HYPER-KAMIOKANDE

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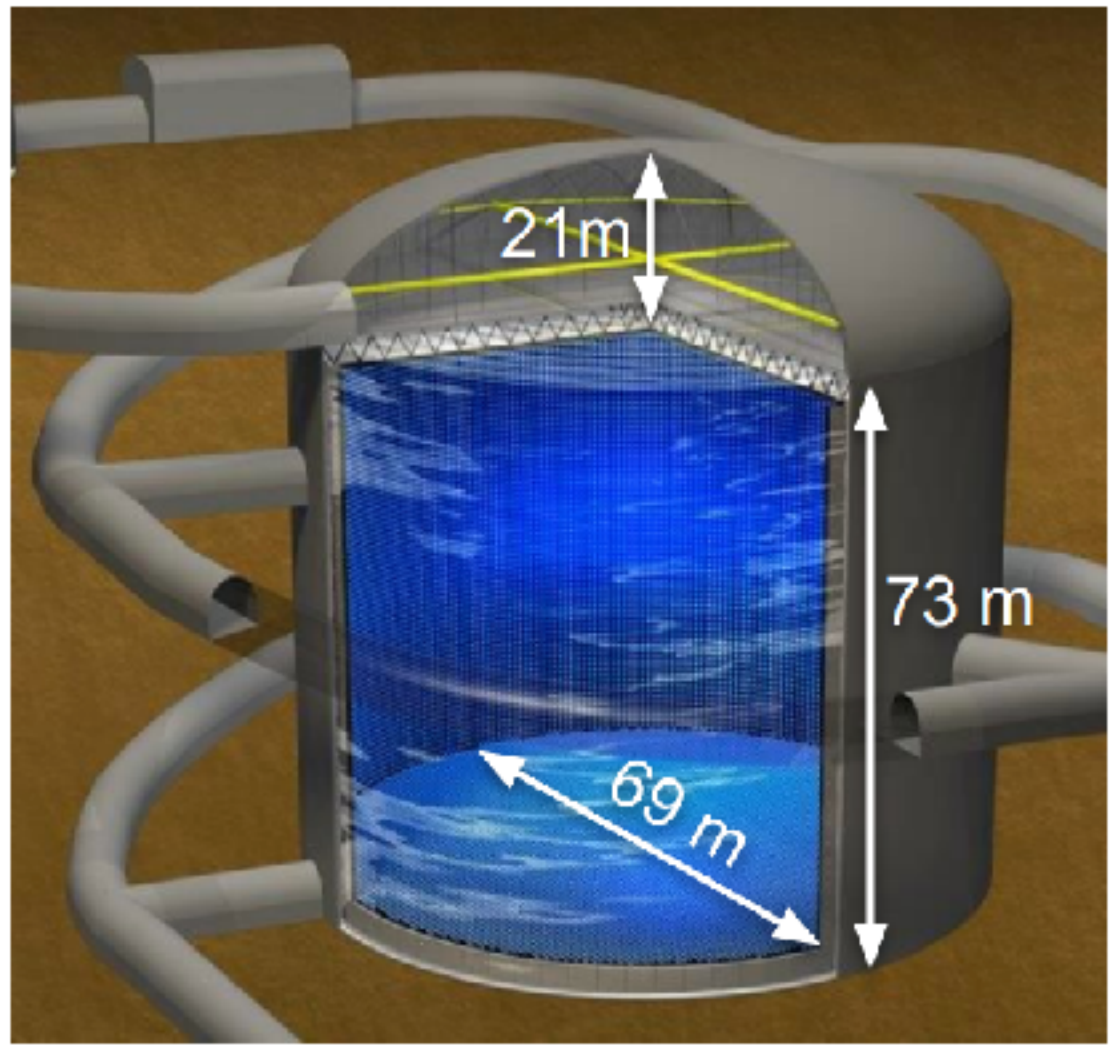
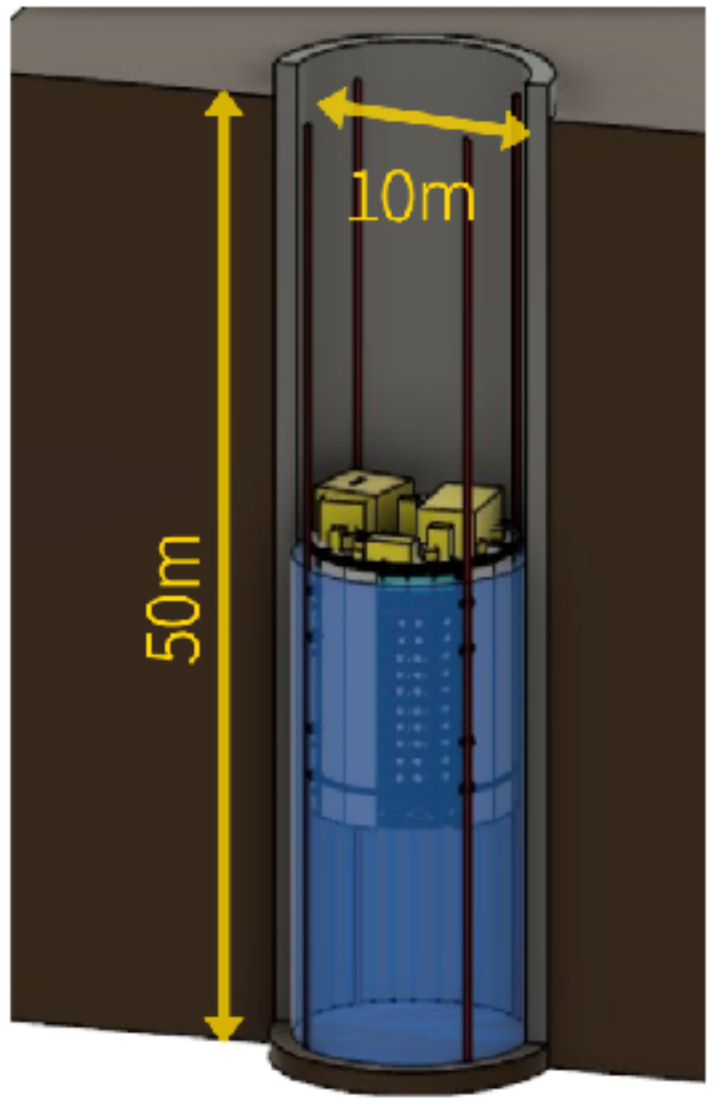
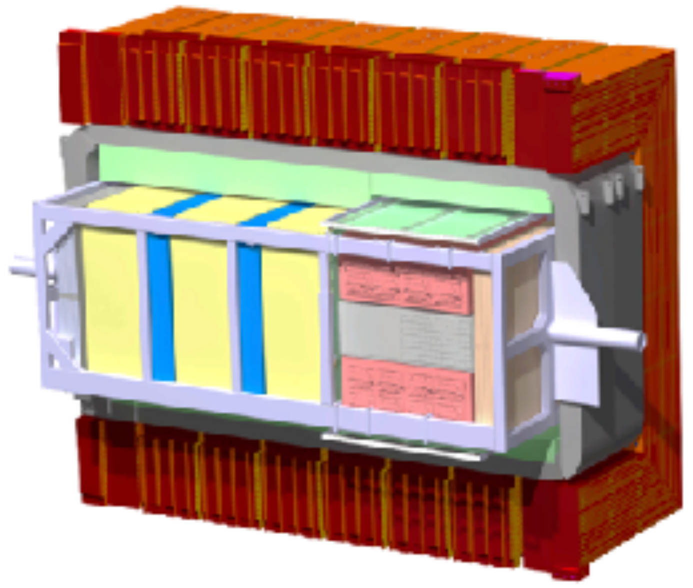
HYPER-KAMIOKANDE OVERVIEW

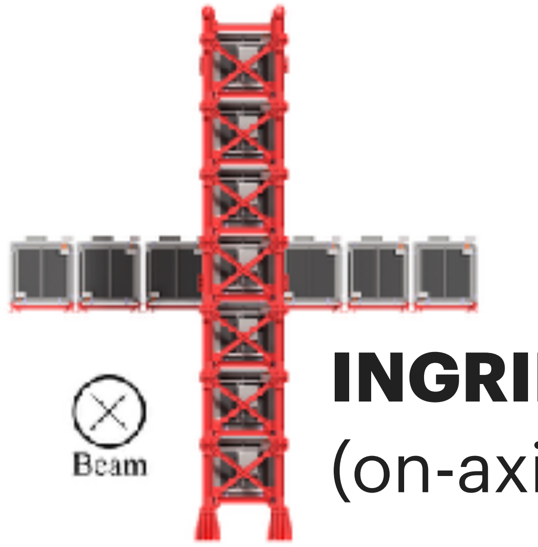


Intermediate Water Cherenkov Detector (IWCD)
850 m from target
(1.5º-4º off-axis)

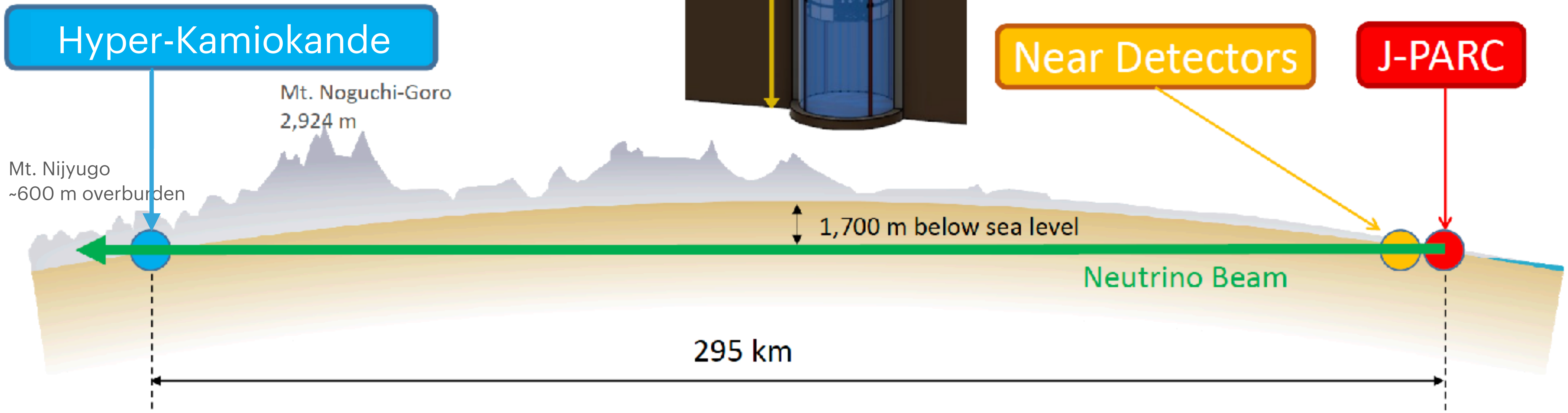


ND280 (2.5º off-axis)

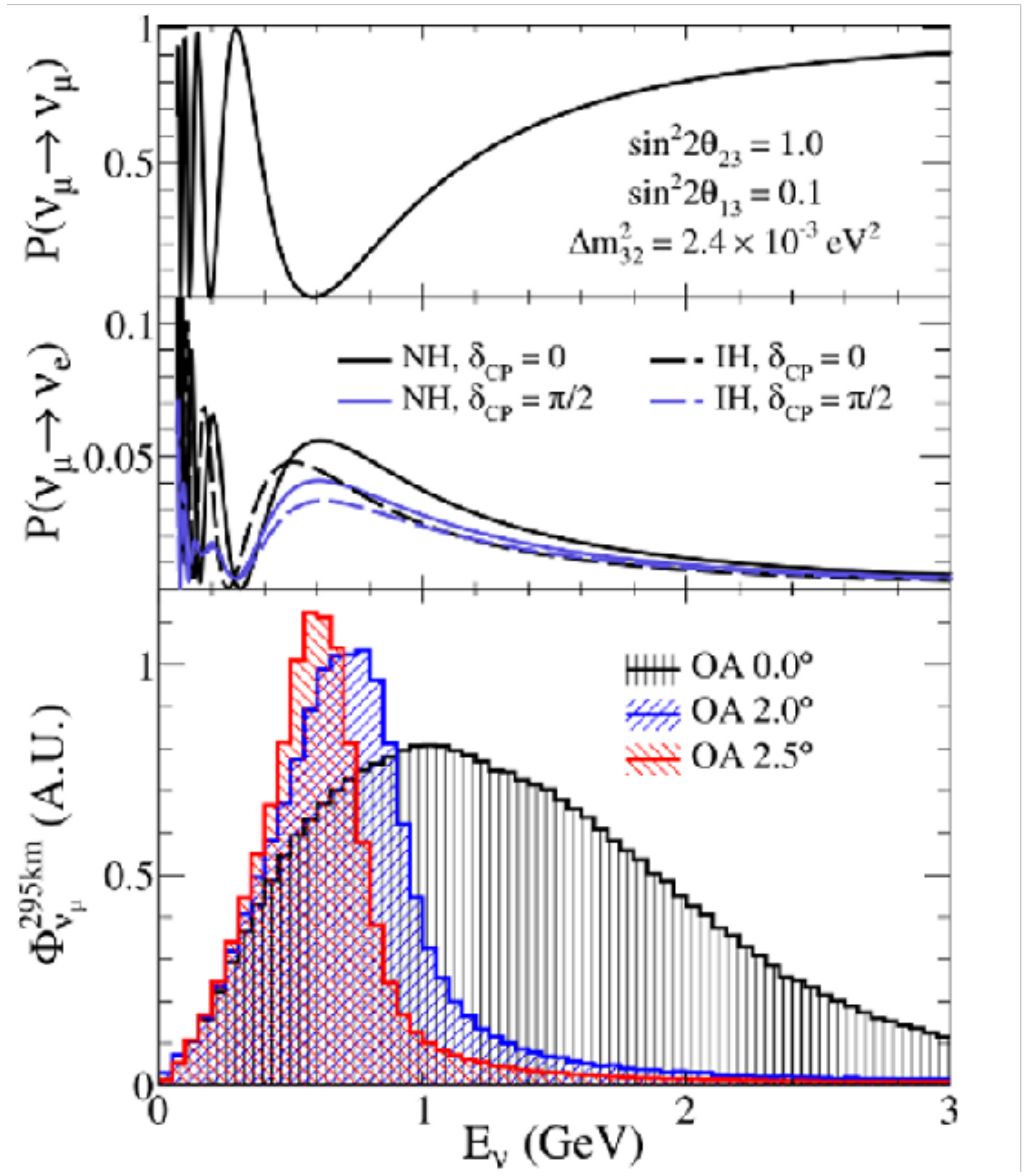




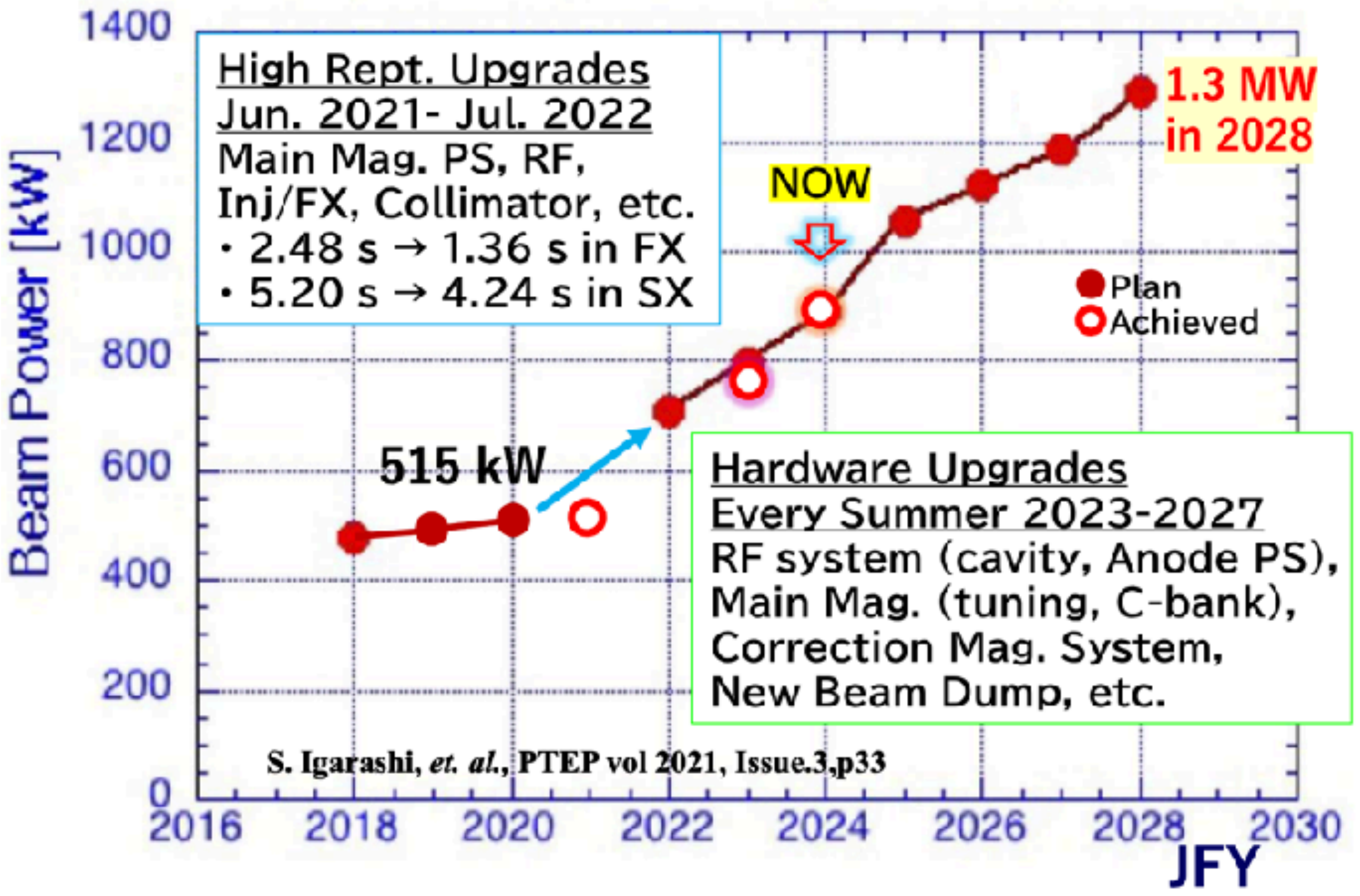
INGRID
(on-axis)



HYPER-K NEUTRINO BEAM



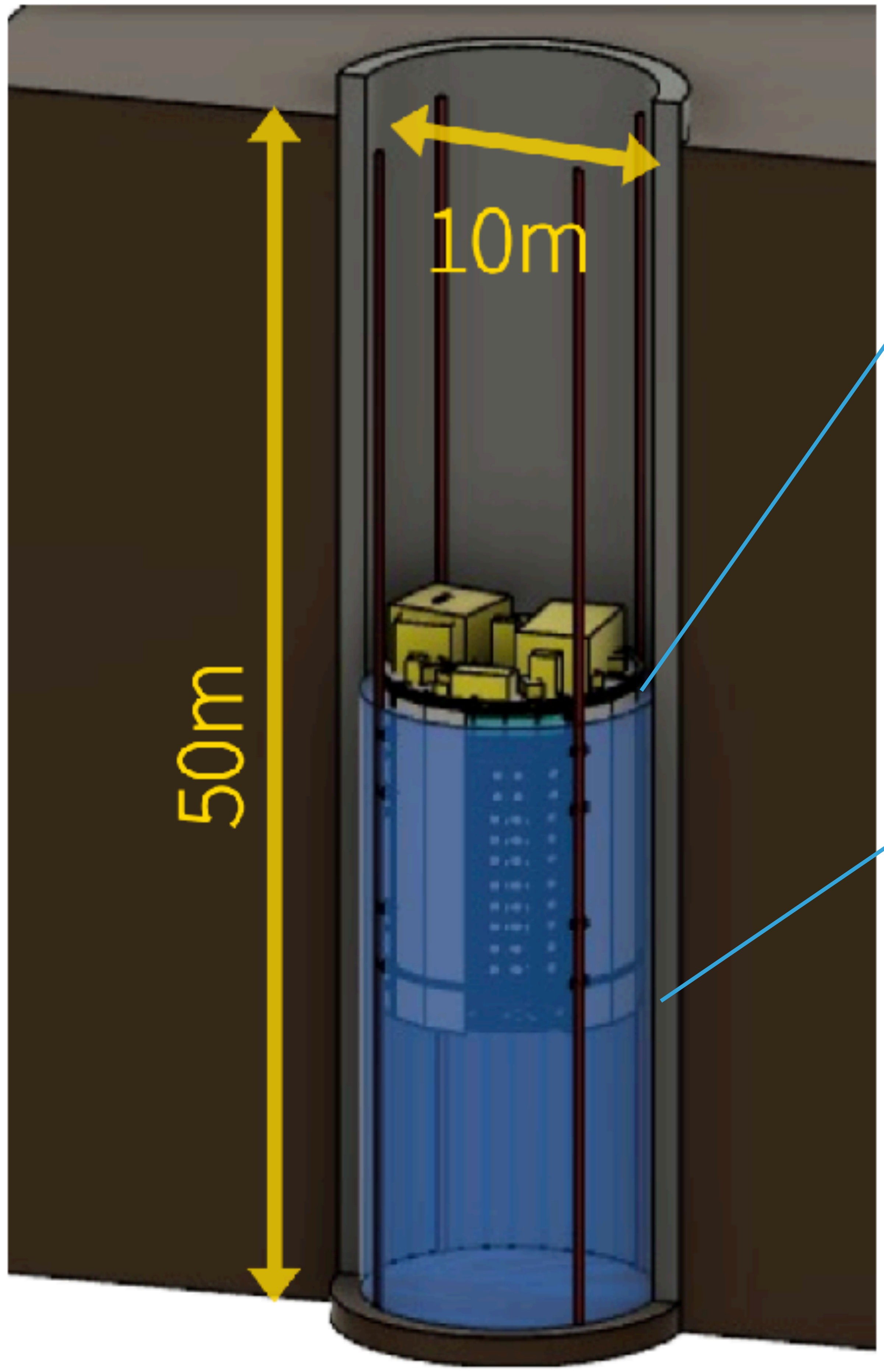
- Off-axis beam at 2.5º
- 30 GeV proton beam will be upgraded to 1.3 MW for Hyper-K operation
  - Upgrade to reduce the time between beam spills from 1 spill every 2.48s → 1.36s → 1.28s → 1.16s
  - Improve stability to increase the number of protons per spill
- Expected to collect 2.7×10^{21} POT per year

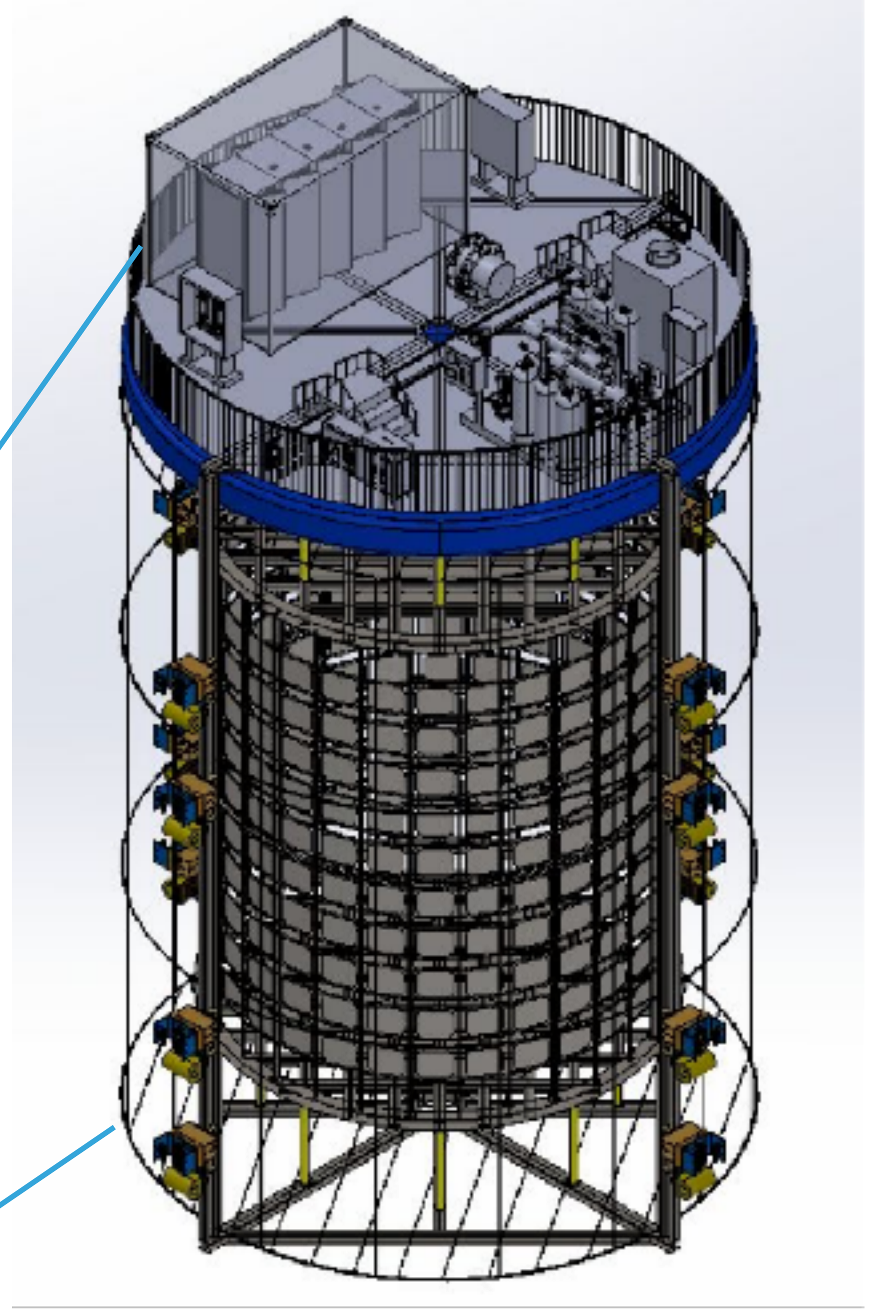


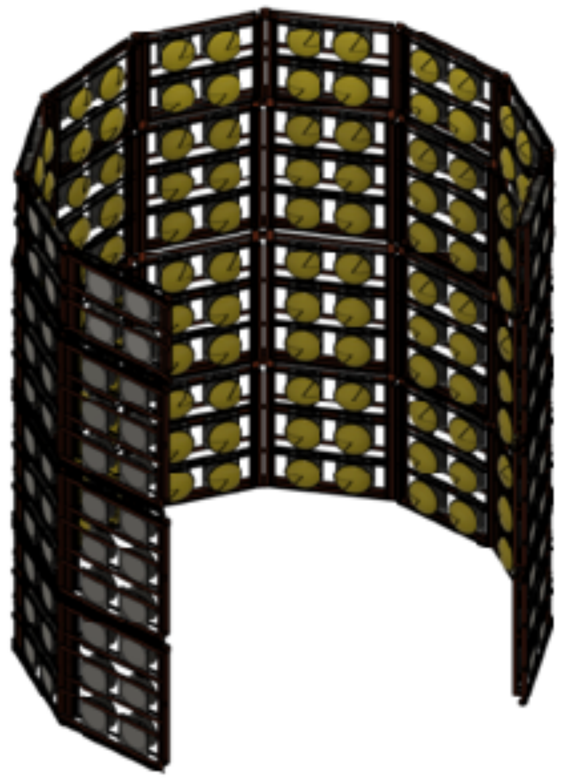
- Target for 1.3 MW developed and ready for installation at J-PARC in summer 2026
- Upgrades are needed for 1.3 MW operation, such as
  - Increase cooling capacity
  - Improving maintainability under radioactive environment

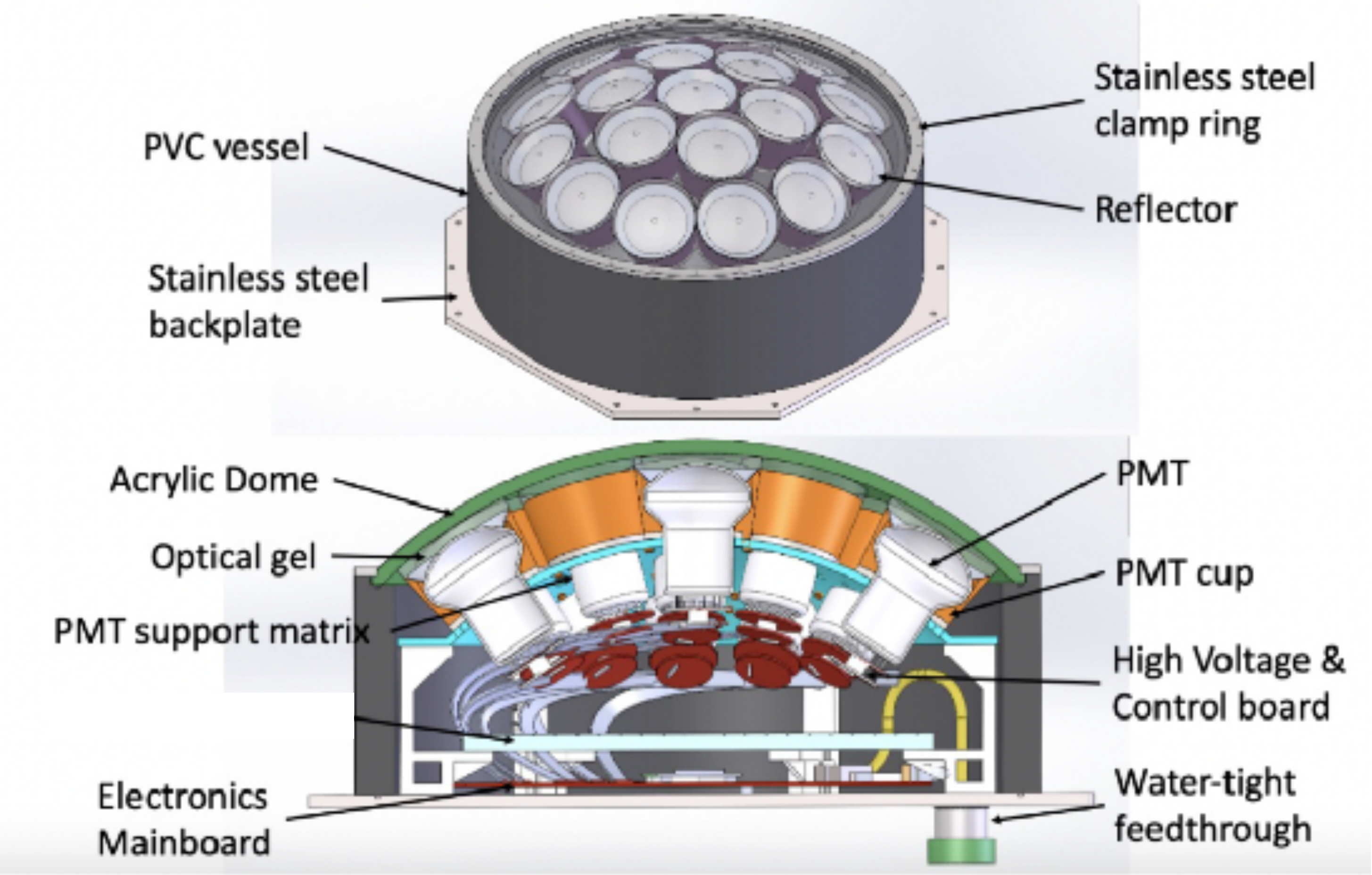
Upgrade technical design report

INTERMEDIATE WATER CHERENKOV DETECTOR (IWCD)



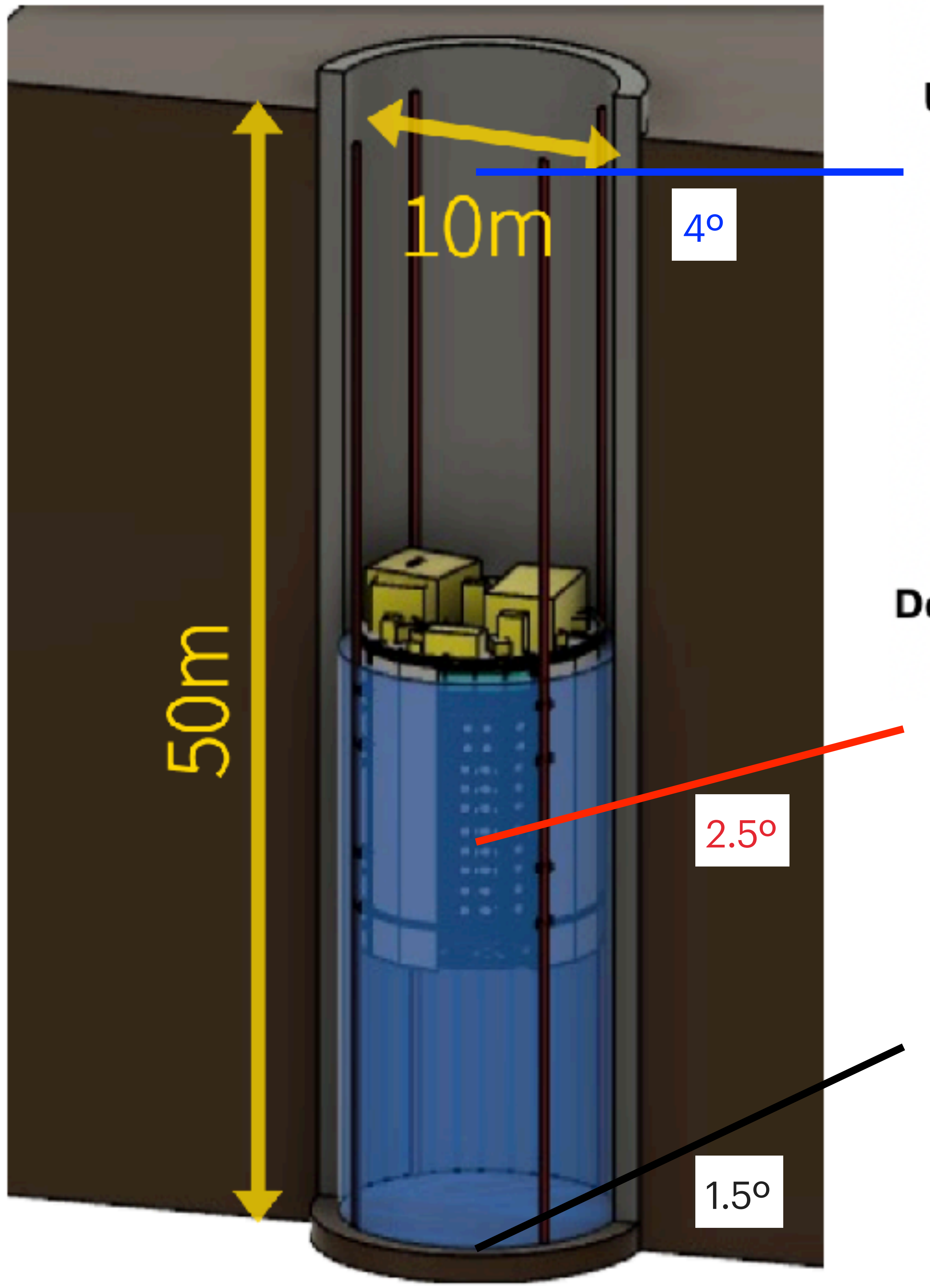


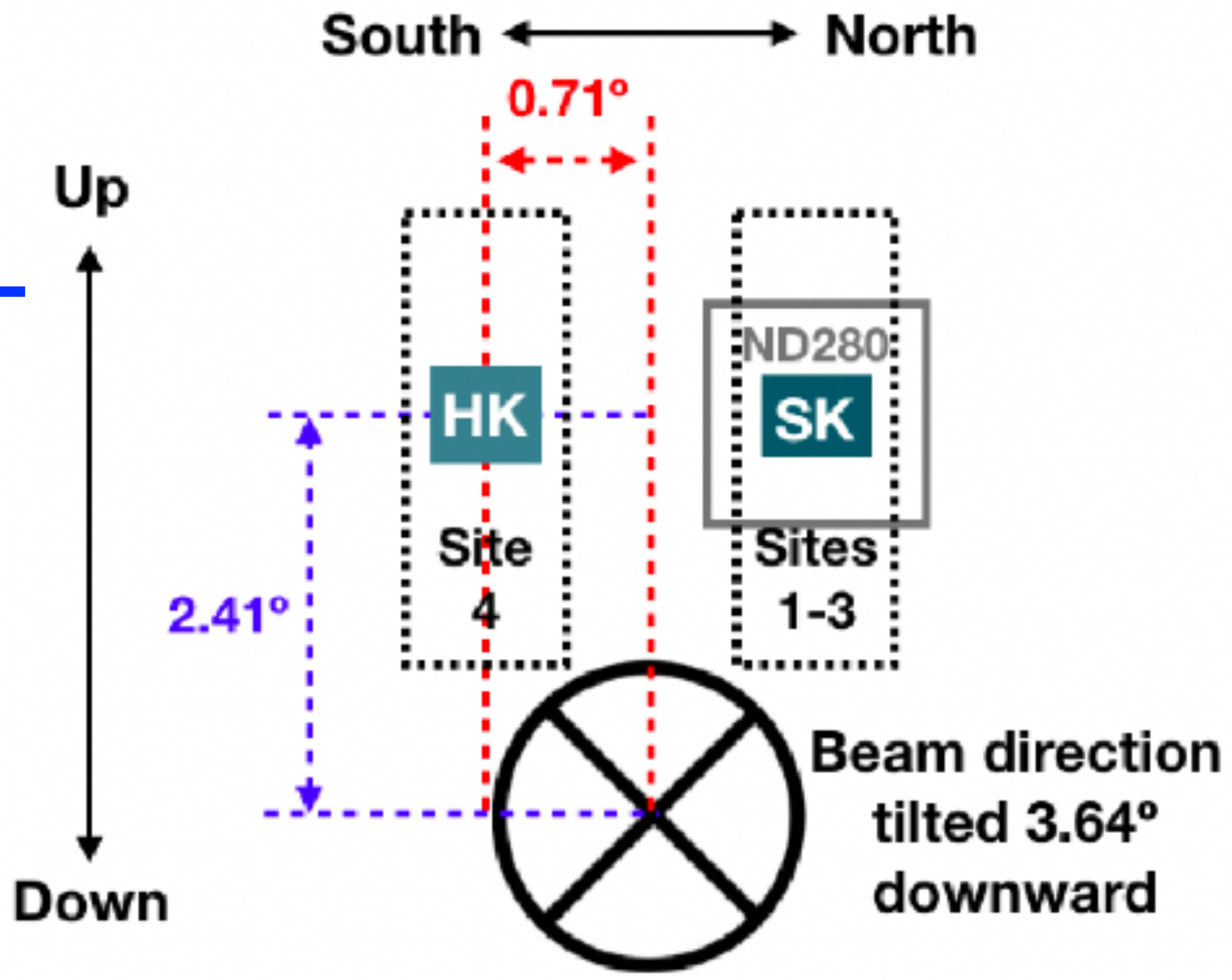




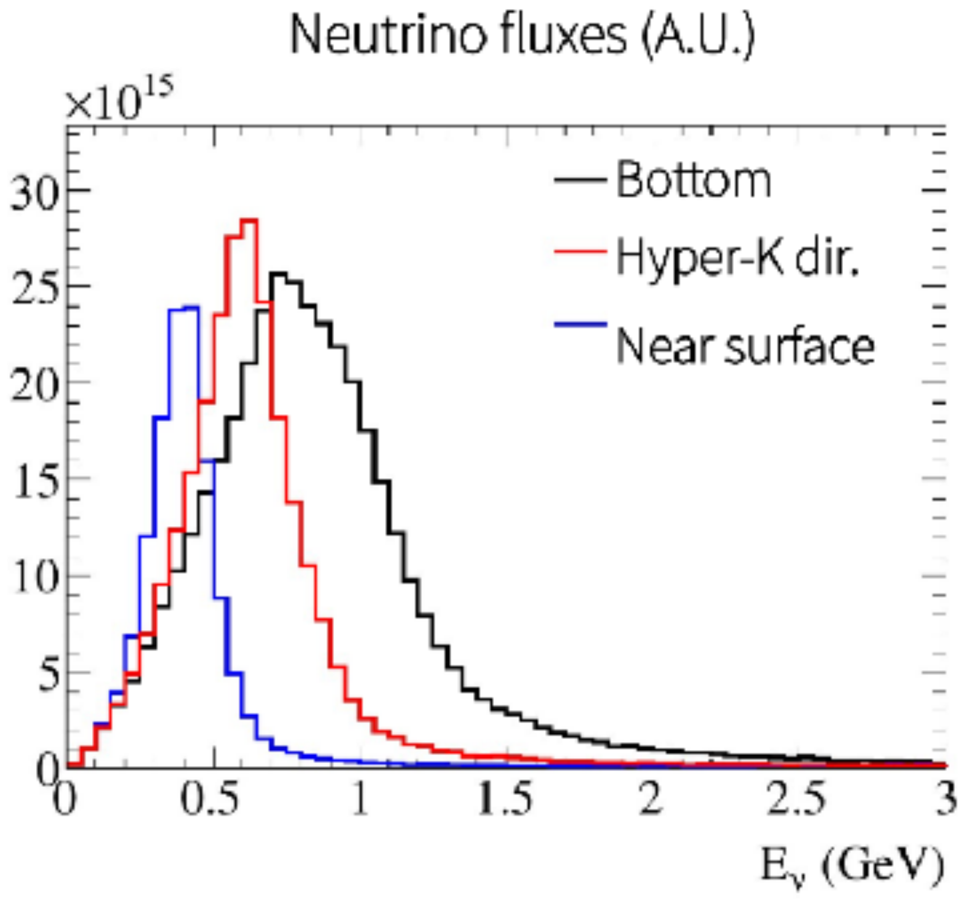
- Located 850m from the neutrino source
- Detector can move vertically in 50m deep pit, position controlled by water level
- 300 ton mass in instrumented volume
- Multi-PMT photosensors with good spatial and timing resolution (<1 ns) containing 19 8-cm diameter PMTs and integrated electronics

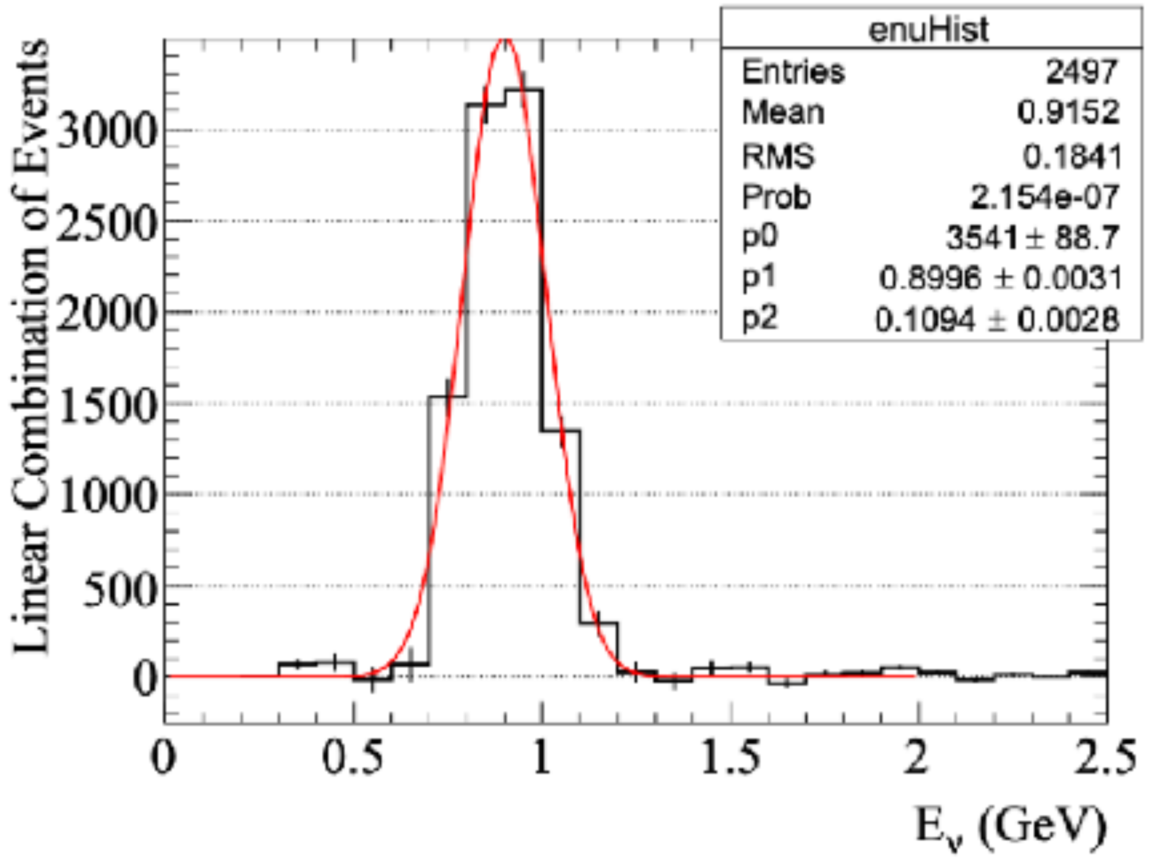
INTERMEDIATE WATER CHERENKOV DETECTOR (IWCD)

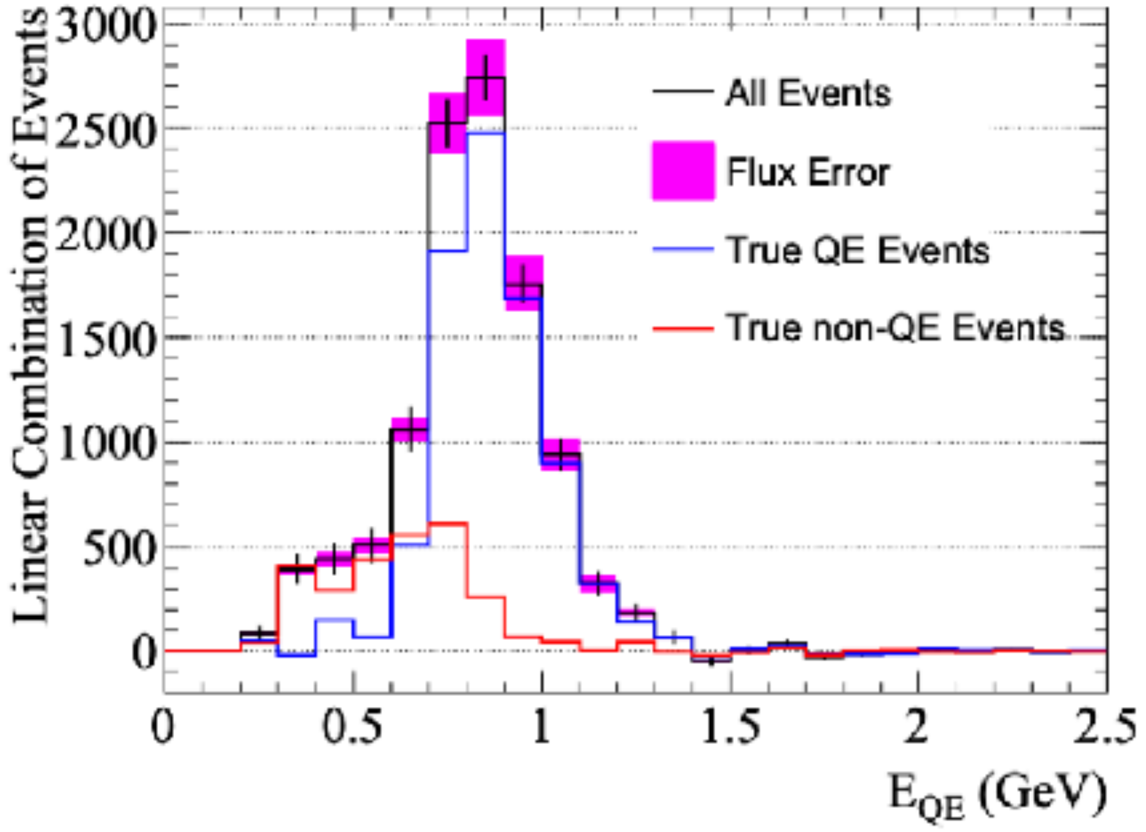




- Spans 1.5º to 4º off-axis
- Measurements with the “PRISM” method at different off-axis angles
  - “Mono”-energetic spectra to study neutrino-nucleus scattering
  - Predict spectra after oscillations at HK detector







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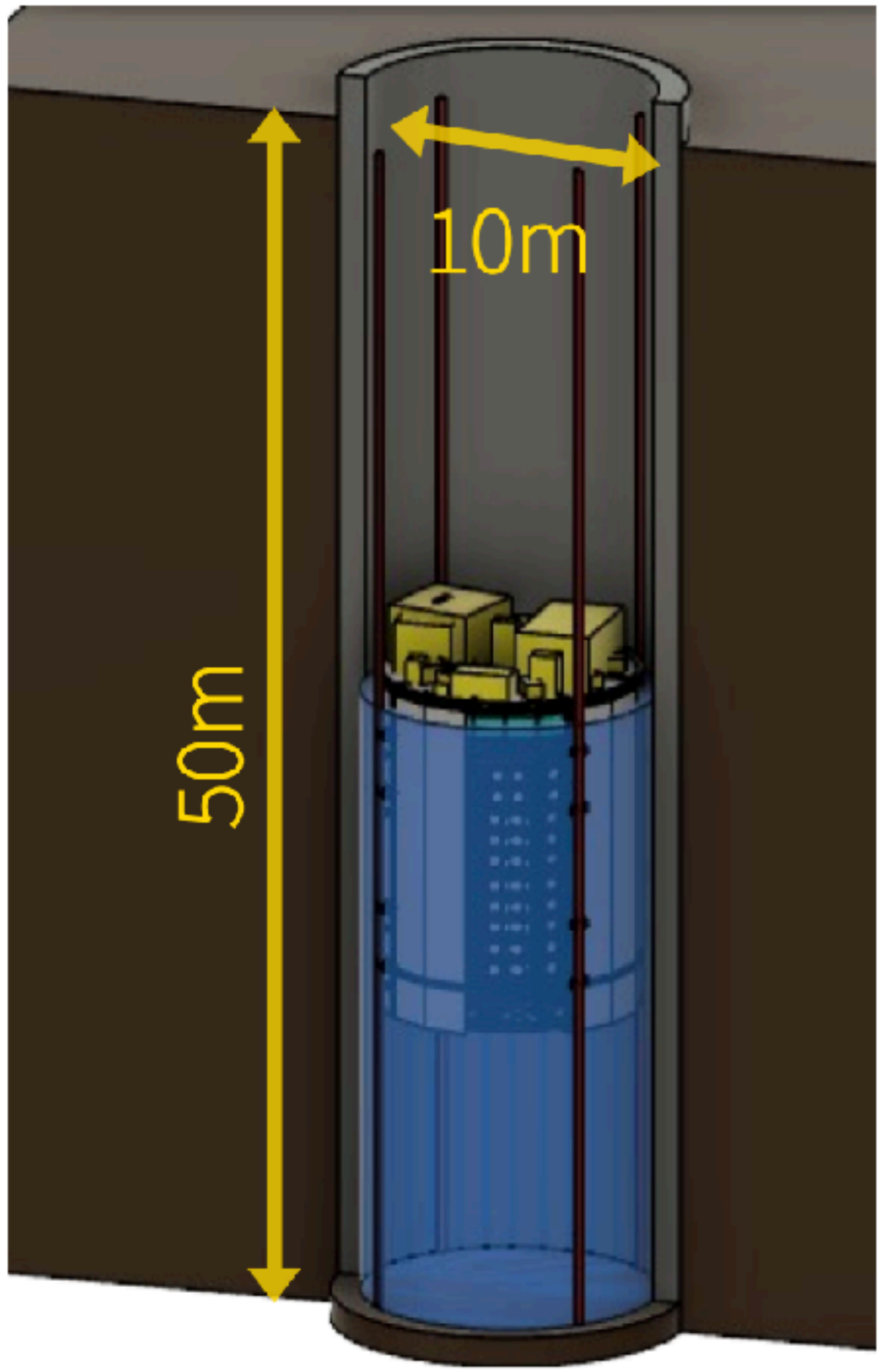
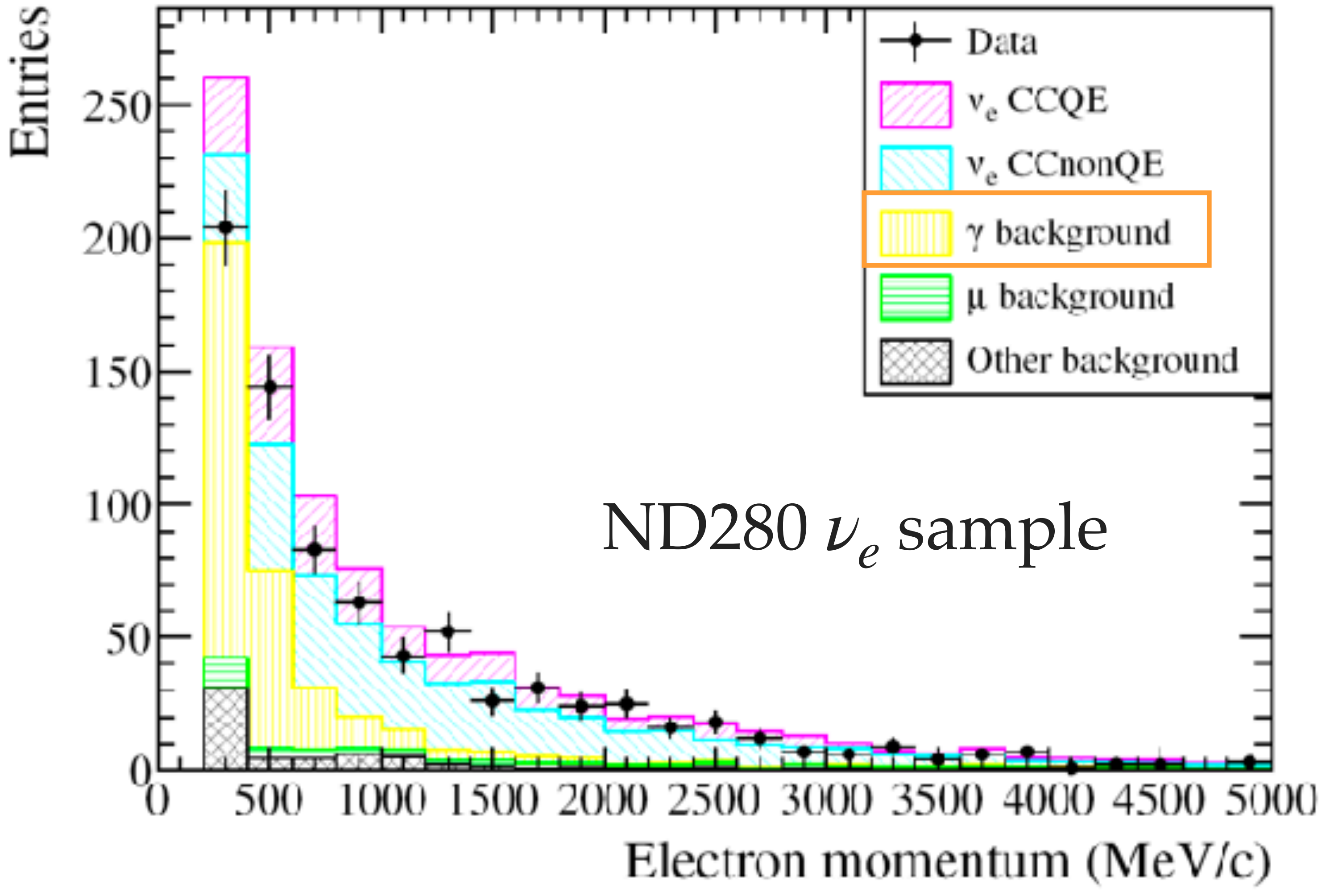
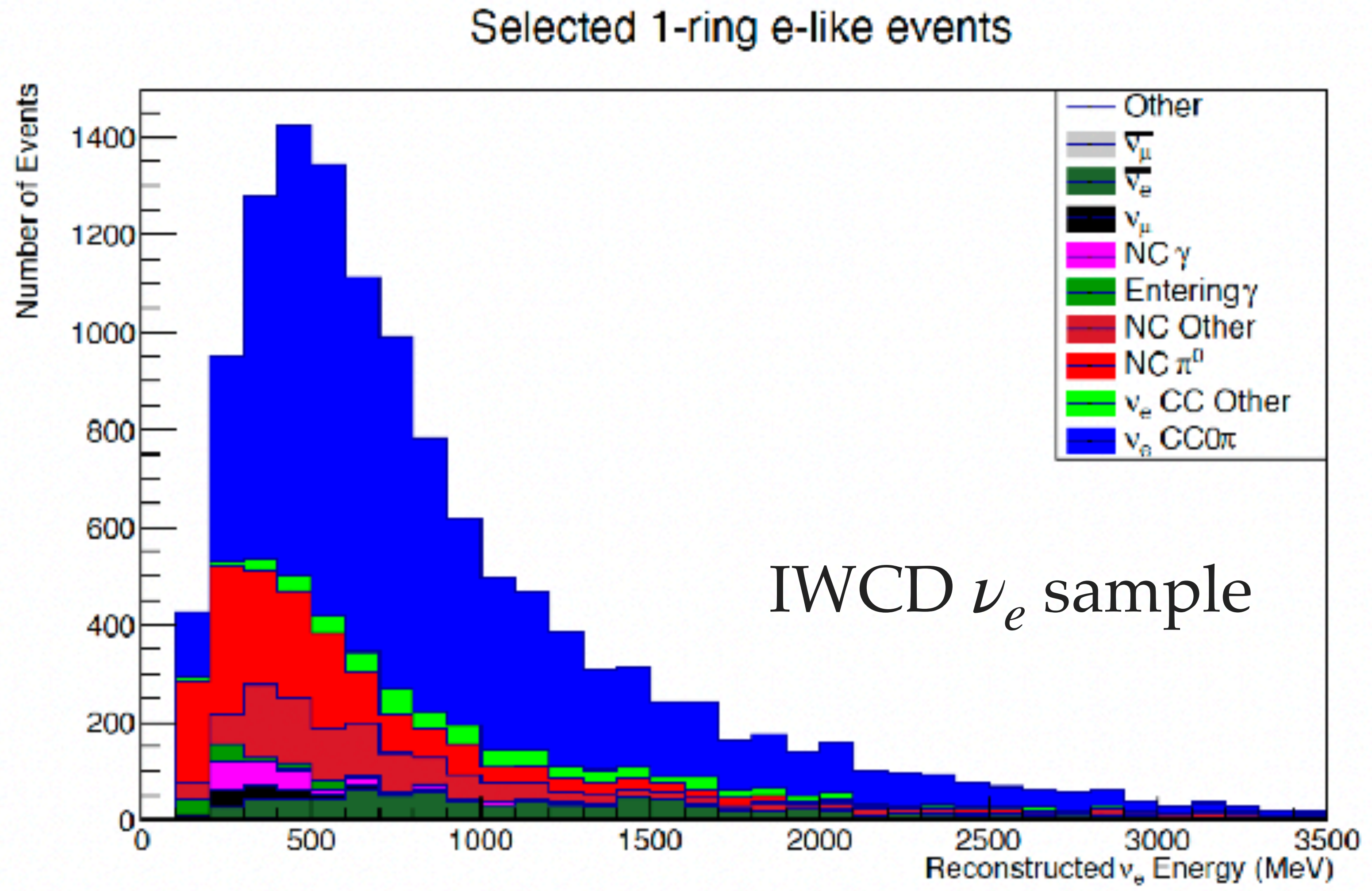
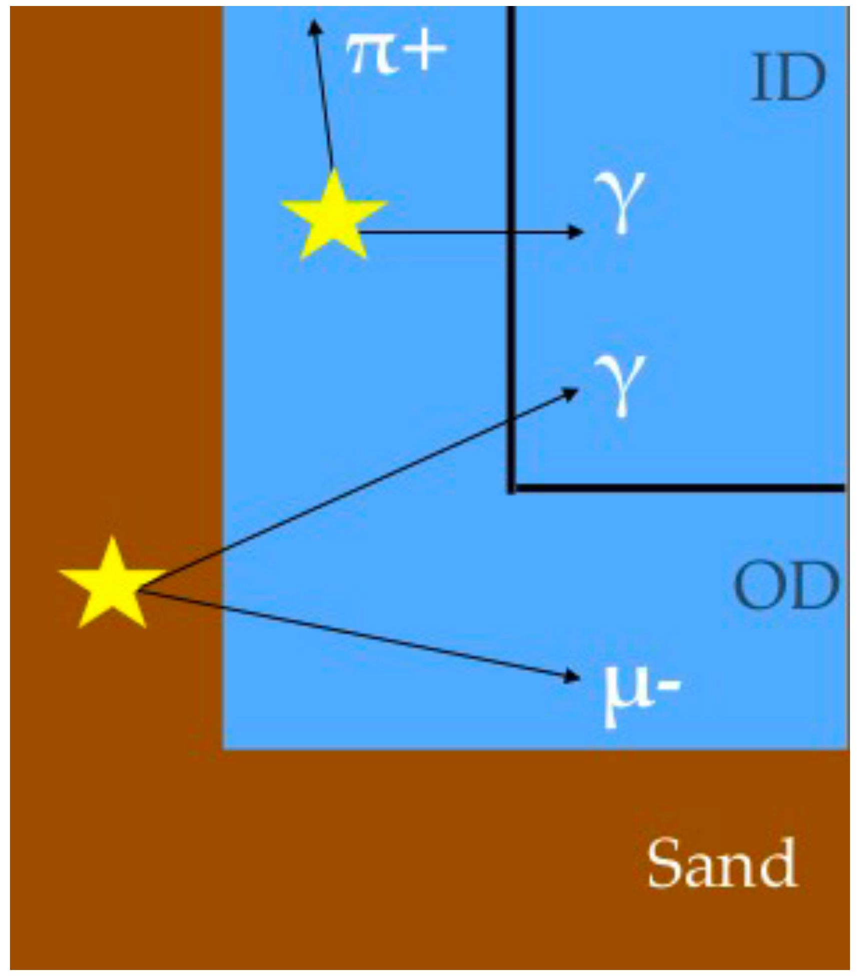






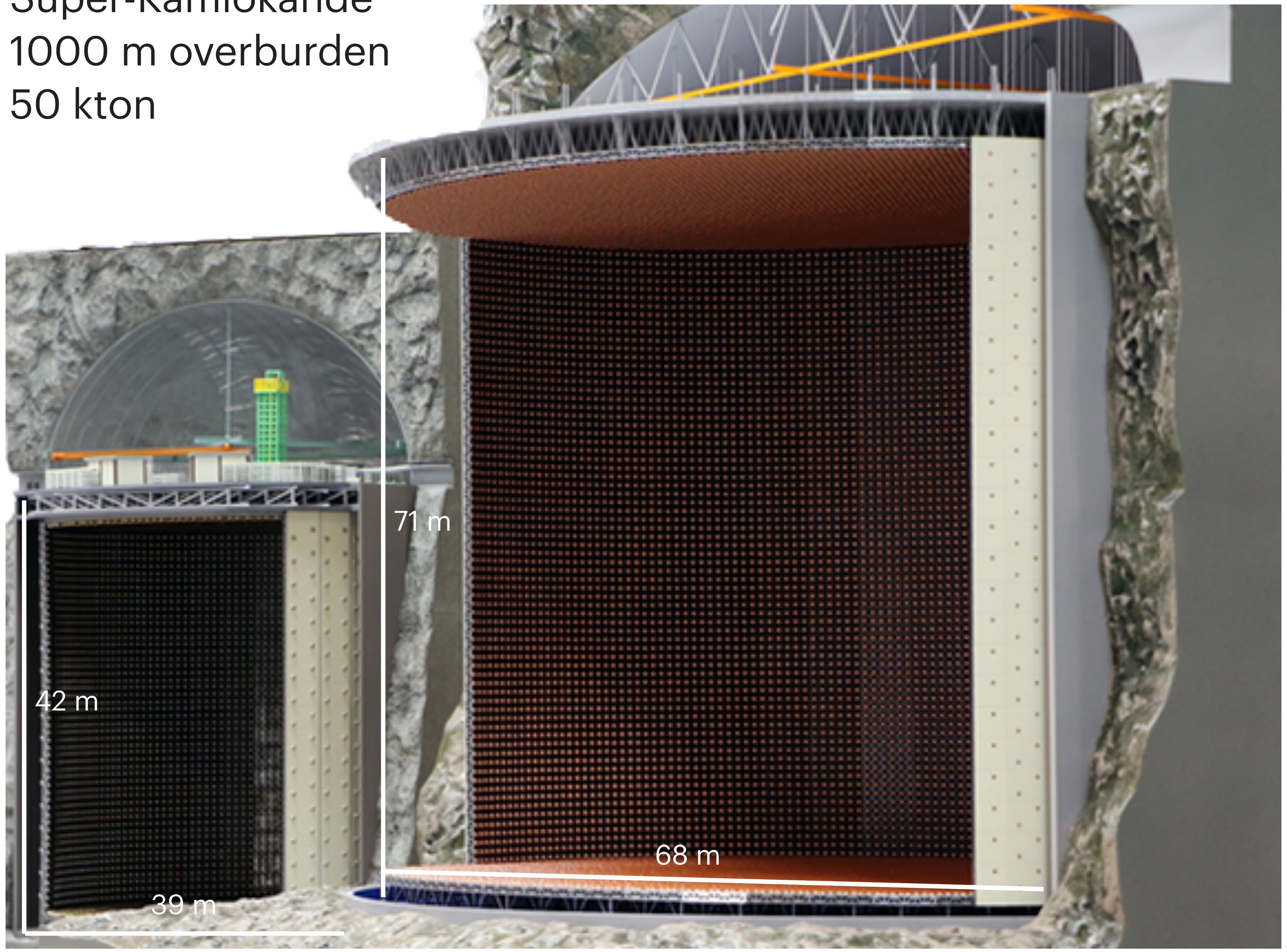


- IWCD can measure the 1% intrinsic beam ν_e / $\bar{\nu}_e$
  - Self-shield against entering gammas, a dominant background for ND280 ν_e / $\bar{\nu}_e$ measurement
  - IWCD can improve the constraint on $(\sigma_{\nu_\mu}/\sigma_{\nu_e})/(\sigma_{\bar{\nu}_\mu}/\sigma_{\bar{\nu}_e})$, which is currently estimated by theory at ~5%

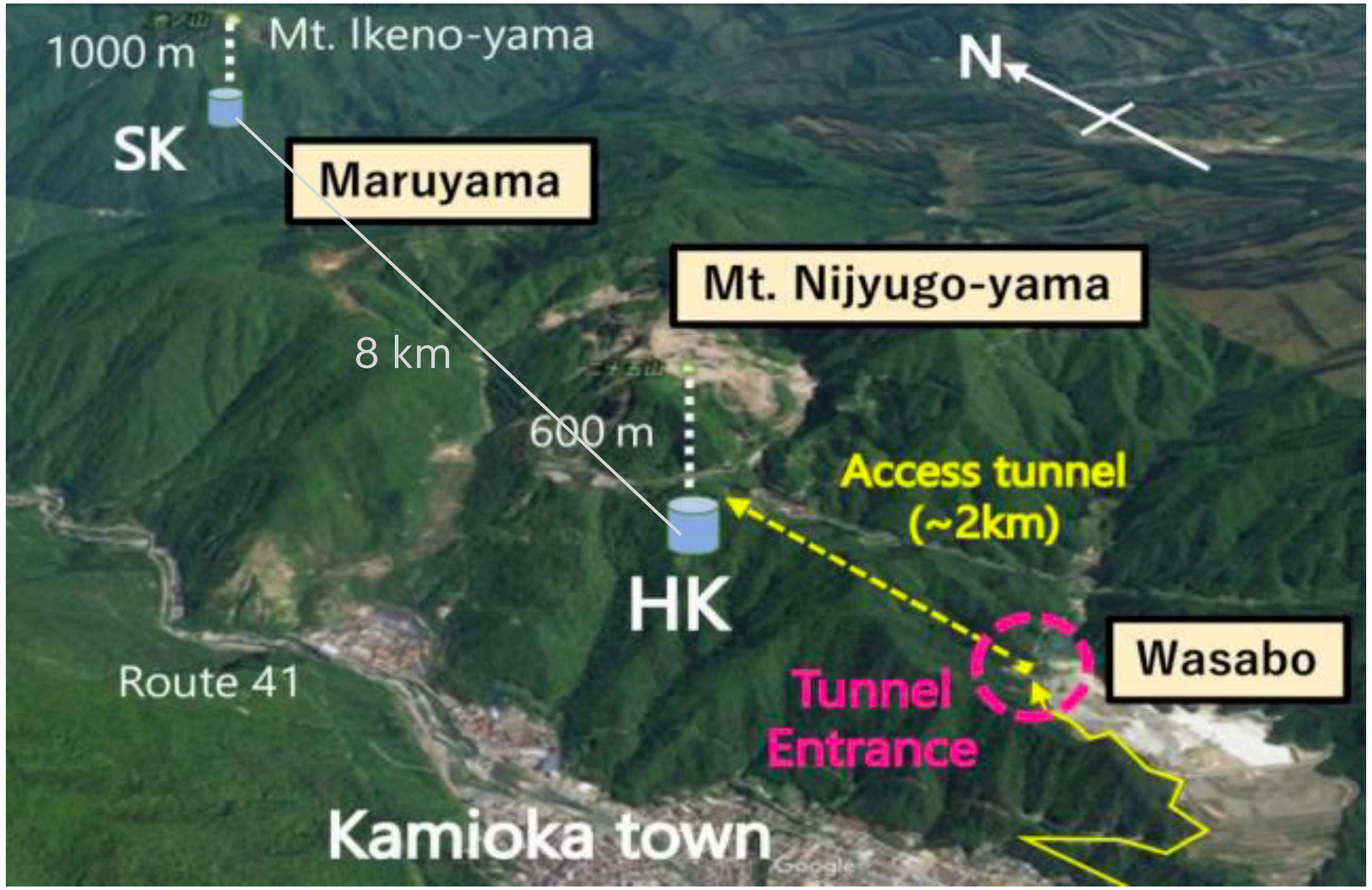
FAR DETECTOR

Hyper-Kamiokande
~600 m overburden
258 kton

Super-Kamiokande
1000 m overburden
50 kton



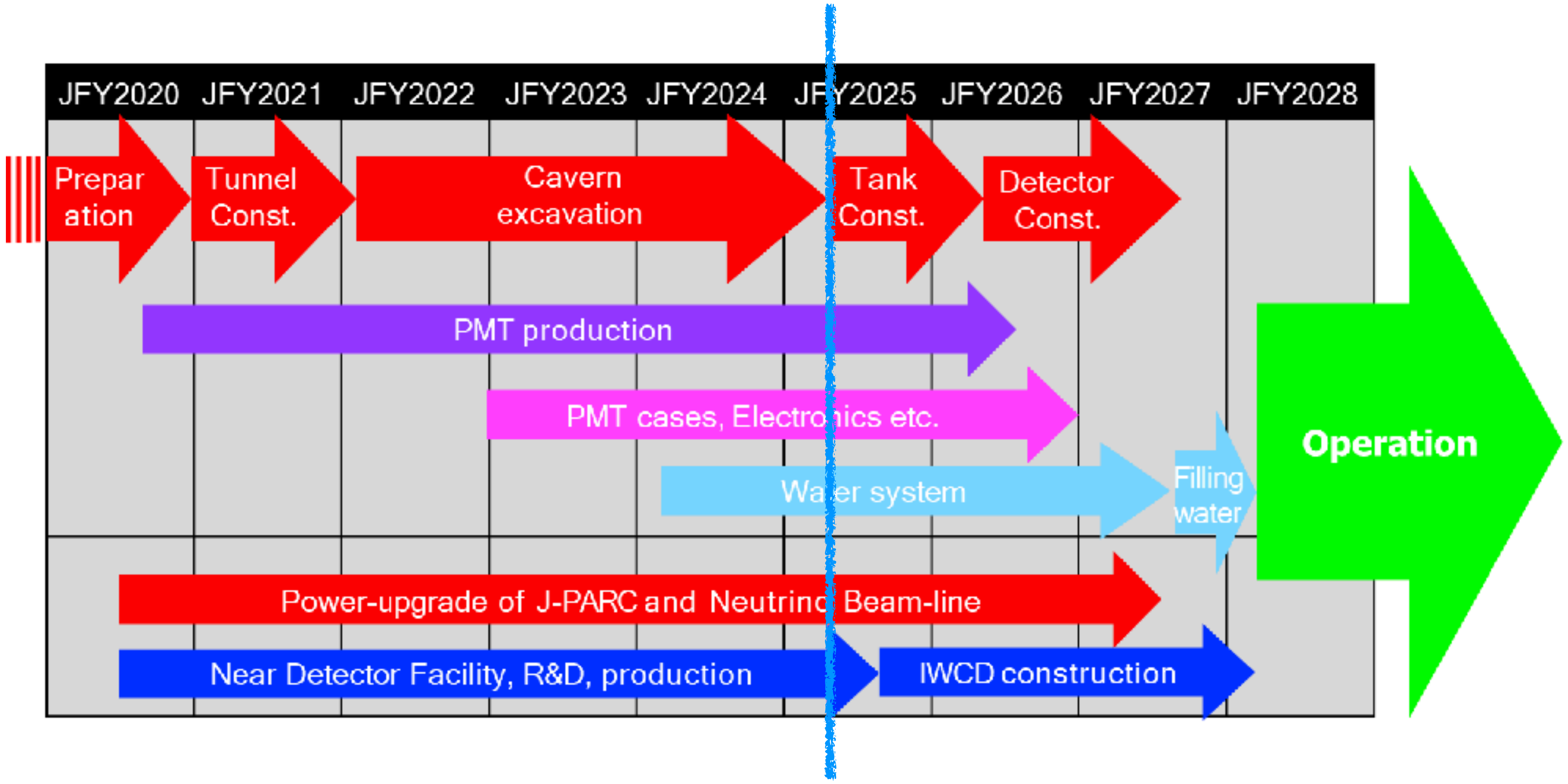
- 600 m below Nijyugo-yama near Kamioka Town
- 8.4 x in fiducial mass compared to Super-K



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

FAR DETECTOR

- 600 m below Nijyugo-yama near Kamioka Town
- 8 x increase in fiducial mass compared to Super-K
- **Cavern excavation completed in July, 2025**
- Tank lining construction has started



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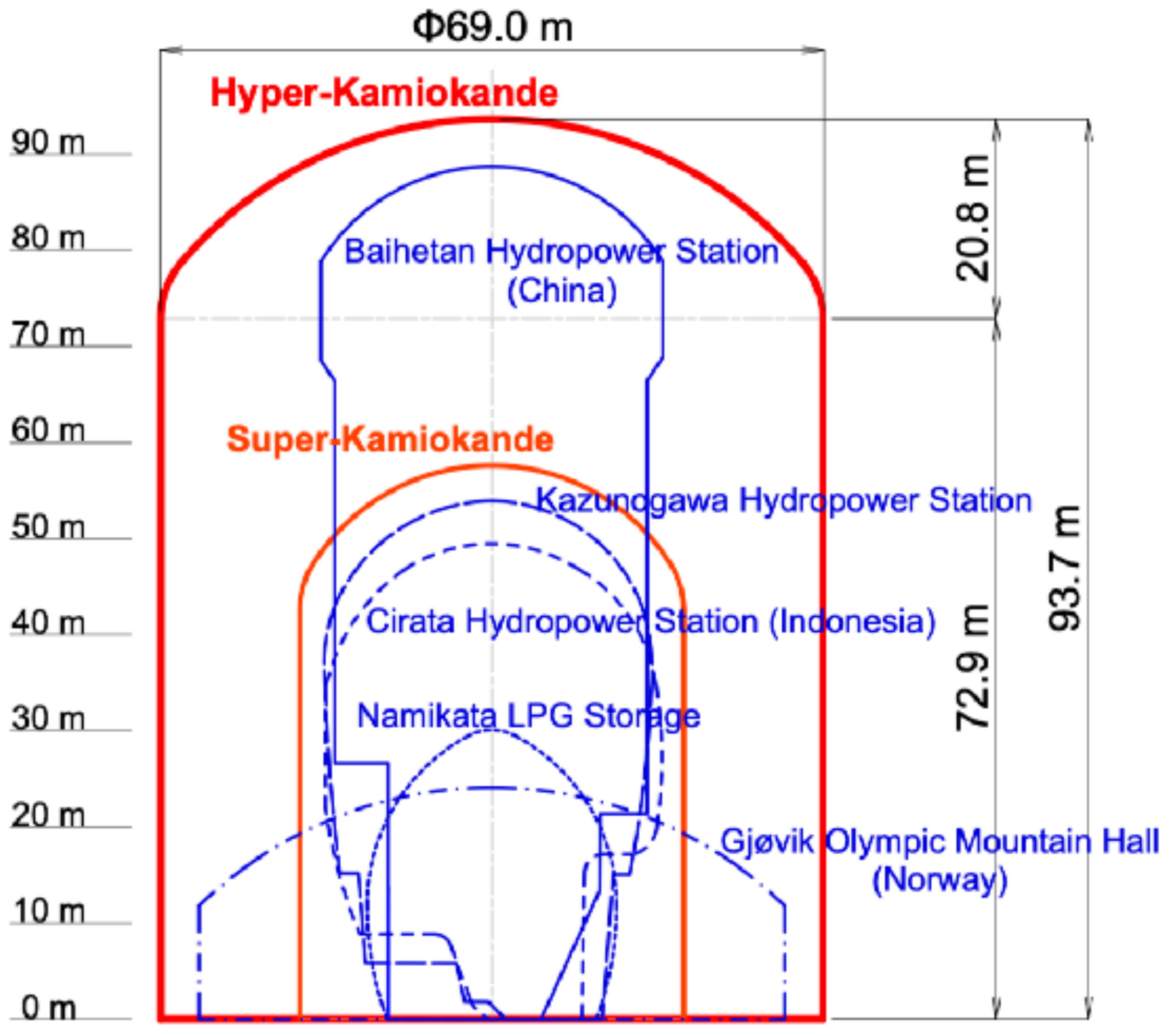
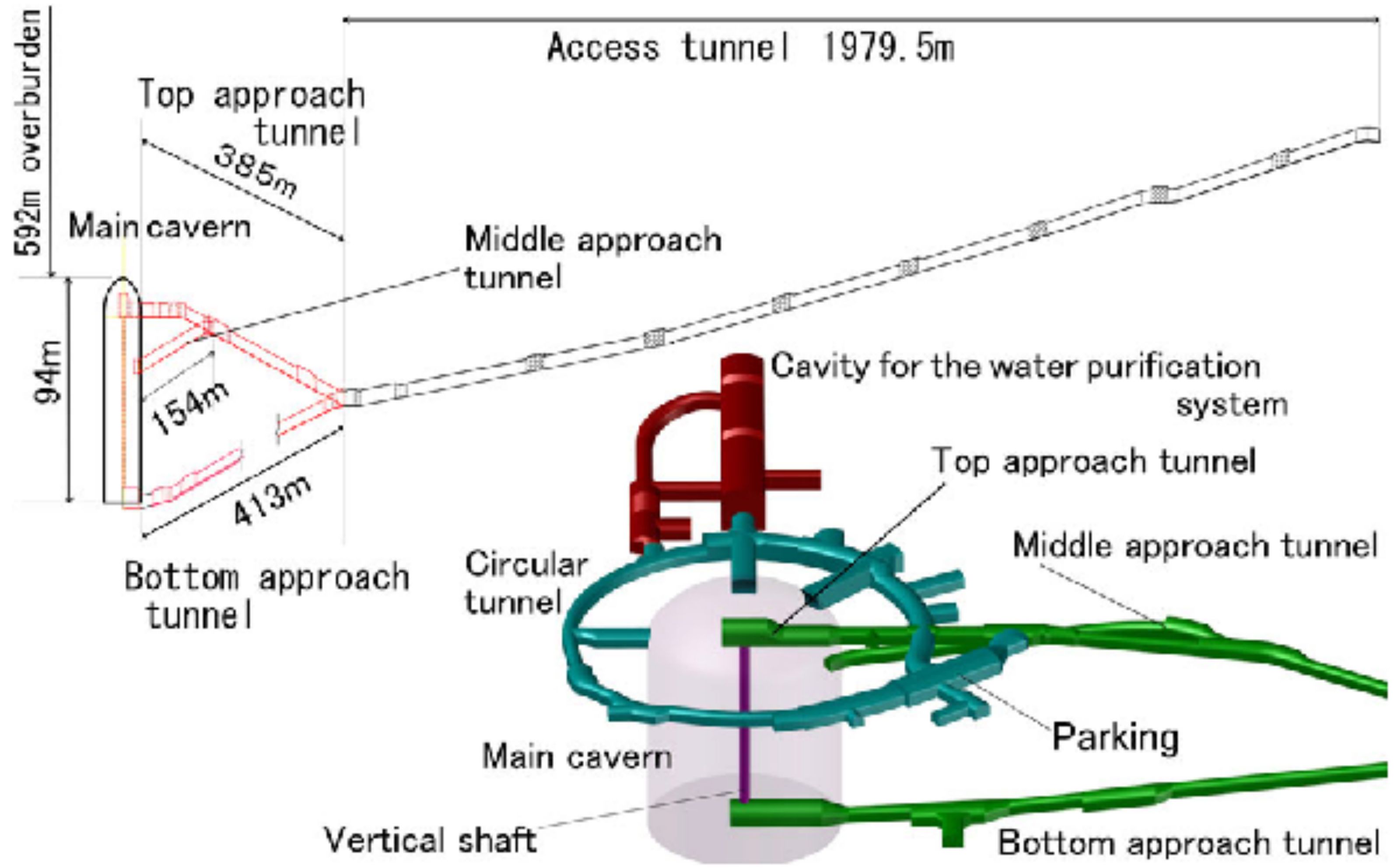
FAR DETECTOR

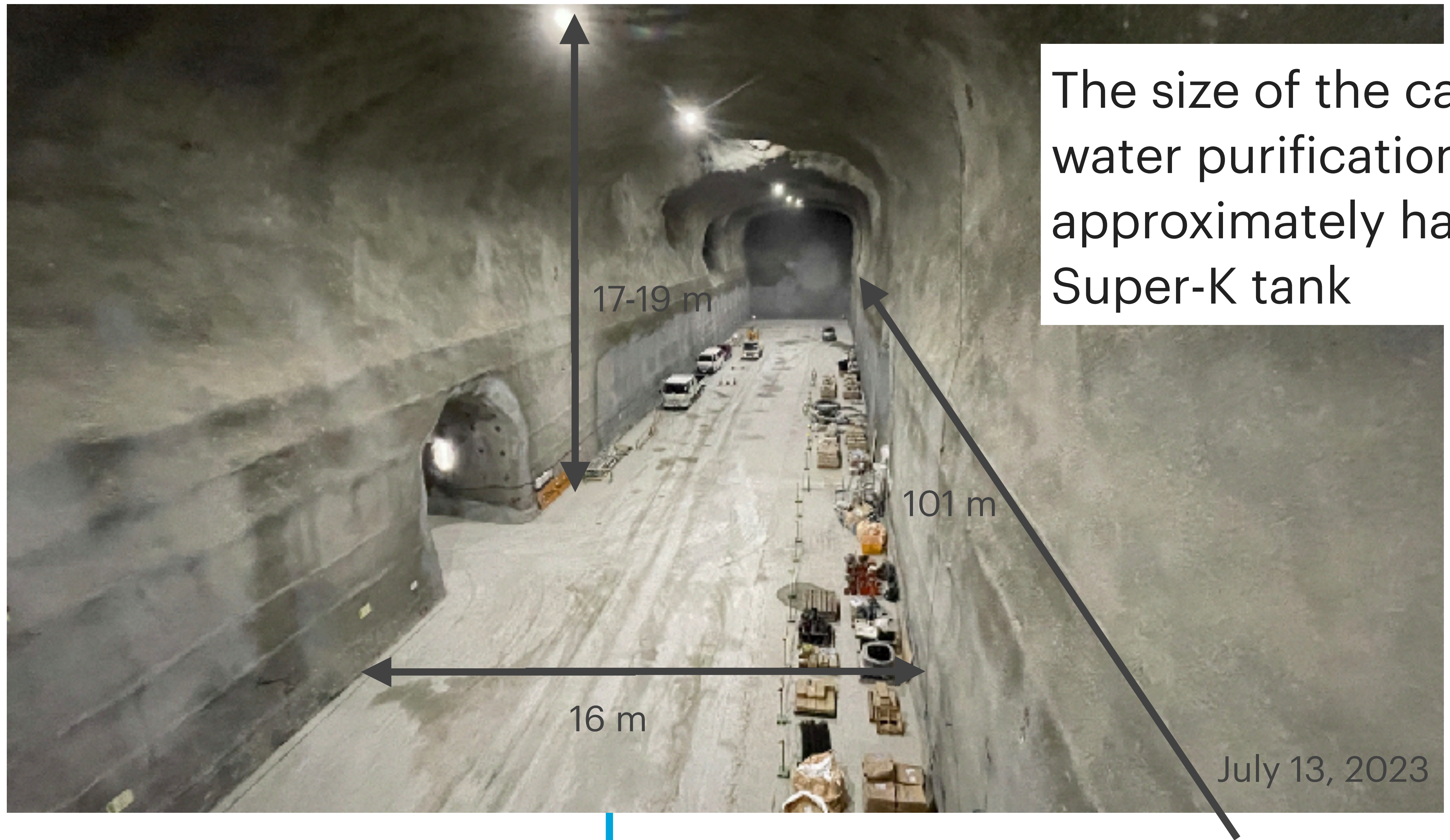
- 600 m below Nijyugo-yama near Kamioka Town
- 8 x increase in fiducial mass compared to Super-K
- **Cavern excavation completed in July, 2025**
  - The HK cavern is one of the largest man-made spaces ever excavated in bedrock



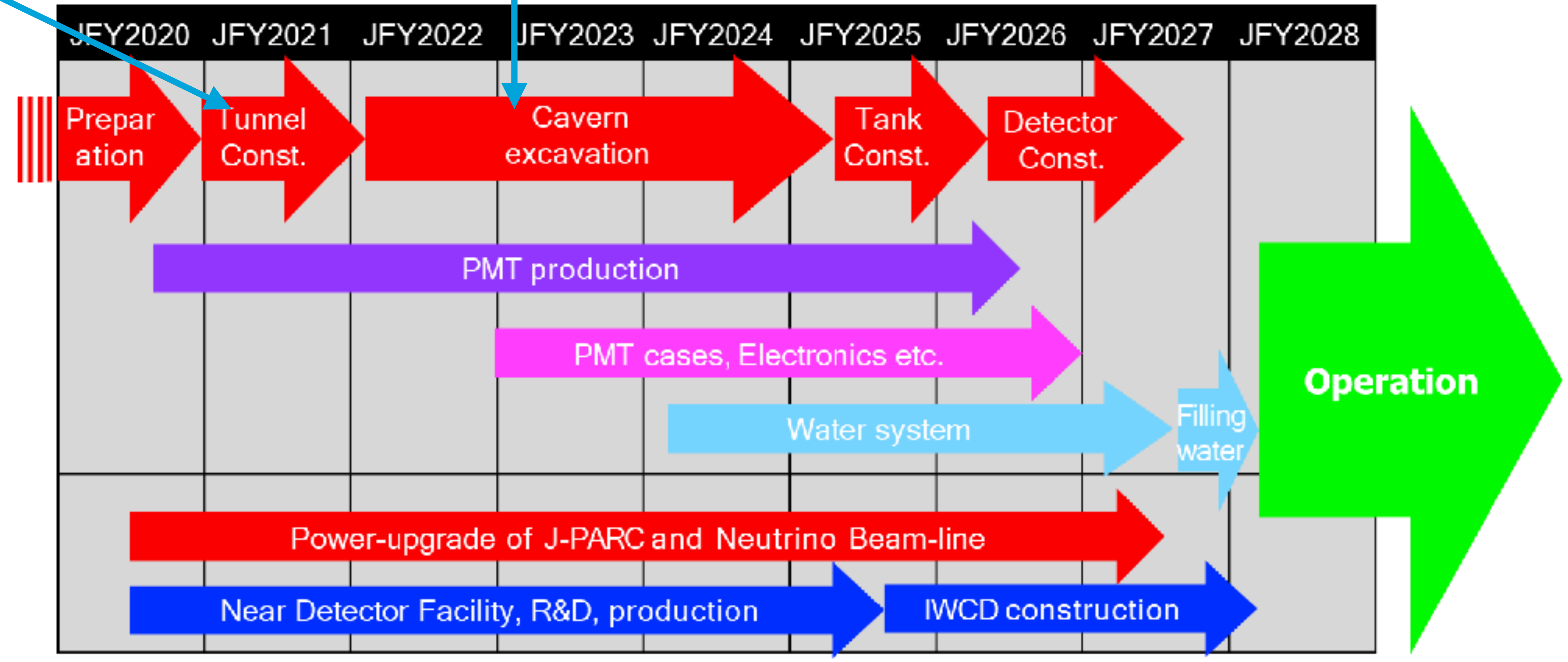
CAVERN EXCAVATION

Excavation work began in May 2021





The size of the cavity for the water purification system is approximately half that of Super-K tank



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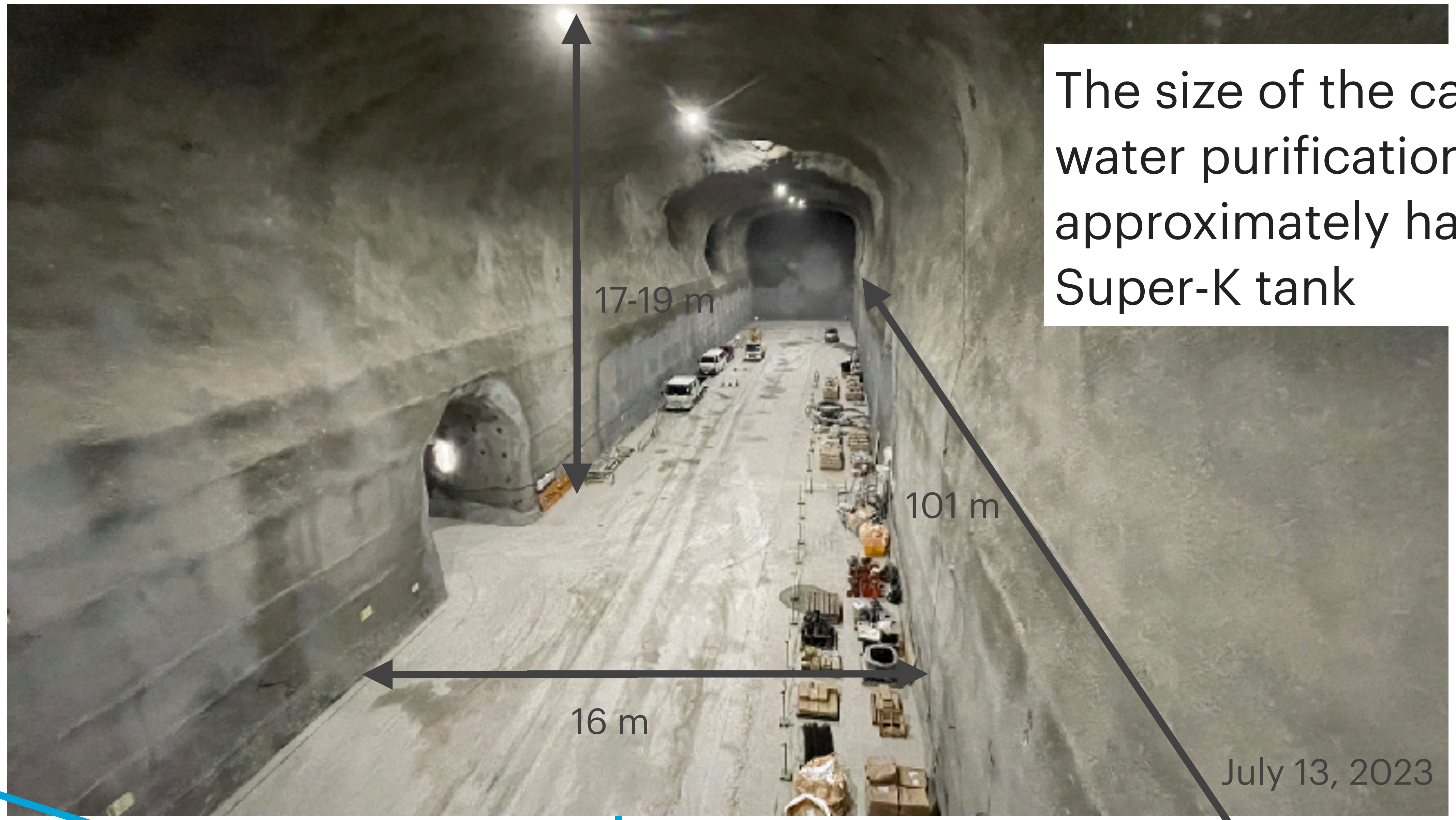

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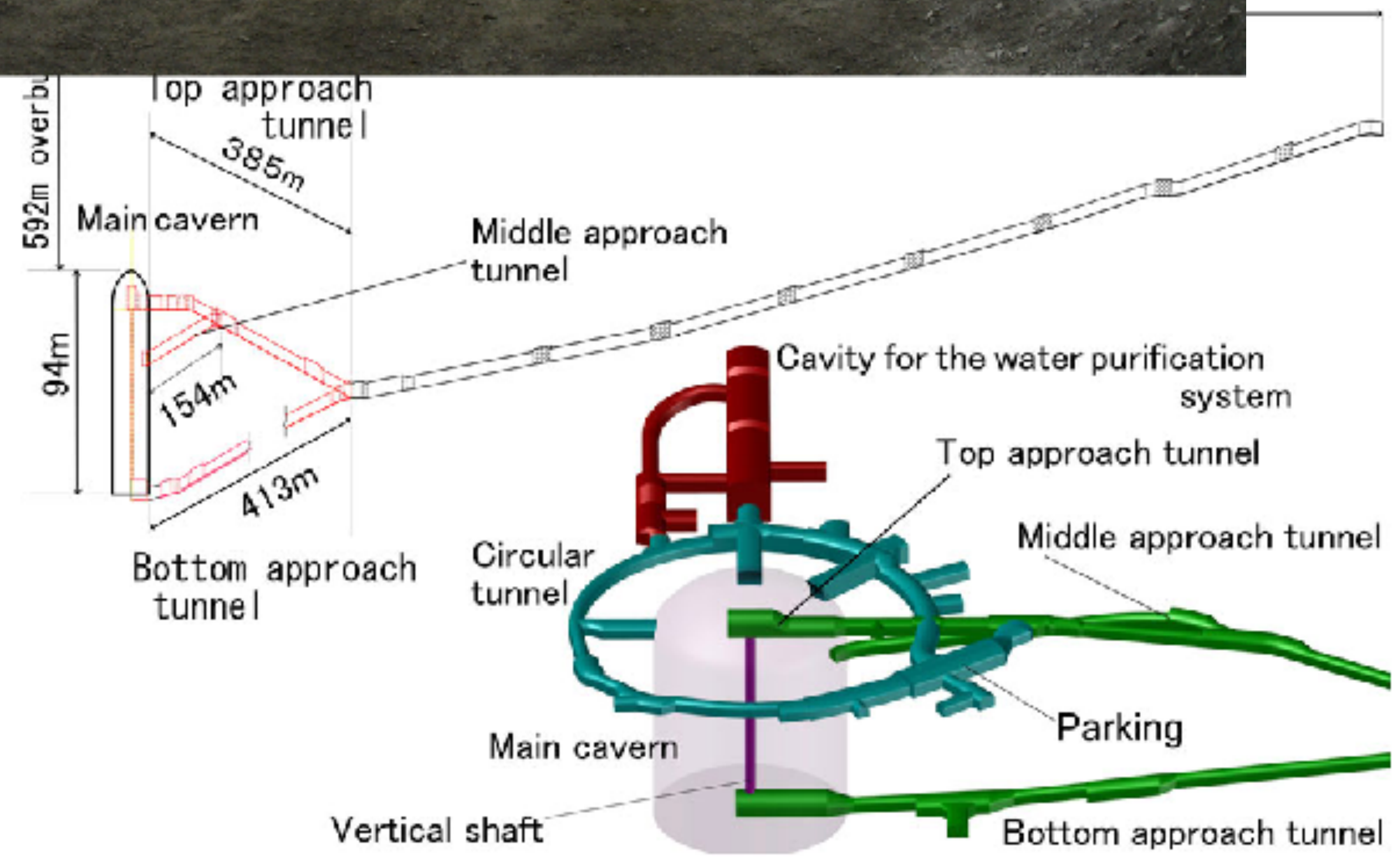
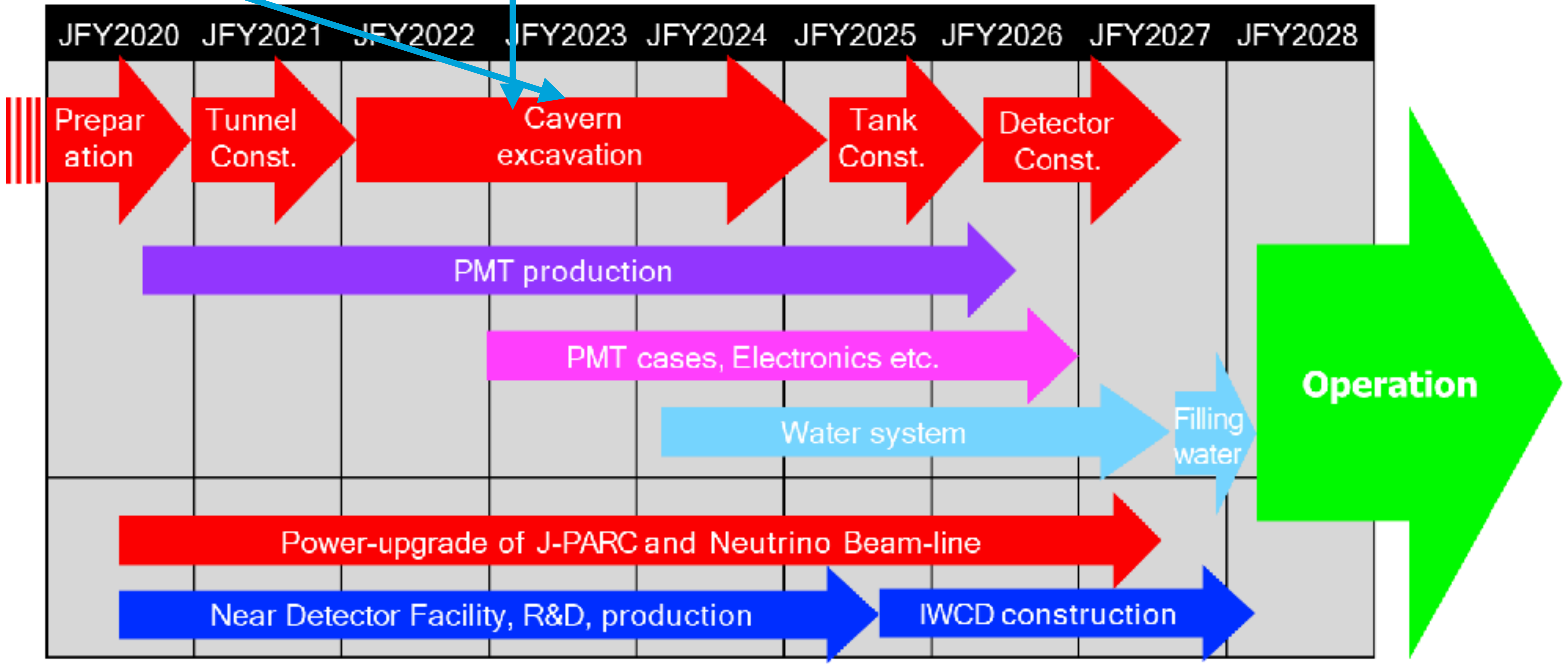
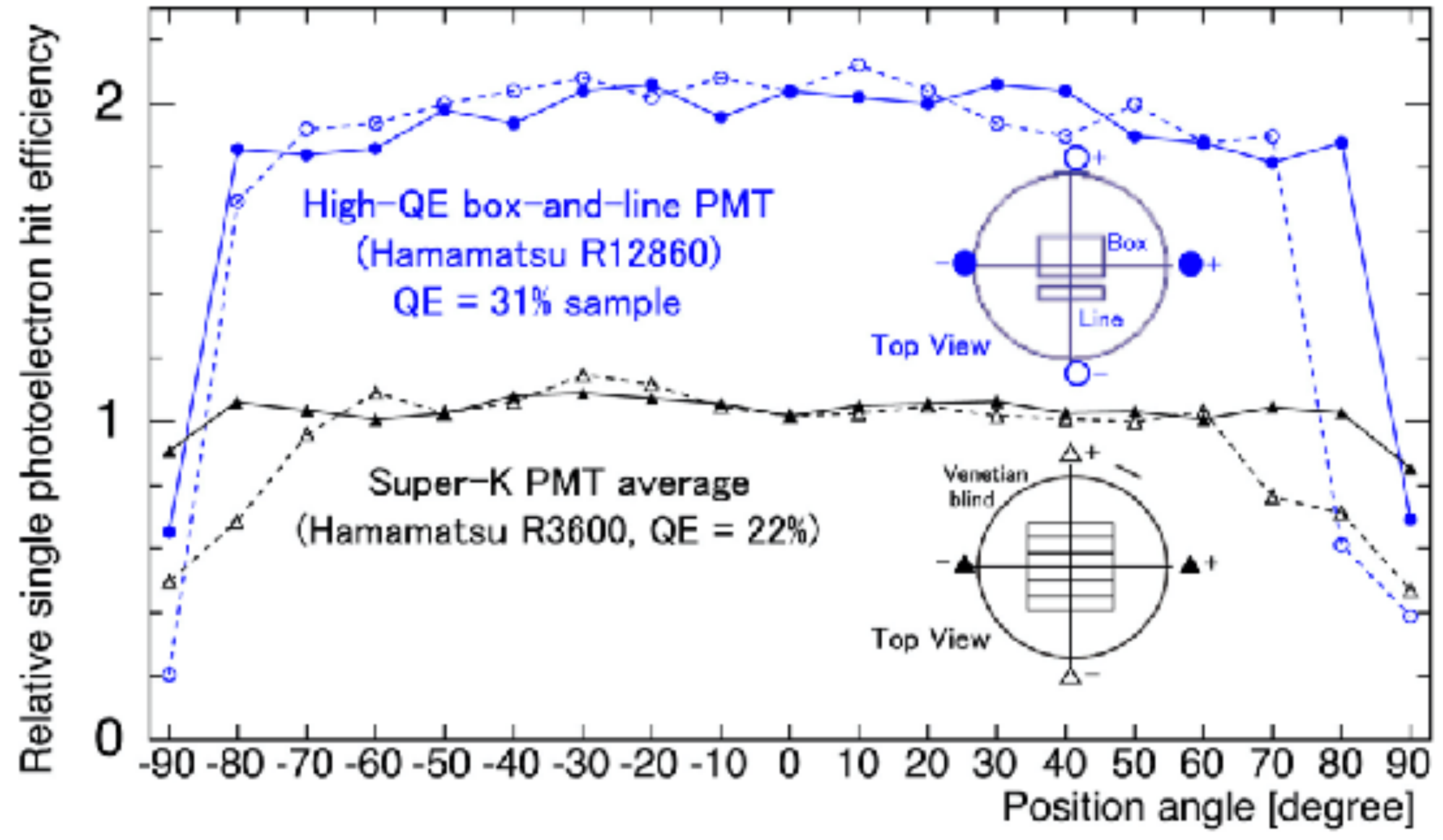
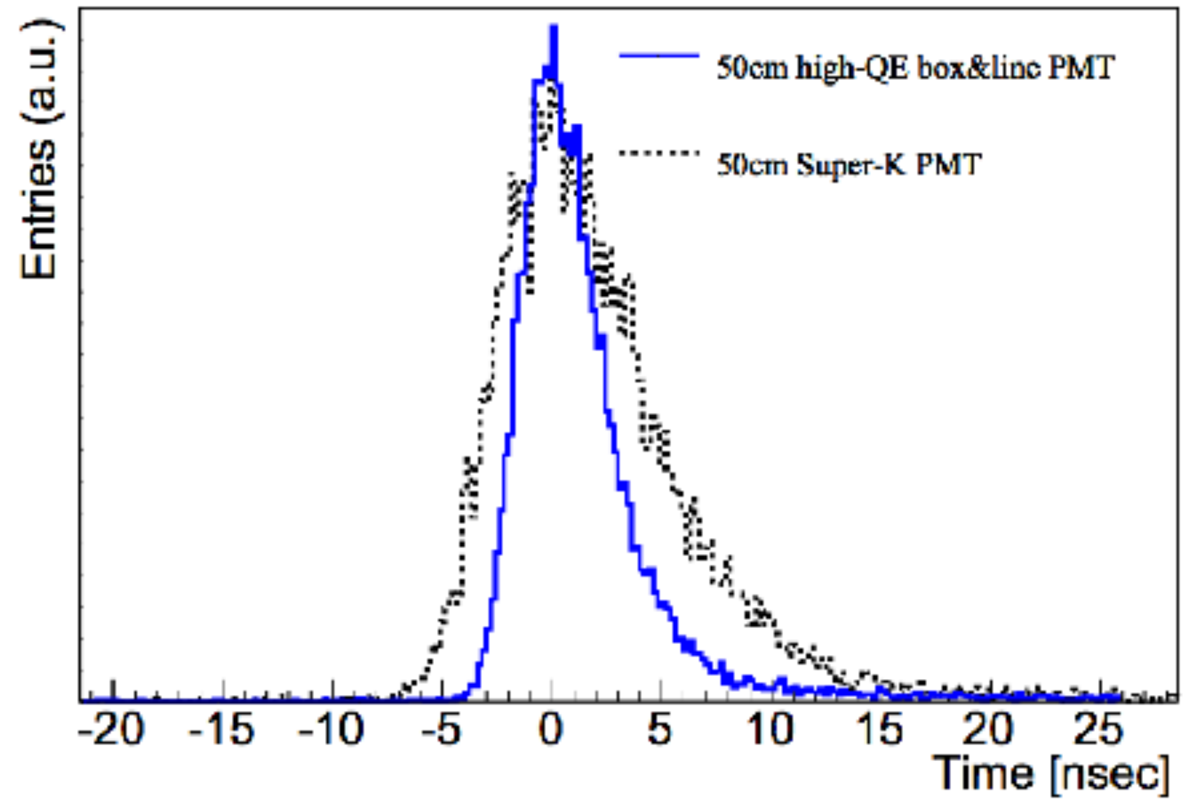


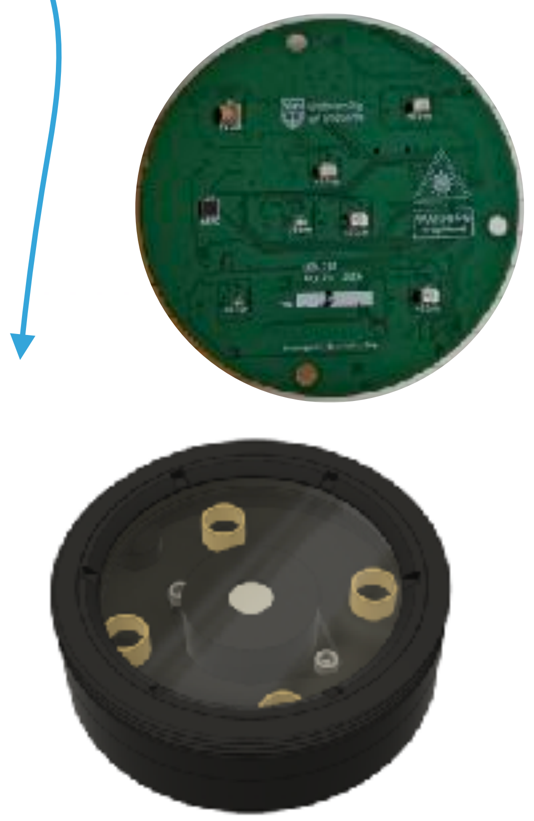


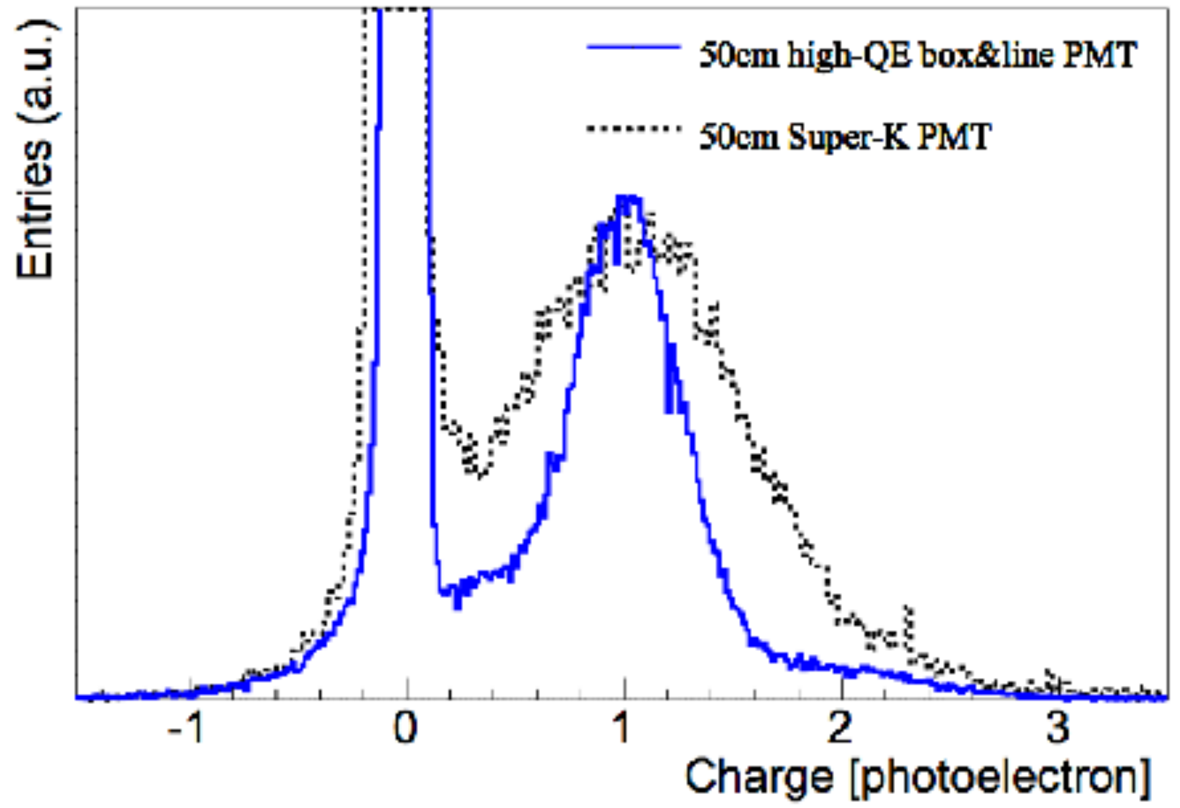
FAR DETECTOR

- 20,000 20-inch Box&Line PMTs
  - 20% photocathode coverage
  - X2 quantum efficiency and better charge/timing resolution
- Also 800 multi-PMTs for calibration purposes
  - 200 mPMTs contain 35 LED light sources each with <1 ns pulse width
- 3,600 3" PMT+WLS plate in outer detector
- Mass production well underway with over 15,000 PMTs delivered



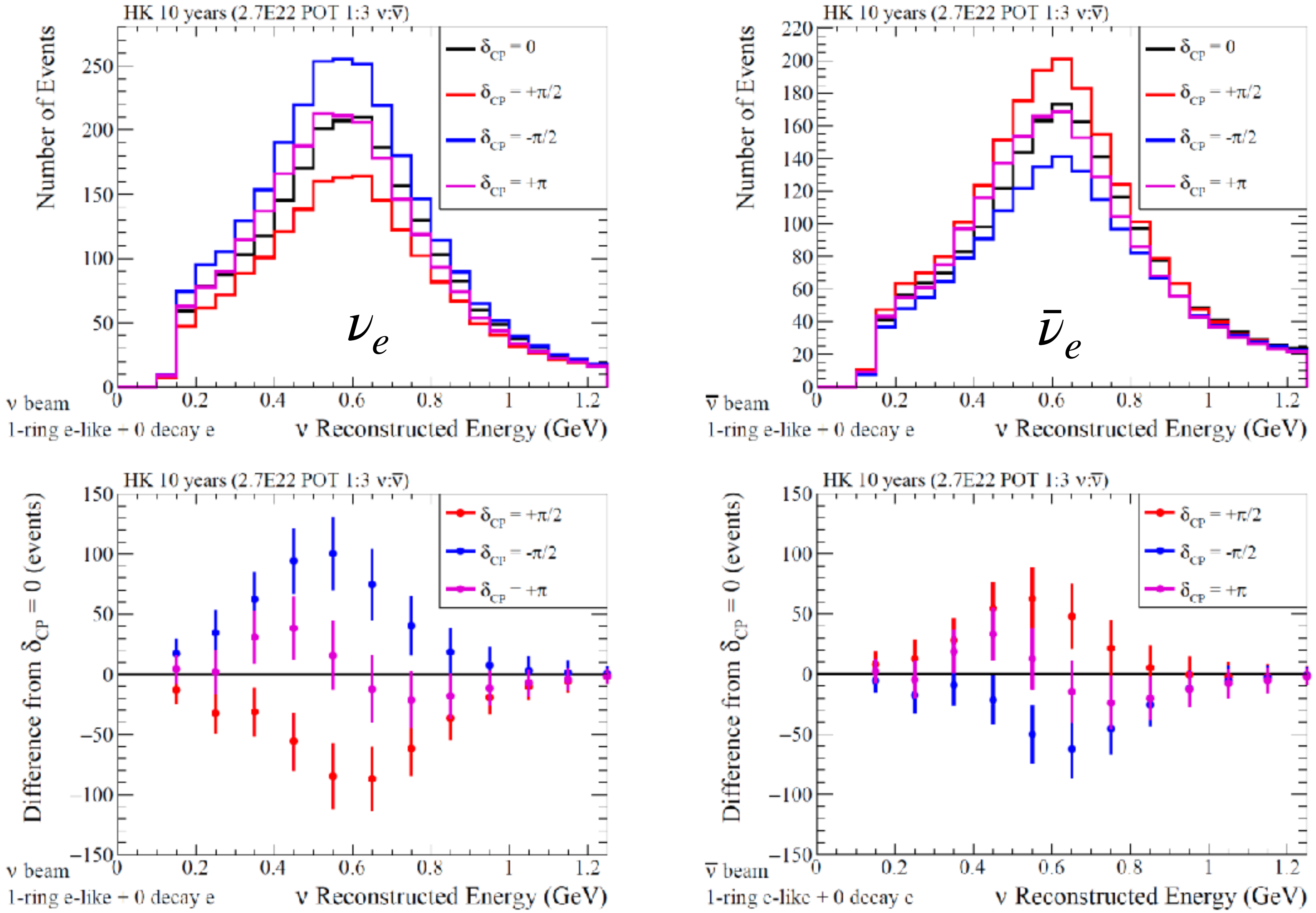




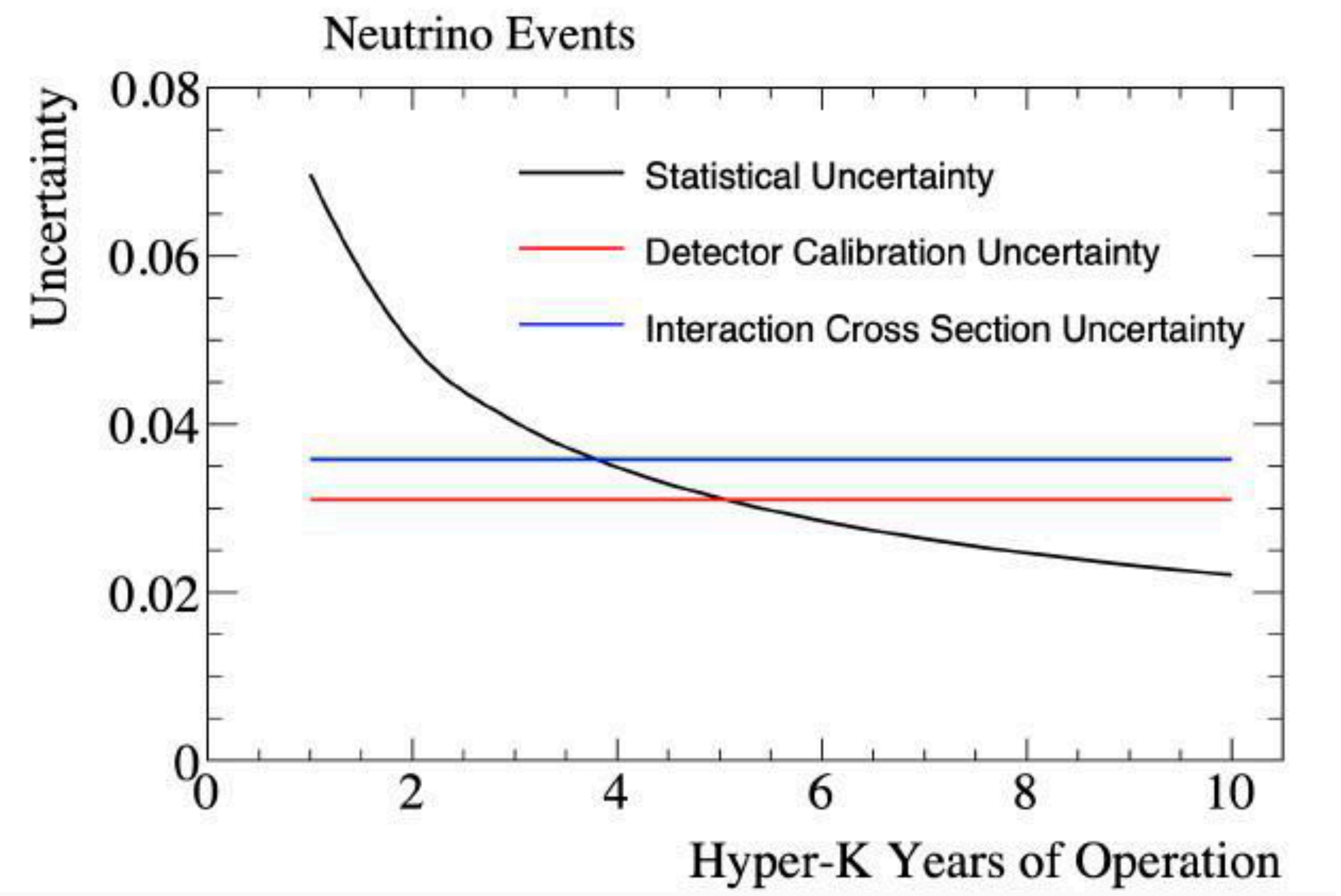


- Mass QA testing of 200 PMTs

HYPER-K 10-YEAR PROJECTION



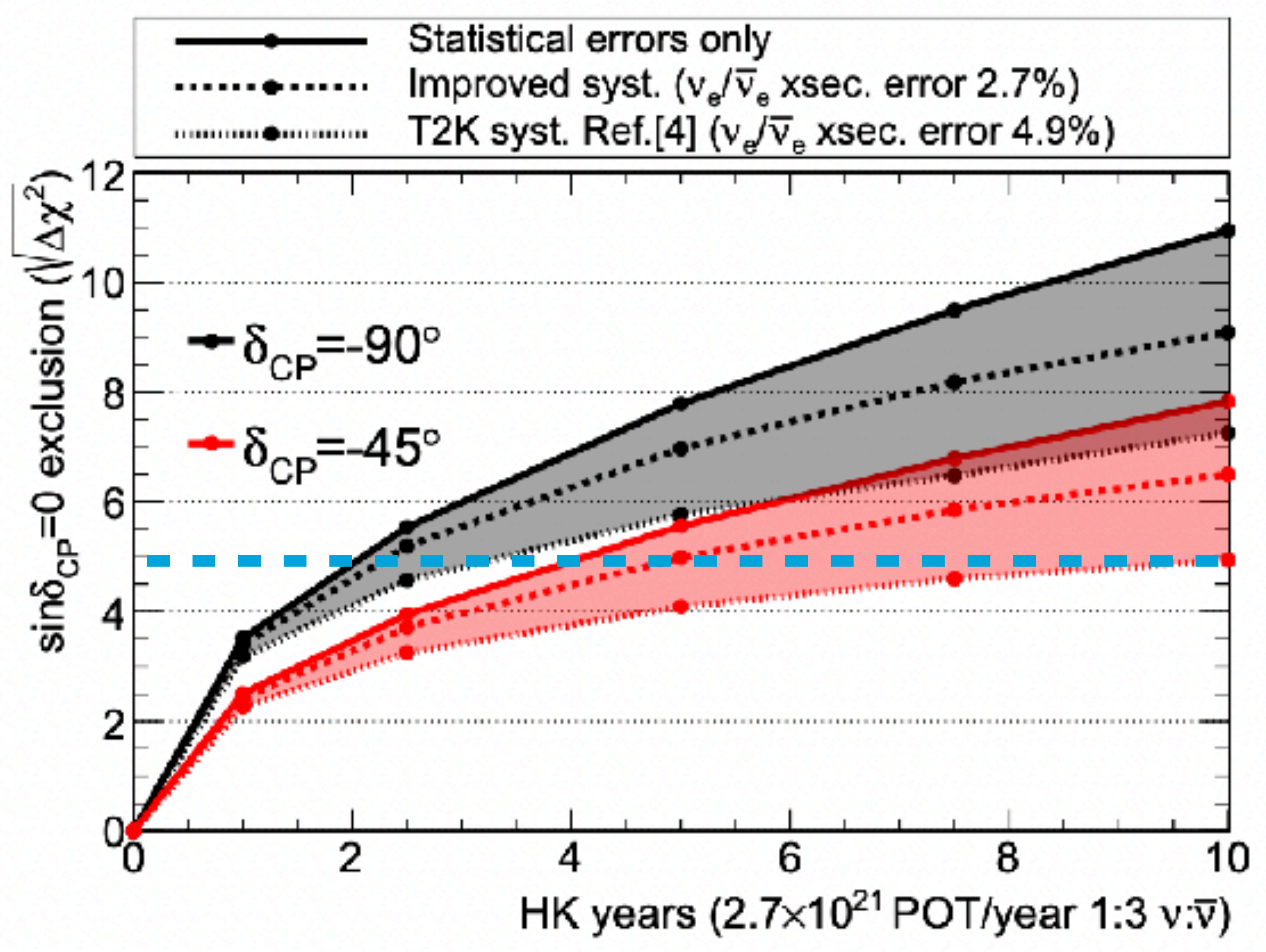
- Thousands of ν_e and $\bar{\nu}_e$ events after 10 years
- Systematic uncertainties will soon surpass statistical uncertainty

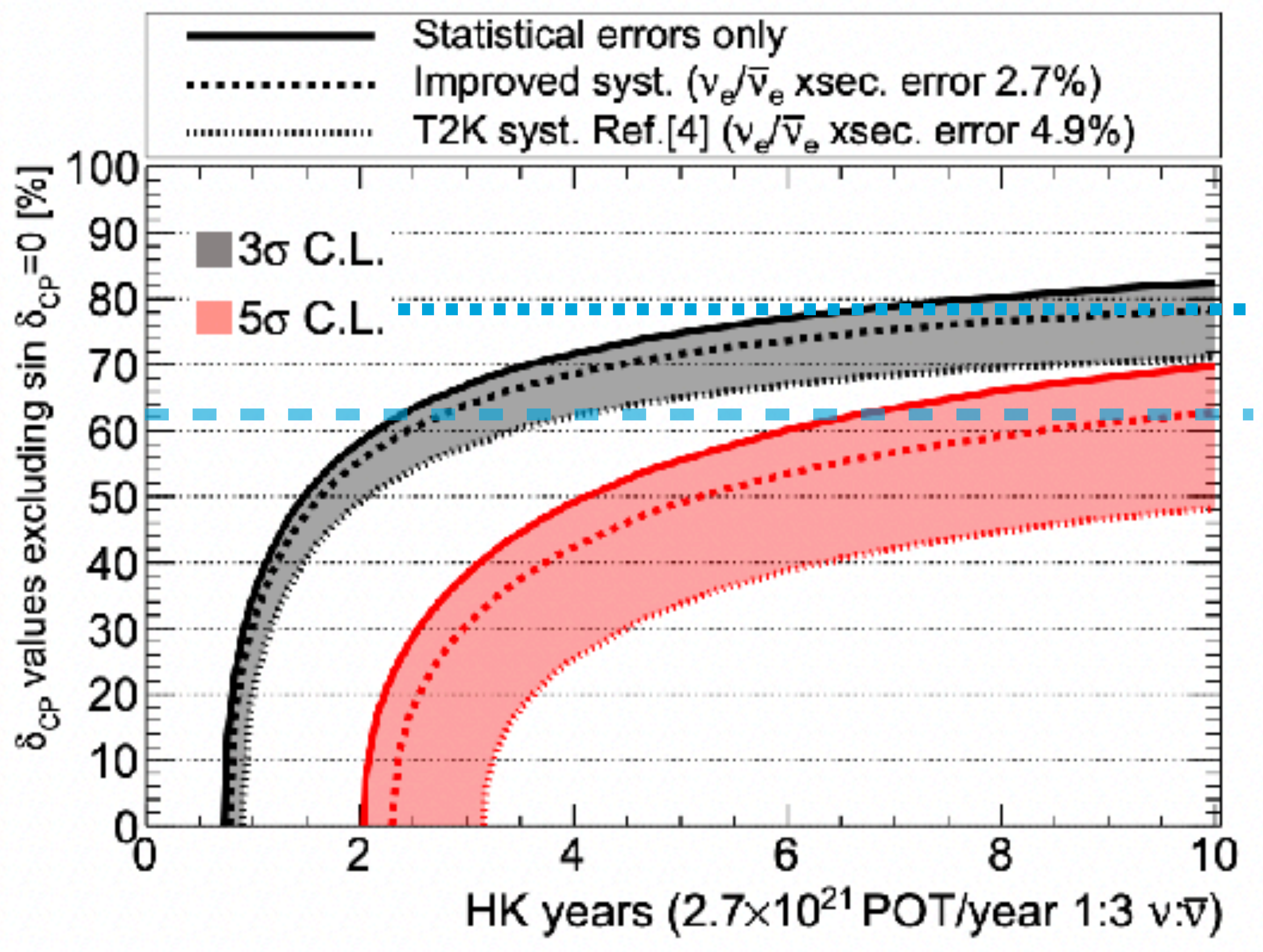


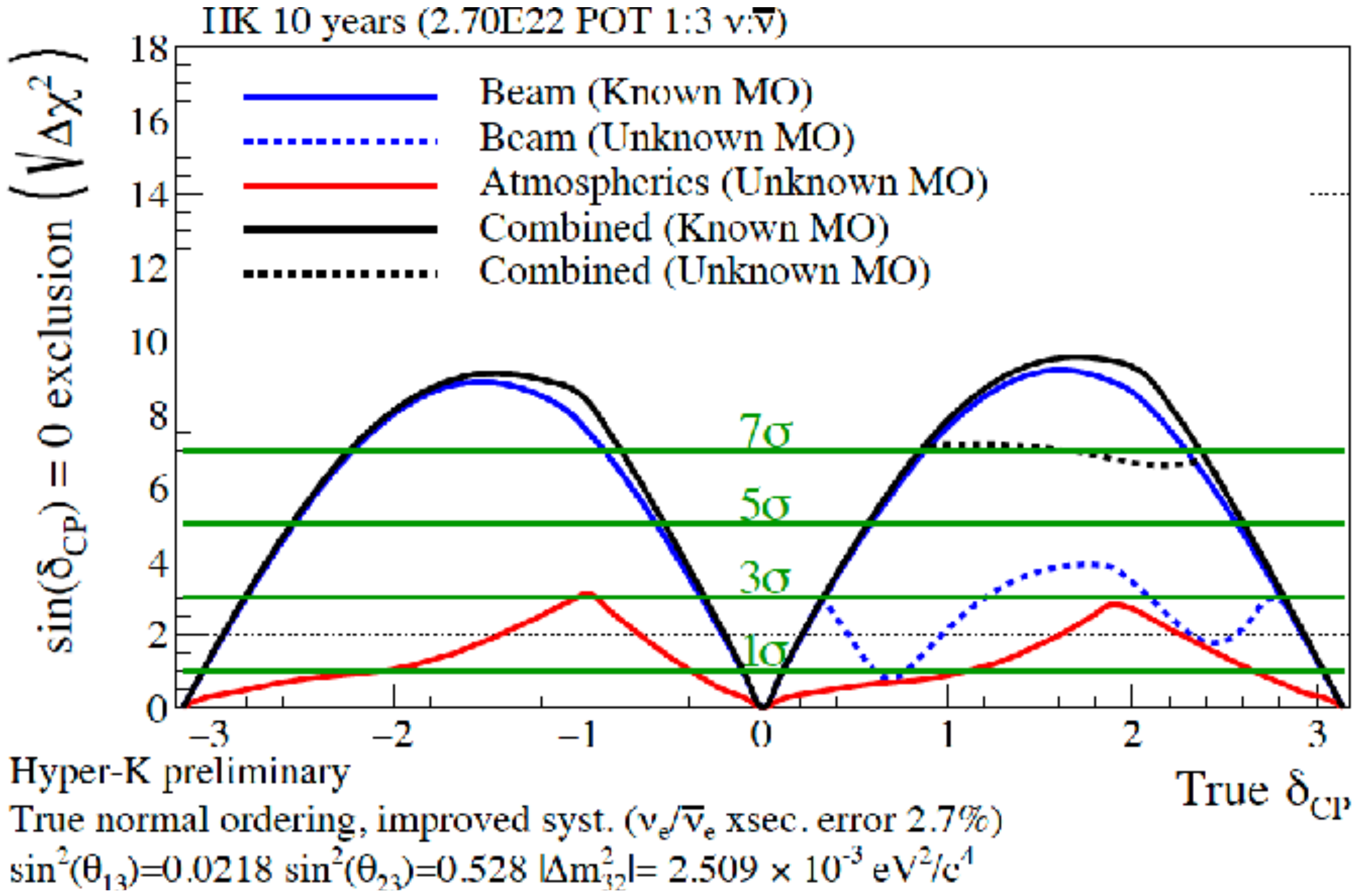
HYPER-K SENSITIVITY

Matter effect

$$\frac{Prob(\nu_\mu \to \nu_e) - Prob(\bar{\nu}_\mu \to \bar{\nu}_e)}{Prob(\nu_\mu \to \nu_e) + Prob(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq -0.28 \sin\delta_{CP} + 0.07$$







- Discovery of CPV may be possible after a few years of data taking
  - Important to reduce systematic uncertainties!
- Evidence of CPV for over 75% of δ_{CP} values at 3σ, over 60% of δ_{CP} values at 5σ
- Hyper-K atmospheric neutrino data is sensitive to mass ordering

HYPER-K SENSITIVITY

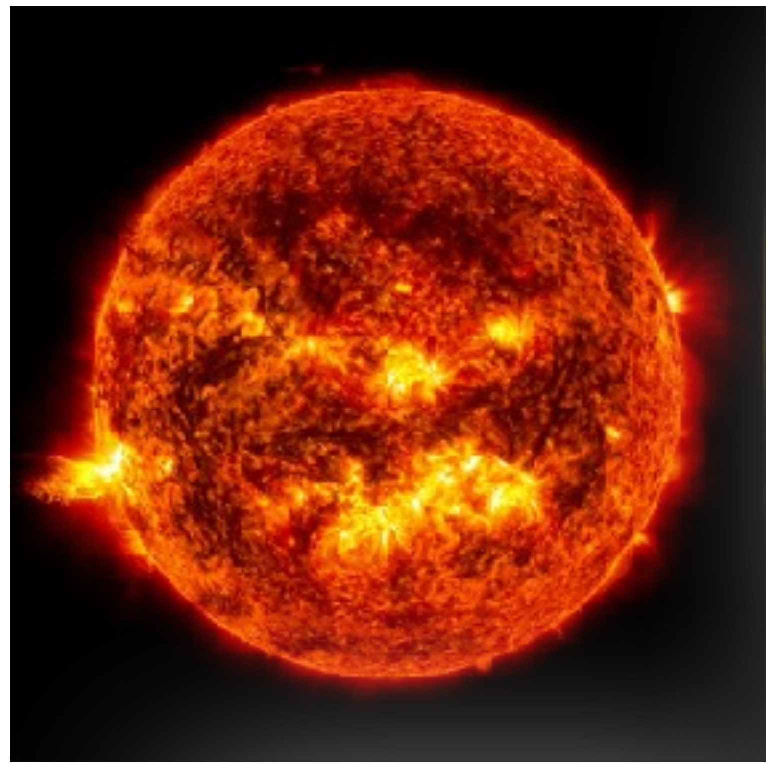
HK sensitivity paper

- Precision for δ_{CP} in 6°-20° range, depending on true value
- Uncertainty on Δm^2_{32} reaching ~0.35%

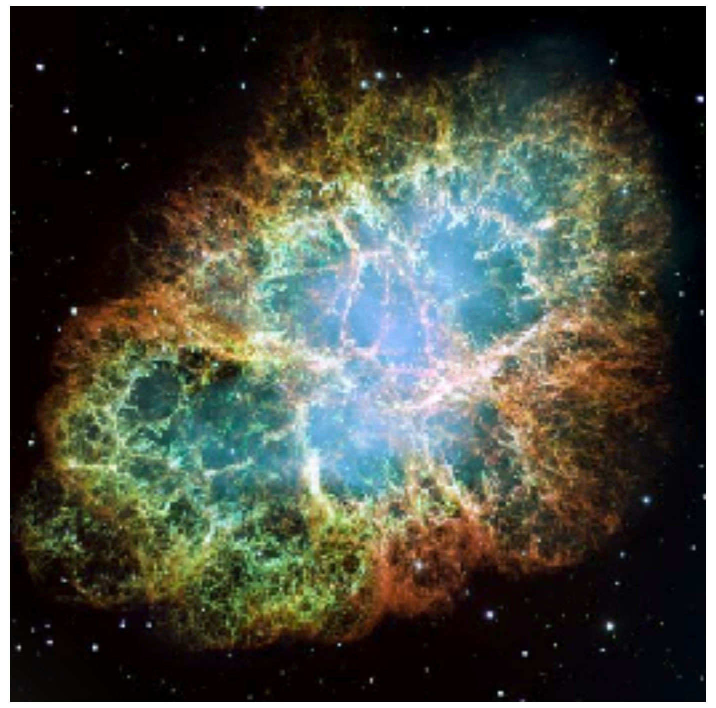
OTHER PHYSICS IN HYPER-K

- Hyper-K is a multi-purpose detector without the beam neutrinos
- Solar neutrino @ Hyper-K
  - 2σ tension in Δm^2_{21} between solar neutrino experiments and KamLAND
  - Hyper-K will test this to > 4σ after 10 years
- Supernova neutrinos @ Hyper-K
  - 50k ~ 80k events from a SN at 10 kpc (galactic centre)
  - > 4σ discovery of diffuse SN neutrino background after 10 years
- Further pushes proton decay lifetime limits in benchmark channels

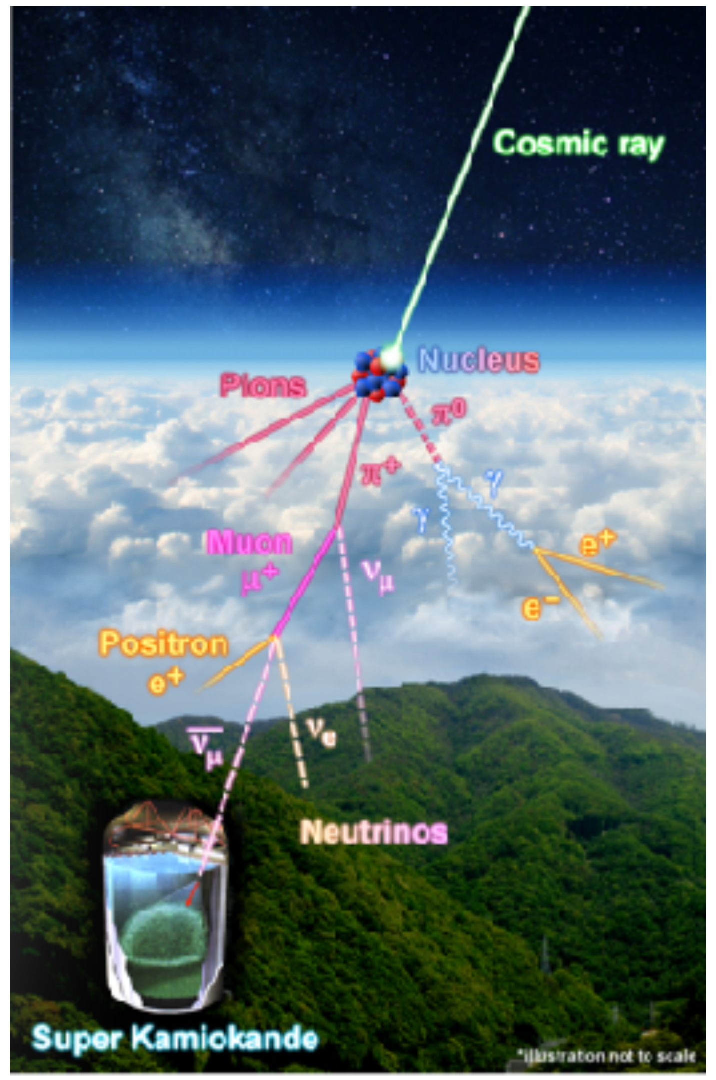
Solar neutrino

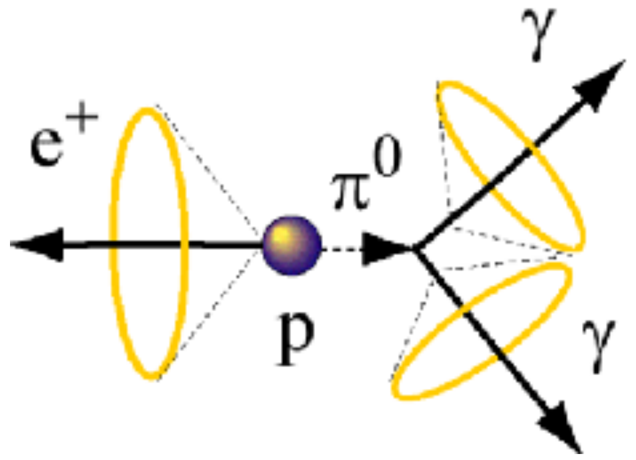


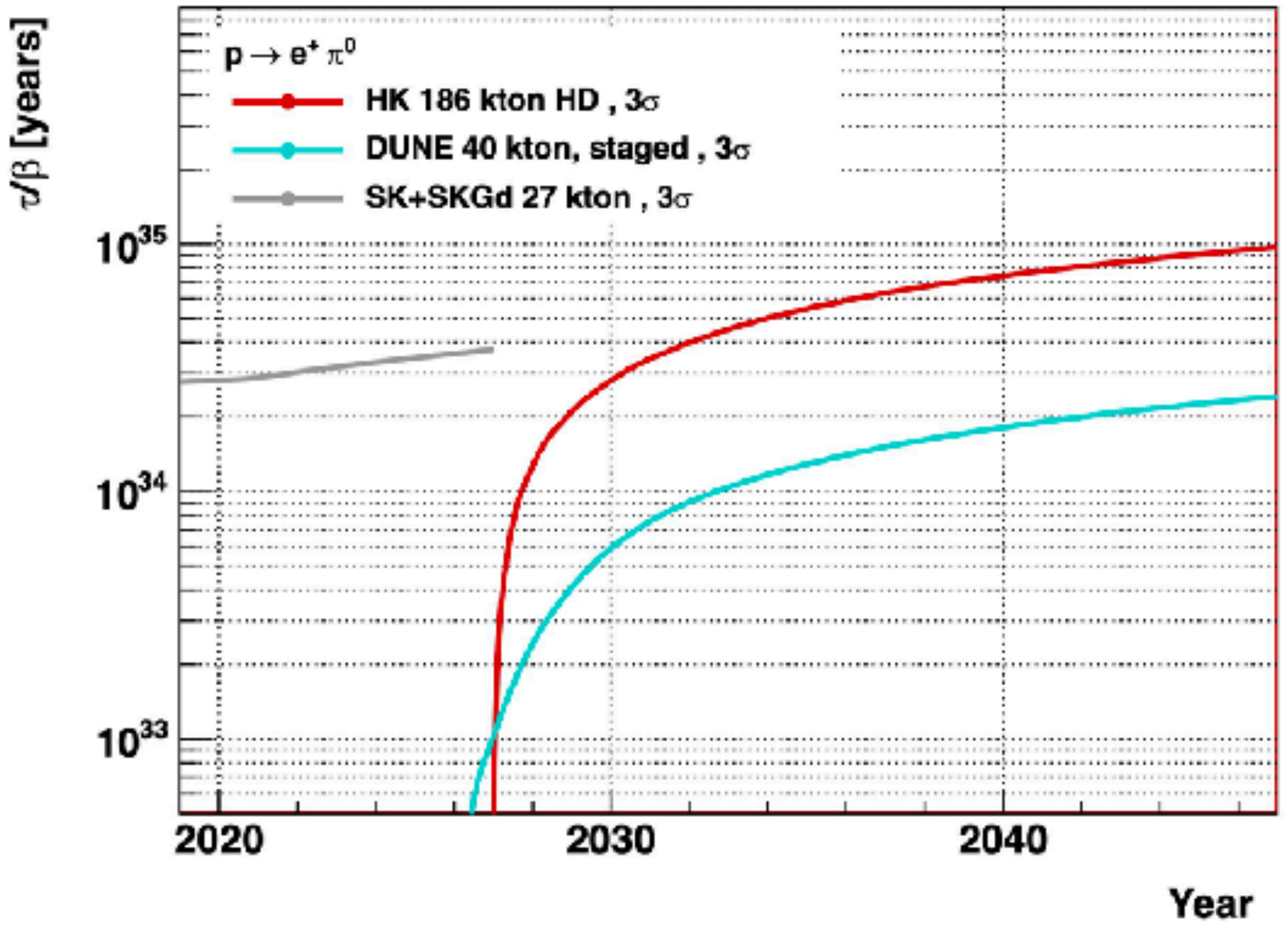
Supernova neutrino



Atmospheric neutrino







CHALLENGES OF SYSTEMATIC UNCERTAINTIES

T2K systematics	FHC 1Re	FHC 1Rμ	RHC 1Re	RHC 1Rμ	FHC 1Re1De	FHC/RHC 1Re
Flux-xsec	3.6%	2.1%	4.3%	3.4%	4.9%	4.4%
Detector	3.1%	2.1%	3.9%	1.9%	13.2%	1.1%
All	4.7%	3.0%	5.9%	4.0%	14.1%	4.6%

Improved systematics	FHC 1Re	FHC 1Rμ	RHC 1Re	RHC 1Rμ	FHC 1Re1De	FHC/RHC 1Re
Flux-xsec	1.8%	0.9%	1.6%	0.9%	1.8%	1.9%
Detector	1.1%	0.8%	1.5%	0.7%	4.9%	0.4%
All	2.1%	1.2%	2.2%	1.1%	5.2%	2.0%

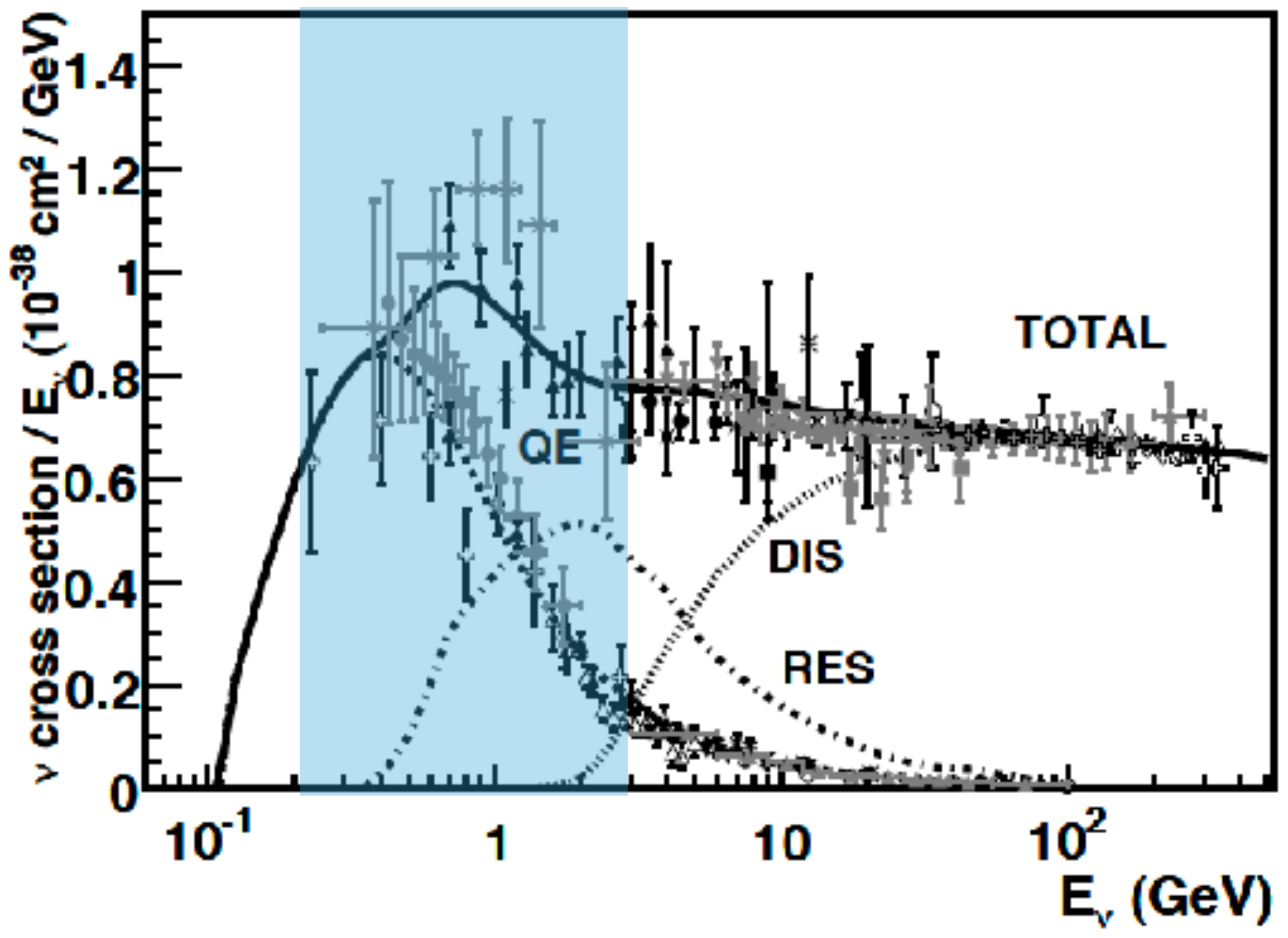
$$R(\vec{x}) = \Phi(E_\nu) \times \sigma(E_\nu, \vec{x}) \times \epsilon(\vec{x}) \times P(\nu_A \rightarrow \nu_B)$$

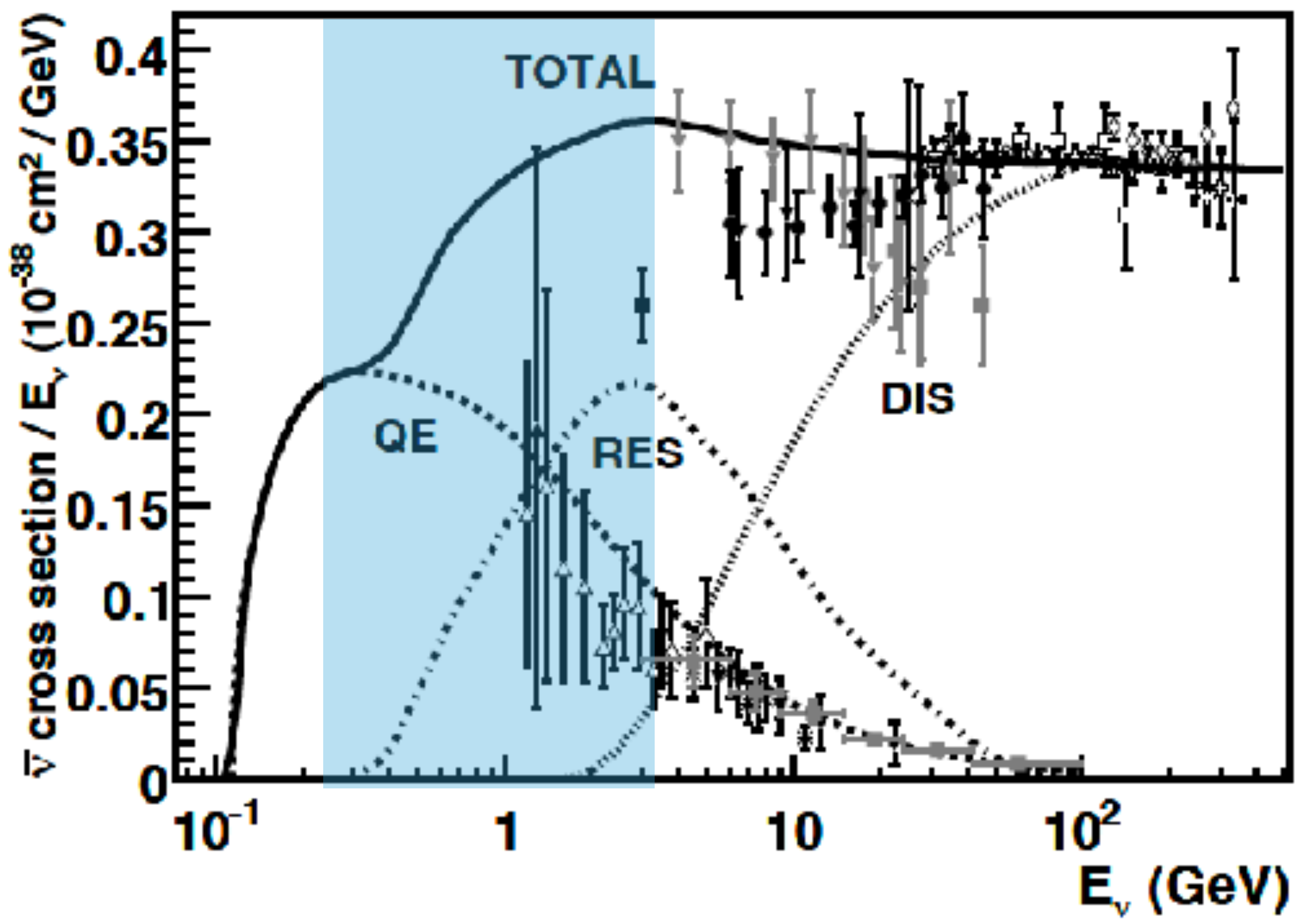
Neutrino rate at far detector | Neutrino flux | Neutrino Cross section | Detector efficiency | Oscillation probability

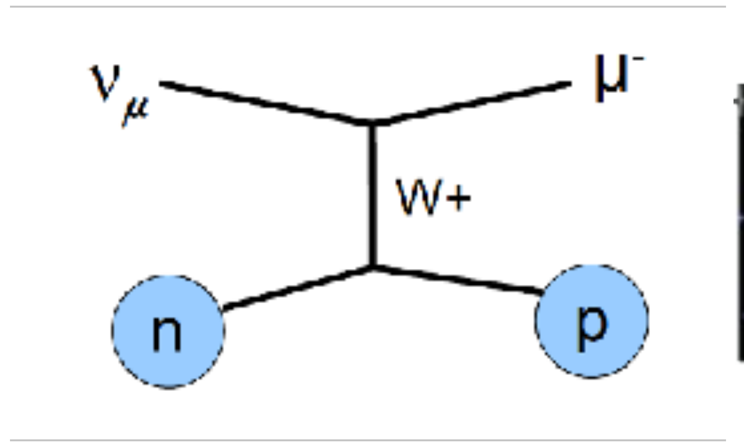
- Hyper-K aims to more than halve systematic uncertainties compared to T2K
  - IWCD helps reduce flux⊗xsec uncertainty
    - ν_e ($\bar{\nu}_e$) cross section measurement
  - Better understanding of the detector is needed → Best if can be test with control samples

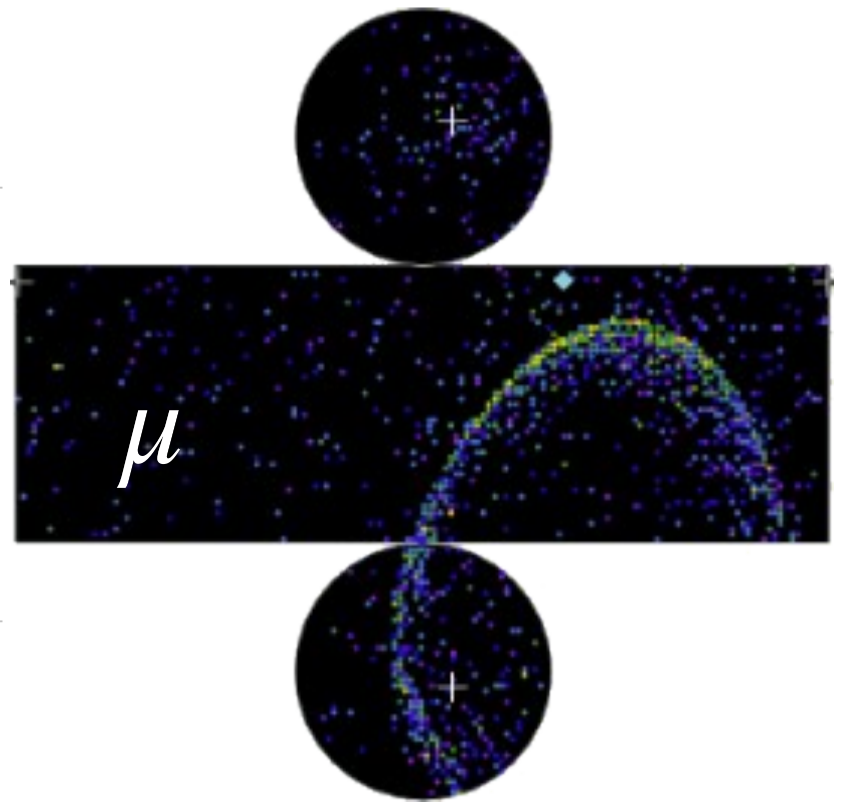
NEUTRINO ENERGY RECONSTRUCTION

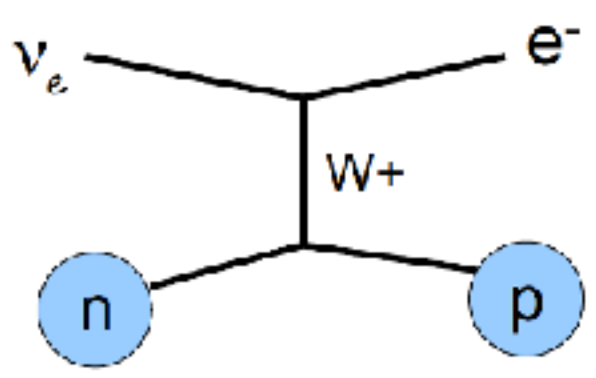
- Selecting CCQE events with one electron or muon in the final state
  - Neutrino energy reconstruction in water Cherenkov detectors based on lepton kinematics:
    $$E_\nu^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_l^2 + 2\,(m_n - E_b)\,E_l}{2\,(m_n - E_b - E_l + p_l\cos\theta)}$$, where E_b is the nucleon removal energy

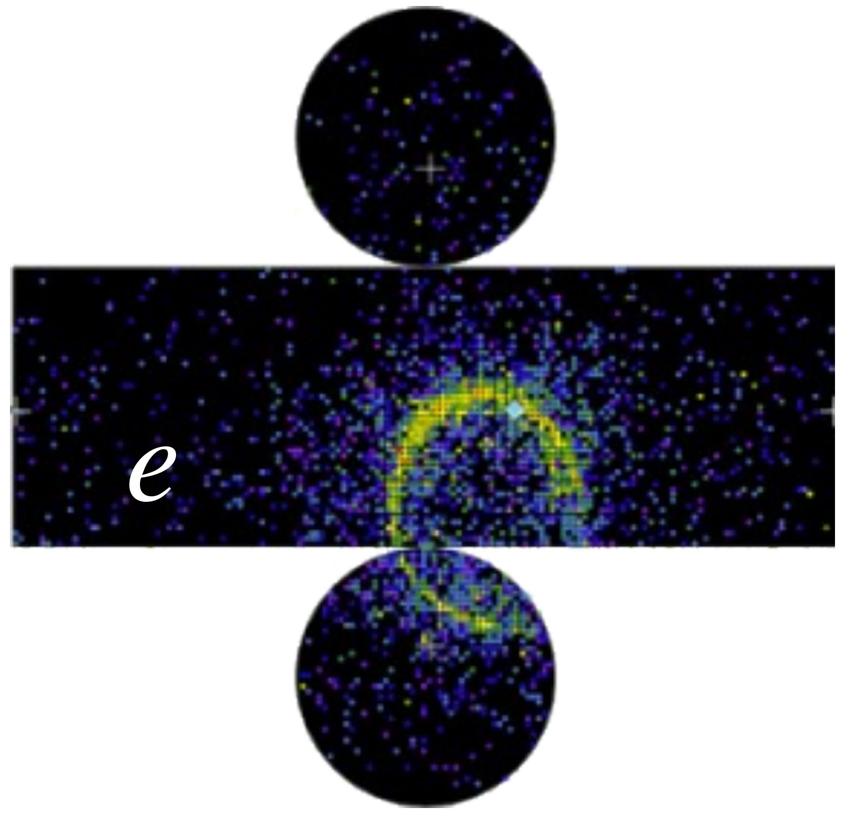












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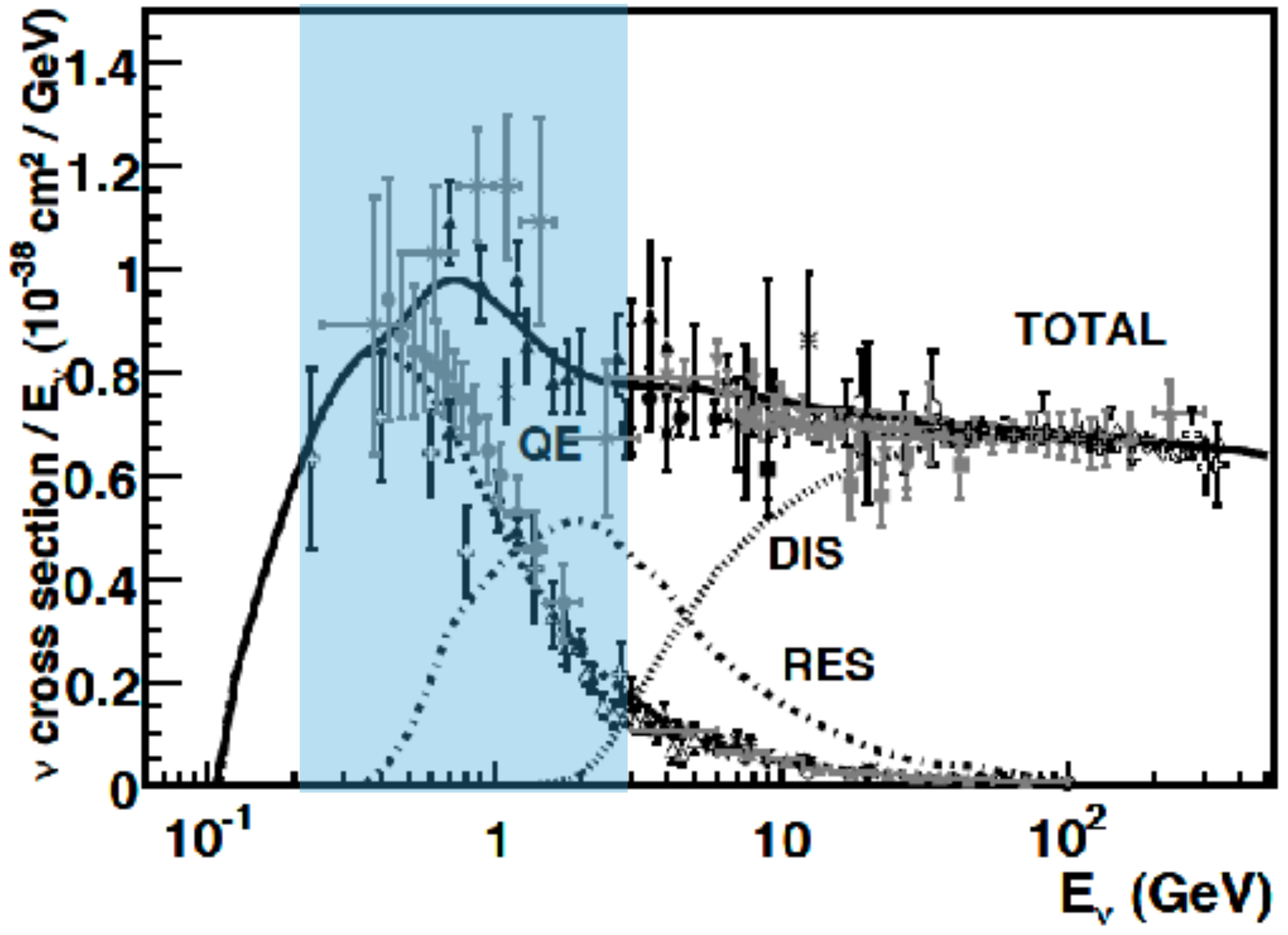
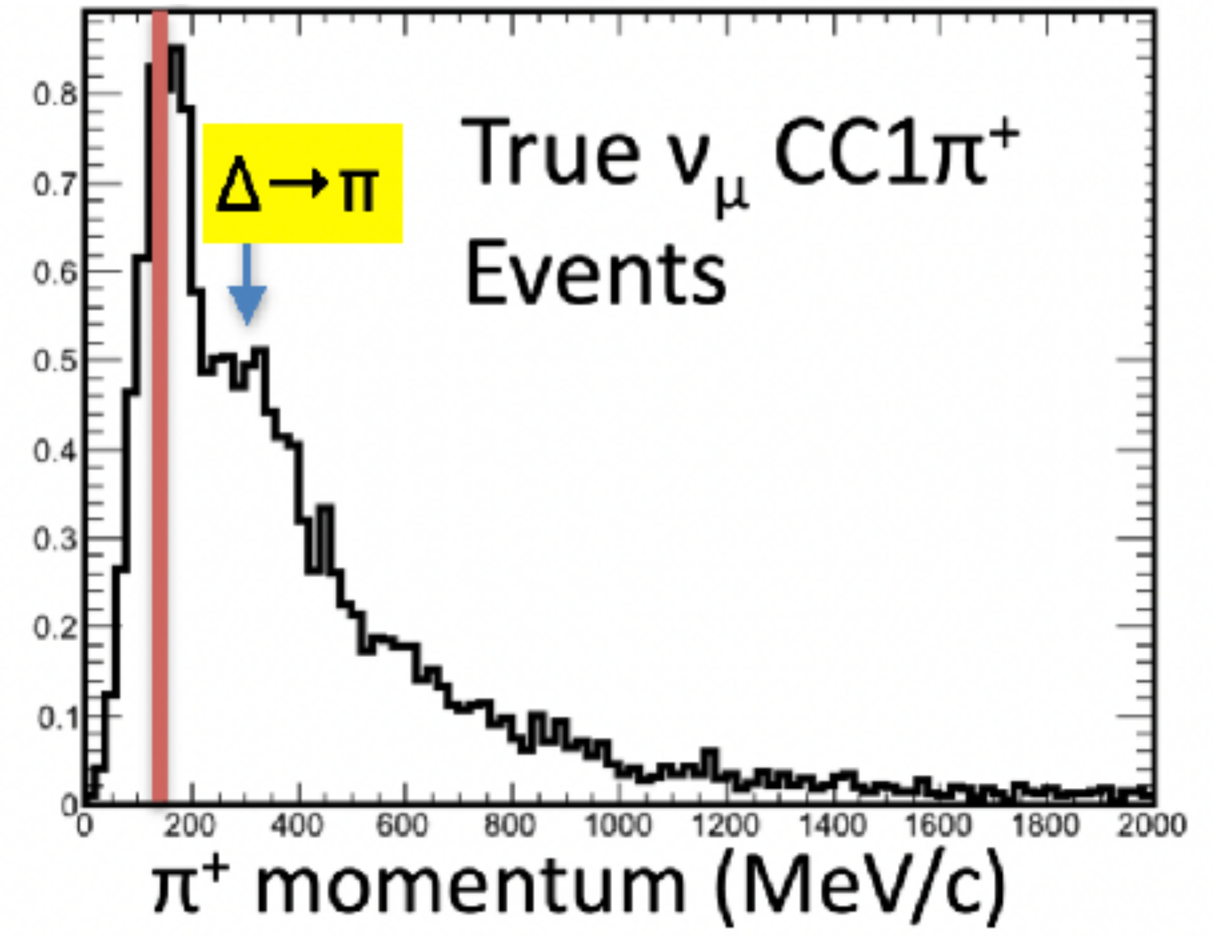
  - Neutrino energy reconstruction in water Cherenkov detectors based on lepton kinematics:

$$E_\nu^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_l^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l + p_l \cos\theta)}$$

, where E_b is the nucleon removal energy

- Resonant and NC pion production and DIS events can also mix in if the charged pions are below Cherenkov threshold or fake a lepton





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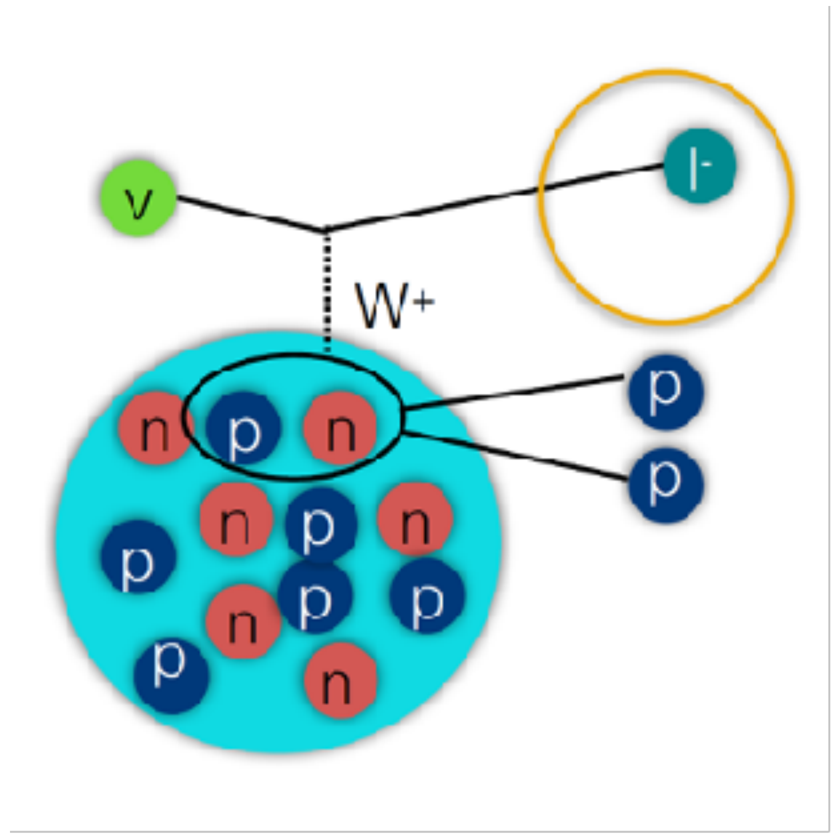
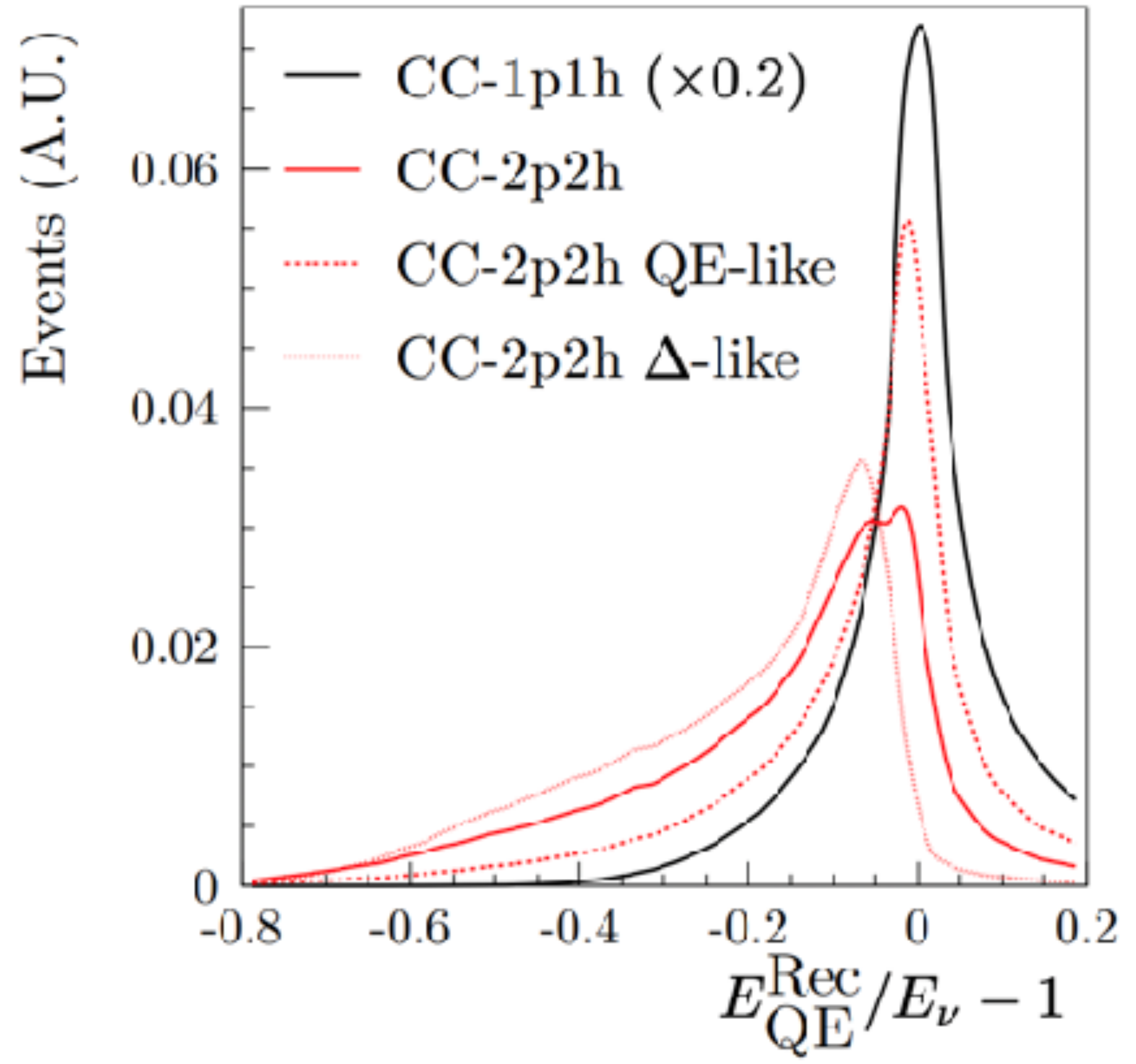
- Resonant and NC pion production and DIS events can also mix in if the charged pions are below Cherenkov threshold or fake a lepton
- Multi-nucleon interactions (e.g. 2p-2h) can cause bias in neutrino energy reconstruction





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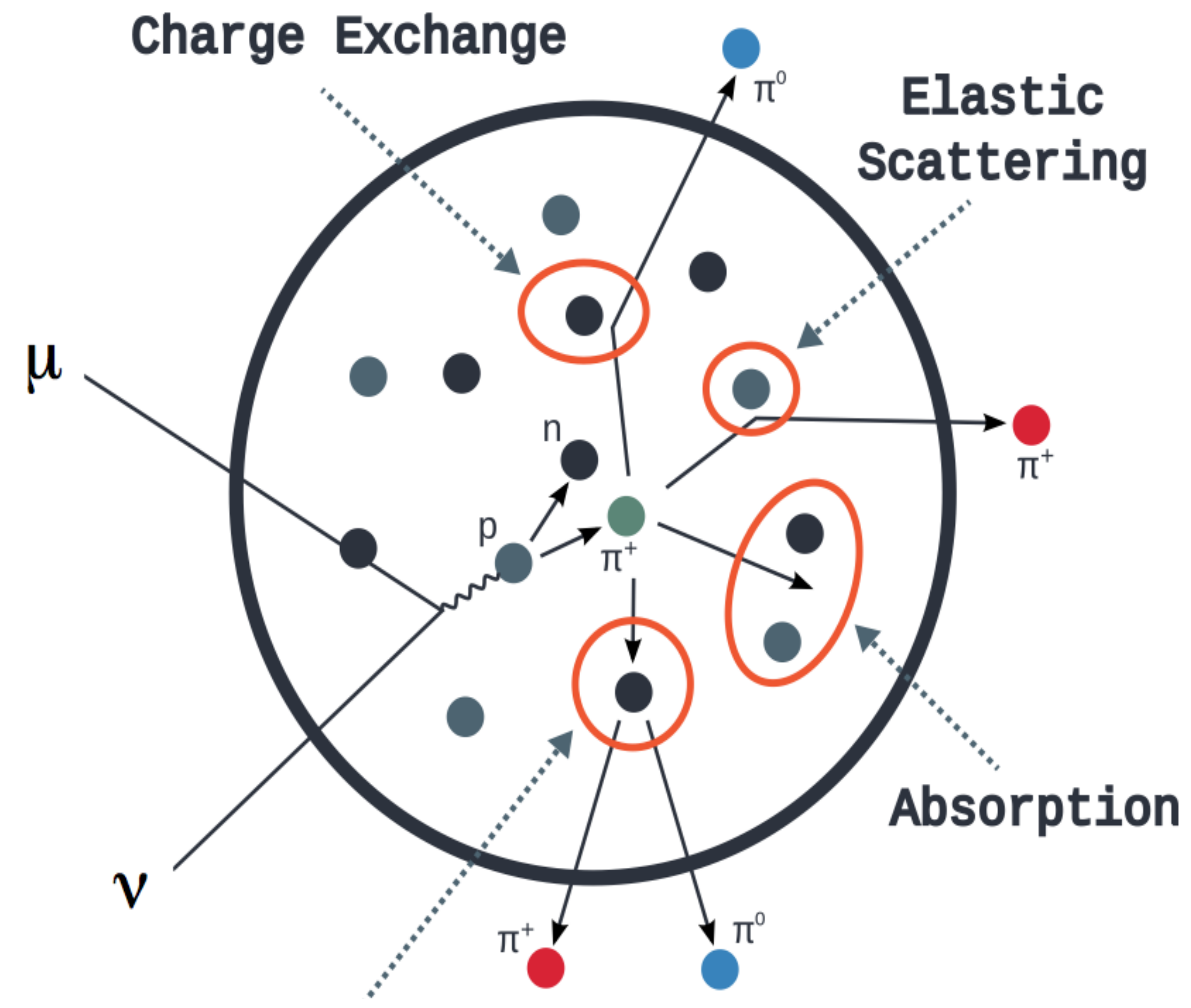
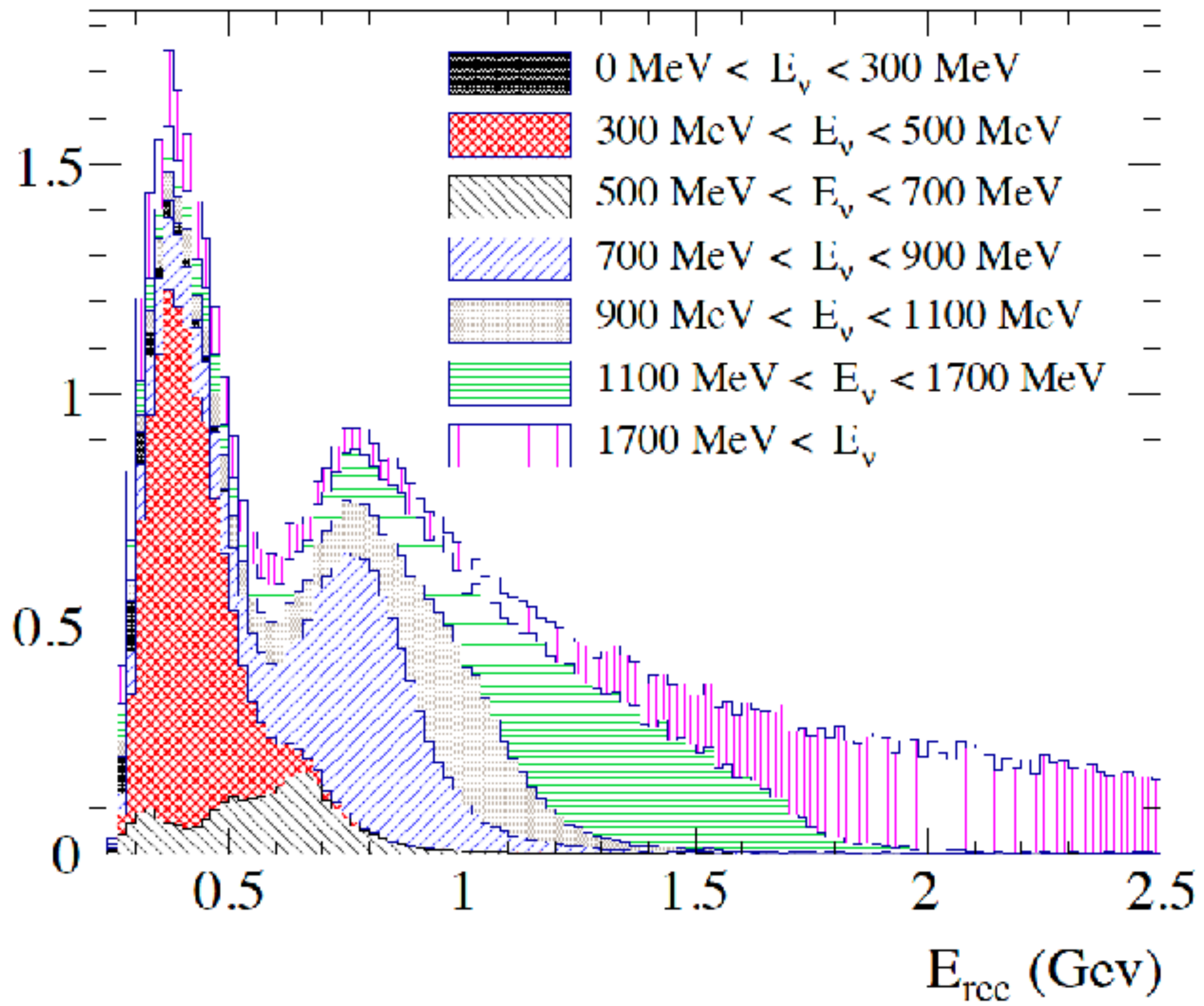
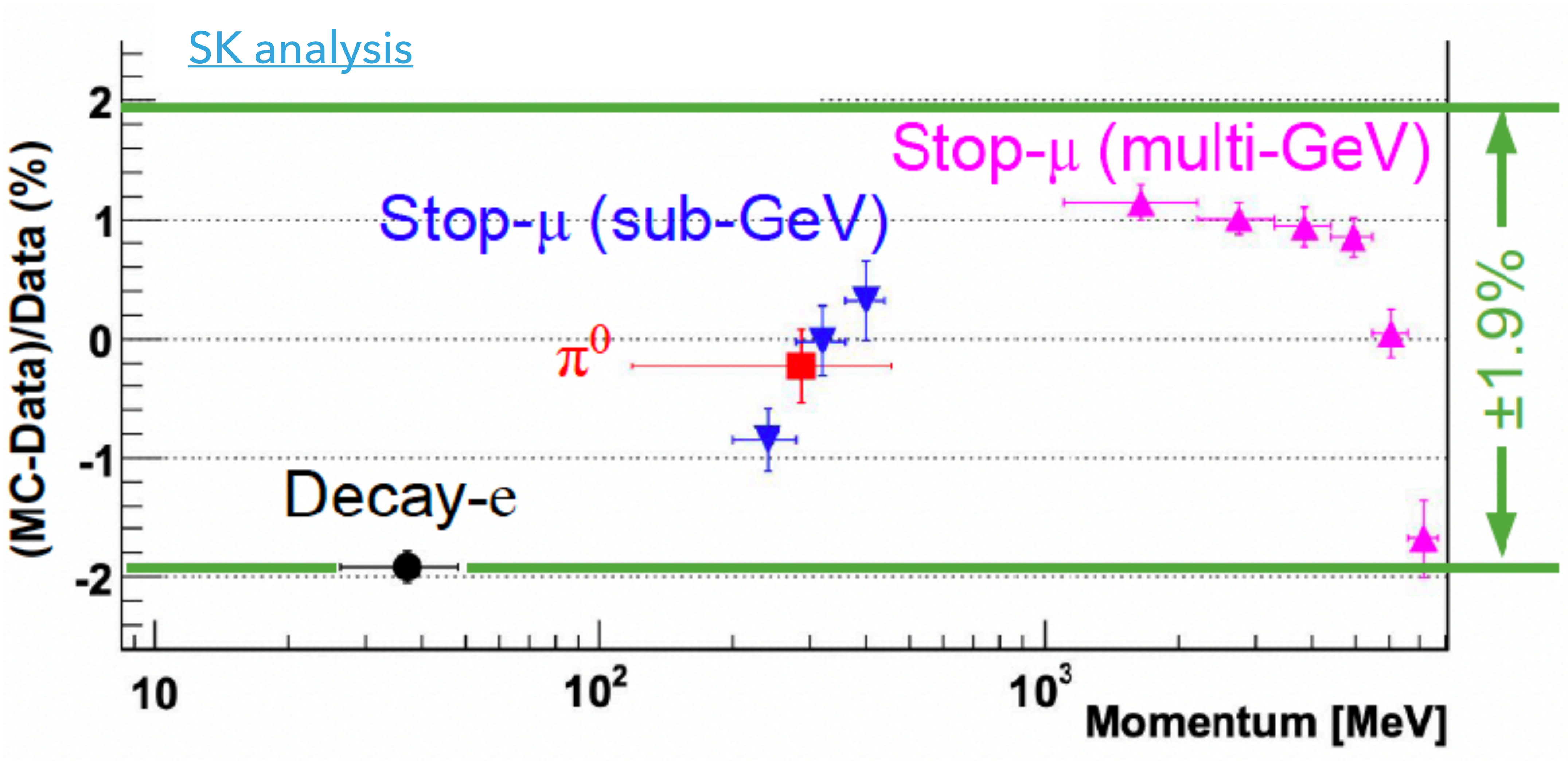
- Selecting CCQE events with one electron or muon in the final state
  - Neutrino energy reconstruction in water Cherenkov detectors based on lepton kinematics:
    $$E_\nu^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_l^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l + p_l\cos\theta)}$$, where E_b is the nucleon removal energy
- Resonant and NC pion production and DIS events can also mix in if the charged pions are below Cherenkov threshold or fake a lepton
- Multi-nucleon interactions (e.g. 2p-2h) can cause bias in neutrino energy reconstruction
- Final state interactions (FSI) and secondary interactions (SI) can further obscure event reconstruction



DETECTOR SYSTEMATIC UNCERTAINTY



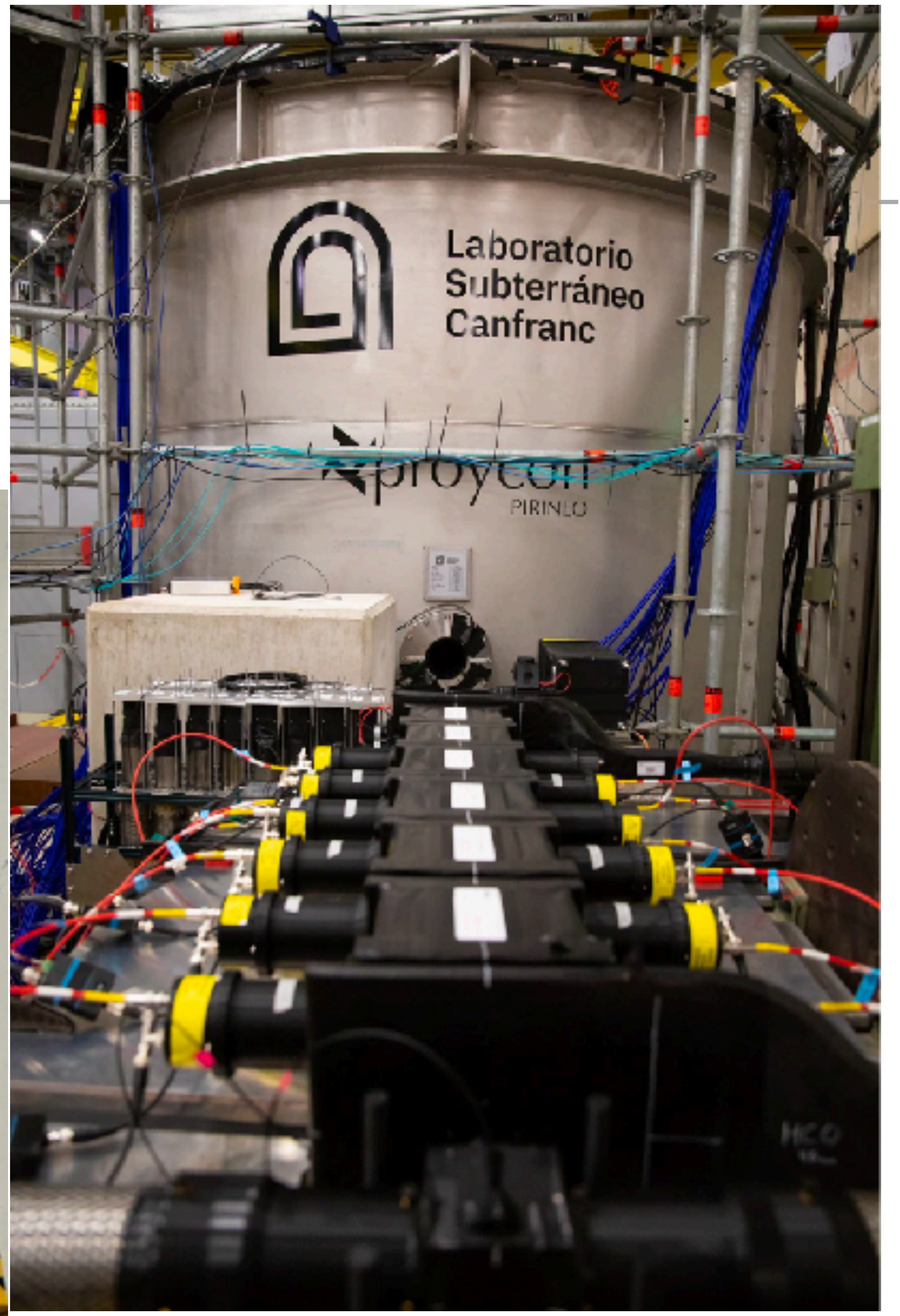
- The way neutrino energy is reconstructed in water Cherenkov detectors leads to "feed-down" effect
  - IWCD can probe this effect with measurements at different off-axis angles and make flux⊗xsec measurement more robust
  - **This means understanding the detector is ever more crucial**

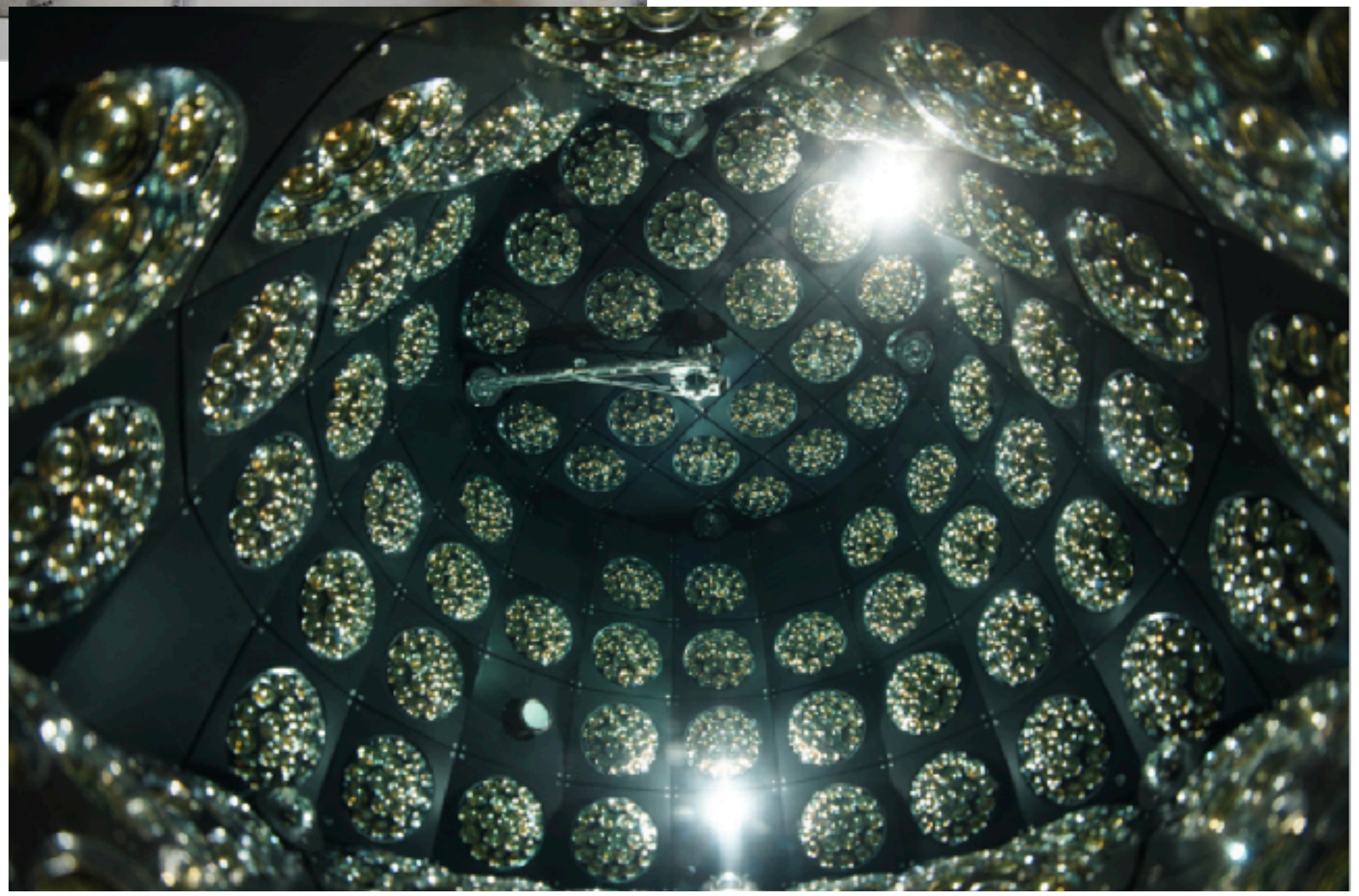


- Control samples are used to estimated SK detector systematic uncertainties
  - Based on data/MC differences
  - Will not be reduced with increased statistics alone
- Progress on detector calibration
  - Can we test it on actual data? —> Yes! With WCTE

WATER CHERENKOV TEST EXPERIMENT (WCTE)

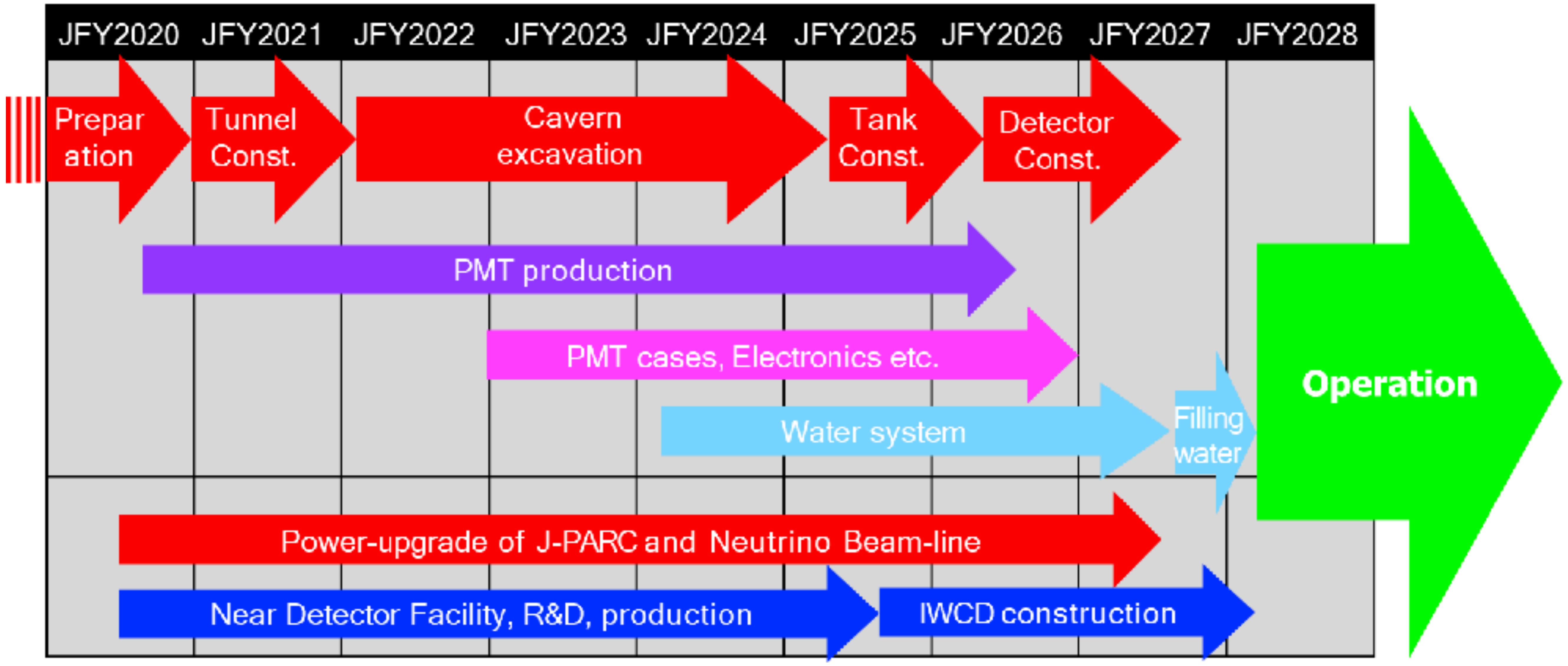
- Water Cherenkov Test Experiment (WCTE) acts as prototype for IWCD
  - 93 IWCD mPMTs and 4 Hyper-K mPMTs installed
  - Testbed for water Cherenkov detector systems and new calibration techniques
  - Detector height/diameter is ~1/2 of IWCD
- Operated in CERN T9 (East Hall) beam line from Oct. 2024 to Jun. 2025
  - Pure water and Gd-doped operations
- Data collected for $\pi^{\pm}, p, e^{\pm}, \mu^{\pm}, \gamma$ at 0.08 ~ 1.8 GeV/c
- Also opportunity for important reconstruction and physics studies
  - Pion hadronic scattering
  - Muon/electron scattering to probe nuclear effects
  - Study of particle identification techniques and capability with tagged data
  - Neutron production by hadrons in water
  - …





SUMMARY

- Hyper-K is well positioned for operation in 2028
  - **Cavern excavation completed in July!**
- Wide-ranging physics discoveries to come
  - Discovery of CPV in the lepton sector
  - Precision measurement of neutrino oscillation
  - Neutrino astrophysics & proton decay
  - Lowering systematic uncertainties will be crucial
    - Efforts are underway



22 countries, ~650 members in 2025

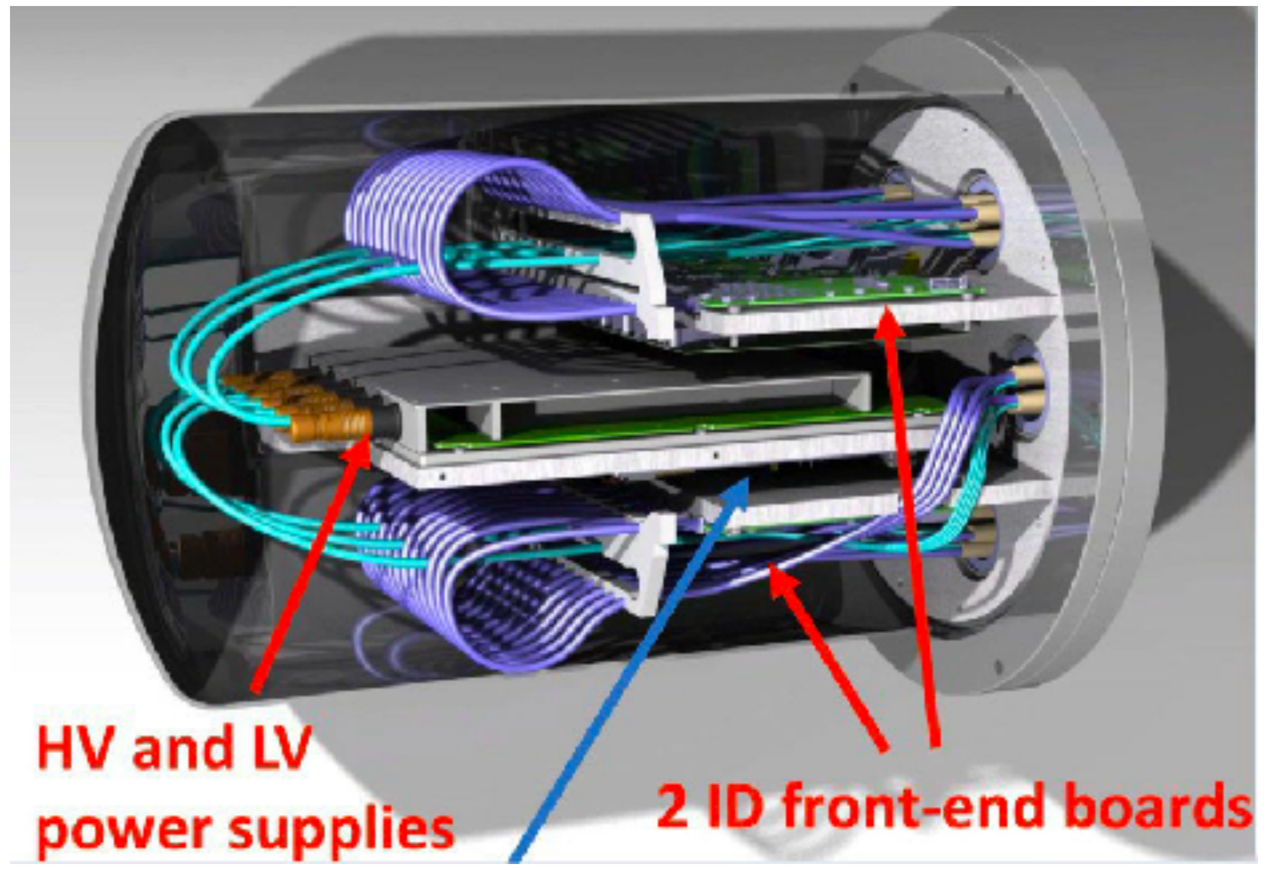
THANK YOU FOR YOUR ATTENTION.
ANY QUESTIONS?

Relevant posters:

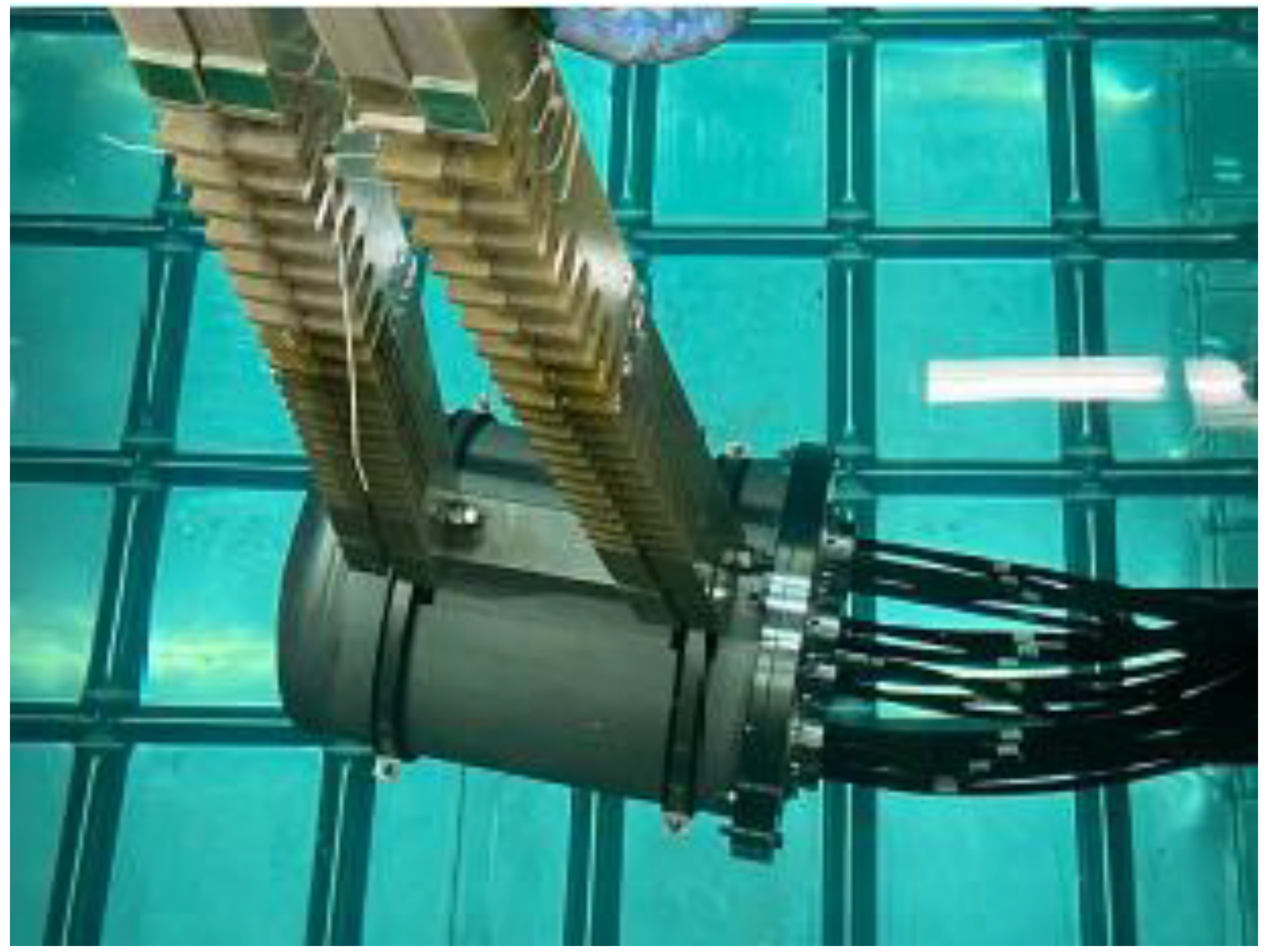
“The Water Cherenkov Test Experiment: Detector and Physics Lessons Towards Hyper-Kamiokande”

“Leveraging Water Cherenkov Detector Technologies for Water Quality Monitoring”

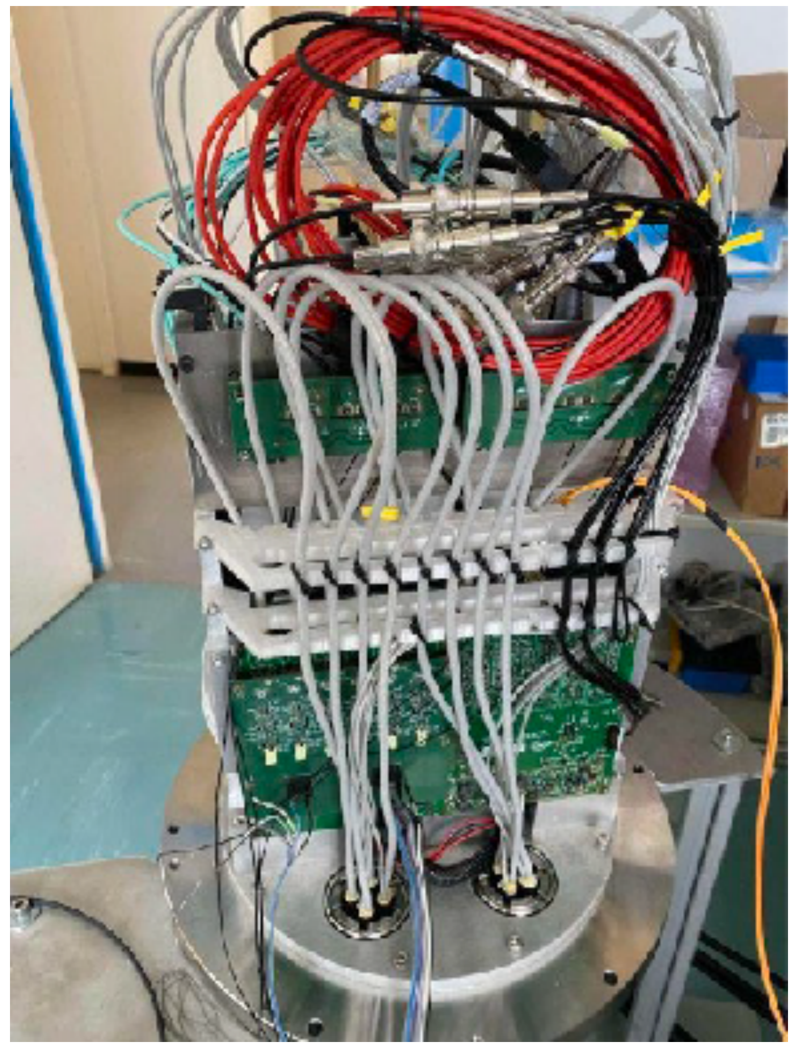
HK PMT ELECTRONICS, COVER, AND OD PMT

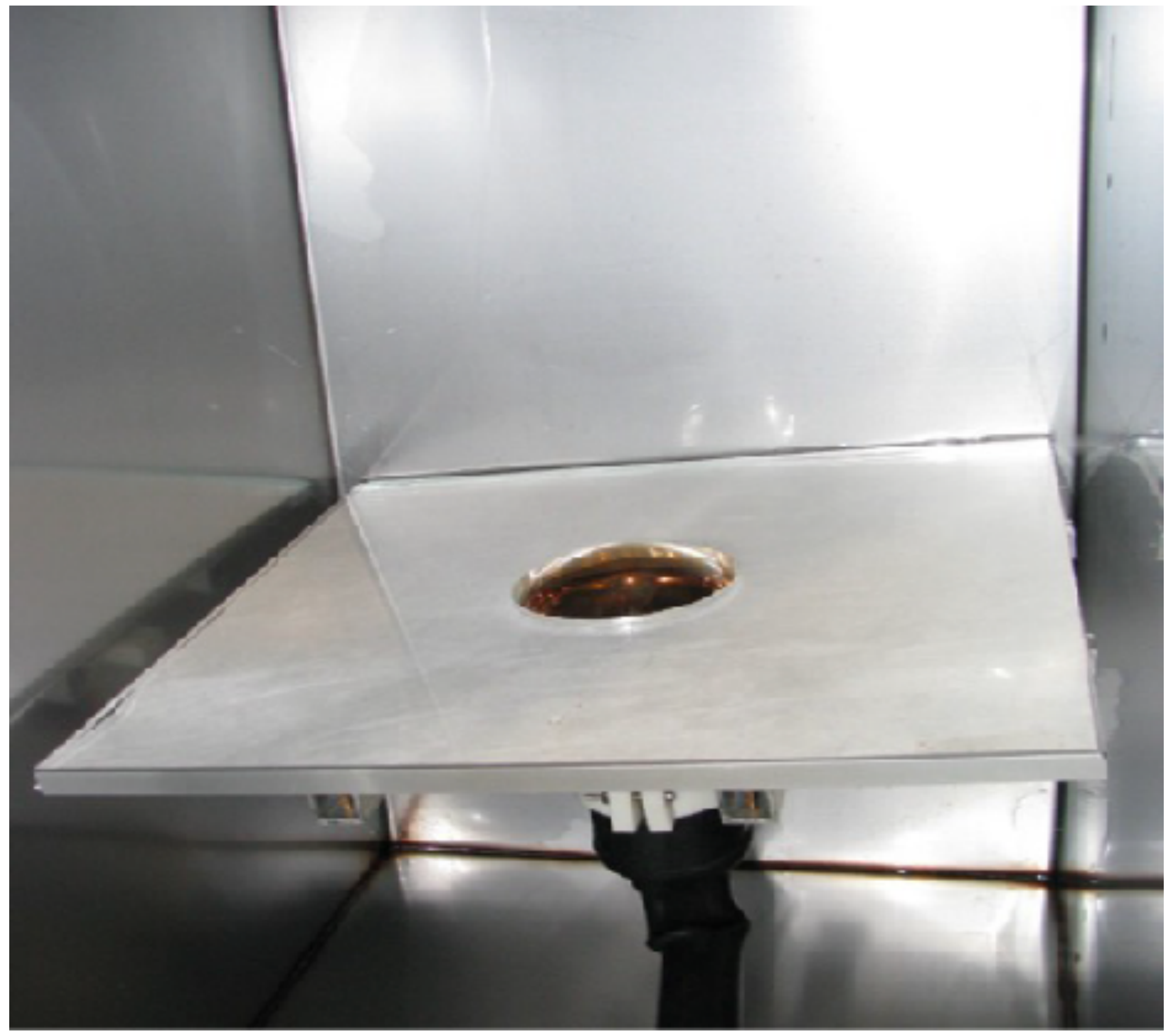


Data processing and timing boards

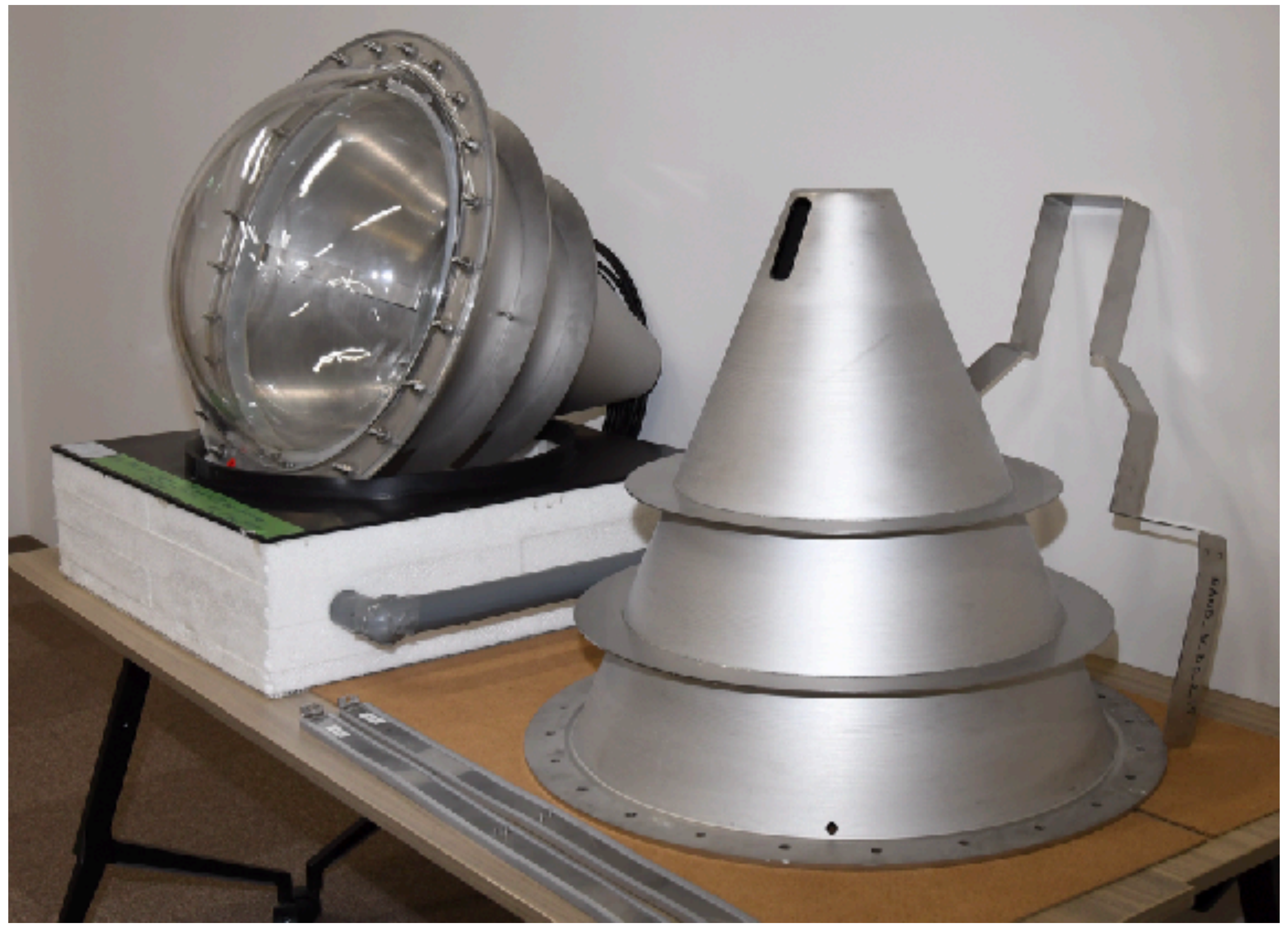


- PMT electronics will be house in pressure vessels under water





- OD PMT and WLS plate



- 20″ PMT cover

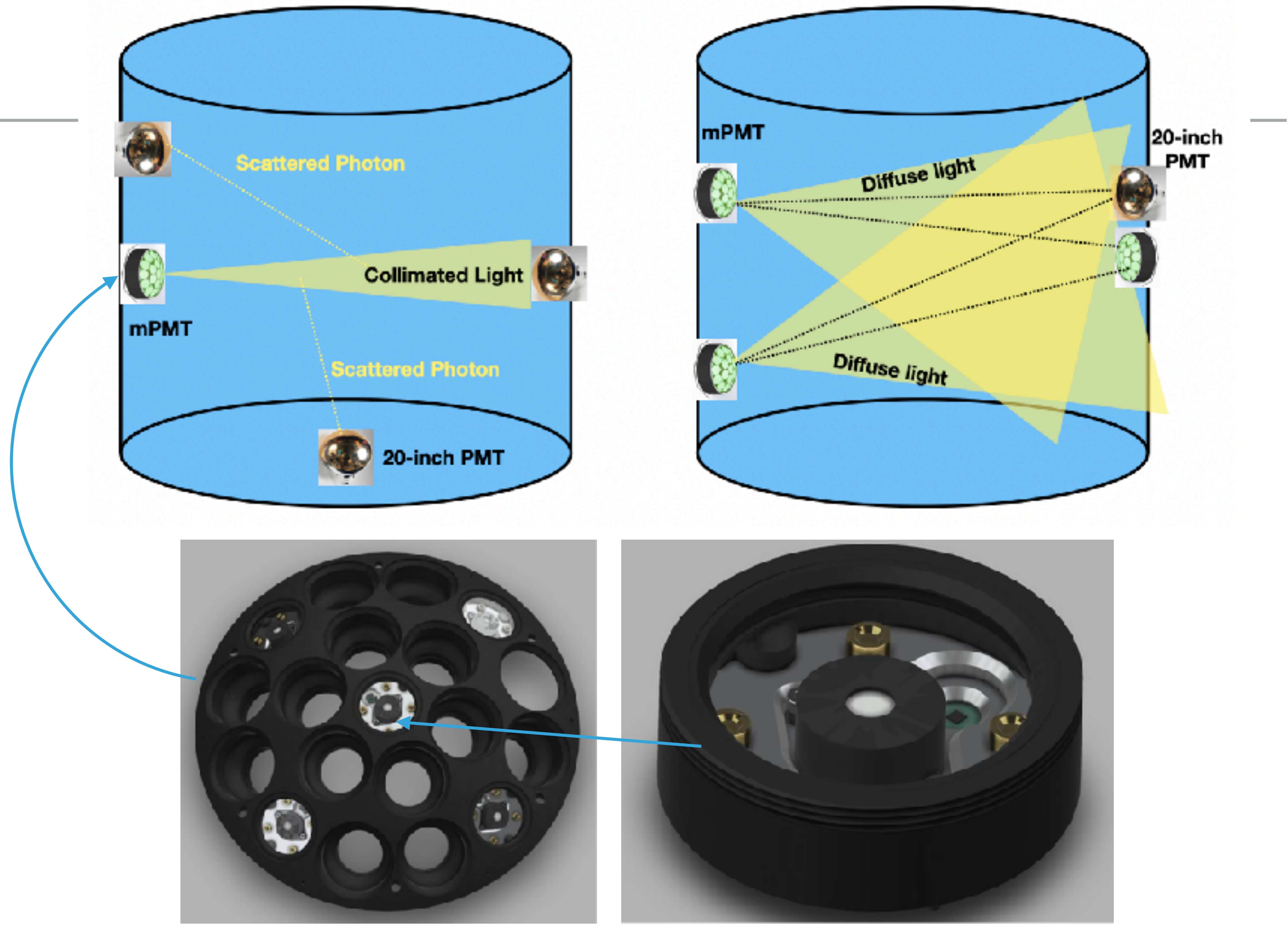
OTHER QA AND INSTALLATION TEST

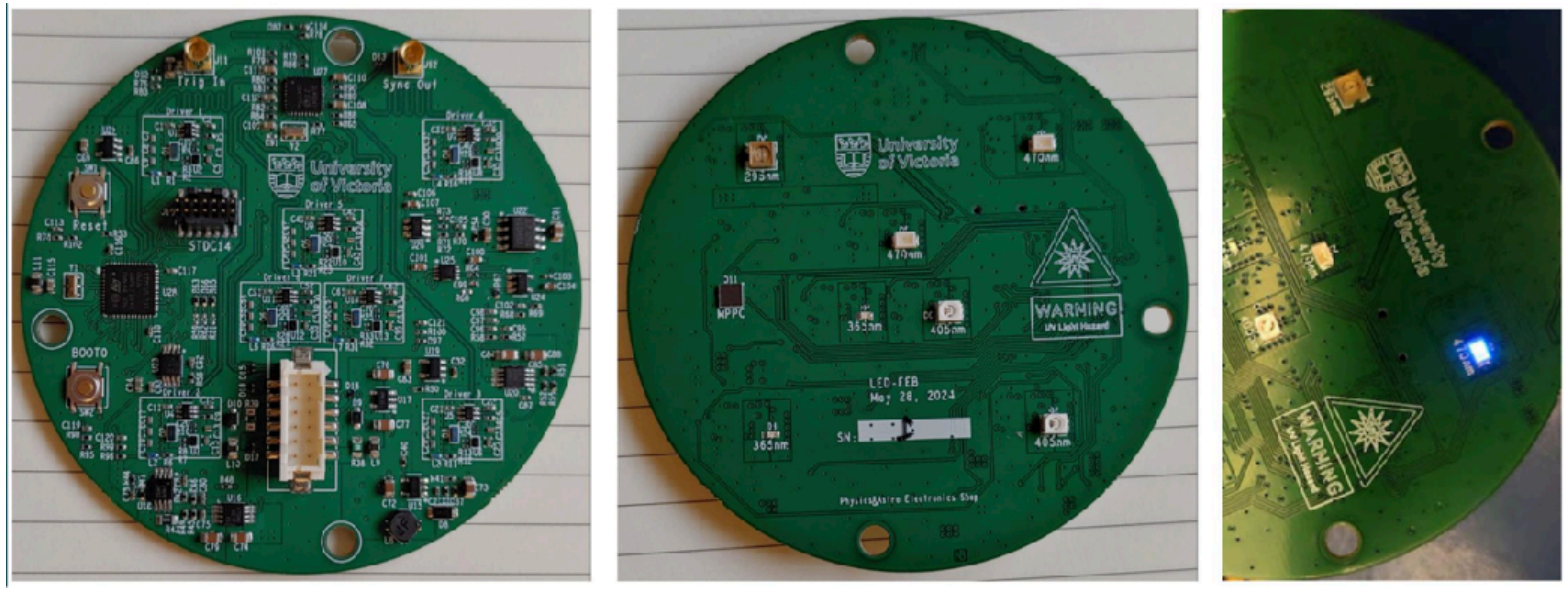
Mock-up ID, OD PMT installation test

mPMT

PULSED LIGHT SOURCES IN HYPER-K

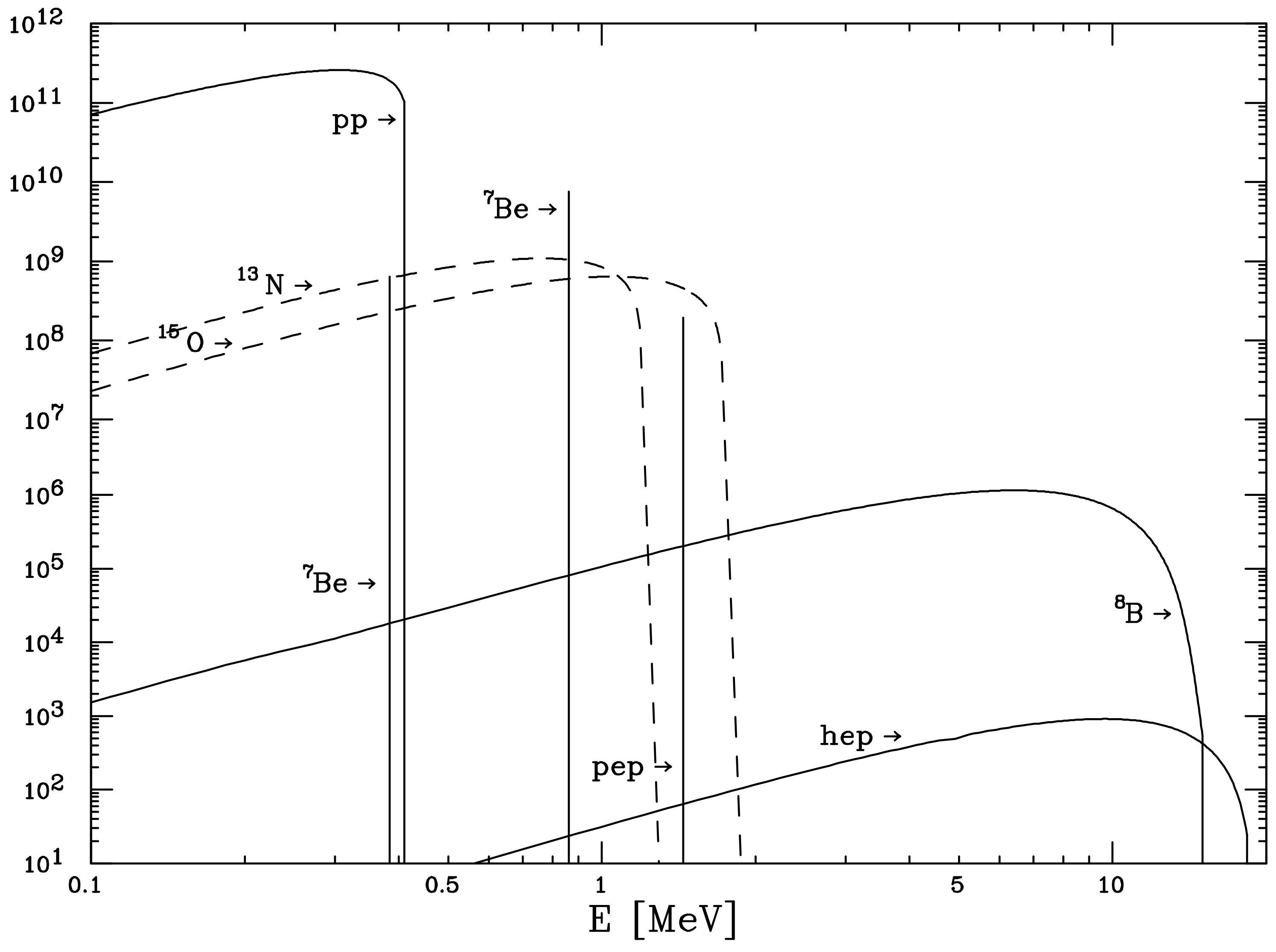
- For 200 mPMTs in HK we would replace 5 PMTs with LED units
  - Each of the five LED units will have 7 LEDs with wavelengths ranging from 295 nm to 550 nm,
    - < 1 ns pulse width
    - Same LED driving circuit also used by WCTE mPMTs and beam monitor calibration
- 4,000 collimated light sources to calibrate photon scattering, absorption and reflection
- 3,000 Wide-angle light sources to calibrate PMT timing and angular response calibration

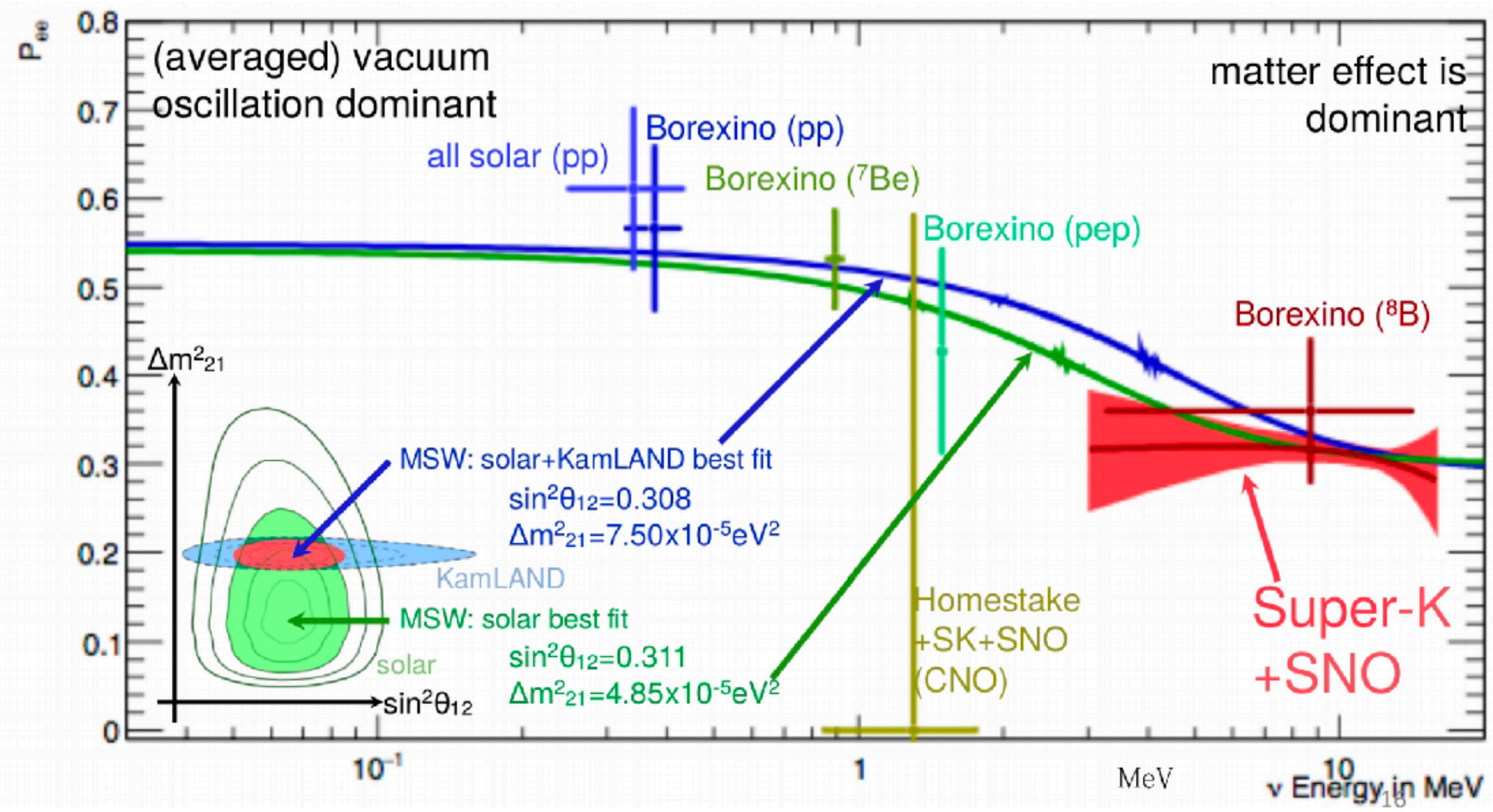




One of the 470 nm LED is pulsed at 10 MHz to be easily visible by eye

SOLAR NEUTRINOS

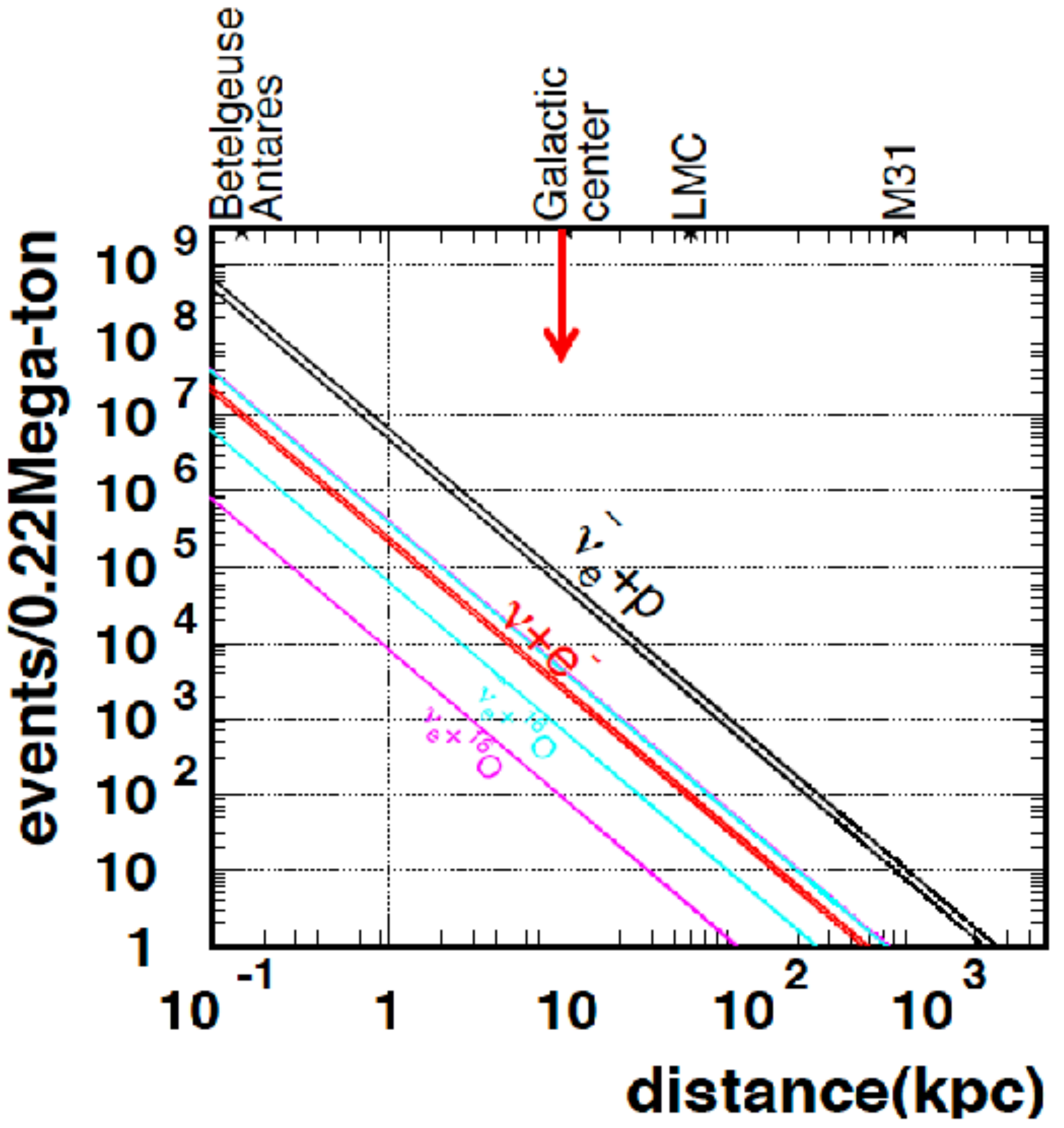


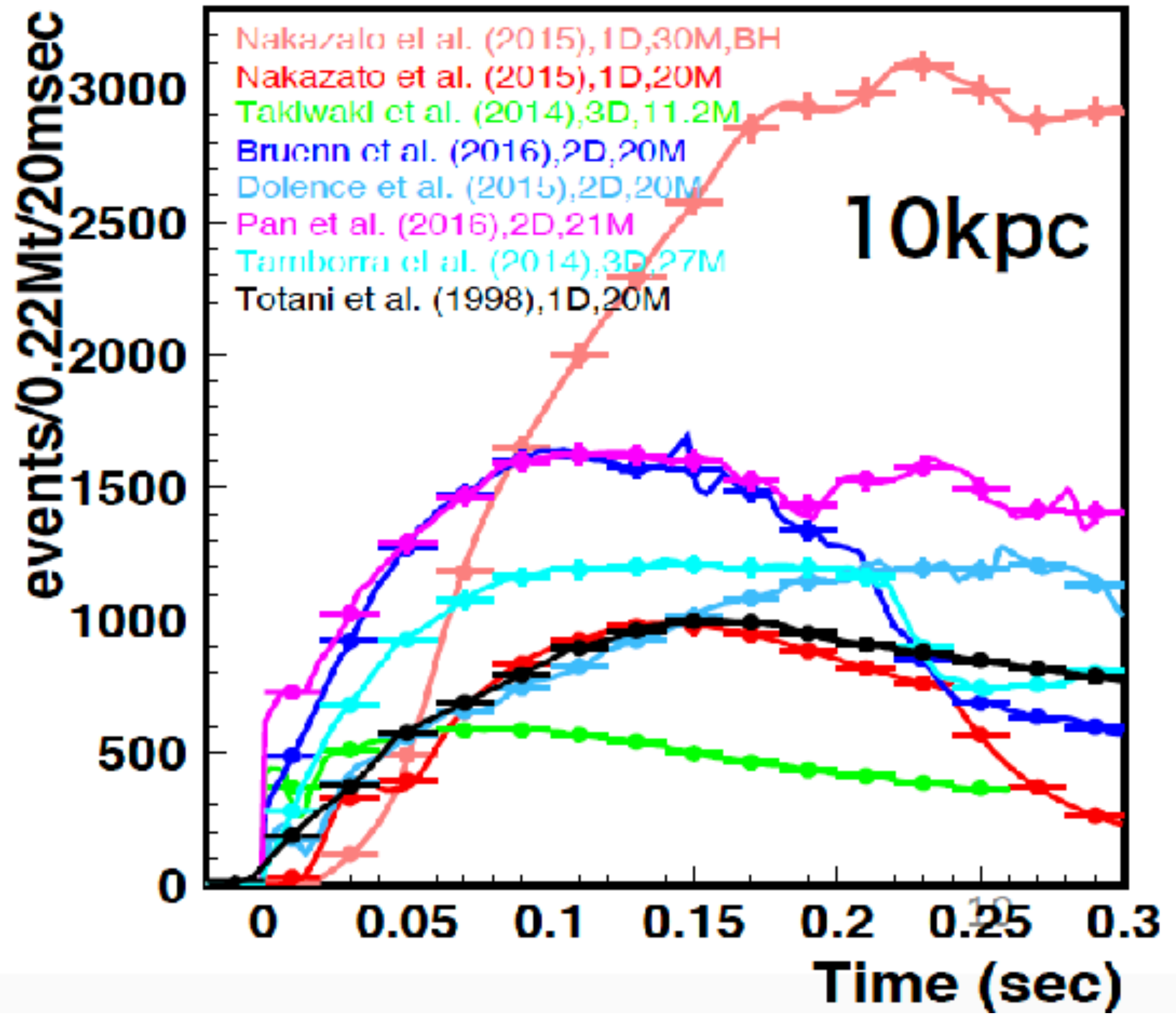


- > 100 solar $\nu + e \rightarrow \nu + e$ events per day in Hyper-K
- 2σ tension in Δm^2_{21} between solar neutrino experiments and KamLAND
  - Hyper-K will test this to > 4σ after 10 years
- Super-K and SNO predict slower "upturn": non -standard interaction in the dense Sun? Light sterile neutrinos?
  - Hyper-K will be able to test it to > 3σ after 10 years

SUPERNOVA NEUTRINOS

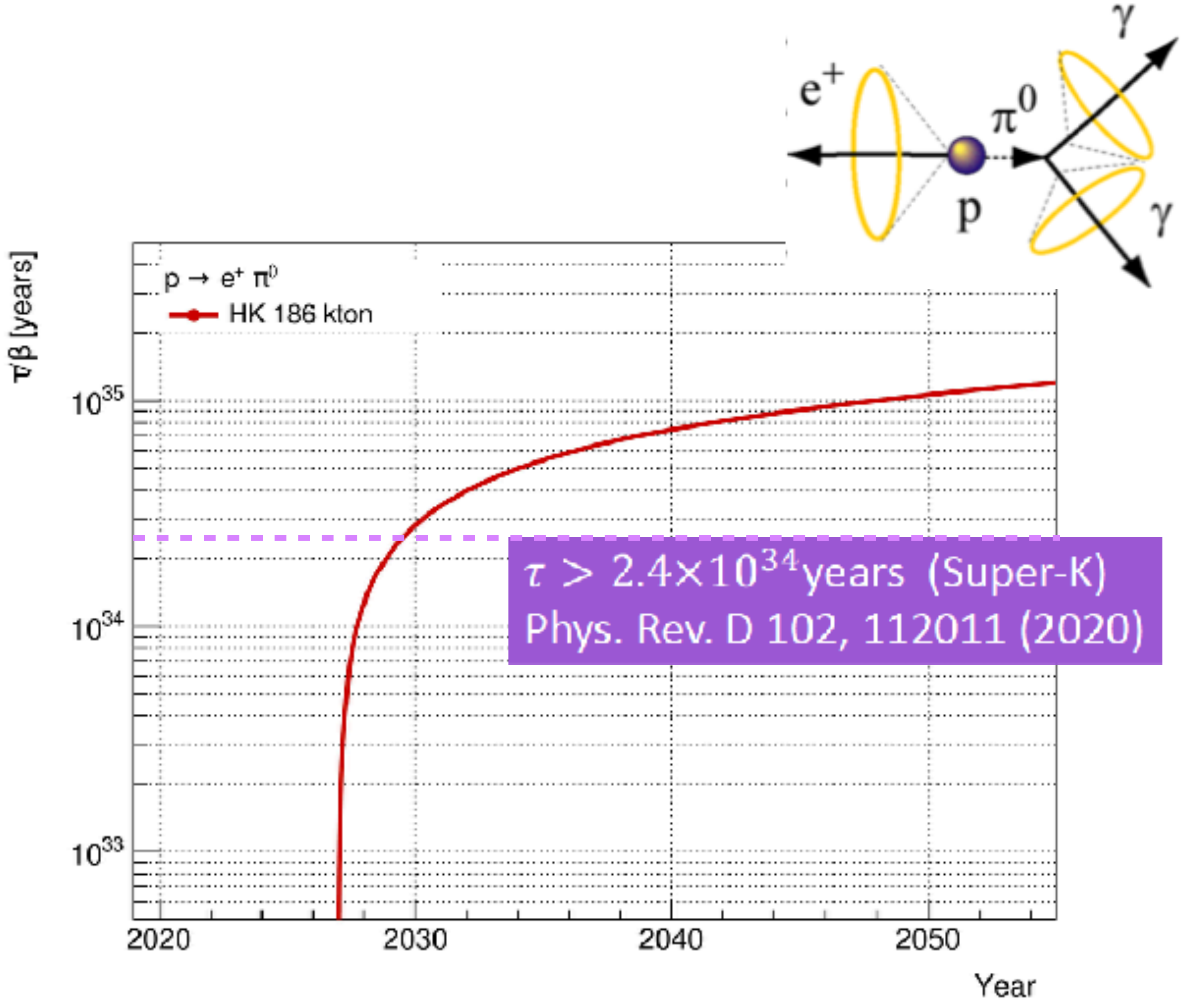
- Core collapse supernova (SN) emit neutrinos of flavors
  - Neutrinos carry 99% of the energy
  - Measure SN neutrino time profile and energy spectrum → SN modelling
  - Hyper-K will detect 50k ~ 80k events from a SN at 10 kpc (galactic centre)
    - Super-K detected 11 neutrinos from SN1087A (51 kpc)
    - Majority of SN neutrinos detected in HK are $\bar{\nu}_e$ inverse beta decays
  - DUNE will detect thousands of events mostly through ν_eCC interactions
  - Hyper-K and DUNE are complimentary
- Diffuse SN neutrino background (DSNB) from all the SN explosions in the Universe → guaranteed steady source of SN neutrinos
  - Cosmic star formation history
  - Expect >4 sigma discovery with 10 years of HK

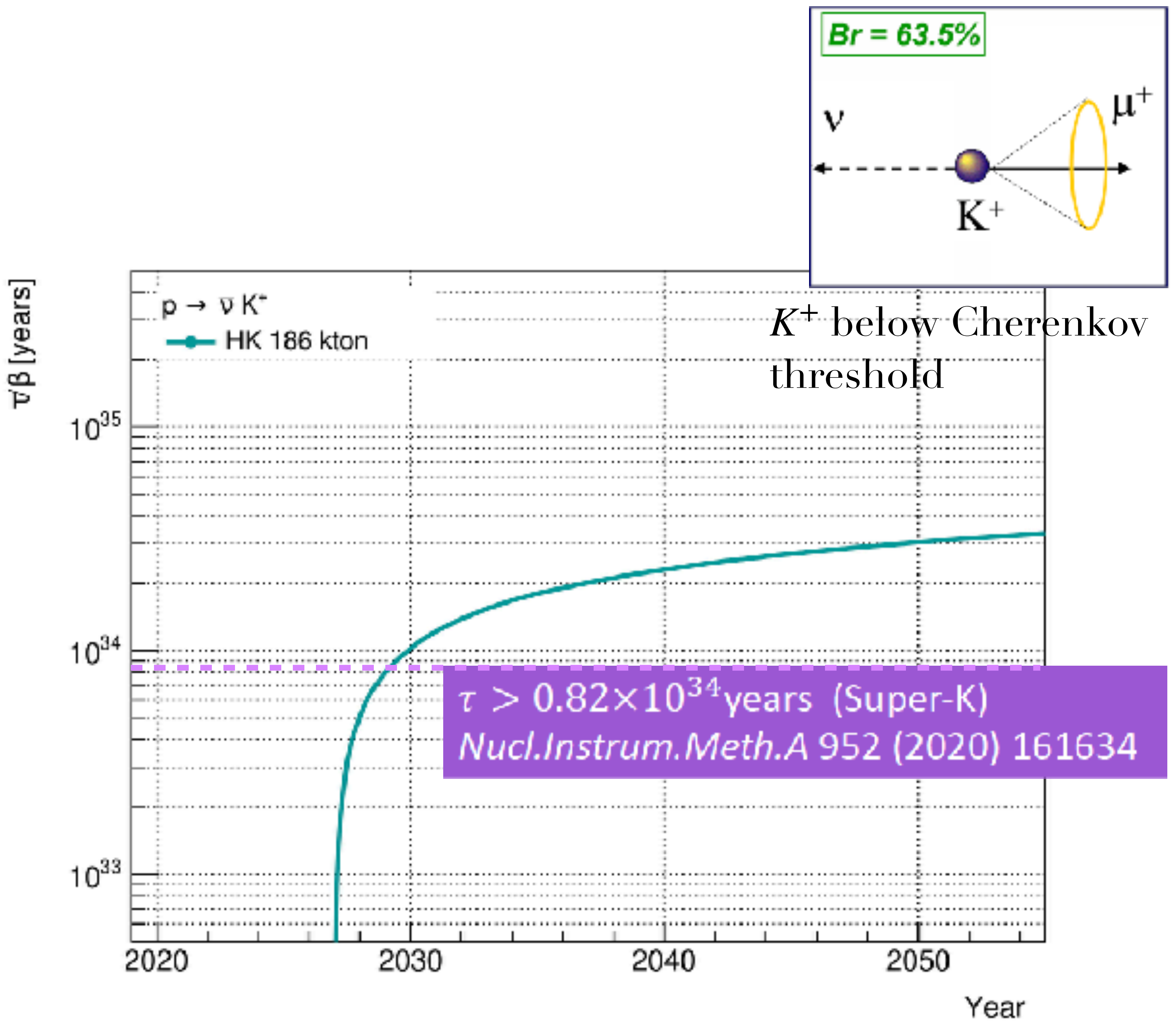




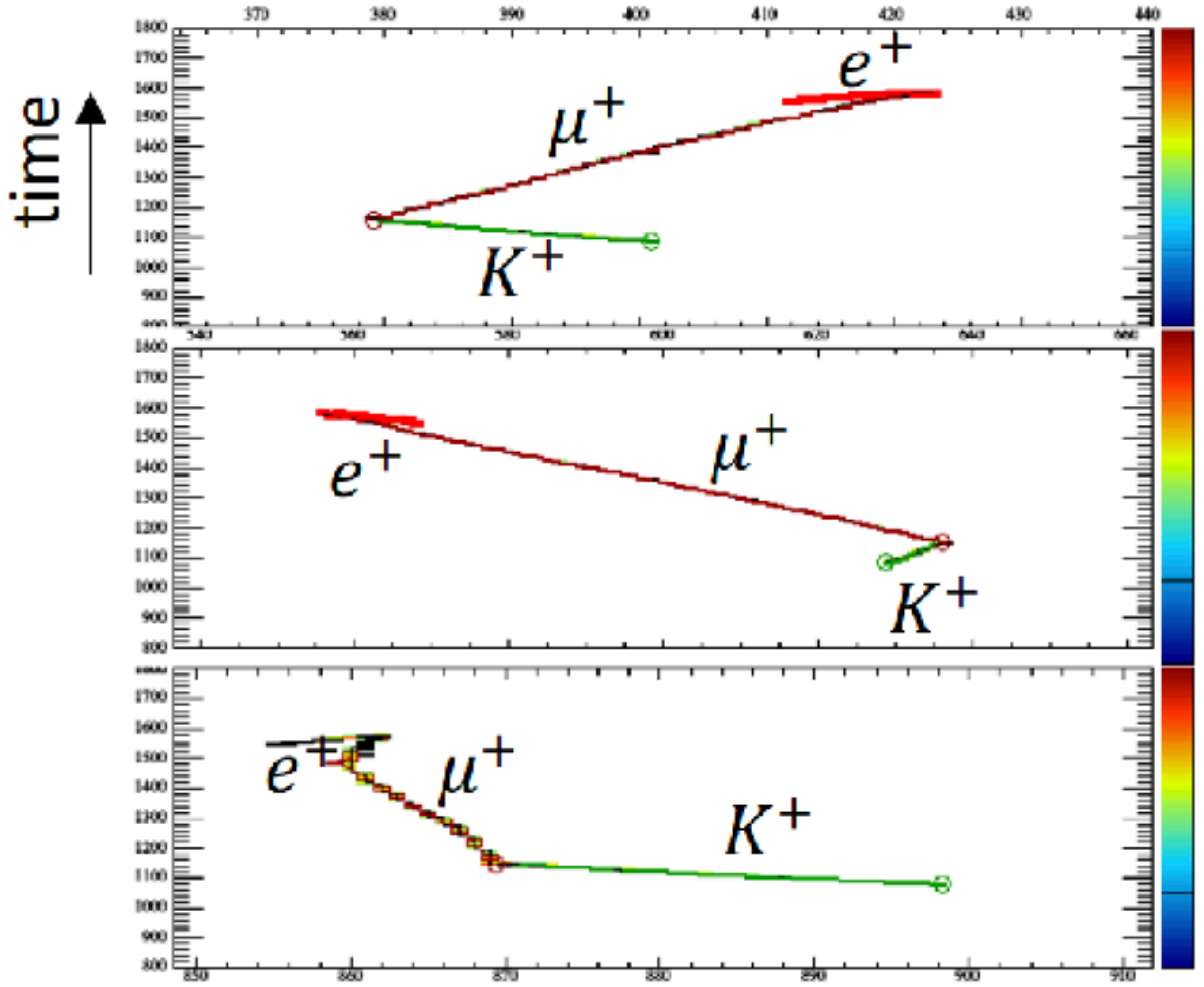
PROTON DECAY

- GUTs predict proton decay
- Decades of search in Super-K has not returned any positive proton decay signal
  - HK and DUNE will push the limits further





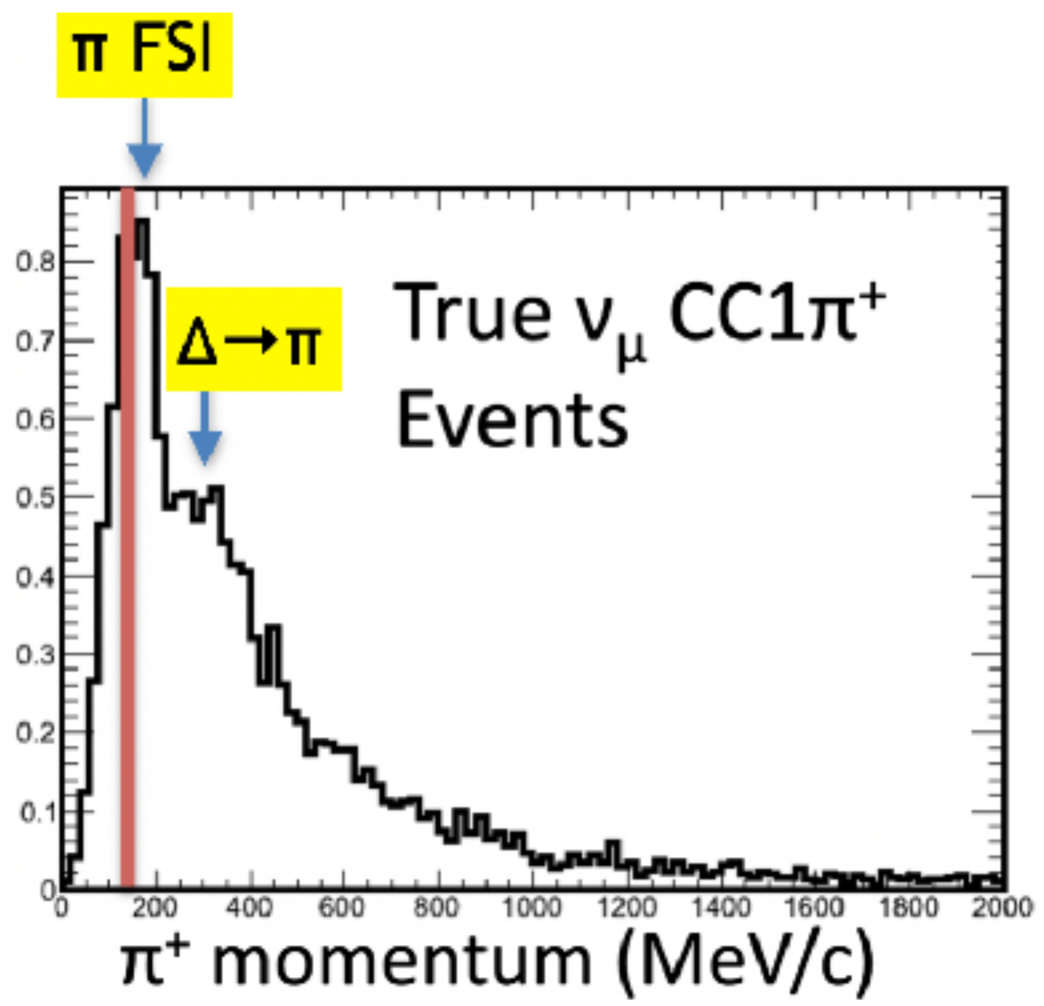
$p \to K^+\nu$ event in DUNE



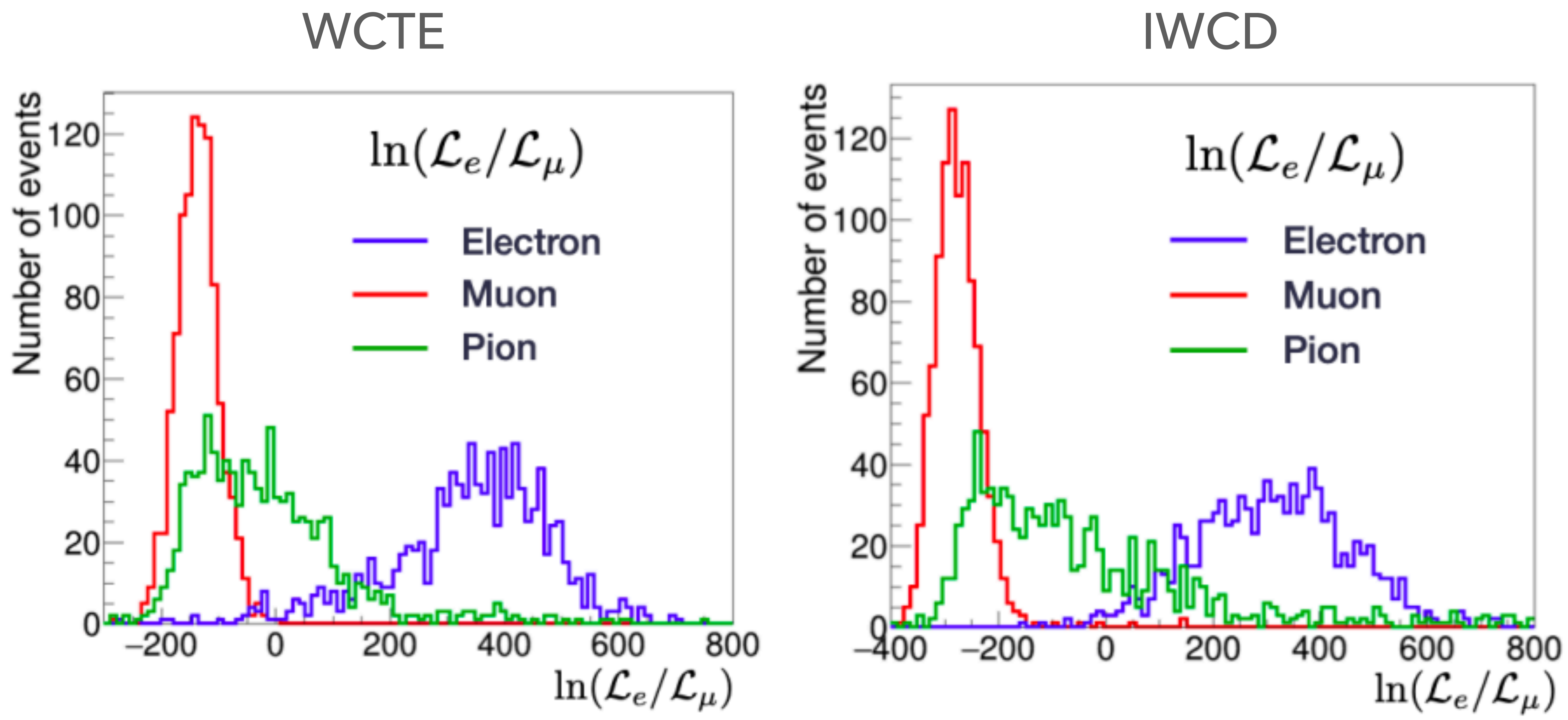
$p \to K^+\nu$ lifetime limit of 1.3×10^{34} years can be set by DUNE with 40 kton fiducial mass and 10 years running

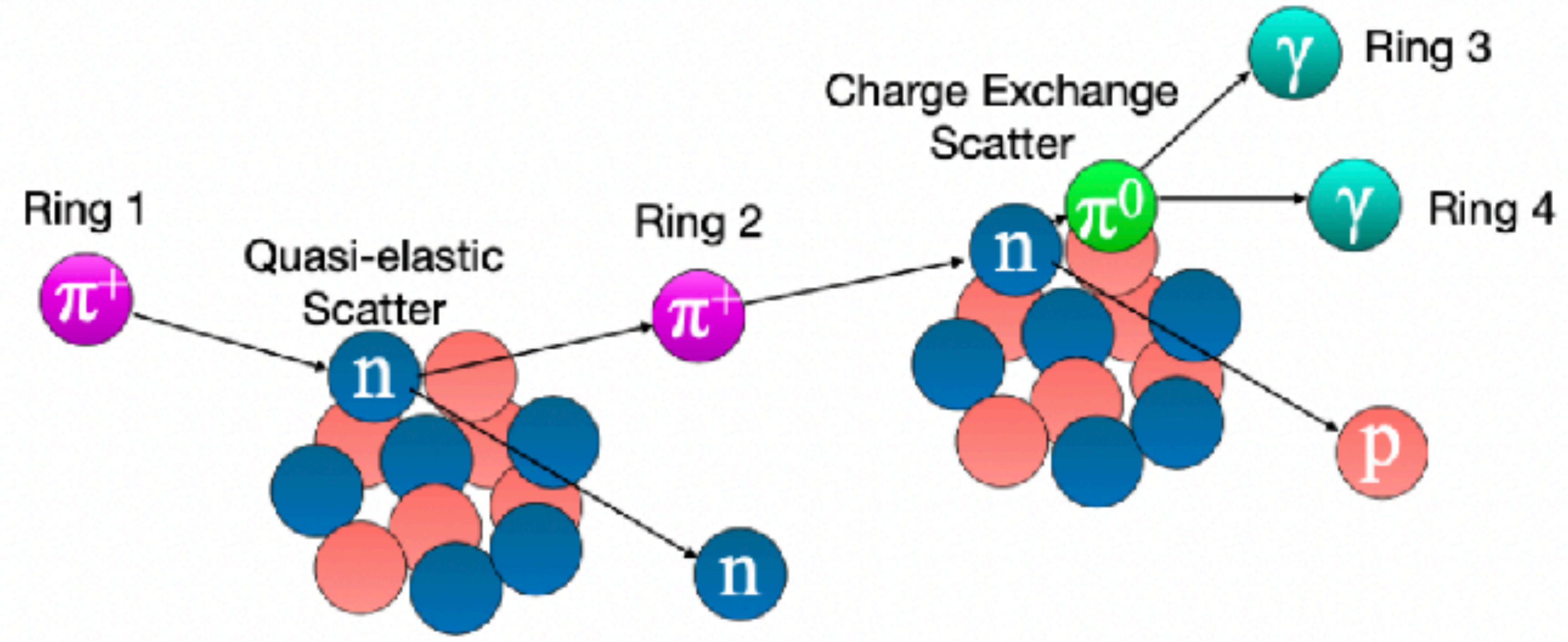
WCTE PHYSICS GOALS (1)

- Study pion interactions in water
    - Absorption, charge exchange, quasi-elastic scattering
- Study $e/\mu/\pi$ PID in a water Cherenkov detector



~500 MeV/c pions produced by neutrino interactions

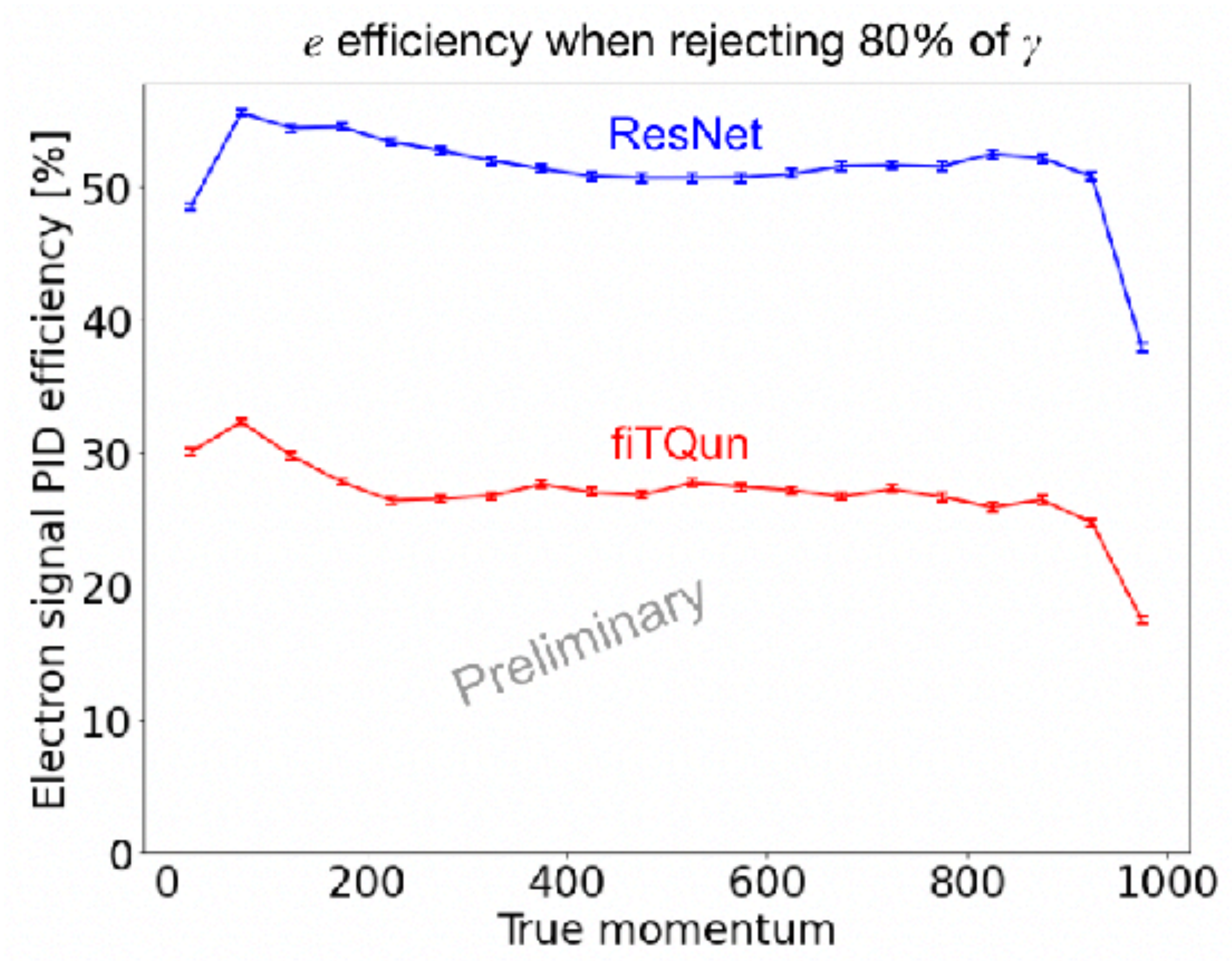




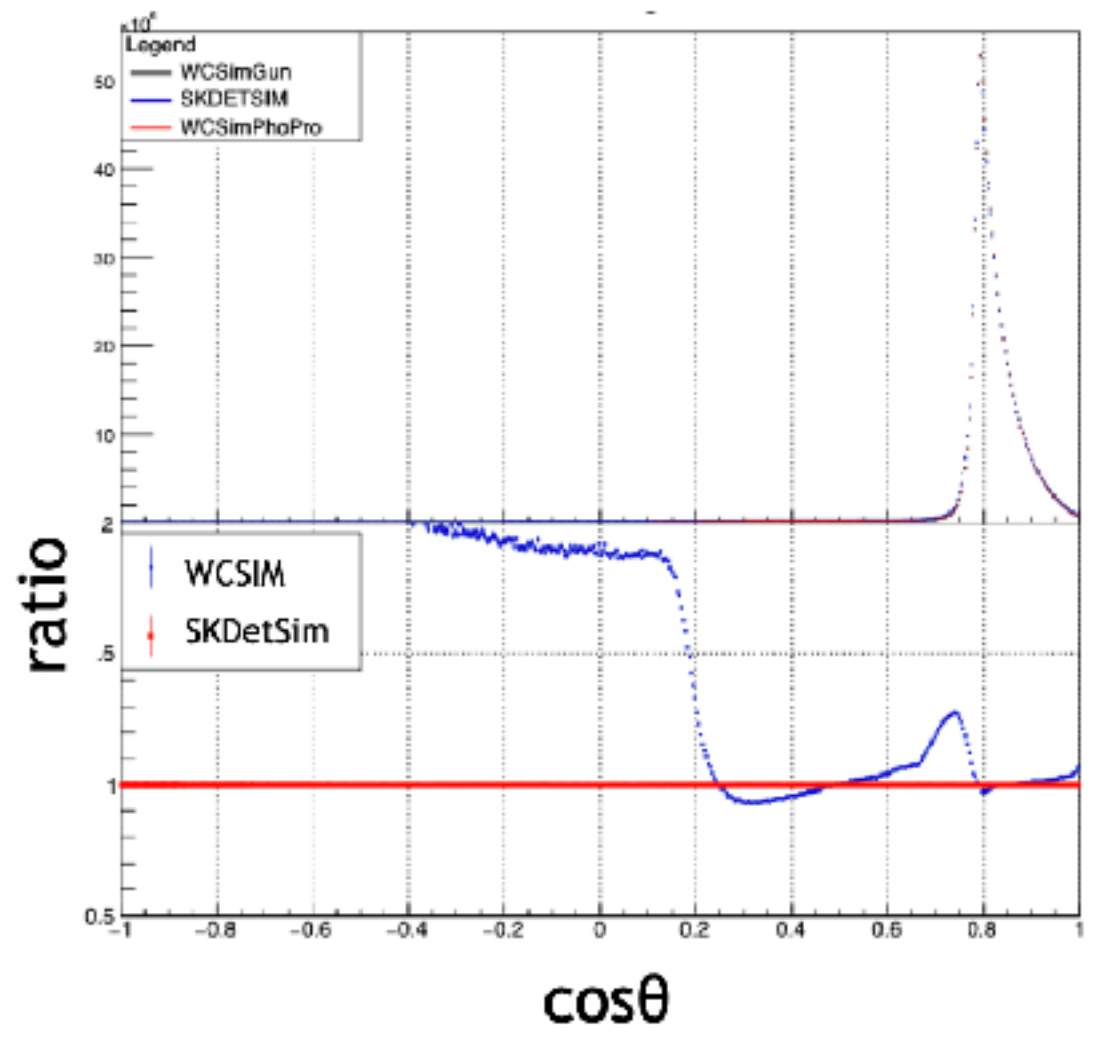
WCTE PHYSICS GOALS (2)

- Study pion interactions in water
  - Absorption, charge exchange, quasi-elastic scattering
- Study $e/\mu/\pi$ PID in a water Cherenkov detector
- Study $e/\mu/\pi^0$ energy reconstruction in a water Cherenkov detector
- Tagged gamma measurements
  - e/γ separation in IWCD
  - Pion photoproduction in water

IWCD Gamma Rejection with ML



Cherenkov photon angle distribution



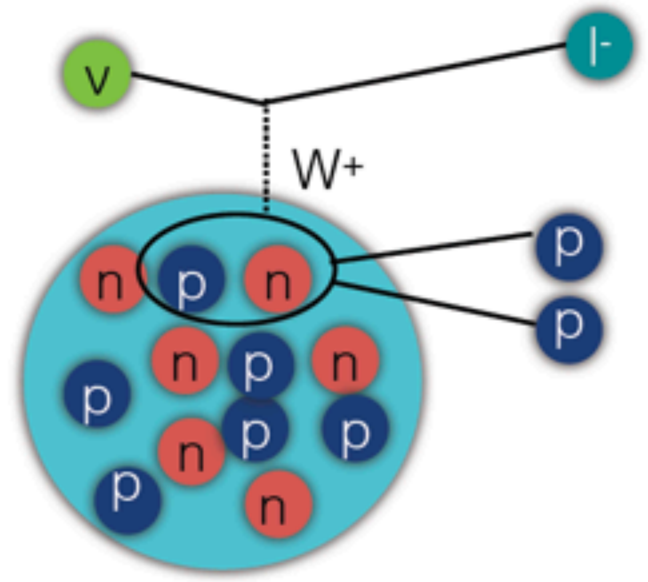
Discrepancy between MC in the backward direction

Error source	1-Ring e FHC	1-Ring e RHC	1-Ring e FHC 1 d.e.	1-Ring e FHC/RHC
SK Detector	2.8	3.8	13.2	1.5
SK FSI+SI+PN	3.0	2.3	11.4	1.6
Flux + Xsec (ND unconstrained)	15.1	12.2	12.0	1.2
Flux + Xsec (ND constrained)	3.2	3.1	4.1	2.7
Nucleon Removal Energy	7.1	3.7	3.0	3.6
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	2.6	1.5	2.6	3.0
NC1γ	1.1	2.6	0.3	1.5
NC Other	0.2	0.3	1.0	0.2
$\sin^2\theta_{23} + \Delta m^2_{21}$	0.5	0.3	0.5	2.0
$\sin^2\theta_{13}$ PDG2018	2.6	2.4	2.6	1.1
All Systematics	8.8	7.1	18.4	6.0

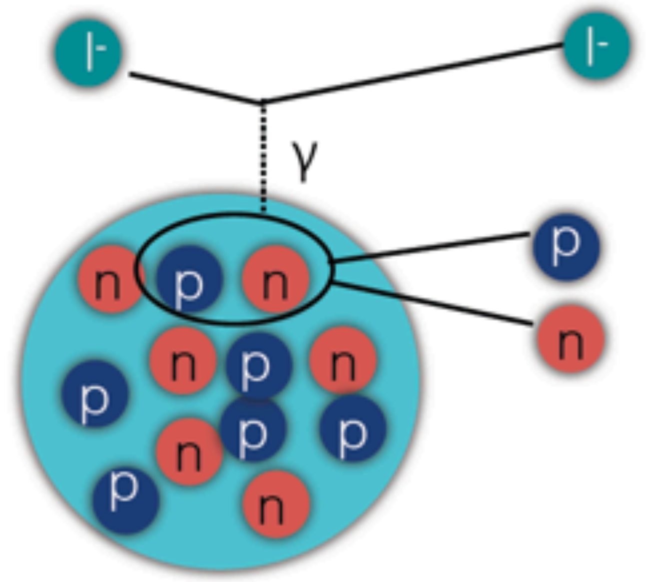
WCTE PHYSICS GOALS (3)

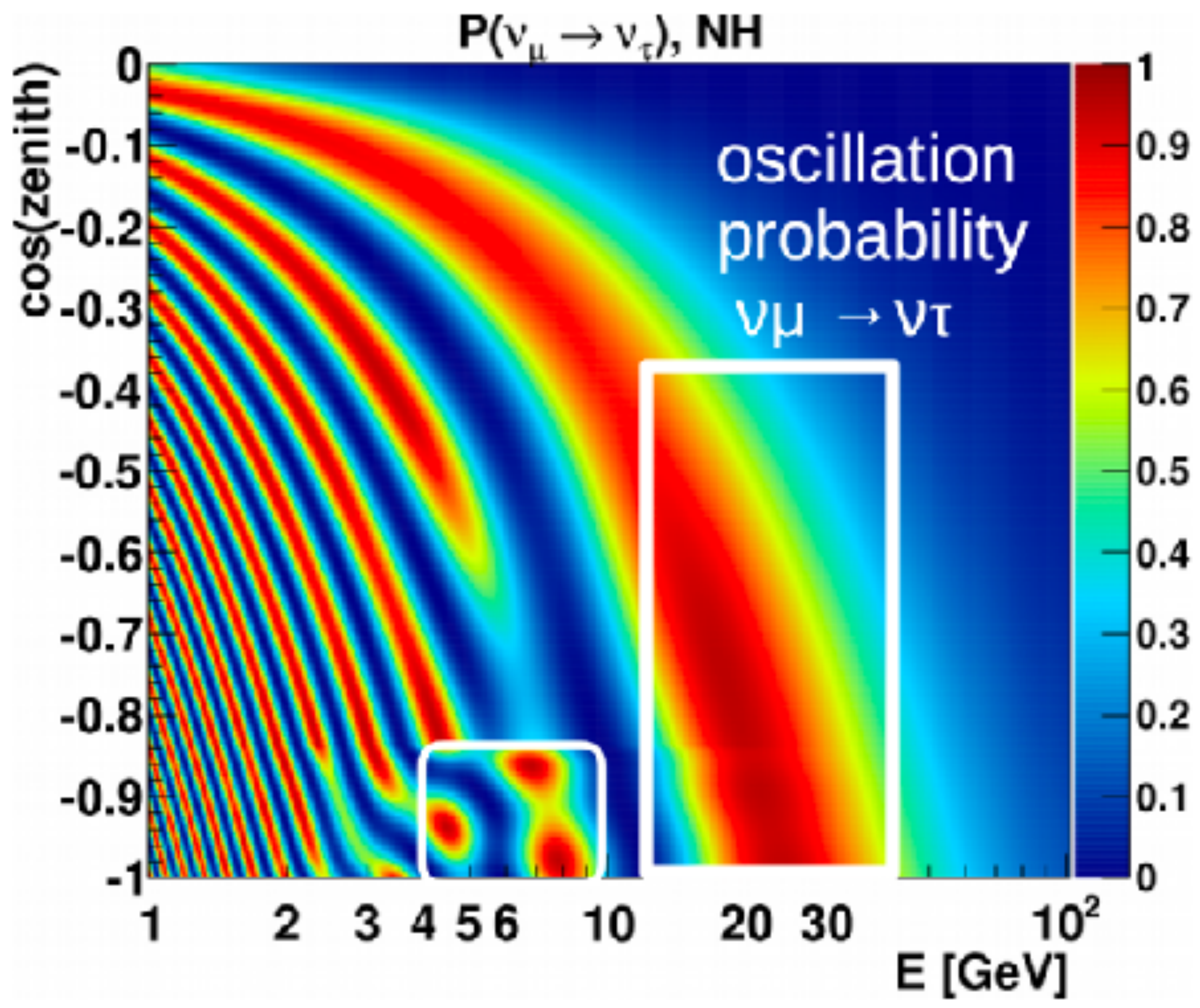
- Study pion interactions in water
  - Absorption, charge exchange, quasi-elastic scattering
- Study $e/\mu/\pi$ PID in a water Cherenkov detector
- Study $e/\mu/\pi^0$ energy reconstruction in a water Cherenkov detector
- Tagged gamma measurements
  - e/γ separation in IWCD
  - Pion photoproduction in water
- High momentum measurements
  - e/μ scattering on oxygen
  - GeV proton detection for dark matter search
  - Kaon measurements for proton decay and atmospheric ν_τ appearance

Neutrino-nucleus scattering



Electron/muon-nucleus scattering





2-body τ decay BR=0.7%:

$\tau^- \rightarrow K^- + \nu_\tau$

3-4 events in the current SK data, 10-20 events for HK

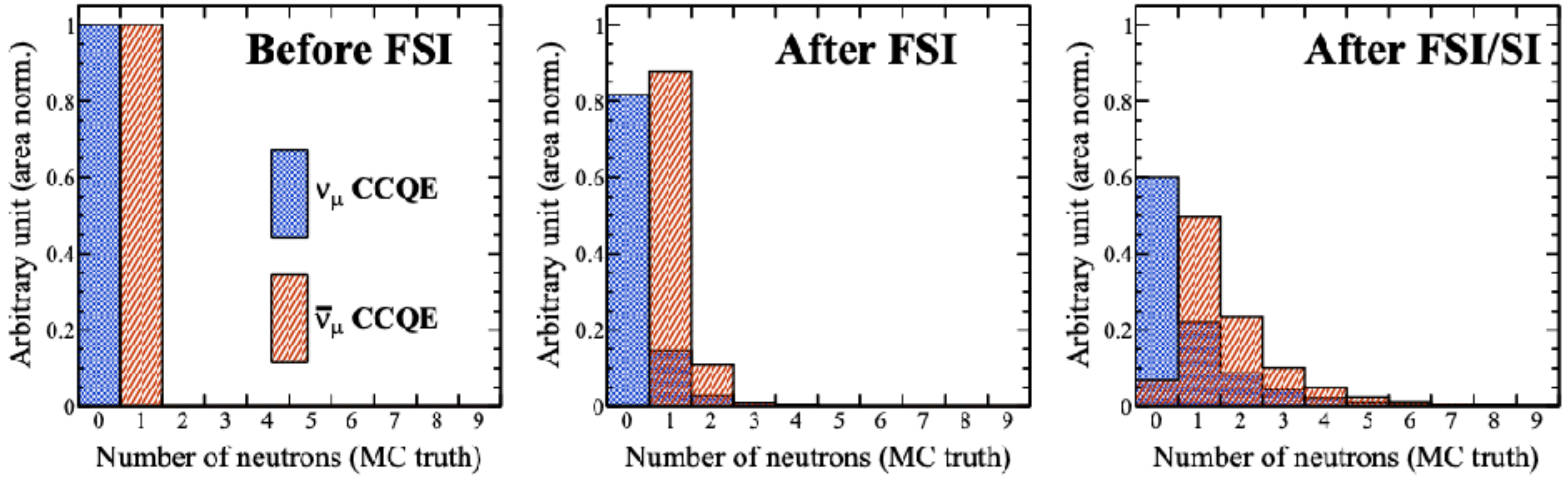
Proton decay $p \rightarrow K^+\nu$

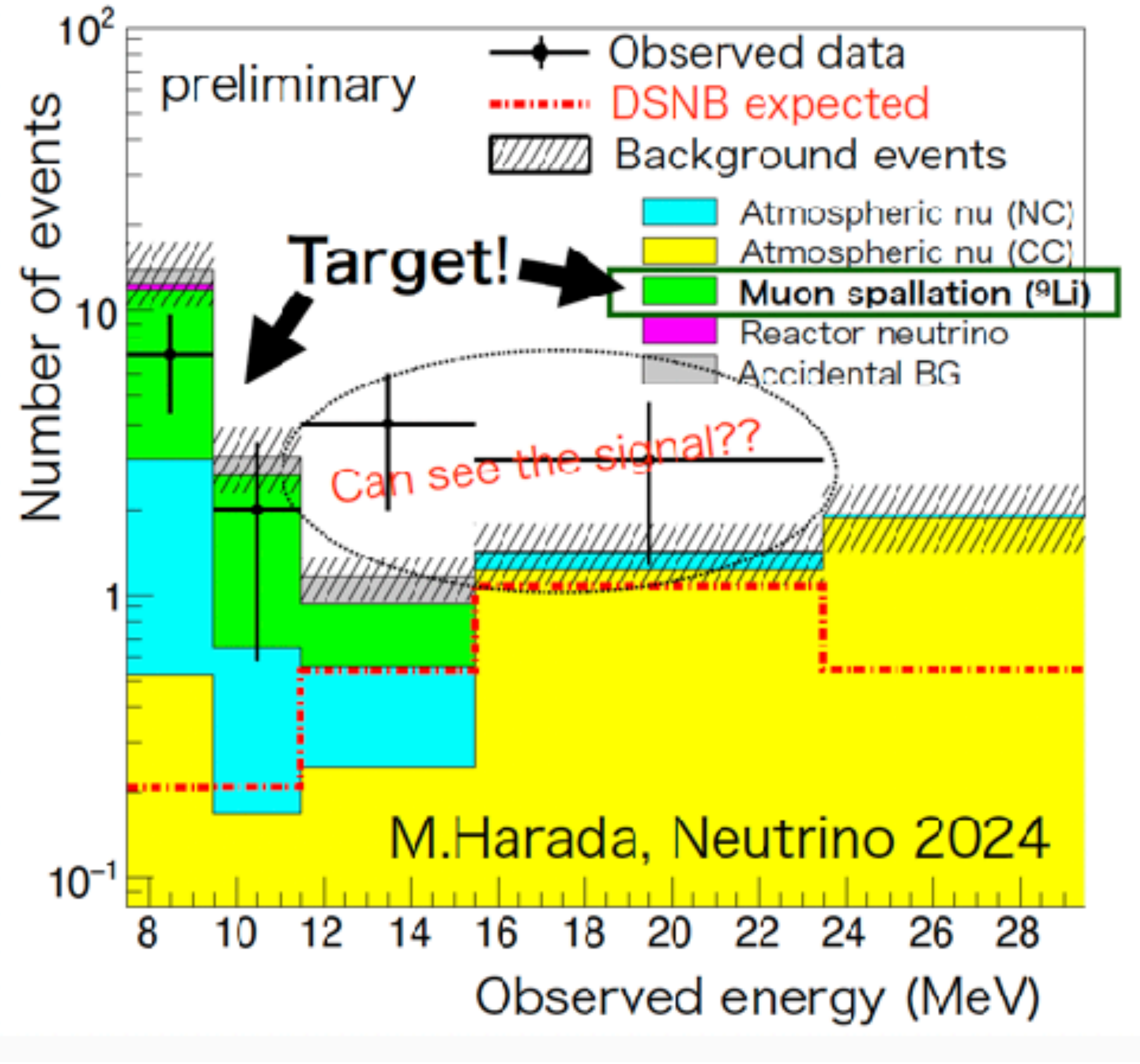
1.1GeV K^+ stops in the tank

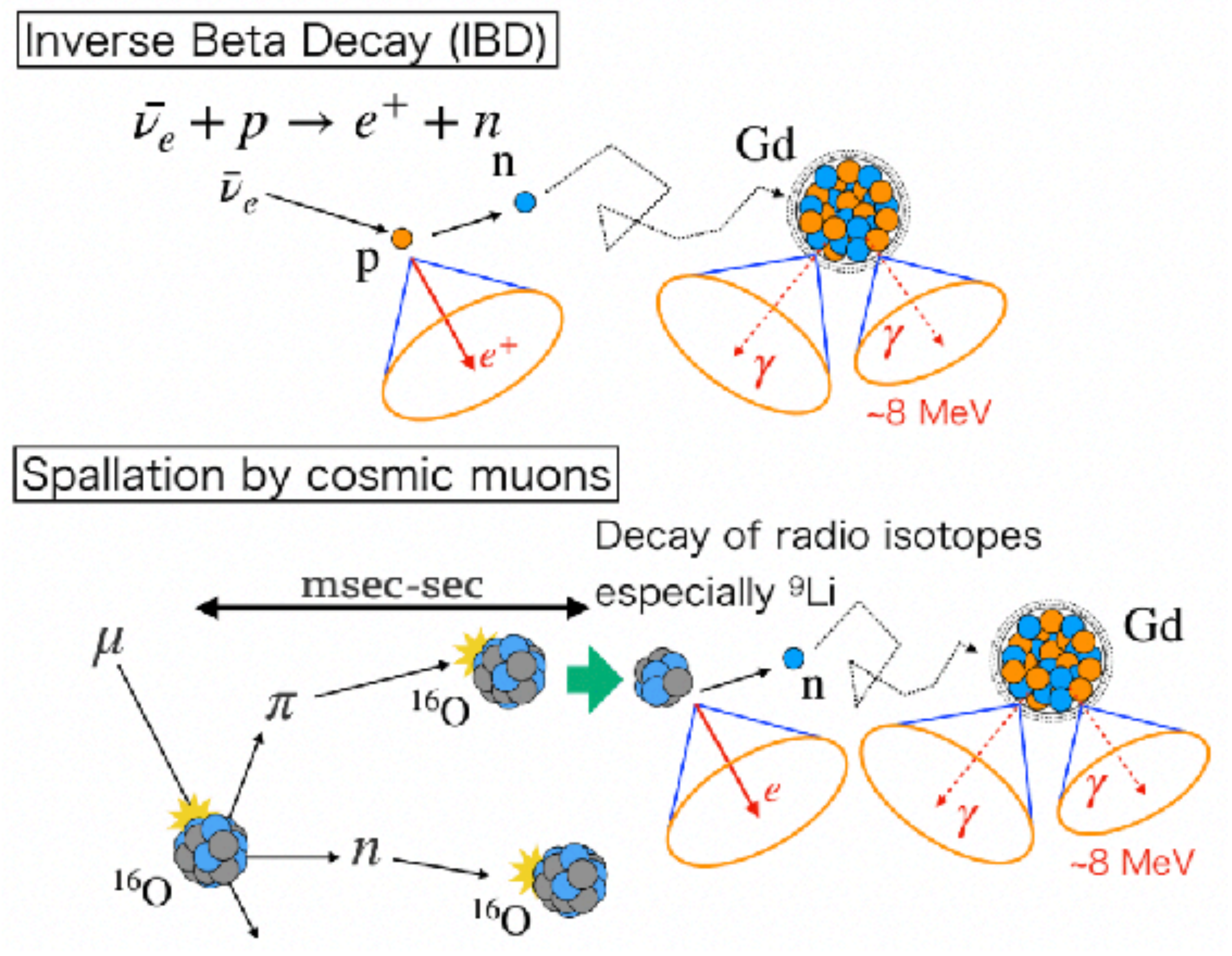
WCTE PHYSICS GOALS (4)

- Gd-phase physics
  - Neutron tagging for neutrino/antineutrino separation
    - Secondary neutron production in water from proton, stopped μ^- and $\pi^\pm$
  - Neutron production from 2p-2h in quasi-elastic scattering
  - Photonuclear reaction with gamma beam
  - 9Li production from π^-
    - Cosmogenic 9Li are a significant background for DSNB search

Neutron production in CCQE interactions in T2K

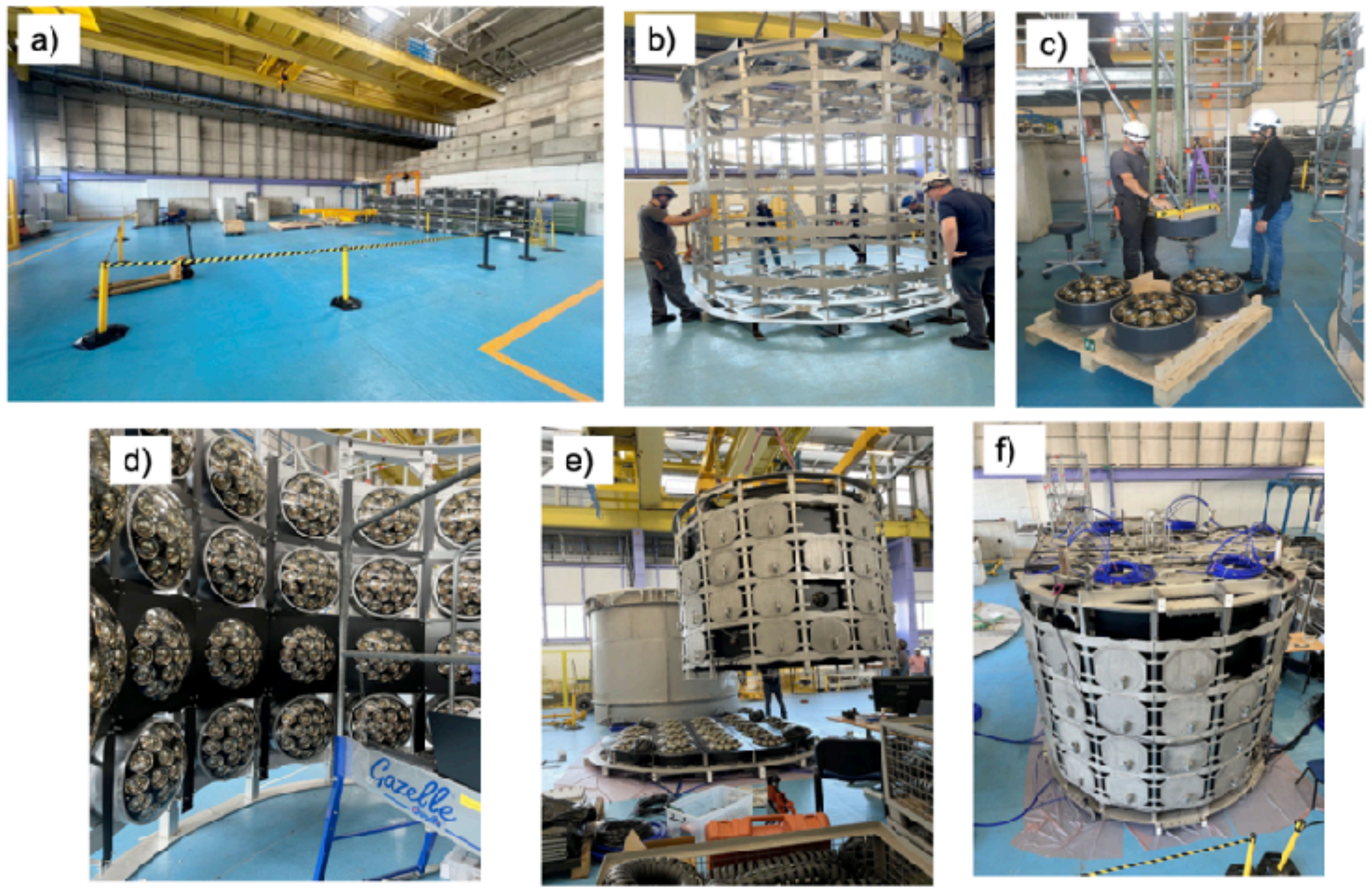


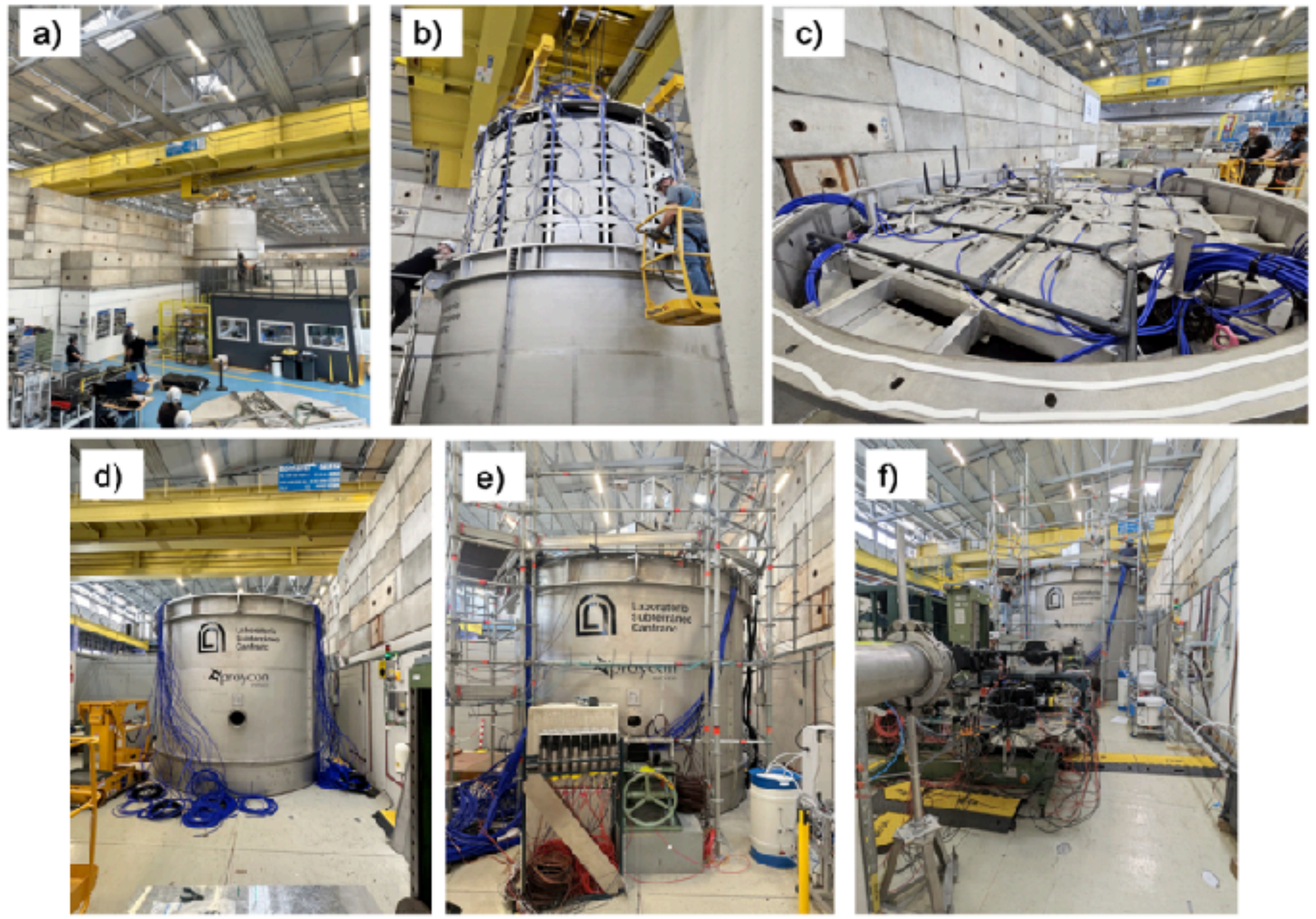




WCTE TIMELINE

- Detector assembly and installation July 2024 - Oct. 2024
- 1st detector commissioning Oct. - Nov. 2024
- 2nd detector commissioning, Mar. 2025
- Data taking in pure water April - May 2025
- Data taking in Gd water, May 2025
- Decommissioning and disassembly, June 3, 2025 - present

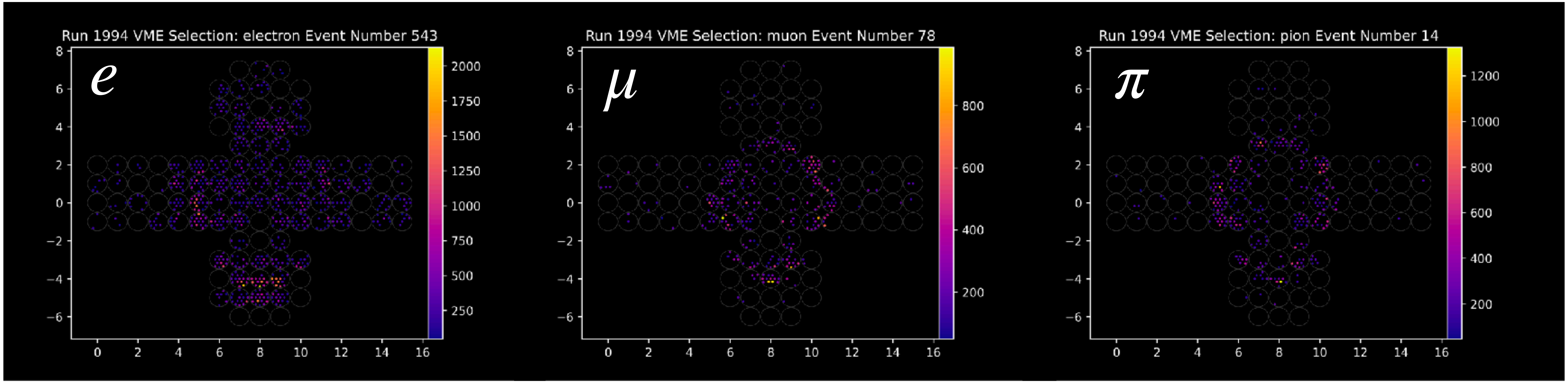




WCTE TIMELINE

20 “bad” mPMTs (ADC corruption problem) in 2024 run are recovered by firmware update –> 83 working IWCD mPMTs

- Detector assembly and installation July 2024 - Oct. 2024
- 1st detector commissioning Oct. - Nov. 2024
- 2nd detector commissioning, Mar. 2025
- Data taking in pure water April - May 2025
- Data taking in Gd water (0.03%), May 2025
- Decommissioning and disassembly, June 3, 2025 - present



Ring structures clearly seen in the small water Cherenkov detector with small “Dwall”!

WCTE TIMELINE

- Detector assembly and installation July 2024 - Oct. 2024
- 1st detector commissioning Oct. - Nov. 2024
- 2nd detector commissioning, Mar. 2025
- Data taking in pure water April - May 2025
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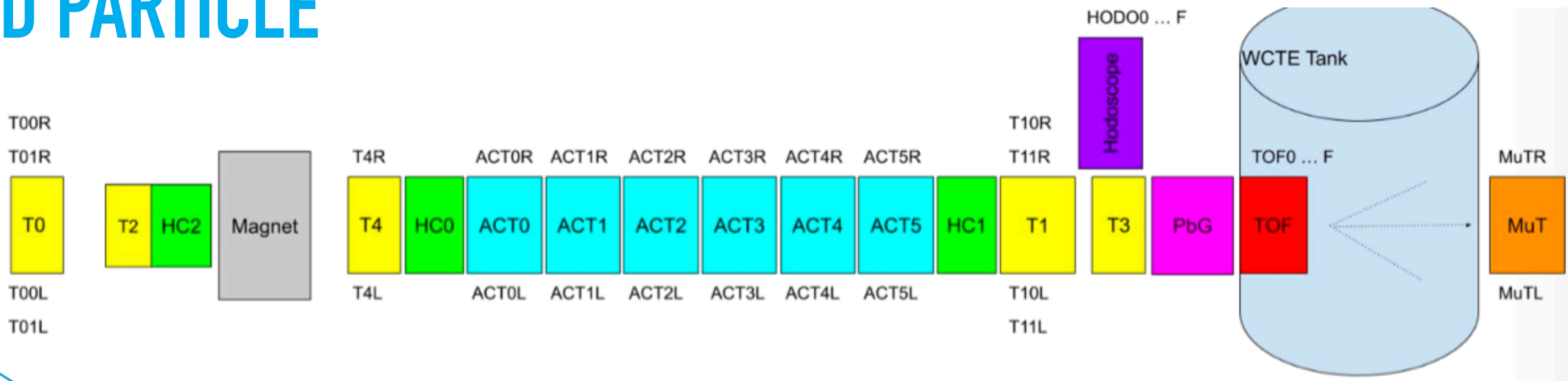
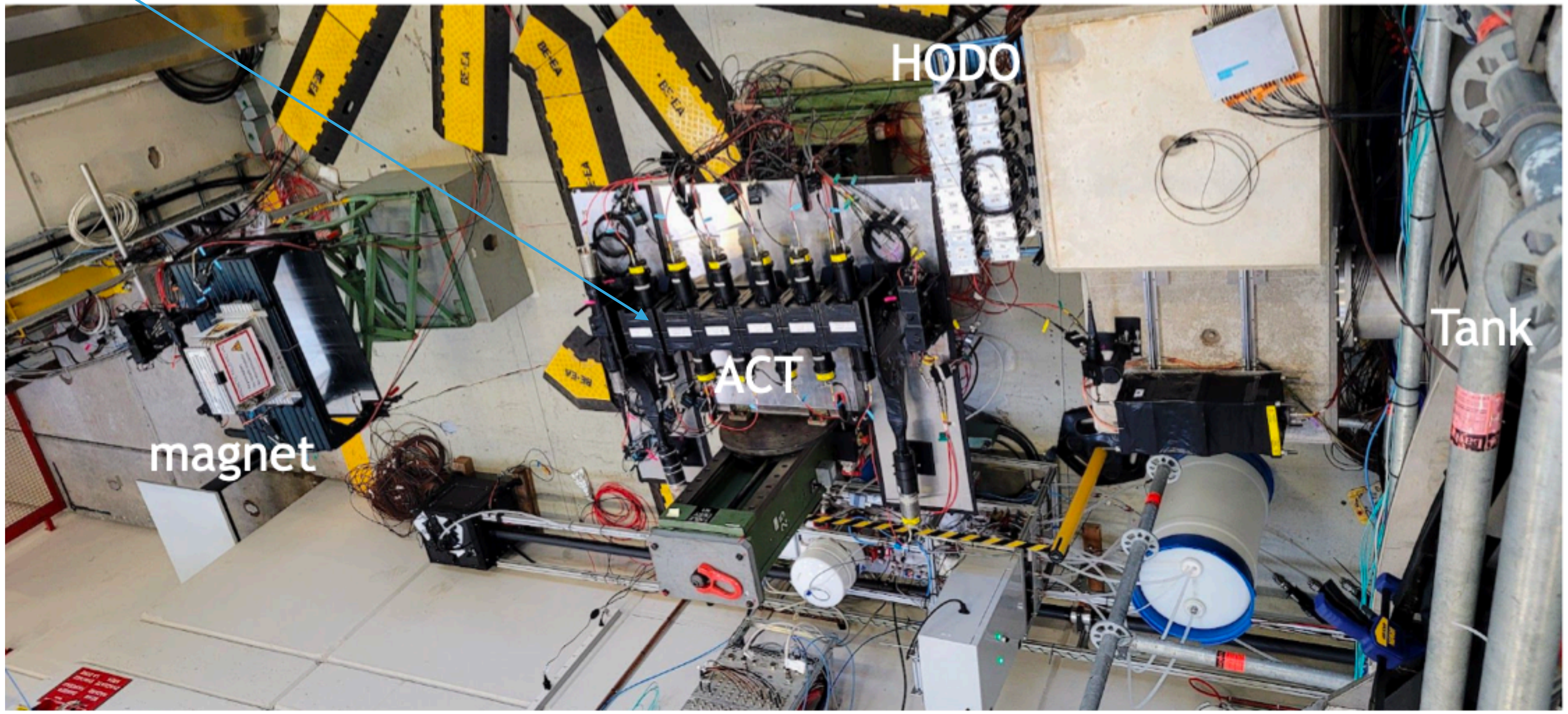
BEAM DETECTORS – CHARGED PARTICLE

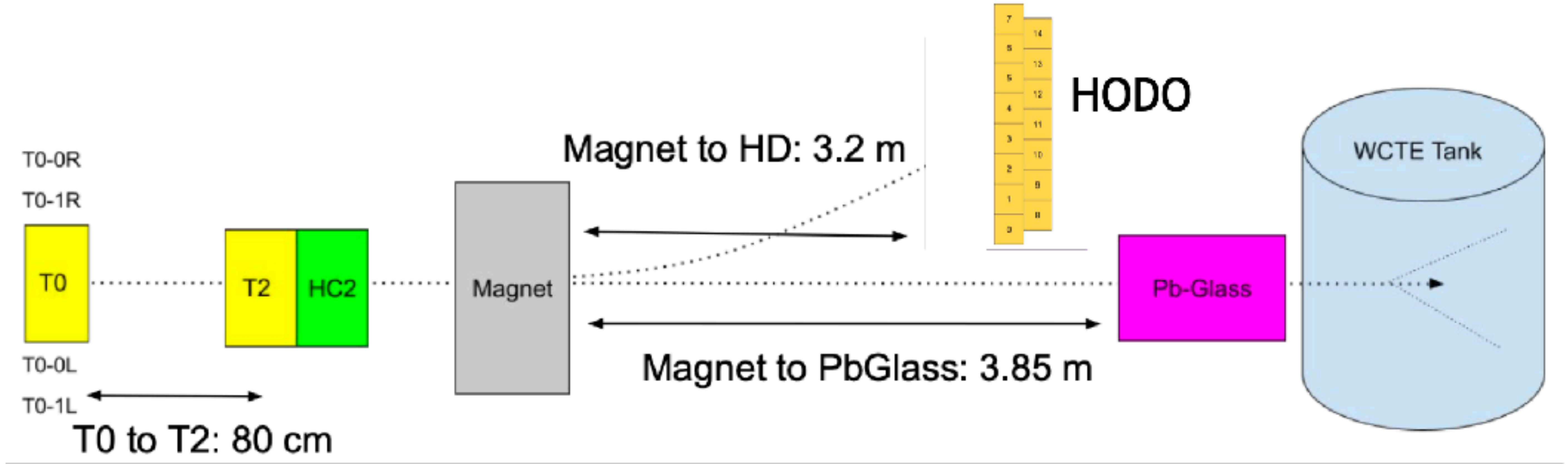


- A series of trigger scintillator detectors, hole counters, aerogel Cherenkov threshold (ACT) detectors, and a TOF detector are used to distinguish charged particles, measure beam momentum, and provide WCTE trigger
  - Refractive index of ACTs ranges from 1.01 to 1.15

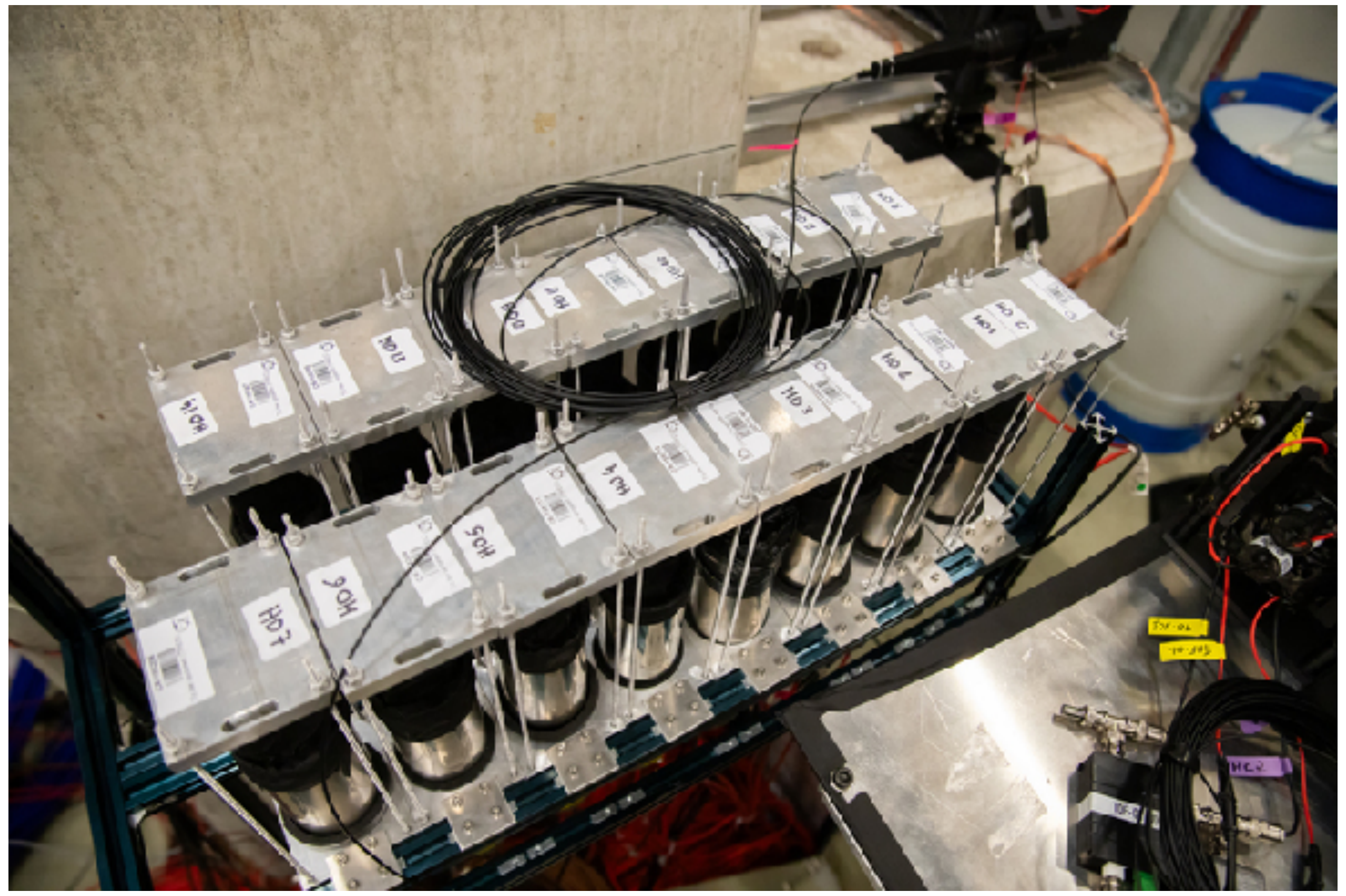


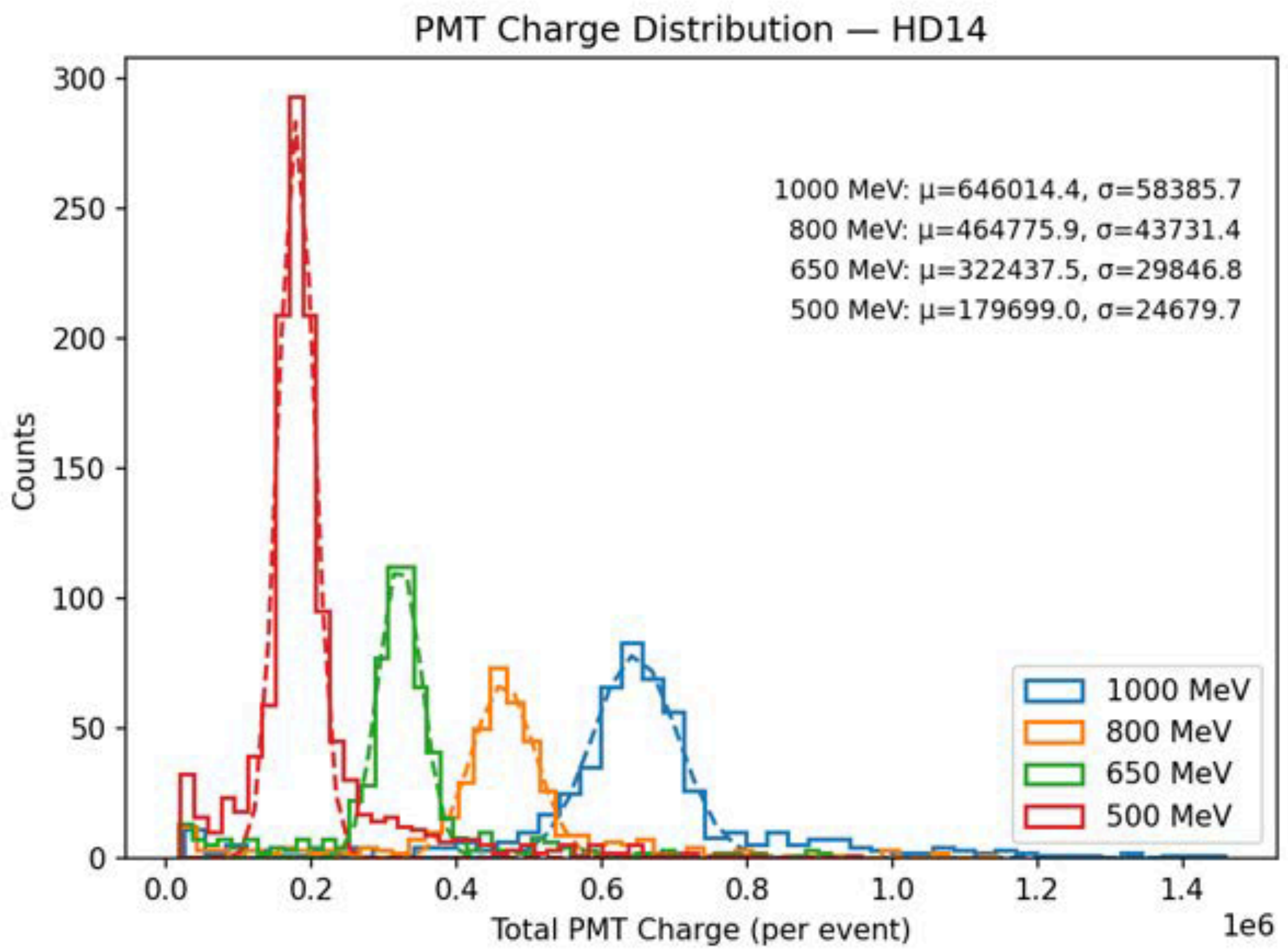
BEAM DETECTORS – TAGGED PHOTON

- Electrons that undergo Bremsstrahlung emit gammas along beam direction; gamma energy inferred from electron trajectory after it is bent by permanent magnet



  - Beam momentum is calibrated using time-of-flight measurements
  - Magnet/hodoscope spectrometer response is calibrated with beam

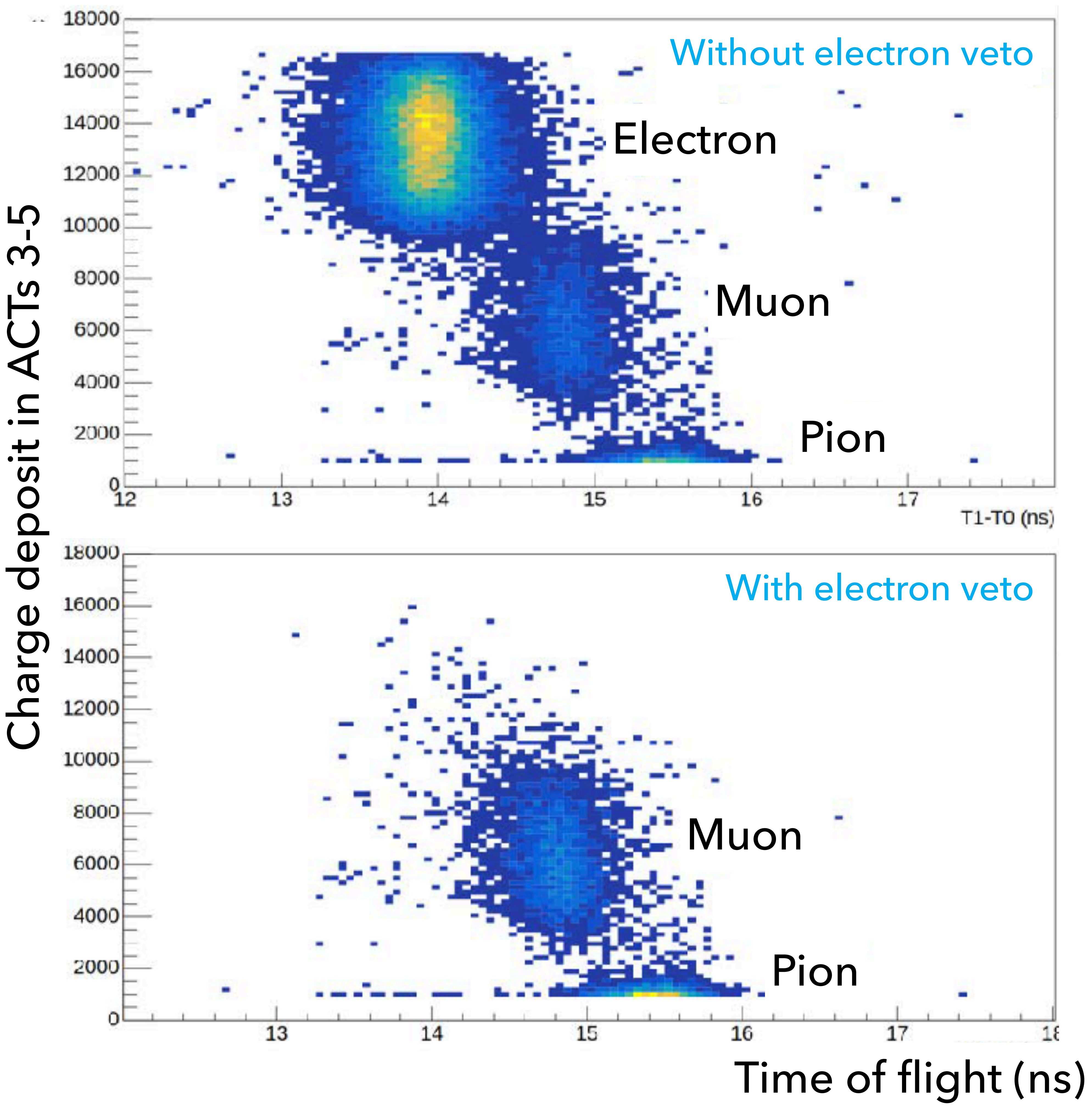




BEAM DETECTORS – PERFORMANCE

The beam detectors have been donated to CERN and could be used for HK-related test beam activities in the future

Charged particle separation



Tagged gamma