PRECISION MEASUREMENT OF NEUTRINO OSCILLATIONS WITH HYPER-KAMIOKANDE

XIAOYUE LI
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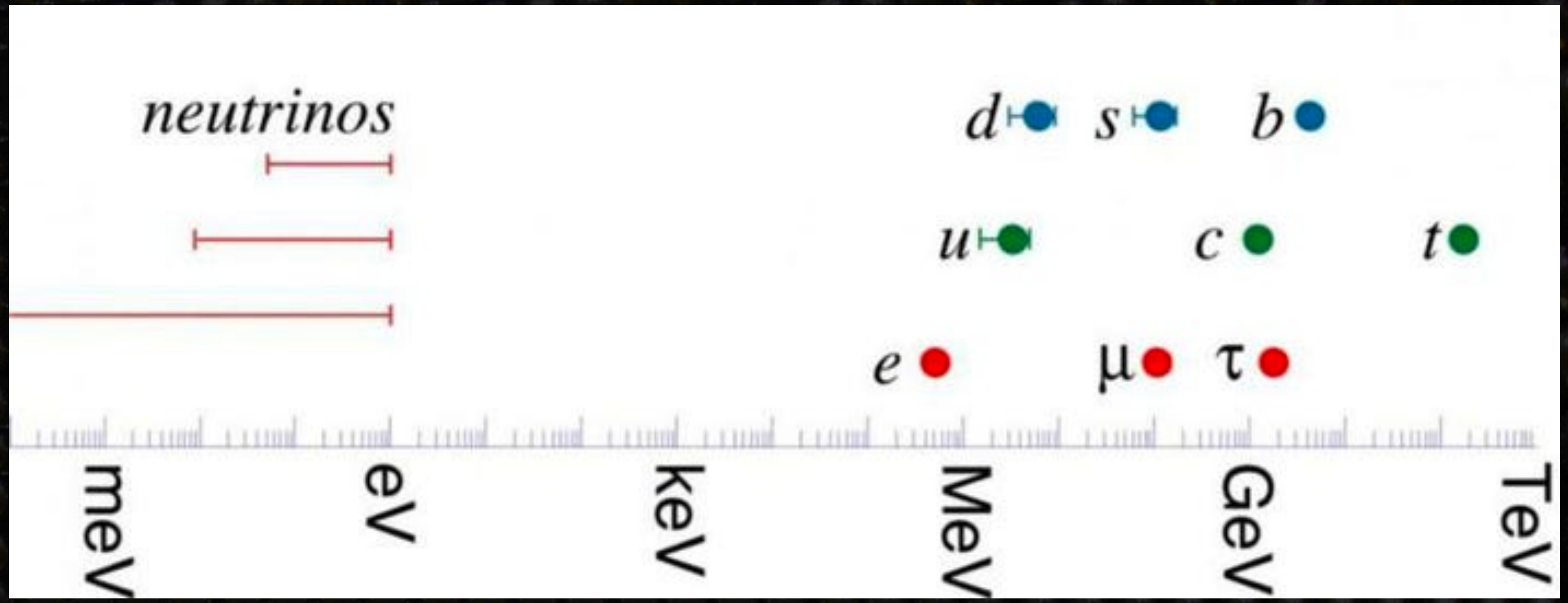
FEBRUARY 16-19, 2023

OUTLINE

- Introduction
  - Neutrino mixing and neutrino oscillations
  - Measuring neutrino oscillation parameters
  - Long baseline experiment: T2K
- Hyper-Kamiokande
  - Sensitivity and progress
  - The main systematic uncertainties and how to reduce them
  - Effort toward better detector calibration

NEUTRINO MIXING

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



- Mixing matrix, aka Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U^*_{PMNS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix},\ U_{PMNS} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}$$

- Decomposition of unitary PMNS matrix

$$U_{PMNS} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & e^{-i\frac{\alpha_{21}}{2}} & 0\\ 0 & 0 & e^{-i\frac{\alpha_{31}}{2}}\end{pmatrix}$$

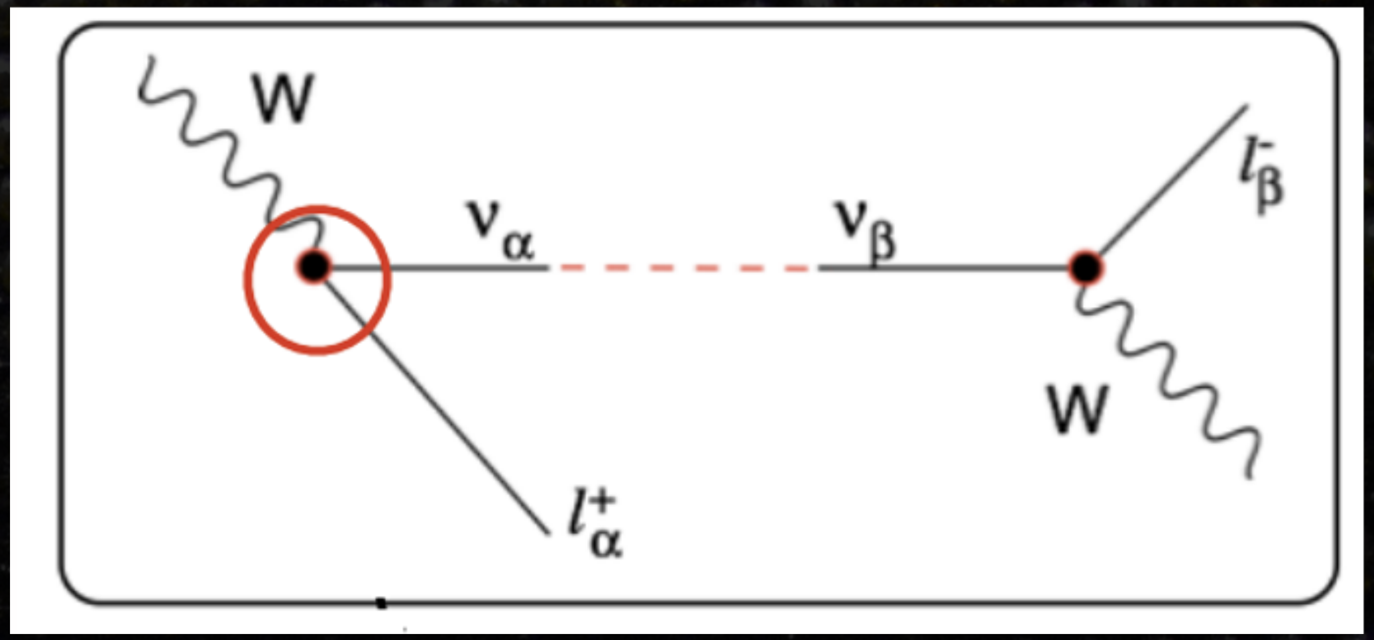
Only present if neutrinos are Majorana

$$s_{ij} = \sin\theta_{ij}$$

$$c_{ij} = \cos\theta_{ij}$$

NEUTRINO OSCILLATION

- Neutrinos are produced through weak interaction in flavor eigenstates $|\nu_k\rangle$ and propagate in the mass eigenstates $|\nu_\alpha\rangle$
  - Oscillation probability in vacuum $P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U^*_{\alpha j} e^{-i\frac{m_j^2 L}{2E}} U_{\beta j} \right|^2$
    - L (baseline) and E (neutrino energy) of an experiment determines which parameters it can measure



- KamLAND
  - Reactor neutrino $\bar{\nu}_e$
  - E: a few MeV
  - L: ~180km
  - $\frac{L}{4E} \sim 0.5 \times 10^5 \mathrm{eV}^{-2}$, $\Delta m^2_{21} \approx 7.6 \times 10^{-5} \mathrm{eV}^2$
  - $P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21}}{4E} L\right)$

$\Delta m^2_{ij} = m_i^2 - m_j^2$

- Long baseline (LBL) experiments
  - Accelerator neutrino $\nu_\mu / \bar{\nu}_\mu$
  - E: ~1 GeV
  - L: a few hundred km
  - $\frac{L}{4E} \sim 0.5 \times 10^3 \mathrm{eV}^{-2}$, $\Delta m^2_{32} \approx 2.5 \times 10^{-3} \mathrm{eV}^2$
  - $P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32}}{4E} L\right)$

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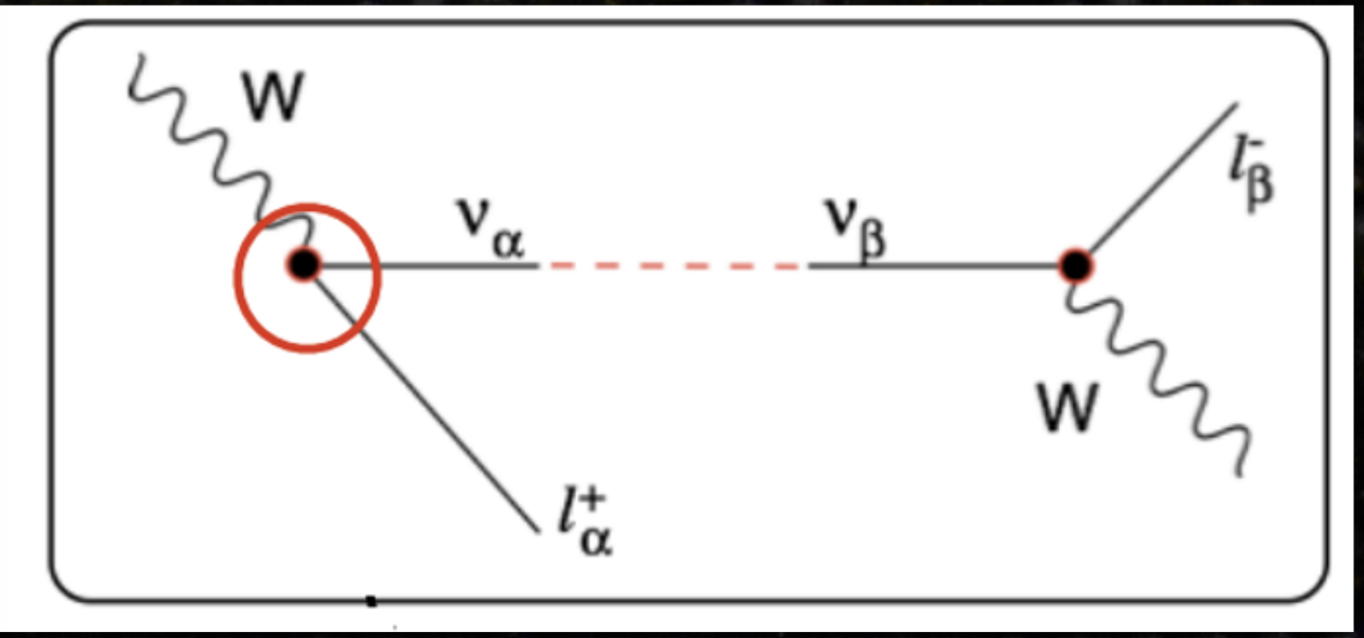
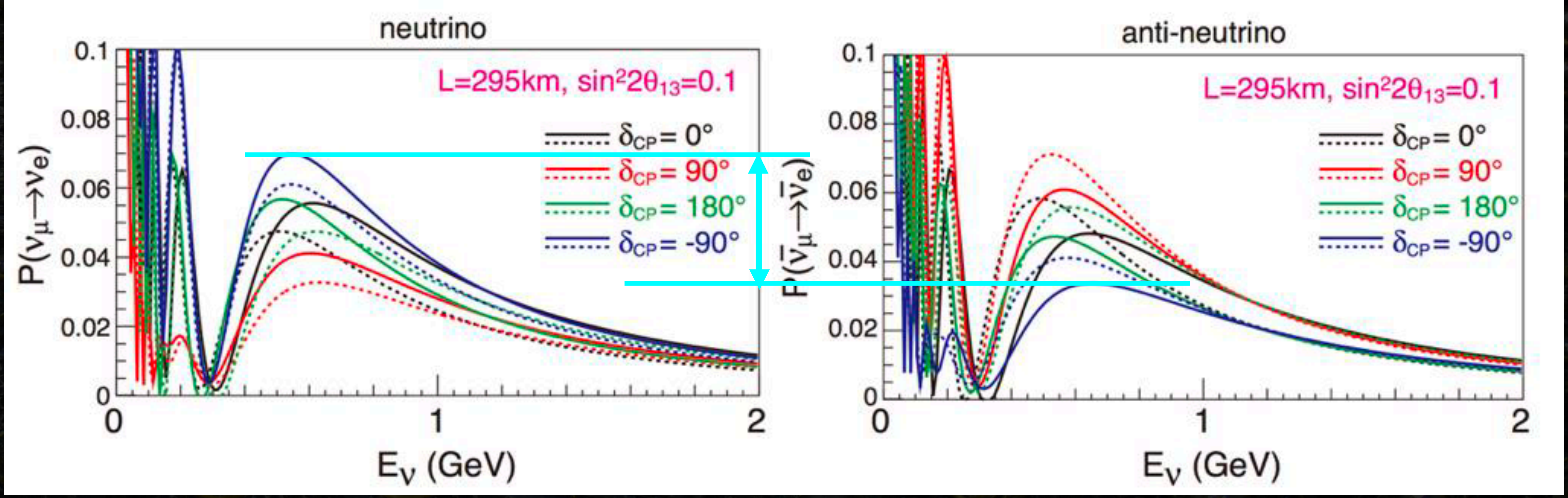


- CP-violation in the lepton sector if $\delta_{CP} \neq 0, \pm\pi$
  - $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$
  - δ_{CP} can be probed by comparing ν and $\bar{\nu}$ oscillation



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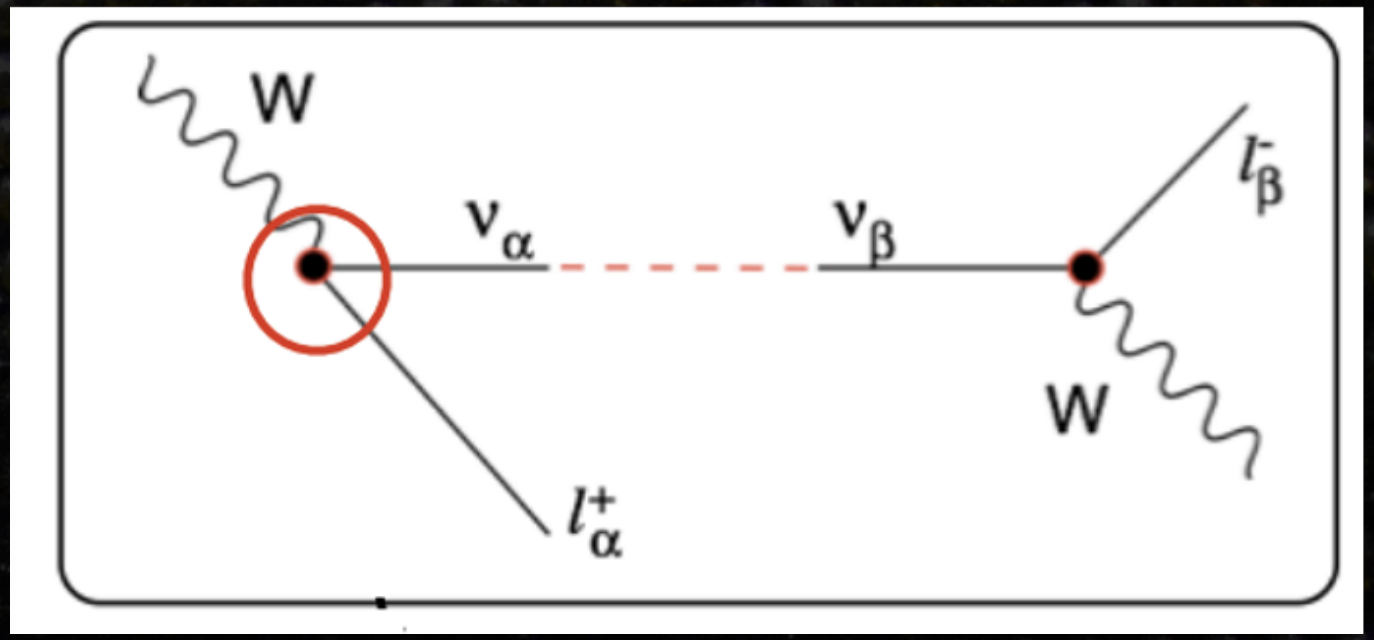

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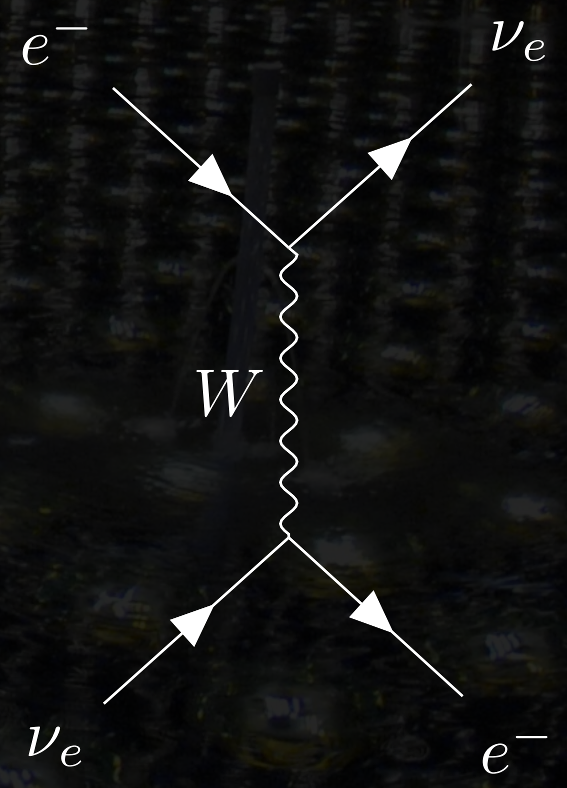
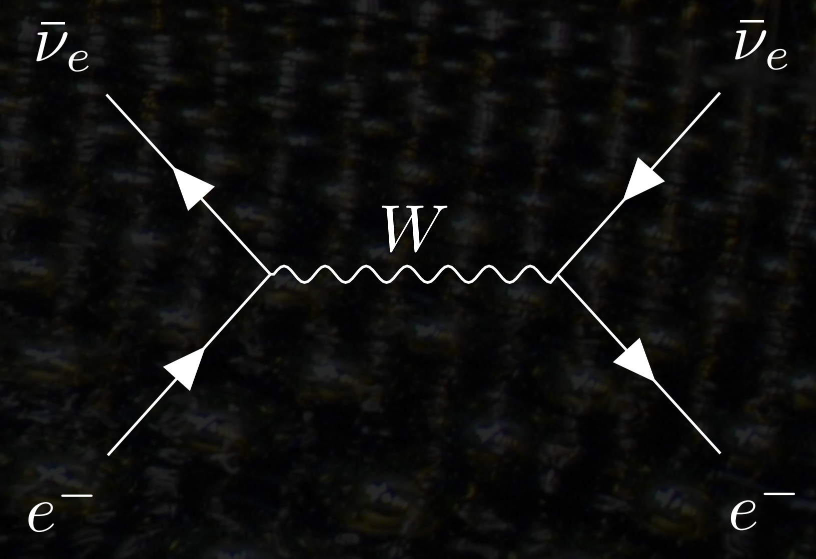
- The "matter effect" (or MSW effect) can modify the oscillation probabilities
  - ν_e and $\bar{\nu}_e$ interaction with e^- in matter
  - Effects different for ν and $\bar{\nu}$
  - Sensitive to the sign of Δm^2_{32} in long baseline and atmospheric neutrino measurements





CURRENT UNDERSTANDING OF NEUTRINO OSCILLATIONS

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$

$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$

Solar & reactor

$\sin^2(\theta_{23}) = 0.539 \pm 0.022 \quad (S = 1.1) \quad$ (Inverted order)

$\sin^2(\theta_{23}) = 0.546 \pm 0.021 \quad$ (Normal order)

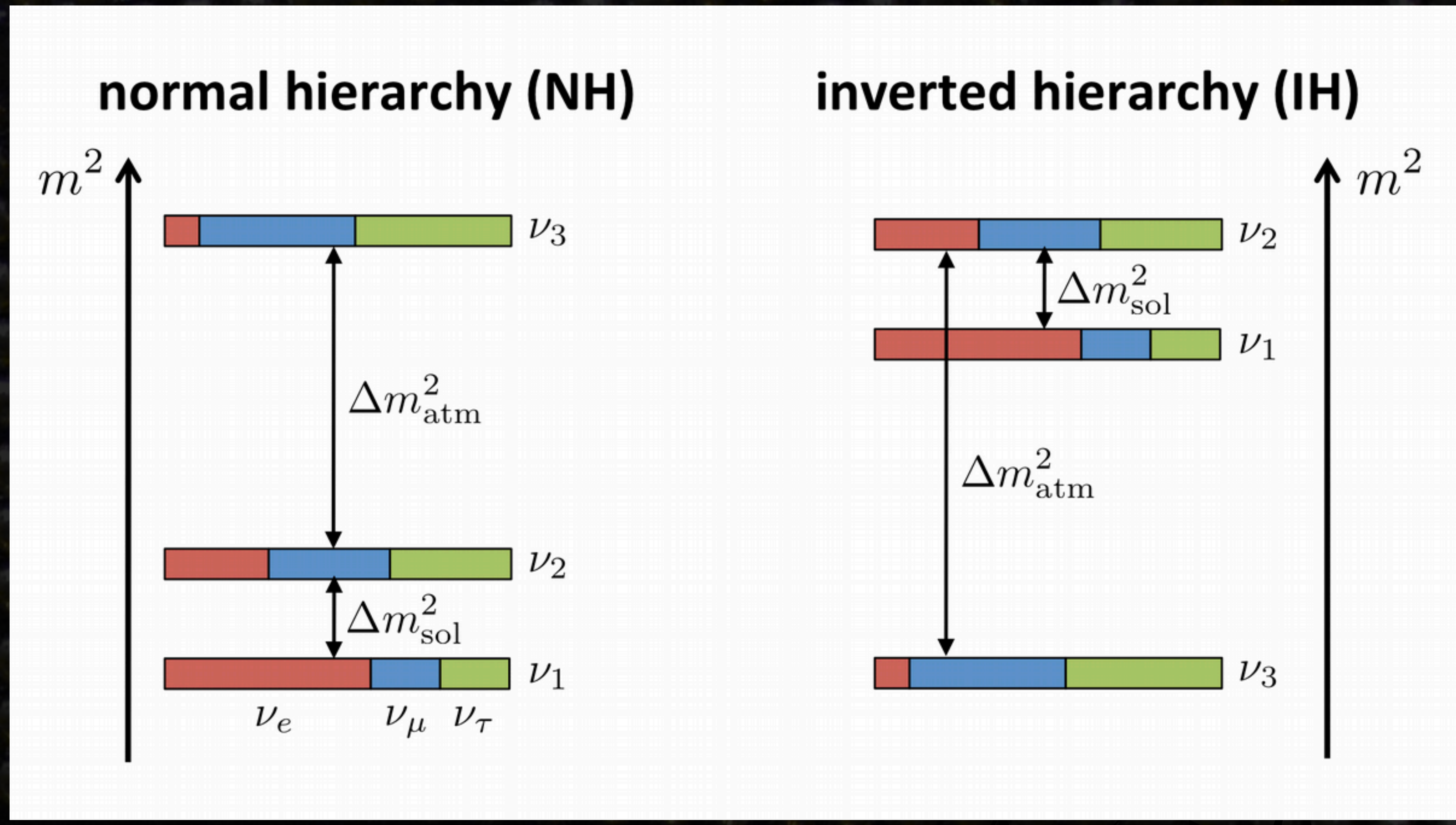
$\Delta m^2_{32} = (-2.536 \pm 0.034) \times 10^{-3}\ \mathrm{eV}^2 \quad$ (Inverted order)

$\Delta m^2_{32} = (2.453 \pm 0.033) \times 10^{-3}\ \mathrm{eV}^2 \quad$ (Normal order)

Atmospheric & LBL

$\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$

Reactor



- Is m_3 larger than m_1?
- Is there CP-violation in the lepton sector?
- What are the absolute masses of neutrinos?
- Are neutrinos Dirac or Majorana?
- Are there sterile neutrinos?

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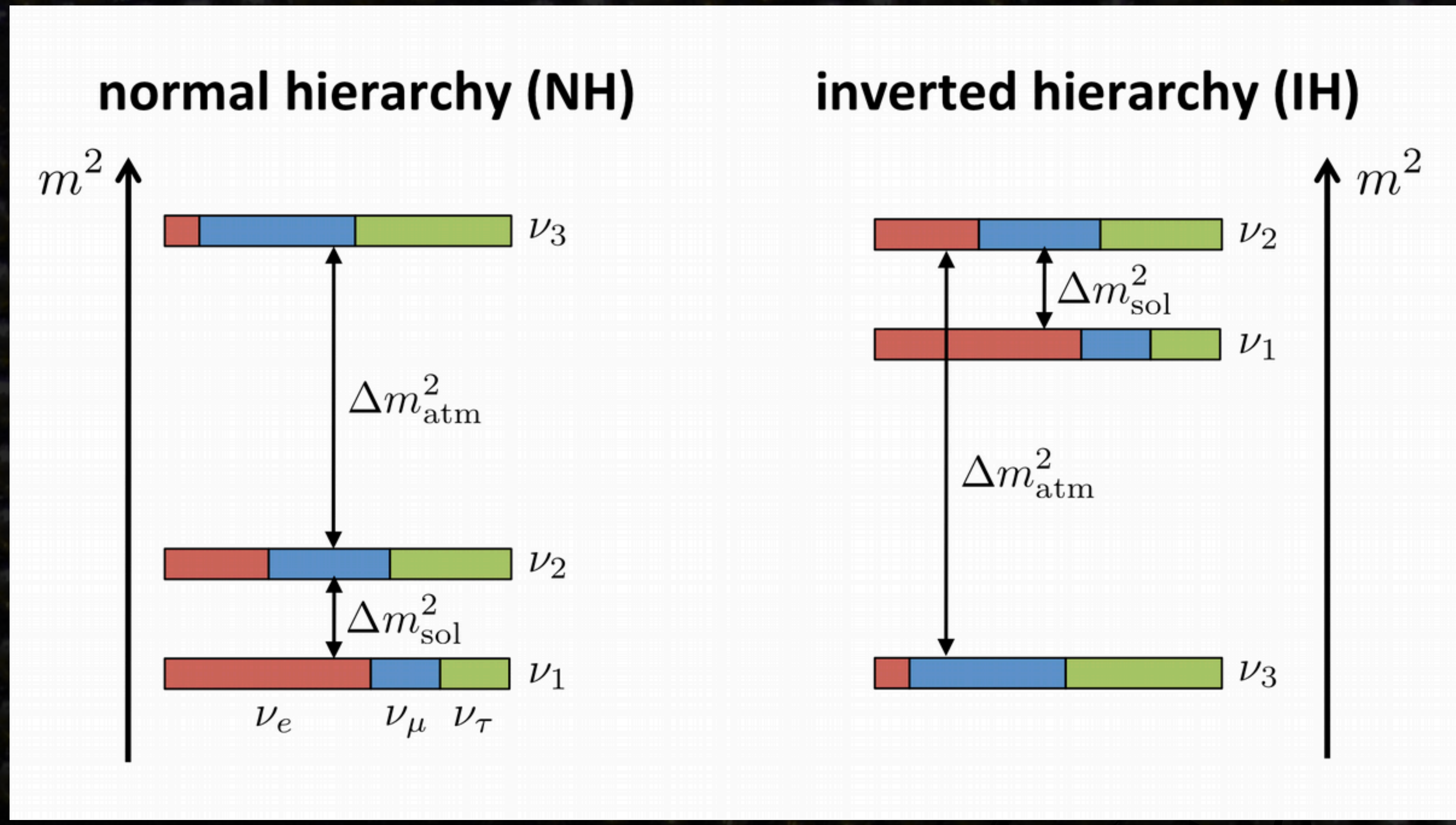

- Is m_3 larger than m_1? — LBL & atmospheric & reactor
- Is there CP-violation in the lepton sector? — LBL
- What are the absolute masses of neutrinos? — E.g. KATRIN, Project 8 & cosmology
- Are neutrinos Dirac or Majorana? — Neutrinoless double beta decay experiments
- Are there sterile neutrinos? — All of the above & SBL

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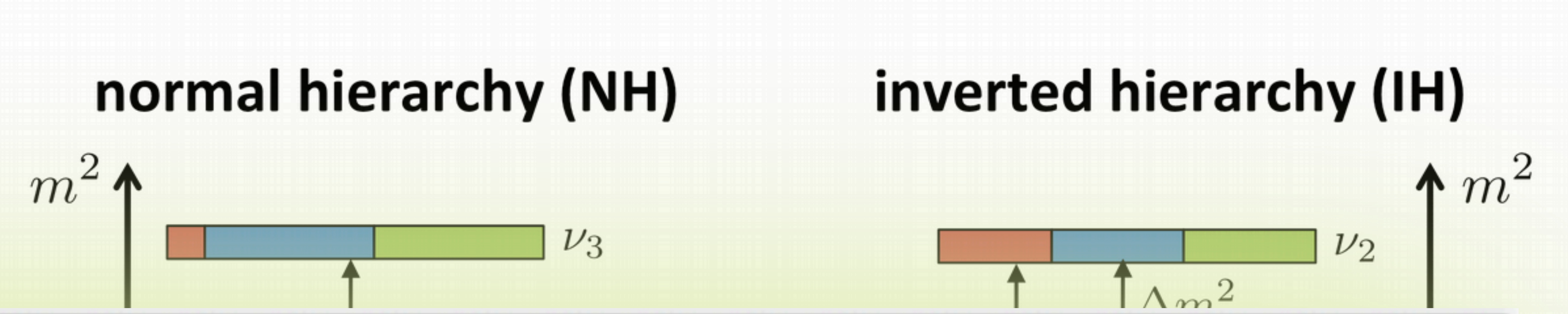
Solar & reactor



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$\sin^2(\theta_{13}) = (2.20 \pm$

Mitigating Cosmogenic Backgrounds in nEXO — *Soud Al Kharusi*
KC 303, Banff Centre — 14:45 - 15:00

Rapid characterization of SiPMs for nEXO and future noble liquid experiments — *Ms Bindiya Chana*
KC 303, Banff Centre — 15:00 - 15:15

Detection of Supernova Neutrinos in the SNO+ Detector — *Jasmine Corning*
KC 303, Banff Centre — 15:15 - 15:30

Poster "Denoising of p-Type Point Contact (PPC) HPGe Detector Signals with Generative Adversarial Networks"
Tiani Ye

- Is m_3 larger th
- Is there CP-vio
- What are the absolute masses of neutrinos? — E.g. KATRIN, Project 8 & cosmology
- Are neutrinos Dirac or Majorana? — Neutrinoless double beta decay experiments
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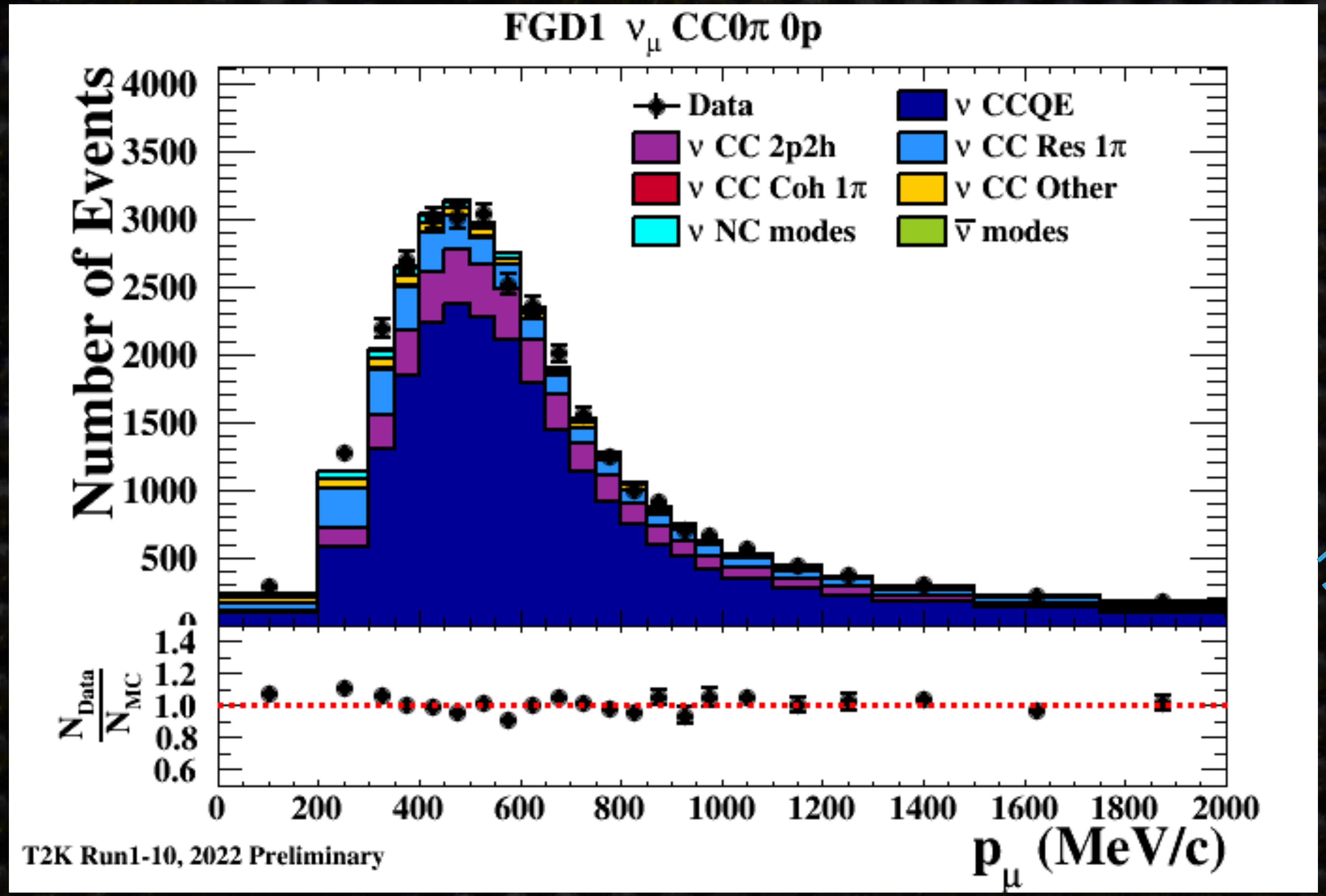
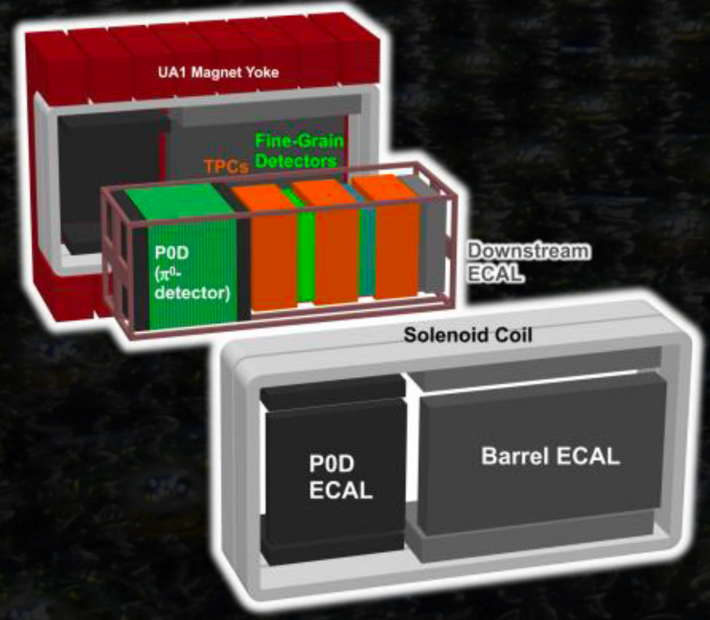
LONG BASELINE EXPERIMENT: T2K

Neutrino spectrum before oscillation

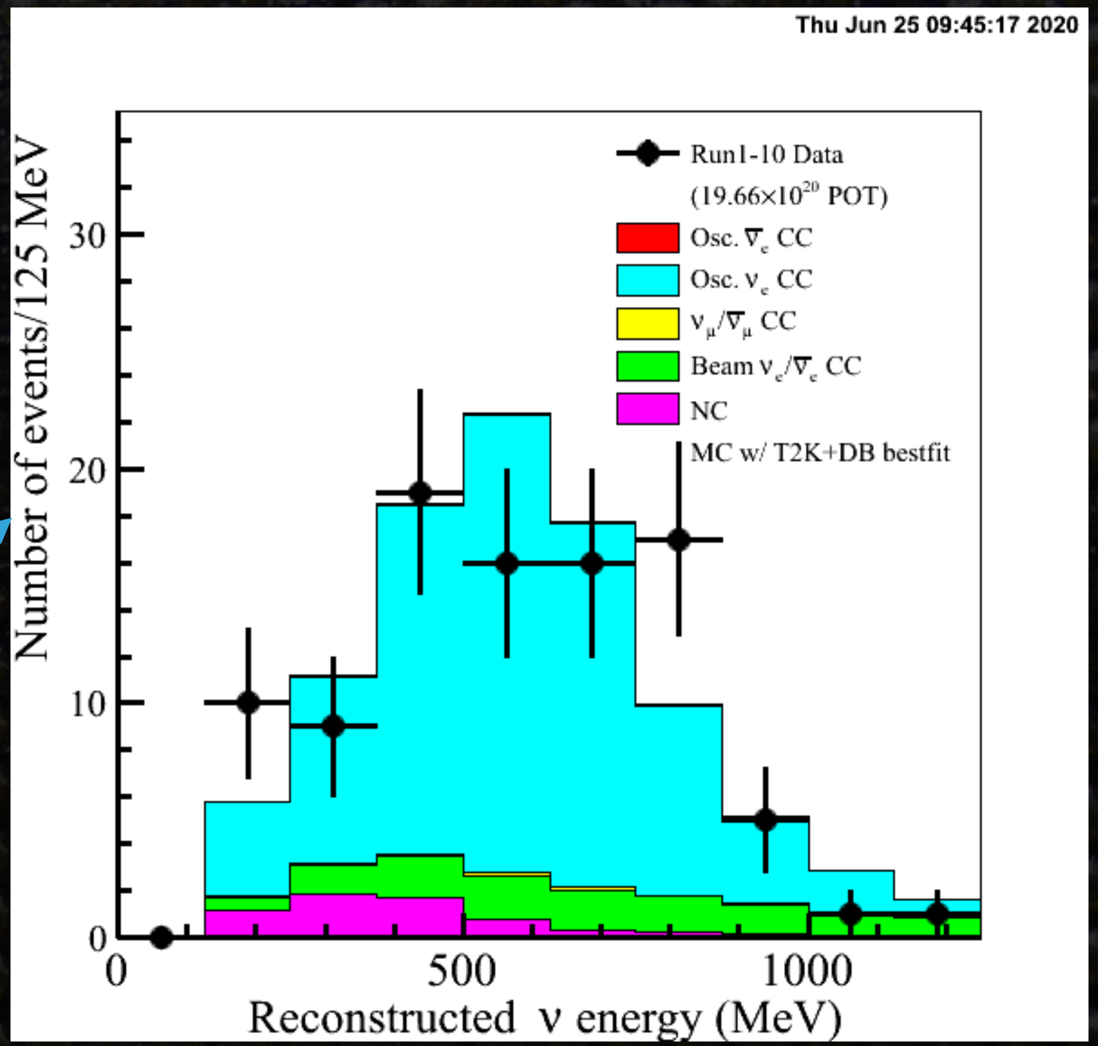


Near detector



Neutrino beam

$\nu_\mu \rightarrow \nu_e$



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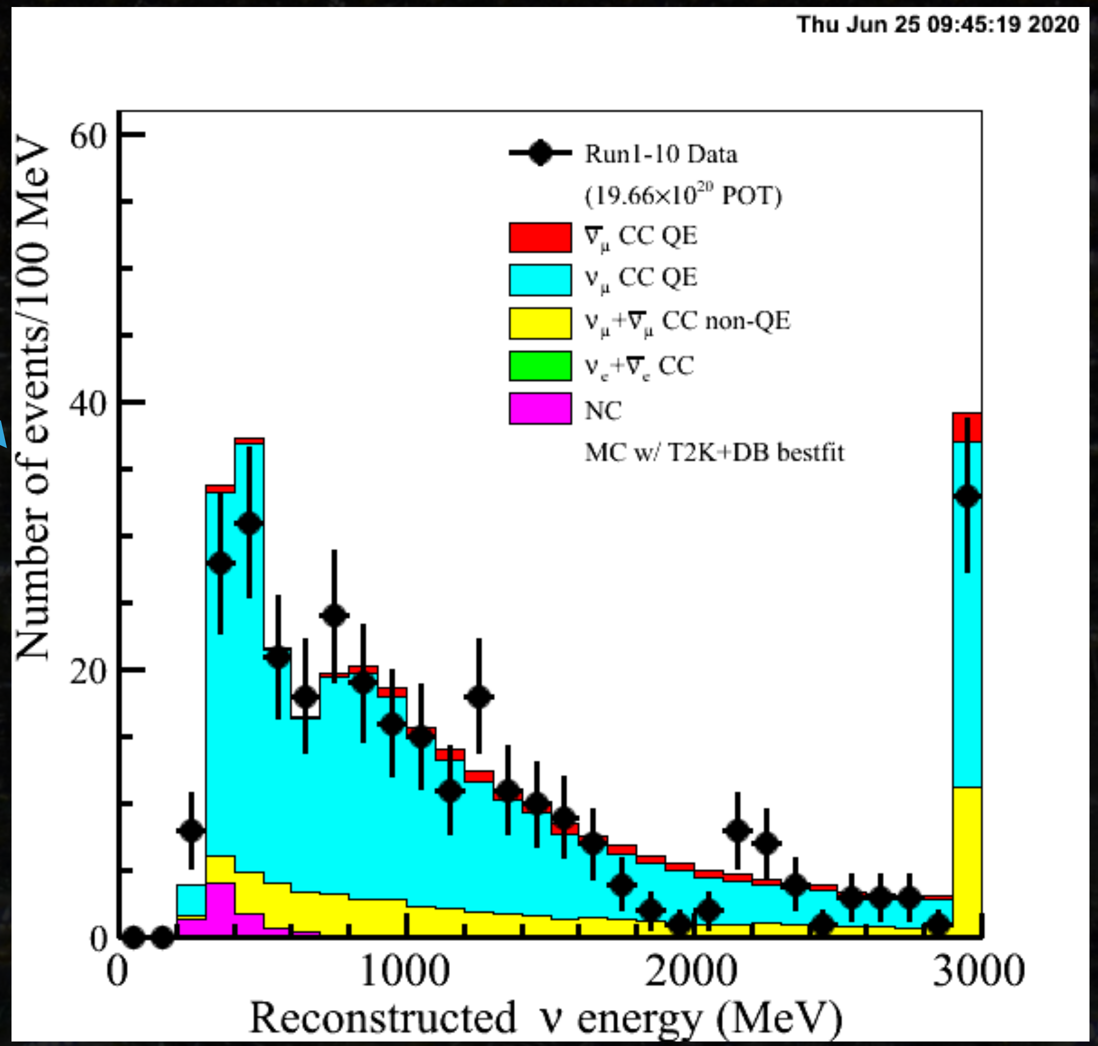
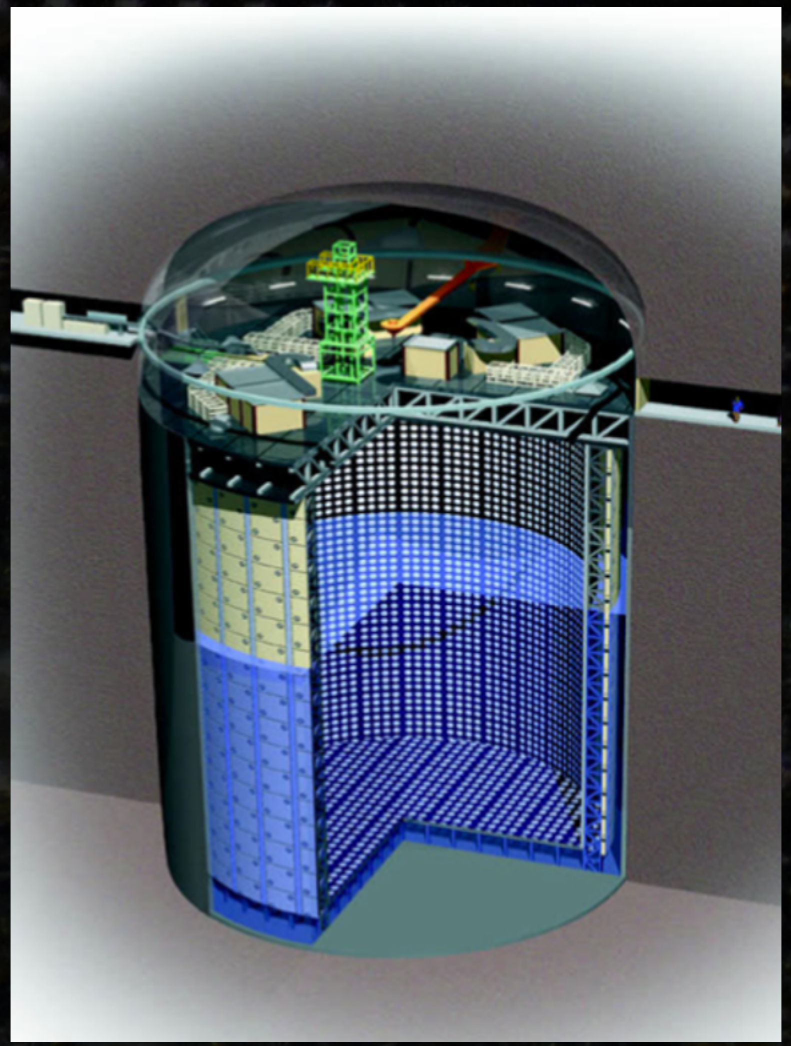


Neutrino spectra after oscillation

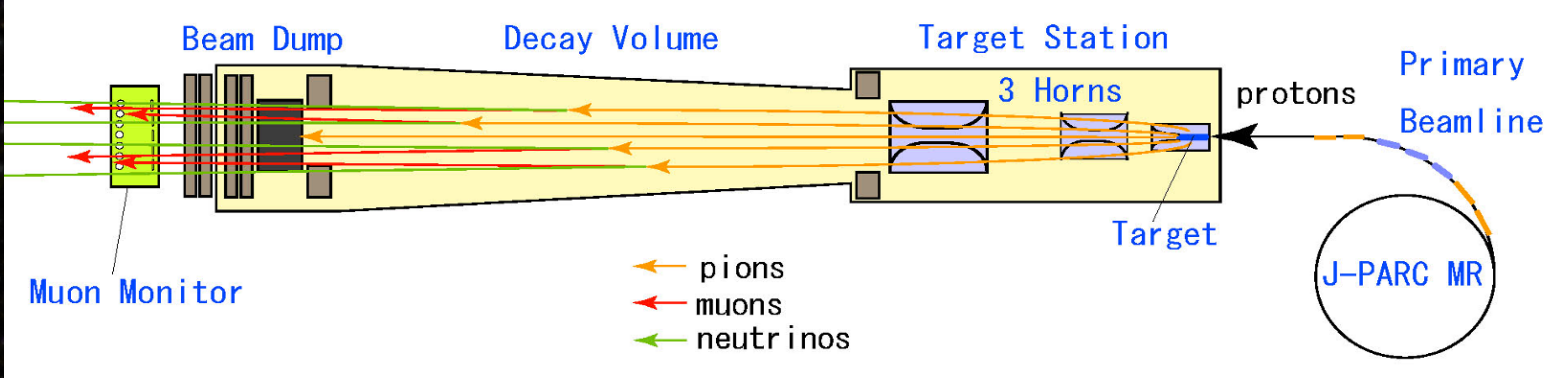
Far detector

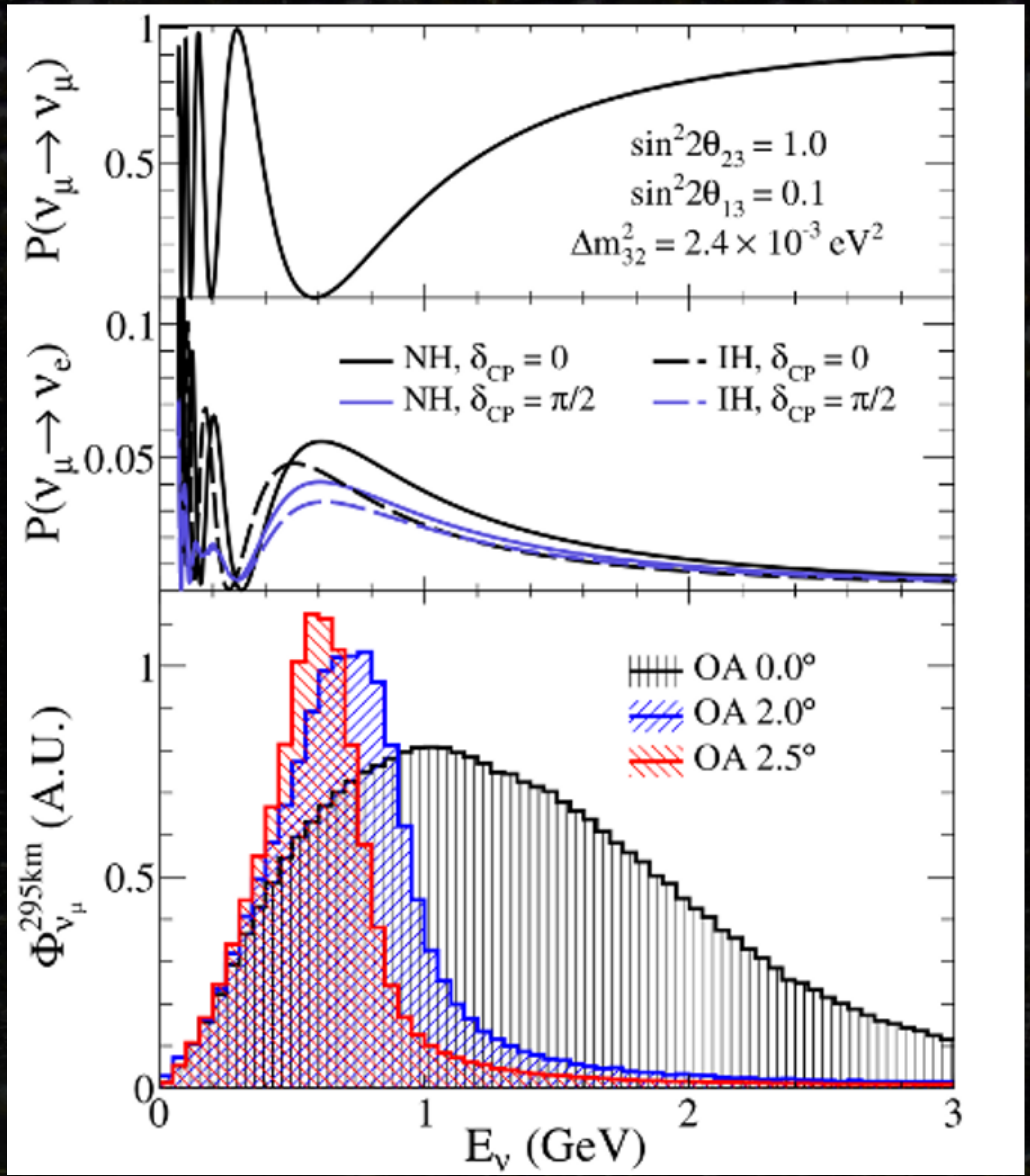


280 m

295 km

LONG BASELINE EXPERIMENT: T2K





- Magnetic horns focus positively charged or negatively charged pions and kaons
- Neutrinos are produced via the decay of pions and kaons
- Neutrino fluxes vary as a function of off-axis angle
- Current beam power ~500 kW

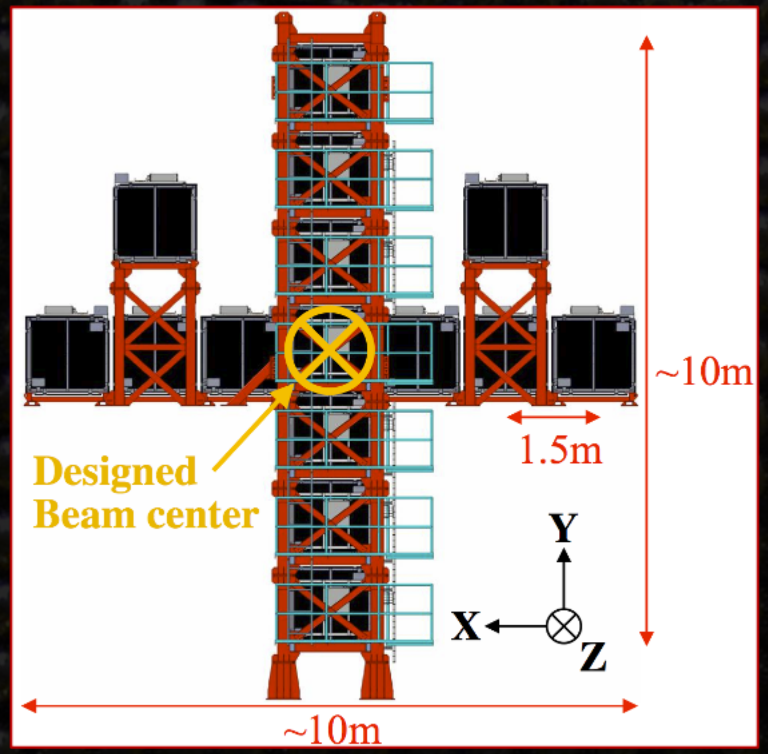
Neutrino beam

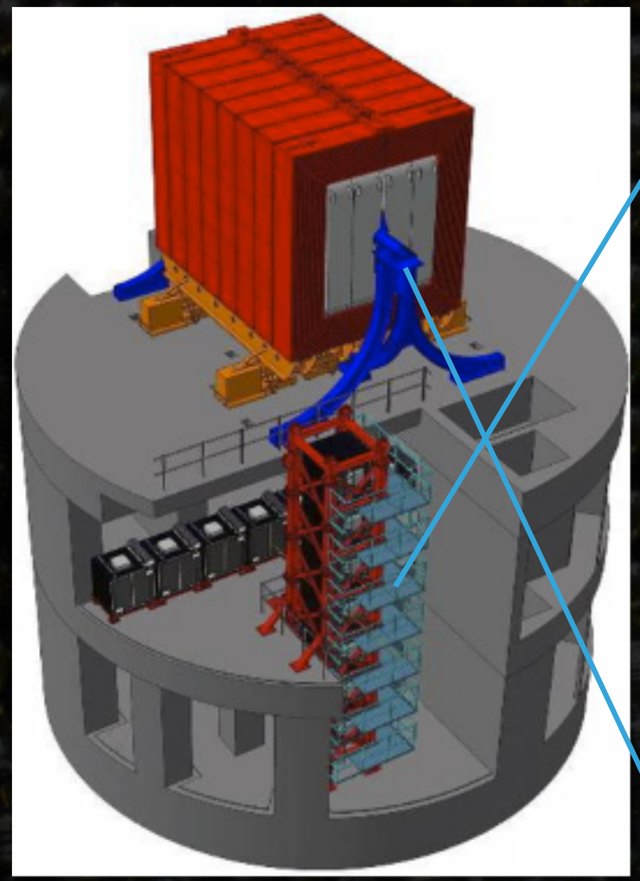
280 m

295 km

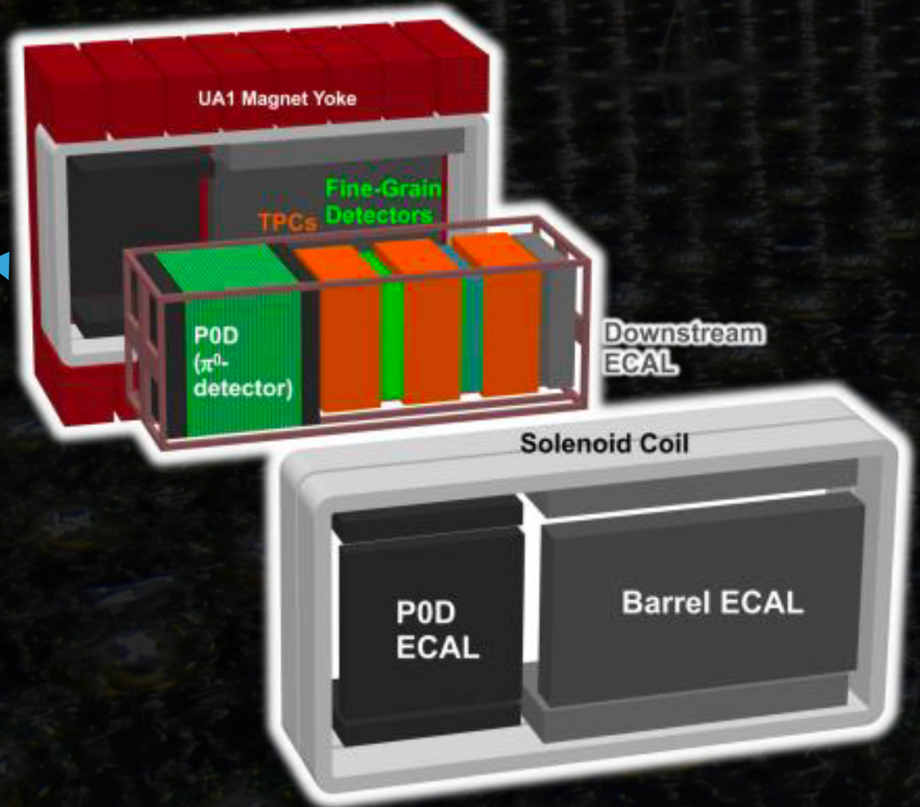
LONG BASELINE EXPERIMENT: T2K

INGRID, on-axis





Near detector



ND280, 2.5° off-axis

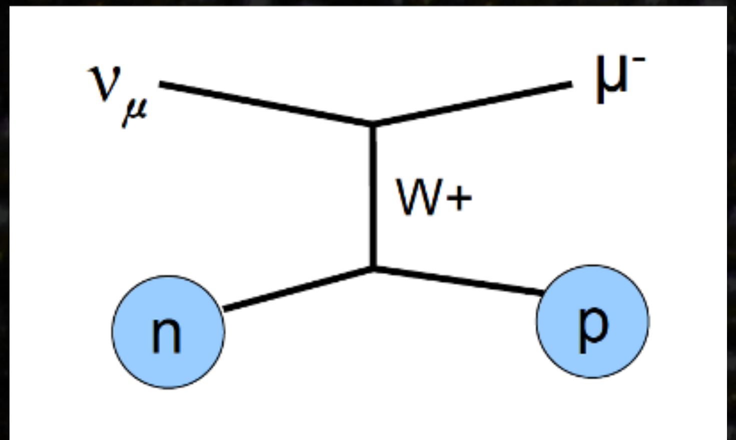
- On-axis detector monitors neutrino beam profile and event rate
- Off-axis detector measures neutrino interactions at 2.5° off-axis angle
  - Unoscillated neutrino fluxes
  - Constrains neutrino fluxes and interaction cross-section at the same time
  - Tracker and calorimeter
  - Several different nuclear targets
  - Magnet to differentiate positively charged and negatively charged particles produced by neutrino interactions

280 m

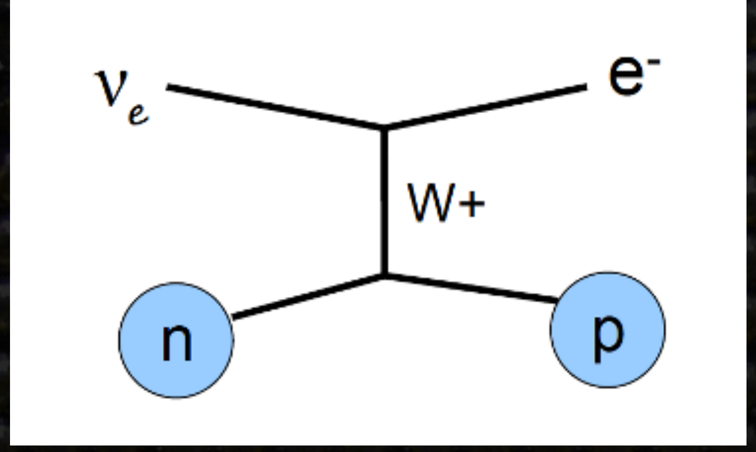
295 km

LONG BASELINE EXPERIMENT: T2K

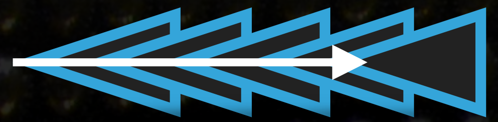
ν_μ CCQE



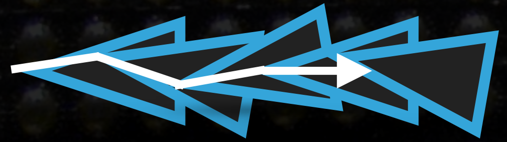
ν_e CCQE

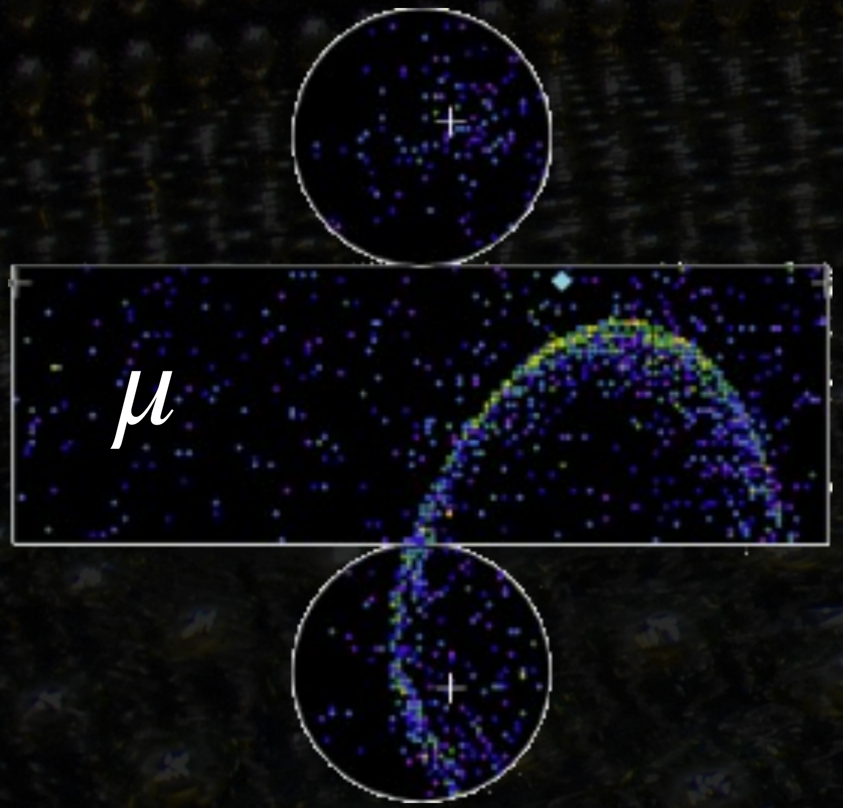


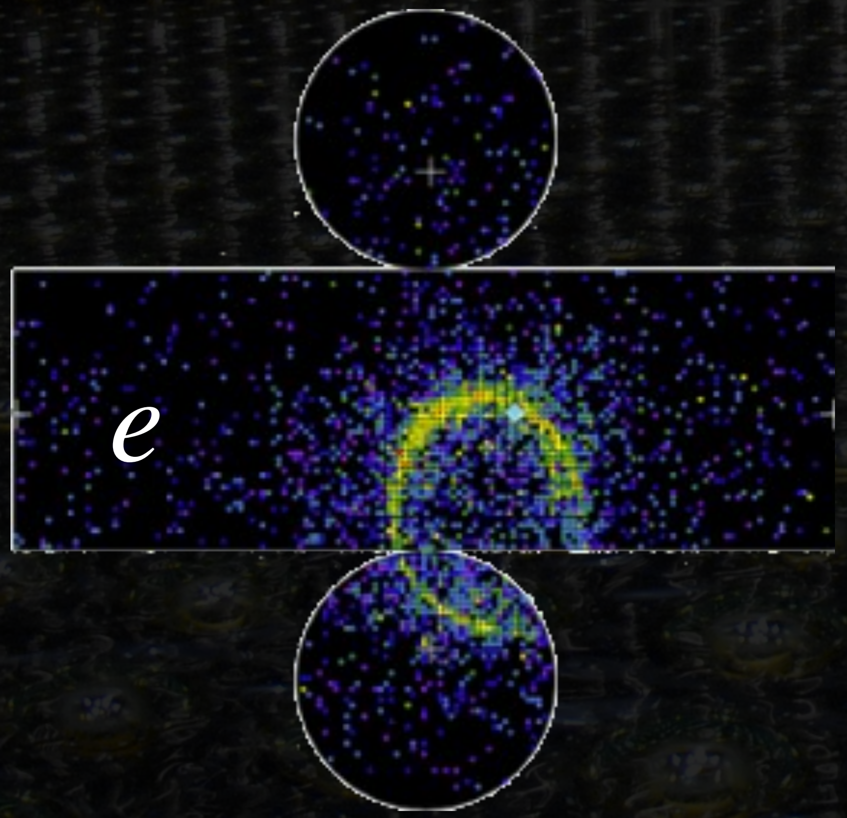
muon

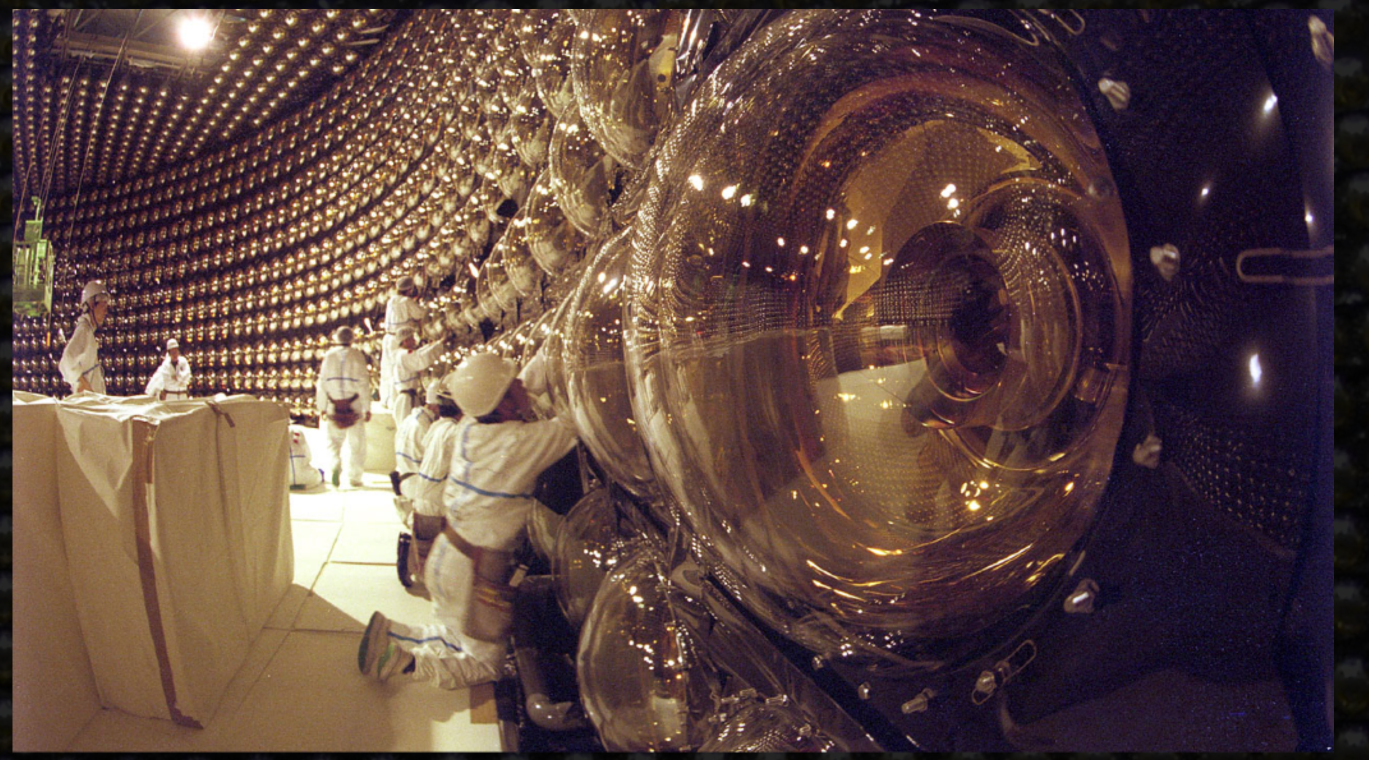


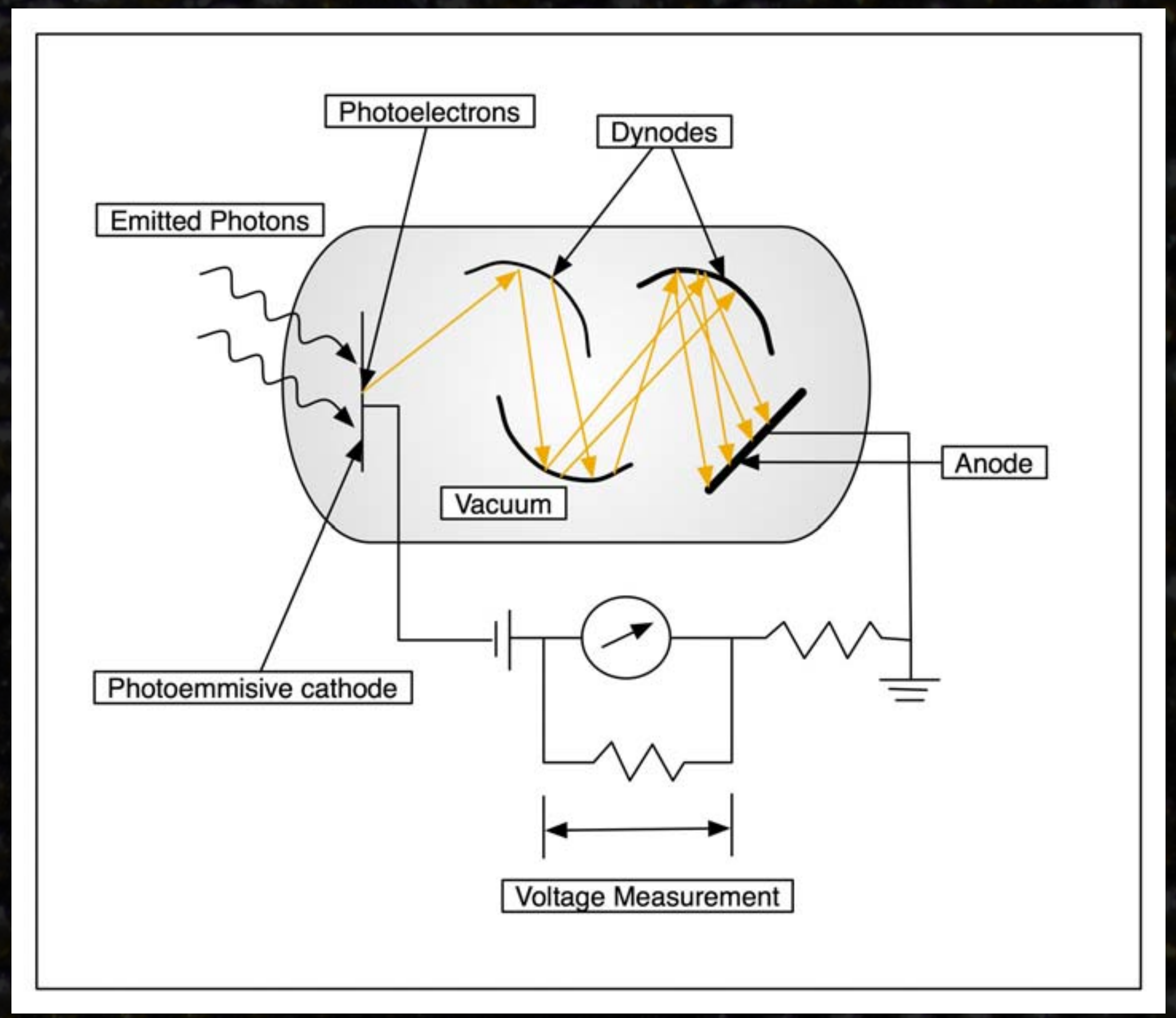
electron



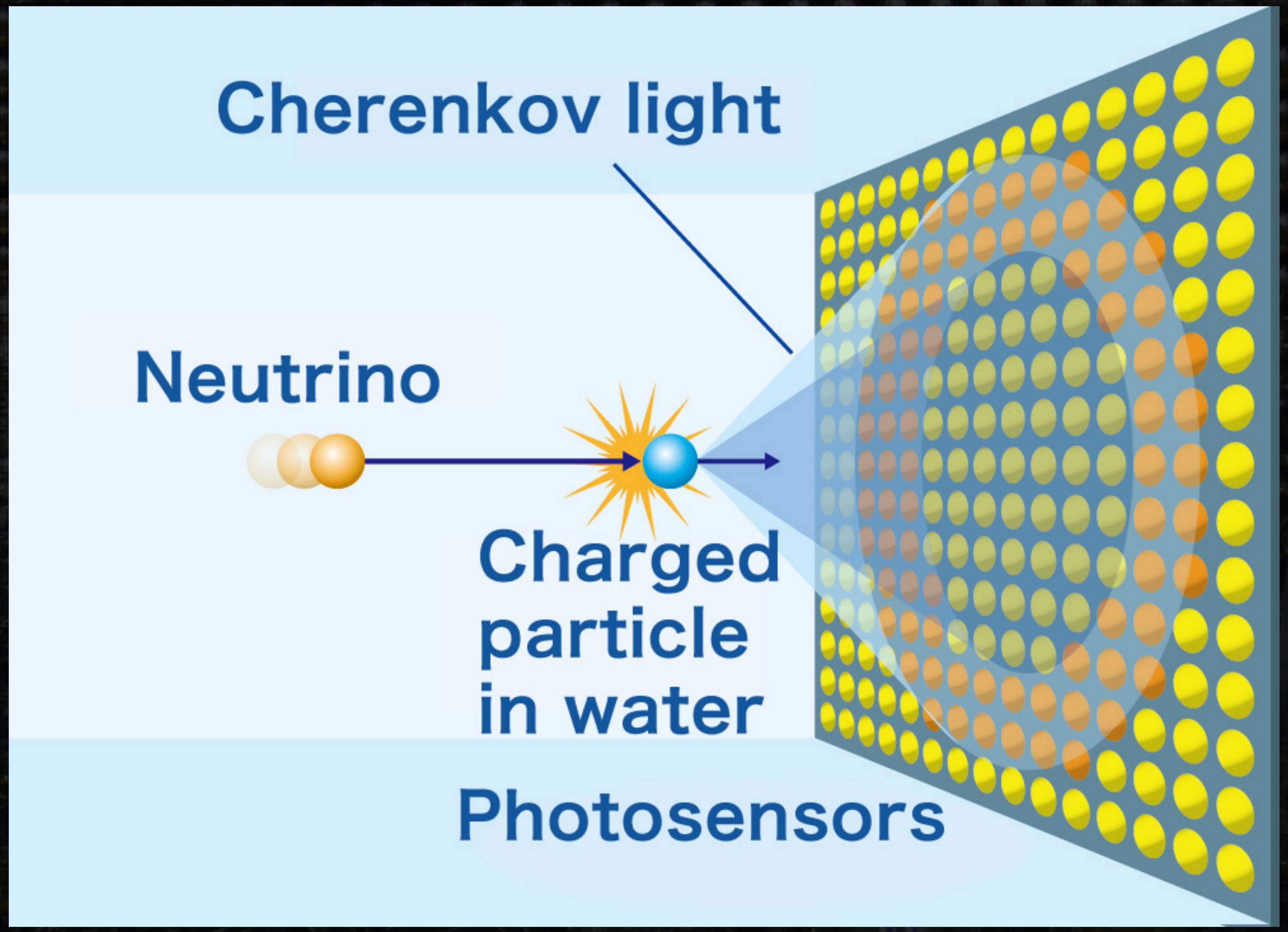


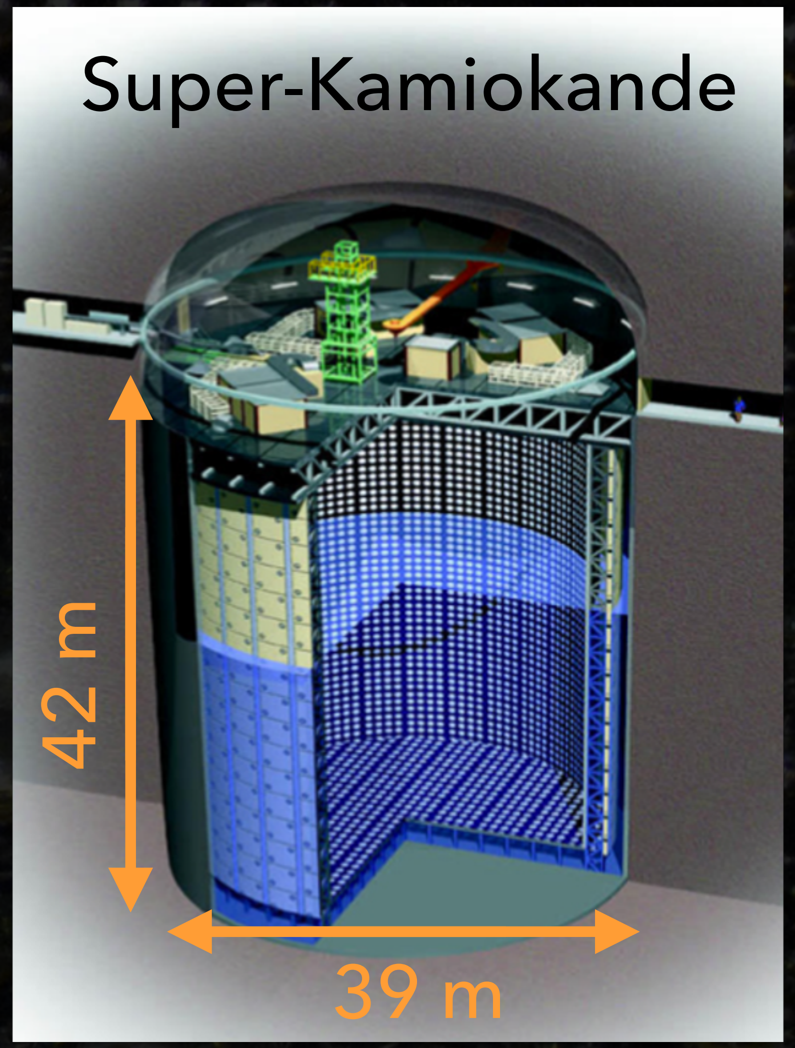






Far detector



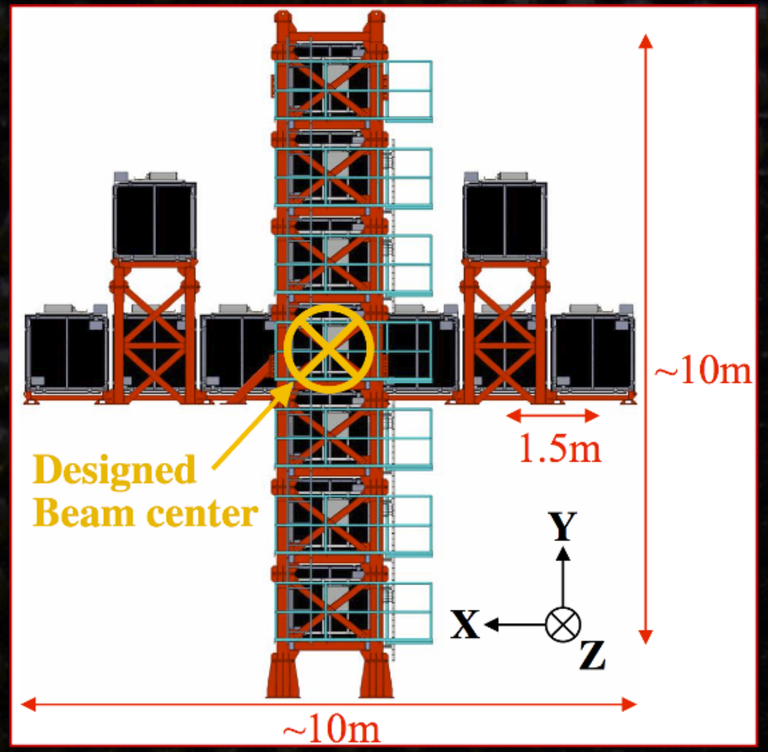


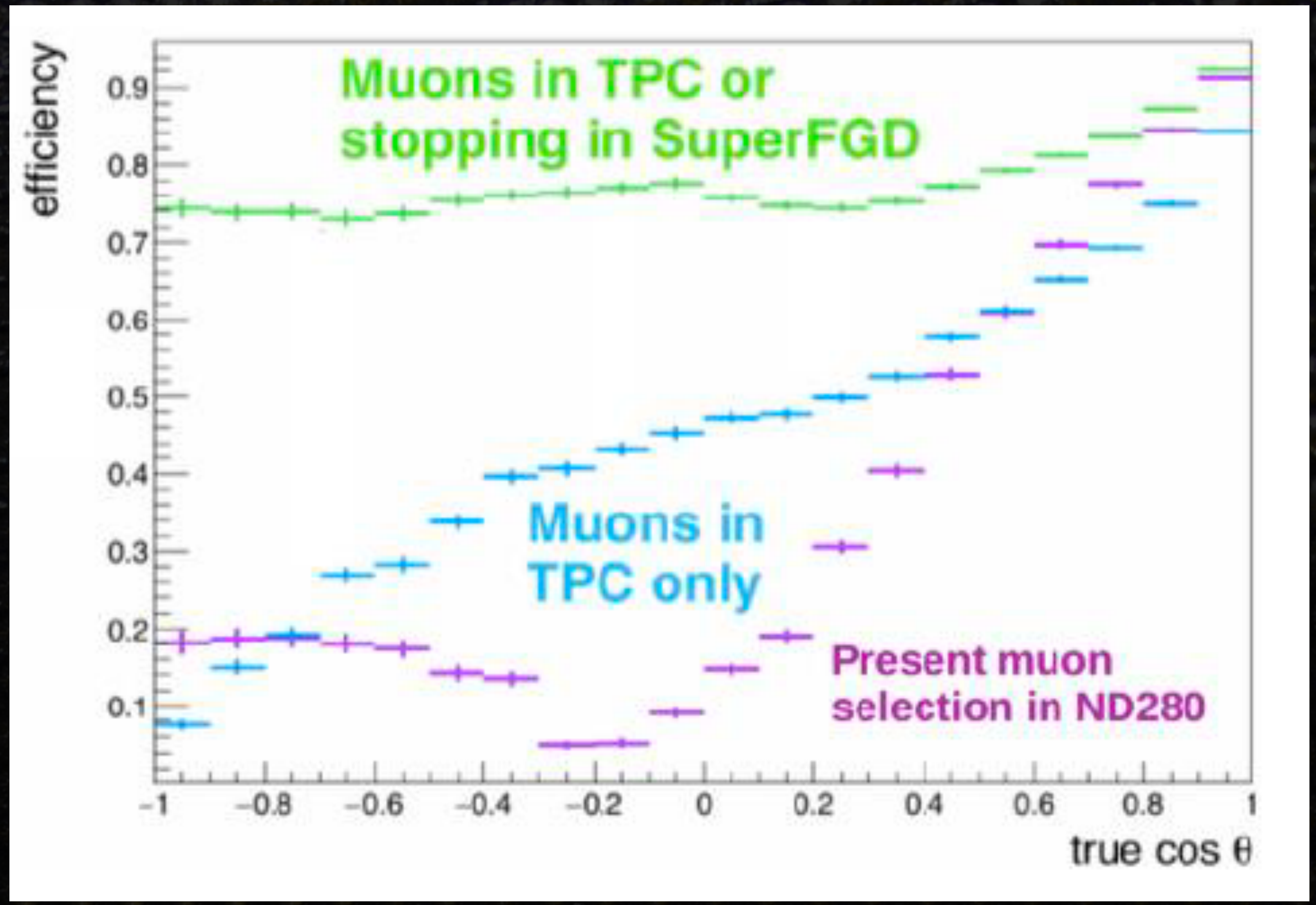
280 m

295 km

HYPER-KAMIOKANDE

Near detector

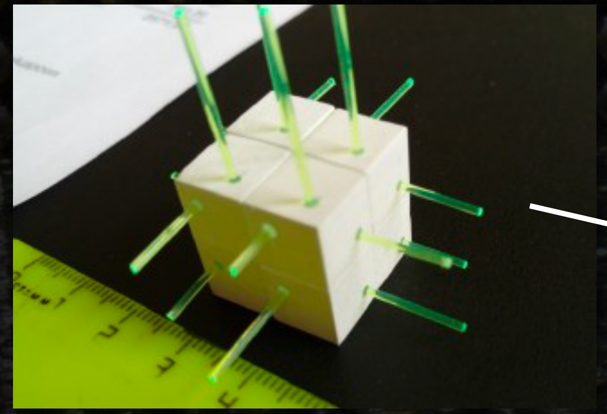




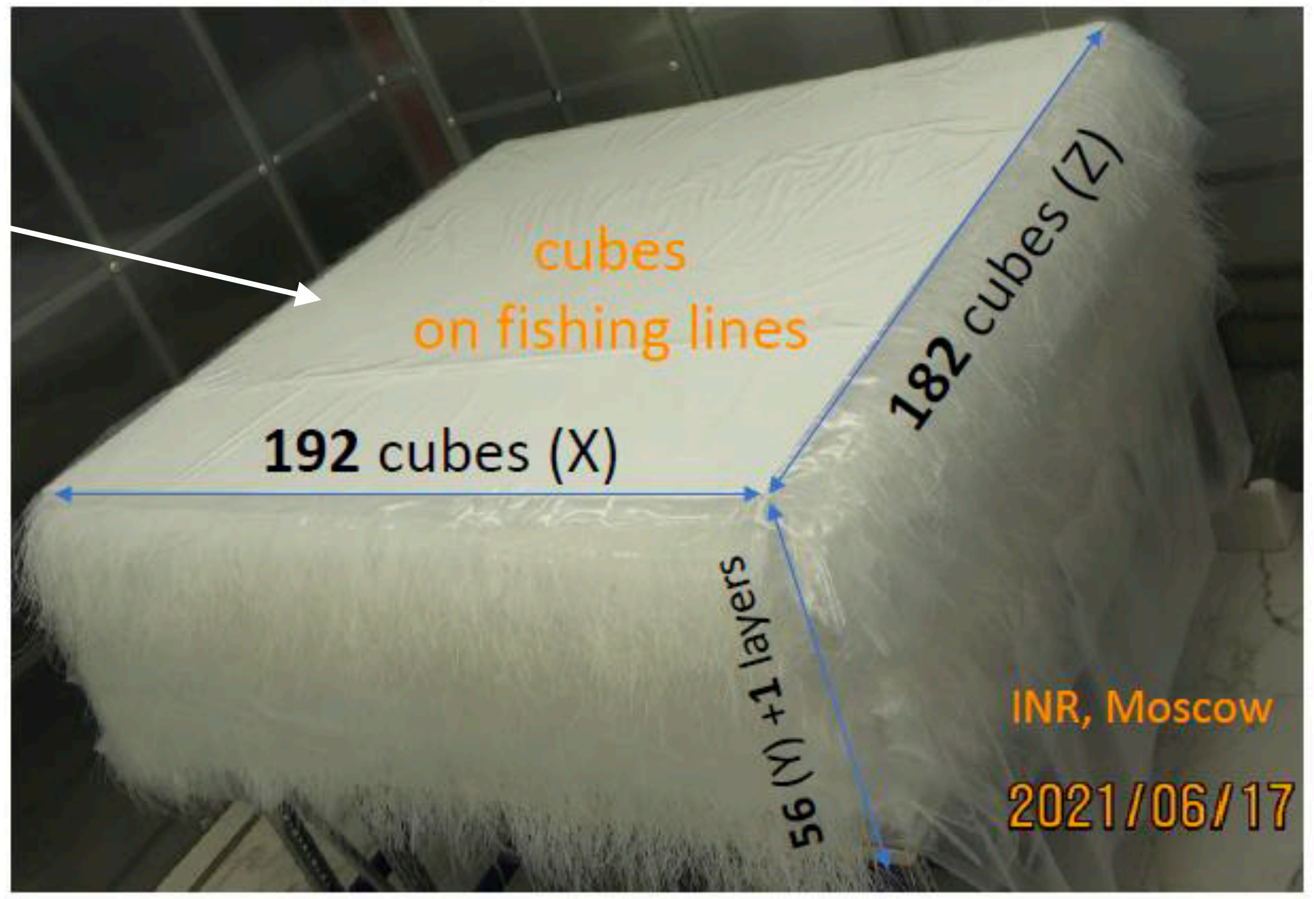
- 4π coverage
- Neutron measurement

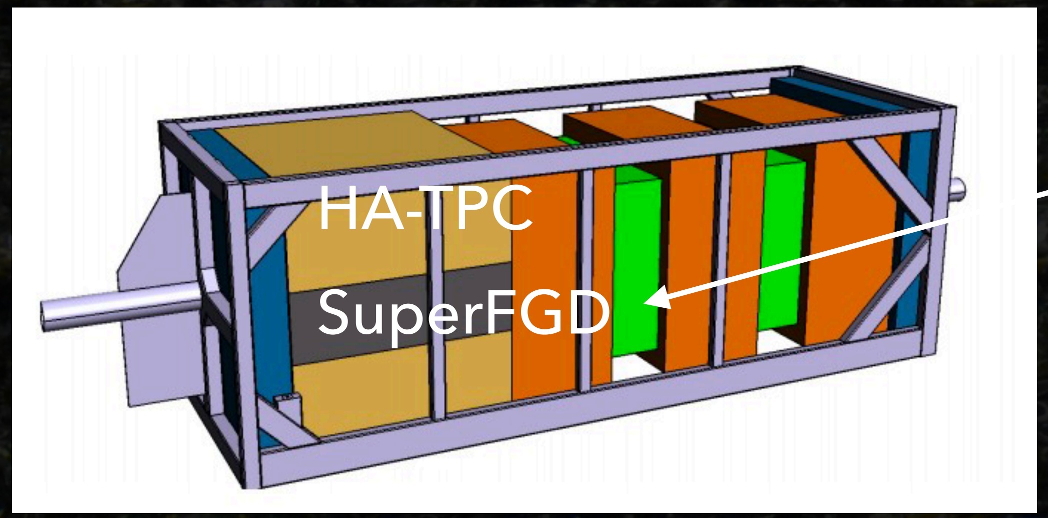
Neutrino beam

- Beam power 500 kW –> 1.3 MW



56 (Y) +**1** spare layers x **192** cubes (X) x **182** cubes (Z)
[1,991,808 cubes in total]





2.5° off-axis, ~0.6 GeV

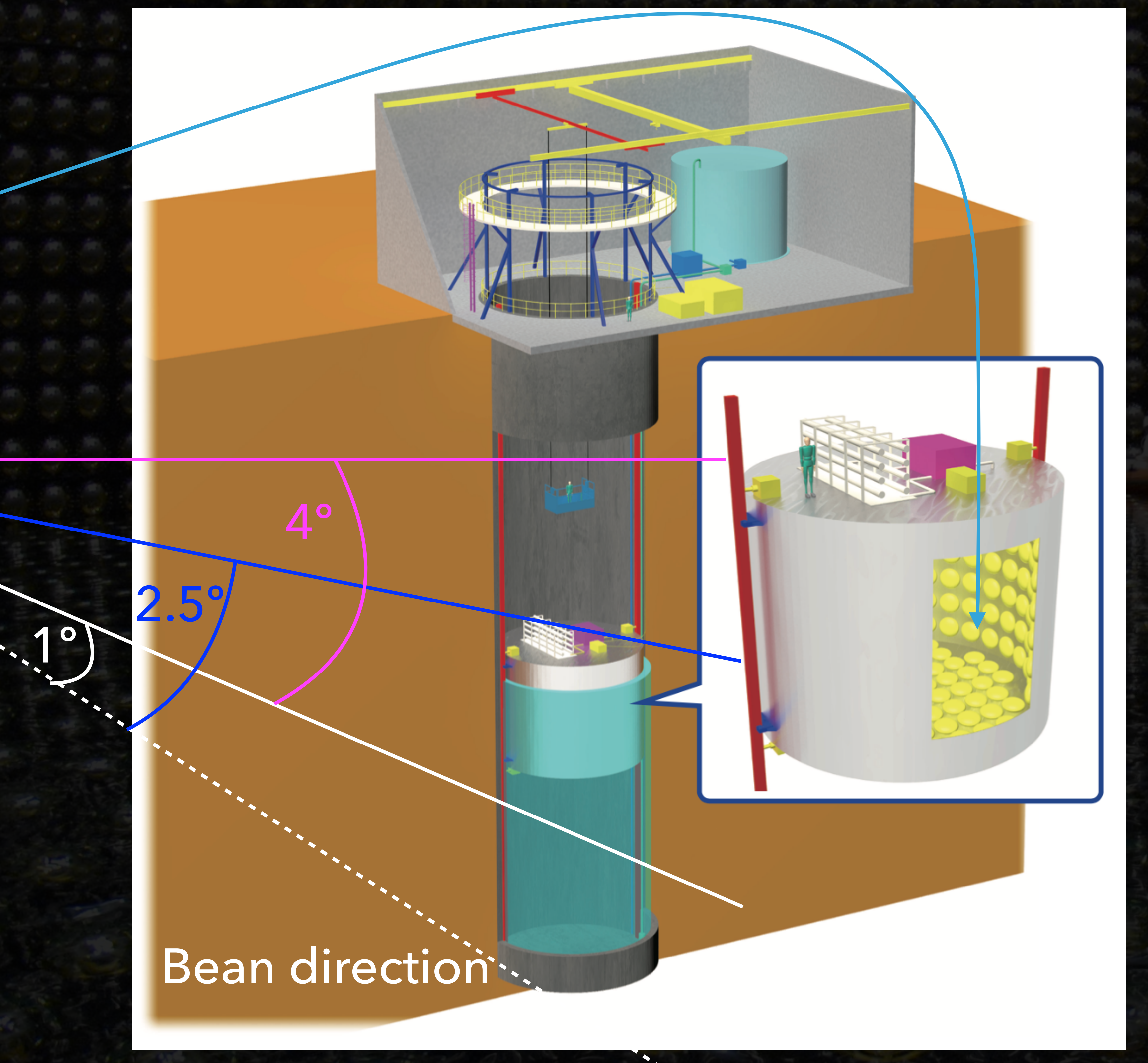
3D-array of 1-cm scintillator cubes (184x192x56)

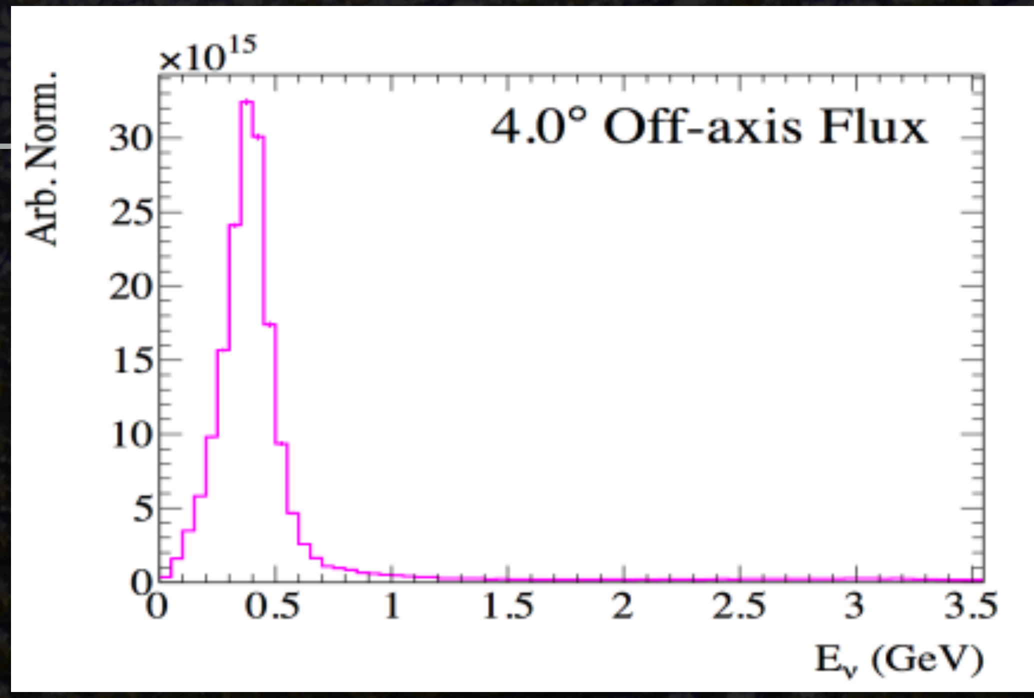
280 m ~1 km 295 km

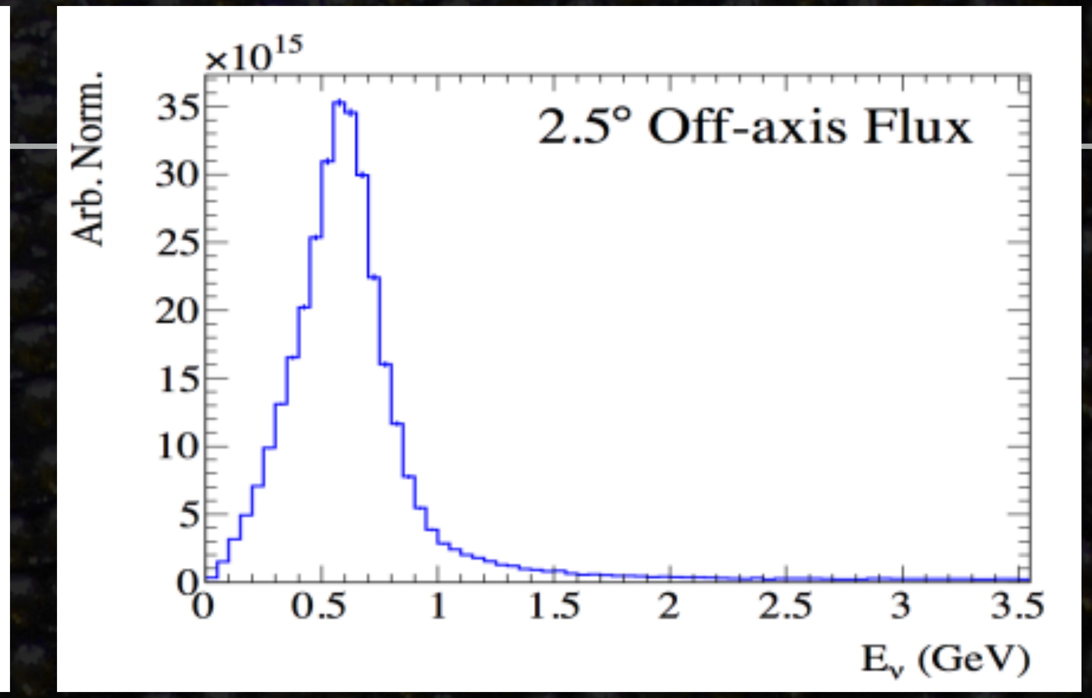
HYPER-KAMIOKANDE

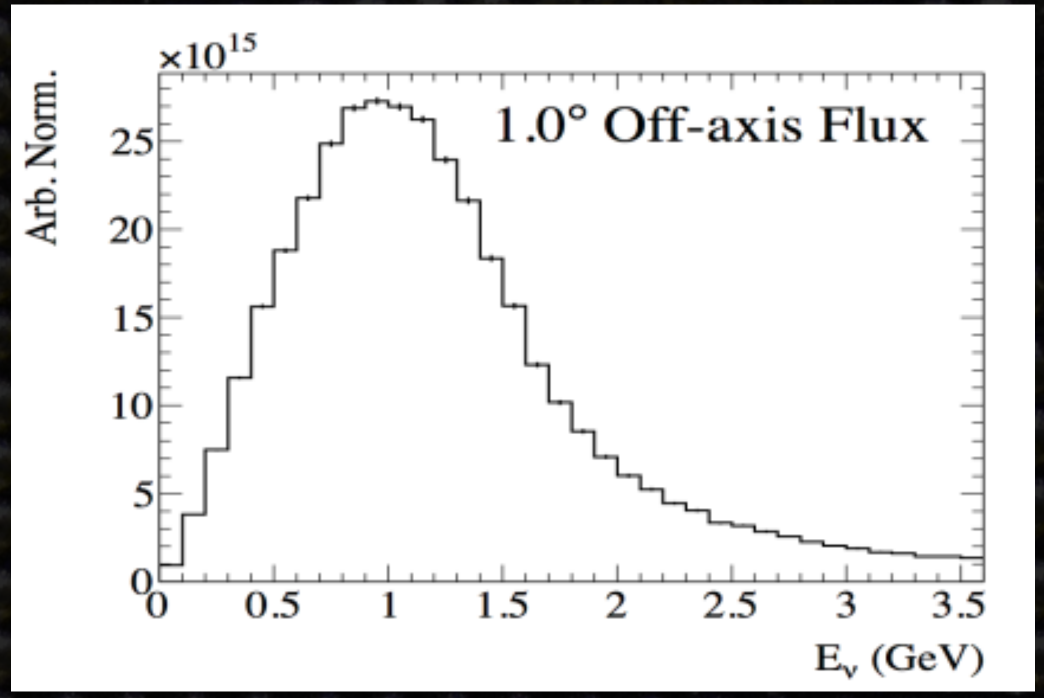
mPMT

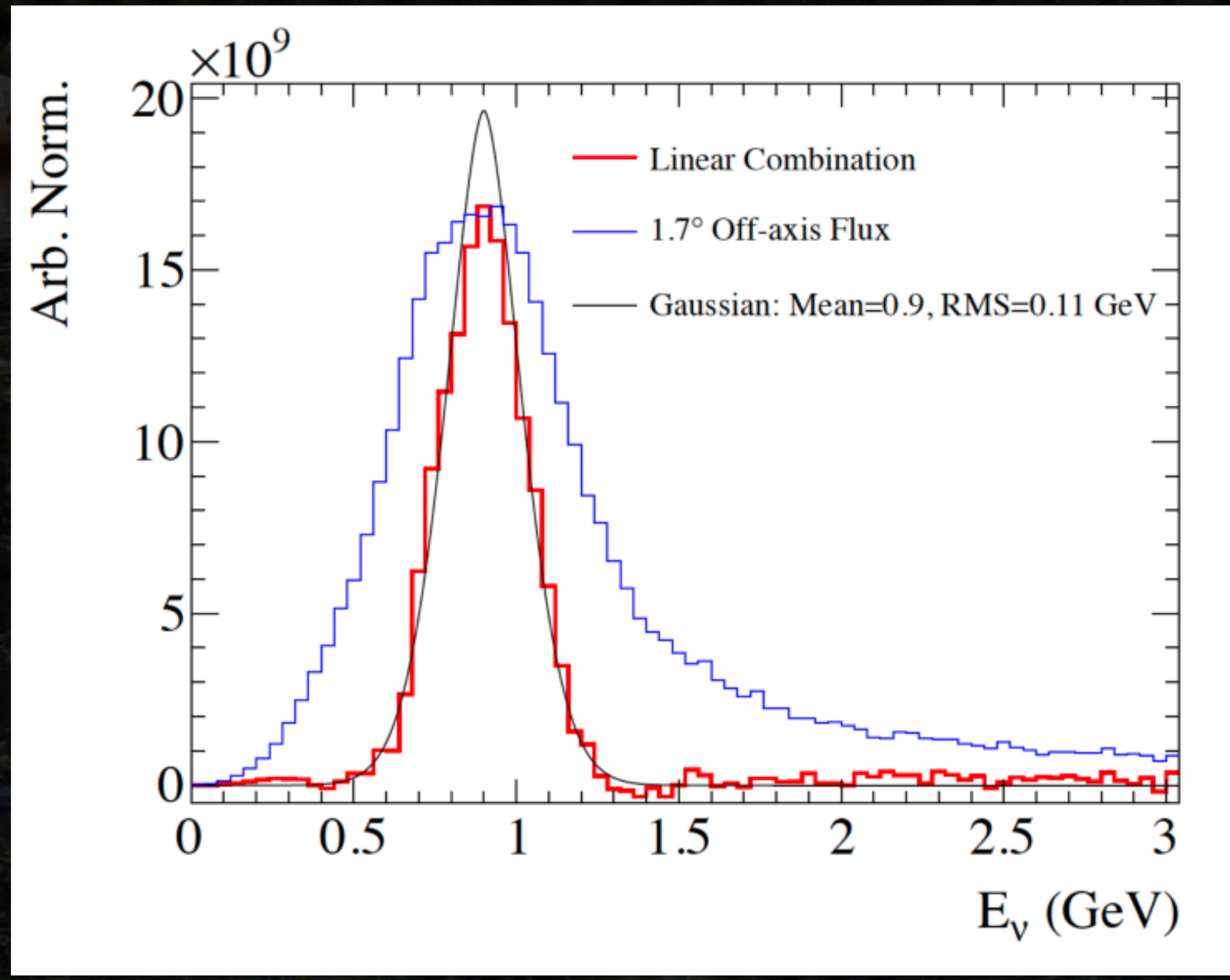
Intermediate Water Cherenkov Detector (IWCD)



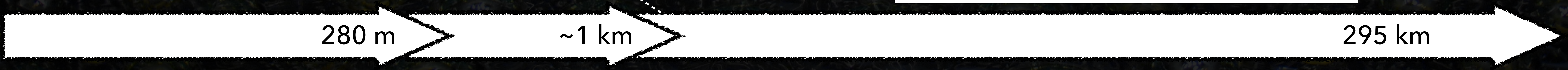






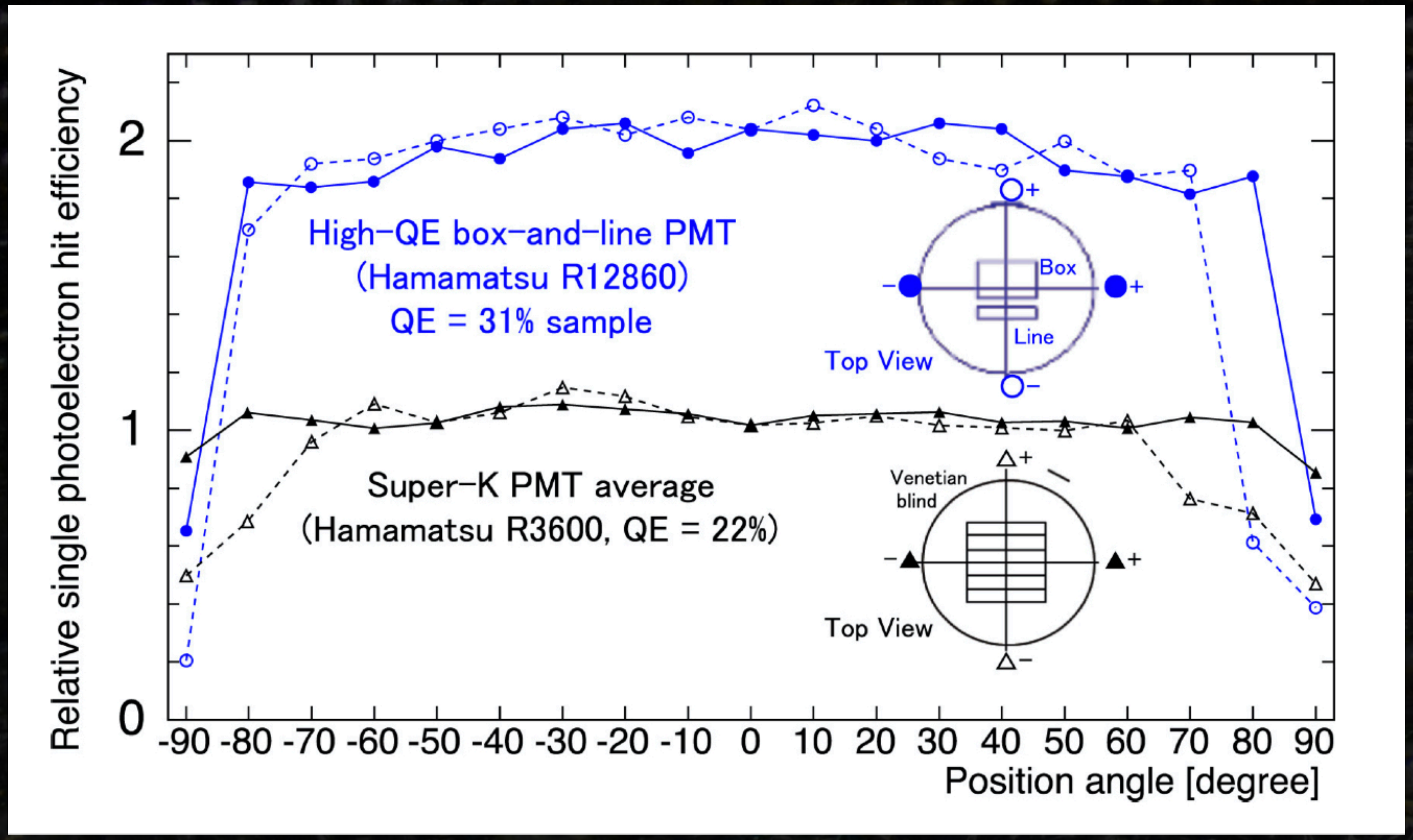


- Linear combination of the neutrino fluxes at different off-axis angles can mock up a quasi mono energetic beam
- Cross-section independent measurements possible

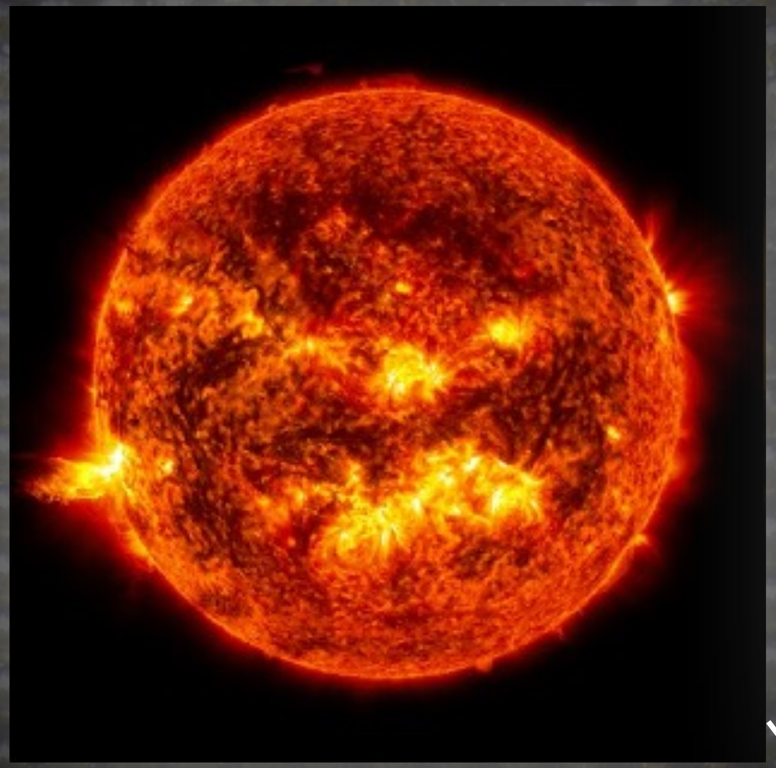


HYPER-KAMIOKANDE

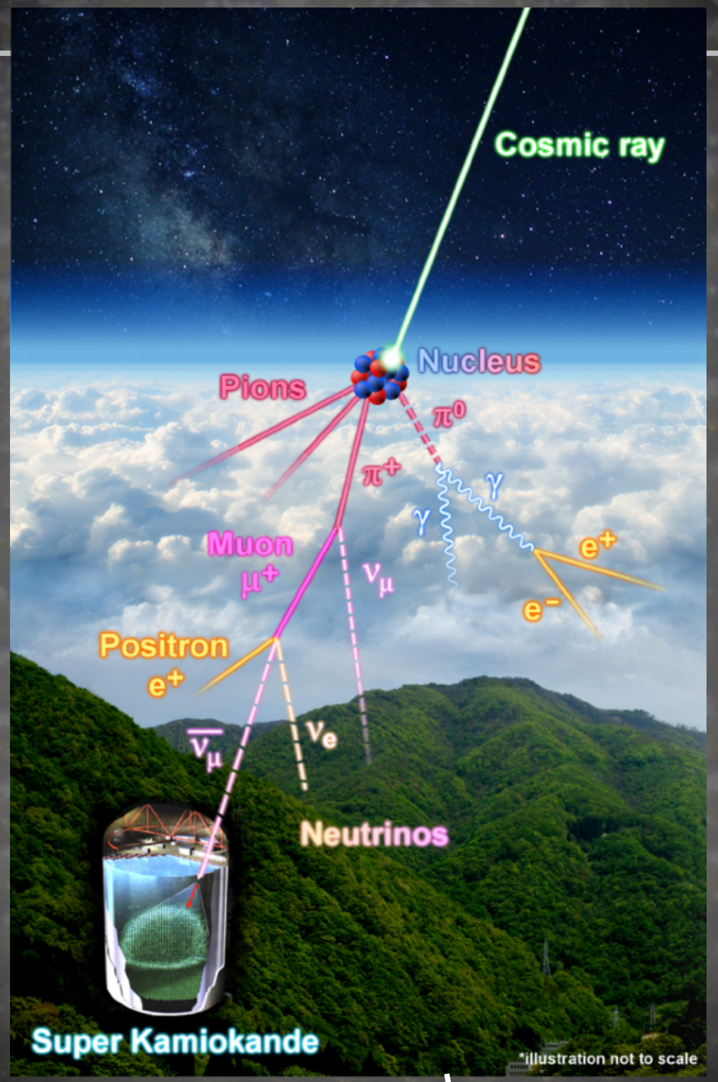
- 8.6X fiducial volume compared to Super-K
- 20,000 20″ PMTs, 20% photocathode coverage
    - 2X detection efficiency compared to Super-K PMTs
    - Better energy and timing resolution
- A few hundreds of mPMTs



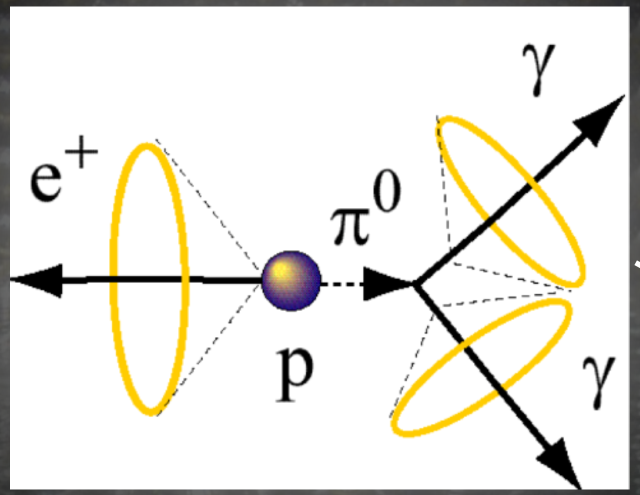
Solar neutrino



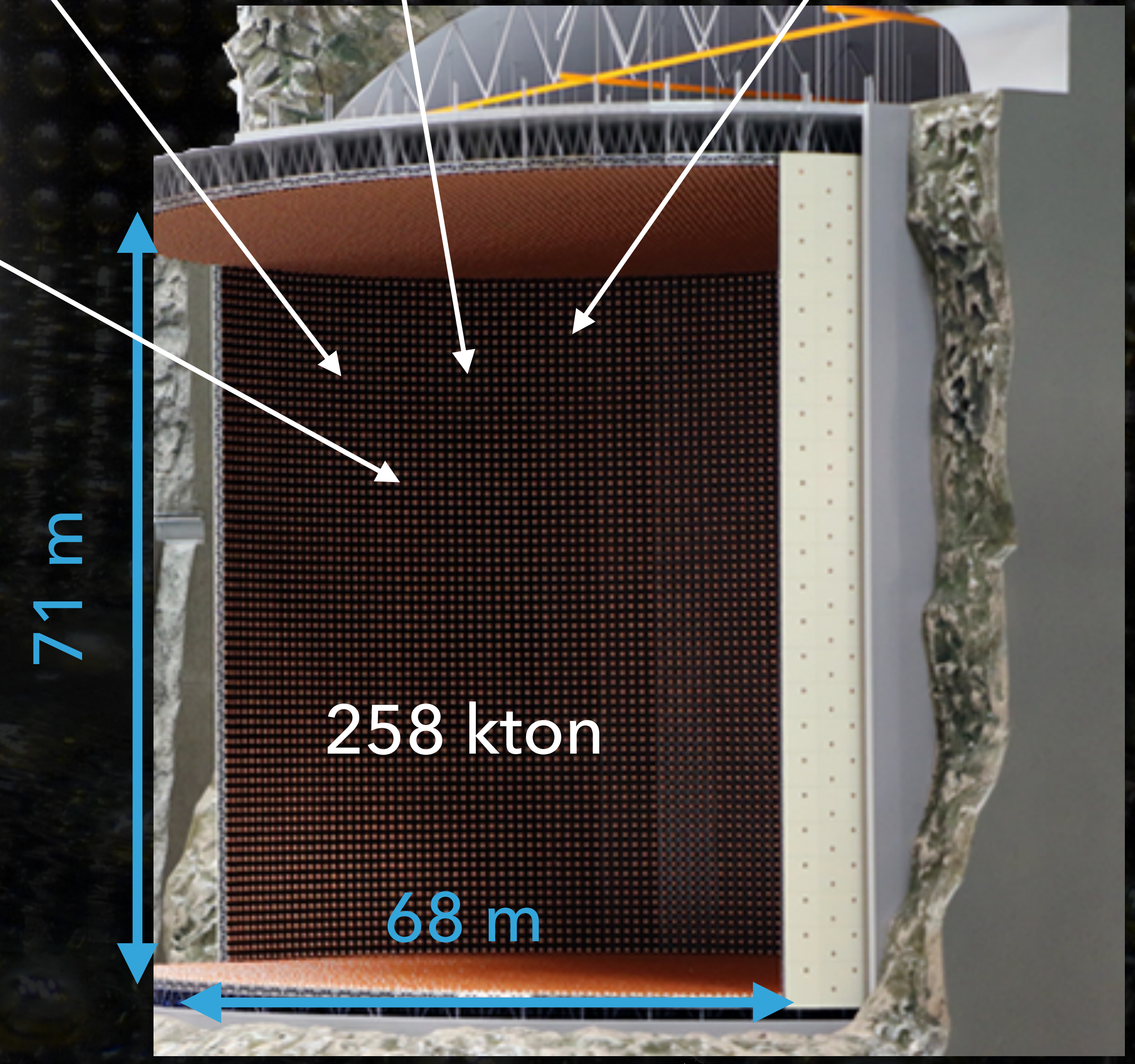
Atmospheric neutrino



Supernova neutrino



Proton decay

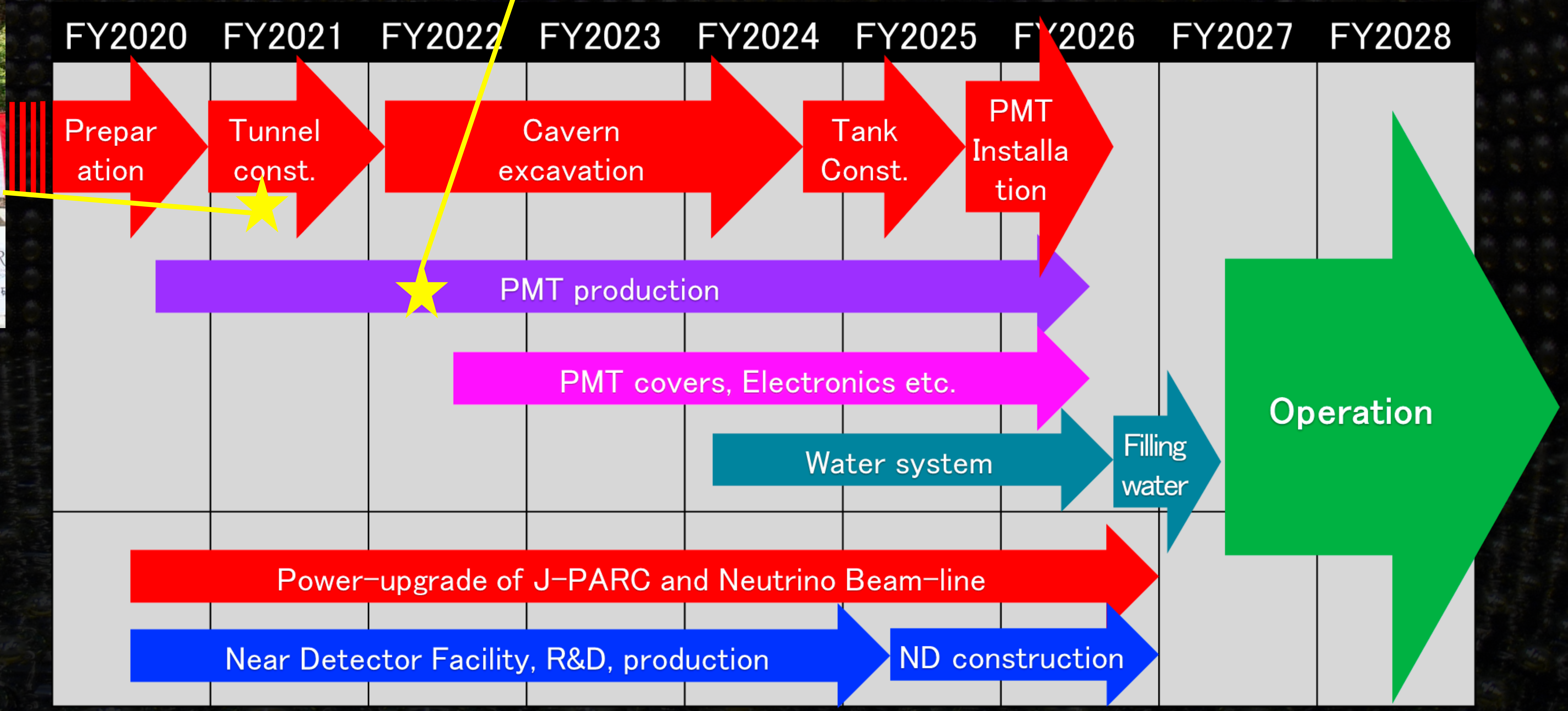


280 m → ~1 km → 295 km

HYPER-K: RECENT PROGRESS

May 2021, Groundbreaking

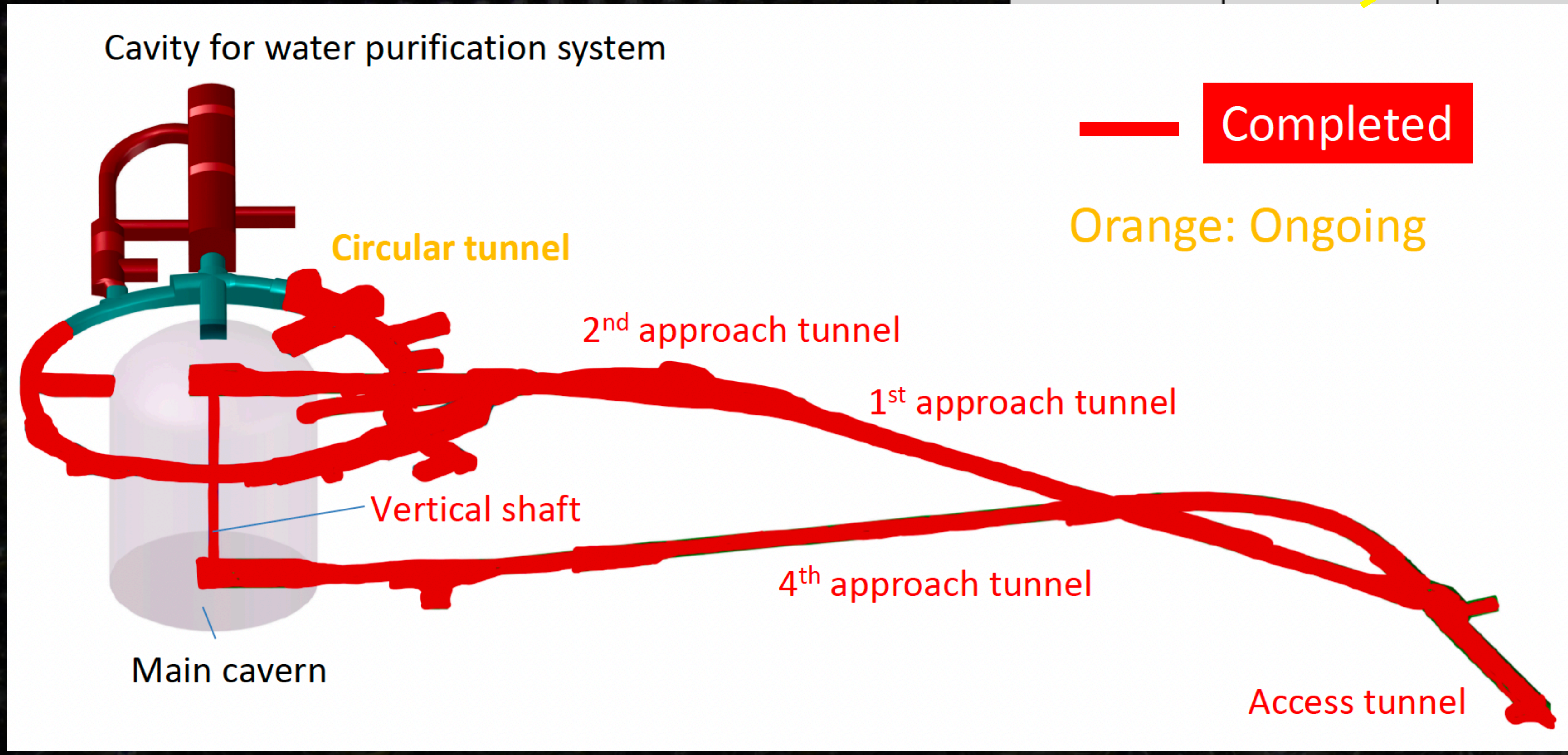
Total of 3,772 PMTs (~20%) delivered by April 2022



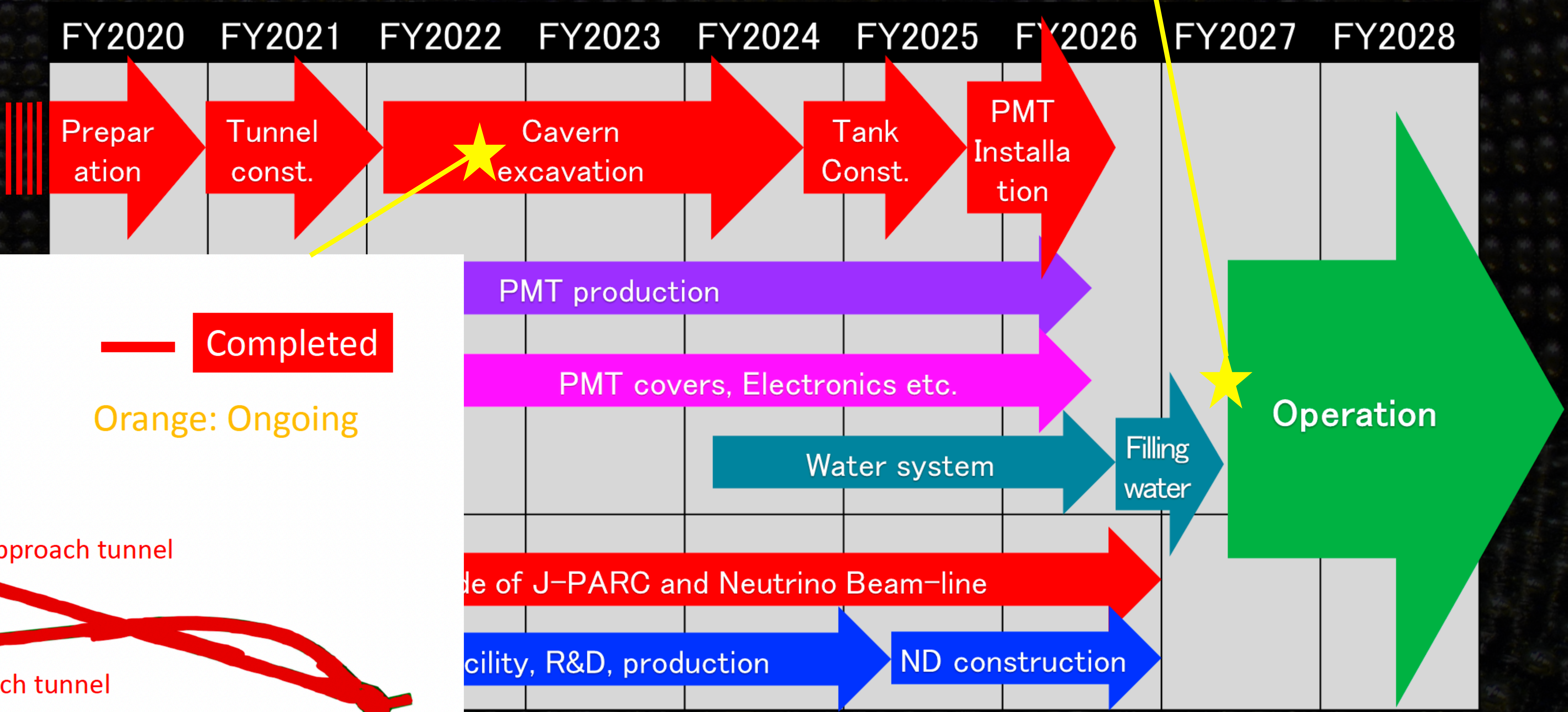
HYPER-K: RECENT PROGRESS

Reached dome centre

Approach tunnels completed

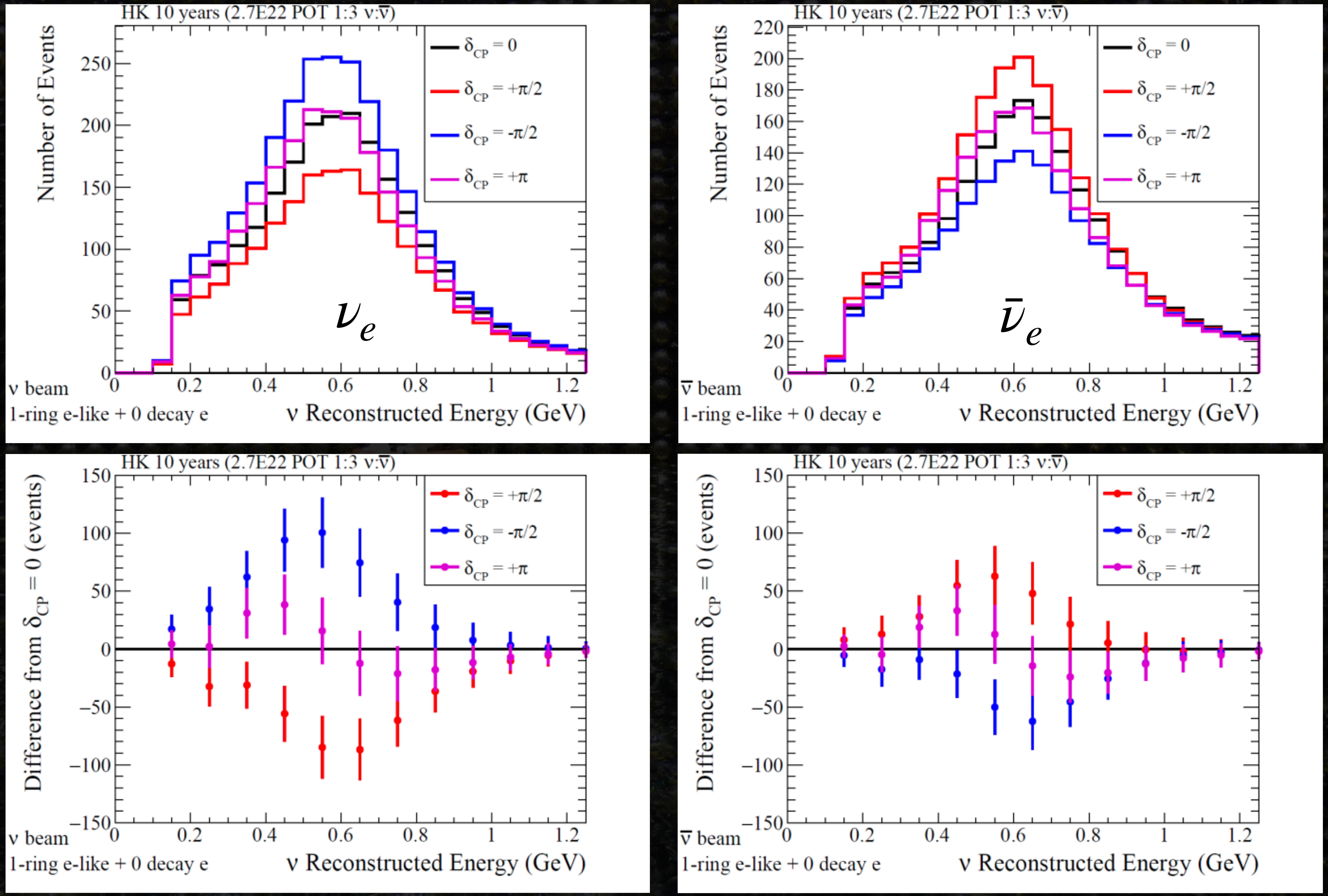


First light in 2027!

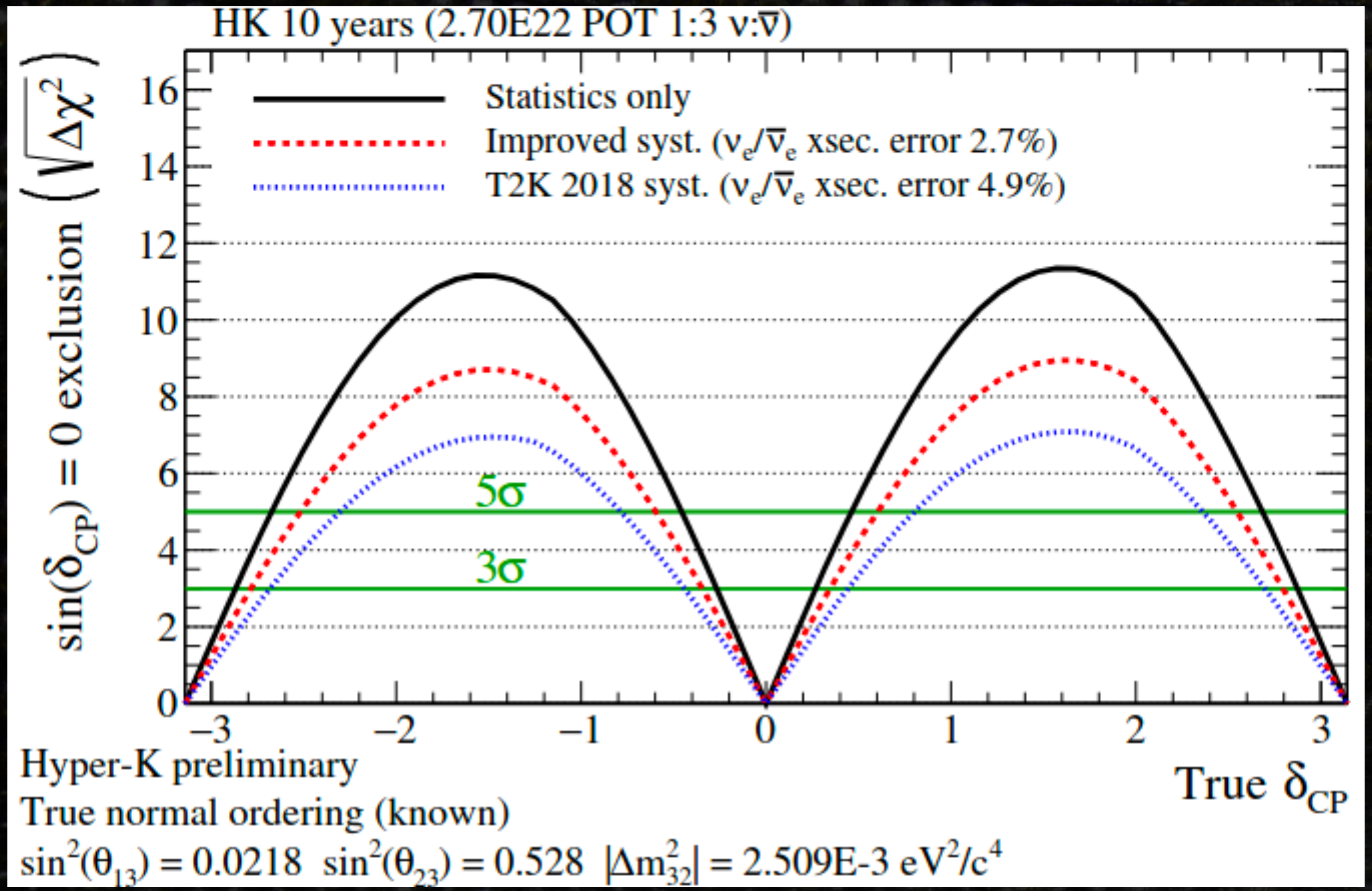


HYPER-K 10-YEAR PROJECTION

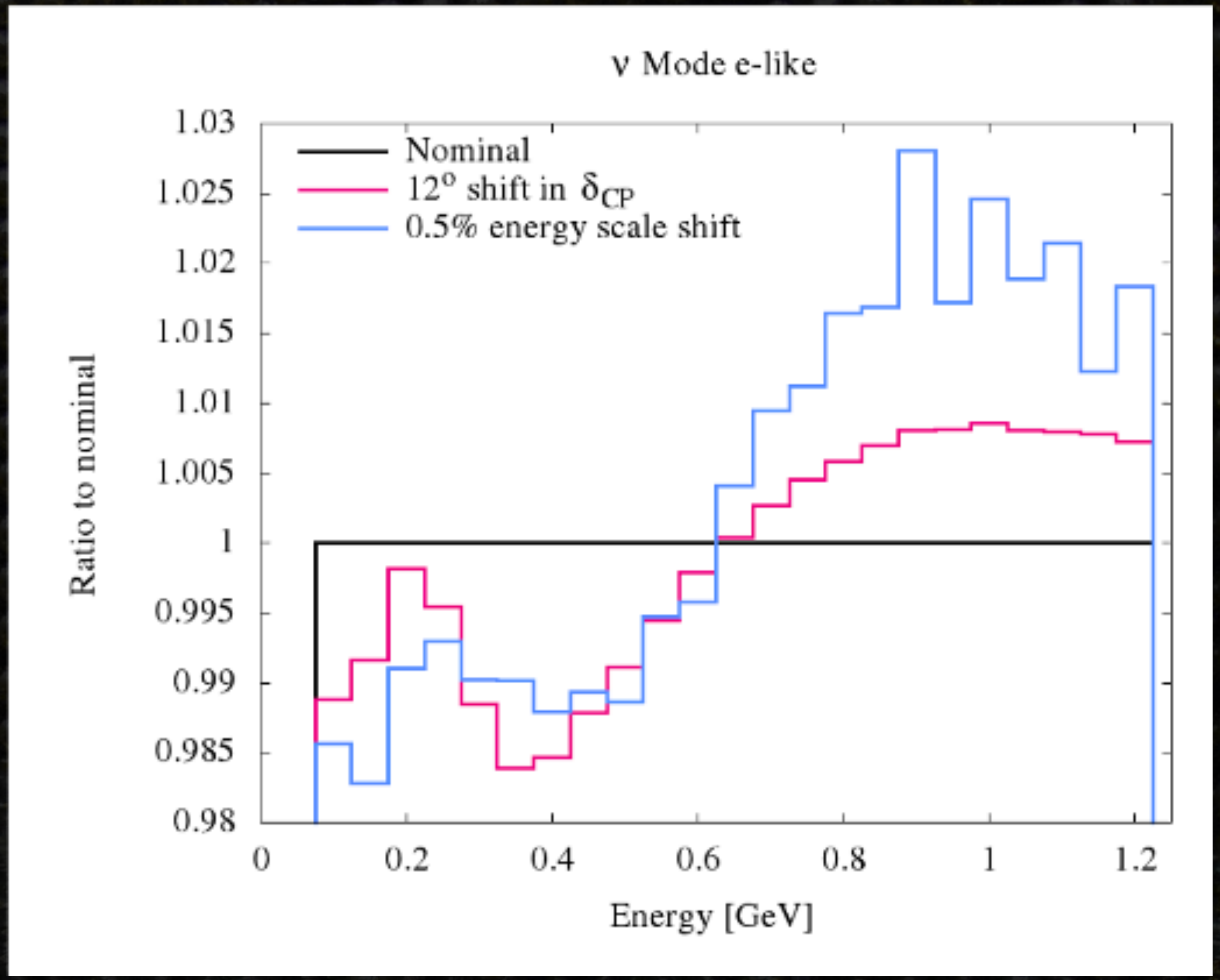
- Thousands of ν_e and $\bar{\nu}_e$ events
- Systematic uncertainties will surpass statistical uncertainty:
  - Neutrino flux
  - Cross Sections
  - Cross section effects on neutrino energy reconstruction
  - Energy Scale/Resolution
  - Particle Identification
  - Kinematics reconstruction



HYPER-K SENSITIVITY



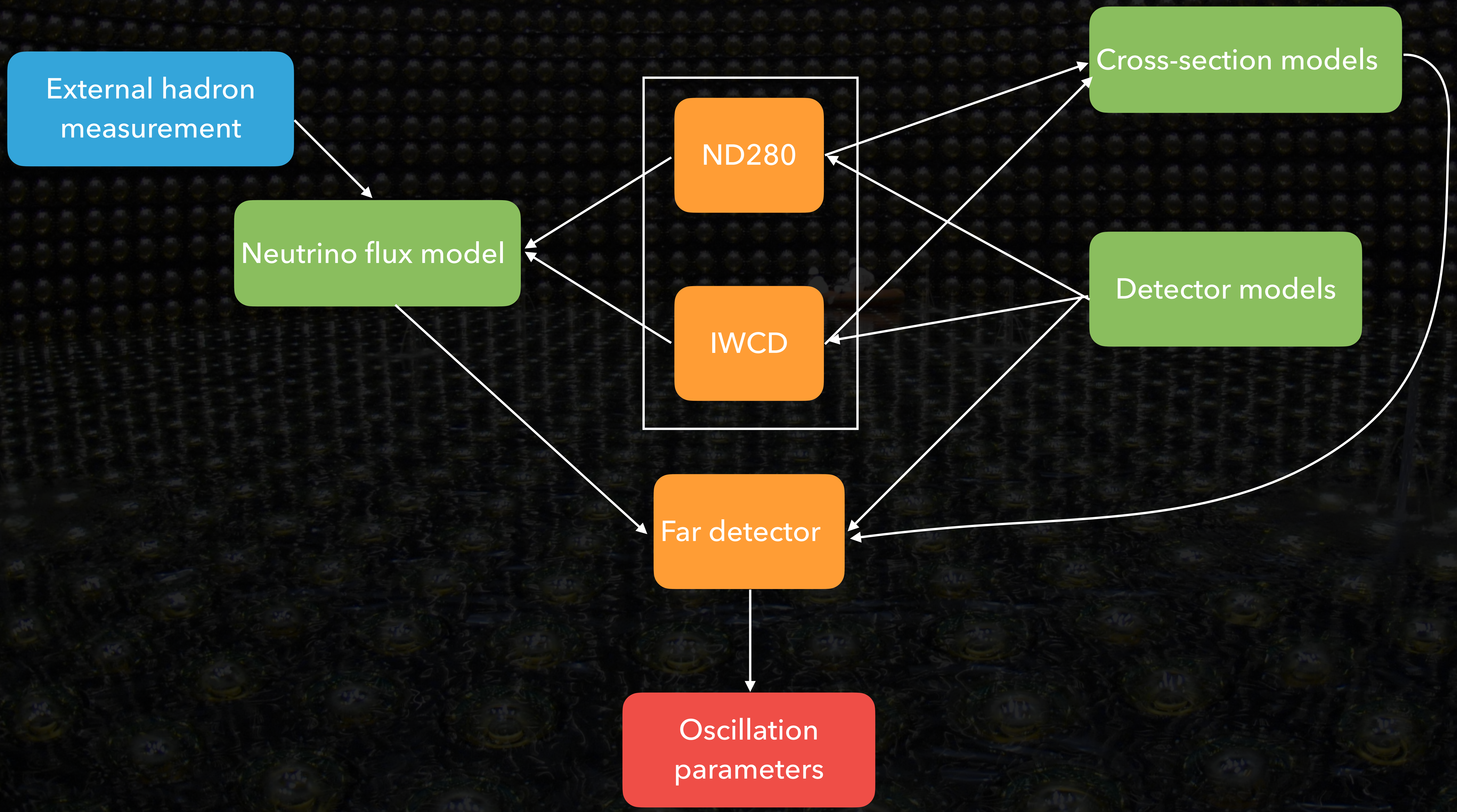
Exclusion power of CP-conservation with different true value of δ_{CP} (with known MH)



Hyper-K requires <1% detector systematic uncertainties and <0.5% energy scale uncertainty, more than halved relative to T2K

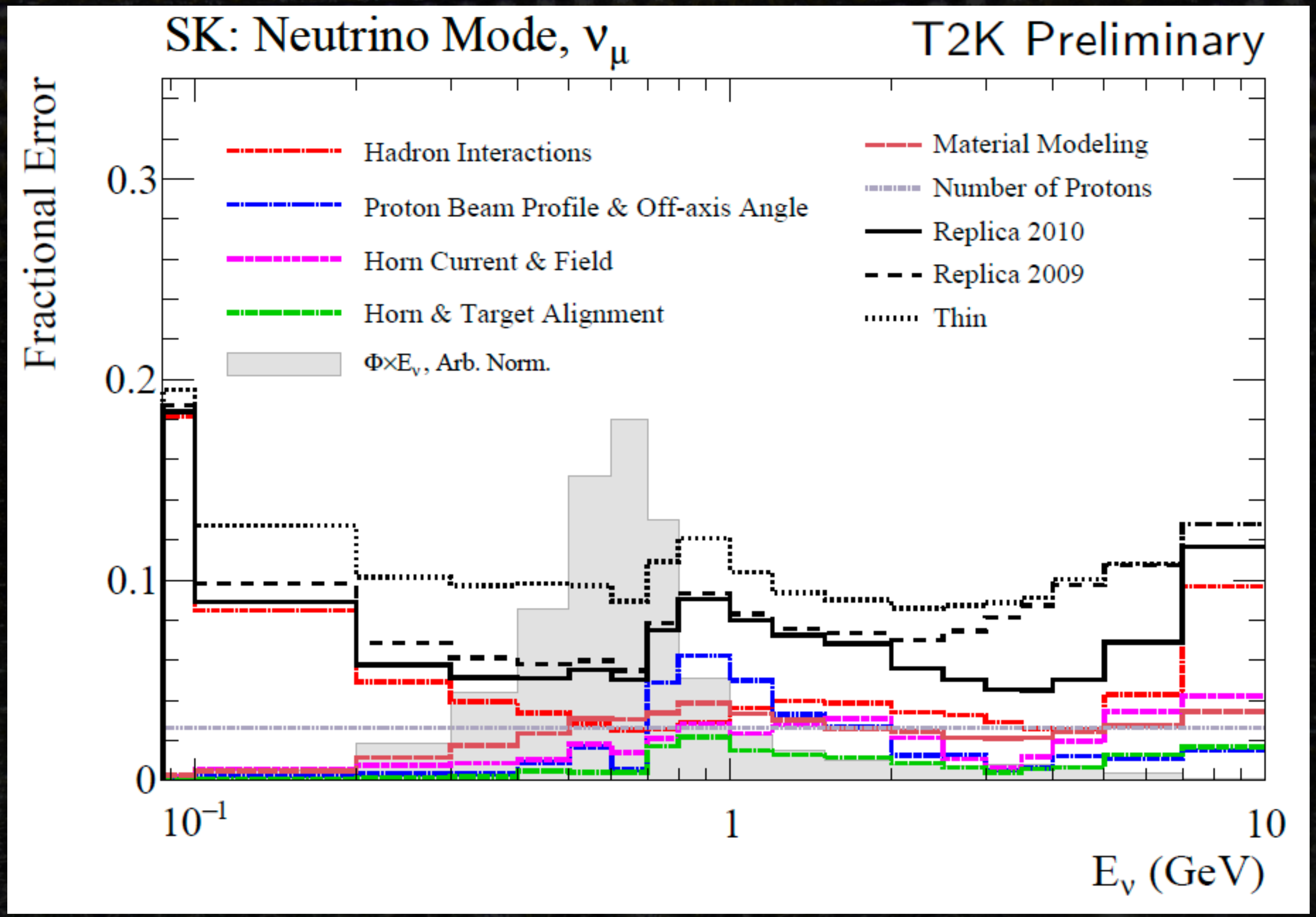
- The systematic uncertainty on neutrino interaction cross-section, particularly the $\nu_e/\bar{\nu}_e$ cross-section, will have the largest impact on δ_{CP} –> IWCD
- The energy scale uncertainty also degrades the sensitivity to δ_{CP} –> improved detector calibration and test beam measurements

CONSTRAINING SYSTEMATIC UNCERTAINTIES



CONSTRAINING SYSTEMATIC UNCERTAINTIES

External hadron measurement → Neutrino flux model



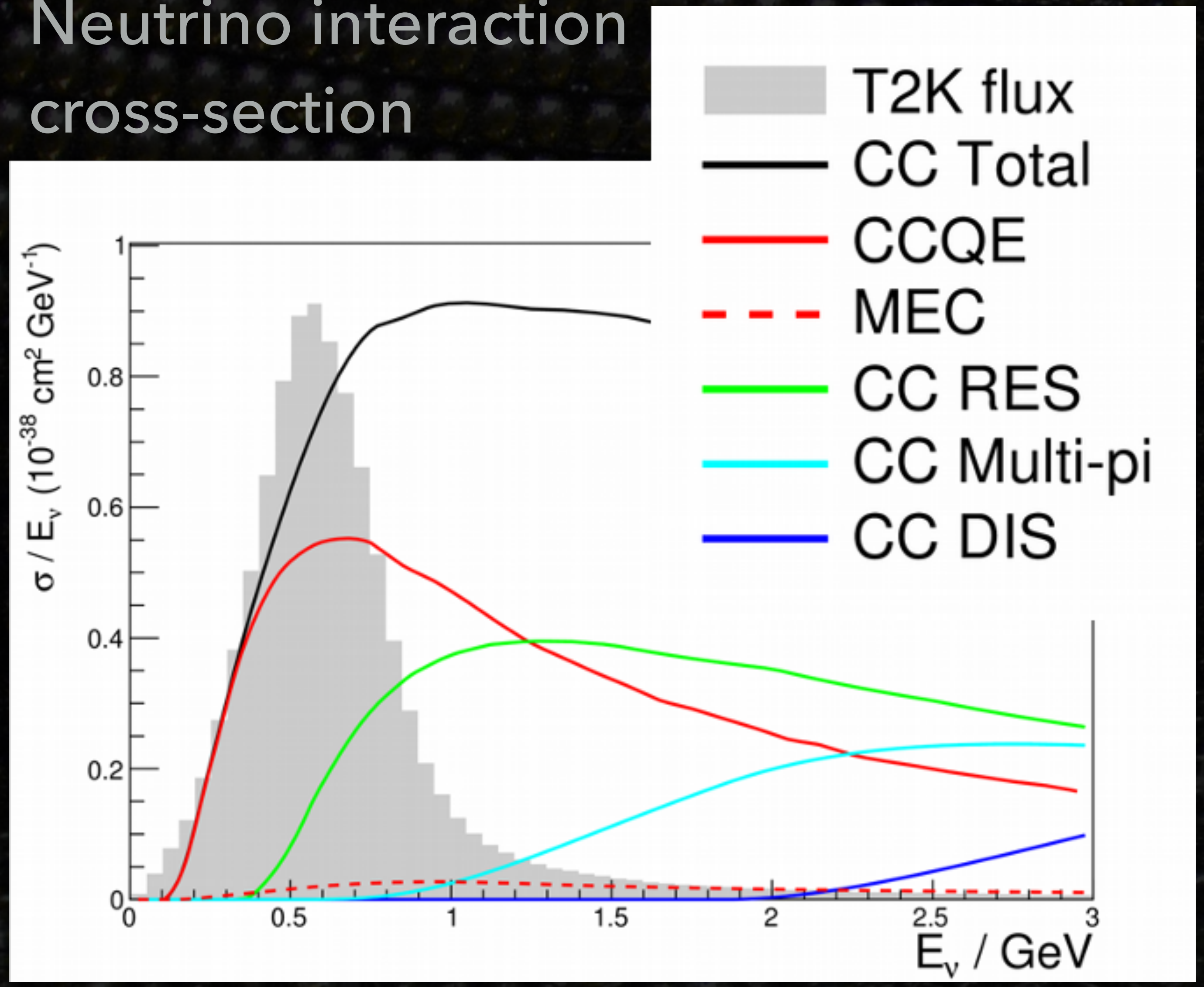
- External hadron production data from NA61/SHINE (measurements done on a T2K replica target) reduces flux uncertainties
- EMPHATIC data will be used to further reduce the flux uncertainties

EMPHATIC

Measurement of kaon-carbon forward scattering with EMPHATIC spectrometer *Mr Bruno Ferrazzi*
KC 303, Banff Centre 17:00 - 17:15

CONSTRAINING SYSTEMATIC UNCERTAINTIES

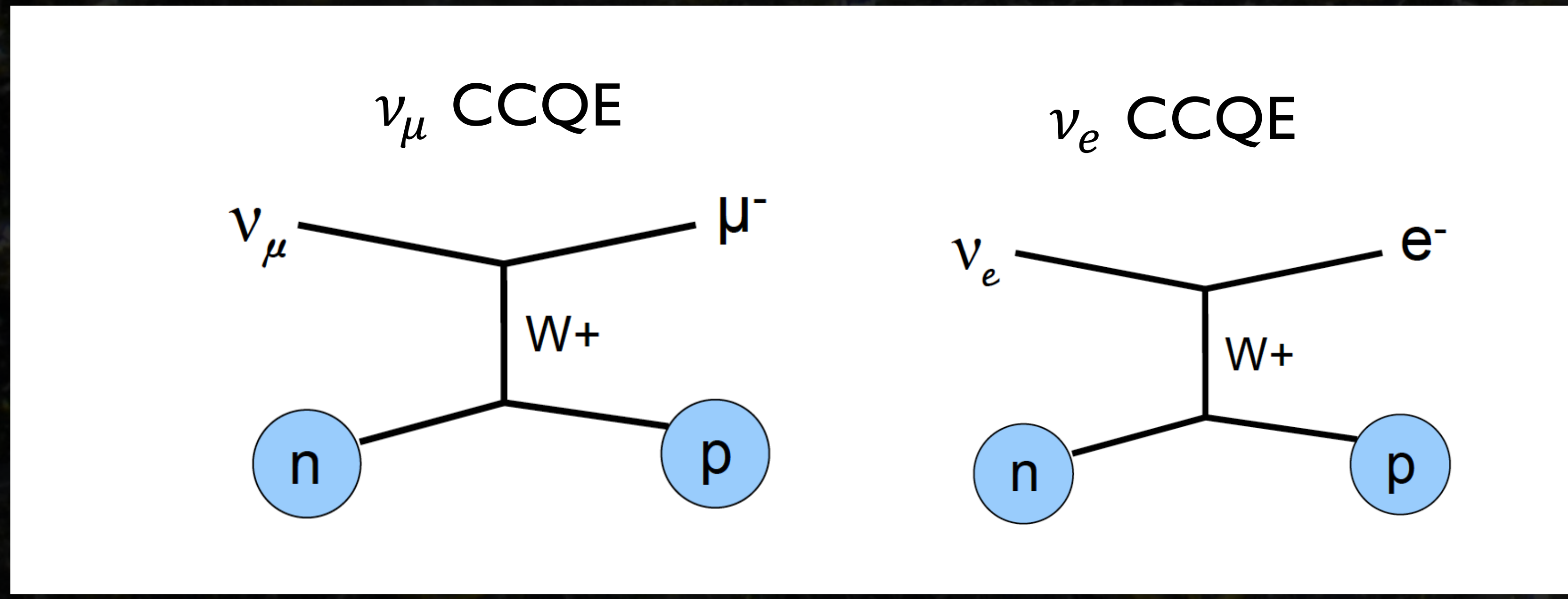
Neutrino interaction cross-section



Cross-section models

Correct measurements of oscillation parameters highly depend on the correct modelling of neutrino interactions; but model-building is overwhelmingly difficult!

"Measurement of the inelasticity distribution of neutrino interactions for 100 GeV < Eν < 1 TeV with IceCube DeepCore", Maria Liubarska, 3:30 pm

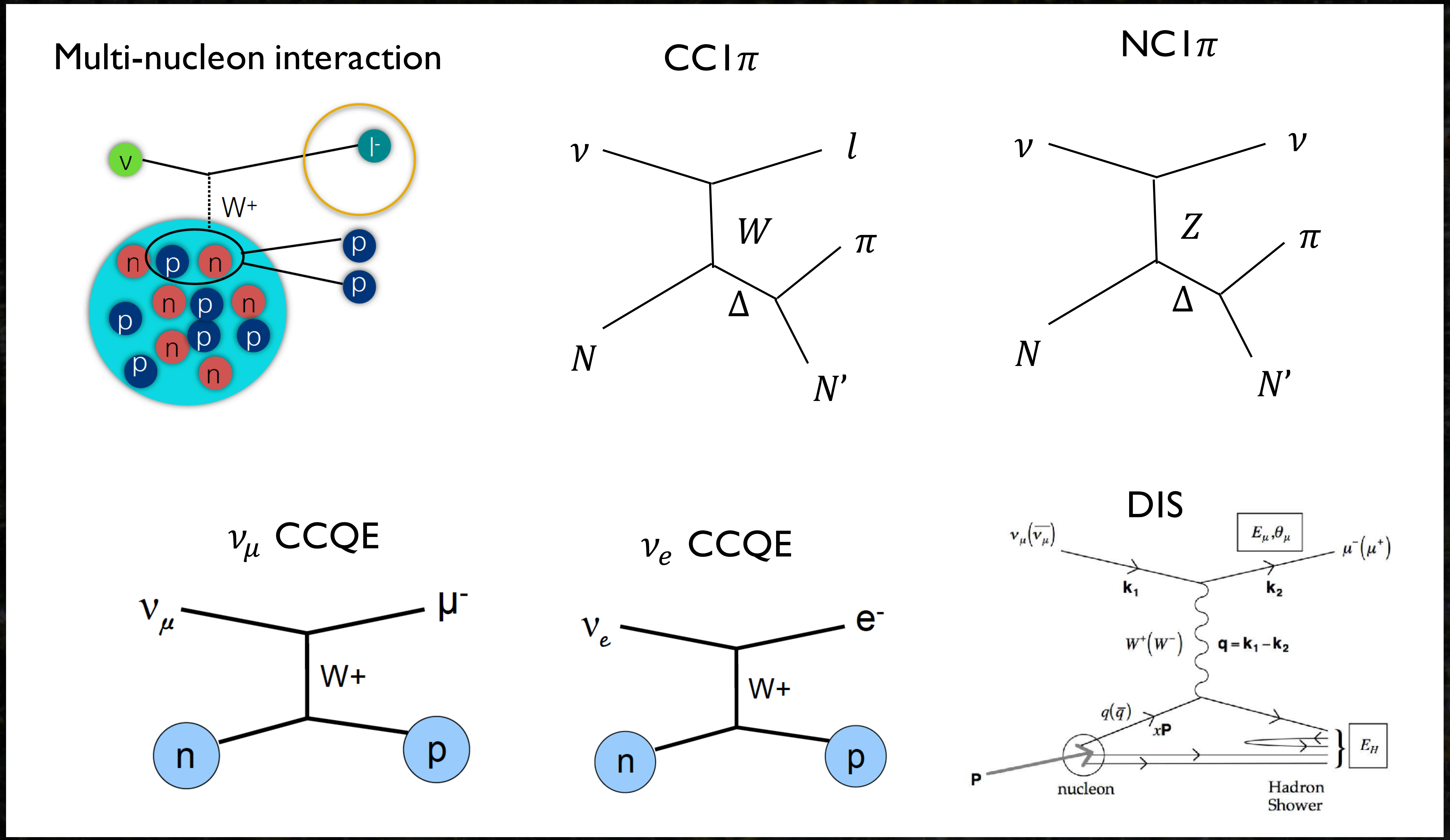


Neutrino energy can be calculated if lepton kinematics are known

CONSTRAINING SYSTEMATIC UNCERTAINTIES

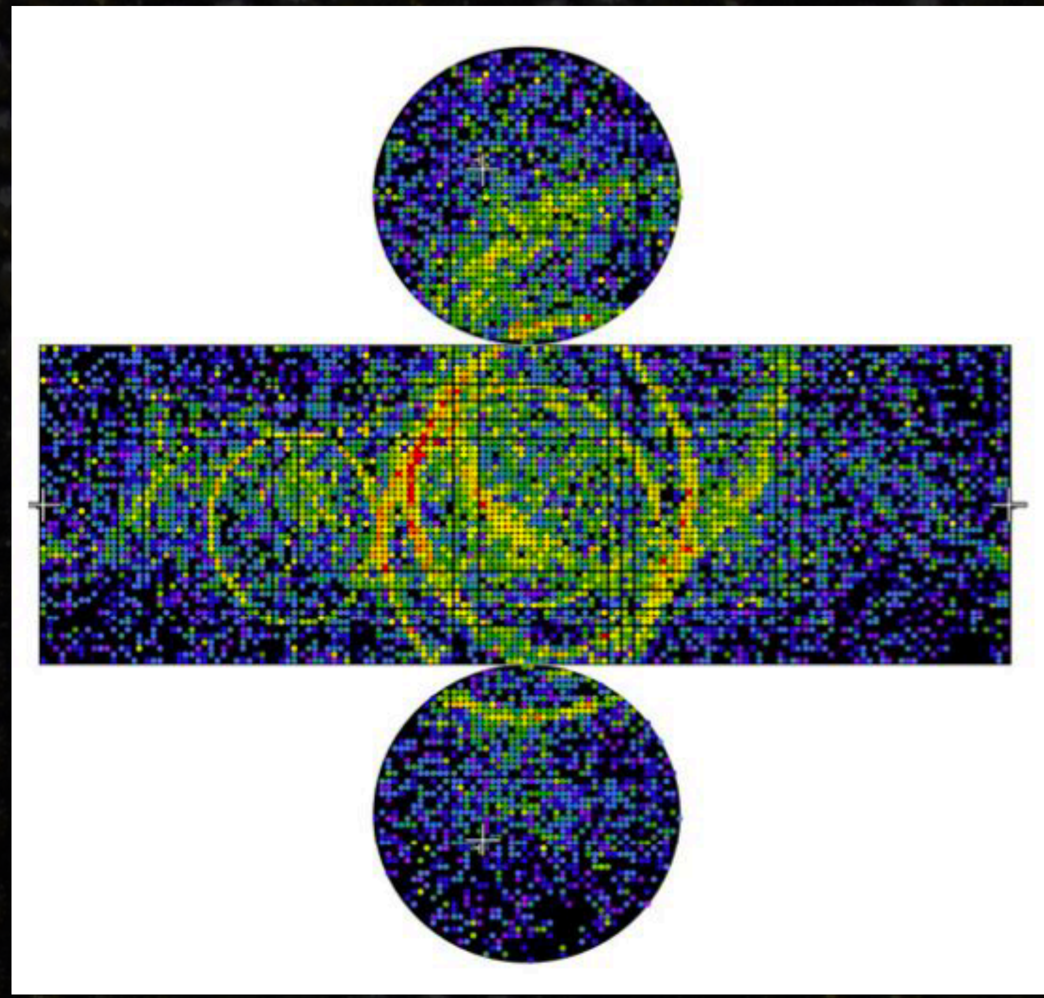
Cross-section models

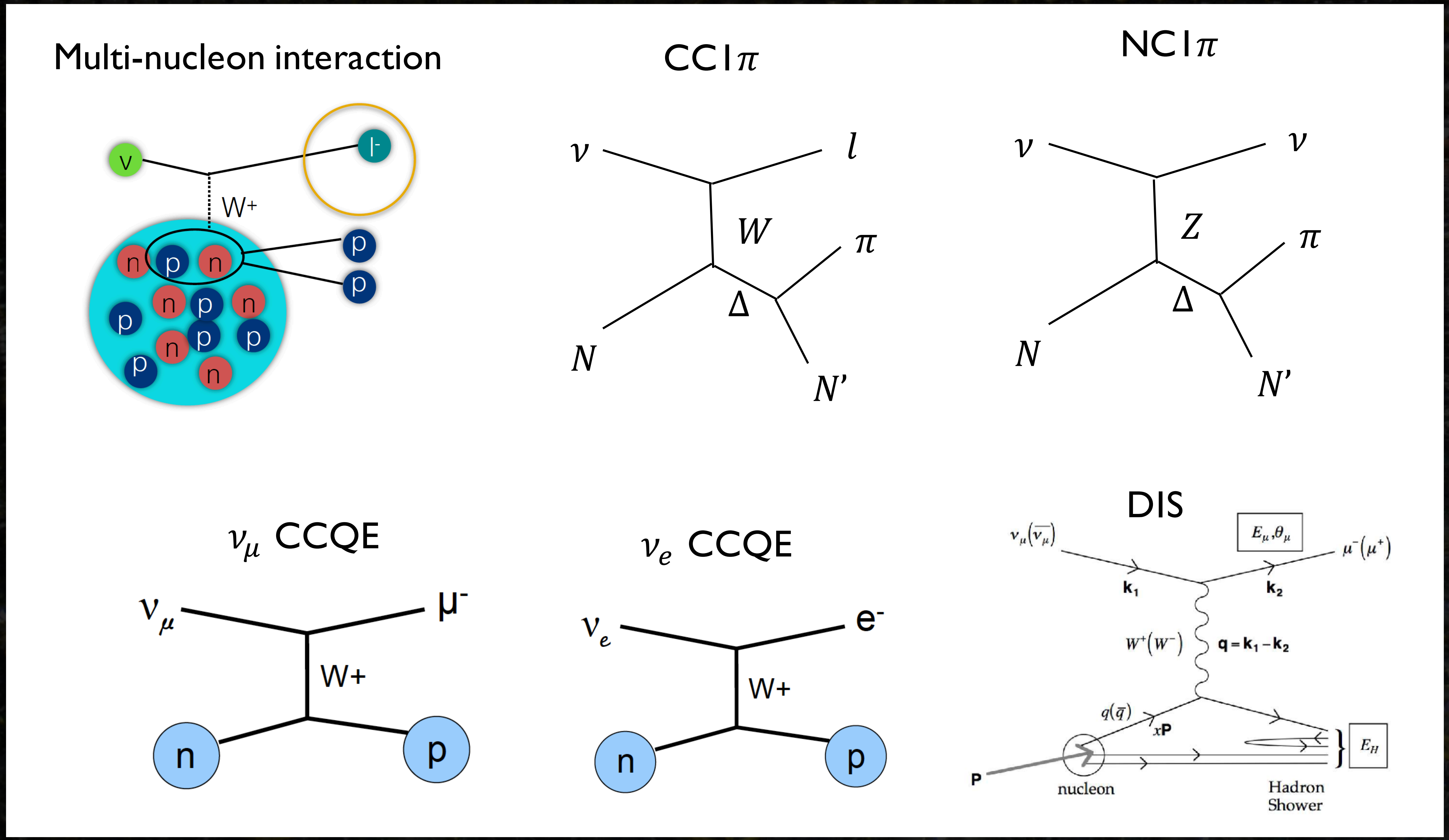
Correct measurements of oscillation parameters highly depend on the correct modelling of neutrino interactions; but model-building is overwhelmingly difficult!



CONSTRAINING SYSTEMATIC UNCERTAINTIES

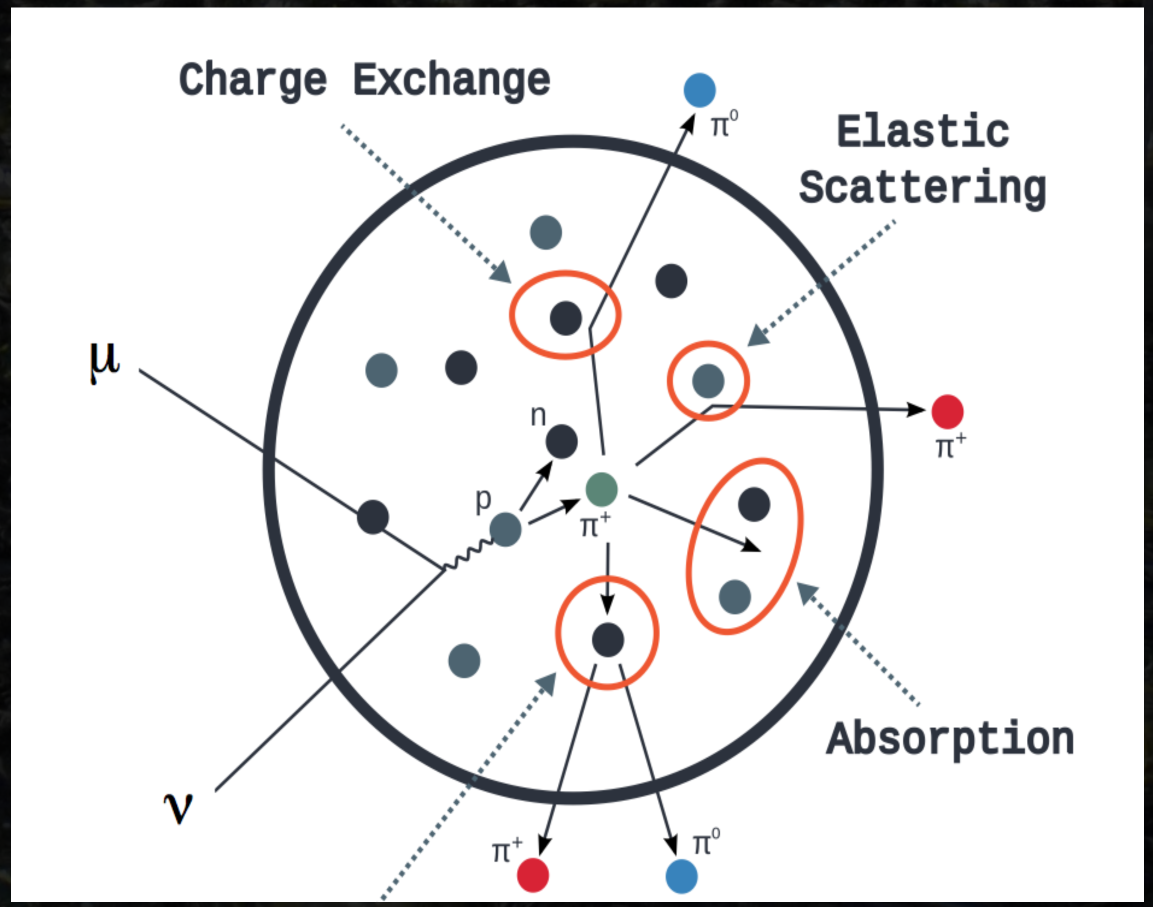
Cross-section models





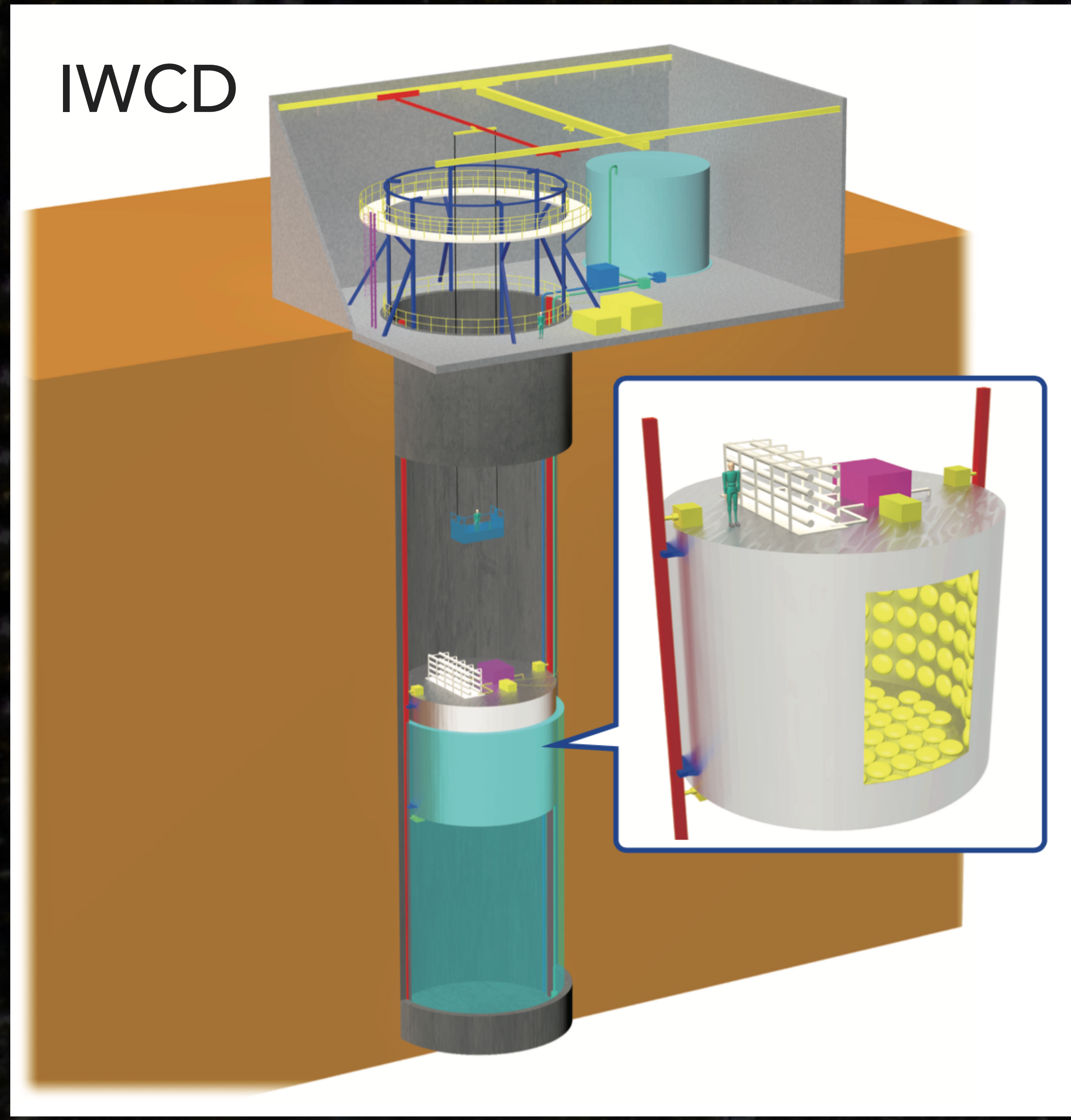
+

Final state interaction (FSI)

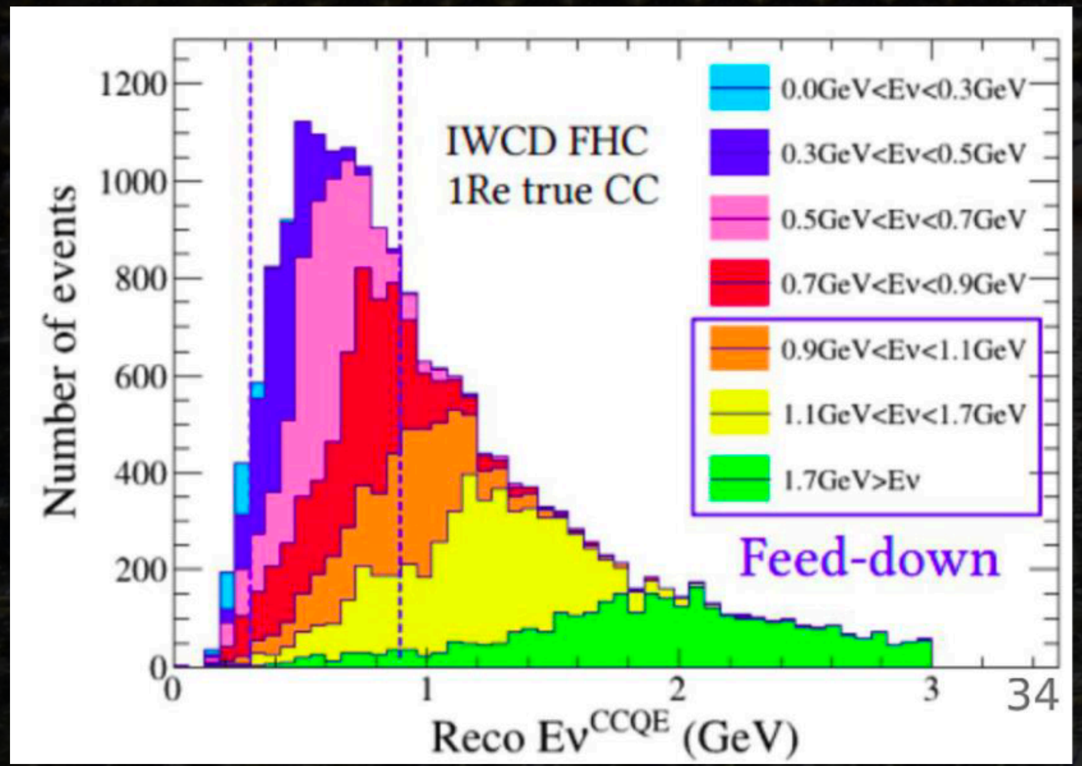


+ secondary interaction

CONSTRAINING SYSTEMATIC UNCERTAINTIES



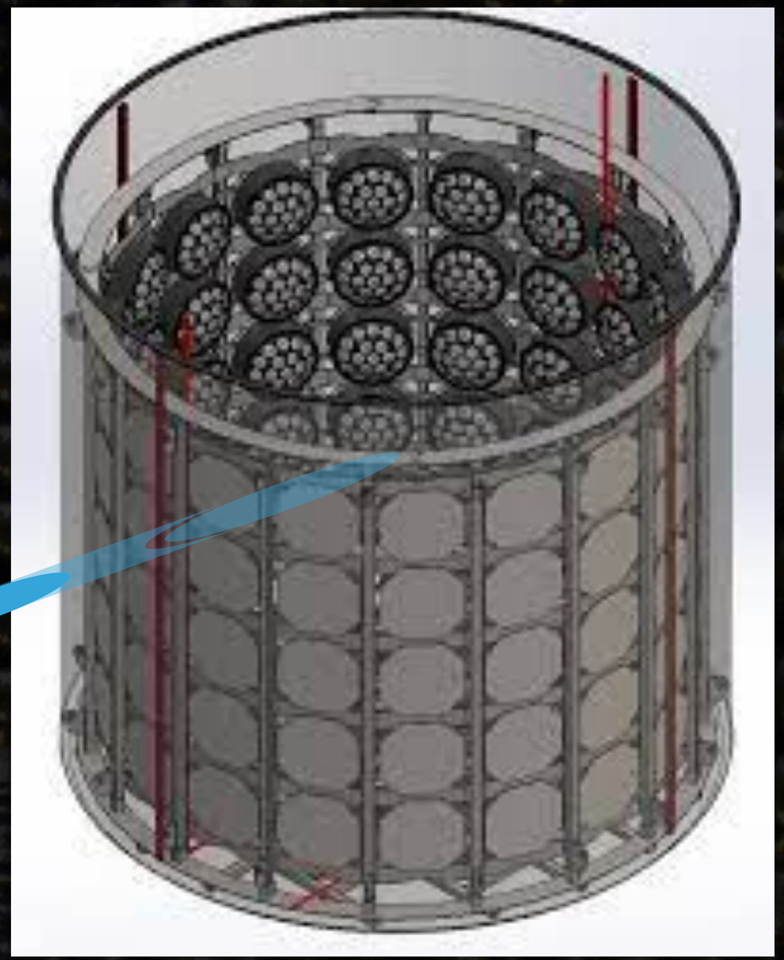
"Feed-down" effect in neutrino energy reconstruction



- The ability to measure neutrino interactions at different energies is important for understanding neutrino energy reconstruction
- $\nu_e/\bar{\nu}_e$ cross-section measurement can be improved due to better γ rejection than ND280

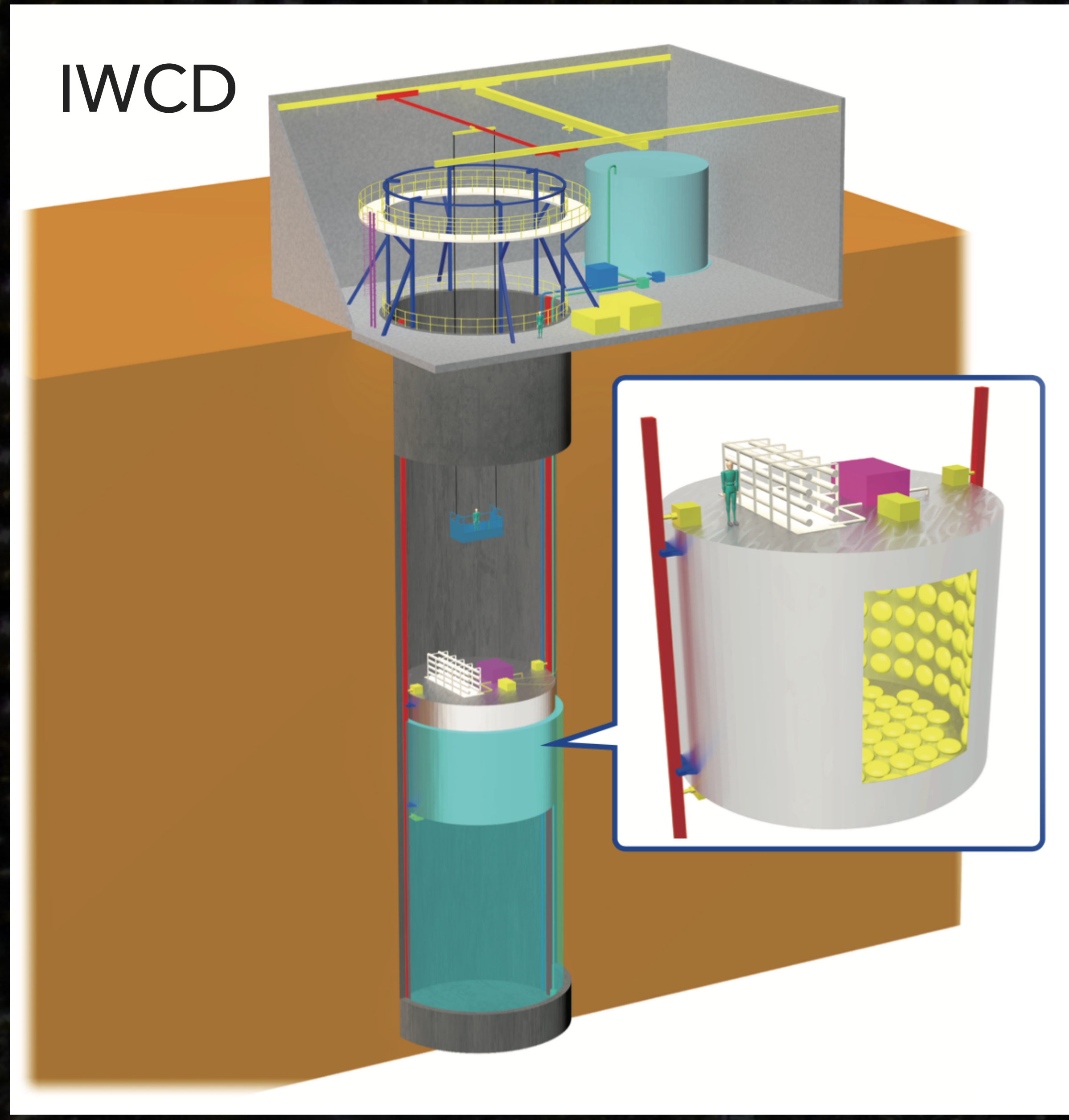
Water Cherenkov Test Experiment

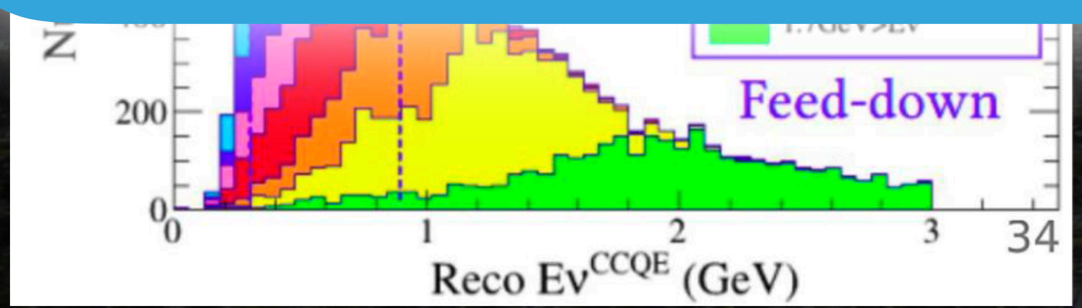
"Threshold Aerogel Cherenkov Detectors of WCTE", Poster by Sirous Yousefnejad



- T9 test beam @ CERN
  - 0.2 - 1.1 GeV π, p, e, μ
  - Measurement of π secondary interaction and scattering can improve neutrino interaction modelling
- Prototype of IWCD: test of mPMT and calibration techniques
- Data taking in 2024

CONSTRAINING SYSTEMATIC UNCERTAINTIES



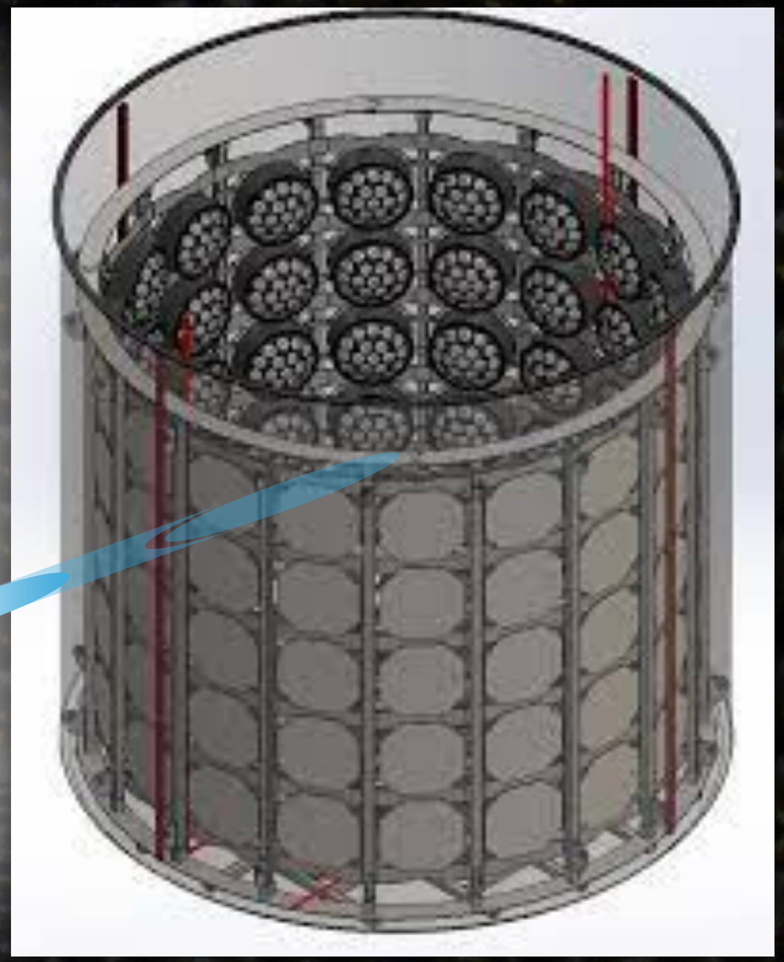


A better detector model for the Hyper-K water Cherenkov detectors is needed.

More sophisticated detector calibration methods are necessary.

- The ability to measure neutrino interactions at different energies is important for understanding neutrino energy reconstruction
- $\nu_e/\bar{\nu}_e$ cross-section measurement can be improved due to better γ rejection than ND280

Water Cherenkov Test Experiment



- T9 test beam @ CERN
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  - Measurement of π scattering can improve neutrino interaction modelling
- Prototype of IWCD: test of mPMT and calibration techniques
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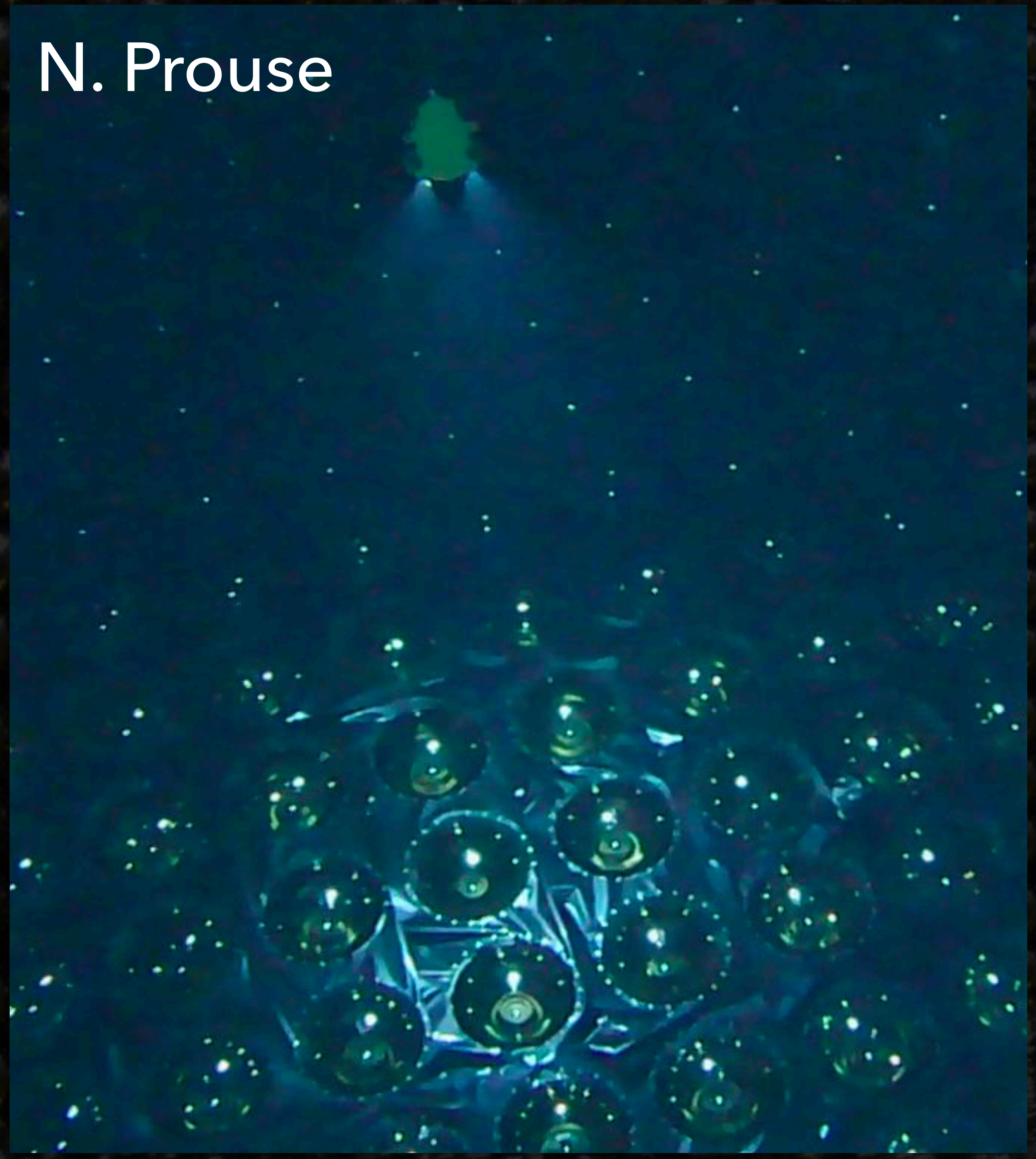
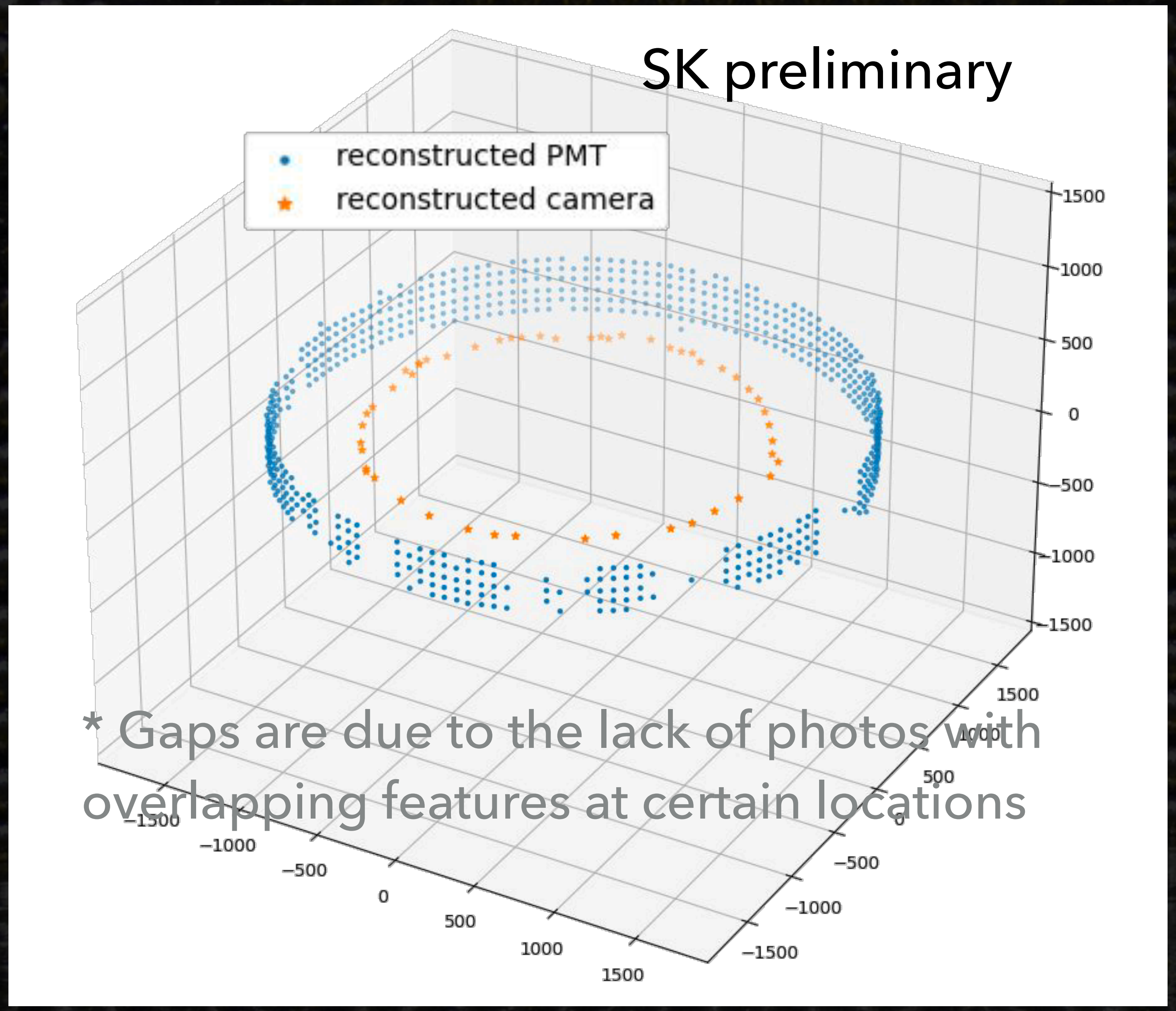
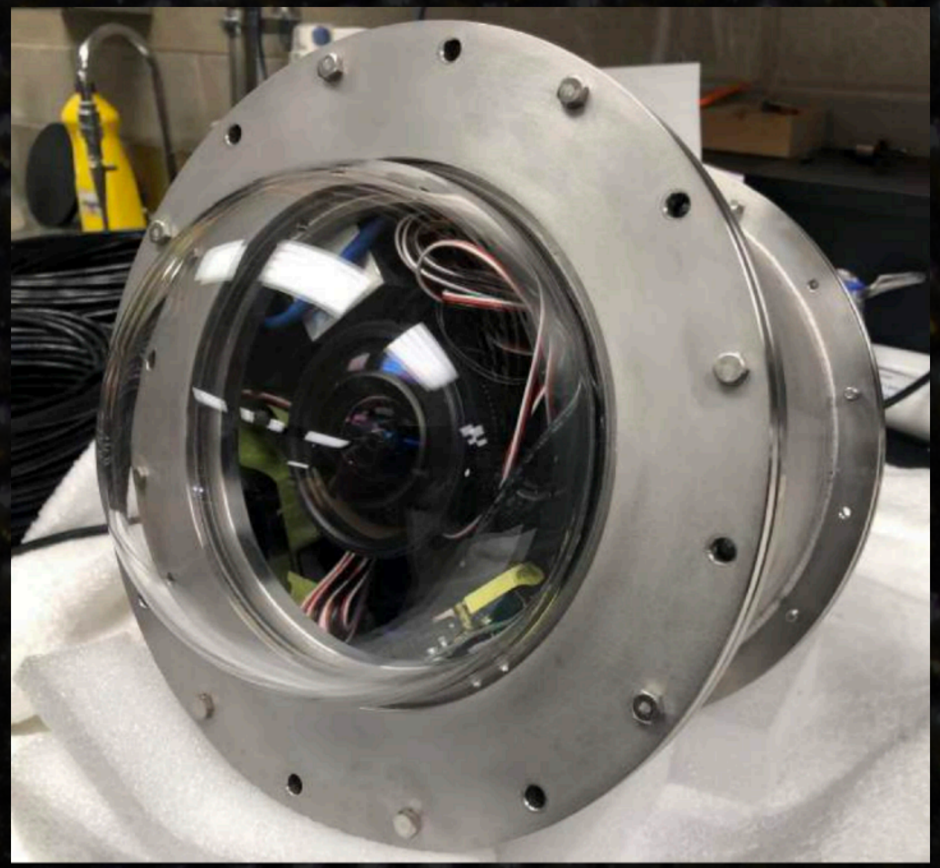
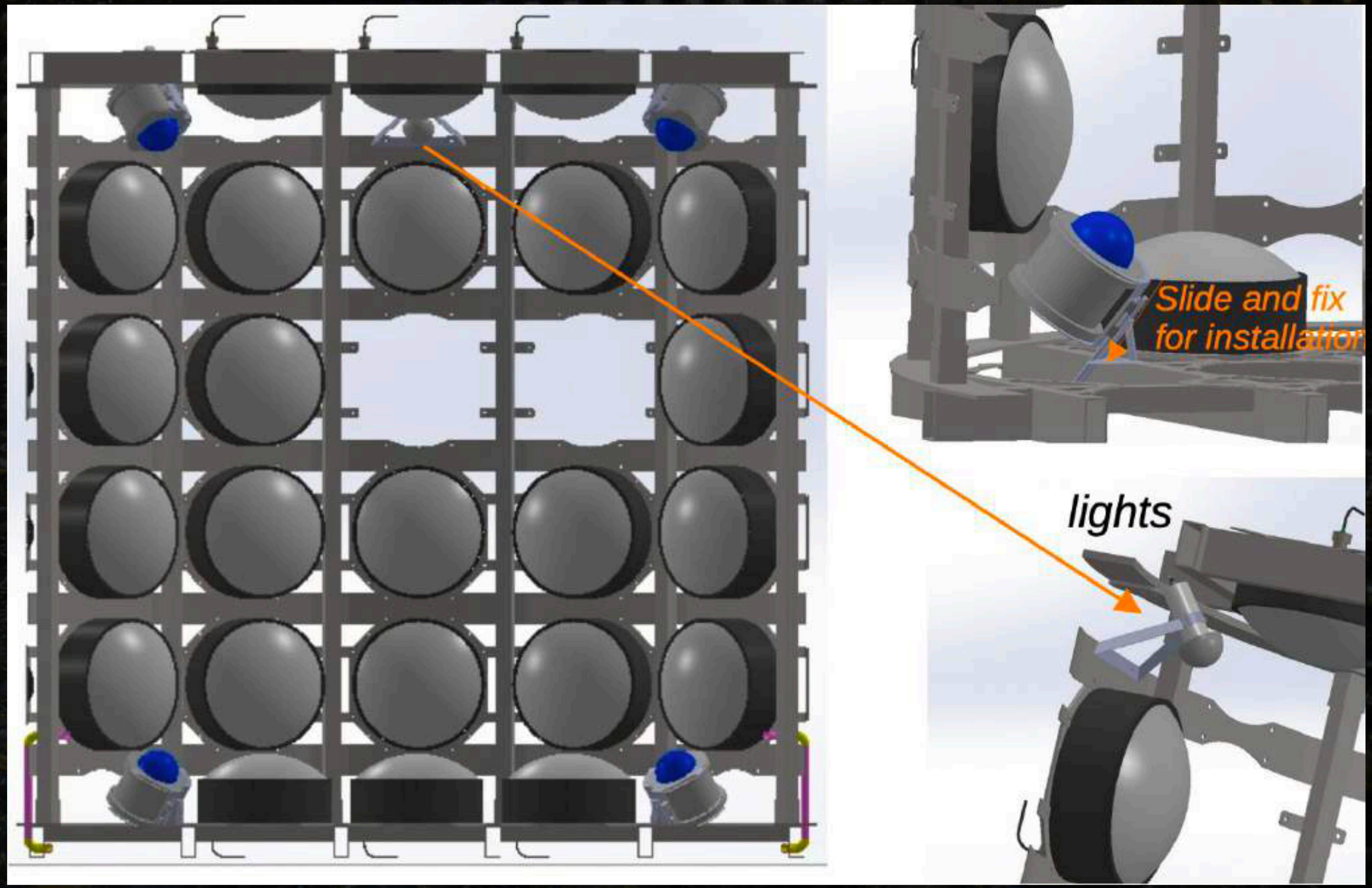
CALIBRATION SYSTEMS @ TRIUMF — PHOTOGRAMMETRY





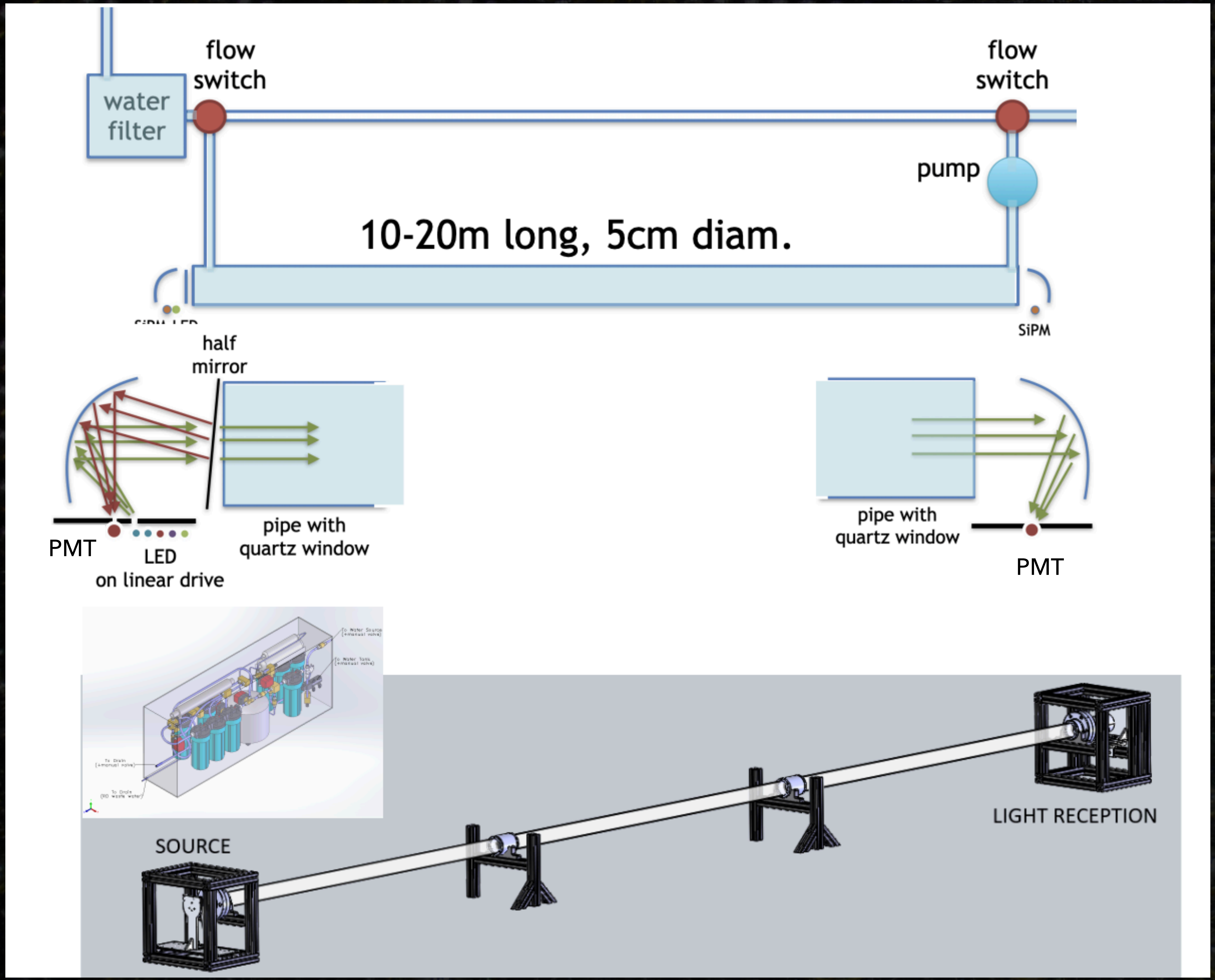
First assembled camera module @UWinnipeg



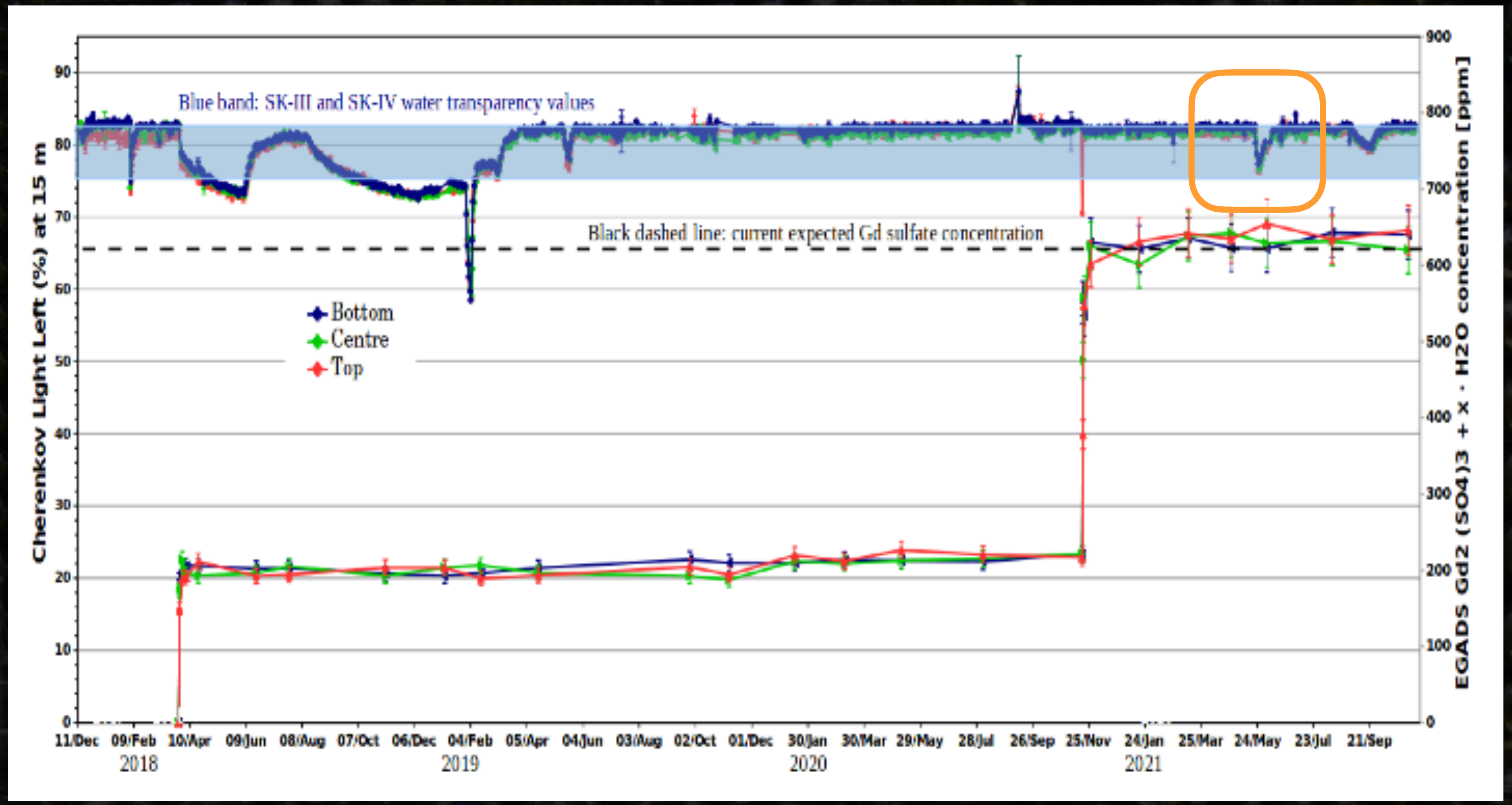


- Use photogrammetry to measure the position of PMTs and calibration sources in-situ
  - The first survey was done in SK using underwater ROV
  - WCTE and IWCD will utilize fixed cameras
  - Reduce fiducial volume error

CALIBRATION SYSTEMS @ TRIUMF — WATER MONITORING SYSTEM



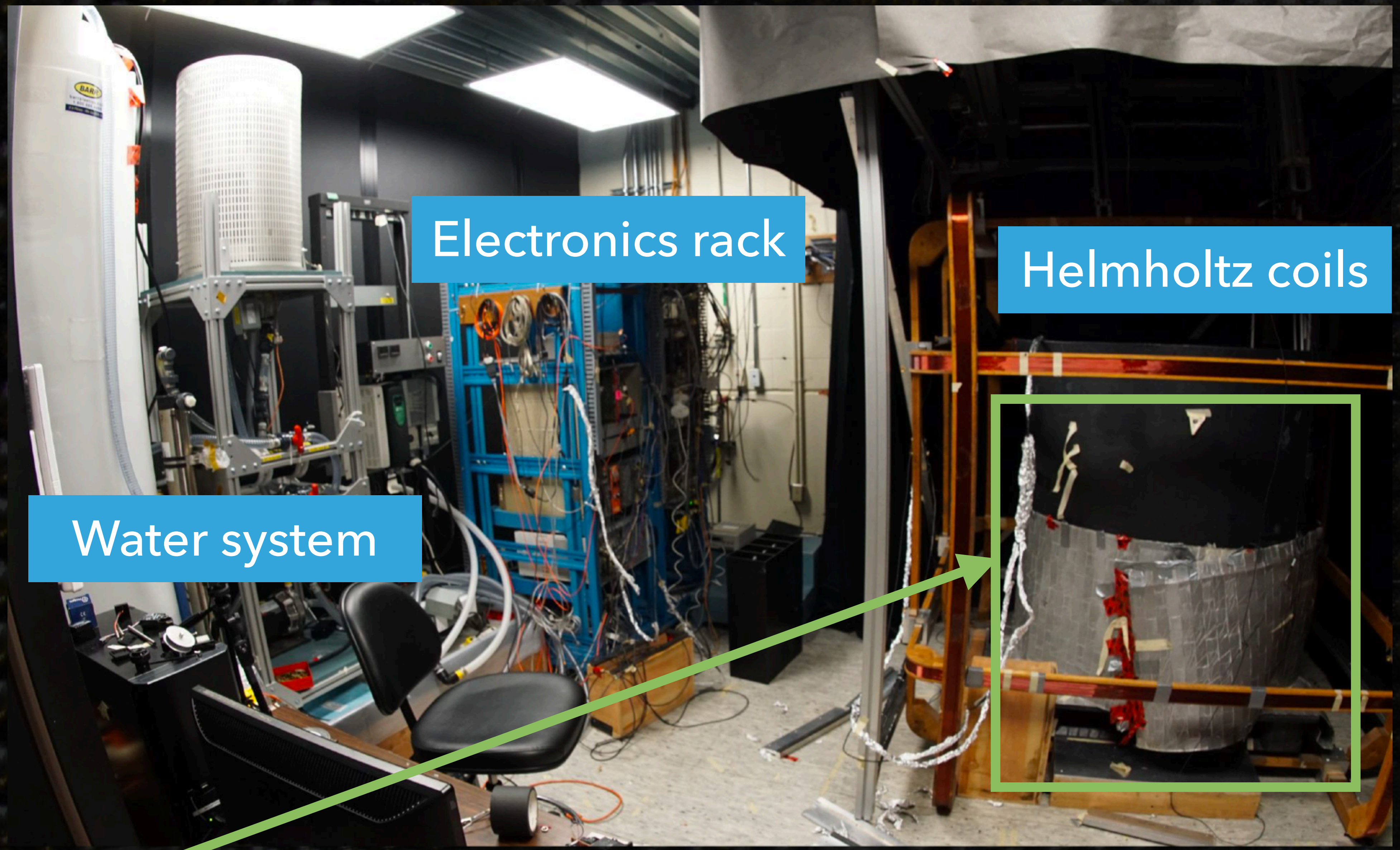
Light transmission through 15 m of water

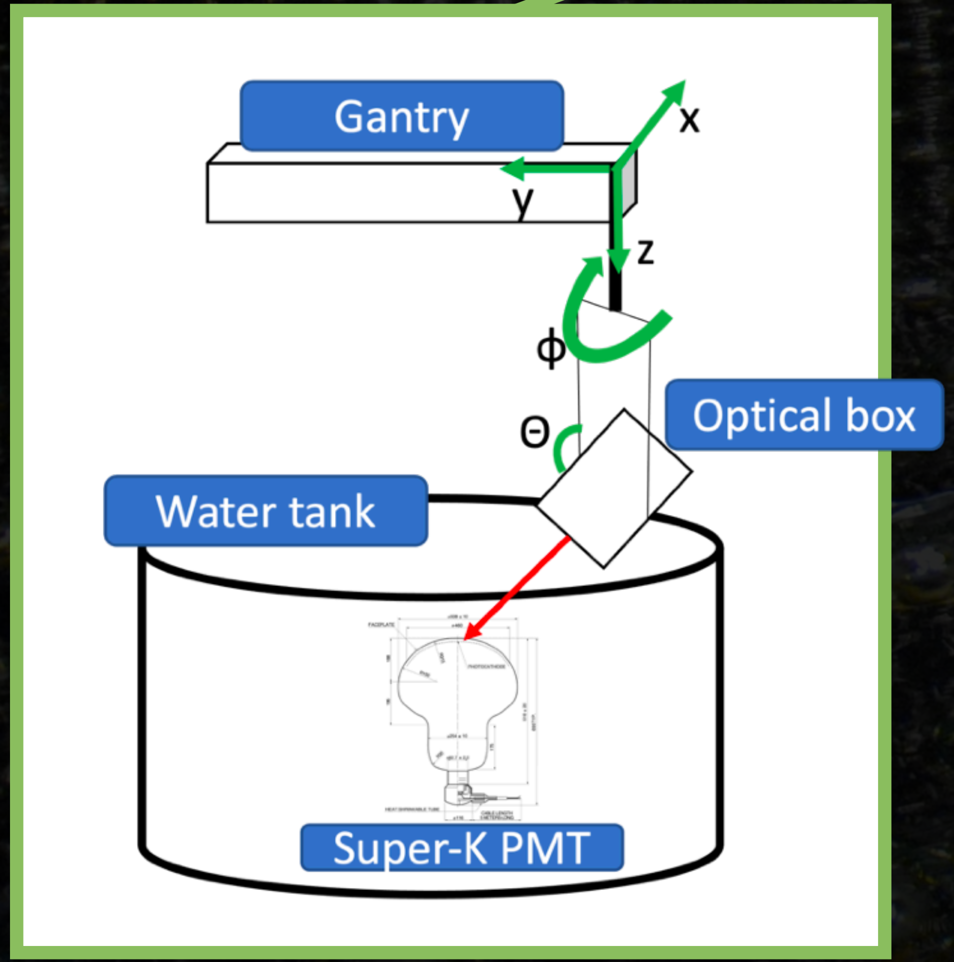


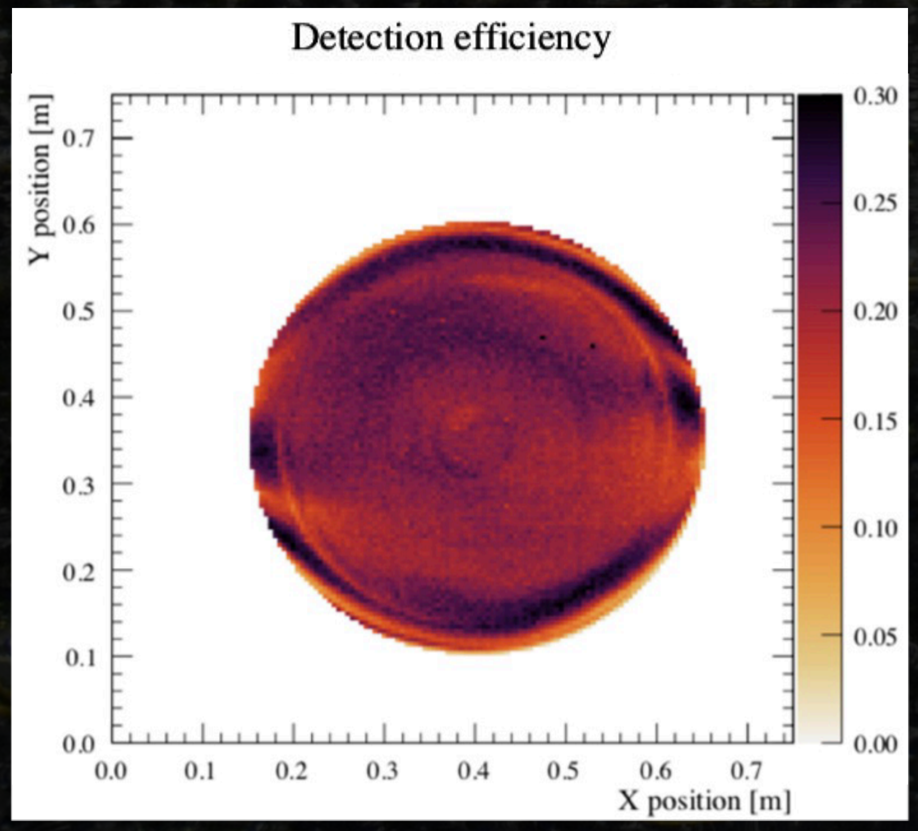
- Light propagation in water needs to be precisely calibrated and monitored
- Pulsed LED (230 - 700 nm) with <1 ns width
- Applications in drinking water monitoring
- First mechanical prototype built

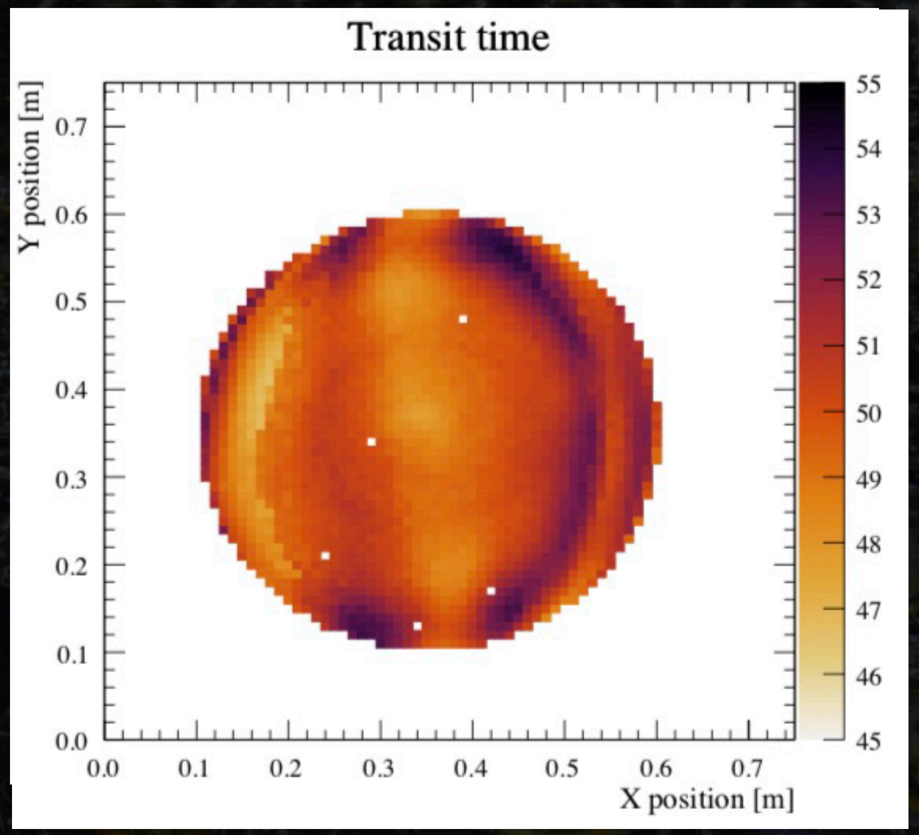
CALIBRATION SYSTEMS @ TRIUMF — PTF

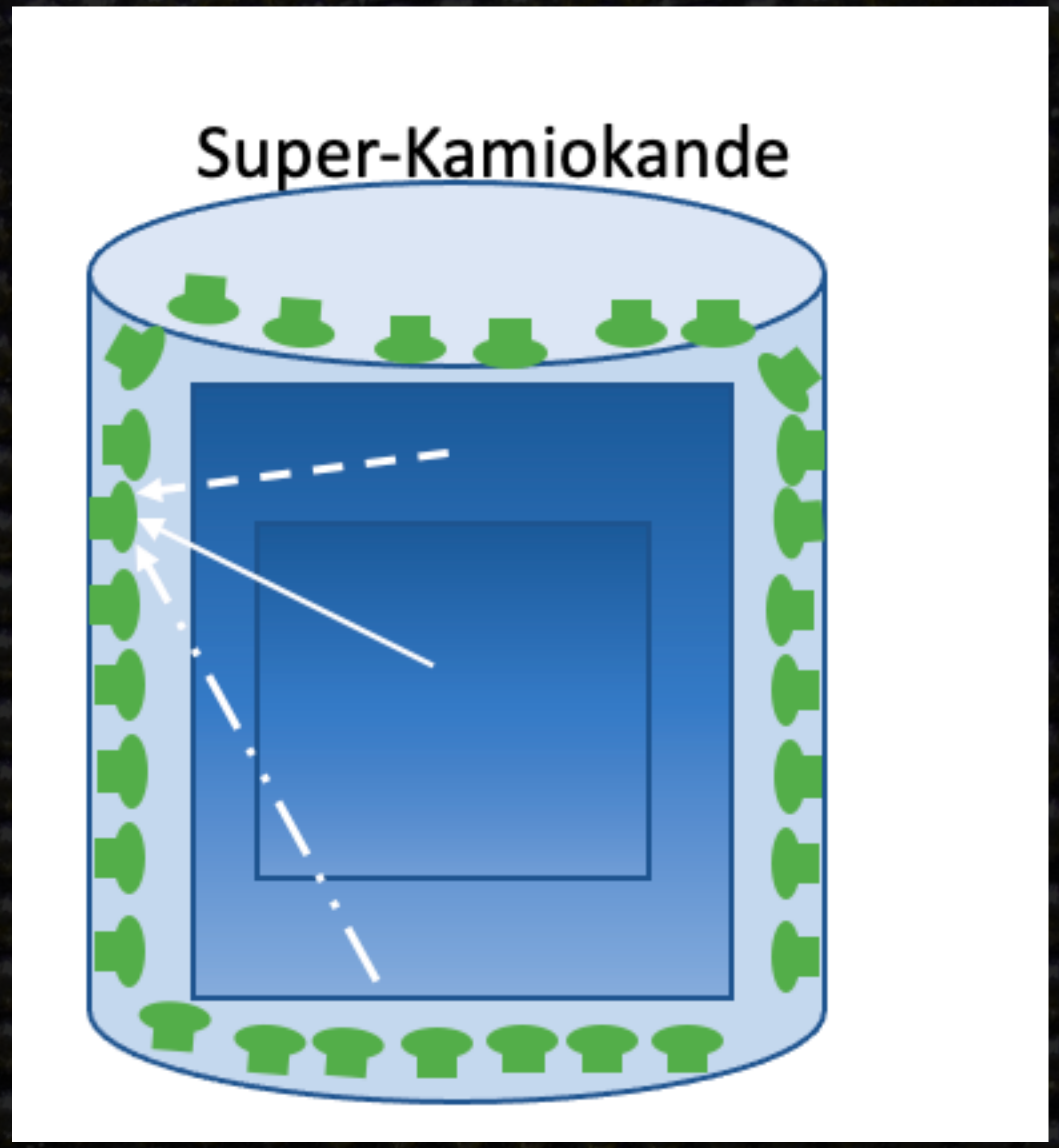
MSc V. Gousy-Leblanc







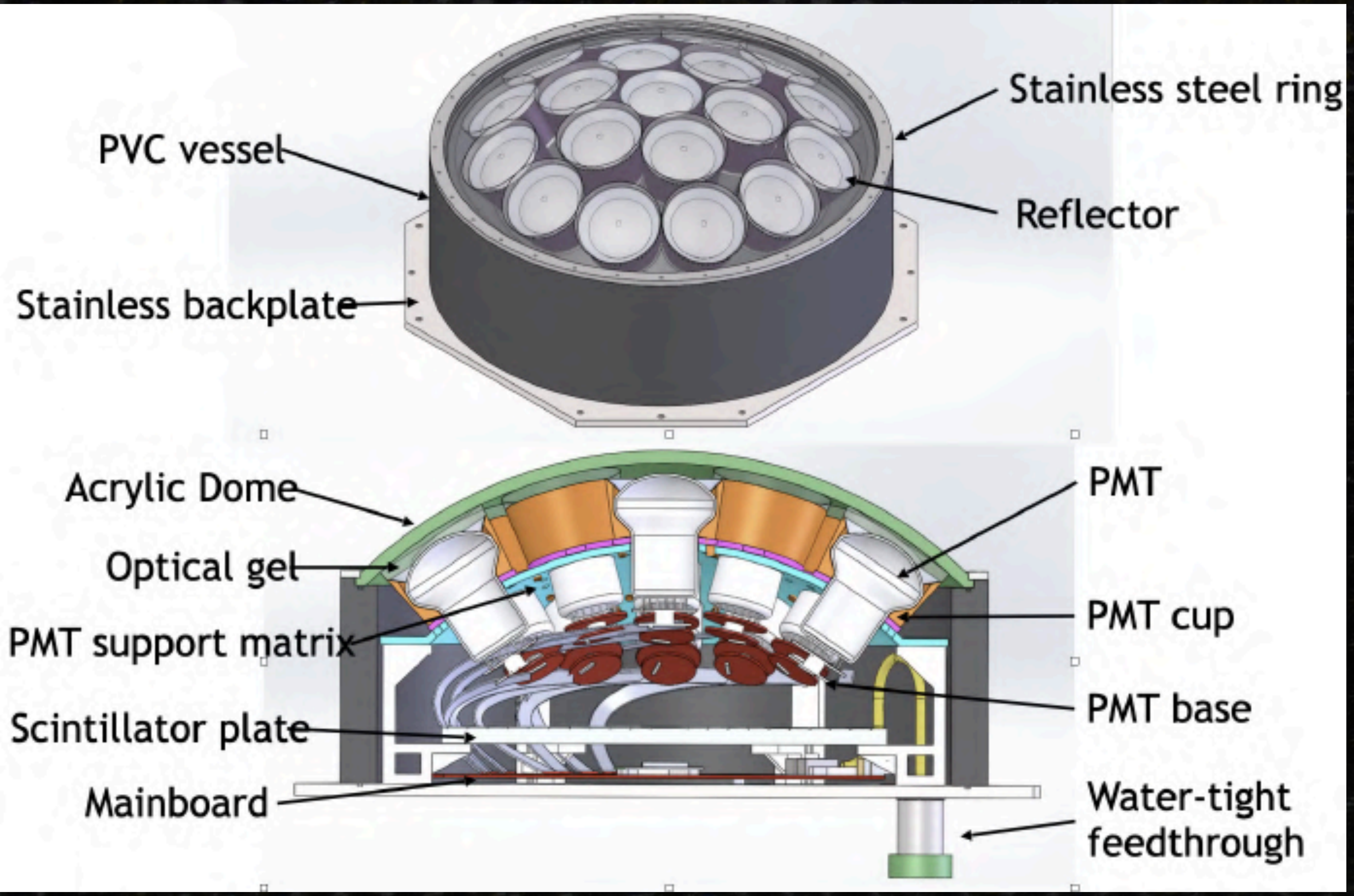


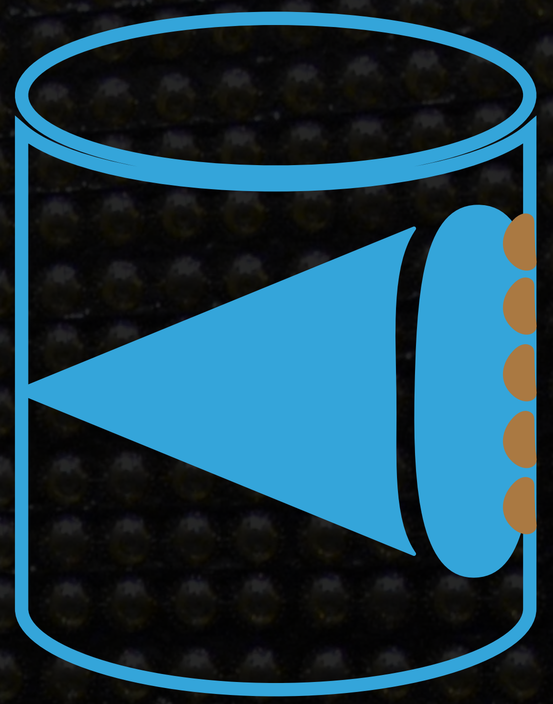


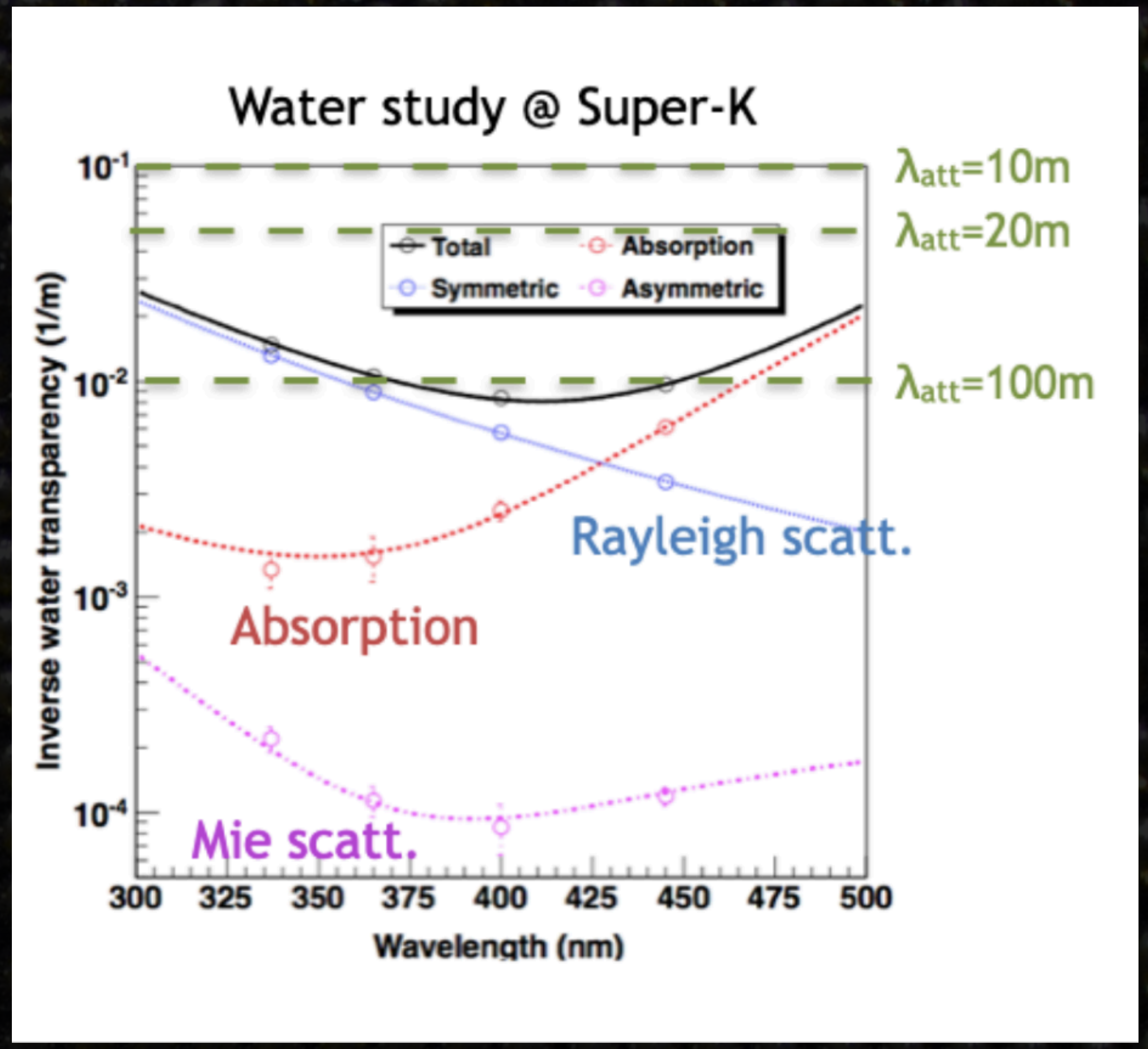
PMT angular response can produce degenerate effects as water quality variation

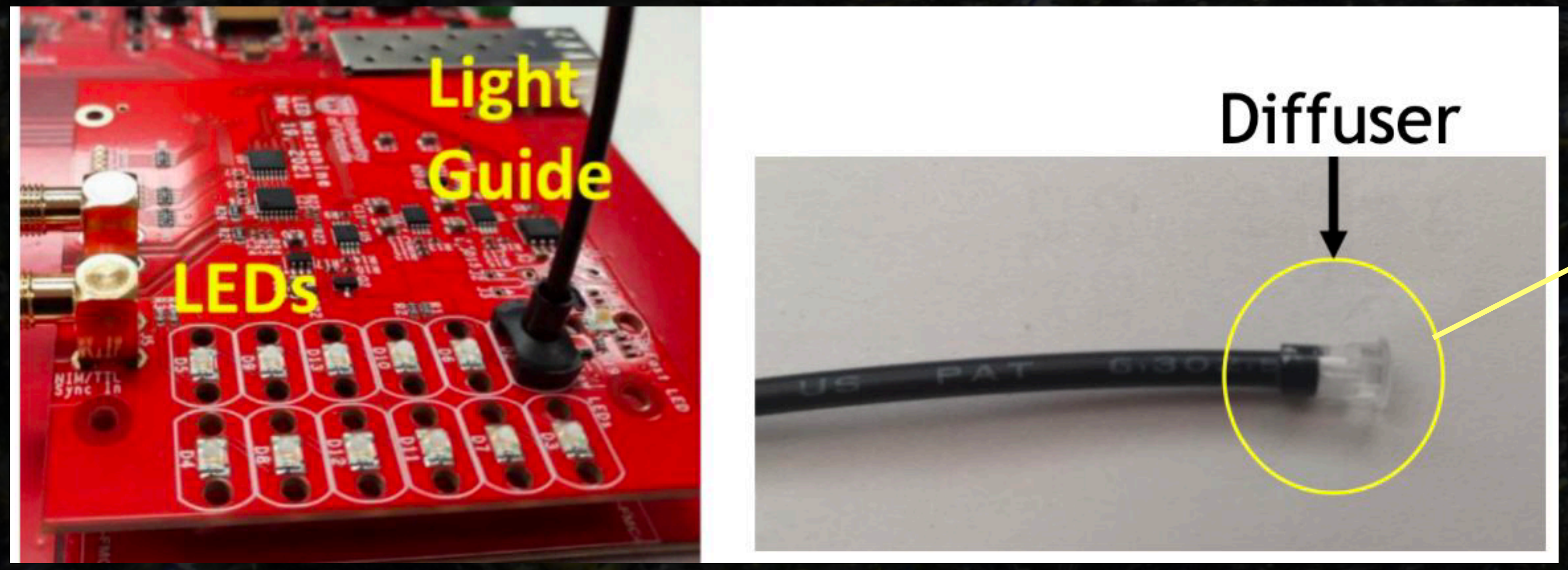
- Photosensor Test Facility (PTF)
  - Single photon level
  - Variable x, y, θ, ϕ, wavelength and polarization
  - Variable magnetic field
  - Will also be used to calibrate mPMT

CALIBRATION SYSTEMS @ TRIUMF — MPMT









WCTE mPMT

- mPMT instrumented with fast pulsed LED
  - Calibration of water parameters and internal reflection of the detector
- mPMTs instrumented amongst 20” PMTs can help break the degeneracy between water parameters and PMT angular response
  - Multiple angles
  - Better timing resolution than 20” PMTs

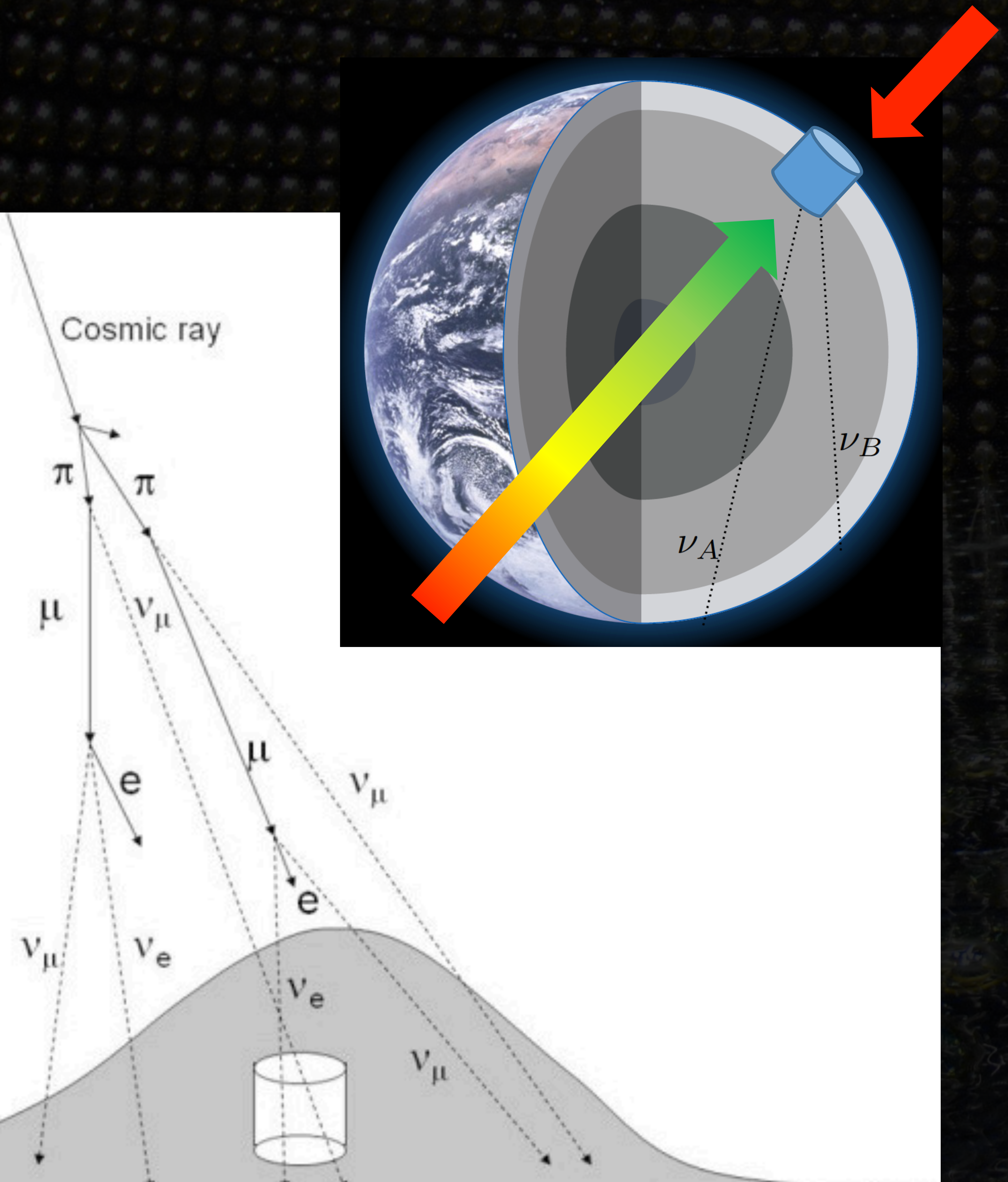
FUTURE PROSPECT

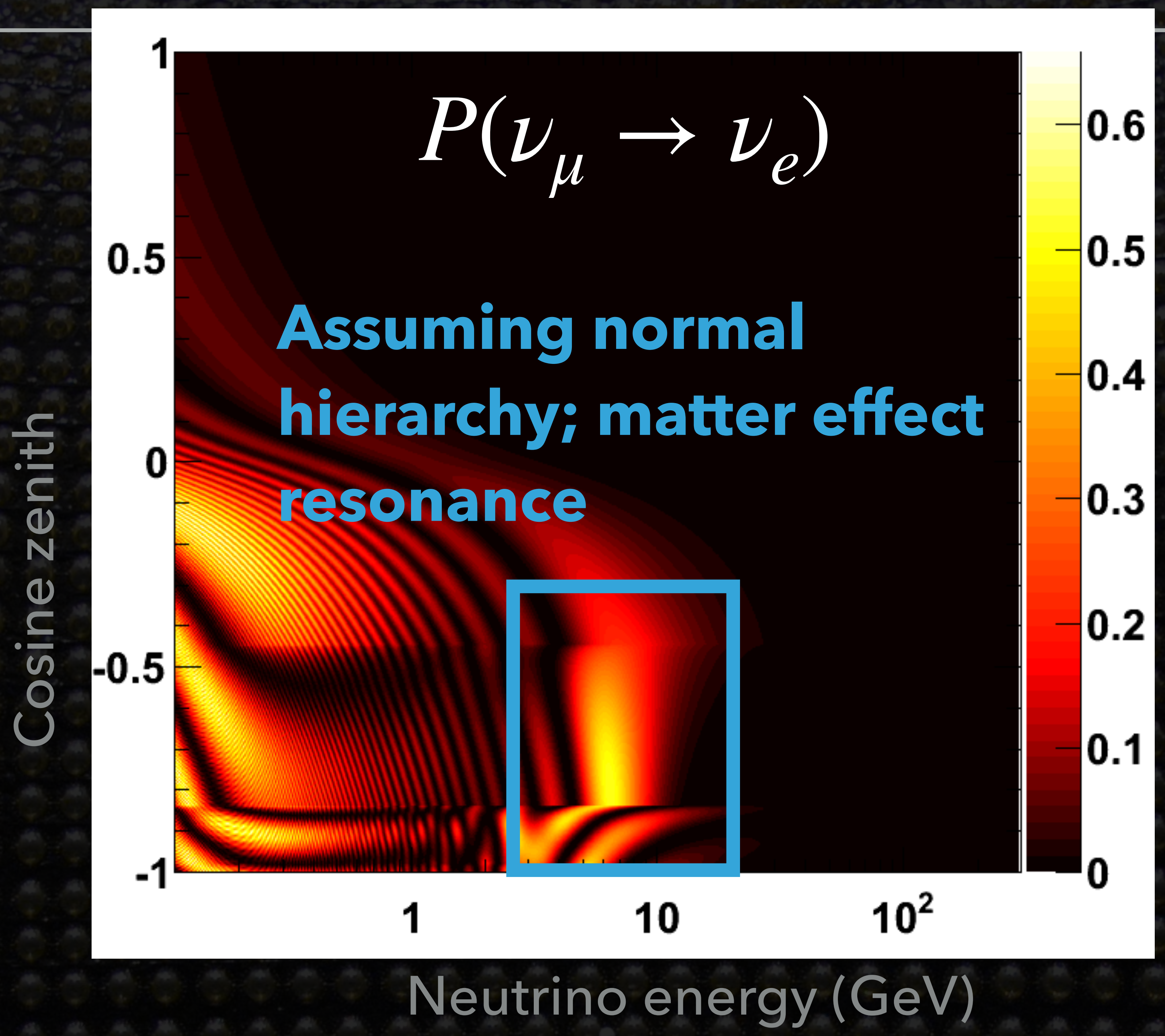
- Hyper-Kamiokande will be able to determine whether there is CP-violation in the lepton sector for most of the phase-space
  - Its success relies on the reduction of systematic uncertainties
  - A multi-purpose experiment that can study many other interesting physics subjects!
- Lots of effort to reduce systematic uncertainties
  - WCTE, IWCD
  - Improved detector calibration methods are being developed

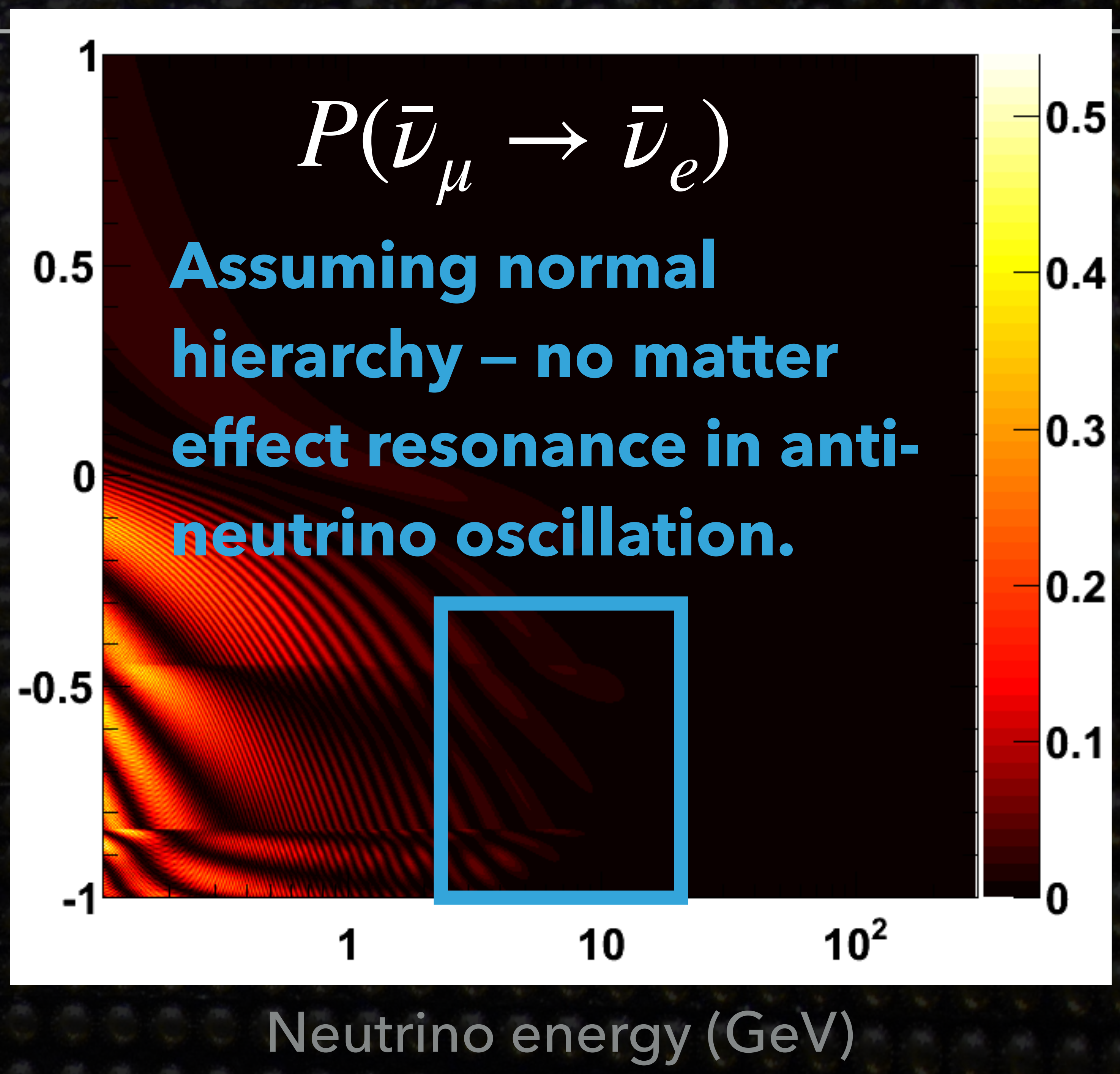
THANK YOU

NEUTRINO OSCILLATION

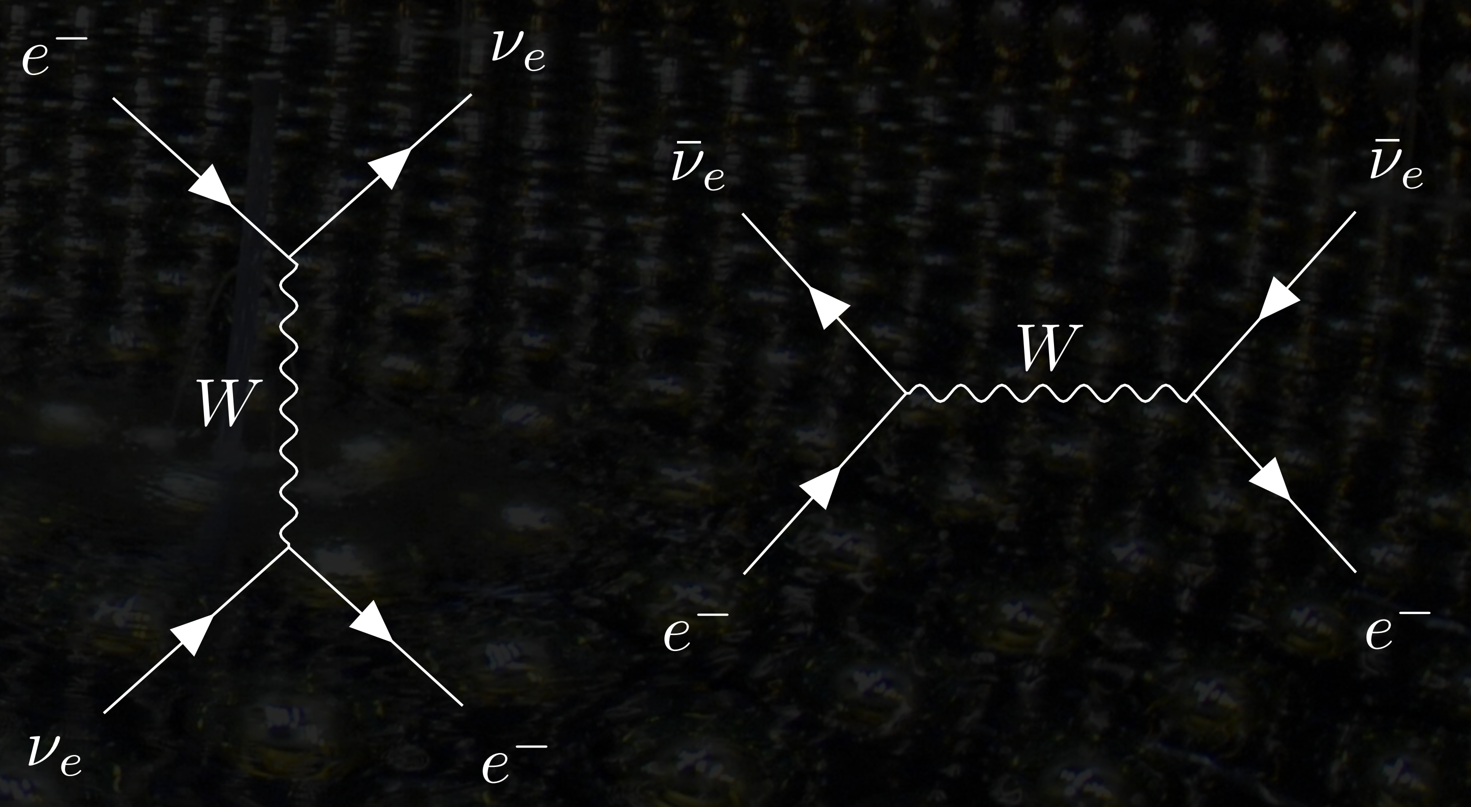
Atmospheric neutrino





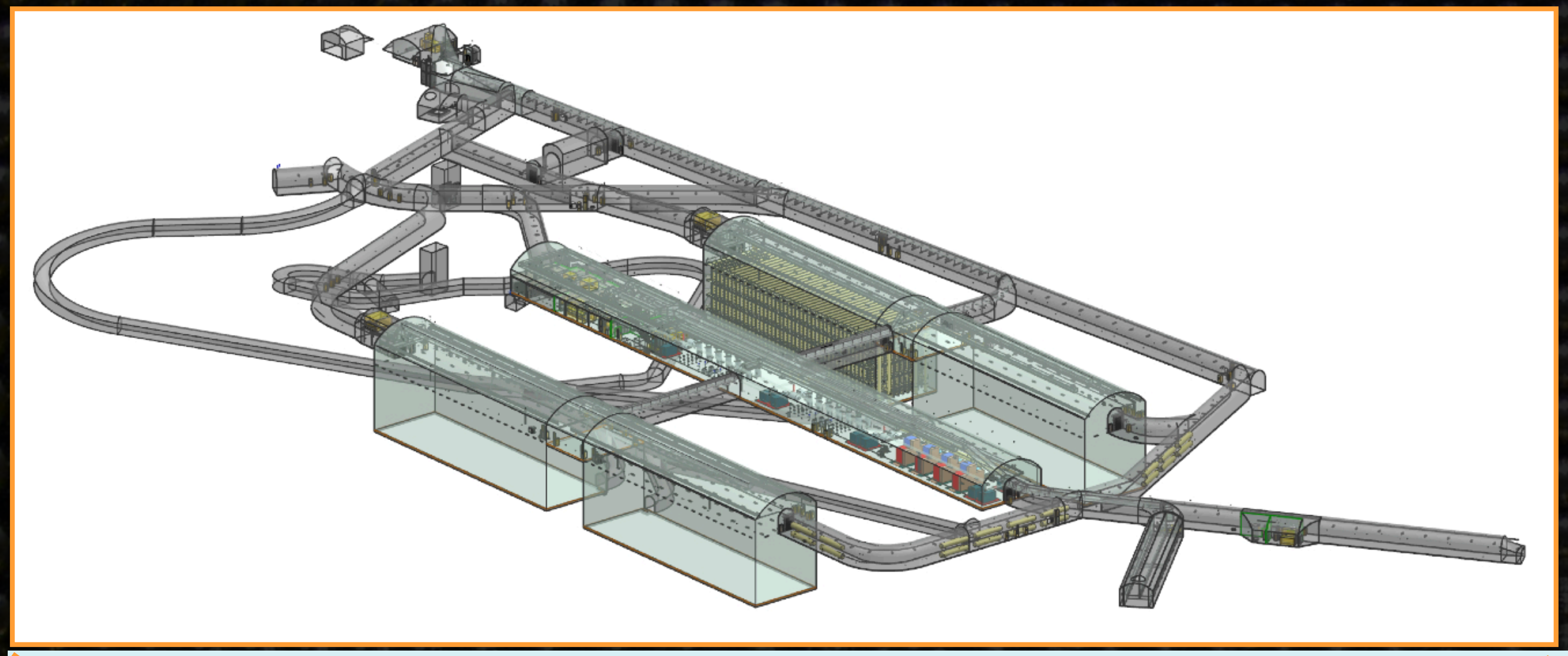


- The "matter effect" (or MSW effect) can modify the oscillation probabilities
  - ν_e and $\bar{\nu}_e$ interaction with e^- in matter
  - Effects different for ν and $\bar{\nu}$
  - Sensitive to the sign of Δm^2_{32} in long baseline and atmospheric neutrino measurements



DEEP UNDERGROUND NEUTRINO EXPERIMENT (DUNE)

- On-axis FD: two oscillation maxima
- Liquid Argon Time Projection Chamber (LArTPC)
- 10-kton fiducial mass $\times 4$



- 1.2 MW neutrino beam, upgradable to 2.4 MW
  - Beam is optimized for δ_{CP} measurement
- ND design concept is an integrated system with multiple detectors including highly segmented LArTPCs, magnetized trackers, EM calorimeters and possibly a movable detector