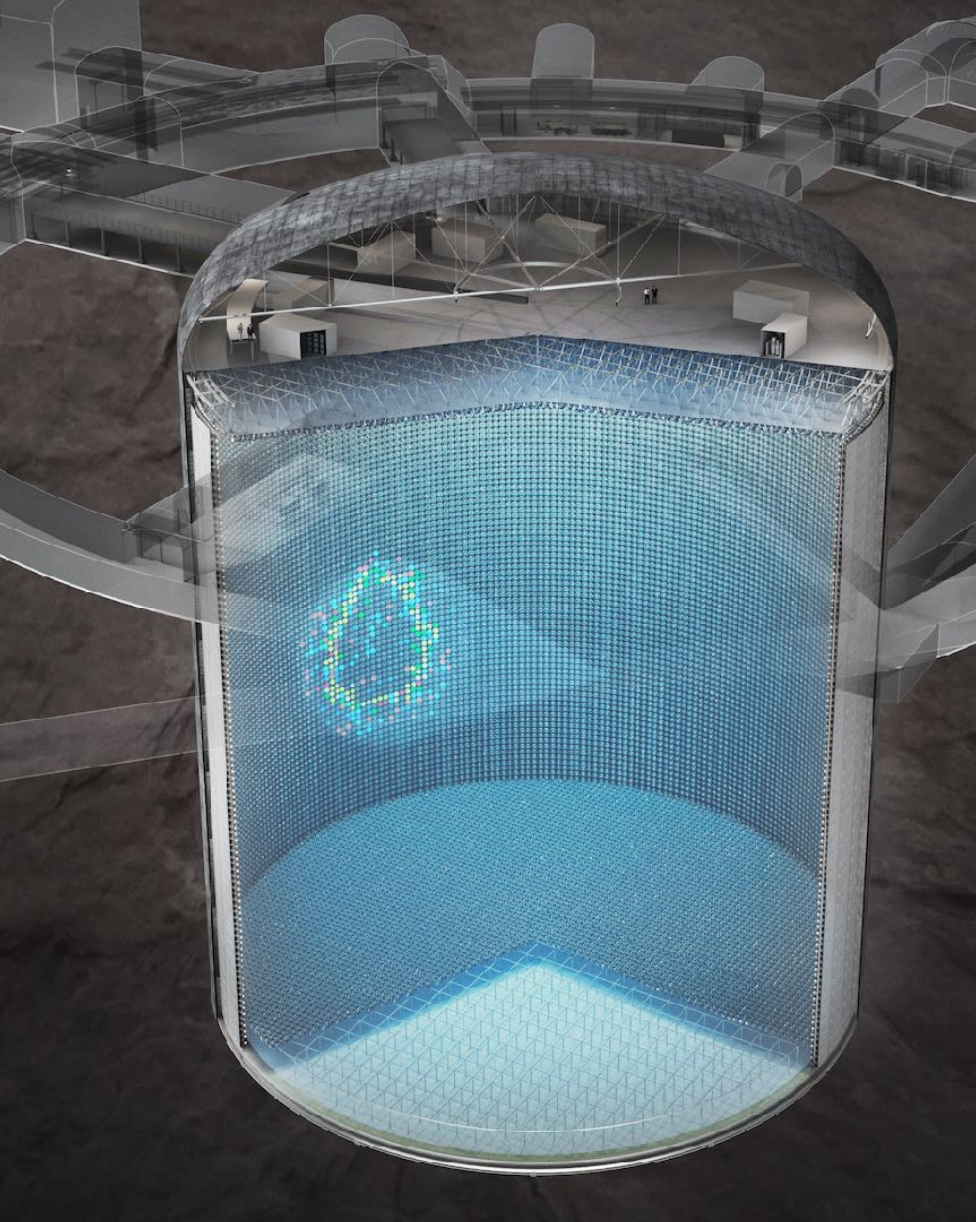


Hyper-Kamiokande Project Updates

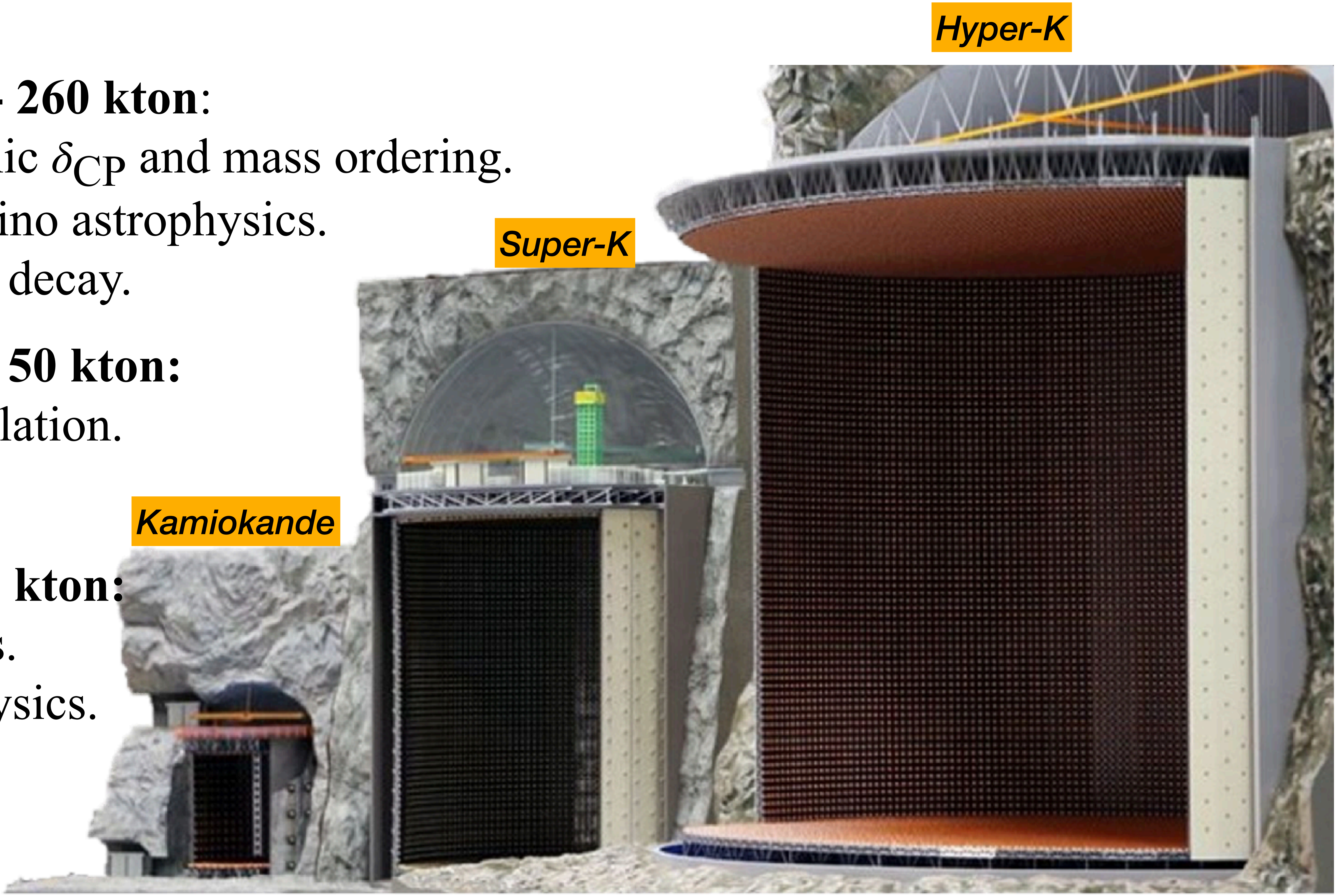
Physics Program and Current R&D Progress

Luan Koerich
for the Hyper-K Collaboration

Lake Louise Physics Institute 2024

Introduction to Kamioka Experiments

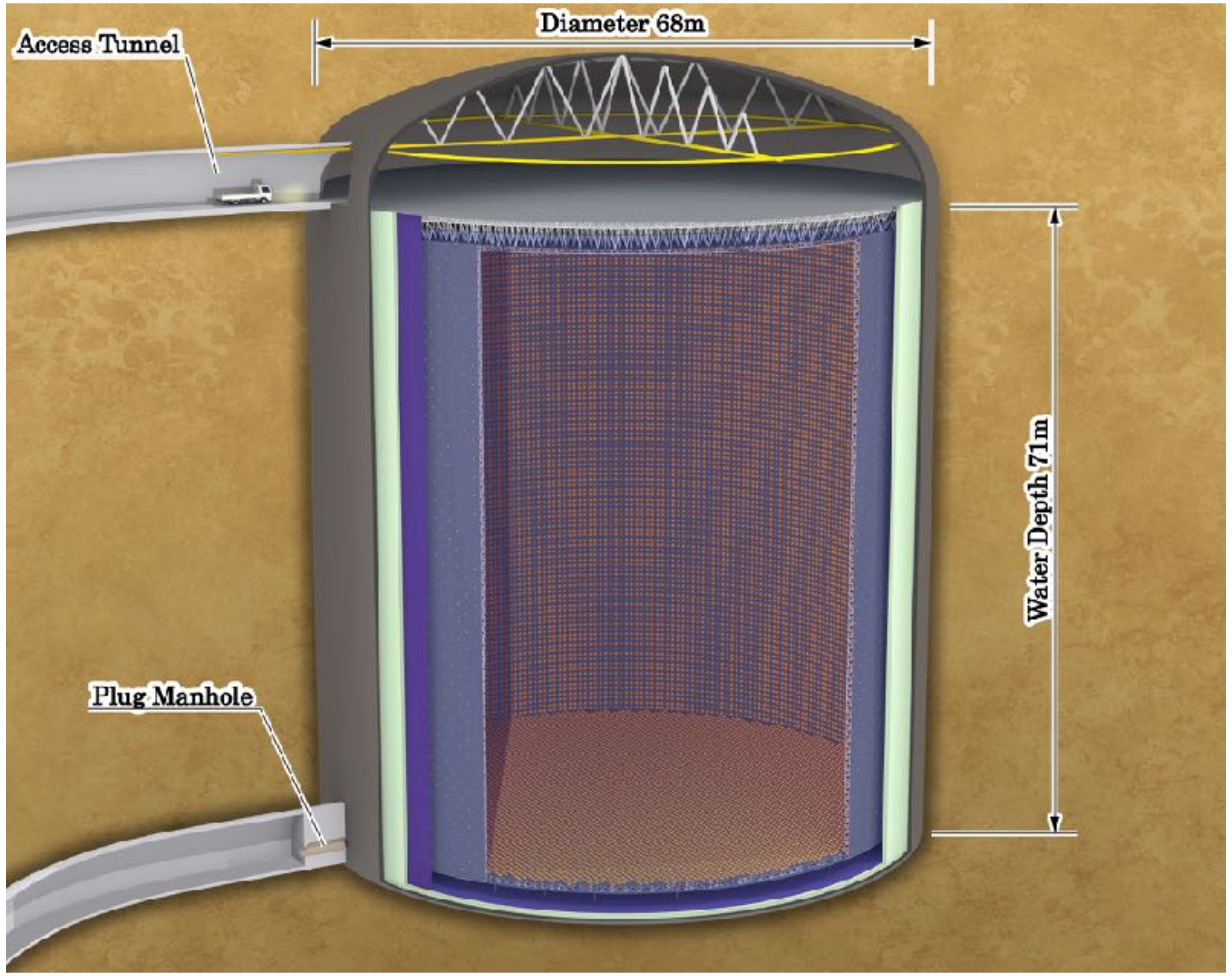
- **Hyper-Kamiokande (2027) - 260 kton**:
  - Toward discovery of leptonic δ_{CP} and mass ordering.
  - Higher sensitivity for neutrino astrophysics.
  - Extended search for proton decay.
- **Super-Kamiokande (1996) - 50 kton:**
  - Discovery of neutrino oscillation.
  - Limits for proton decay.
- **Kamiokande (1983-1996) - 3 kton:**
  - Supernova 1987A neutrinos.
  - Advent of neutrino astrophysics.



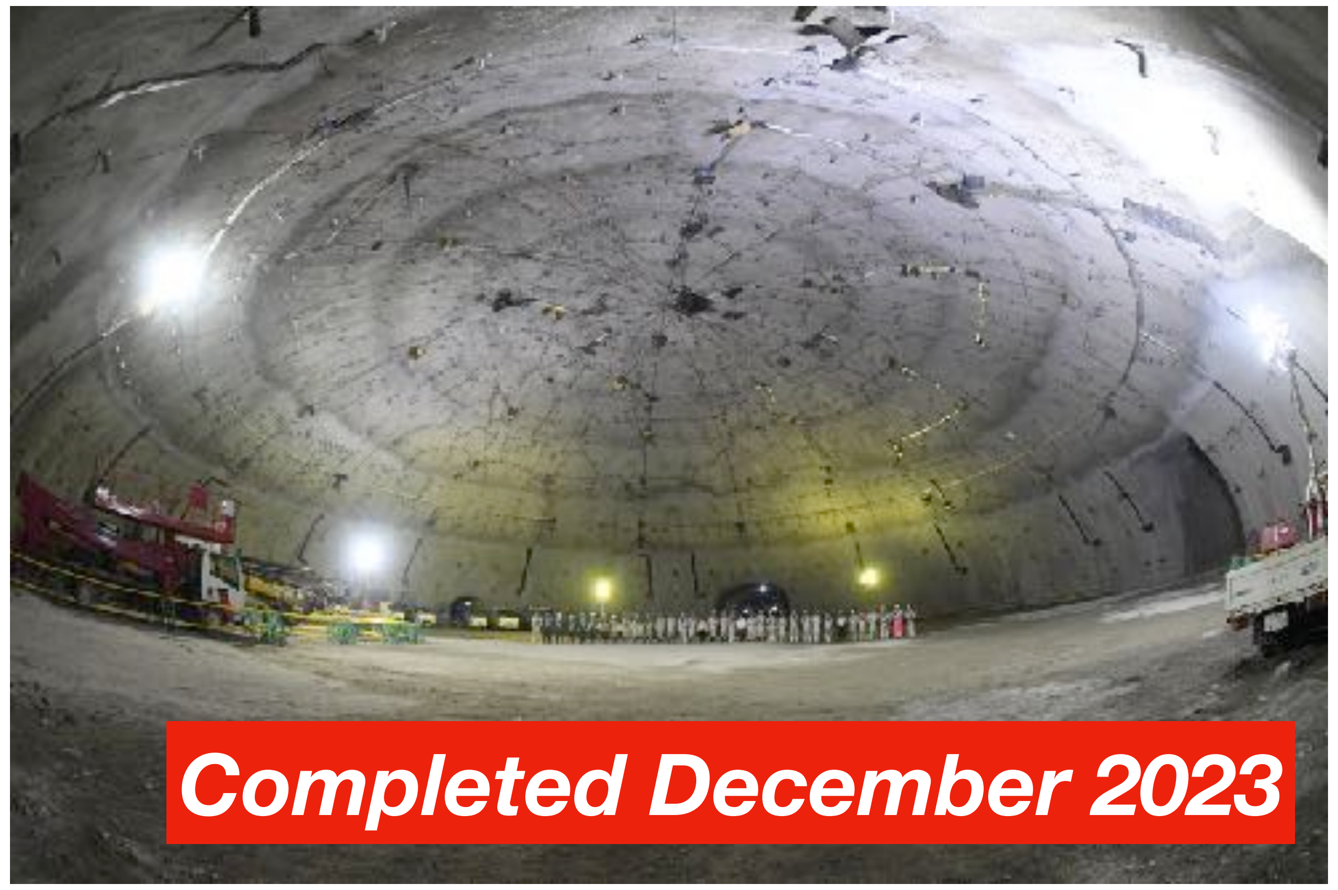
HK Excavation

- With 68 m in diameter and 71 m in height, ~600 m rock overburden in the Kamioka Mine.
- Excavation in progress: **Access tunnel and dome excavation completed!**

HK is 8 km south to SK



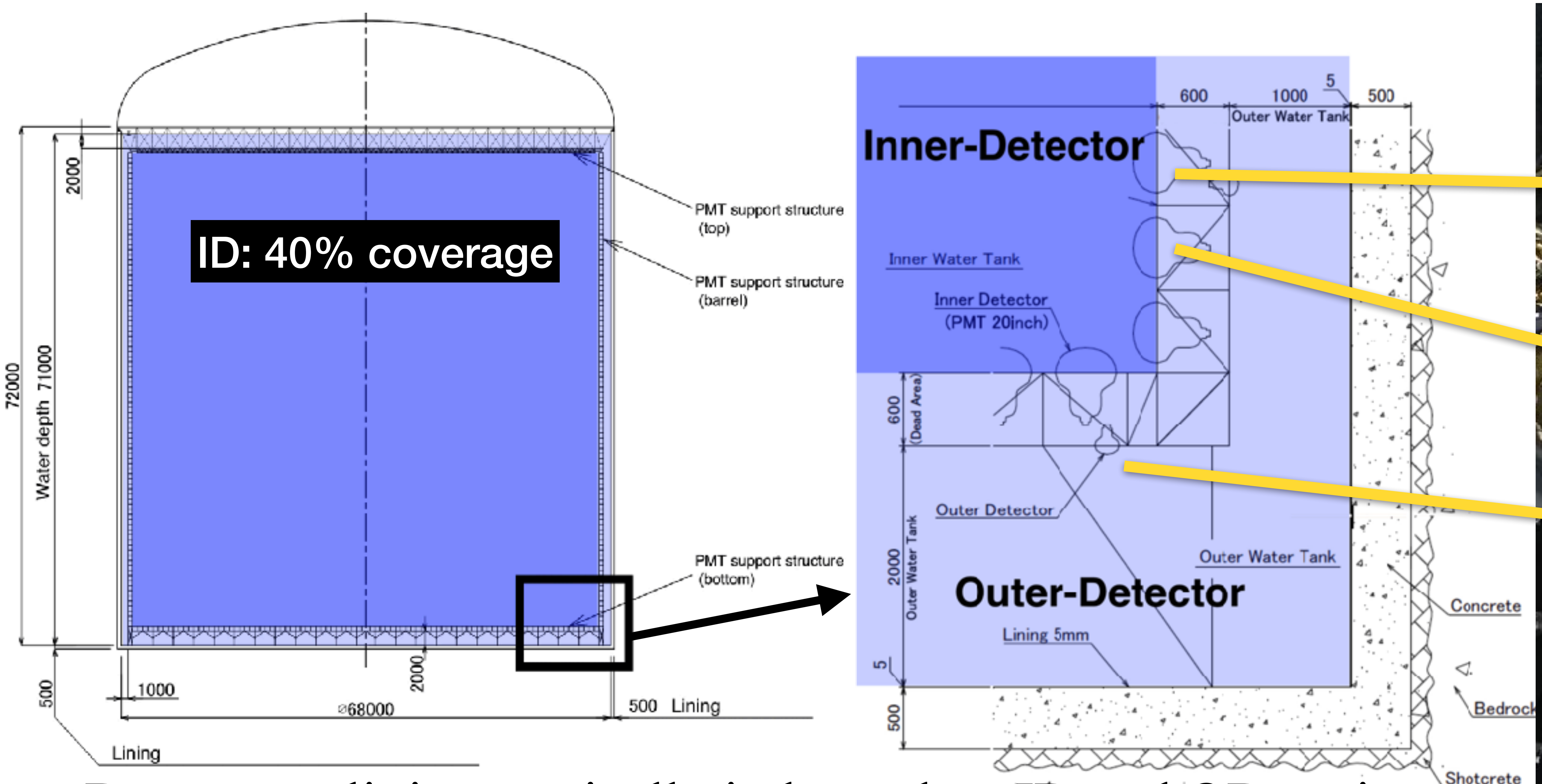
HK Detector



Access Tunnel and Dome

HK Detector

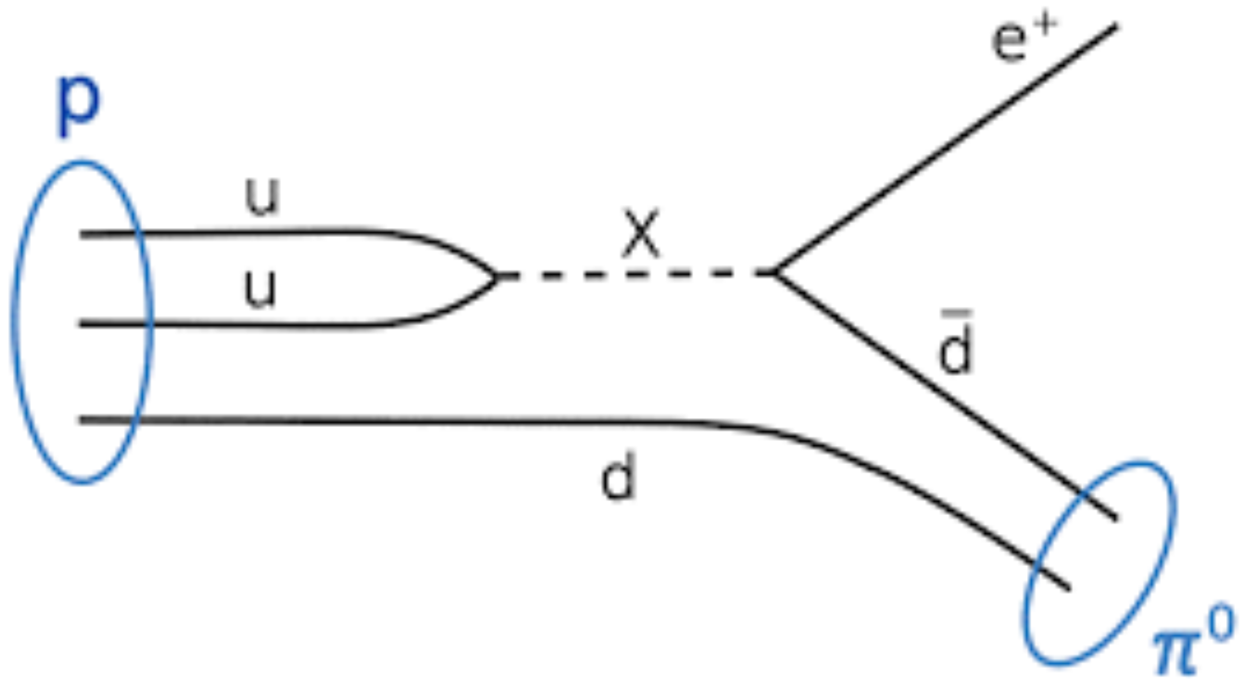
- **Target:** 258 kton of ultra pure water, ~8 times the fiducial mass of Super-Kamiokande.
- **Photo-sensors:** ID contains 50-cm PMT and multi-PMT system; OD uses 8-cm PMTs.
- ID walls are covered in black sheet, while OD walls are lined with WLS plates and Tyvek.



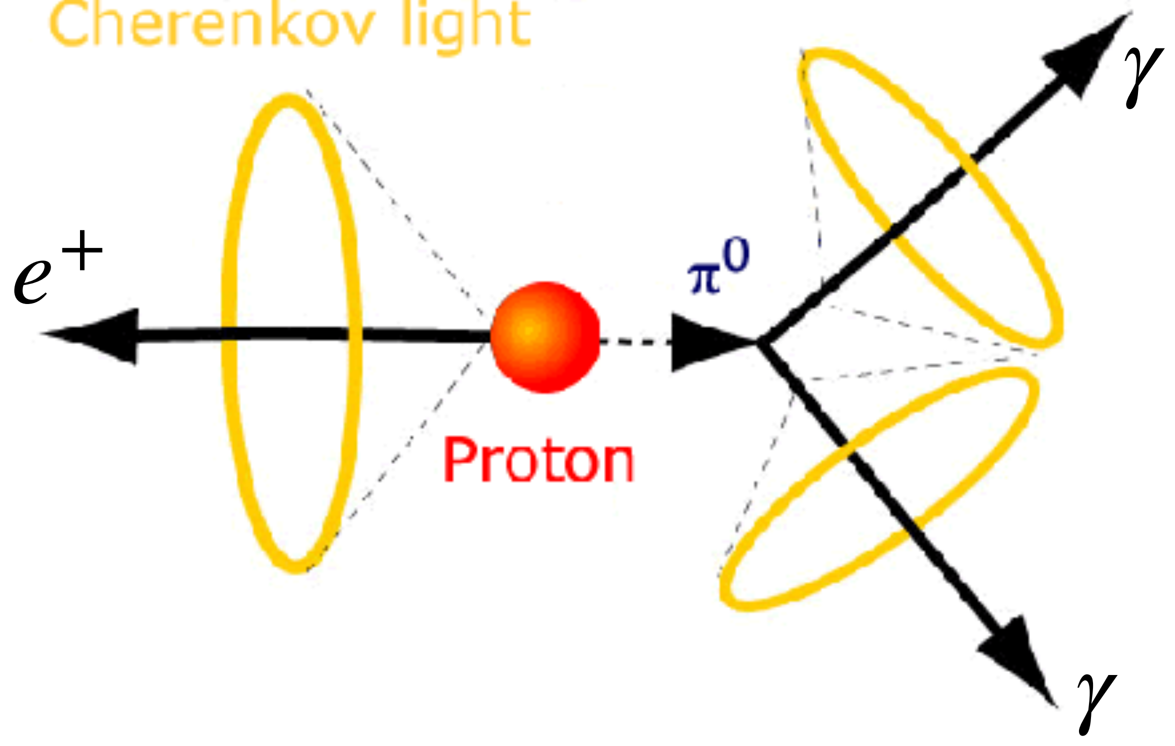
Detector split into optically independent ID and OD regions.

HK in the Search for Proton Decay

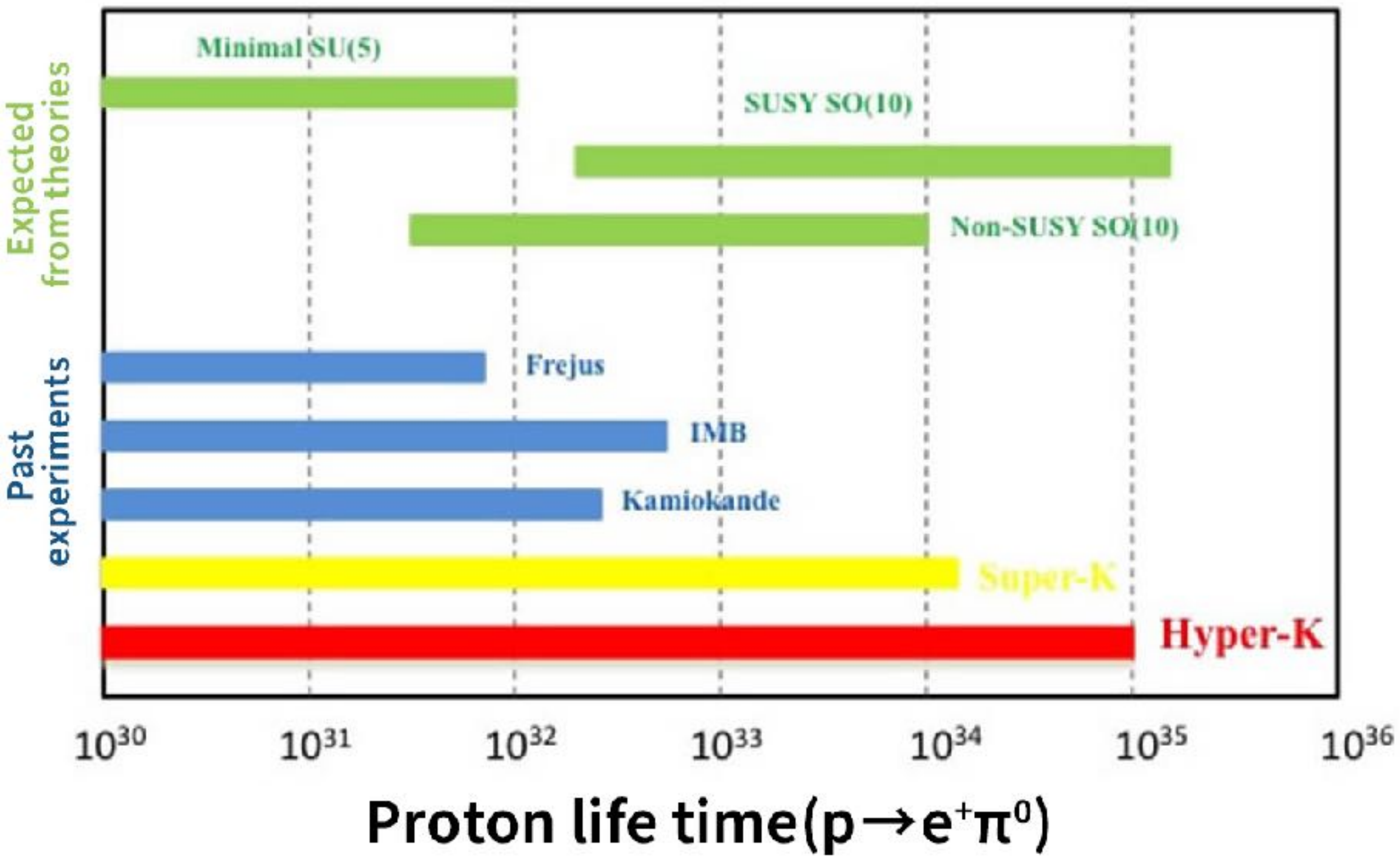
- Grand Unified Theories (GUT) predict proton lifetime of $\tau \sim 10^{30}$ years.
- No. of protons in Super-K detector and lack of proton decay detection $\rightarrow \tau > 2.4 \times 10^{34}$ years.
- Larger sample of protons in HK tank may improve limit to 10^{35} years.



Proton Decay: $p \rightarrow \pi^0 + e^+$



Proton Decay Signature

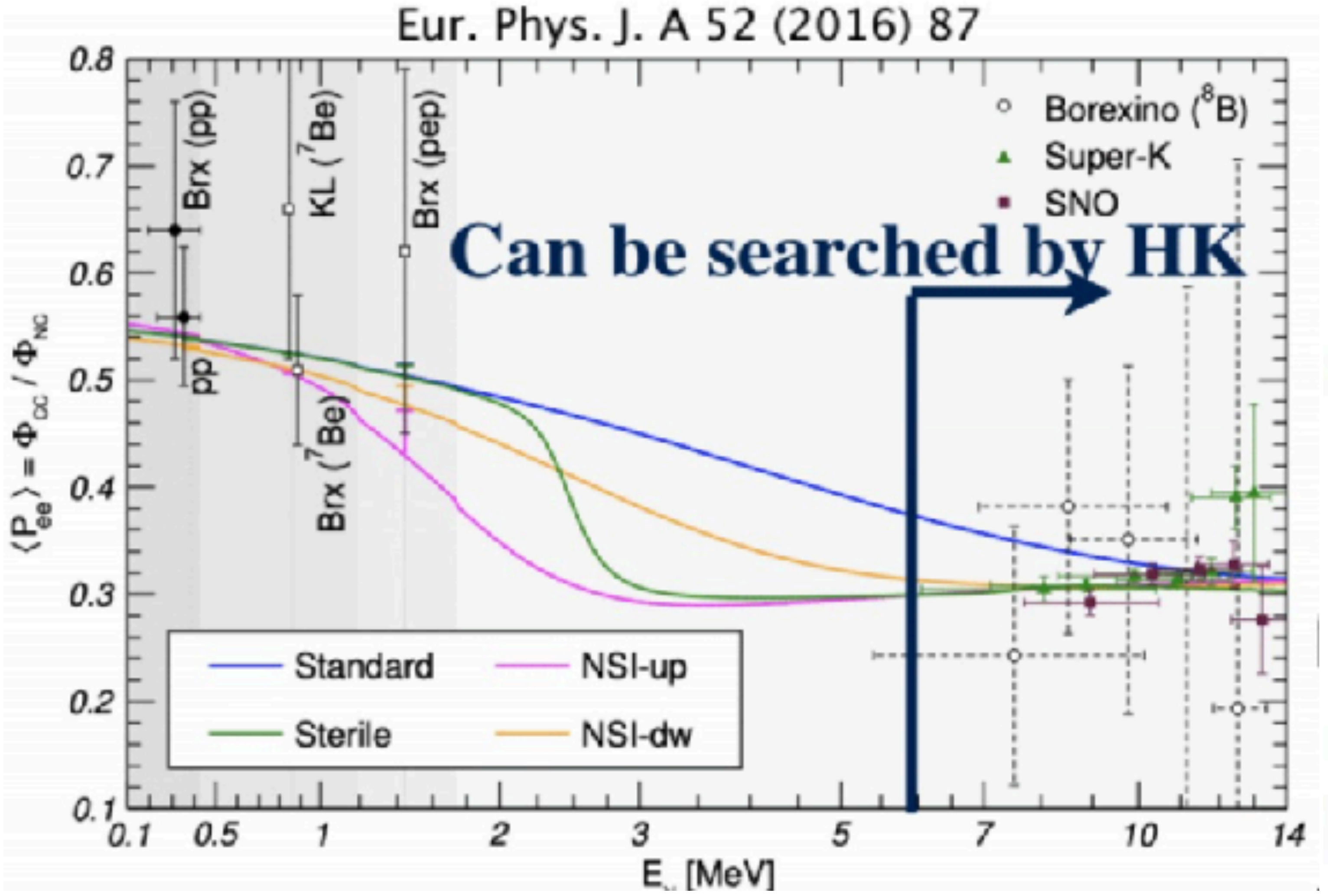


Hyper-K Sensitivity and Expected Decay Time

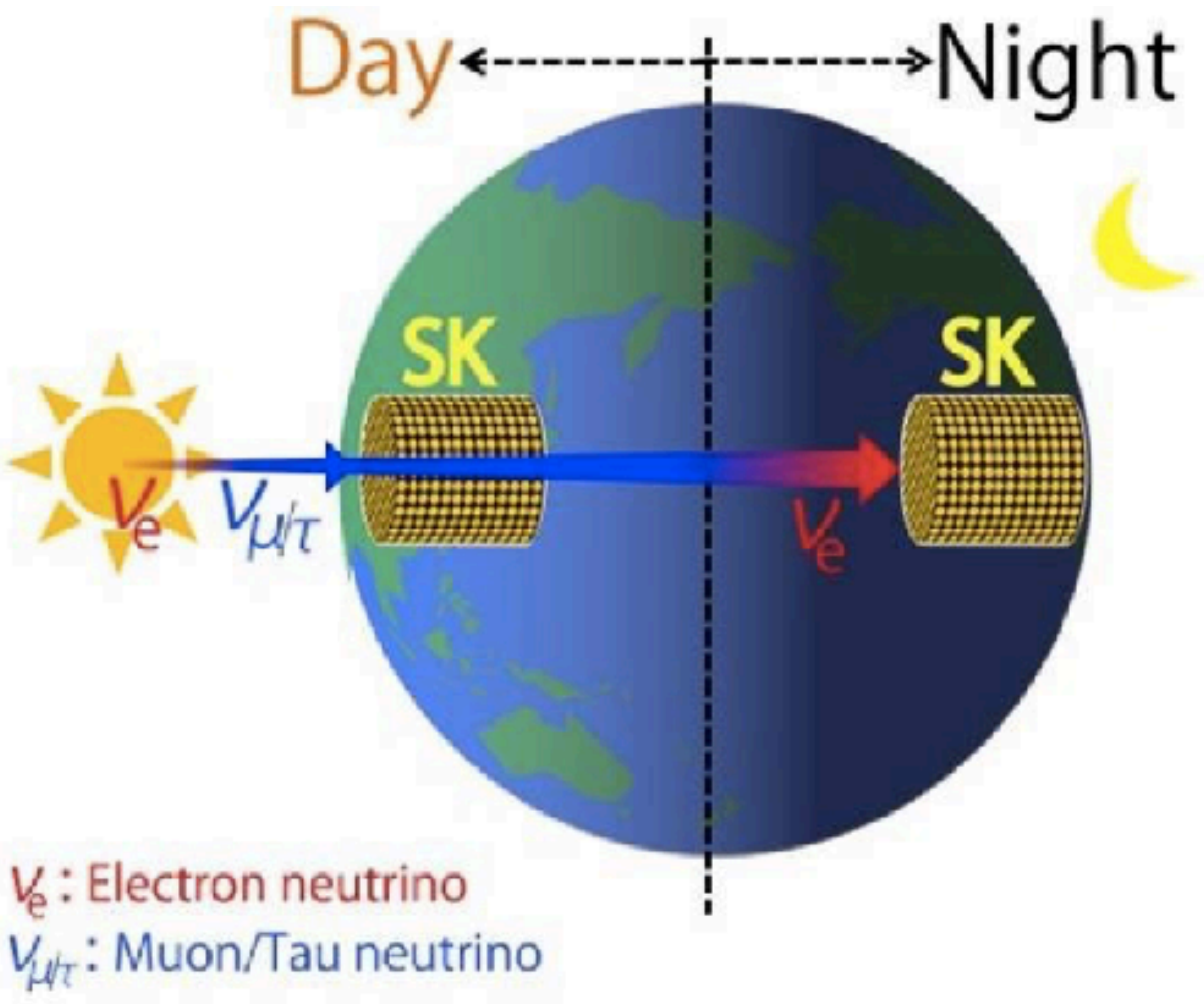
HK as Astronomical Observatory

- **Solar Neutrinos:**
  - *Upturn* in the vacuum-MSW transition.
  - Day-night asymmetry contributes to Δm^2_{21} KamLAND-solar measurement tension.

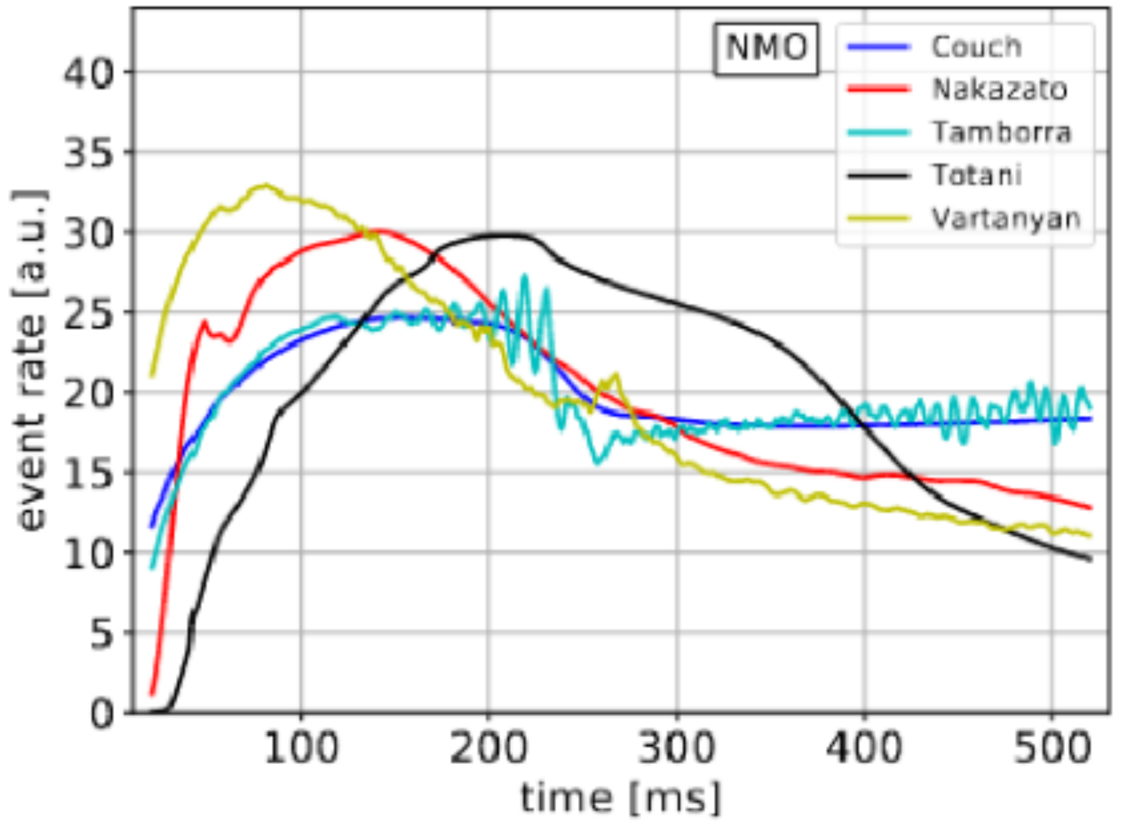
- **Supernova Neutrinos:**
  - Able to distinguish between SN models.
  - Ability to determine direction of supernova with ~1° accuracy, if within 10 kpc.



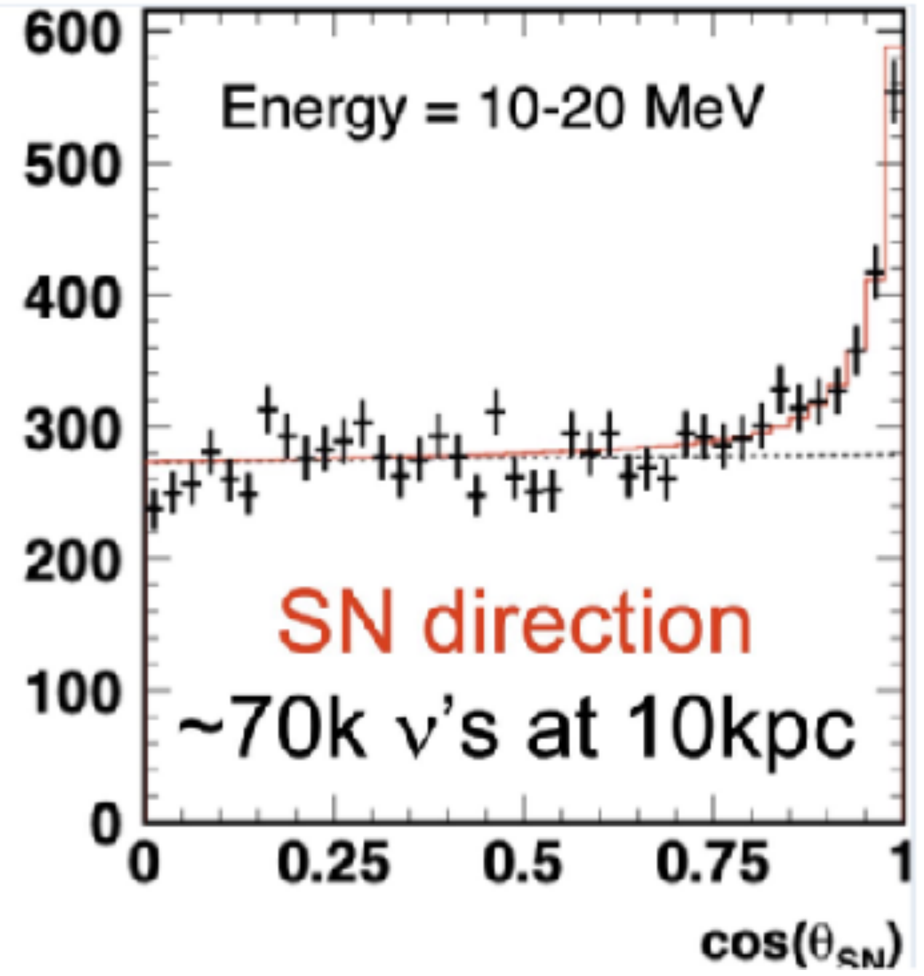
Matter Dominated Media Cause Upturn



MSW Effect Affects Nocturna Neutrino Flux



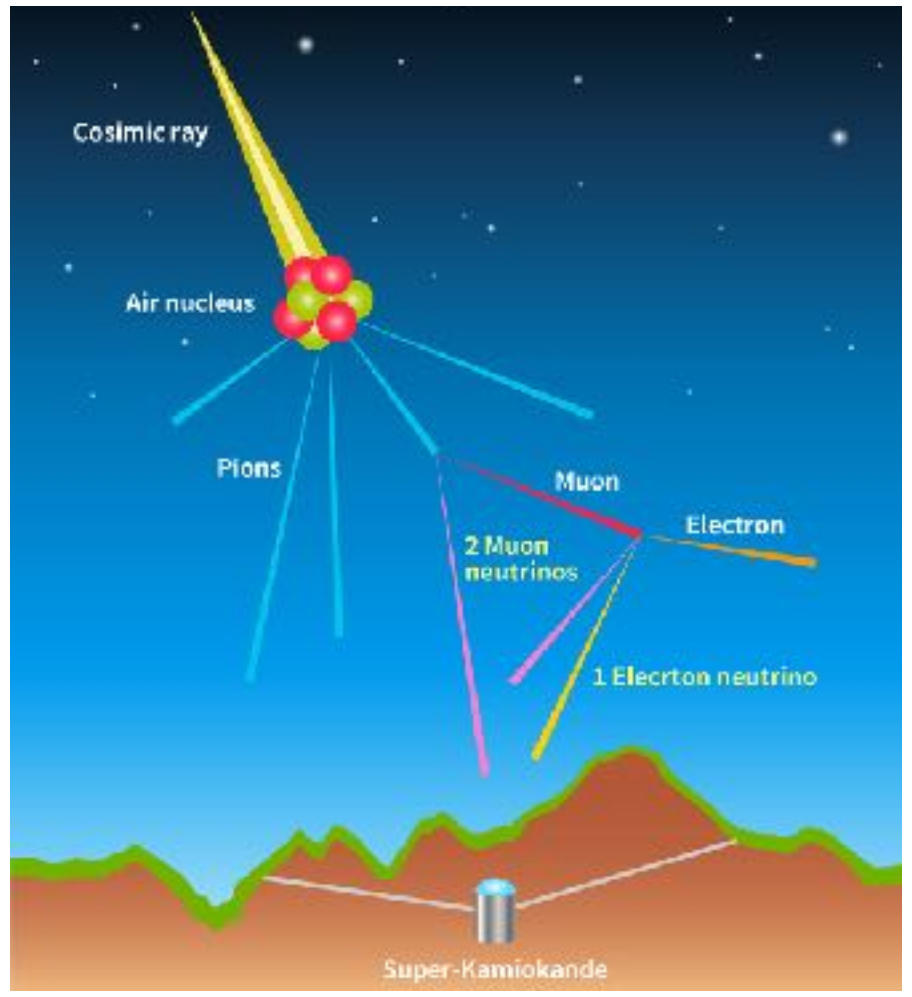
Models to be Discriminated During Accretion Interval



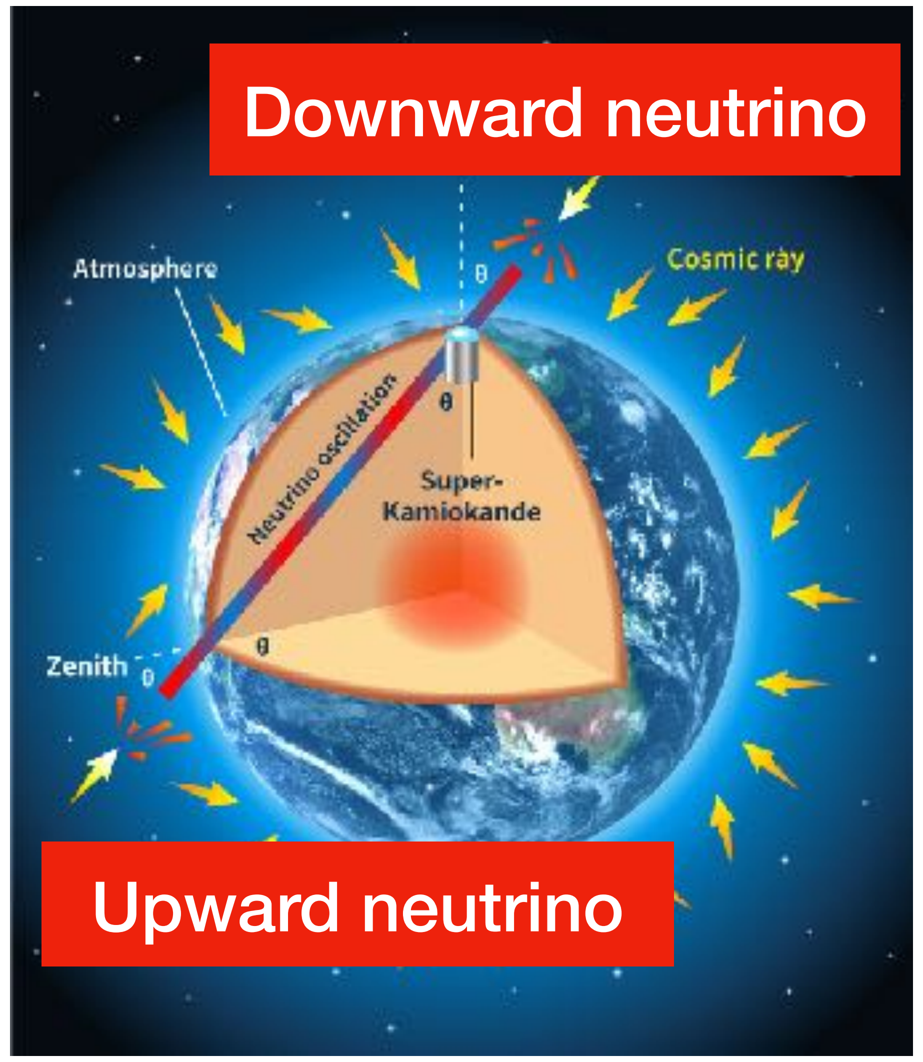
SN Direction

HK for Atmospheric Observations

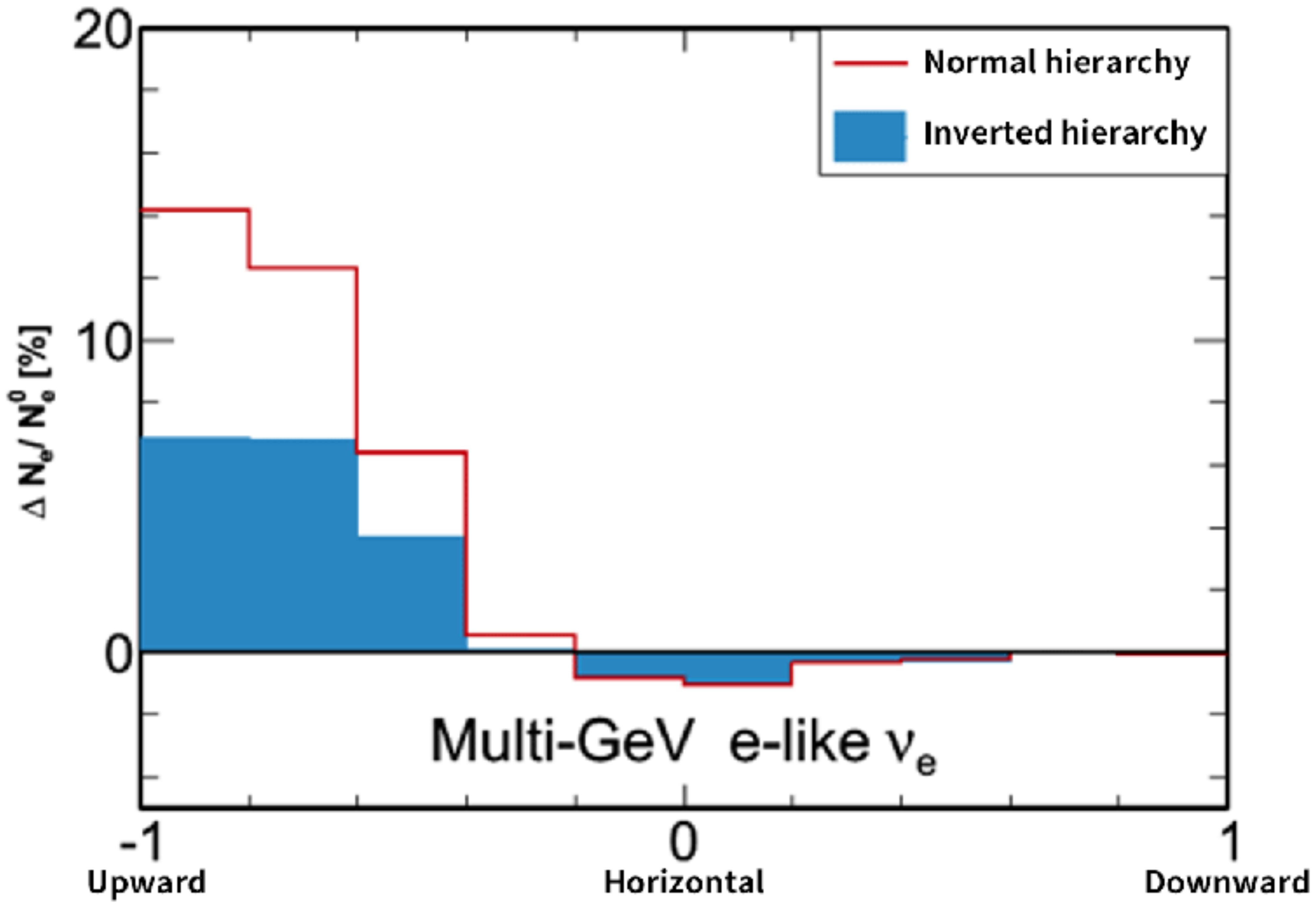
- Upward neutrino travels 13,000 km from opposite side of Earth.
- Normal hierarchy enhances upward neutrino oscillation into ν_e (not $\bar{\nu}_e$).
- Hyper-K → Better statistics and systematics towards up/downward.
- Provides complementary information for δ_{CP} measurements.

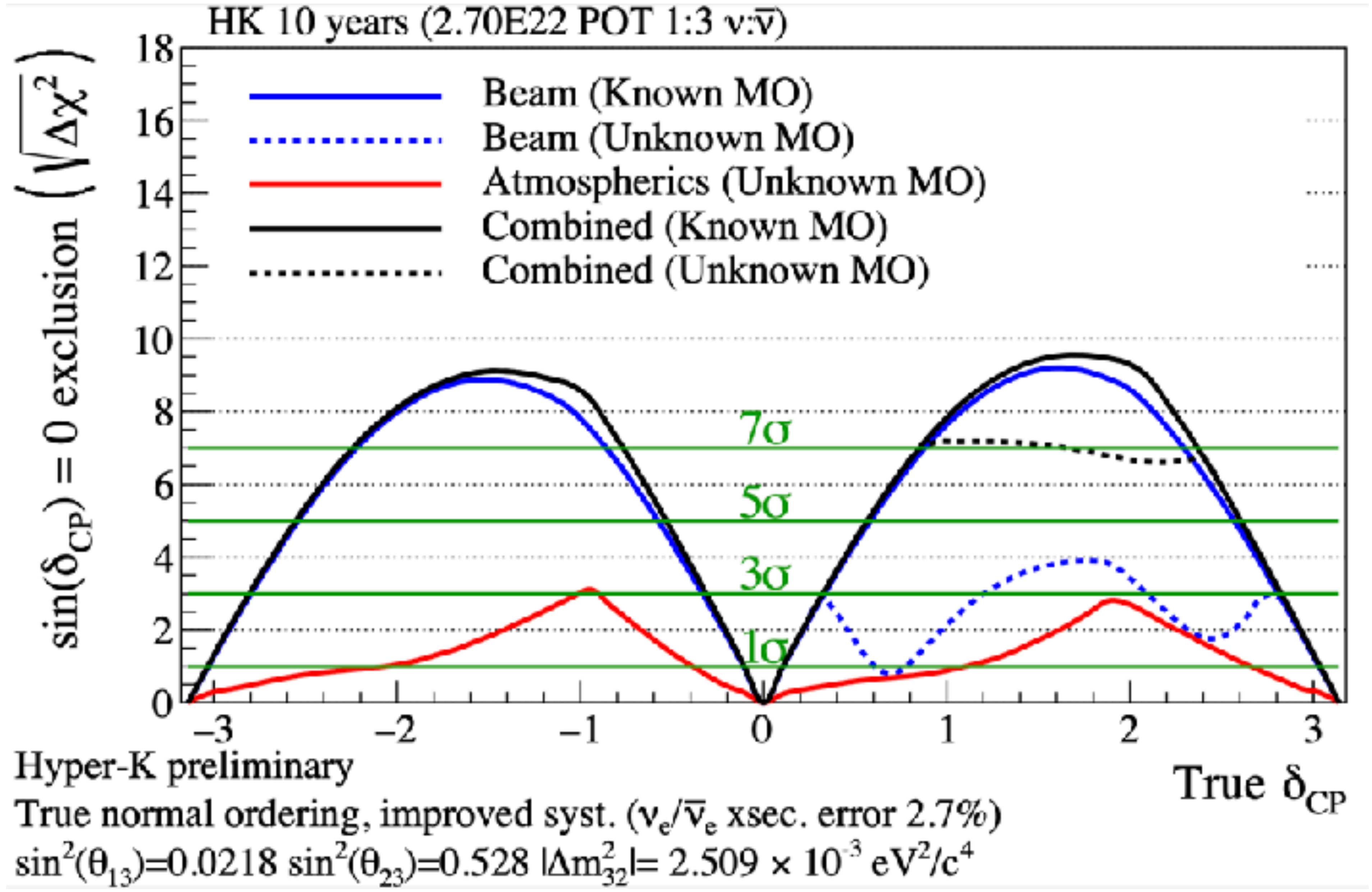


Neutrinos in the Air Shower



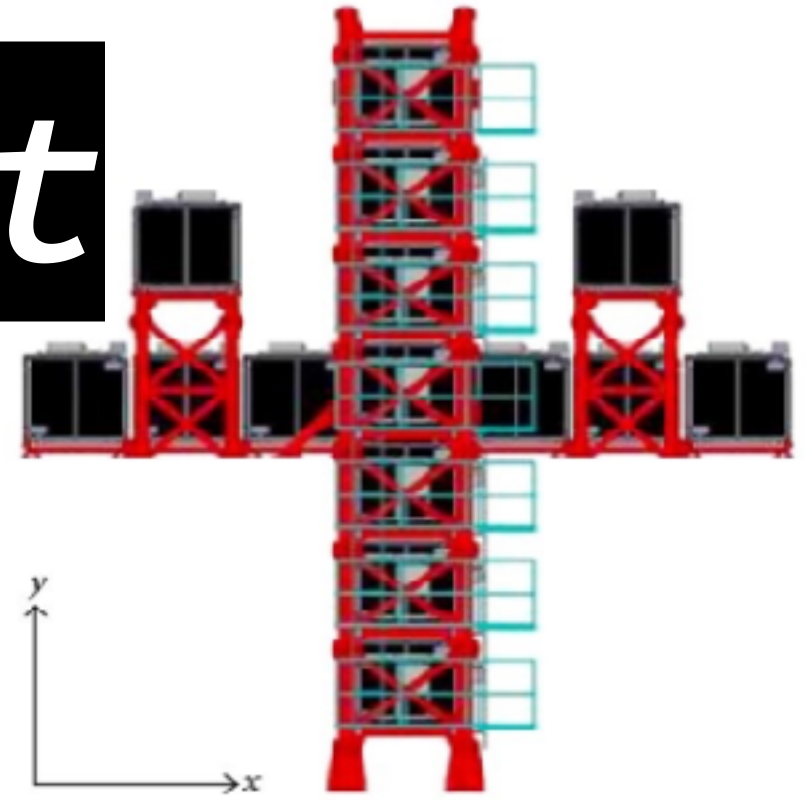
Up and Downward Neutrinos



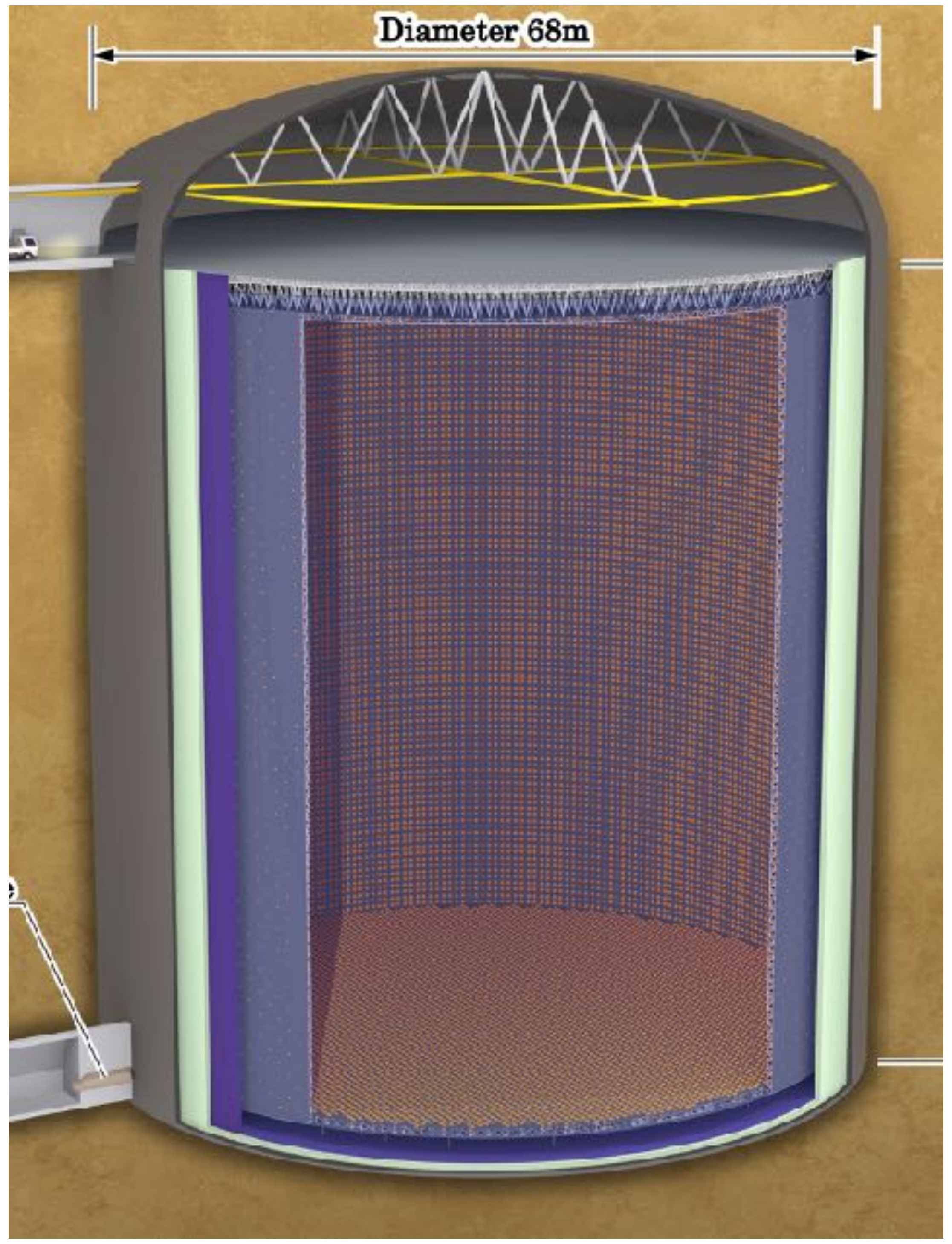


HK as Long Baseline Experiment

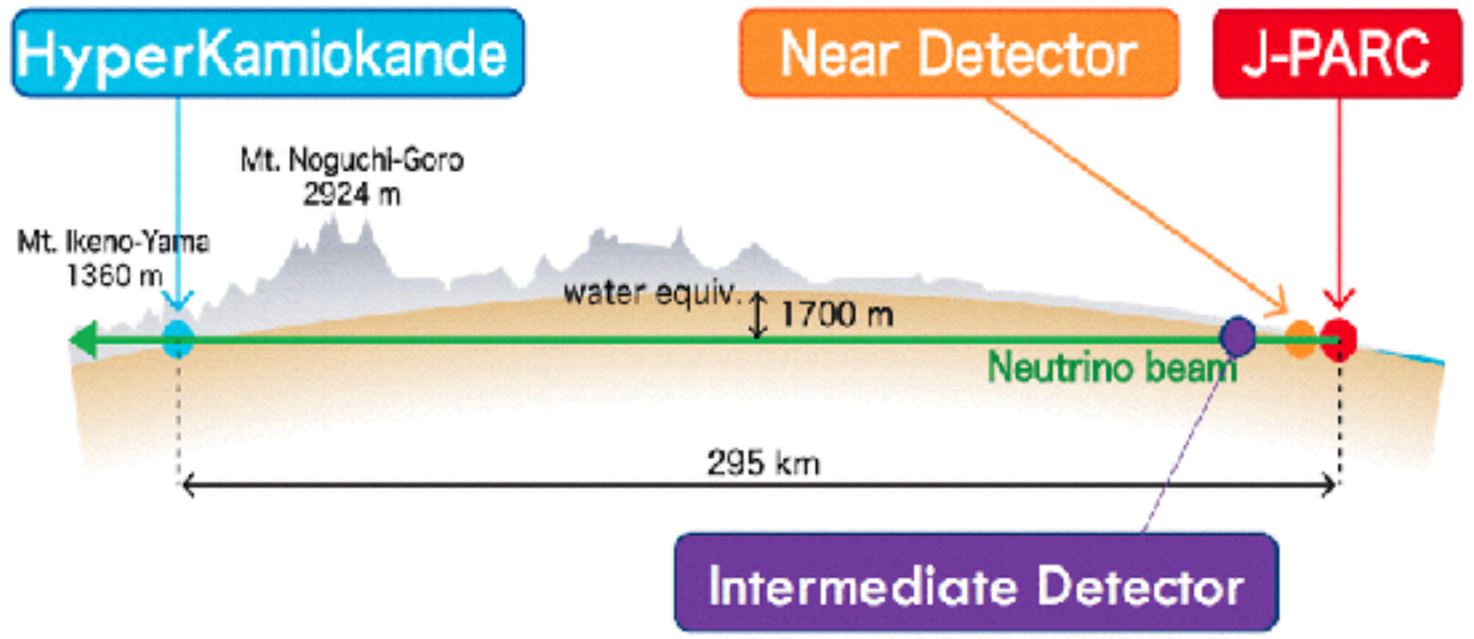
- Based on the successful T2K long-baseline neutrino experiment.
- HK will act as the far detector for the $\nu_\mu/\bar{\nu}_\mu$ beam generated at J-PARC.
- Upgraded near detectors (INGRID and ND280) and upcoming IWCD.



INGRID

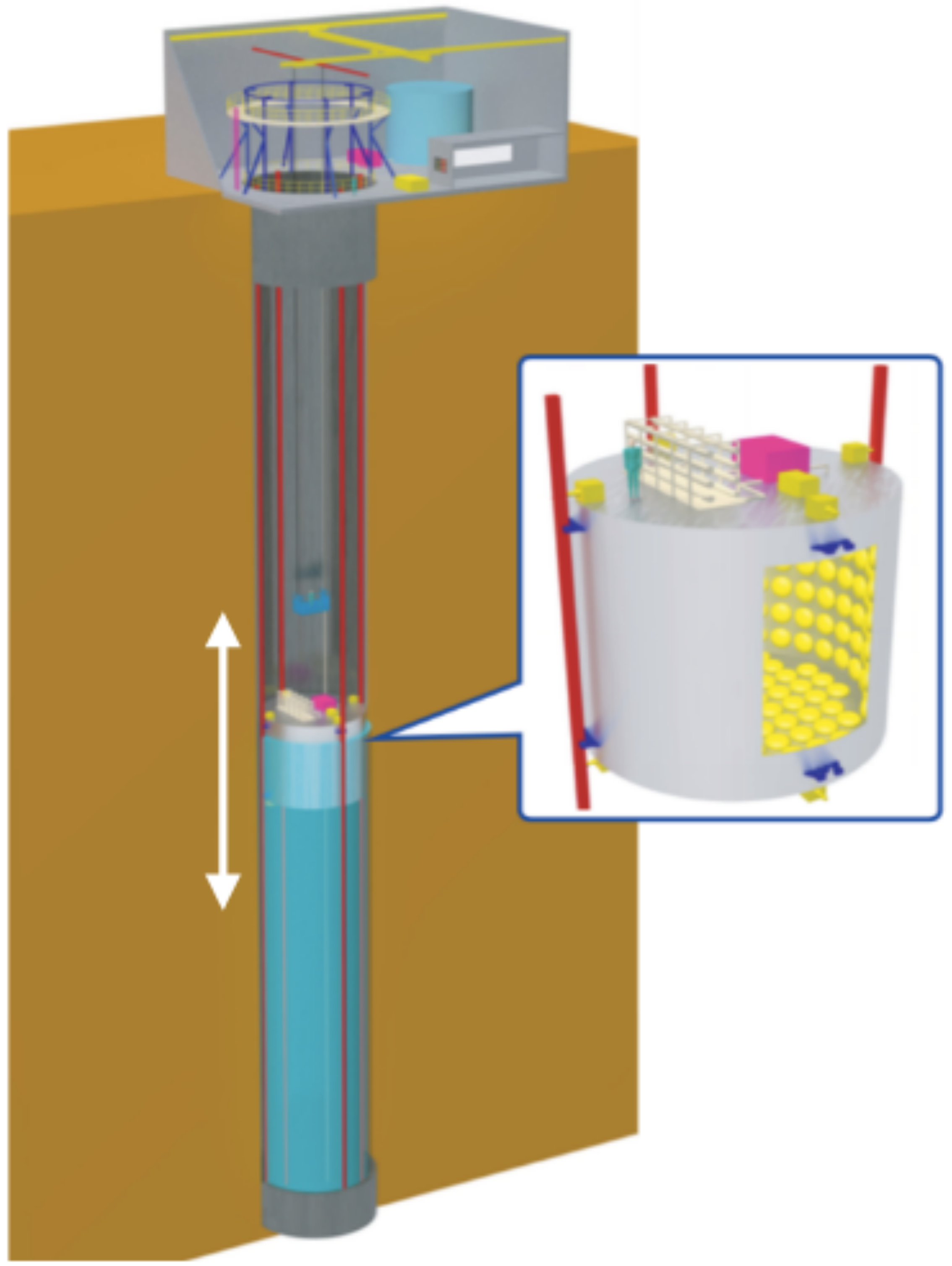


HK as Far Detector

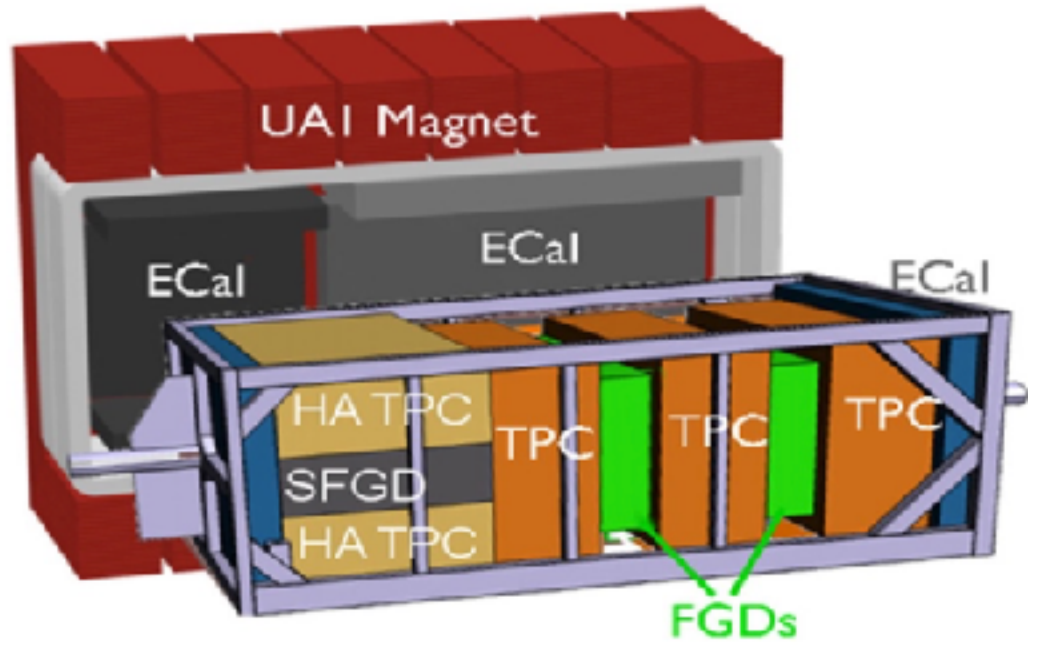


Long Baseline Diagram

Satellite View of HK Baseline



IWCD



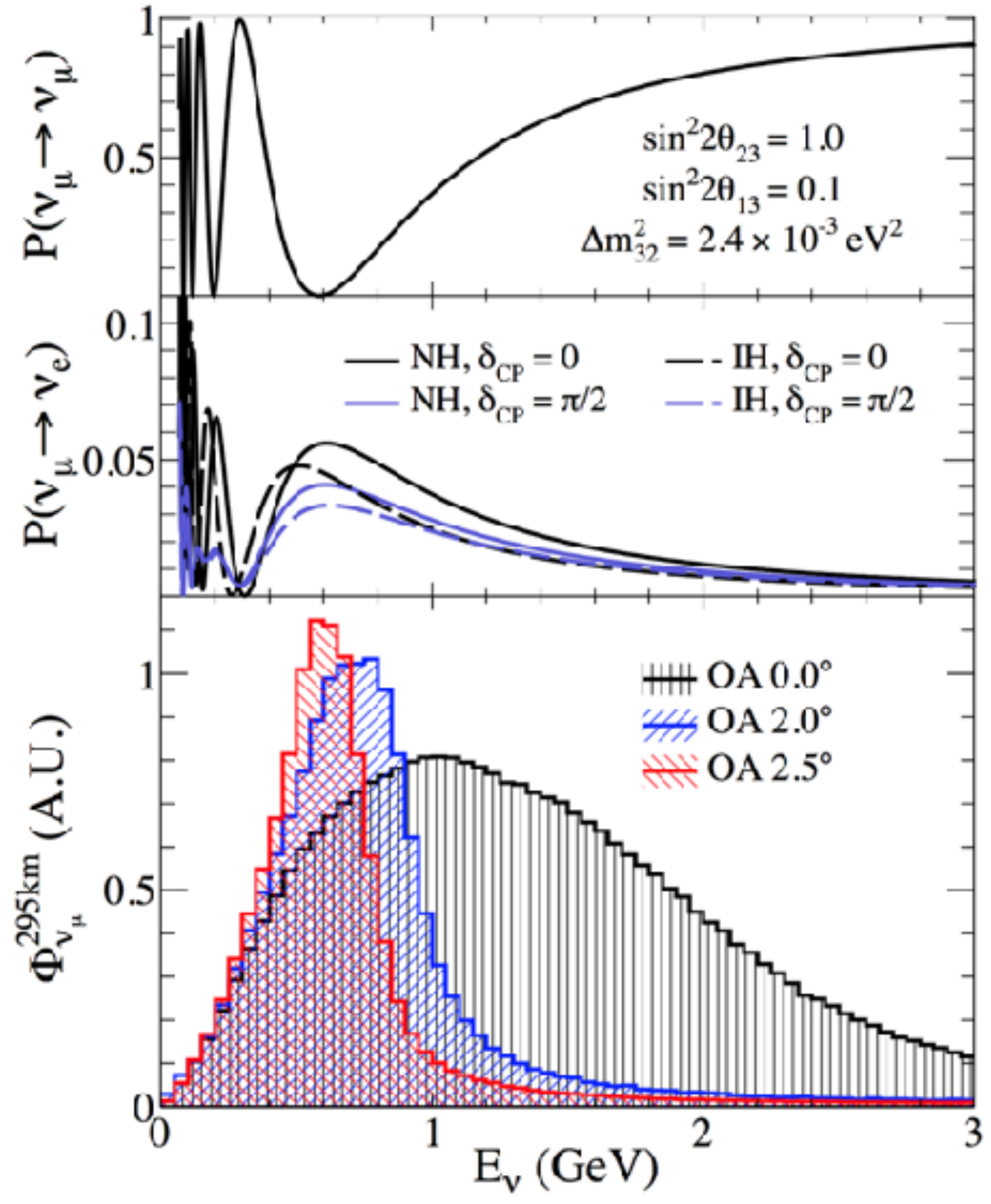
ND280

J-PARC

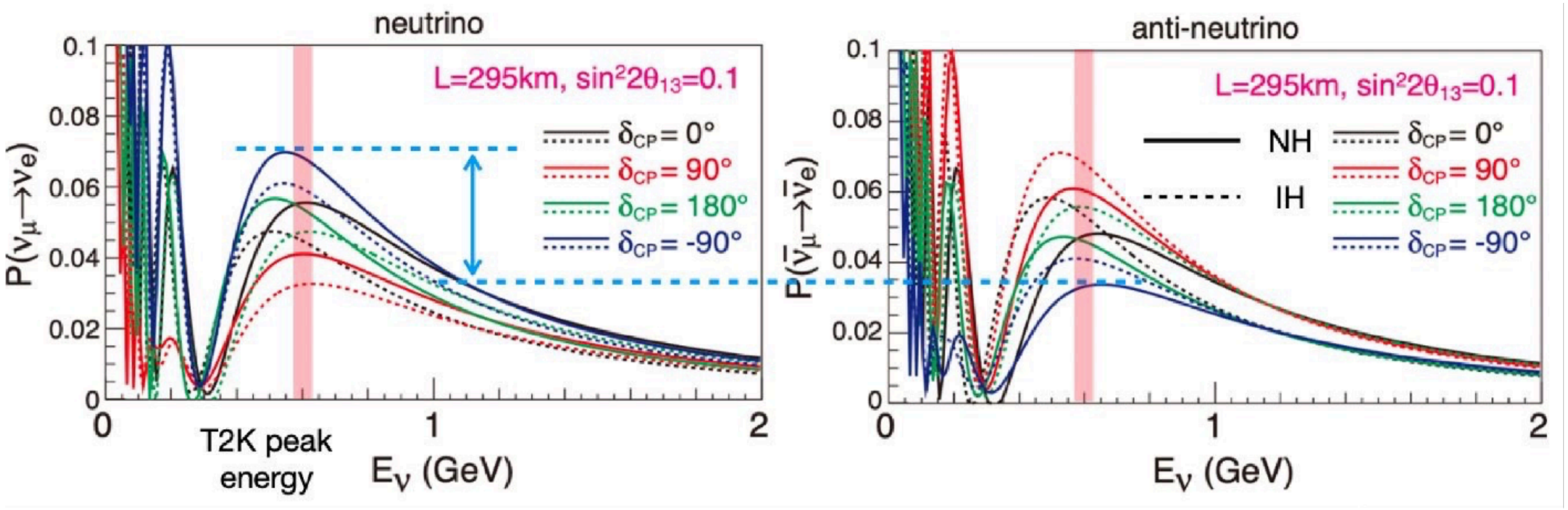
Sensitivity to δ_{CP}

- It is sensitive to δ_{CP}-violation phase, measuring the oscillation $\nu_\mu/\bar{\nu}_\mu \rightarrow \nu_e/\bar{\nu}_e$.
- At a distance of 295 km, oscillation is maximal at 2.5˚ off-axis angle to the neutrino beam.

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



Oscillation is Maximal at 2.5˚ OA

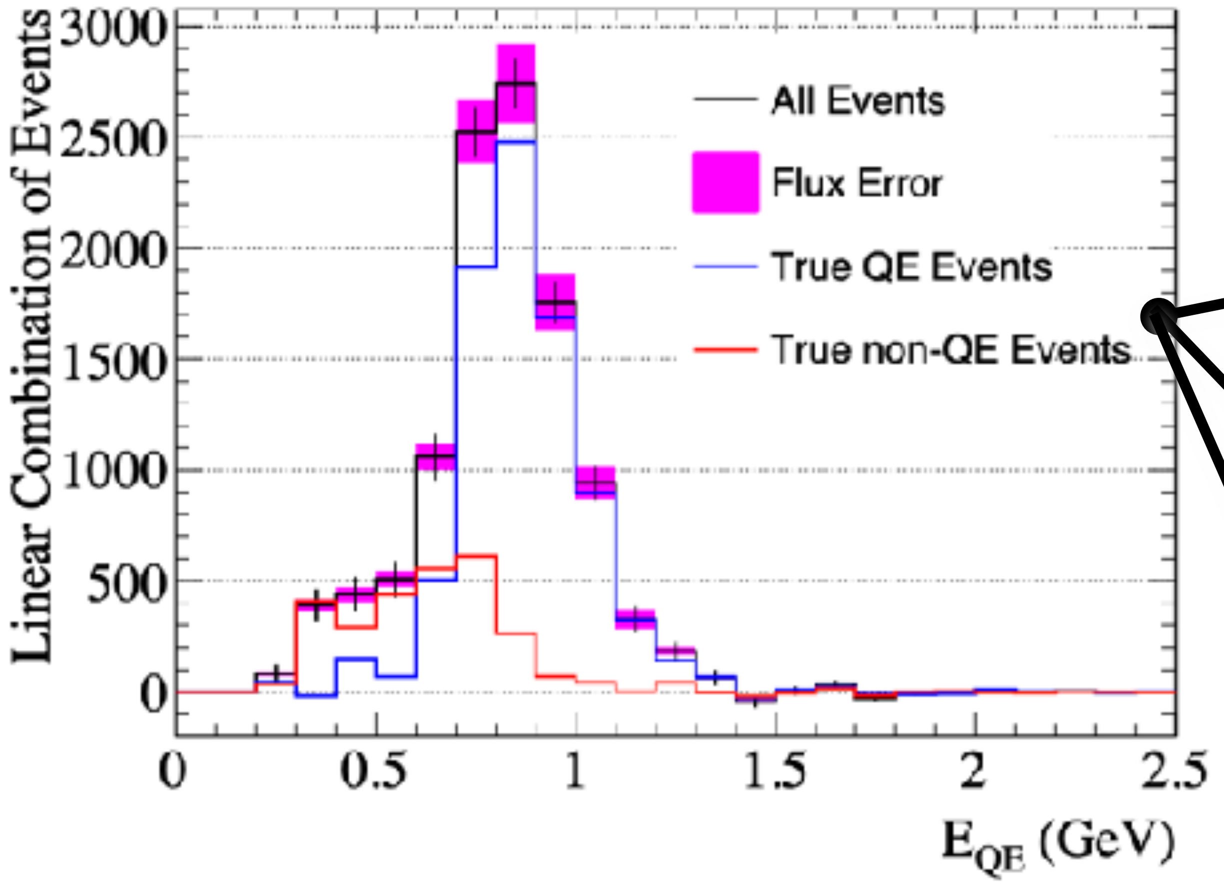


- 10 years of operation, HK expects 1000 ν_e and $\bar{\nu}_e$ events.

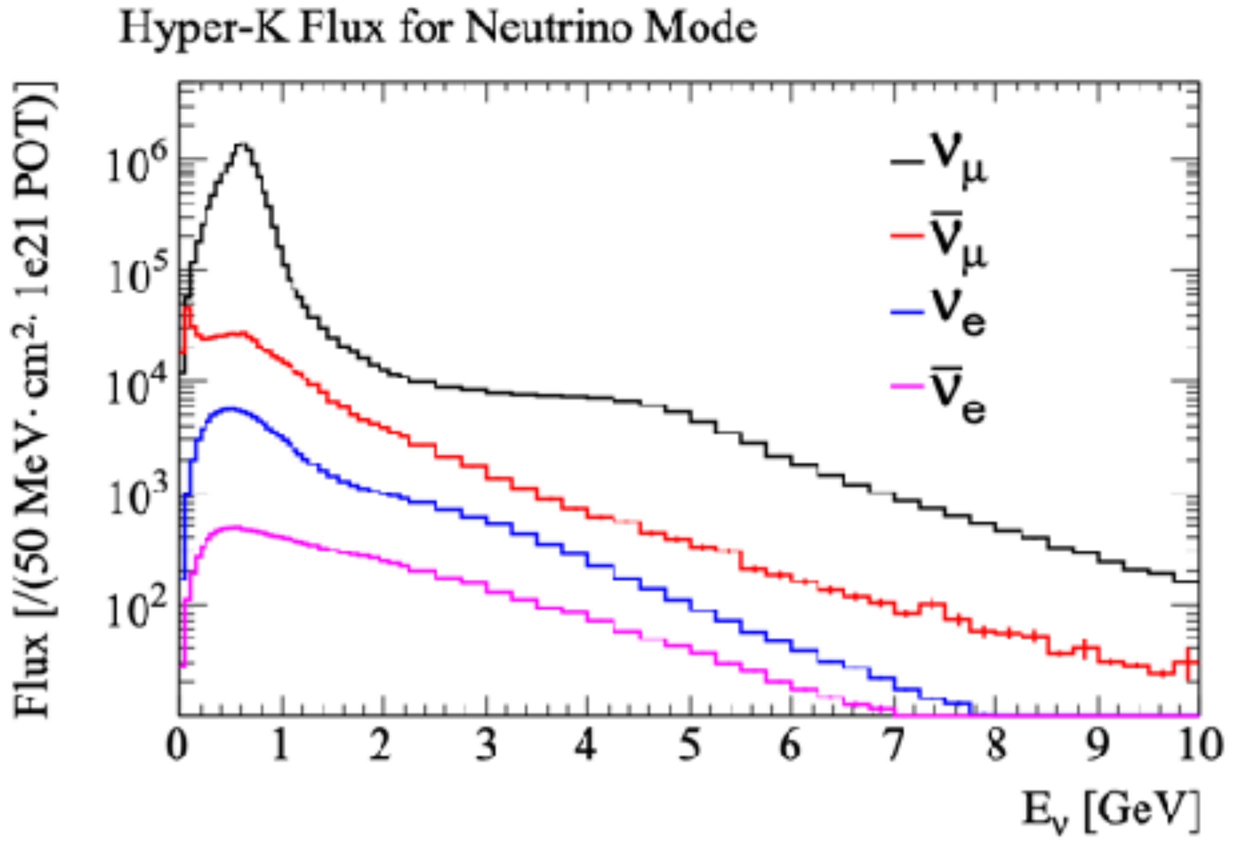
Intermediate Water Cherenkov Detector

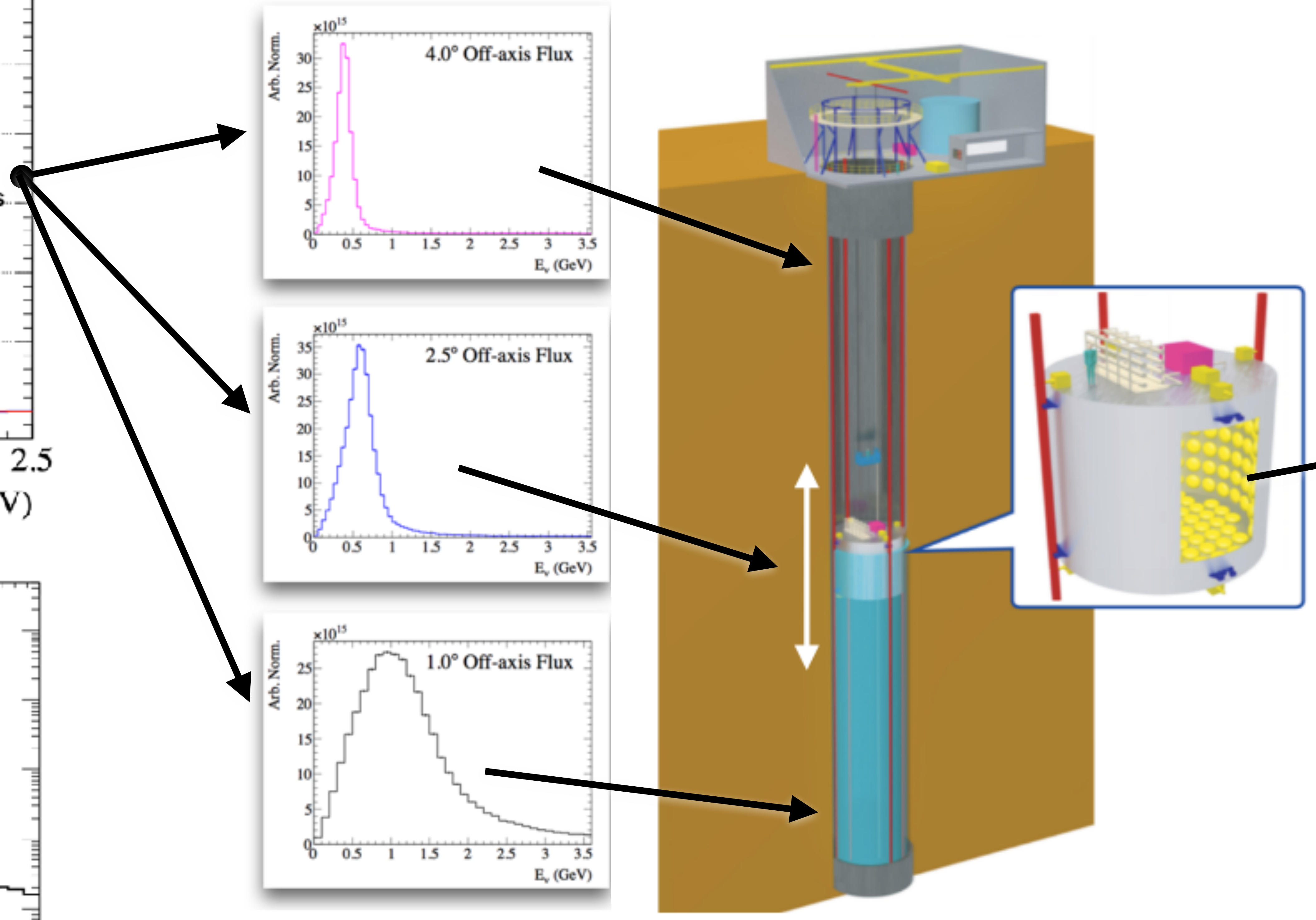
- At 1 km distance to J-PARC, uses nuPRISM approach to measure the beam energy espectrum.
- Reproduction of neutrino energy spectrum at far detector. Bypassing of oxygen cross-section models.
- Introduction of the mPMT system, with directional information, higher granularity and improved timing.

At IWCD



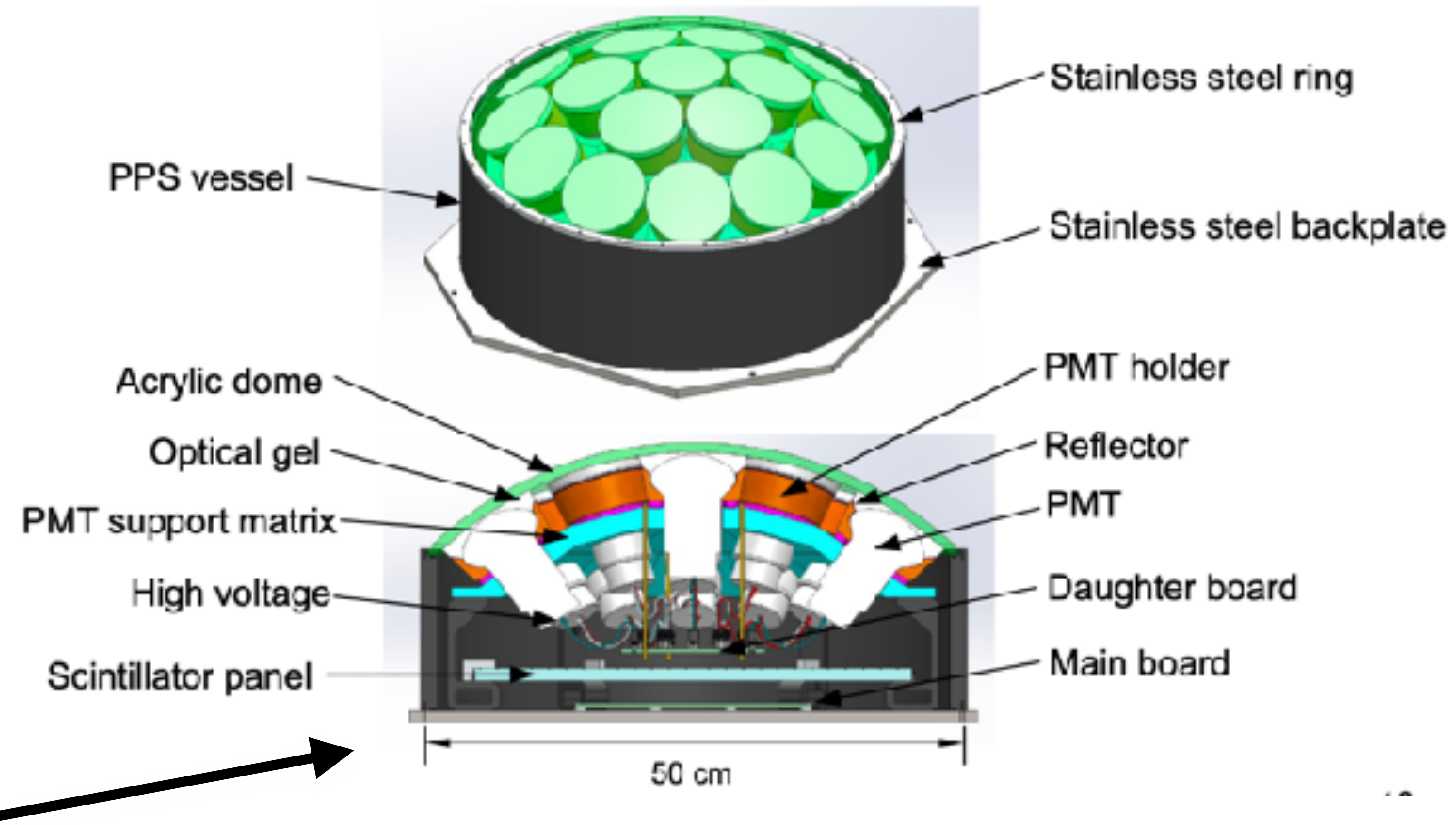
At HK Far Detector





Energy Spectrum

IWCD

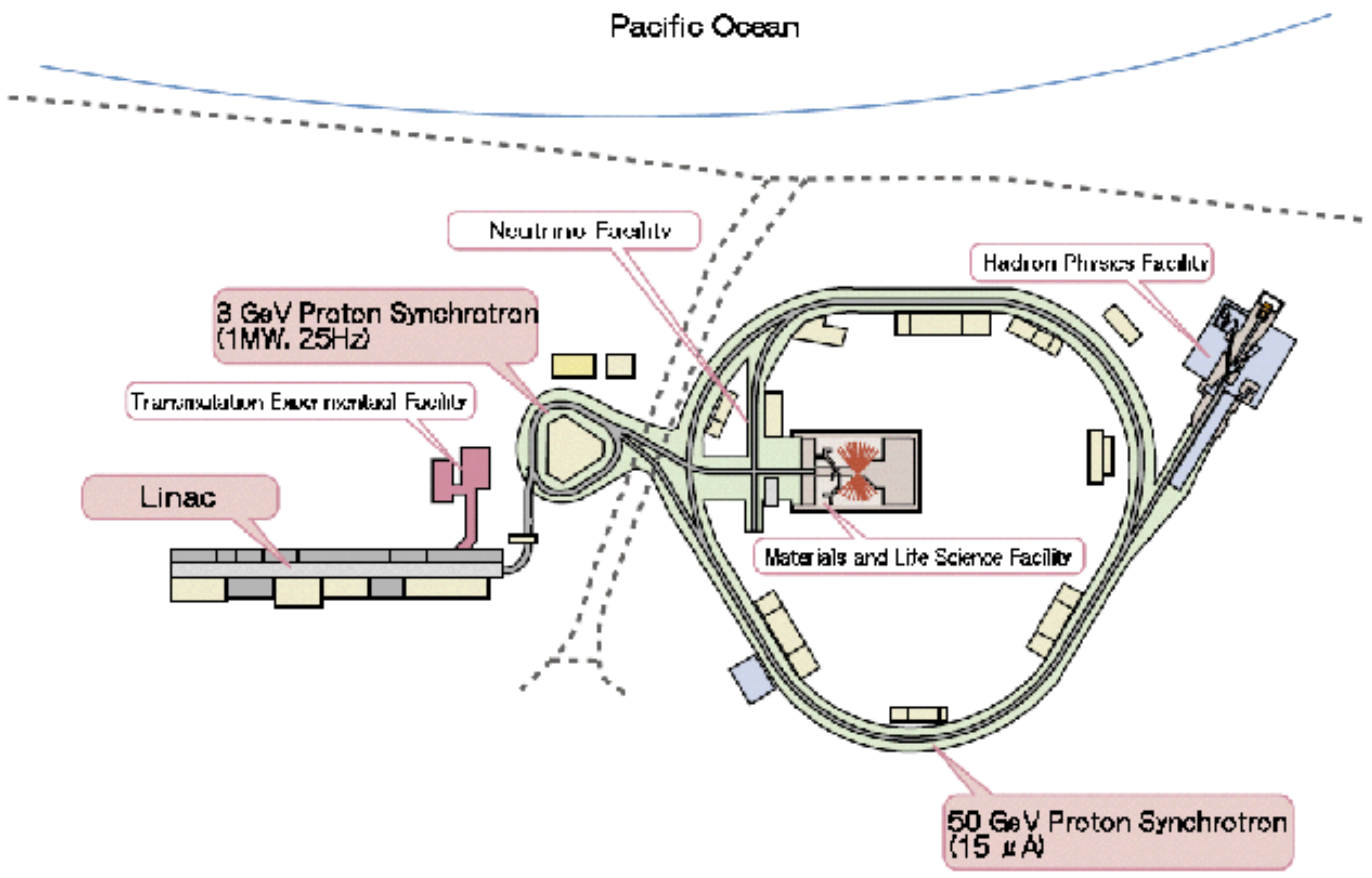


mPMT Internal Components

mPMT Prototype

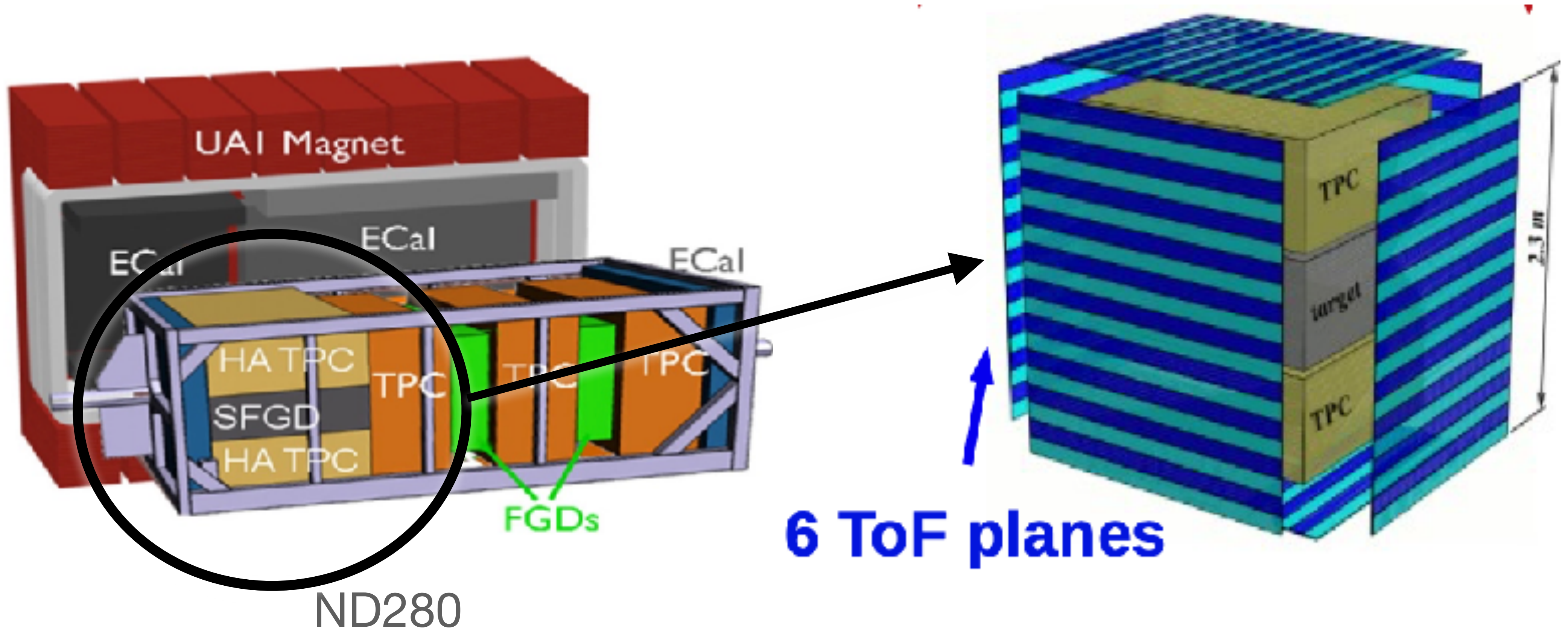
J-PARC and Near Detector Upgrades

- **Upgrading J-PARC neutrino beam:**
  - Power increase: 515 kW → 1.3 MW.
  - Horn currents: 250 kA → 320 kA.
  - Extraction cycle: 2.48 s → 1.32 s → 1.16 s.



Higher beam intensity improves HK statistics.

- **Upgrading ND280 Complex:**
  - Fine Grained Detector → Super FGD.
  - Horizontal Time Projection Chambers.
  - Time of Flight Planes.



Overall improvement in systematics.

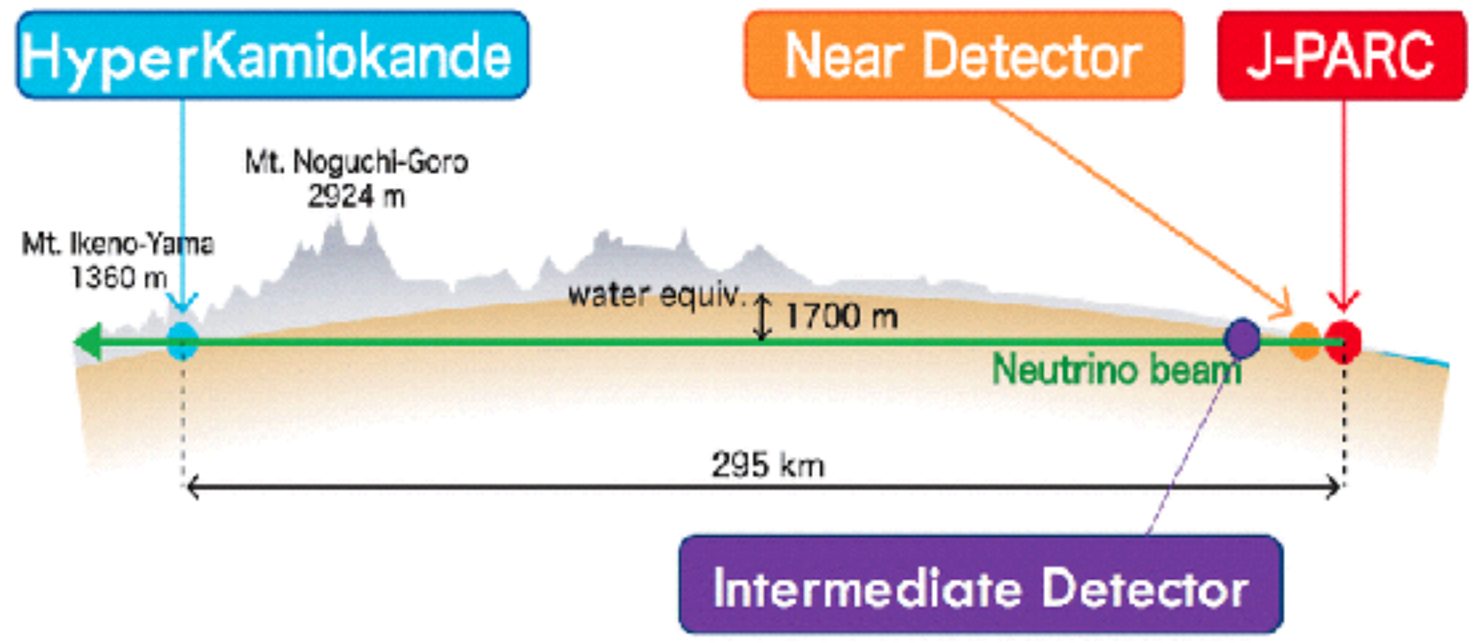
- Improved angular acceptance.
- Improved hadronic information.
- Better π^0 ($\gamma \rightarrow e^- + e^+$) identification.

Toward Discovery of Leptonic δ_{CP}

- Could a leptonic δ_{CP} explain matter-antimatter asymmetry in the Universe?
- Complementary approach between IWCD and ND280 for the **improvement of δ_{CP} uncertainties.**

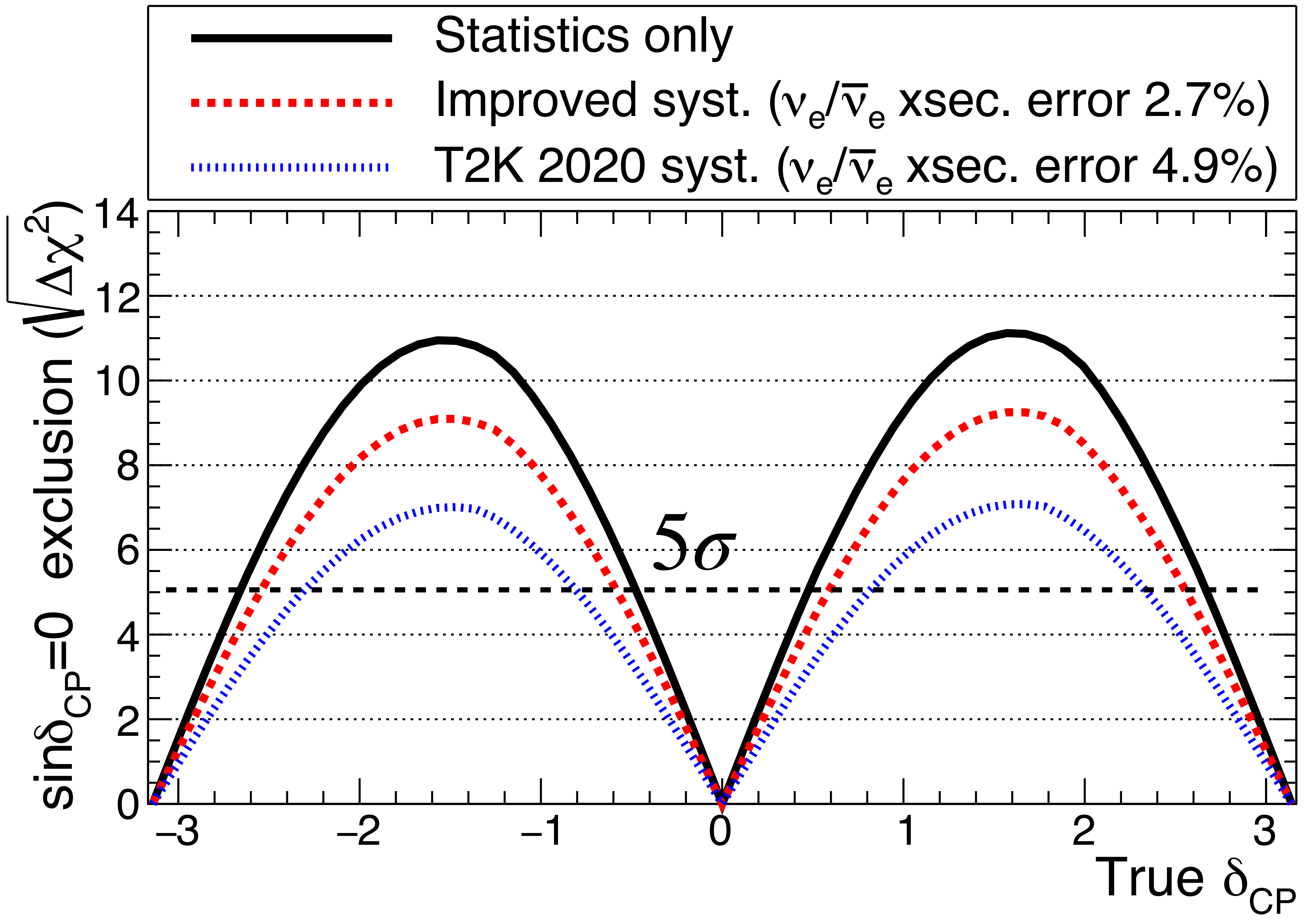
Systematic Source	Required Precision	For Which Measurement	Detector	Achievable Precision
$\sigma(\nu_e)/\sigma(\nu_\mu)$	3-5%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim 0$, θ_{23} precision at $\sin(\theta_{23})\sim 0.5$	IWCD	3.5-5%
$\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	3-5%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim 0$, θ_{23} precision at $\sin(\theta_{23})\sim 0.5$	IWCD	4-7%
Wrong-sign background normalization	9%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim 0$	ND280	TBD (expect <9%)
Intrinsic ν_e,$\bar{\nu}_e$ and NC backgrounds	3-4%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim 0$	IWCD	2.3% (neutrino)
Normalization of non-QE with E_ν>0.7 GeV	5%	θ_{23} precision at $\sin(\theta_{23})\neq 0.5$	IWCD	5% (neutrino)
Normalization of non-QE with all energies	5%	δ_{cp} precision at $\sin(\delta_{cp})\sim 0$, Δm^2_{32} precision	IWCD, ND280*	5% (IWCD neutrino), <4% (N280 neutrino), <7% (ND280 antineutrino)

A Few Sources of Systematic Uncertainties / Credits: Mark Harz.

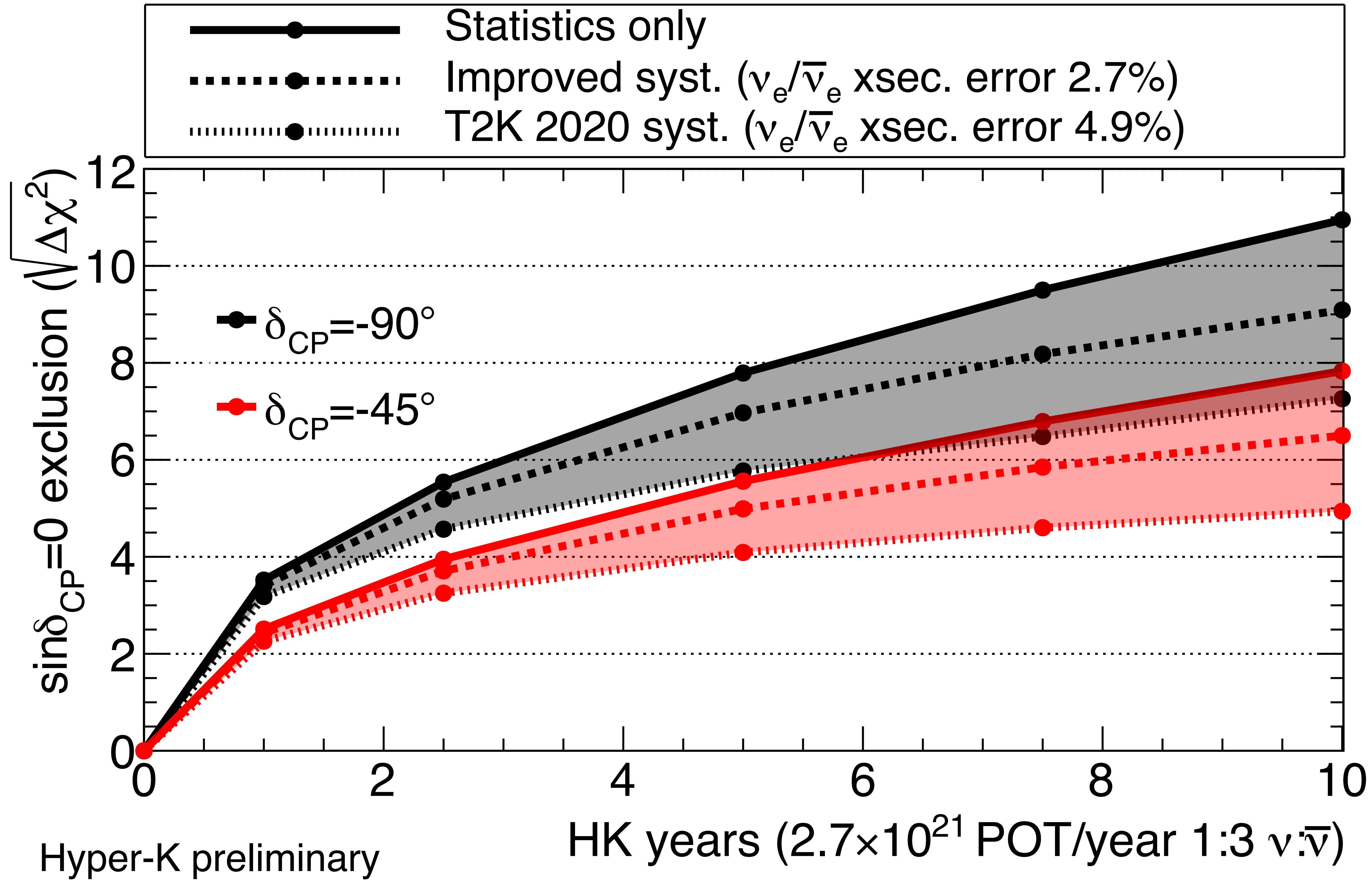


Long Baseline Diagram

Toward Discovery of Leptonic δ_{CP}



Hyper-K preliminary
True normal ordering (known), 10 years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)
$\sin^2\theta_{13}$=0.0218±0.0007, $\sin^2\theta_{23}$=0.528, $\Delta m^2_{32}=2.509\times10^{-3}\mathrm{eV}^2/c^4$



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$\sin^2\theta_{13}$=0.0218±0.0007, $\sin^2\theta_{23}$=0.528, $\Delta m^2_{32}=2.509\times10^{-3}\mathrm{eV}^2/c^4$

- With known mass hierarchy and improved systematics: true $\delta_{CP} = -\pi/2 \rightarrow 5\sigma$ CP violation.

Conclusions

- Hyper-Kamiokande acts as cosmological and atmospheric observatory, and far detector for long-baseline neutrino experiments.
- HK detector offers 8 times fiducial mass as Super-K.
- Excavation reached important milestones with completion of access tunnel and dome.
- Larger proton sample aims for larger lower limit in proton decay time.
- Statistics and sensitivity allows for rich physics program, aiming to measure solar, supernova and relic neutrinos.
- Determination of mass ordering problem and discovery of CP-violation in lepton sector may be achieved by improving systematic uncertainties in long-baseline detector complex.
- Introduction of the IWCD and mPMT system to control the systematics.
- Upgraded J-PARC neutrino beam line and near detector complex.