UNIVERSIDAD
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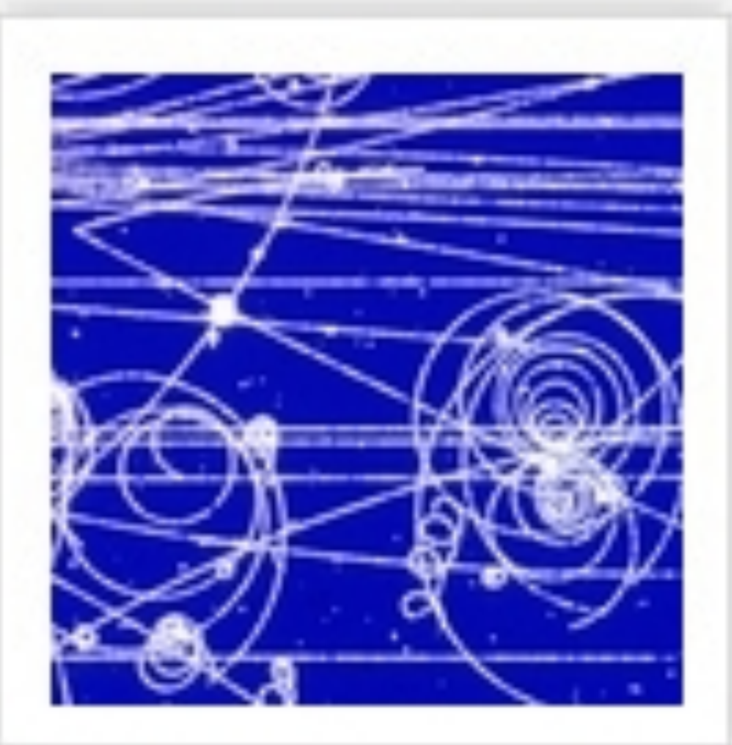
(Some) Neutrino experiments results and future experiments



LI - International Meeting on Fundamental Physics

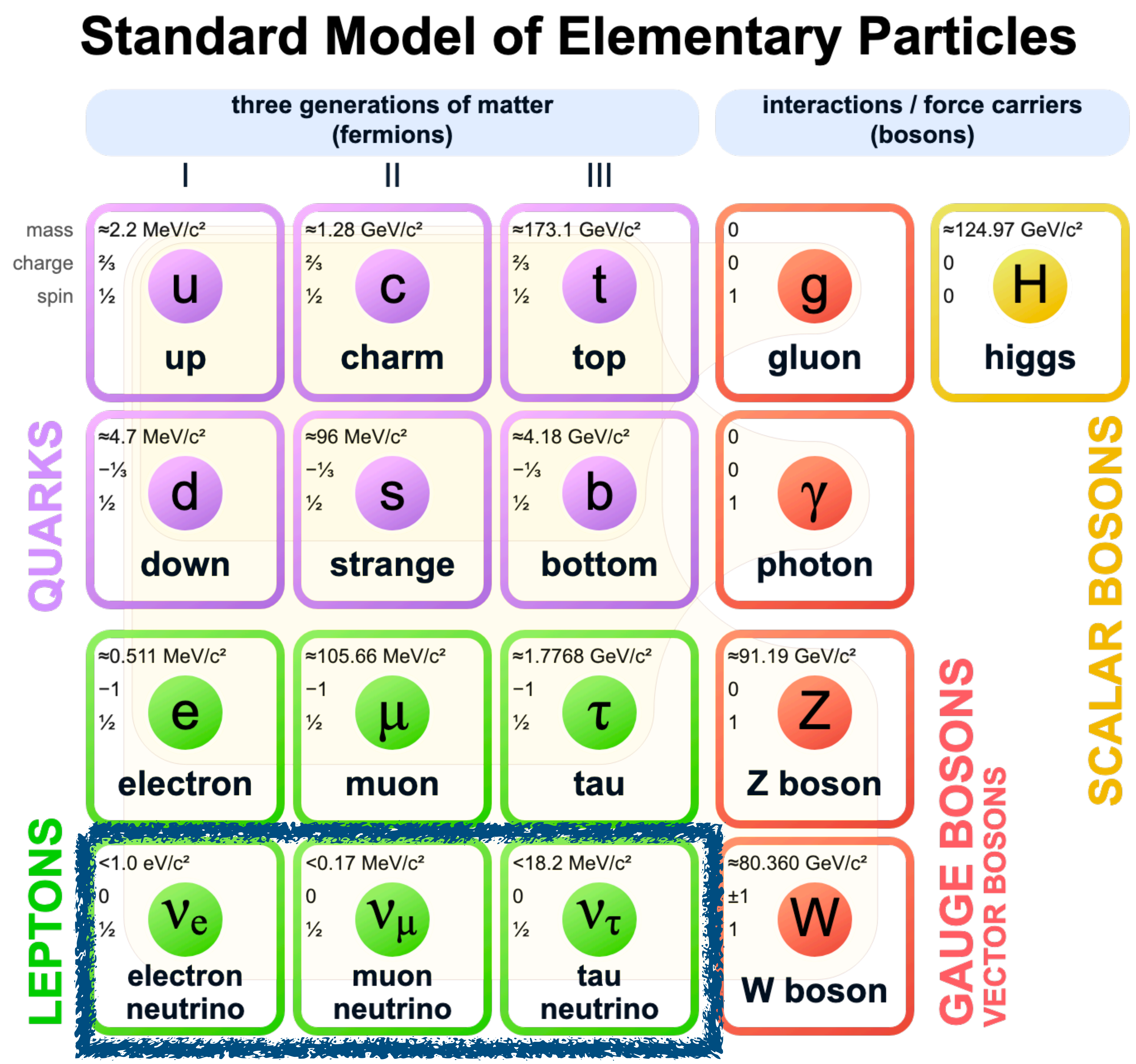
Diego García Gámez

11-09-2024

Why study neutrinos? A bit of motivation …

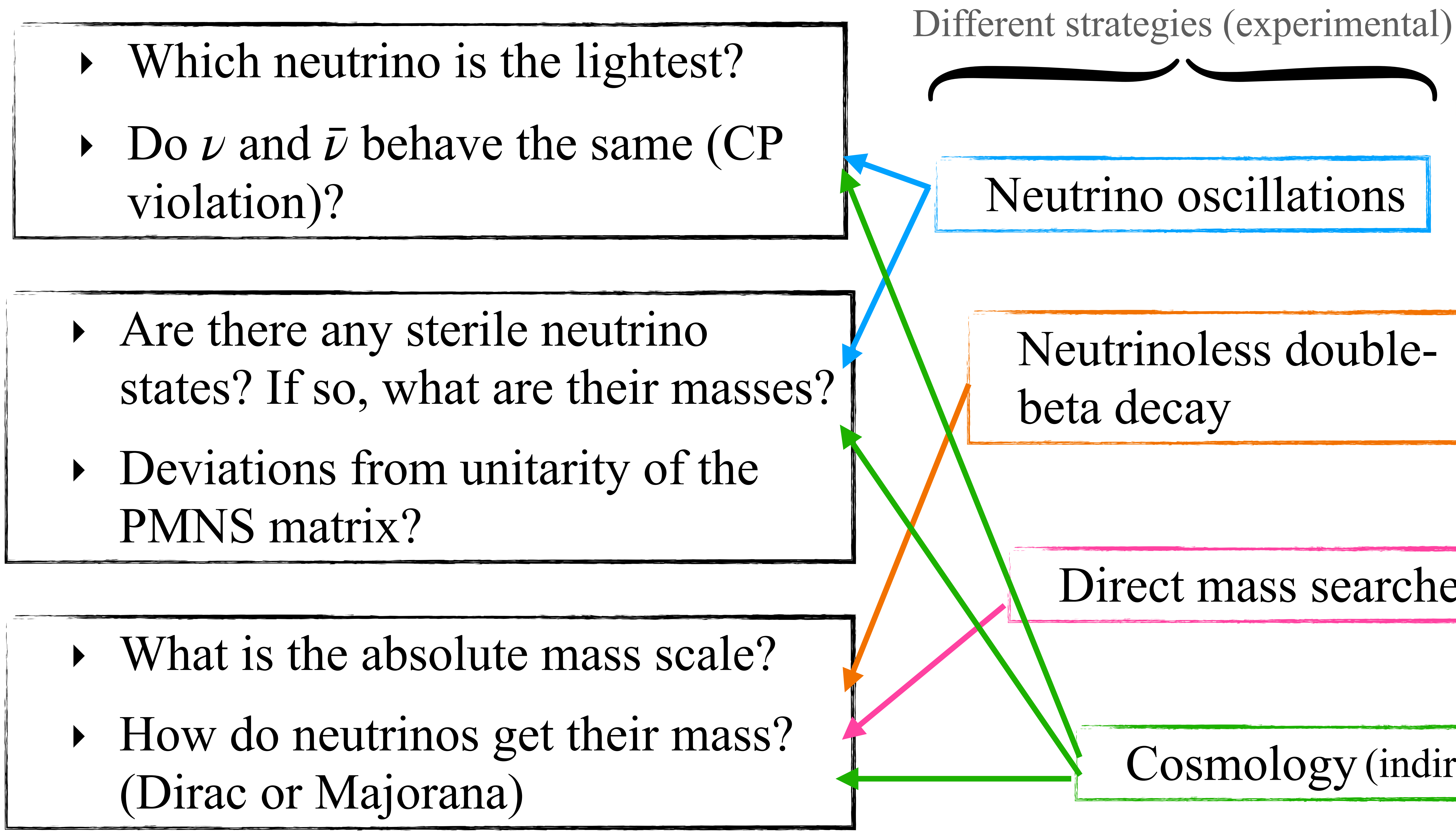
List of reasons that make them special:

- The least known of all SM fermions
  - Lightest ones
  - Only Electrically neutral ones
  - Most penetrating ones
- Neutrino masses imply new physics Beyond Standard Model
- The most abundant of all fermions in the Universe with a strong impact on its evolution
- Their nature is related to the fundamental symmetries of nature (lepton number)
- Neutrinos could be the key to explaining why the Universe is basically made of matter (baryon asymmetry).



What are we trying to learn?

- Last 20 years have been a revolution for neutrino physics, but still fundamental questions to answer:



- Which neutrino is the lightest?
- Do ν and $\bar{\nu}$ behave the same (CP violation)?

- Are there any sterile neutrino states? If so, what are their masses?
- Deviations from unitarity of the PMNS matrix?

- What is the absolute mass scale?
- How do neutrinos get their mass? (Dirac or Majorana)

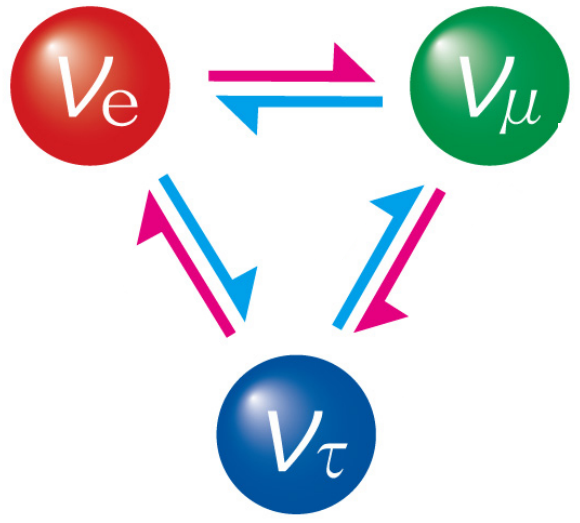
Different strategies (experimental)

Neutrino oscillations

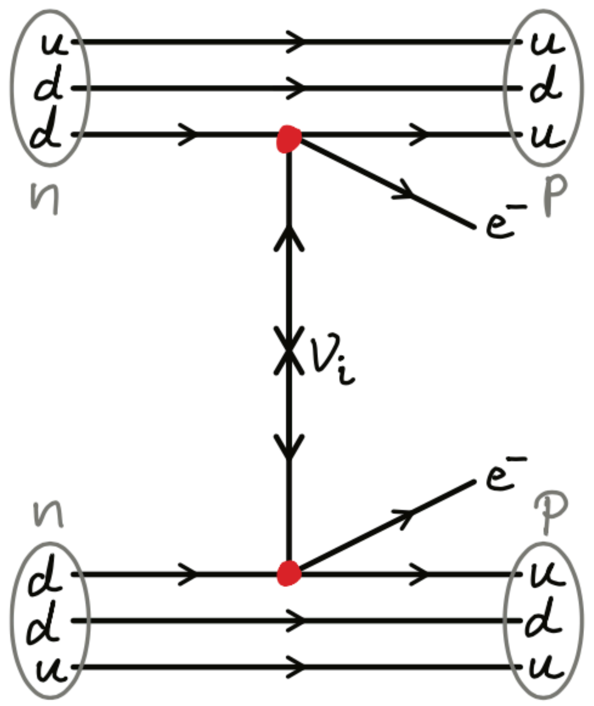
Neutrinoless double-beta decay

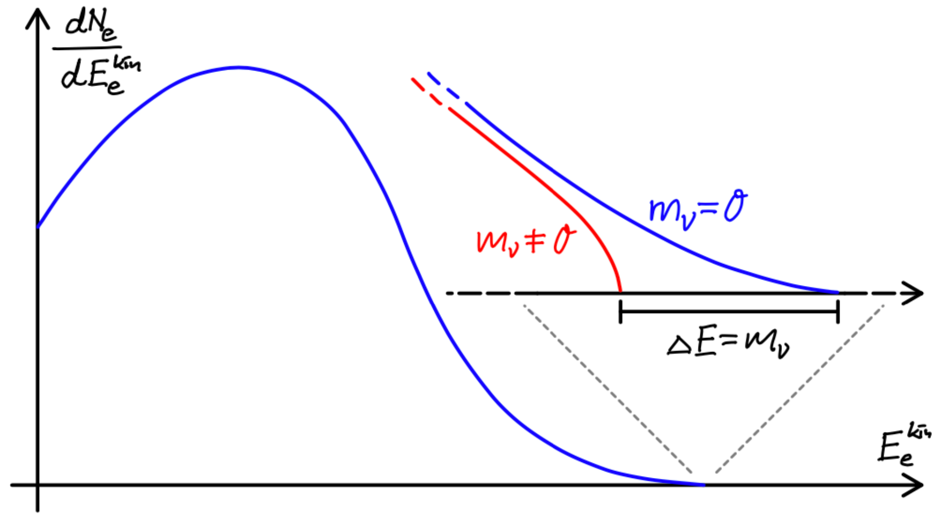
Direct mass searches

Cosmology (indirectly)



Neutrino oscillation between three generations

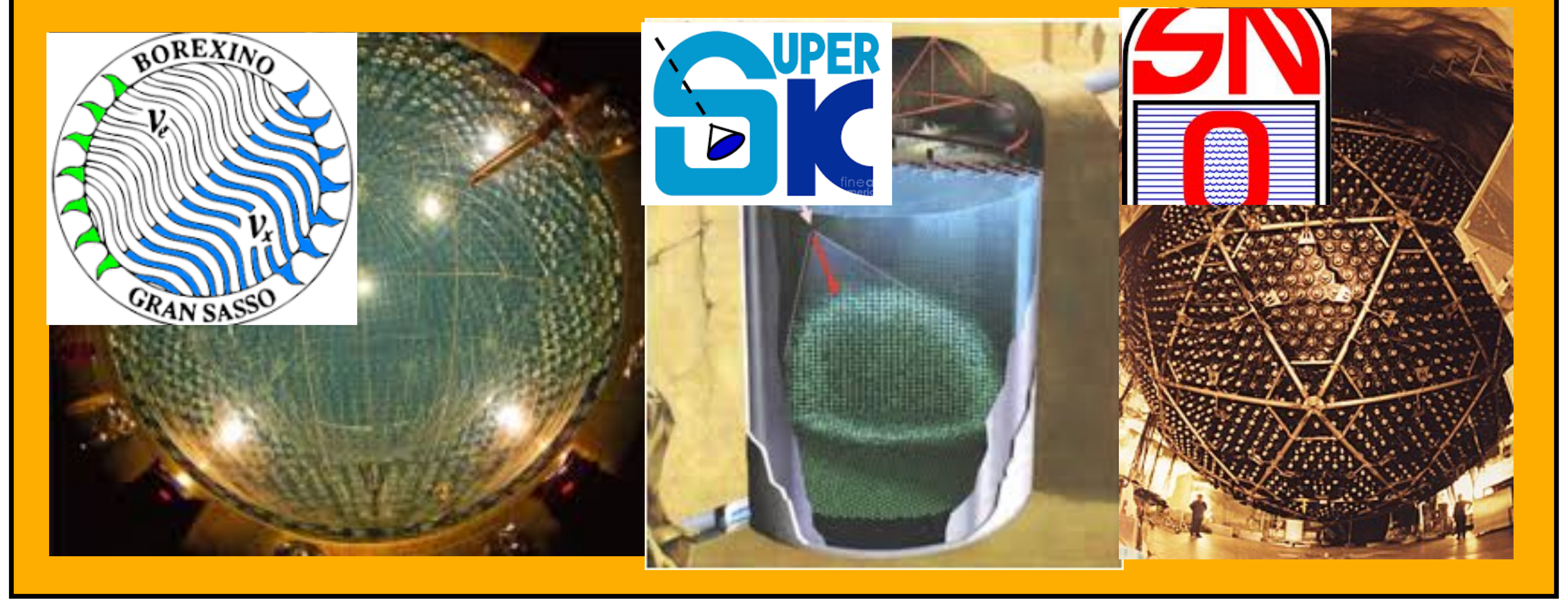




Understanding neutrinos: a world-wide effort

Accelerator:

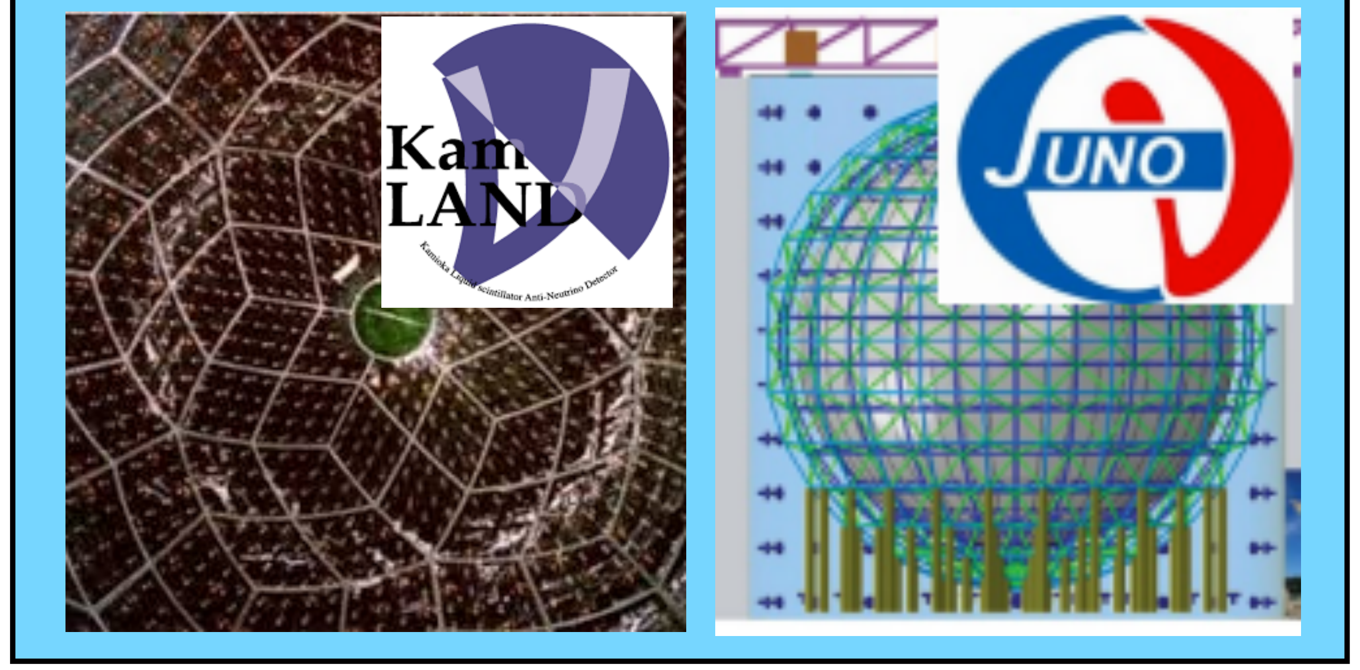
Solar:



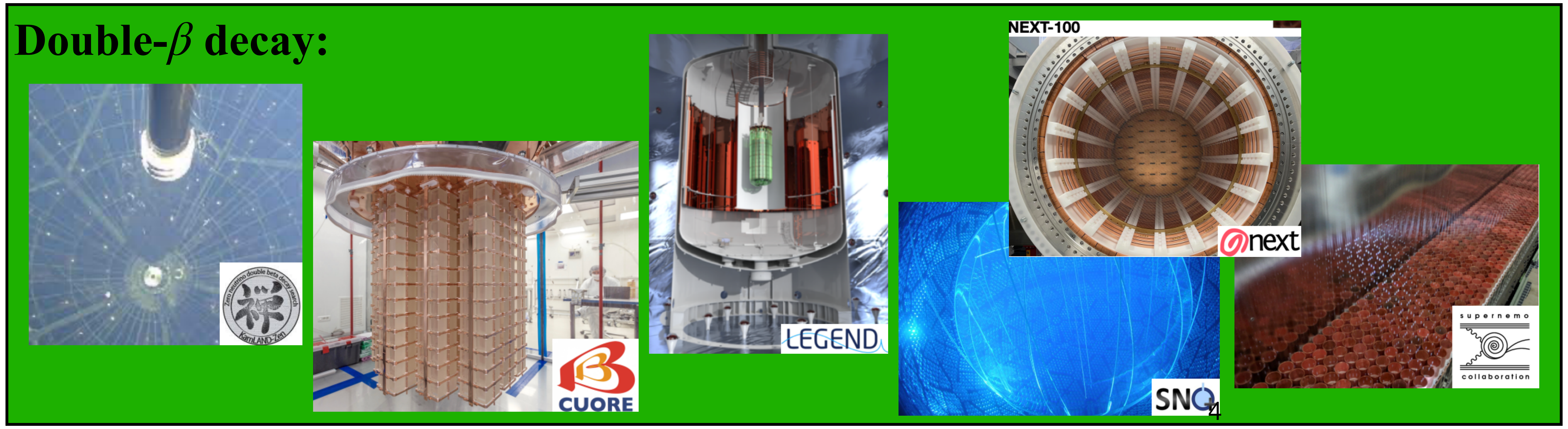
Astrophysical:

Reactor:

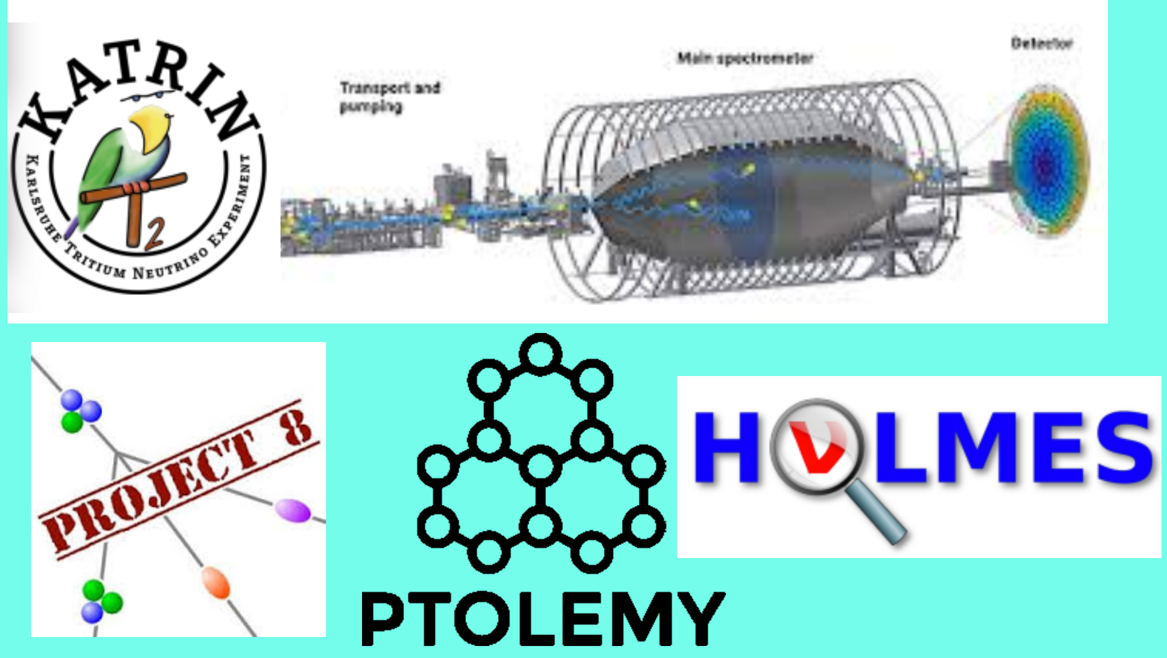
Reactor:



Double-β decay:



Radioactive isotope:



(And more!)

Understanding neutrinos: a world-wide effort

This talk: Long baseline neutrino oscillation experiments past, present and future

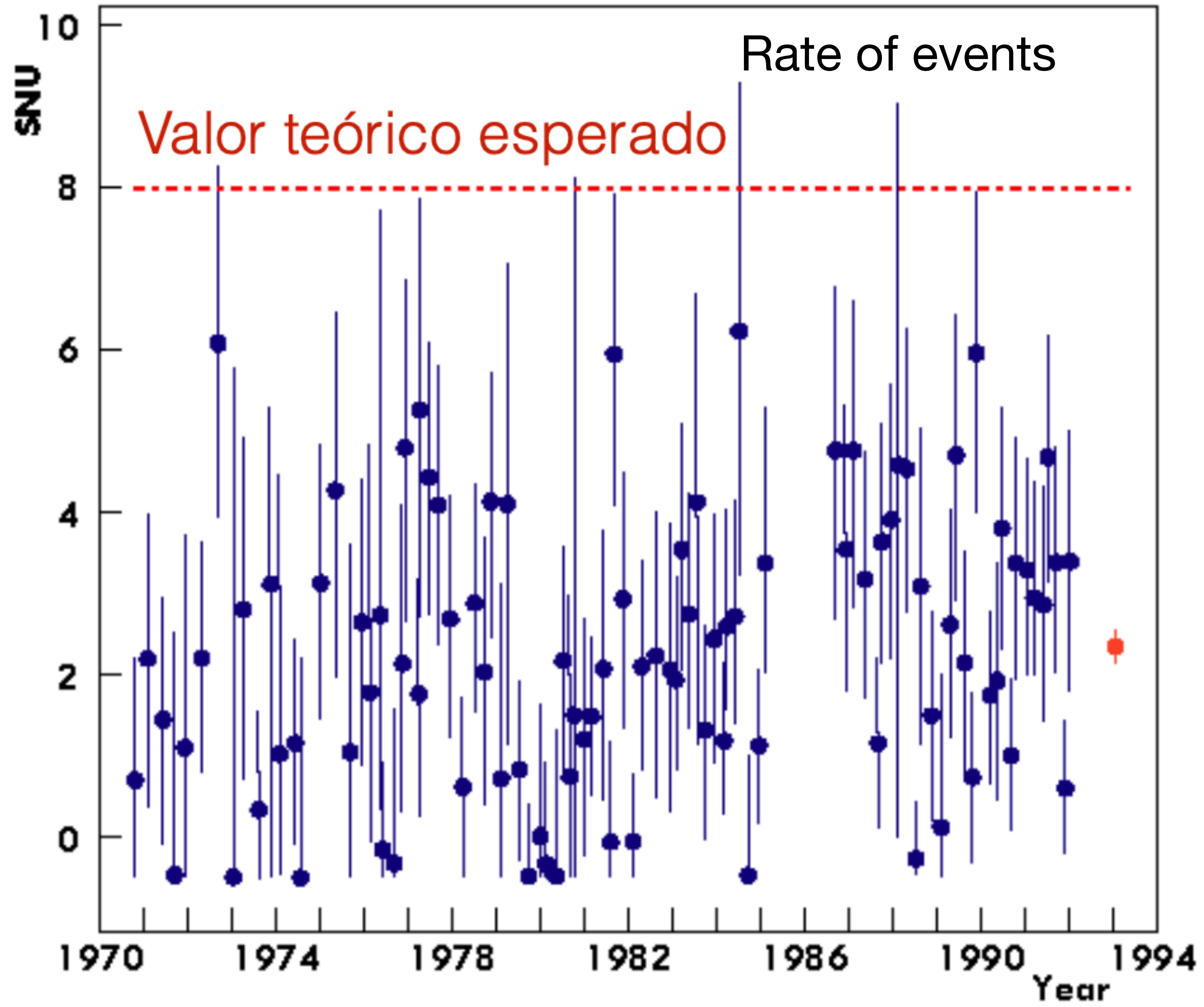
(And more!)

(First) Solar Neutrino experiments and “the solar neutrino problem”

Nuclear fusion in the Sun produces a large flux of ν_e with E < 20 MeV. They have been studied with different experiment/technologies:

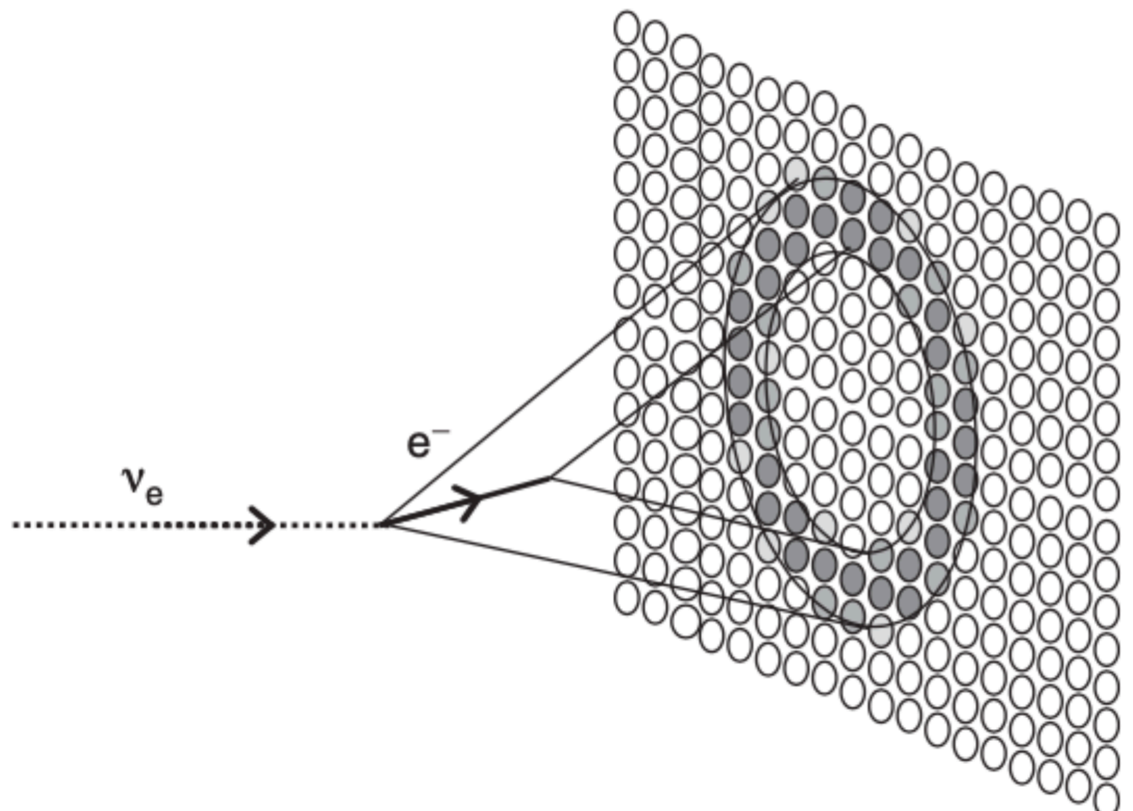
- Radio Chemical: (Homestake, SAGE, GALLEX)
  - Inverse beta decay, e.g. : $\nu_e + {}^{37}_{17}Cl \rightarrow {}^{37}_{18}Ar + e^-$
  - ^{37}Ar atoms where extracted from the detector and counted through their radioactive decays: ${}^{37}_{18}Ar + e^- \rightarrow {}^{37}_{17}Cl + \nu_e + \text{Auger electron}$

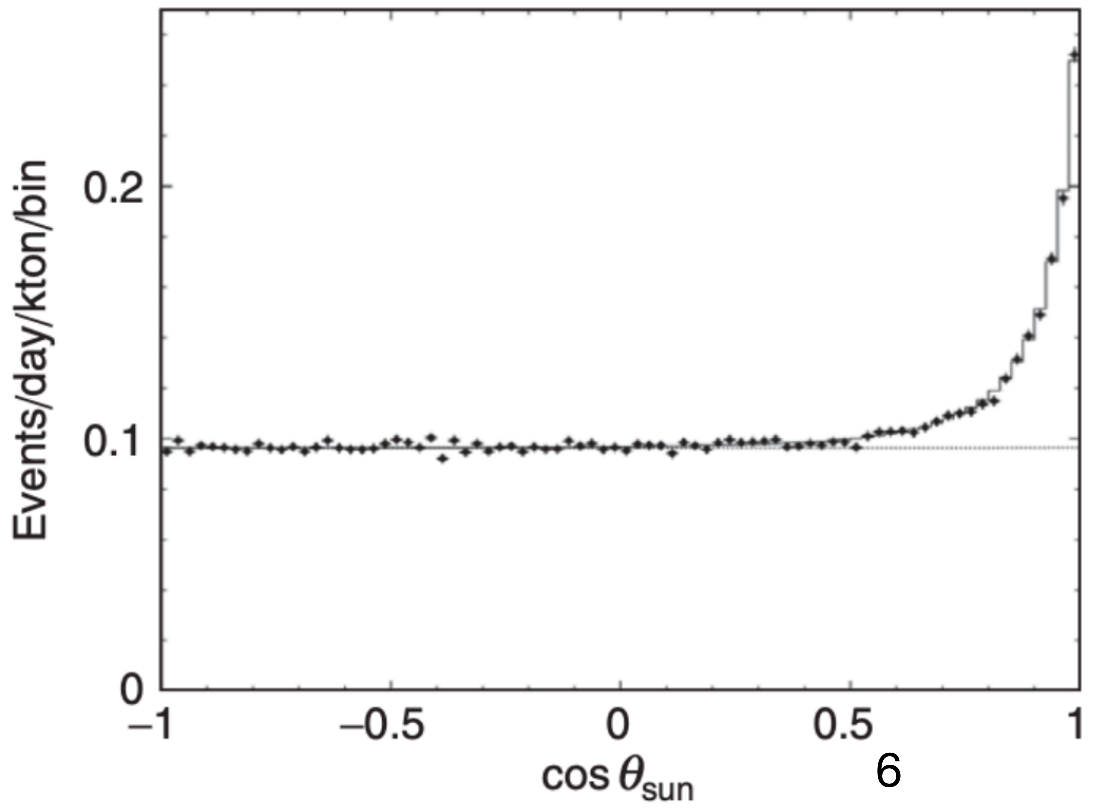
SNU Solar Neutrino Unit = 1 captura por segundo por 10^{36} átomos de ^{37}Cl



More than 20 years of measurements: one third of the expected value (about 2000 atoms collected)

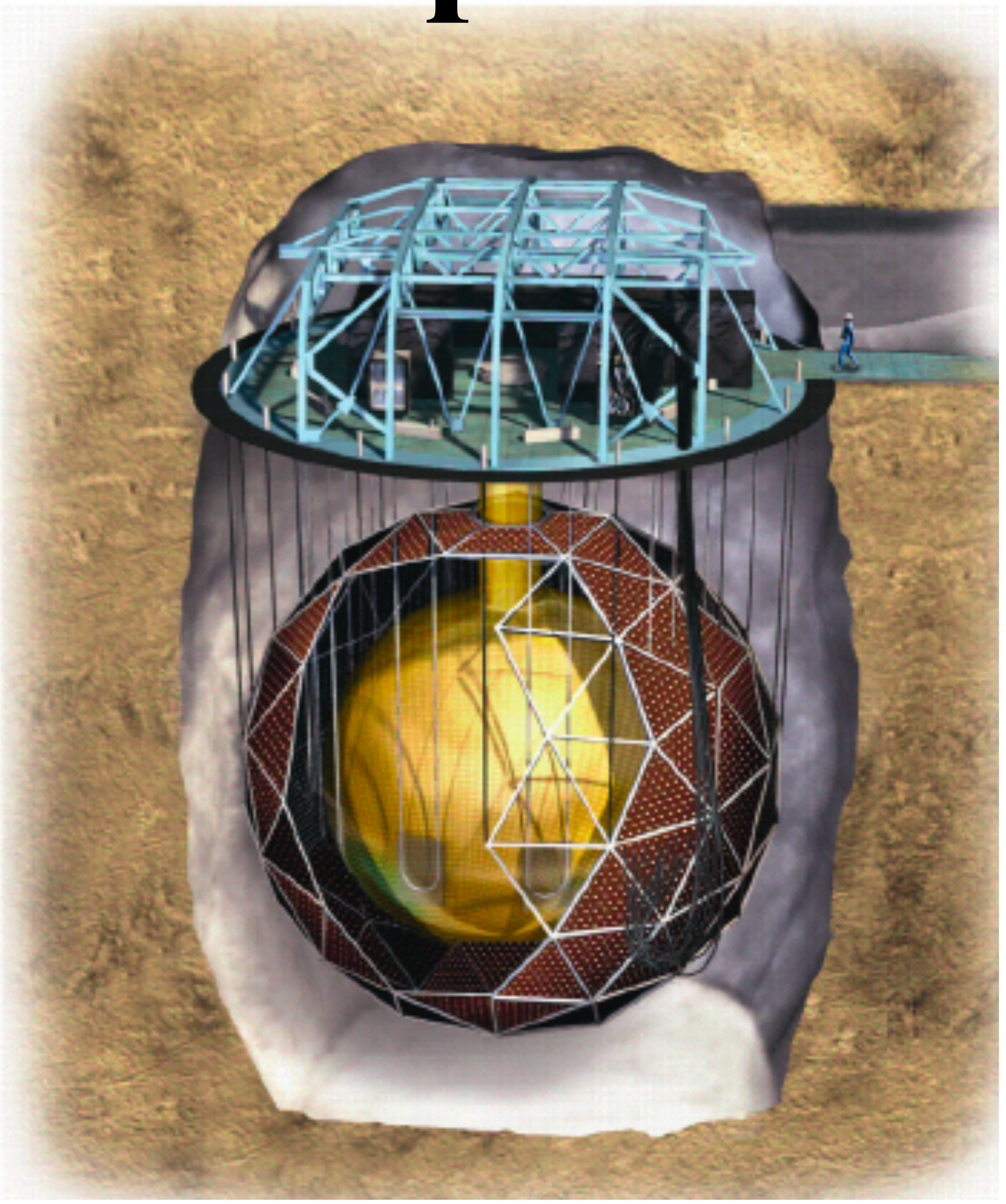
- Water Cherenkov: (Super Kamiokande, since 1996)
  - Detect Cherenkov light from ES: $\nu_e + e^- \rightarrow \nu_e + e^-$
  - CC process ($\nu_e + n \rightarrow p + e^-$) is kinematically forbidden (Oxygen is a doubly magic nucleus)





- Clear evidence of neutrinos from the Sun, but **measured flux about half that expected!**

SNO experiment



- SNO consisted of 1,000 tons of heavy water, D_2O, inside a 12m diameter vessel, viewed by 9,600 PMTs.

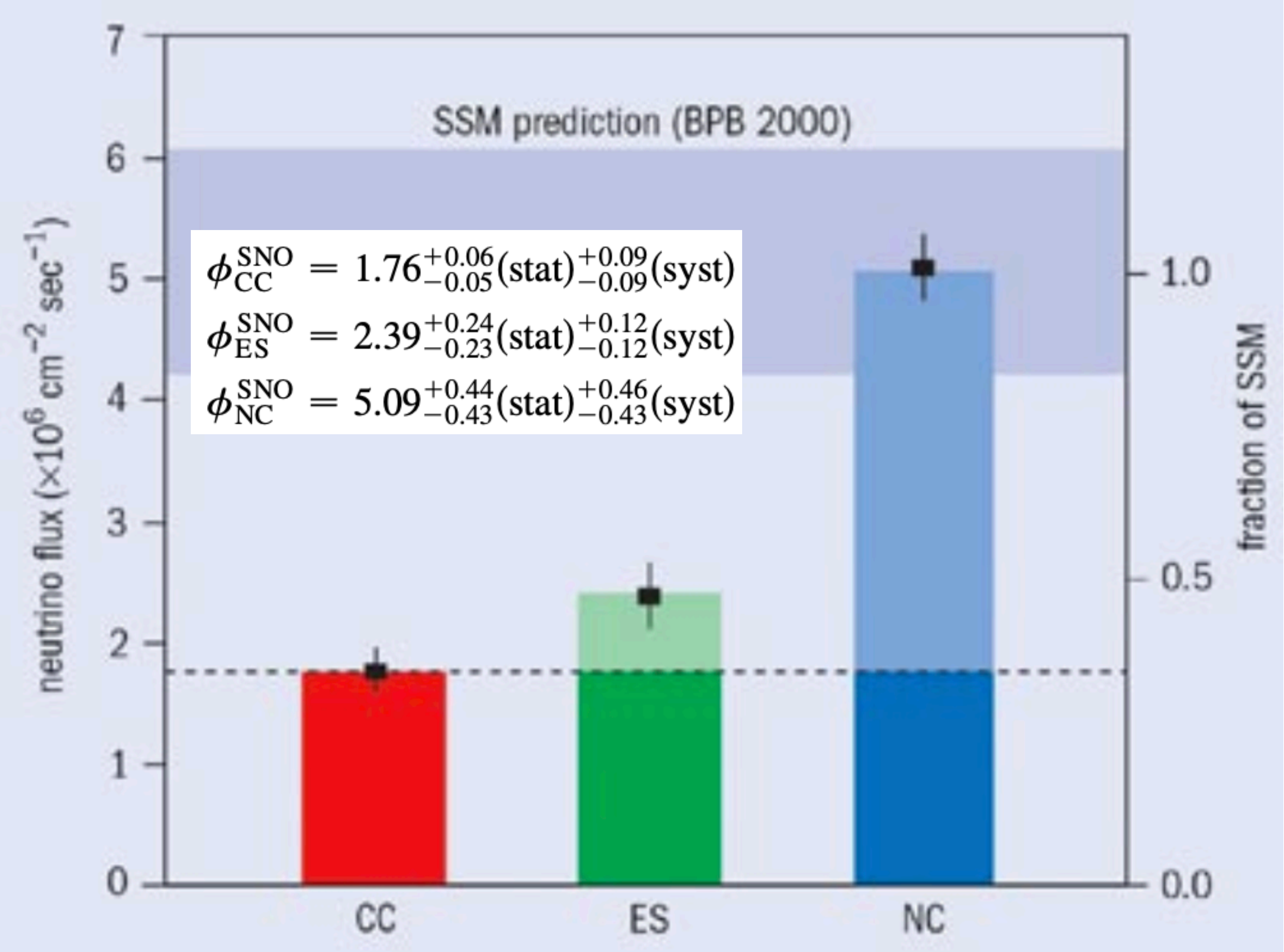
CC $\nu_e + d \Rightarrow p + p + e^-$

ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

NC $\nu_x + d \Rightarrow p + n + \nu_x$

- The Sudbury Neutrino Observatory (SNO) experiment (1999-2006) in Canada was designed to measure both the ν_e and total neutrino flux from the Sun.

- Key point: three different physical processes with different sensitivities to the fluxes of electron, muon and tau neutrinos.

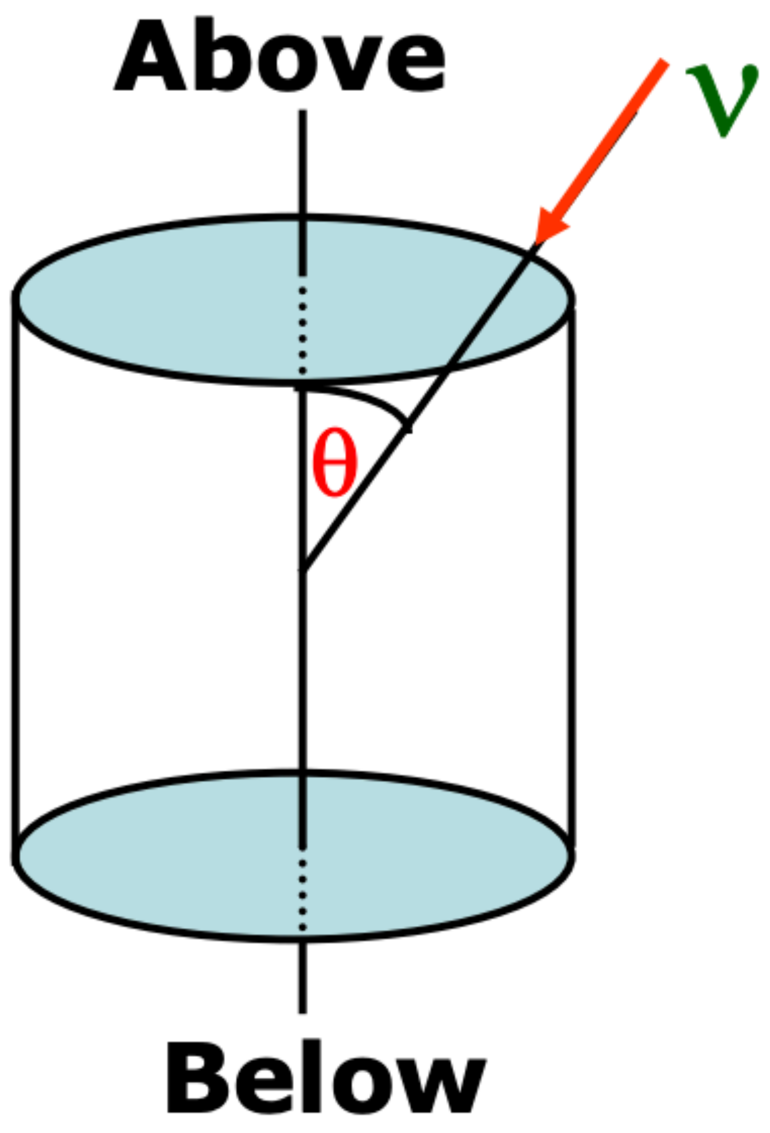


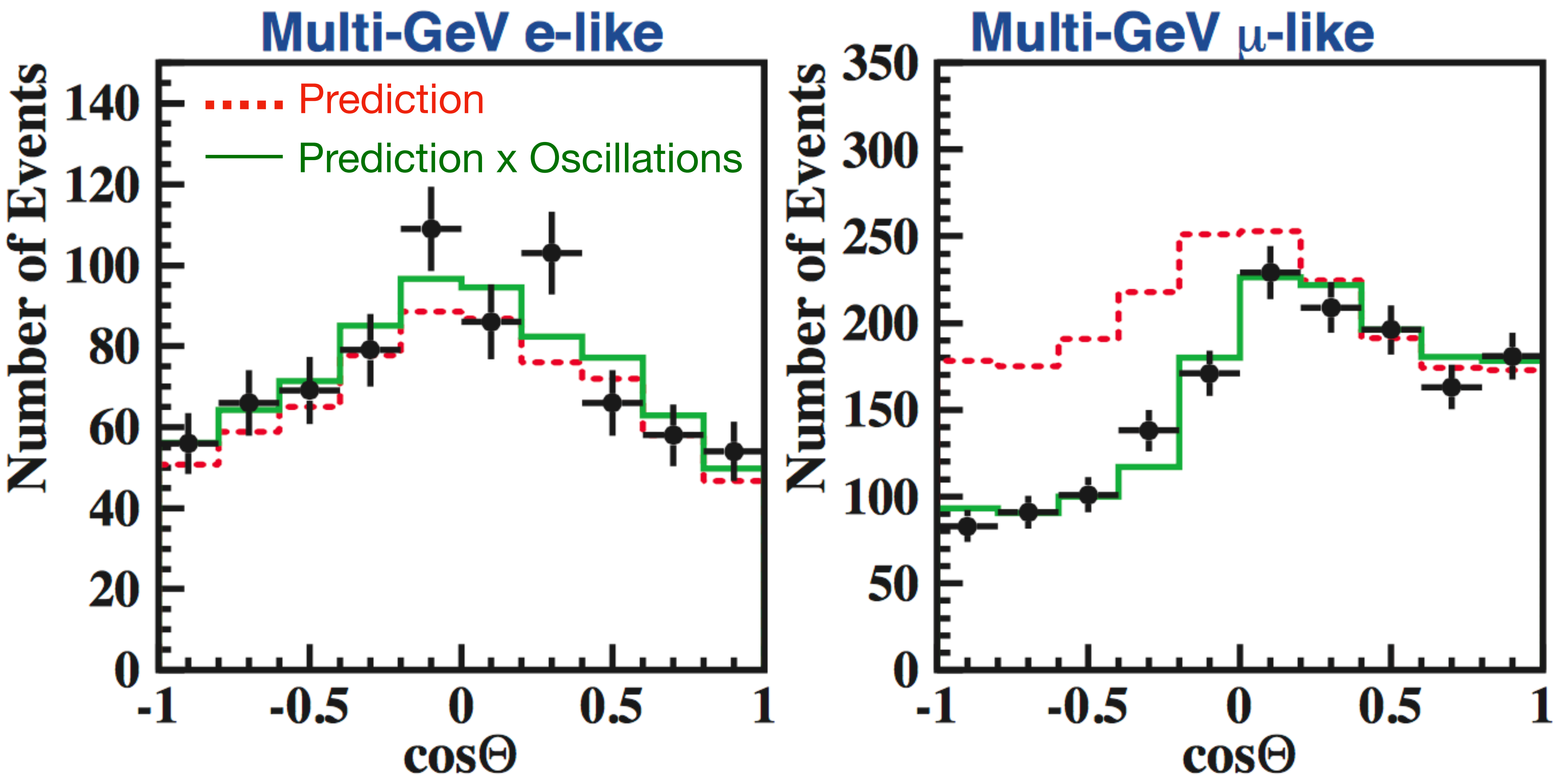
- The SNO data demonstrate that the total flux of neutrinos from the Sun is consistent with the theoretical expectation, but rather than consisting of only ν_e, there is a large ν_μ and/or ν_τ component.

- SNO provides clear evidence of neutrino flavour transformations over large distances.

Super Kamiokande Atmospheric Results

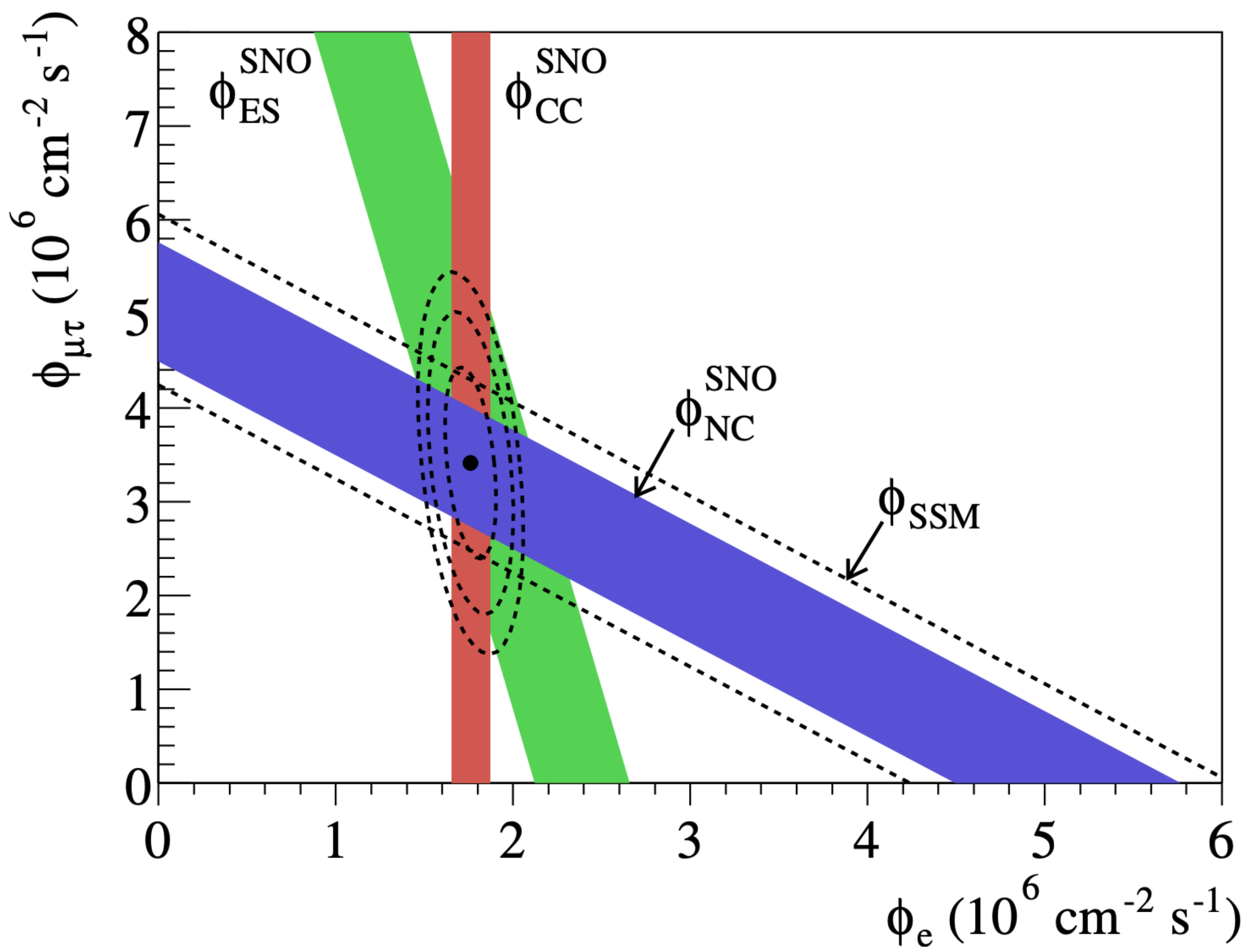
- SK made important contribution to solve the problem!
- Typical energy $E_\nu \approx 1\,GeV$: (much greater than solar neutrinos – no confusion)
- Measure rate as a function of angle with respect to local vertical
- Neutrinos coming from above travel ~20 km; from below (i.e. other side of the Earth) travel ~12800 km

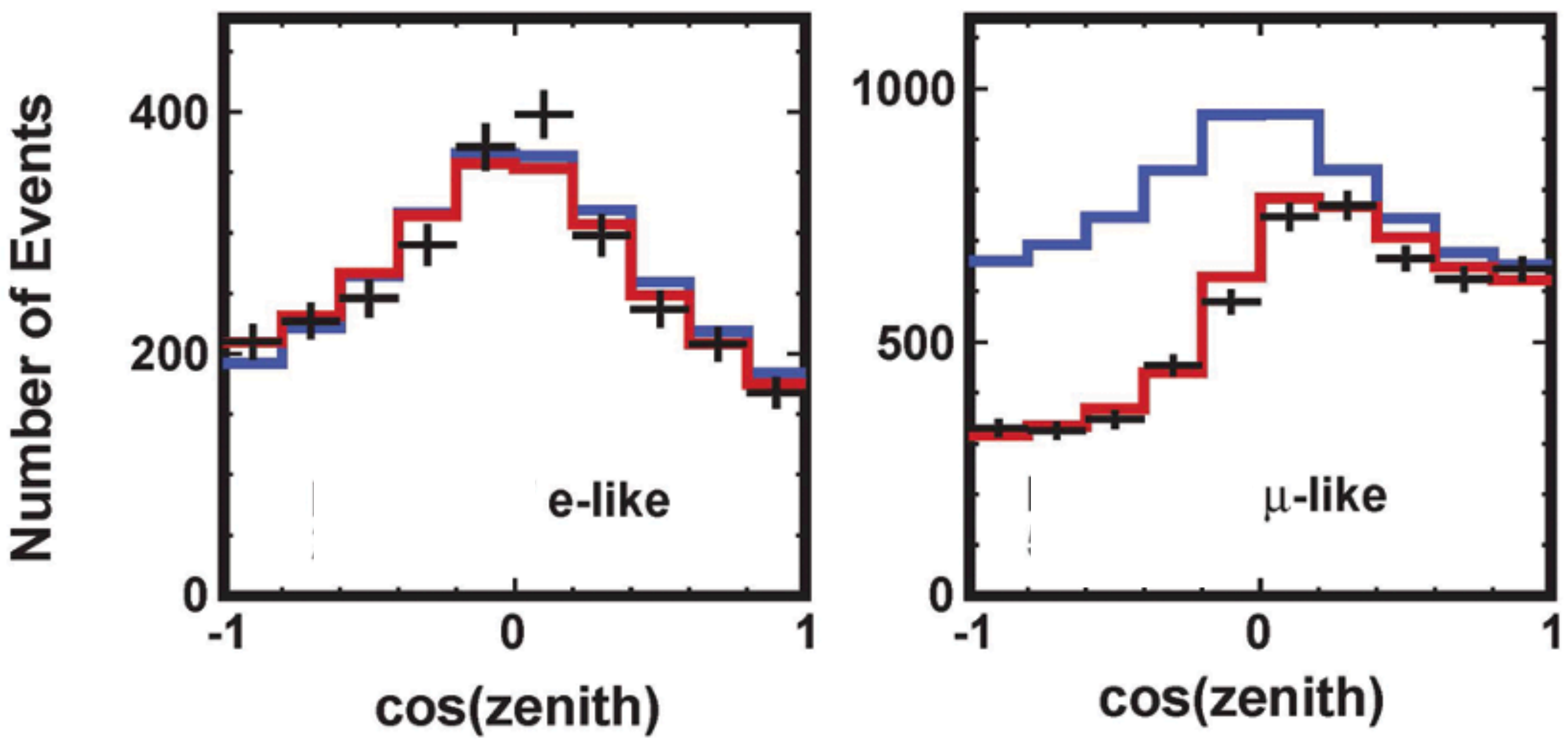


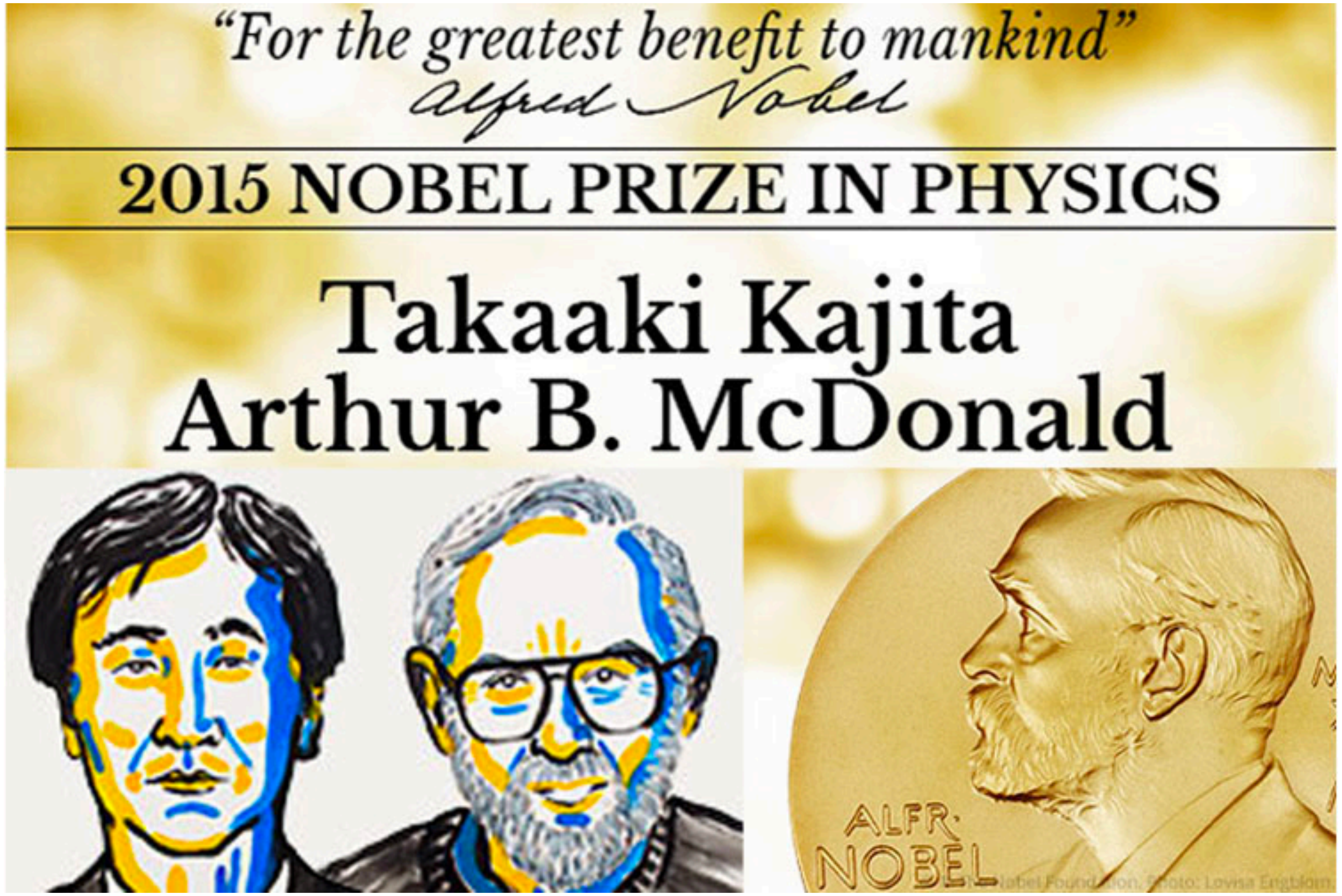


- Data agrees with predictions for ν_e
- Strong evidence for disappearance of ν_μ for large distances
- Consistent with $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Don't detect the oscillated ν_τ as typically below interaction threshold of 3.5 GeV

The “solar” and “atmospheric” neutrino anomalies (1960s – 1990s). Resolution







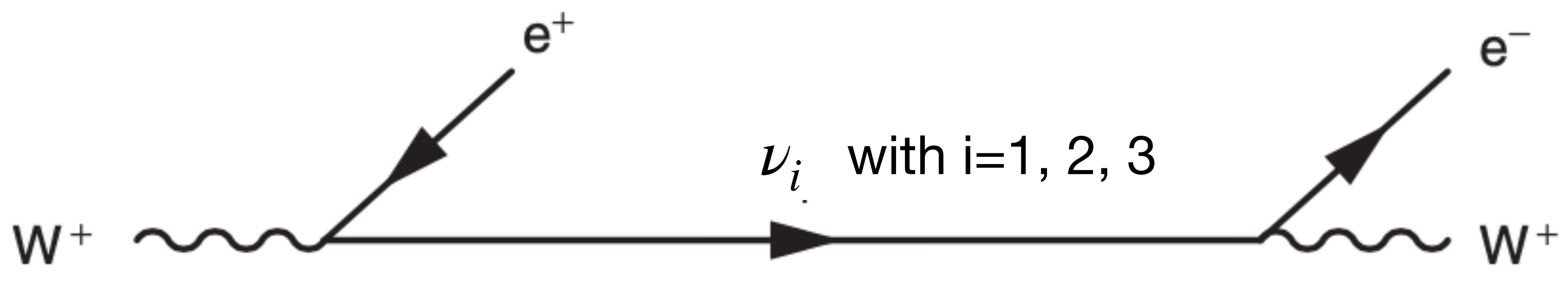
Neutrinos can change ‘flavours’ and have mass

Neutrino Mixing (brief reminder)

- We know that the neutrino flavour transformations observed by some experiments can be explained by the phenomenon of neutrino oscillations. How can this happen?

- There is no reason to believe that the neutrino mass eigenstates (the fundamental particles) ν_1, ν_2 and ν_3 should correspond to the weak eigenstates, ν_e, ν_μ and ν_τ (produced along with the respective flavour of charged lepton in a weak interaction)

- Since it is not possible to know which mass eigenstate is produced in an interaction, the system has to be described by superposition of ν_1, ν_2 and ν_3.



- In quantum mechanics, the basis of weak eigenstates can be related to the basis of mass eigenstates by a matrix U_{PMNS} (Pontecorvo–Maki–Nakagawa–Sakata),

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS Matrix

- The PMNS matrix is usually expressed in terms of 3 rotation angles $\theta_{12}, \theta_{23}, \theta_{13}$ and a complex phase δ_{cp}

$$
\mathrm{U}_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}
$$

$$\begin{cases} \theta_{23} \simeq 45^\circ \\ \text{Octant not known} \\ \text{(new symmetry?)} \end{cases}$$

$$\nu_\mu \to \nu_\mu$$
$$\nu_\mu \to \nu_\tau$$

Atmospheric and long baseline

$$\begin{cases} \theta_{13} \simeq 10^\circ \\ \delta_{\text{cp}} \text{ not known} \\ \text{(CP violation?)} \end{cases}$$

$$\nu_e \to \nu_e$$
$$\nu_\mu \to \nu_e$$

Reactor and long baseline

$$\theta_{12} \simeq 35^\circ$$

$$\nu_e \to \nu_e$$
$$\nu_e \to \nu_\mu,\ \nu_\tau$$

Solar and reactor

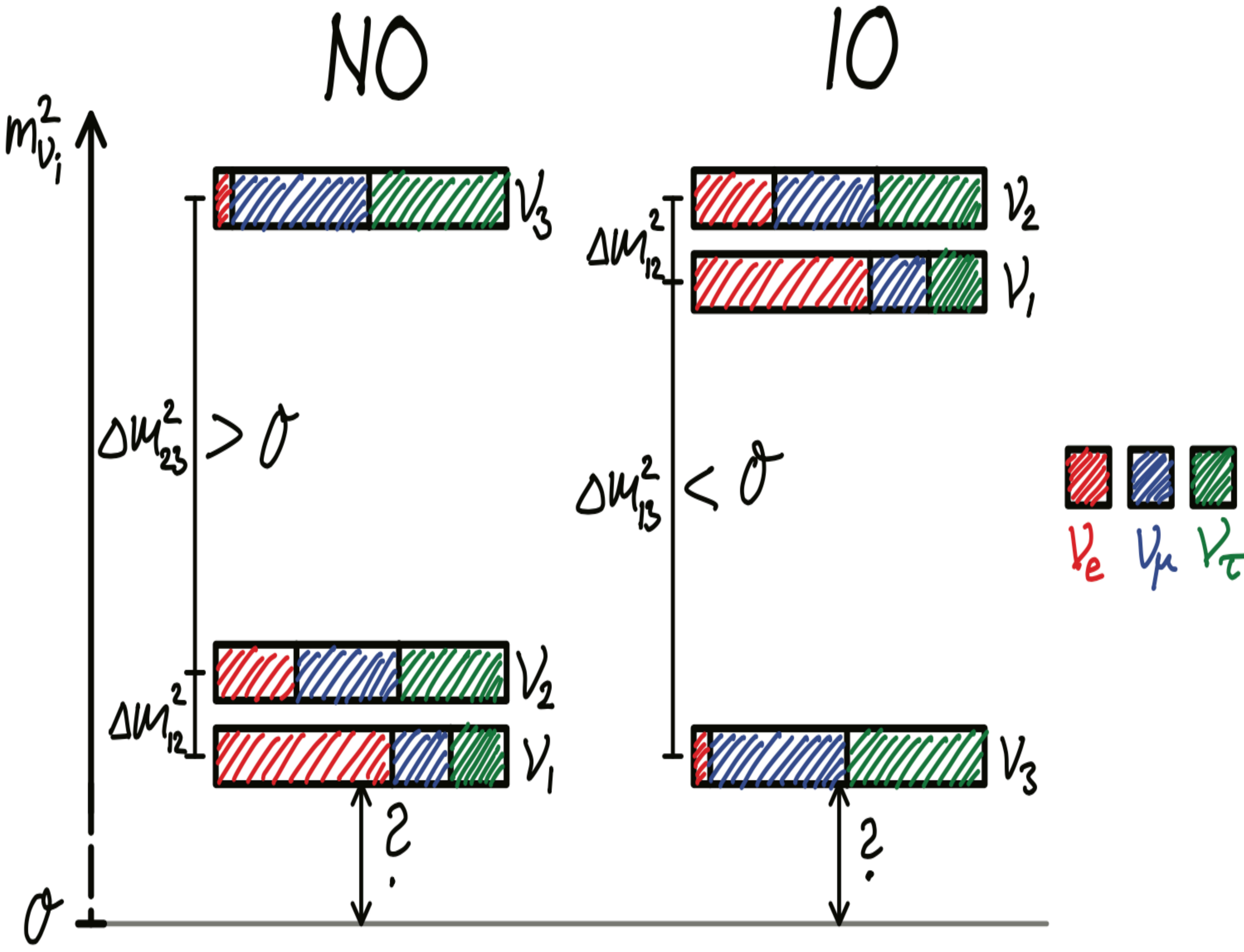
Mass Ordering

- Neutrino oscillation probabilities depend on the PMNS parameters and the neutrino mass splittings: $\Delta m^2_{ij} \equiv m^2_{\nu_i} - m^2_{\nu_j}$ (with i, j = 1, 2, 3)

- In solar oscillation, the matter effect allows fixing the sign of the mass splitting $\Delta m^2_{21} > 0$
  $\Rightarrow m_{\nu_2} > m_{\nu_1}$

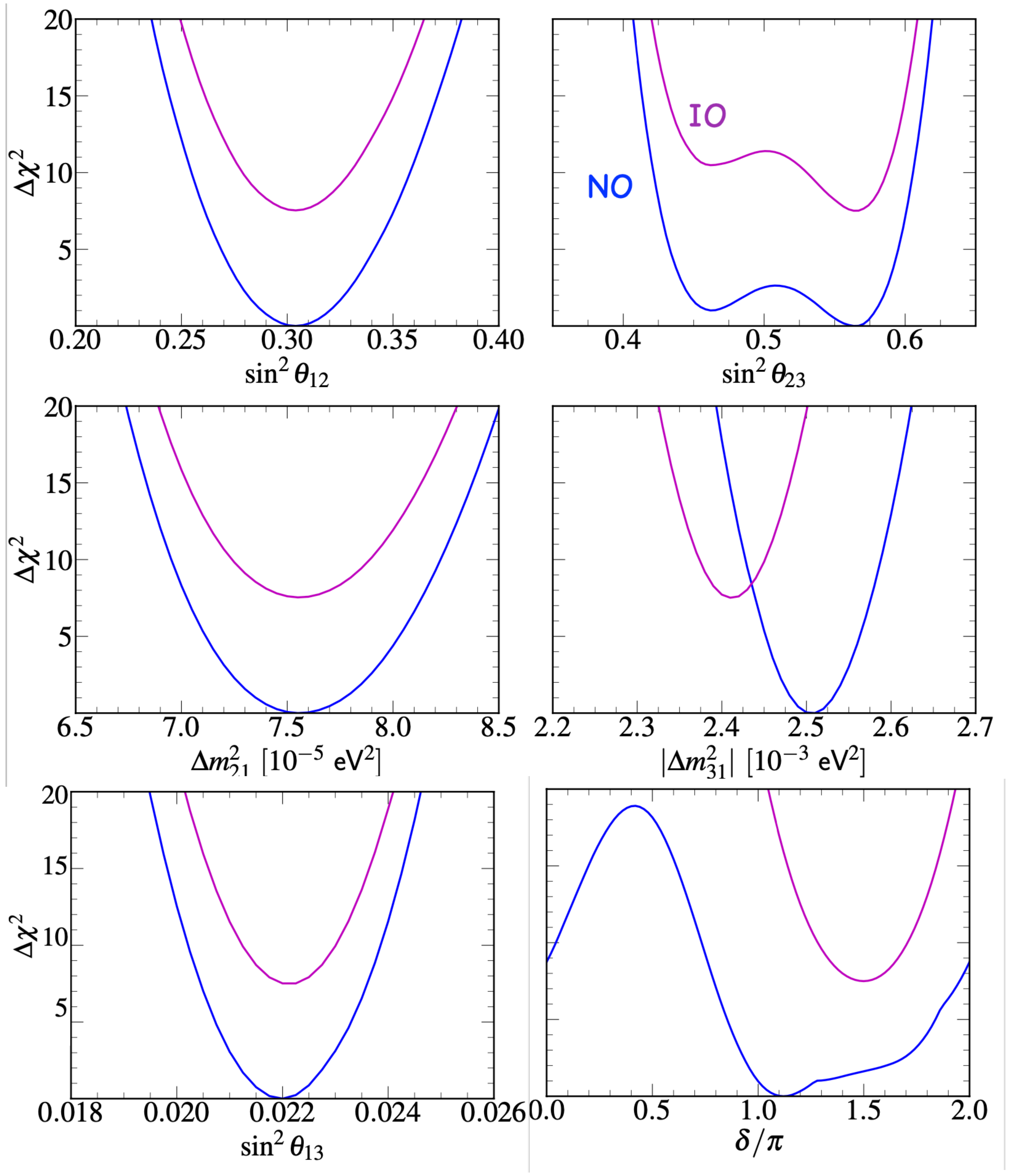
- This allows two possibilities:
  - Normal Ordering (NO): $m_{\nu_3} > m_{\nu_2} > m_{\nu_1}$
  - Inverted Ordering (IO): $m_{\nu_2} > m_{\nu_1} > m_{\nu_3}$

$\Rightarrow$Different implications in the dynamics of neutrino oscillations



Current status of measurements

- Combining data of all neutrino oscillation experiments, it is possible to make a definite determination of all the oscillation parameters
- This is done in so-called global analyses that fit the theoretical parameters to the experimental data

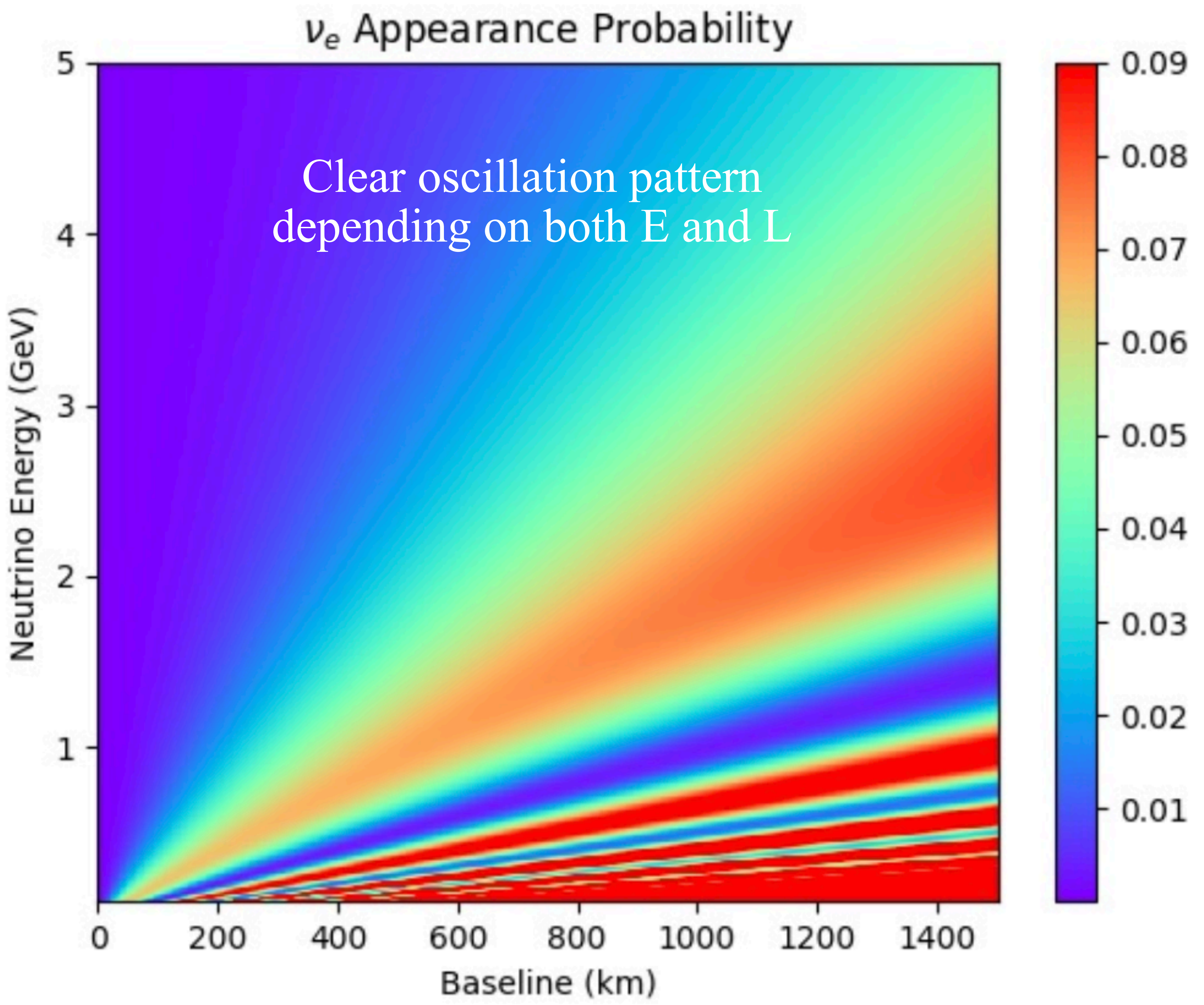


parameter	best fit ± 1σ	3σ range	Relative 1σ uncertainty
Δm^2_{21} [10^{-5}eV^2]	$7.55^{+0.22}_{-0.20}$	6.98–8.19	2.7 %
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (NO)	$2.51^{+0.02}_{-0.03}$	2.43–2.58	1.0 %
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (IO)	$2.41^{+0.03}_{-0.02}$	2.34-2.49	
$\sin^2\theta_{12}/10^{-1}$	$3.04^{\pm}0.16$	2.57–3.55	5.4%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.64^{+0.15}_{-0.21}$	4.23–6.04	3-4%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.64^{+0.15}_{-0.18}$	4.27–6.03	
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.20^{+0.05}_{-0.06}$	2.03–2.38	2.6%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.20^{+0.07}_{-0.04}$	2.04–2.38	
δ/π (NO)	$1.12^{+0.16}_{-0.12}$	0.76–2.00	10-15%
δ/π (IO)	$1.50^{+0.13}_{-0.14}$	1.11–1.87	

[M. Tortola Neutrino 2024]

Oscillation Probability: Appearance channel

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & \sin^2\theta_{23}\ \sin^2 2\theta_{13}\ \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\ \Delta_{31}^2 \\
& + \sin 2\theta_{23}\ \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \\
& \times \Delta_{31} \frac{\sin(aL)}{(aL)}\ \Delta_{21}\ \cos(\Delta_{31} + \delta) \\
& + \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2}\ \Delta_{21}^2,
\end{aligned}
$$



Clear oscillation pattern depending on both E and L

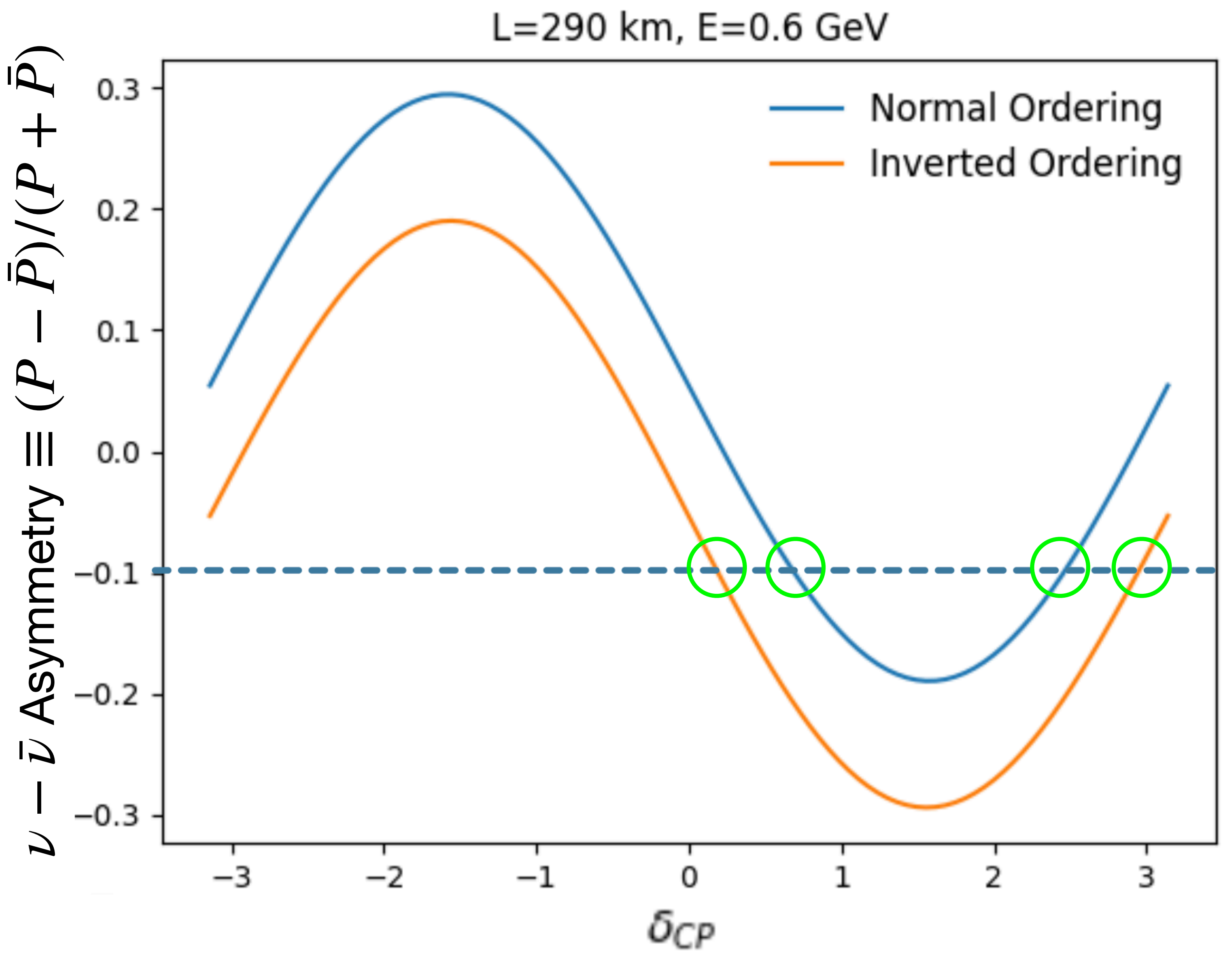
- $\Delta_{ij} = \Delta m_{ij} L/4E_\nu \Rightarrow$ Dependence on L/E (we can "control" with our experiment design)
- $a = G_F \underset{\uparrow}{n_e}/\sqrt{2} \Rightarrow$ Matter effect from coherent forward scattering on electrons (appears multiplying L)

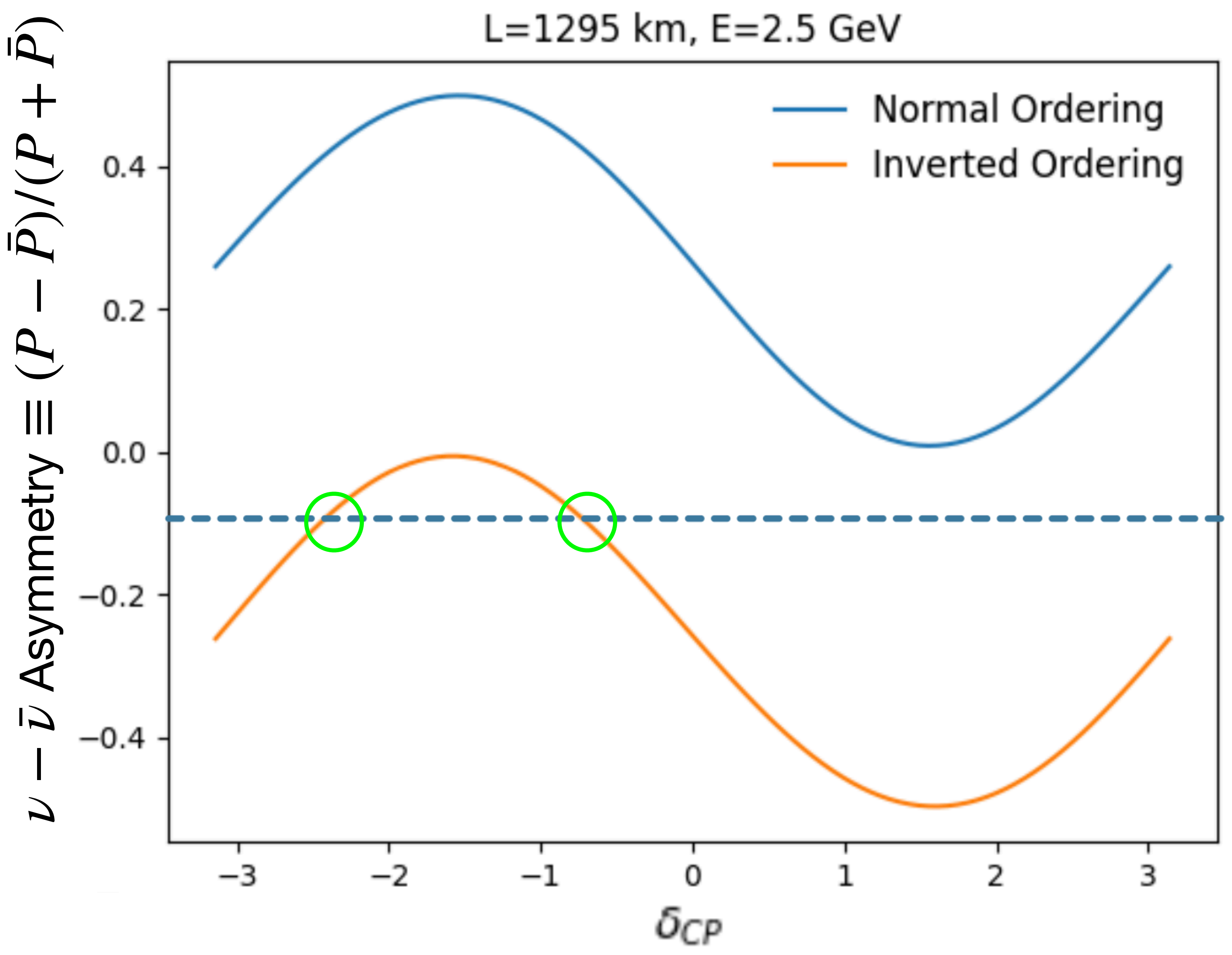
(Electron density of the medium)

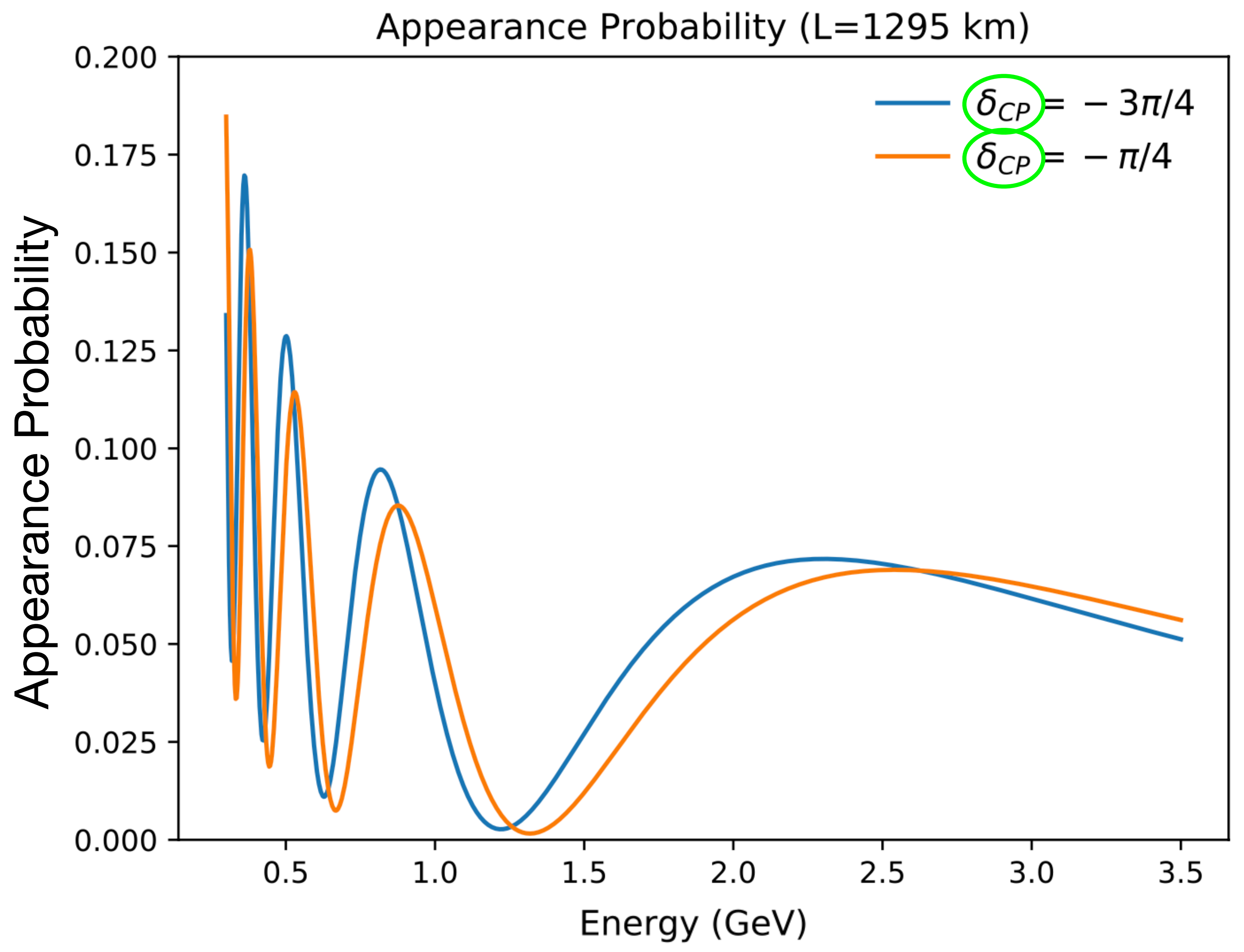
- δ and a switch signs in going from the $\nu_\mu \to \nu_e$ to $\bar{\nu}_\mu \to \bar{\nu}_e$ channel:
  - δ and matter effects create opposite effects in neutrinos and antineutrinos ⇒ $\nu/\bar{\nu}$ (matter/antimatter) asymmetry is introduced by both CP violation and the matter effect

Parameter space

- Experiments are sensitive to many parameters, if we can resolve degenerate effects







Short Baselines ⇒ small matter effects

Asymmetry measurement alone has degenerate possible values for both δ_{cp} and mass ordering

Long Baselines ⇒ large matter effects

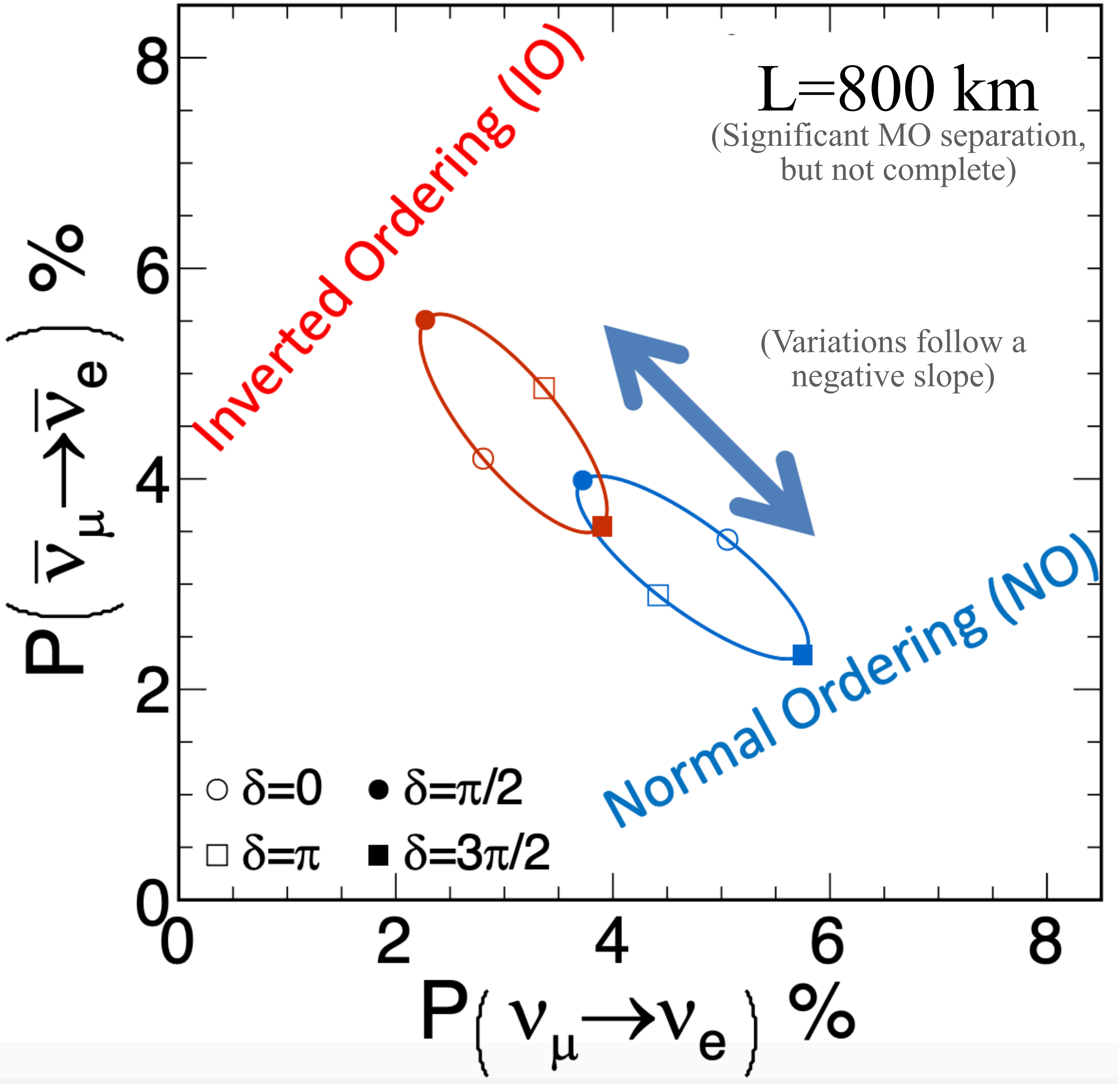
Asymmetry measurement alone has degenerate possible values only for δ_{cp} (mass ordering degeneracy lifted)

Long Baselines ⇒ large matter effects

Energy dependence of oscillation can resolve δ_{cp} degeneracy

Bi-probability plots

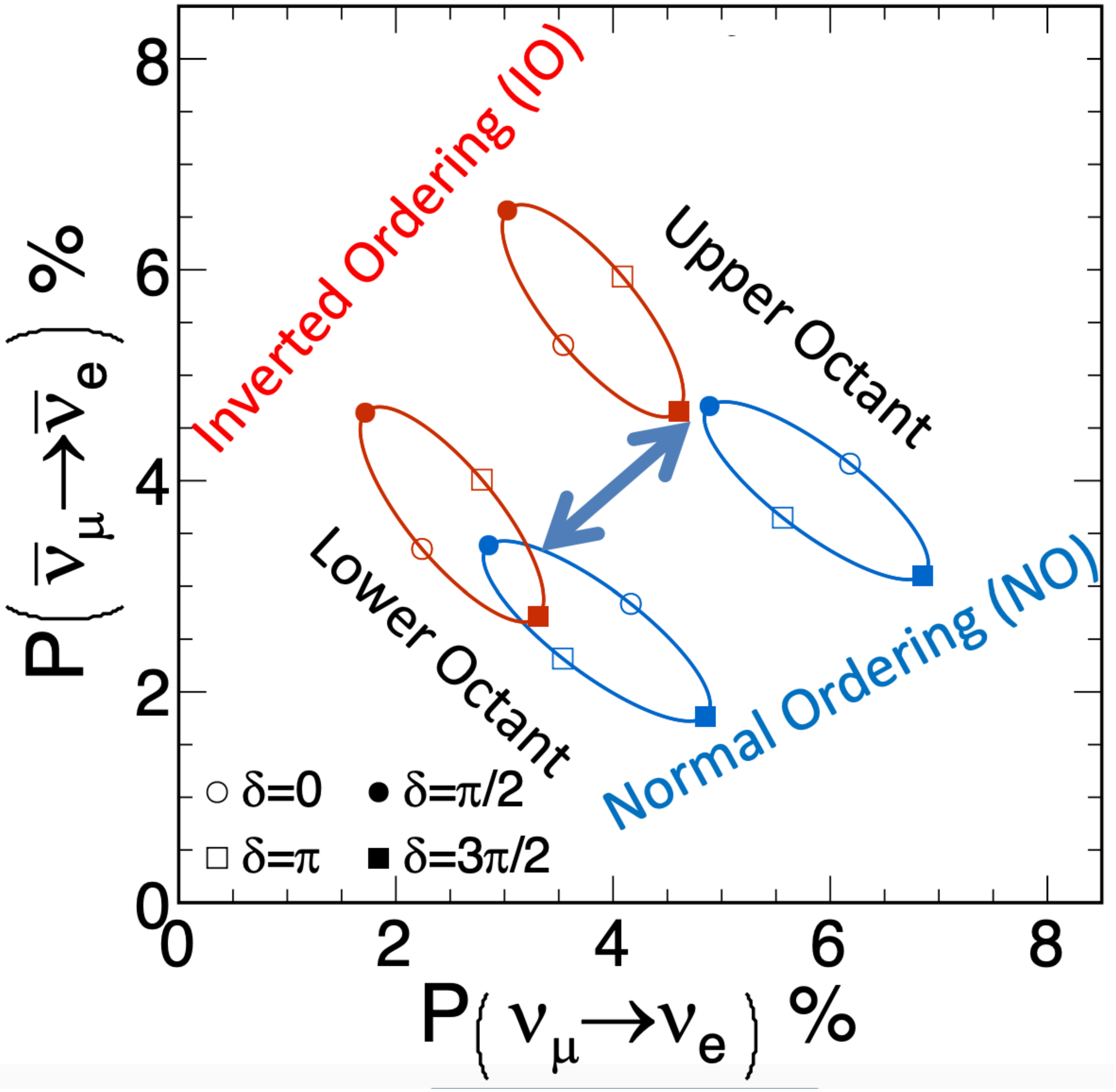
δ/matter effects introduce opposite neutrino-antineutrino effects


L=800 km

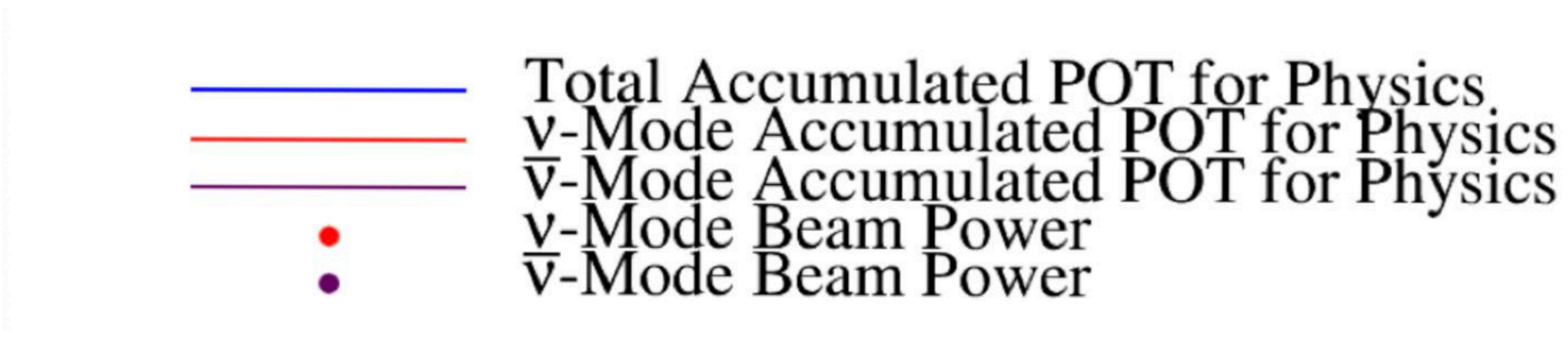
(Significant MO separation, but not complete)

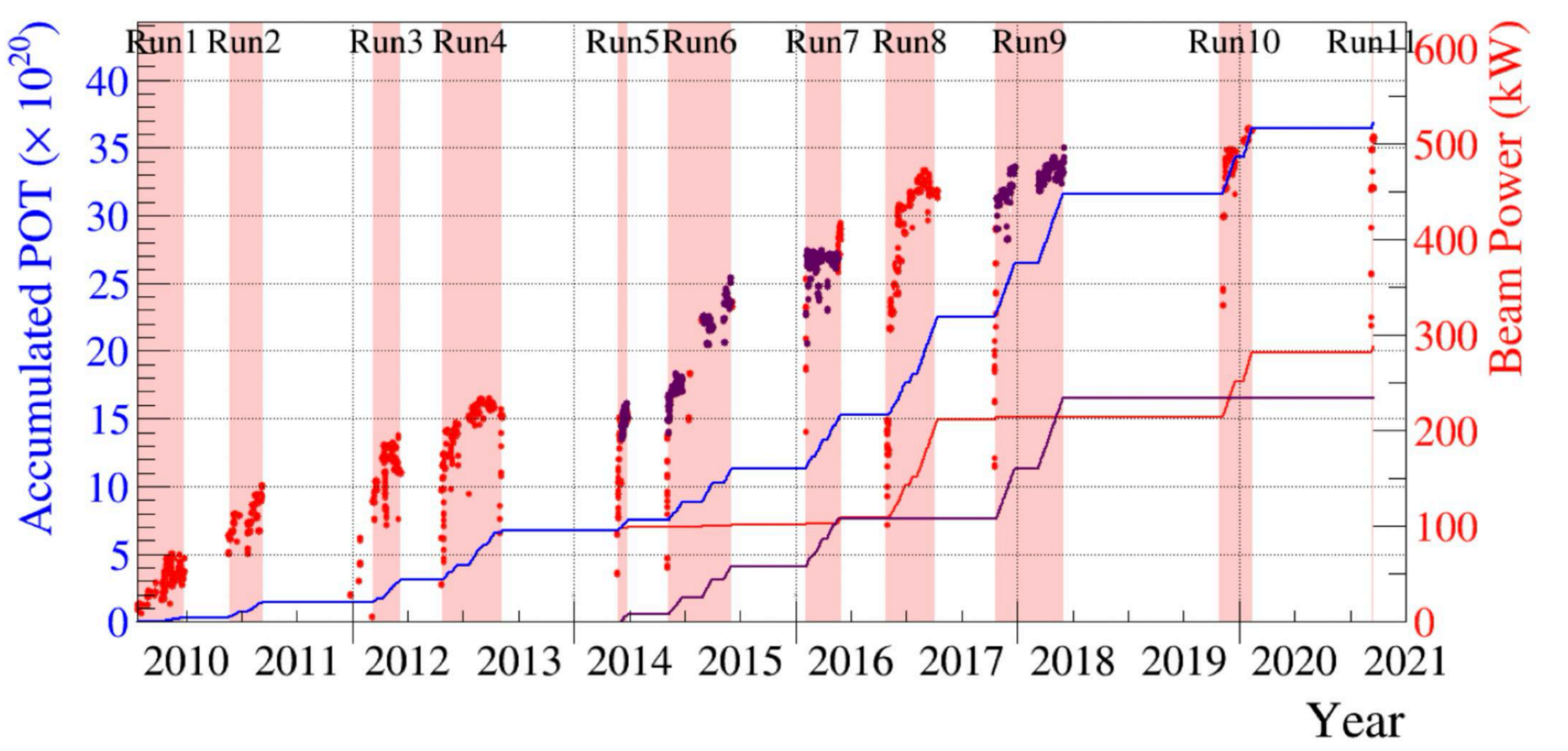
(Variations follow a negative slope)

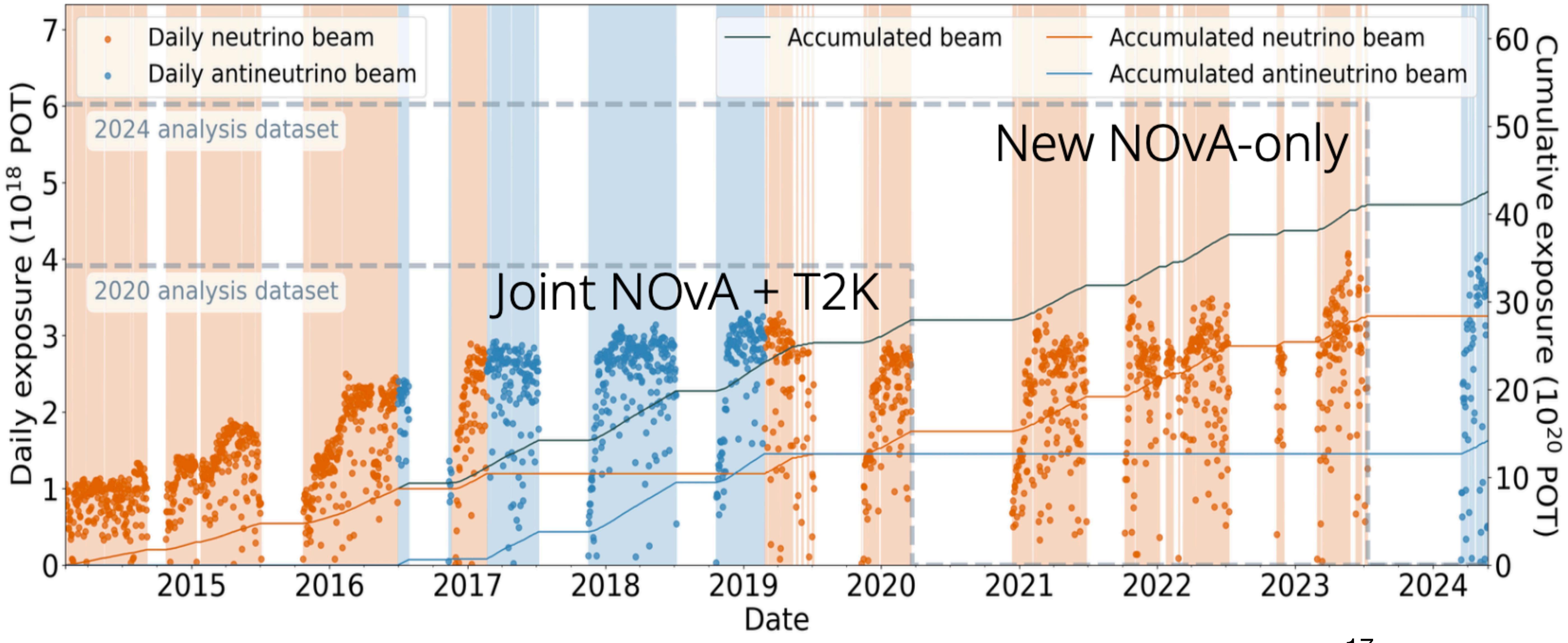
The octant creates the same effect in neutrinos and antineutrinos



Present experiments: T2K and Nova







2014-2023:

10 years of beam to NOvA!

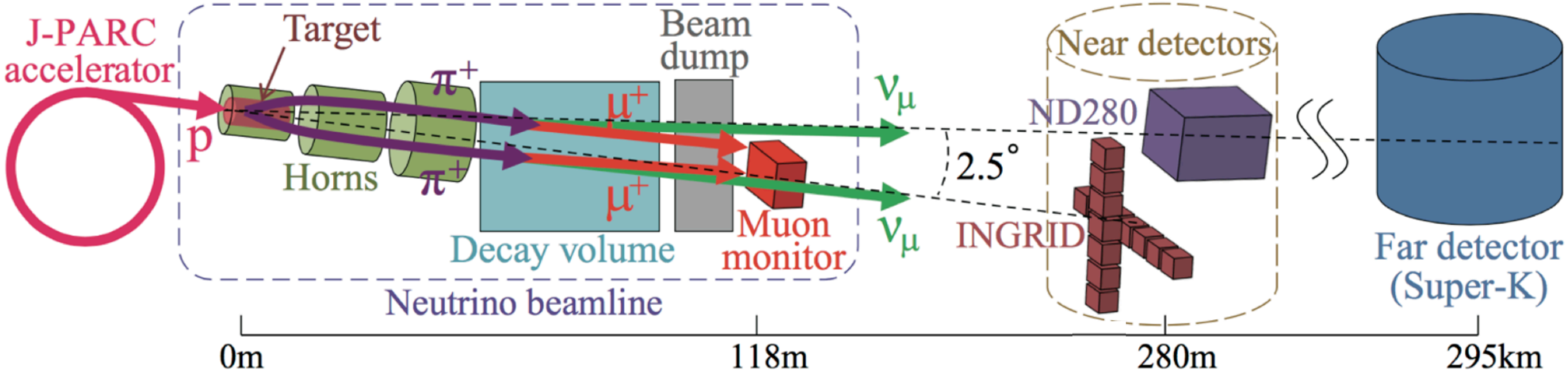
Latest analysis:

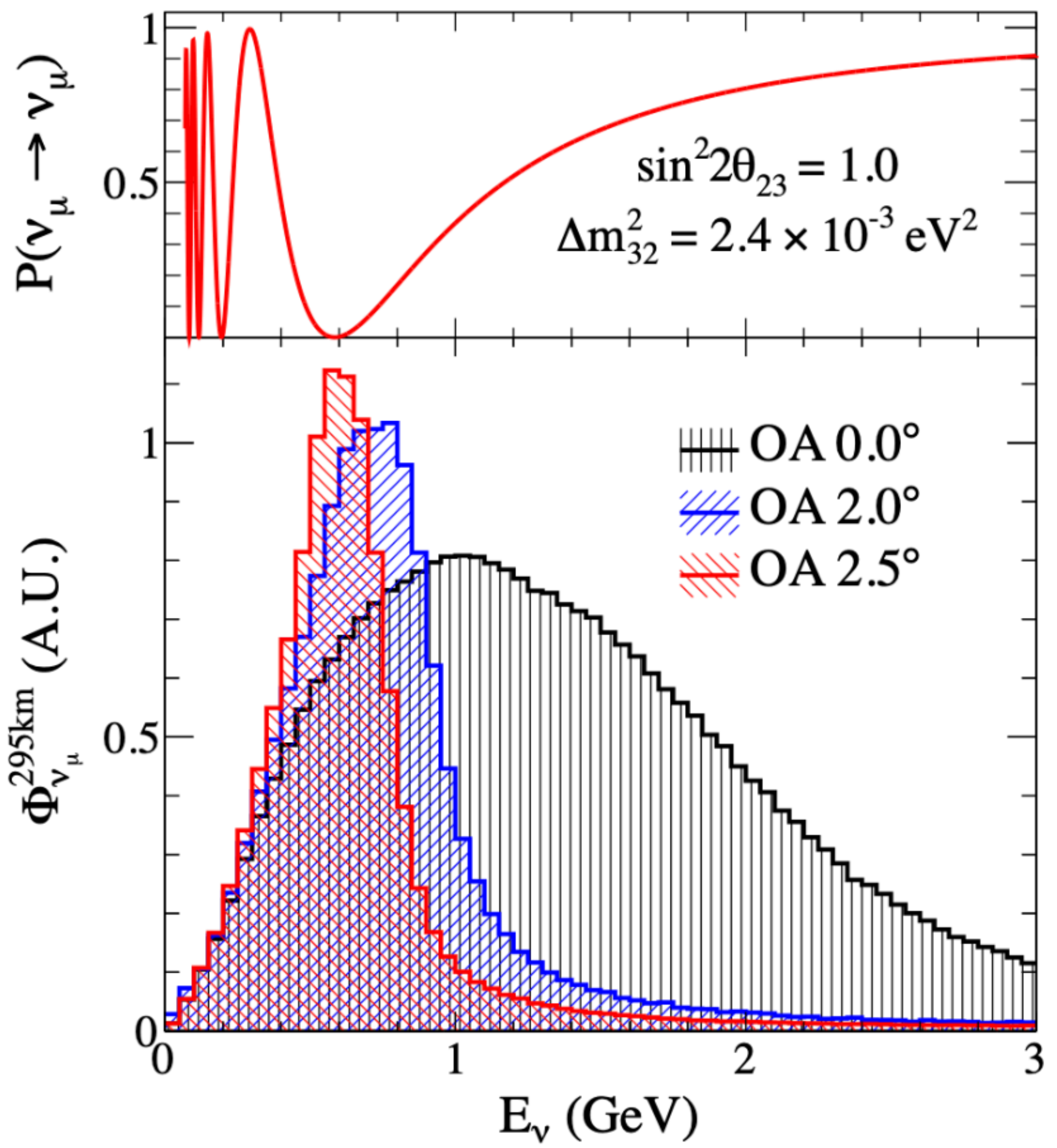
+96% neutrino beam

ν: 26.61×10^{20} POT

$\bar{\nu}$: 12.50×10^{20} POT

T2K Experiment



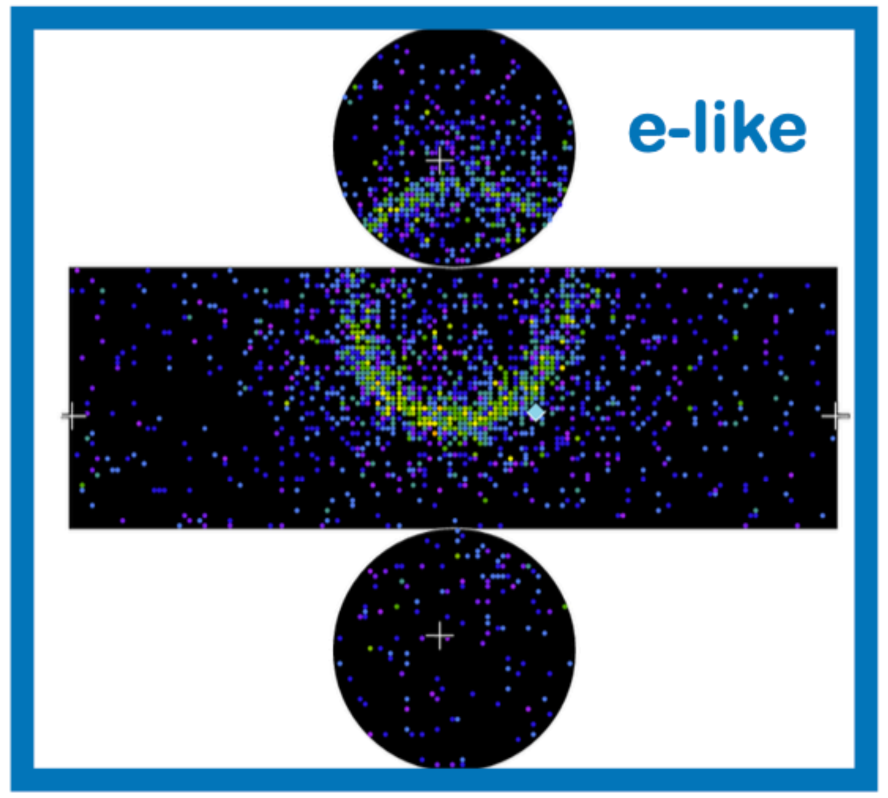


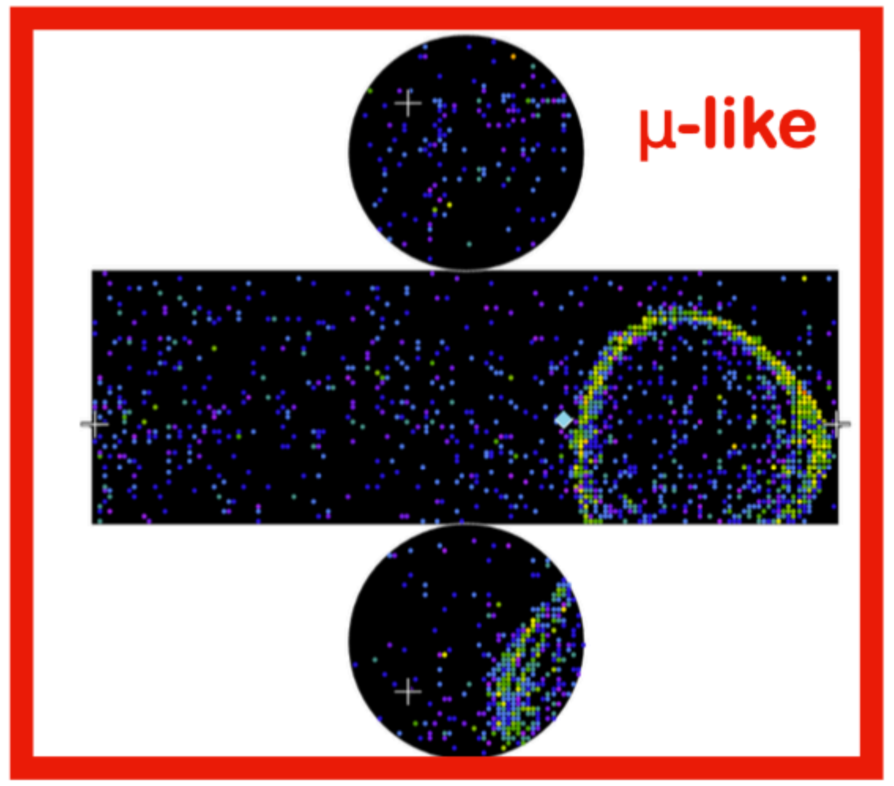
- High intensity $\nu_\mu/\bar{\nu}_\mu$ beam (~600 MeV), located 2.5º off-axis from the far detector.

- Off-axis technique: enhance the neutrino energy spectrum at a certain neutrino energy, typically that one that maximizes the oscillation probability

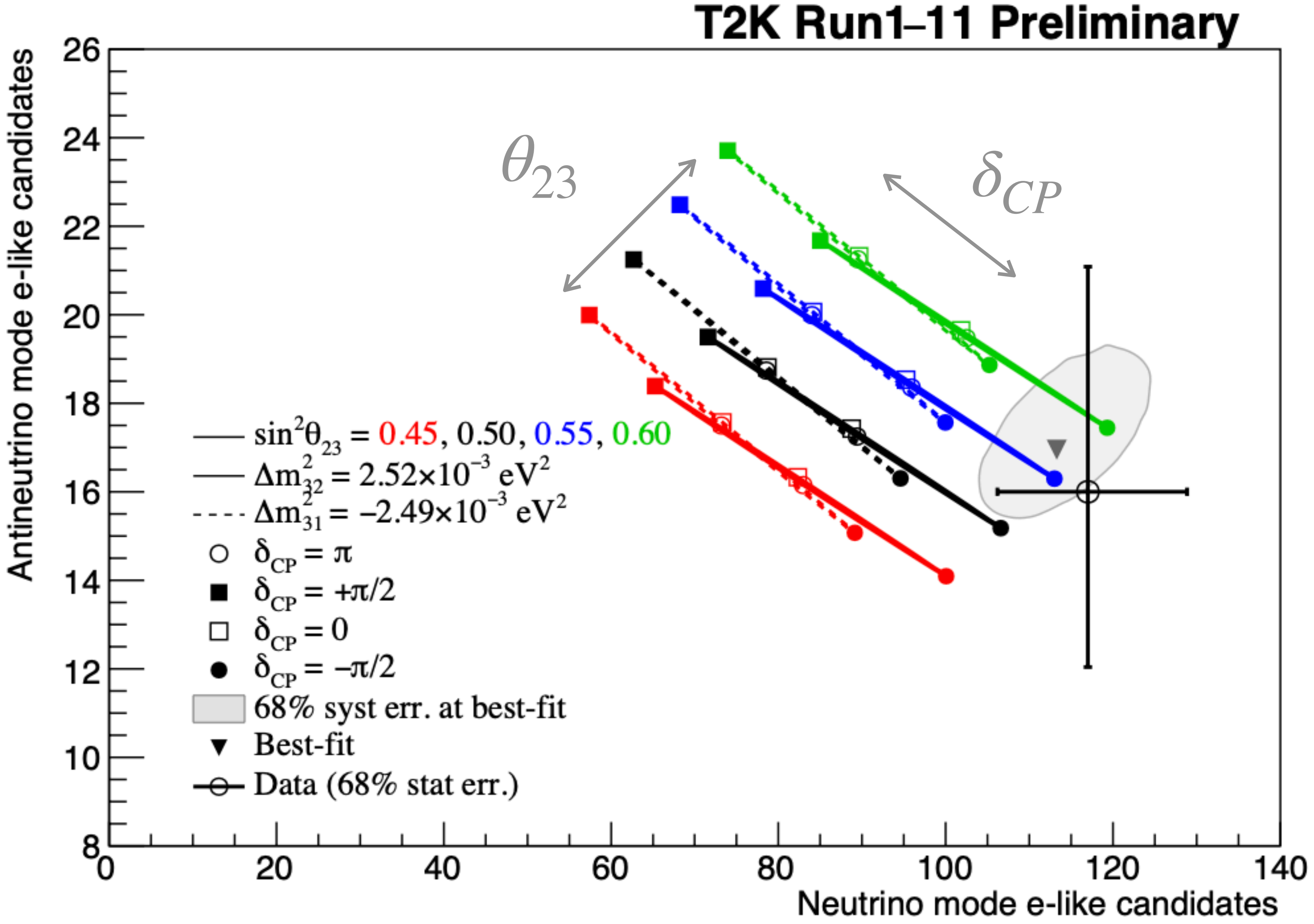
- Several near detectors: monitor the beam, reduce systematic uncertainties in oscillation analyses, and measure neutrino cross-sections

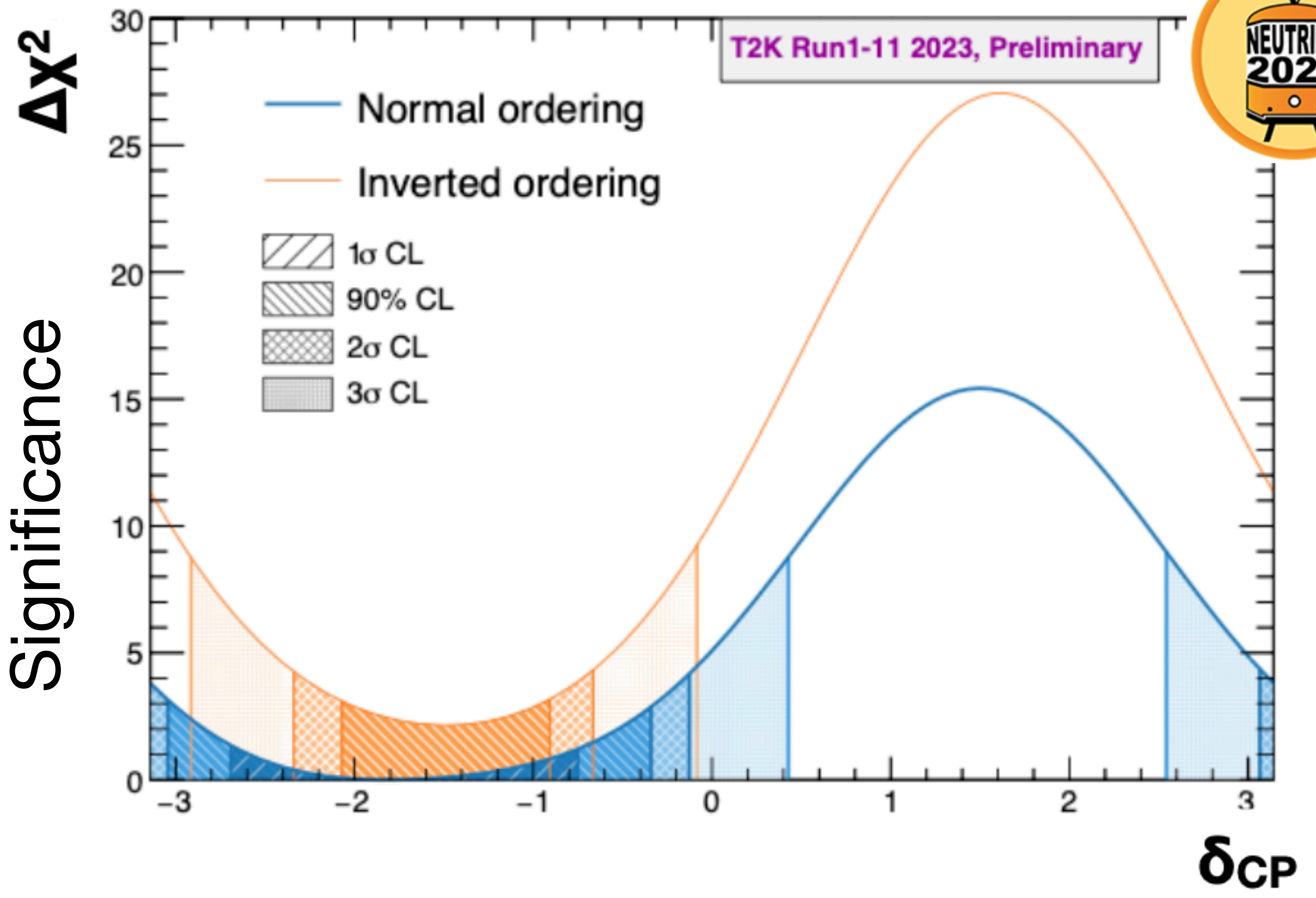
- Far detector is Super-Kamiokande: 50 kton water Cherenkov detector, ~11k 20” PMTs, added 0.03% Gd in 2022 to improve neutron tagging efficiency

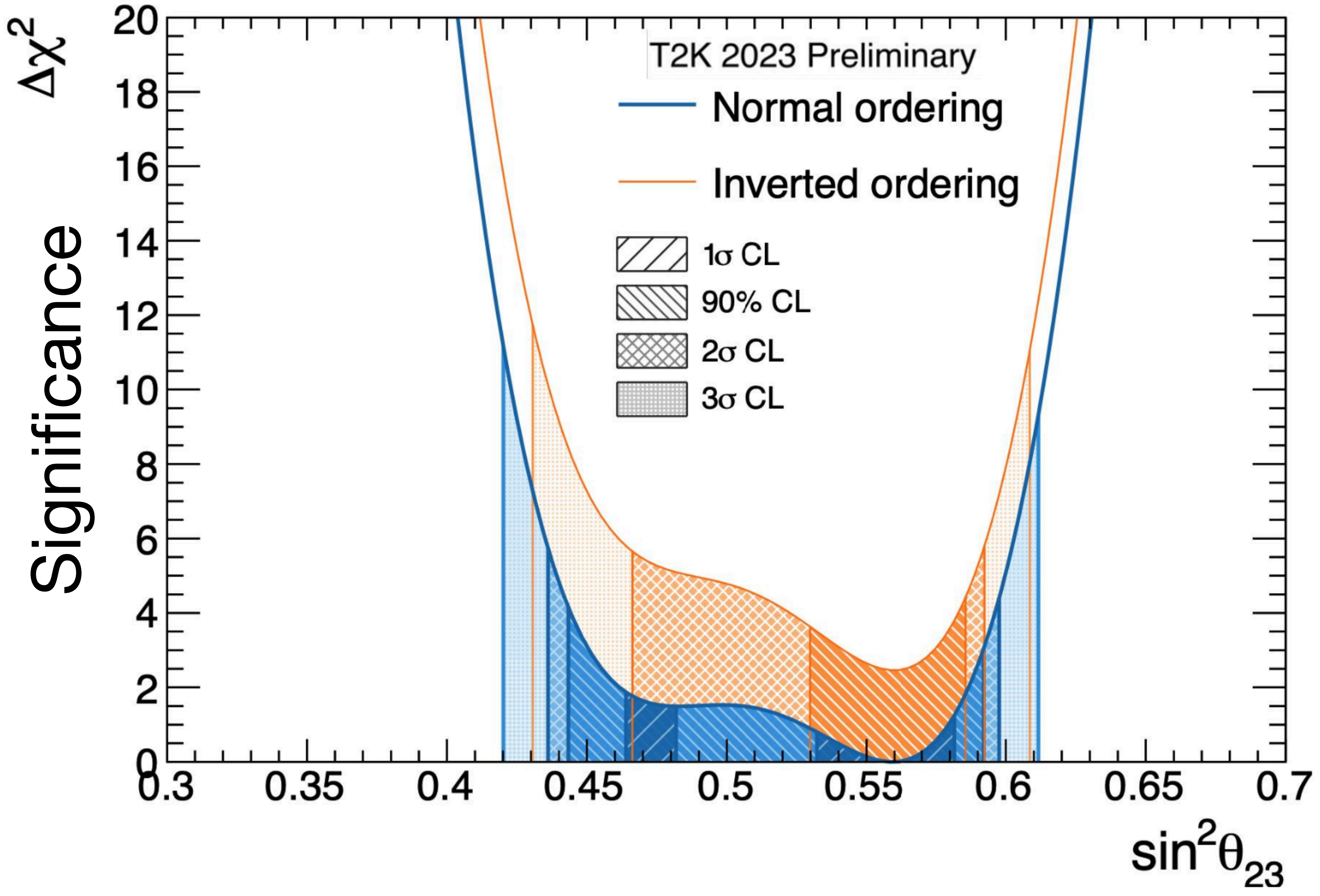




T2K Recent Results





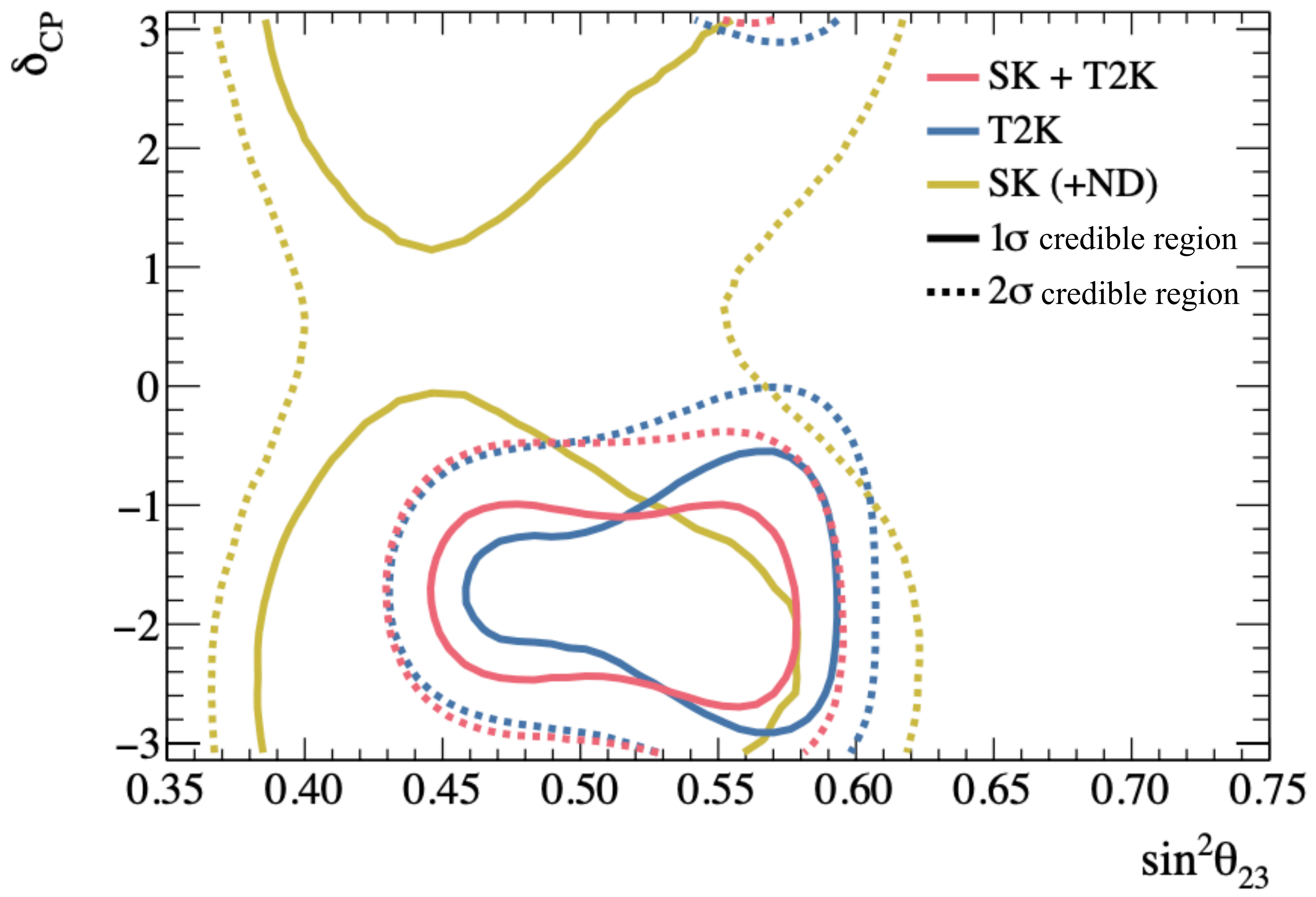


- Including Run 11 (10% of statistics in ν-mode): first data with SK-Gd
- Preference for $\delta_{CP} \approx -\pi/2$, and CP-conservation excluded at 90% C.L.
- Slight preference for normal ordering and upper octant but none of them is significant

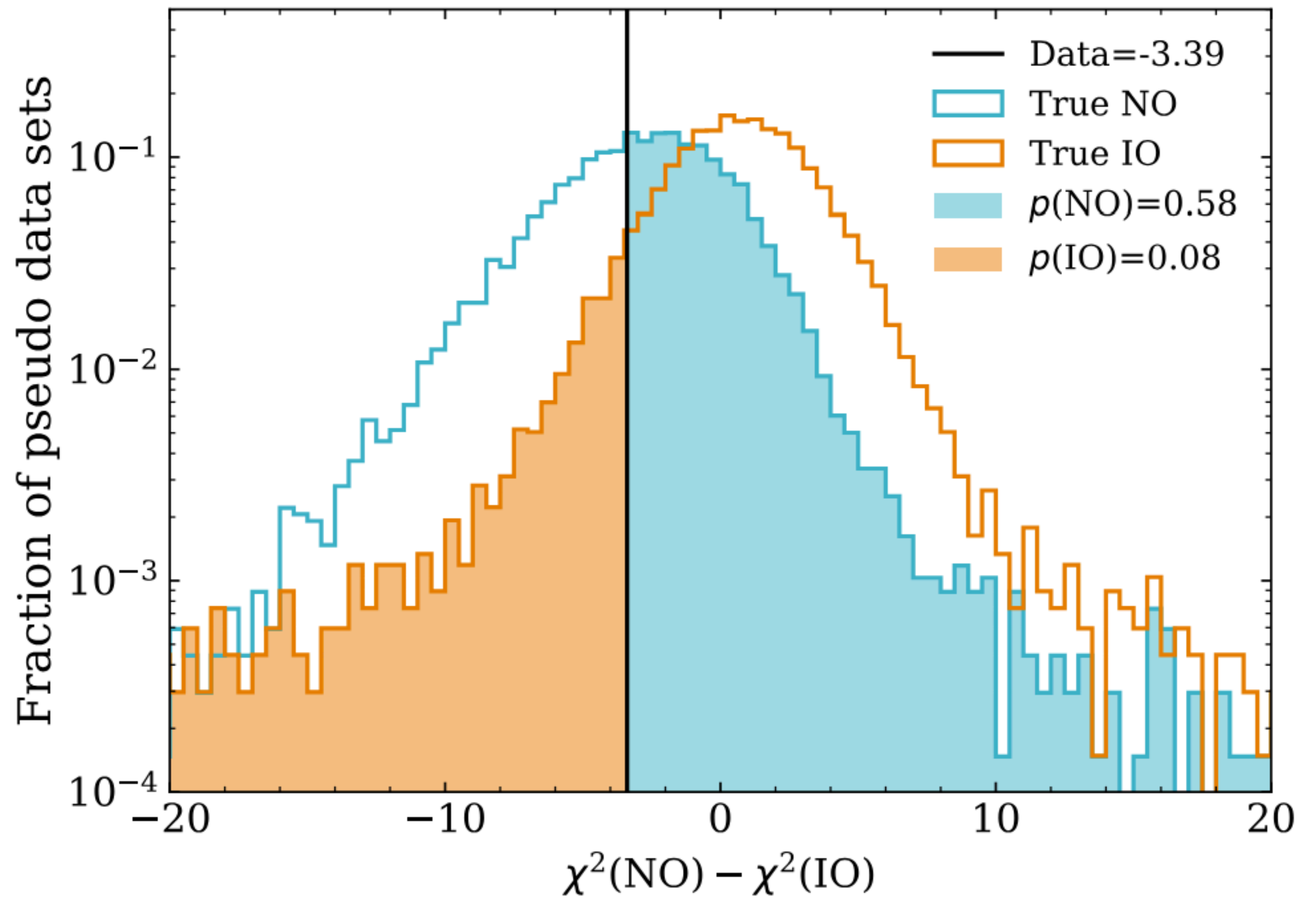
Fist T2K + SK Joint Analysis

- T2K has good sensitivity to δ_{CP} but mild sensitivity to mass ordering
    - T2K's baseline probes the first oscillation maximum and matter effects have a limited impact.
- SK has good constraint on mass ordering but not on δ_{CP}
    - Upward-going neutrinos (travel ~13,000 km) experience large matter effects
    - Limited information about the incoming neutrino direction, and a broader range of neutrino energies.
- Adding SK atmospheric sample allows to break the degeneracies between δ_{CP} and the mass ordering ⇒ boost sensitivity to CP:
    - This analysis finds a 1.9σ exclusion of CP-conservation and a preference for the normal mass ordering (IO p-value is 0.08)

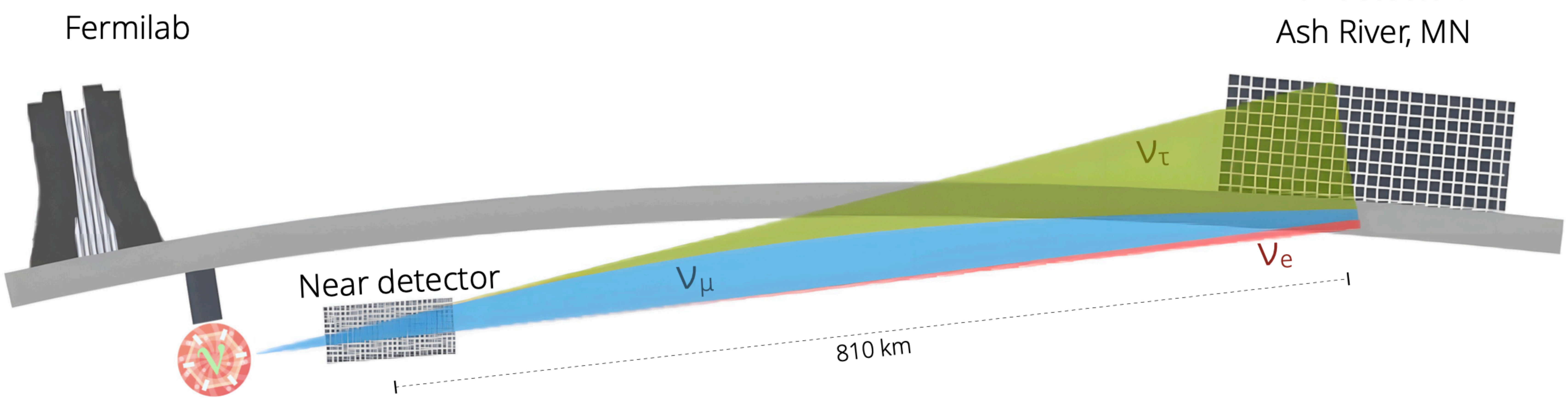
arXiv:2405.12488

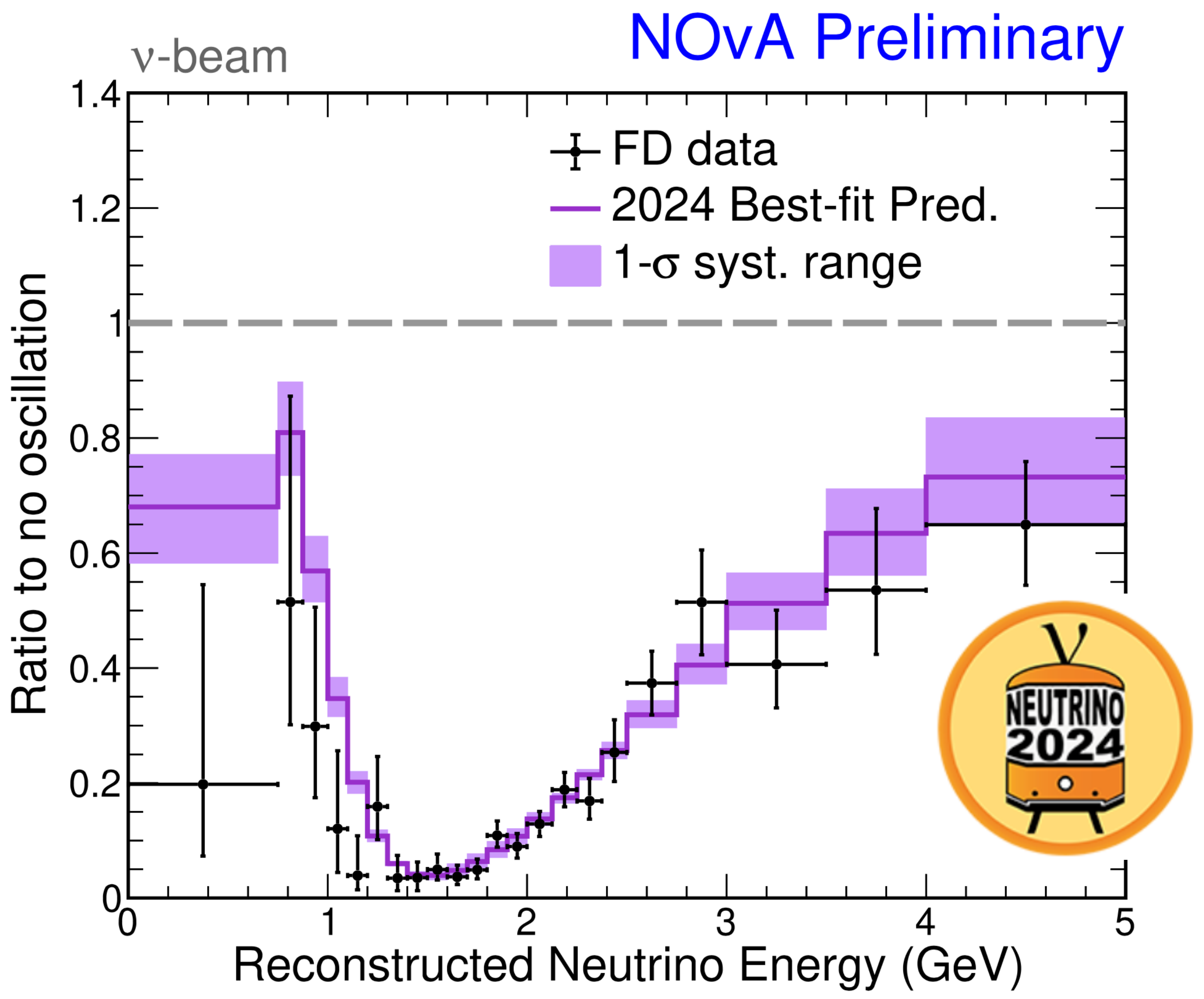


Distribution of the MO test statistic



Nova Experiment

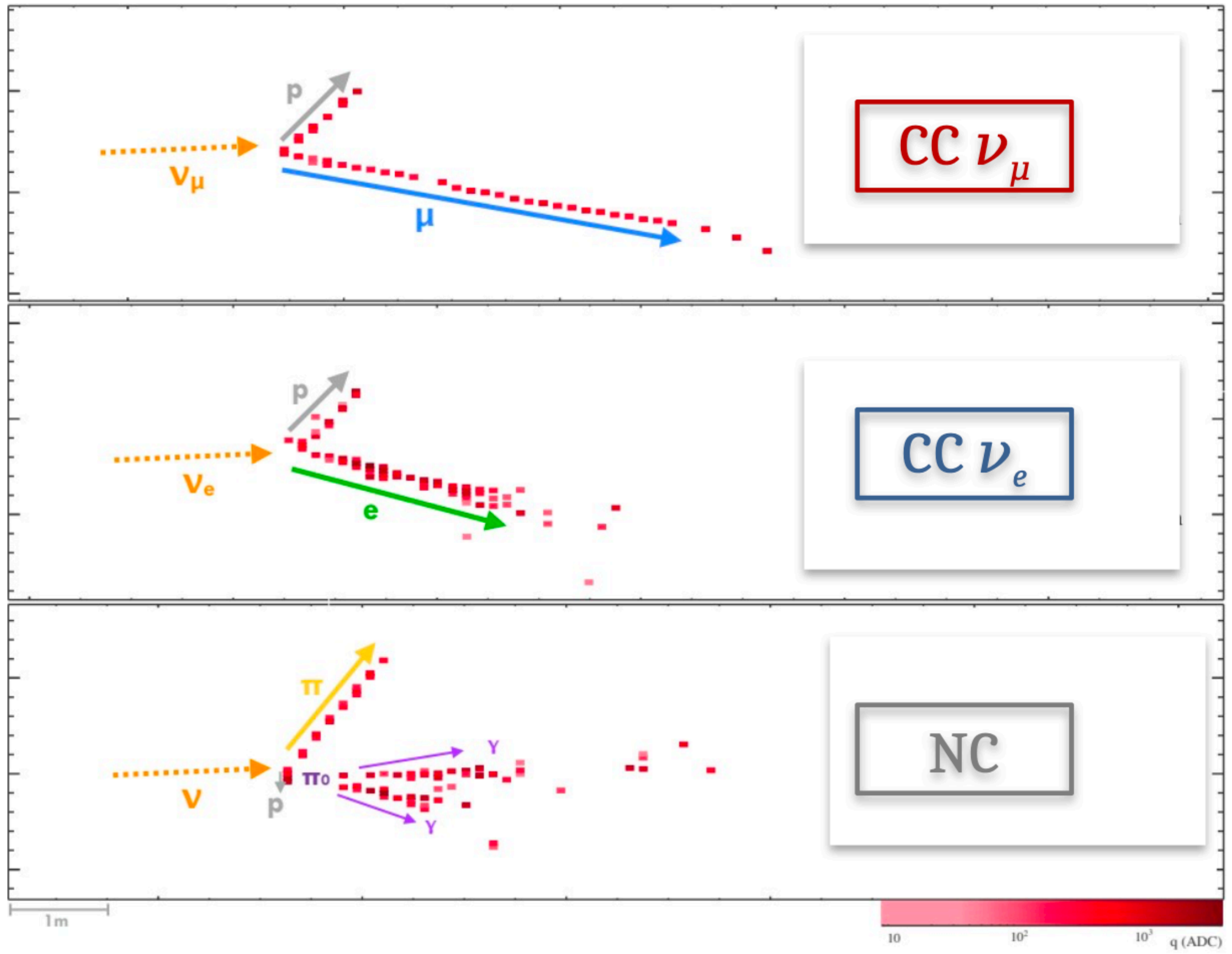




1. Make a beam of ν_μ

2. Select ν_μ and ν_e candidates at both detectors

3. Interpret E_ν distributions

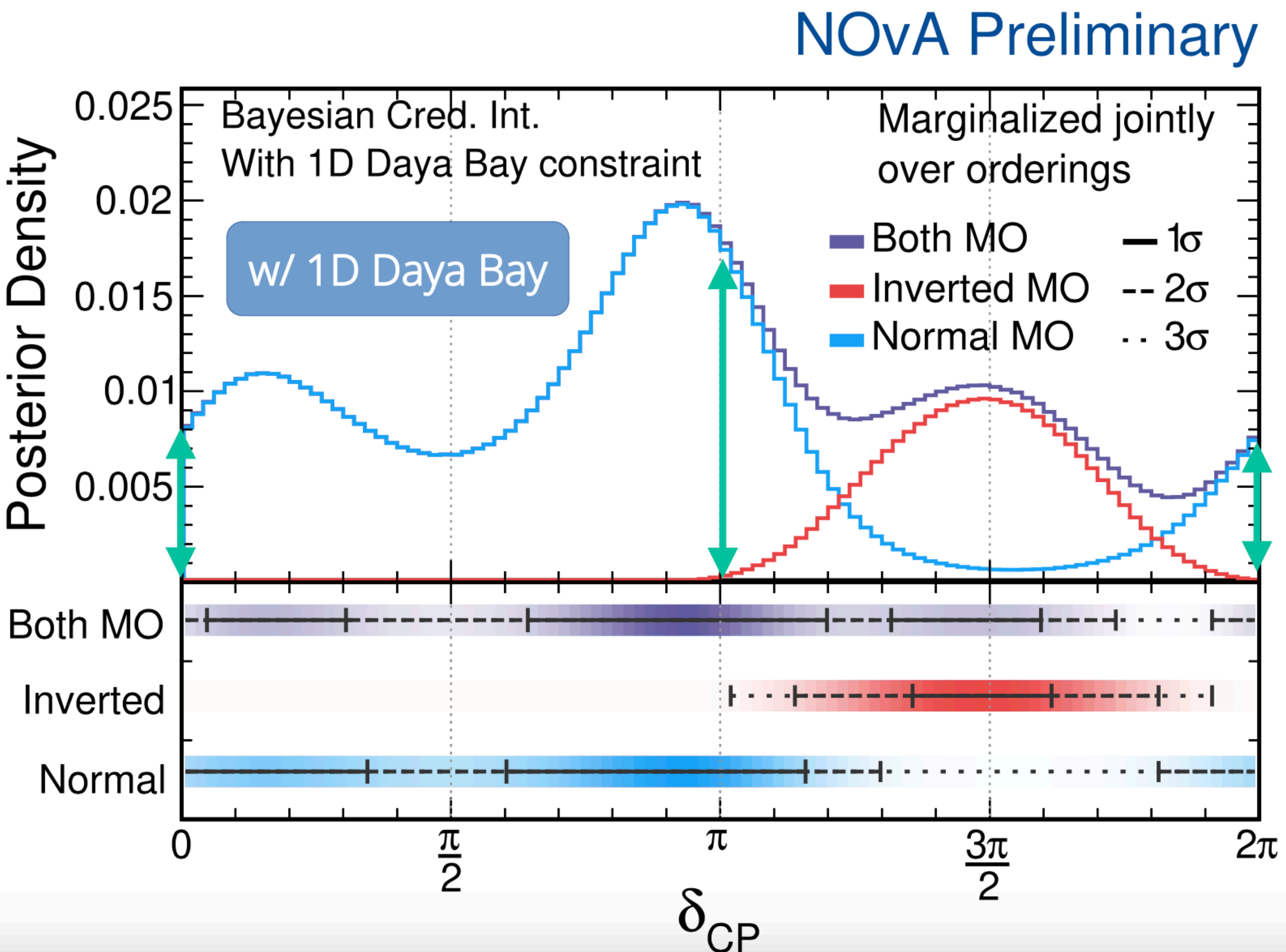


- Muon neutrinos from the NuMI beam at Fermilab, with 14.6 mrad (0.84º) off-axis peaks at ~2 GeV

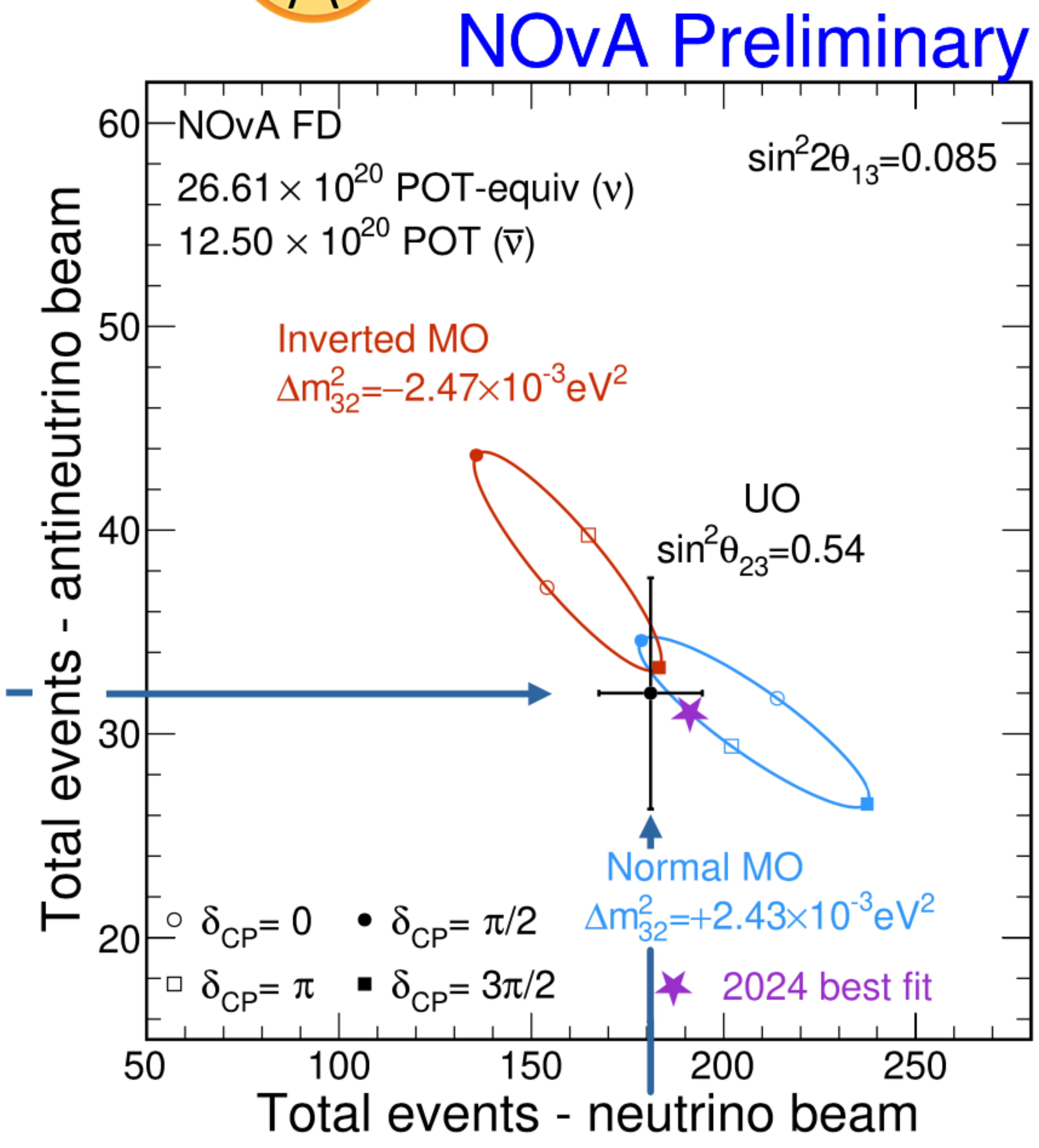
- ND & FD are segmented liquid scintillator detectors (4×6 cm² PVC cells), that differ in size:
  - ND: 290 tons, ~4×4 m² × 16 m
  - FD: 14,000 tons, ~16×16 m² × 60 m

Nova Recent Results

- Expanding new selection to lower energy regions (< 1GeV) ⇒ Increases mass ordering sensitivity by ~few %:
    - For now, ν only; analogous $\bar{\nu}$ sample currently too small
- Data favors region where matter & CP violation effects oppose one another (degenerate region)



- CPC values favored in NO but outside the 3σ interval in IO

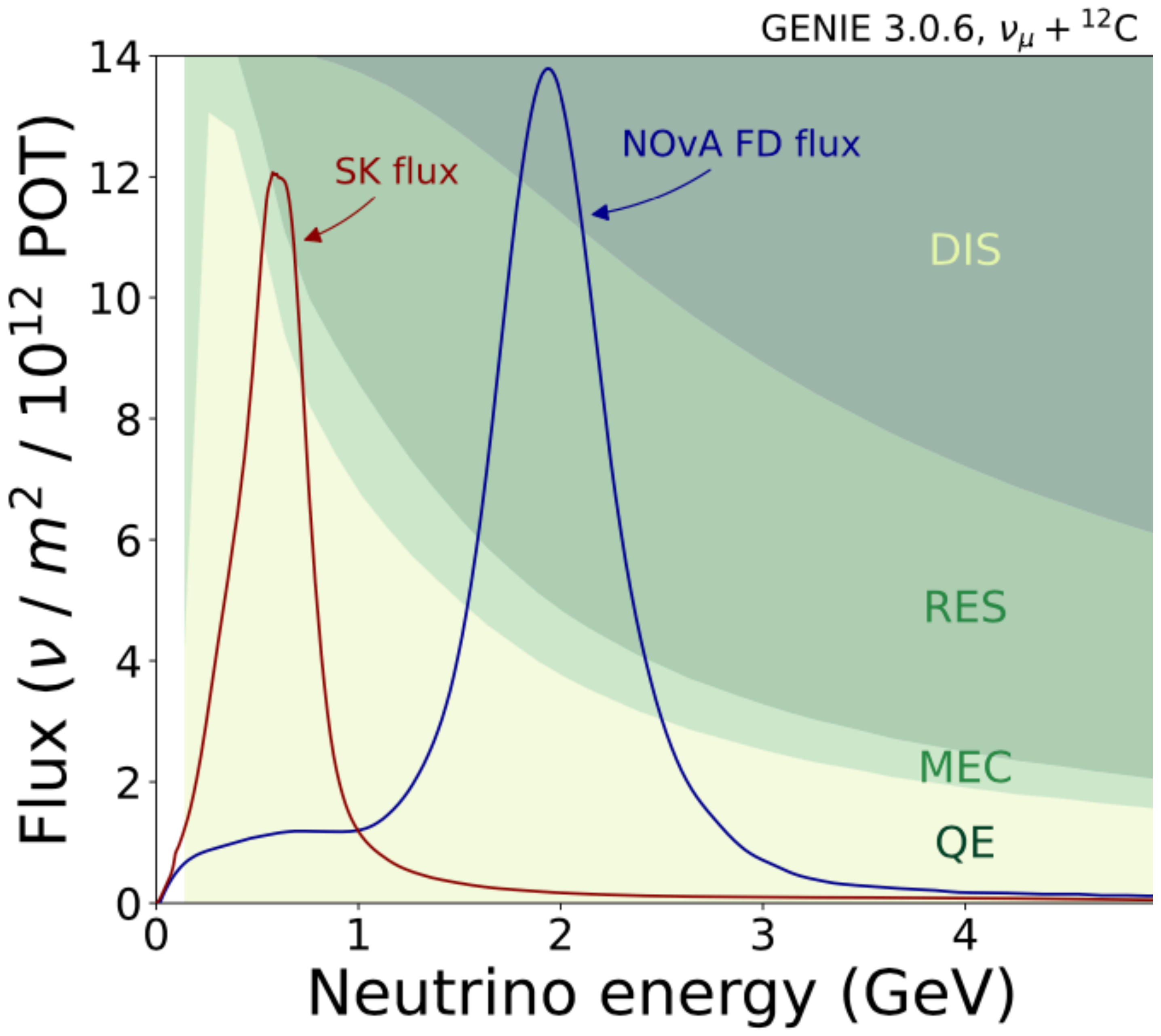


32 $\bar{\nu}_e$ data candidates

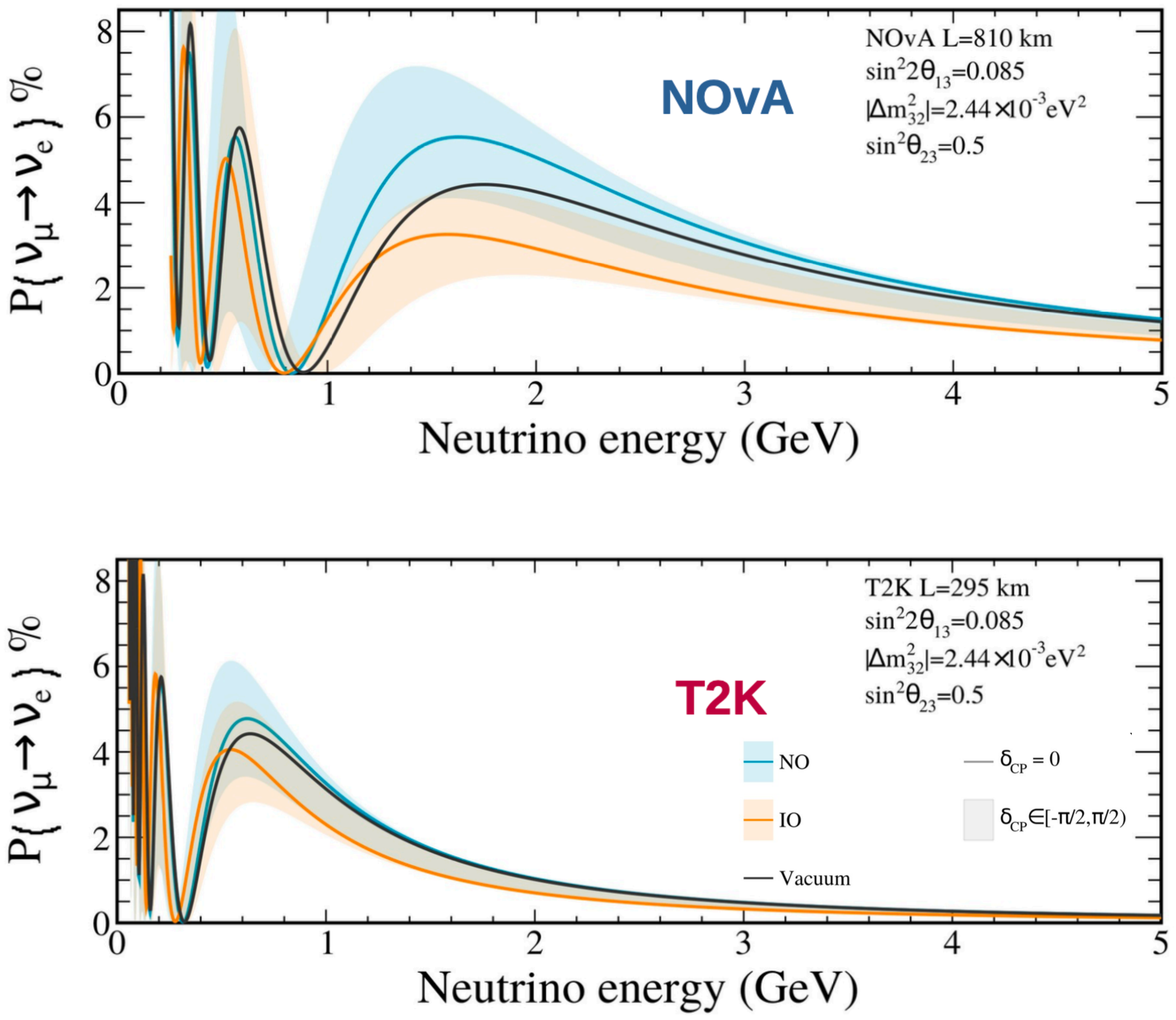
181 ν_e data candidates

T2K vs Nova

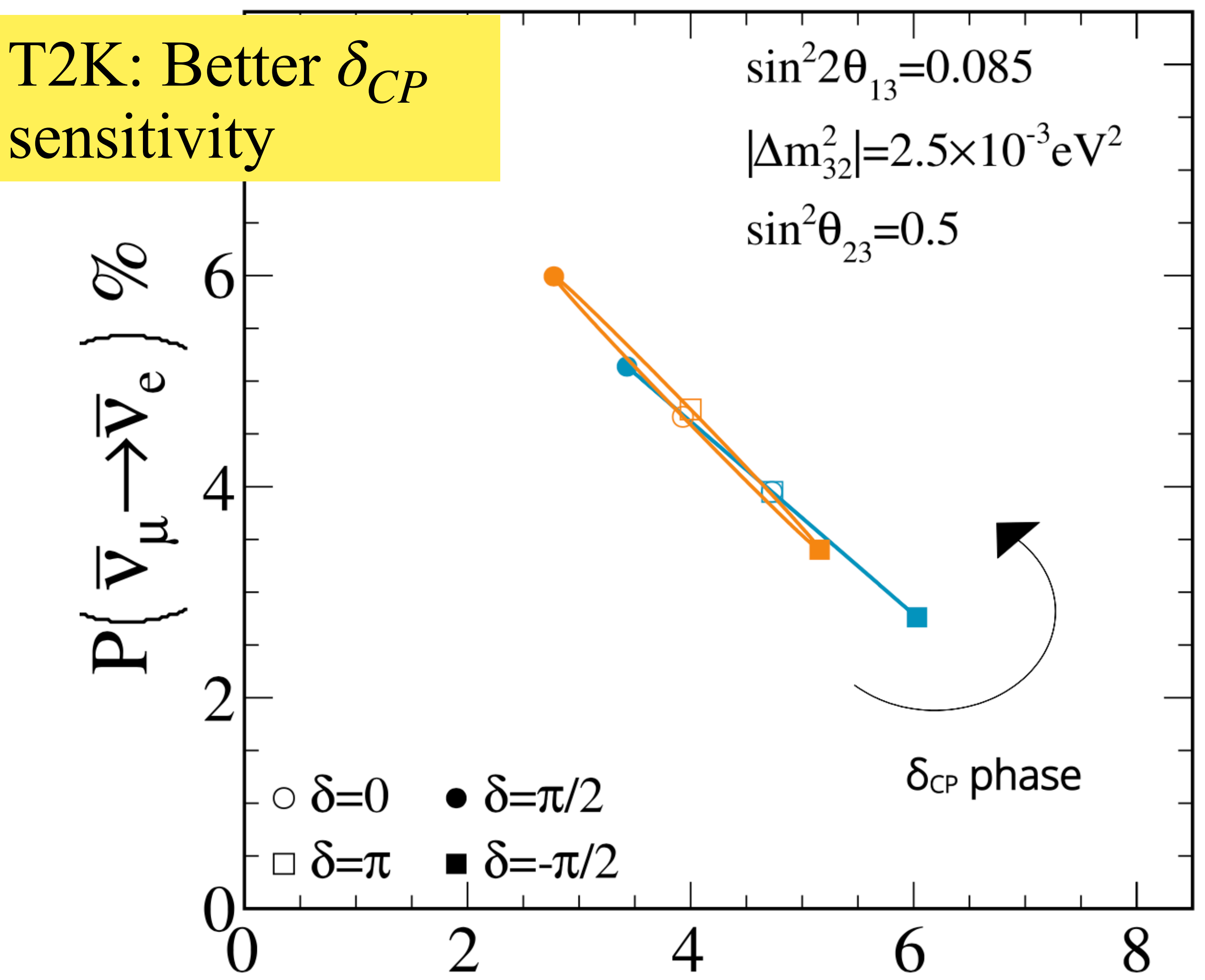
- T2K and Nova are complementary: both interested in the same PMNS physics, but explore with different experimental considerations



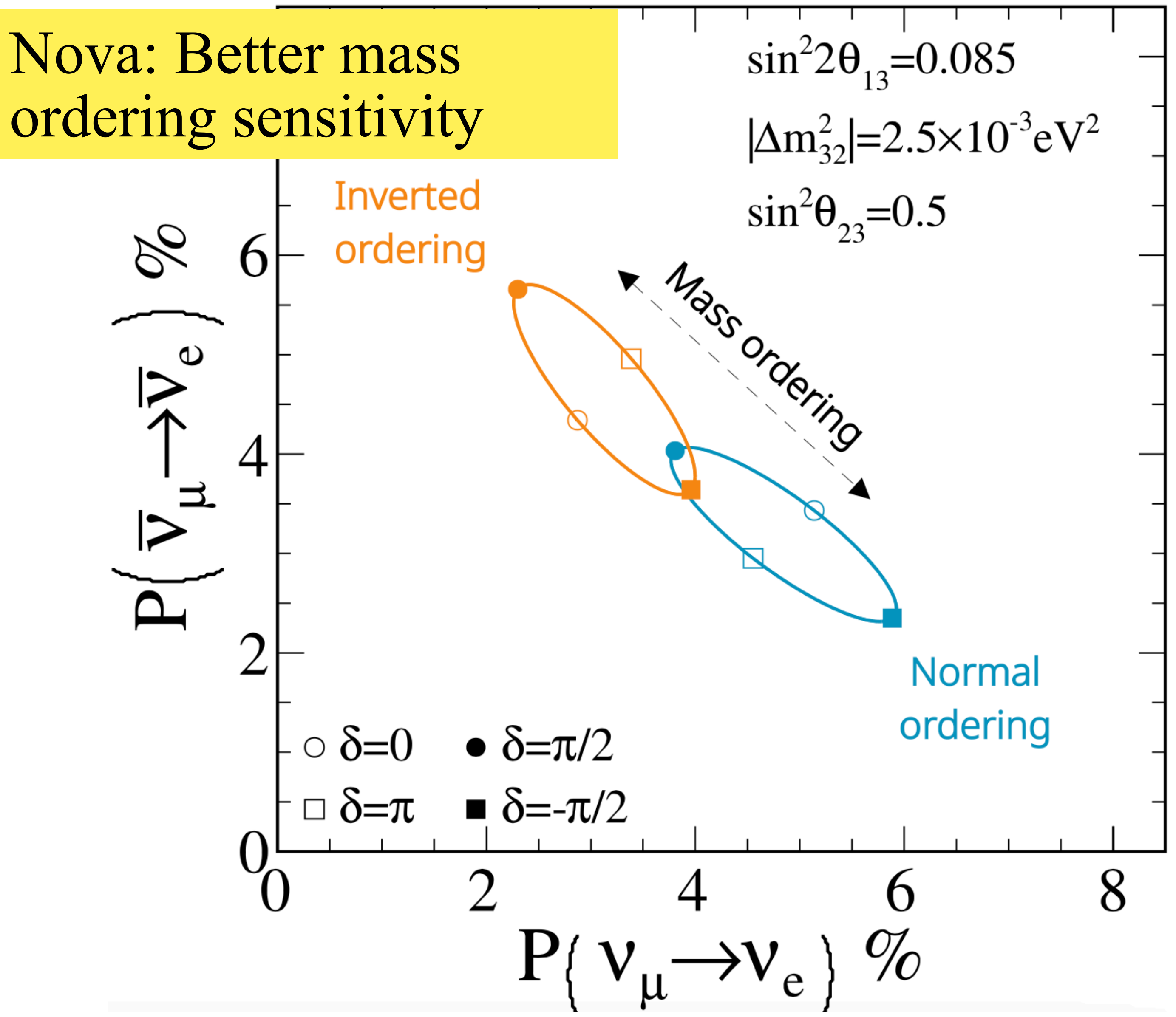
Different energy ⇒ leads to qualitatively different neutrino interactions



Different baseline ⇒ Matter asymmetry grows with baseline (easier mass ordering studies)



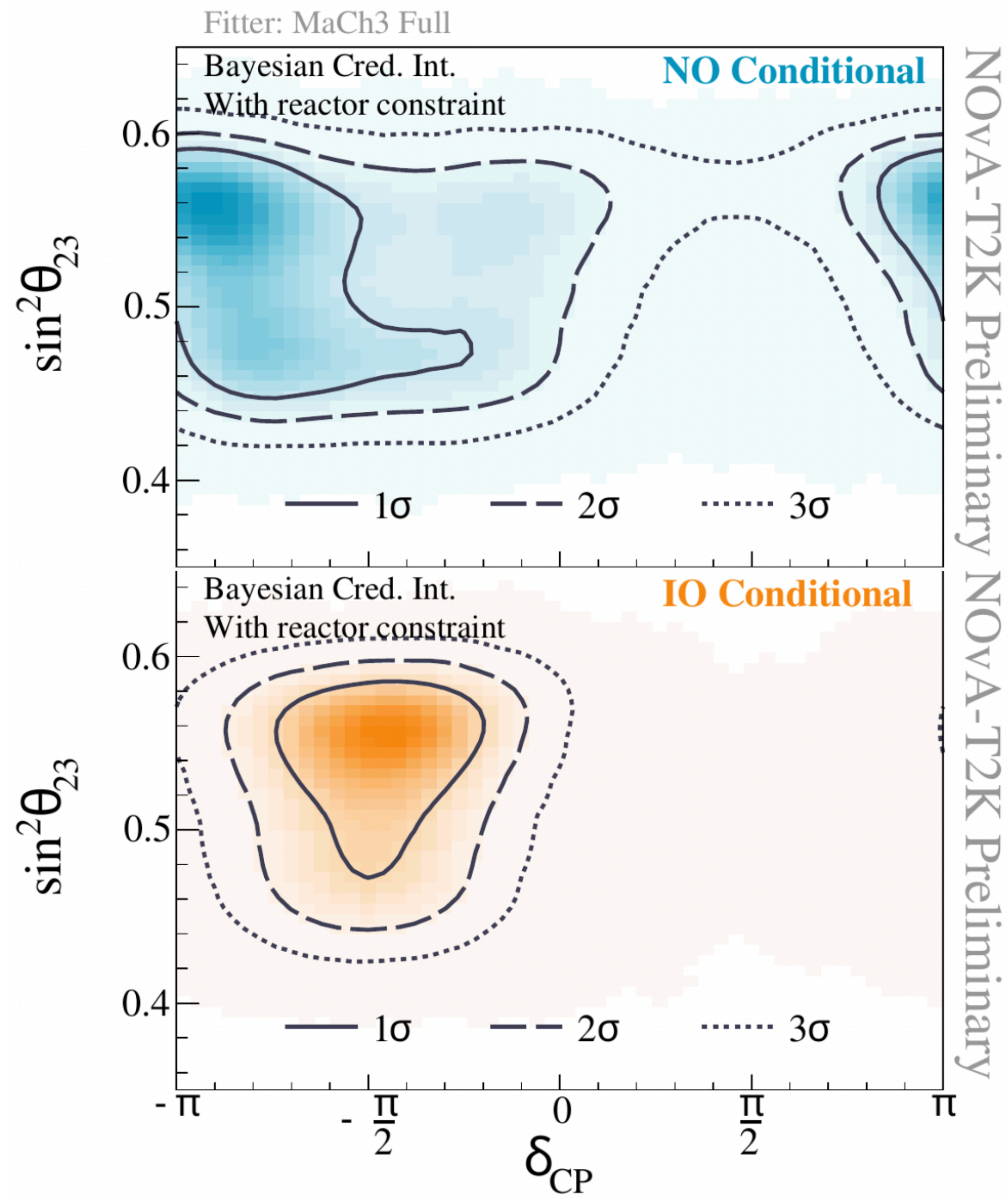
T2K: Better δ_{CP} sensitivity

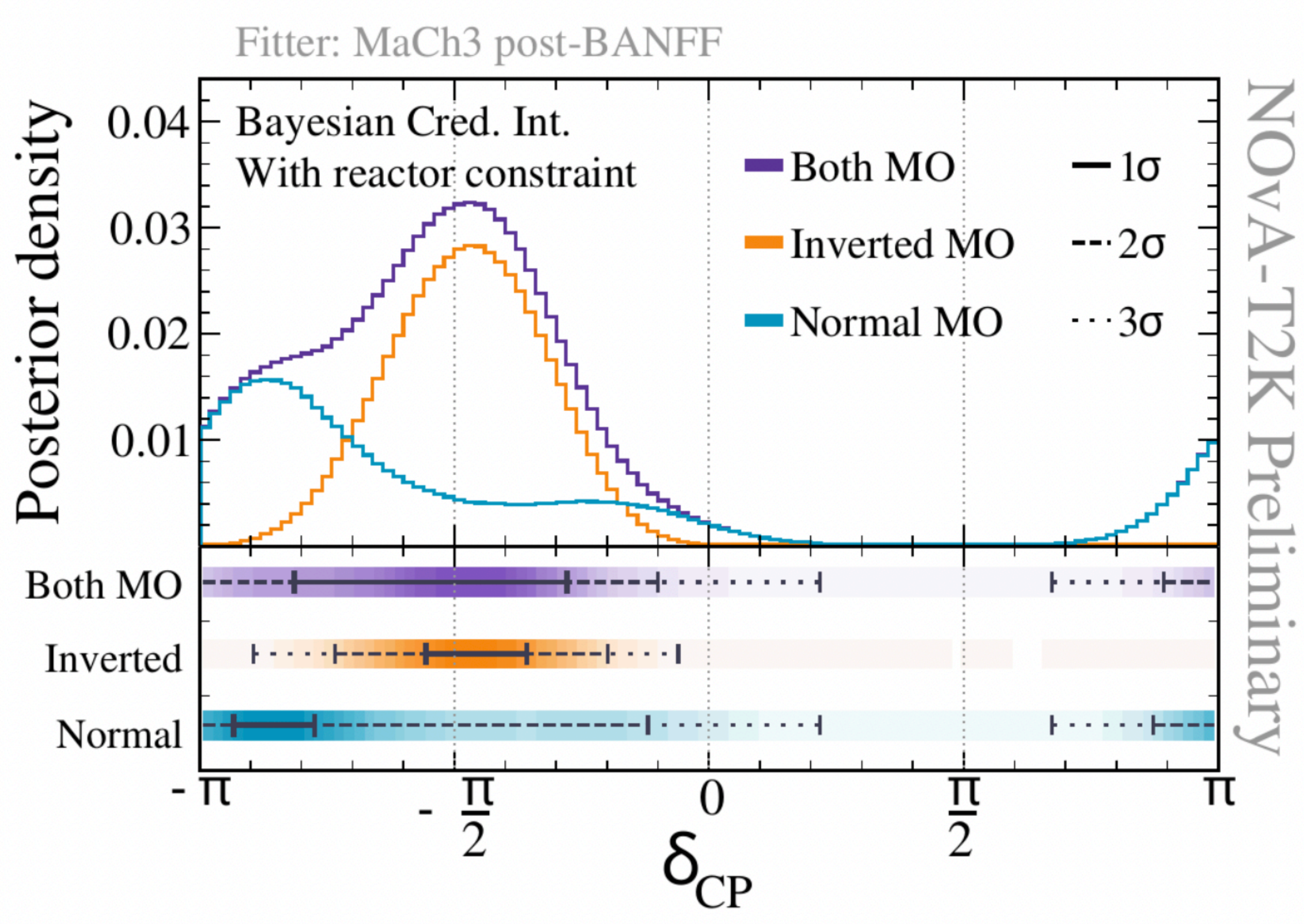


Nova: Better mass ordering sensitivity

Joint Analysis probes both spaces lifting degeneracies of individual experiments

T2K + Nova Joint Analysis

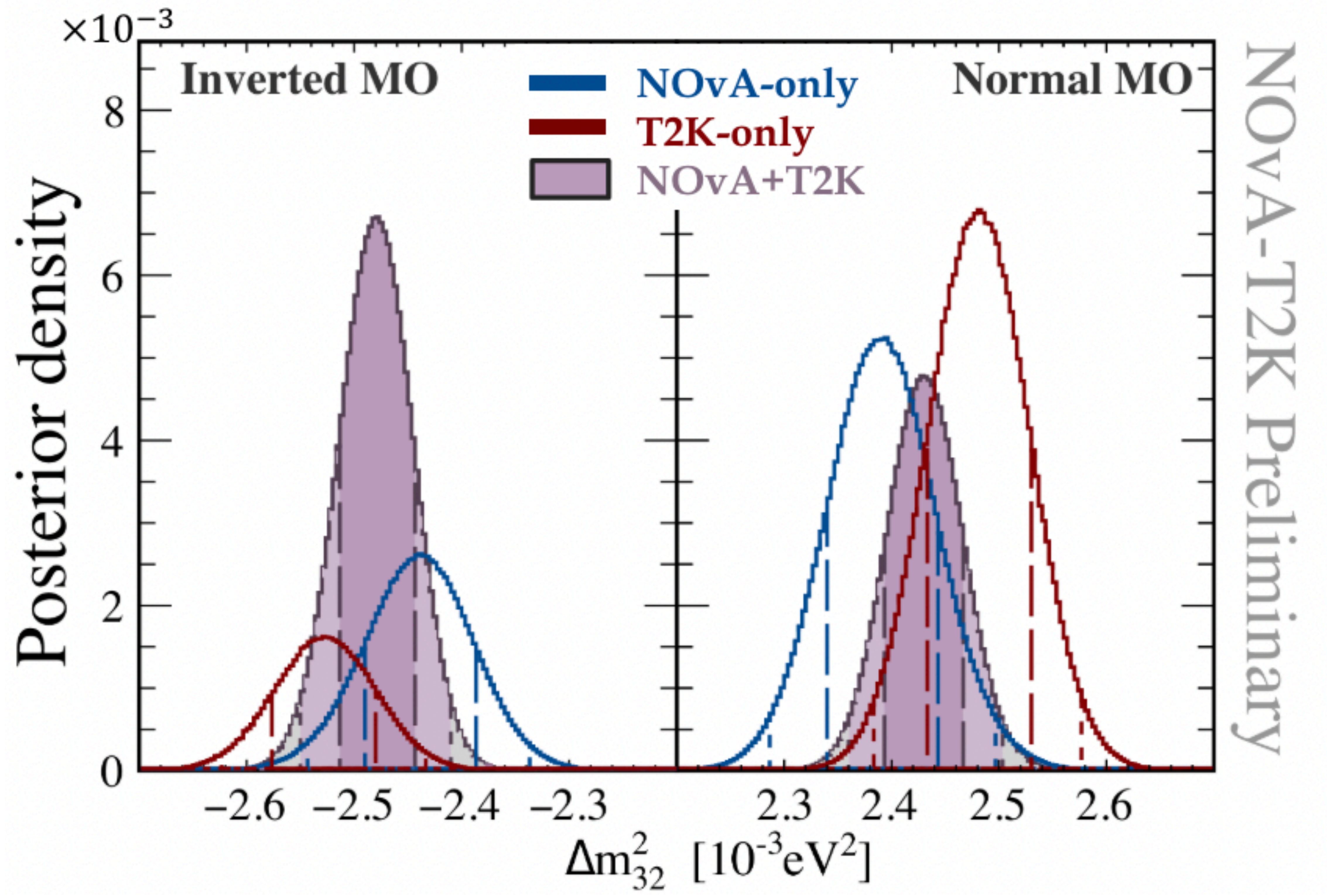


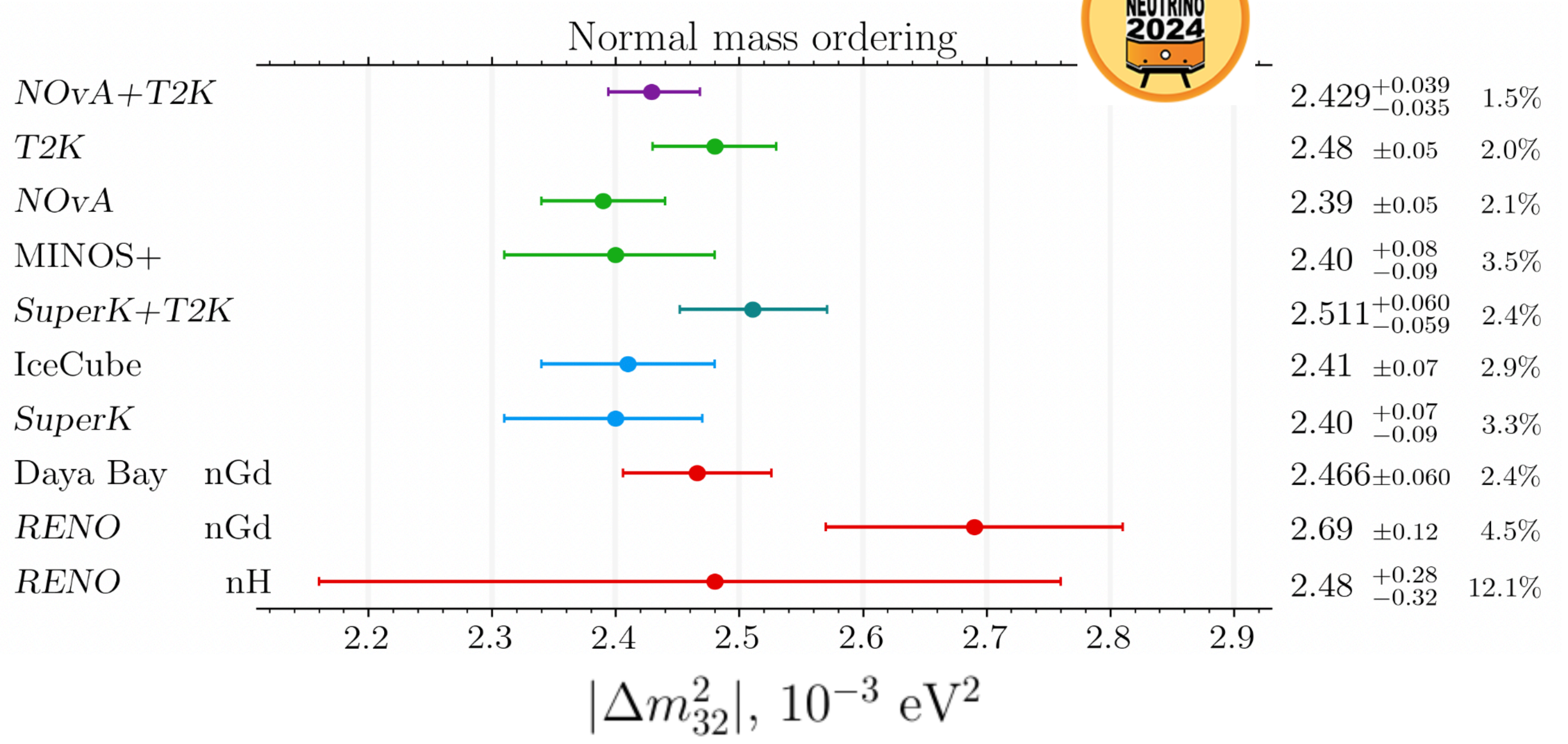


- Small difference seen in octant preference depending on the mass ordering
- Measurements remain consistent with the maximal mixing hypothesis for θ23

- CP conservation excluded at 3σ in inverted ordering:
  - Preference for $\delta_{CP} = -\frac{\pi}{2}$
- Wide range of allowed δ_{CP} values in normal ordering:
  - Preference for $\delta_{CP} = \pm\pi$

T2K + Nova Joint Analysis





- Smallest uncertainty on $|\Delta m^2_{32}|$ in both normal and inverted mass orderings.

- Individual experiments prefer normal mass ordering.

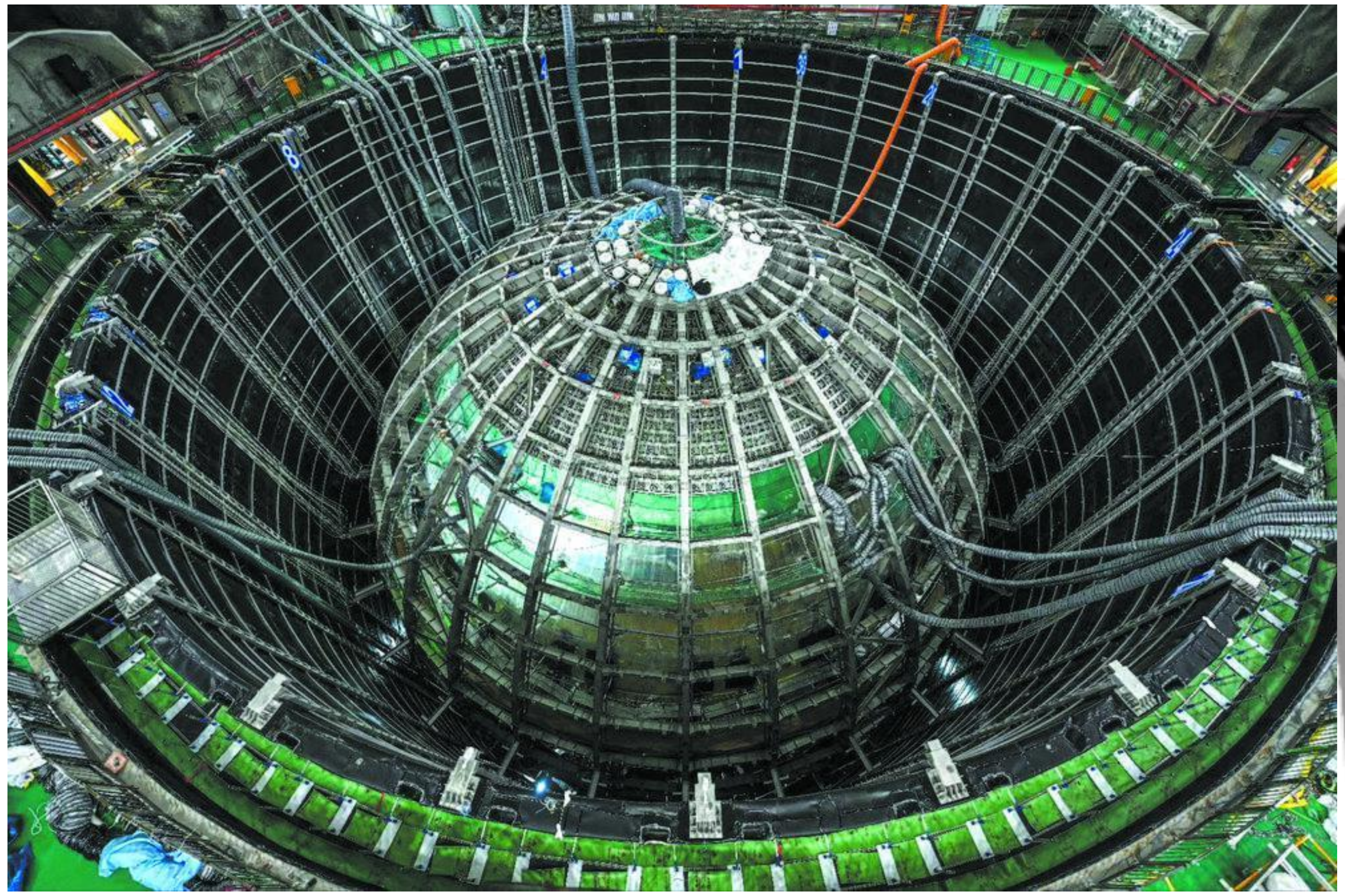
- Best fit in the inverted ordering for joint fit with reactor constraint but no significant preference (57% posterior).

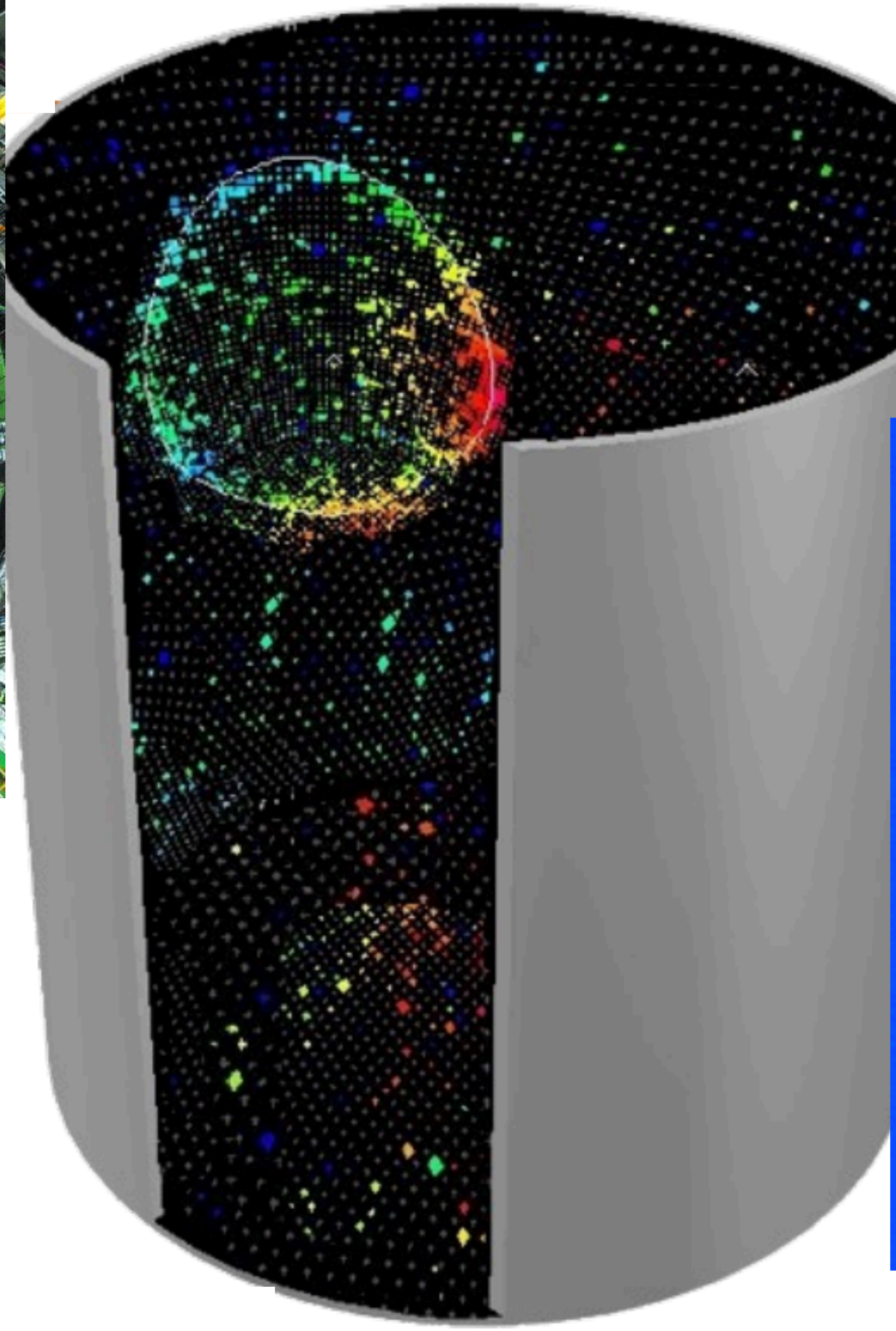
Mild preference for Inverted Ordering but **influenced by θ_{13} constraint**

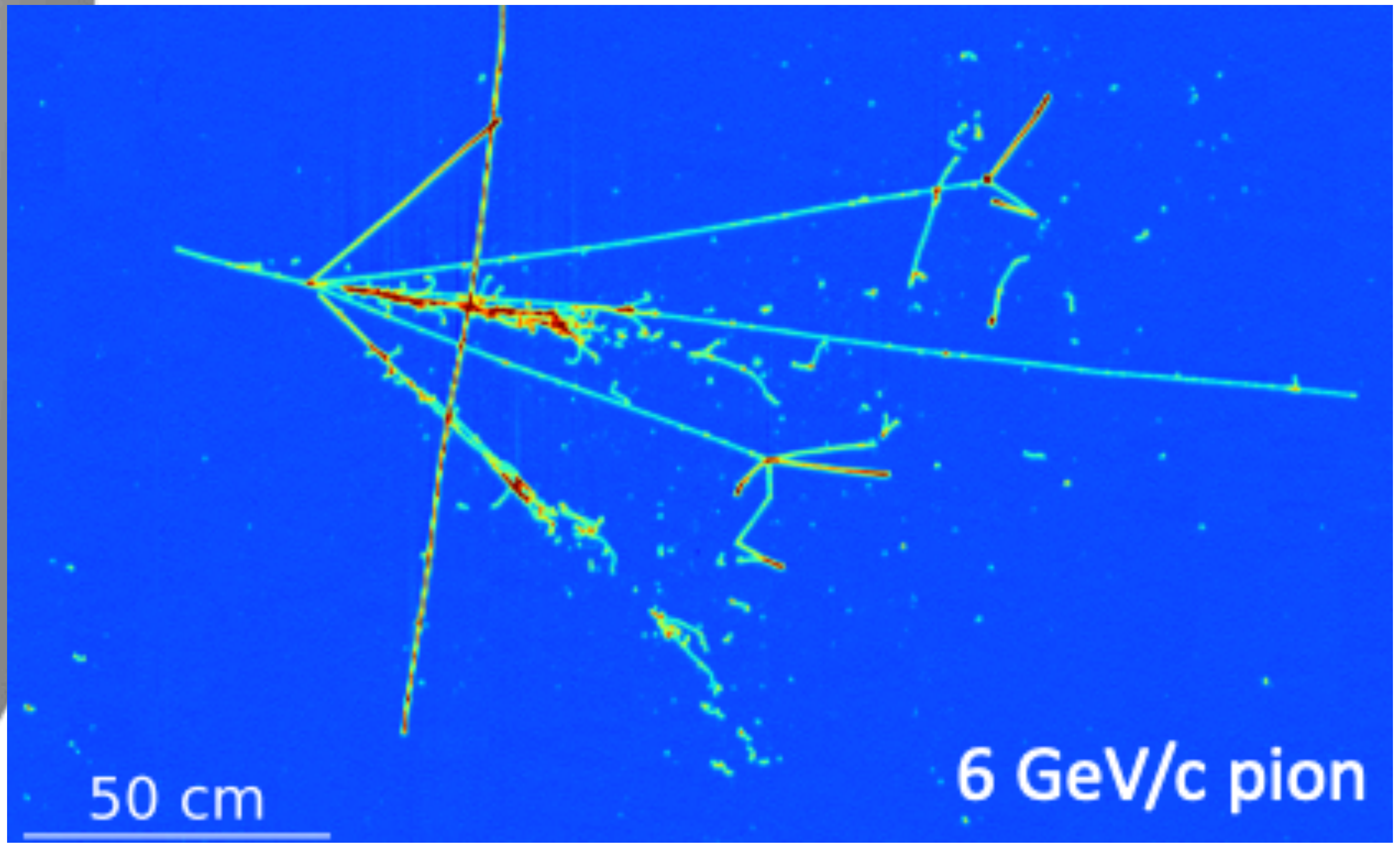
NOvA+T2K only	NOvA+T2K + 1D θ_{13}	NOvA+T2K + 2D (θ_{13}, Δm^2_{32})
IO (71%)	IO (57%)	NO (59%)

- Not real conclusive statement

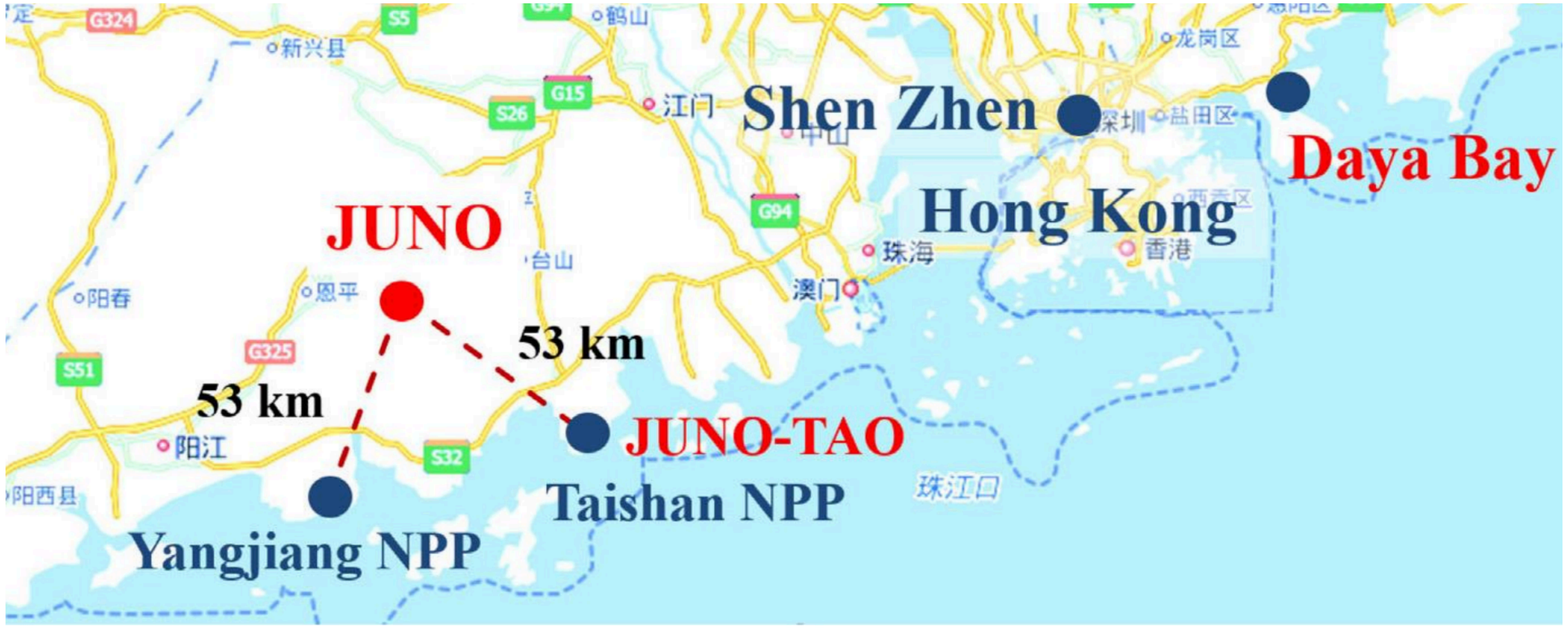
Future Experiments: JUNO, HYPER-KAMIOKANDE and DUNE







Jiangmen Underground Neutrino Observatory (JUNO)



- Primary physics goal: determine the neutrino mass ordering by measuring the $\bar{\nu}_e$ oscillations

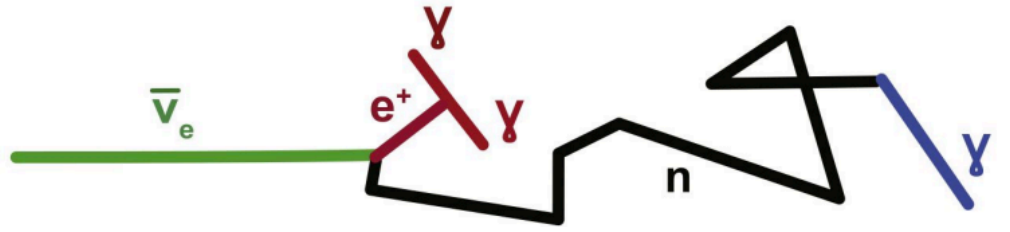
- ~ 53 km from two Nuclear Power Plants

- Liquid scintillator detector
  - ~ 700 m underground lab in southern China

- Anticipate finishing the construction in 2024 and start the detector filling

Detection channel: Inverse Beta Decay
(rate = 50 events/day)

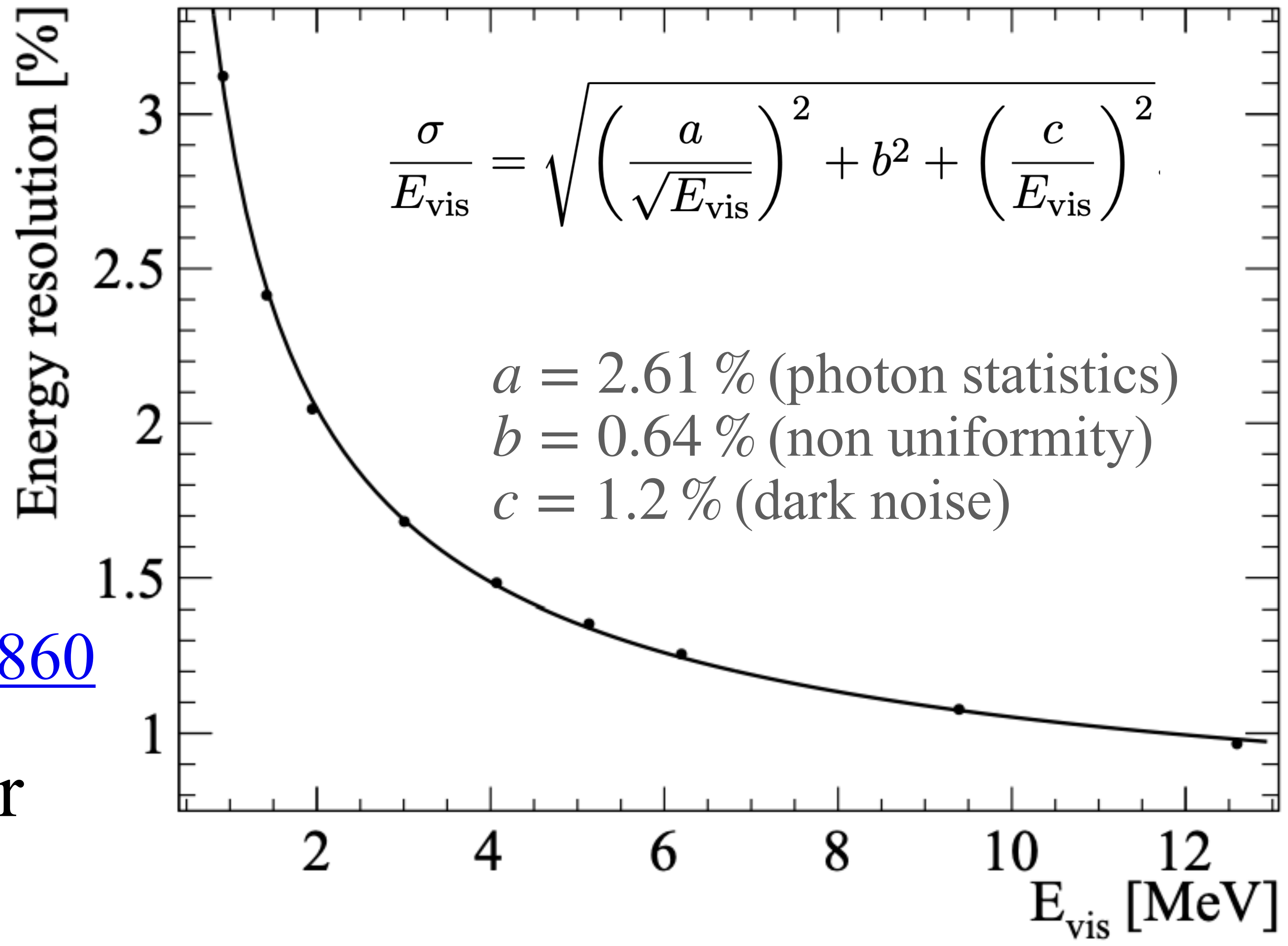
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



Prompt signal:
Handle for energy
$E_\nu \simeq E_{e^+} + \Delta m_{n-p} + T_n$

Delayed signal:
N capture on H
2.2 MeV within ~200 μs

- Excellent energy resolution: 3%/$\sqrt{E}$(MeV)

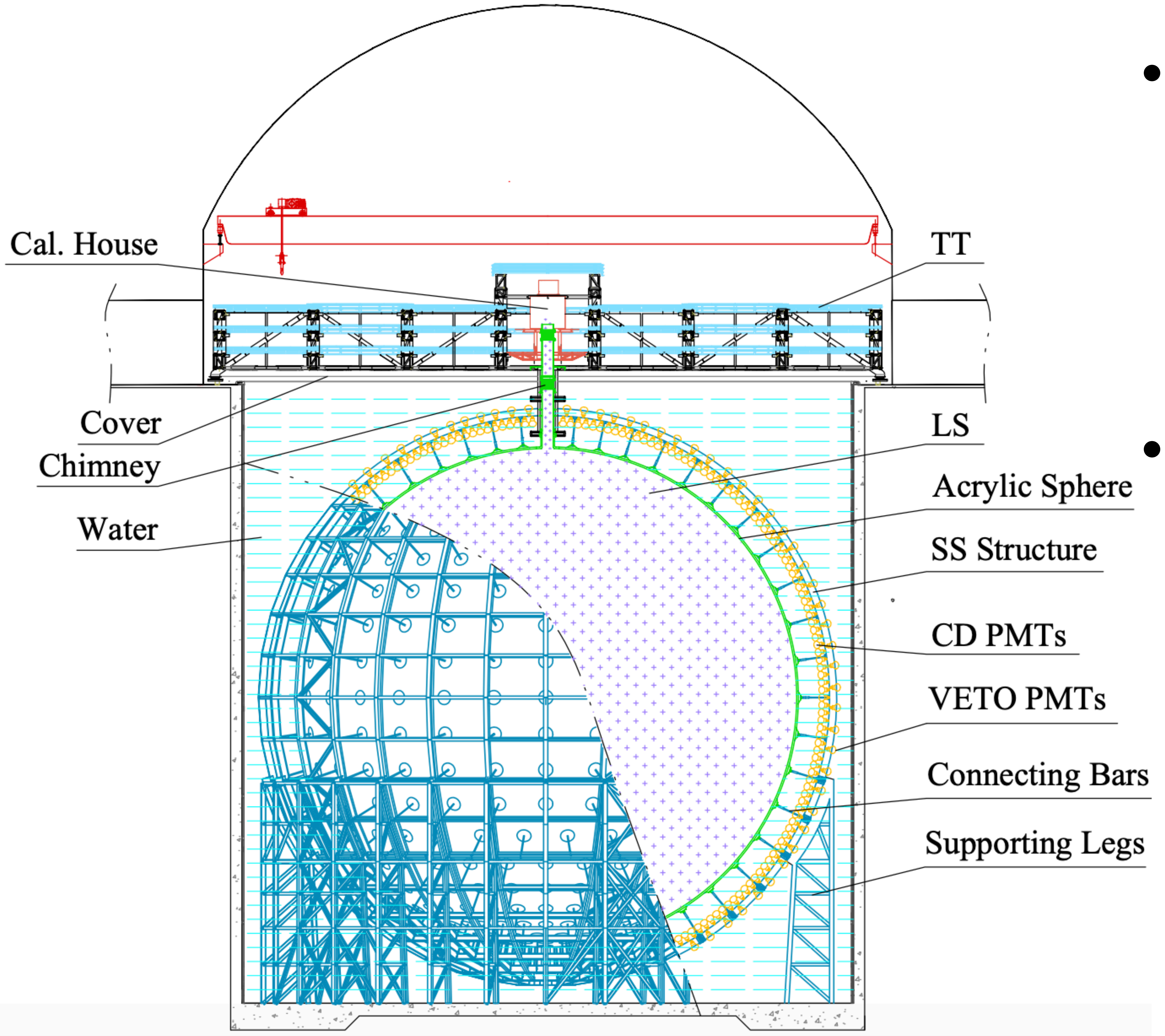


$$\frac{\sigma}{E_{\rm vis}} = \sqrt{\left(\frac{a}{\sqrt{E_{\rm vis}}}\right)^2 + b^2 + \left(\frac{c}{E_{\rm vis}}\right)^2}$$

$a = 2.61\,\%$ (photon statistics)
$b = 0.64\,\%$ (non uniformity)
$c = 1.2\,\%$ (dark noise)

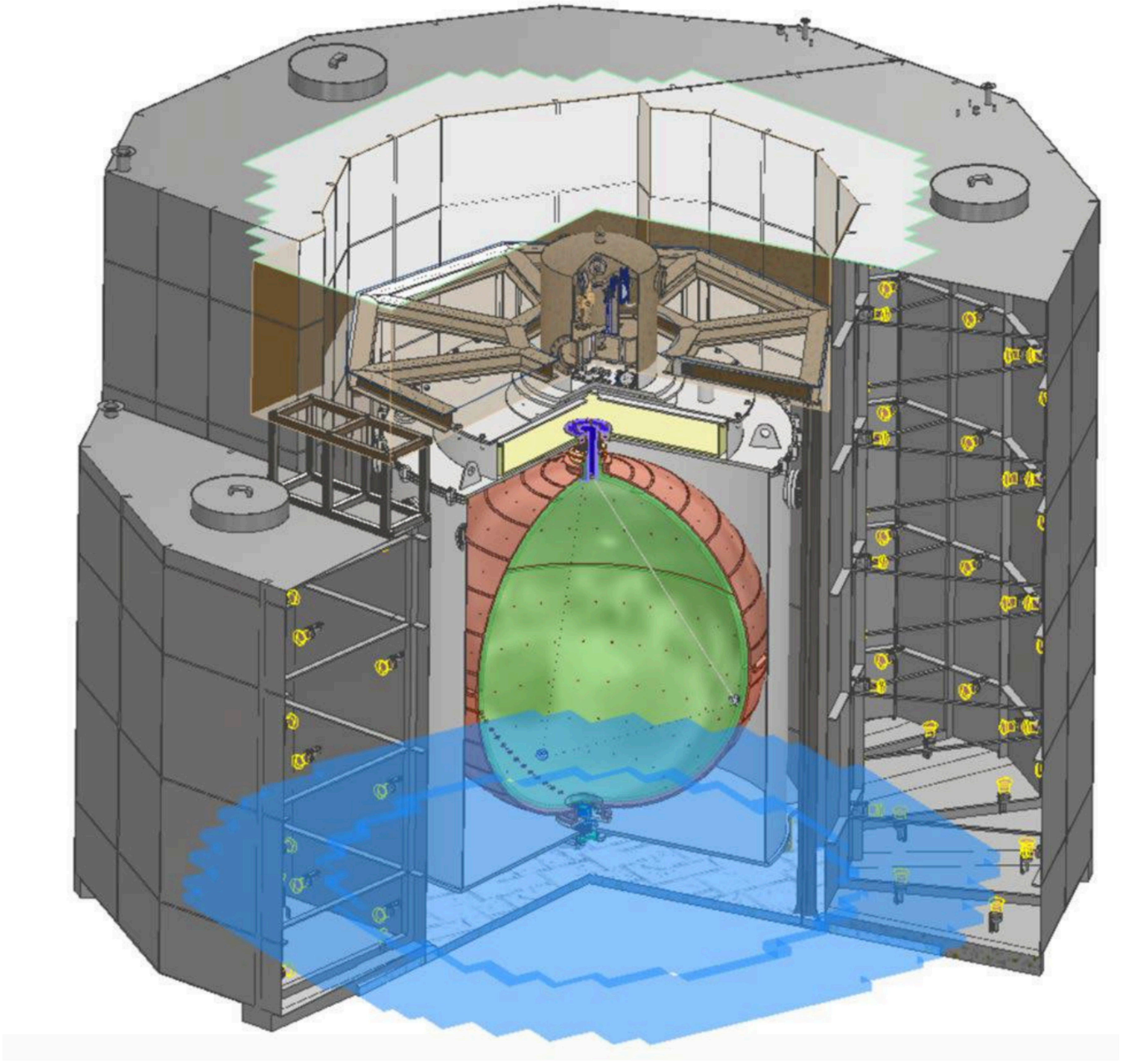
arXiv:2405.17860

The Juno Detector



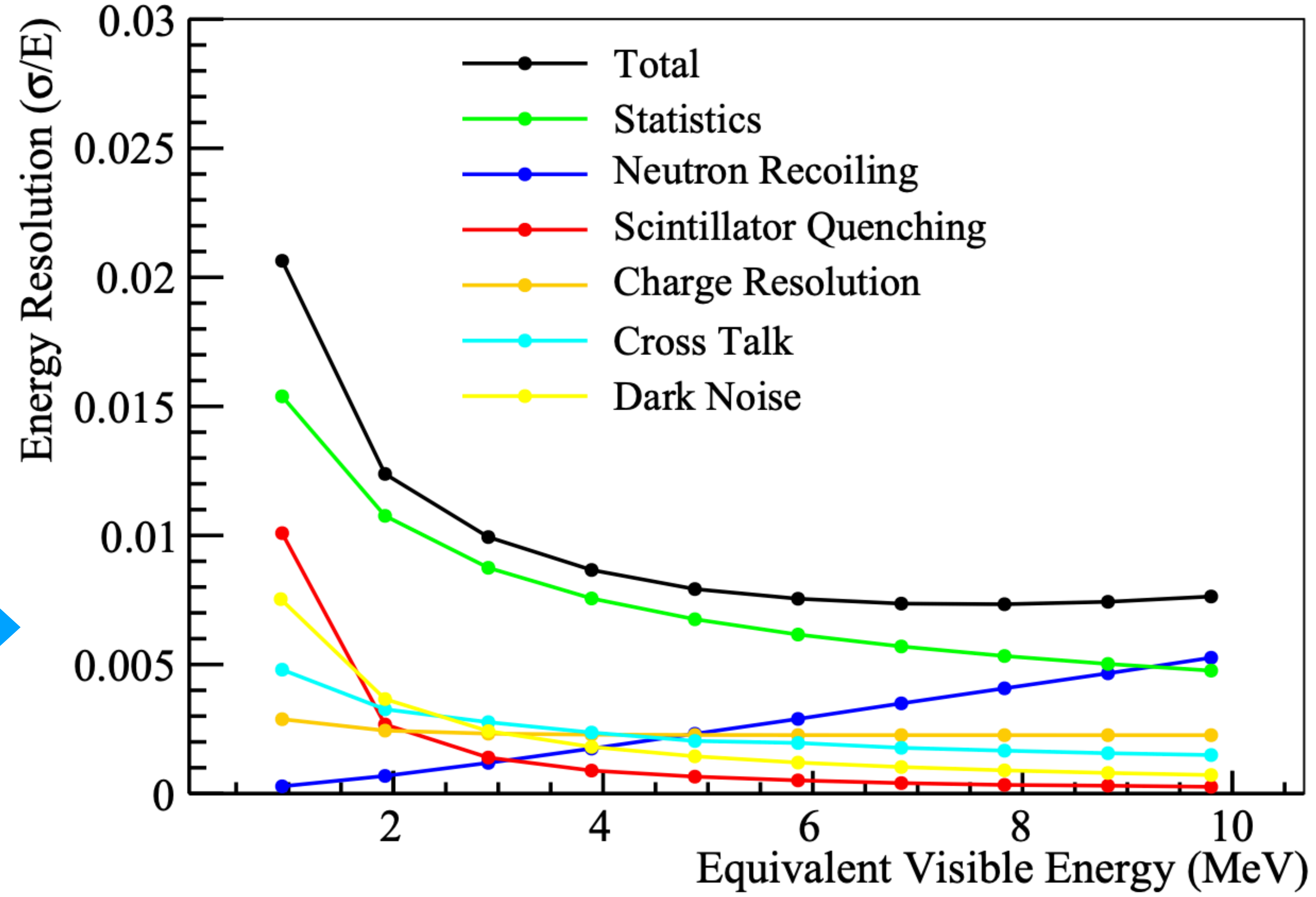
- The JUNO detector consists of a central detector, a water Cherenkov detector and a muon tracker (veto detectors)
- **Central detector**:
  - 35.4 m spherical acrylic vessel, containing 20 kton LS
  - Surrounded by 17612 Large (20”) PMTs and 25600 Small (3”) PMTs (75.2% coverage)
- **Veto detectors**:
  - Water Cherenkov detector:
    - 35 kton ultra pure water to shield backgrounds from the rock
    - Instrumented w/ 2400 20” PMTs on SS structure
  - Top tracker
    - Plastic scintillator strips refurbished from OPERA
    - 3 layers, ~60% coverage on the top (of the surface above the WCD)

JUNO-TAO



- The Taishan Antineutrino Observatory (TAO) is a satellite experiment of JUNO
- TAO consists of a spherical 2.8 tons (1 ton fiducial) Gd-LS detector (1.8 m diameter) at 44 m from a reactor core (4.6 GW)
- Viewed by 10 m^2 SiPMs (~50% PDE) and providing around 95% photon coverage
  - Operated at − 50 °C to lower the dark noise
- IBD rate: 2000 events/day
- Veto system:
  - Water Cherenkov tank
  - Top Tracker (Plast. Scint)

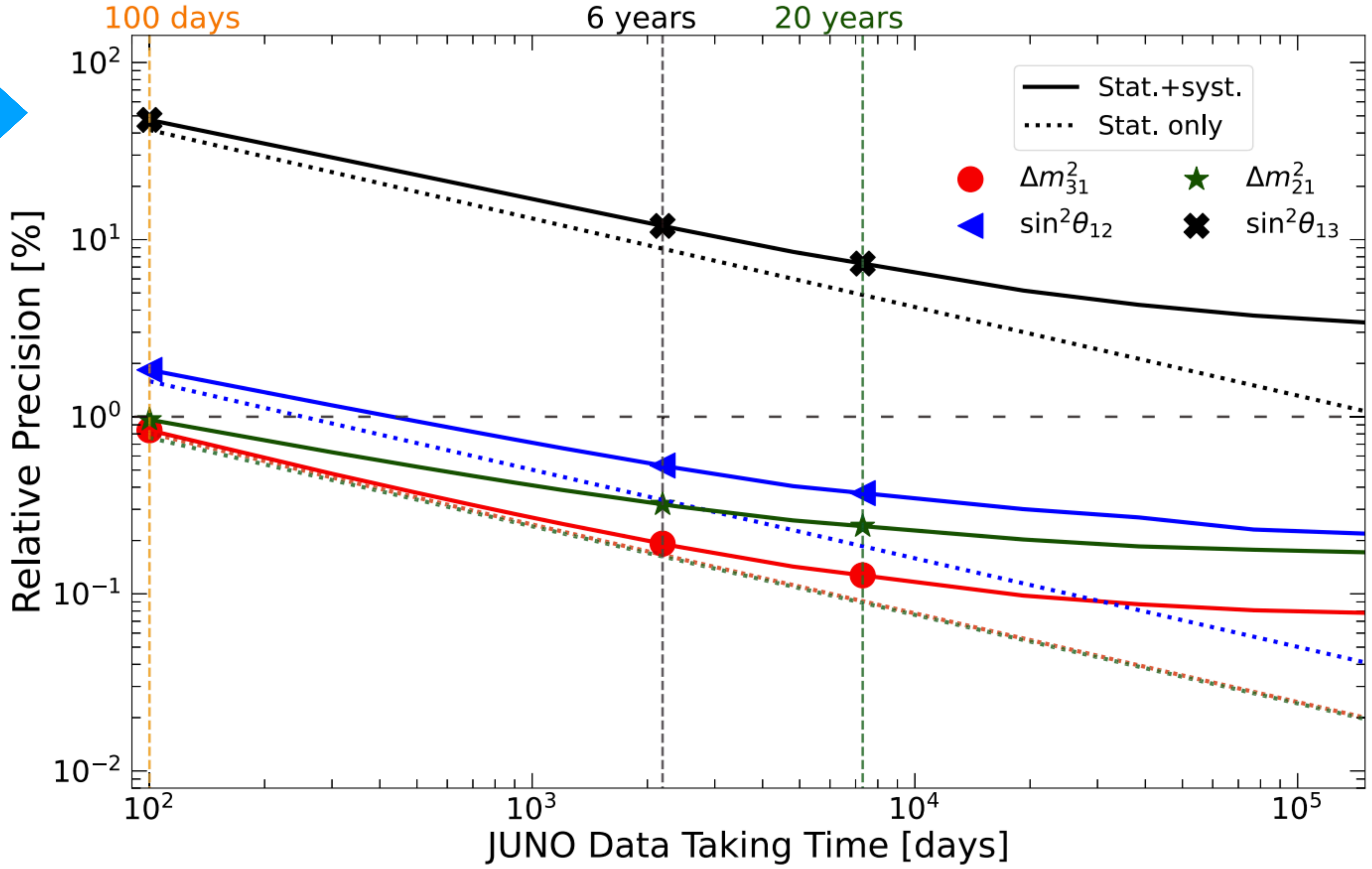
arXiv:2005.08745



- TAO will measure the reactor $\bar{\nu}_e$ spectrum with unprecedented energy resolution: $< 2\%/\sqrt{E}$(MeV)
- TAO detector will start data taking at similar time as JUNO

JUNO Precision Measurement of Oscillation Parameters

- Relative precision of the oscillation parameters as a function of JUNO data taking time



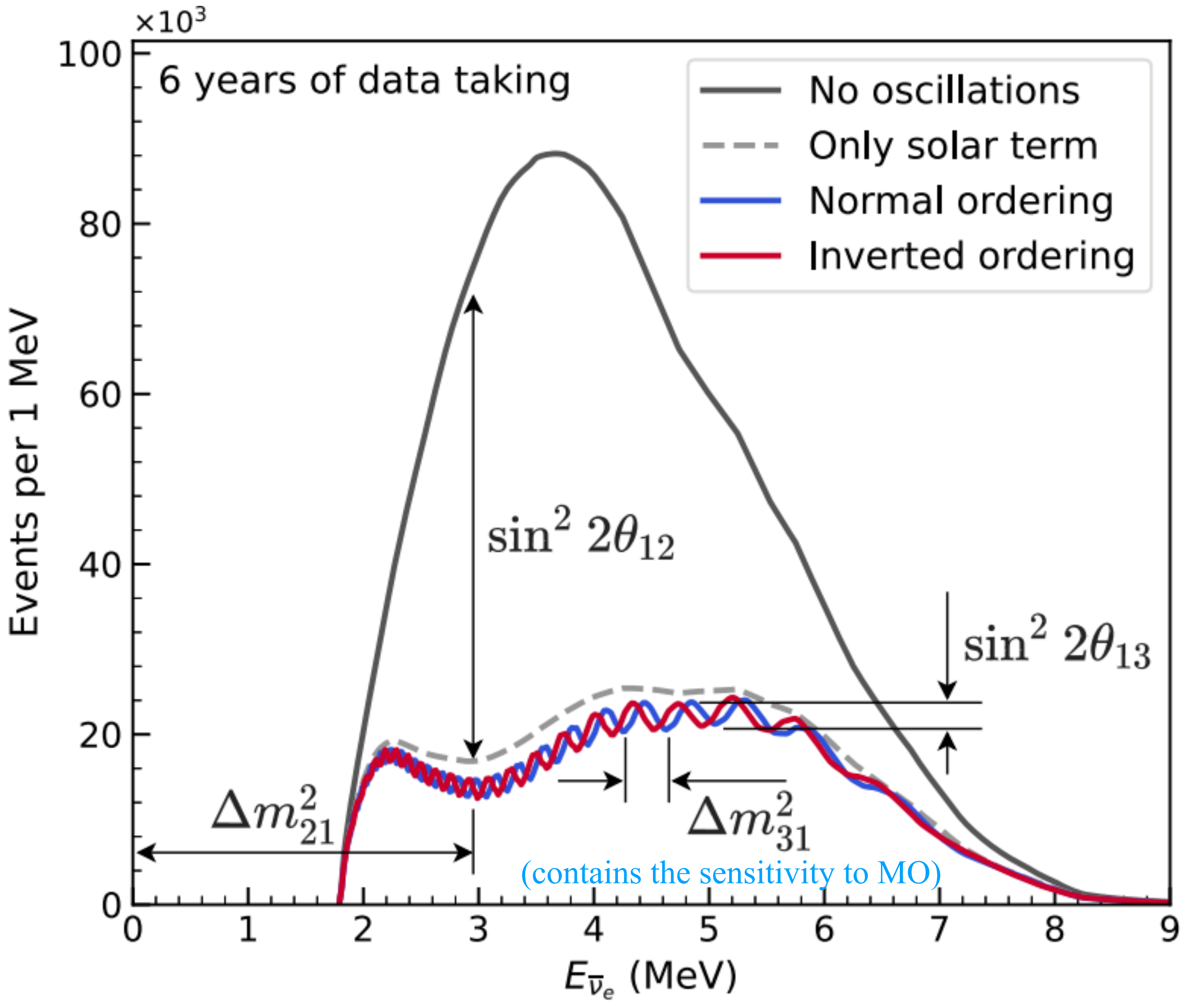
- Current knowledge (level of few %) compared with 100 days (statistics dominated), 6 years (nominal), and 20 years (systematics-dominated) of JUNO data:
  - Exceptional sensitivity to Δm^2_{21}, Δm^2_{31} and $\sin^2\theta_{12}$:
    - Leading measurements in 100 days
    - Precision < 0.5% in 6 years

	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)	±0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)	±0.0016 (7.3%)

Neutrino Mass Ordering with JUNO

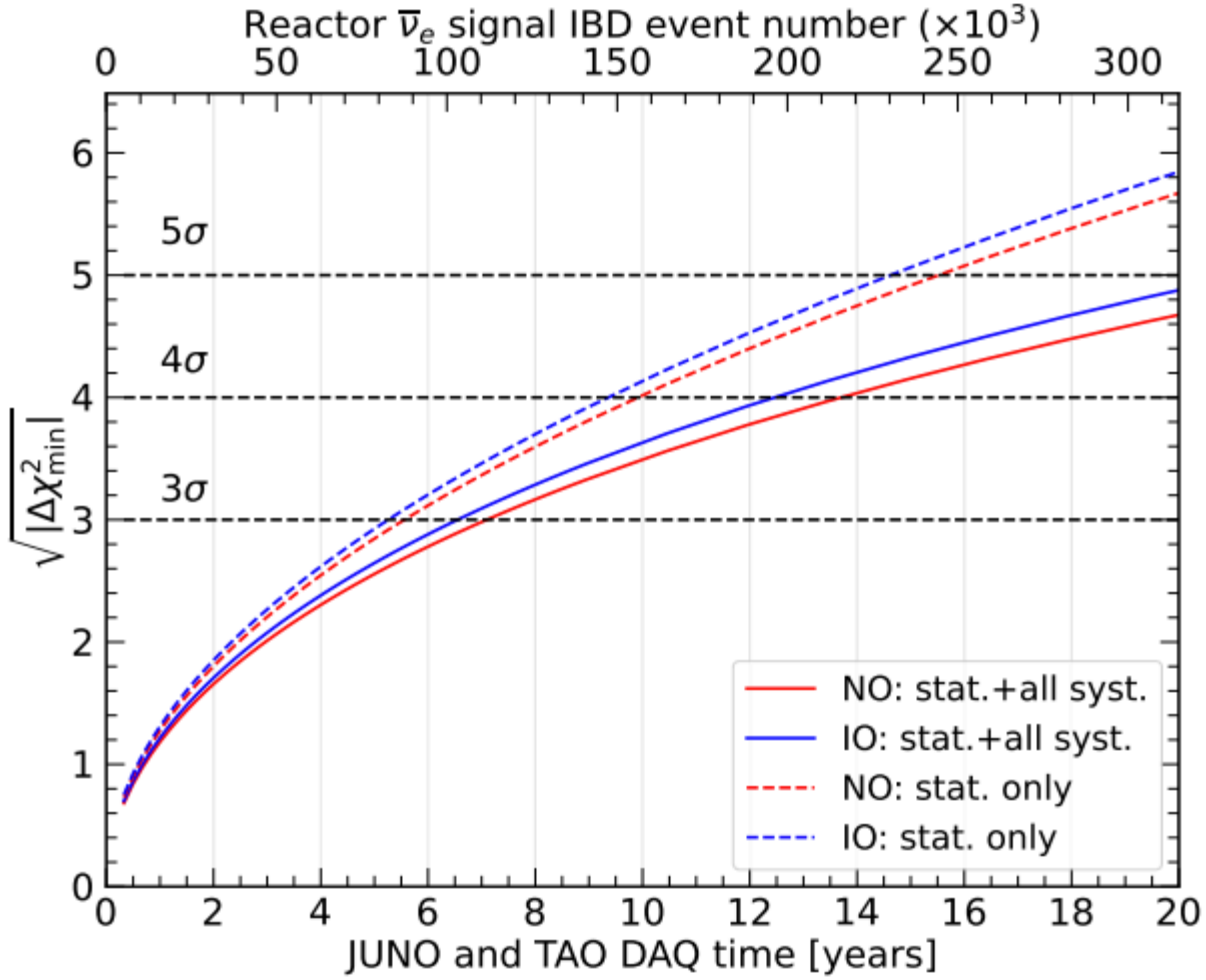
arXiv:405.18008

- JUNO reactor antineutrino energy spectrum without and with the effect of neutrino oscillation



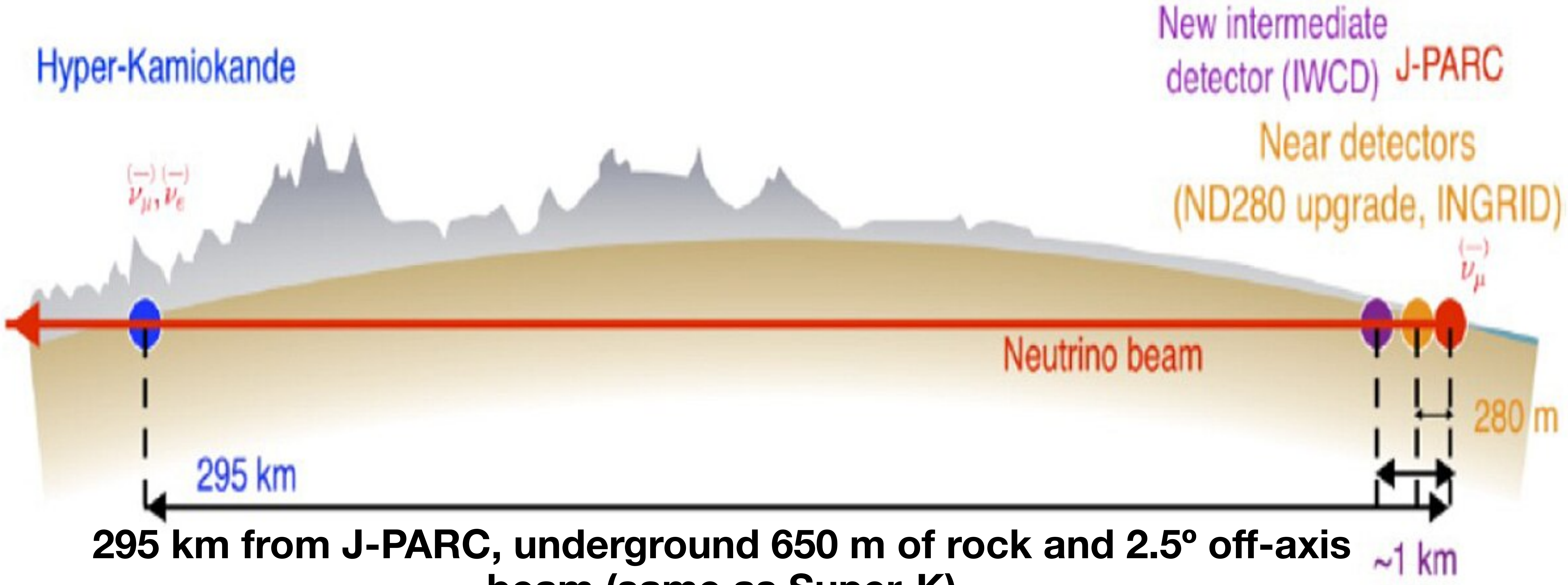
(contains the sensitivity to MO)

- Clear spectral features driven by the oscillation parameters ⇒ Rich information available in a high-resolution measurement of the spectrum

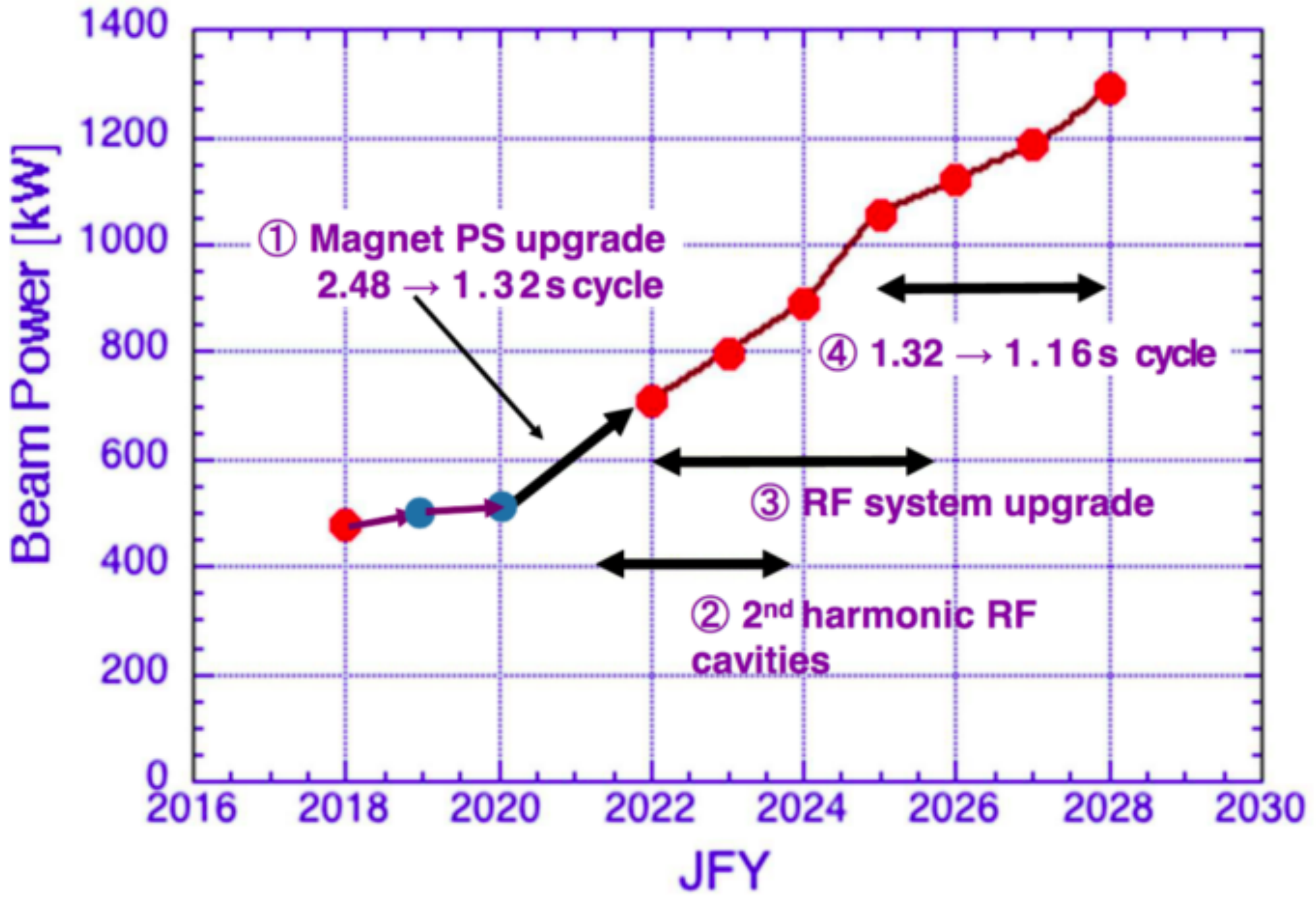


- JUNO can determine the neutrino mass ordering with 3σ significance after 7 years
- Combined reactor and atmospheric neutrino analysis in progress

Hyper-Kamiokande Experiment

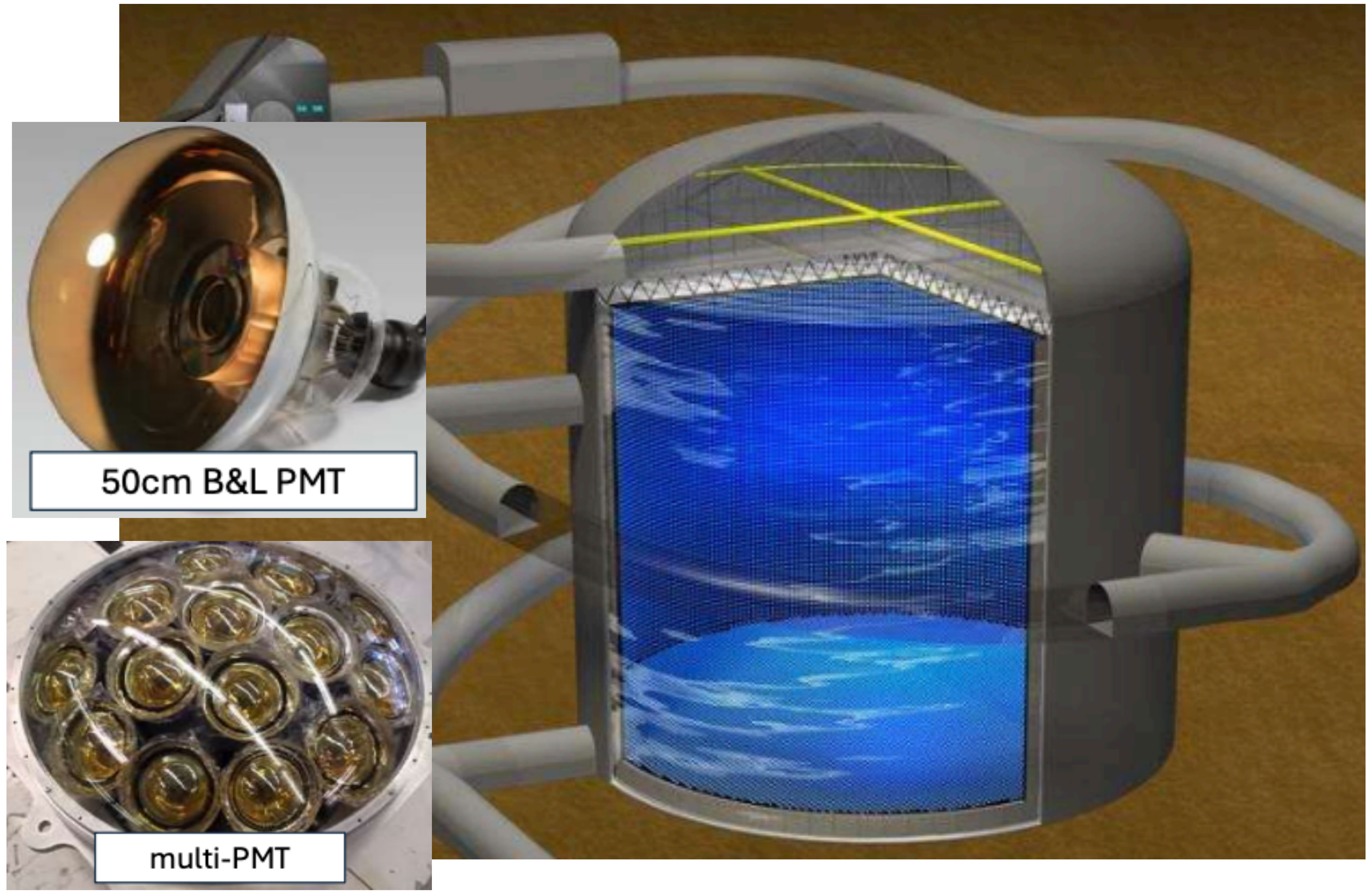


295 km from J-PARC, underground 650 m of rock and 2.5º off-axis beam (same as Super-K)

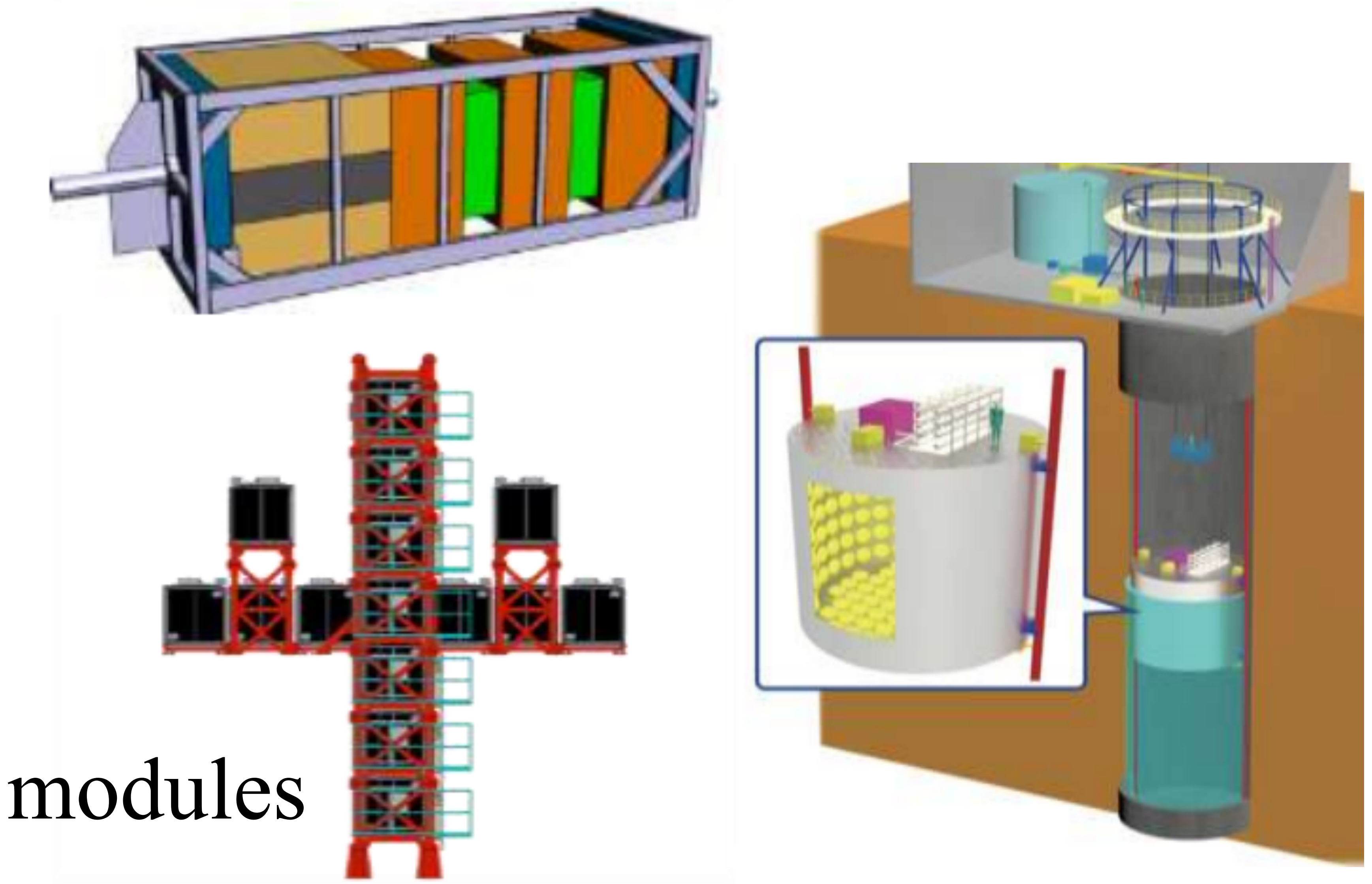


- It will continue the successful history of the Kamiokande, Super-Kamiokande, and T2K experiments.
- Hyper-K will have an upgraded neutrino beam with the goal of 1.3 MW Beam Operation (800 kW this summer).
- Further improvements are expected thanks to the combination of ND280 upgrade and IWCD.

Hyper-K Detectors



- HK Far Detector (water Cherenkov):
  - 71 m (height) x 68 m (diameter) = 258 kt mass (188 kt fiducial) ⇒ x8 SK mass
  - 20,000 of 50 cm PMTs (2x better QE and ΔT than SK)
  - Additional photo-coverage from multi-PMT modules:
    - 800 of 8 cm PMTs grouped in modules of 19 units
    - Improved position, timing and direction resolution

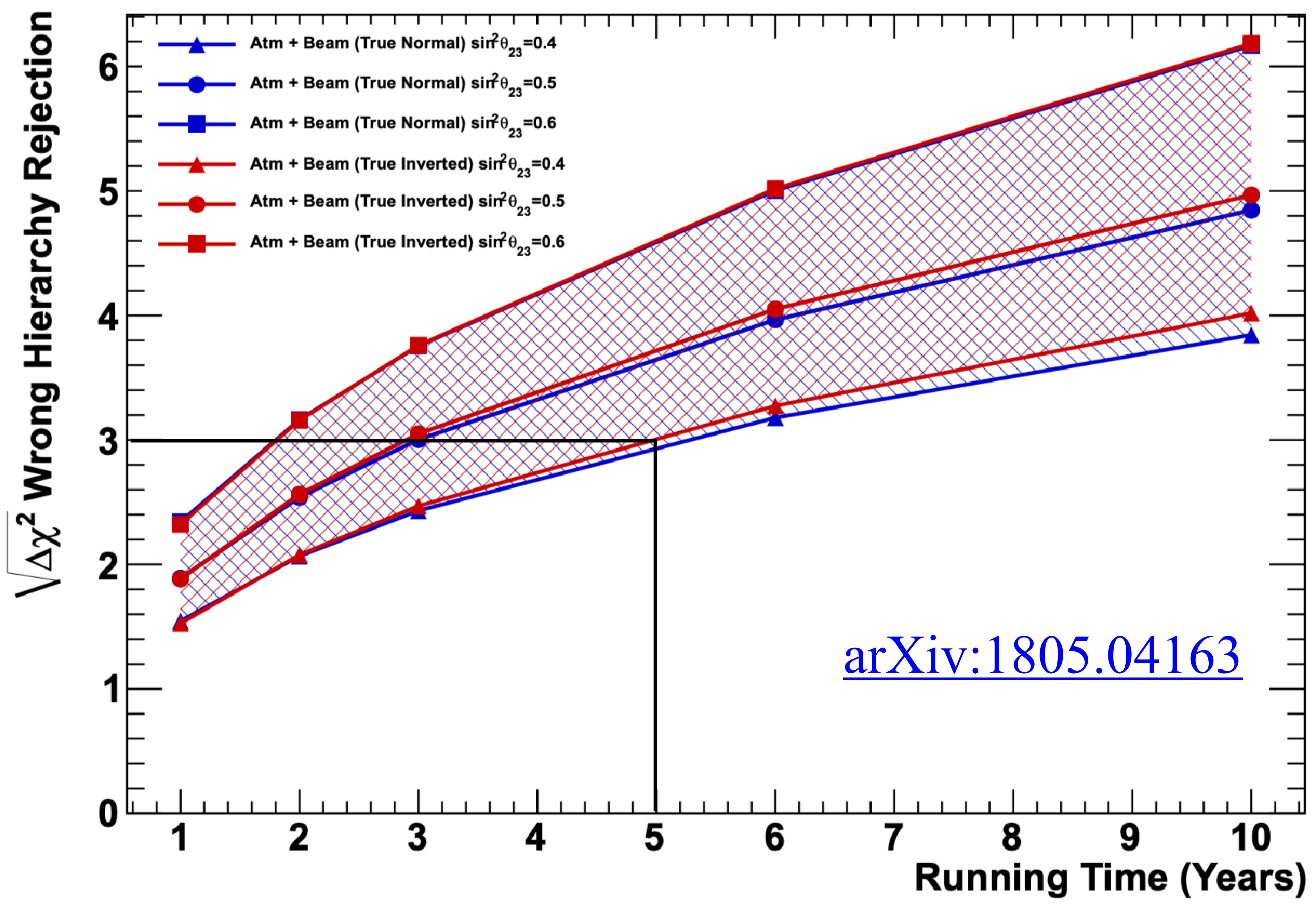


- HK Near Detectors:
  - Upgraded T2K near detectors: larger angular acceptance and better short track reconstruction to reduce systematic errors
  - New intermediate Water Cherenkov Detector (IWCD):
    - Moves vertically in ~50 m (spans off-axis angles: 1.7º - 4.0º)
    - 6 m (height) x 8 m (diameter) surrounded with ~500 multi-PMT modules
    - Gd doped for enhanced neutron detection

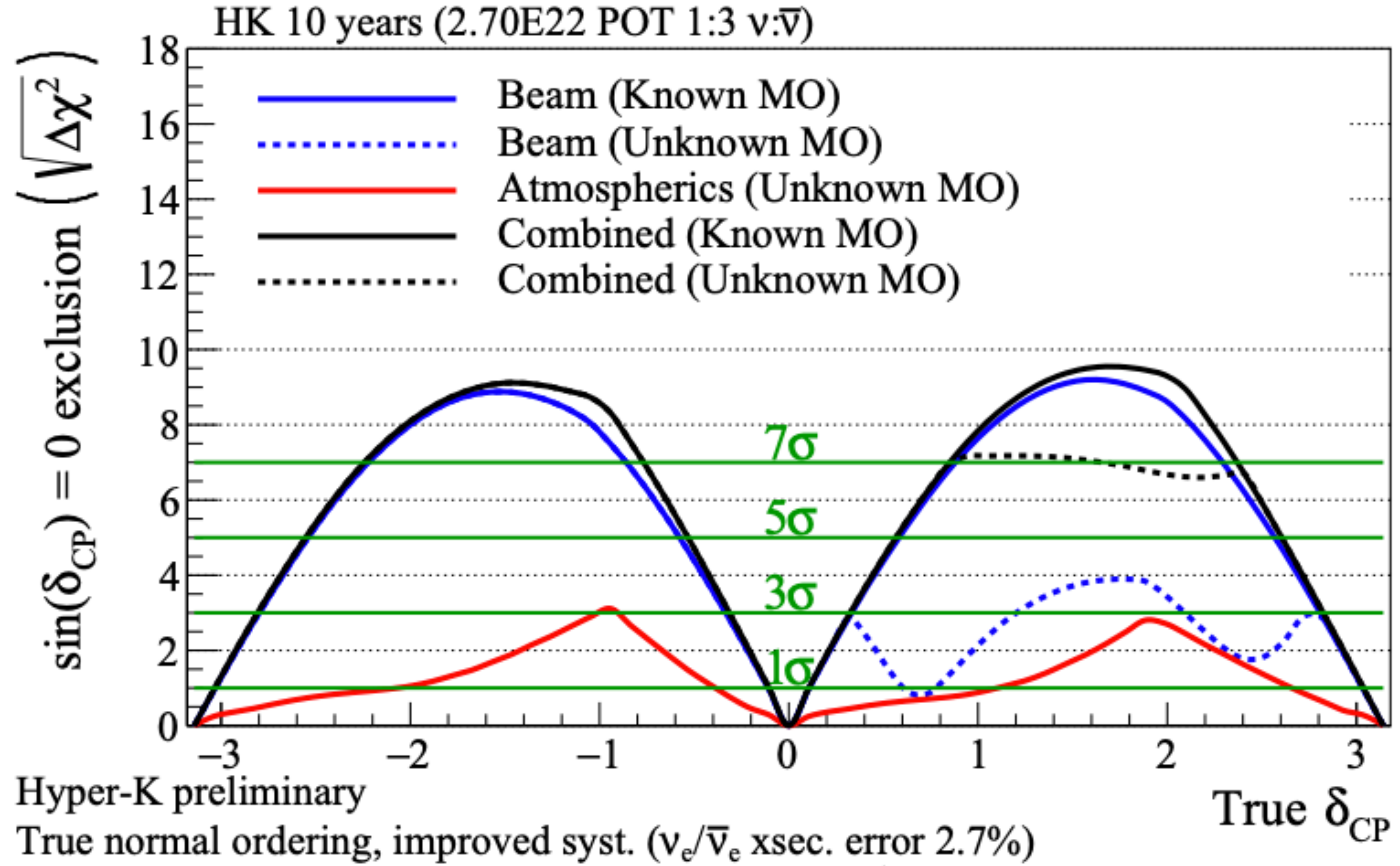
HK sensitivity to MO and CPV

- HK with a BL=295km ⇒ Small matter effects and large CPV effect
- Combination of Beam and atmospheric ν measurements: $E \in [0.1, 10^3]\, GeV$ & $L \in [10, 13000]\, km$ ⇒ Resolve parameters degeneracy
- Study matter effects on Earth to determine MO
    - After 5 years the combined beam + atmospheric analysis show better than 3σ ability to reject incorrect MO
- Sensitivity to exclude CP violation using **beam neutrinos**, **atmospheric neutrinos** and **the combination of the two**:
    - Will allow HK to reach a 5σ statement on CP violation regardless of the true MO (10 years)

Evolution of the combined sensitivity over time

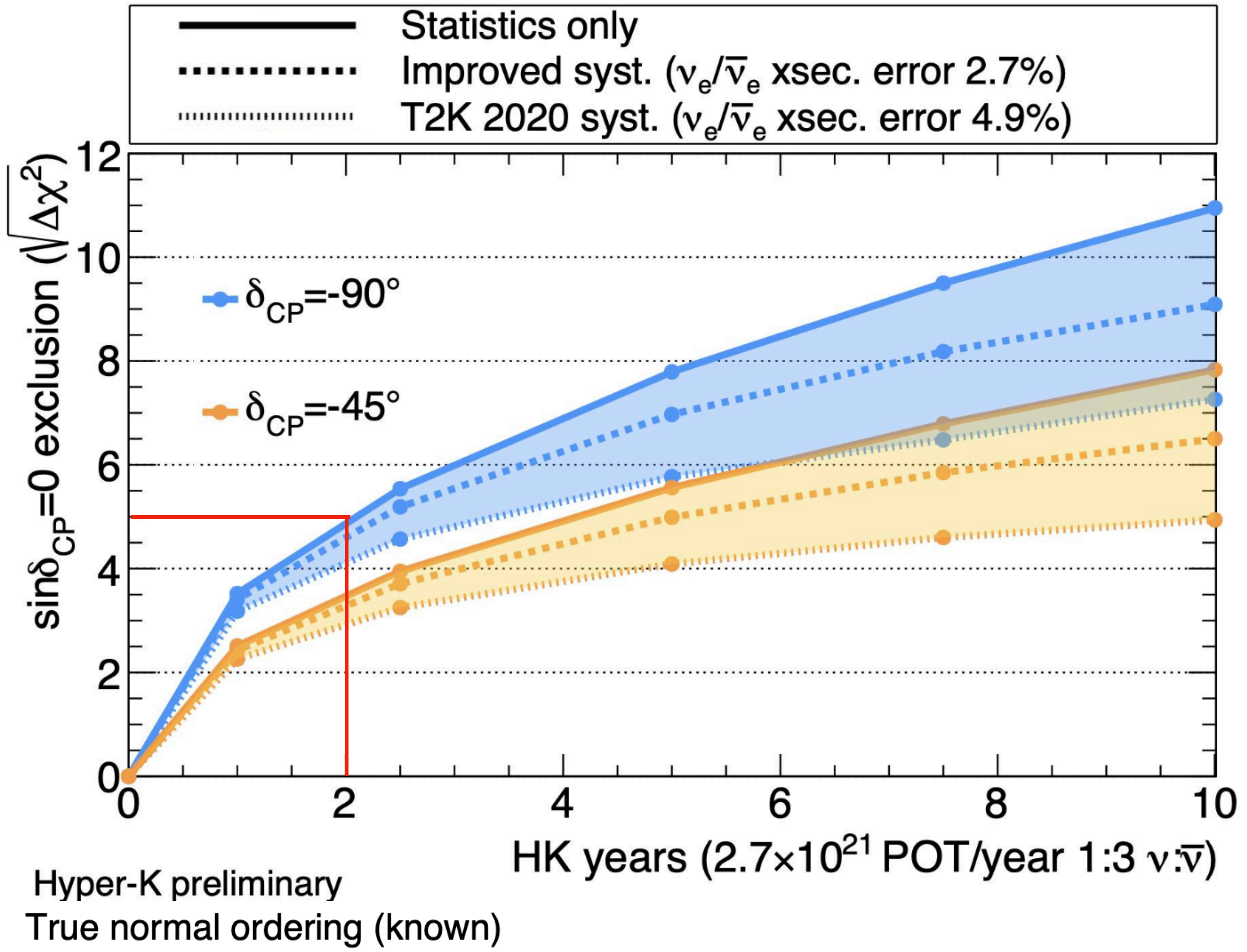


arXiv:1805.04163

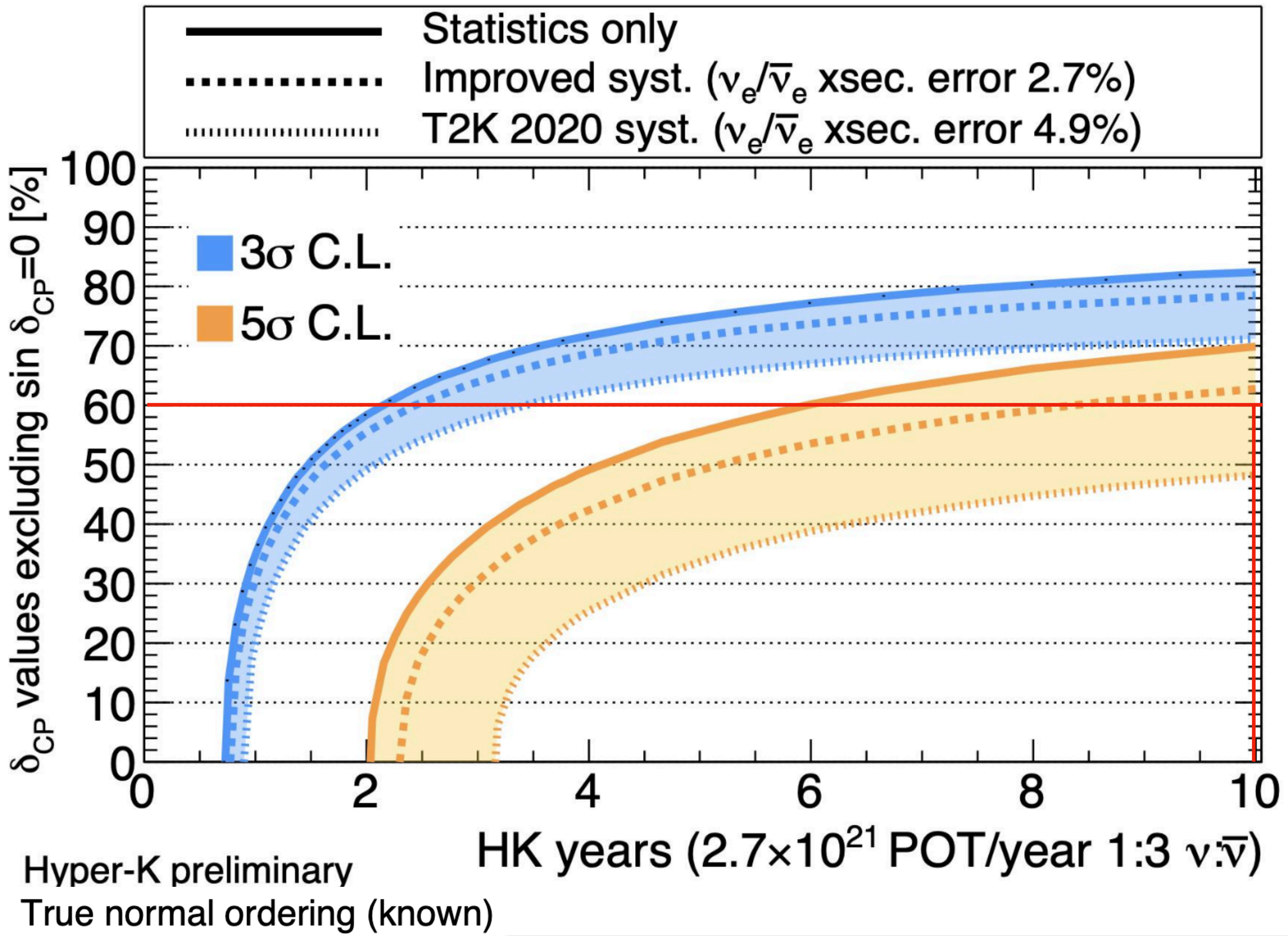


Hyper-K preliminary
True normal ordering, improved syst. ($\nu_e/\bar{\nu}_e$ xsec. error 2.7%)
$\sin^2(\theta_{13})=0.0218$ $\sin^2(\theta_{23})=0.528$ $|\Delta m^2_{32}| = 2.509 \times 10^{-3}\ \mathrm{eV}^2/c^4$

Hyper-K sensitivity to CPV

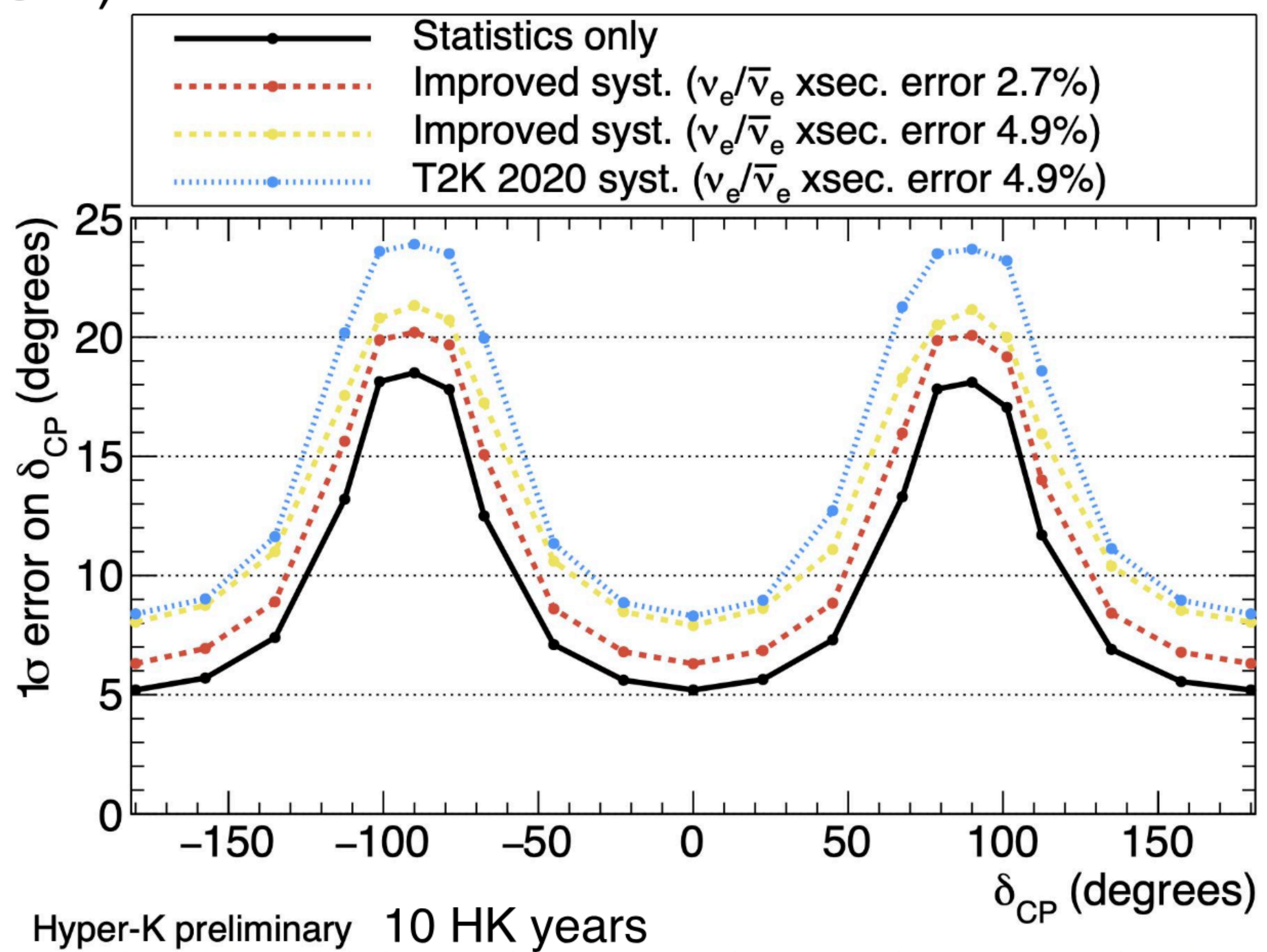


Projected sensitivity to CPV

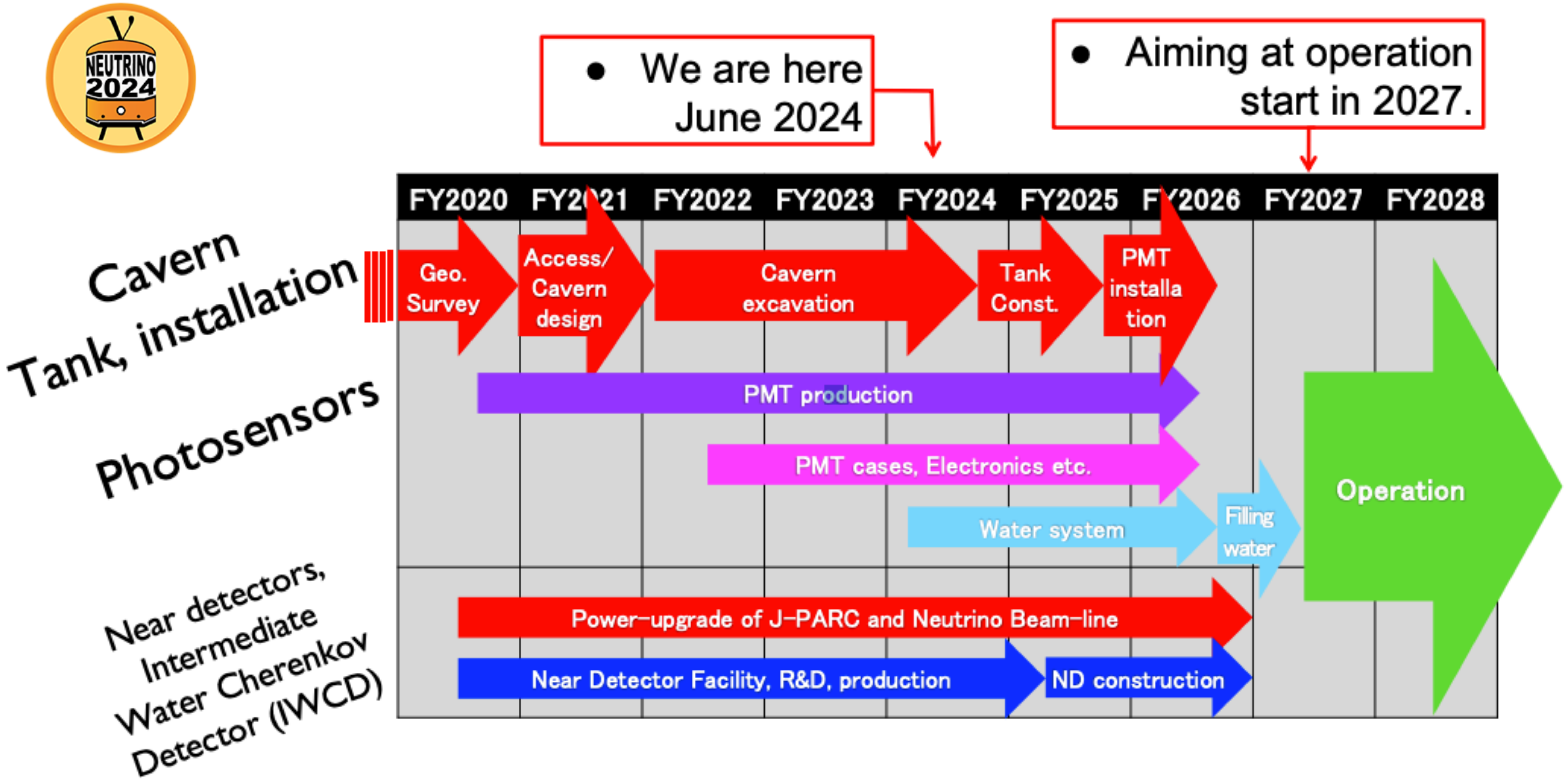


Fraction of δ_{CP} to exclude $sin\delta_{CP} = 0$

- Detect CP violation within two years if $\delta_{CP} = -\pi/2$
- Exclude CP conservation at the 5σ level for more than 60% of δ_{CP} values after 10 years
  - The speed at which CP violation can be discovered depends on the systematic error model
- 1σ resolution of δ_{CP} in 10 years: ~20º for δ_{CP}=-90º; ~6º for δ_{CP}=0º



Building Hyper-K: construction schedule



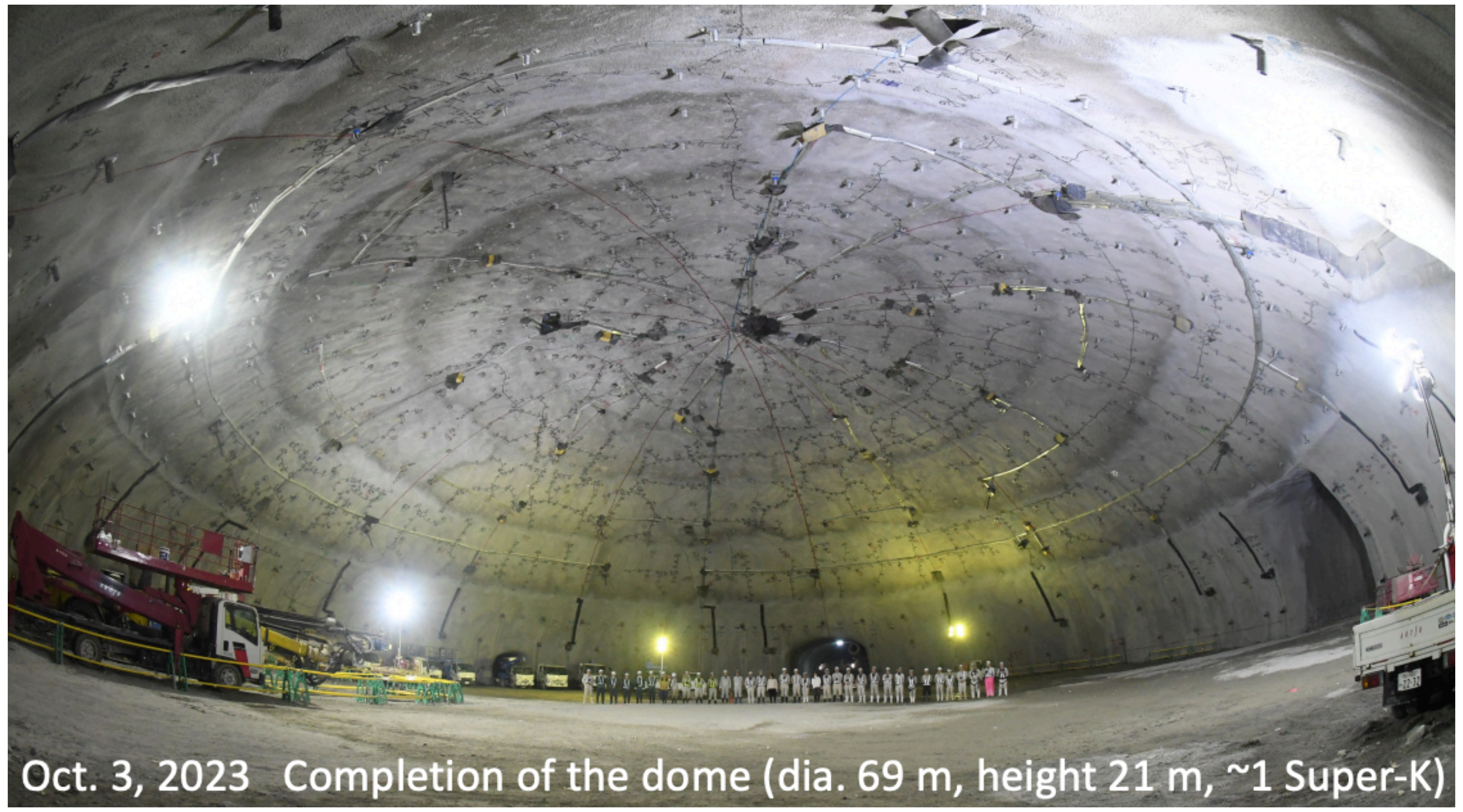
- We are here June 2024
- Aiming at operation start in 2027.

FY2020 FY2021 FY2022 FY2023 FY2024 FY2025 FY2026 FY2027 FY2028

Cavern Tank, installation: Geo. Survey → Access/ Cavern design → Cavern excavation → Tank Const. → PMT installation

Photosensors: PMT production; PMT cases, Electronics etc.; Water system → Filling water → Operation

Near detectors, Intermediate Water Cherenkov Detector (IWCD): Power-upgrade of J-PARC and Neutrino Beam-line; Near Detector Facility, R&D, production → ND construction

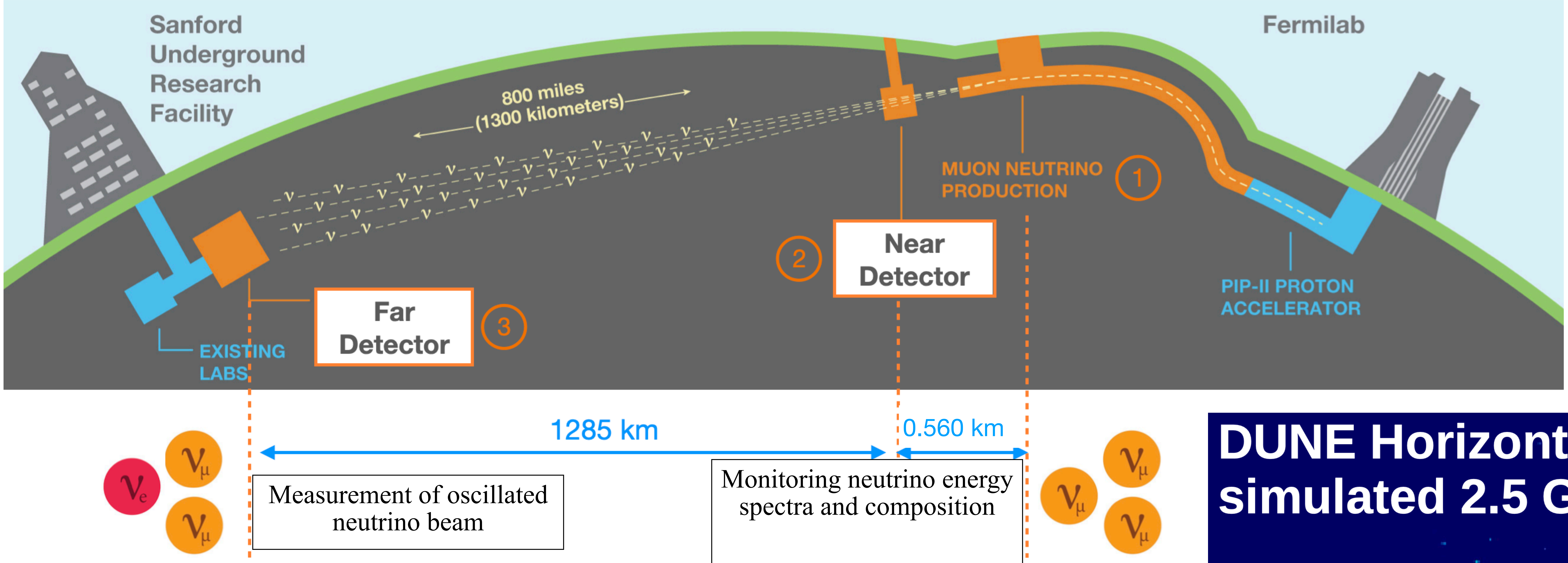


Oct. 3, 2023 Completion of the dome (dia. 69 m, height 21 m, ~1 Super-K)

Excavation of the HK cavern will be completed by the end of this year!

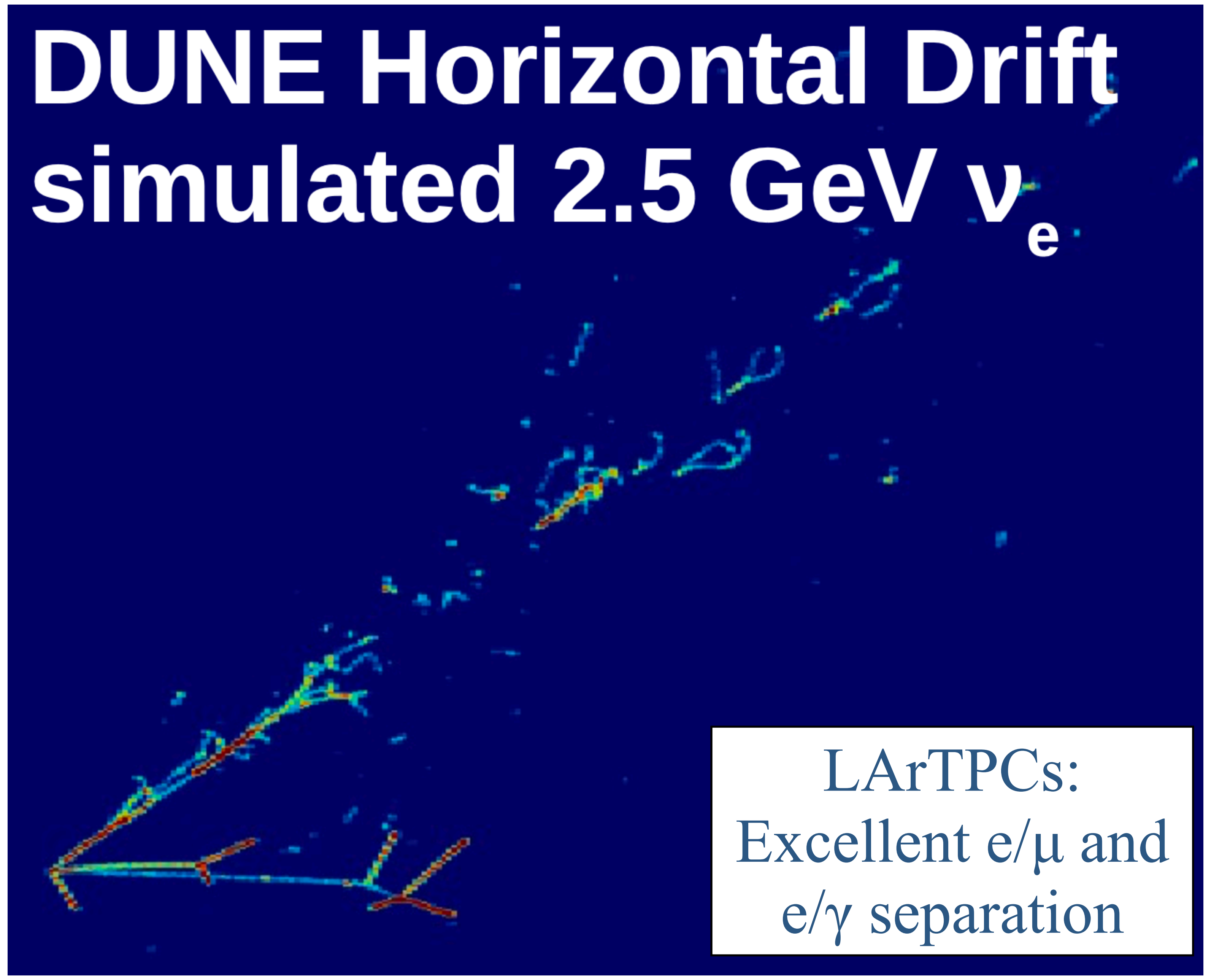
- Access tunnel and dome competed
- Cavern excavation underway
- PMT production on schedule
- First data taking planned for 2027

Deep Underground Neutrino Experiment (DUNE)



Measurement of oscillated neutrino beam

Monitoring neutrino energy spectra and composition



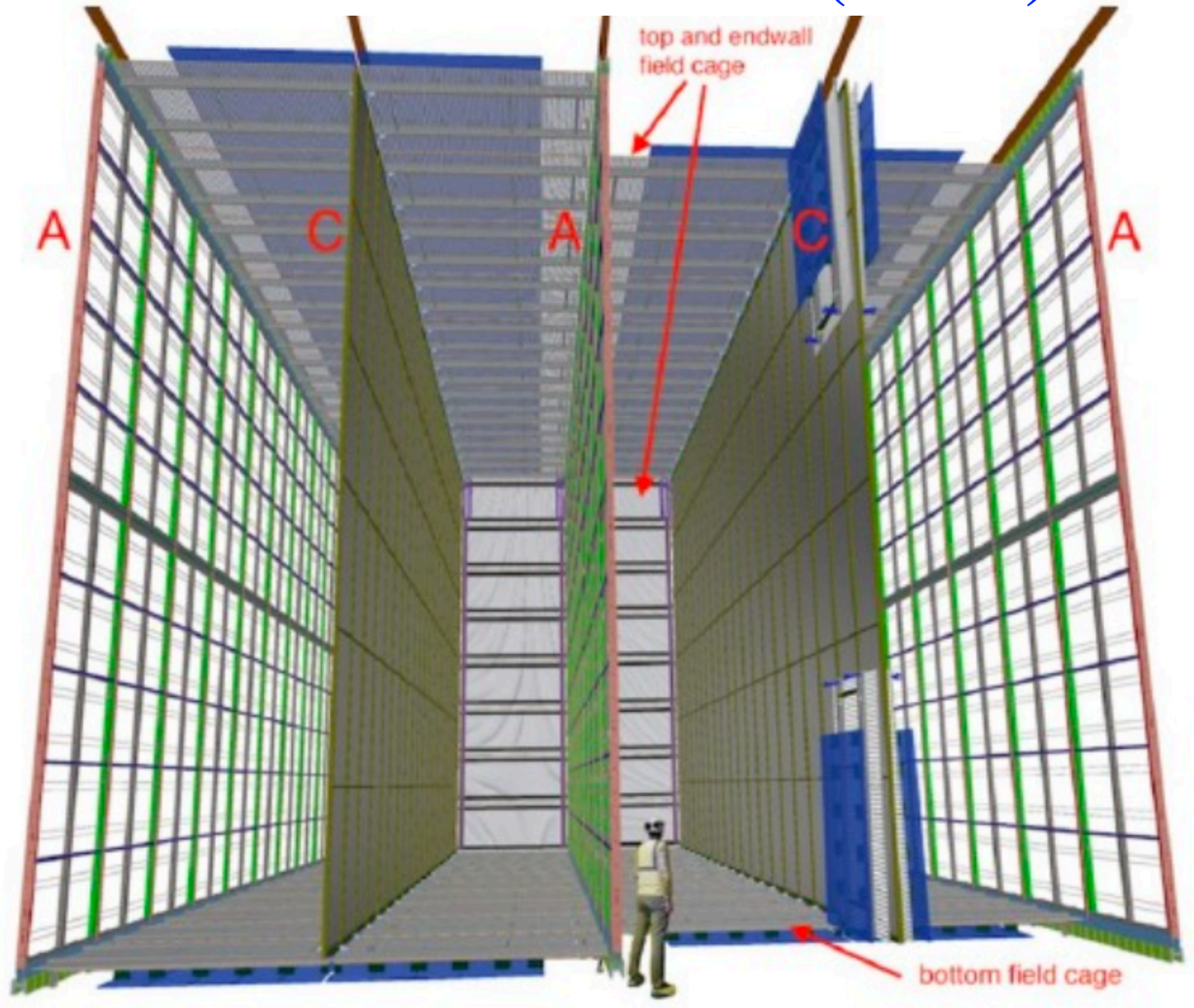
DUNE Horizontal Drift simulated 2.5 GeV ν_e

LArTPCs: Excellent e/μ and e/γ separation

- Powerful neutrino beam (>2 MW) will be sent from Fermilab (Chicago) to SURF (South Dakota) along 1300 km distance
- Four liquid argon far detector modules (≥40 kt fiducial mass) at 1.5 km deep underground
- Near detector complex at 560 m from the beam and 60 m underground

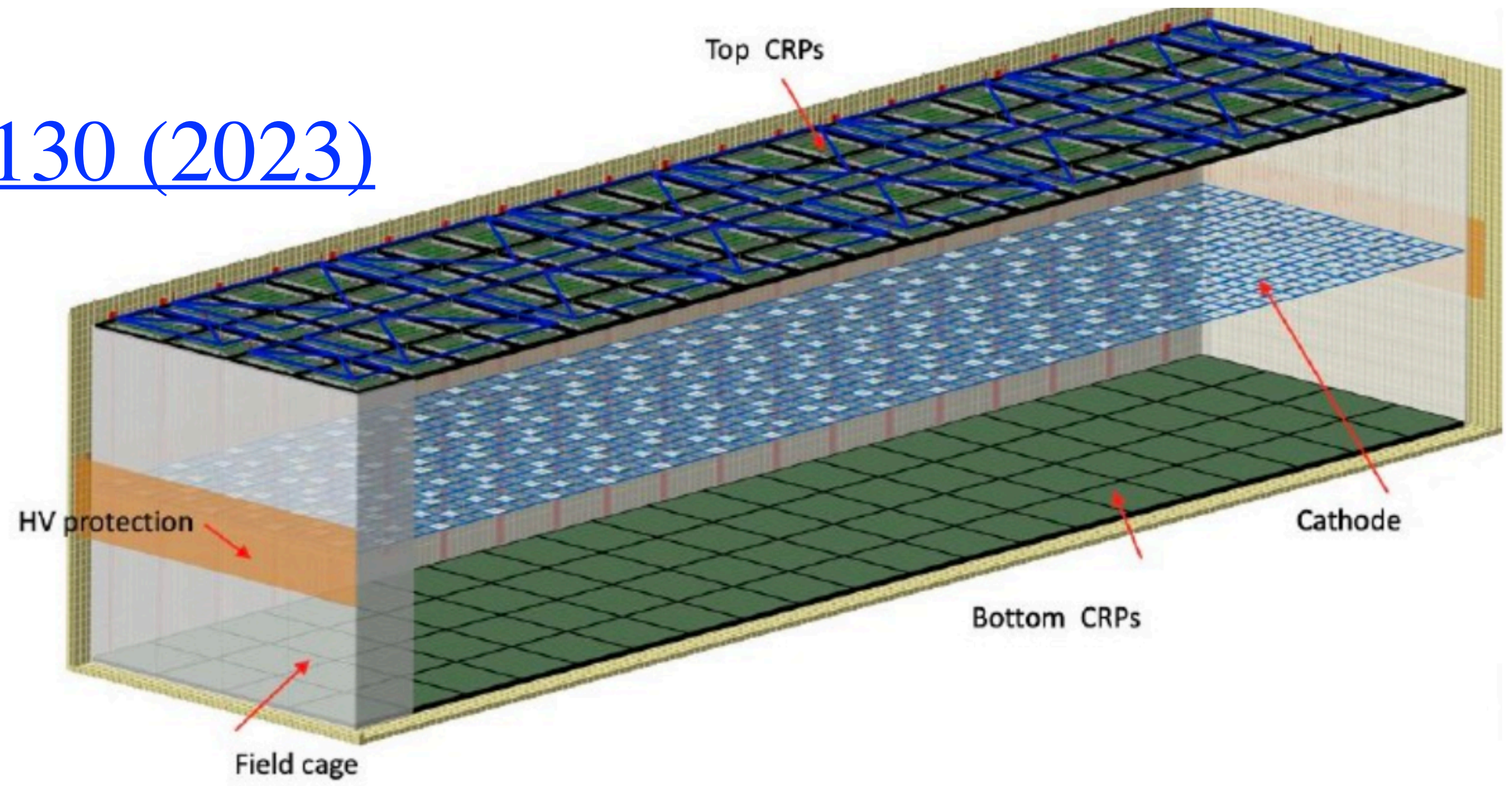
DUNE Detectors

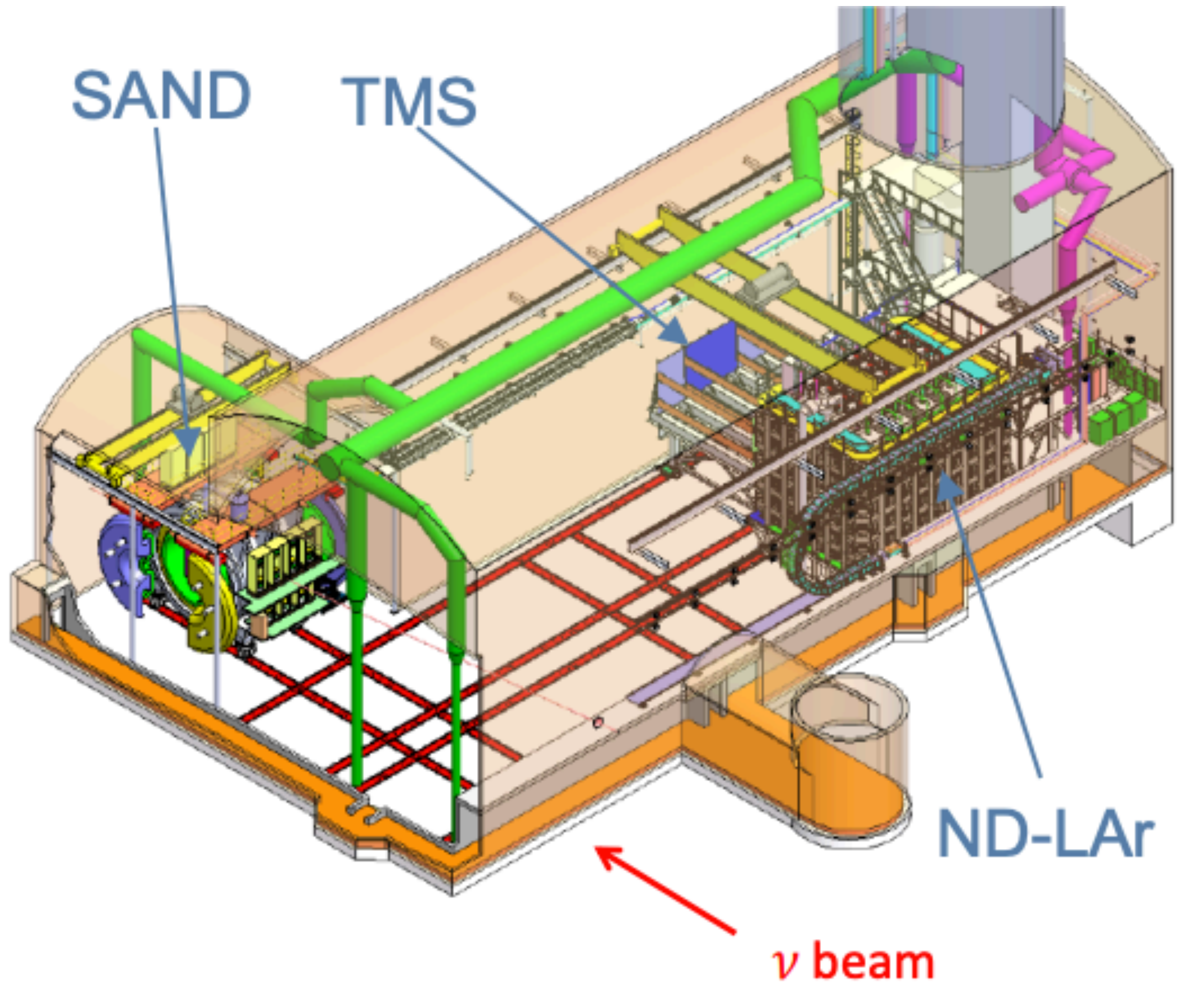
JINST 15 T08010 (2020)



- Far detectors TPC size: 12.0 m (heigh) × 14.0 m (width)× 58.2 m (length)
- Two different readout technologies for the Far Detectors:
  - Horizontal drift (HD) ⇒ wire readout planes, 4 drift regions (A|C|A|C|A with 3.5m drift)
  - Vertical drift (VD) ⇒ central cathode defining 2 drift regions (A|C|A with 6.25m drift), anode constructed of perforated PCBs with etched electrodes forming the charge readout

arXiv:2312.03130 (2023)

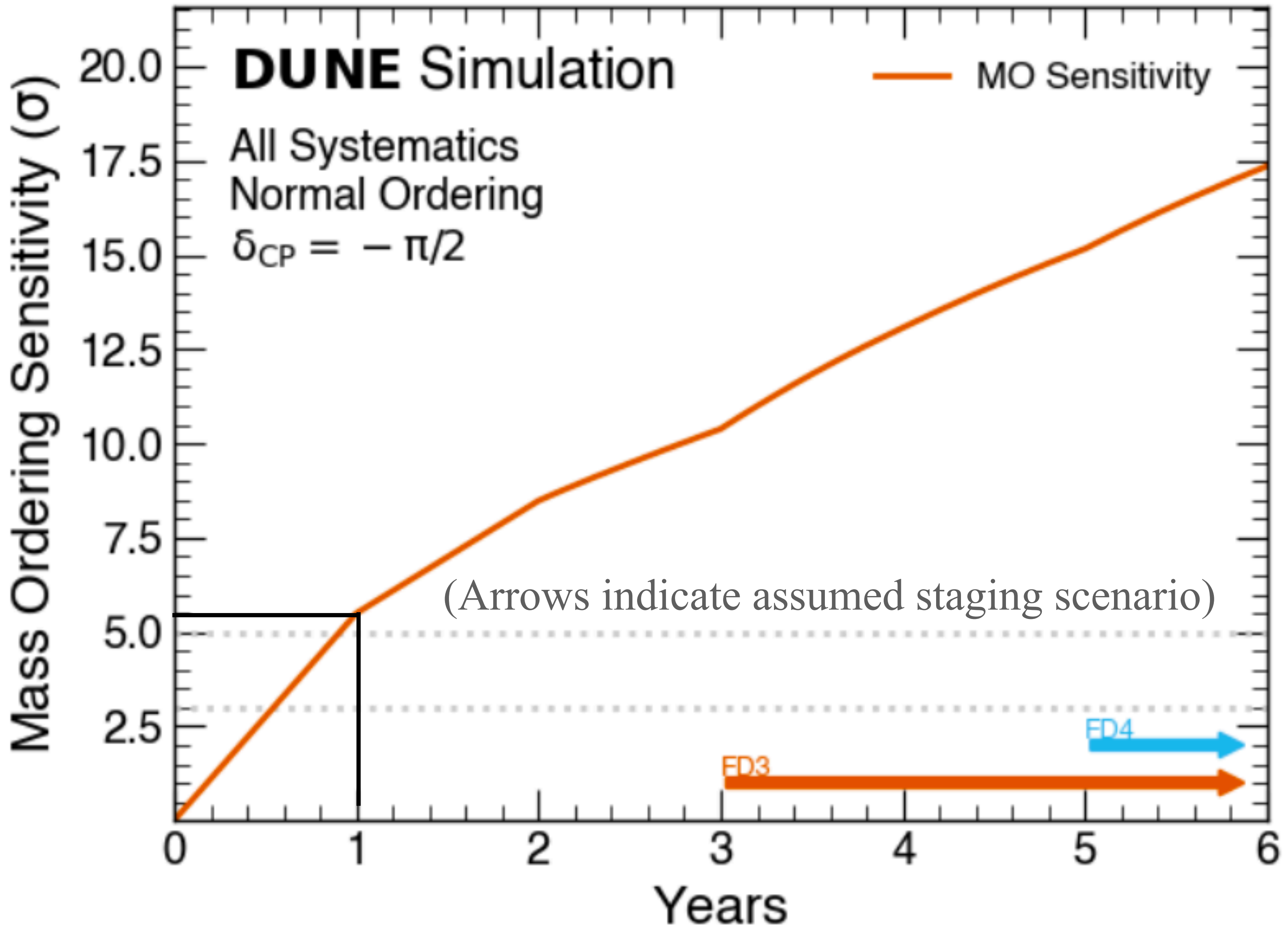


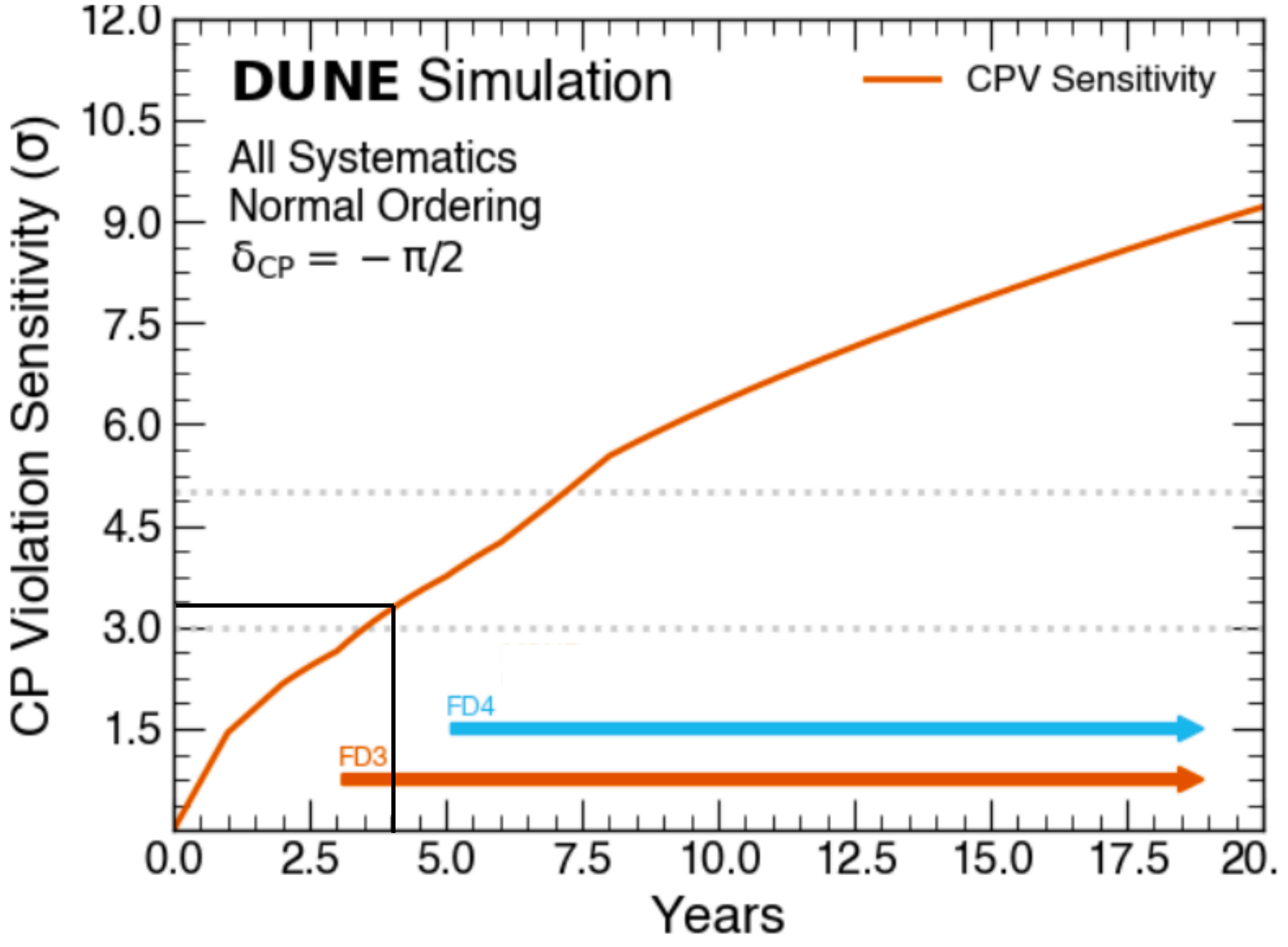


- VD easier to install ⇒
  - 1st DUNE module
  - Baseline design for modules 3 & 4
- Near detector complex with three different detection systems on and off axis:
  - Movable detector system (3.3º at 33m): LArTPC (ND-LAr) with muon spectrometer (TMS)
  - On-axis magnetized tracker + calorimeter (SAND) for beam monitoring and neutrino measurements

DUNE sensitivity to MO and CPV

Eur. Phys. J. C 80, 978 (2020)

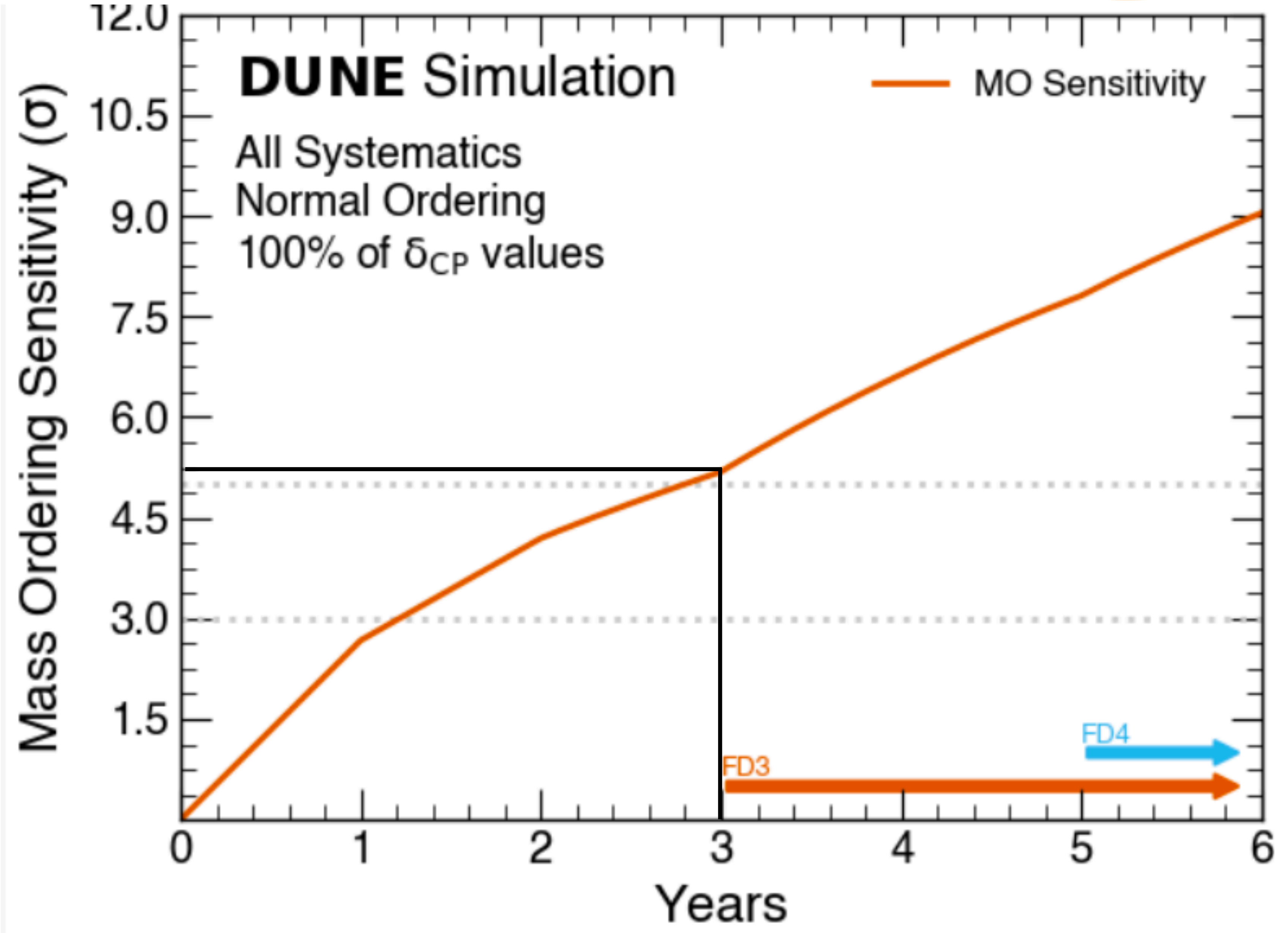


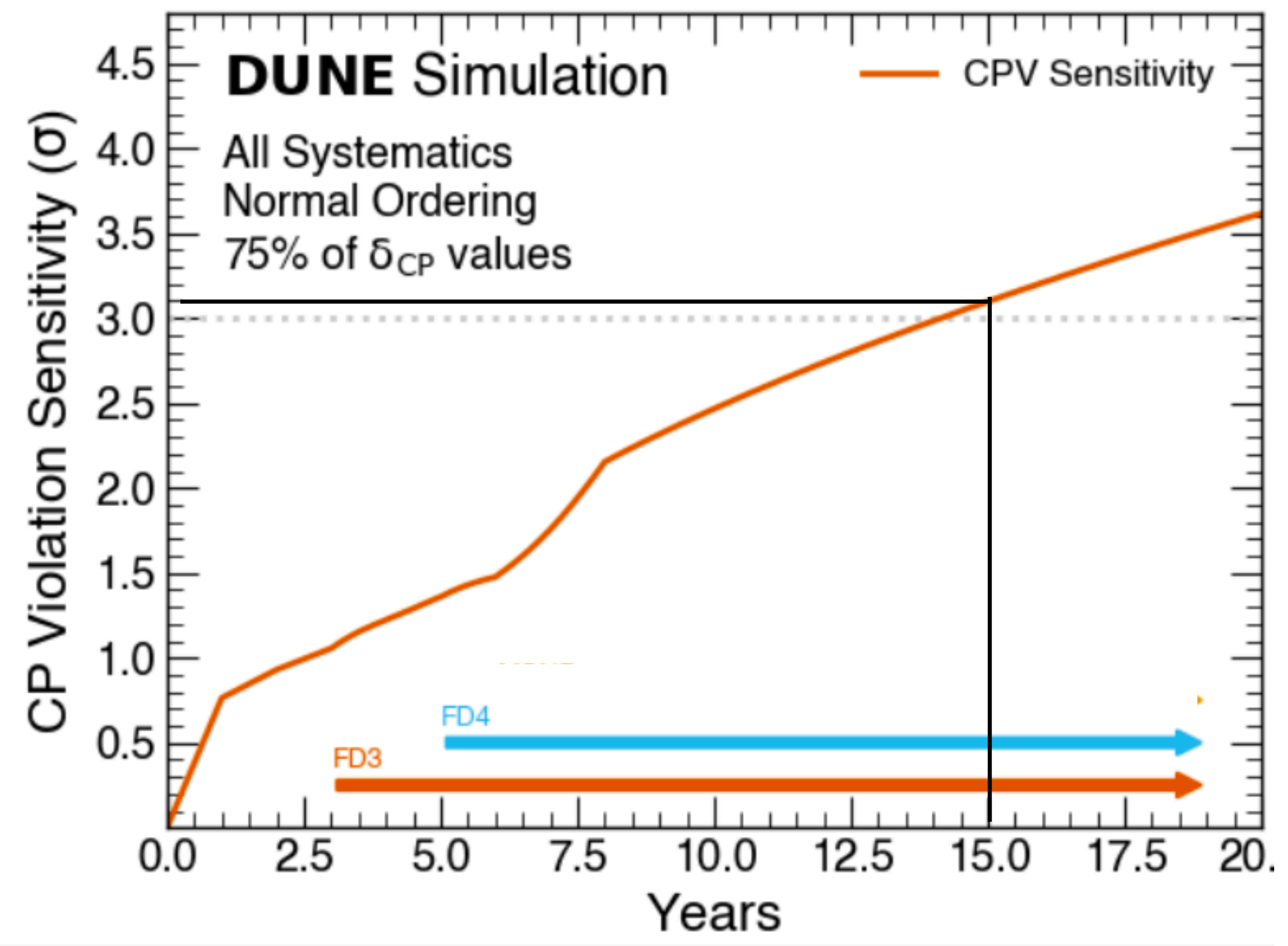


$\delta_{CP} = -\pi/2 \Rightarrow$ DUNE has >5σ MO sensitivity in 1 year and >3σ CPV sensitivity in 3.5 years.

For worst-case oscillation scenarios ⇒ DUNE has >5σ mass ordering sensitivity in 3 years.

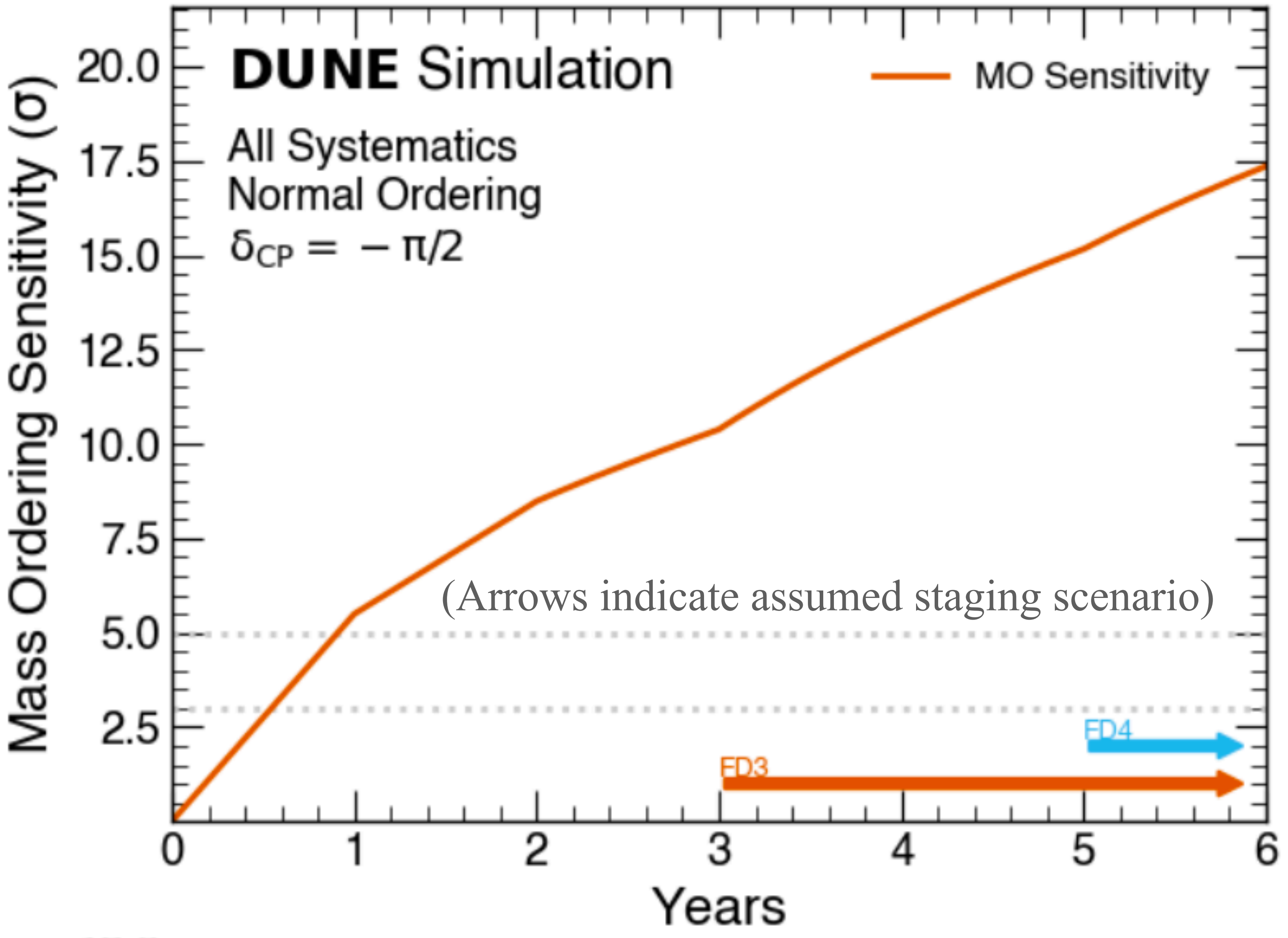
In long term (~15 years) ⇒ DUNE can establish CPV over 75% of δ_{CP} values at >3σ.



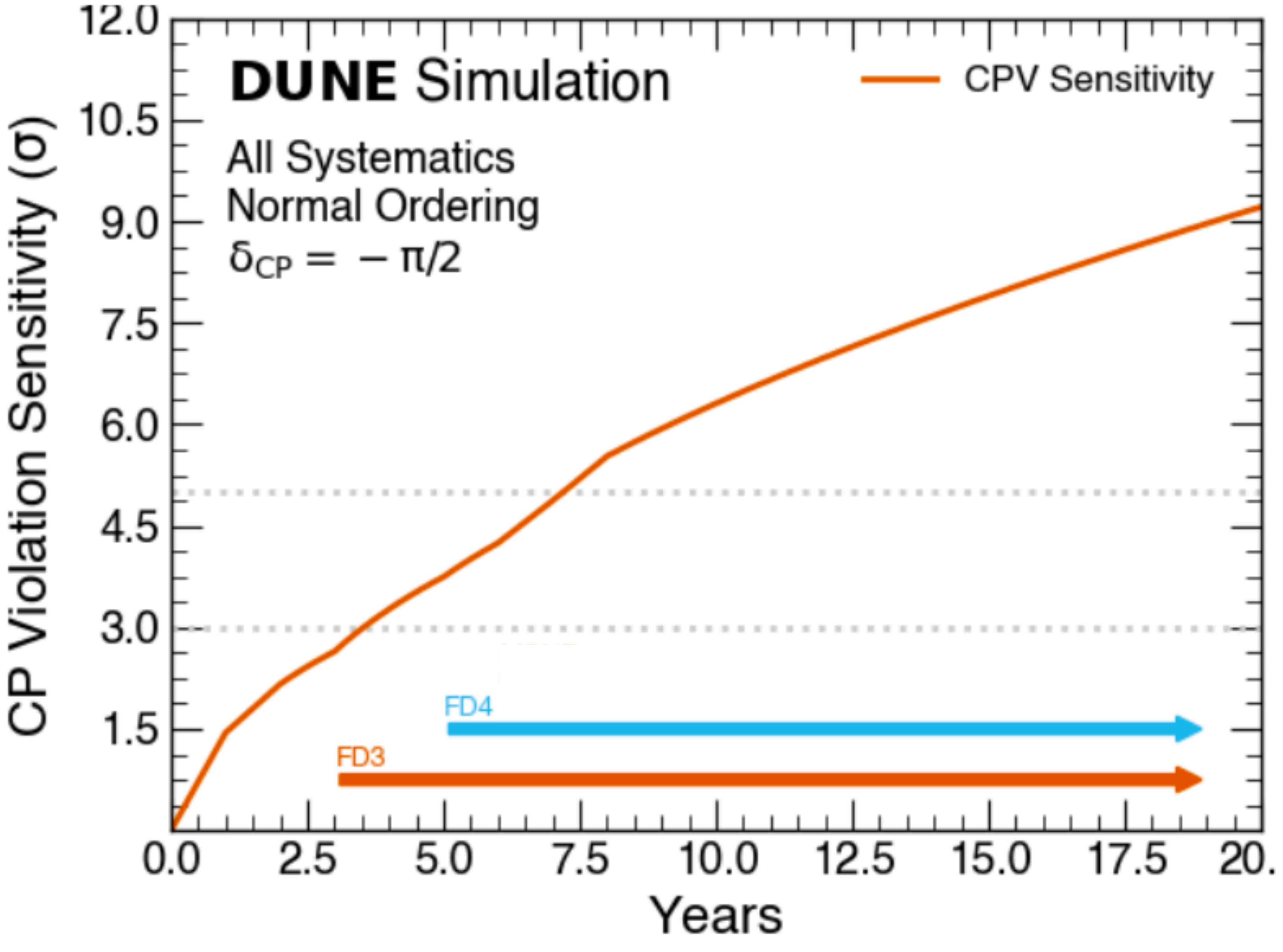


DUNE sensitivity to MO and CPV

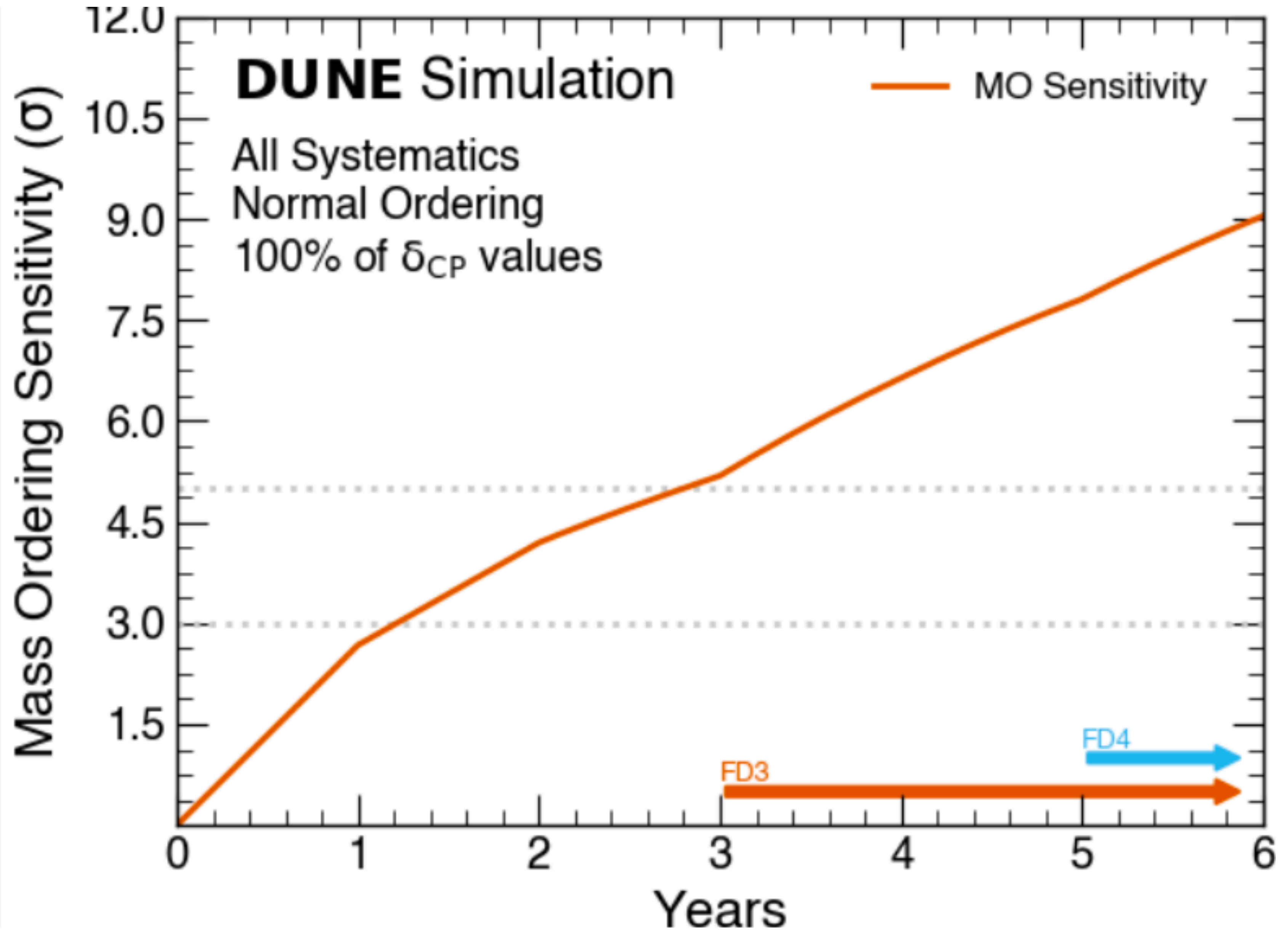
Eur. Phys. J. C 80, 978 (2020)



$\delta_{CP} = -\pi/2 \Rightarrow$ DUNE has $>5\sigma$ MO sensitivity in 1 year and $>3\sigma$ CPV sensitivity in 3.5 years.

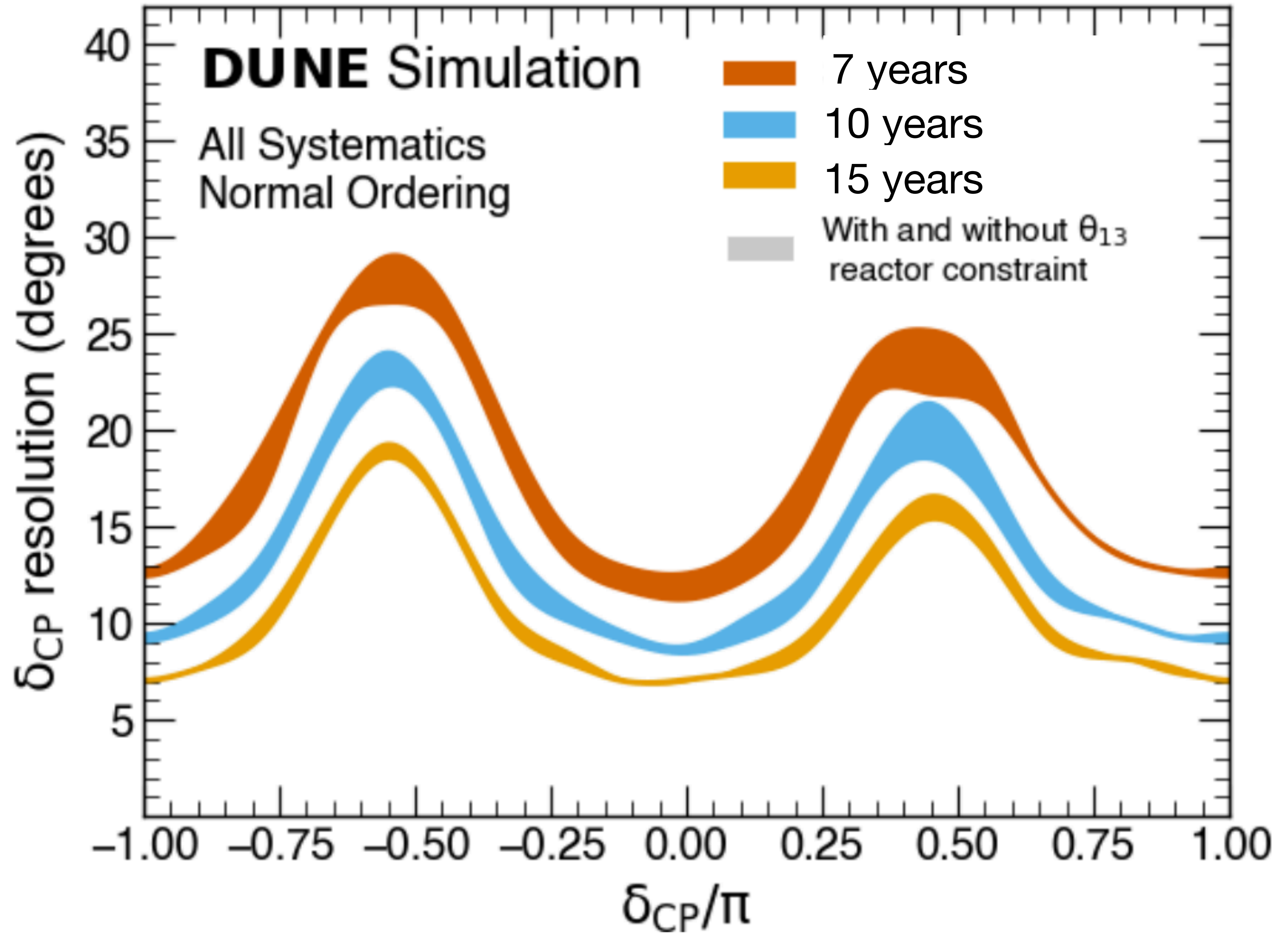


For worst-case oscillation scenarios ⇒ DUNE has $>5\sigma$ mass ordering sensitivity in 3 years.



In long term (~15 years) ⇒ DUNE can establish CPV over 75% of δ_{CP} values at $>3\sigma$.

δ_{CP} ultimate precision ~6°-16°



Building DUNE: construction schedule

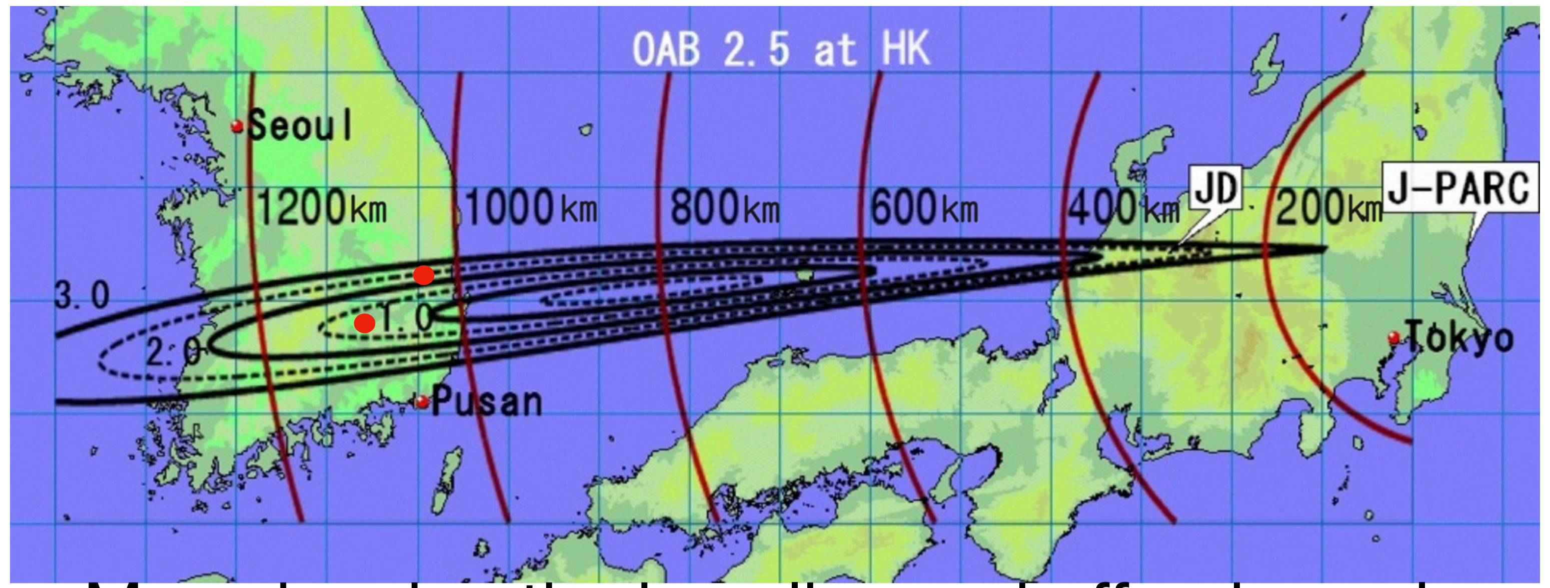

Transport to A Coruña harbour: April


Loaded on vessel ~mid May

- Far site excavation is complete
- Building & Site Infrastructure work continue until mid-2025
- Cryostat warm structure sent to US from CERN to be installed in 2025-26
- Far Detector installation in 2026-27
- Purge and fill with argon in 2028
- Physics in 2028 or early 2029
- Beam physics with Near Detector 2031

Ideas/Proposals to expand the physics reach of future LBL facilities

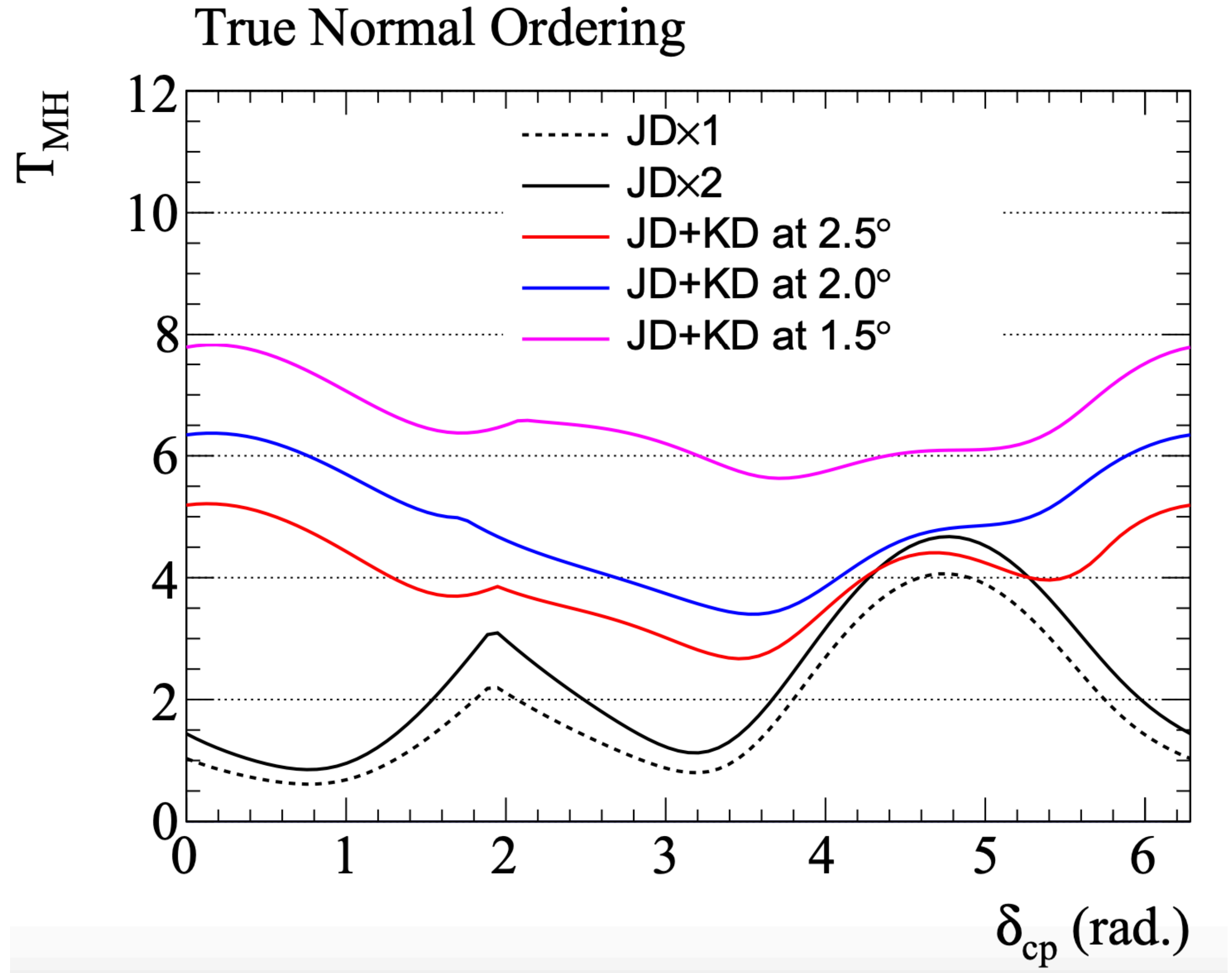
Korea Neutrino Observatory



Map showing the baseline and off-axis angle of the J-PARC beam in Japan and Korea

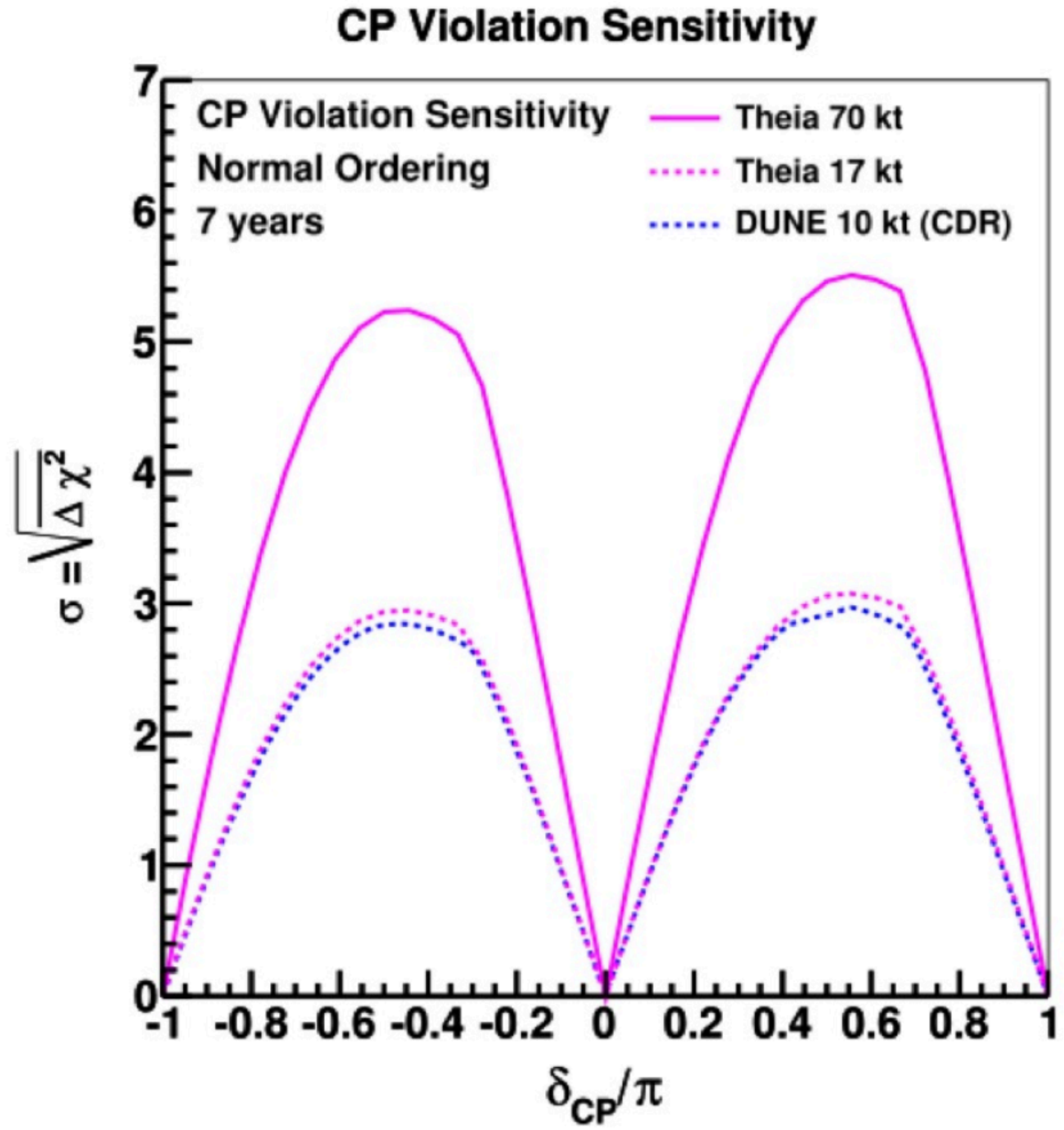
- South Korea exposed to the beam at a 1–3º OAA and BL 1000–1300 km

Significance to reject the wrong MO (10 years)



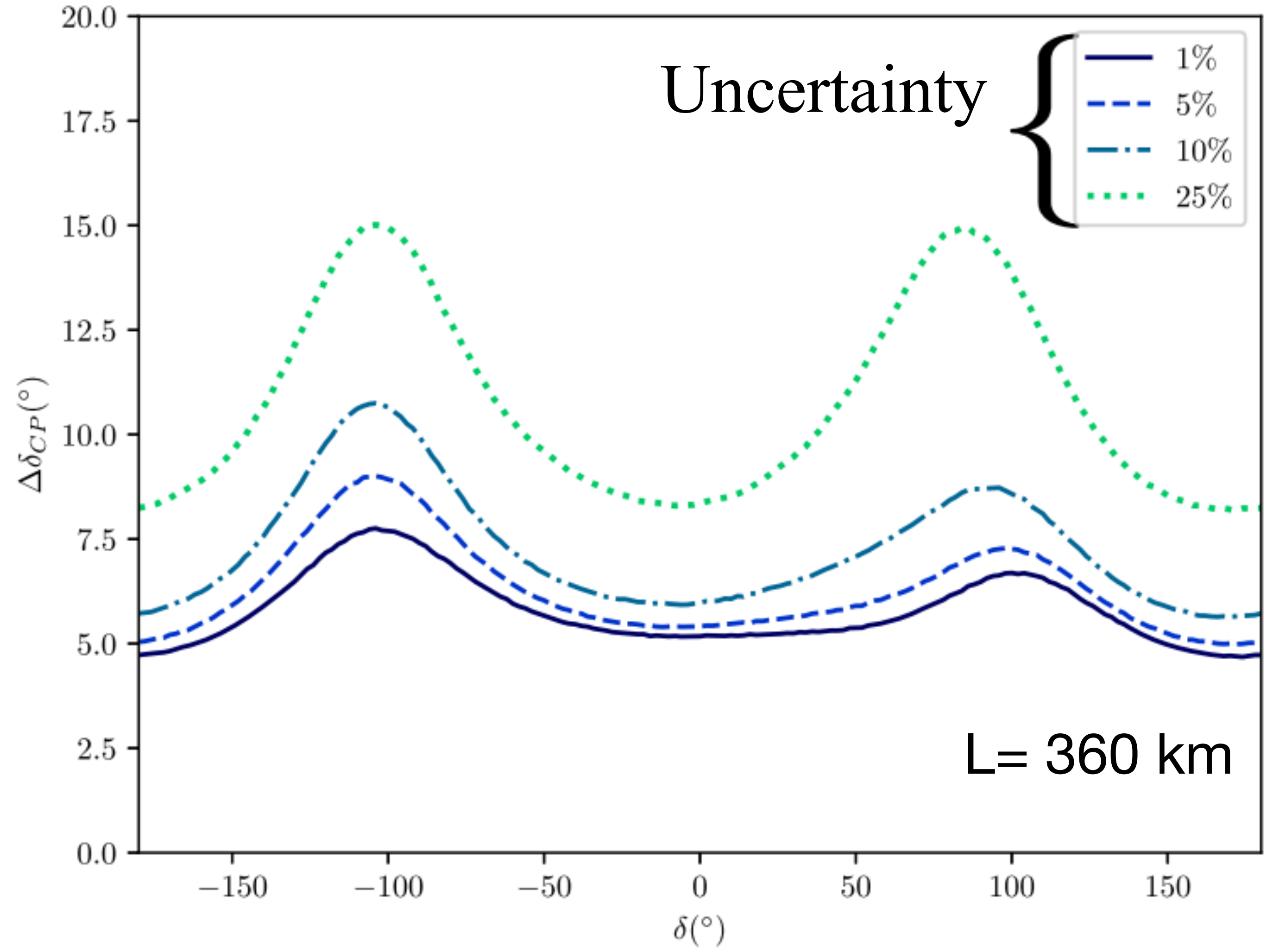
THEIA concept

- DUNE FD4 "Module of Opportunity" (design not closed)
- THEIA is a proposed large-scale neutrino detector designed to use both Cherenkov and scintillation signals
- Similar sensitivity for neutrino oscillation program as LAr:



European Spallation Source neutrino Super Beam

- Measuring CPV at the 2nd oscillation maximum: x2.5 higher sensitivity than at 1st maxima
- The facility is under construction in Lund, Sweden: 1st beam on target in 2025
- $\Delta\delta_{CP} < 8°$ for all δ_{CP} values for systematic uncertainties better than 5%



Conclusions

- Neutrino oscillations remain one of the priority topics in Particle and Astroparticle Physics.

- Long-baseline neutrino oscillation is described by a complex parameter space, which introduces degenerate effects that make the correct interpretation of the observed neutrino and antineutrino spectra difficult.
    - Complementary experiments (different size, medium target, technology, baselines) help to resolve the degeneracies introduced by the different parameters.

- The planned new generation of experiments, with more capable detectors and powerful (anti-)neutrino beams, is needed to measure the MO and for CPV discovery.

Other References

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- *Particle Data Group*, Phys. Rev. D 110, 030001 (2024)
- *A modern introduction to neutrino physics*, Frank F. Deppisch, IoP (2019)
- *Global analysis of three-neutrino oscillations*, Mariam Tórtola (IFIC), Neutrino Conference 2024
- *Long baseline neutrino oscillation phenomenology*, Elizabeth Worcester (BNL), Neutrino Conference 2024
- *T2K experiment status and plans*, Claudio Giganti (LPNHE), Neutrino Conference 2024
- *New neutrino oscillation results from NOvA with 10 years of data*, Jeremy Wolcott (Tufts University), Neutrino Conference 2024
- *JUNO*, Jun Cao (Institute of High Energy Physics), Neutrino Conference 2024
- *Hyper-Kamiokande*, Shigetaka Moriyama (Kamioka Observatory), Neutrino Conference 2024
- *DUNE*, Chris Marshall (University of Rochester), Neutrino Conference 2024
- *Other future Long Baseline Projects*, Alfons Weber (Johannes Gutenberg-Universität Mainz), Neutrino Conference 2024

Back-Up

Neutrino oscillations in matter (in brief)

$$sin^2 2\theta_m = \frac{sin^2 2\theta}{sin^2 2\theta + (cos2\theta - \xi)^2} \qquad \xi = \frac{2VE}{\Delta m^2} = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2} \qquad \Delta m^2_{eff} = \Delta m^2 \sqrt{sin^2 2\theta + (cos2\theta - \xi)^2}$$

- Mixing matrix can accordingly be expressed with the mixing angle in matter:

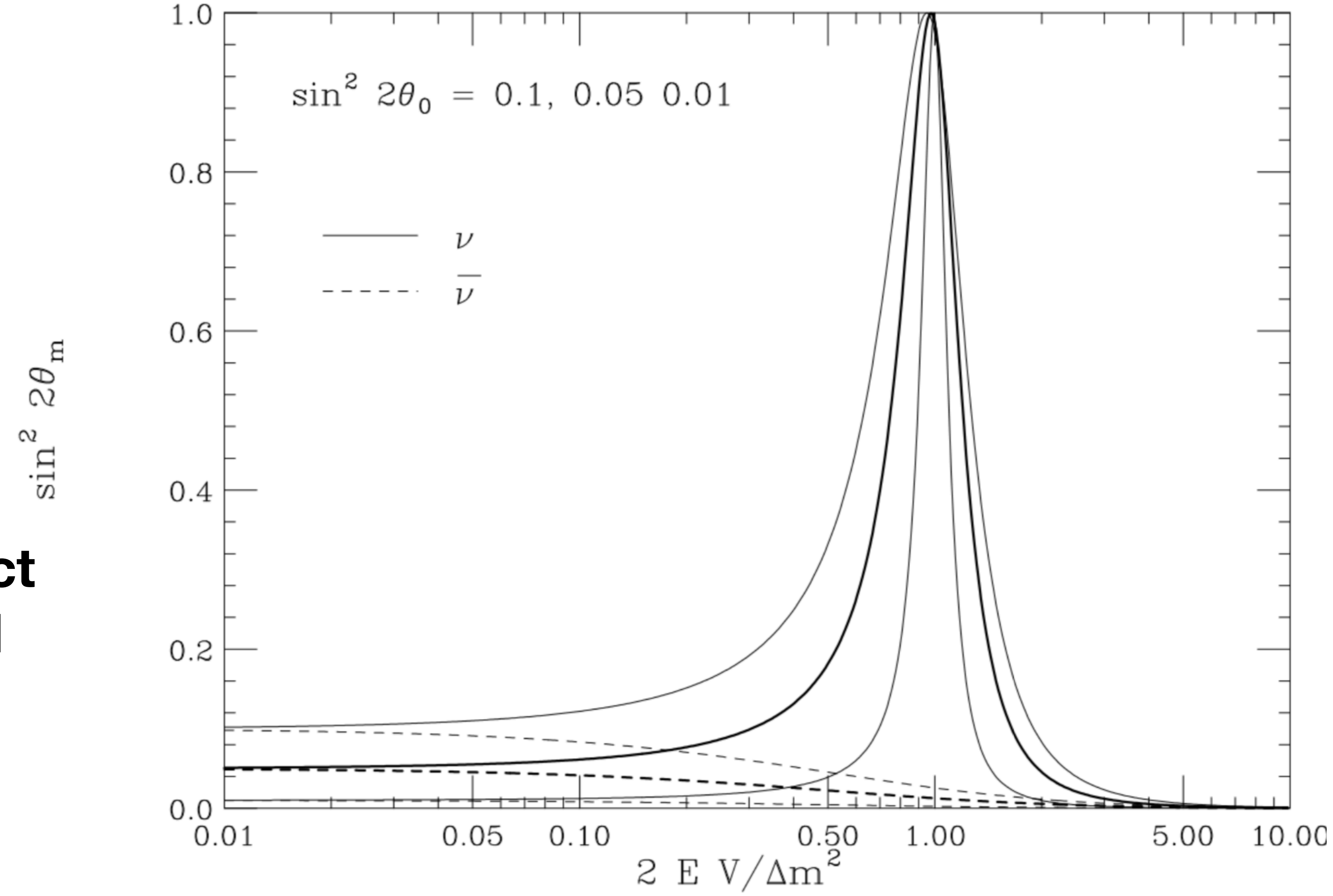
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} cos\theta_m & sin\theta_m \\ -sin\theta_m & cos\theta_m \end{pmatrix} = \begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix} \qquad P_m(\nu_e \rightarrow \nu_\mu) = sin^2 2\theta_m sin^2 \frac{\Delta m^2_{eff} L}{4E}$$

- In the low density limit ($\xi \rightarrow 0$): recover the vacuum case

- The mixing amplitude becomes maximal ($\theta_m = \pi/4$) if:

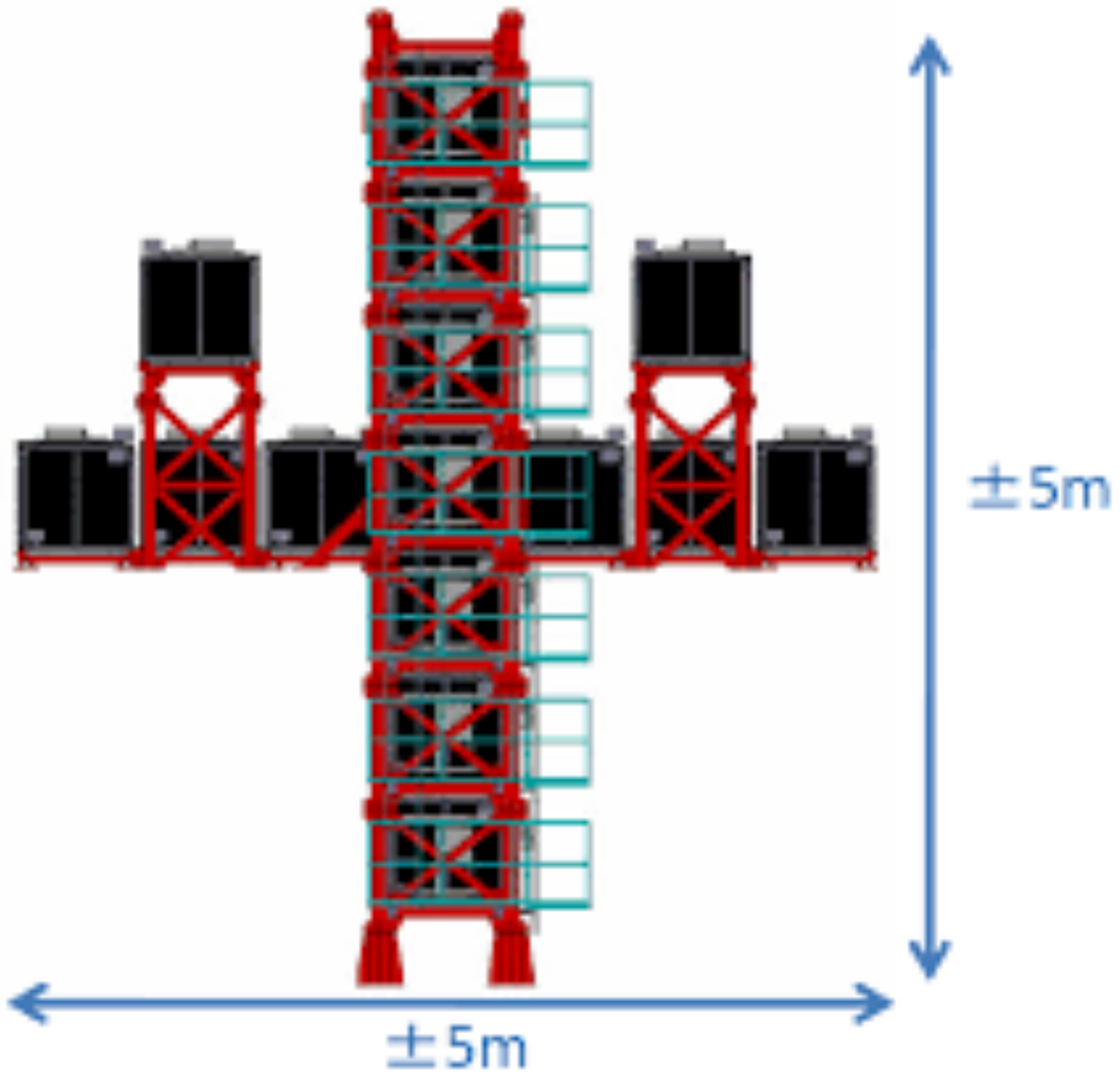
$$\left.\begin{aligned} \xi = cos2\theta \ \Rightarrow 2VE = \Delta m^2 cos2\theta \\ N_e = \frac{\Delta m^2 cos2\theta}{2\sqrt{2}EG_F} \end{aligned}\right\}$$

Resonance! MSW effect (Mikhev, Smirnov and Wolfenstain)

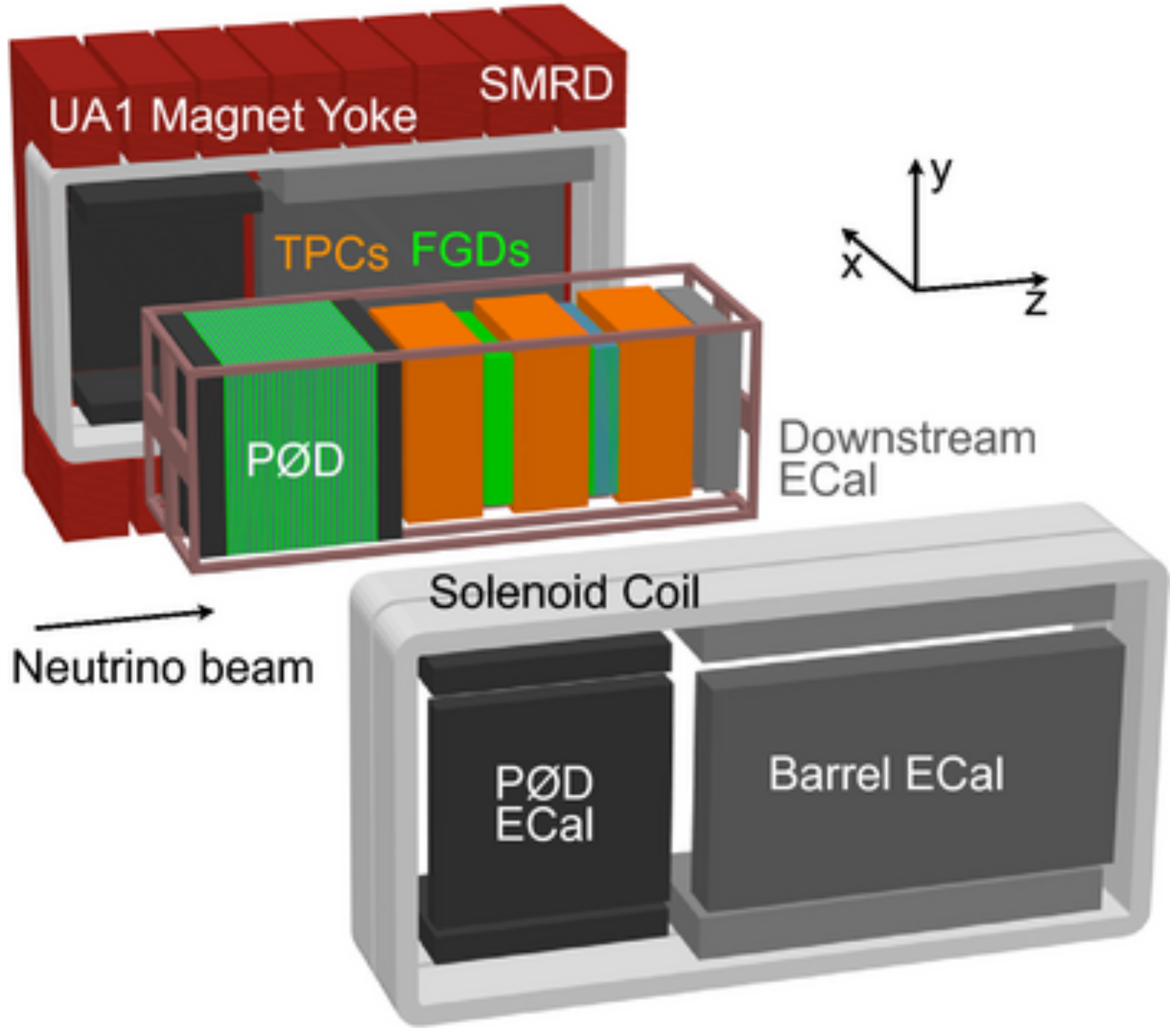


T2K Near Detectors

- Except for the Time Projection Chambers in ND280, the entire active material (enabling particle tracking) of the near detectors is plastic scintillator.
- **INGRID detector:**
  - 16 identical modules arranged in the shape of a cross (10 m).
  - A single module consists of alternating layers of iron and a plastic scintillator.



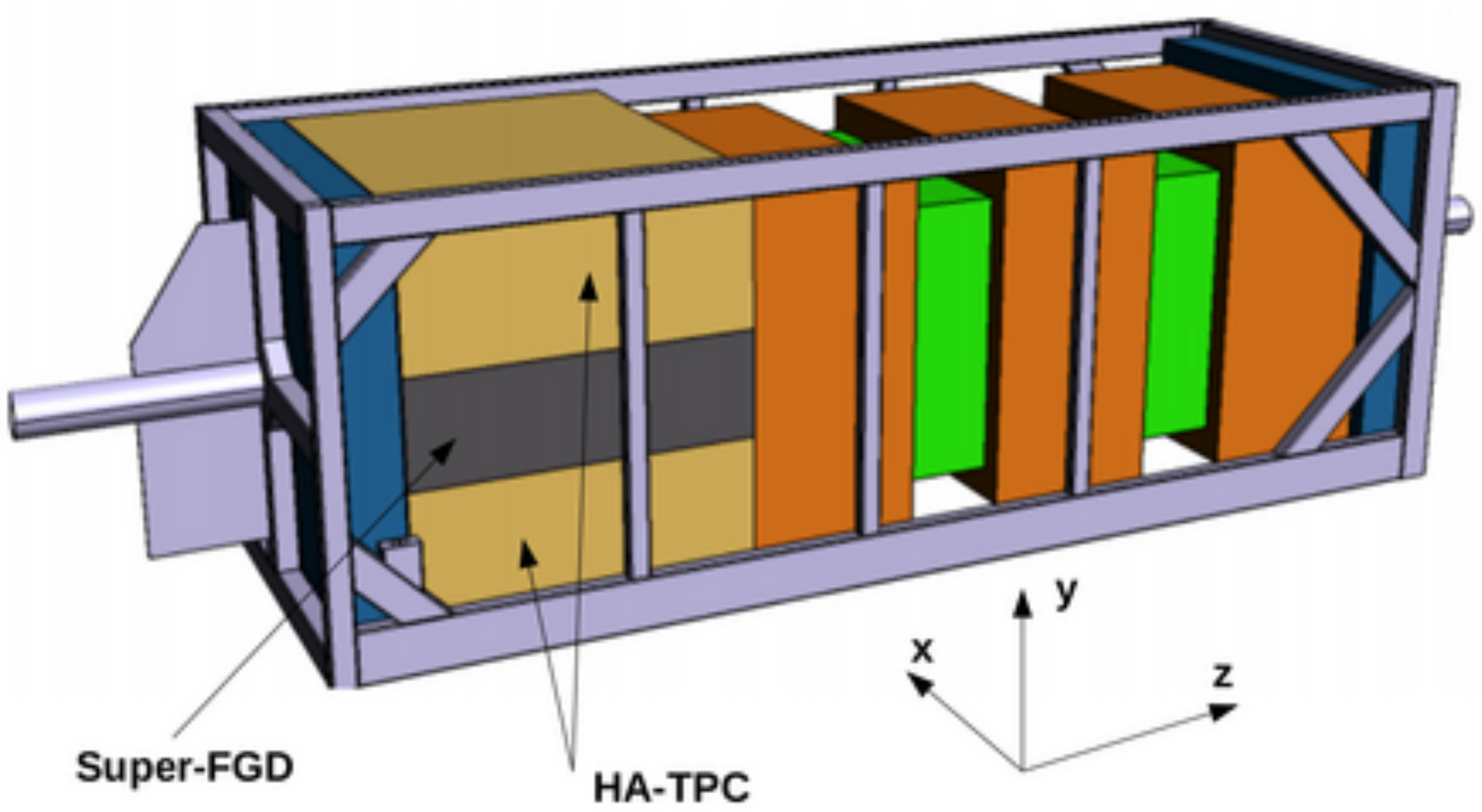
- **ND280 detector.** A set of inner sub-detectors:
  - Pi-Zero (P0D) detector (plastic scintillator module planes interleaved with thick bags fillable of water and thick brass sheets)



  - A tracker with 2 Fine-Grained Detectors interleaved with 3 Time Projection Chambers:
    - TPC: argon-based drift gas under atmospheric pressure and readout with MicroMegas modules
    - FGD: 1st composed of scintillator layers only, while 2nd composed of alternating layers of scintillator and water
  - Electromagnetic Calorimeter (ECal): surrounds the inner detectors (P0D, TPCs, FGDs) and consists of scintillator layers sandwiched with lead absorber sheets
  - The Side Muon Range Detector (SMRD): consists of scintillator modules which are inserted into the gaps in the magnet.

T2K Near Detectors: Upgraded

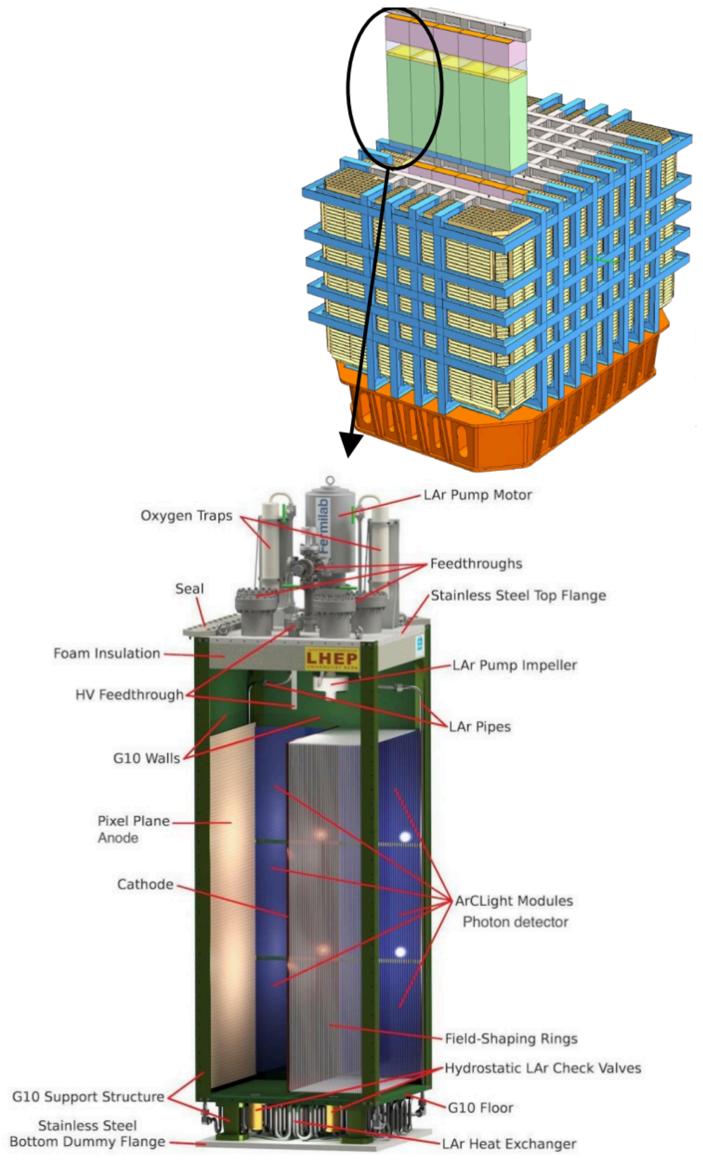
- **Goals of the upgrade:**
  - Detection thresholds need to be lowered
  - Increase the angular acceptance and the efficiency to discriminate FW and BW going tracks
  - Larger fiducial mass



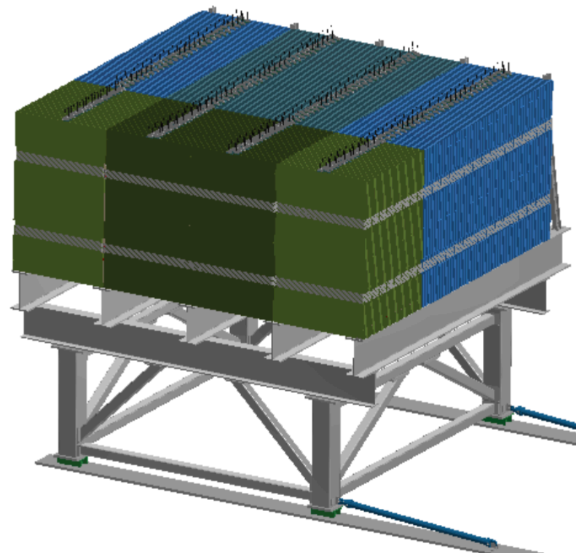
- **ND280 upgrade:**
  - The existing tracker will maintain its sandwiched structure but with a larger fiducial volume (more ν-interactions)
  - P0D sub-detector will be replaced by three novel sub-detectors:
    - a scintillating 3D target (Super Fine-Grained Detector or SuperFGD): 2 million 1 cm^3 scintillating polystyrene cubes
    - two new TPCs on top and below the SuperFGD (High-Angle TPCs or HATPCs): design similar to that of the existing TPCs
    - six Time-of-Flight (TOF) detectors surrounding the new structure: a series of plastic scintillator layers designed to identify the particle direction sense through the measurement of the time of flight for each crossing track with a timing resolution of the order of 140 ps.

DUNE Near Detectors

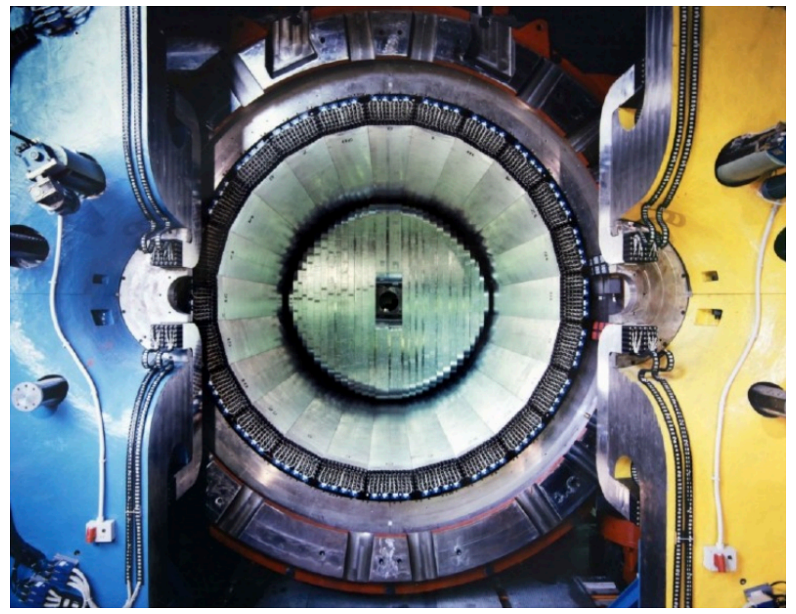
- **ND-LAr:**
  - Modular array (7x5) of liquid argon TPC
    - Reduces pileup
  - Pixelated readout
    - Direct to 3D images
  - Modules optically isolated
  - Provides sample of interactions on the same target as far detector



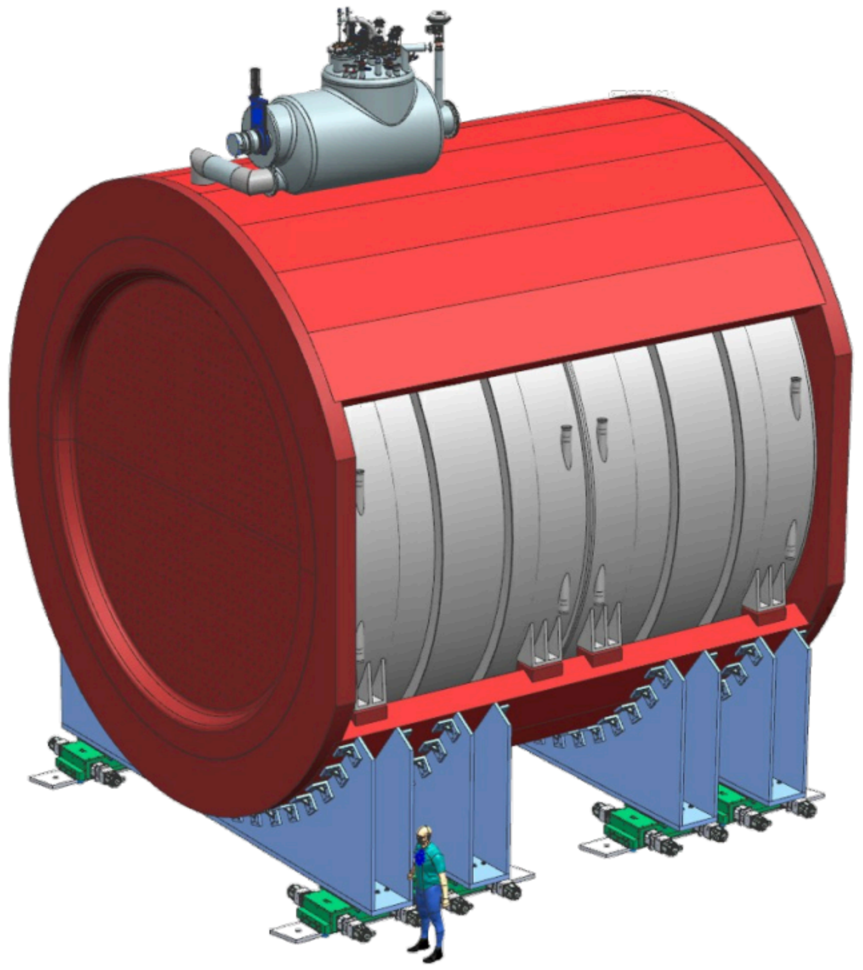
- **TMS (The Muon Spectrometer):**
  - Catch muons that exit ND-LAr
  - Steel/scintillator layers
  - Magnetic field provides sign-selection
  - Muon momentum measured from range and/or curvature



- **SAND (System for on-Axis Neutrino Detection):**
  - Remains on-axis
    - Sensitive to any changes to beam conditions on short timescales
  - Low density tracker/ spectrometer
  - Argon target region
  - Solenoid magnet repurposed from KLOE



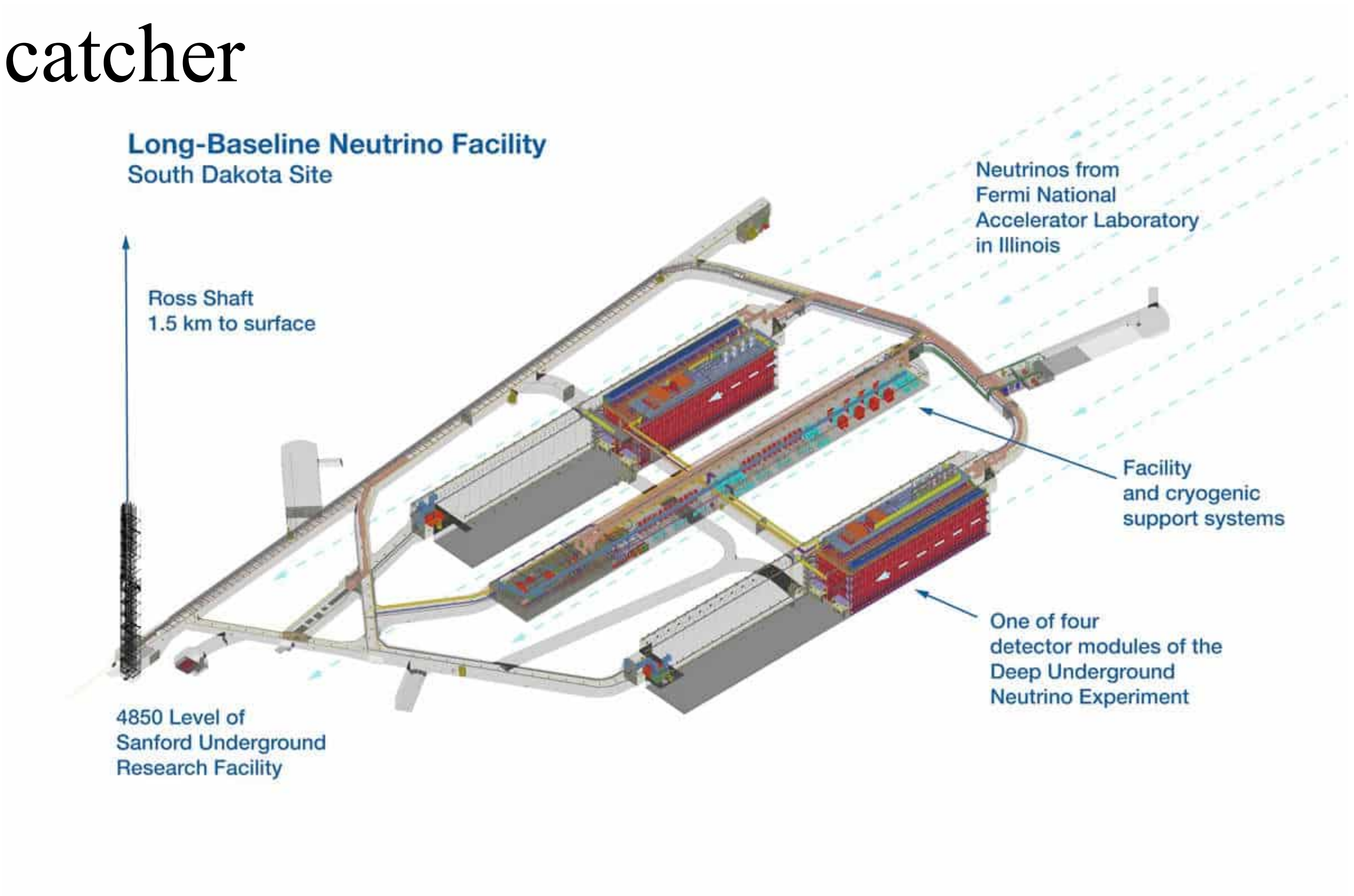
- **Future Upgrade Potential:**
  - High-pressure gas TPC a promising option
  - Lower density than liquid argon
    - Lower thresholds
    - Less scattering → cleaner measurement of pions and electrons
  - If magnetised, it can replace TMS



DUNE Phases

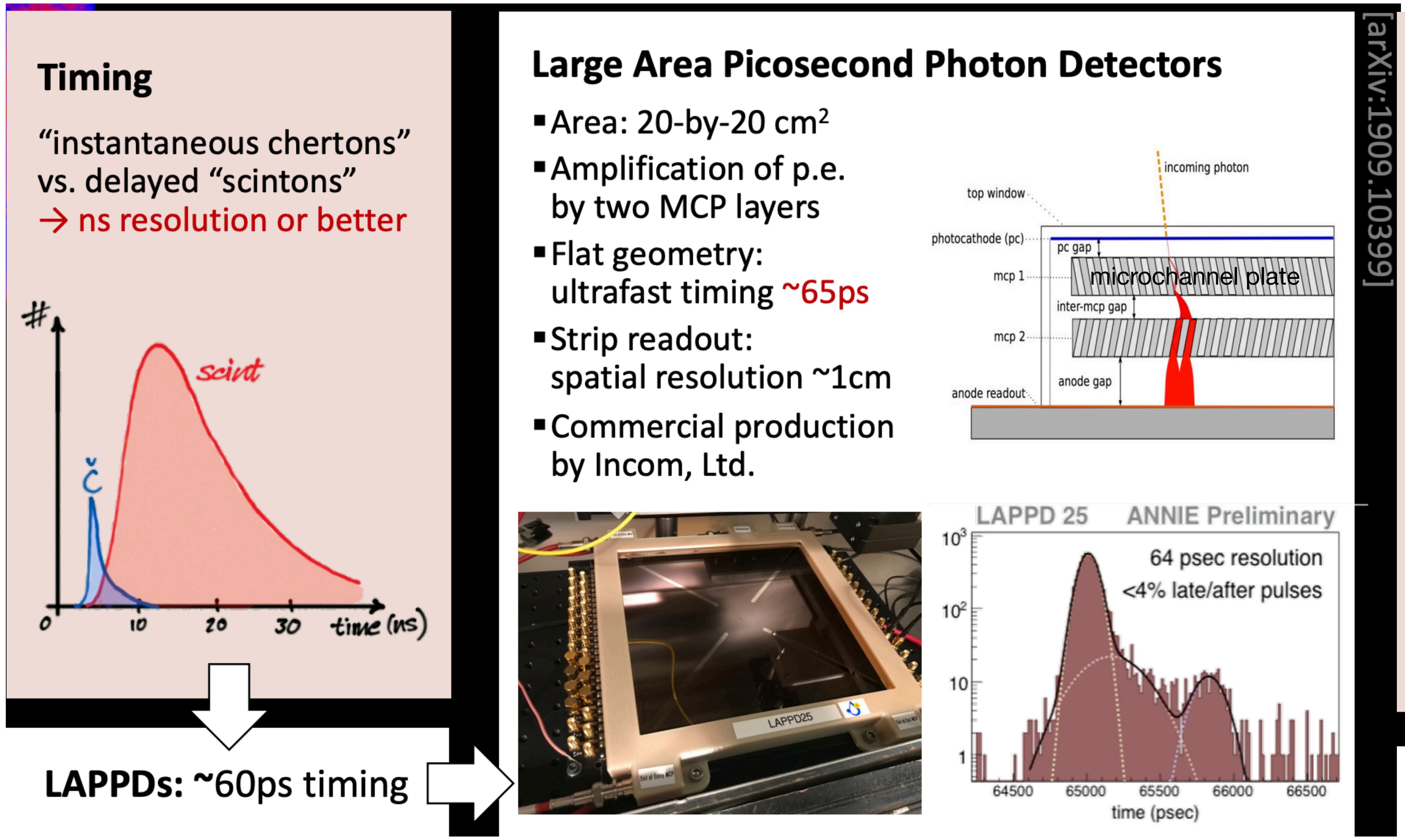
- **DUNE Phase I** (2026 start detector installation; 2029 physics; 2031 beam + ND):
  - Full near + far site facility and infrastructure
  - Two 17 kt LArTPC modules
  - Upgradeable 1.2 MW neutrino beamline
  - Movable LArTPC near detector with muon catcher
  - On-axis near detector

- **DUNE Phase II:**
  - Two additional FD modules (≥40 kt fiducial in total)
  - Beamline upgrade to >2 MW (ACE-MIRT)
  - More capable Near Detector (ND-GAr)



P5 report endorses FD3, ACE-MIRT, and MCND in the next decade, and R&D toward FD4

How to resolve the Cherenkov/scintillation signals?



Timing

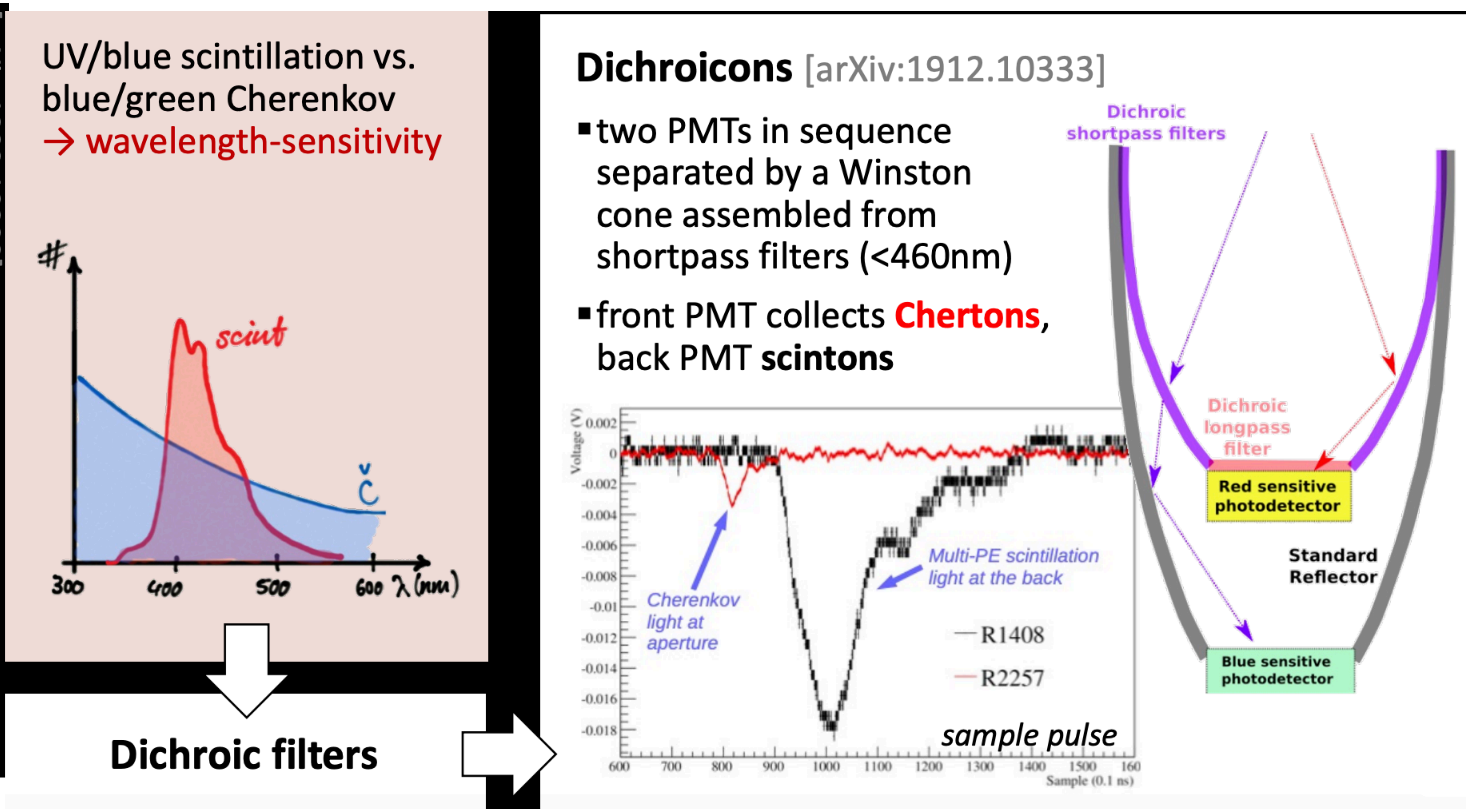
“instantaneous chertons” vs. delayed “scintons”
→ ns resolution or better

LAPPDs: ~60ps timing

Large Area Picosecond Photon Detectors

- Area: 20-by-20 cm^2
- Amplification of p.e. by two MCP layers
- Flat geometry: ultrafast timing ~65ps
- Strip readout: spatial resolution ~1cm
- Commercial production by Incom, Ltd.

[arXiv:1909.10399]



UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity

Dichroic filters

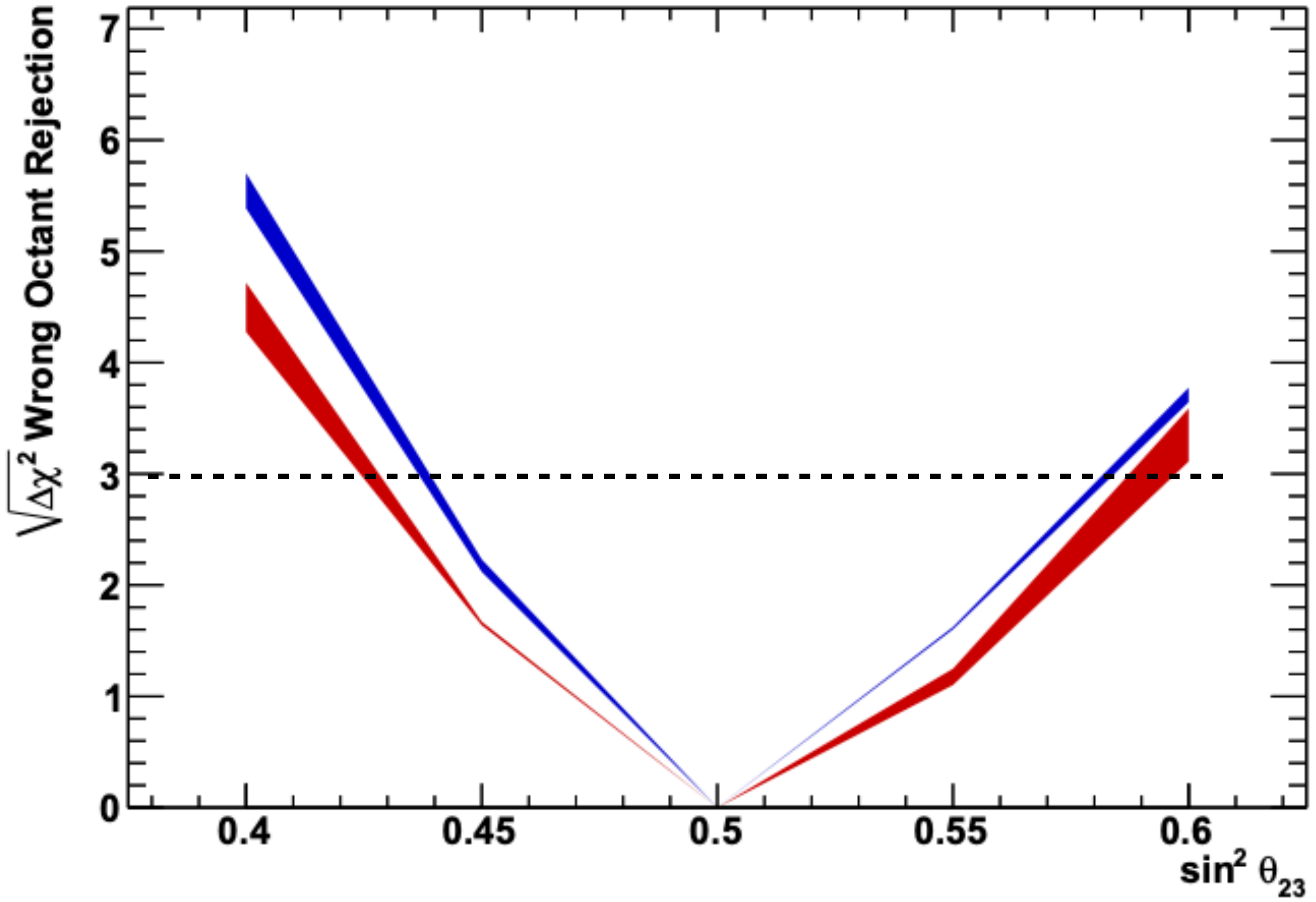
Dichroicons [arXiv:1912.10333]

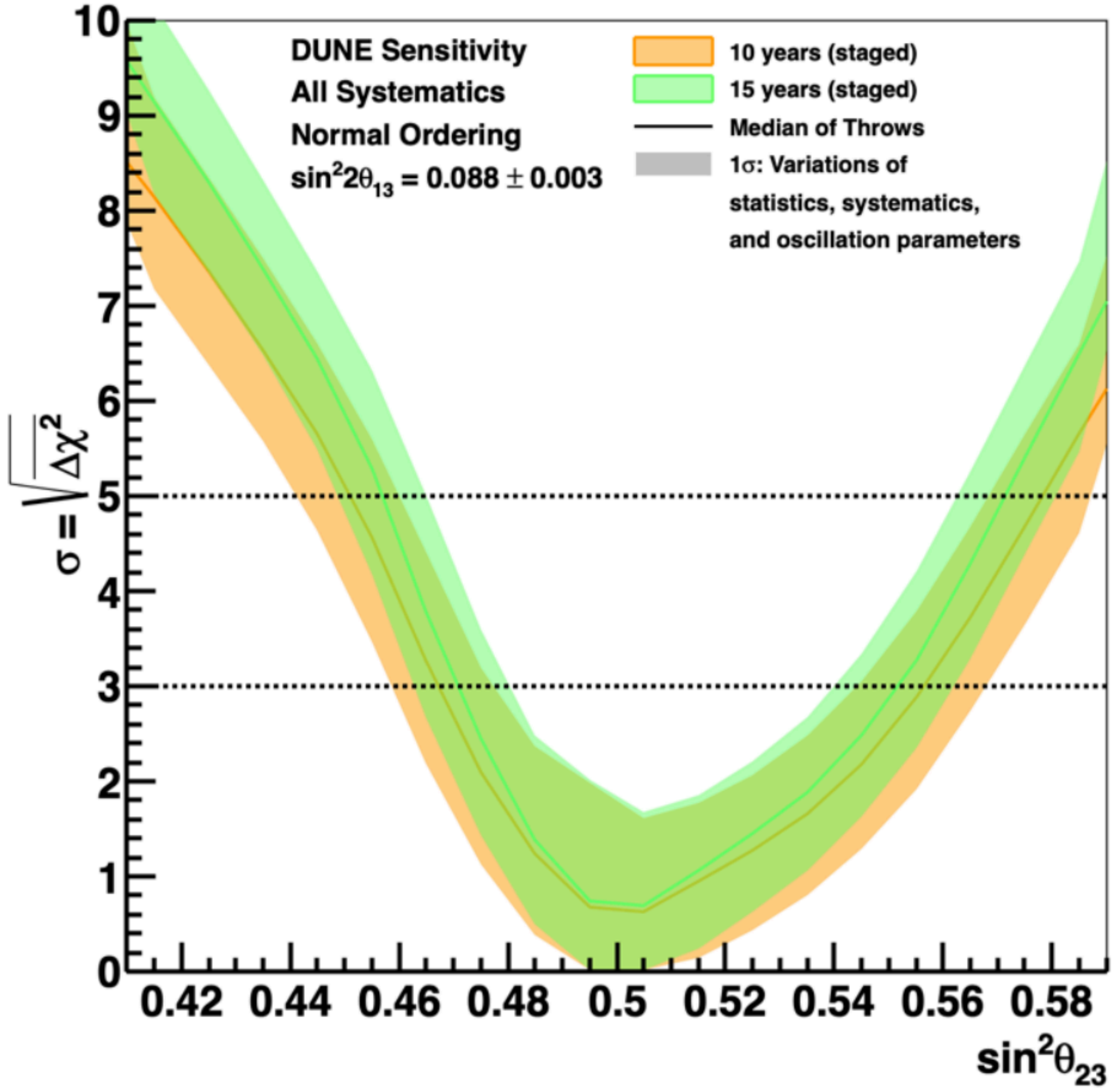
- two PMTs in sequence separated by a Winston cone assembled from shortpass filters (<460nm)
- front PMT collects **Chertons**, back PMT **scintons**

sample pulse

Slides from Michael Wurm “Theia concep” at *“DUNE Module of Opportunity Workshop”* (Valencia)

Octant sensitivity of HK and DUNE



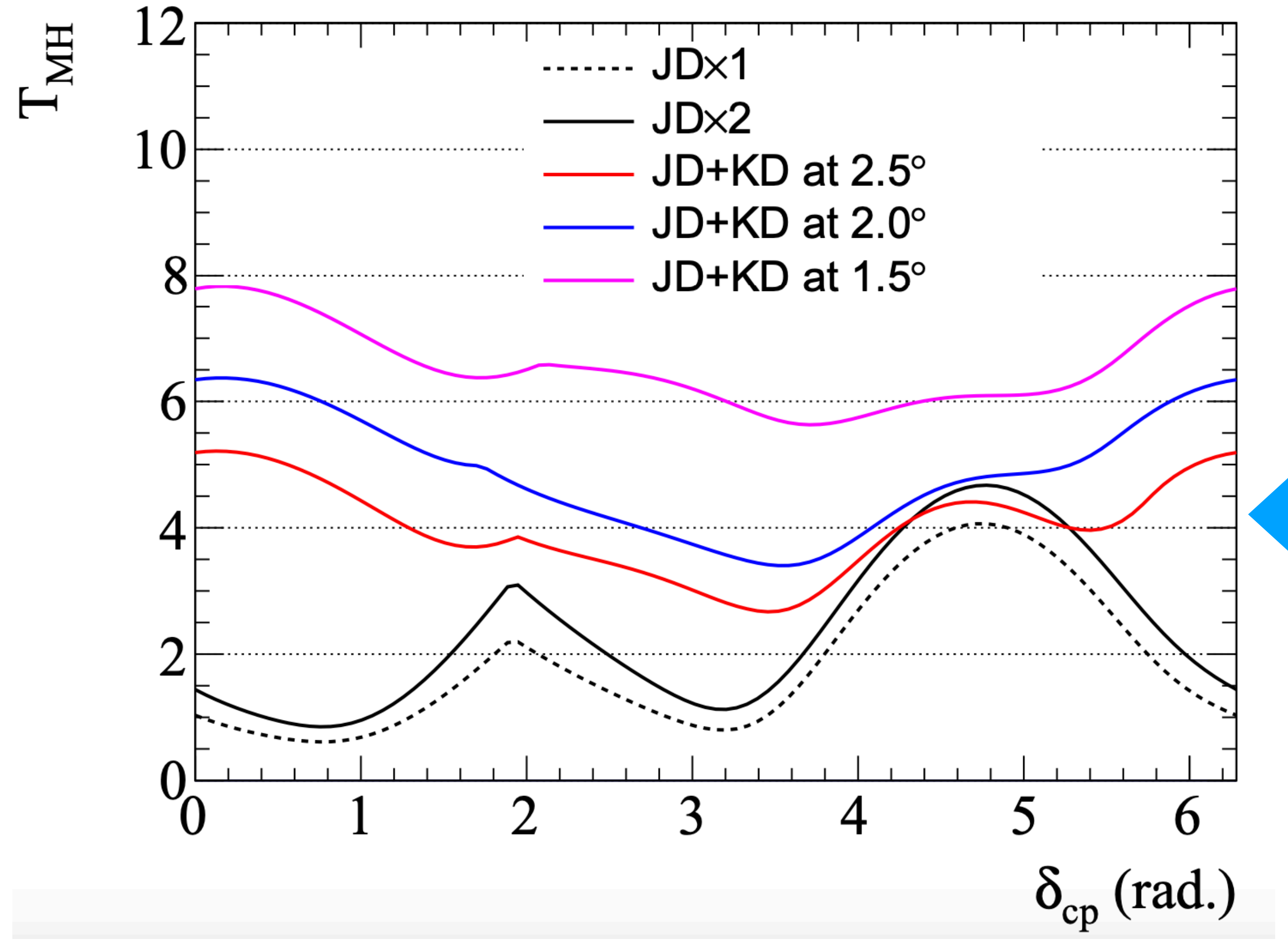


- HK atmospheric neutrinos (10 years) can resolve the octant at 3σ if $|\theta_{23}$ - 45º$|$ > 4º (>2.3º for Atm. + Beam)
- DUNE will have significant sensitivity to the θ_{23} octant for values of $sin^2\theta_{23}$ less than about 0.47 (43.3º) and greater than about 0.55 (47.8º)

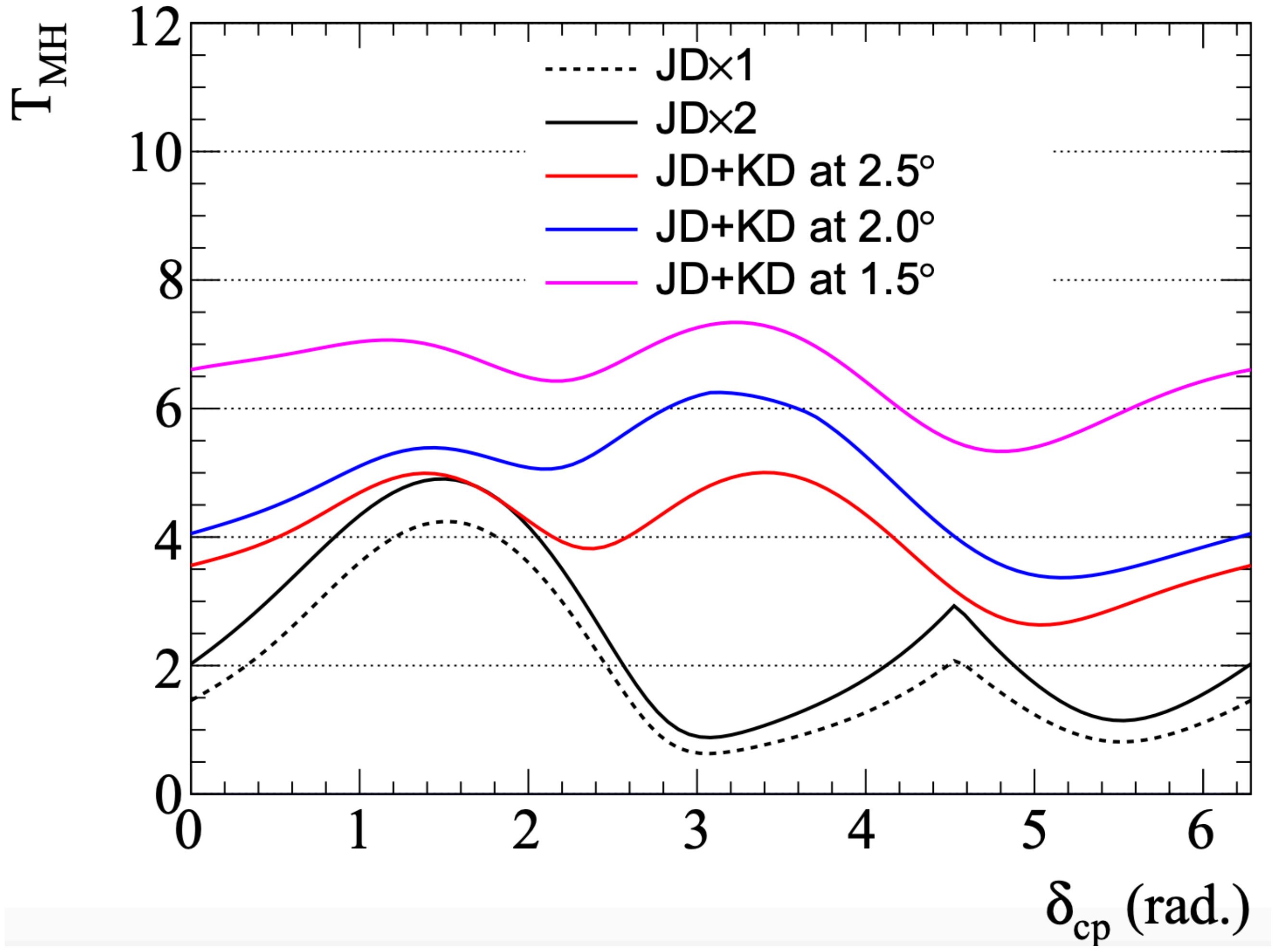
KNO Physics Potential

Significance to reject the wrong MO (10 years)

True Normal Ordering



True Inverted Ordering

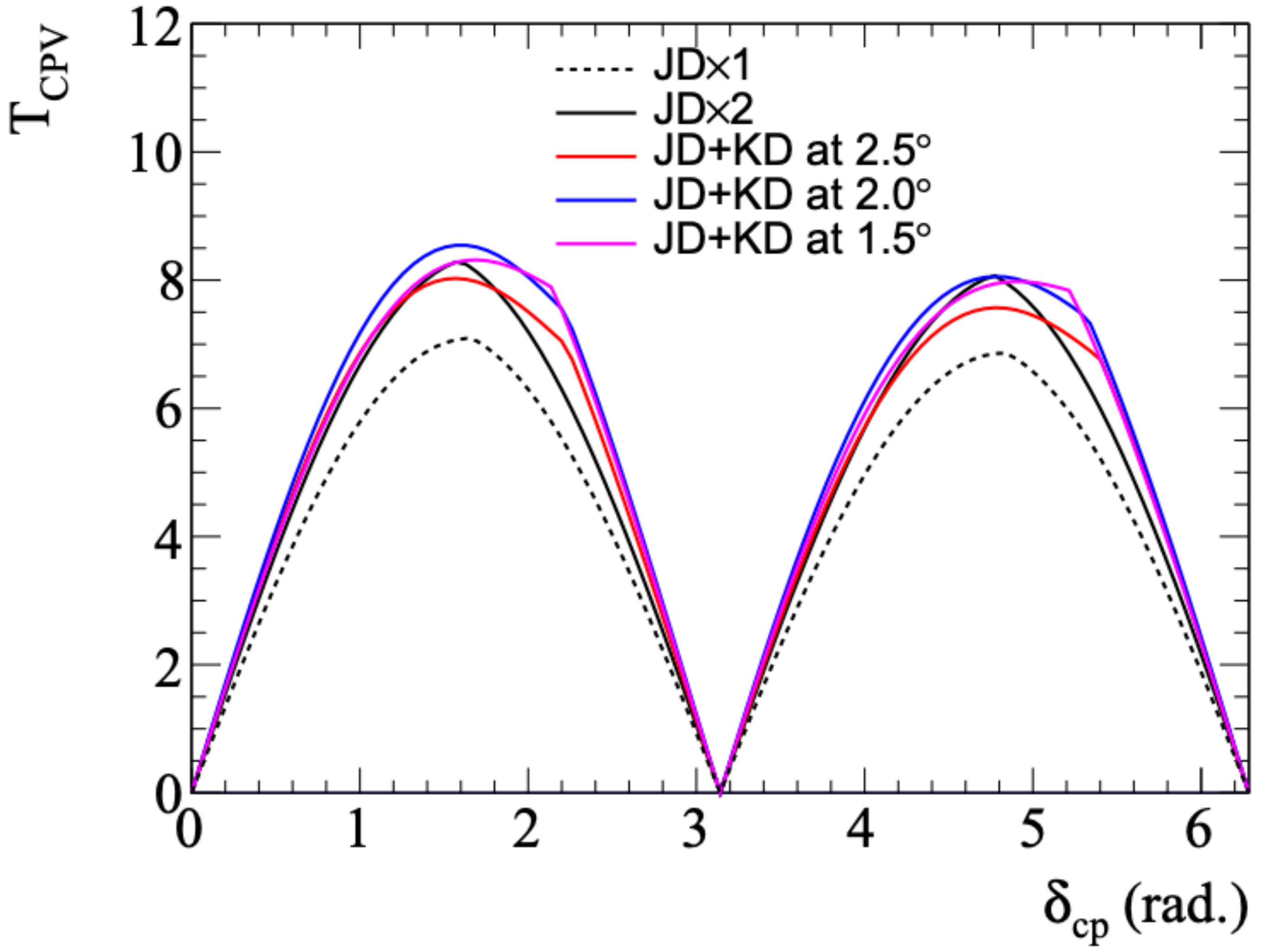


- The significance is largest for the configuration with the Korean detector at 1.5°: more on-axis ⇒ more events in the 1-2 GeV range where the matter effect is large
- For this configuration, the significance to reject the wrong mass ordering is greater than 5σ for all values of δ_{cp}

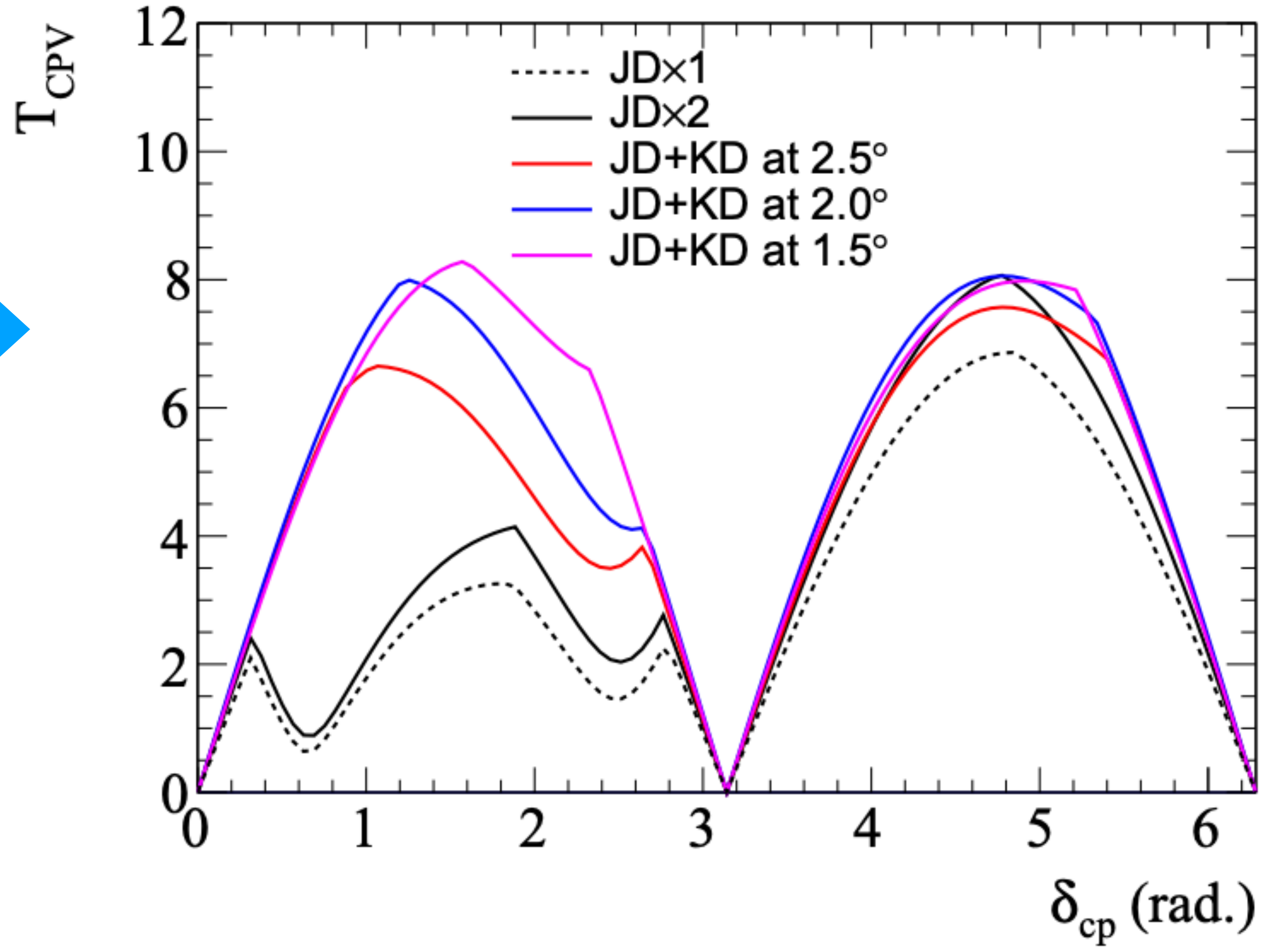
- When the MO is known, all four two-detector configurations have similar sensitivity
- If MO is unknown, the configuration with the Korean detector gives some fraction of δ_{cp} values for which a 5σ discovery is possible (breaking the MO-δ_{cp} degeneracy)

Significance to reject CP conservation (10 years)

True Normal Ordering, Ordering Known



True Normal Ordering, Ordering Unknown

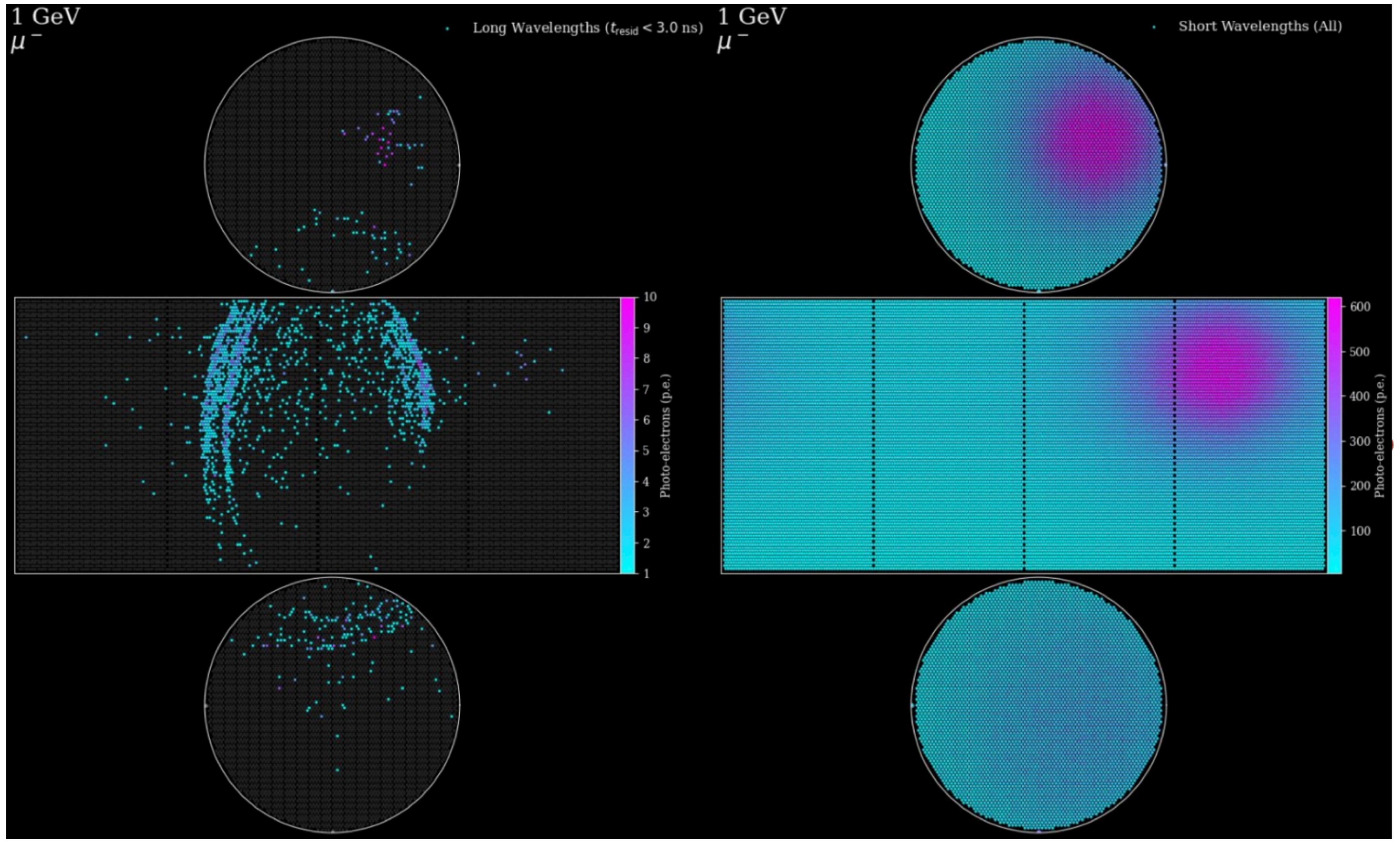


THEIA concept

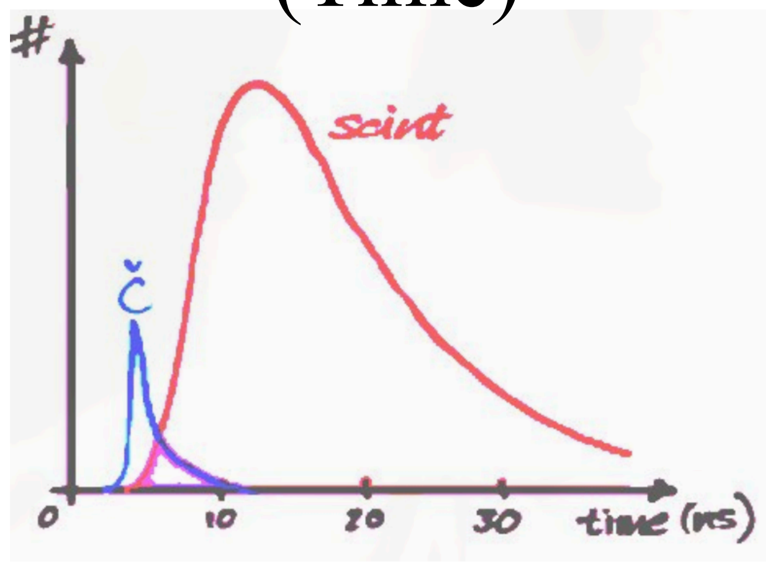
- DUNE FD4 “Module of Opportunity” (design not closed): More ambitious designs are being considered including pixel readout, integrated charge-light readout, low background modules, and **non-LAr technologies**

- THEIA is a proposed large-scale neutrino detector designed to use both Cherenkov and scintillation signals to enable a rich program of fundamental physics

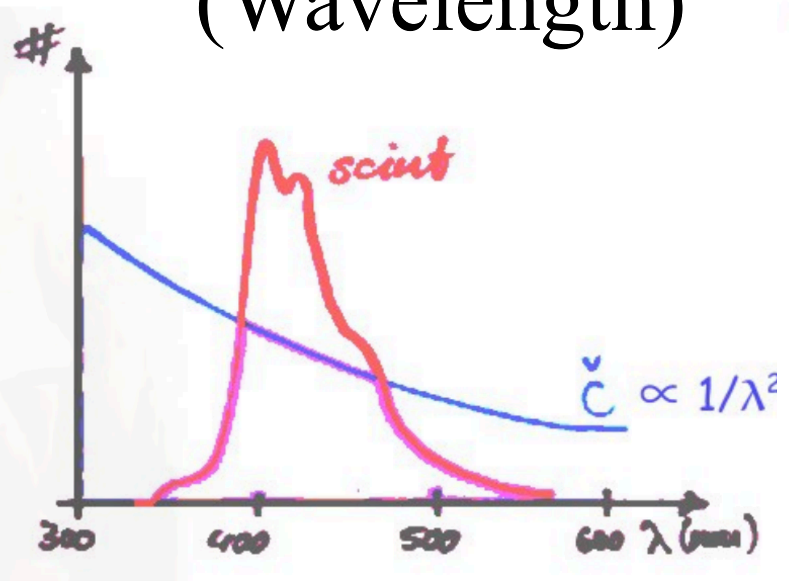
- Why Cherenkov & scintillation:
  - Cherenkov photons discriminate events based on directionality/topology (multiple tracks).
  - Scintillation is abundant, providing good resolution & low E thresholds
  - Combine both signals to improve background rejection



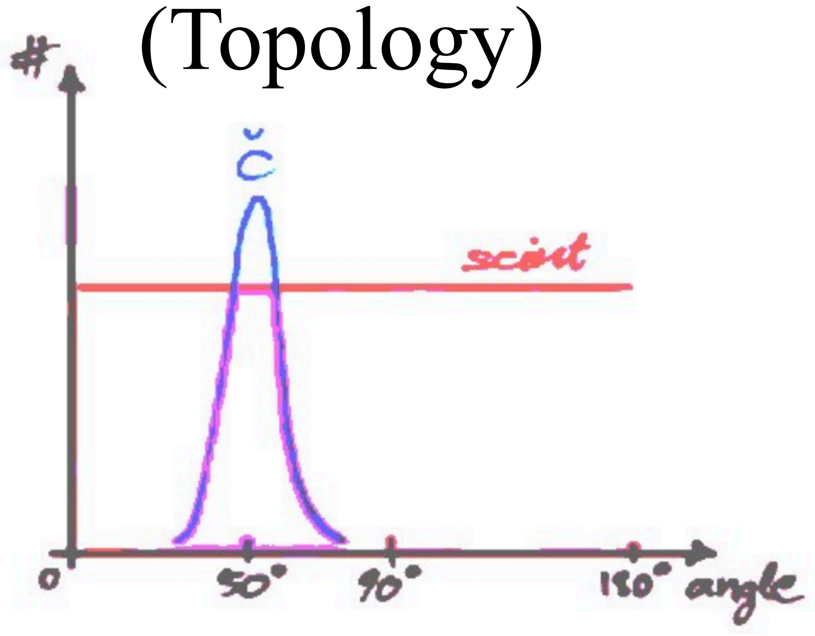
(Time)



(Wavelength)

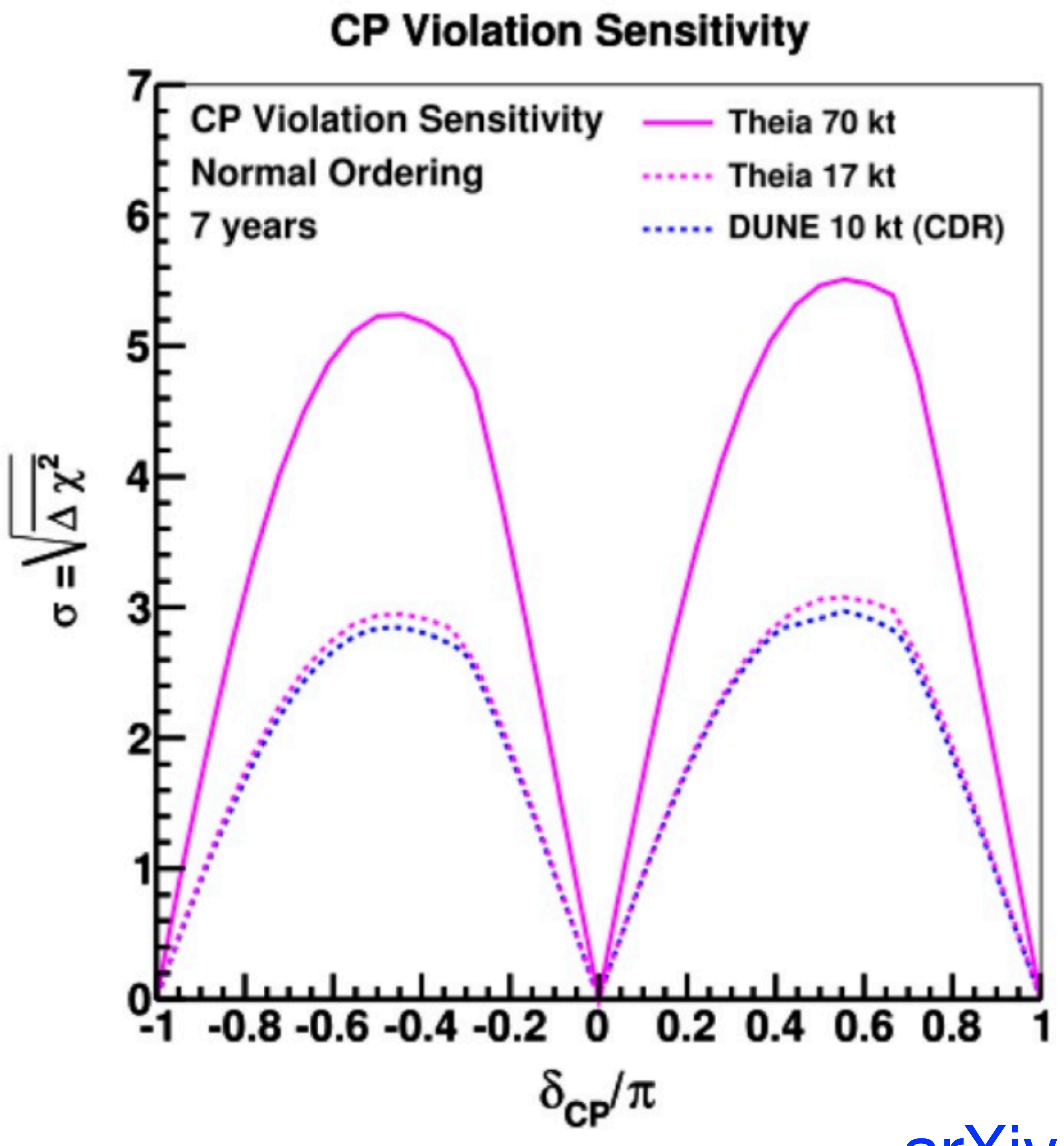


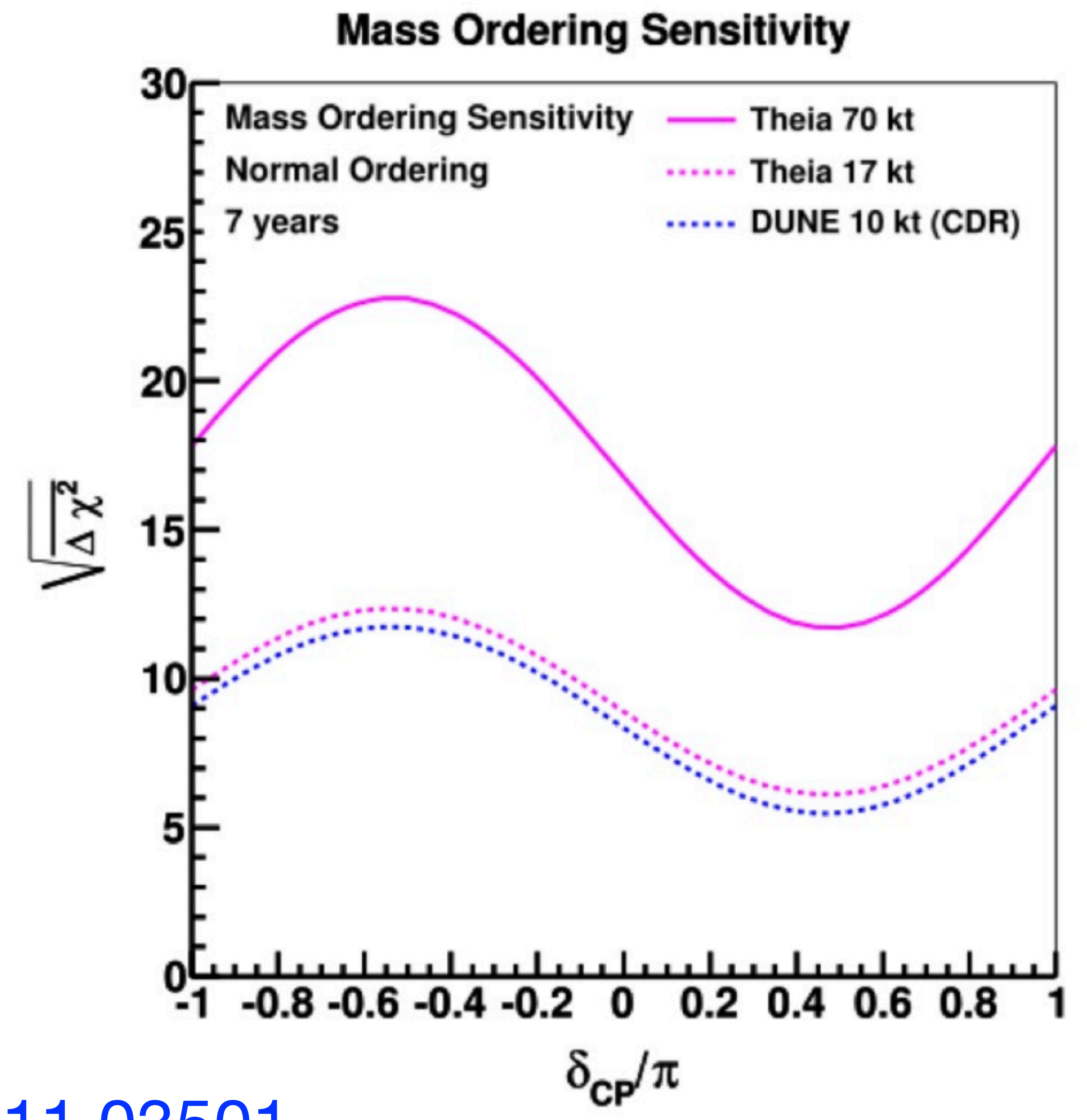
(Topology)



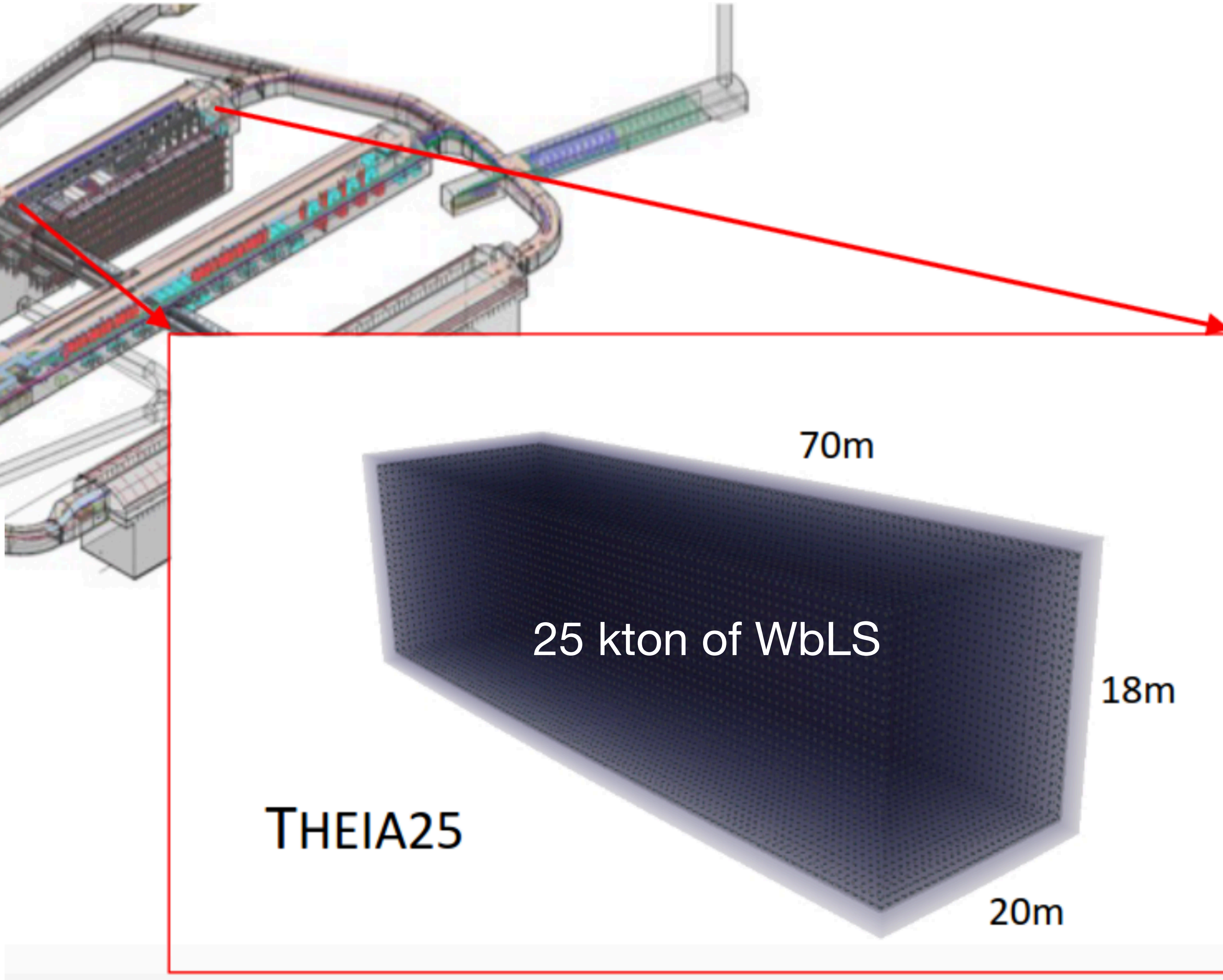
THEIA for Long-baseline oscillations

- Ideally situated as the DUNE 4th far detector
- Similar sensitivity for neutrino oscillation program as LAr:





arXiv:1911.03501



- A different technology and medium target offers a distinct set of detector systematic and neutrino interaction uncertainties ⇒ independent cross-check of the extracted oscillation parameter values

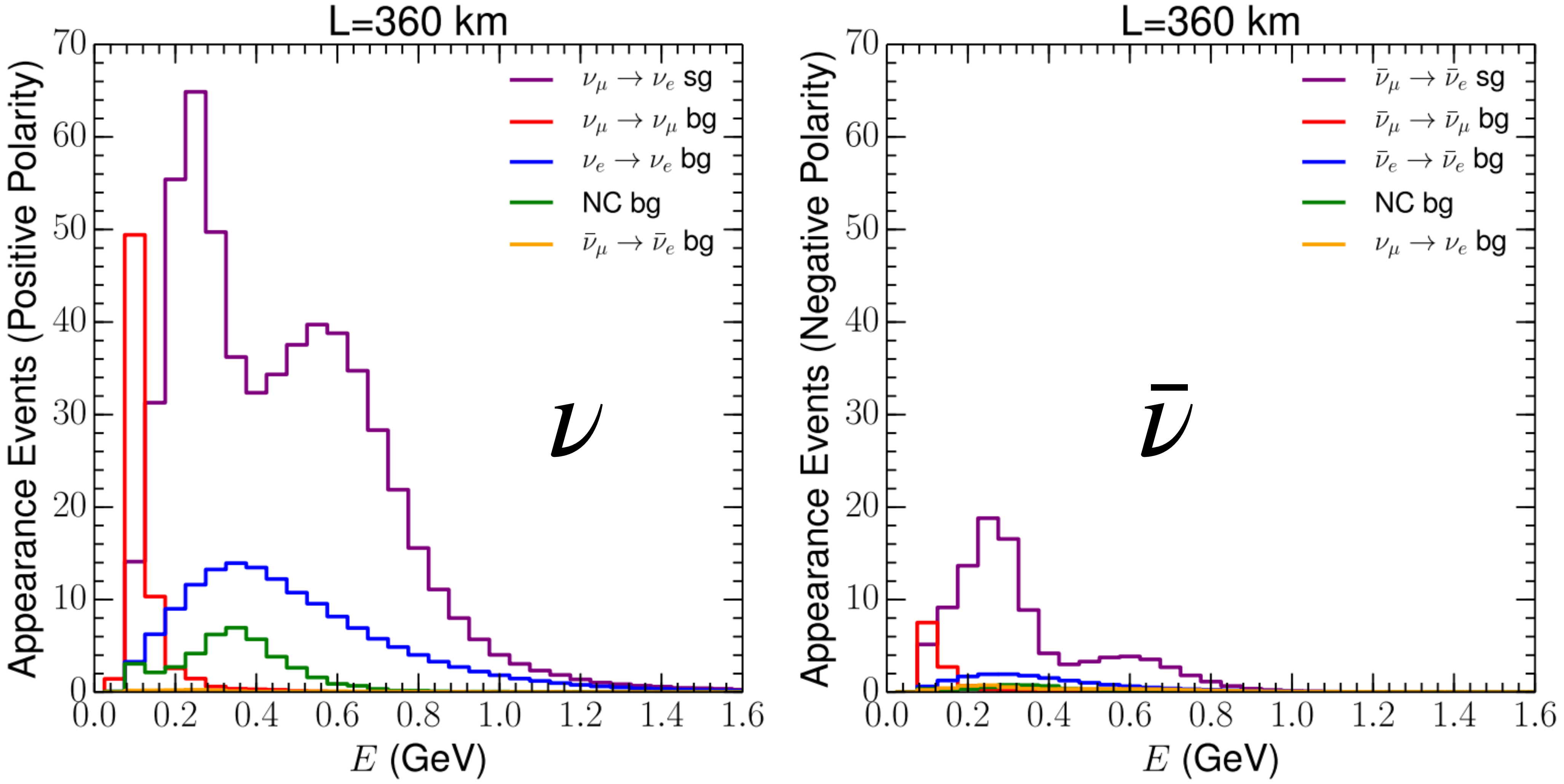
European Spallation Source neutrino Super Beam (ESSνSB)

- The ESSνSB is a long-baseline neutrino project that aims in measuring CPV at the 2nd oscillation maximum, where the sensitivity is x2.5 higher than at 1st maxima

- The ESS facility is under construction in Lund, Sweden (1st beam on target in 2025)

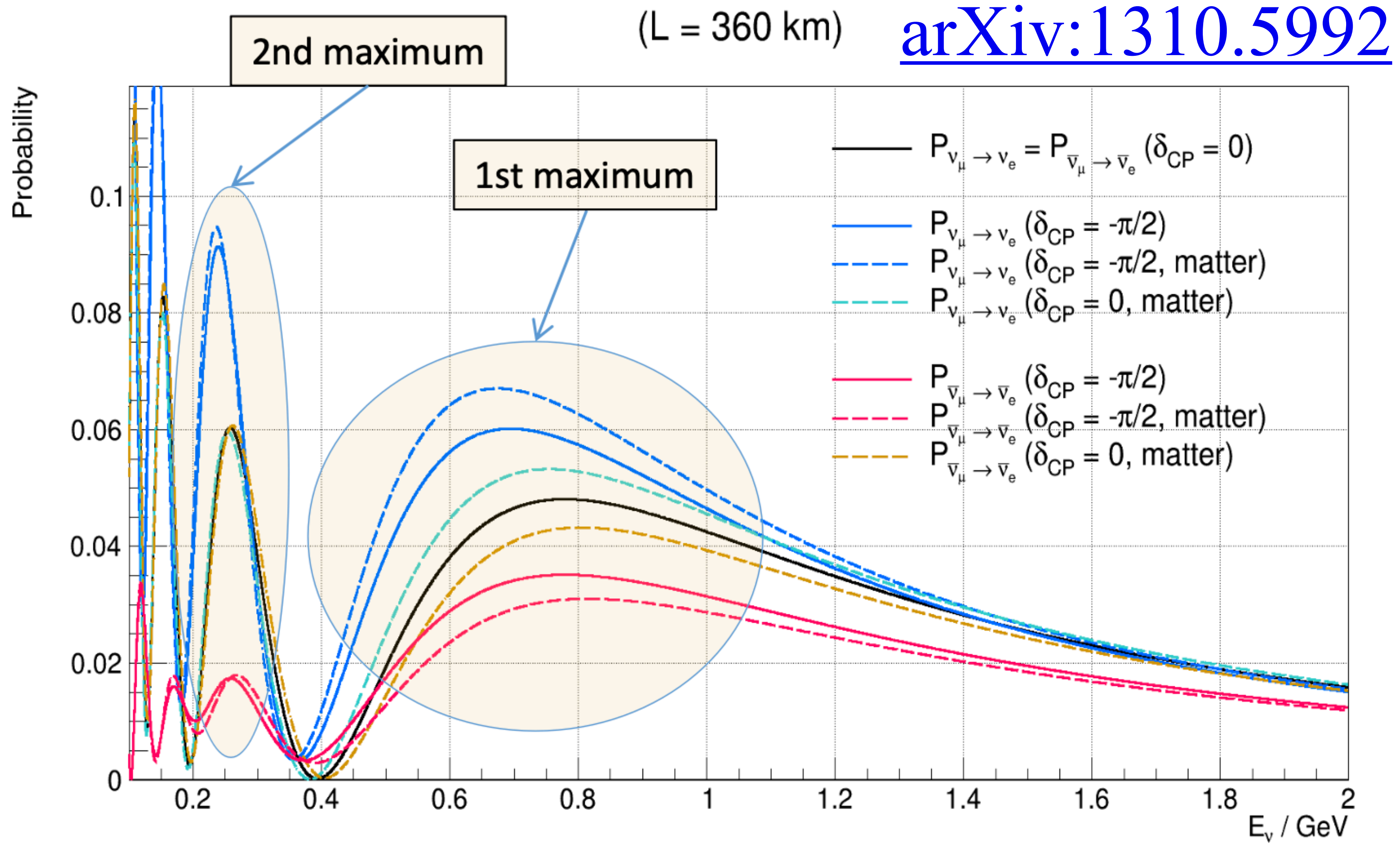
- Event rates for the different signal and BG components of the e-like sample at a BL=360 km

EPJST 231:3779–3955



- The neutrino flux observed by the detector mainly corresponds to the second oscillation maximum

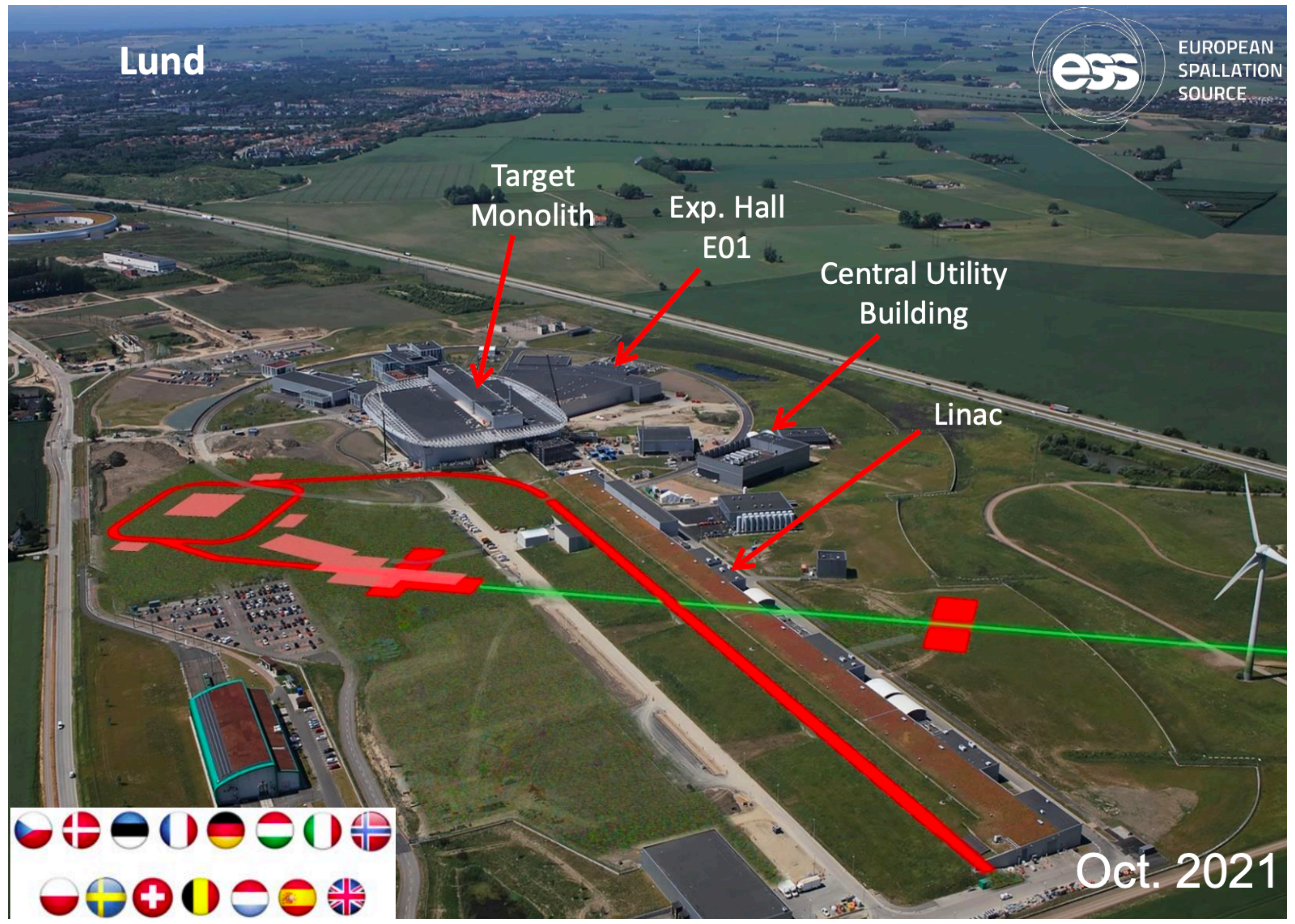
arXiv:1310.5992



$$A \equiv \frac{|P(\nu_\mu \to \nu_e) - \bar{P}(\bar{\nu}_\mu \to \bar{\nu}_e)|}{[P(\nu_\mu \to \nu_e) + \bar{P}(\bar{\nu}_\mu \to \bar{\nu}_e)]}$$

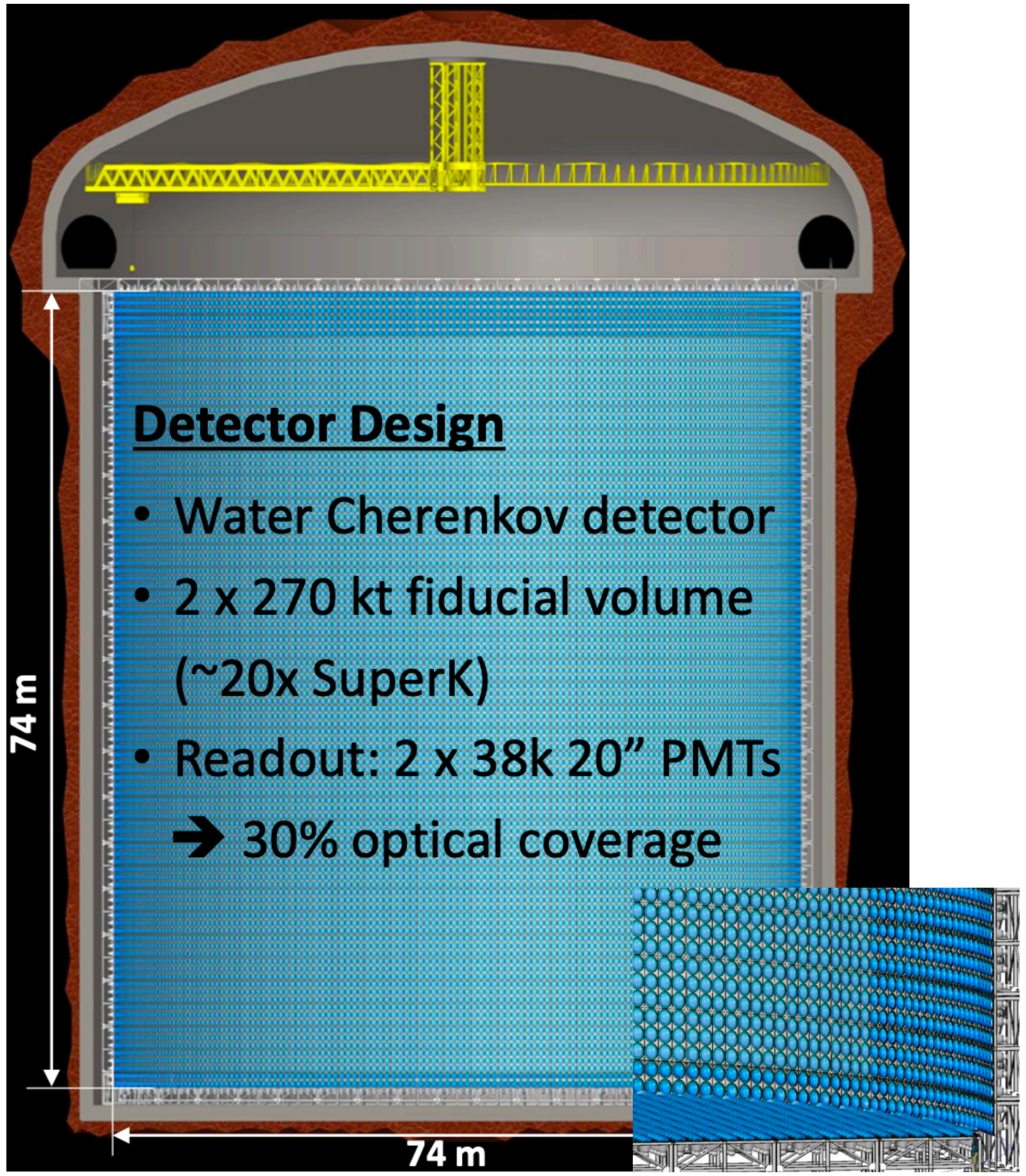
$A_{CP}(1st\ Osci.max) = \mathbf{0.3} \cdot sin\delta_{CP}$

$A_{CP}(2nd\ Osci.max) = \mathbf{0.75} \cdot sin\delta_{CP}$



ESSνSB Detectors

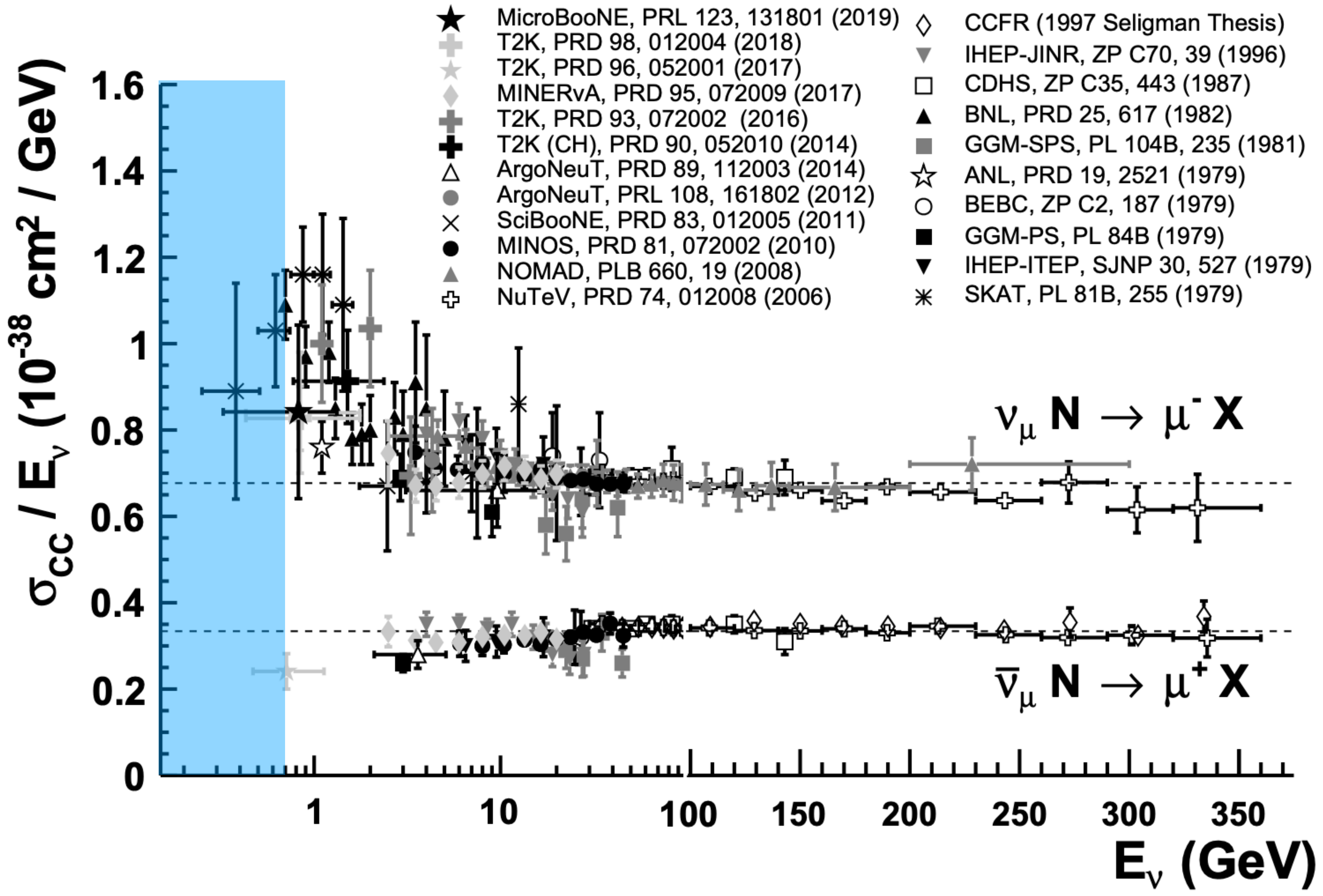
- Far detector:
  - Baseline 360 km
  - Depth to ground level: 1000 m



Detector Design

- Water Cherenkov detector
- 2 x 270 kt fiducial volume (~20x SuperK)
- Readout: 2 x 38k 20” PMTs
  ➔ 30% optical coverage

- Systematic errors need to be reduced to $\lesssim 5\,\%$
- ν-nucleus cross section dominant sys. uncertainty in ESSνSB
- Missing measurements at the ESSνSB region (below 600 MeV)



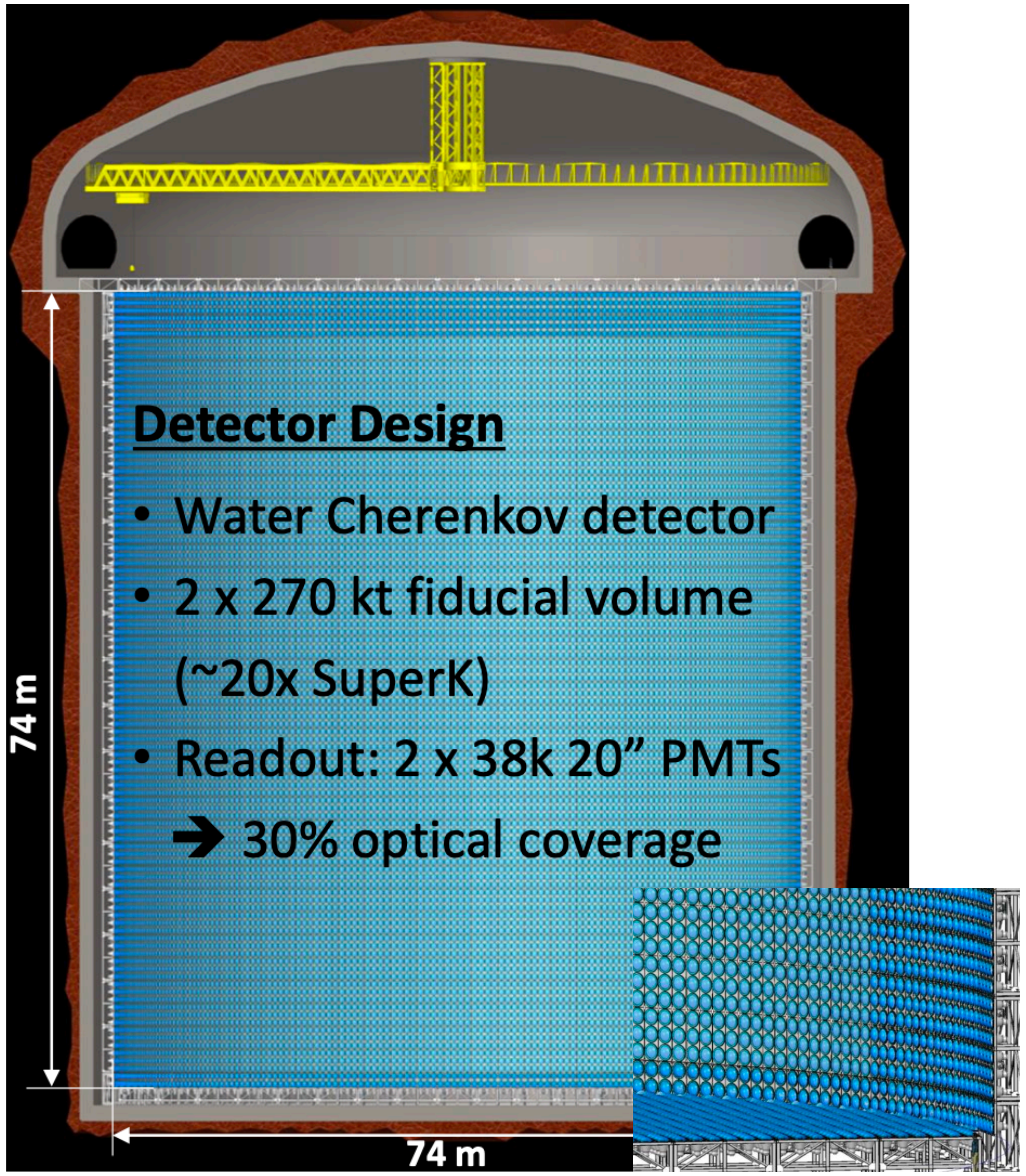
pdg.lbl.gov/2022/reviews

Measurements of per nucleon ν_μ and $\bar{\nu}_\mu$ CC inclusive scattering cross sections divided by neutrino energy as a function of neutrino energy

- ESSνSB+ (started in 2023), aims to measure the ν-nucleus cross-section in 0.2 to 0.6 GeV range

ESSνSB Detectors

- Far detector:
  - Baseline 360 km
  - Depth to ground level: 1000 m

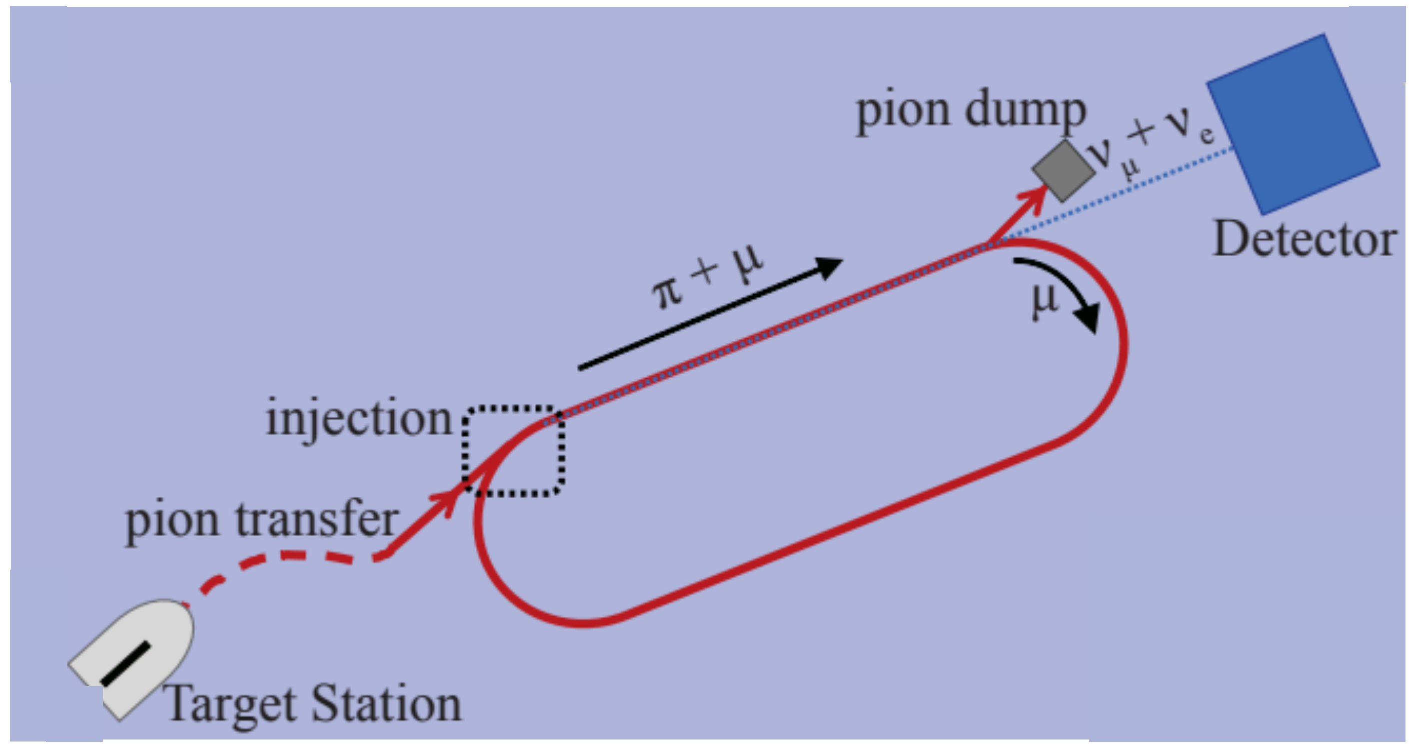


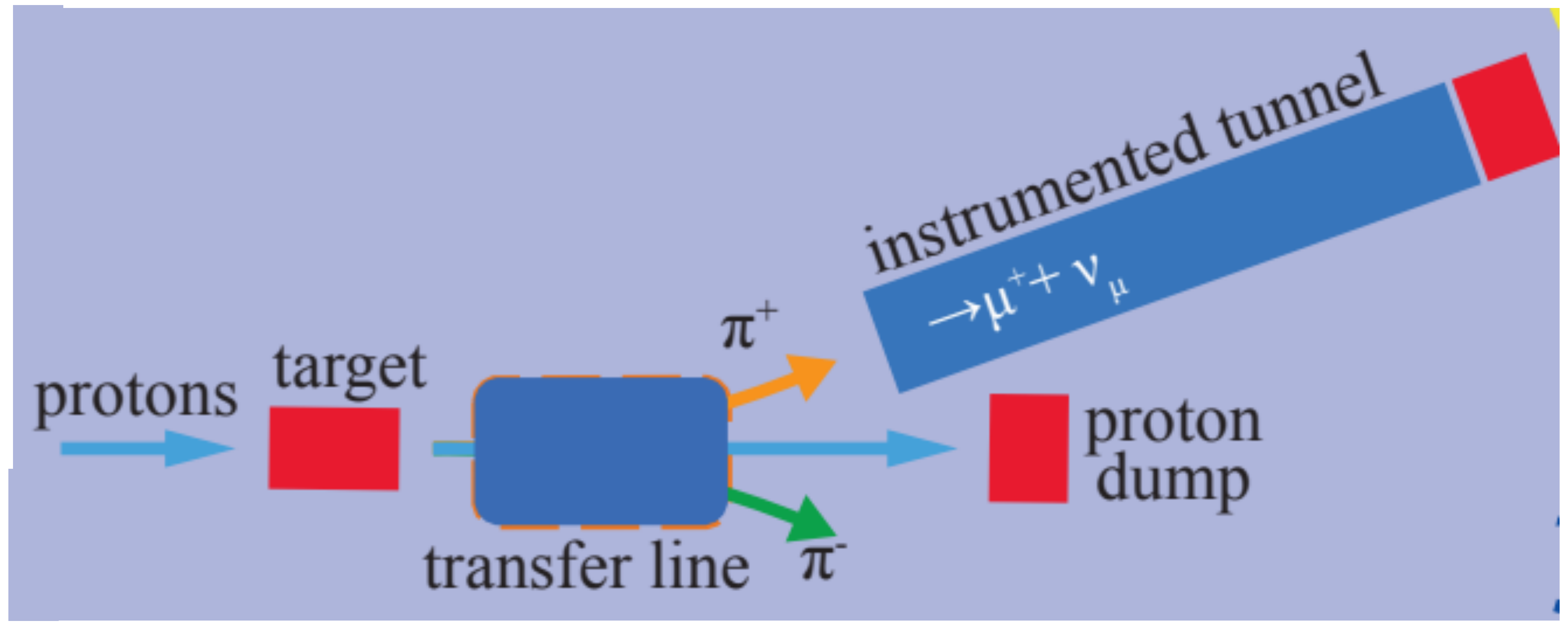
Detector Design

- Water Cherenkov detector
- 2 x 270 kt fiducial volume (~20x SuperK)
- Readout: 2 x 38k 20” PMTs
  ➔ 30% optical coverage

- Systematic errors need to be reduced to $\leq 5\,\%$
- ν-nucleus cross section dominant sys. uncertainty in ESSνSB
- Missing measurements at the ESSνSB region (below 600 MeV)

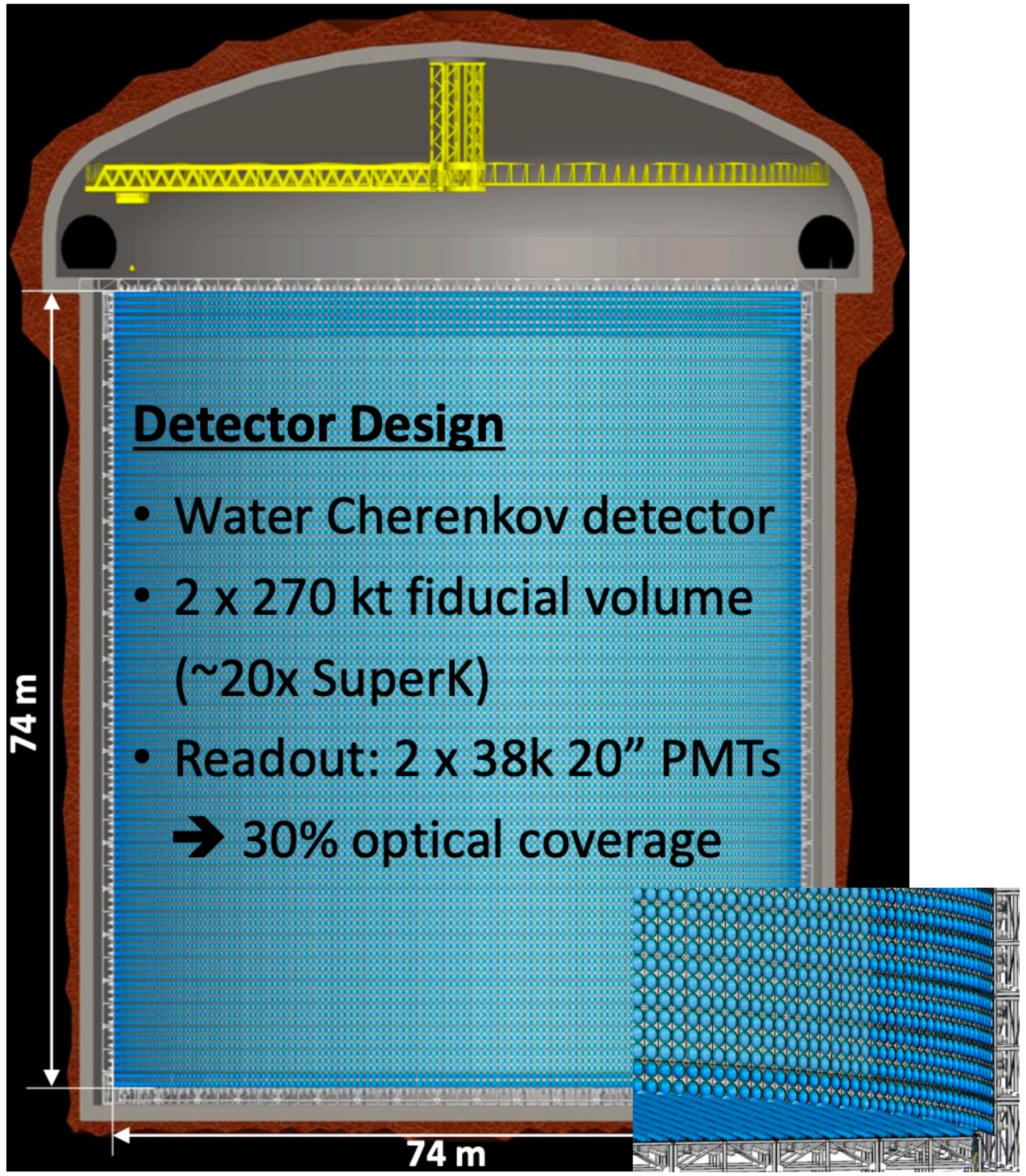
- ESSνSB+ (started in 2023), aims to measure the ν-nucleus cross-section in 0.2 to 0.6 GeV range:
  - Using a low energy beam produced by muons circulating in a muon storage ring (LEνSTORM) and a low energy monitored beam (LEMNB) produced by pion decays





ESSνSB Detectors

- Far detector:
  - Baseline 360 km
  - Depth to ground level: 1000 m



Detector Design

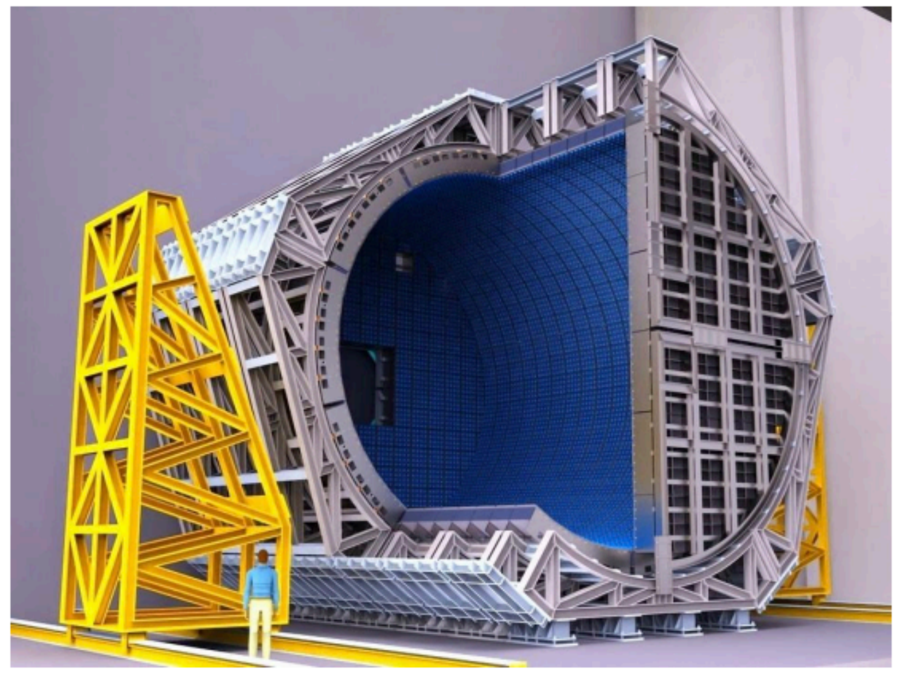
- Water Cherenkov detector
- 2 x 270 kt fiducial volume (~20x SuperK)
- Readout: 2 x 38k 20” PMTs

  ➔ 30% optical coverage

- Systematic errors need to be reduced to $\leq 5\,\%$
- ν-nucleus cross section dominant sys. uncertainty in ESSνSB
- Missing measurements at the ESSνSB region (below 600 MeV)

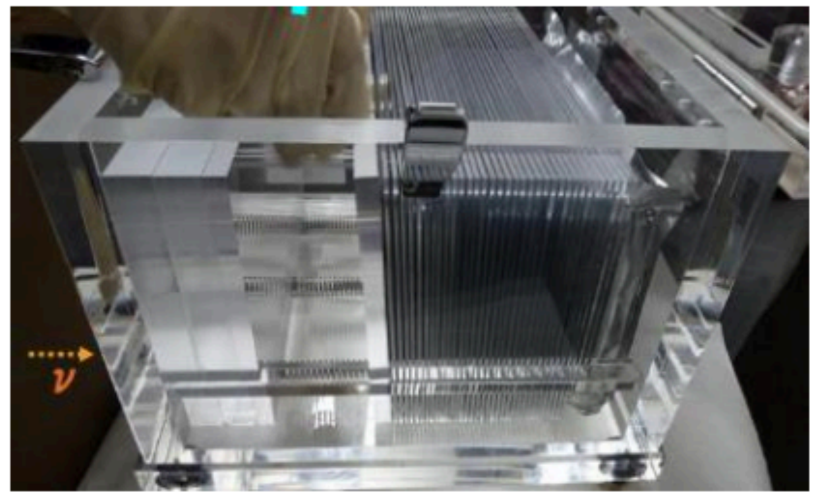
- ESSνSB+ (started in 2023), aims to measure the ν-nucleus cross-section in 0.2 to 0.6 GeV range

- ESSνSB near detectors (END):



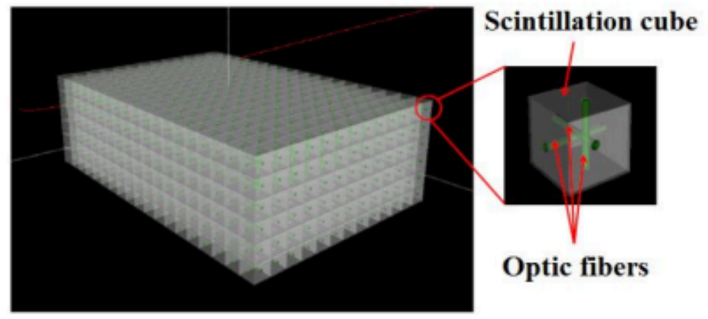
Near water Cherenkov detector

- 475 t fiducial mass
- high statistics xsec measurement
- beam monitoring



Emulsion detector (νIKING)

- water target, 1 t fiducial mass
- precise interaction topology measurement

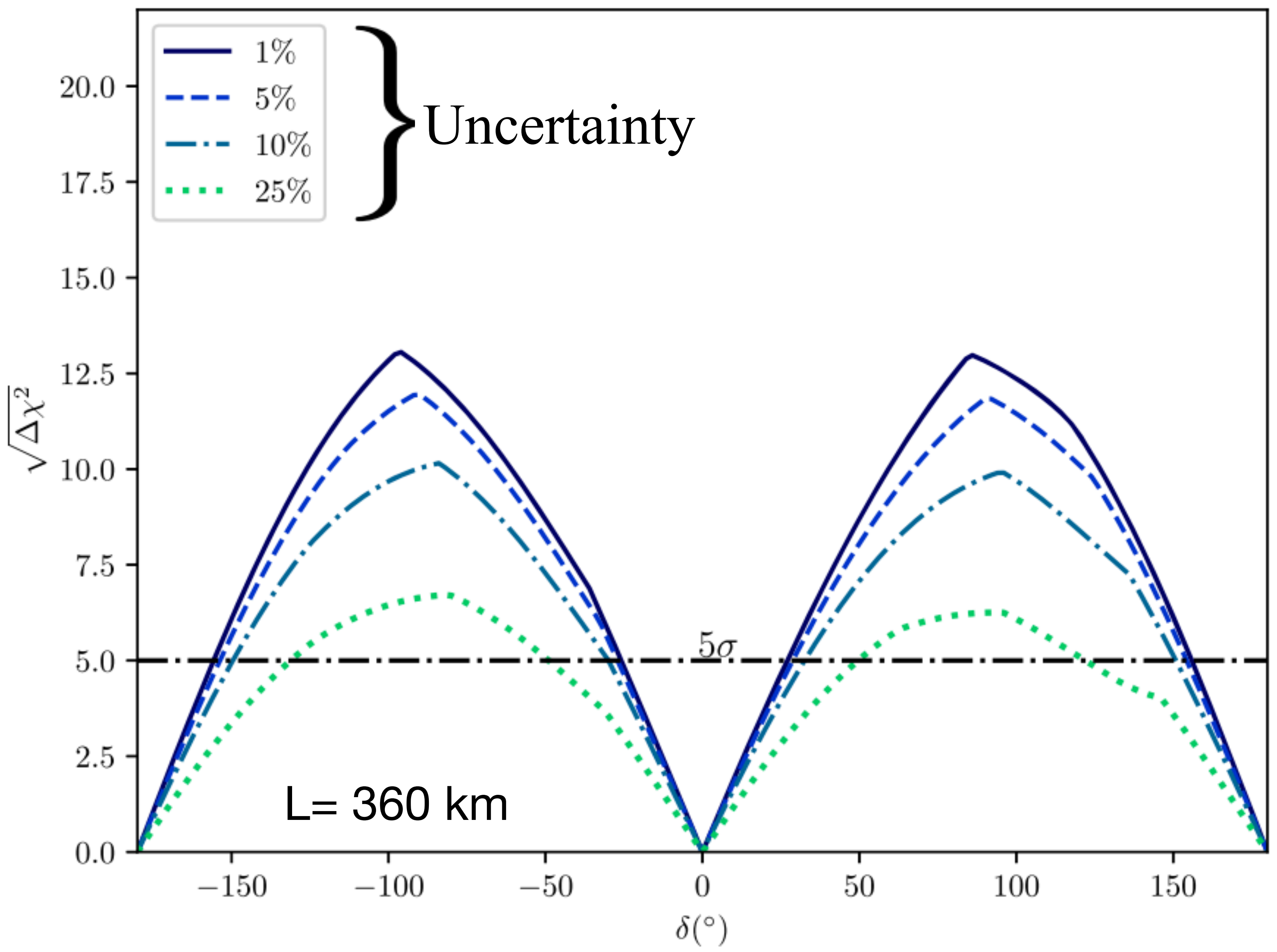


SFGD-like detector

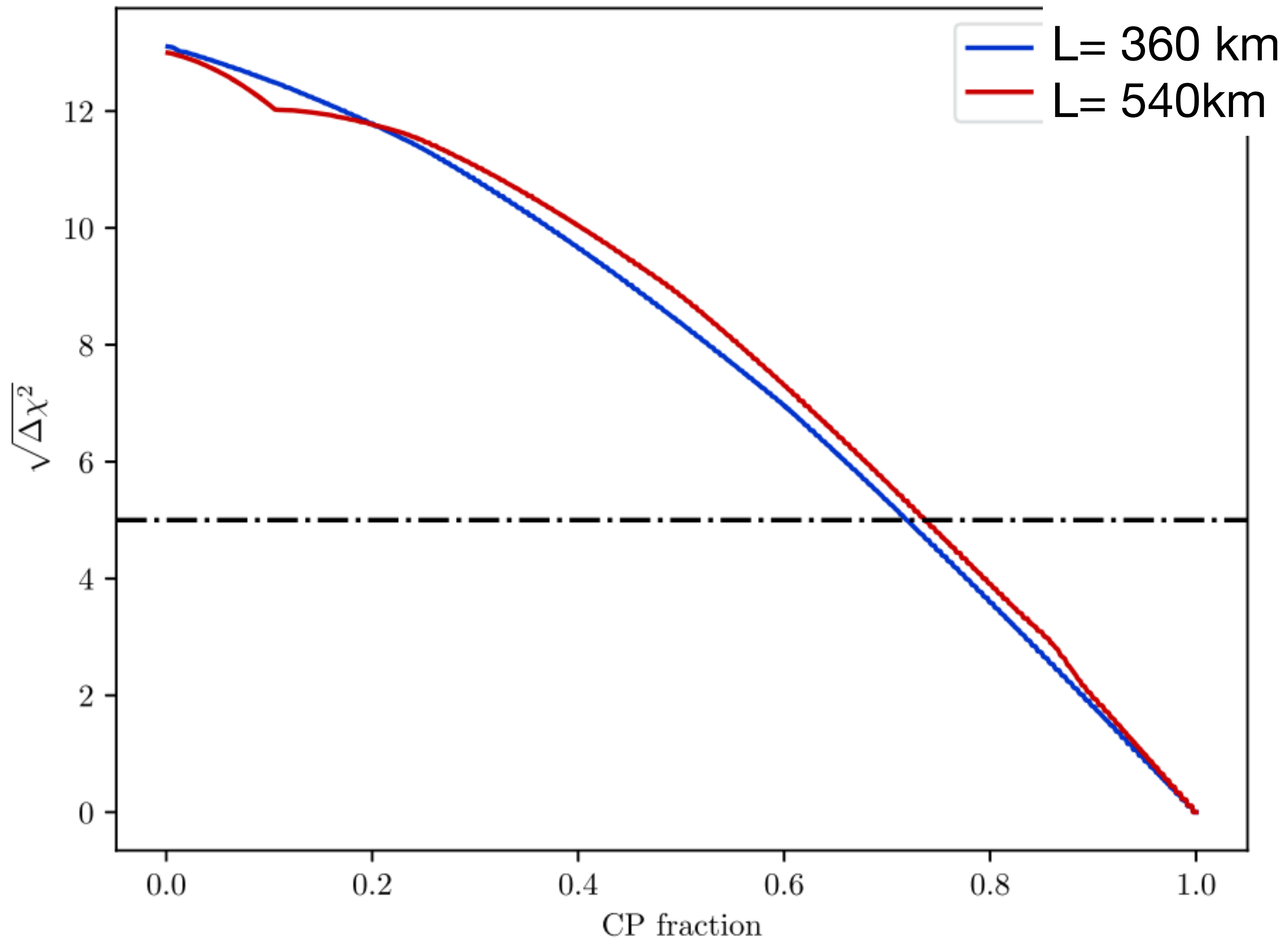
- plastic scintillator
- 1 t fiducial mass
- 1x1x1 cm^3 cubes with semi-independent readout
- calorimetry possible

ESSνSB expected sensitivity to δ_{cp}

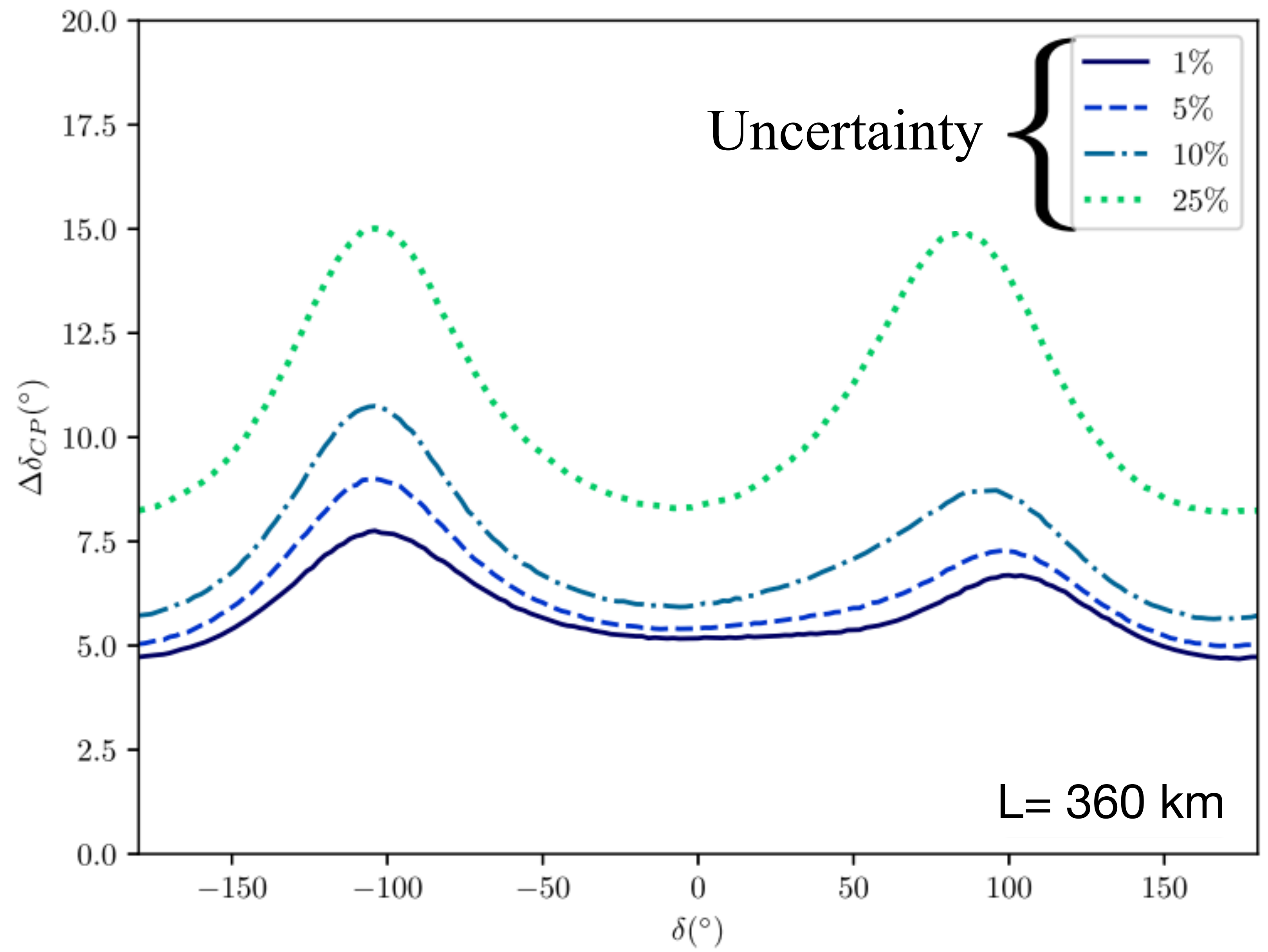
EPJST 231:3779–3955



- CP discovery potential for different systematic uncertainties (5 years ν + 5 years $\bar{\nu}$):
  - Even for 25% uncertainty (very conservative), a significant portion of the values of δ would still allow a discovery of CP violation above the 5σ level



- Fraction of values of δ for which a given significance for CPV could be established:
  - Covers 72% of δ_{CP} values in 10 years @ 5 σ C.L.



- Precision to measure the CP violating phase δ:
  - $\Delta\delta_{CP} < 8°$ for all δ_{CP} values for systematic uncertainties better than 5%