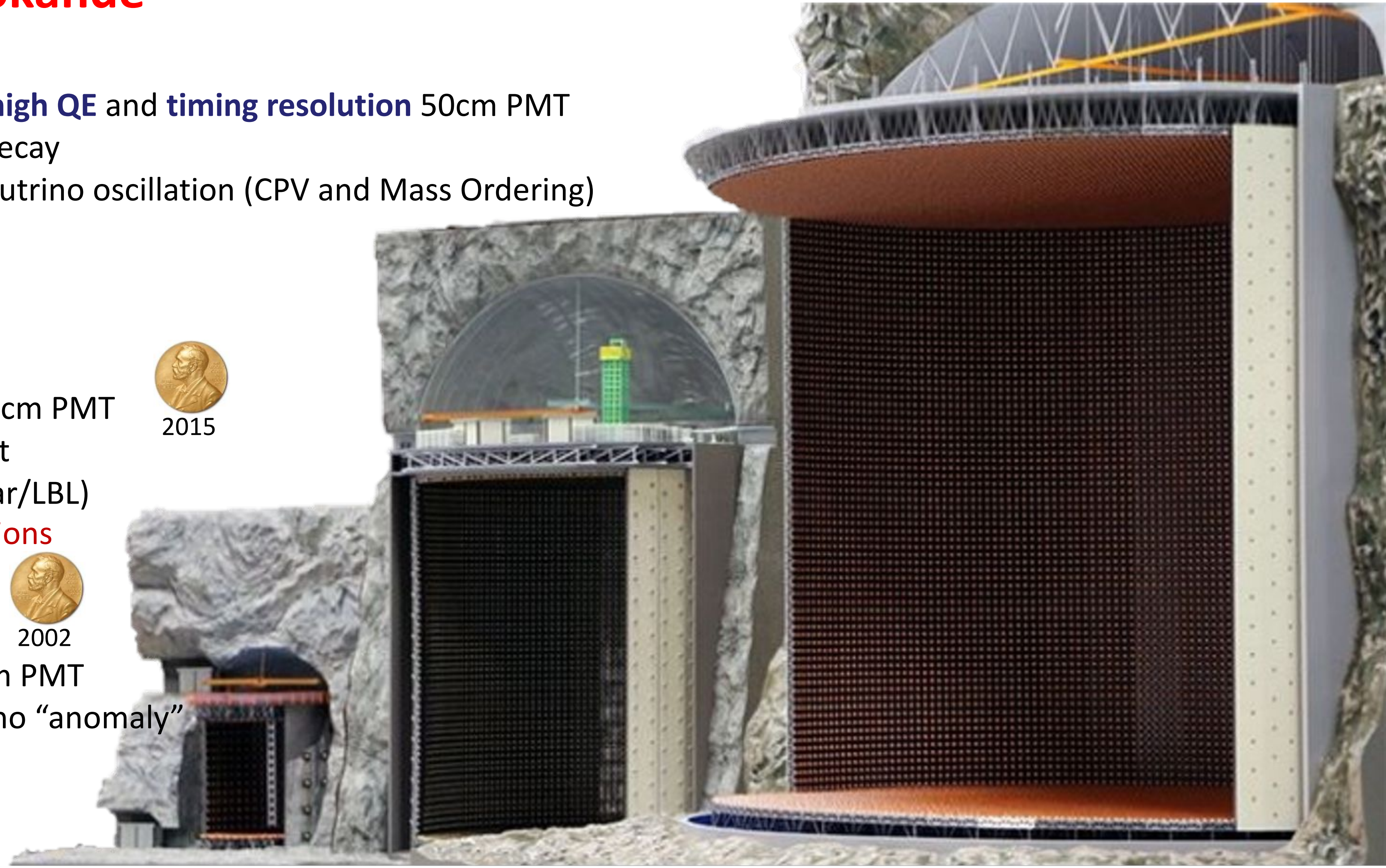
Hyper-Kamiokande (2027 -)
258 kton, **40% coverage** w/ **high QE** and **timing resolution** 50cm PMT
Extended search for proton decay
Precision measurement of neutrino oscillation (CPV and Mass Ordering)
Neutrino Astrophysics
Explore new physics

Super-Kamiokande (1996 -)
50 kton, 40% coverage w/ 50cm PMT
Proton decay: world best-limit
Neutrino oscillation (atm/solar/LBL)
Discovery of neutrino oscillations

2015

2002

Kamiokande (1983-1996)
3 kton, 20% coverage w/ 50cm PMT
Atmospheric and solar neutrino “anomaly”
Supernova 1987A
Birth of neutrino astrophysics



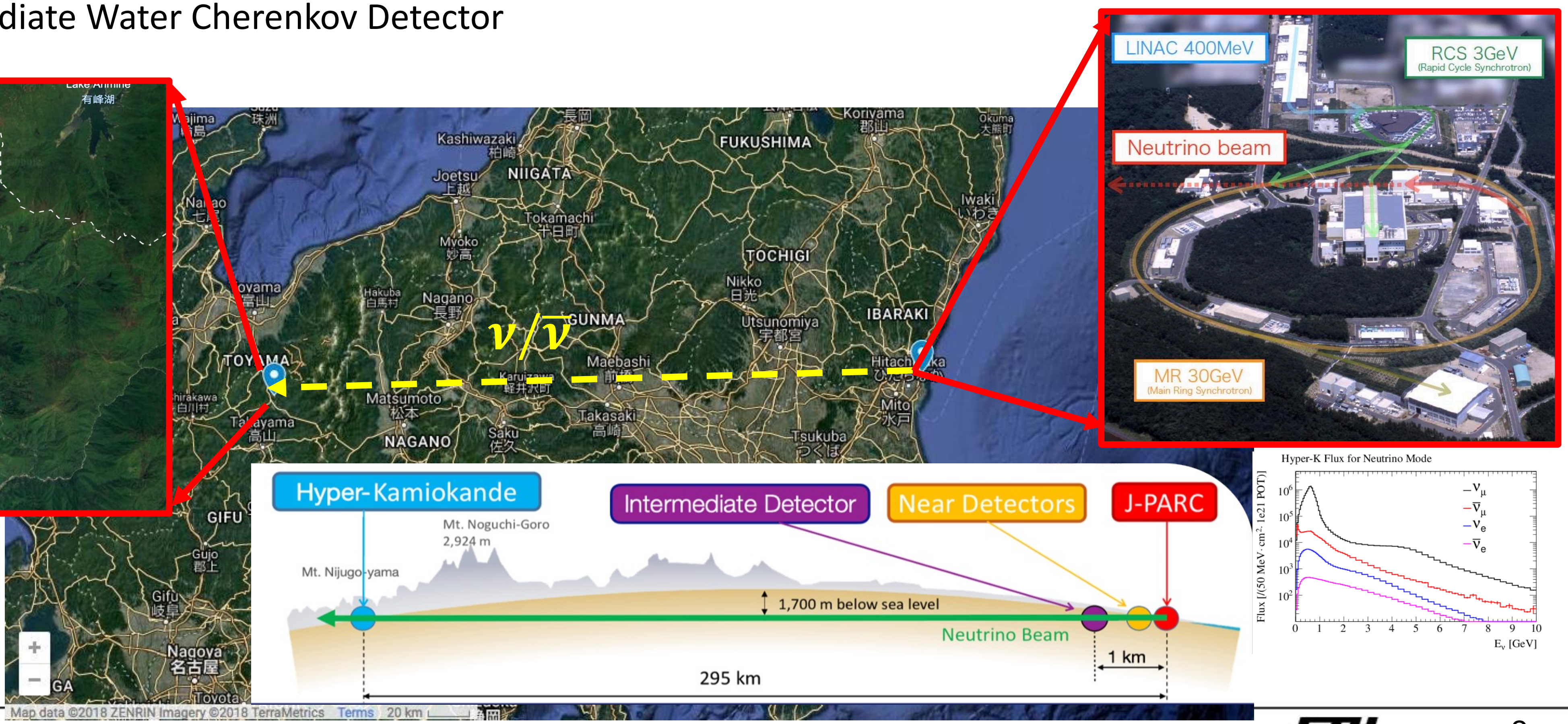
https://www-sk.icrr.u-tokyo.ac.jp/en/

The Hyper-Kamiokande Project

- Including a neutrino beam, near detector complex and far detector
- Constructing Hyper-Kamiokande far detector at Kamioka
  - 8 km south of Super-Kamiokande
  - 295 km from J-PARC and 2.5° off-axis
  - 600 m rock overburden
- Constructing intermediate Water Cherenkov Detector

Upgrading J-PARC neutrino beam:

- Power from 515 kW to **1.3 MW**
- Horn current from 250 kA to **320 kA**
- cycle 2.48 s to 1.32 s and finally to 1.16 s
- **ν : $\bar{\nu}$ mode → 1:3**



arXiv:1805.04163

Near Detectors

- Existing near detectors complex located at 280 m from target: **constrain flux and neutrino interaction model uncertainity and measure event rates before oscillation takes place**

- On-axis detector: measure beam direction with <0.25 mrad accuracy, monitor event rate to ensure stable beam operation

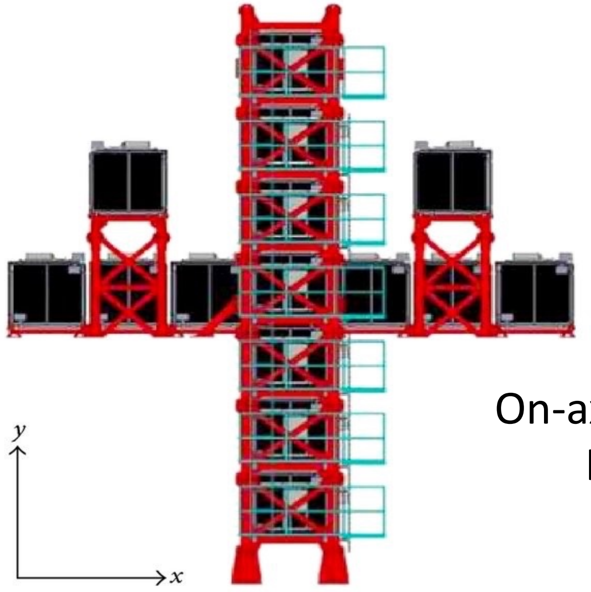
- Off-axis magnetized tracker:

ND280 off-axis detector upgraded by replacing pi0 detectorby three new subdetectors. **SuperFGD**, fine grained, fully active PS detector (2M 1x1x1 cm^3 cubes) , **High-Angle TPCs** and **Time of Flight planes** installed inside UA1 magnet

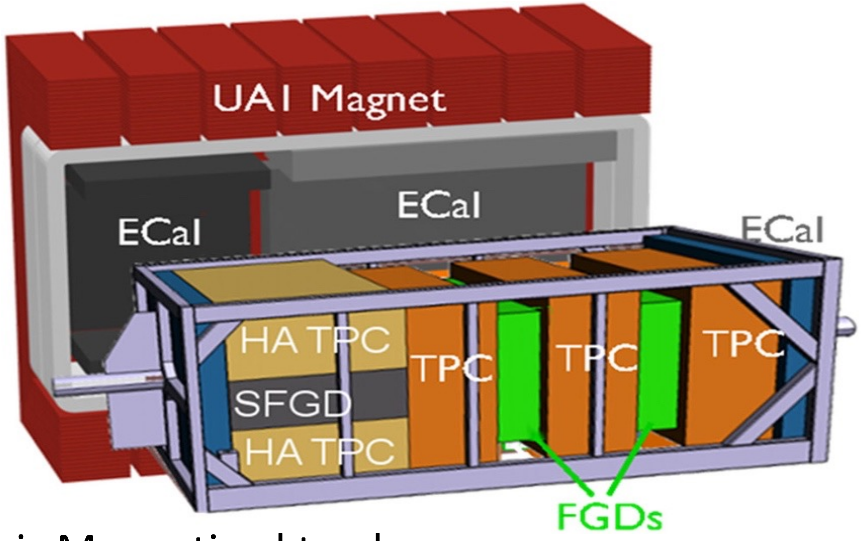
→ SuperFGD improves capability to reconstruct low-energy particles and neutrons

→ the improve the angular acceptance

→ **charge separation, measurement of wrong-sign background, study of recoil system, constrain predictions for far detector**



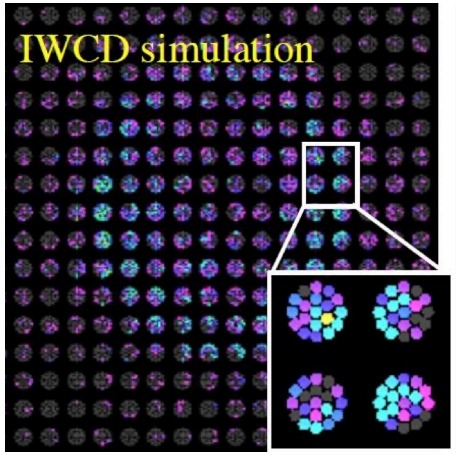
On-axis detector
INGRID

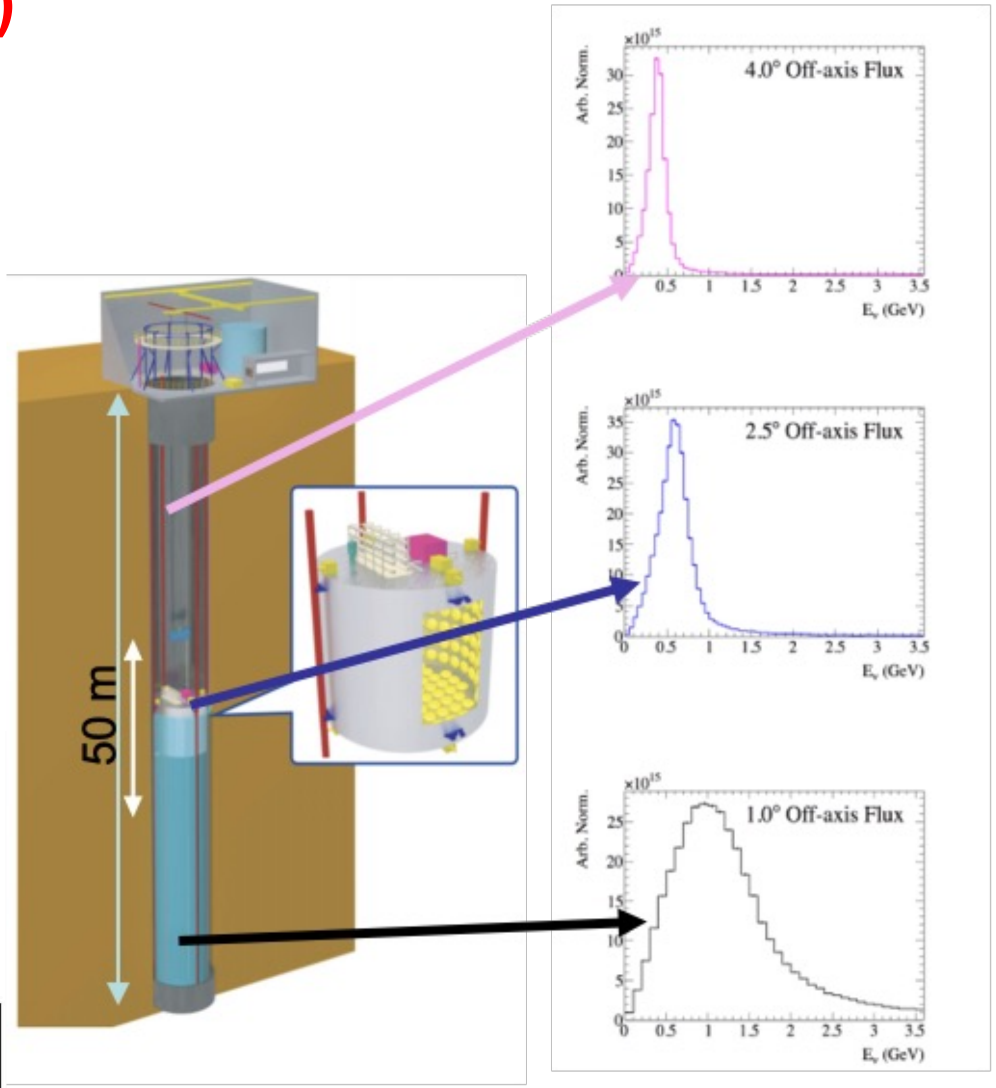


Off-axis Magnetized tracker
Super-FGD → Upgrade for HK

Intermediate Water Cherenkov Detector (IWCD)

- About **1 kton water Cherenkov detector**, ~8 m diameter and ~6 m in height, located at ~1 km from target
- **Precise cross-section measurements on water**
    - **Same detection technique** and **target material** as Hyper-K
    - **Reduce highly systematic uncertainties** on ν cross-section models, detector model
- Use **PRISM approach**, moving IWCD vertically
    - Constrain flux at different off-axis angles (1 to 4 degrees)
    - Different E_ν peaks
    - Linear combinations mimic mono-energetic beam
- Instrumented with **multi-PMTs** (mPMT)
    - ~400 mPMT; 19 8 cm PMTs in a module
    - **High granularity and timing res.**



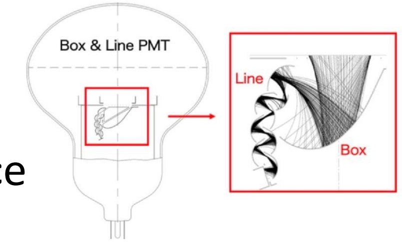


Far Detector: The Hyper-Kamiokande detector

- 71 m in height, 68 m in diameter; 258 kton of ultrapure water
- Divided into two optically separated parts using high reflectivity Tyvek sheets: the Inner Detector (ID) as the main active volume and the Outer Detector (OD), covering the ID to act as a veto against incoming particles.
- 216 kton inner detector with **fiducial volume of ~188 kton**

Inner detector:

- 64.8 m diameter, 65.8 m height.
- ~**20000 50 cm PMTs** (Box&Line PMT R12860)
  - High QE, time resolution, pressure tolerance **(x2 better than SK)**
  - dark rate reduction, low radioactivity, cover development
  - long-term performance evaluation in Super-K
- ~**800 multi-PMT modules,** increase overall light collection, providing improved timing and vertex resolutions as well as particle identification



Outer detector:

- 1 m barrel or 2m top/bottom thick.
- **3600 8 cm PMTs + WLS plates** to enhance Cherenkov photon yields.

OD-PMT + WLS plate

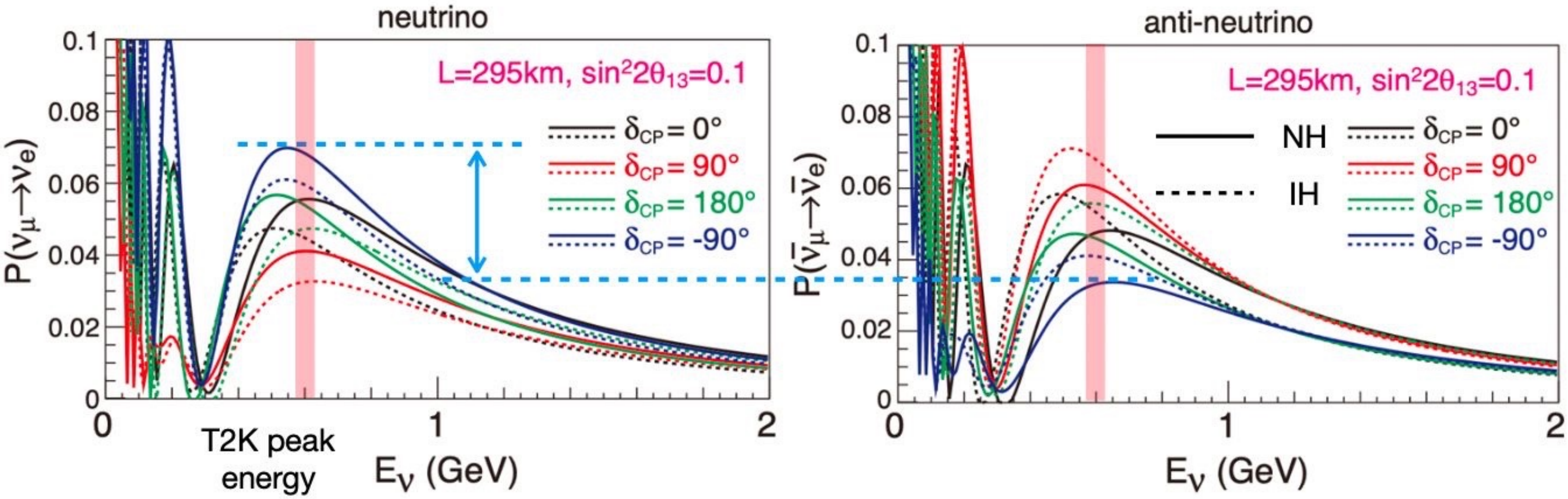
multi-PMT

Physics program 1: Oscillation measurement

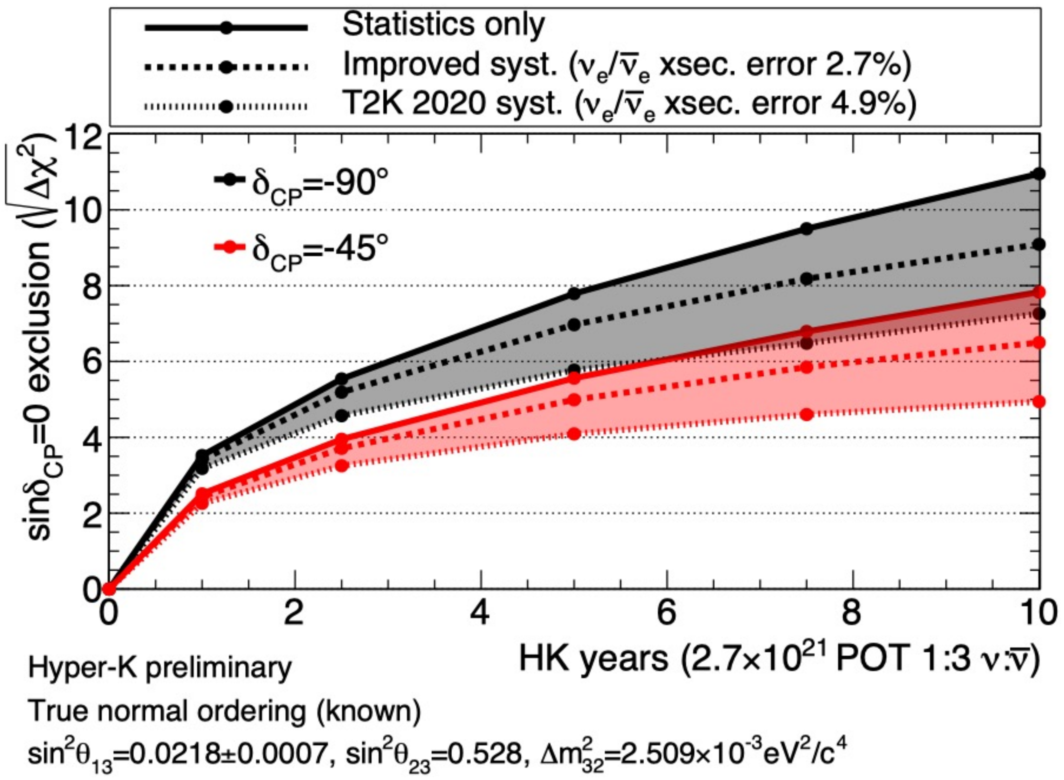
- **Measuring CP violation in neutrinos** by comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

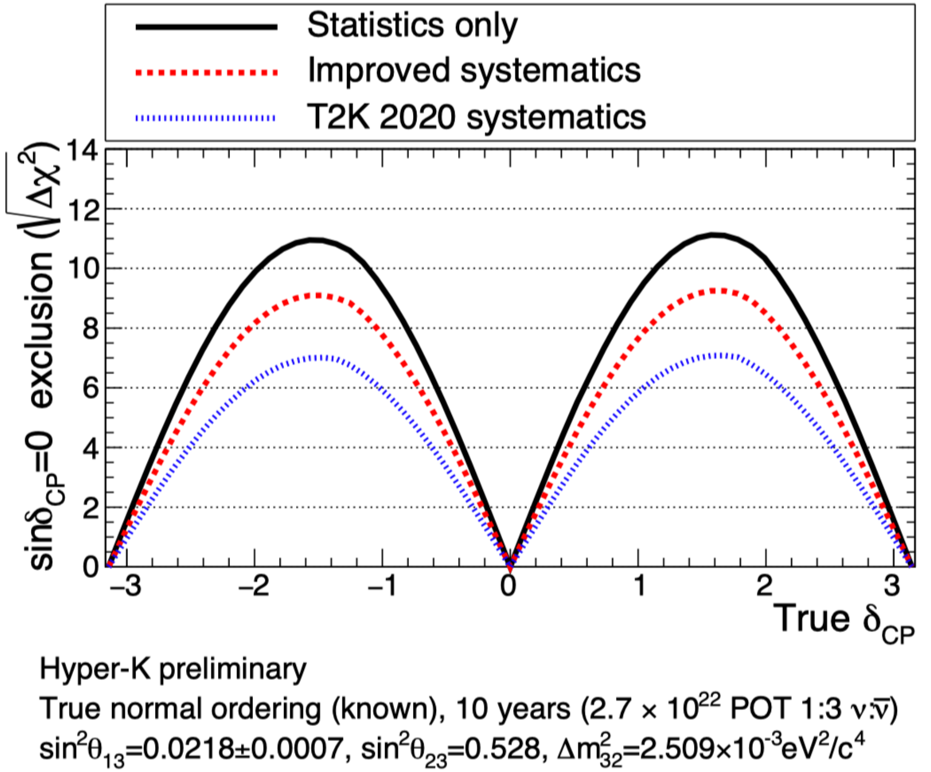
$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 4 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} sin\delta_{CP} \left[sin\left(\frac{\Delta m_{21}^2 L}{2E}\right) + sin\left(\frac{\Delta m_{23}^2 L}{2E}\right) + sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) \right]$$

- At L = 295 km, Eν ≈0.6 GeV: effect of CP violation up to 28% while matter effect only 7%
- After **10 years of operations**, expecting more than **1000 ν_e and $\bar{\nu}_e$ signal events** with few statistical uncertainty
- Near detectors very curial to constrain far detector expectation



Sensitivity on CP violation





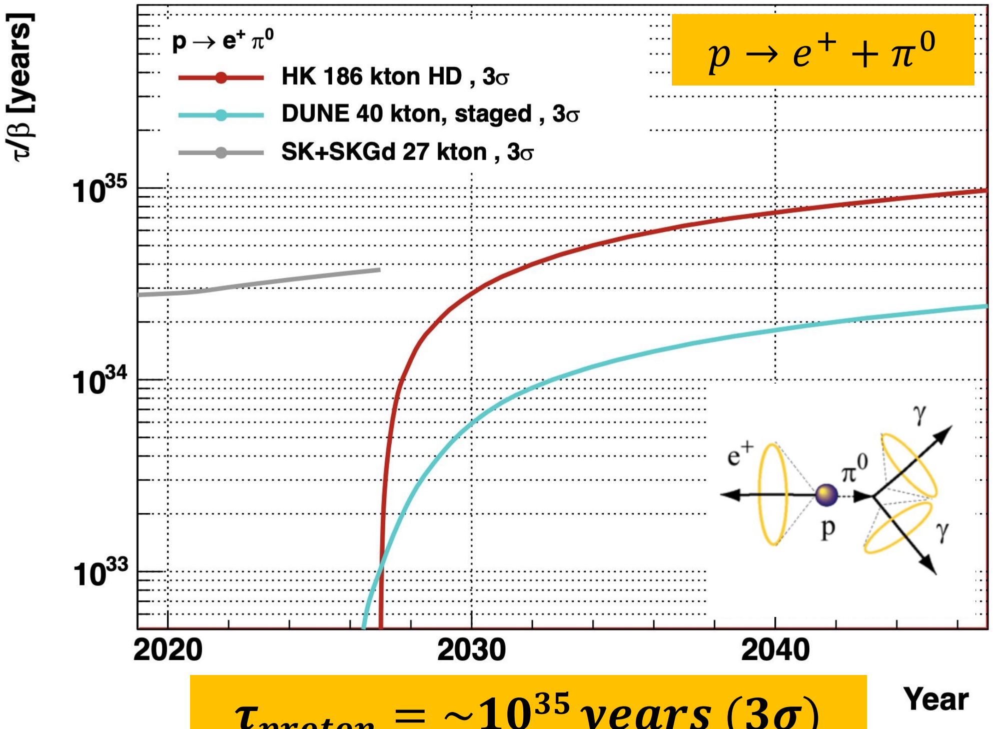
- Profiting from the first day well understood neutrino beam and near detector complex (15 years of run by T2K)
  - fast and precise measurement of CPV
- Assuming known mass hierarchy and improvement on systematic errors, we expect **in 2-3 years** to **exclude CP conservation at 5σ for true $\delta_{CP} = -\frac{\pi}{2}$**.
- Adding IWCD and near detector complex have sizable impact on reduction of systematic uncertainty.
- After 10 years of operation, **60% of δ_{CP}values excluded at more than 5σ**.

Proton Decay

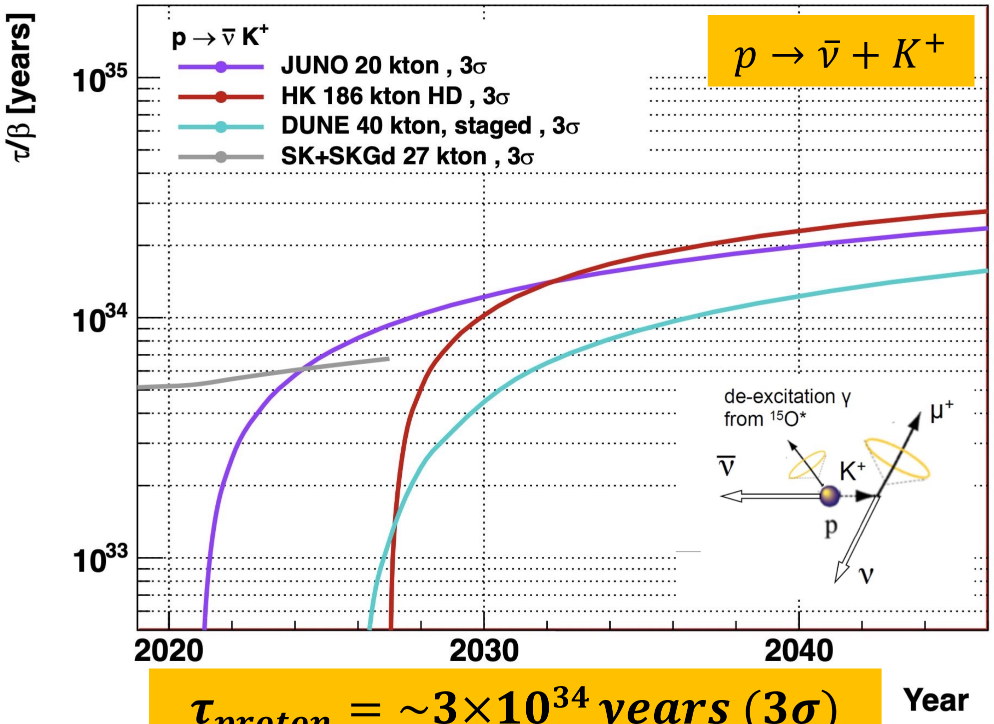
- Proton decay is a key phenomenon of Grand Unified Theories beyond the Standard Model
- Two favorite modes from two dominant classes of GUT models:

$$p \rightarrow e^+ + \pi^0 \text{ and } p \rightarrow \bar{\nu} + K^+$$

- Hyper-Kamiokande **10 years operation** assuming $\tau_{proton} = 1.7\times10^{34}\,years$ (~SK limit)



$\tau_{proton} = \sim10^{35}\,years\,(3\sigma)$



$\tau_{proton} = \sim3\times10^{34}\,years\,(3\sigma)$

Very clean event topology in Water Cherenkov detectors

Requires 2γ & reconstructed energy = Invariant M_P

Background: Atmospheric ν producing e.g. a π^0

arXiv:1805.04163

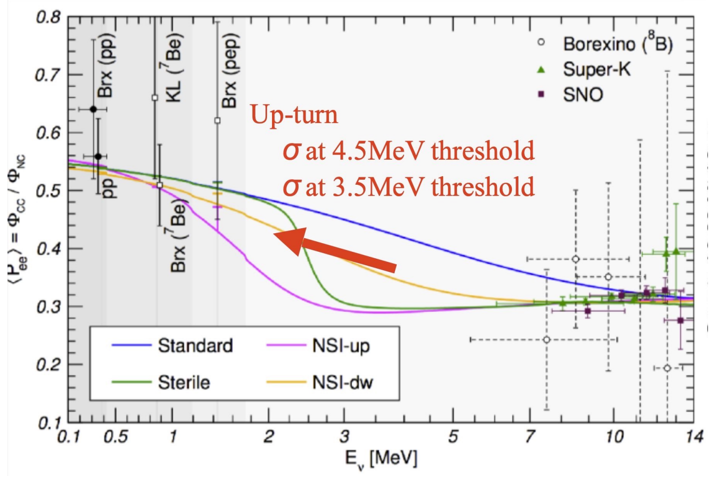
Signature:

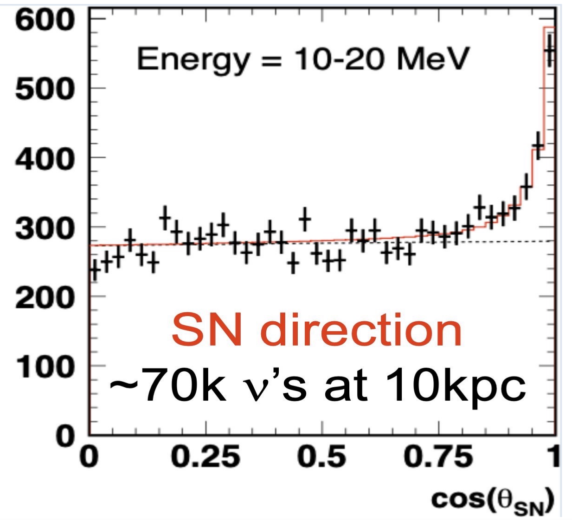
$K^+ \rightarrow \mu^+ + \nu$ (64%) 236 MeV μ^+

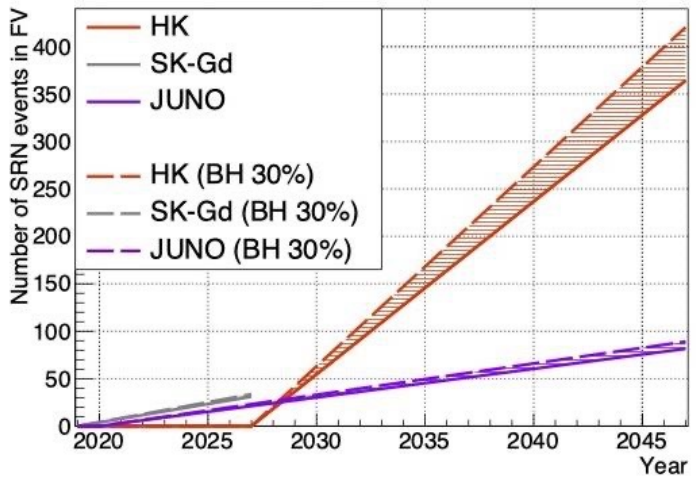
$K^+ \rightarrow \pi^+ + \pi^0$(21%) 205 MeV π^+ back to back photons

Neutrino Astrophysics

- Hyper-Kamiokande as a **multimessenger observatory**, through observation of a few ~10 MeV neutrinos with time, energy and direction information.
- **Detecting solar neutrino interactions** with unprecedented statistical power allows to study upturn at the vacuum-MSW transition, day/night asymmetry, the first measurement of hep solar neutrinos
- For a **supernova at 10kpc**, large number of neutrino events above 7 MeV would be detected within a few seconds. The direction of the supernova can be reconstructed with an accuracy of about 1°: study explosion mechanism, black hole/neutron star formation. arXiv:2101.05269
- Studying **Supernova Relic neutrinos** (SRN) provides information on stellar collapse, nucleosynthesis, and history of the universe
- And more

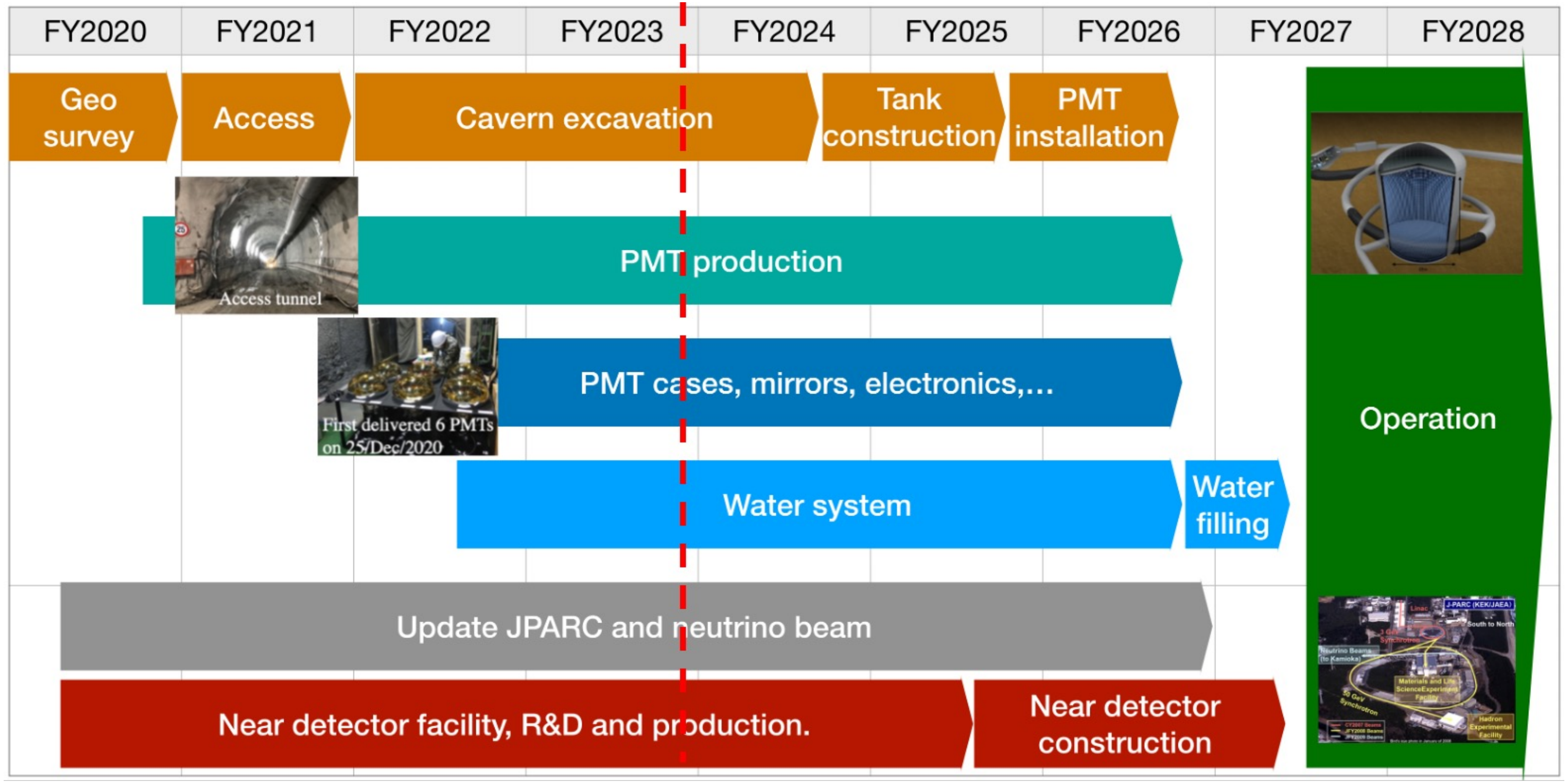






ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

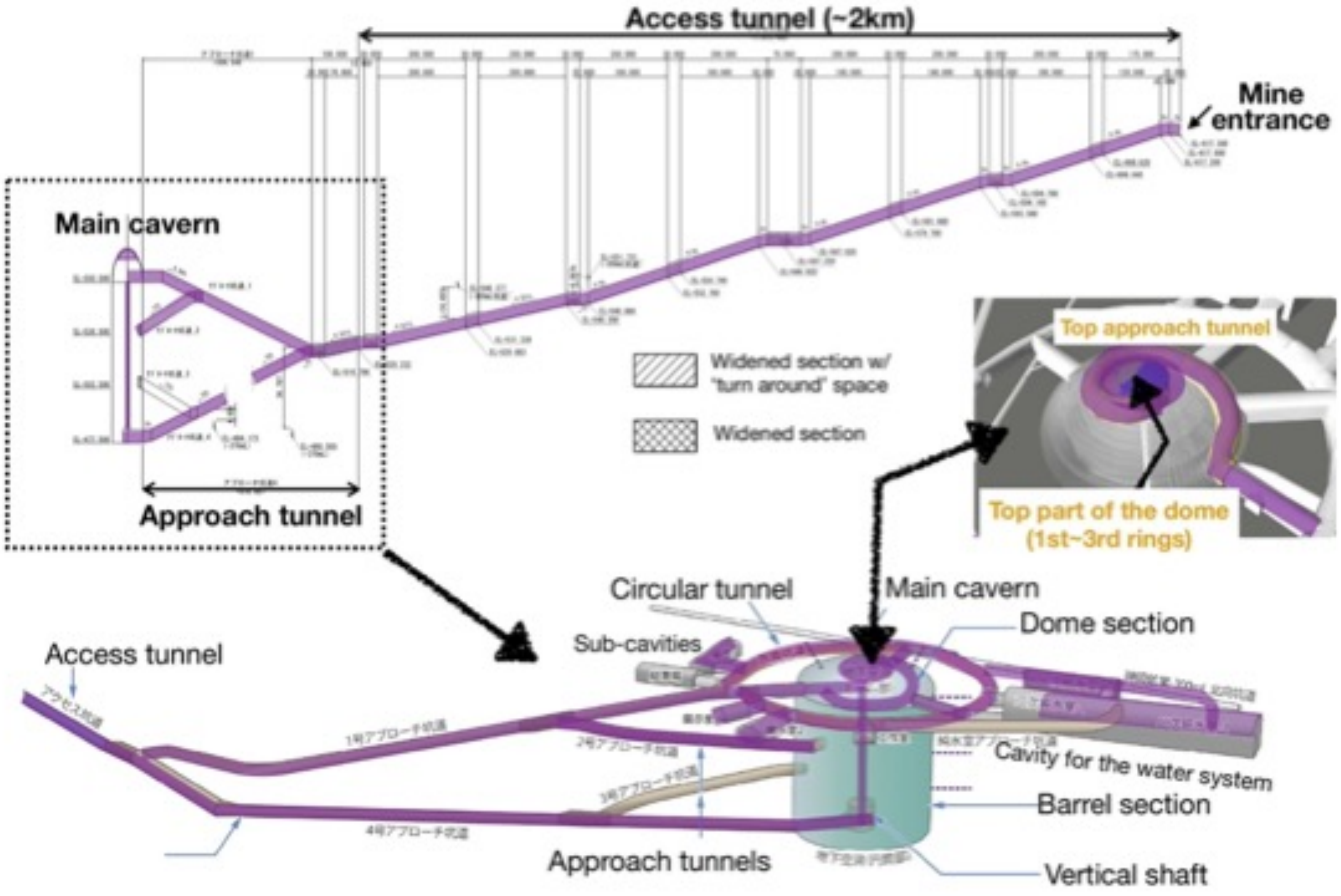
Schedule



- Approved in 2019 by Japanese government.
- **7 years construction** from year 2020; **start operation in 2027**.

Hyper-Kamiokande cavern excavation

- Geographical surveys and site preparation work **in 2020**
- Excavation started **in 2021**
- Access tunnel excavation completed on **25/02/2022**
- Approach & circular tunnel excavation completed, and reaching the center of the cavern dome on **23/06/2023**
- Main cavern excavation has started on-time!
- **Dome section completed in 2023**
- Barrel section to be **completed in 2024**



Excavation of the dome section completed on October 3, 2023

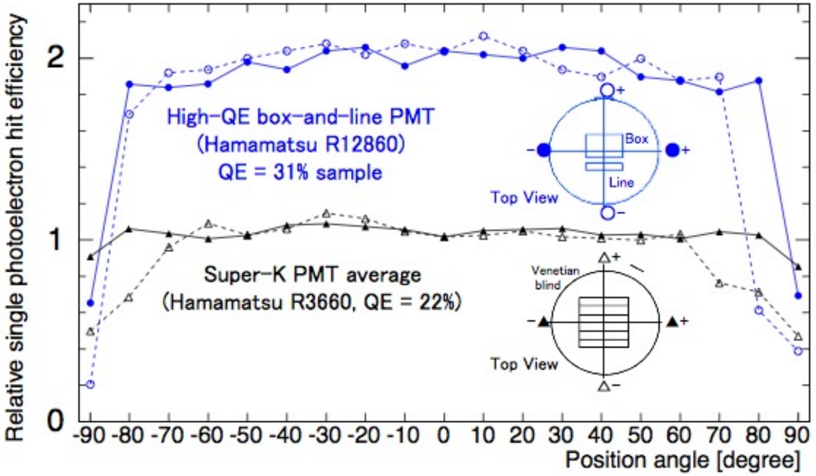
- 69 m diameter, 21 m height,
- one of the largest human made underground space

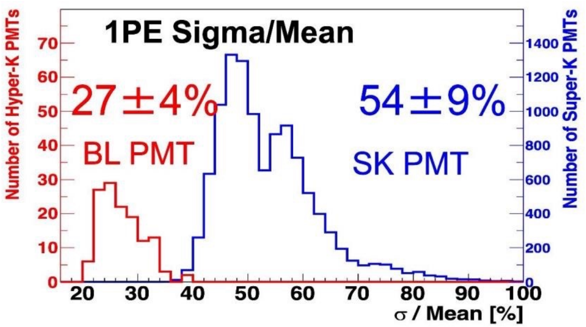
- Excavation of the barrel section is ongoing (72 m)

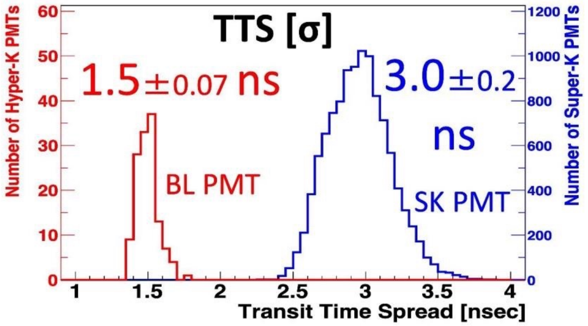
https://www-sk.icrr.u-tokyo.ac.jp/en/news/detail/738

Hyper-Kamiokande 50 cm PMTs

50 cm PMT production ongoing, **>6000 already delivered**
Screening both at Hamamatsu and Kamioka





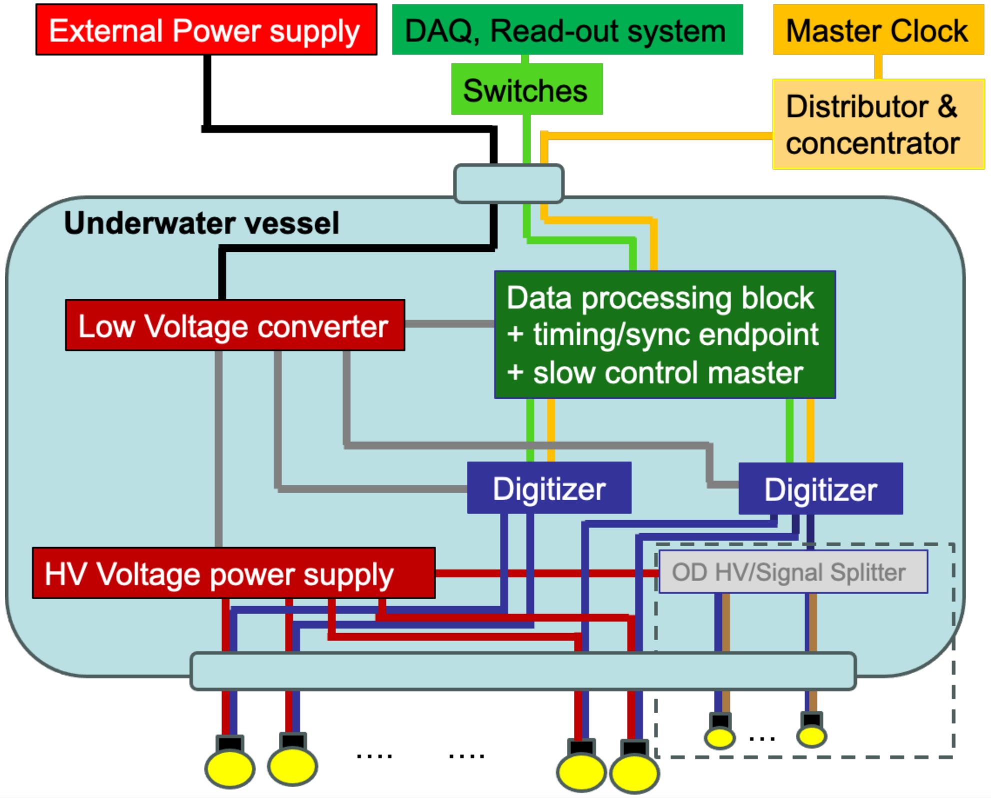


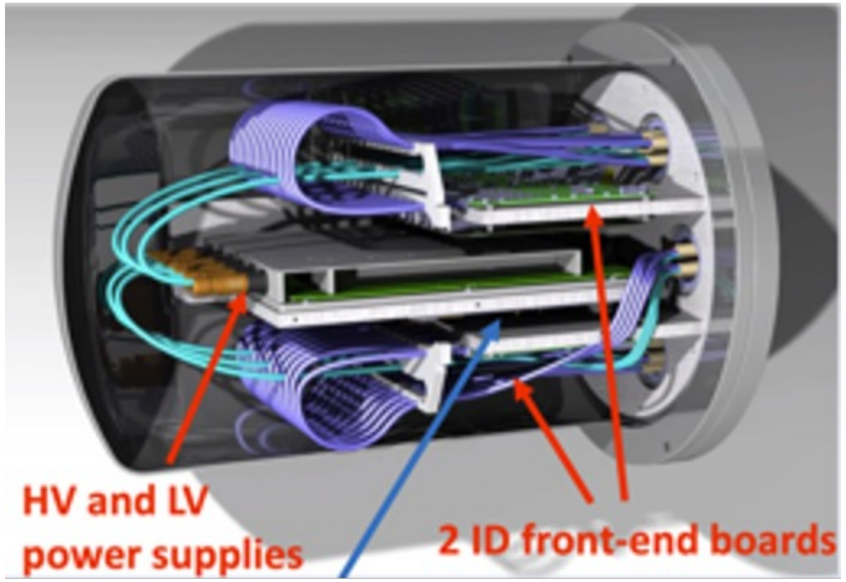
- **x2 better photodetection efficiency**
- **x2 better charge resolutions**
- **x2 better time resolutions**
- **Low dark rate (4kHz)**
- **X2 better pressure tolerance; enable deeper tank design**

Hyper-Kamiokande Electronics

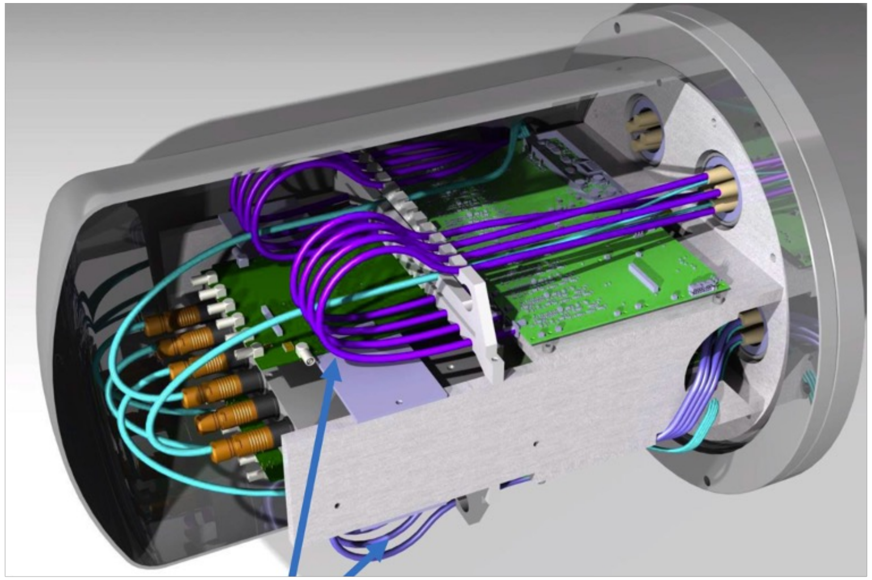
HK electronics including Low voltage, High Voltage Power supply boards, Data Processing boards and Digitizer boards to be **placed in underwater vessels**:

- Reduce the length of the cables to PMTs
- **Inner detector vessels**: 24 ID PMTs
- **Hybrid outer + inner detector vessels**: 20 ID + 12 OD PMTs.





Data processing and timing boards



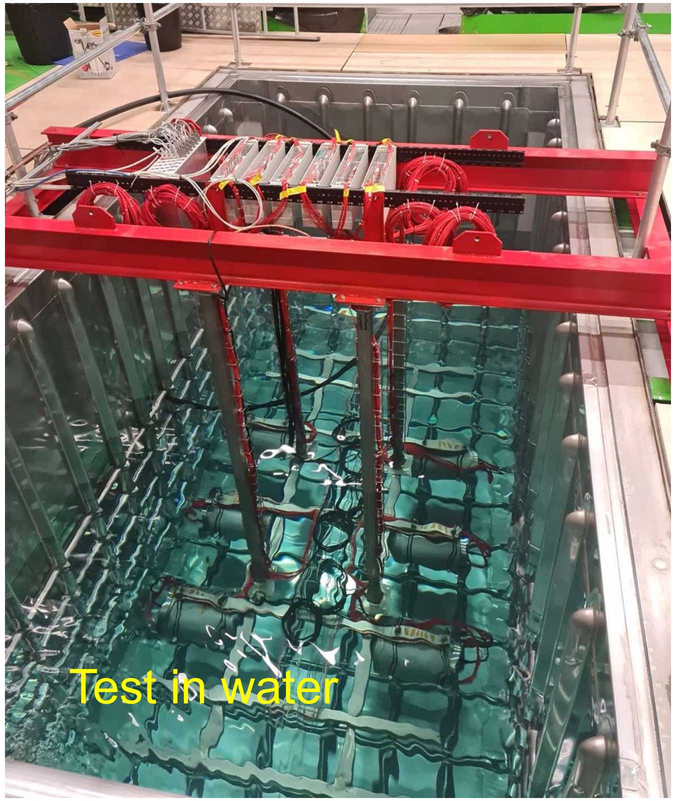
2 OD front-end boards

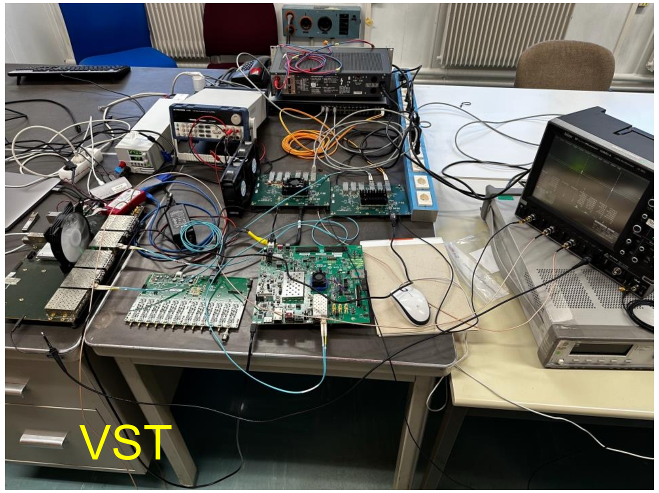
Hyper-Kamiokande electronic prototypes

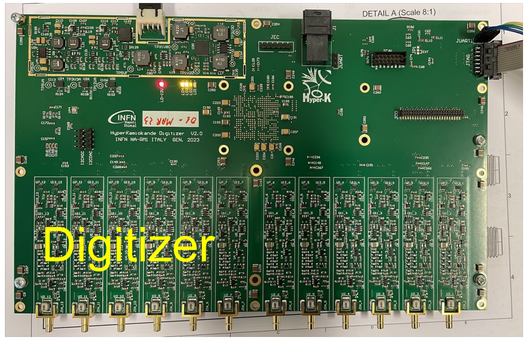
- Custom design of Digitizers, DPB, OD HV/signal splitter, timing boards will be finalized

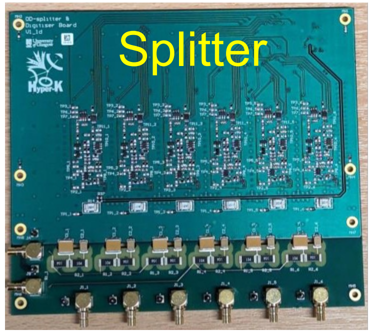
- Industrial productions: LV and HV satisfying requirement for PMTs and FEB power requirement, redundant and reliable system; procurement finalized

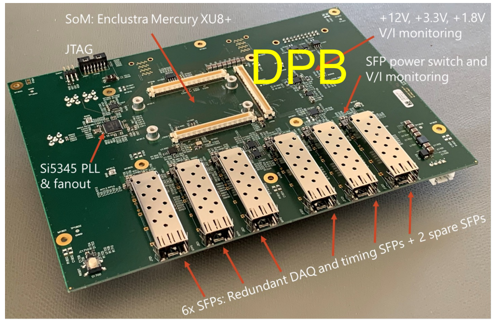
- **Testing prototypes ongoing**:
  - LV and HV prototypes together with dummy DPB and Digitizer boards under the test in water to study water tightness of the vessel, heat transfer, stability of LV and HV
  - Testing communications among the boards; vertical slice test
  - Assembly and testing underwater vessel with all prototypes underway

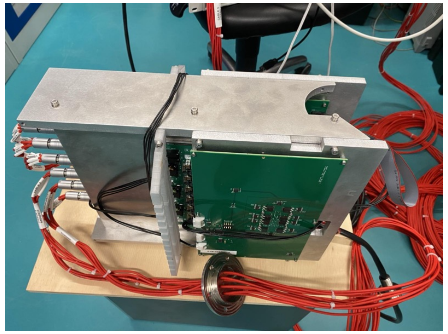








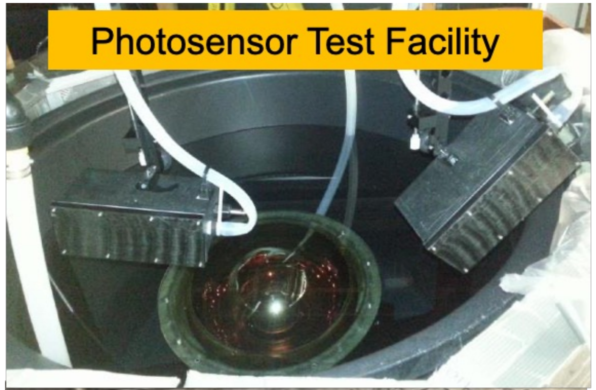


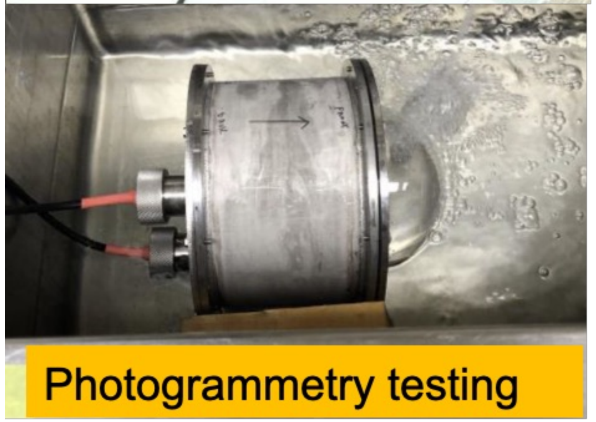


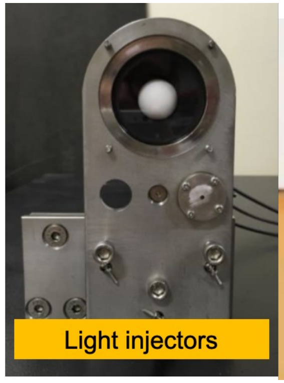
Hyper-K Calibration

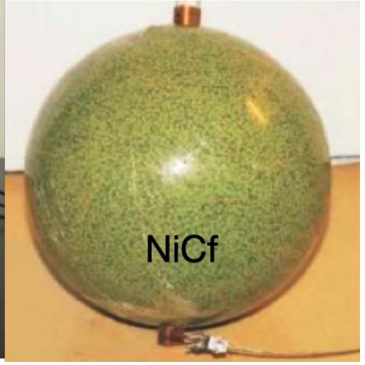
Extensive program of calibration sources to determine detector parameters and measure systematics.

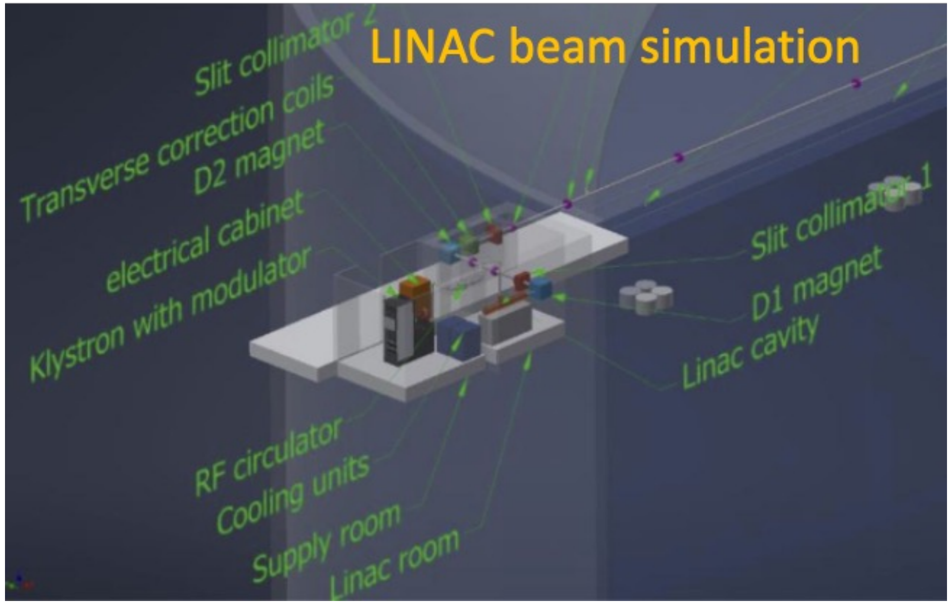
- Pre-calibration of photosensors
- Photogrammetry
- Light injection:
  - Diffusers and collimators
  - mPMT system
  - OD injections
- Electron LINAC:
  - 3-24 MeV electrons
- Radioactive sources:
  - Deuterium-tritum neutron generation - ^{16}N to gammas
  - AmBe + BGO - tagged neutrons.
  - Ni/Cf - 9 MeV γ cascade

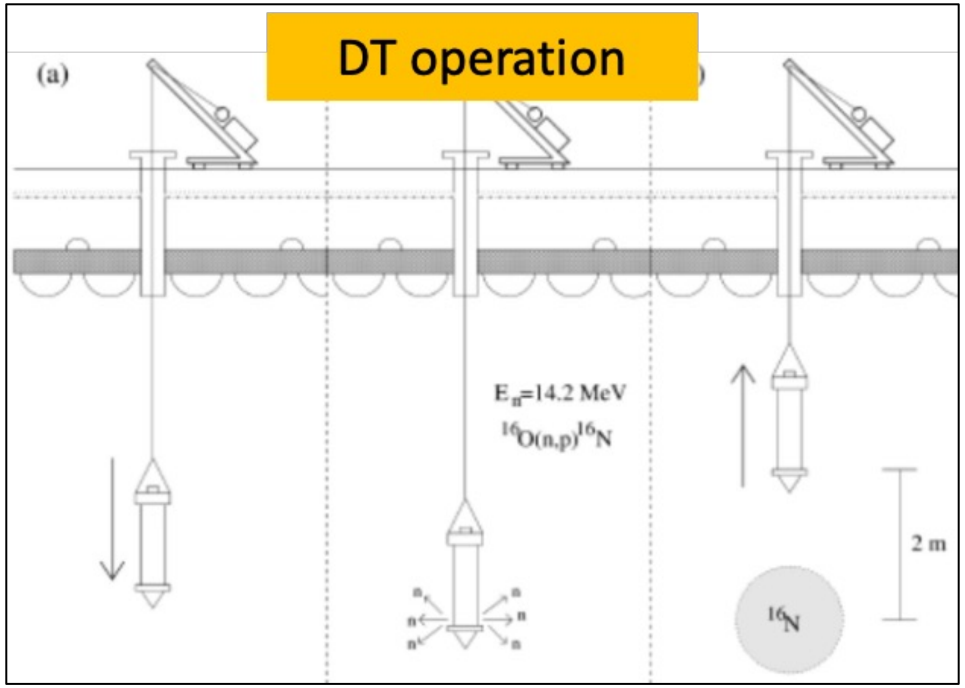












Summary

- Hyper-Kamiokande is 3rd generation water Cherenkov detector in Kamiokande, ~10xSuperKamiokande

- It will play a central role in exploring the future of particle physics; such as
    - Discovery of CP violation with 5σ for ~60% parameter region
    - Search for proton decay to test GUT, probing $\tau > 10^{35}$ years
    - Study supernova neutrinos

- Hyper-Kamiokande construction on schedule
    - World's largest underground facility
    - Access tunnel and cavern dome excavation completed
    - 50 cm PMT production and quality assurance test underway
    - Front-end electronics prototype under the test and design being finalized
    - Near detector upgrade and design of intermediate water Cherenkov detector being finalized
    - Neutrino beam upgrade to 1.3 MW

Thank you!

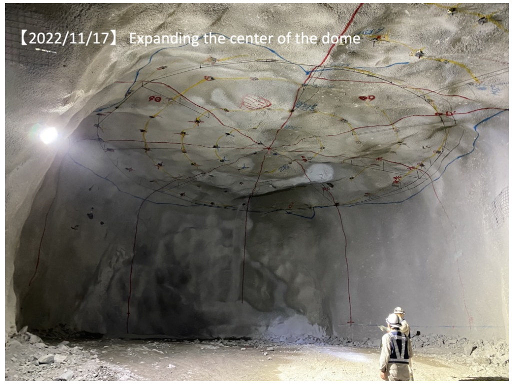
Backup


【2021/05/06】 Start of the tunnel excavation


【2021/09/24】 Looking back to the entrance


【2022/05/10】 Junction to the top and bottom


【2022/11/04】 connecting the circumference tunnel


【2022/11/17】 Expanding the center of the dome

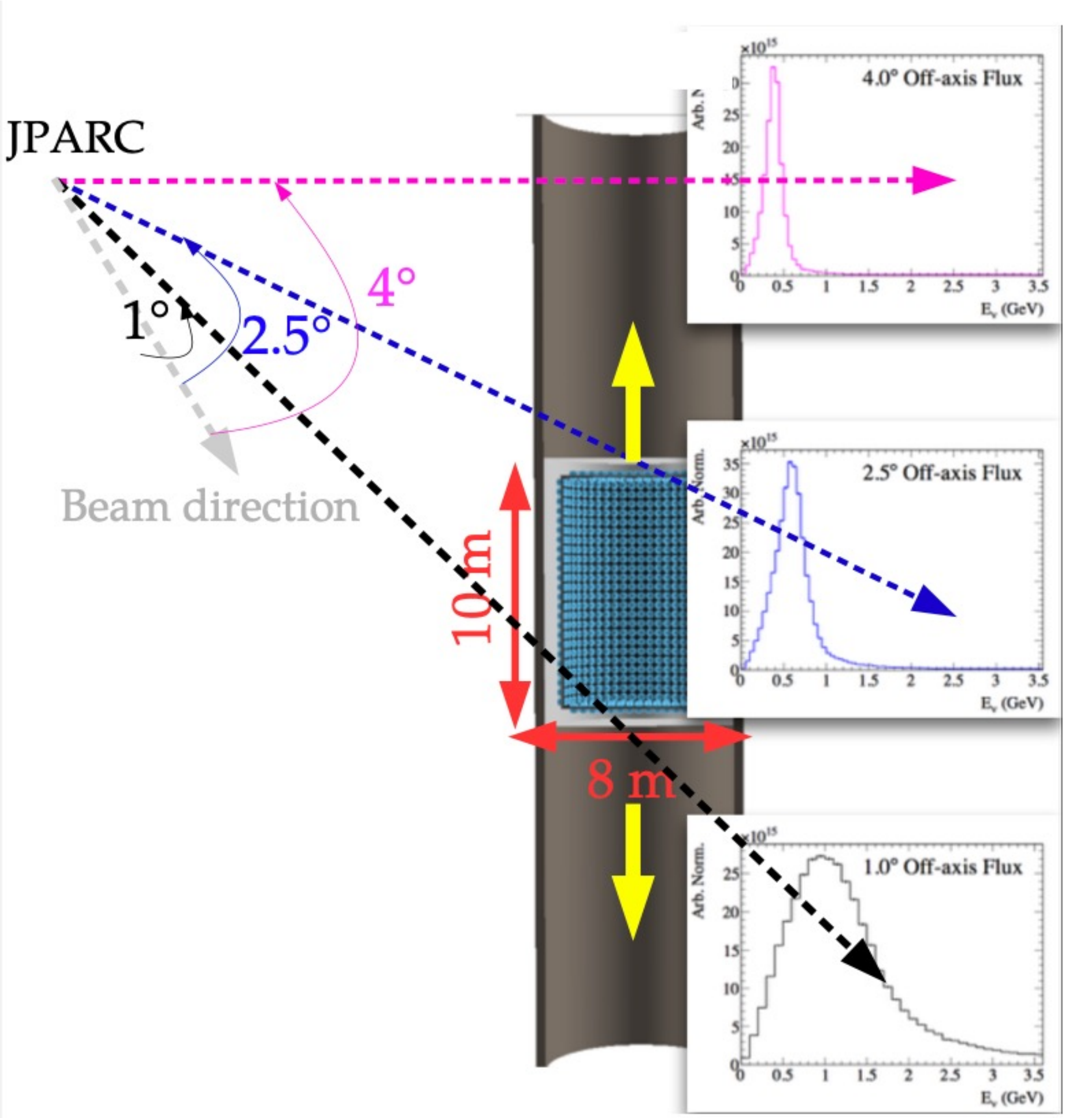

【2023/03/14】 Expanding the center of the dome


【2023/10/03】 Completion of the 69 m diameter dome
(~1 Super-K)


【2023/07/13】 Cavern for water purification system (~1/2 of Super-K)

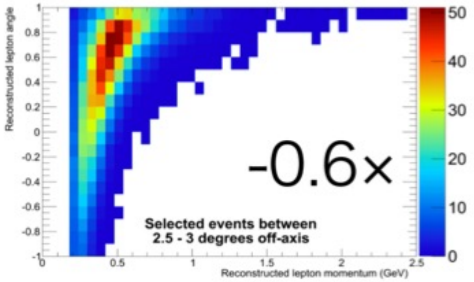

【2022/07/01】 The center of the HK dome

Intermediate Water Cherenkov Detector



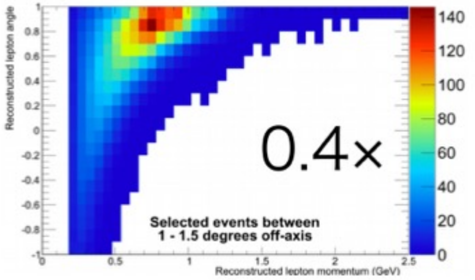
1. HK flux = linear combination of different off-axis angles.

2.Take same combination of



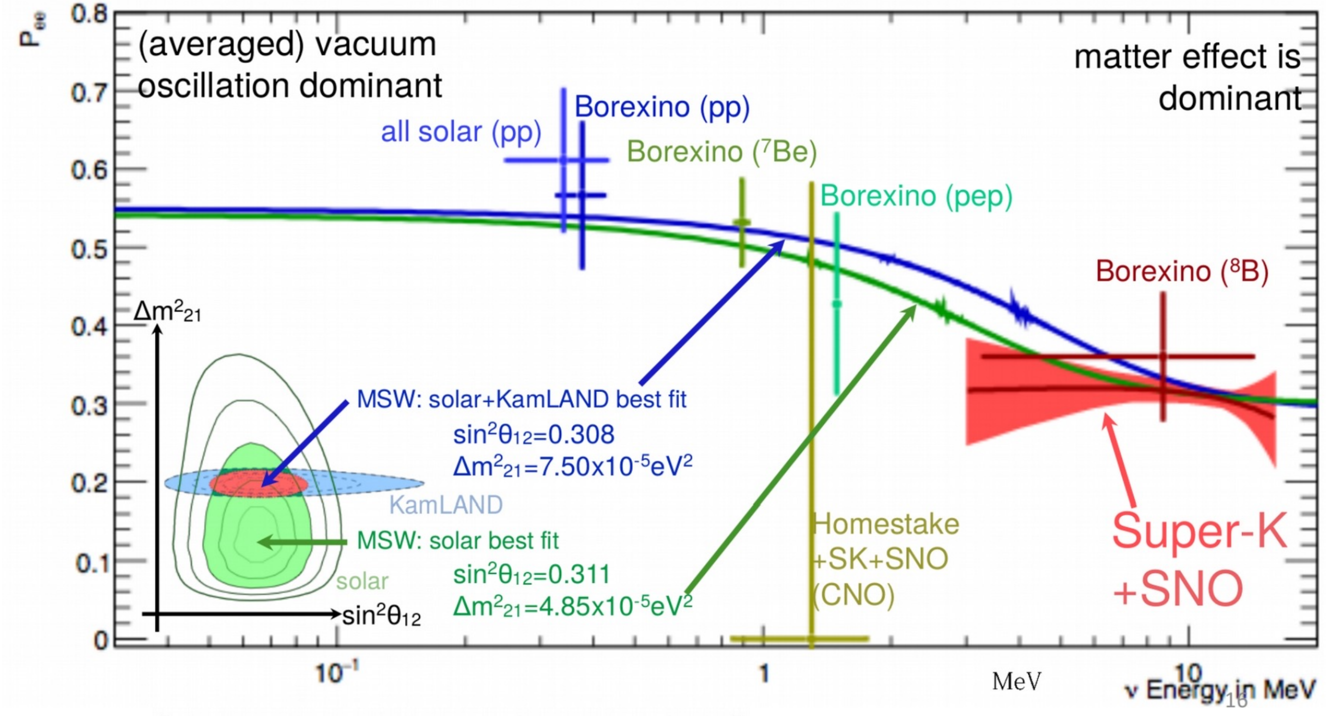
reconstructed number of neutrinos (e.g. in p_μ/θ_μ)

→ Drastically reduce use of cross-section models !

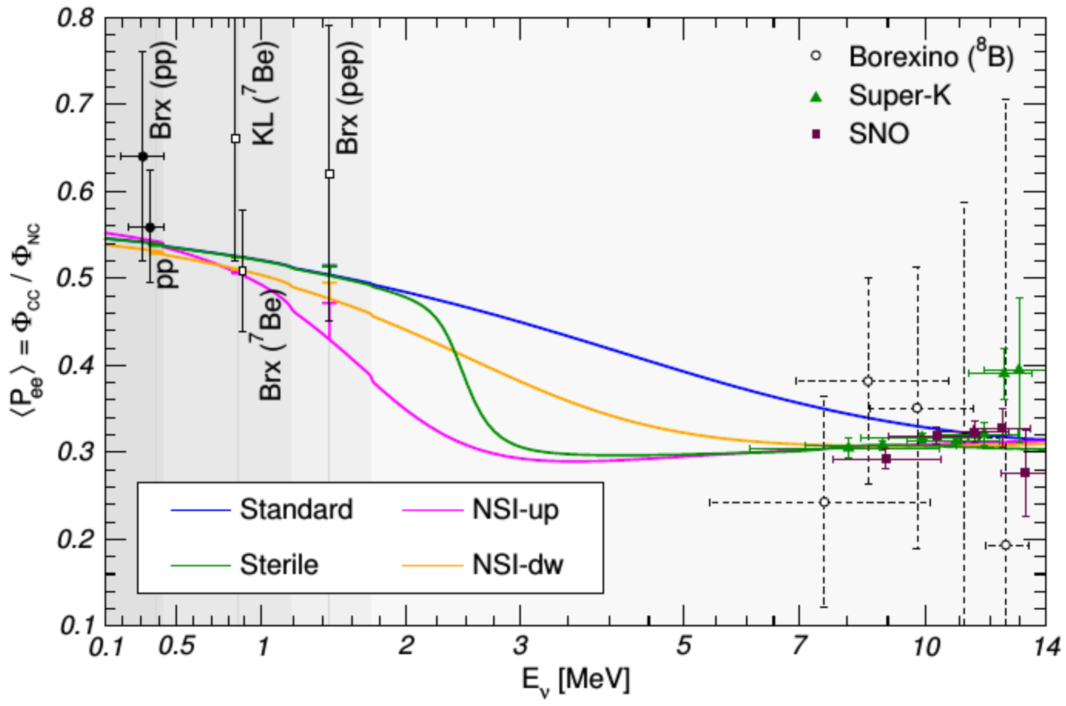


Solar neutrinos: upturn

- SuperK/SNO found a high matter effect in the Sun
- SuperK deviates from standard upturn scenario > 2σ . [Moriyama S., SK, Neutrino 2016
- Solar upturn shifted to lower energies

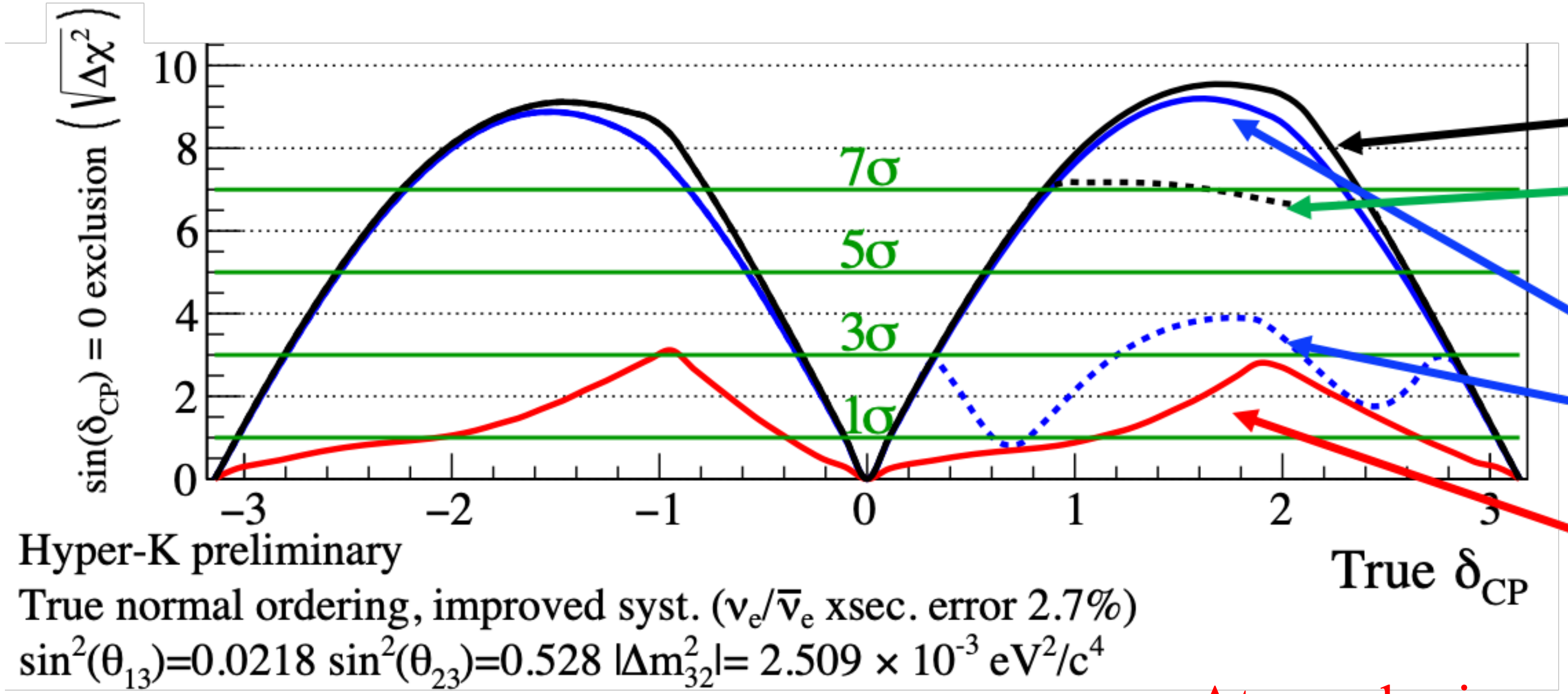


[Ikeda M., SK, Neutrino 2018]



[arXiv:1507.0587]

Combination of beam and atmospheric neutrino observations
⇒ Resolve parameters degeneracy



	$\sin^2\theta_{23}$	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

Atmospheric neutrino:
sensitive to mass ordering by Earth's matter effects
→ Constraints on mass ordering enhance sensitivity to CP violation by long-baseline