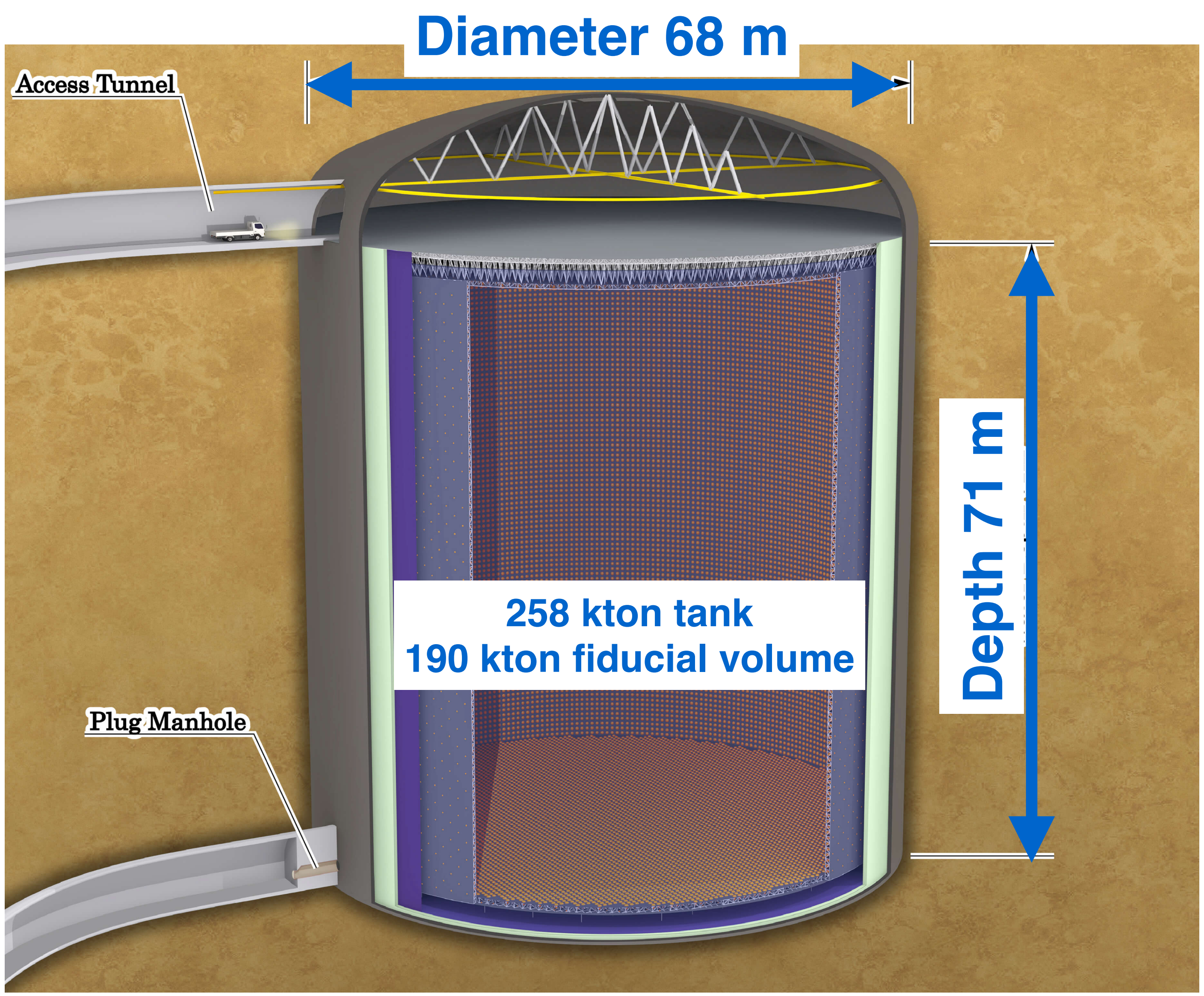
Hyper-Kamiokande experiment

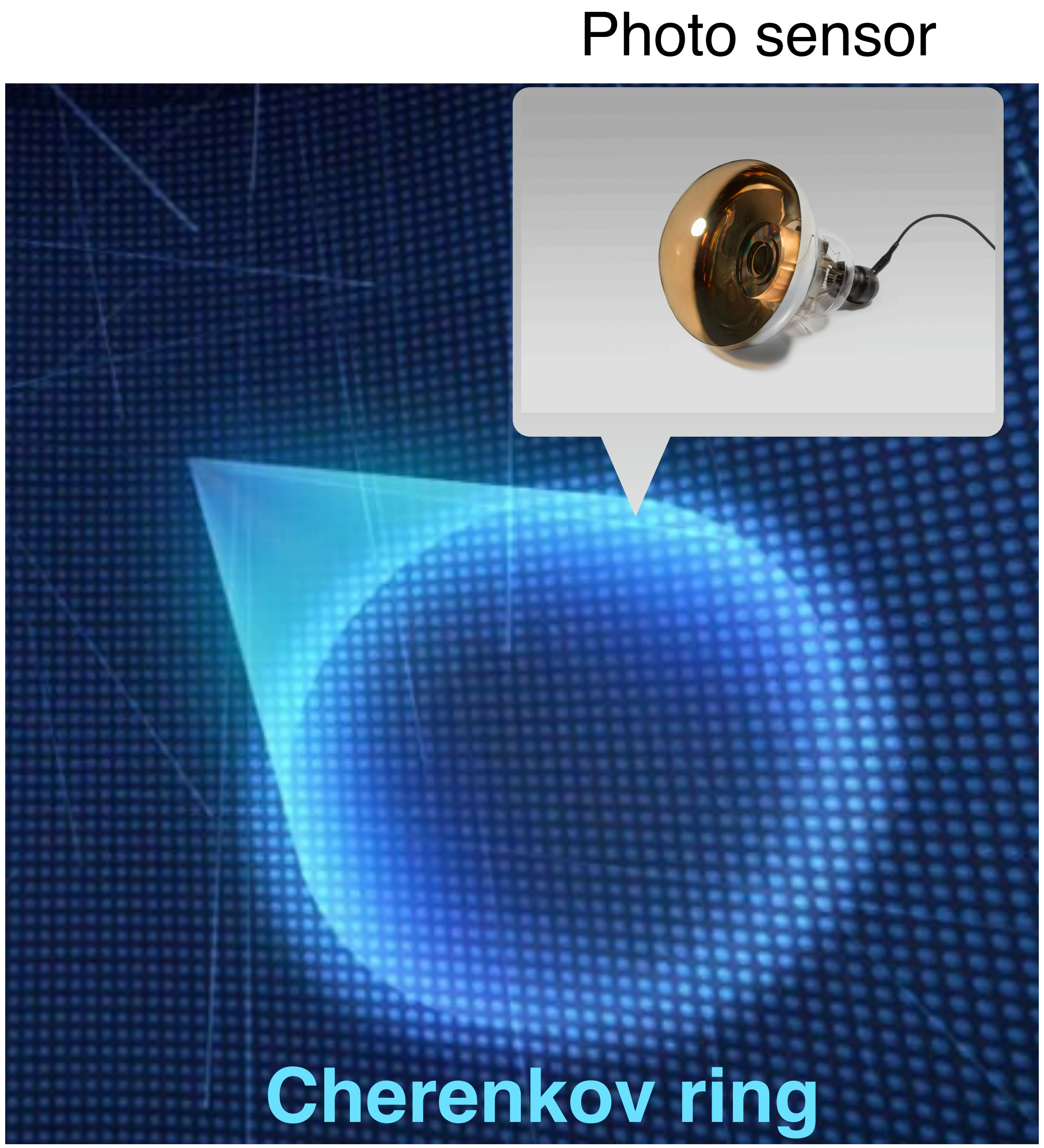
Yohei Noguchi on behalf of the Hyper-Kamiokande collaboration
The University of Tokyo, ICRR, Kamioka Observatory

The 29th International Workshop on Weak Interactions and Neutrinos
Sun Yat-sen University Zhuhai, 4th July 2023

Hyper-Kamiokande detector

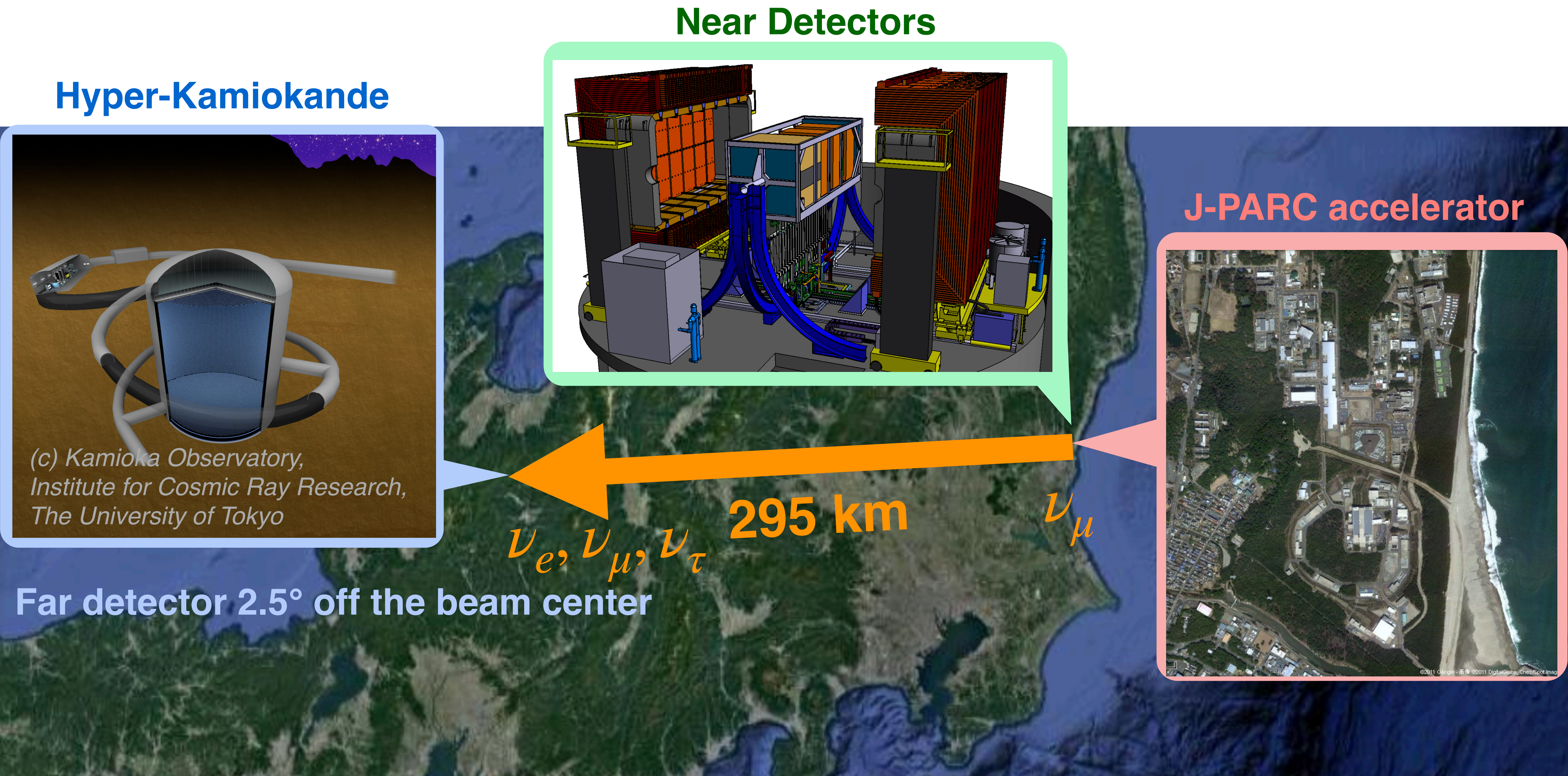
- Next generation water Cherenkov detector in Kamioka, Japan.
- 258 kton water tank: fiducial mass ×8 larger than Super-K.
- 20,000 improved photomultiplier tubes (PMTs) to detect Cherenkov light.





Hyper-Kamiokande project

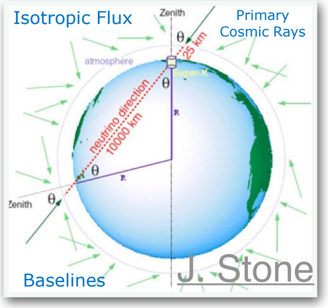
- **Joint project combining a large water Cherenkov detector and even more intense neutrino beam with the J-PARC accelerator.**
- **Upgraded near detectors constraining the neutrino beam before oscillation**



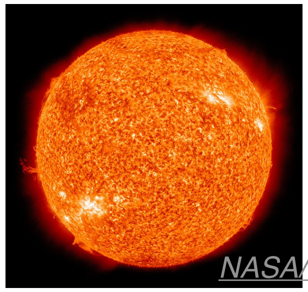
Physics targets at Hyper-Kamiokande

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

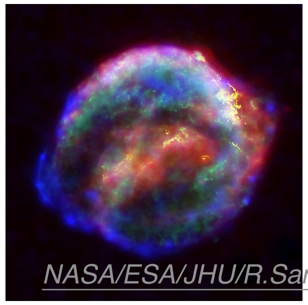
- Neutrino oscillation
  - *Accelerator + atmospheric neutrinos:*
    - CP violation as the "origin" of the matter dominant universe.
    - Mass ordering.
  - *Solar neutrinos:*
    - Non-standard oscillations and interactions through matter effects in the electron neutrino disappearance.



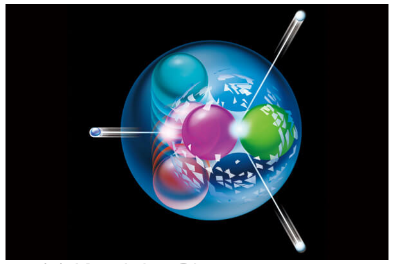
J. Stone


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

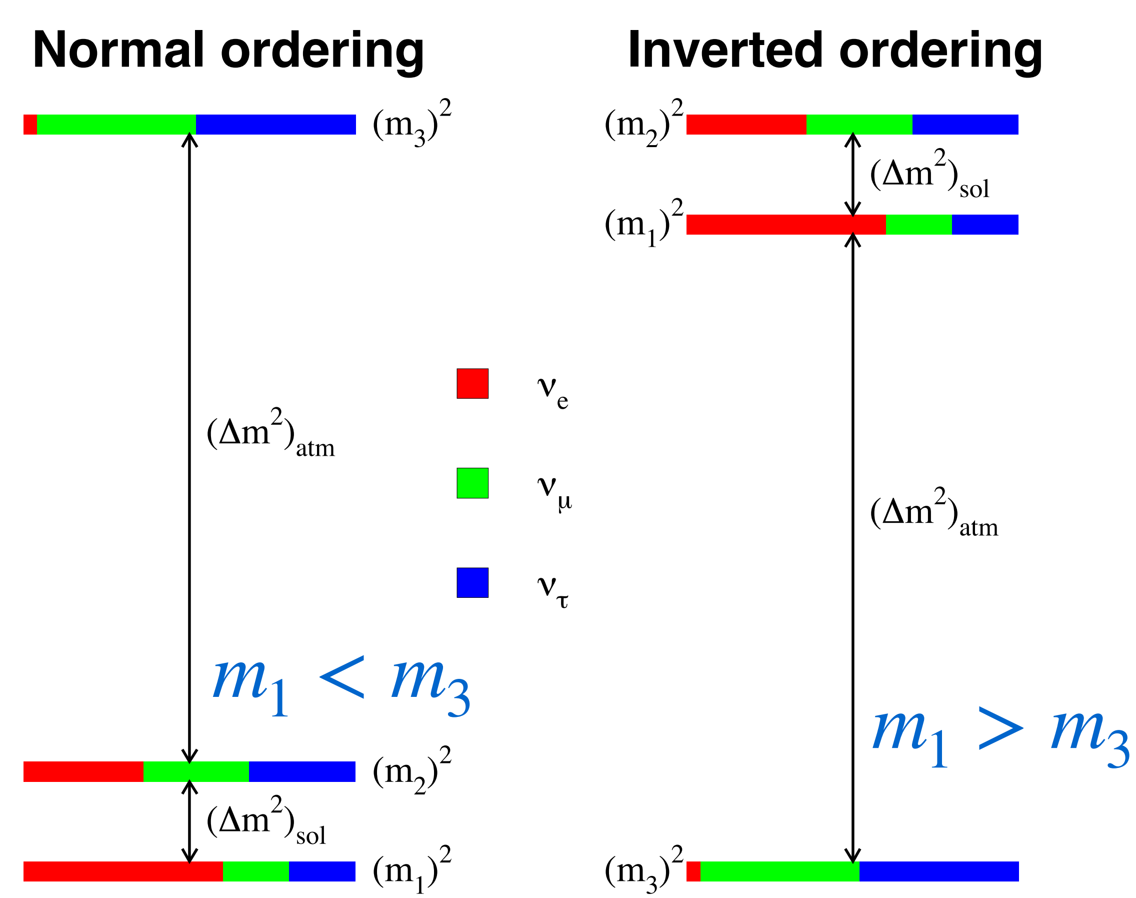
- **Neutrino oscillation takes place because of the flavor-mass mixing:**

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

Various baseline lengths and energies →

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

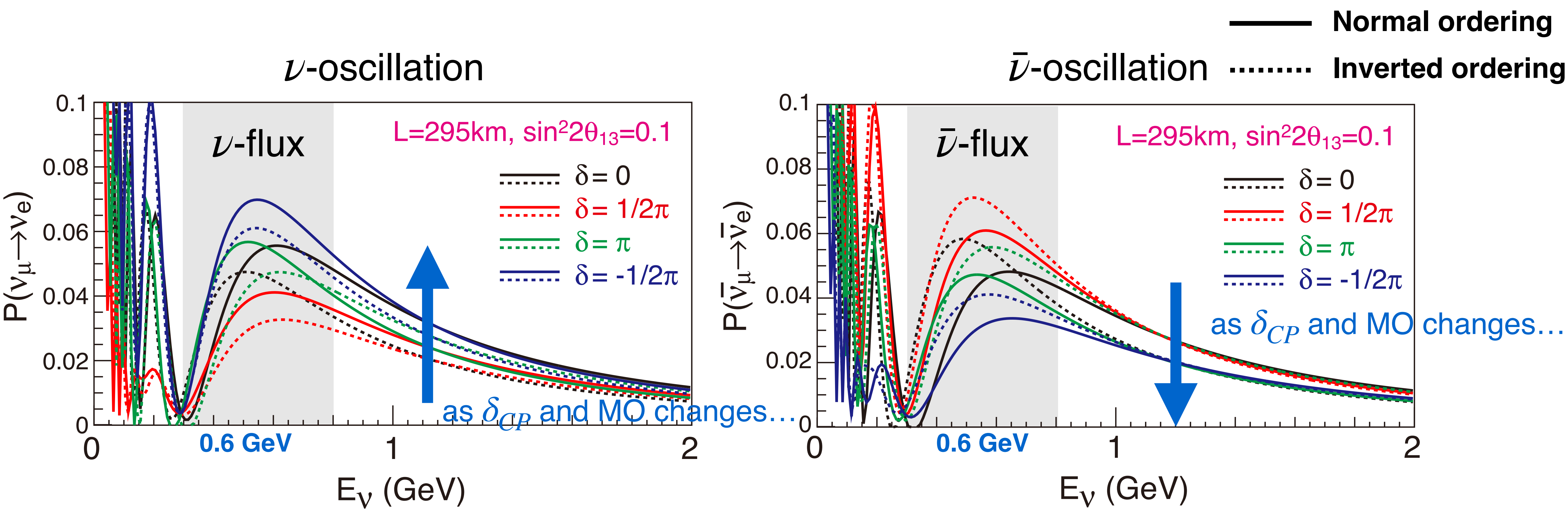
- **Open questions in the neutrino oscillation:**
  - **CP violating phase**: δ_{CP}
    - **Possible source of the baryon asymmetry of the universe.**
  - **Mass ordering: sign of** Δm^2_{13}
    - **Oscillation in vacuum → only** $|\Delta m^2_{13}|$
    - **Need to see the matter effect.**



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

Accelerator neutrino oscillation experiment

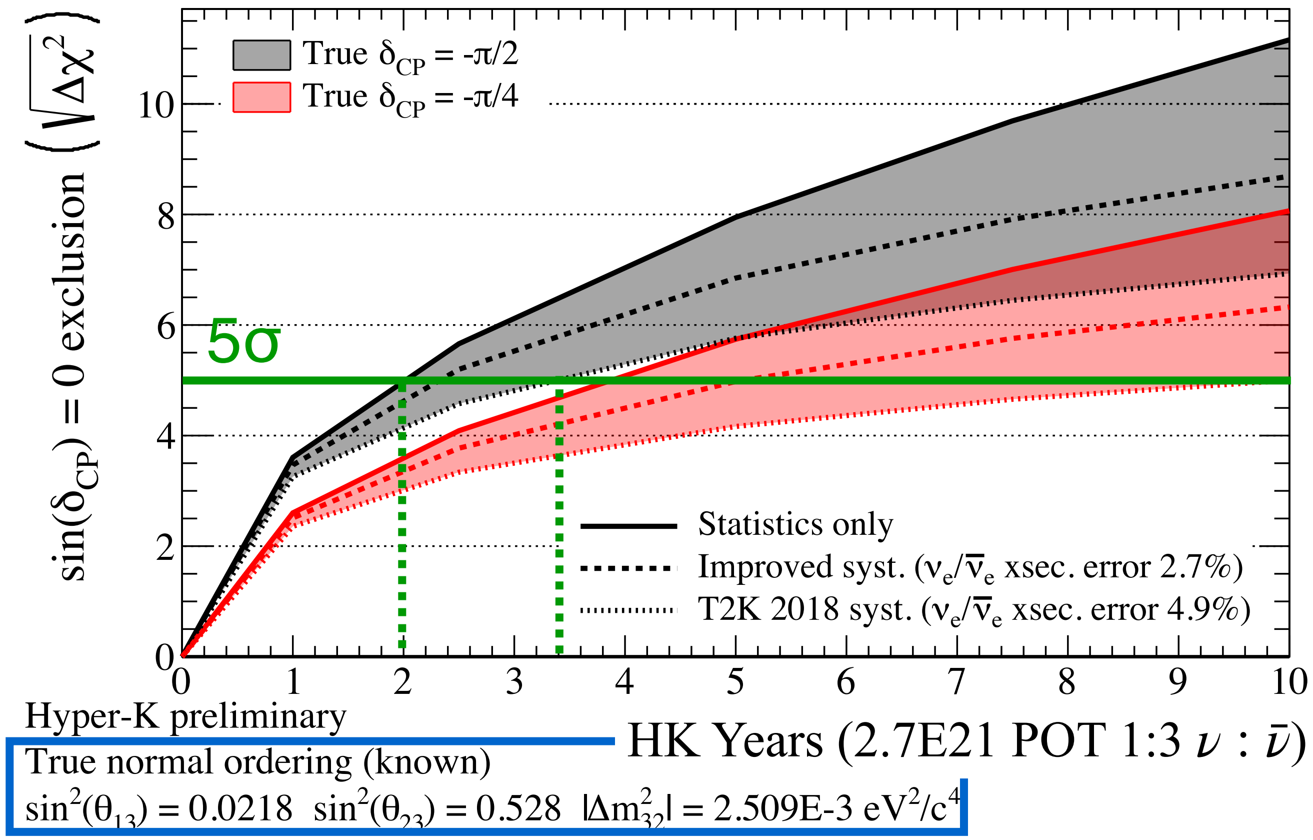
- **CP-symmetry tested with ν-beam and $\bar{\nu}$-beam enabled by the polarity of the focusing magnets.**
- **2.5° off-axis arrangement focuses the neutrinos on the osc. maximum at 0.6 GeV.**

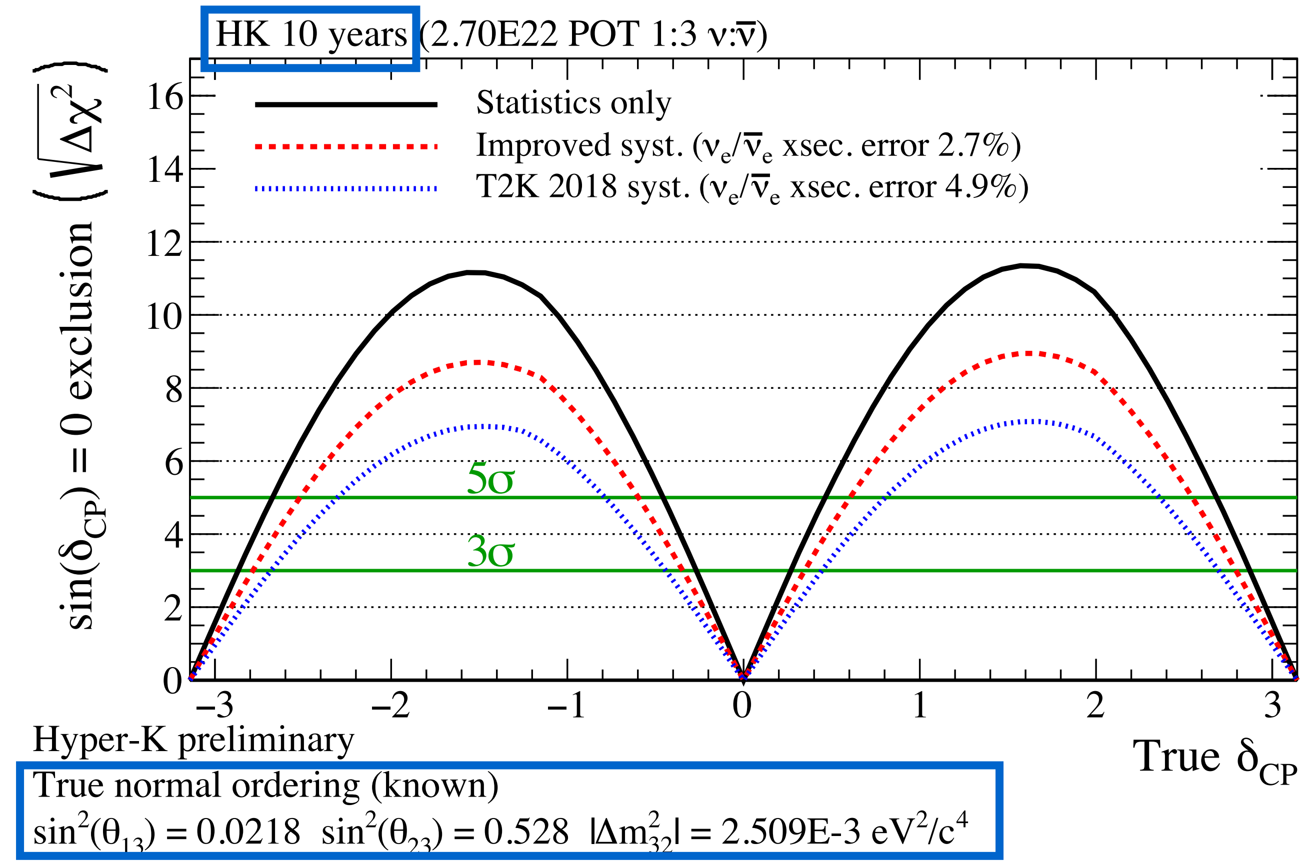


- **Degeneracy between the δ_{CP} phase and the mass ordering in the beam neutrino.**
  - **Need $\nu_\mu \rightarrow \nu_e$ with various travel lengths and energies → <u>atmospheric ν data</u>**

Accelerator neutrino oscillation sensitivities

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



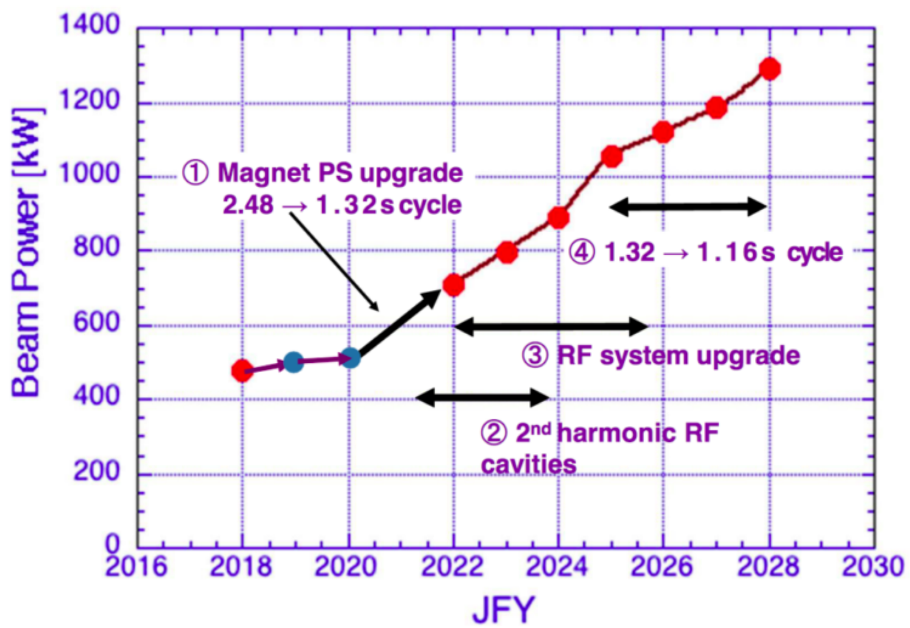


- **In the optimistic case (reduced systematics, known mass ordering):**
  - **2-3 year data give 5σ observation of the CP violation if true $\delta_{CP} = -\pi/2$.**
  - **After 10-year operation, 60% of δ_{CP} values will be excluded with >5σ.**

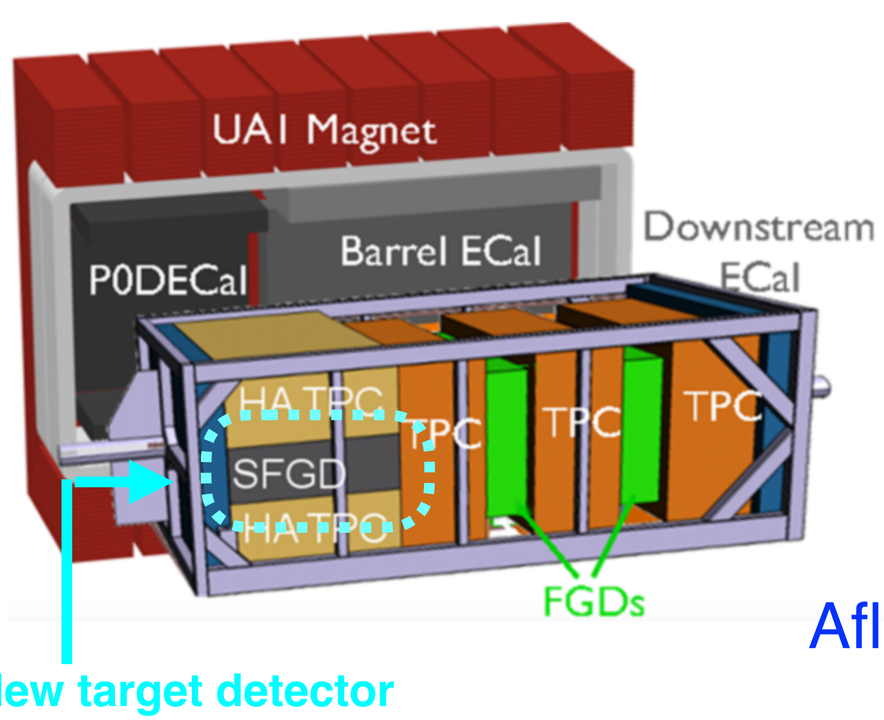
J-PARC accelerator + Near Detector suite

- **Beam power upgraded** **515 kW → 1.3 MW with** **<u>increased numbers of protons in a bunch</u>** **and** **<u>faster repetition cycles.</u>**
- **Upgraded Near Detectors**
  - **Target detector with higher granularity and angular acceptance.**
    - **Aiming to improve physics models involving short tracks.**
  - **Water Cherenkov detector 750 m downstream of the beam.**
    - **Excellent ν_e/ν_μ separation, same target nuclei as the far detector.**

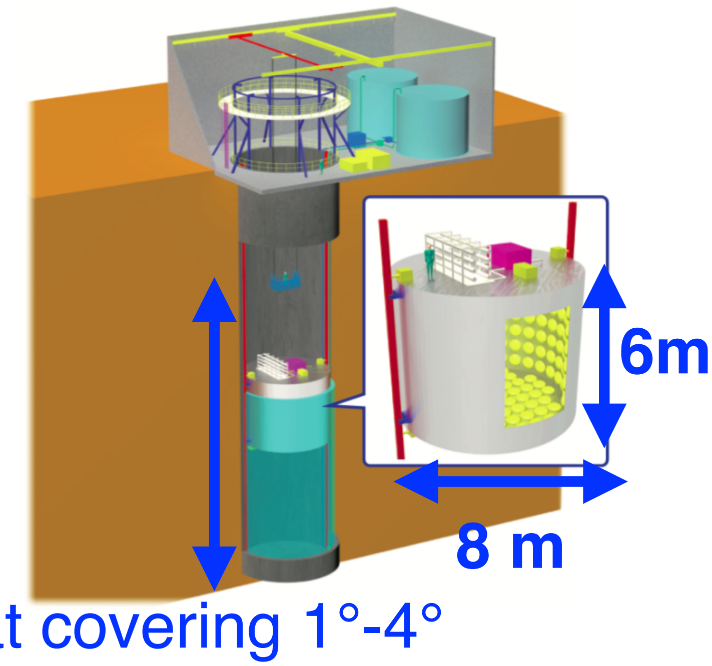
J-PARC power schedule



Upgraded near detector



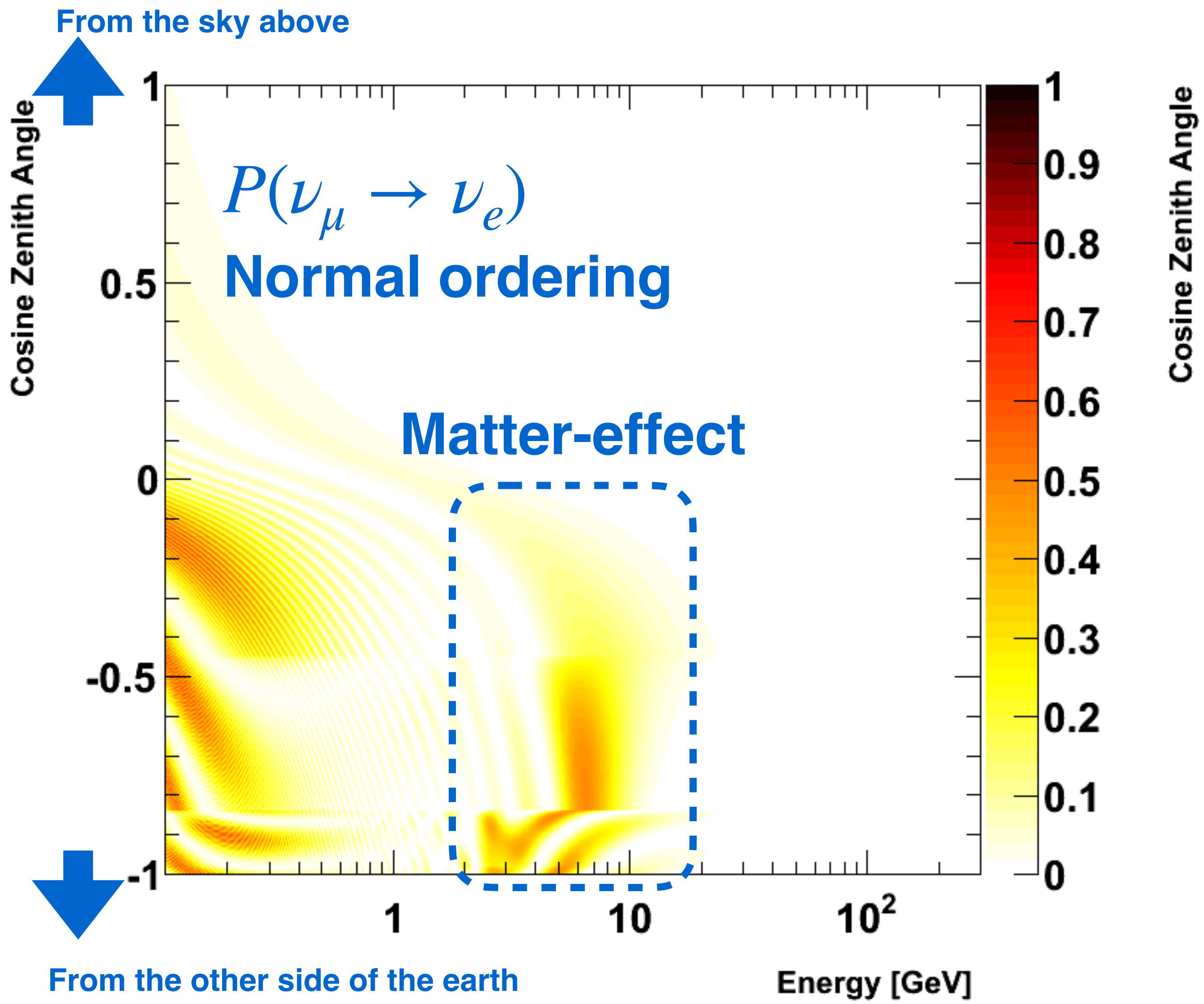
New water Cherenkov detector 750 m away from the ν-beamline

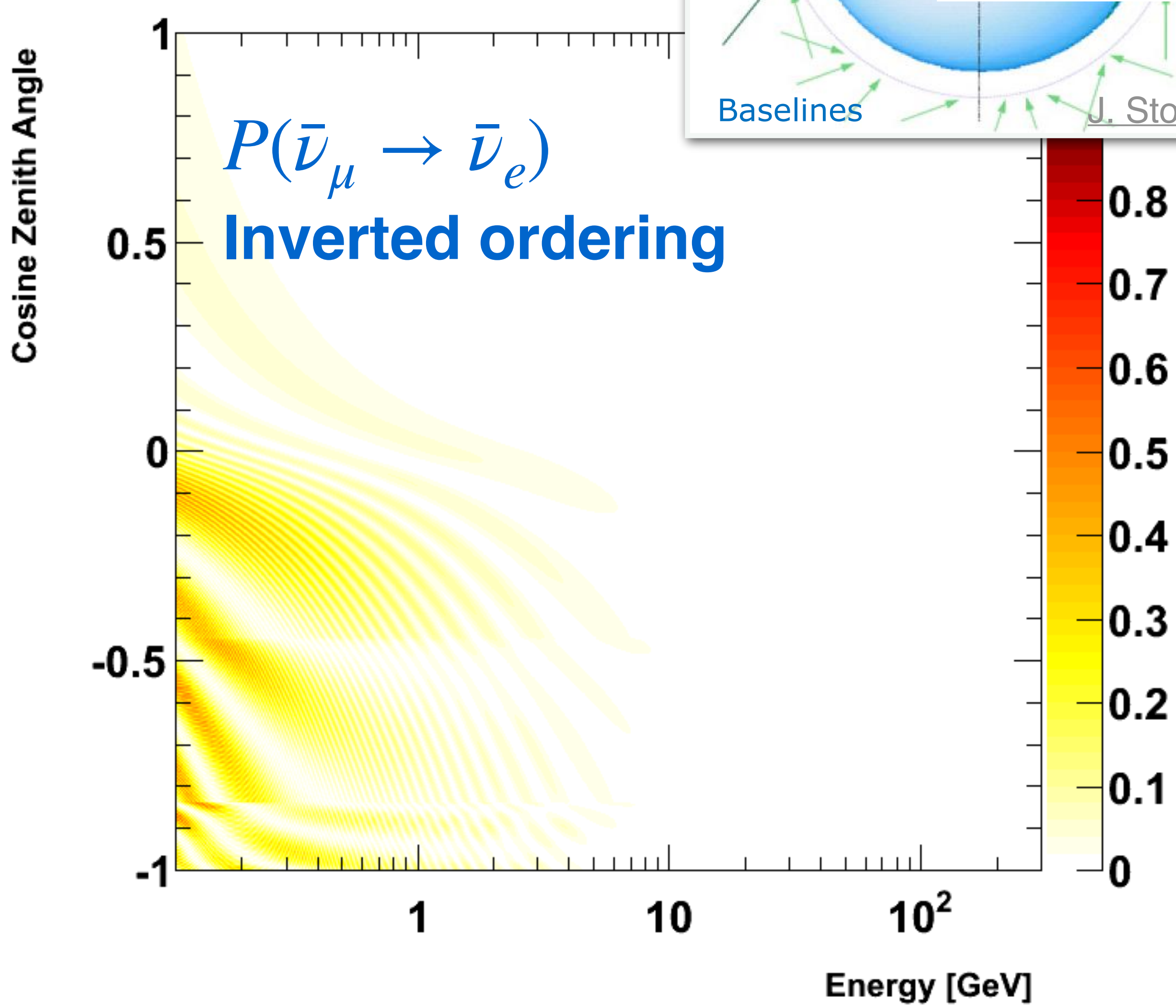


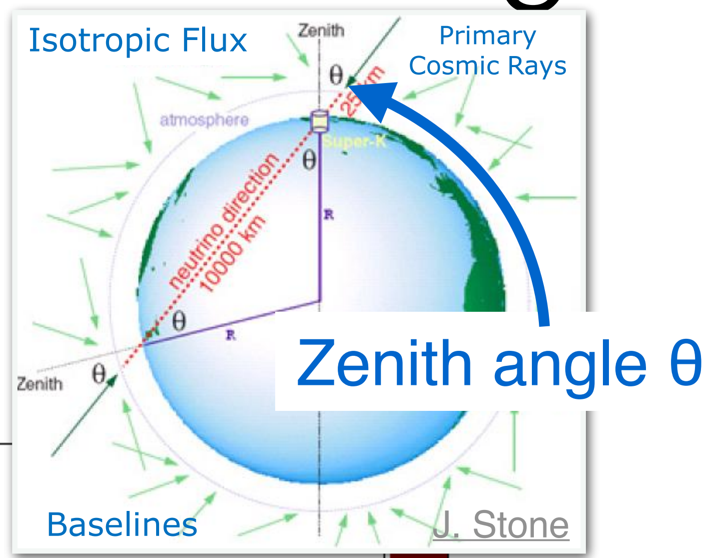
https://t2k-experiment.org/beyond-t2k/

Atmospheric neutrino oscillation

- **Matter-driven resonant enhancement of $P(\nu_\mu \rightarrow \nu_e)$ for NO and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ for IO.**





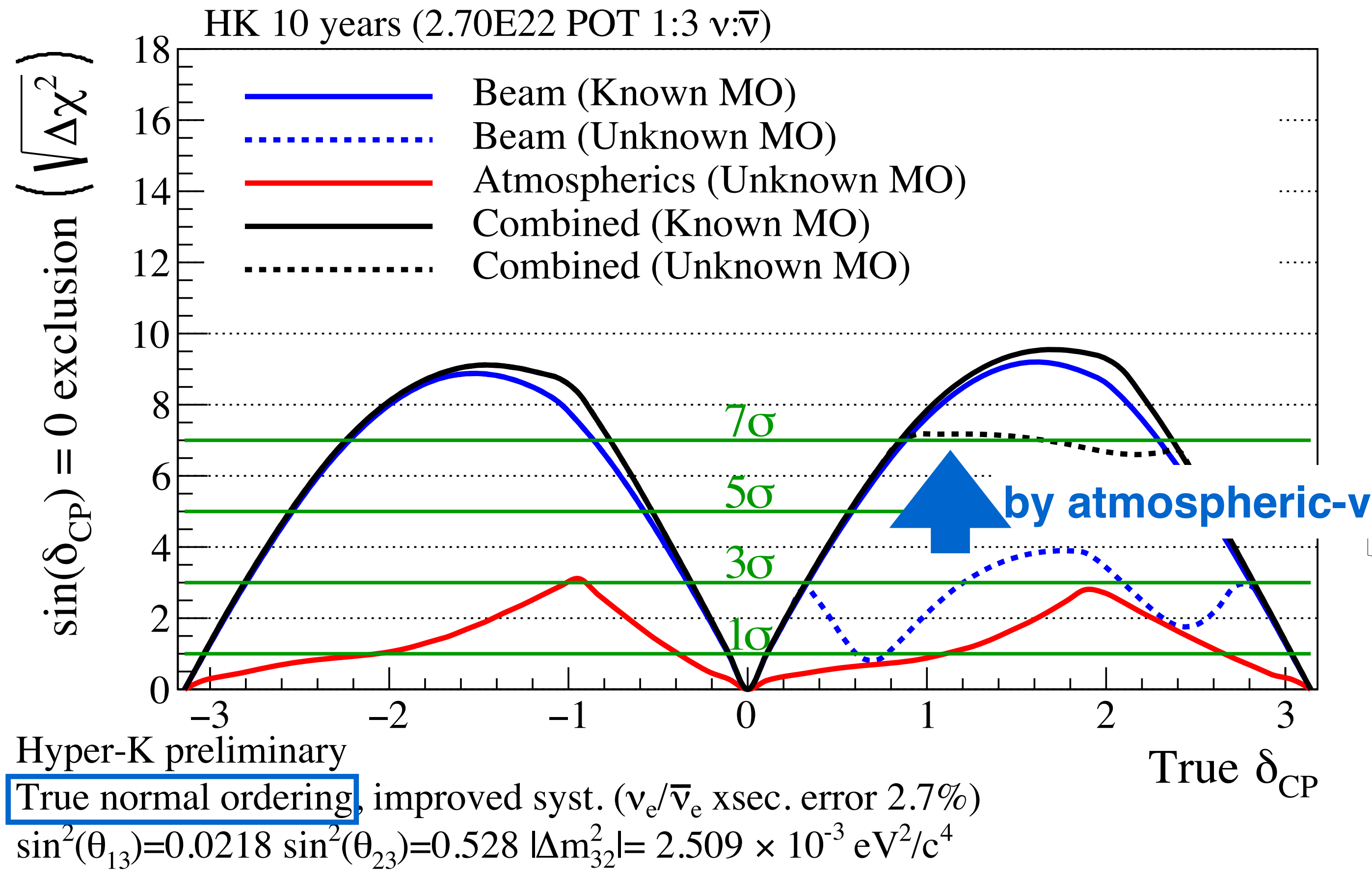


Phys. Rev. D 97 (2018) 072001

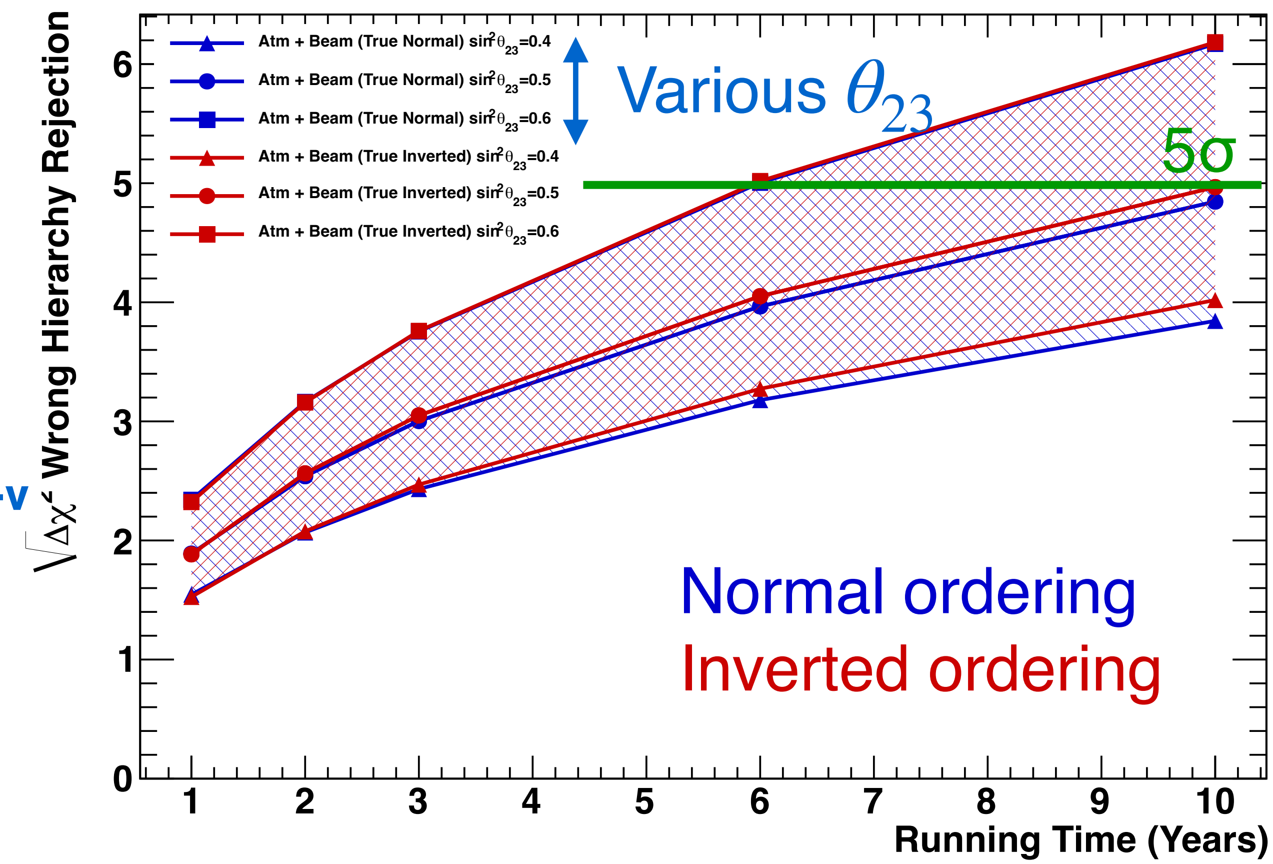
- **Long travel length in the earth results in greater matter effect.**
  ➡ **Good chance to determine the mass ordering.**

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.**

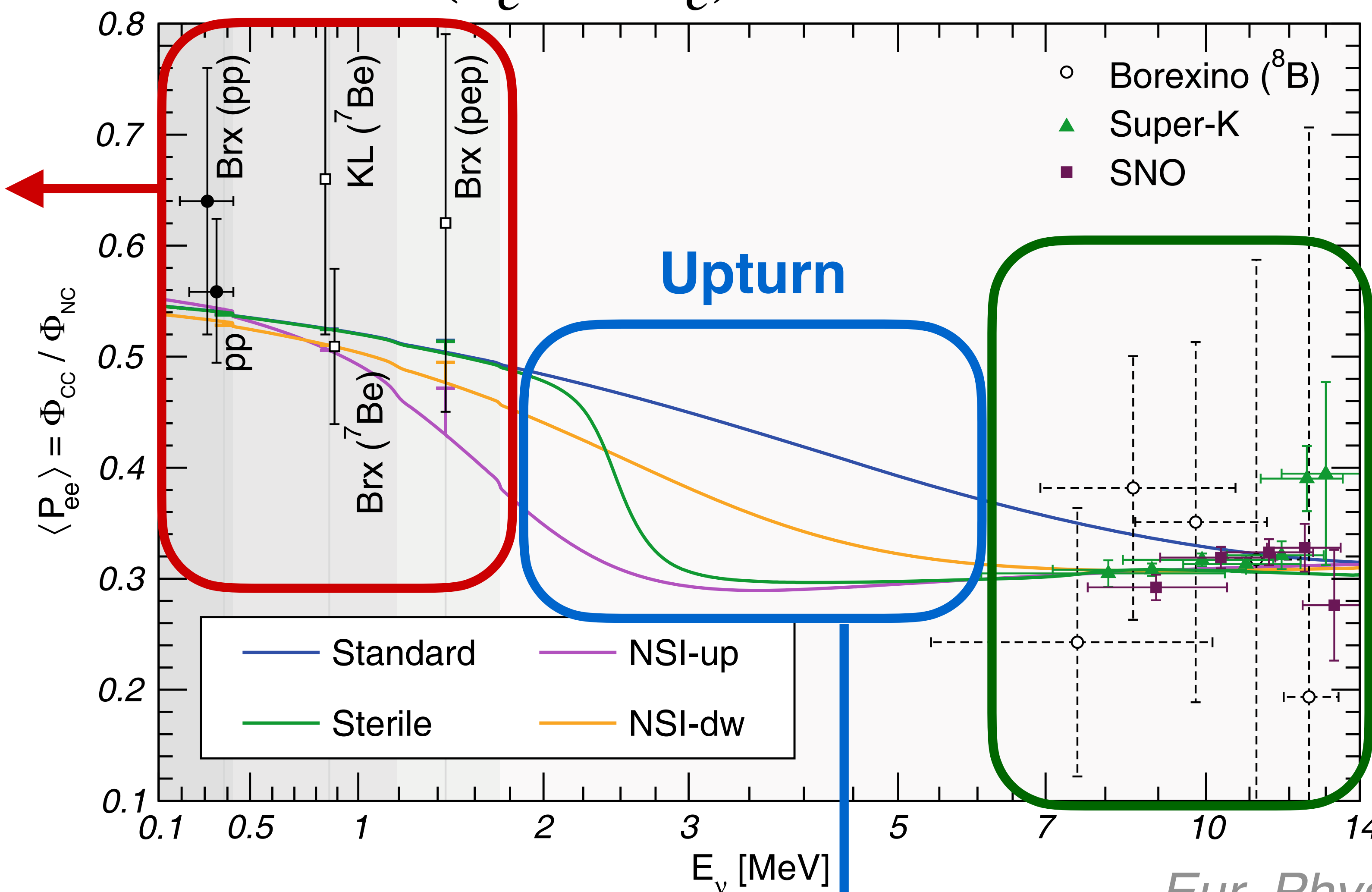
Solar neutrinos

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

$P(\nu_e \rightarrow \nu_e)$ in solar-ν

Vacuum-dominant oscillation

Higher survival probability



Matter-driven oscillation in the sun (MSW effect)

Lower survival probability

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.

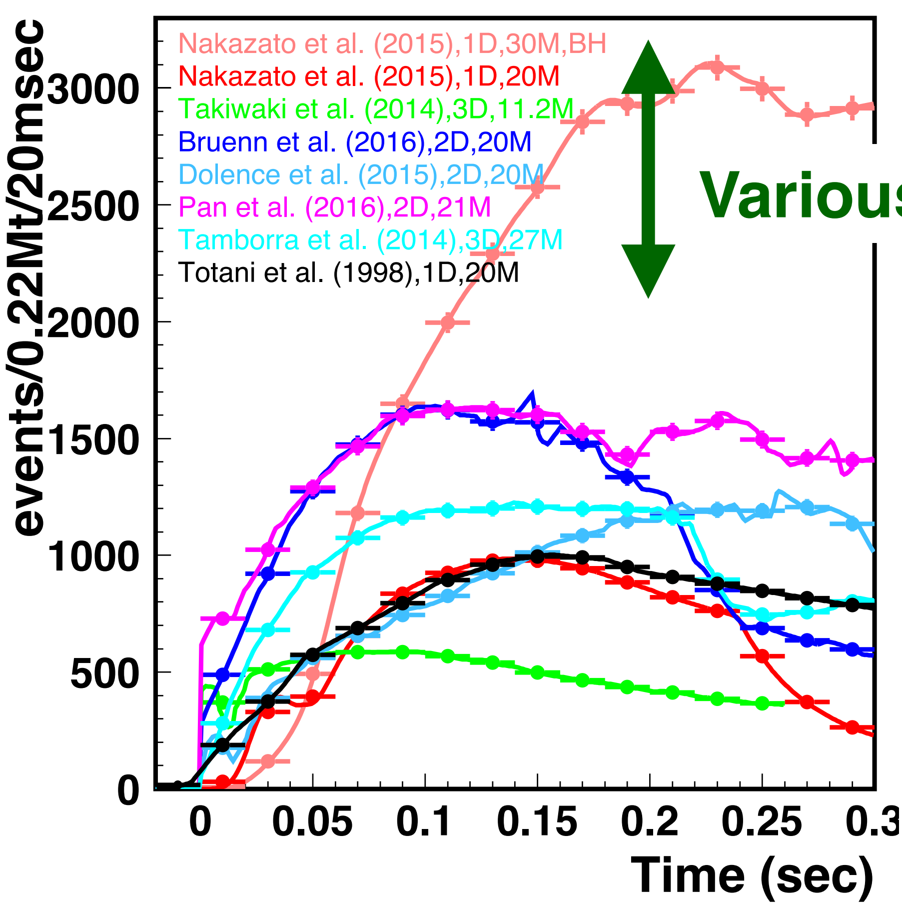
Bursts: single explosion events

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

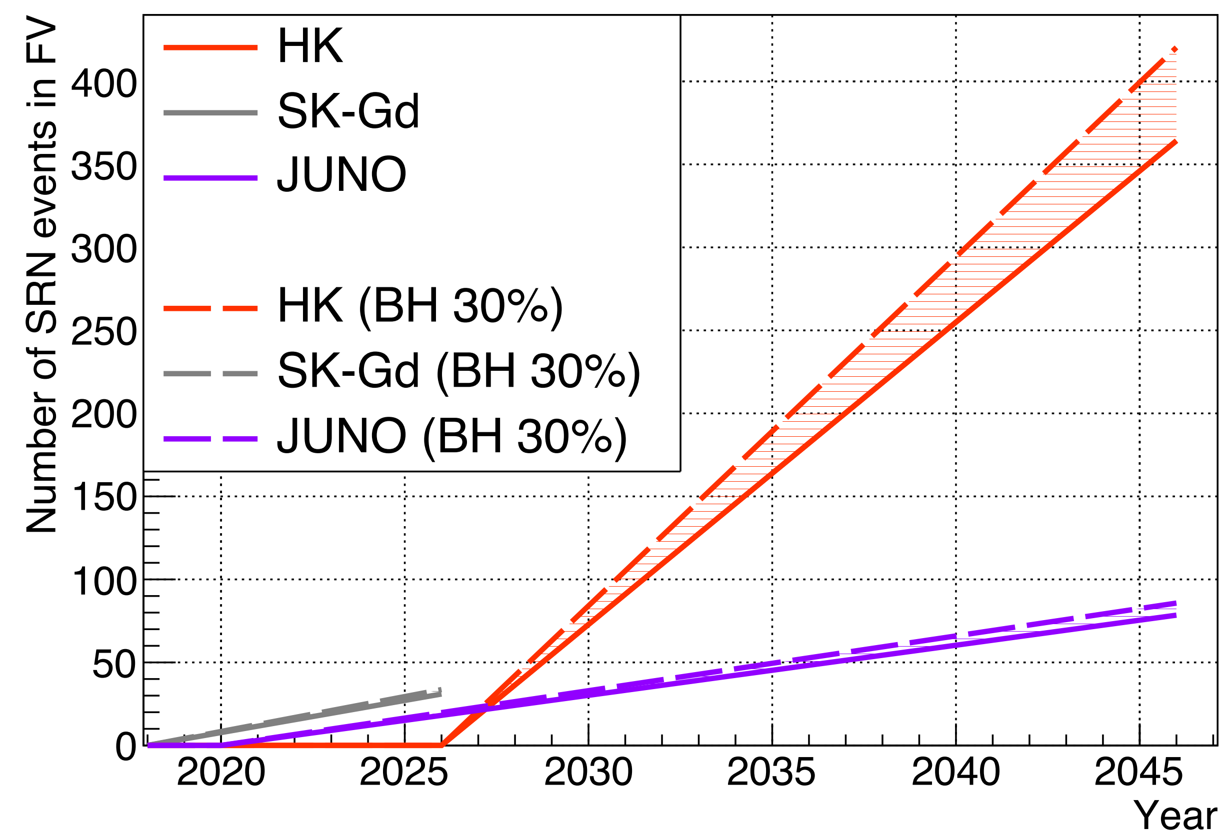
Relic: accumulated SN-ν flux

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

Time evolution of SN-ν events

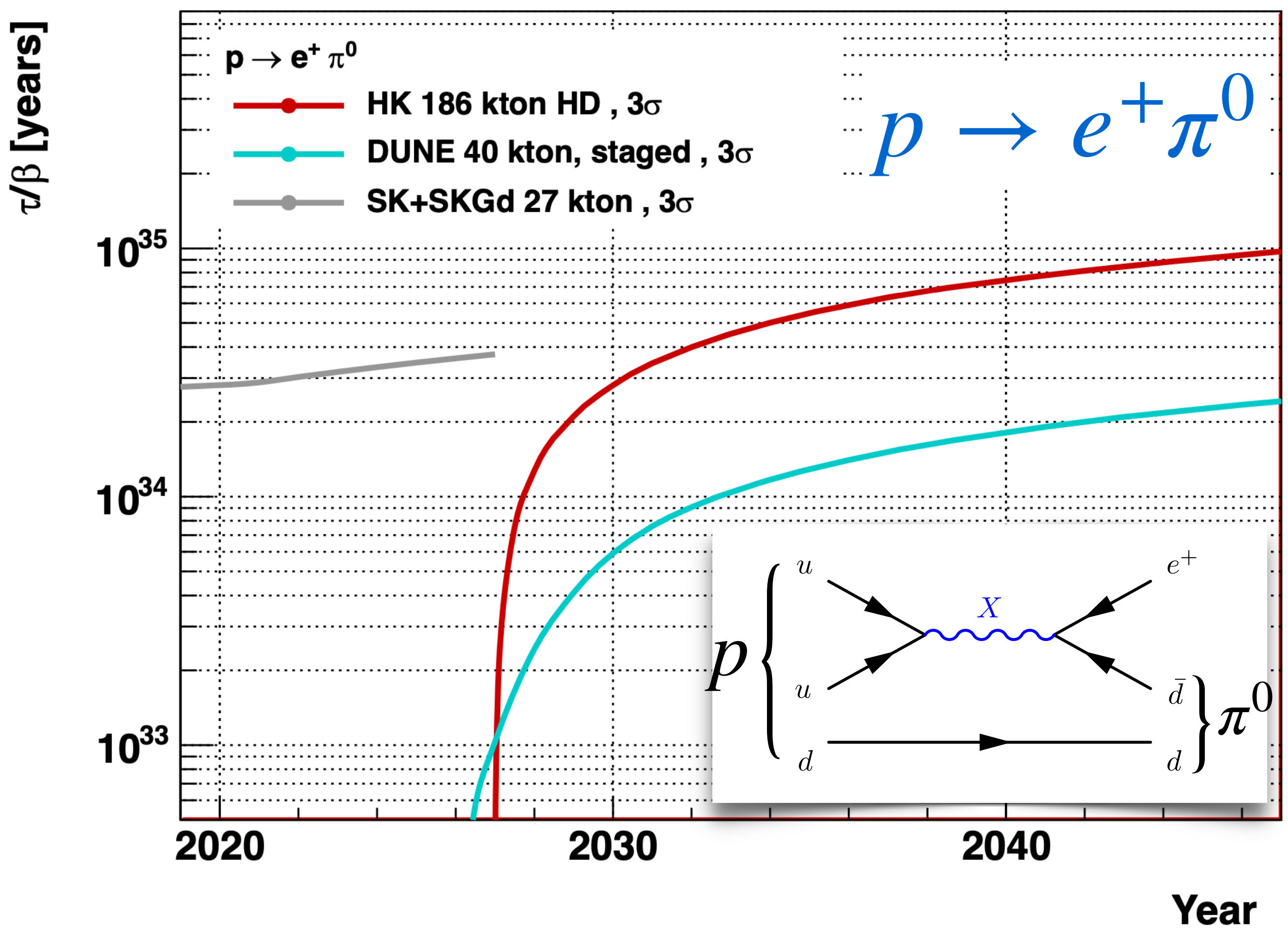


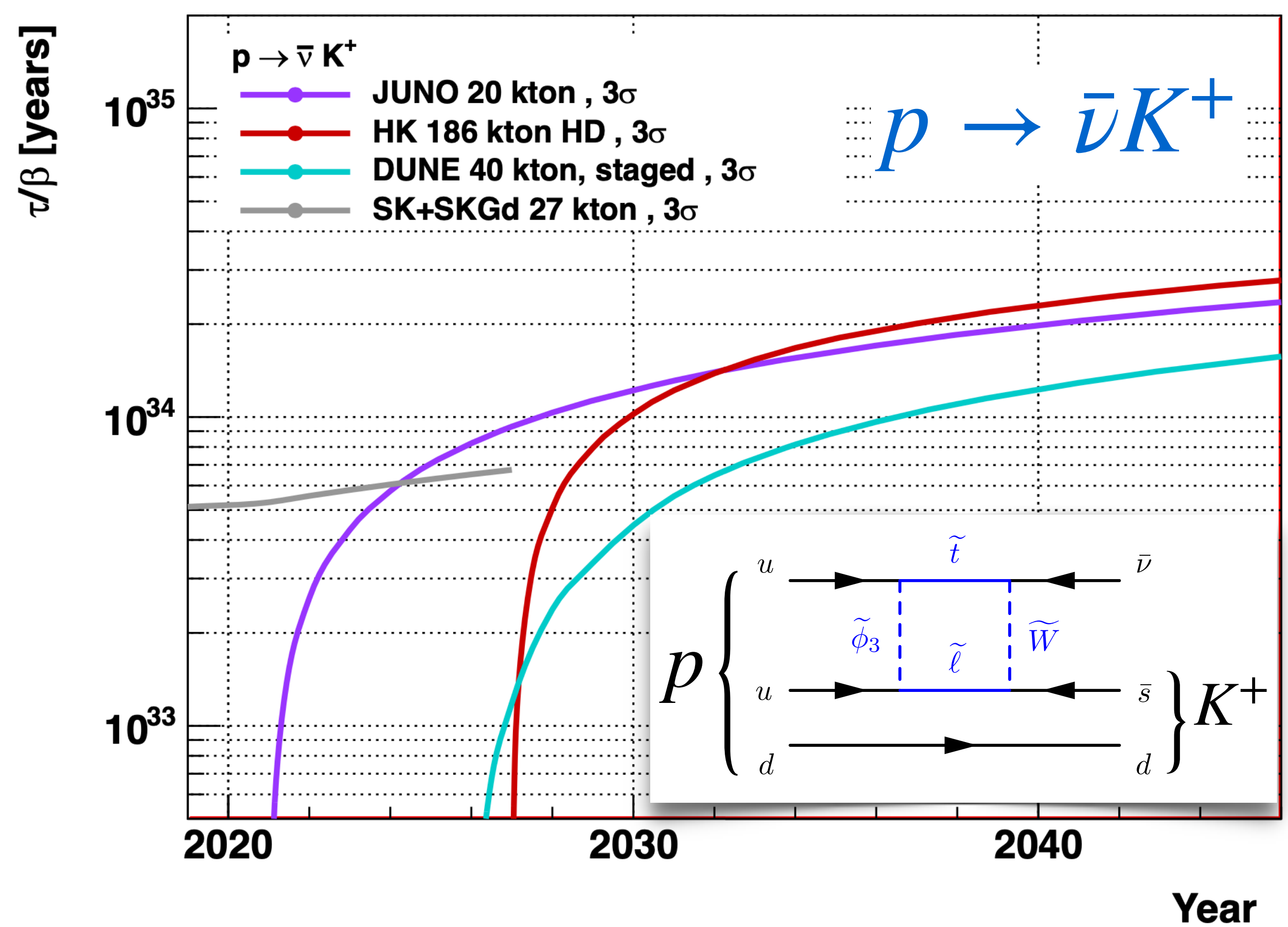
SN-ν events with various detectors



Nucleon decays

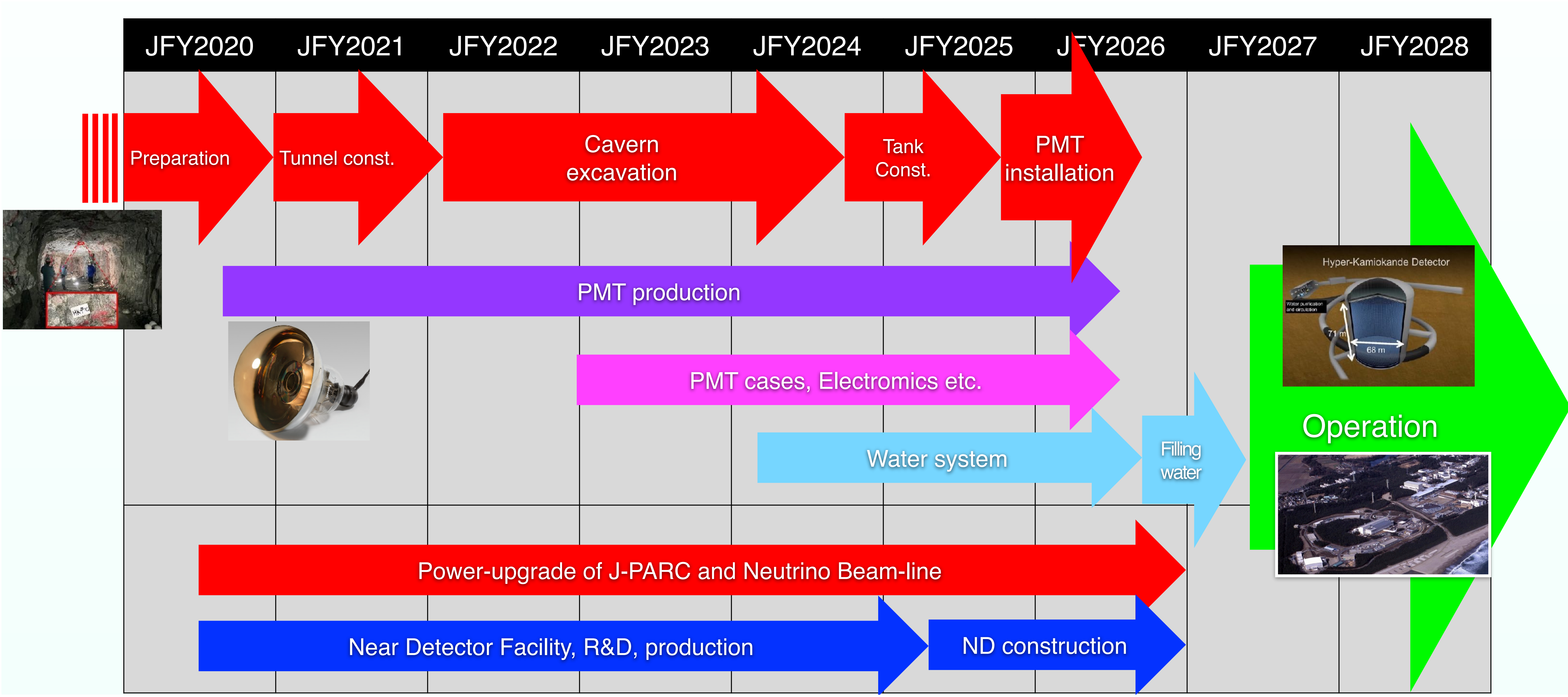
- **Direct evidence of Grand Unified Theory (GUT).**
- **World best sensitivity for many decay modes.**
  - **Including flagship modes: $p \to e^+\pi^0$ and $p \to \bar{\nu}K^+$.**





- **Larger water Cherenkov detector experiment is the unique solution for $\tau(p \to e^+\pi^0) > 10^{35}$ years.**
  - **A key to determine the GUT scale without spares.**

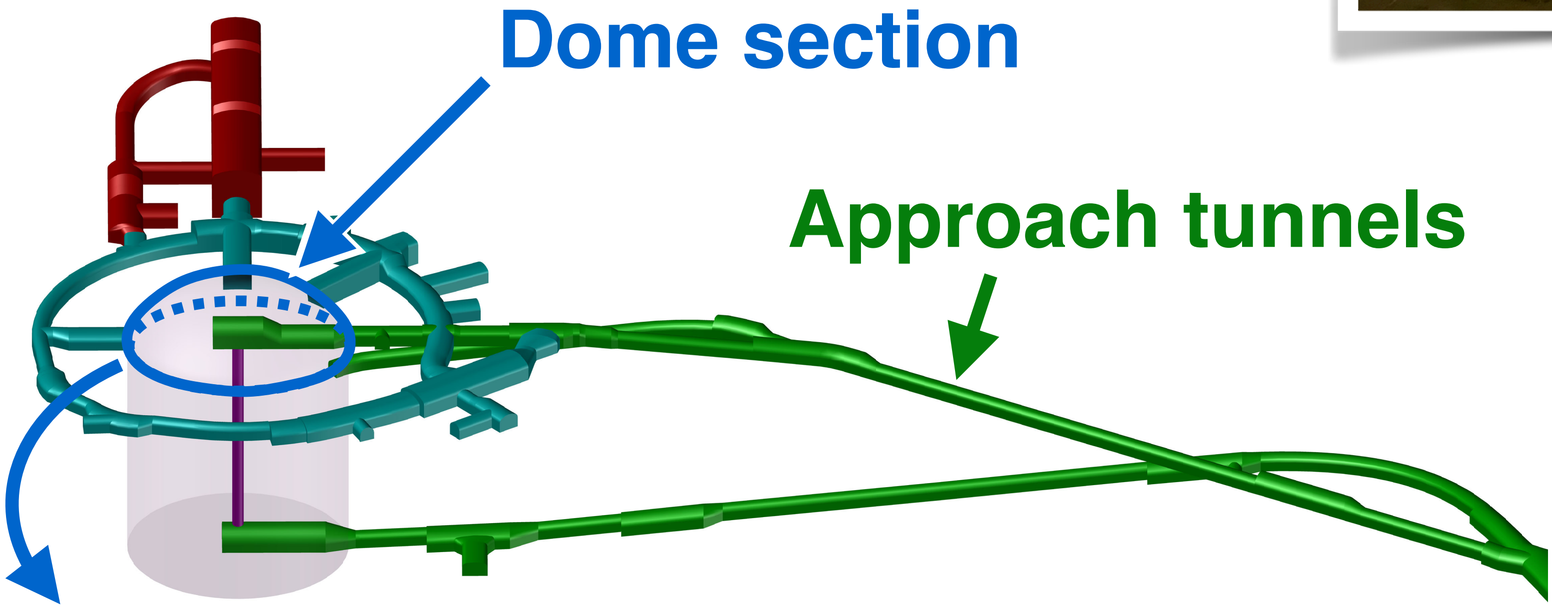
Timeline

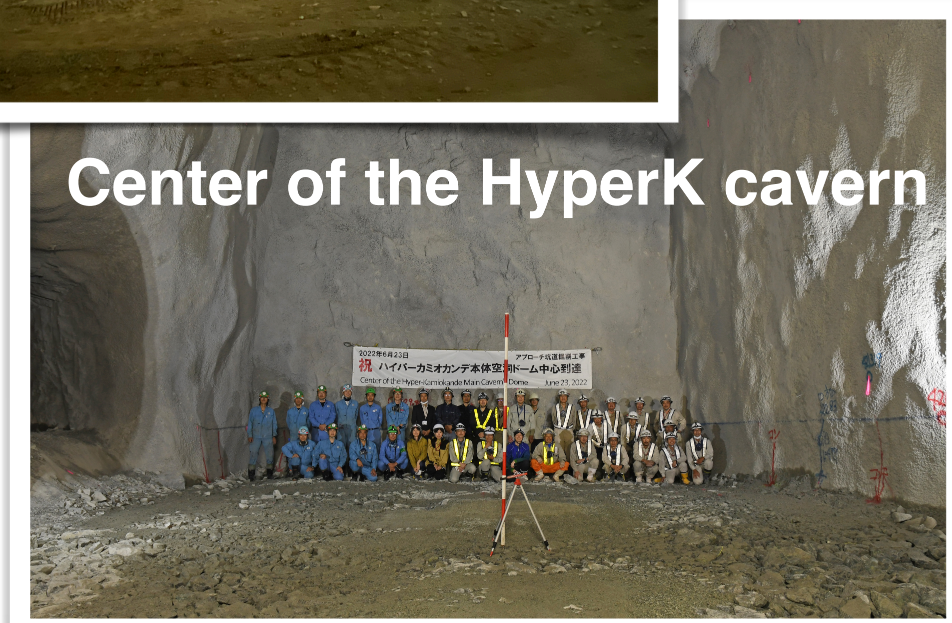


- **Cavern excavation and detector preparation are underway without delay.**
- **Detector installation planned around 2025.**
- **Data-taking planned to start in 2027.**

Cavern excavation

- **Access and approach tunnels: > 2km**
  - **Completed in July 2022.**
- **Dome excavation in progress.**
  - **Takes 12 months**





(c) Kamioka Observatory, ICRR, The University of Tokyo

Dome excavation procedure: from the inner rings to the outer ones

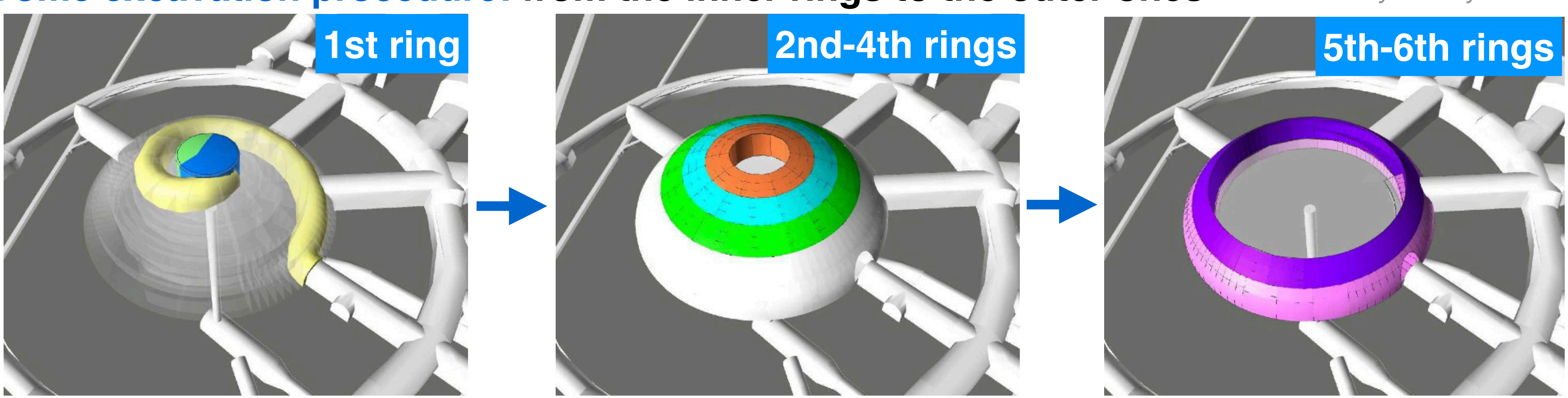
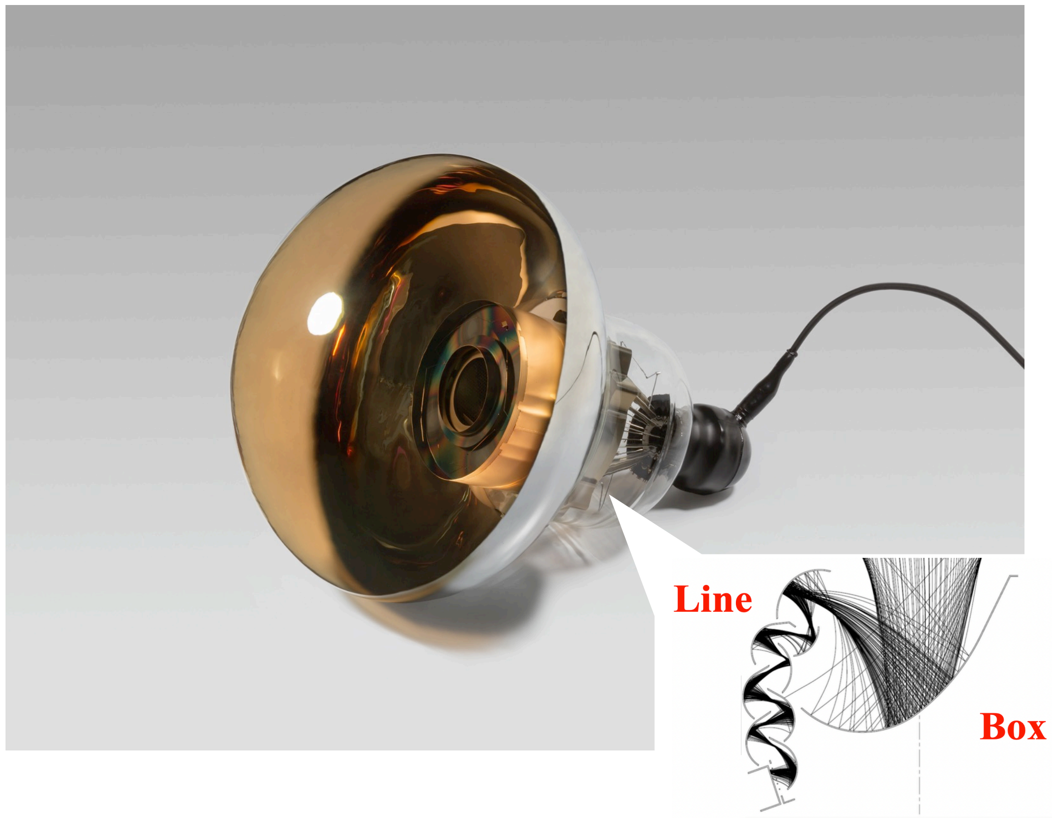


Photo-detectors

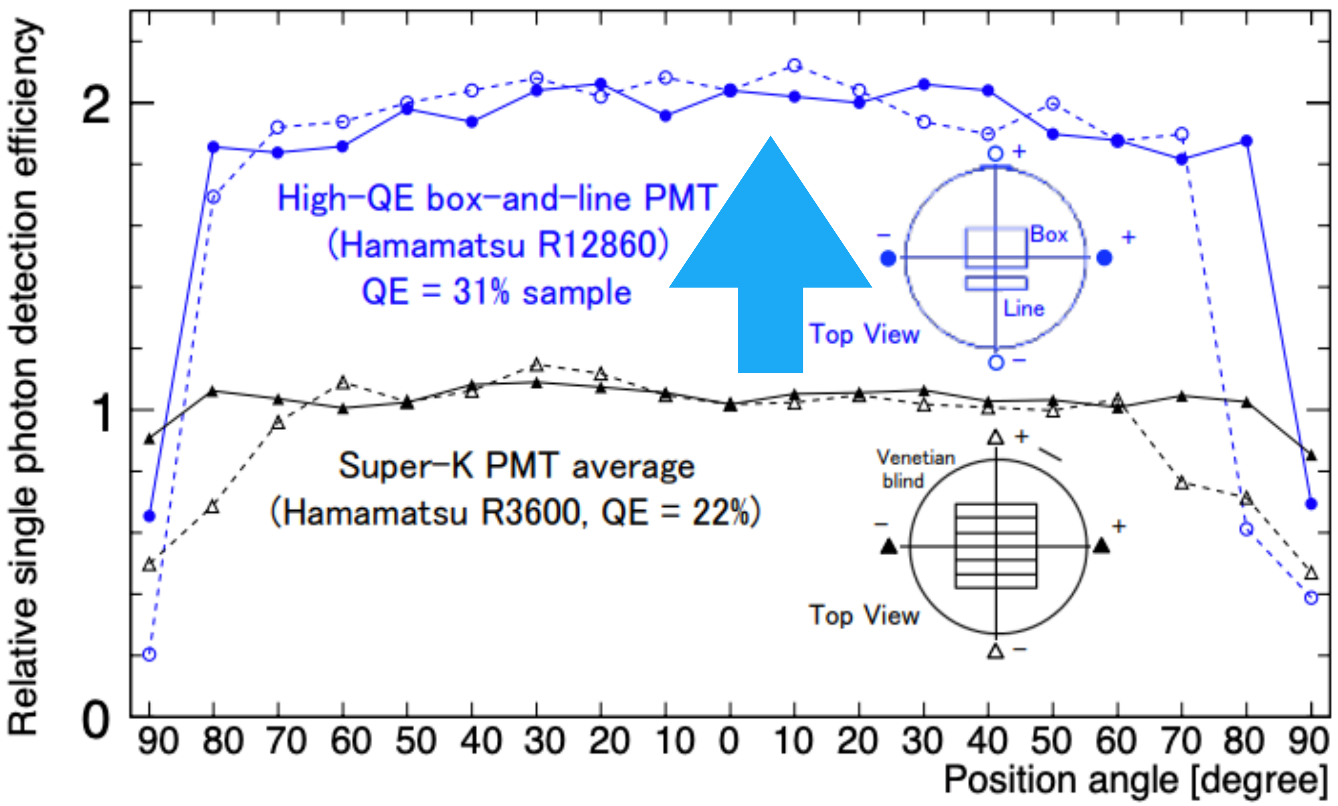
- **50 cm (20") novel photomultiplier tubes (PMTs) from Hamamatsu.**

50 cm Box&Line PMT "R12860"



Upgraded cathode structure

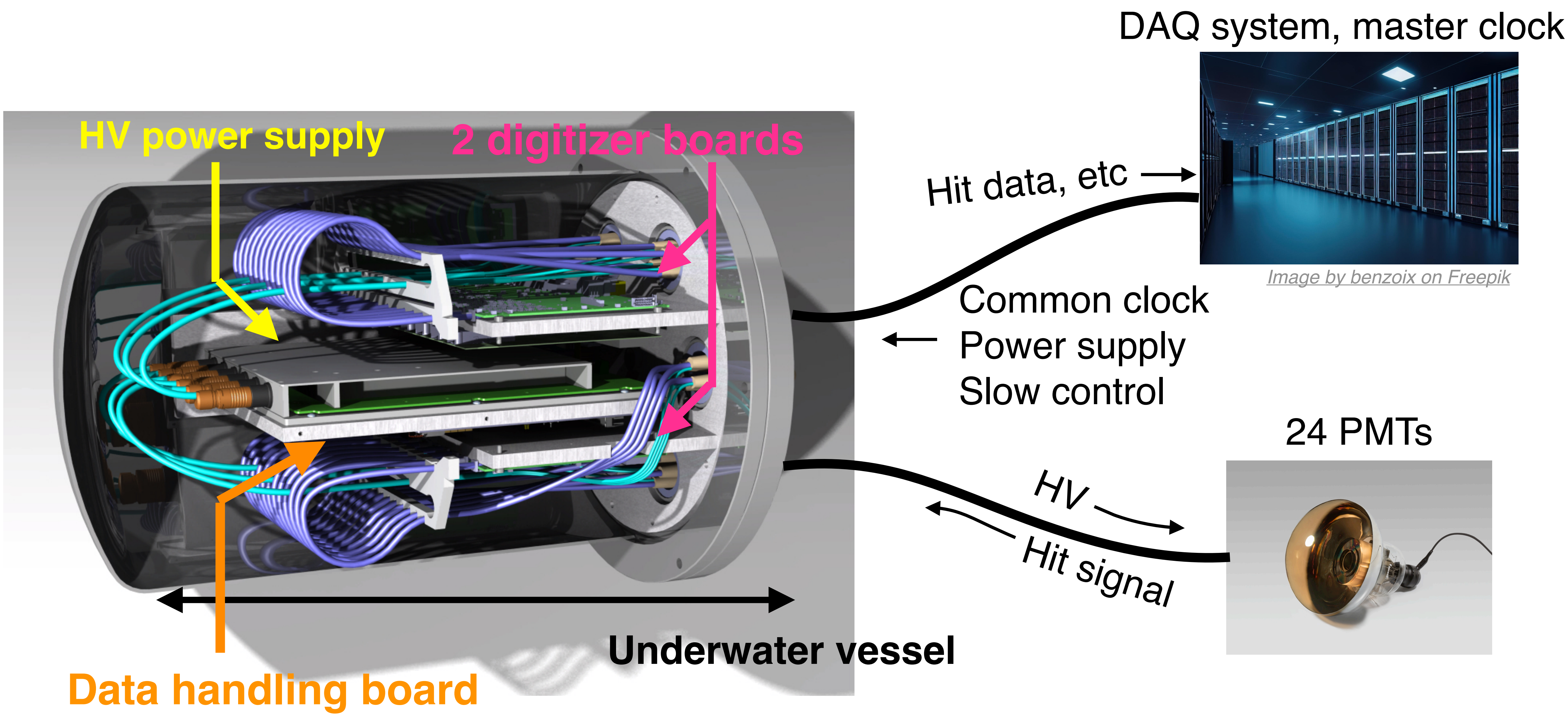
Photo detection efficiency vs angle



- **Same size as used in SuperK but the performance is largely improved:**
  - **Twice higher photo-efficiency compared to SuperK.**
  - **Twice better charge and timing resolutions**
- **20,000 PMTs will be deployed filling 20% photo coverage.**
- **Design finalized. Production and full inspection are ongoing.**

Electronics

- Front-end electronics placed in underwater vessels.
  - Minimizing the length of PMT cables.
  - Digitization is done in the water tight cases.
- Analog FE designed to take full advantage of the improved PMT performance.
- Design being finalized. Working on a system test in/out of the water.



Conclusions

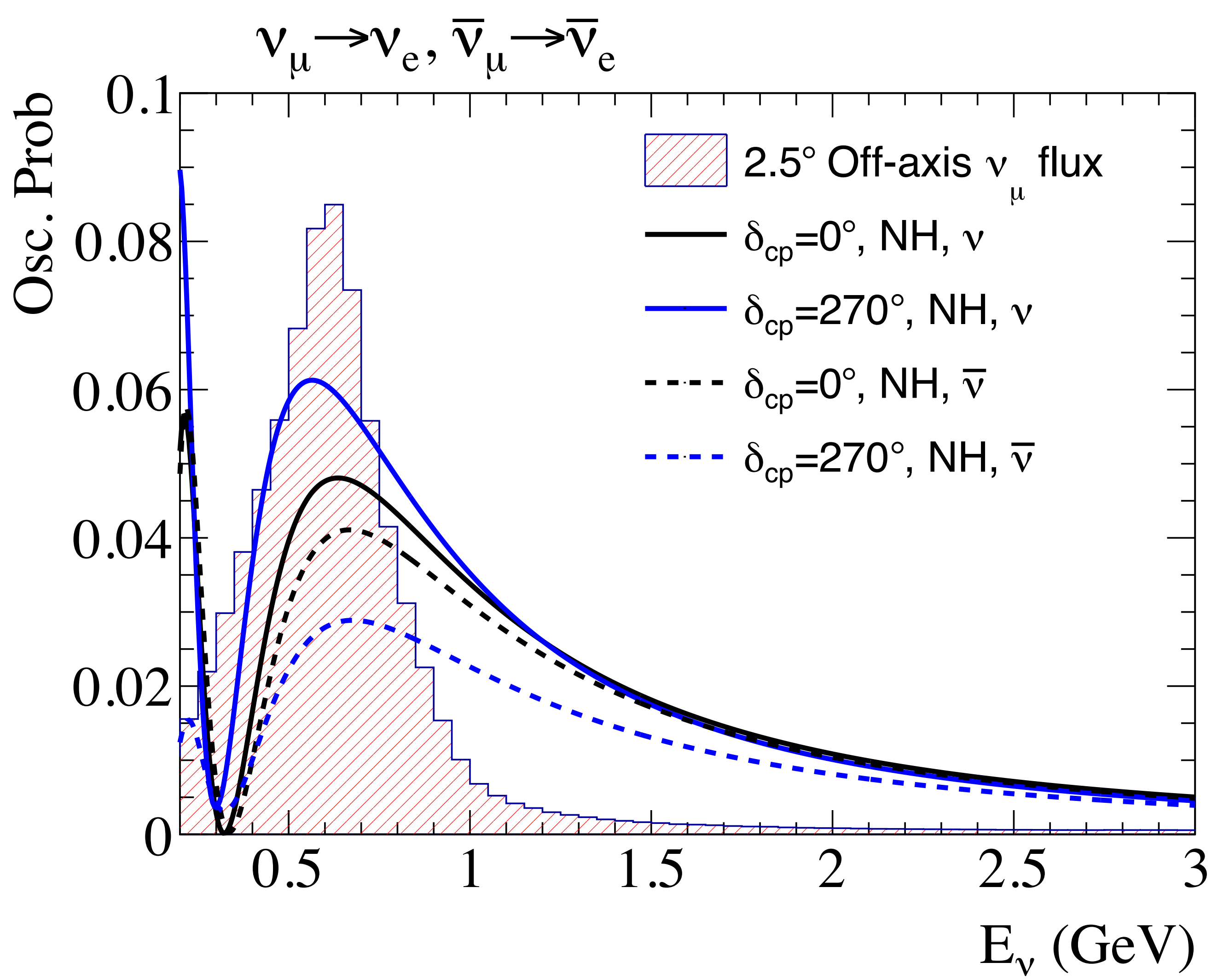
- Hyper-Kamiokande is a next-generation large water Cherenkov experiment aiming for world-leading sensitivities to many aspects of the neutrino physics.
  - 5σ sensitivity to the CP violation in large fraction of the CP phase values as well as the mass ordering.
  - Useful information on star formation 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 slides

Beam energy and oscillation probability

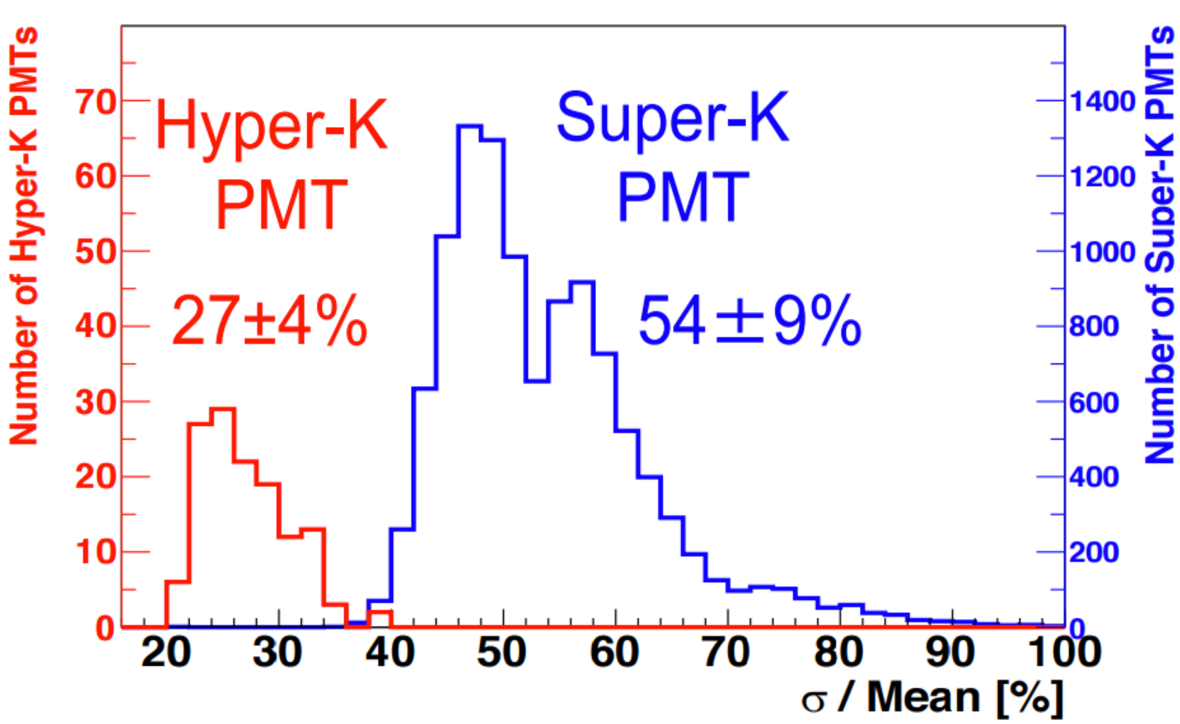
- **2.5 off-axis angle focuses the neutrinos on the first oscillation maximum, ~0.6 GeV.**
- **Advantages:**
  - **Oscillation probability depends on L/E. Energy reconstruction is essential.**
  - **Elastic scattering like (CCQE) events, which allows for precise energy reconstruction, are collected efficiently.**



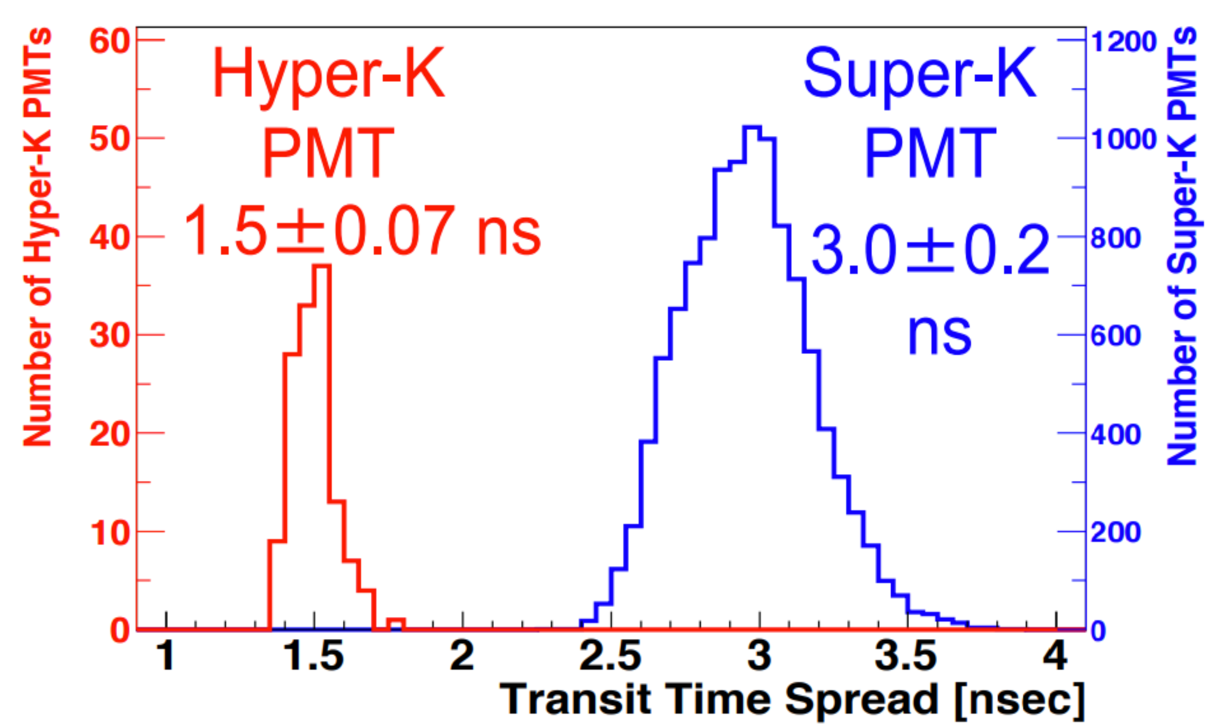
Charge and timing resolution of HyperK PMT

- **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

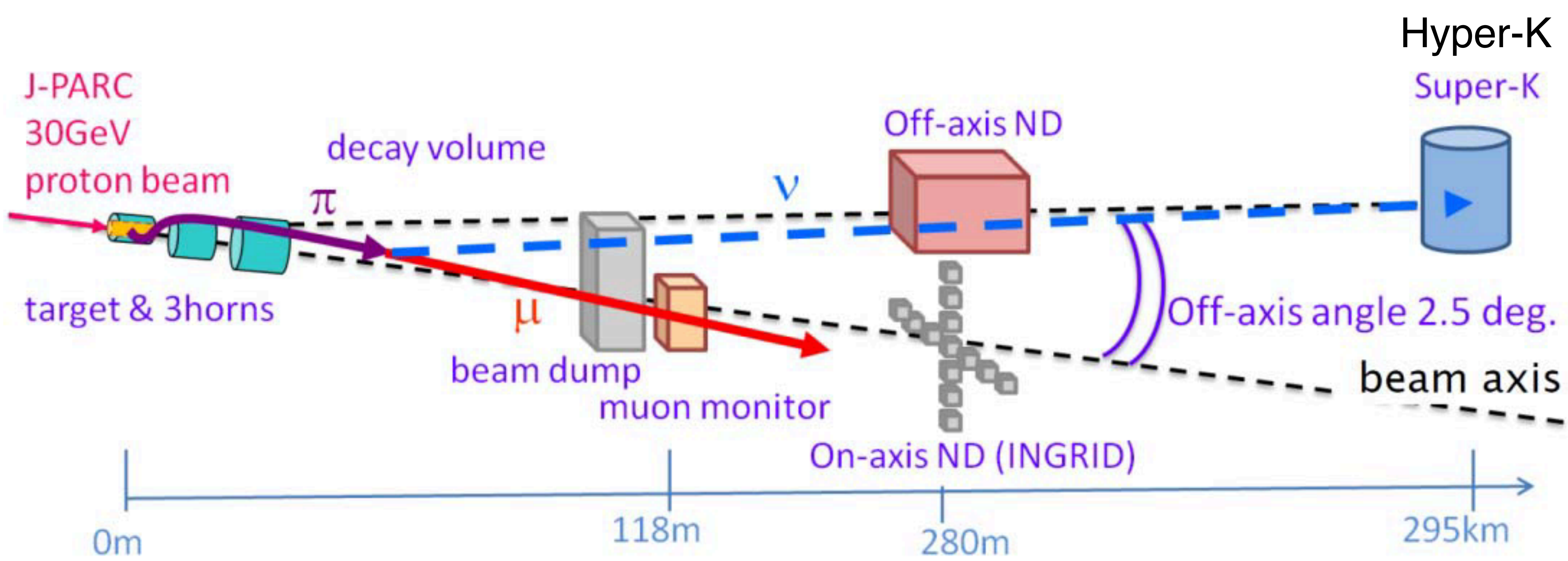


Timing resolution



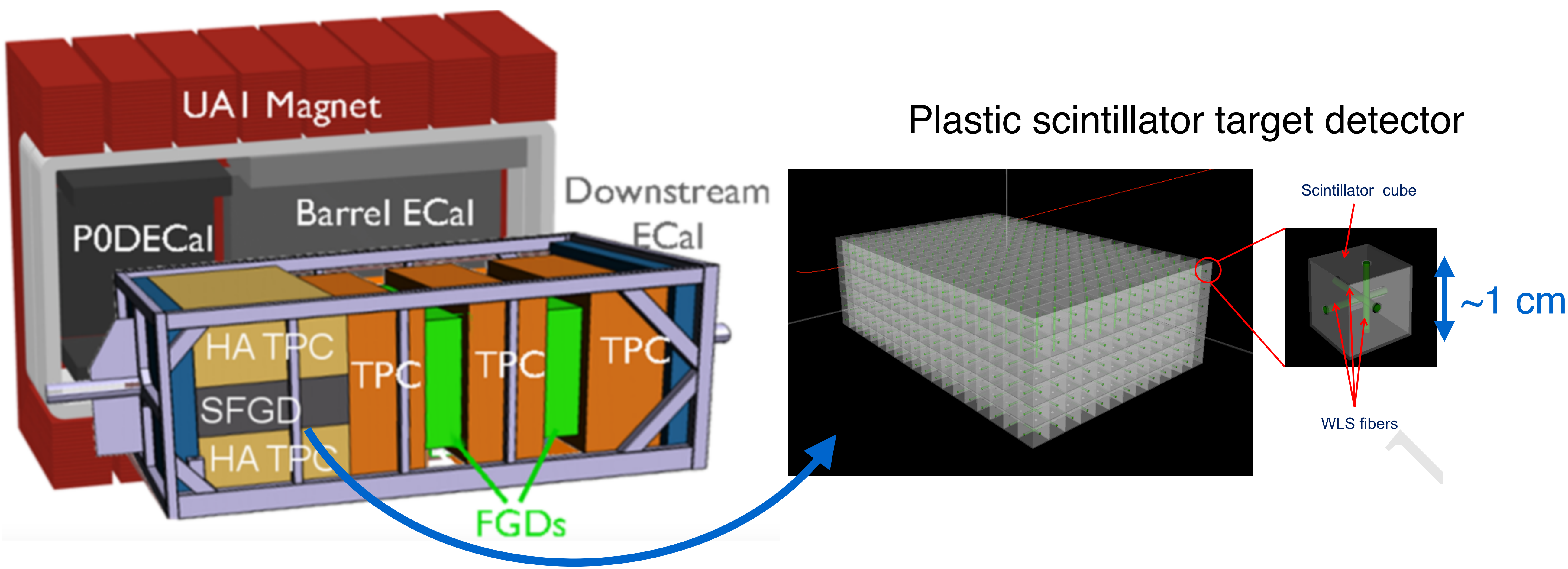
Neutrino beam line at J-PARC

- 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



Near detector 280 m downstream

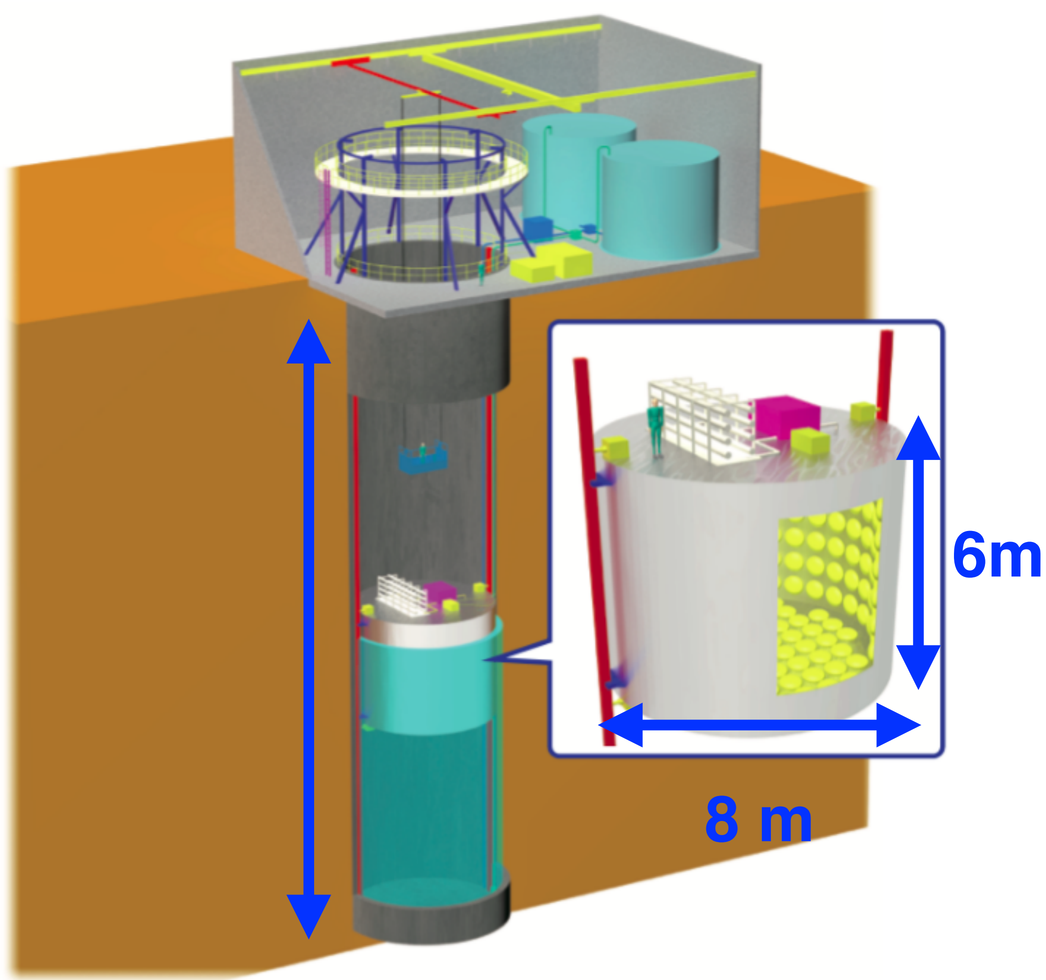
- **Magnetized tracker placed 280 m downstream called ND280.**
- **Measures neutrino flux and interactions at the 2.5° off-axis angle.**
- **Target detector with higher granularity and 4π acceptance for short tracks.**
- **Start operating in June 2023.**



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°