STATUS OF THE HYPER-KAMIOKANDE PROJECT

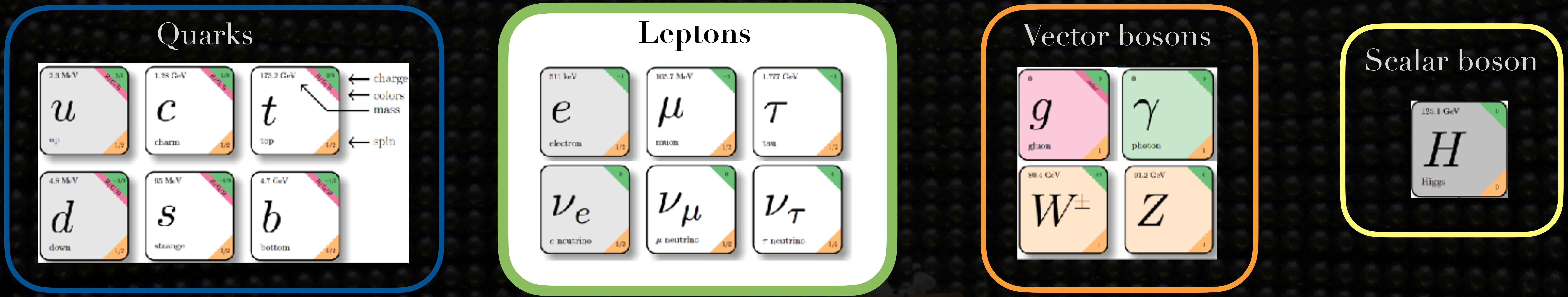
XIAOYUE LI

TRIUMF SCIENCE WEEK

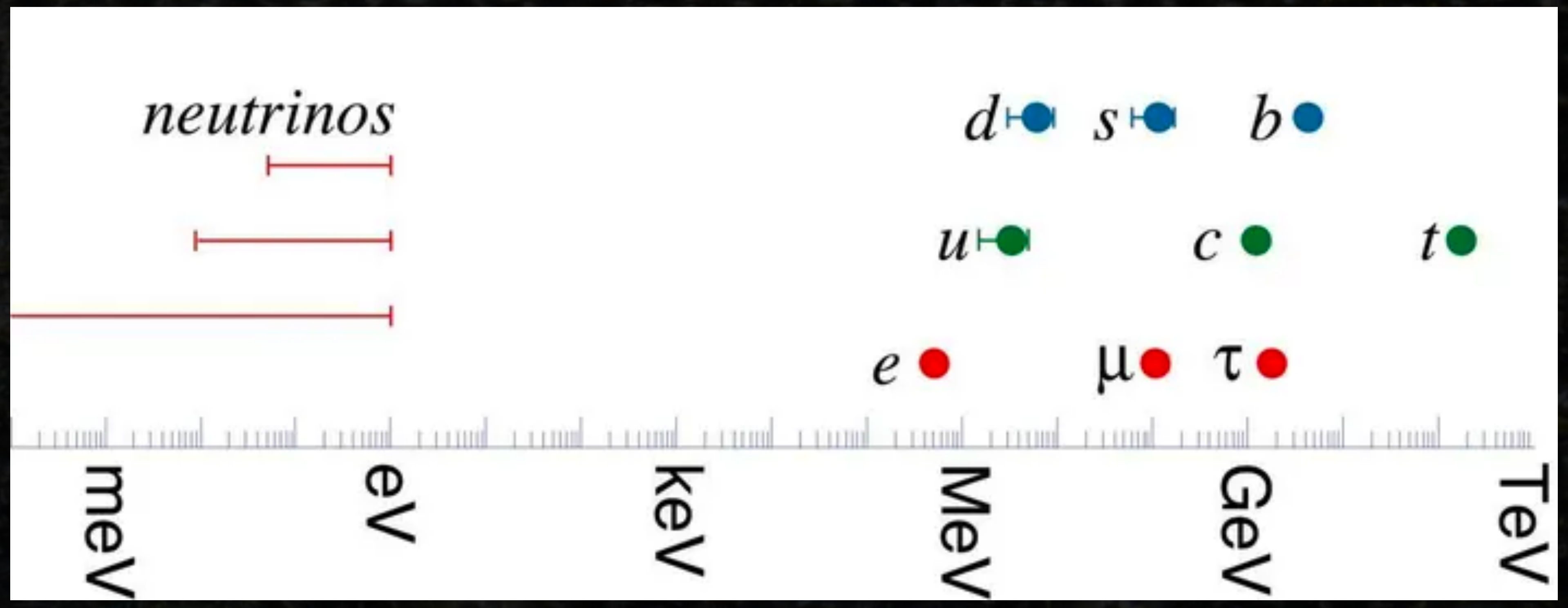
AUGUST 1, 2023

NEUTRINOS IN A NUTSHELL

- Neutrinos are neutral, left-handed, weakly interacting fermions



- Though originally thought to be massless in the Standard Model, neutrinos are found to have non-zero mass by experiments through the discovery of "**neutrino oscillation**"
  - Neutrino masses are very small compared to other fermions → Majorana particles?
    - Testable by neutrino-less double beta experiments such as nEXO



NEUTRINO OSCILLATION

- Neutrinos are produced in flavour eigenstates, but propagate in mass eigenstates
  - $$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$
    Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
  - $$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$
    where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$

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- **Oscillation probability** in vacuum $P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U^*_{\alpha j} e^{-i\frac{m_j^2 L}{2E}} U_{\beta j} \right|^2$,

  where $\Delta m^2_{ij} = m_i^2 - m_j^2$, L is the baseline, and E is the neutrino energy

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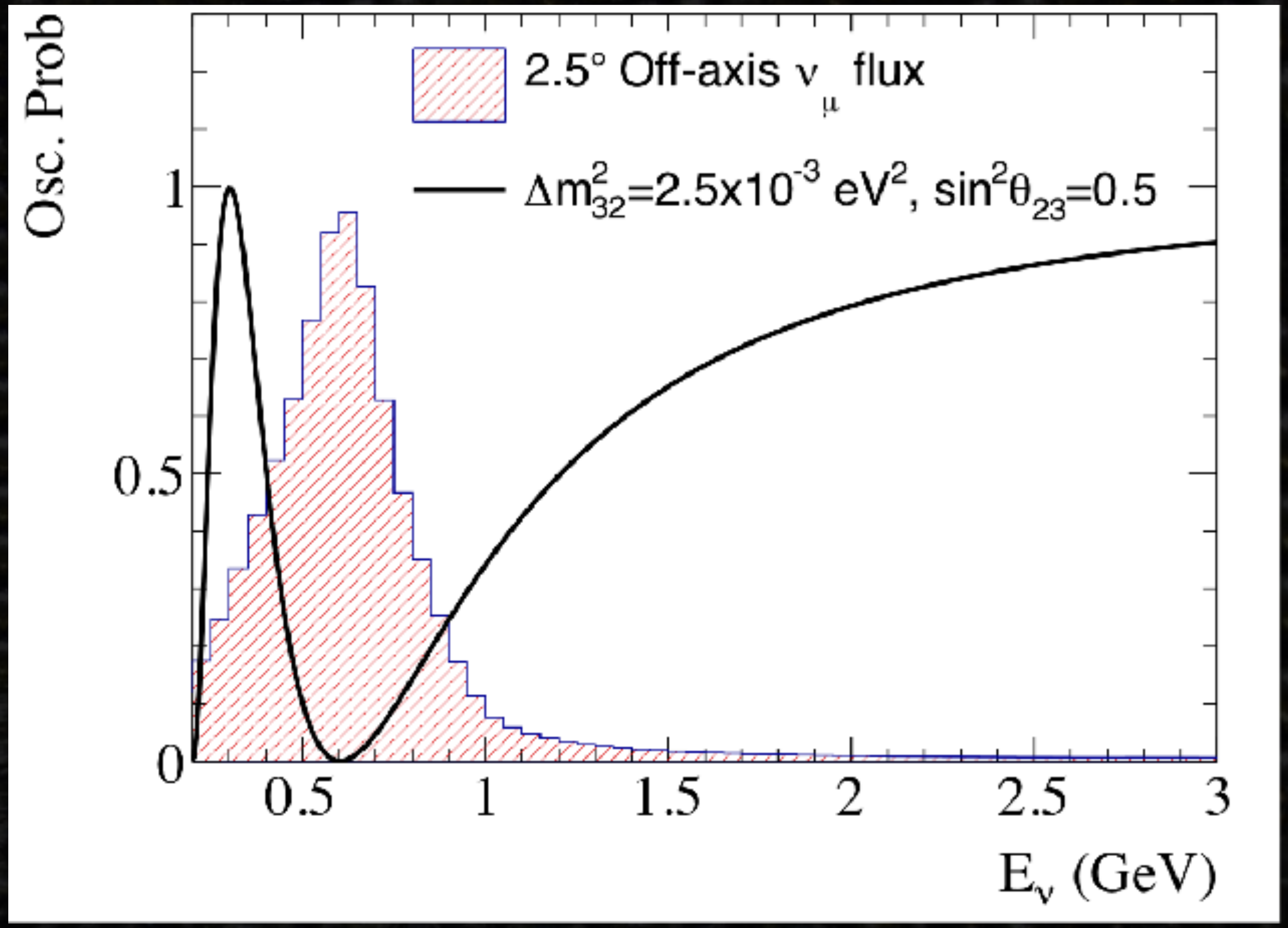
ν_μ survival probability at 295 km baseline



$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32}}{4E} L\right)$$

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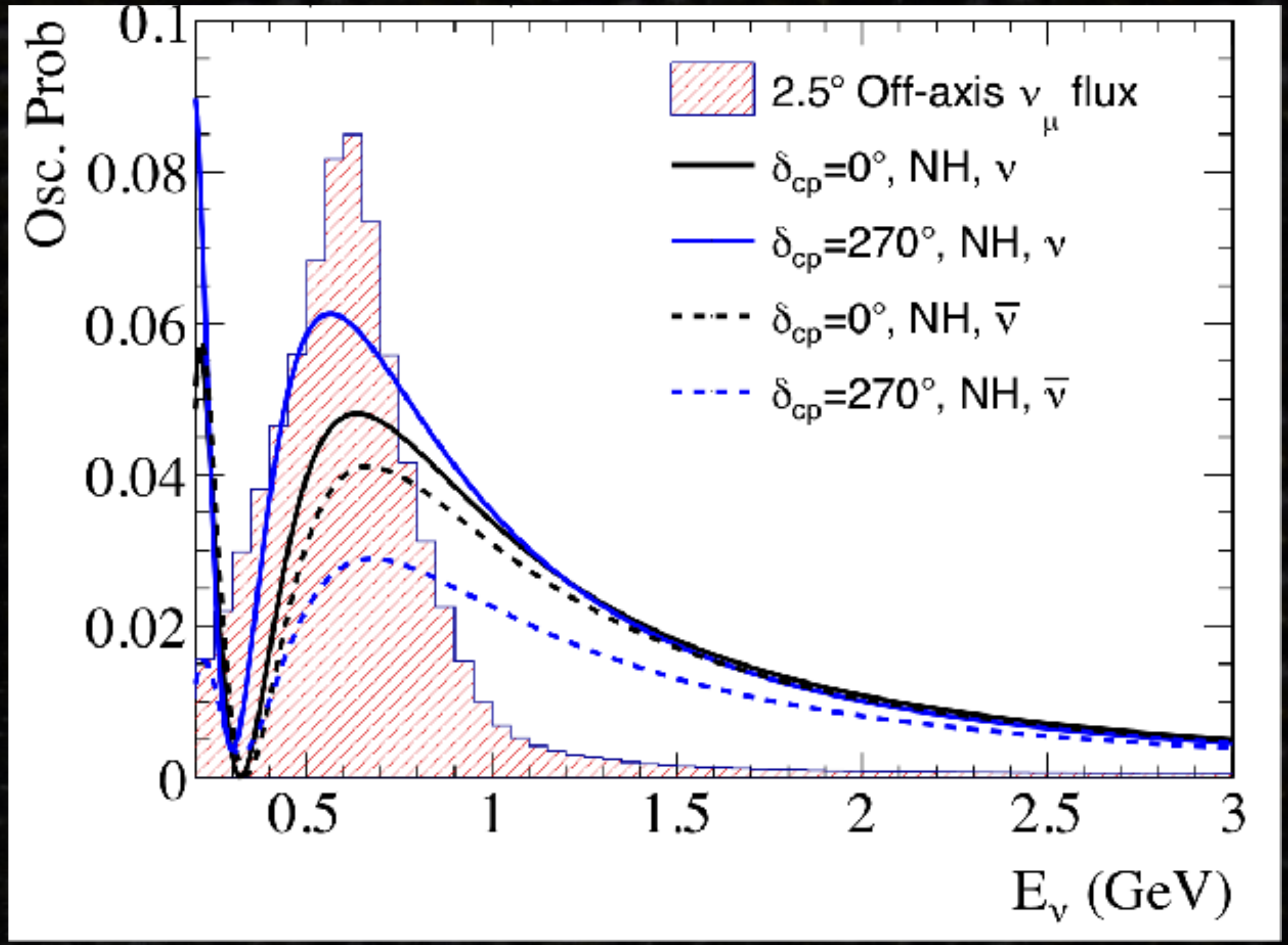
$\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ probabilities at 295 km baseline



- Non-zero δ_{CP} indicates CP-violation in the lepton sector
  - Can contribute to the matter-antimatter asymmetry

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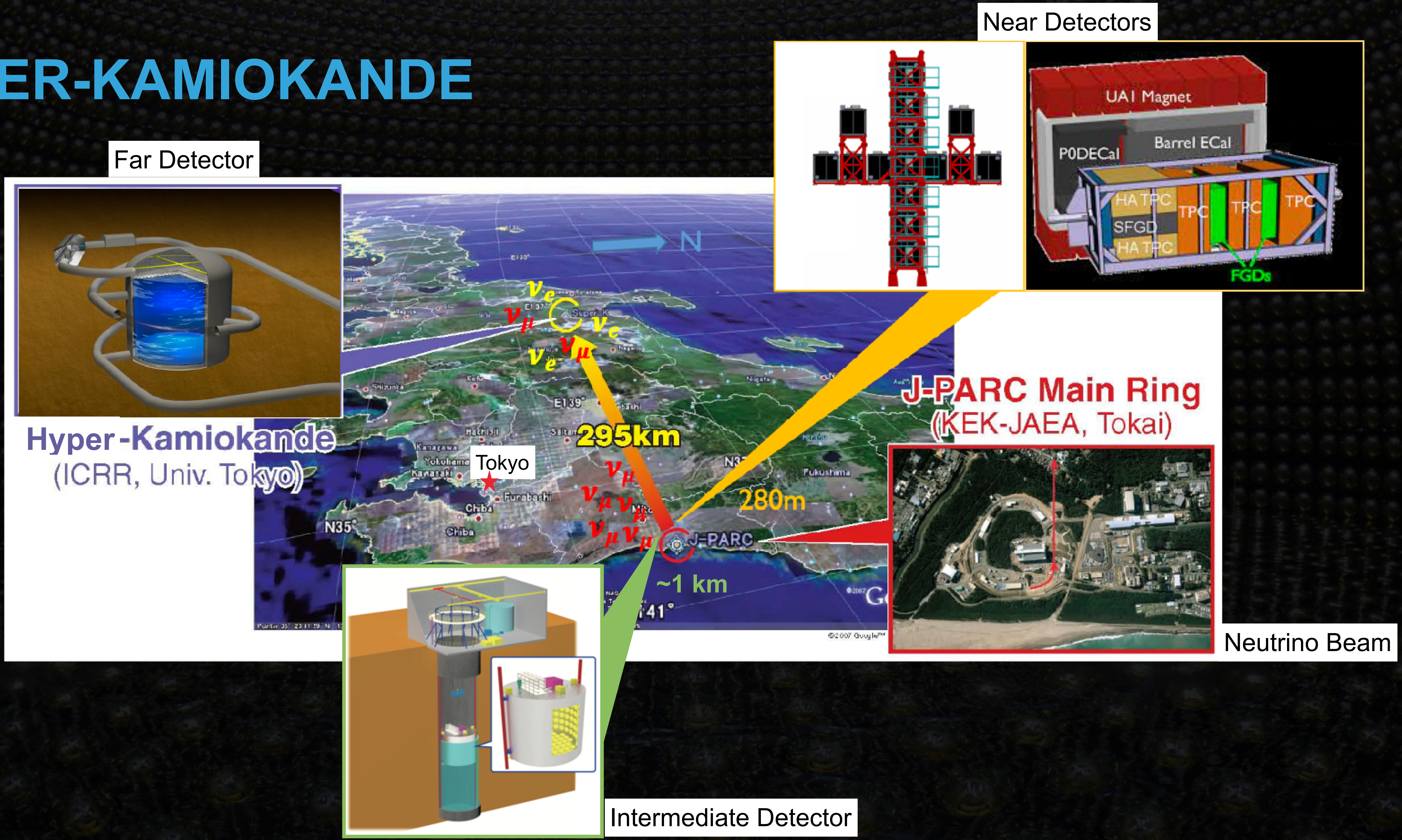
Current knowledge of neutrino oscillation parameters

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$
$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2
$\sin^2(\theta_{23}) = 0.534^{+0.021}_{-0.024}$ (Inverted order)
$\sin^2(\theta_{23}) = 0.547^{+0.018}_{-0.024}$ (Normal order)
$\Delta m^2_{32} = (-2.519 \pm 0.033) \times 10^{-3}$ eV^2 (Inverted order)
$\Delta m^2_{32} = (2.437 \pm 0.033) \times 10^{-3}$ eV^2 (Normal order)
$\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$

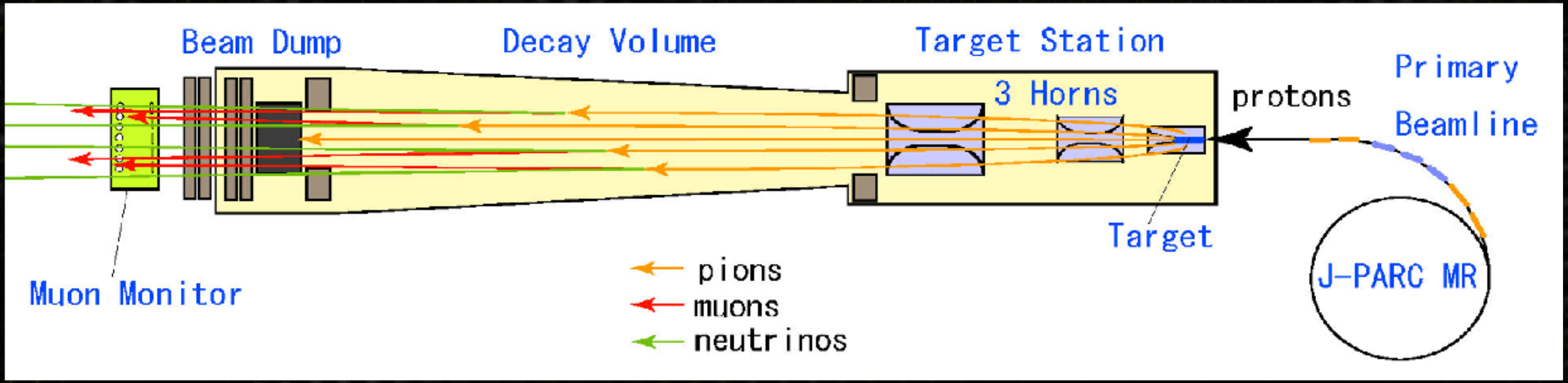
- Unanswered questions
  - Is there CP-violation in the lepton sector?
    - T2K has seen a hint
  - Is m_3 larger than m_1 (neutrino mass ordering)?
- Next-generation long-baseline experiments will provide the answers

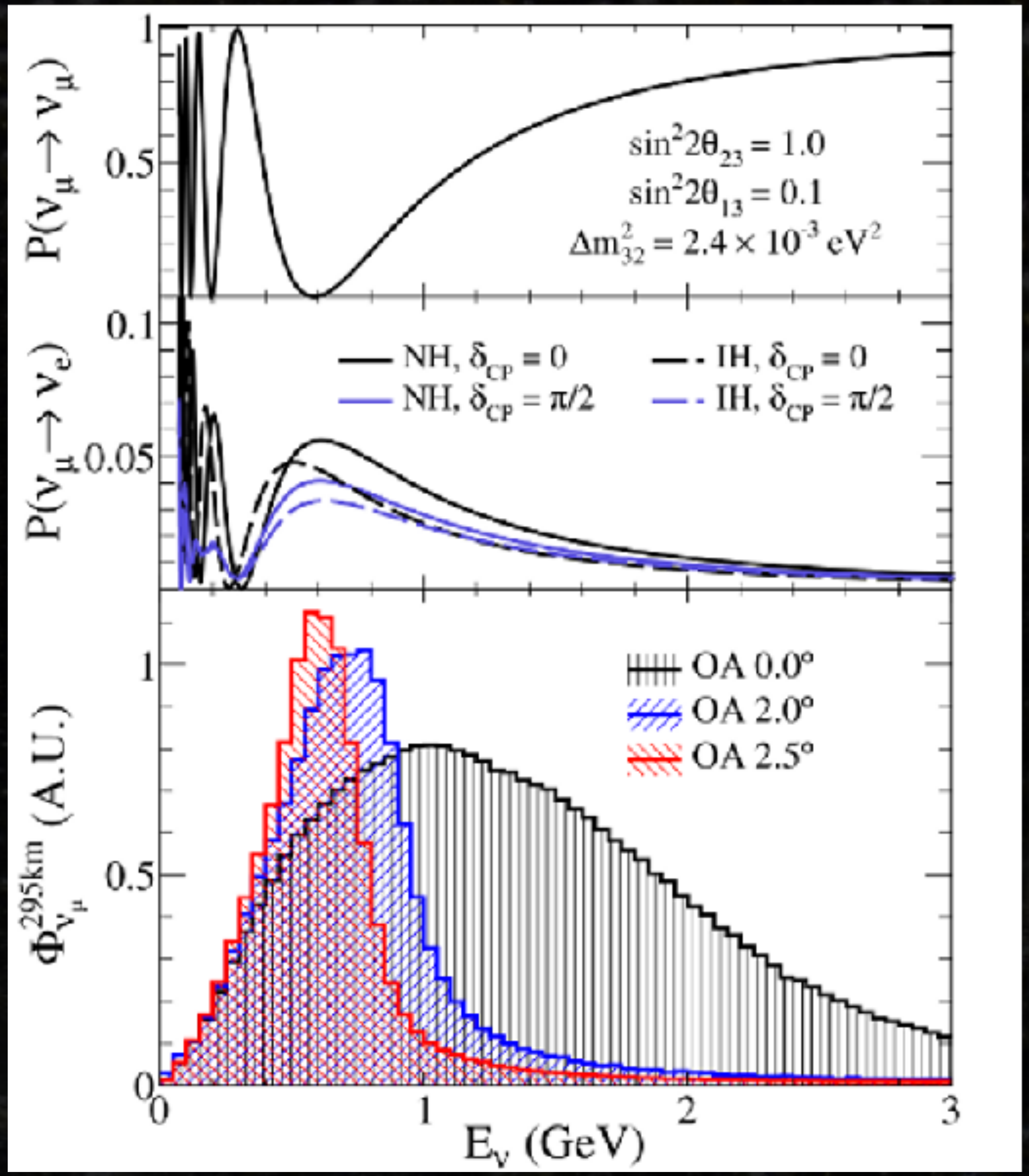
HYPER-KAMIOKANDE



Hyper-Kamiokande

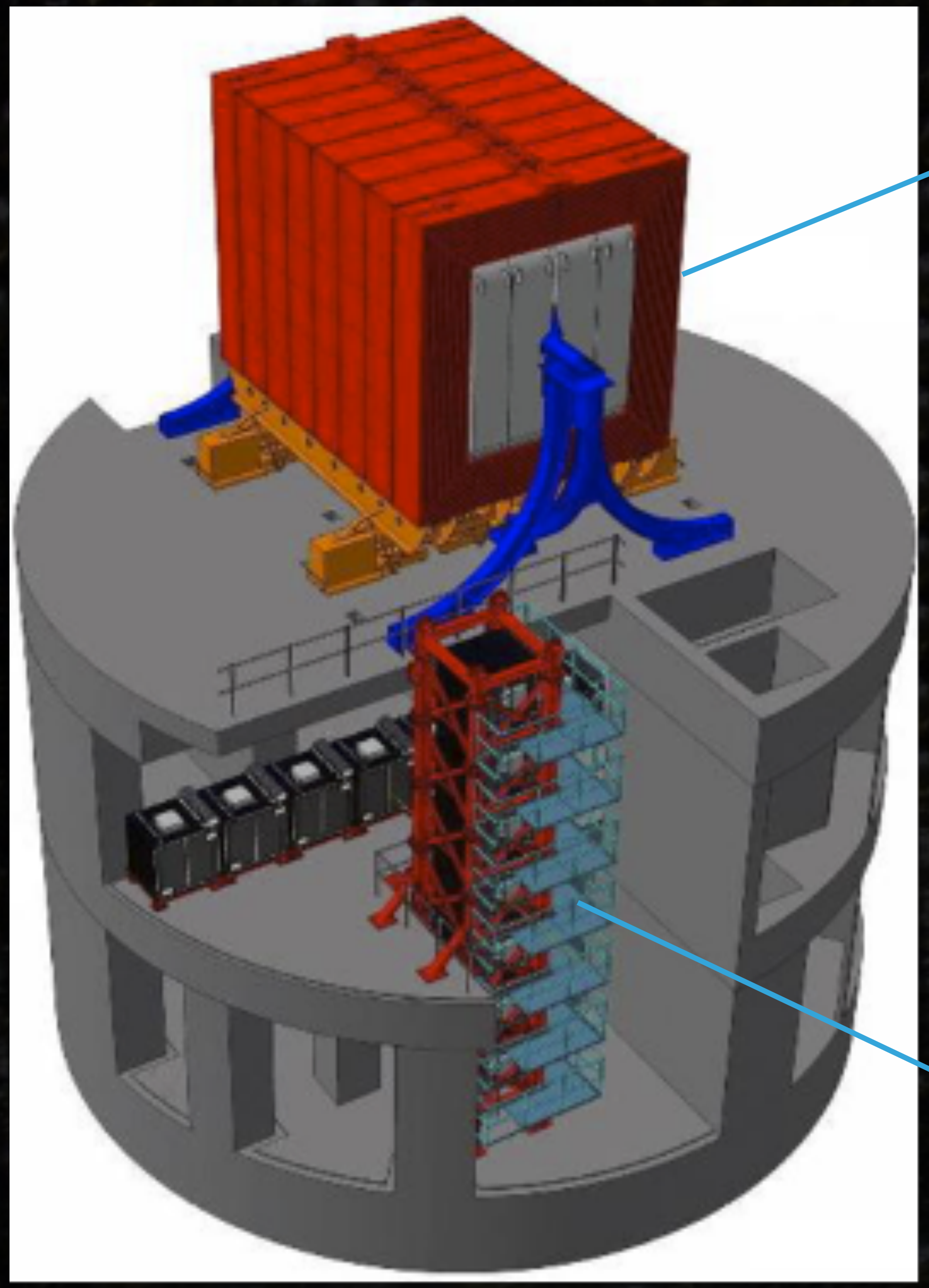
HYPER-K NEUTRINO BEAM

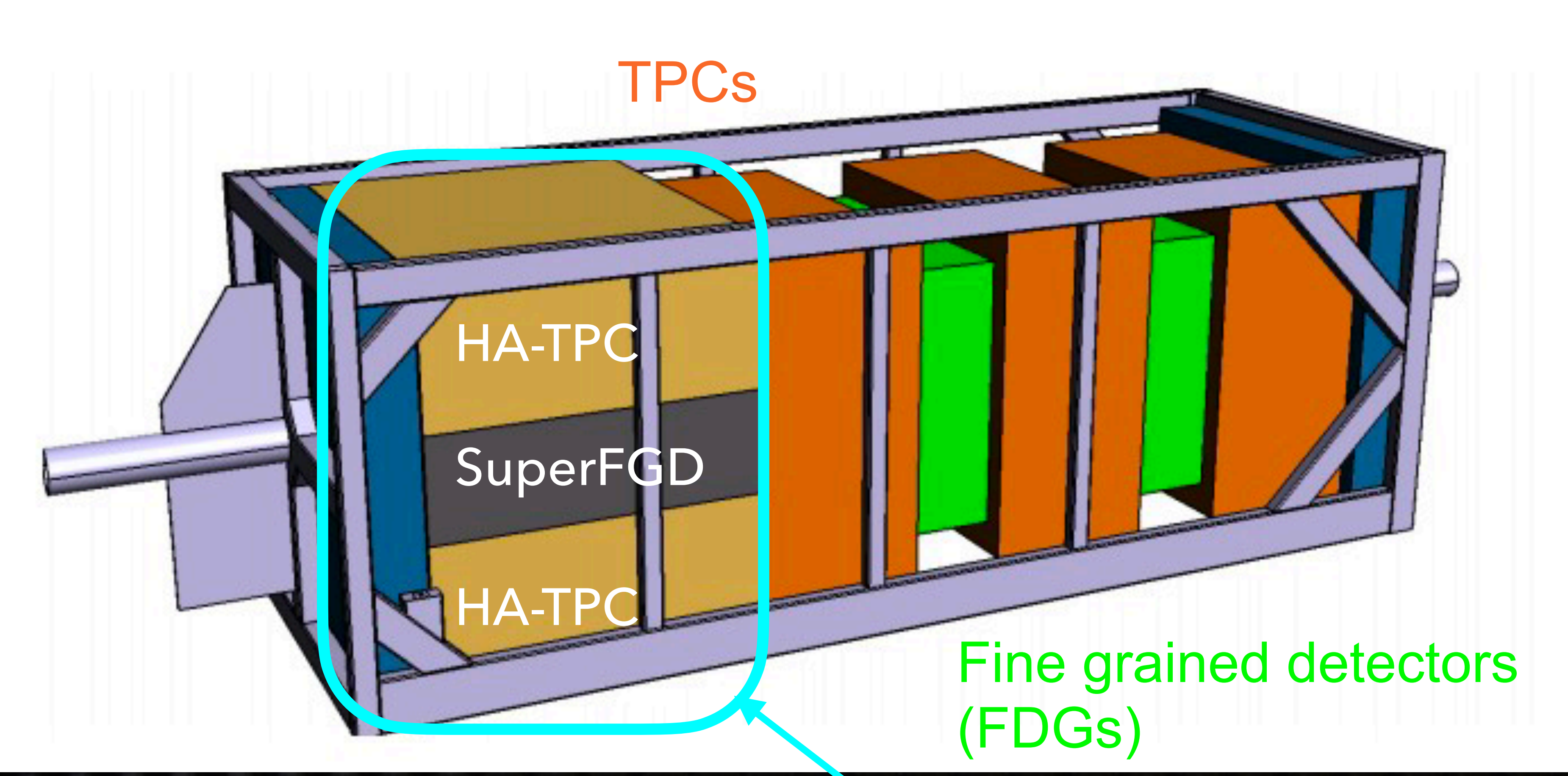


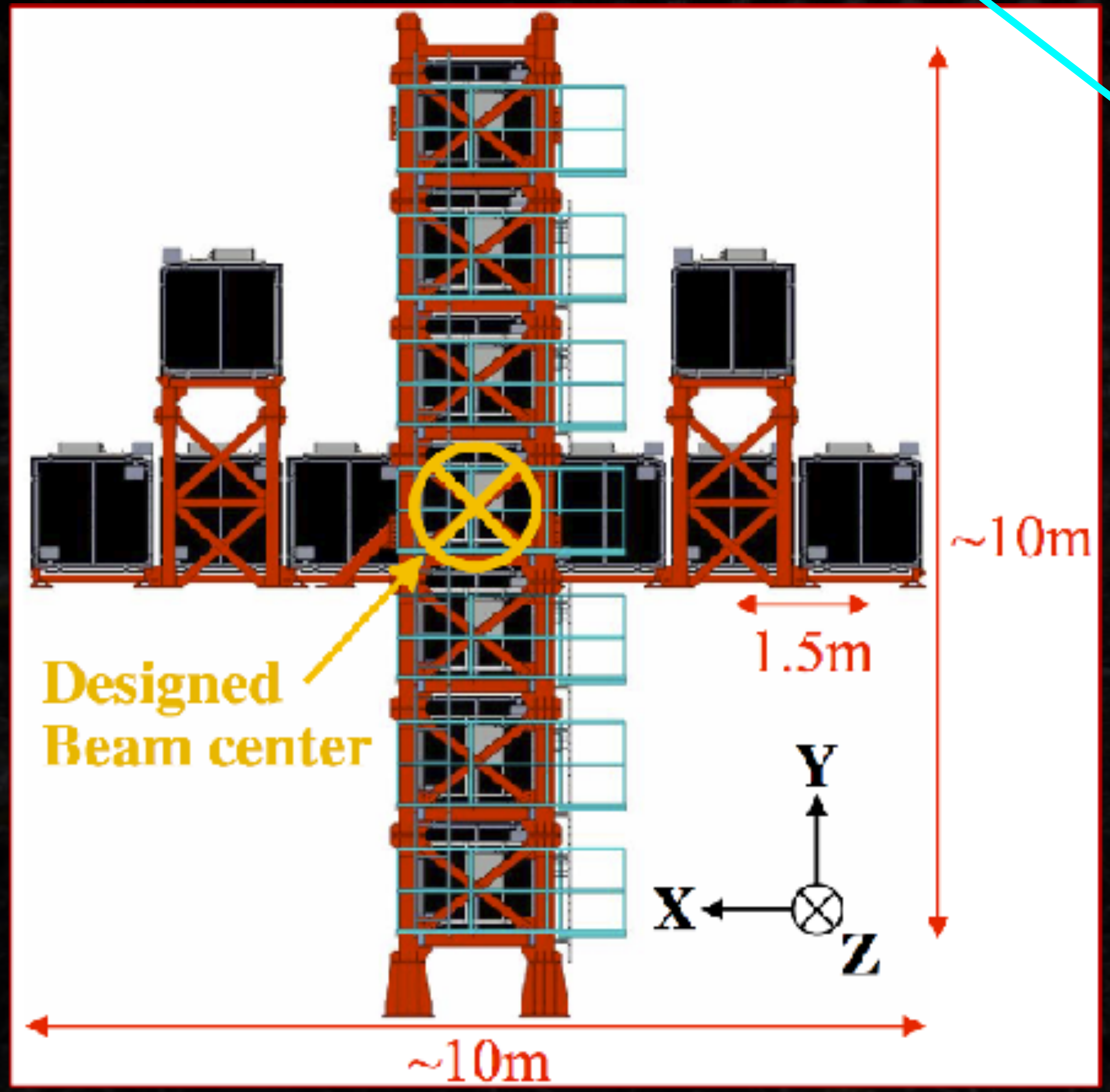


- ν_μ or $\bar{\nu}_\mu$ beam selected by magnetic horn polarity
- 2.5º off-axis beam with energy peaked at 0.6 GeV
  - Peak aligned with oscillation maximum
  - Quasi-elastic (QE) interactions dominate
- Staged J-PARC upgrade to 1.3 MW

HYPER-K NEAR DETECTORS



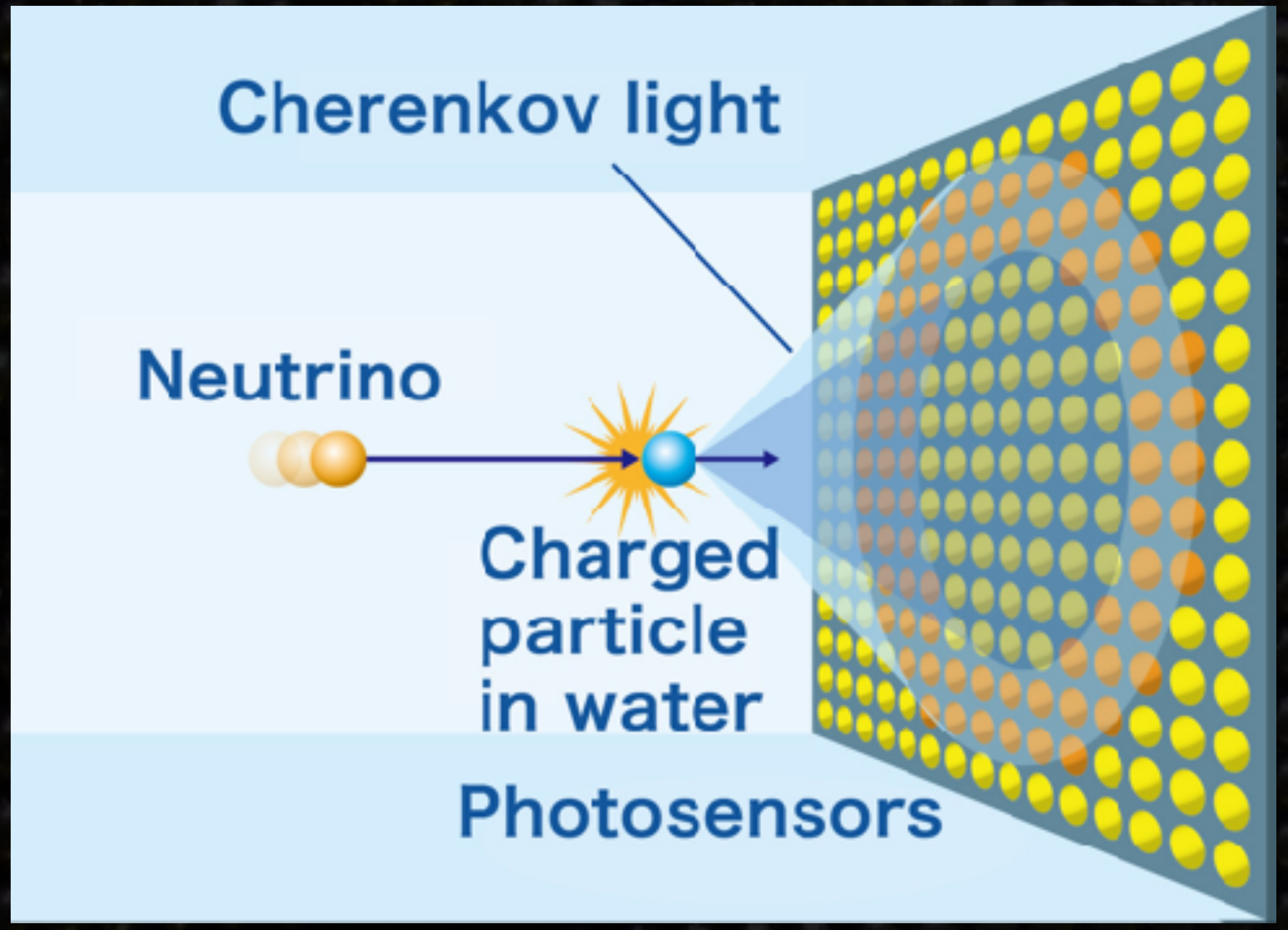


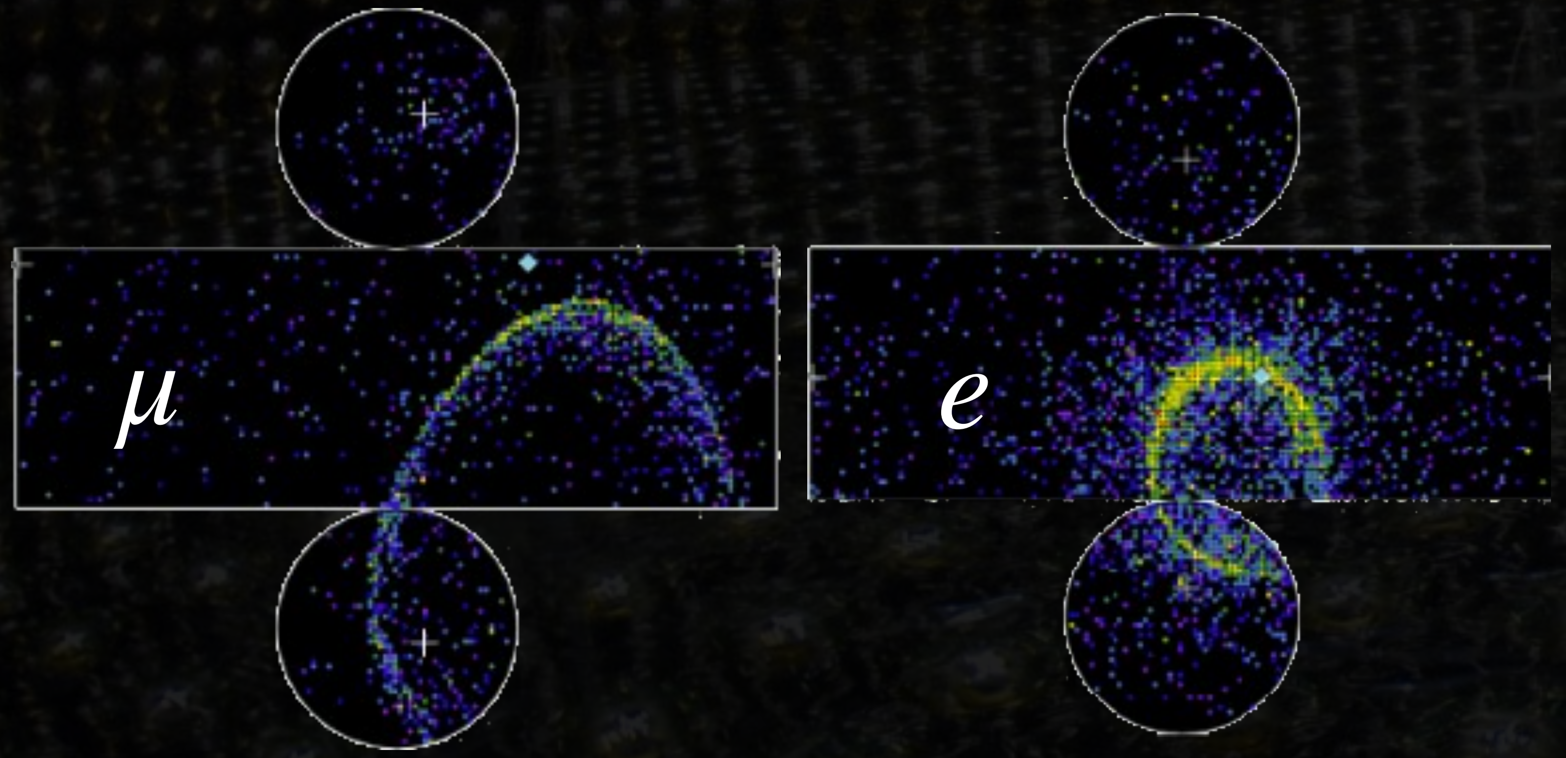


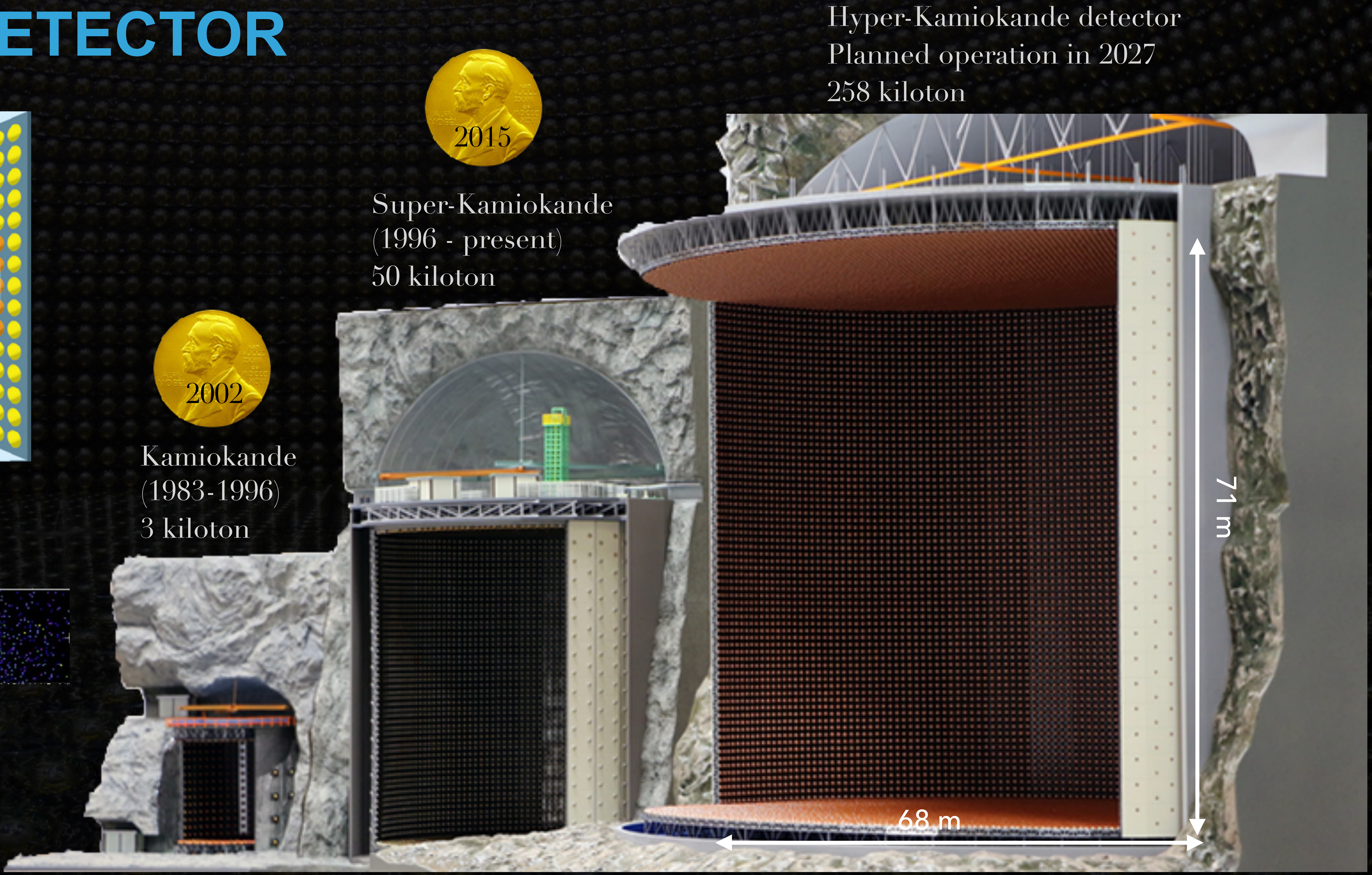
On-axis INGRID detector monitors neutrino beam profile and event rate

- Off-axis detectors ND280 detect neutrinos at 2.5° off-axis angle before oscillation occurs
  - Constrain unoscillated neutrino fluxes ⊗ interaction cross section
  - Magnetic field to distinguish +/- charge
- ND280 upgrade to improve angular acceptance and neutron measurement capabilities

HYPER-K FAR DETECTOR

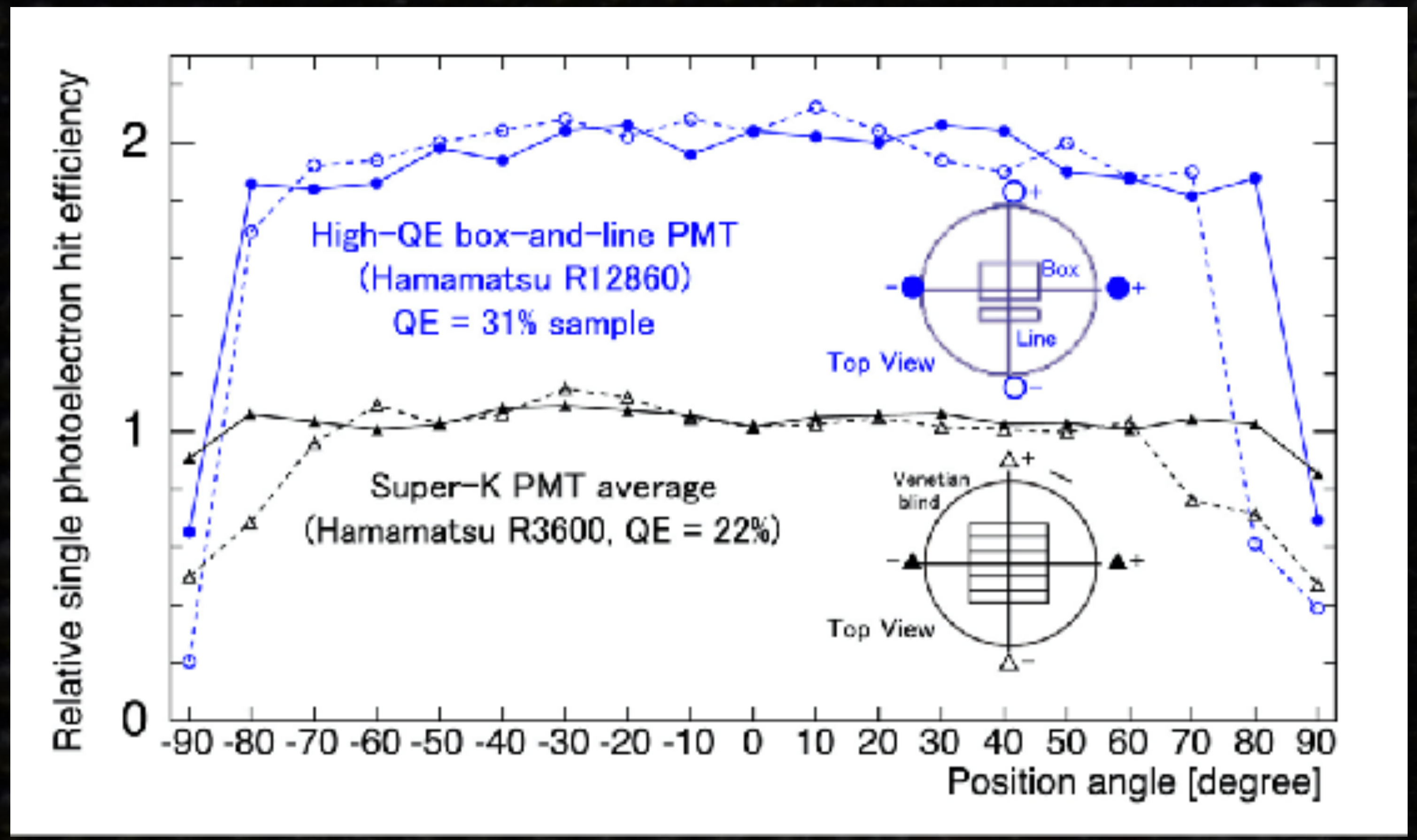


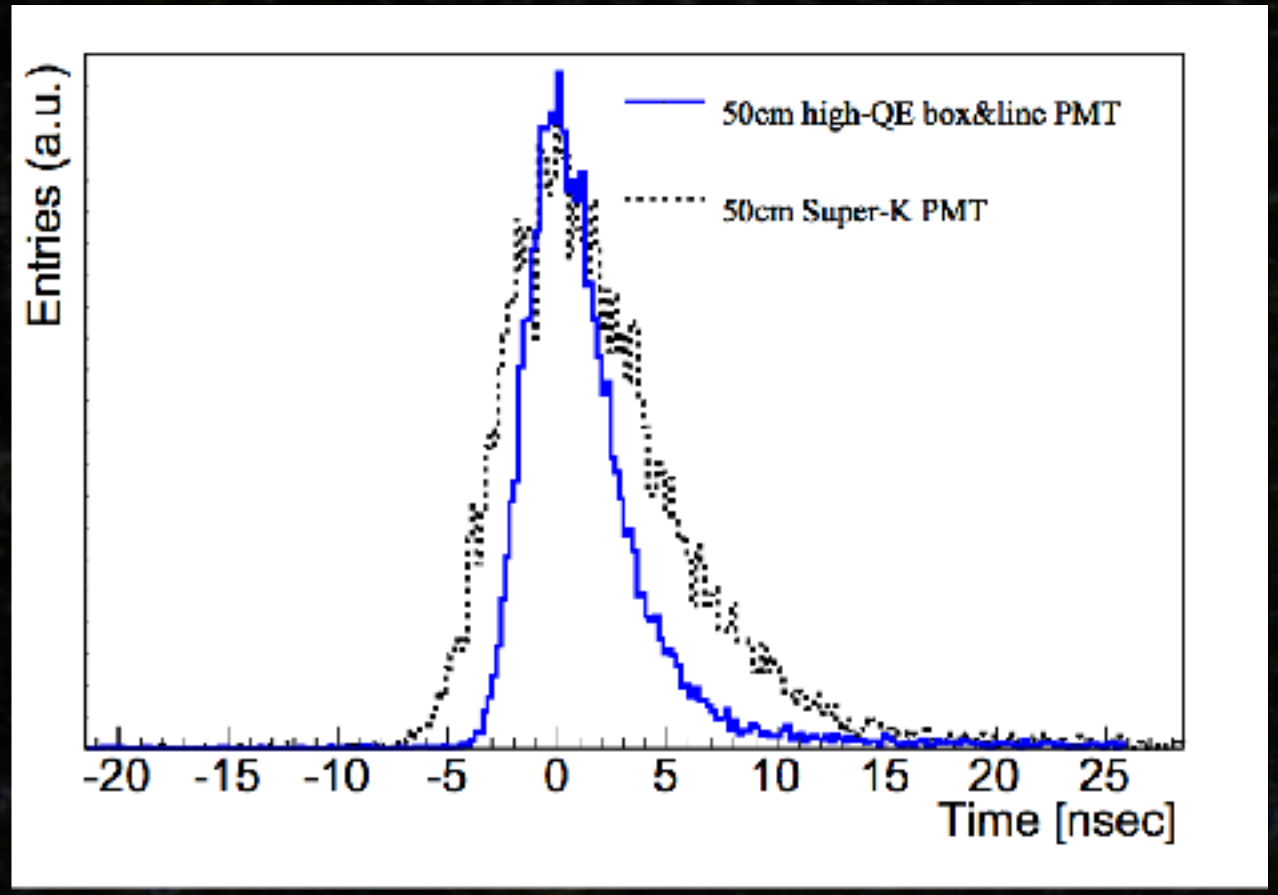


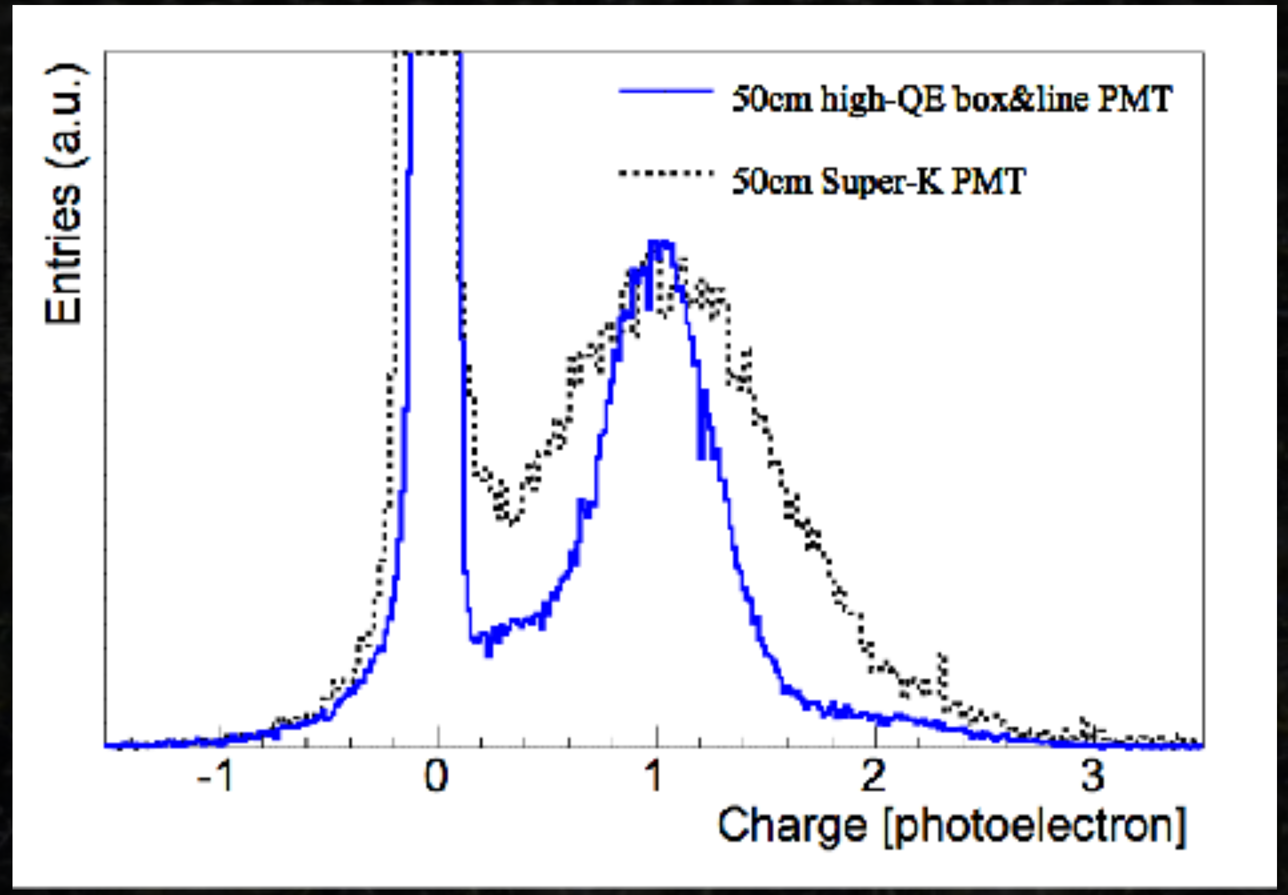


HYPER-K FAR DETECTOR

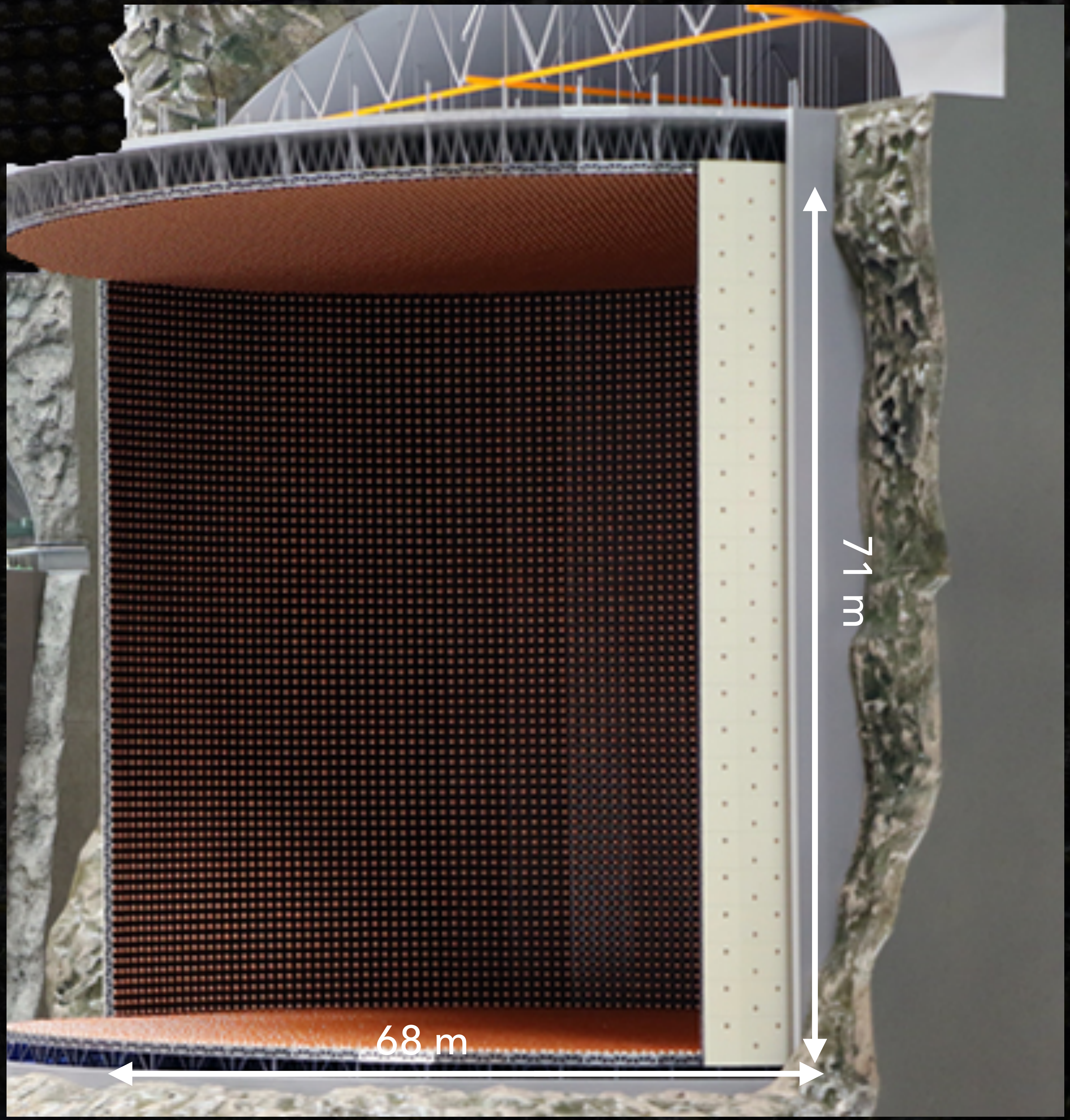
- 20,000 20″ PMTs with 2× the quantum efficiency of Super-K PMTs, better charge and timing resolution





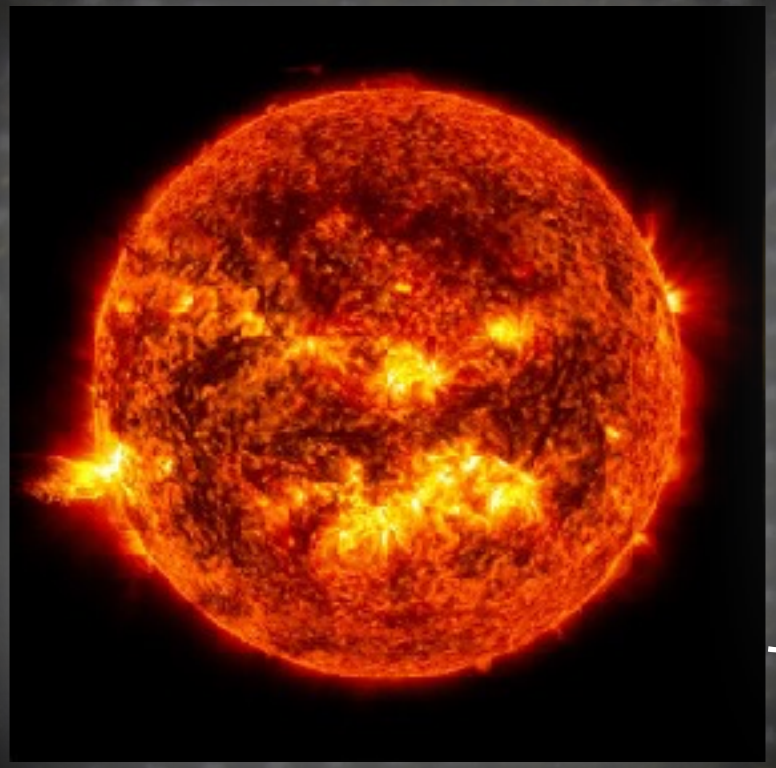


Hyper-Kamiokande detector
Planned operation in 2027
258 kiloton



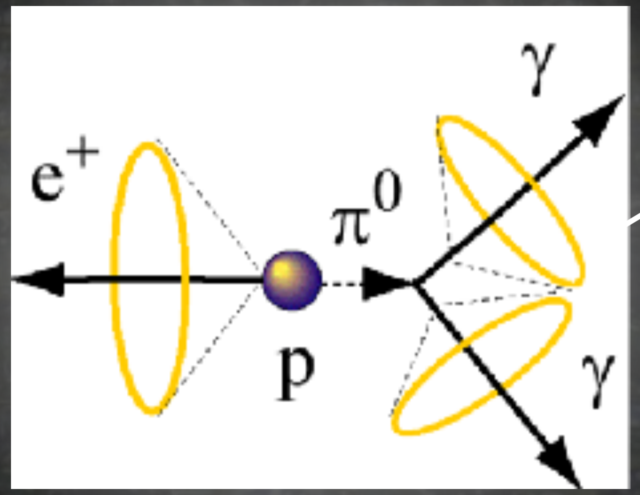
HYPER-K DETECTOR

Solar neutrino



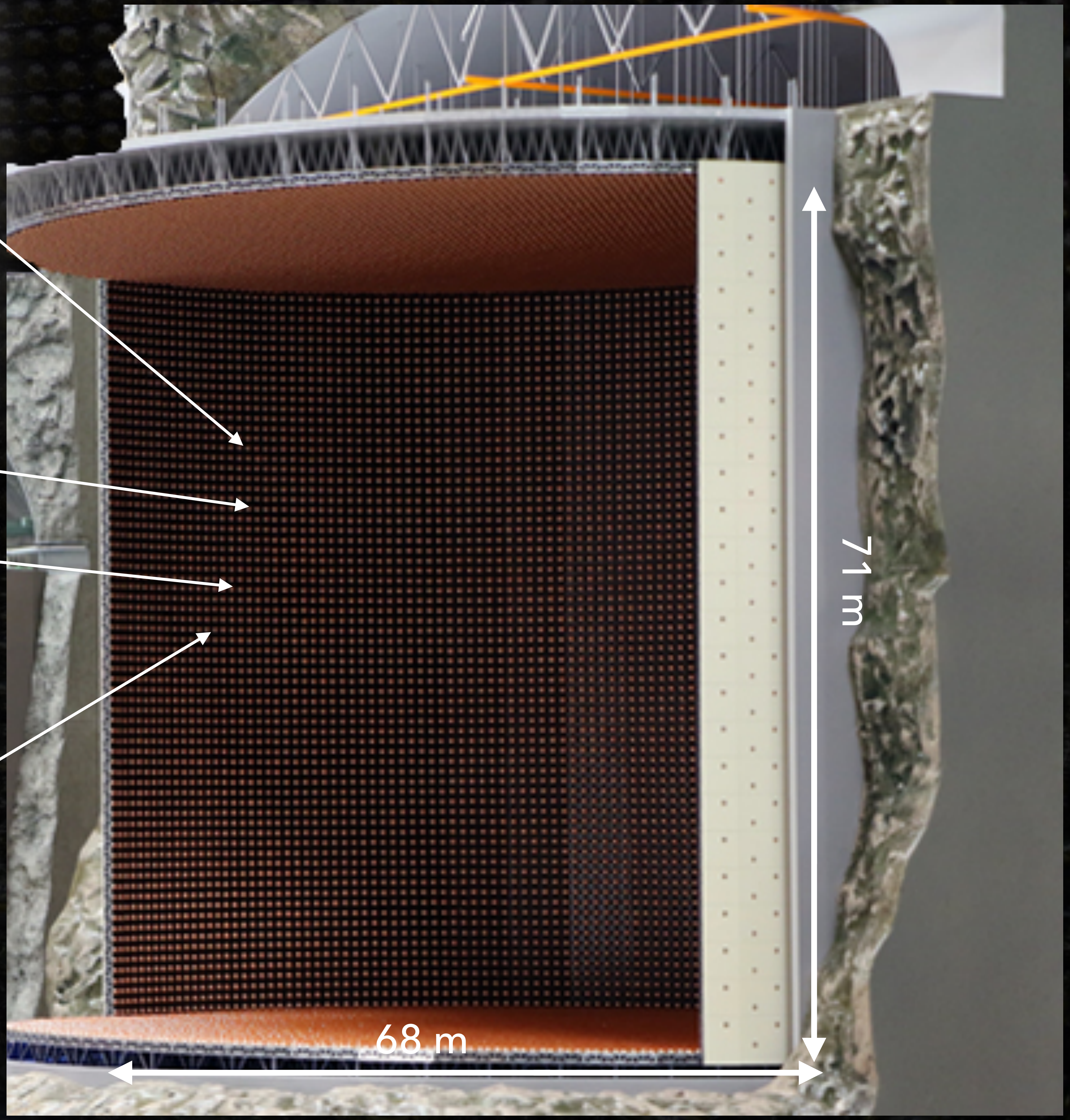
Supernova neutrino

Atmospheric neutrino



Proton decay

Hyper-Kamiokande detector
Planned operation in 2027
258 kiloton

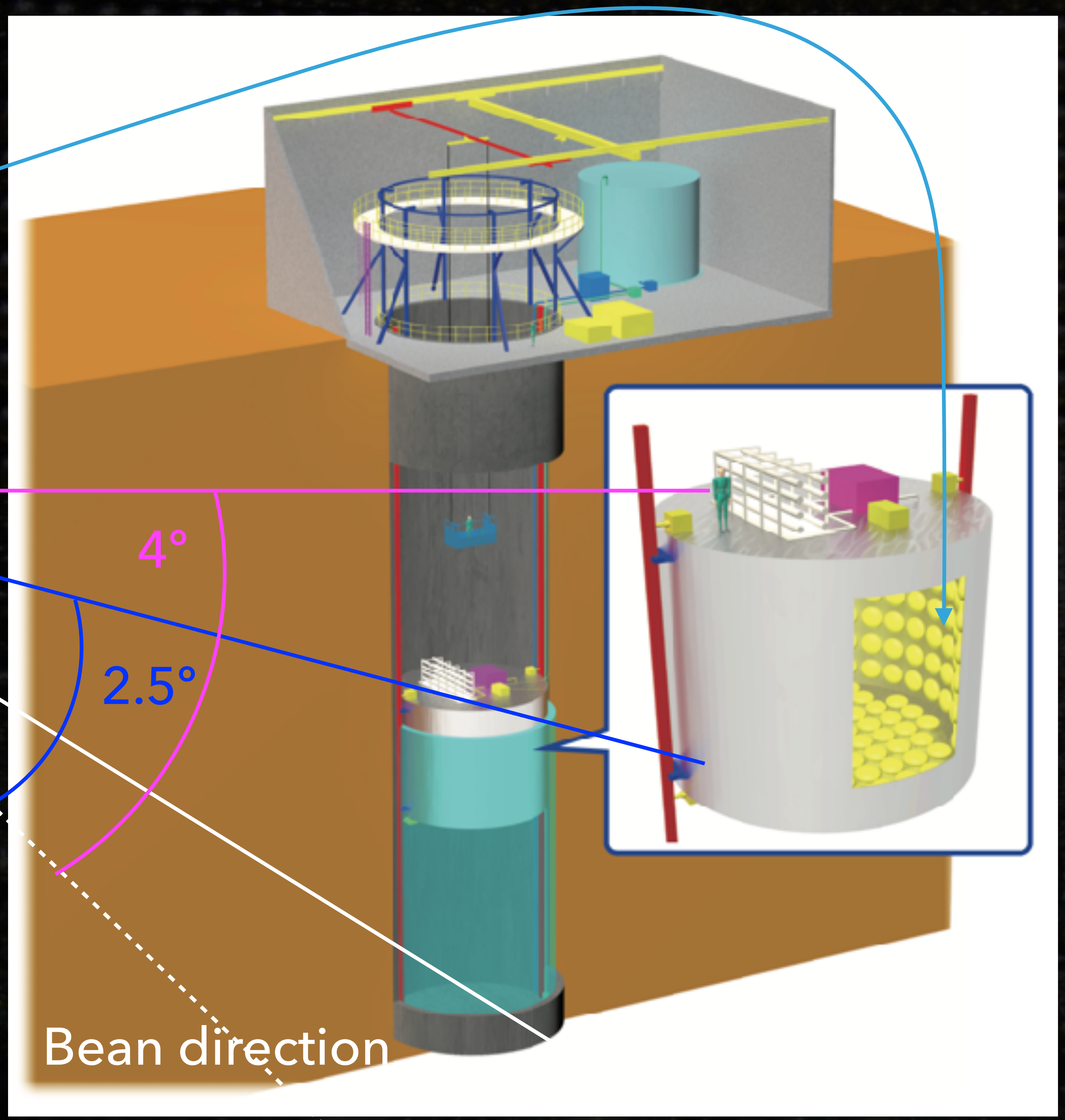


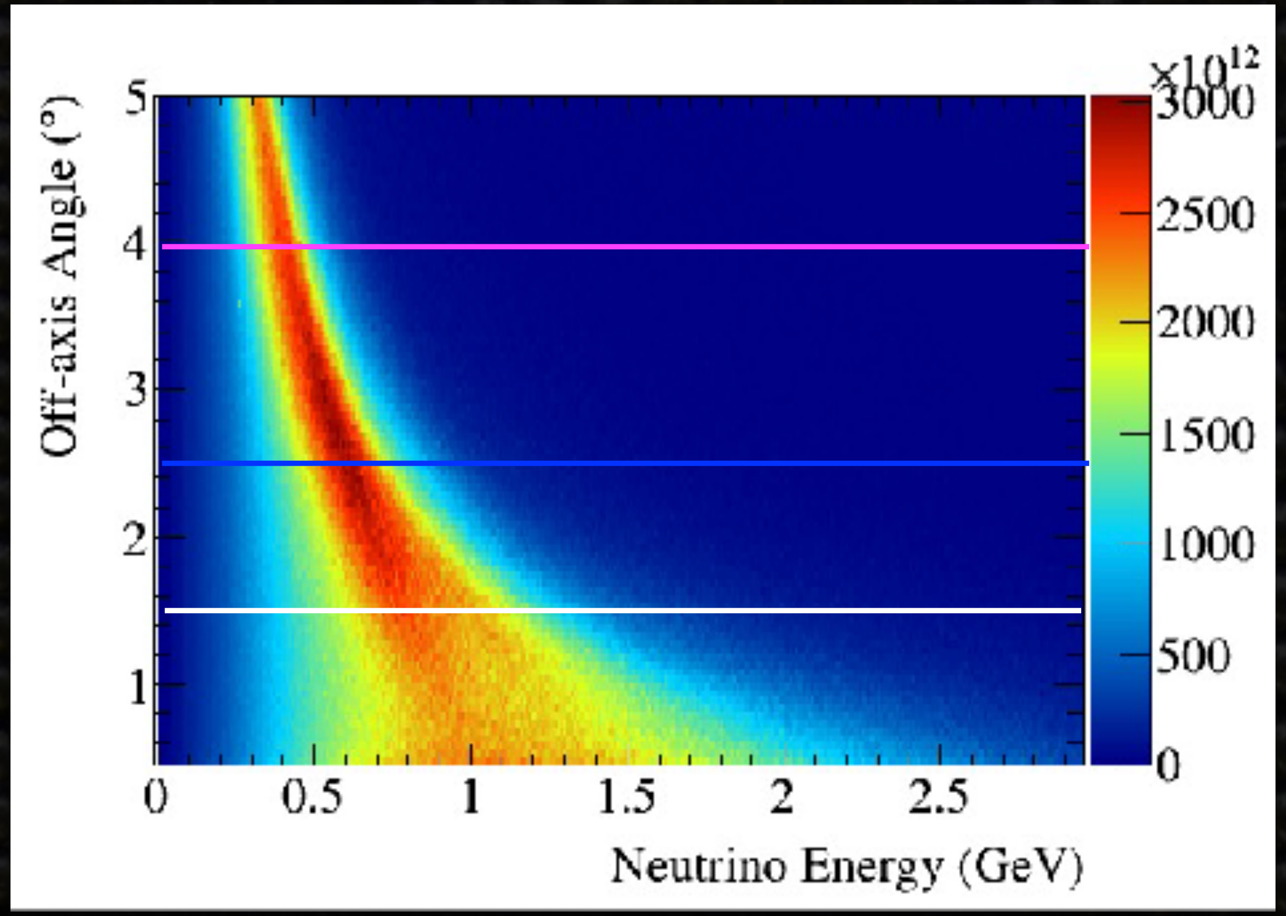
- Hyper-K has a rich physics program beyond long-baseline neutrinos
  - Detecting neutrinos from the Sun, supernovae and the atmosphere
  - Proton decay, dark matter search

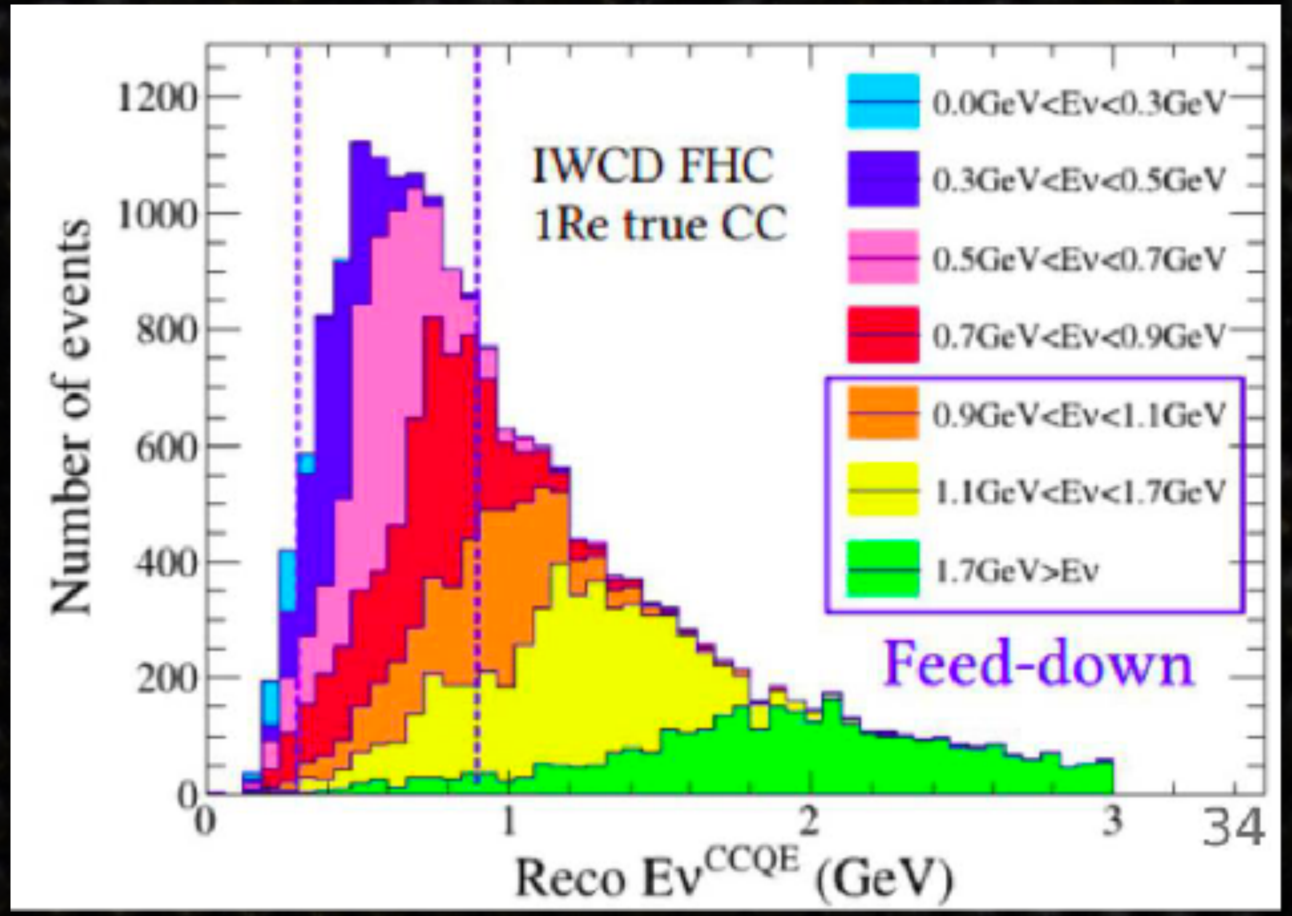
Hyper-Kamiokande

INTERMEDIATE WATER CHERENKOV DETECTOR (IWCD)

mPMT





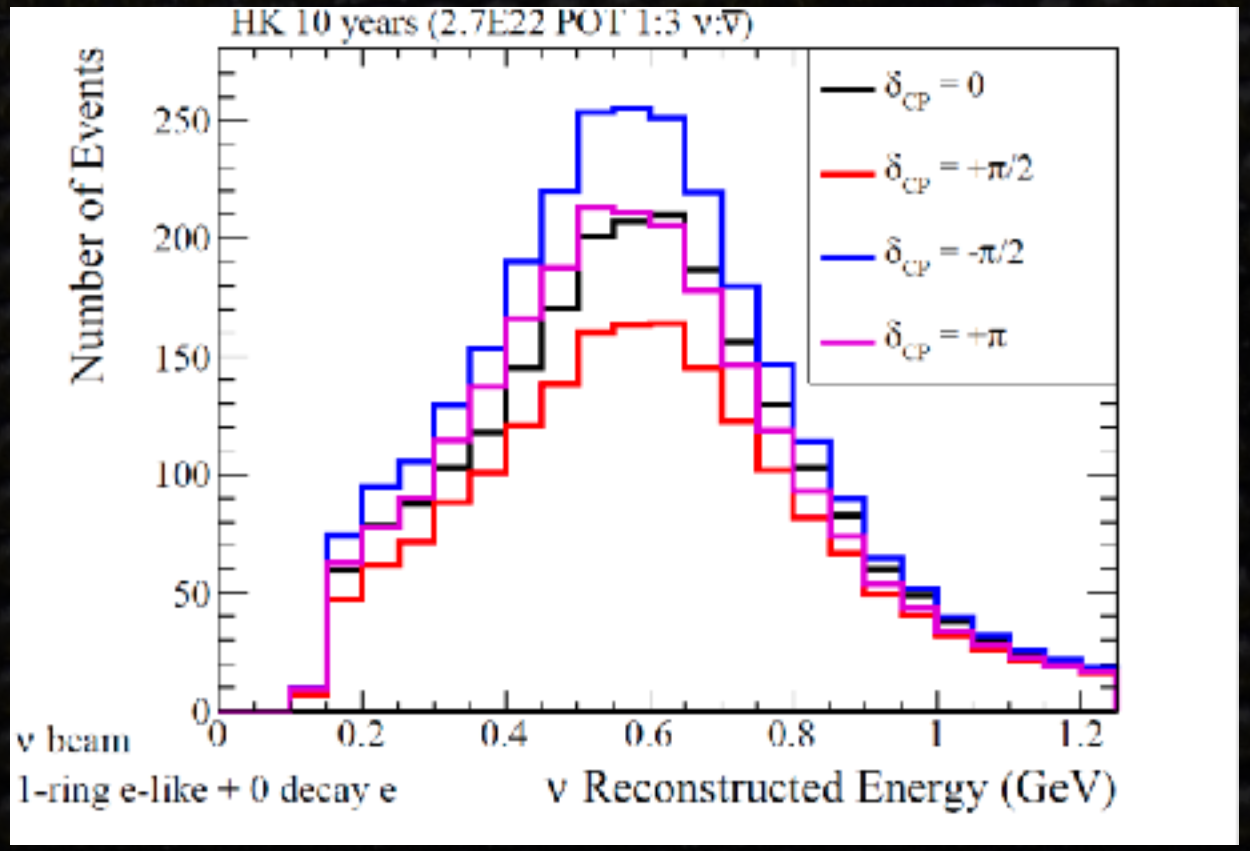


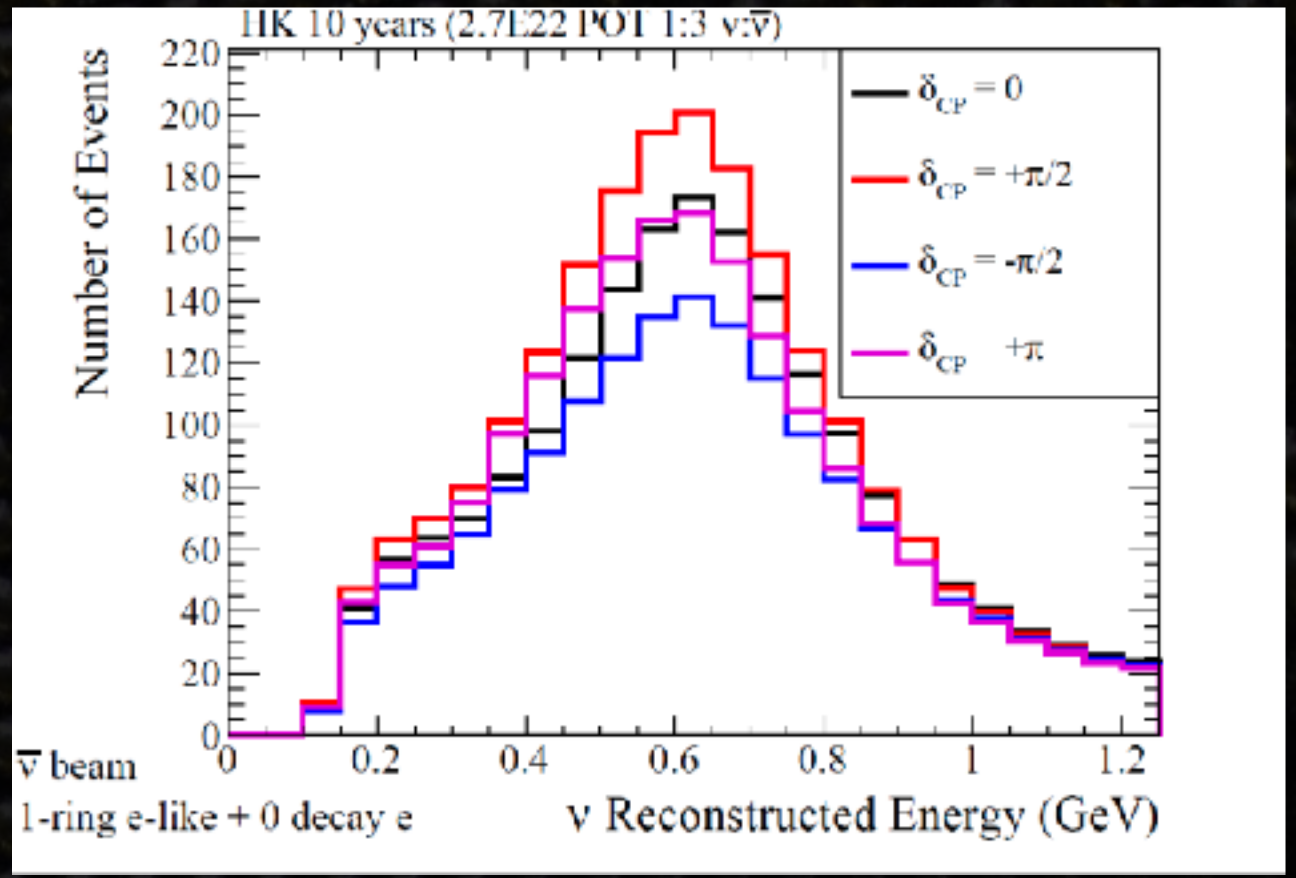
- Multi-PMT (mPMT) modules to increase granularity
- Movable detector to measure neutrinos with different energy spectra
  - Constrain the "feed-down" effect from higher energy non-QE events
- Constrain dominant systematic uncertainty in CP measurement $\nu_e/\bar{\nu}_e$ cross section ratio to better than 4%

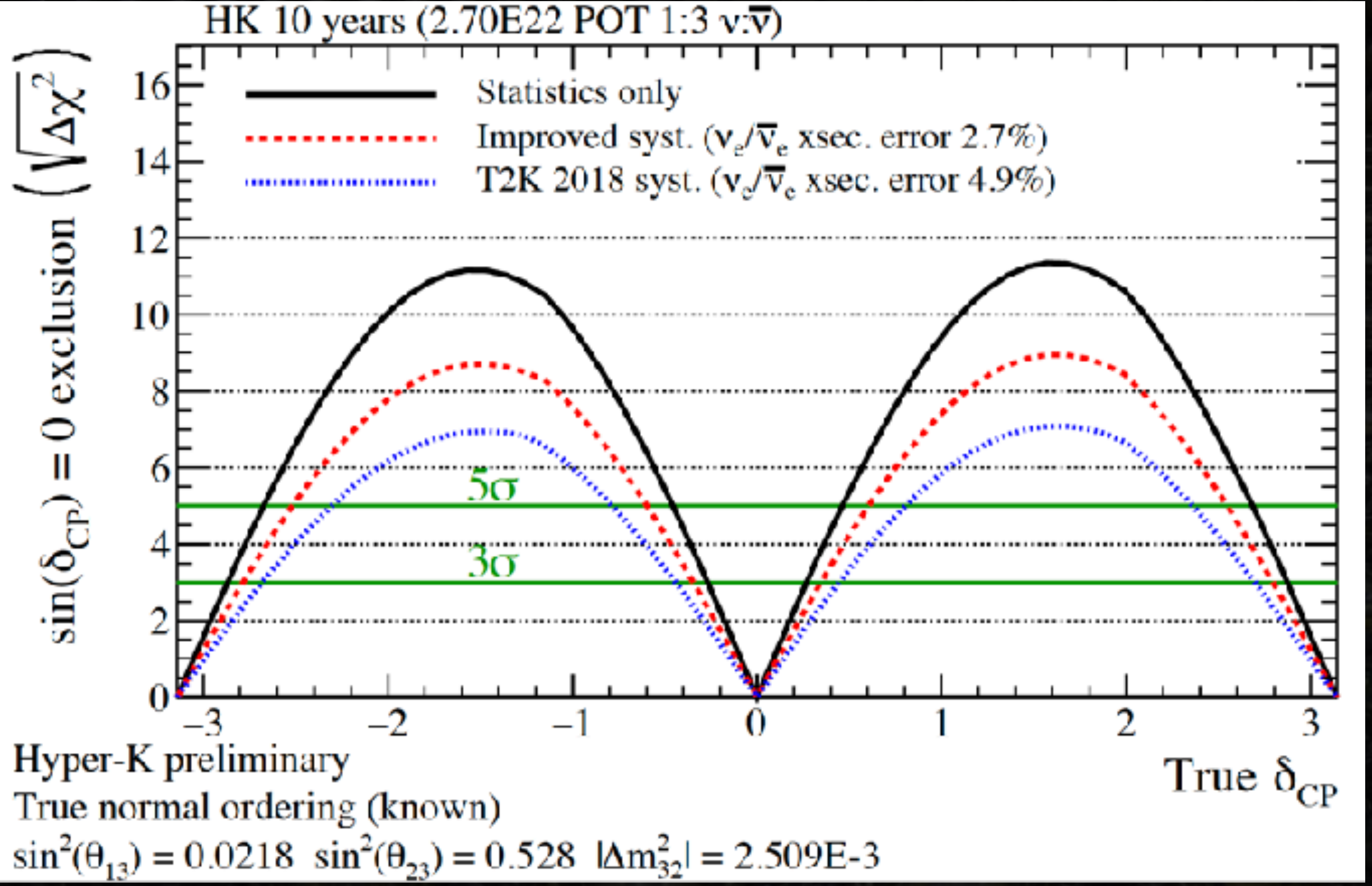
HYPER-K SENSITIVITY - δ_{CP}

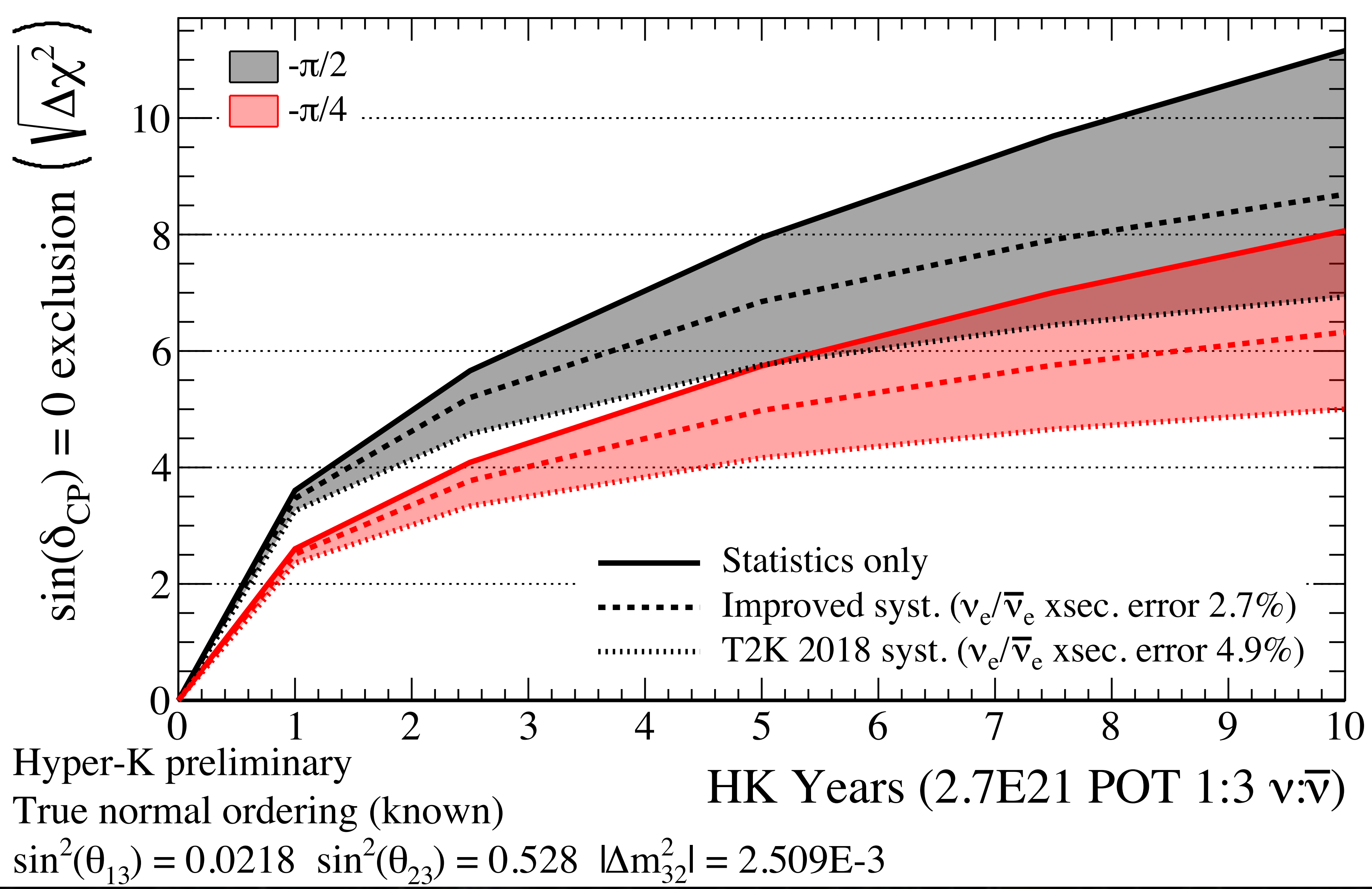
10 years running, 1:3 $\nu : \bar{\nu}$ run plan

- Hyper-K will collected thousands of ν_e and $\bar{\nu}_e$ events over 10 years
- After 10 years of operation, 61% of true δ_{CP} values can be excluded at 5 sigma
  - If $\delta_{CP} = -\pi/2$, 5σ exclusion after 2-3 years of data taking!









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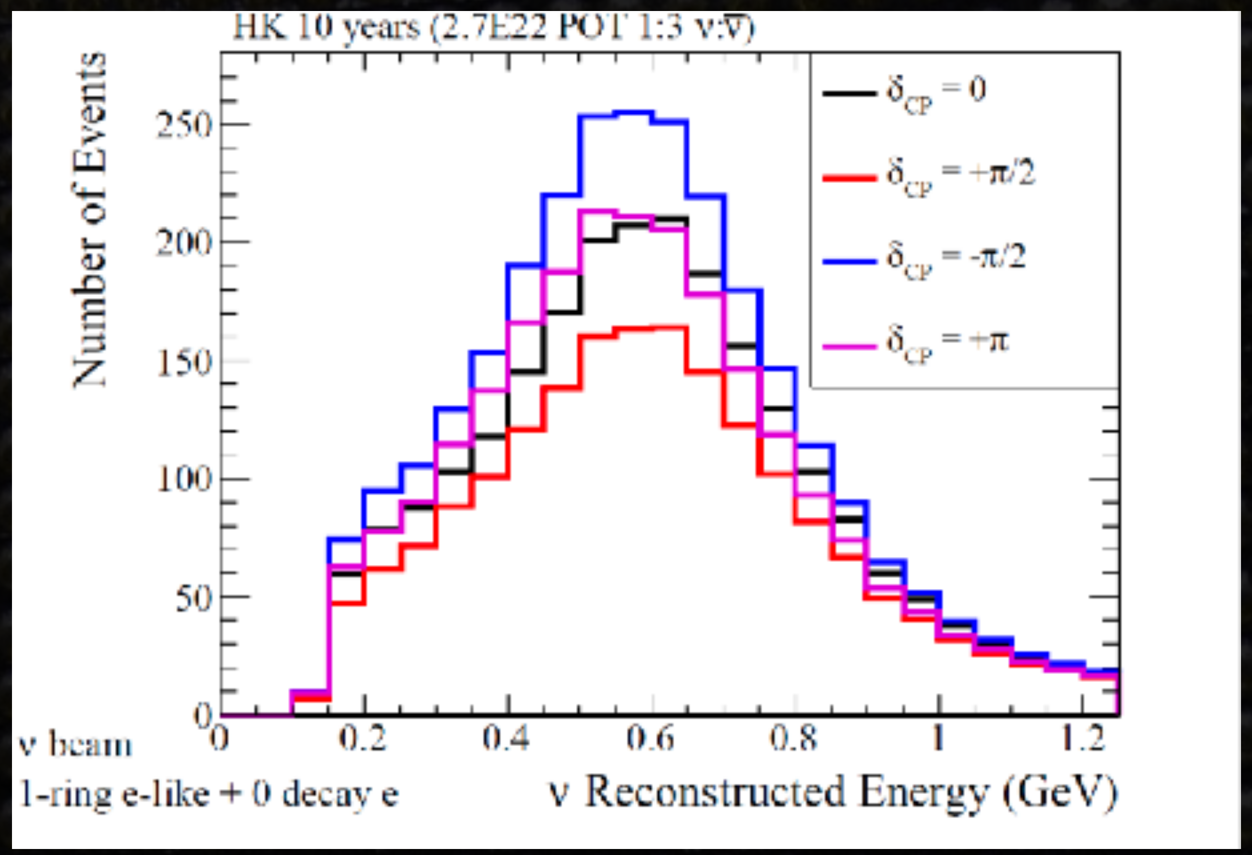
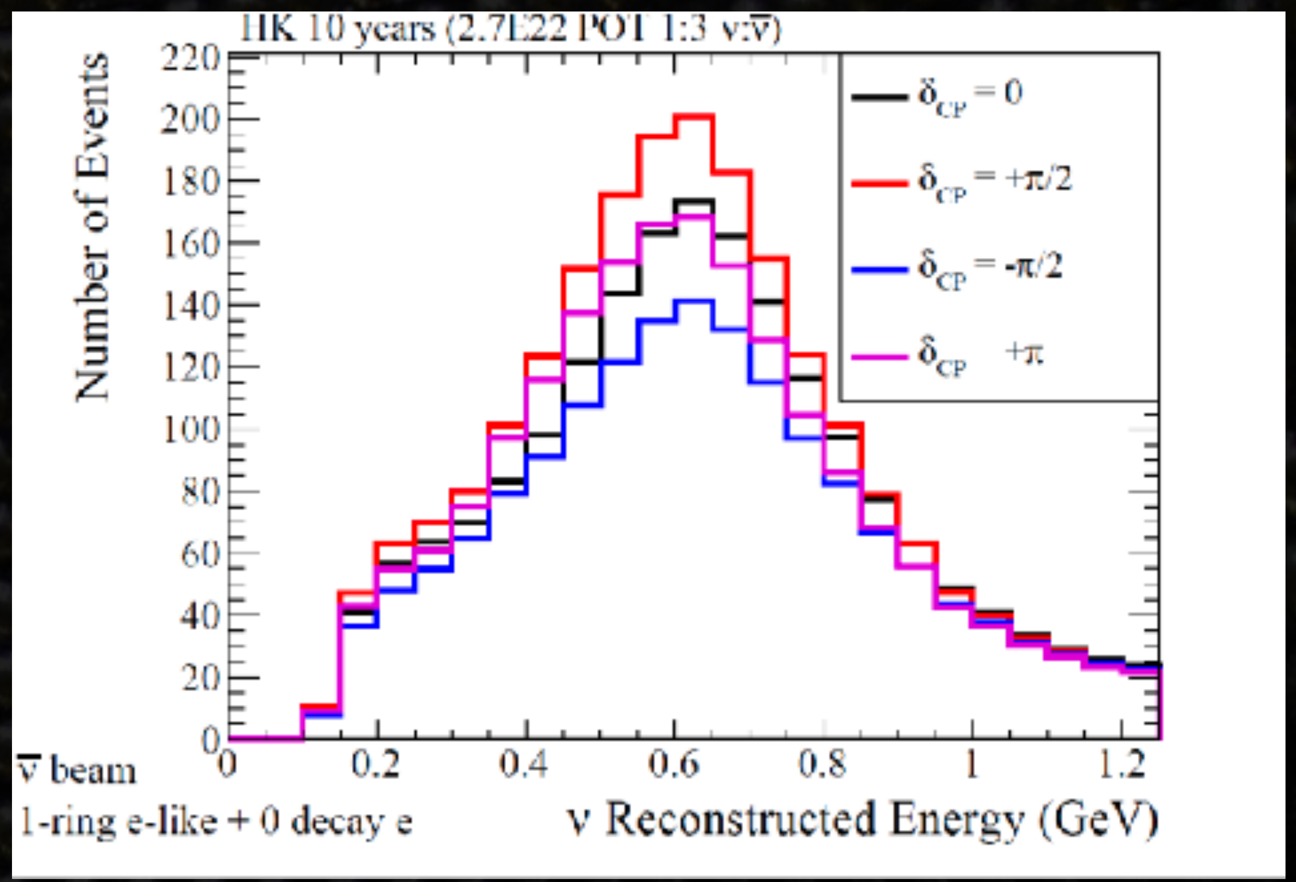
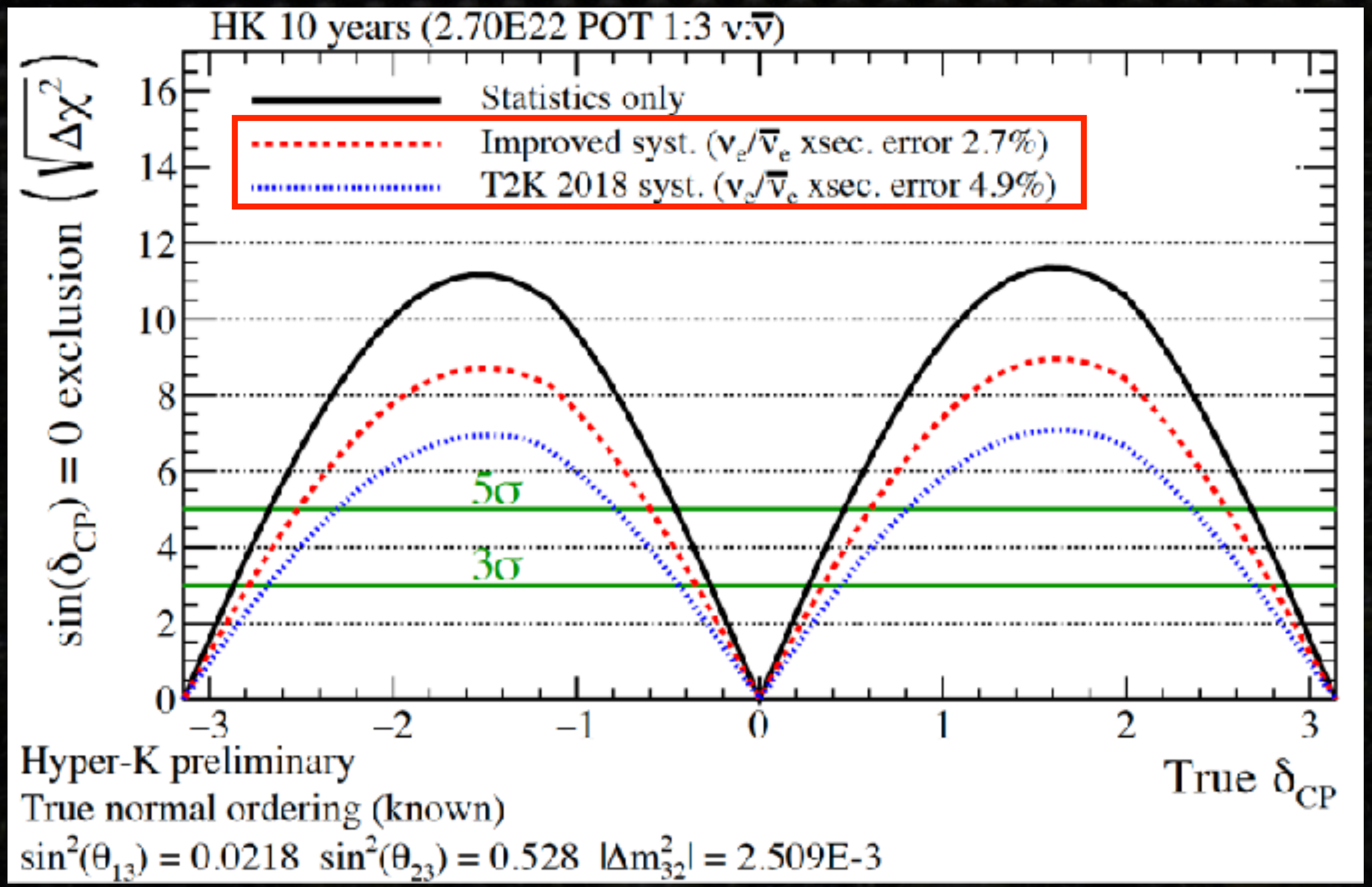
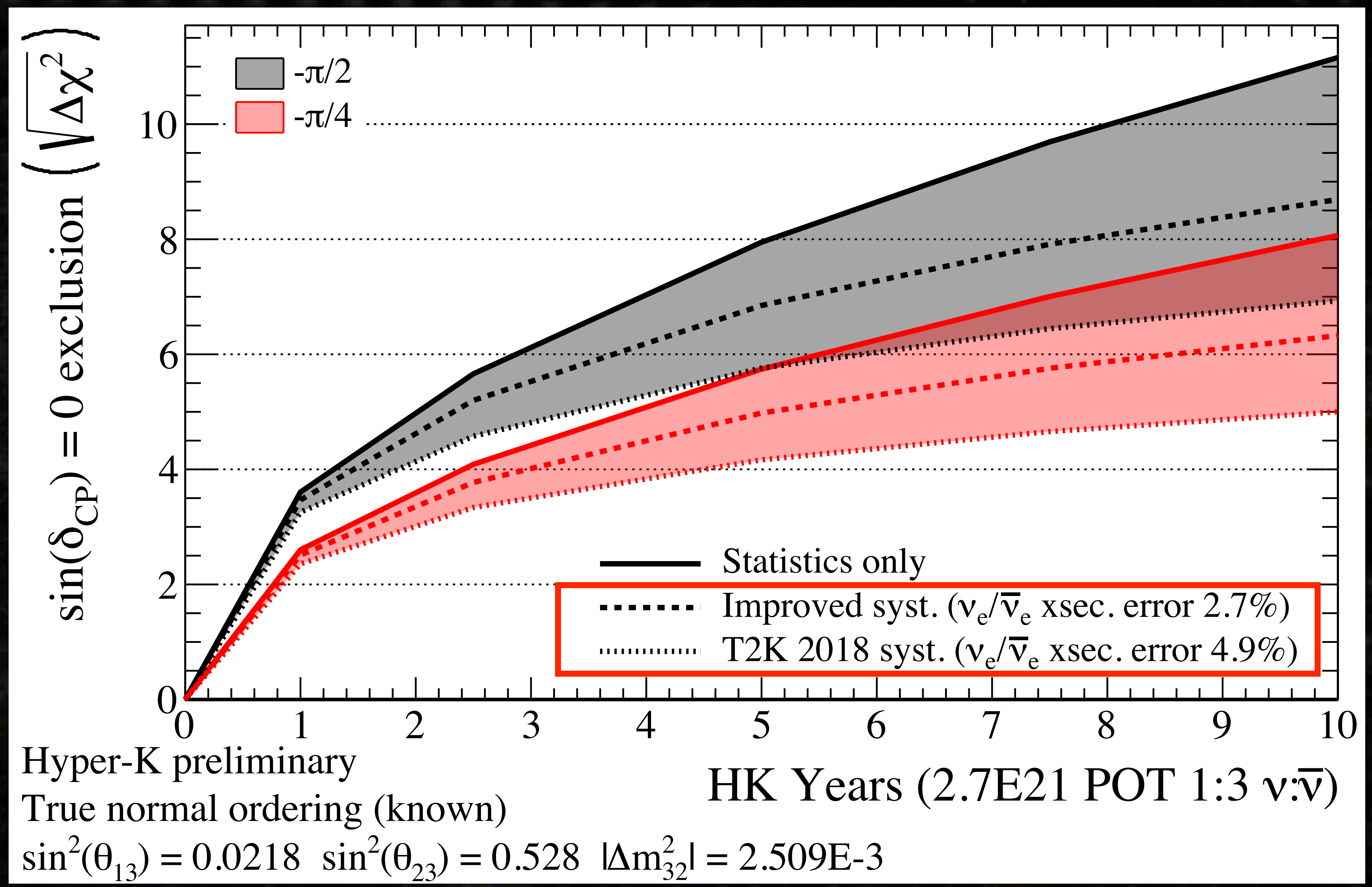




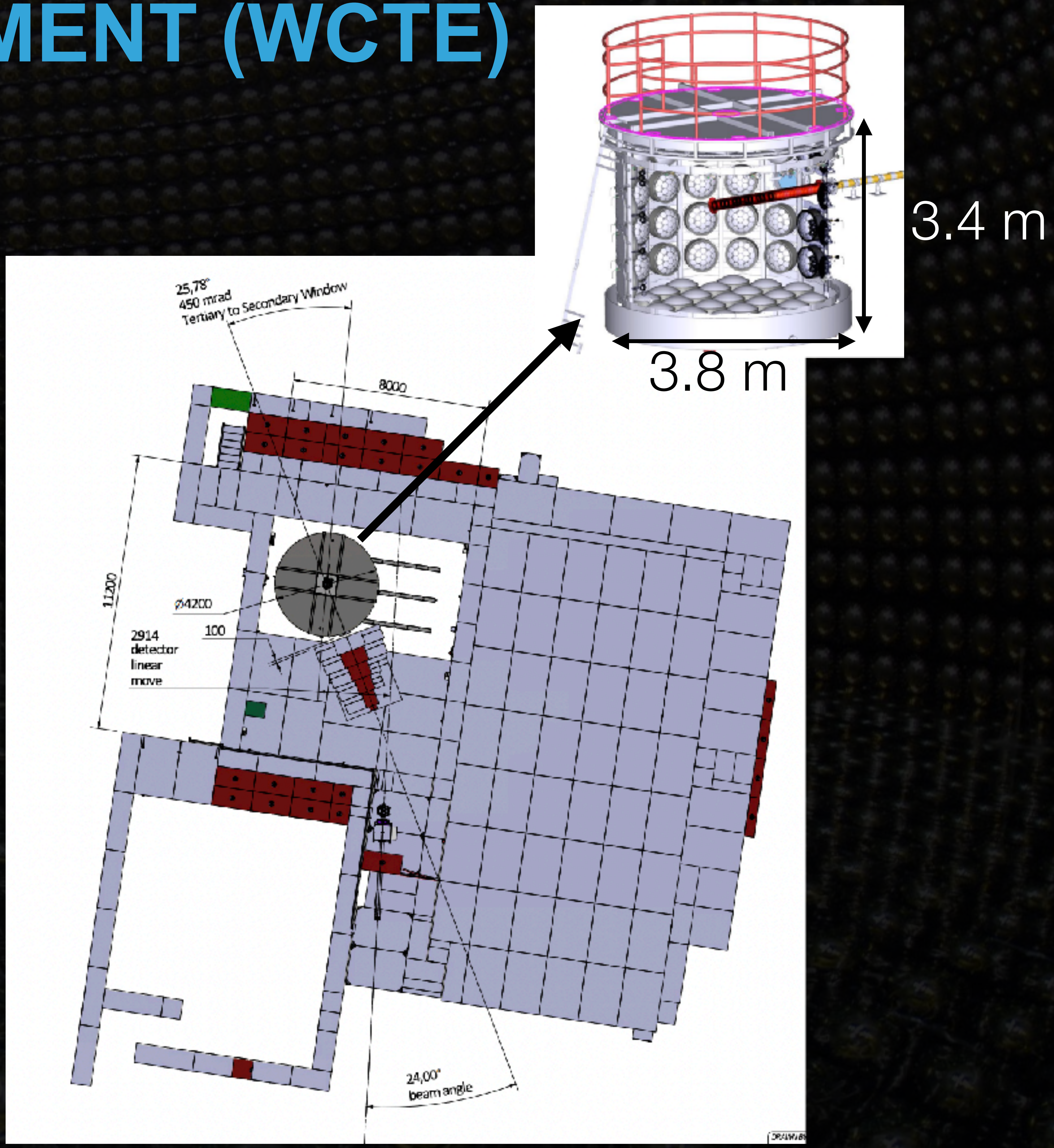
- Hyper-K will collected thousands of ν_e and $\bar{\nu}_e$ events over 10 years
- After 10 years of operation, 61% of true δ_{CP} values can be excluded at 5 sigma
  - If $\delta_{CP} = -\pi/2$, 5σ exclusion after 2-3 years of data taking!
- Reducing systematic uncertainties is crucial for the physics goals
  - Much of our group's work at TRIUMF has been aimed at reducing detector and cross section uncertainties





WATER CHERENKOV TEST EXPERIMENT (WCTE)

- IWCD prototype to be commissioned in spring 2024
  - Test of mPMT and calibration techniques
  - T9 test beam @ CERN
  - 0.3 - 1.1 GeV π, p, e, μ and tagged γ beam
- Lots of interesting results to come with WCTE
  - E.g. test of water Cherenkov event reconstruction using particles of known momentum and vertex
  - Understanding neutrino cross section on water through e/μ scattering
  - … …



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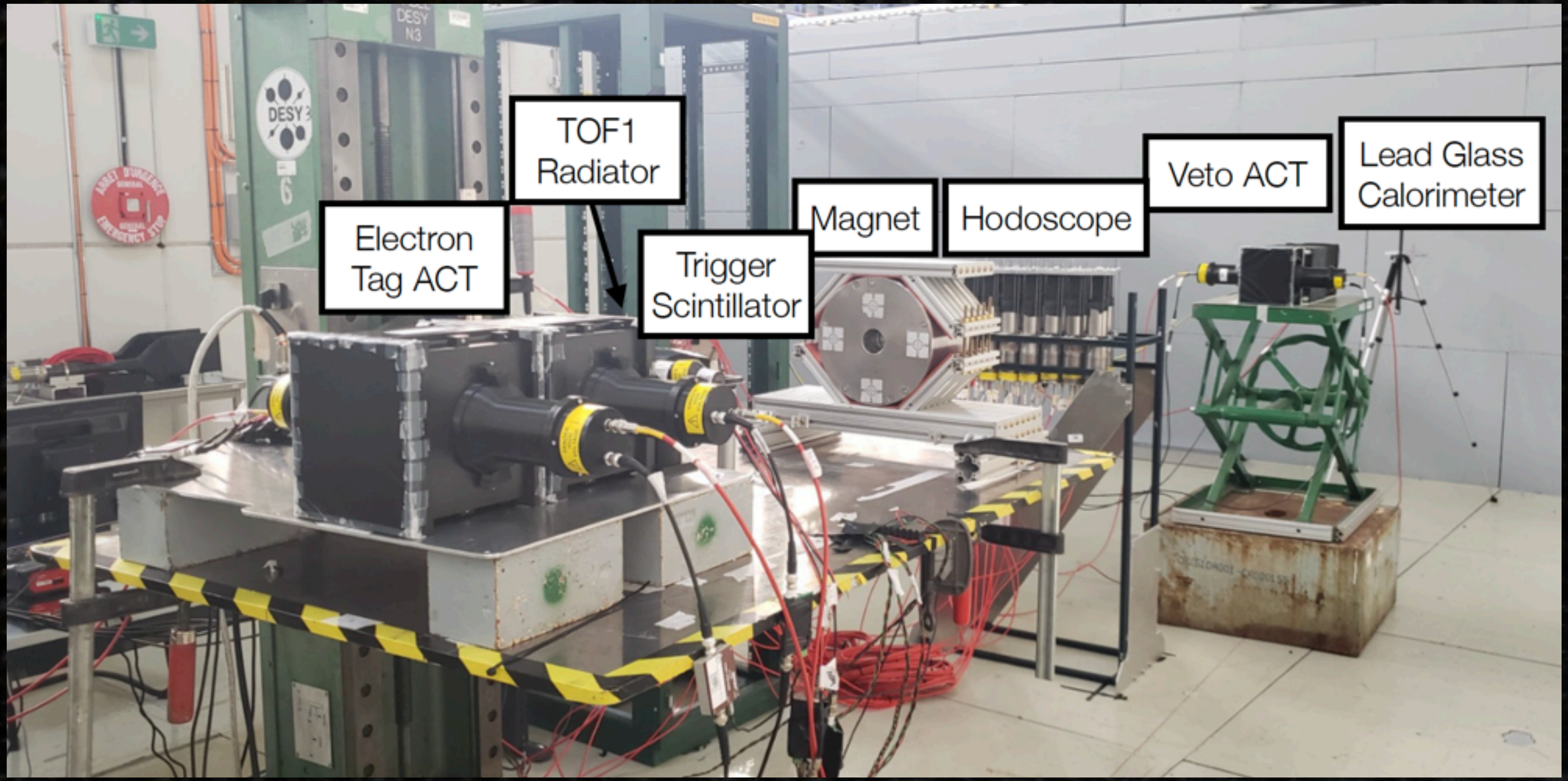
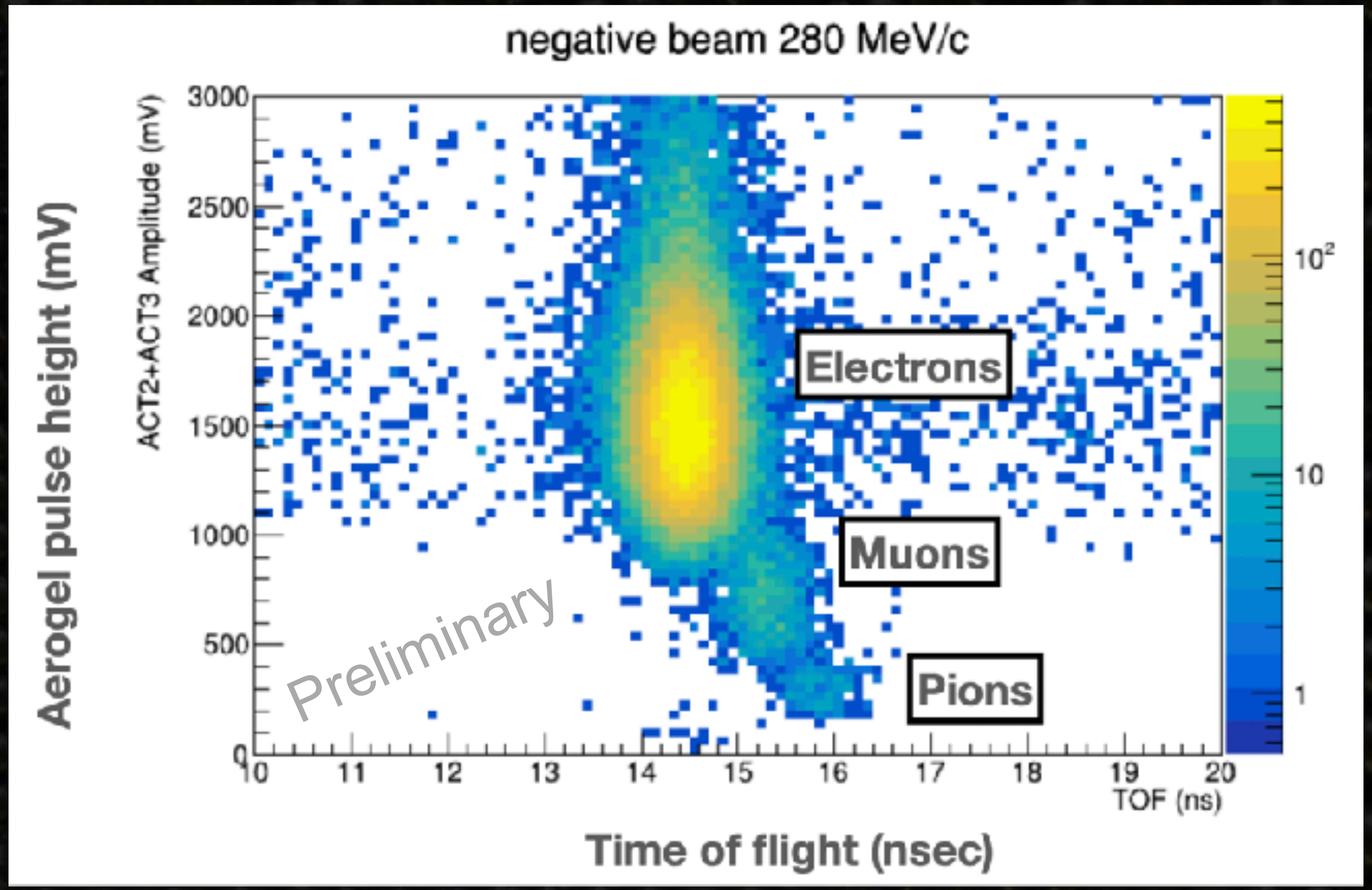
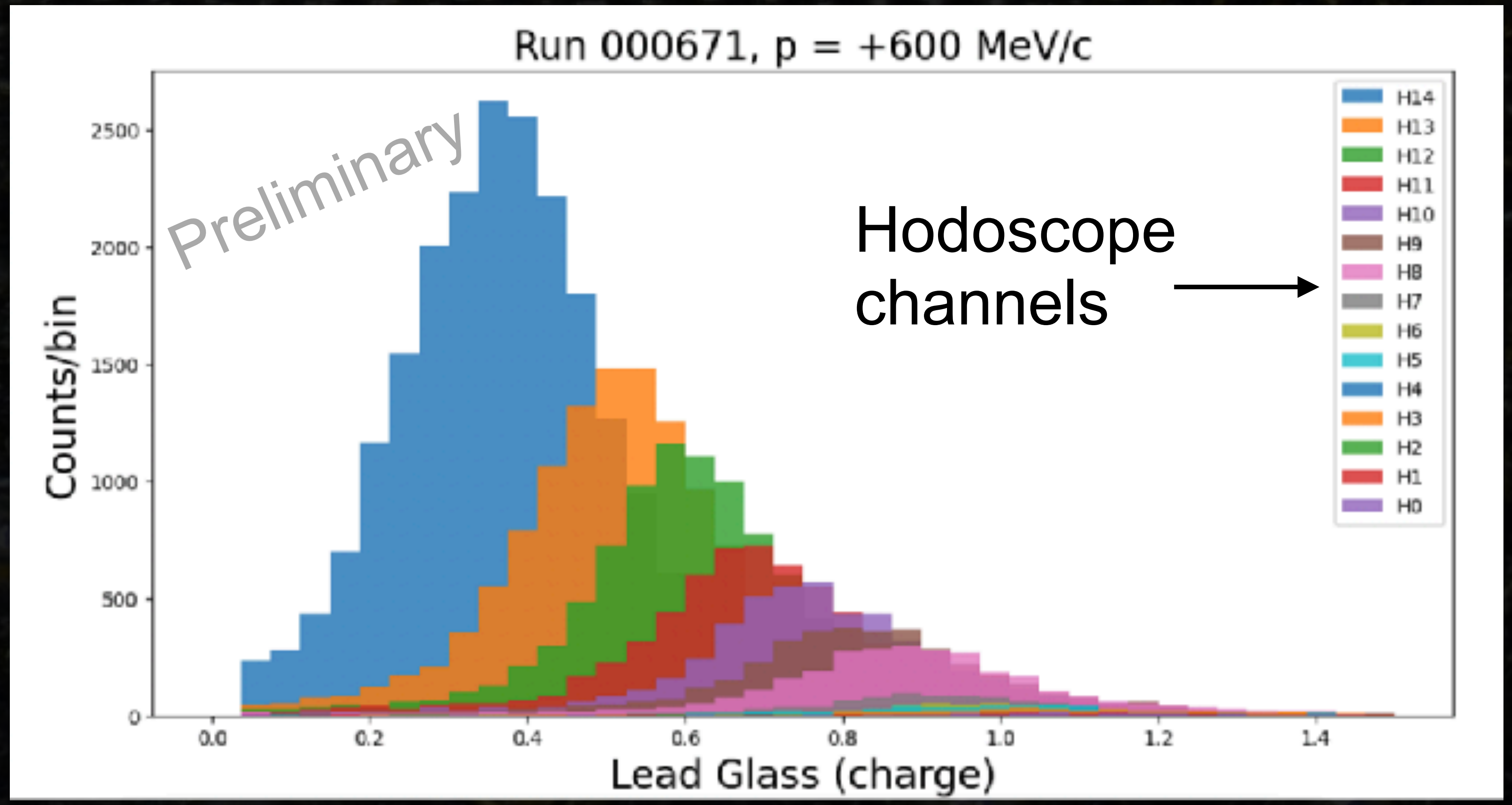
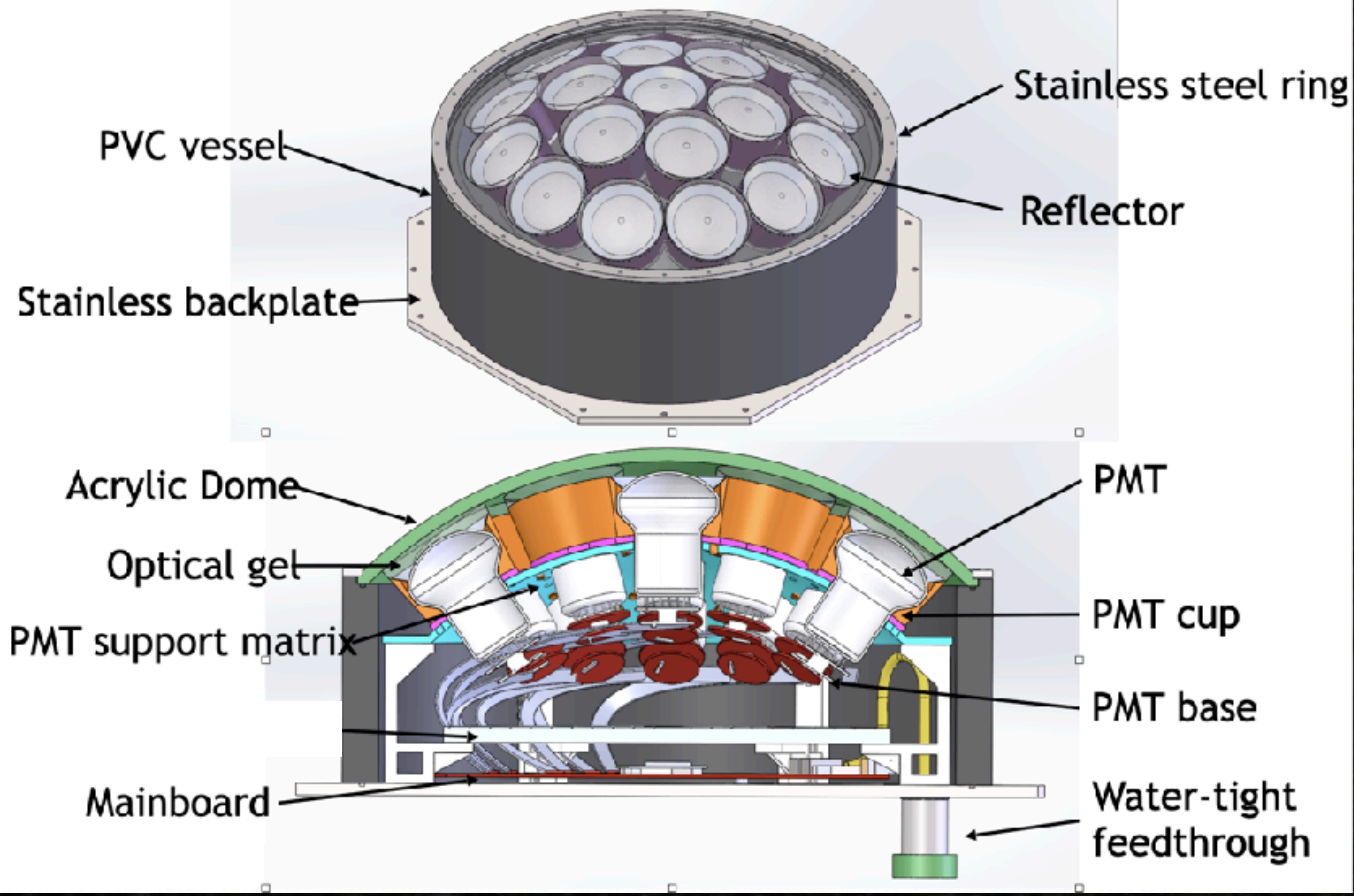






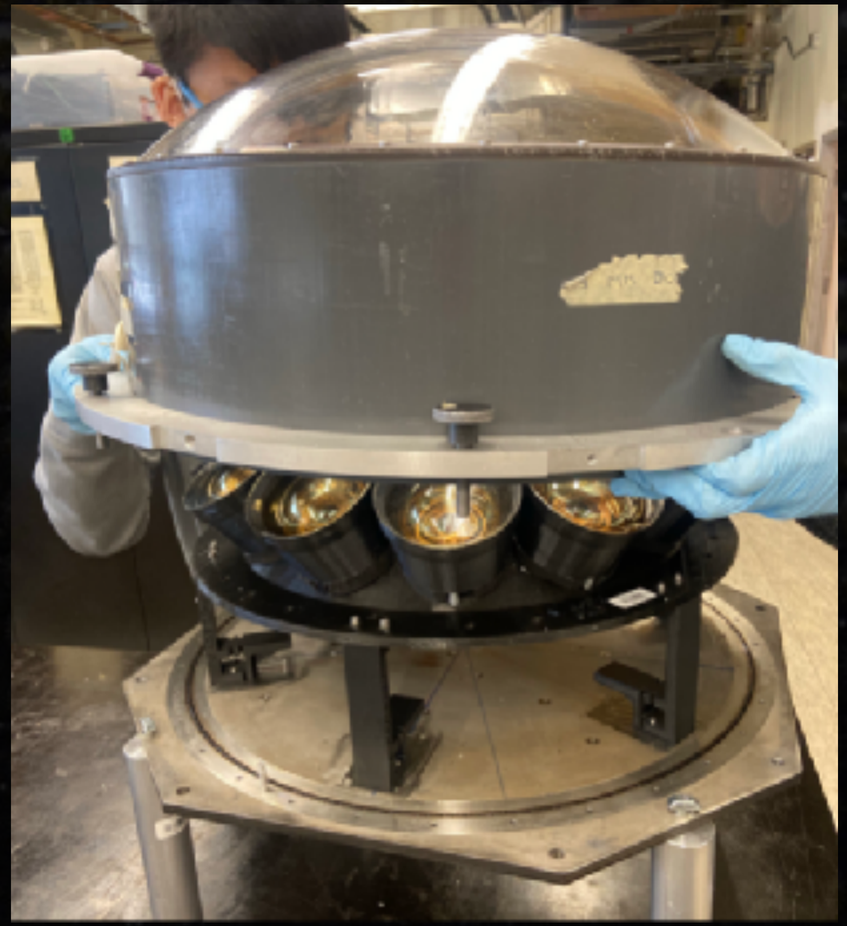
- Beam test at CERN in July 2023
- Demonstrated capability of tagging charged particles of varying momenta and types
- Tagged γ beam also successful

MULTI-PMT DEVELOPMENT

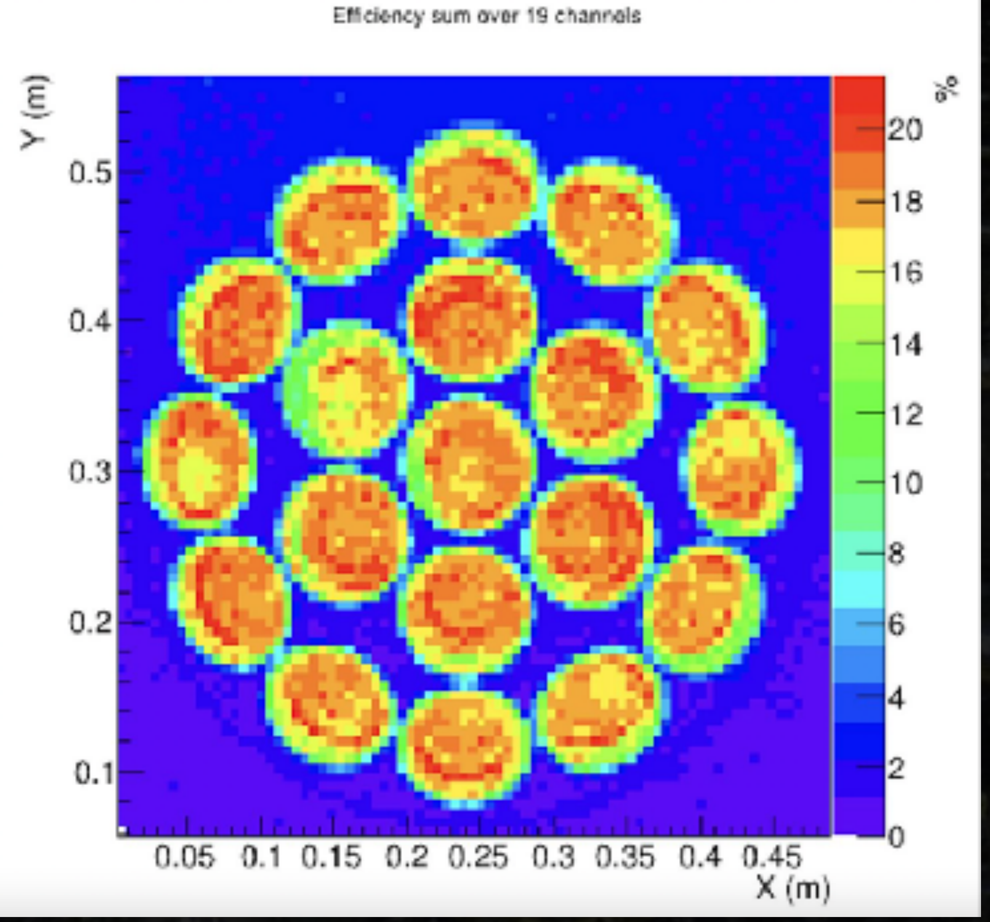


- 19 3″ PMTs in each mPMT module
- TRIUMF will build ~40 mPMTs for WCTE/IWCD using both ex-situ and in-situ gelling method
  - Mass production to begin in late August

Ex-situ gelling

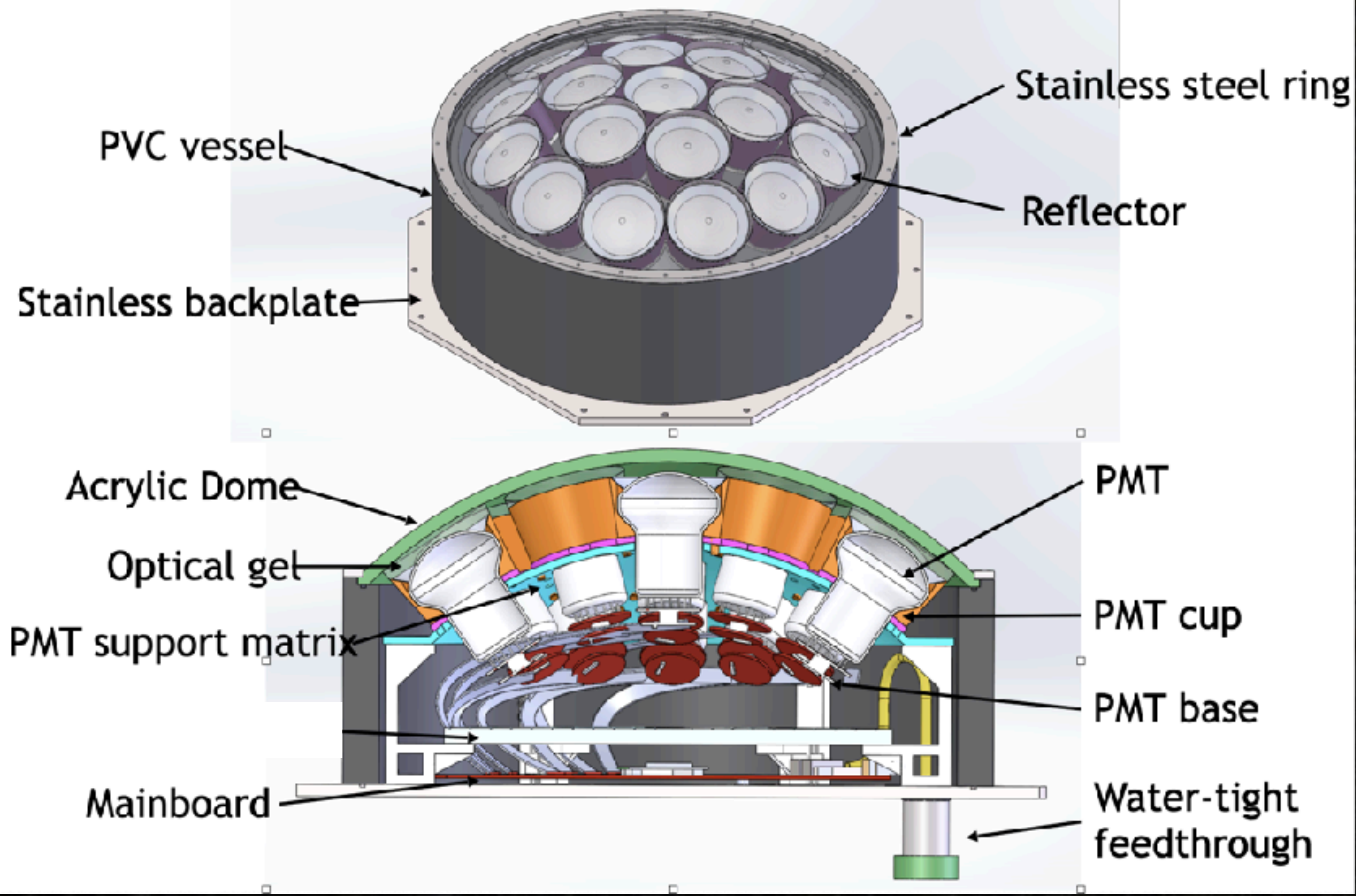


Measured mPMT response



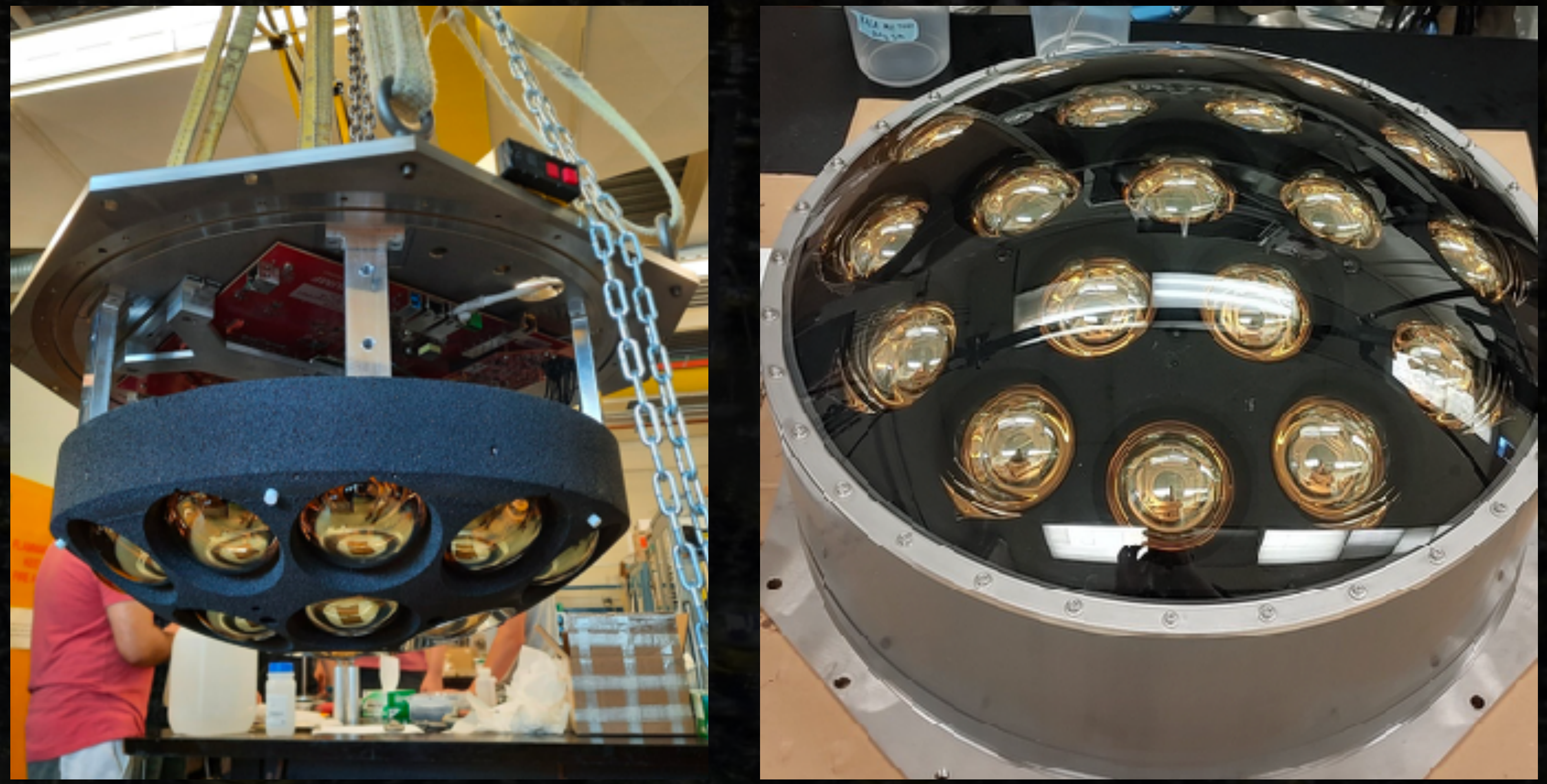
- Detailed mPMT response measured using dedicated test stand
- Longterm immersion test has been performed to monitor inside humidity and pressure change

MULTI-PMT DEVELOPMENT



Ex-situ gelling

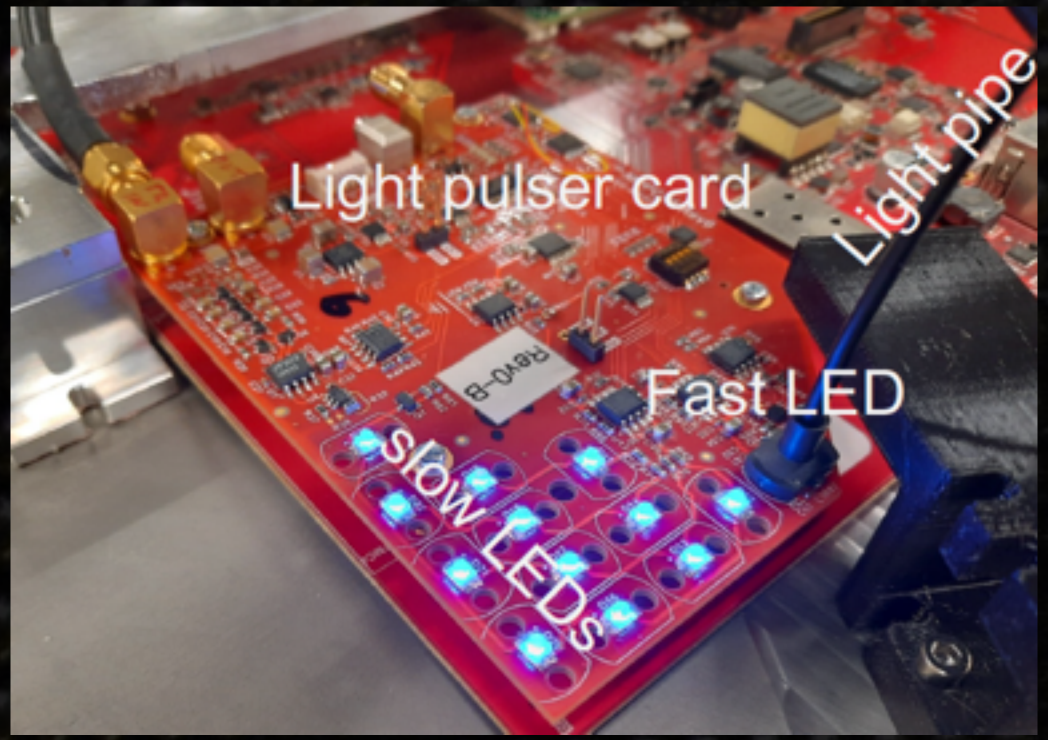
In-situ gelling

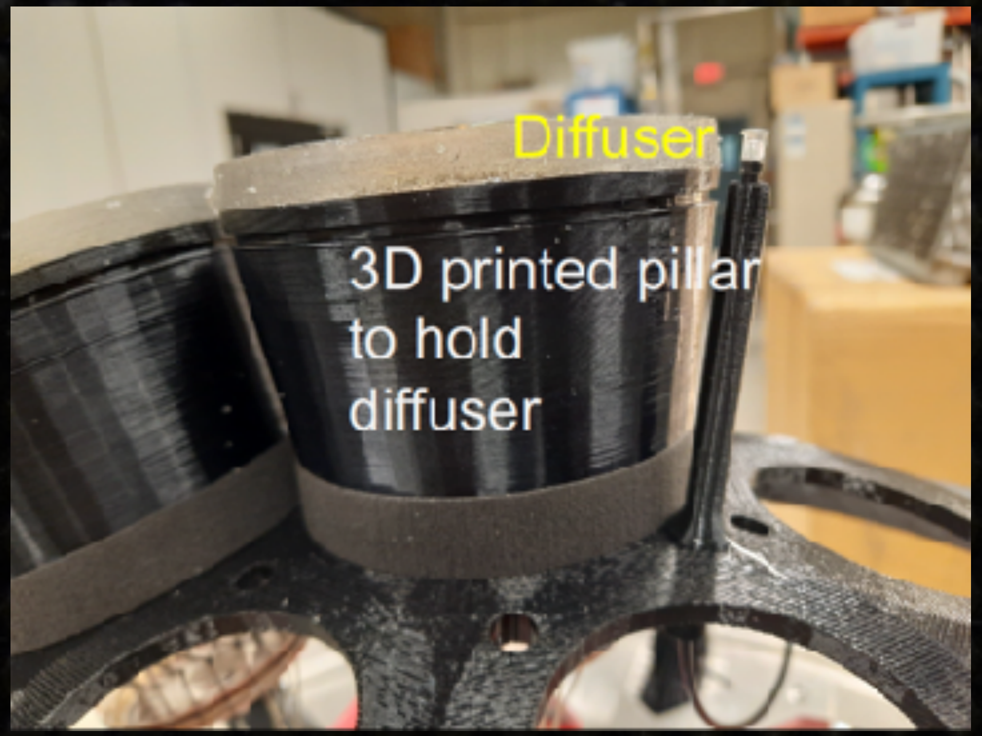


- Will use the experience of WCTE mass production to make the final decision about the mPMT assembly strategy
- Choice between in-situ vs ex-situ gelling strategy for IWCD will be made after WCTE mPMT production

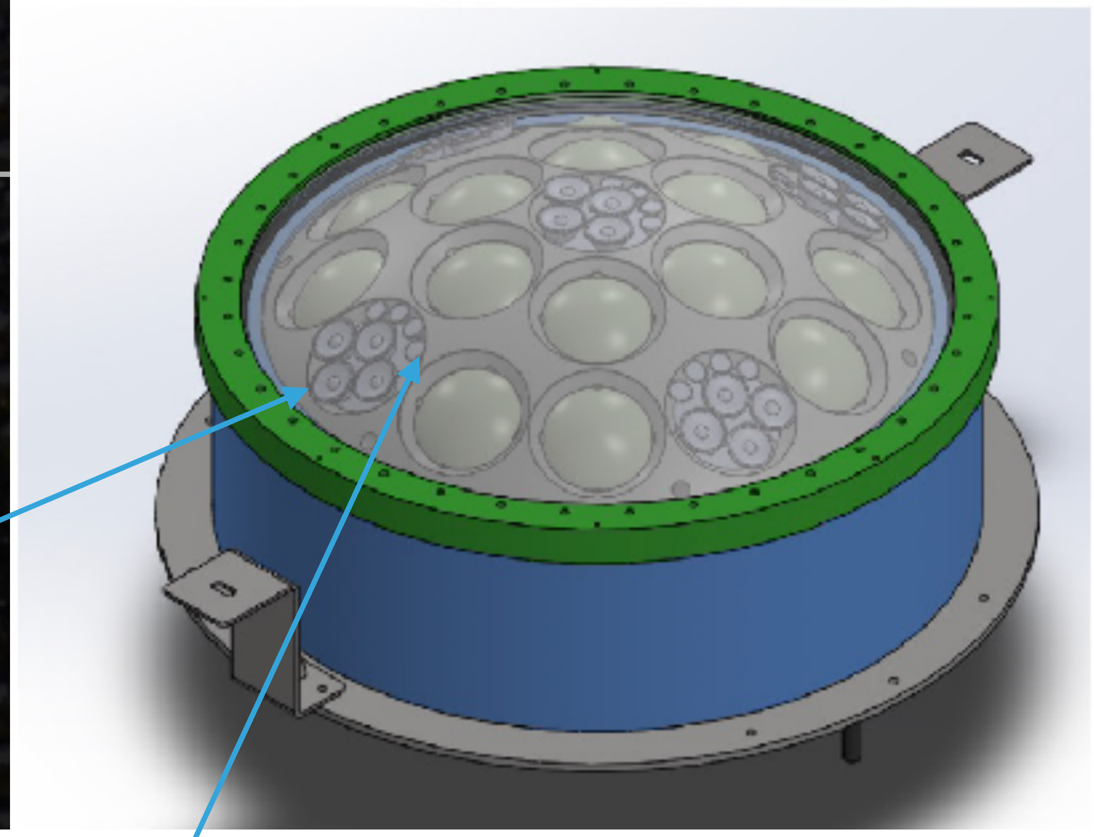
LED CALIBRATION SOURCES IN MPMT

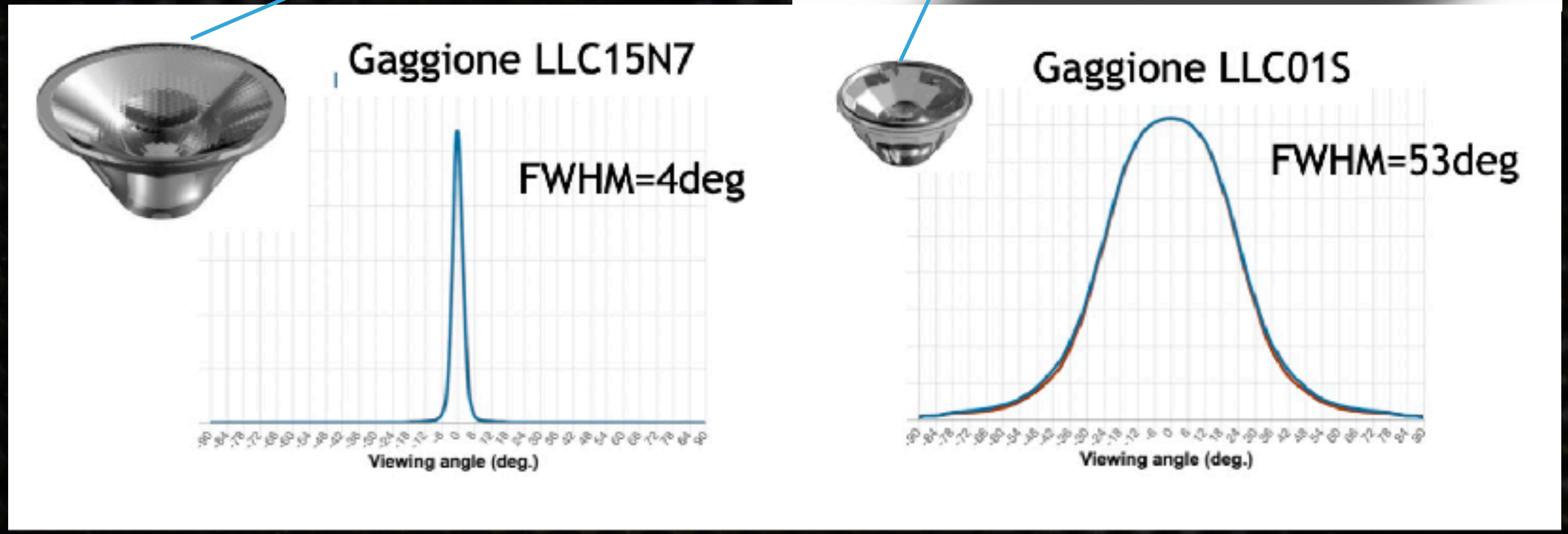
WCTE/IWCD mPMT calibration LED



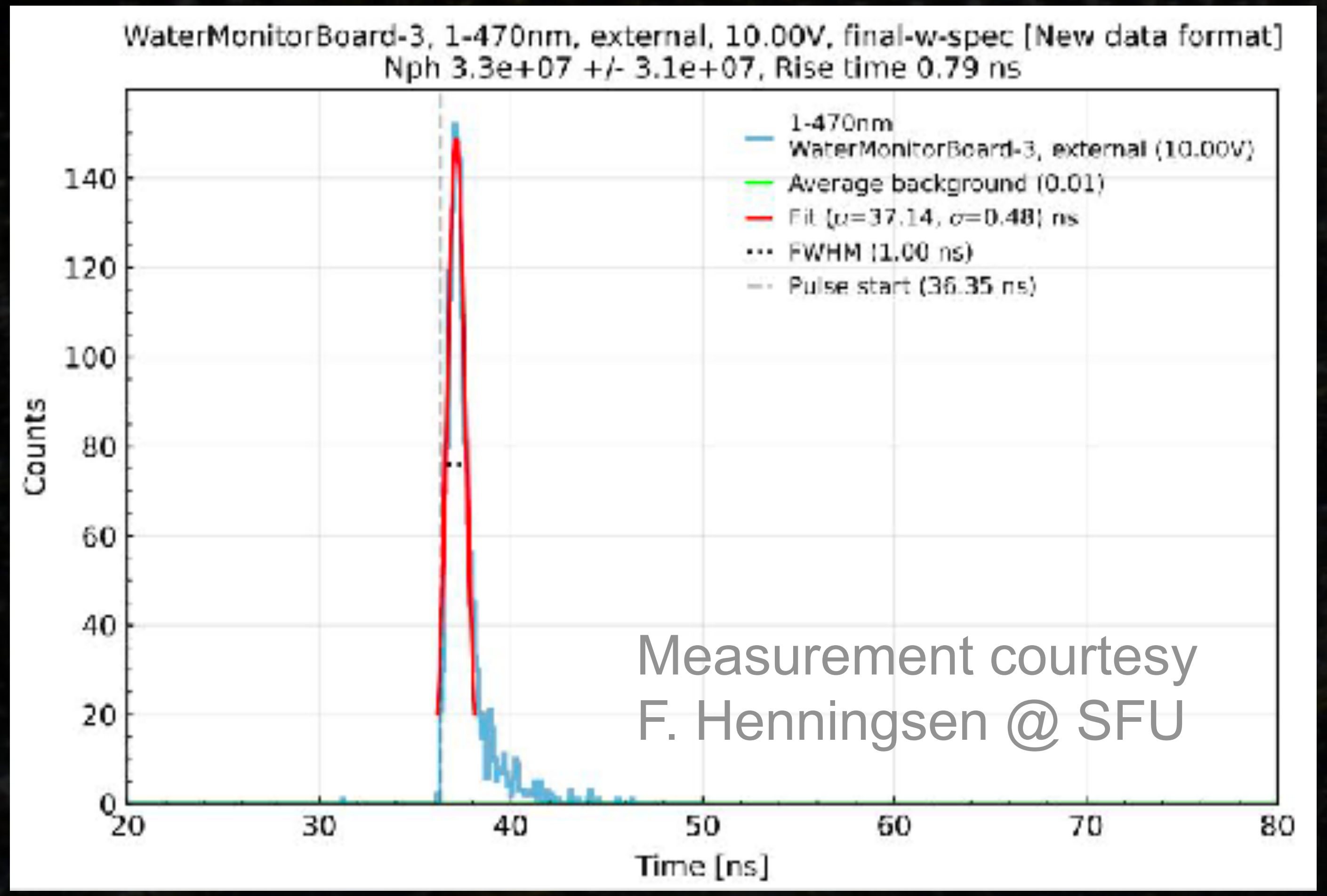


Hyper-K detector mPMT calibration LED



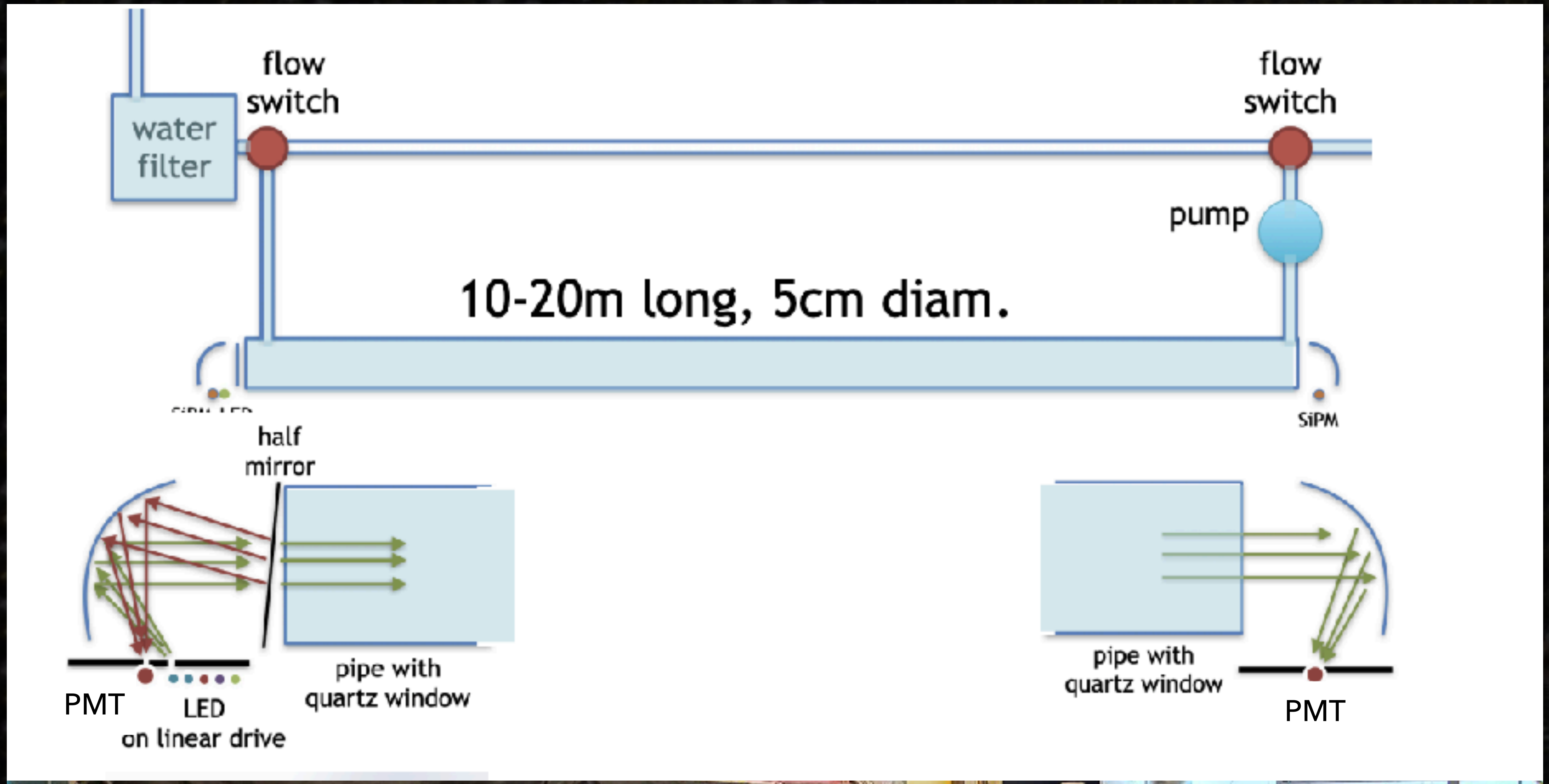


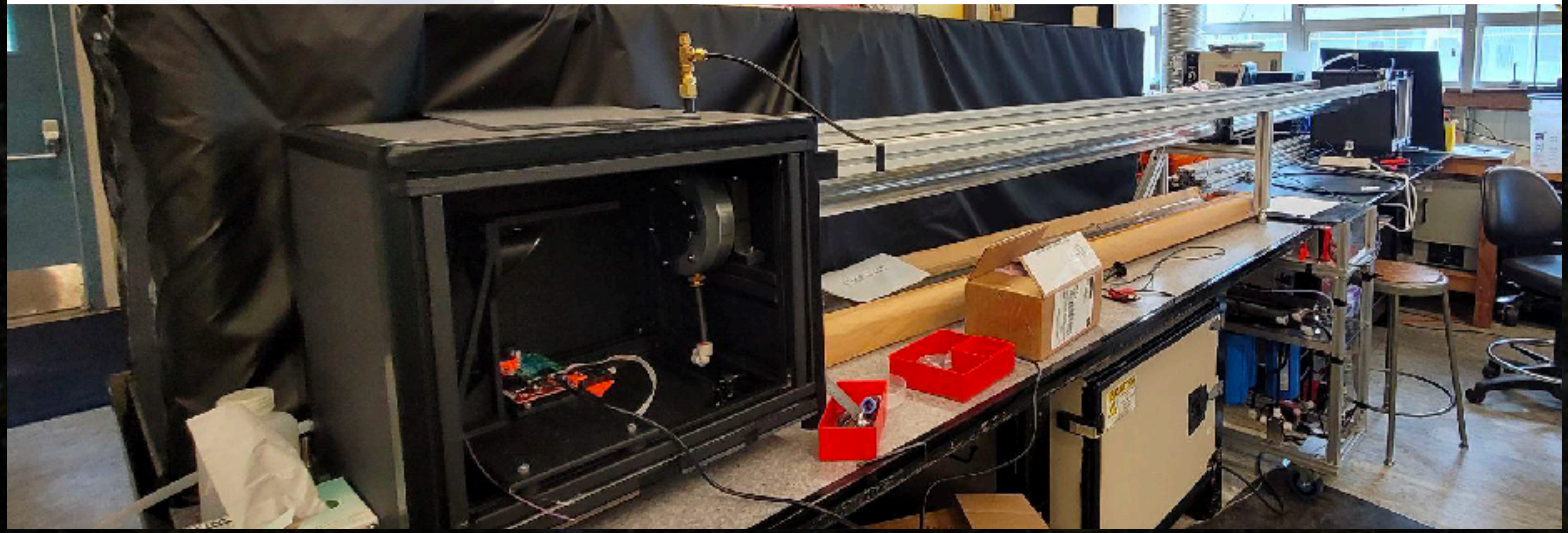
Sub-nsec LED pulser measured timing

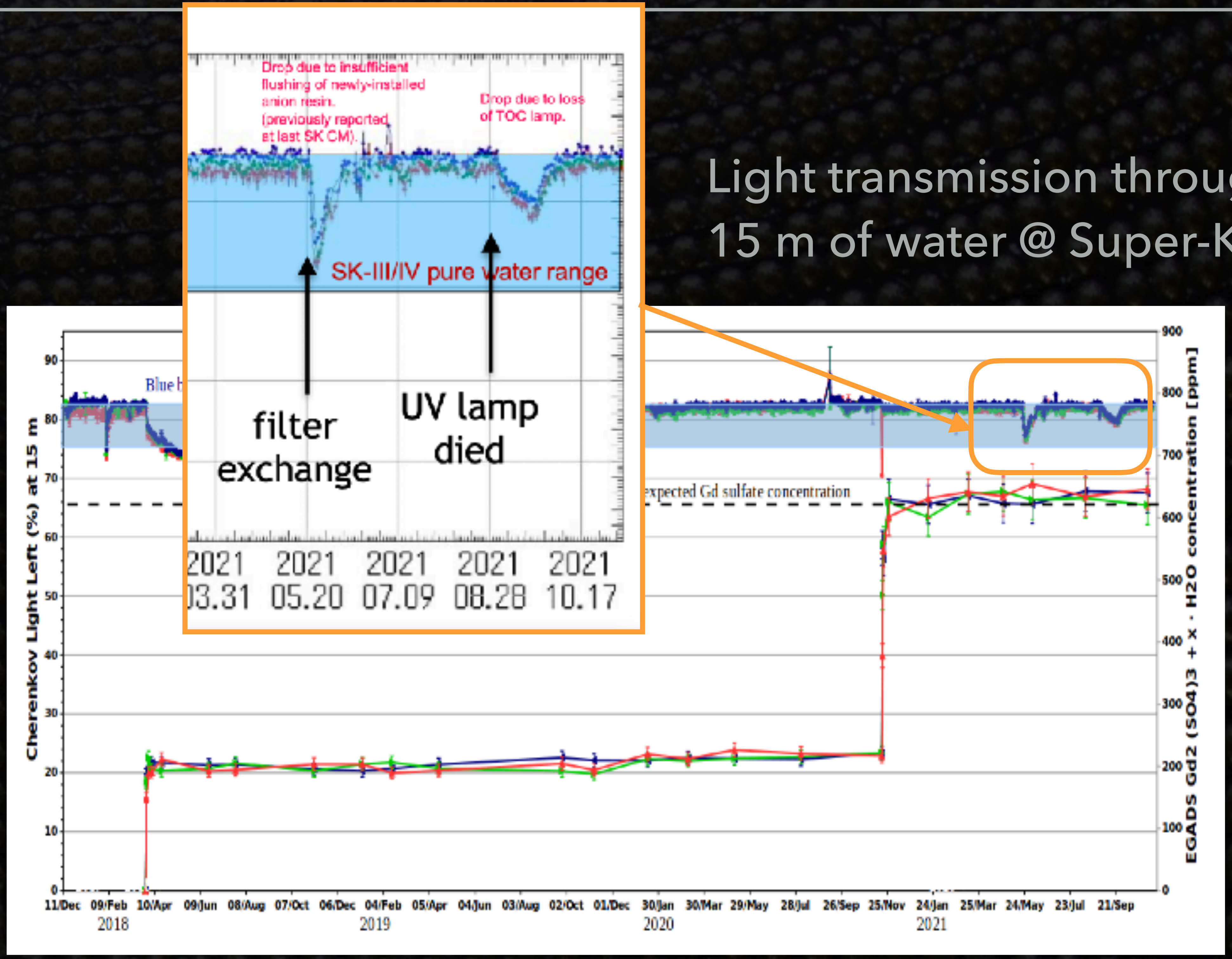


- Calibration light sources will utilize the sub-nsec, low-cost LED driver designed @ UVic
  - From 290 nm to 470 nm
- Each WCTE/IWCD mPMT will contain 3 fast LEDs for timing and detector optical calibration
- Each Hyper-K mPMT will contain 40 LEDs
  - 20 narrow-angle LEDs for water parameter calibration including Raman scattering
  - 20 wide-angle LEDs for PMT angular response calibration

WATER MONITORING SYSTEM







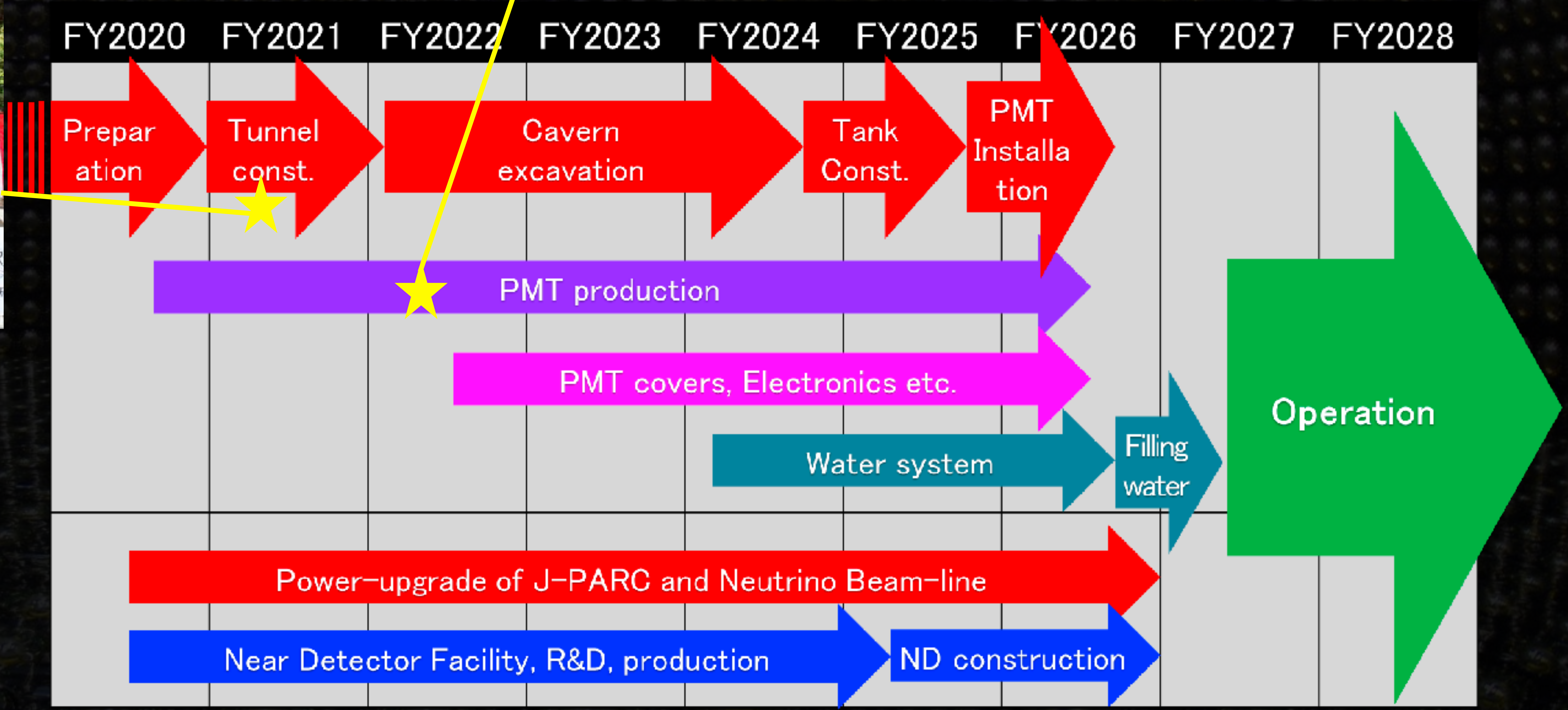
Light transmission through 15 m of water @ Super-K

- Light propagation in water needs to be precisely calibrated and monitored in water Cherenkov detectors
- Pulsed LED (230 - 700 nm) with <1 ns width
- Applications in drinking water monitoring
  - Continuous measurement with high sensitivity
- First prototype has been built @ TRIUMF; alignment and operation studies are ongoing

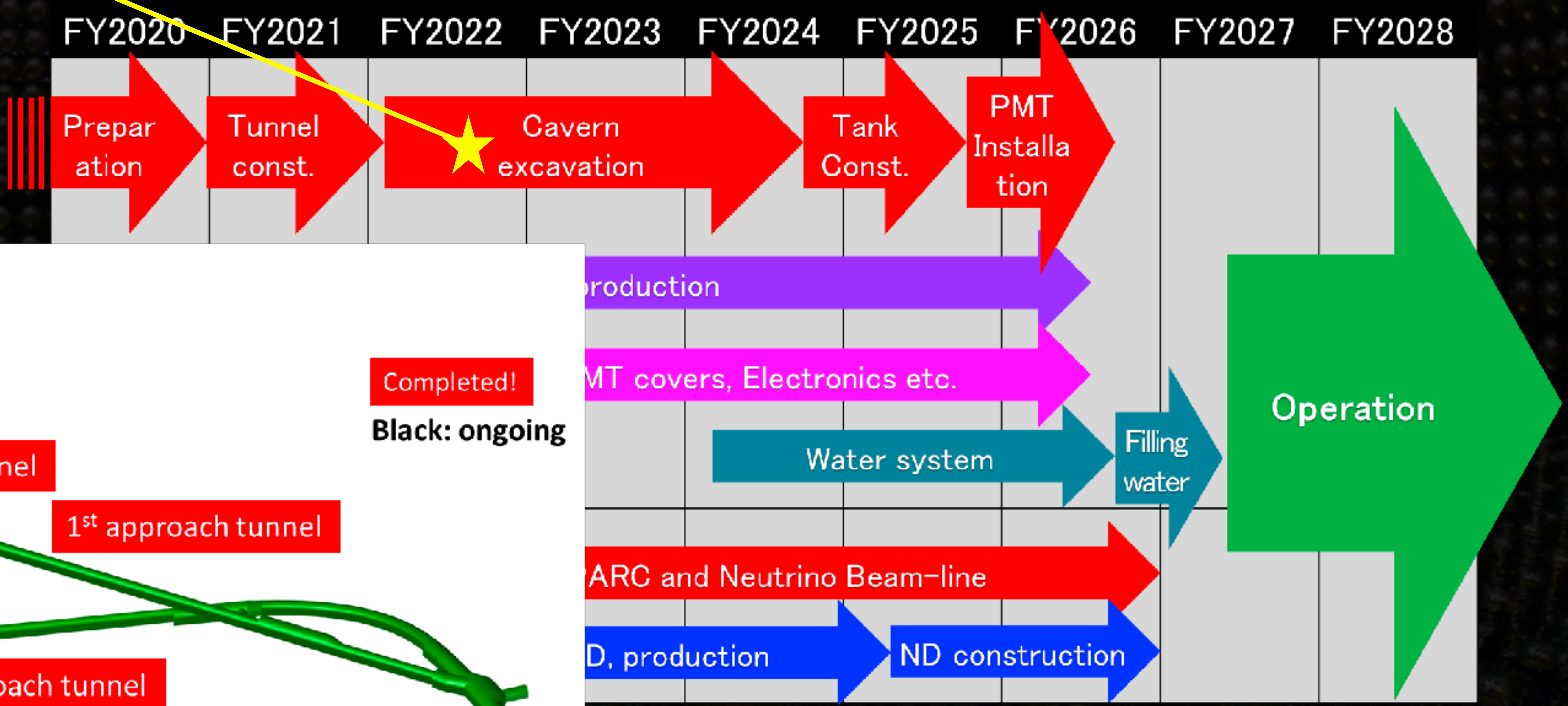
HYPER-K TIMELINE

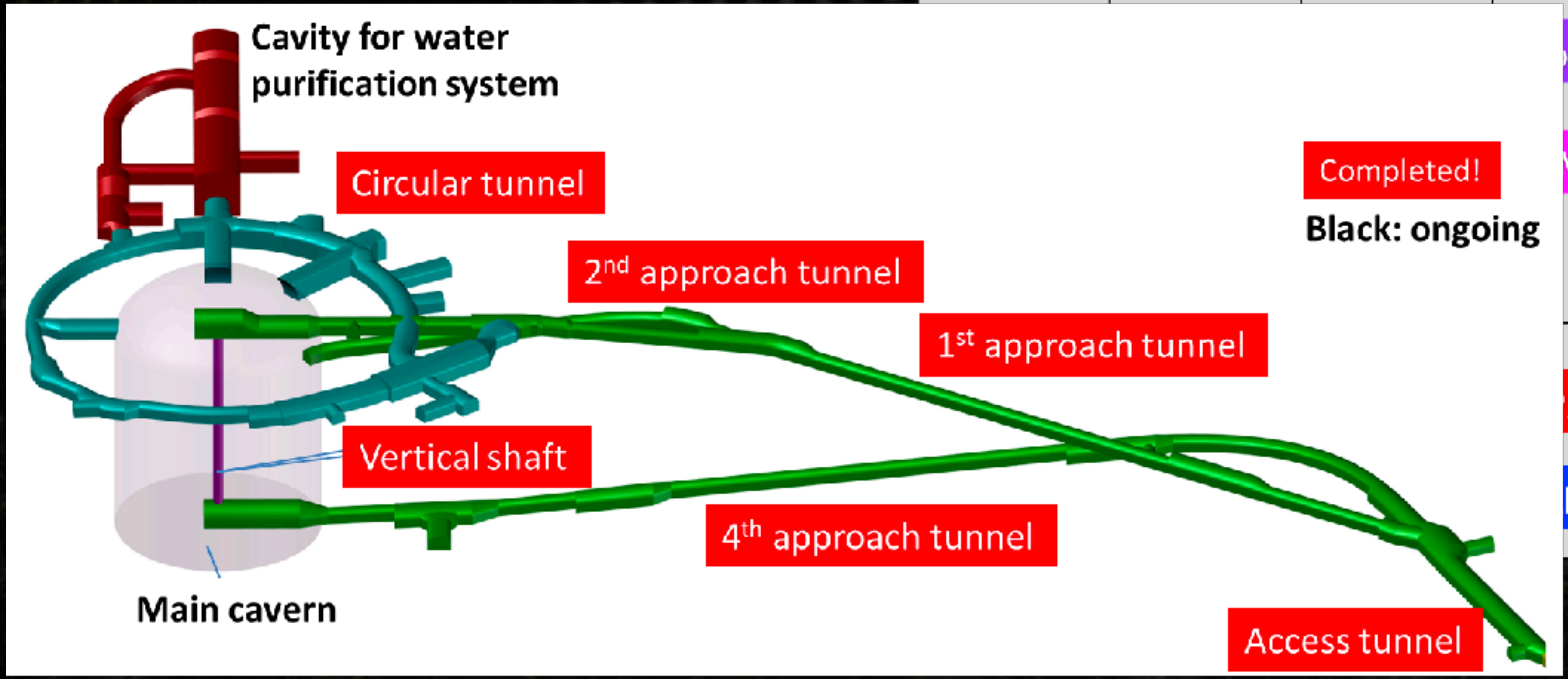
May 2021, Groundbreaking

Total of 3,772 PMTs (~20%) delivered by April 2022



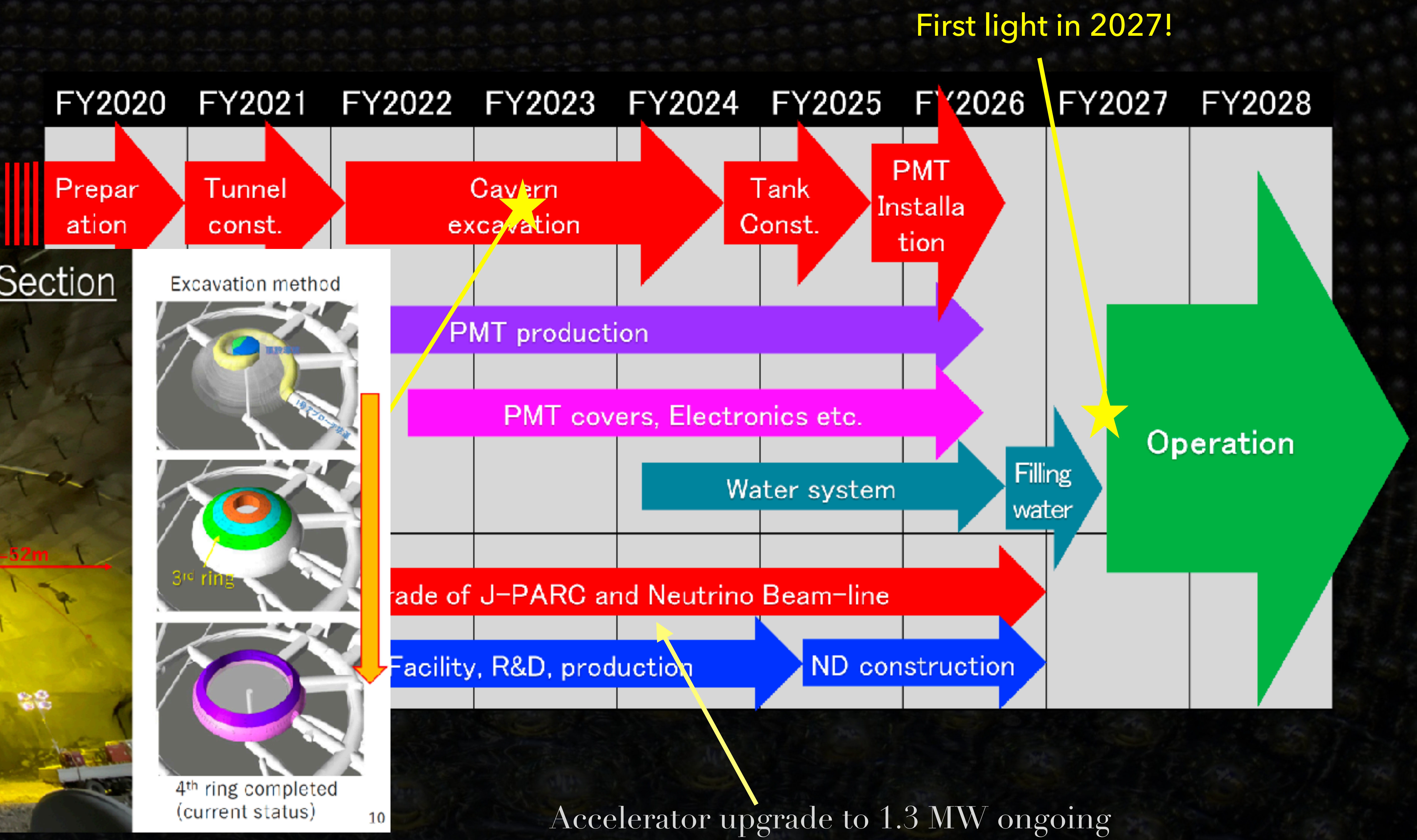
HYPER-K TIMELINE

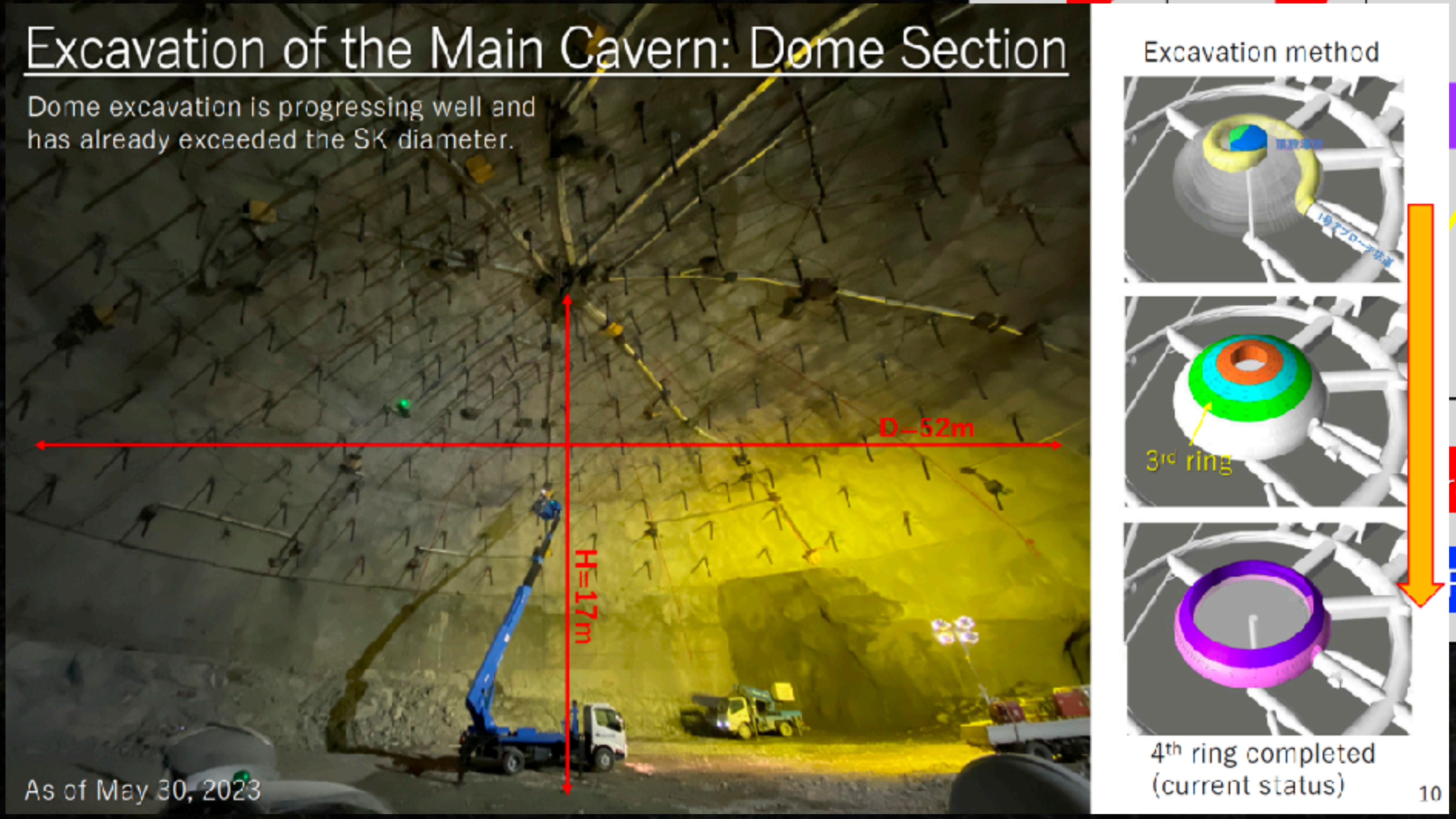




HYPER-K TIMELINE

- Good progress in cavern excavation and accelerator upgrade



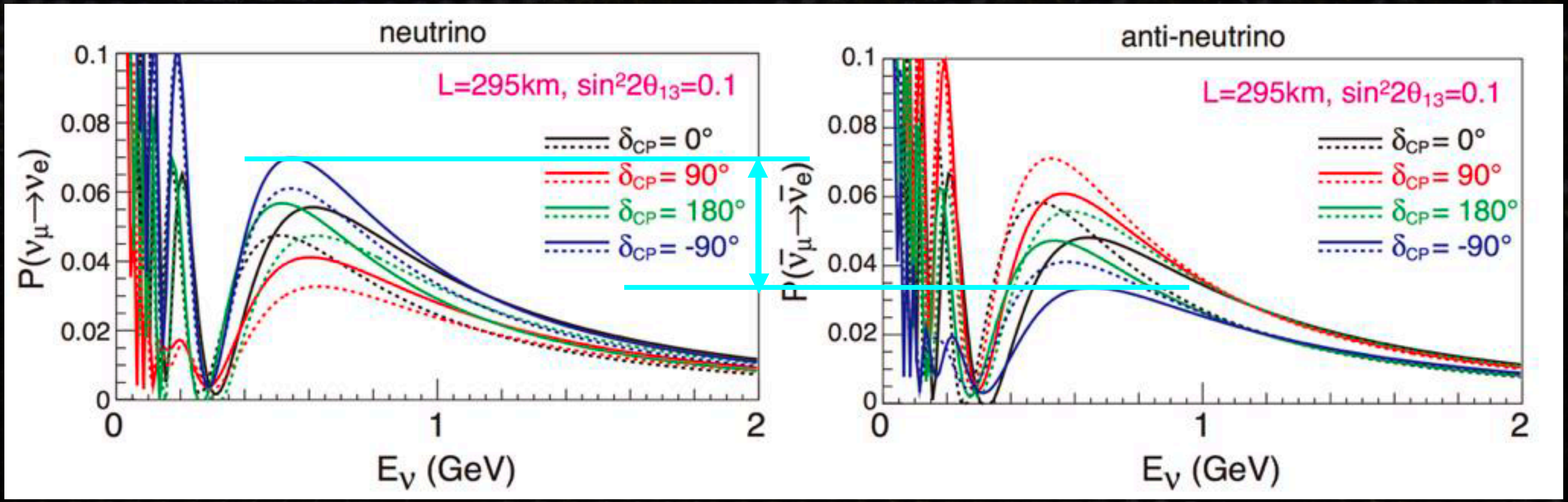


SUMMARY AND OUTLOOK

- Hyper-Kamiokande will provide an definitive answer to some of the remaining questions about neutrinos
  - Scheduled to come online in 2027
  - Discovery of CP-violation in the lepton sector for 60% of the possible phase space
- TRIUMF contributes to many critical components of Hyper-K
  - Leading role in WCTE and IWCD
  - multi-PMT development and production
  - Novel detector calibration systems

SENSITIVITY TO CP-VIOLATION AND MASS ORDERING

- CP-violation in the lepton sector if $\delta_{CP} \neq 0, \pm\pi$
  - $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - δ_{CP} can be probed by the comparison of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$



$$P(\nu_\mu \rightarrow \nu_e) \approx 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}\left(1+\frac{2a}{\Delta m_{31}^2}\left(1-2s_{13}^2\right)\right)$$

Leading term (including matter effect)

$$+8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$

CP-conserving

$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$

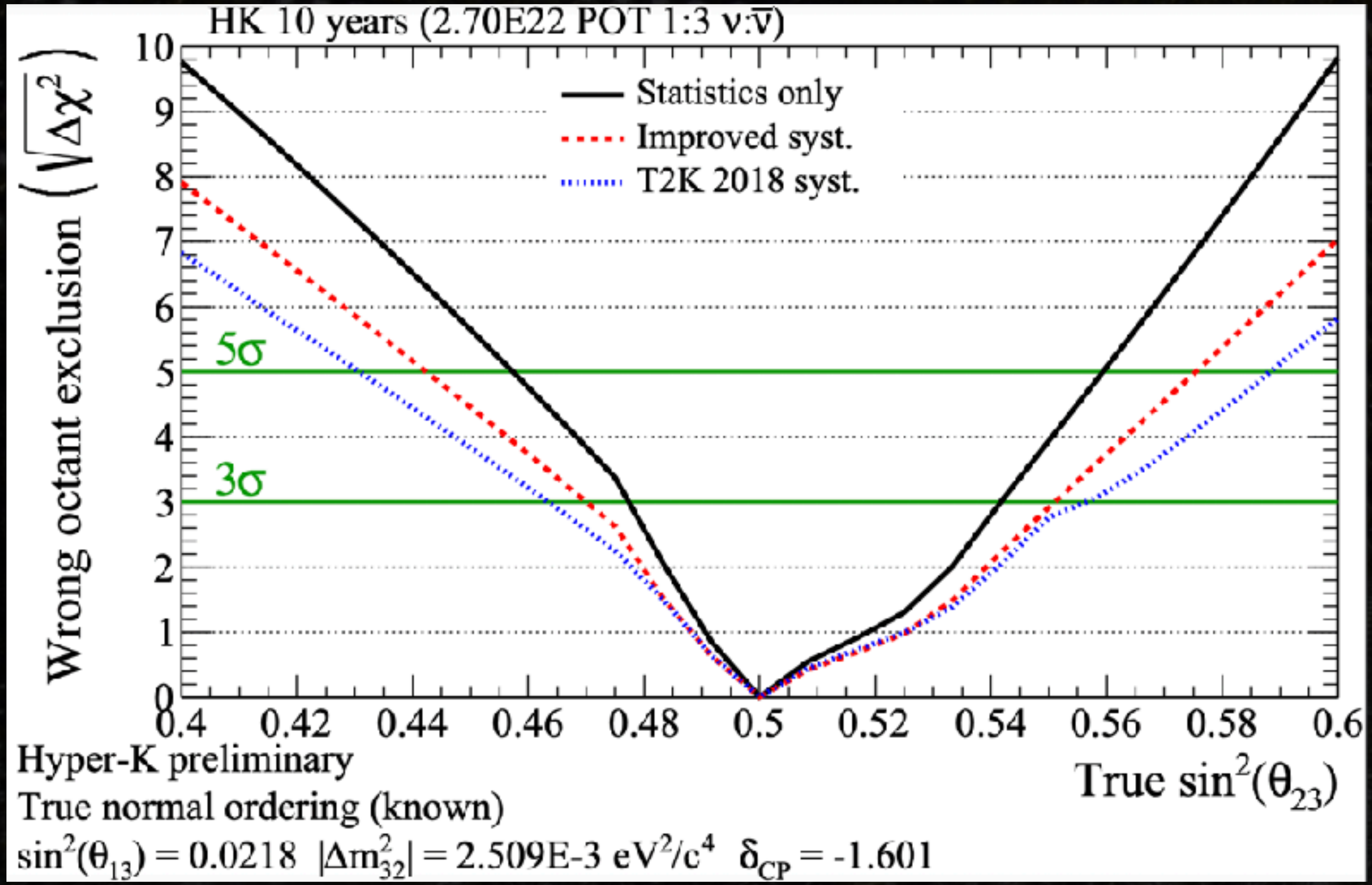
CP-violating

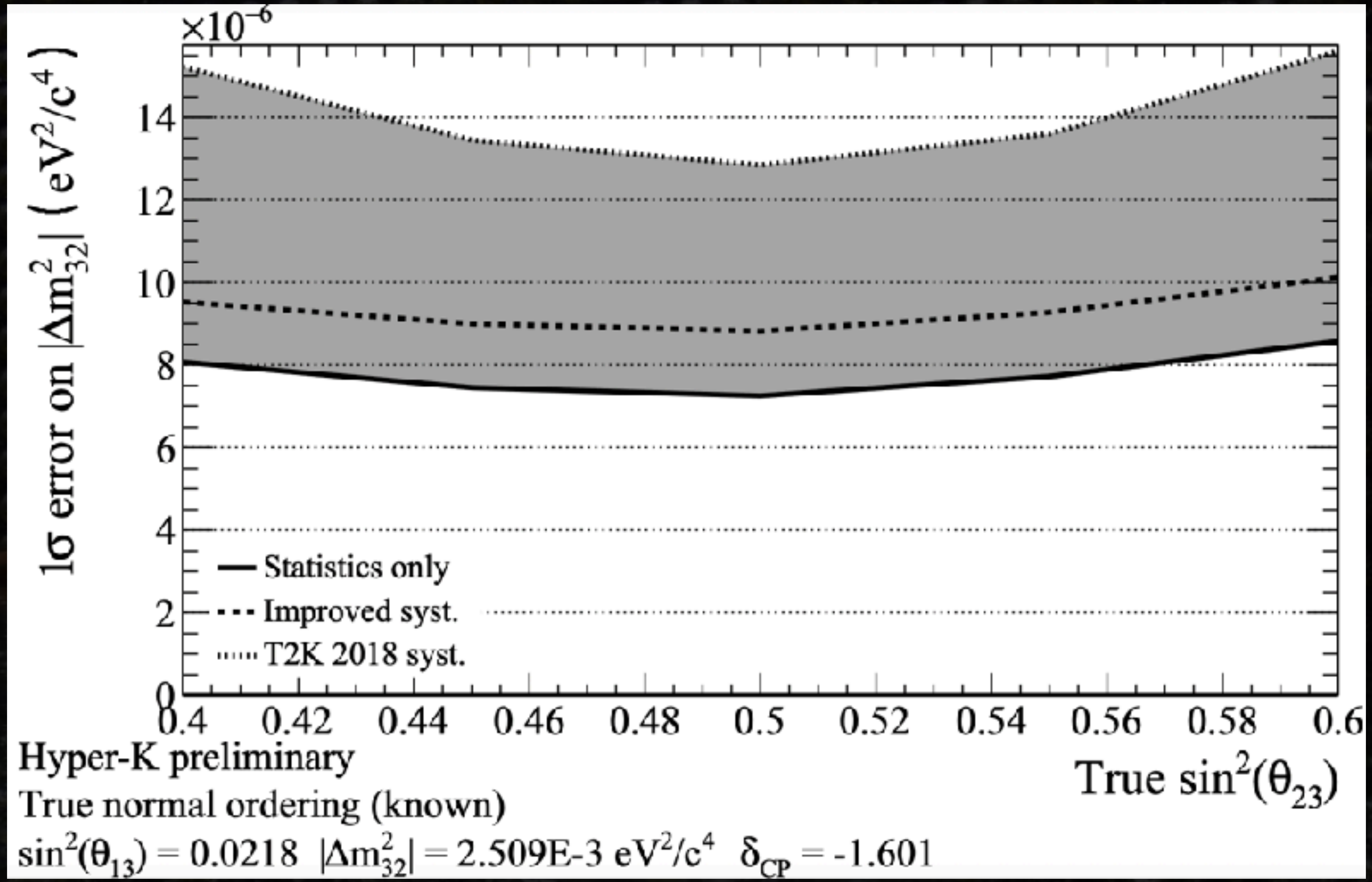
$$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$$

$$\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

$$a \equiv 2\sqrt{2}G_F n_e E = 7.56\times10^{-5}\,\mathrm{eV}^2 \frac{\rho}{\mathrm{gcm}^{-3}}\frac{E}{GeV}$$

HYPER-K Δm^2_{32} AND θ_{23} SENSITIVITY

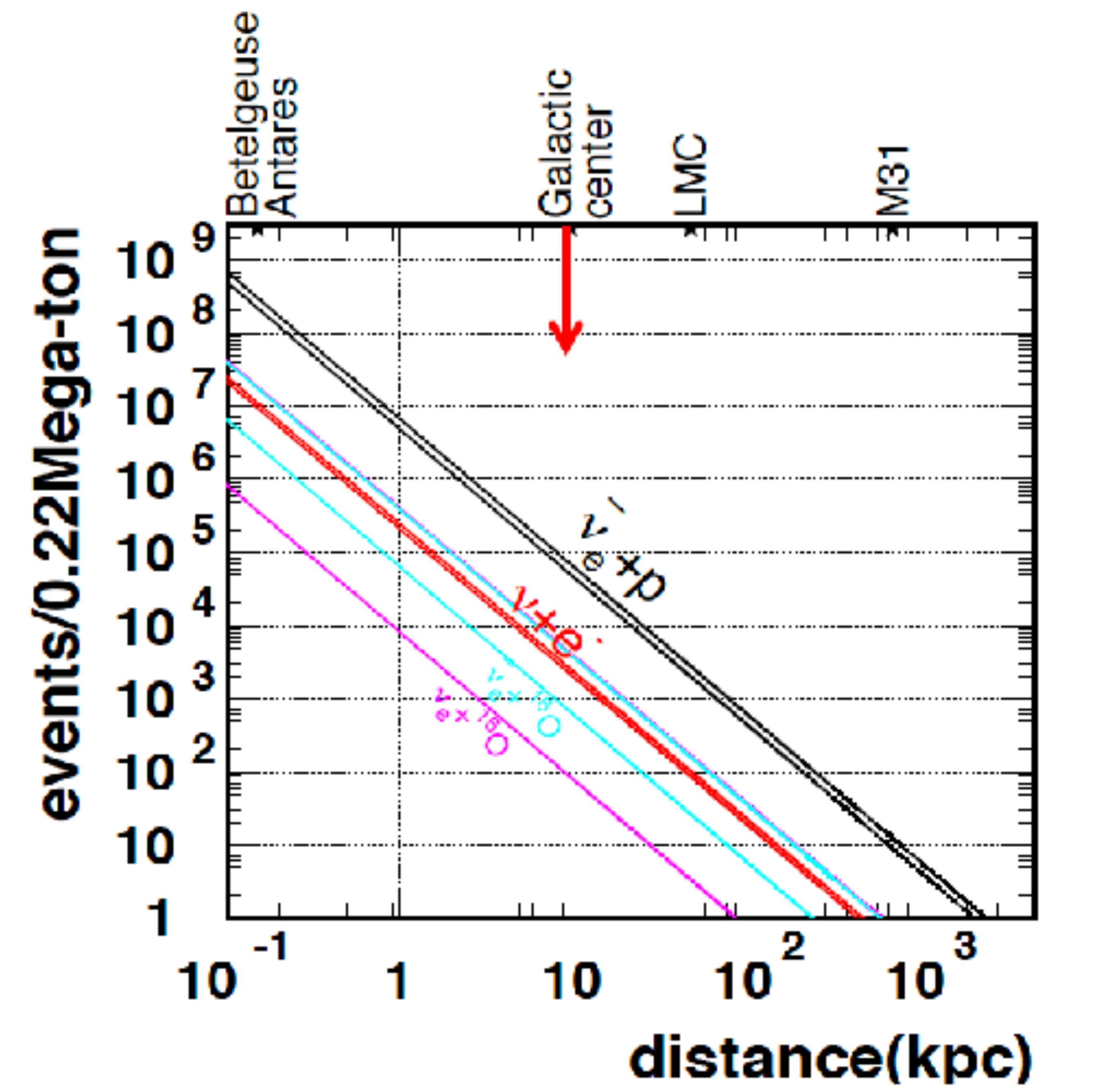


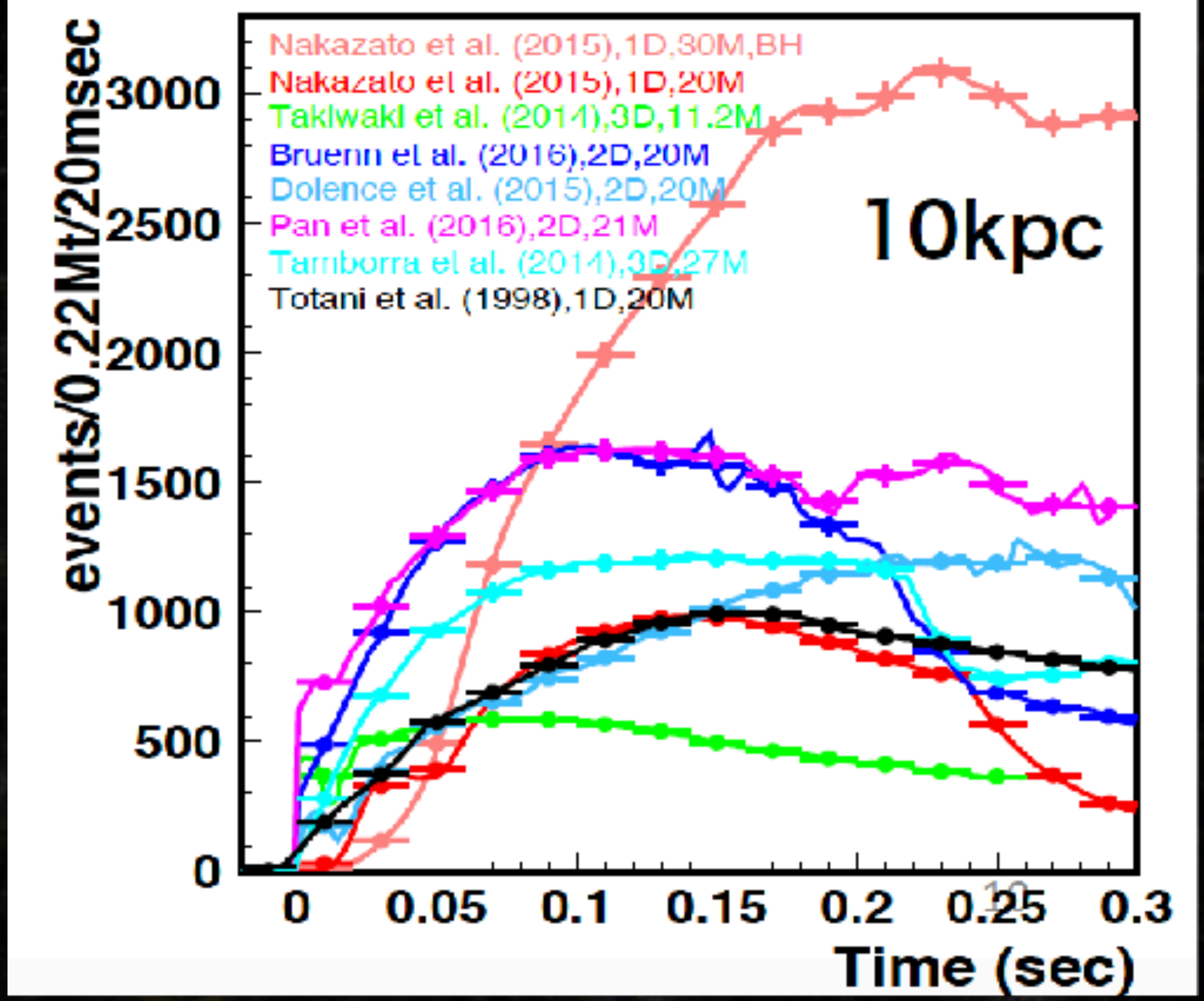


- Wrong octant can be excluded at 3σ, for true $\sin^2\theta_{23} < 0.47$ and $\sin^2\theta_{23} > 0.55$
- 1σ resolution of Δm^2_{32} as a function of true $\sin^2\theta_{23}$

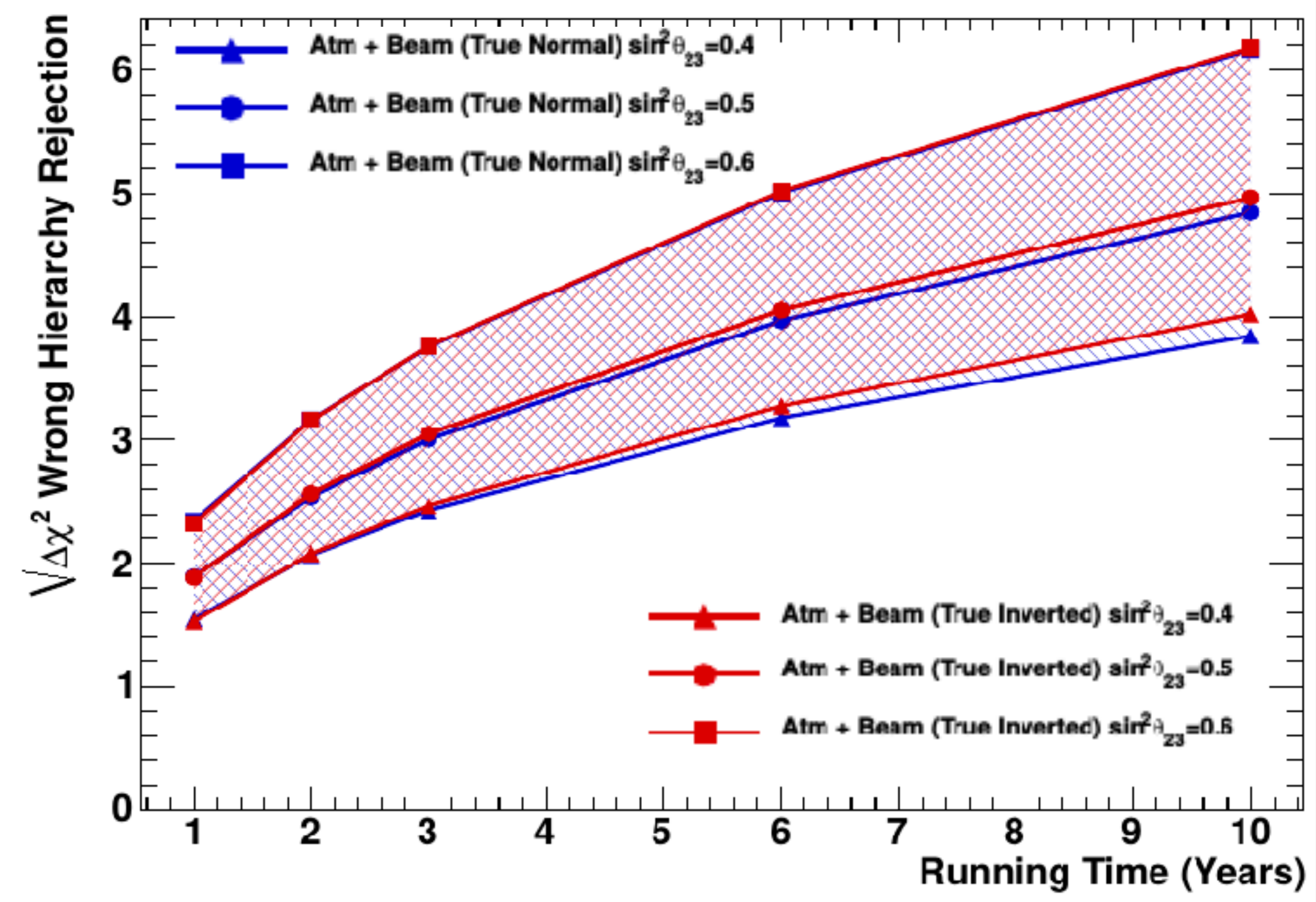
HYPER-K PHYSICS GOALS

- Atmospheric neutrinos improve sensitivity to mass ordering
- $>4\sigma$ discovery potential for diffuse supernova neutrinos
- Supernova burst detectable up to 1 Mpc; 50k ~ 80k events from a SN at 10 kpc
  - Measure SN neutrino time profile and energy spectrum → SN modeling
- Resolve solar neutrino and KamLAND tension to $>4\sigma$
- Further improve proton decay limits

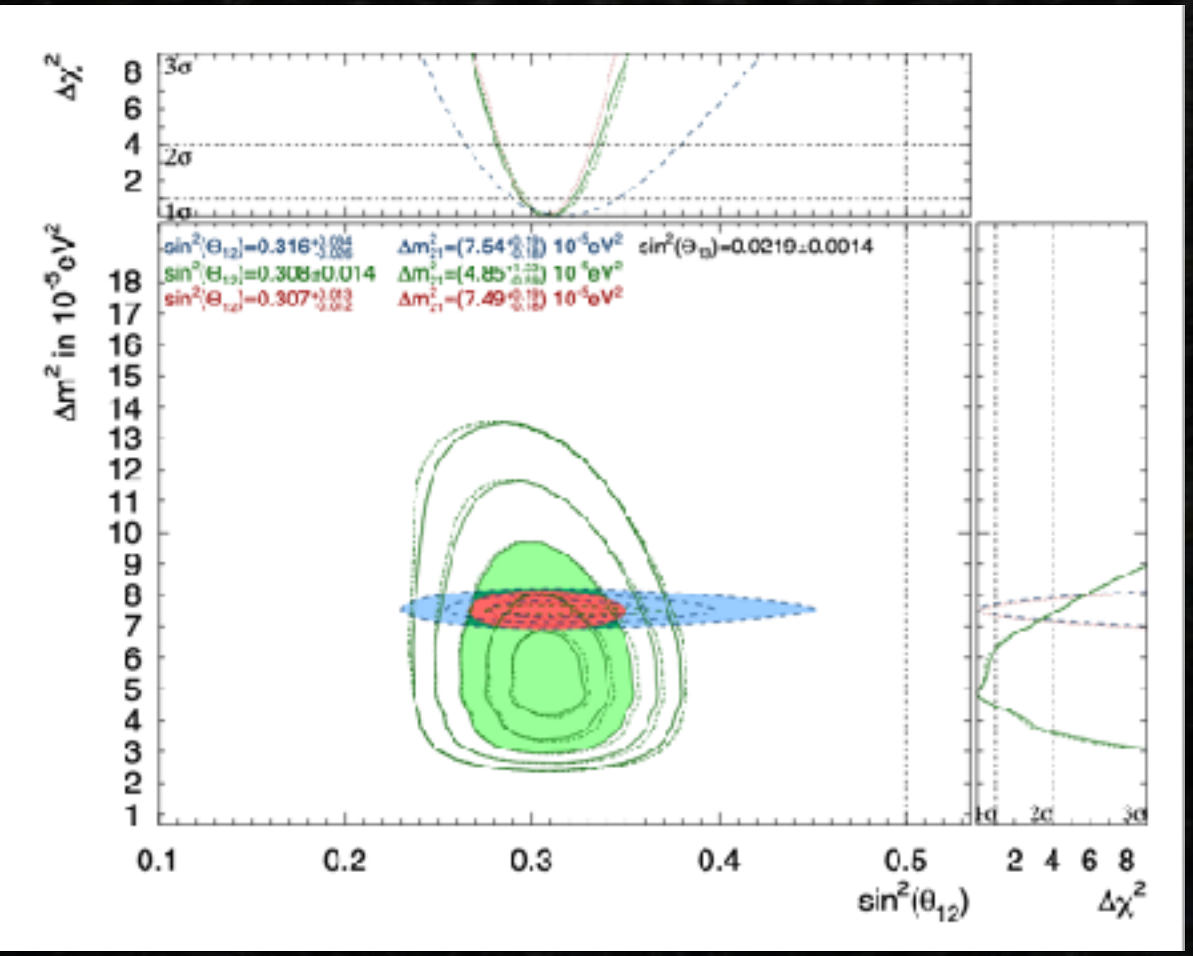




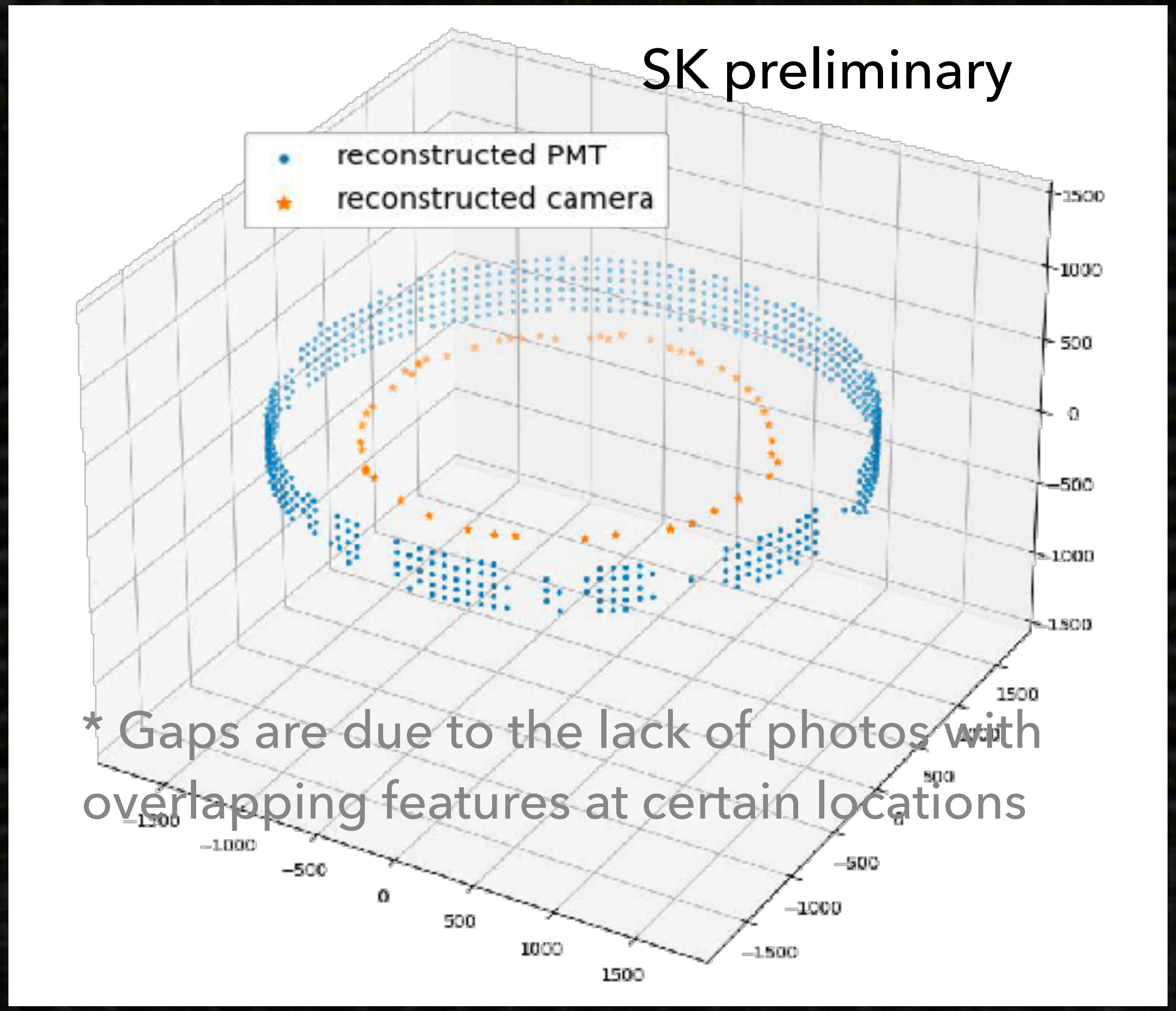
HK atmospheric + beam sensitivity to mass ordering



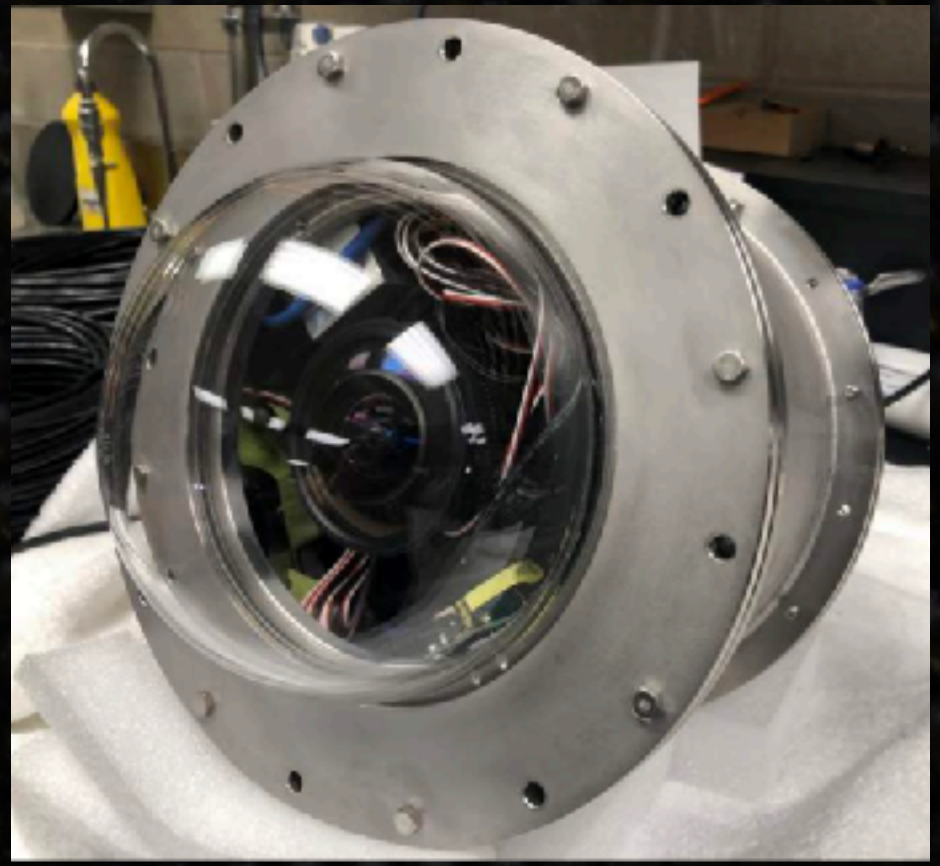
Δm^2_{21} tension

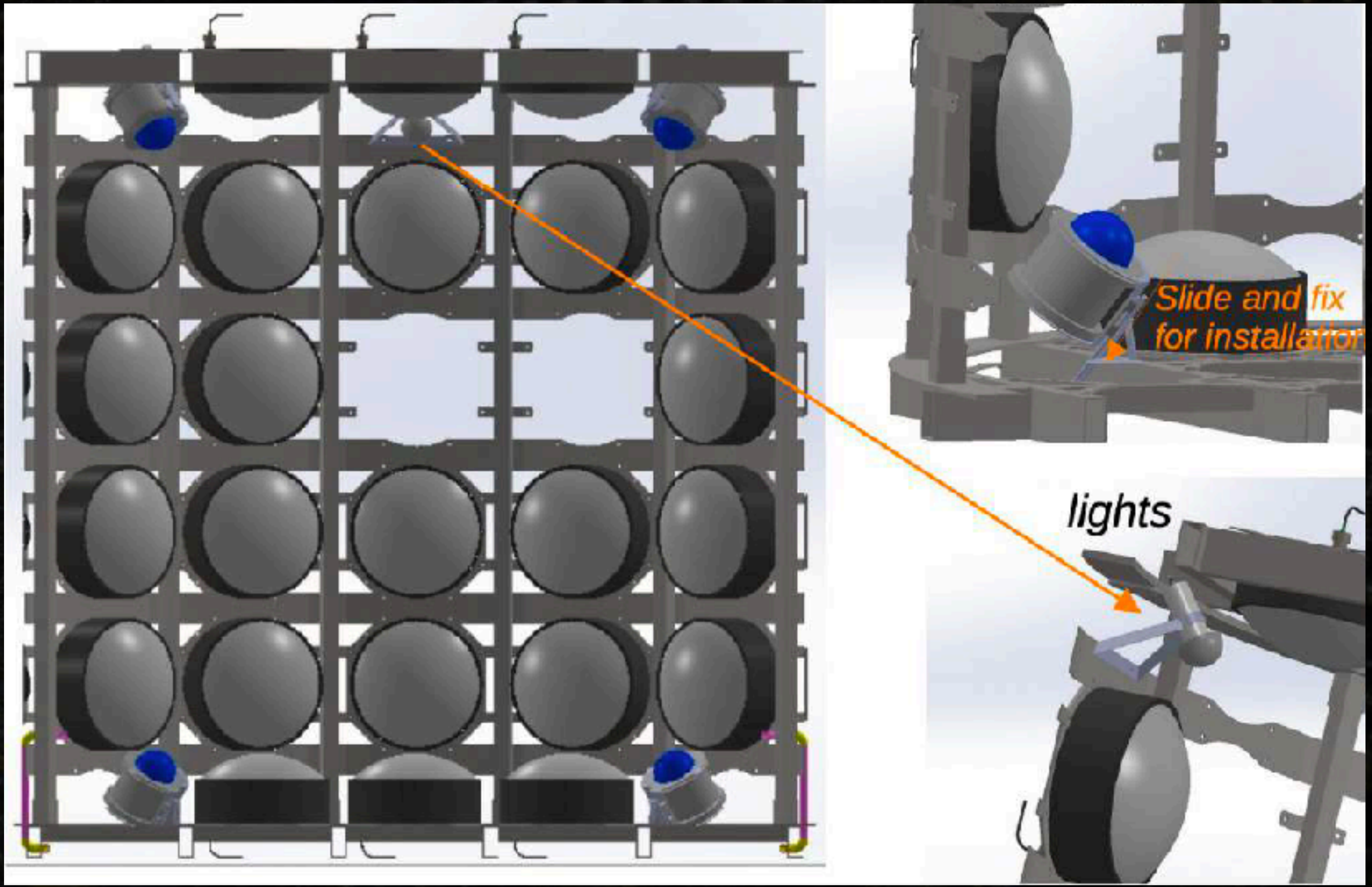


PHOTOGRAMMETRY GEOMETRY CALIBRATION



First assembled camera module @UWinnipeg

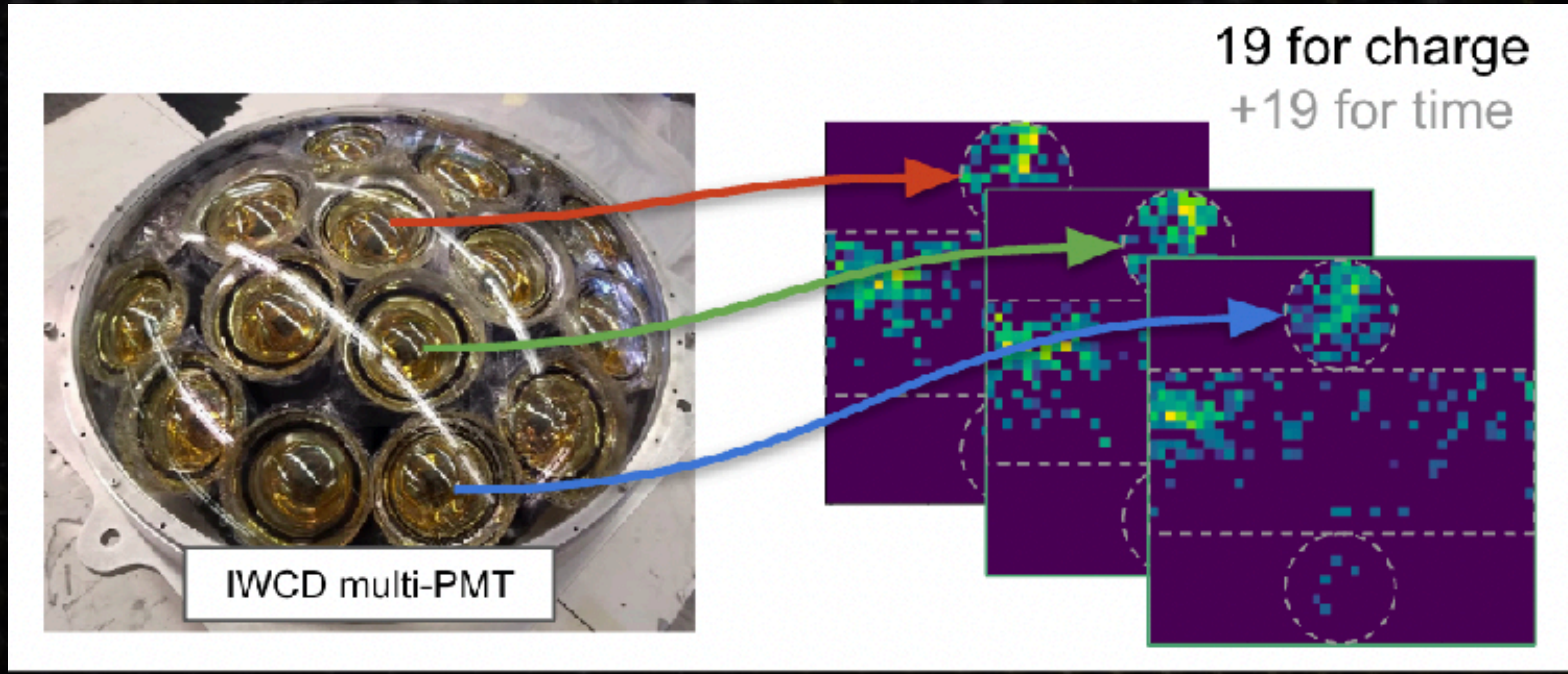




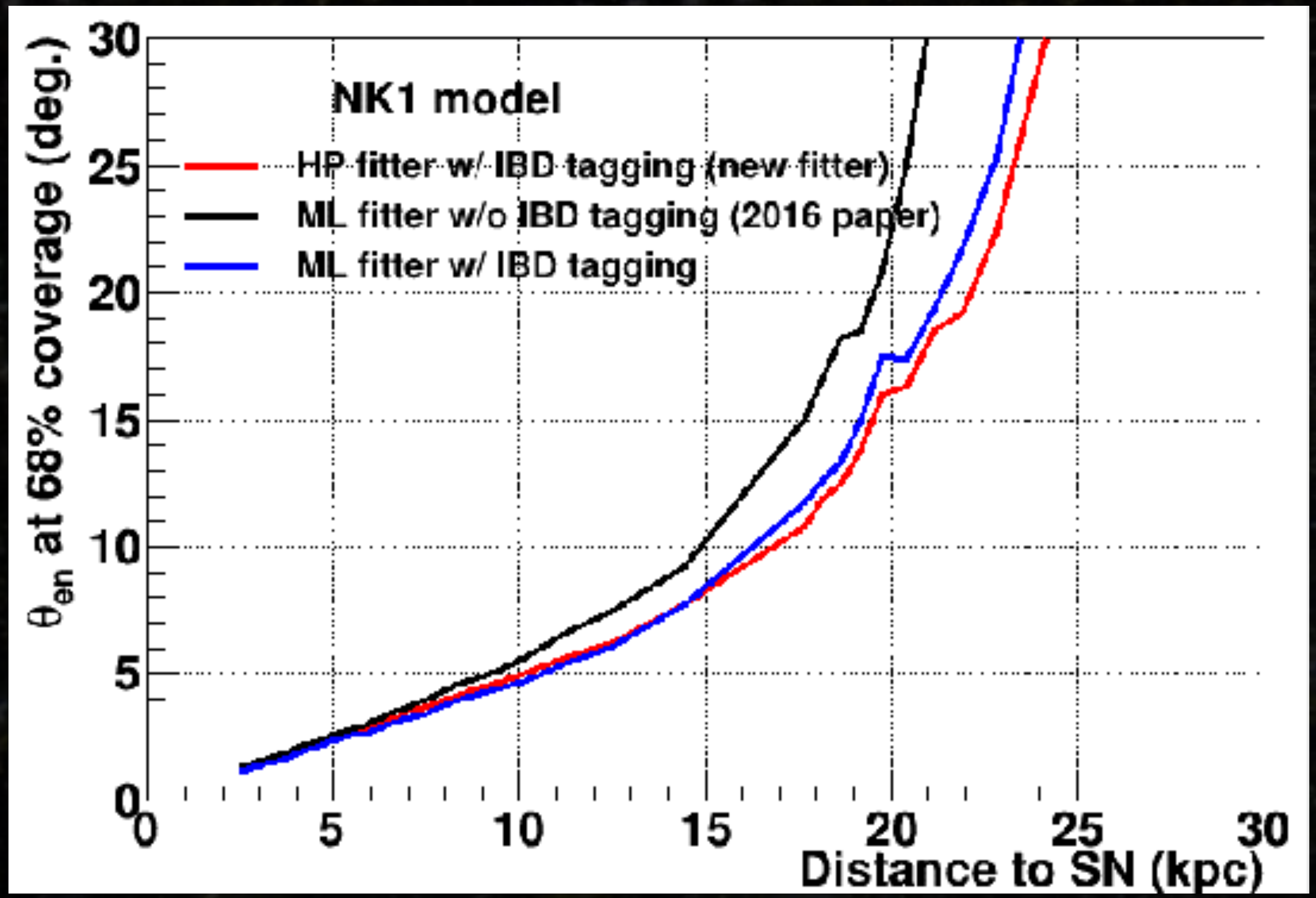
- Use photogrammetry to measure the position of PMTs and calibration sources in-situ
  - The first survey was done in SK using underwater ROV
  - WCTE will utilize fixed cameras; IWCD and Hyper-K will utilize both ROV and fix cameras
  - Reduce fiducial volume error

MACHINE LEARNING EVENT RECONSTRUCTION

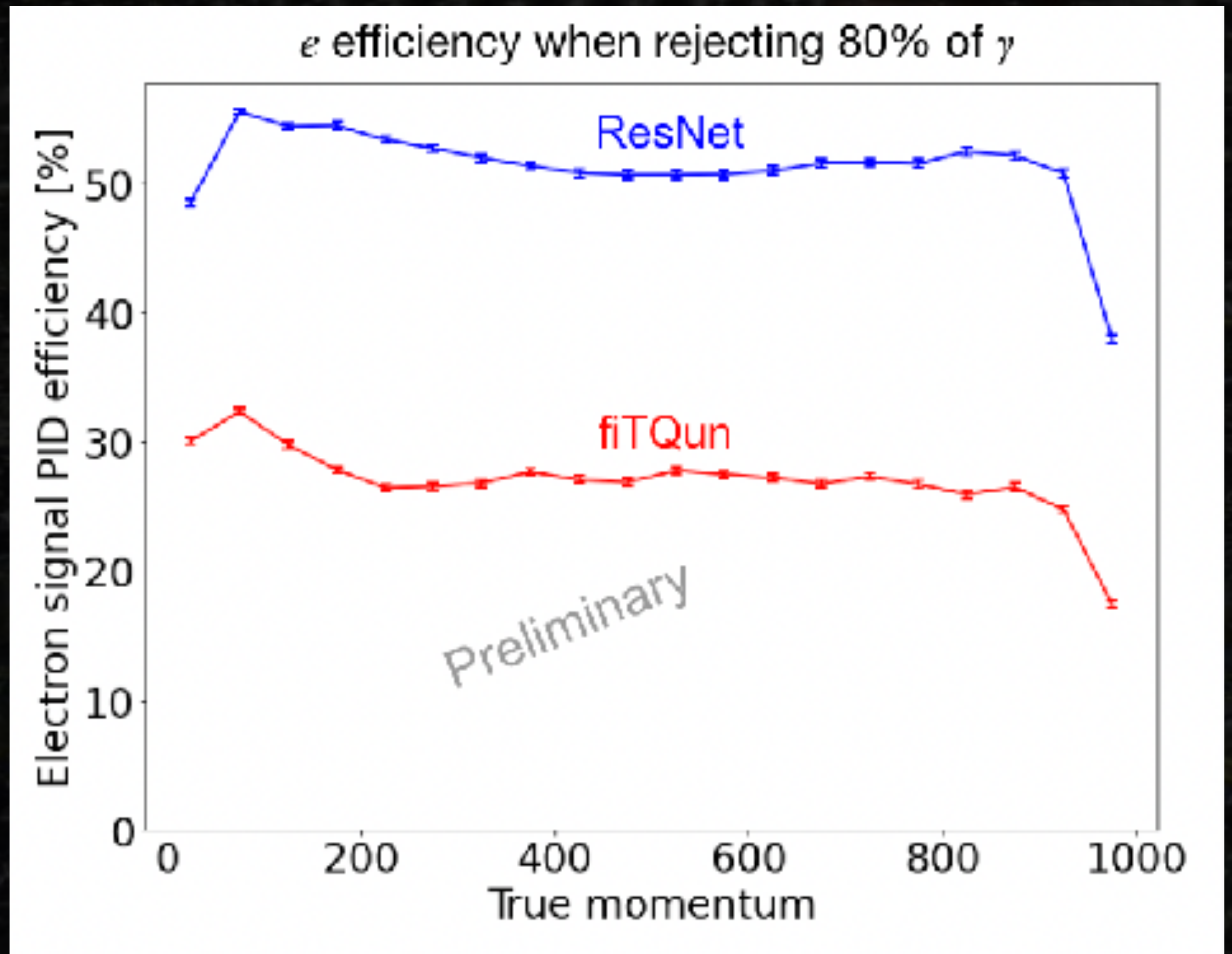
- Machine learning techniques have been applied to event reconstruction in IWCD and Hyper-K
  - Encouraging improvements from traditional method
- Improve supernova direction finding

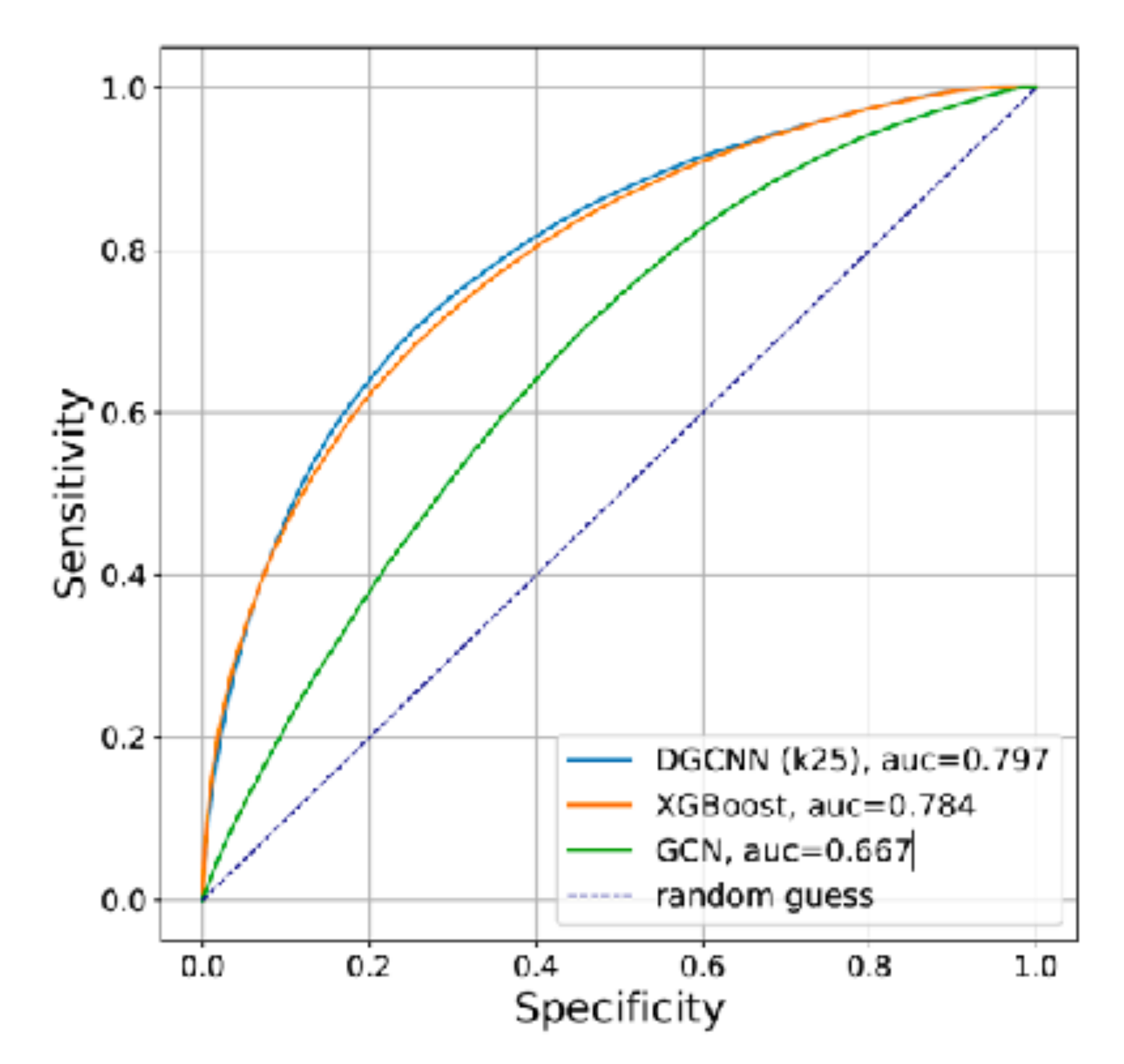


SN direction in Super-K



e/γ separation in IWCD

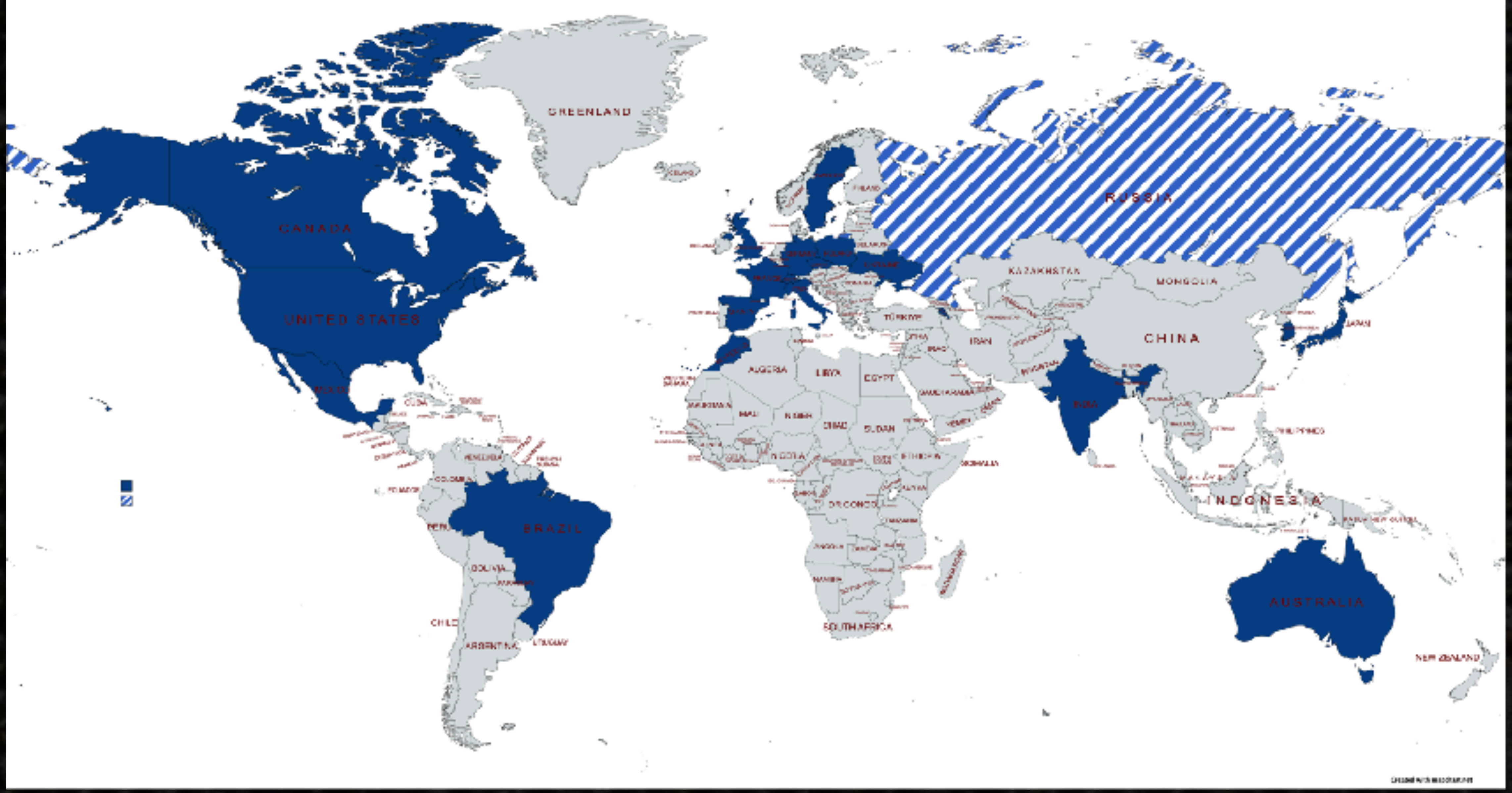


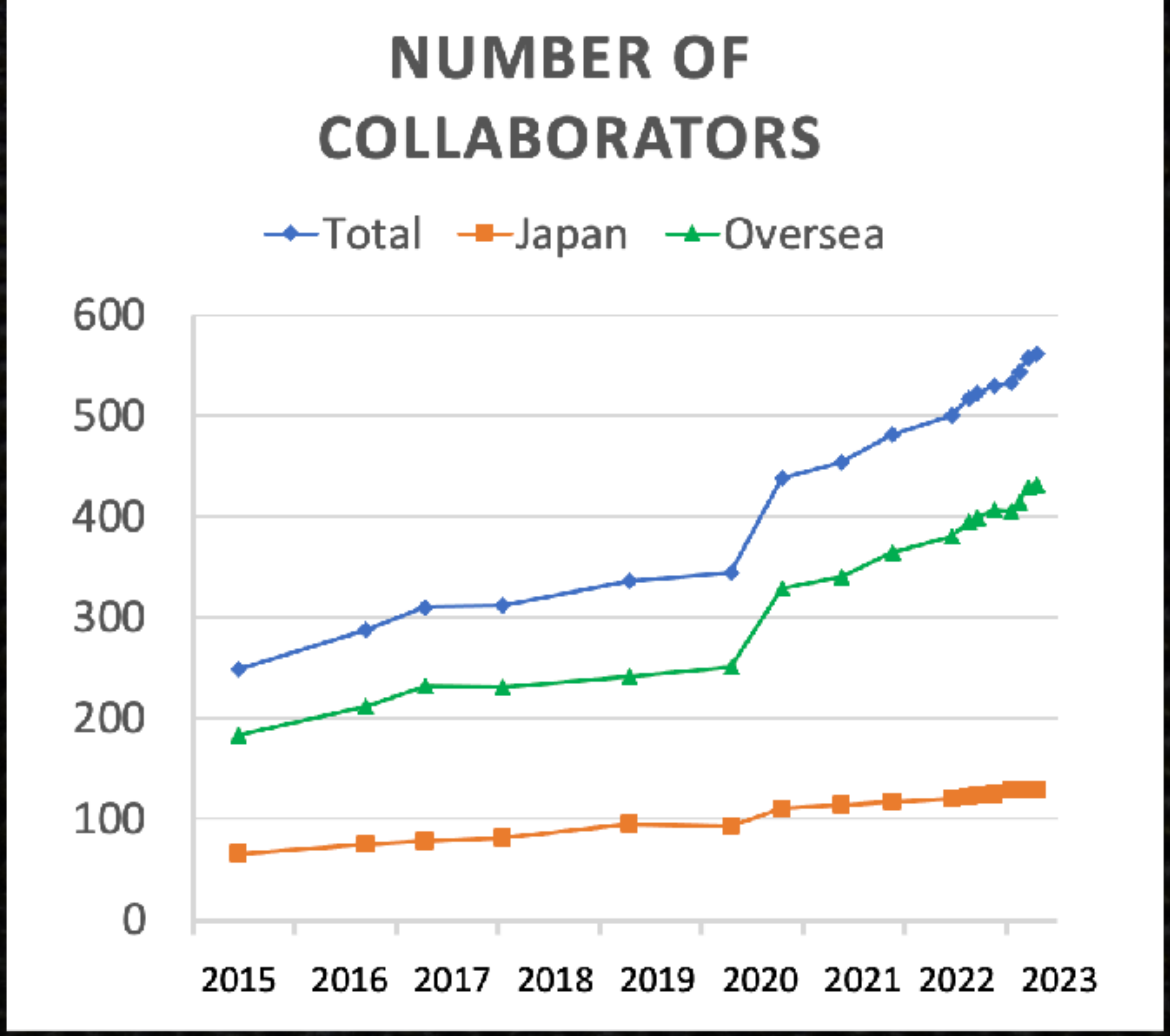


Neutron tagging

"Using Machine Learning to Improve Neutron Identification in Water Cherenkov Detectors", Front. Big Data, 30 September 2022 (https://doi.org/10.3389/fdata.2022.978857)

HYPER-K COLLABORATION





- ~560 collaborators from 21 countries and 101 institutes
- 25% Japanese/75% non-Japanese
- Two Host institutes: University of Tokyo and KEK
- Hyper-Kamiokande has become a CERN Recognized Experiment: RE45