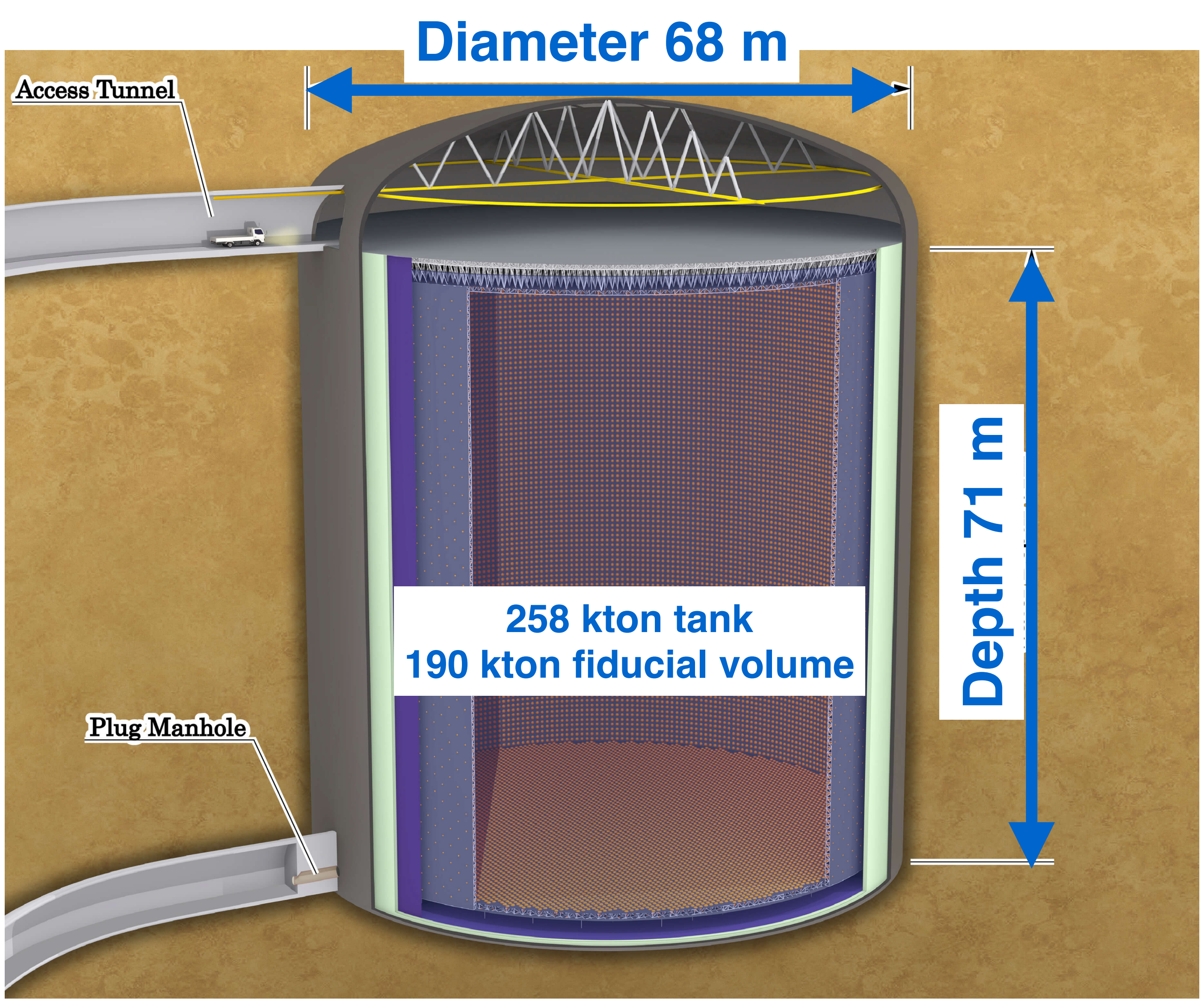
Hyper-Kamiokande

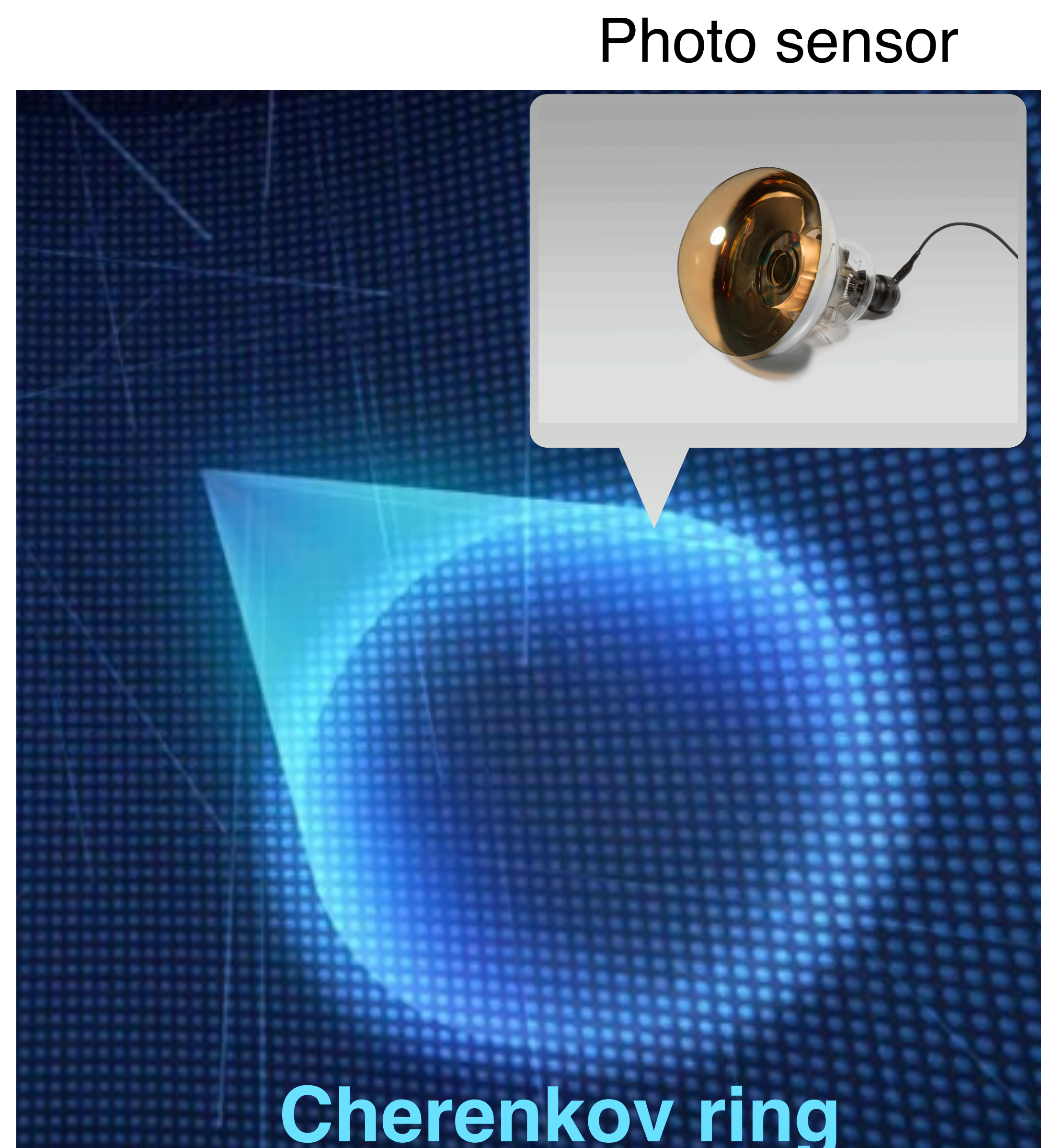
ICRR Young Researcher Workshop, 2024 July 17th

Yohei Noguchi

Hyper-Kamiokande detector

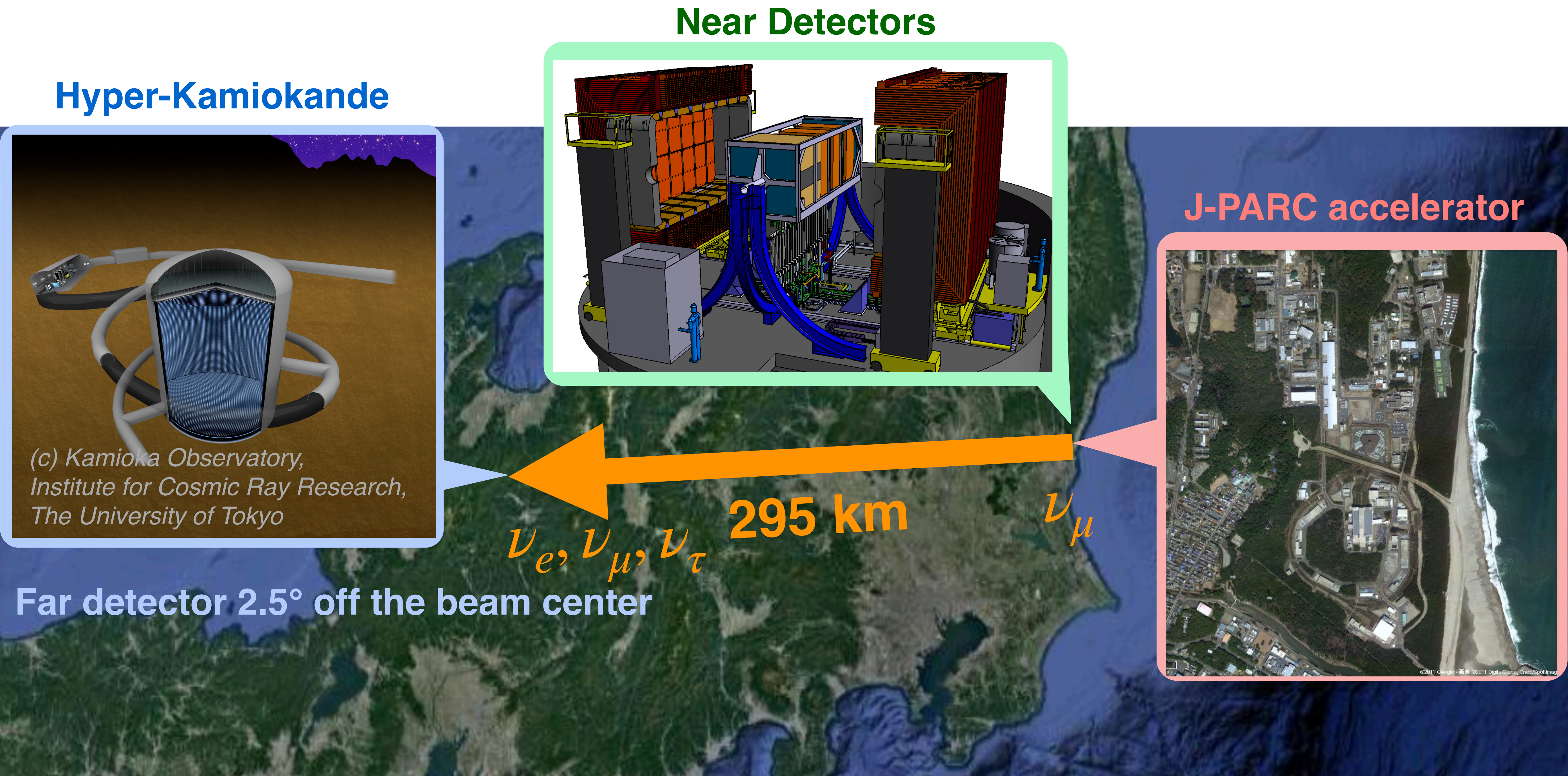
- **Next generation water Cherenkov detector in Kamioka, Japan.**
- **258 kton water tank: fiducial mass ×8 larger than Super-K.**
- **20,000 improved 50 cm PMTs to detect Cherenkov light.**
  - **1,000 multi-PMTs, 3,600 3-inch OD PMTs**





Hyper-Kamiokande project

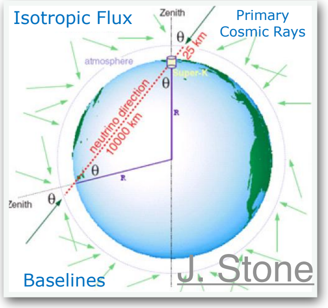
- Joint project combining a large water Cherenkov detector and even more intense neutrino beam with the J-PARC accelerator.
- Upgraded near detectors constraining the neutrino beam before oscillation



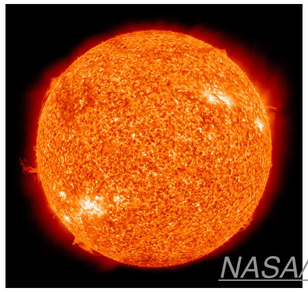
Physics targets at Hyper-Kamiokande

- Many research topics approaching the "origins" of the matters and the universe using neutrinos.

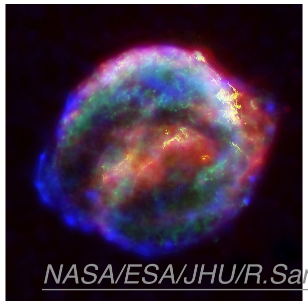
- **Neutrino oscillation**
  - *Accelerator + atmospheric neutrinos (Long Baseline):*
    - CP violation as the "origin" of the matter dominant universe.
    - Mass ordering.
  - *Solar neutrinos:*
    - Non-standard oscillations and interactions through matter effects in the electron neutrino disappearance.



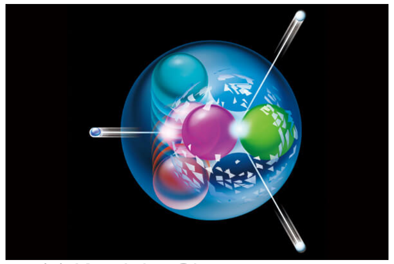
J. Stone


NASA/SDO (AIA)

- **Neutrino astrophysics**
  - *Supernova burst and supernova relic neutrino:* explosion mechanism, the "origin" of nuclei heavier than Fe, and star formation "history" of the universe.


NASA/ESA/JHU/R.Sankrit & W.Blair

- **Nucleon decays**
  - Evidence of the Grand Unified Theory.
  - The "origin" of the Standard Model of the elementary particles.


(c) Kamioka Observatory, Institute for Cosmic Ray Research, The University of Tokyo

Neutrino oscillation

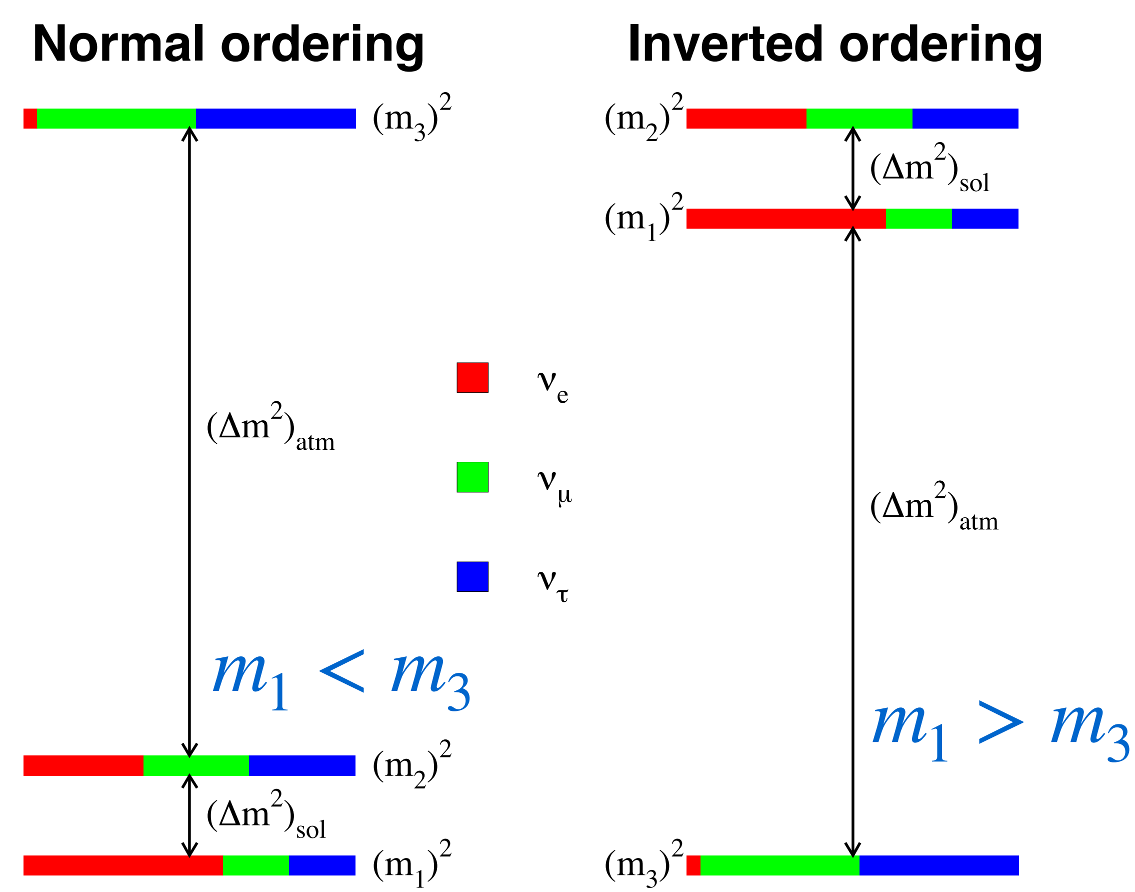
- **Neutrino oscillations take place because of the flavor-mass mixing:**

$$U_{\rm PMNS} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta_{CP}} \\ & 1 & \\ -s_{13}e^{i\delta_{CP}} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

Various baseline lengths and energies ➔

Atmospheric-ν	Reactor-ν	Solar-ν
Accelerator-ν	Accelerator-ν	Reactor-ν
$\theta_{23} \sim 45^\circ$	$\theta_{13} \sim 8^\circ$	$\theta_{12} \sim 34^\circ$

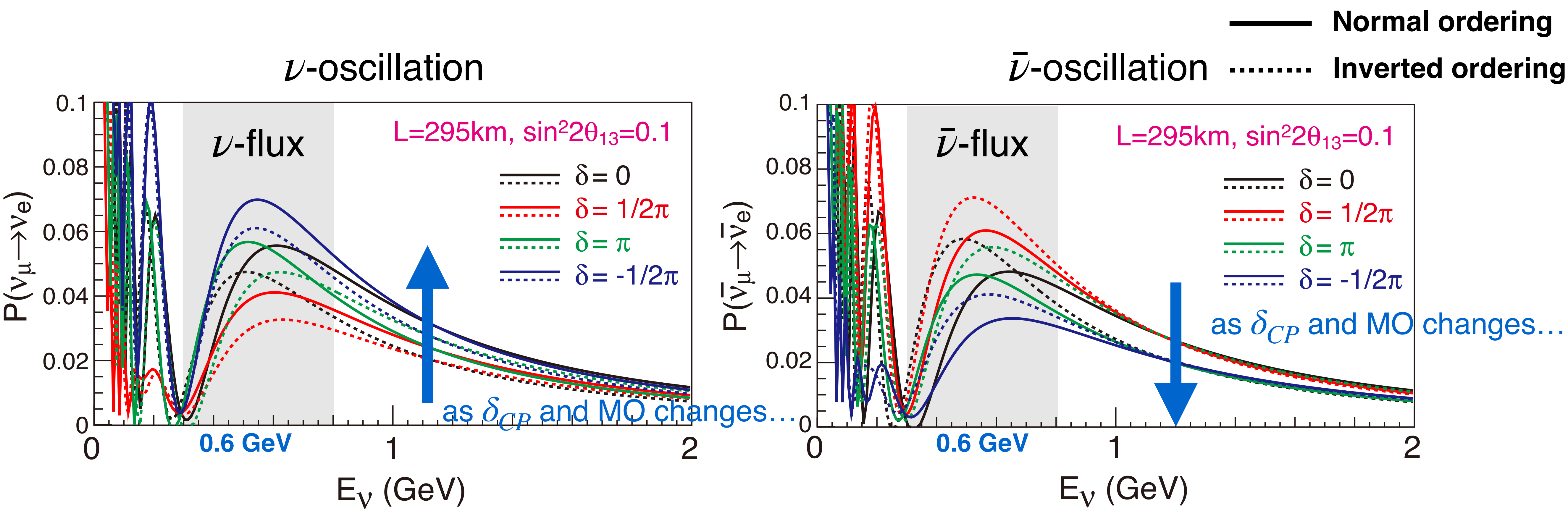
- **<u>Open questions in the neutrino oscillation</u>:**
  - **CP violating phase**: δ_{CP}
    - **Possible source of <u>the baryon asymmetry of the universe.</u>**
  - **Mass ordering**: **sign of** Δm^2_{13}
    - **Oscillation in vacuum → only** $|\Delta m^2_{13}|$
    - **Need to see the <u>matter effect</u>.**



A. de Gouvea, "On Determining the Neutrino Mass Hierarchy", FNAL Theory Seminar (2006)

Accelerator neutrino oscillation experiment

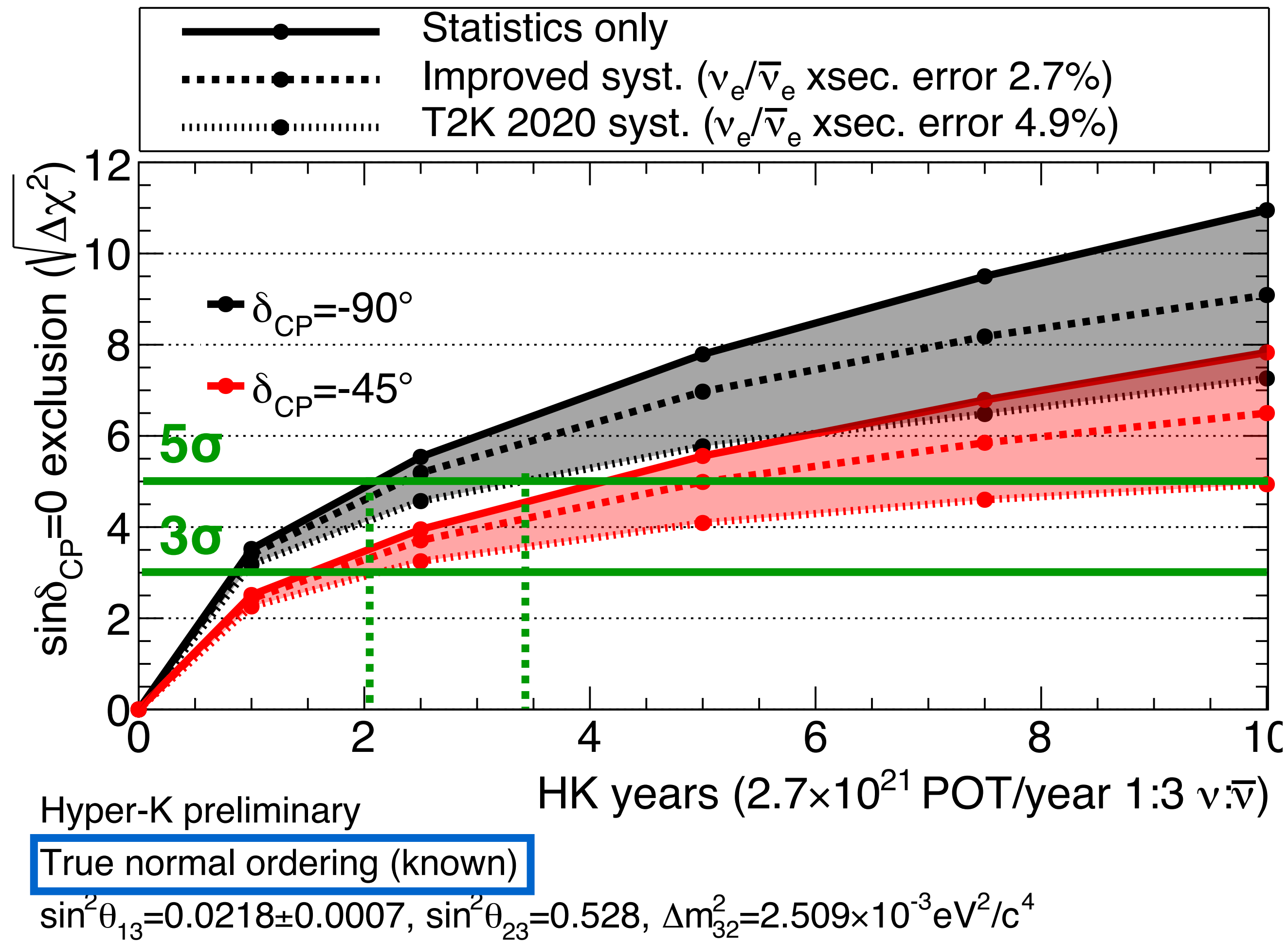
- **CP-symmetry tested with ν-beam and $\bar{\nu}$-beam enabled by the polarity of the focusing magnets.**
- **2.5° off-axis arrangement focuses the neutrinos on the osc. maximum at 0.6 GeV.**

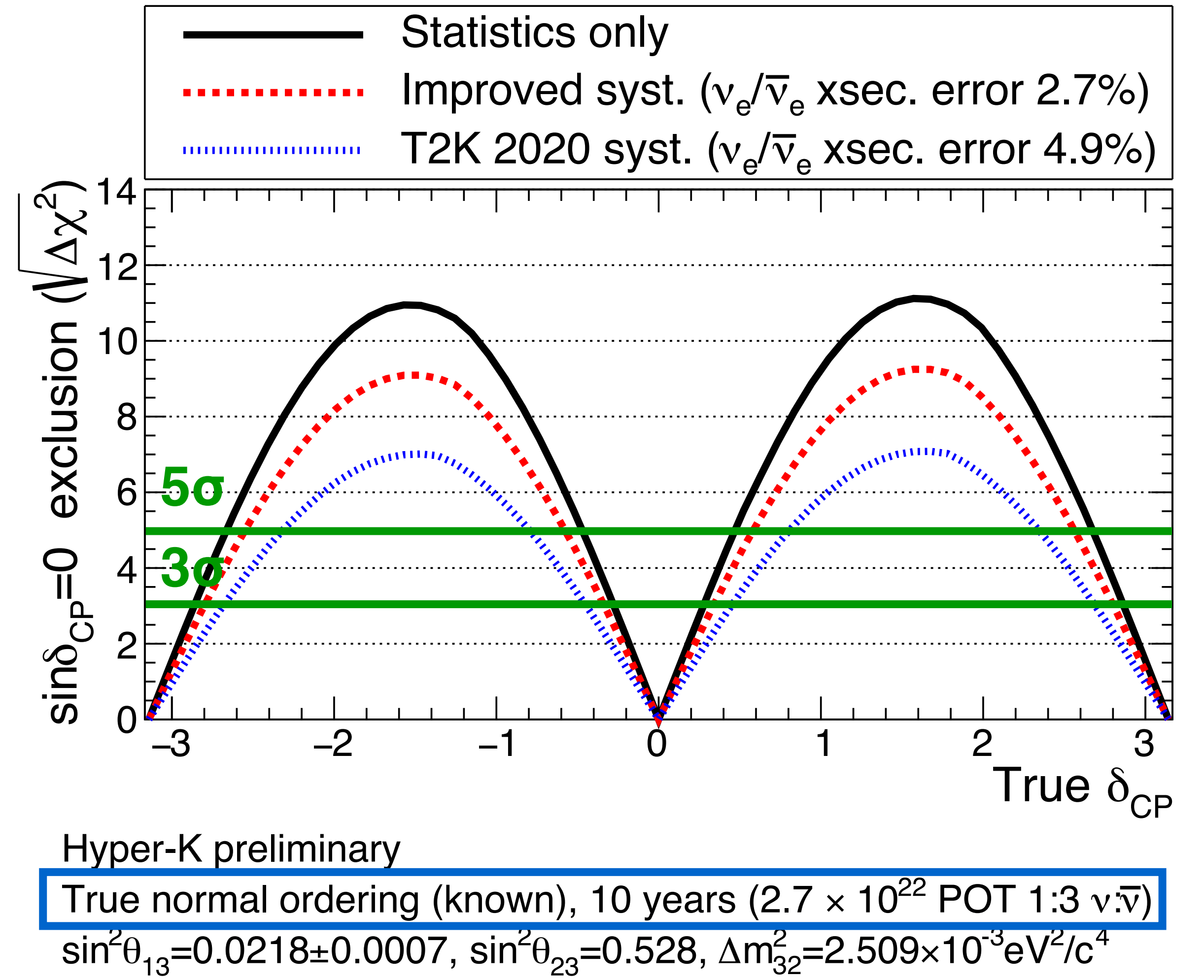


- **Degeneracy between the δ_{CP} phase and the mass ordering in the beam neutrino.**
  - **Need $\nu_\mu \to \nu_e$ with various travel lengths and energies → <u>atmospheric ν data</u>**

Accelerator neutrino oscillation sensitivities

- **For example, if we inject 1:3 $\nu : \bar{\nu}$ beam in protons on the target…**



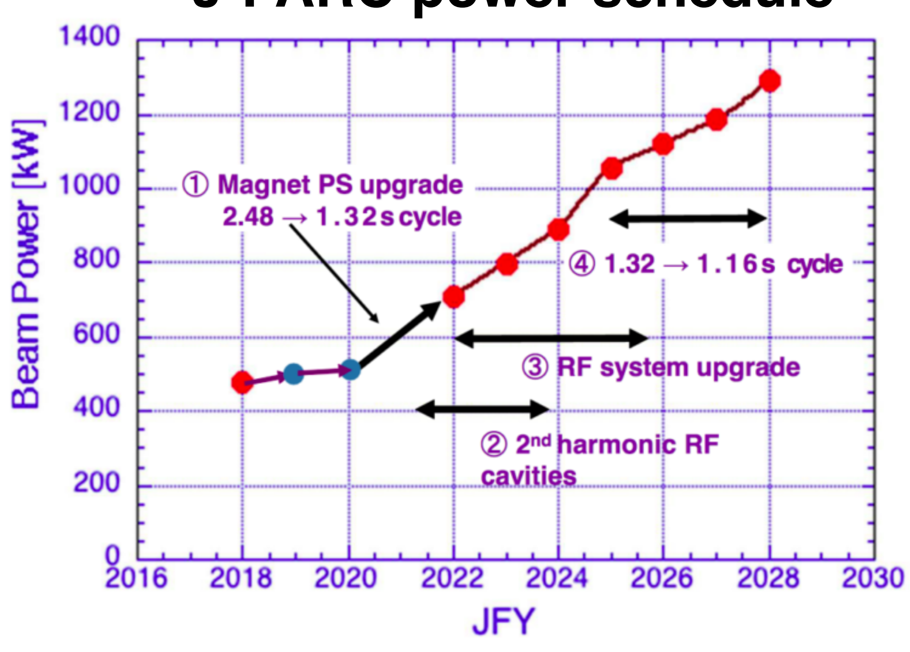


- **In the optimistic case (reduced systematics, known mass ordering):**
  - **2-3 year data give 5σ observation of the CP violation if true $\delta_{CP} = -\pi/2$.**
  - **After 10-year operation, CPC will be excluded with >5σ for 60% of δ_{CP} values.**

J-PARC accelerator + Near Detector suite

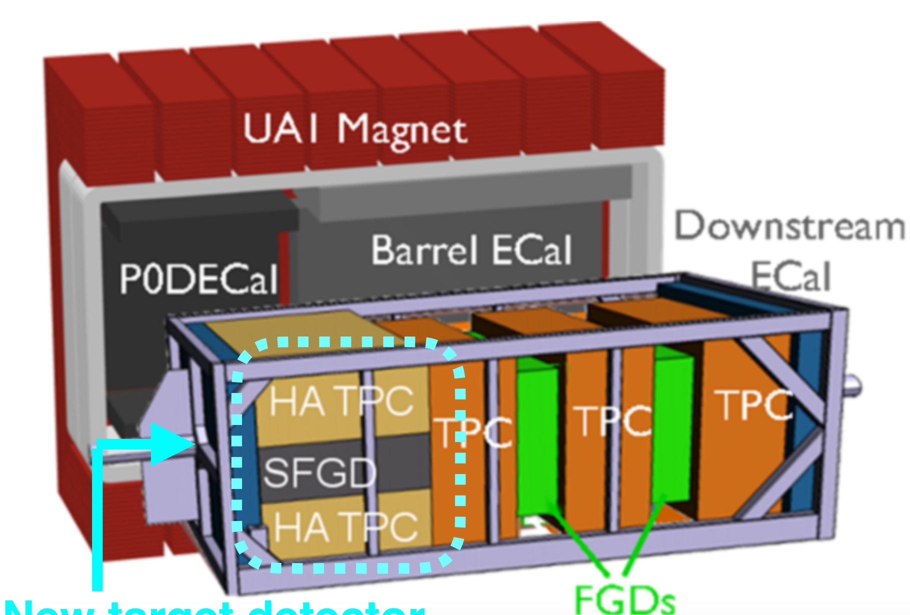
- **Beam power upgraded 515 kW → 1.3 MW with <u>increased numbers of protons in a bunch</u> and <u>faster repetition cycles:</u>**
  - **Reached peak power at 800 kW, achieved stable operation at 700 kW.**
- **Upgraded Near Detectors:**
  - **Target detector with higher granularity and angular acceptance.**
    - **Aiming to improve physics models involving short tracks.**
    - **New SuperFGD and High-Angle TPC is now operational.**
  - **Water Cherenkov detector 750 m downstream of the beam.**
    - **Excellent ν_e/ν_μ separation, same target nuclei as the far detector.**

J-PARC power schedule

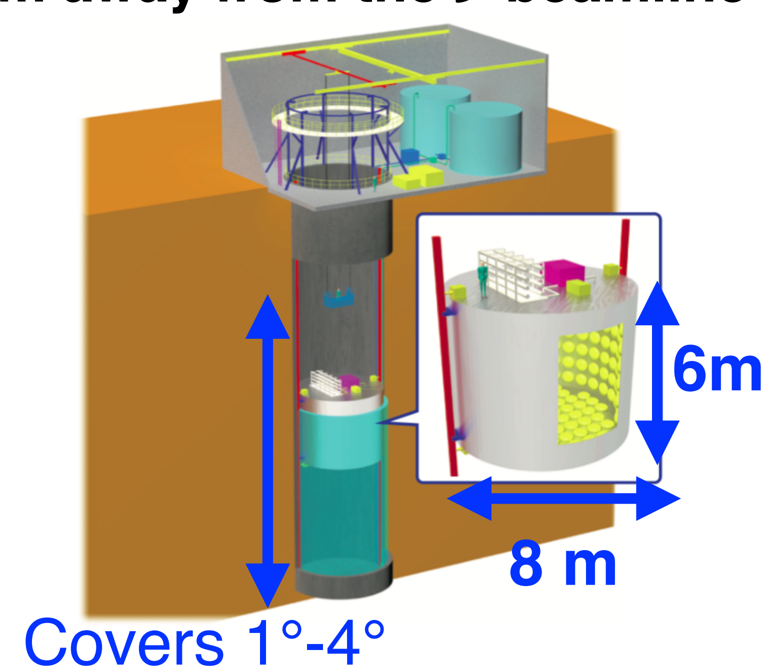


https://t2k-experiment.org/beyond-t2k/

Upgraded near detector

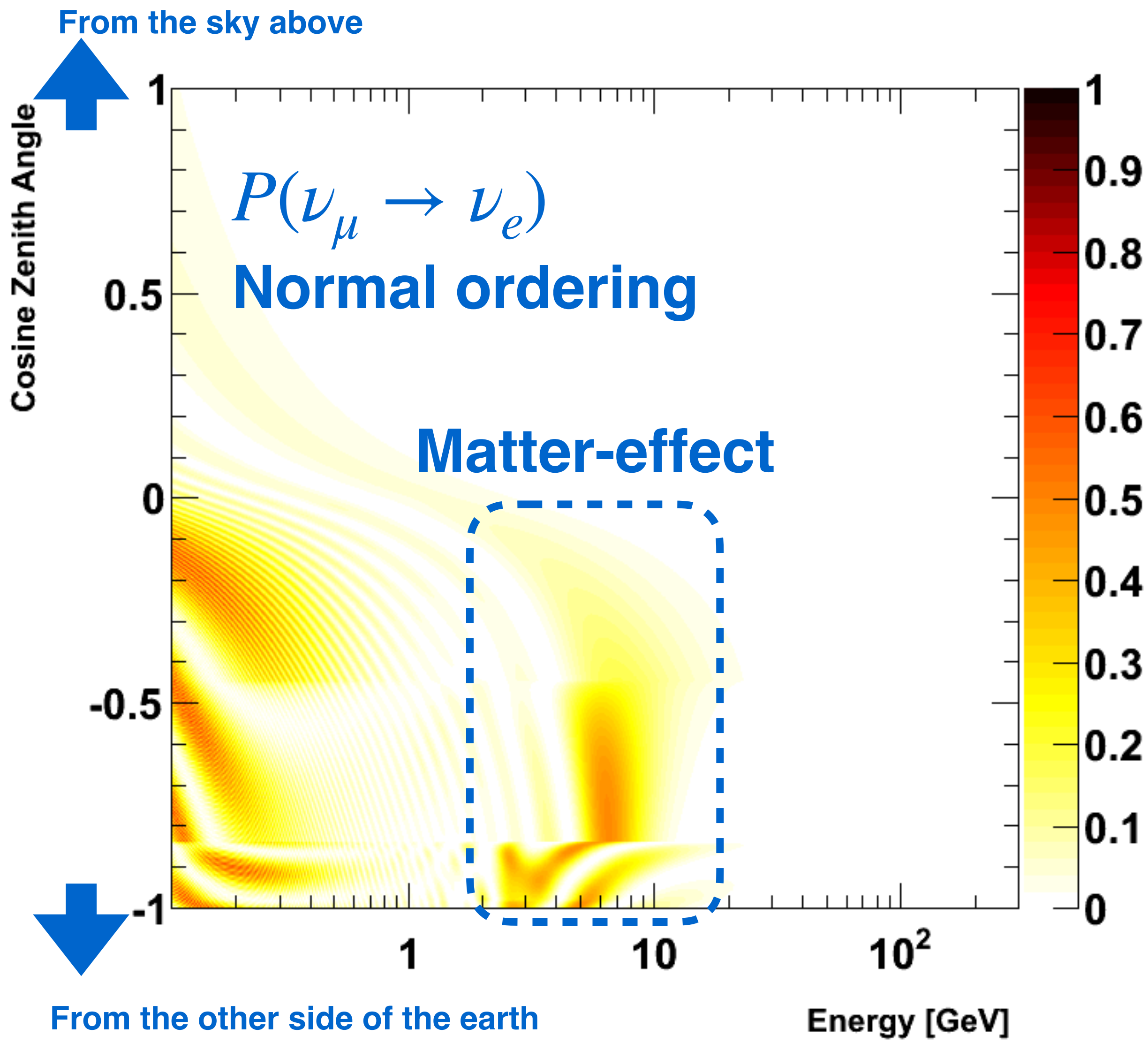


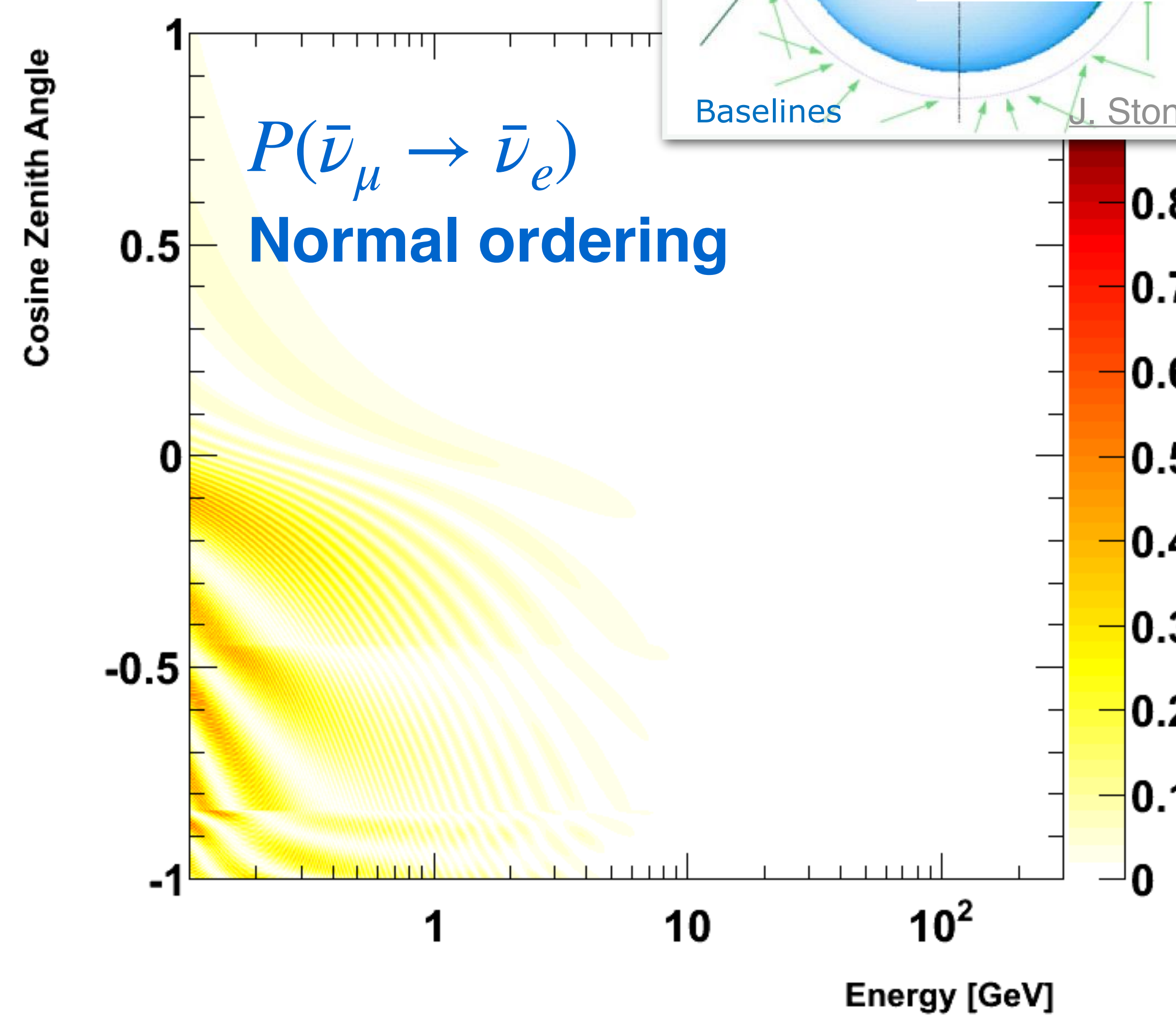
New water Cherenkov detector 750 m away from the ν-beamline

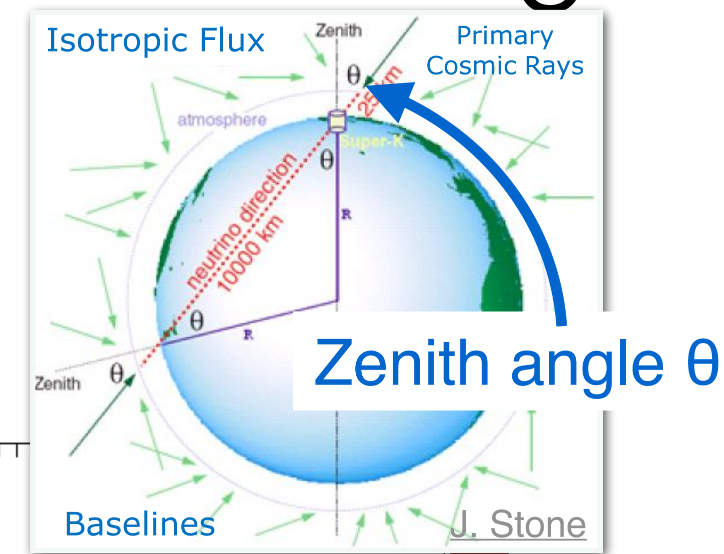


Atmospheric neutrino oscillation

- **Mass Ordering is studied by seeing matter-driven resonant enhancement of $P(\nu_\mu \rightarrow \nu_e)$ for NO and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ for IO.**





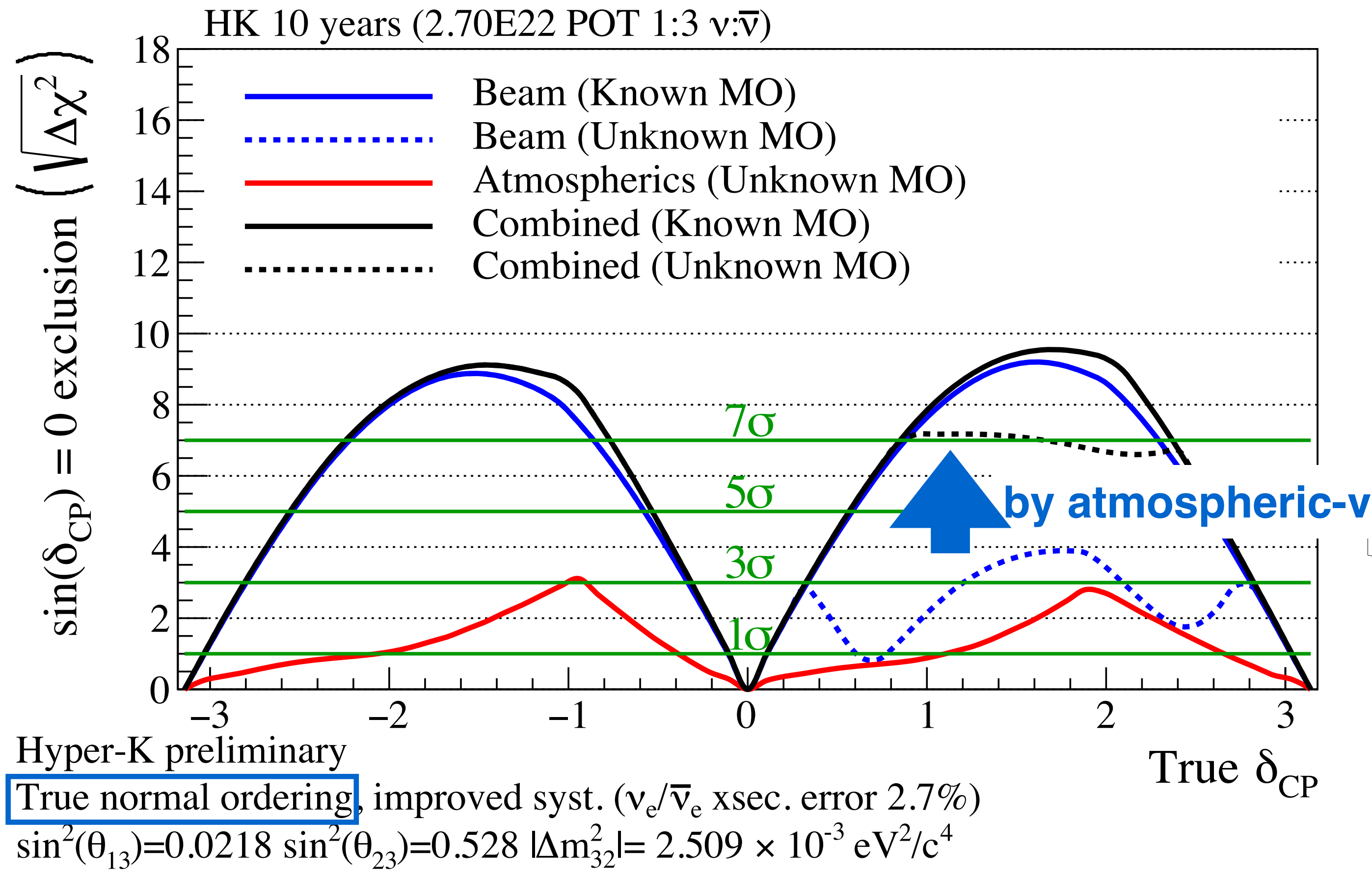


Phys. Rev. D 97 (2018) 072001

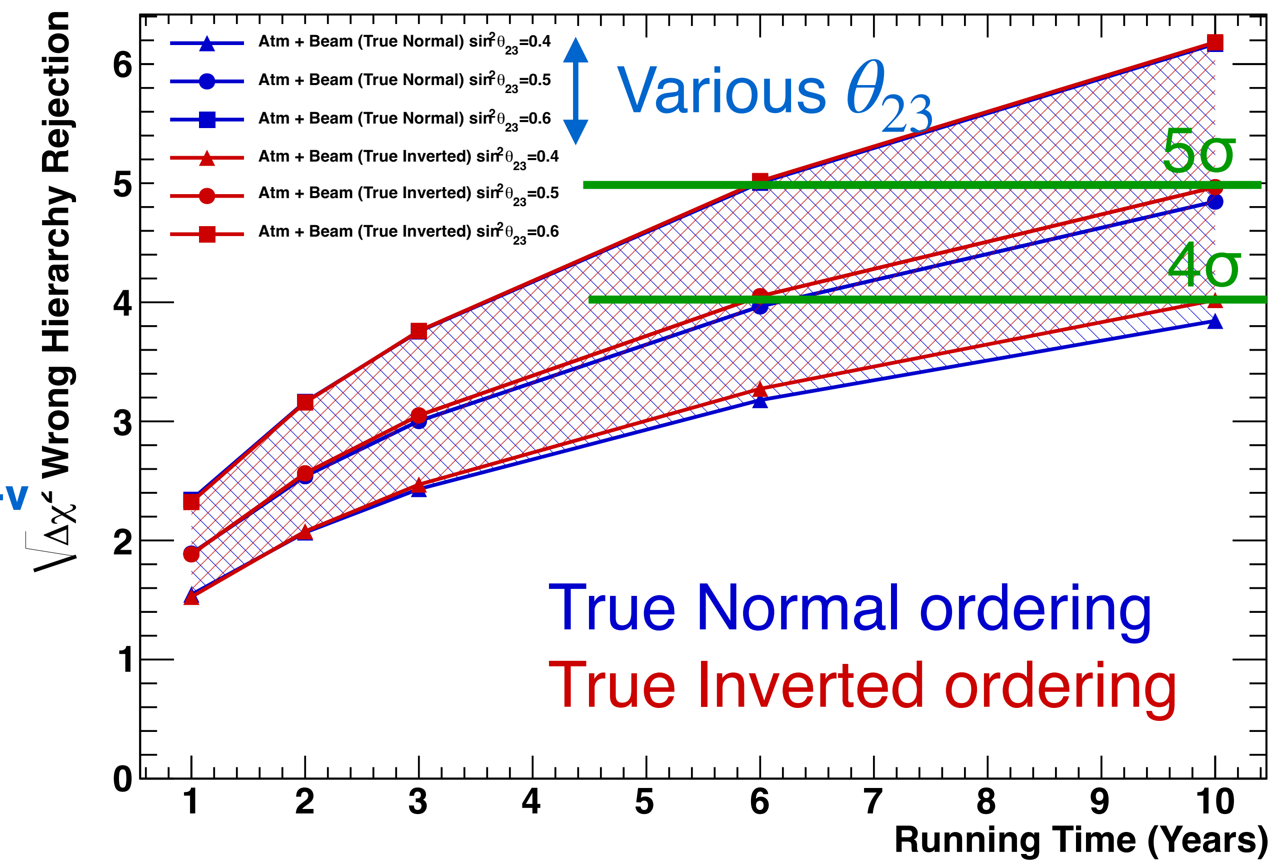
- **Long travel length in the earth results in greater matter effect.**
  - ➡ **Good chance to determine the mass ordering.**

Atmospheric + beam neutrino oscillation

δ_{CP} with unknown mass ordering



Rejection of wrong mass ordering

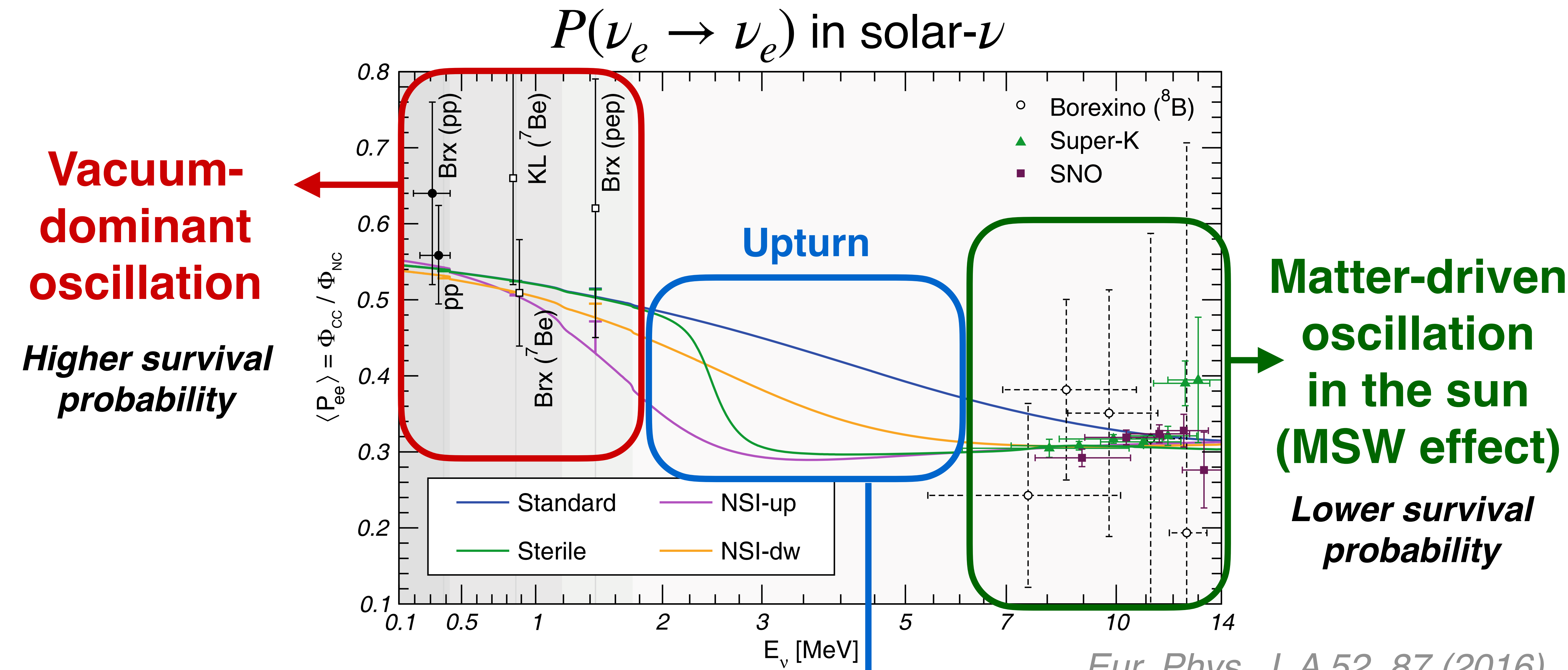


- **Atmospheric neutrino oscillation helps the δ_{CP} measurement by resolving the degeneracy of δ_{CP} and the mass ordering in the beam data.**

- **After 10-year observation mass ordering will be determined with 4σ-5σ.**

Solar neutrinos

- **The sun: ν_e disappearance experiment with extreme matter density.**
  - **Historically useful to study the Δm^2_{12}-induced oscillations and mass hierarchy.**



Eur. Phys. J. A 52, 87 (2016)

Totally unconstrained due to the lack of experimental data
→ Room for non-standard interactions or oscillations

- **HyperK can observe solar-ν flux at 3σ-5σ for 3.5 MeV - 4.5 MeV.**

Supernova neutrinos

- Two interesting topics: supernova bursts and supernova relic neutrino.

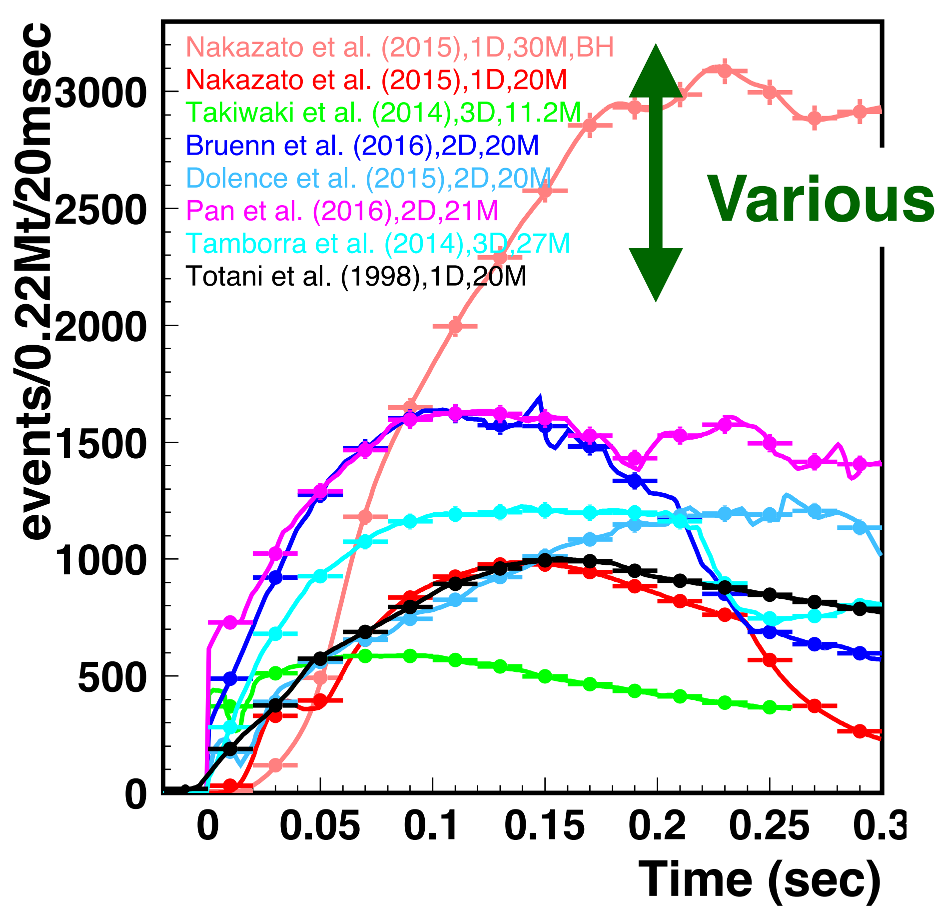
Bursts: single explosion events

- Model discrimination with detailed investigation of the time evolution and spectra.
- Farther supernova explosions

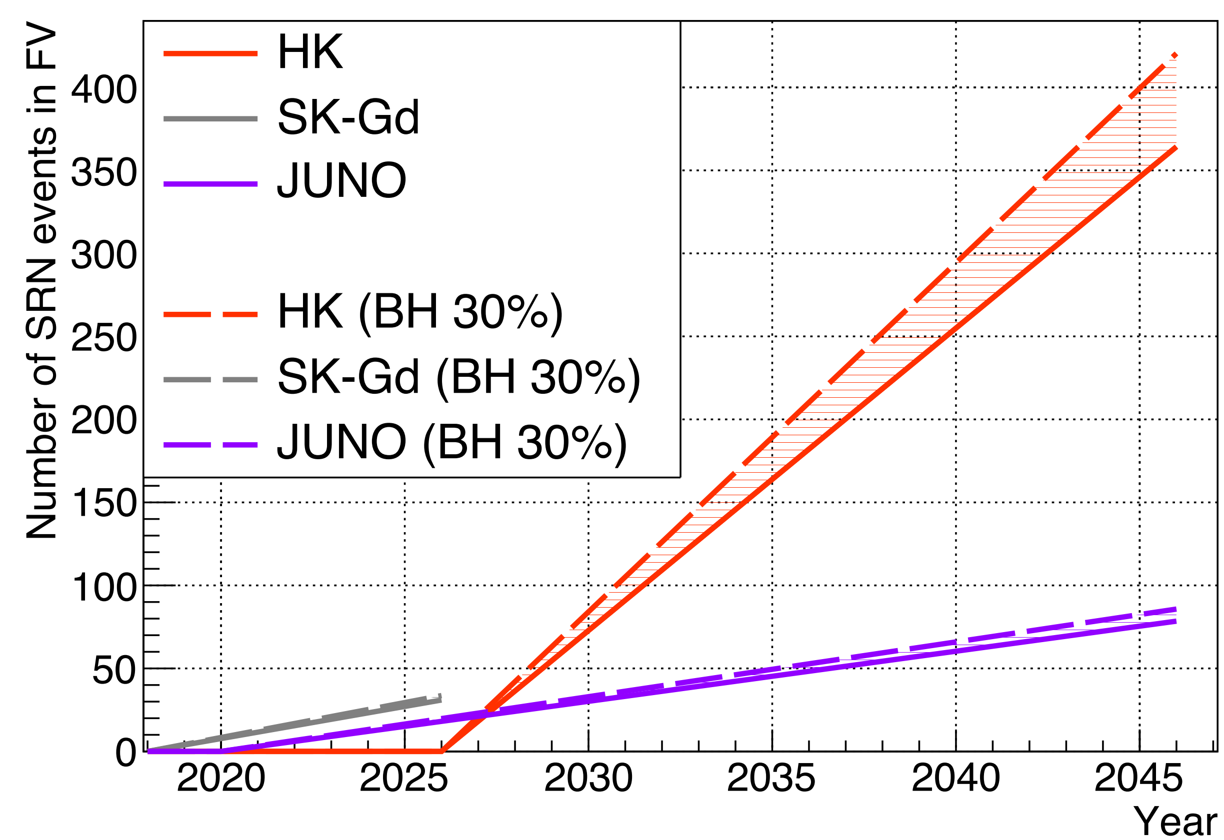
Relic: accumulated SN-ν flux

- Constraints on evolution of the matter and the universe with detailed investigation of ν-spectra.

Time evolution of SN-ν events

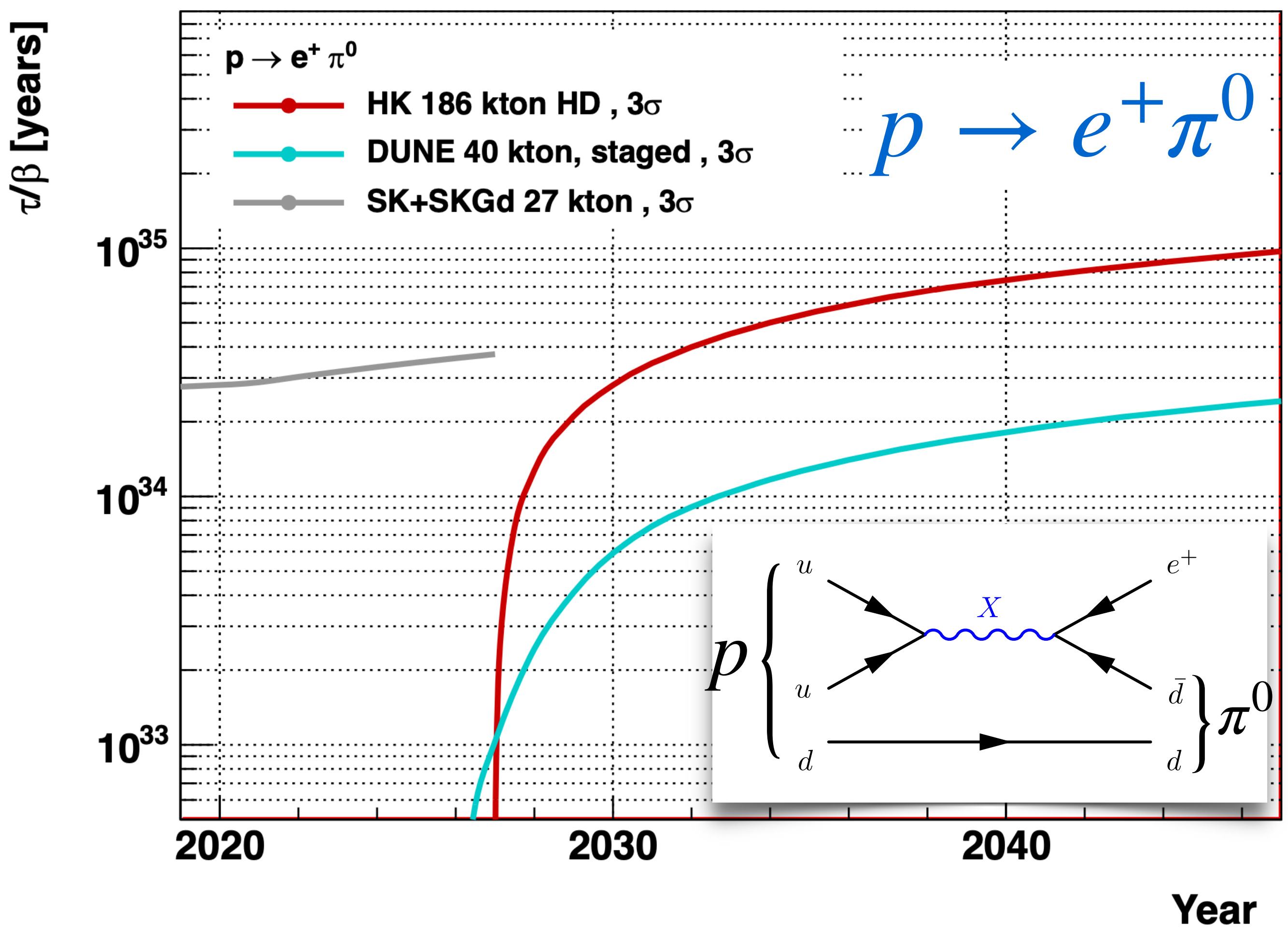


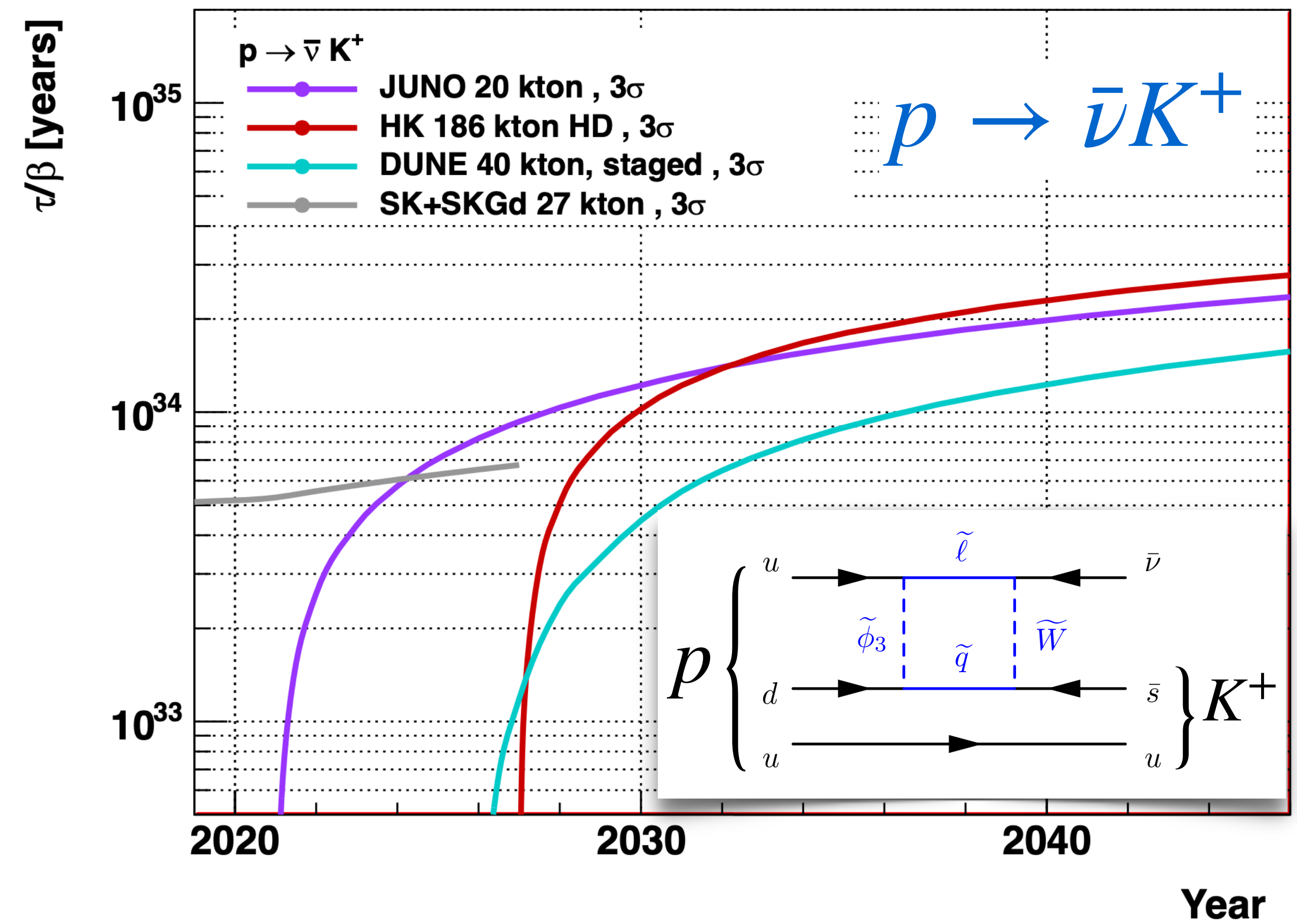
SN-ν events with various detectors



Nucleon decays

- Direct evidence of Grand Unified Theory (GUT).
- World best sensitivity for many decay modes.
    - Including flagship modes: $p \to e^+\pi^0$ and $p \to \bar{\nu}K^+$.



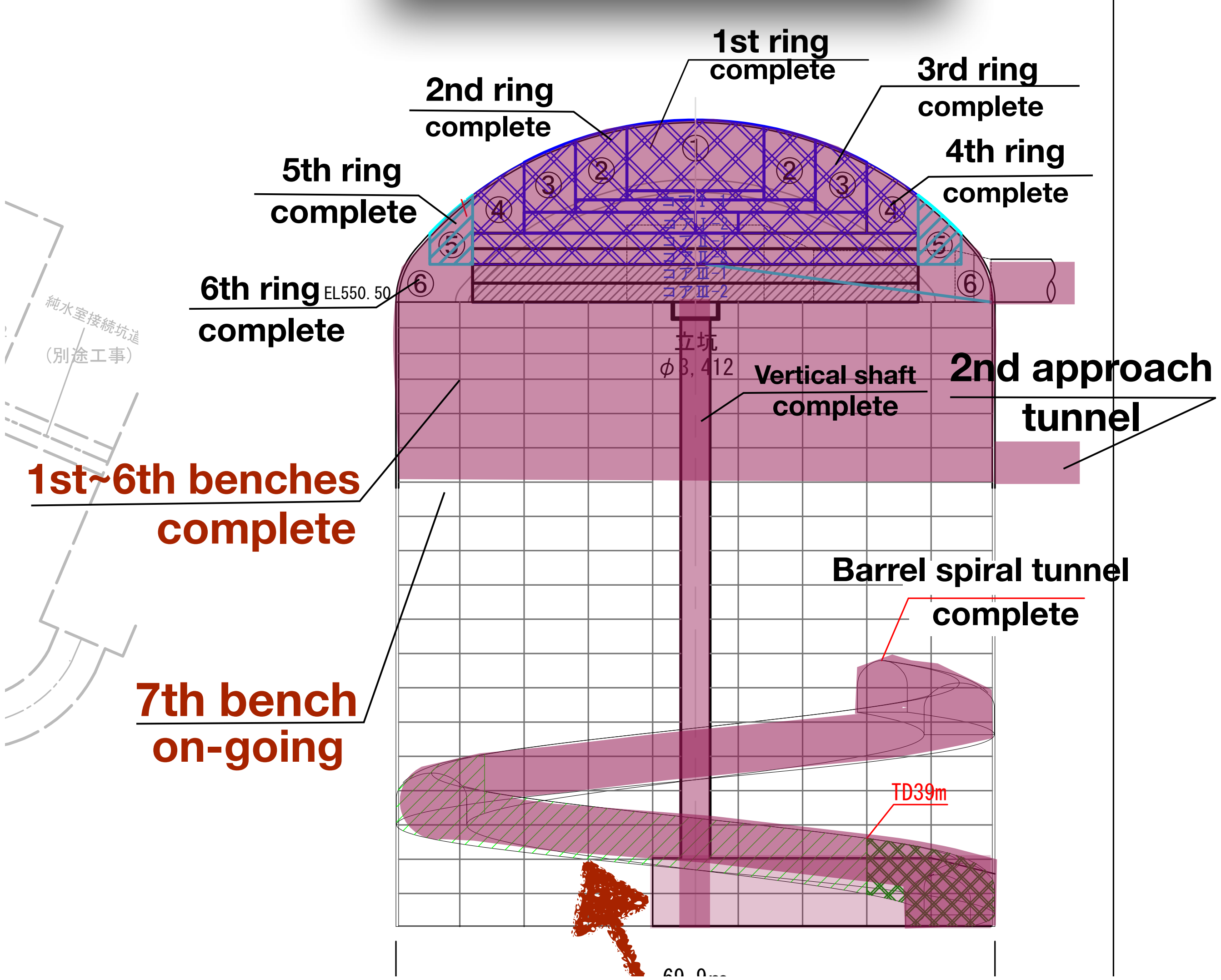


- Larger water Cherenkov detector experiment is the unique solution for $\tau(p \to e^+\pi^0) > 10^{35}$ years.
- Hint to the GUT & SUSY scales by seeing both $p \to e^+\pi^0$ and $p \to \bar{\nu}K^+$.

Excavation status

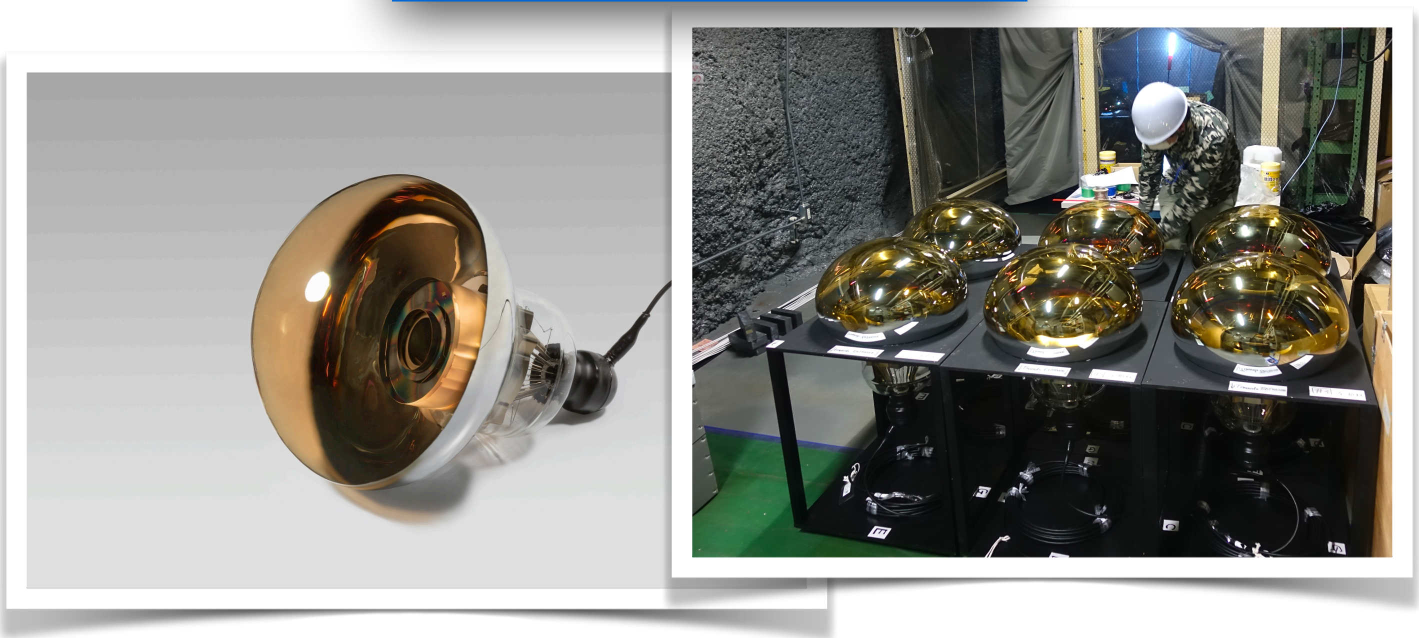
- Excavation progressing steadily.
- 6th bench of the barrel section completed.
- Will have completed by the end of this year.

Main cavern excavation

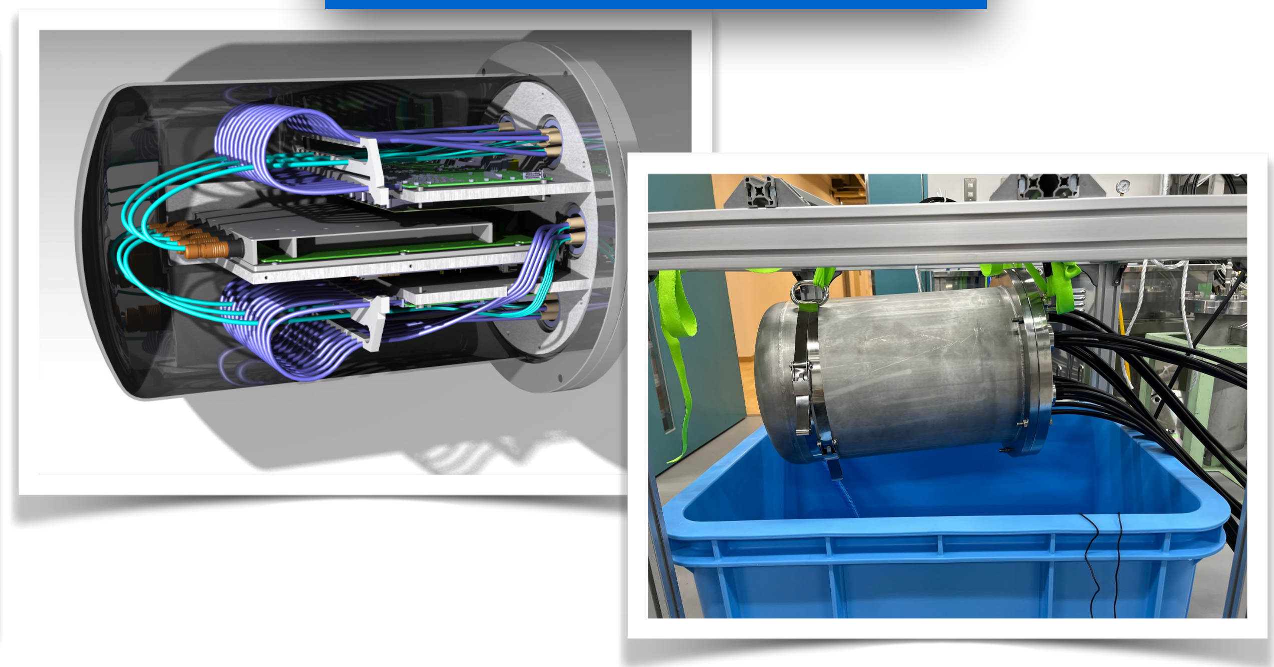


Detector components

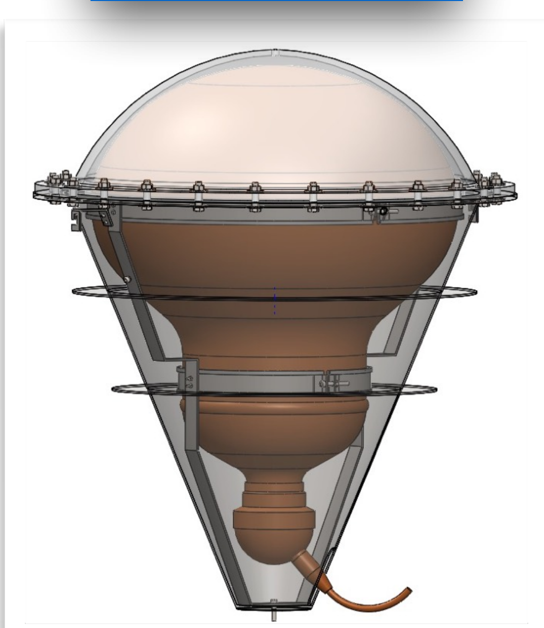
Inner Detector PMT



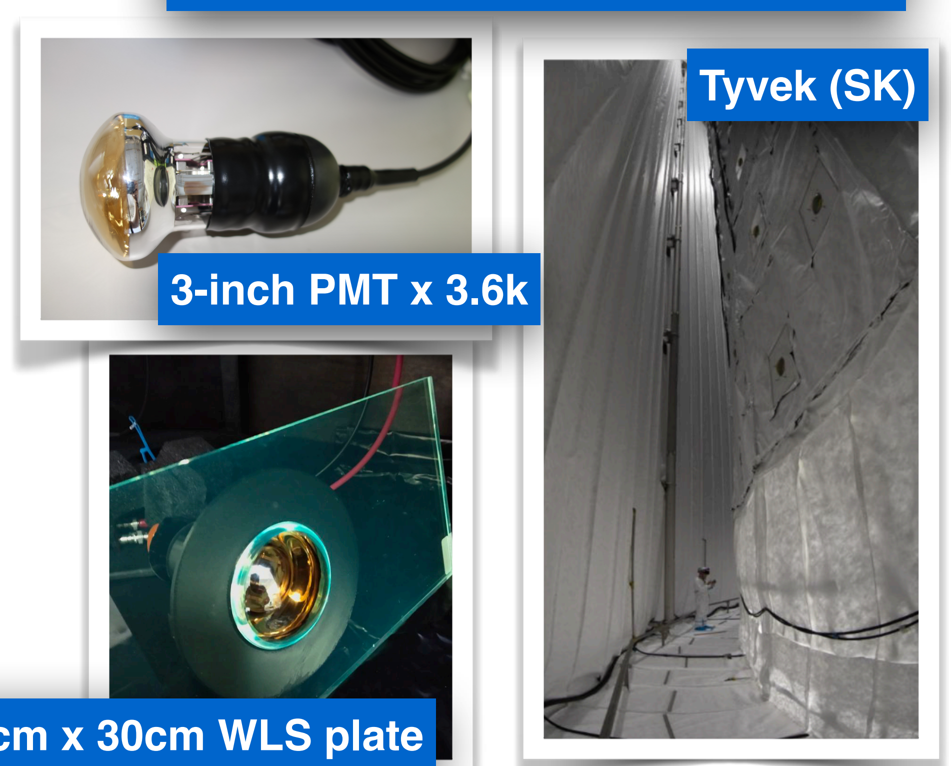
Readout electronics



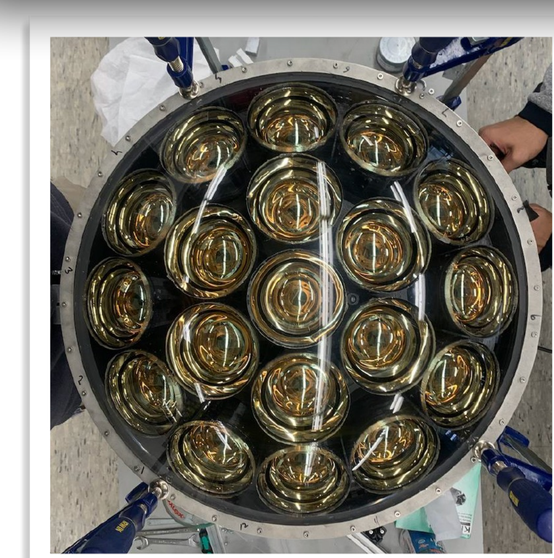
PMT Cover



Outer Detector system



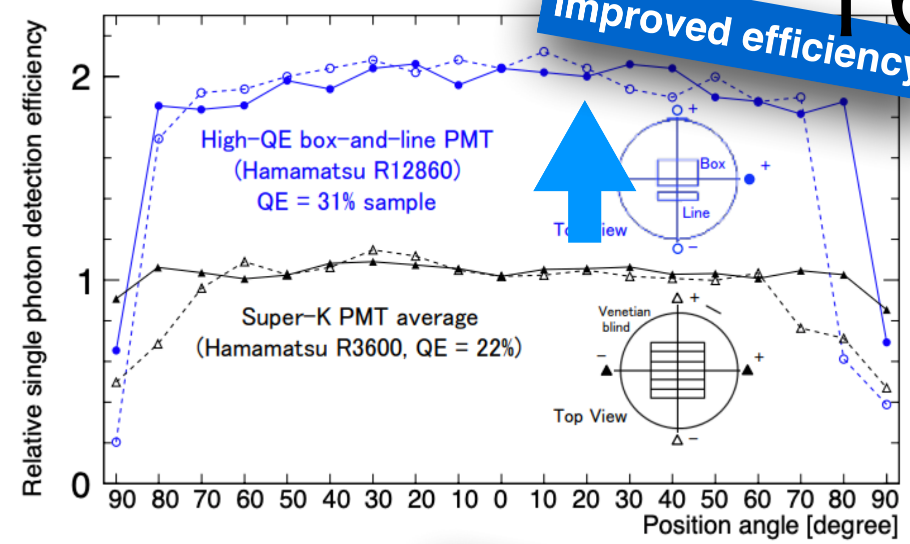
Multi-PMT for ID (1k)



Inner Detector PMTs

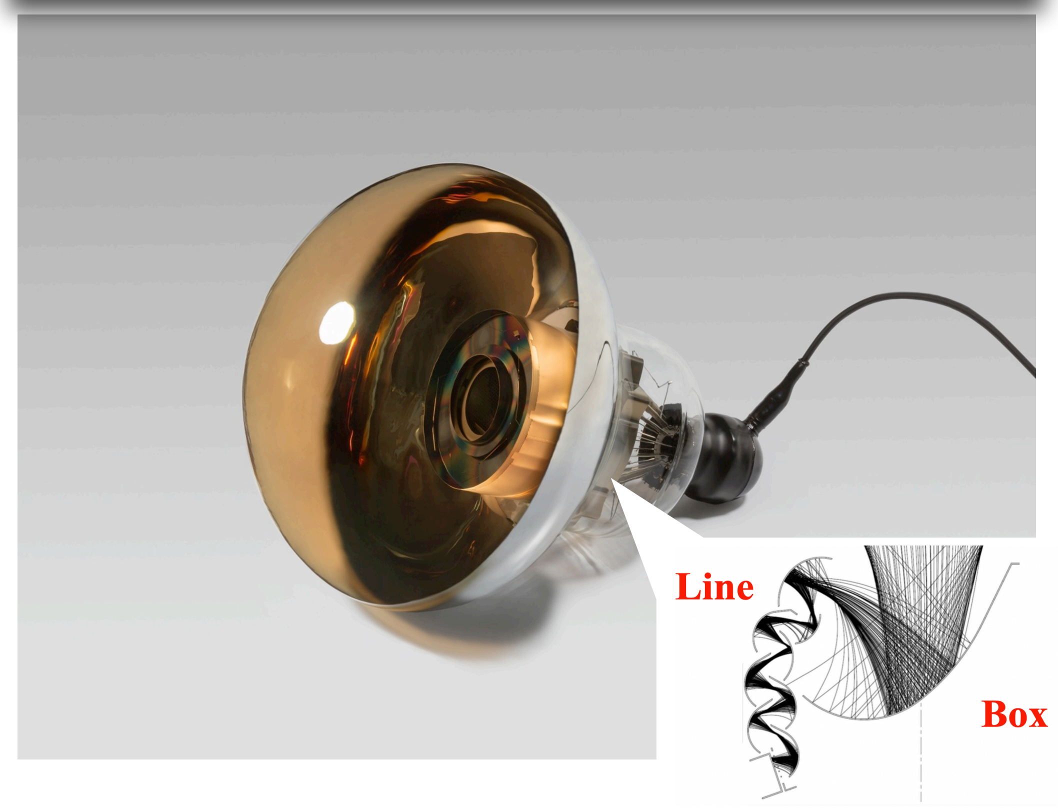
- 20,000 50 cm (20”) Box&Line PMTs.
- 2 times better efficiency, charge and timing resolution.
- 20% photo coverage (half of SuperK).
- Production ongoing:
  - 10,000 tubes delivered. Completed in Sep. 2026.
- Implosion Tests of the covers ongoing in Spain.

Improved efficiency

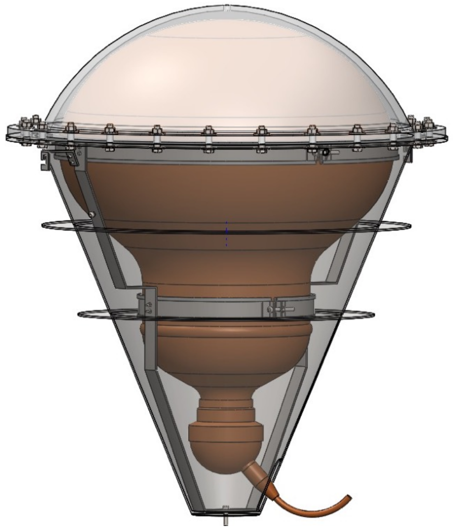


Mass & long-term measurments

50 cm Box&Line PMT "R12860", Hamamatsu



ID PMT cover

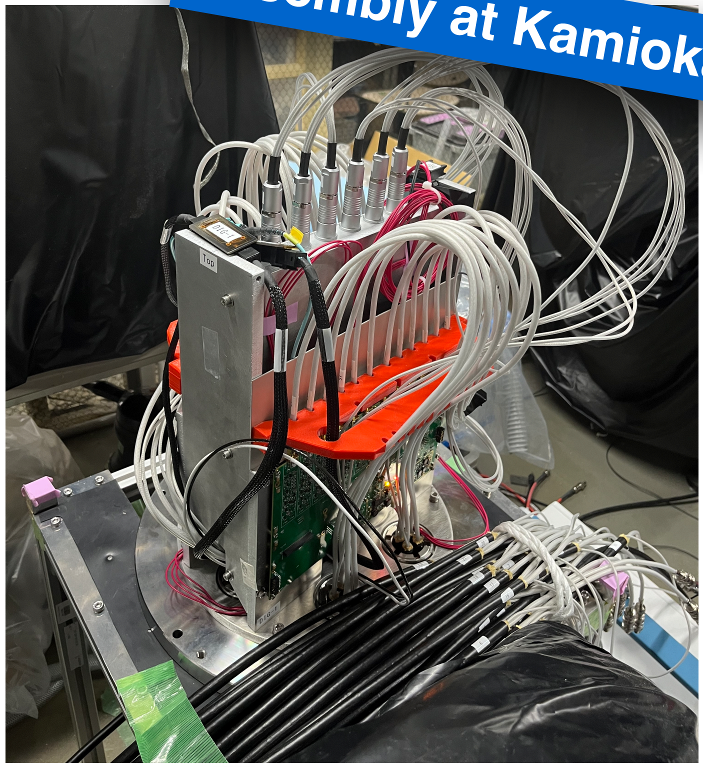


Cover implosion tests

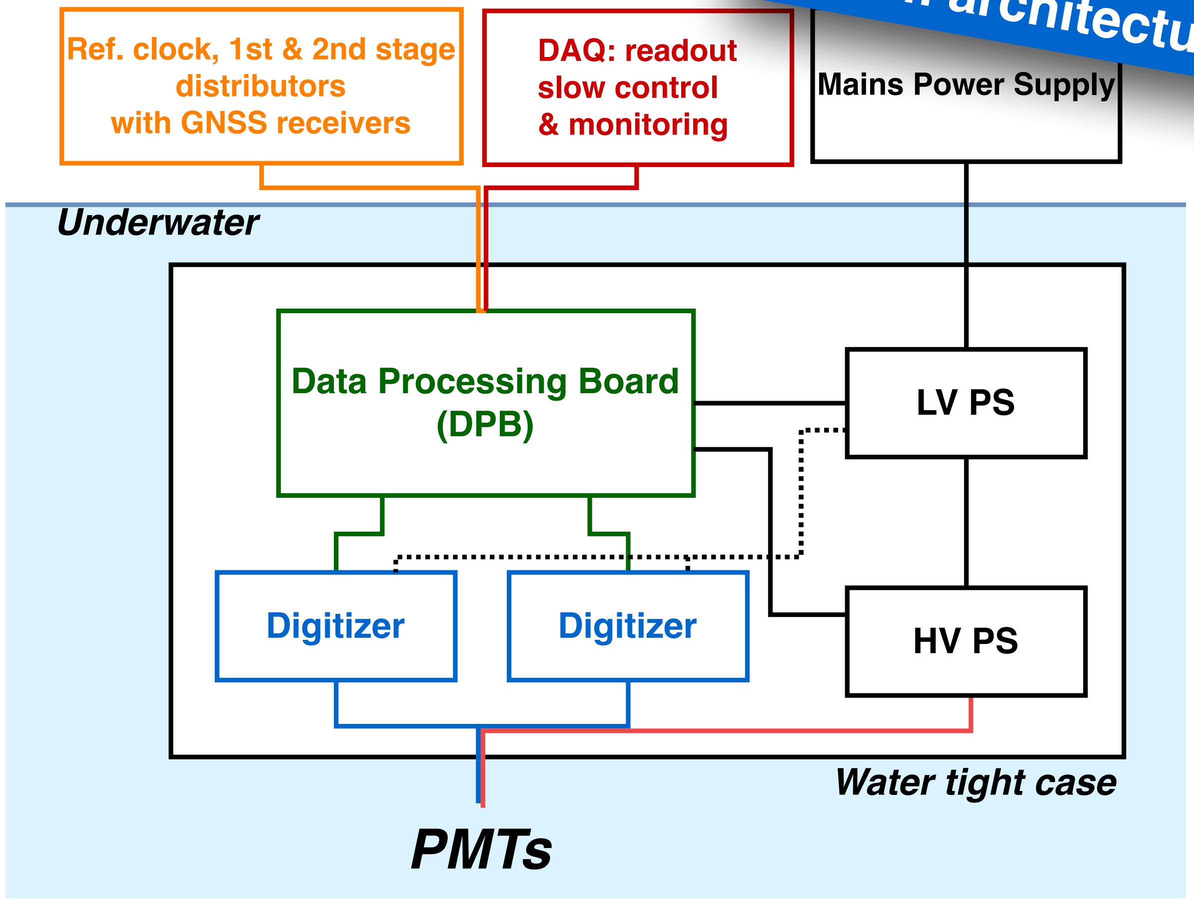
Electronics overview

- Front-end electronics is placed in underwater vessels.
  - Minimizing the length of the PMT cables
  - Digitization done in the 900 vessels.
  - Request failure rate of each component is <1%/10yr.
- Analog FE designed to take full advantage of the improved PMT performance.
- Component developments shared by countries.

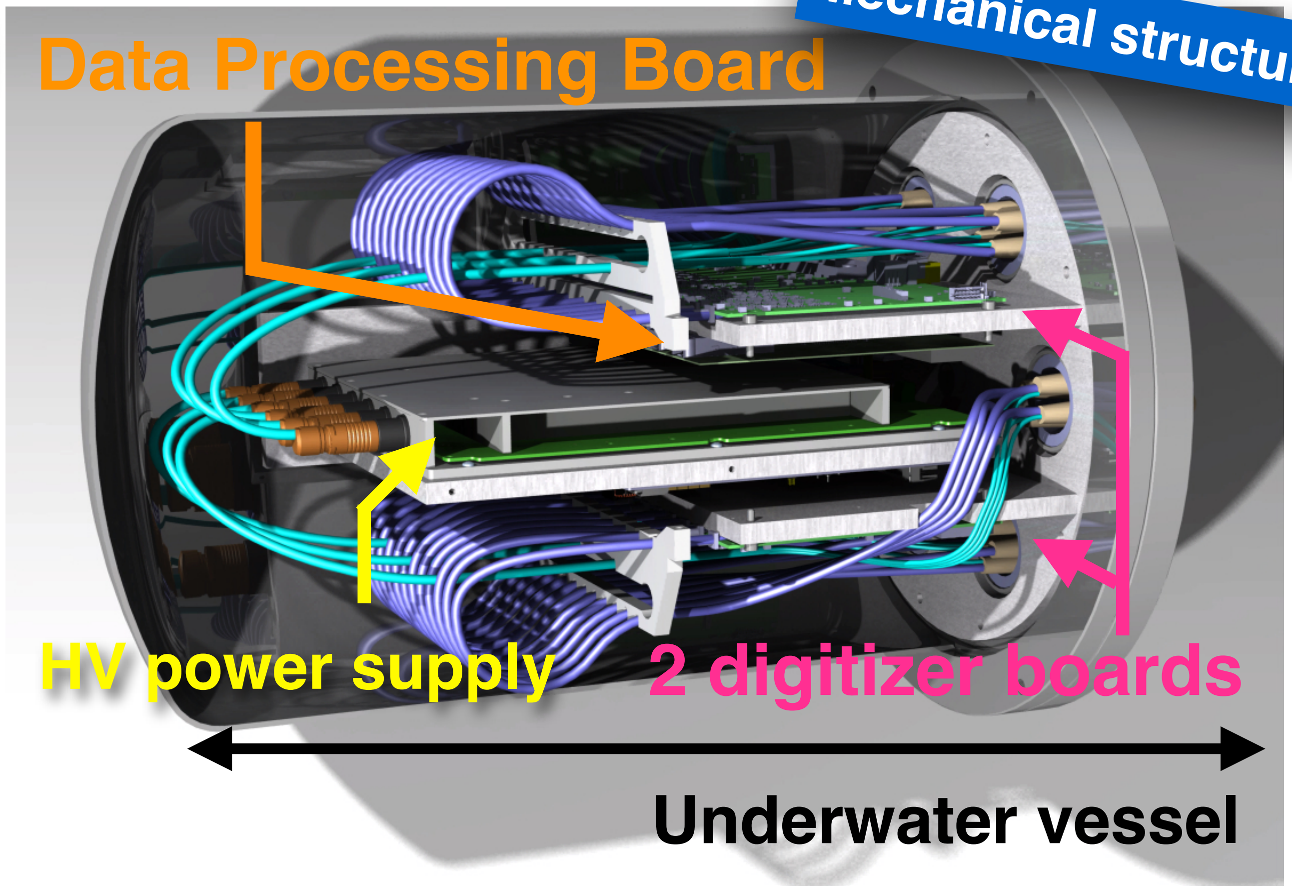
Assembly at Kamioka



System architecture



Mechanical structure



Electronics schedule

- **Integrated tests** being finalized for the mass production.
- **Mass production, assembly, calibration & QA** planned at CERN from 2025.
- **Shipment** to Kamioka and **installation** in parallel.

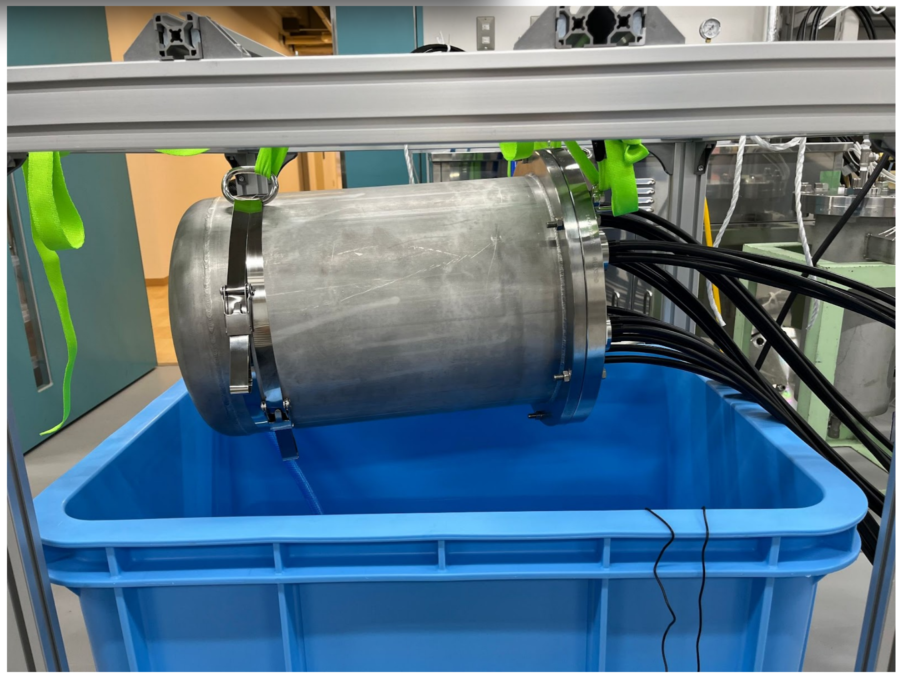
HK electronics schedule

Calendar year / items	2024				2025				2026		
	1Q	2Q	3Q	4Q	1Q	2Q	3Q	4Q	1Q		
Module assembly @ CERN & Transport to Kamioka							Assembly & transport				
Digitizer	Component procurement				Production & transport						
	Calibration system prep.					Test (QA) & Calibration					
Data processing board					Production & delivery						
	Test system prep.					Test (QA)					
LV & HV module	Production										
	Test system prep.			Test (QA)							
Underwater vessel	procurement and production										
Electronics stand			Production								
Underwater PMT cables with feedthrough and connectors		Procurement (Tender)		Production & transport							
Feedthrough with power + fiber cables & breakout fibers production		Procurement (Tender)		Production & transport							
Long underwater fiber + power cables with connector production					Procurement (Tender)		Production & transport				

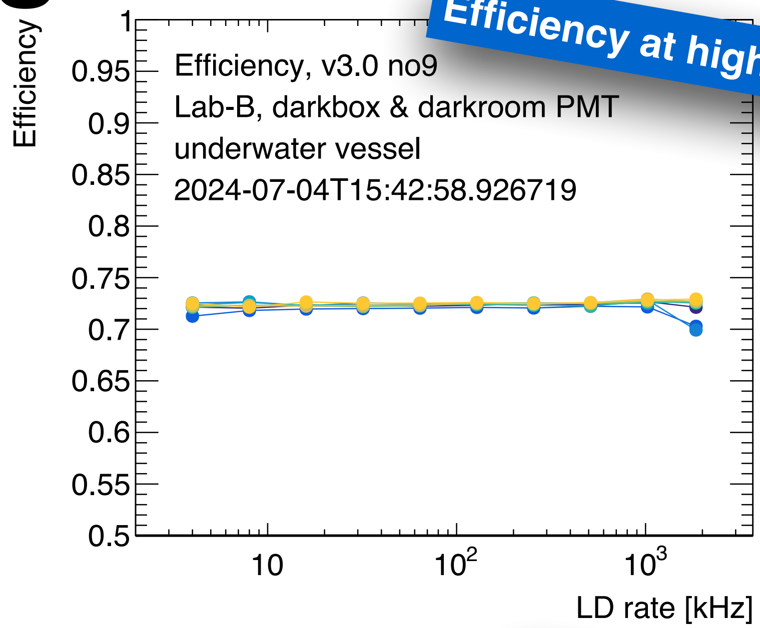
Ongoing tests of the electronics

- Requirements need to be satisfied with a realistic environment:
  - Assembled module in water.
  - With HK PMTs or a function generator.
- Almost all the requirements are confirmed:
  - Efficiency at high rate.
  - Charge and timing performance.
- Need to complete the measurements to move to the production.

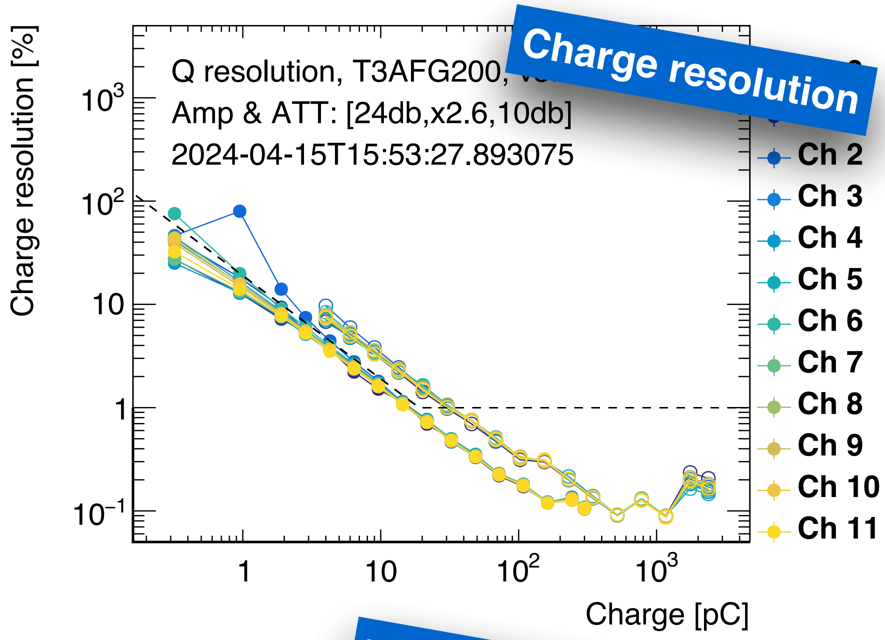
Operation of underwater electronics



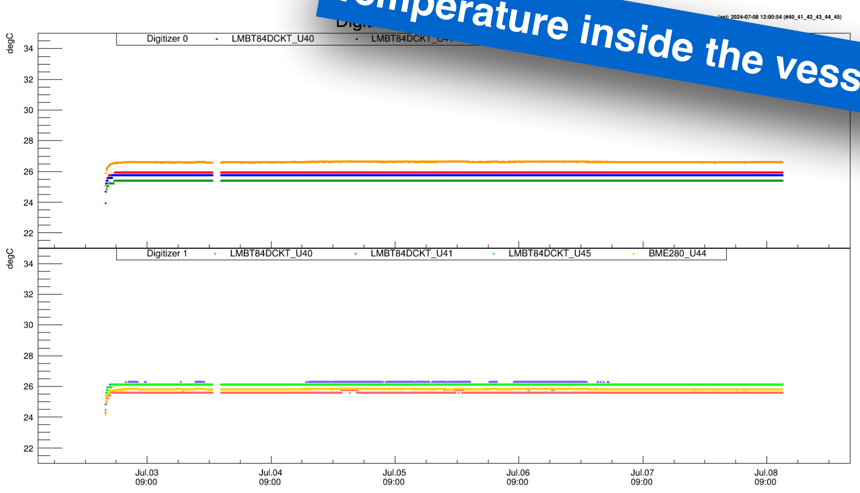
Efficiency at high rate



Charge resolution



Temperature inside the vessel



Conclusions

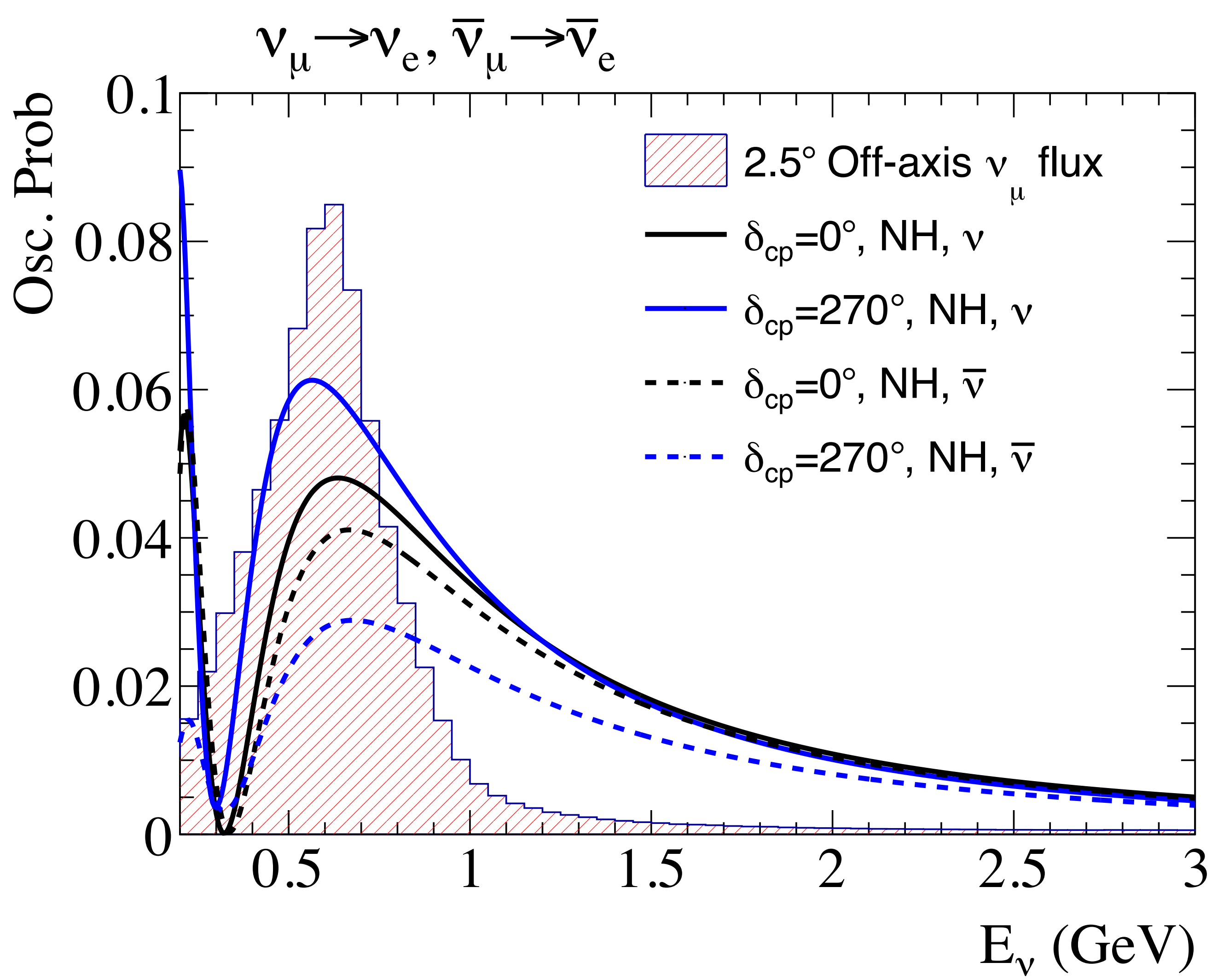
- Hyper-Kamiokande is a next-generation large water Cherenkov experiment aiming for world-leading sensitivities to many aspects of the neutrino physics.
  - 5σ sensitivity to the CP violation in large fraction of the CP phase values as well as the mass ordering.
  - Useful information on star formation and supernova explosions by probing astrophysical neutrinos.
  - More sensitive test of Grand Unification by searching for proton decays.

- Construction of the detector is underway.
  - World-largest underground facility.
  - Production of the novel high-performant photo-sensors.
  - Finalization of the electronics design taking full advantage of them.
  - Gradual increase of the neutrino beam intensity and the near detector suite for better control of the systematic uncertainties.

Backup

Beam energy and oscillation probability

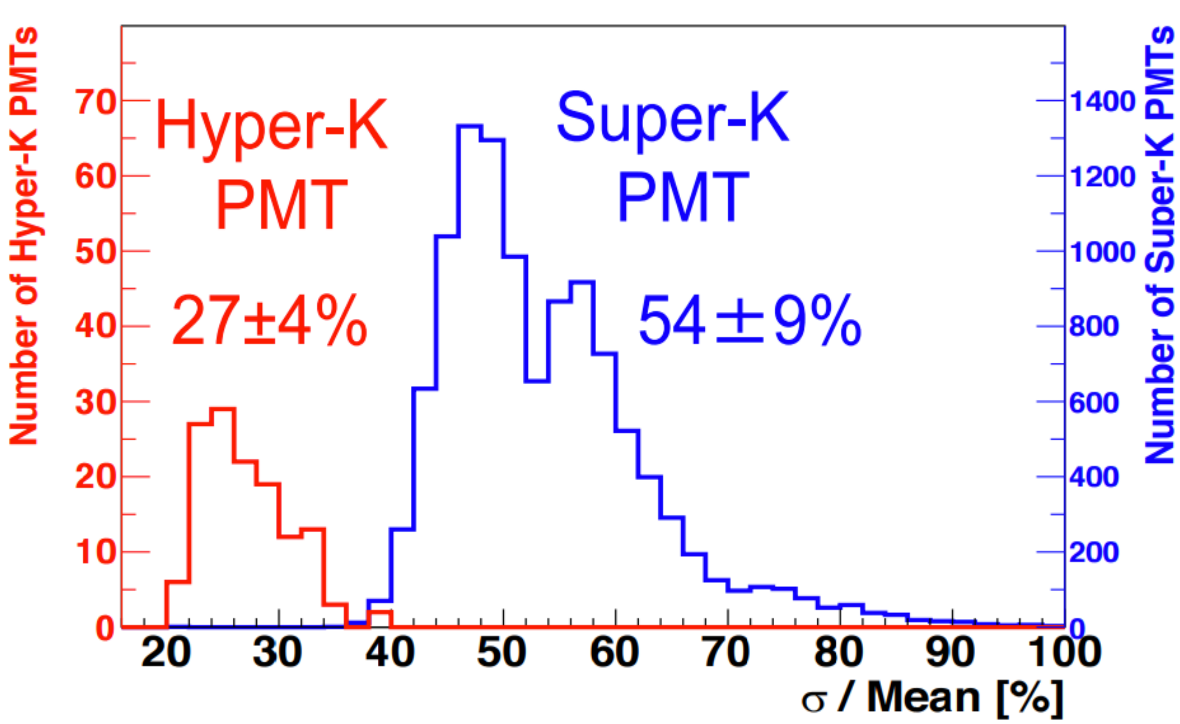
- **2.5 off-axis angle focuses the neutrinos on the first oscillation maximum, ~0.6 GeV.**
- **Advantages:**
  - **Oscillation probability depends on L/E. Energy reconstruction is essential.**
  - **Elastic scattering like (CCQE) events, which allows for precise energy reconstruction, are collected efficiently.**



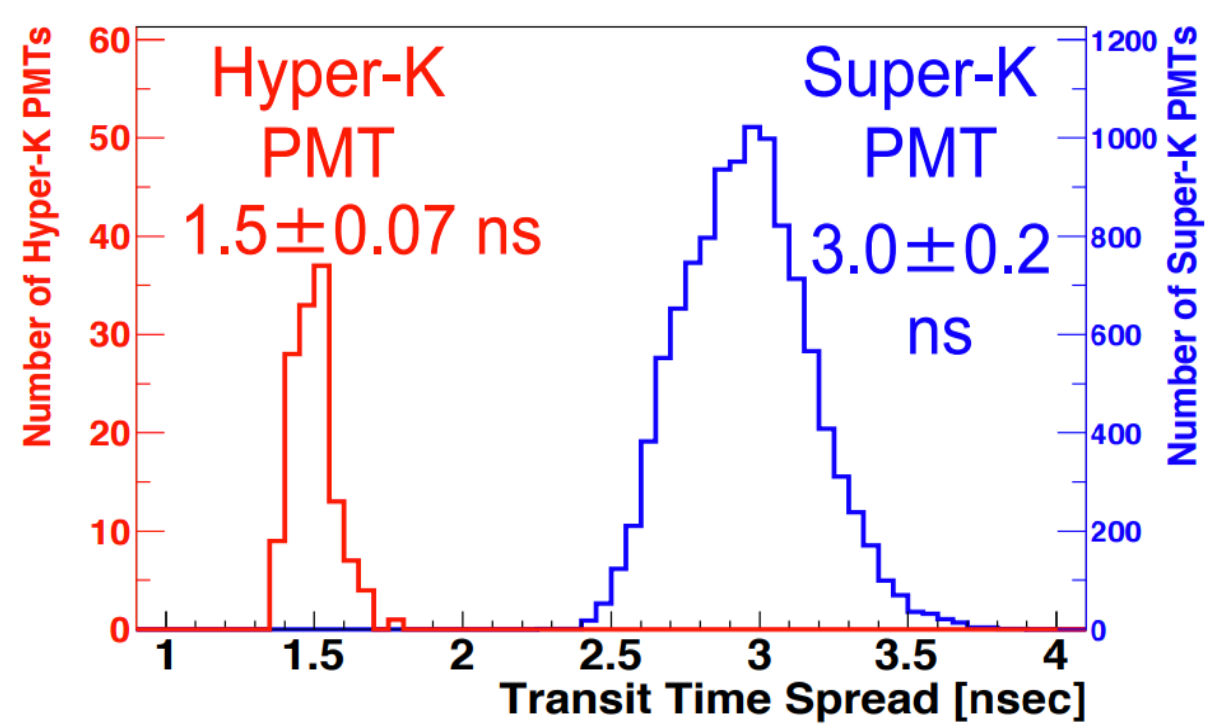
Charge and timing resolution of HyperK PMT

- **Charge resolution:**
  - **Evaluated with 1 photo-electron peak.**
  - **2 times better resolution wrt SuperK.**
- **Timing resolution:**
  - **Transit time spread (e.g. FWHM of the transit time, time between light injection and electric signal.)**
  - **2 times better resolution wrt SuperK.**

Charge resolution

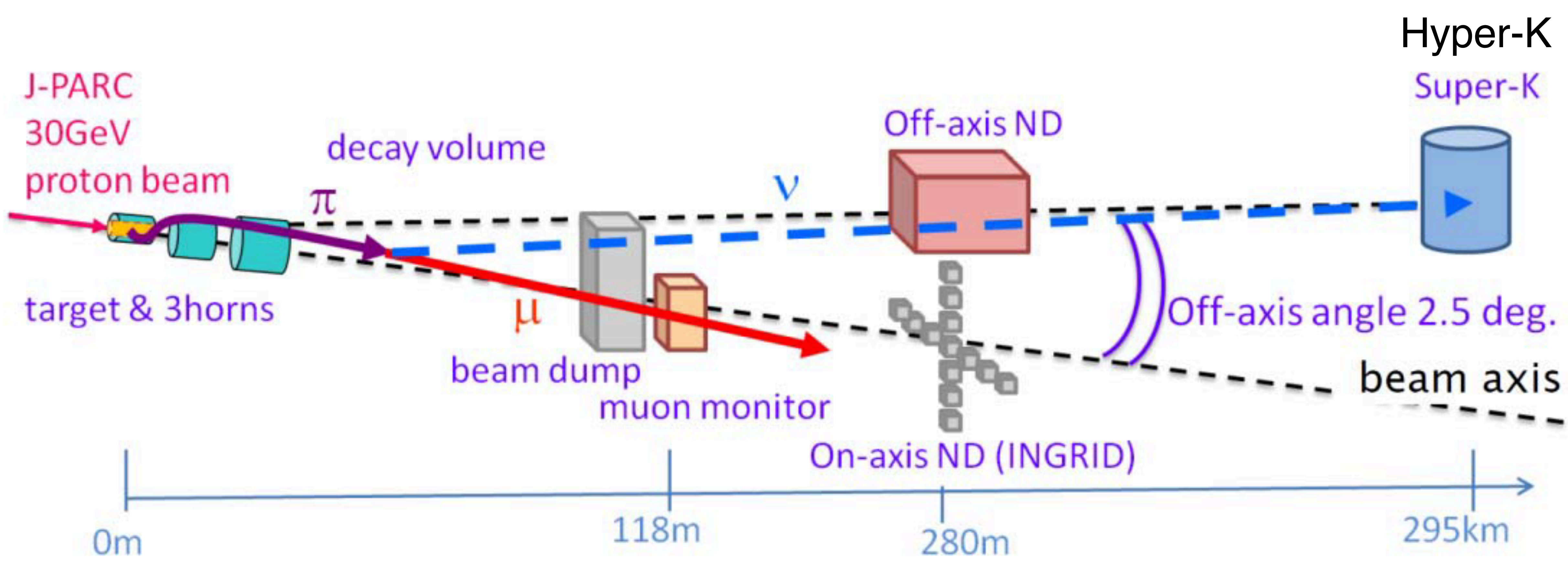


Timing resolution

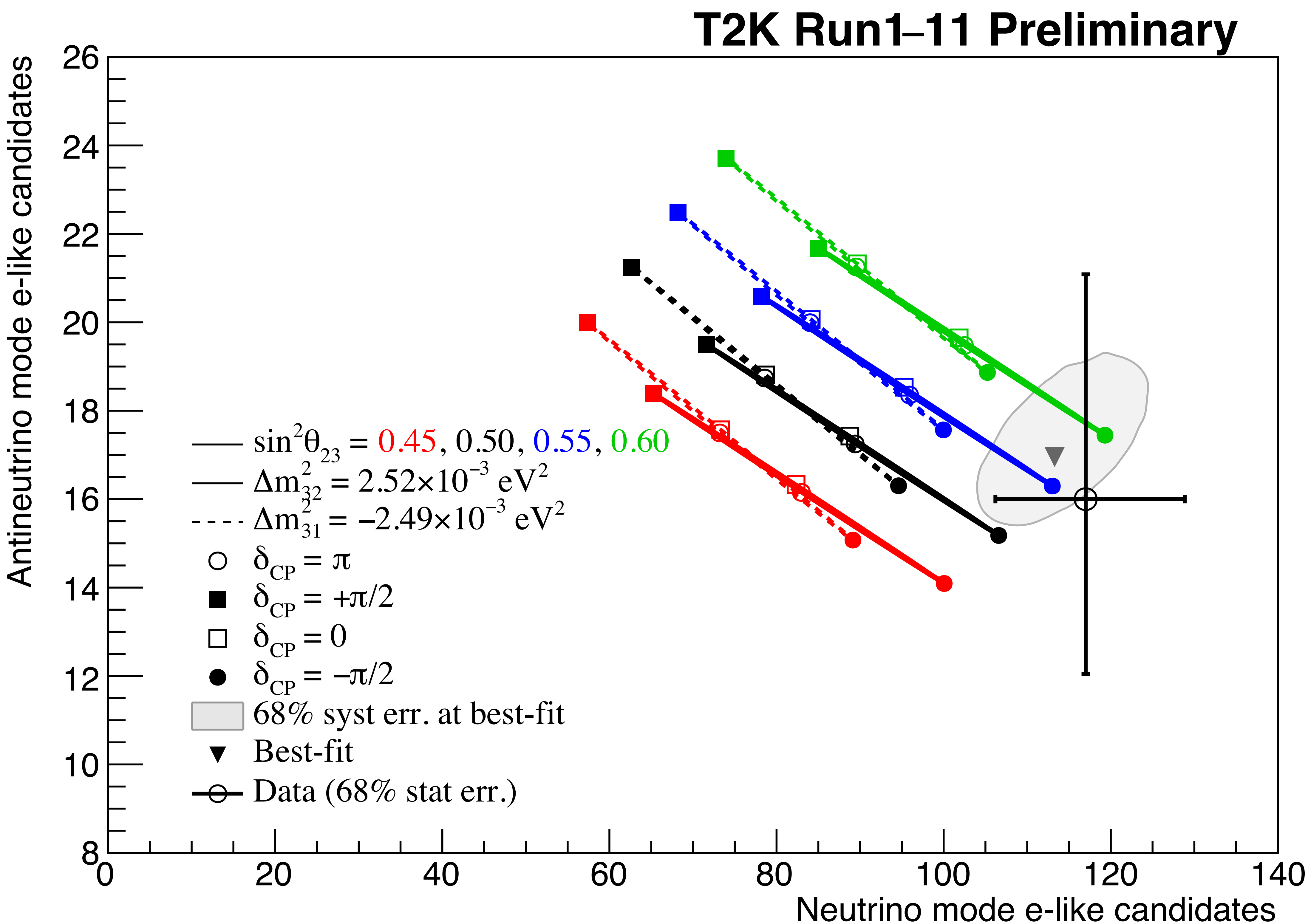


Neutrino beam line at J-PARC

- **Muon neutrinos are generated by charged pion decays in flight.**
- **Magnetic horn focuses on either positive or negative pions.**
- **On-axis detector: beam monitors of muons and neutrinos.**
- **Off-axis detector: far detectors (SuperK, HyperK). Near detector characterizing the ν-flux and the interactions before the oscillation**

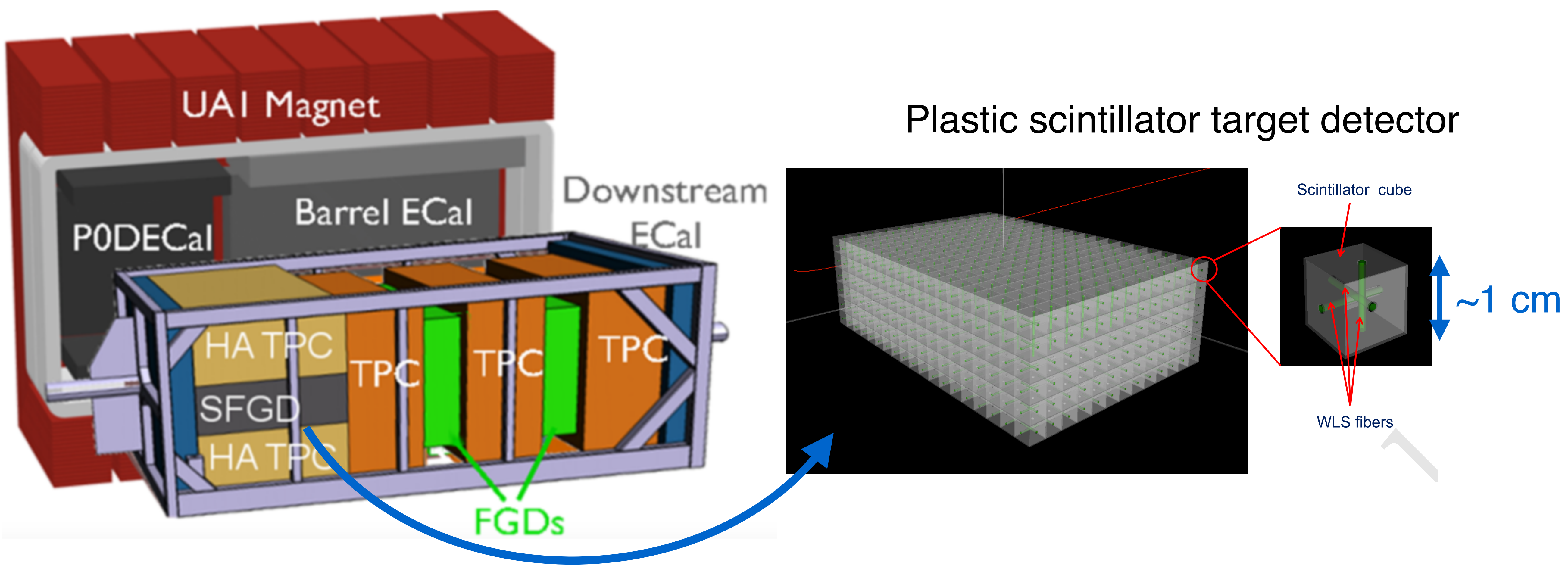


Recent T2K result

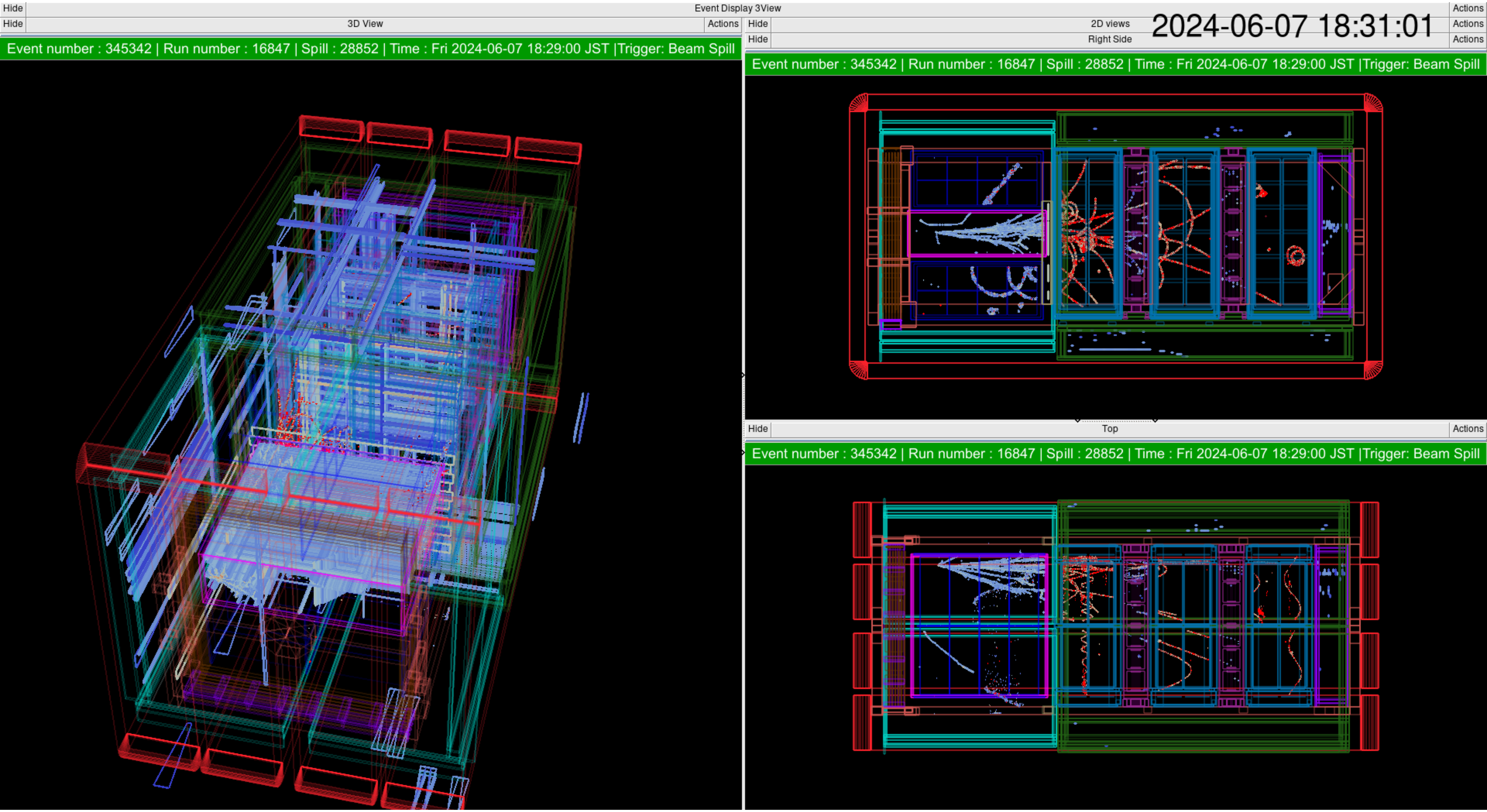


Near detector 280 m downstream

- **Magnetized tracker placed 280 m downstream called ND280.**
- **Measures neutrino flux and interactions at the 2.5° off-axis angle.**
- **Target detector with higher granularity and 4π acceptance for short tracks.**
- **Start operating in June 2023.**



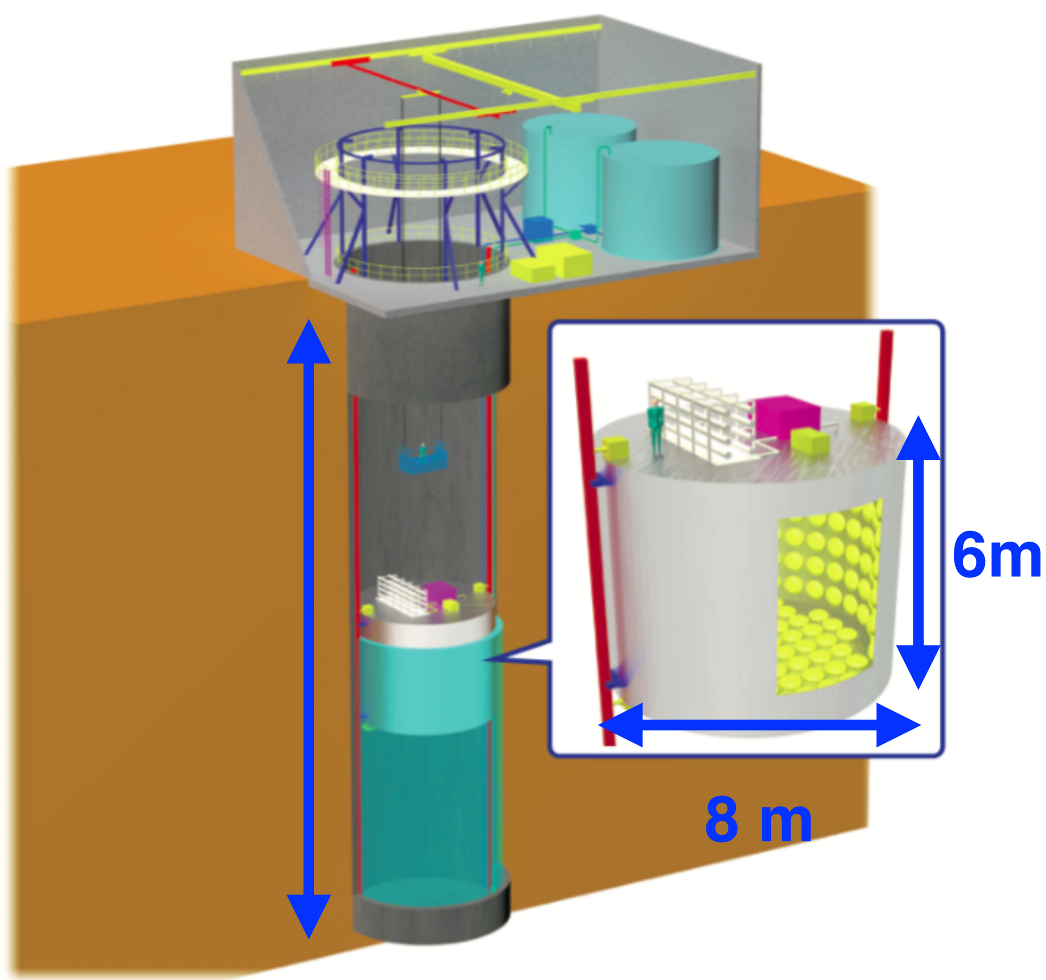
Event in the upgraded ND280



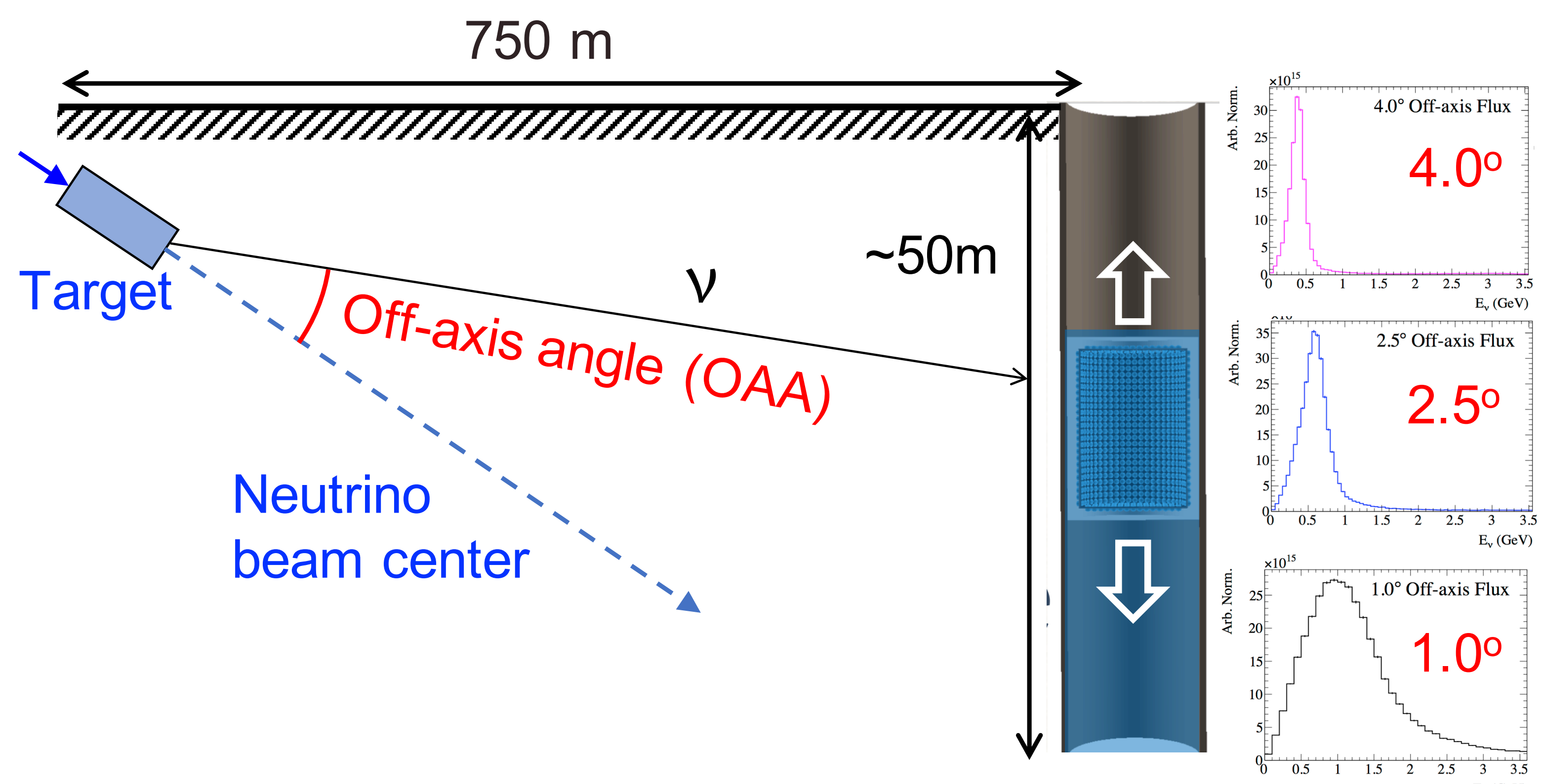
Water Cherenkov detector at 750 m

- A new water Cherenkov detector will be constructed 750 downstream the beamline.
- Multi-PMT module (collection of 3" PMTs) as photo-sensors.
- Moving upward/downward covering 1°-4° off-axis angles.
- Precise measurement of ν_e/ν_μ difference thanks to the excellent ν_e/ν_μ separation of the water Cherenkov detector.

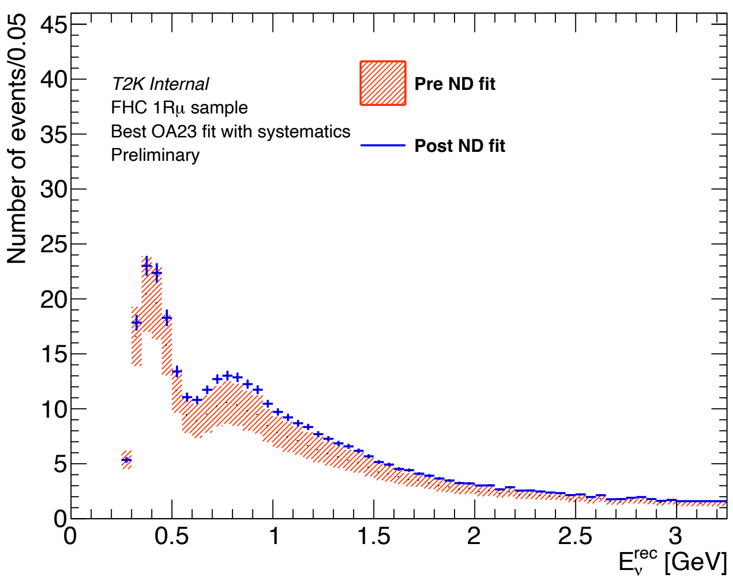
Multi-PMT module

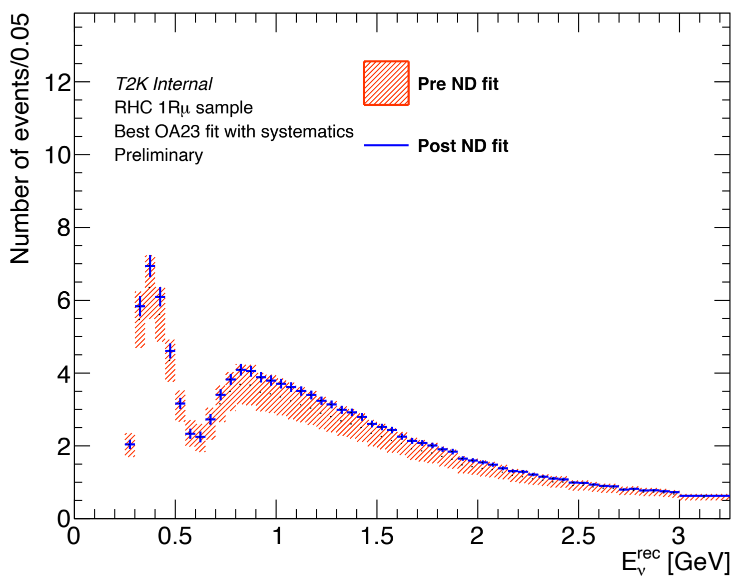


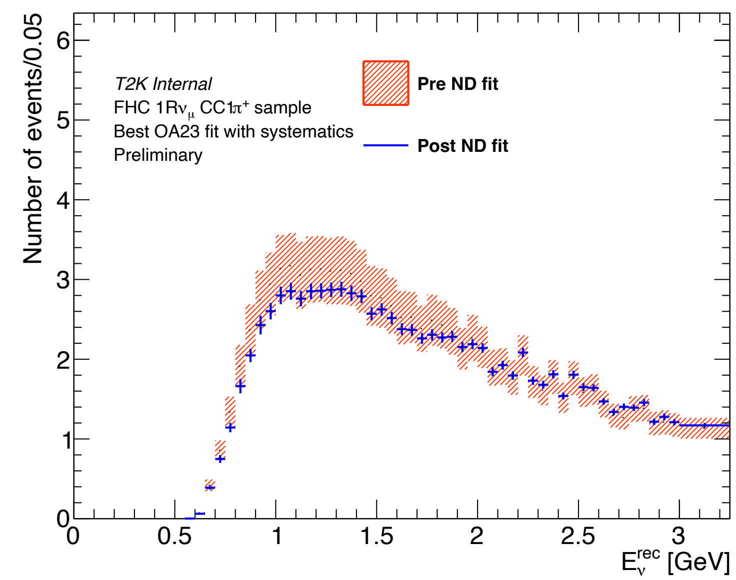
Afloat covering 1°-4°

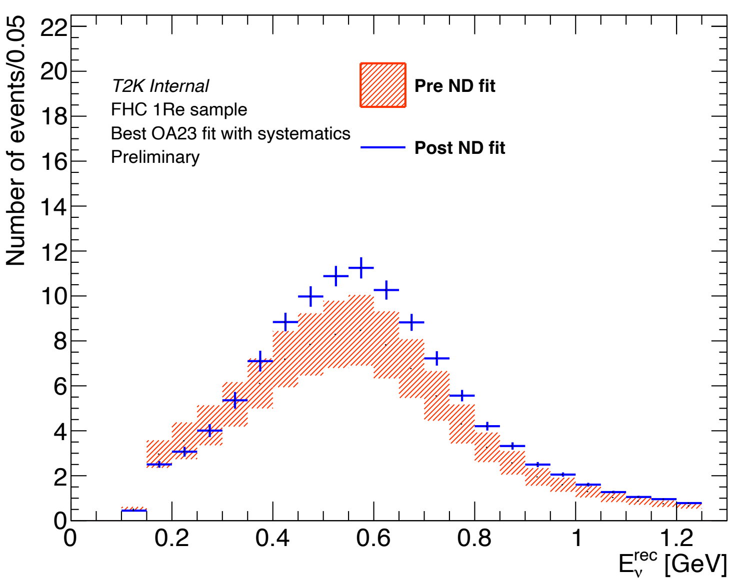


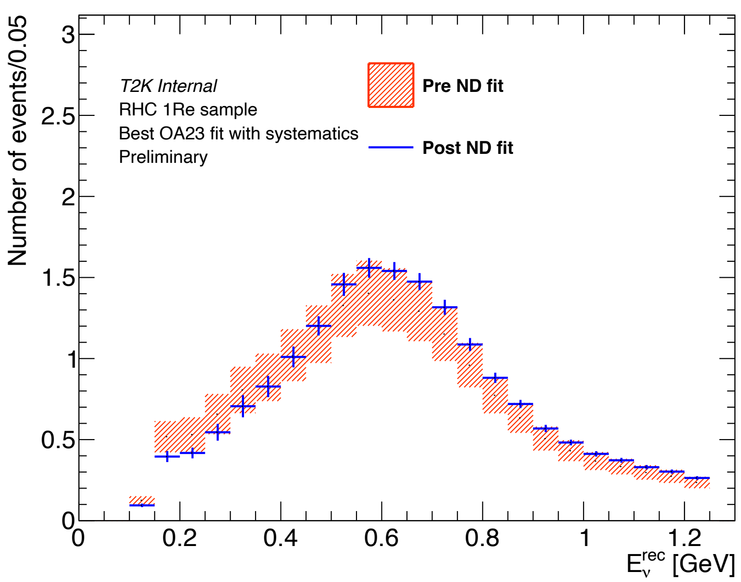
T2K Spectra

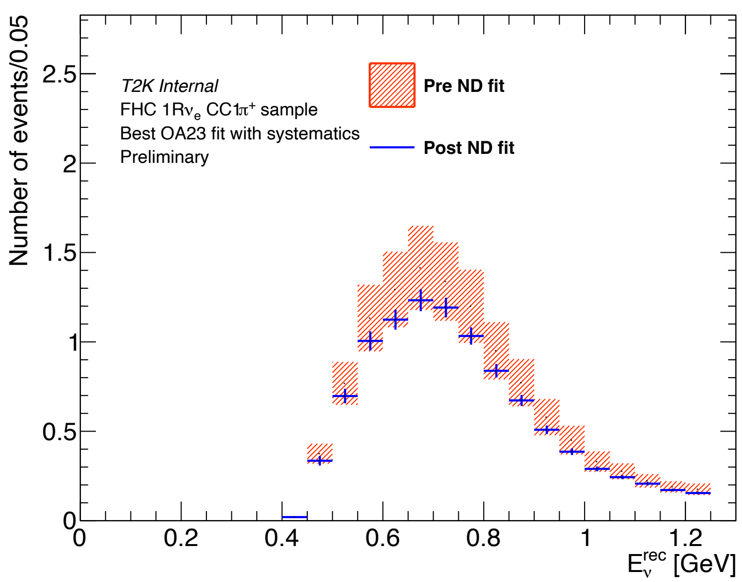

T2K Internal
FHC 1Rμ sample
Best OA23 fit with systematics
Preliminary
Pre ND fit
Post ND fit
Number of events/0.05
E_ν^{rec} [GeV]


T2K Internal
RHC 1Rμ sample
Best OA23 fit with systematics
Preliminary
Pre ND fit
Post ND fit
Number of events/0.05
E_ν^{rec} [GeV]


T2K Internal
FHC 1Rν_μ CC1π^+ sample
Best OA23 fit with systematics
Preliminary
Pre ND fit
Post ND fit
Number of events/0.05
E_ν^{rec} [GeV]


T2K Internal
FHC 1Re sample
Best OA23 fit with systematics
Preliminary
Pre ND fit
Post ND fit
Number of events/0.05
E_ν^{rec} [GeV]


T2K Internal
RHC 1Re sample
Best OA23 fit with systematics
Preliminary
Pre ND fit
Post ND fit
Number of events/0.05
E_ν^{rec} [GeV]


T2K Internal
FHC 1Rν_e CC1π^+ sample
Best OA23 fit with systematics
Preliminary
Pre ND fit
Post ND fit
Number of events/0.05
E_ν^{rec} [GeV]