Solving the Neutrino Mass Hierarchy Problem

Hongyue Duyang

杜杨洪岳

Shandong University

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Chulalongkorn University, Bangkok, Thailand

Outline

- What it the neutrino mass hierarchy (MH) problem, and how to solve it.
- Current experiments' status.
- Next-generation experiments.
- Summary

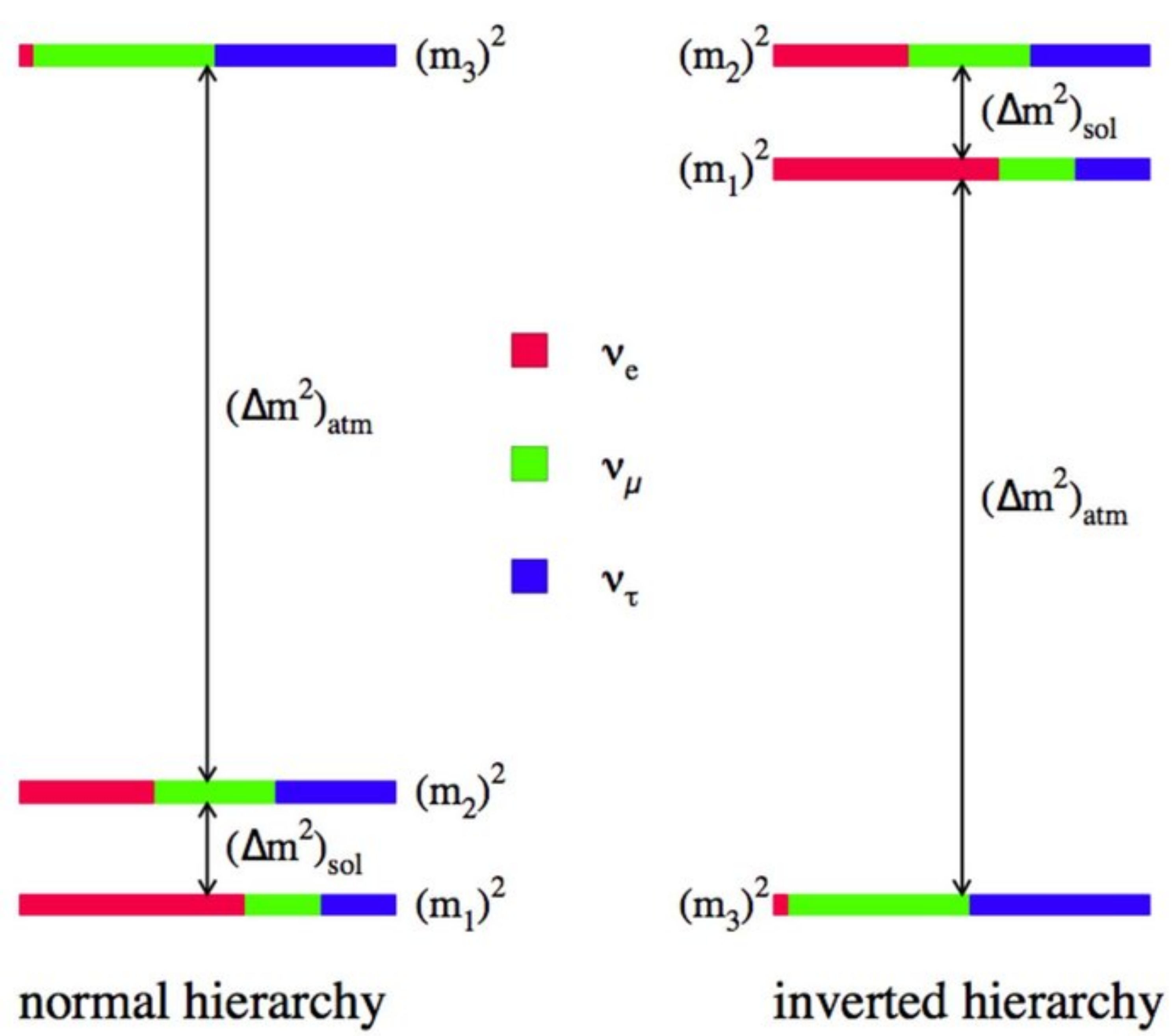
Introduction to the MH problem

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} \mathbf{U}^*_{\alpha i}|\nu_i\rangle$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\Delta_{ij} \qquad \Delta_{ij} = 1.27\Delta m^2_{ij}L/E$$

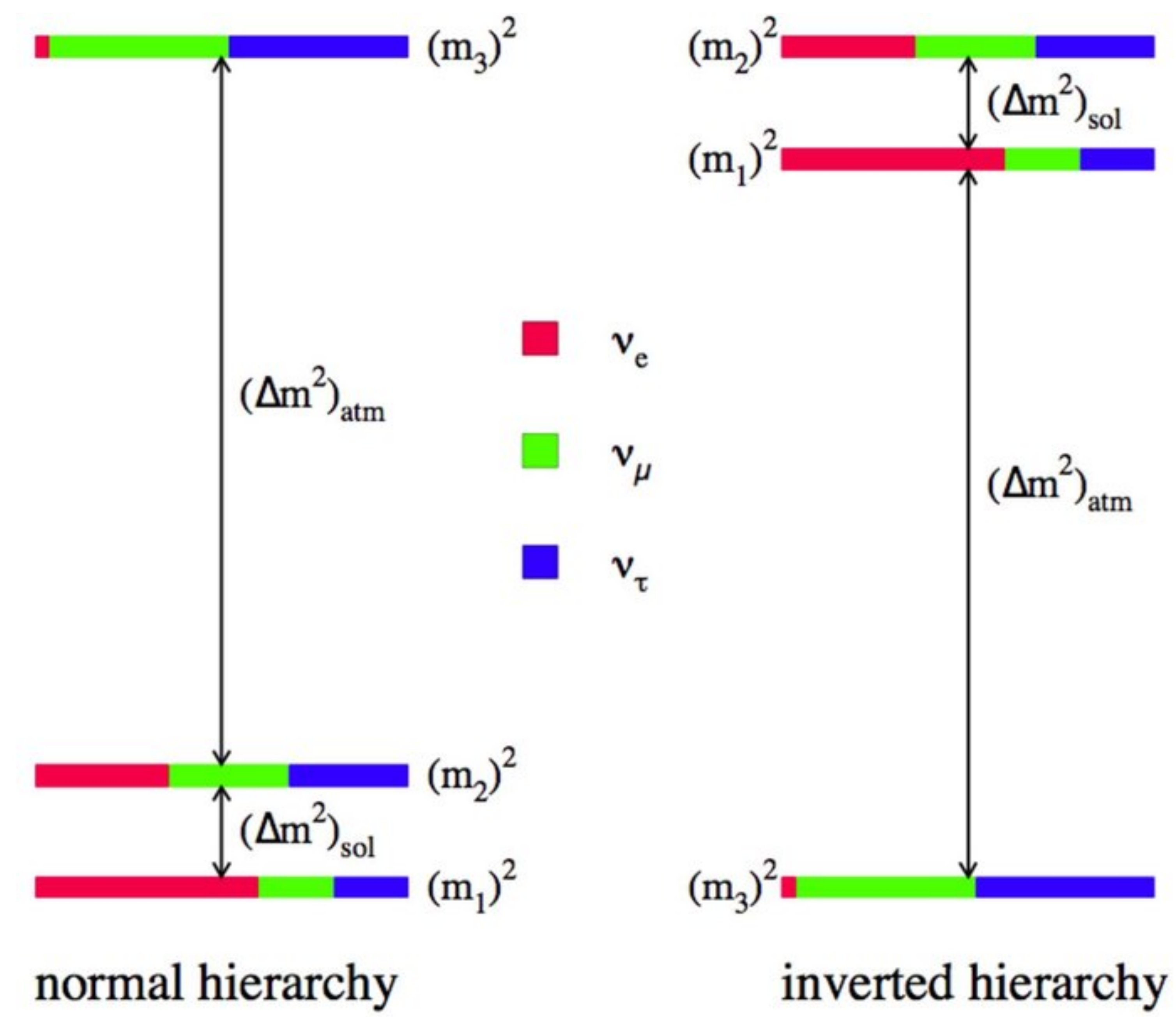
$$\pm 2\sum_{i>j}\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin 2\Delta_{ij},$$



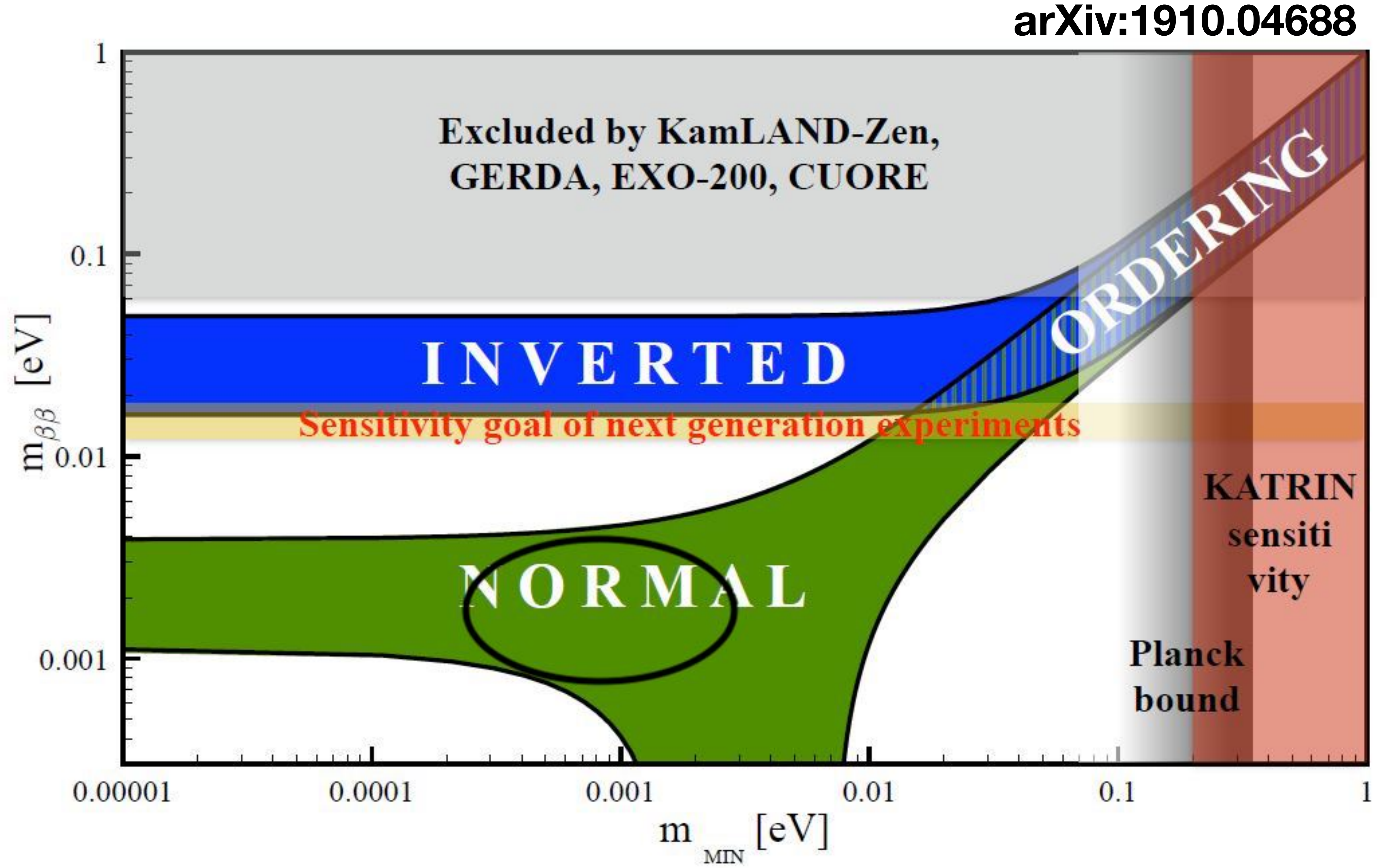
- Neutrino oscillations indicate non-zero neutrino mass, contradicts SM prediction.
- Remaining questions about the neutrino mass:
  - Absolute mass scale?
  - Mass origin (Majorana or Dirac)?
  - **Which is the lightest neutrino mass state (the sign of Δm_{31} or Δm_{32})?**
    - Normal hierarchy (NH): $m_1<m_2<m_3$
    - Inverted hierarchy (IH): $m_3<m_1<m_2$

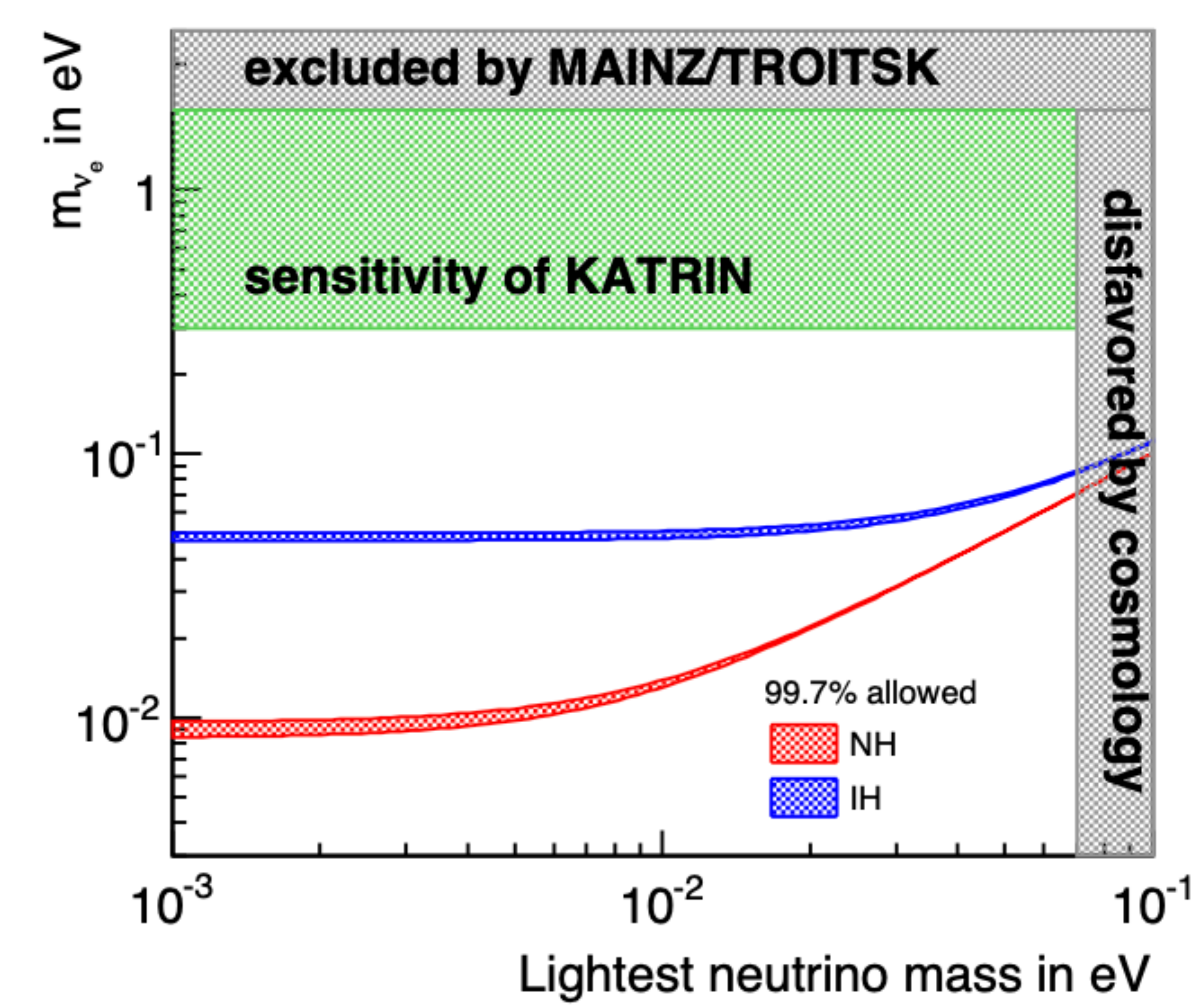
Importance of the MH problem

- Models predict different mass hierarchies.
- Correlates with δ_{CP} and θ_{23} octant measurements.
- Affects the determination of ν mass origin and absolute scale.
  - IH indicates larger effective mass for 0νββ and β decay.
    - Life would be easier for a lot of us if it is IH!
- This talk gives an overview of the current status and the future of solving the MH problem from an experimental point of view.



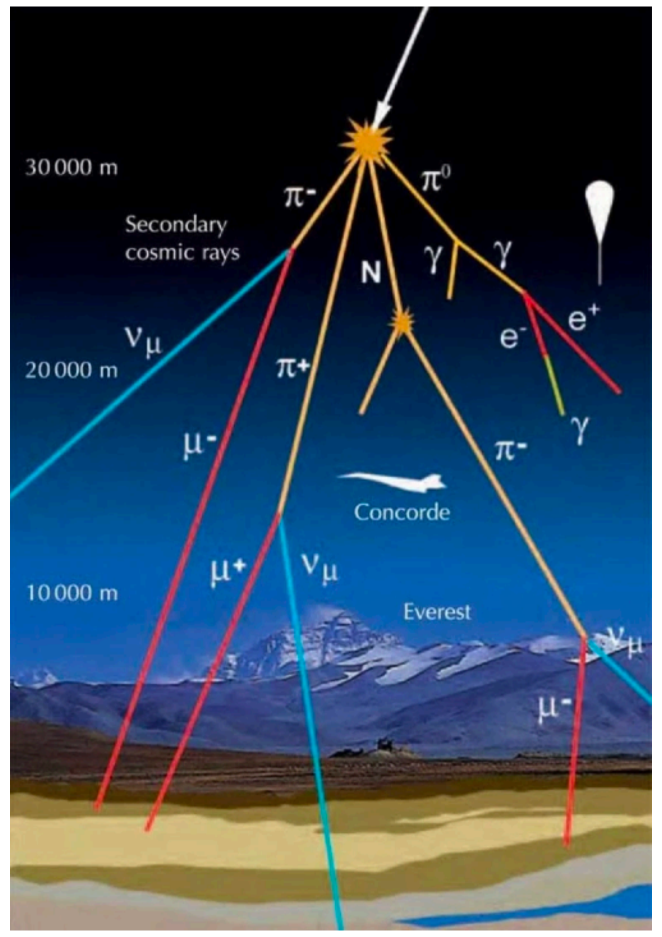
arXiv:1910.04688





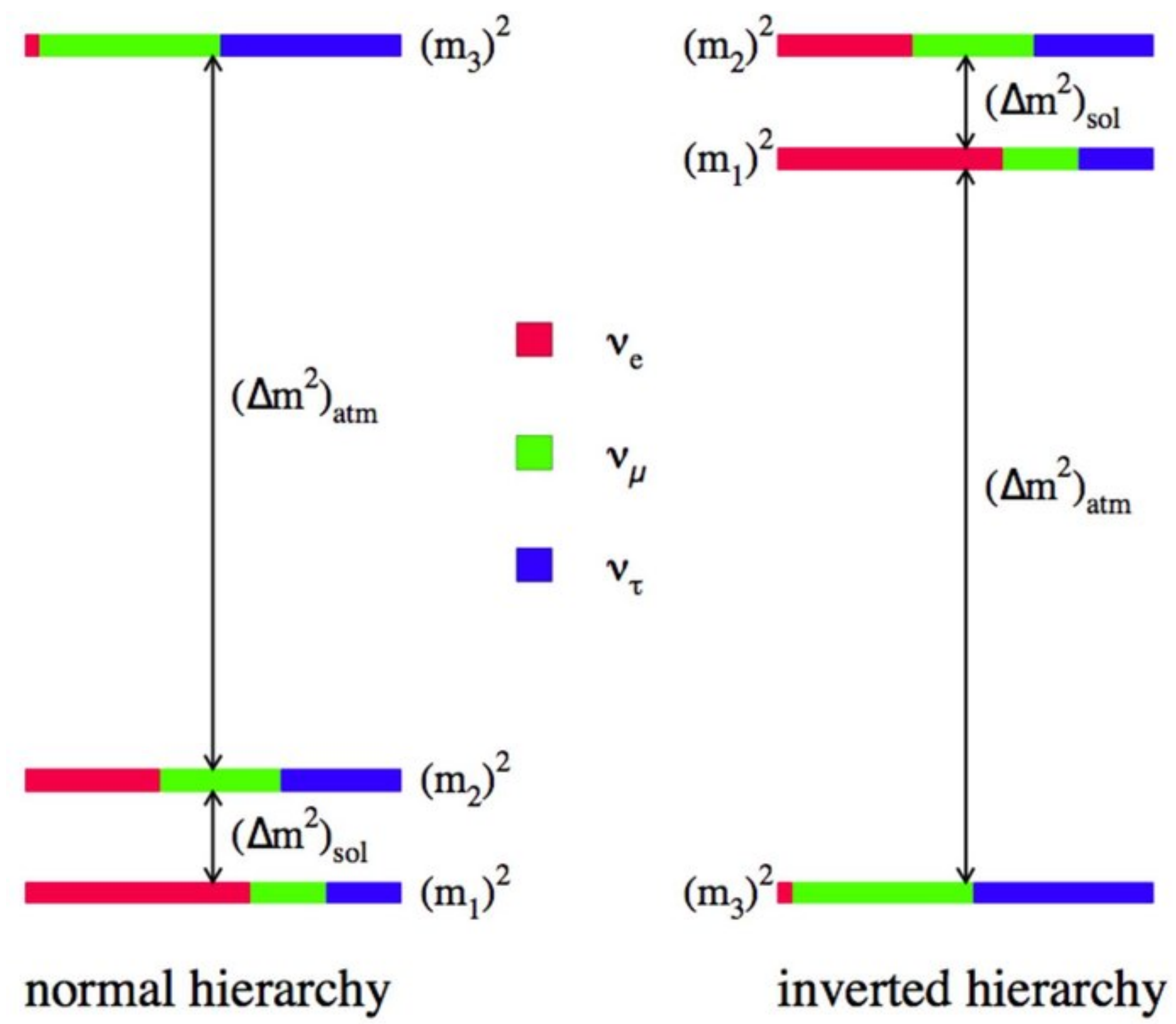
How to determine the MH

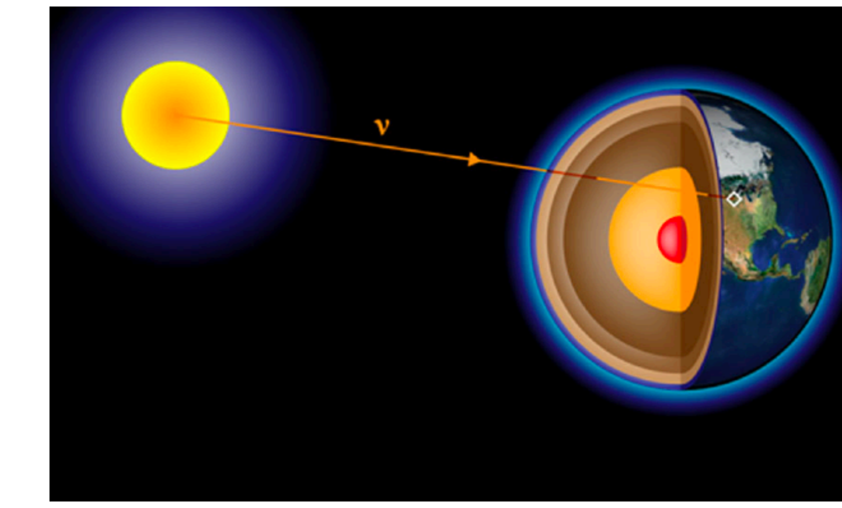
How to Determine MH?



Atmospheric neutrinos

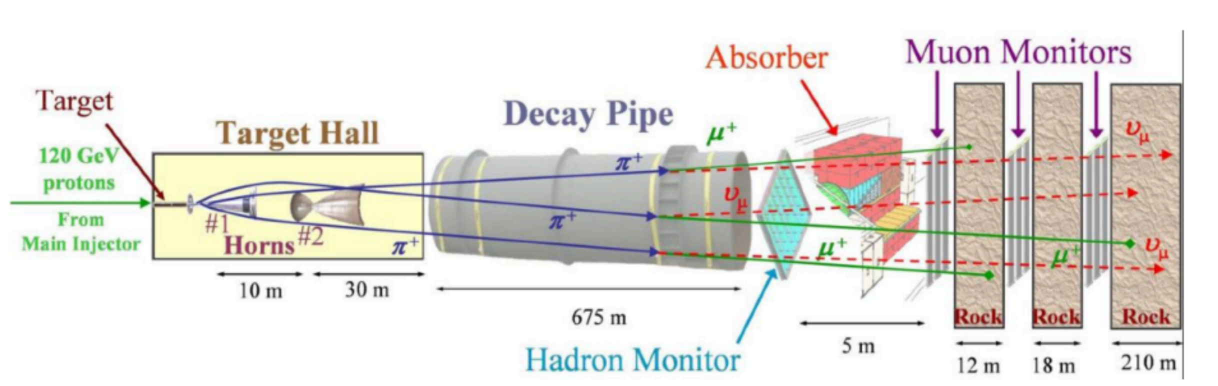
- Matter effect when neutrinos propagating through the earth.





Solar neutrinos

- Historically, sign of Δm^2_{12} is determined by solar neutrinos with the matter effect.



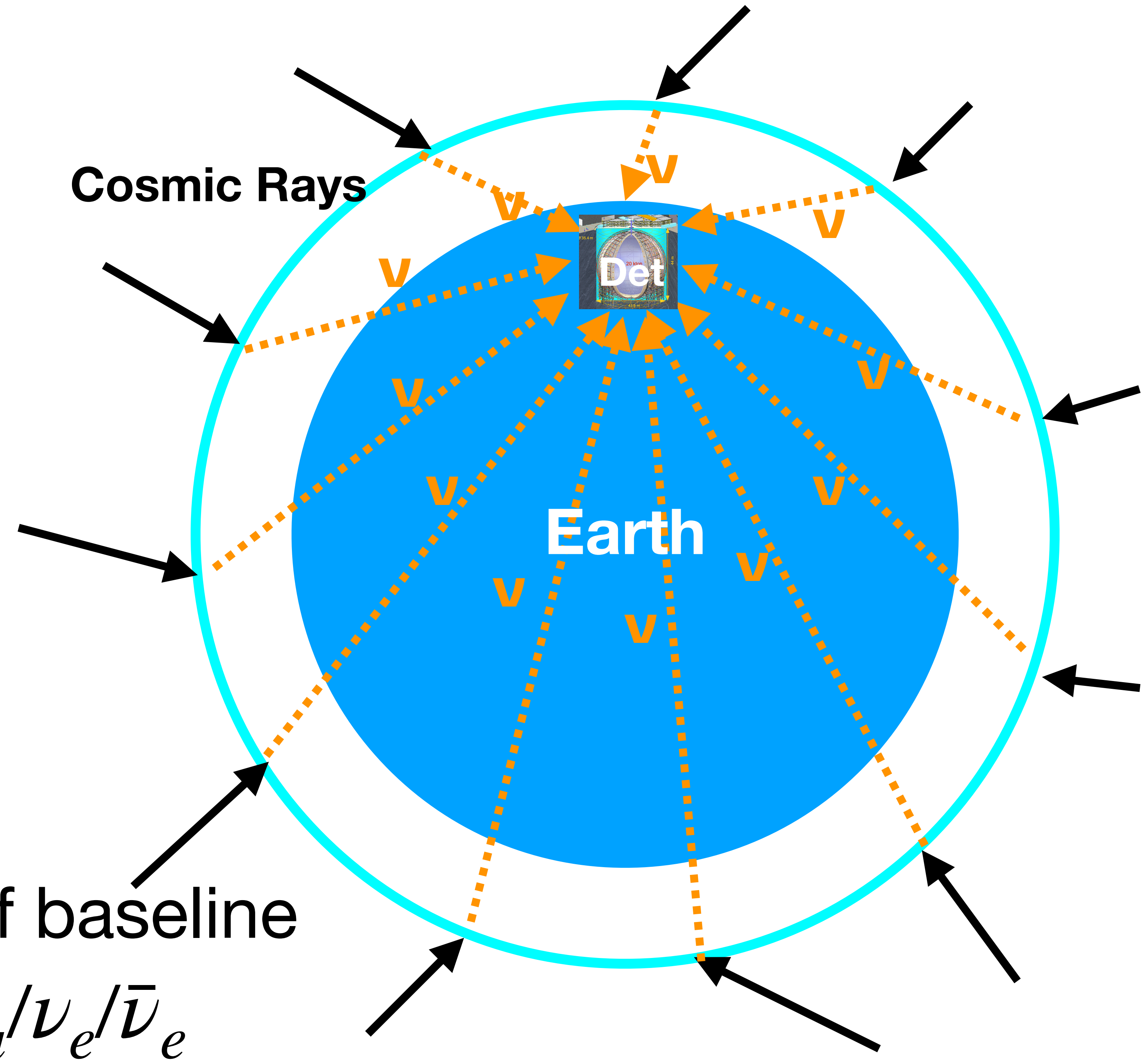
Accelerator neutrinos

- Vacuum oscillation of $\bar{\nu}_e$ disappearance, interference between the Δm^2_{31} and Δm^2_{32} terms

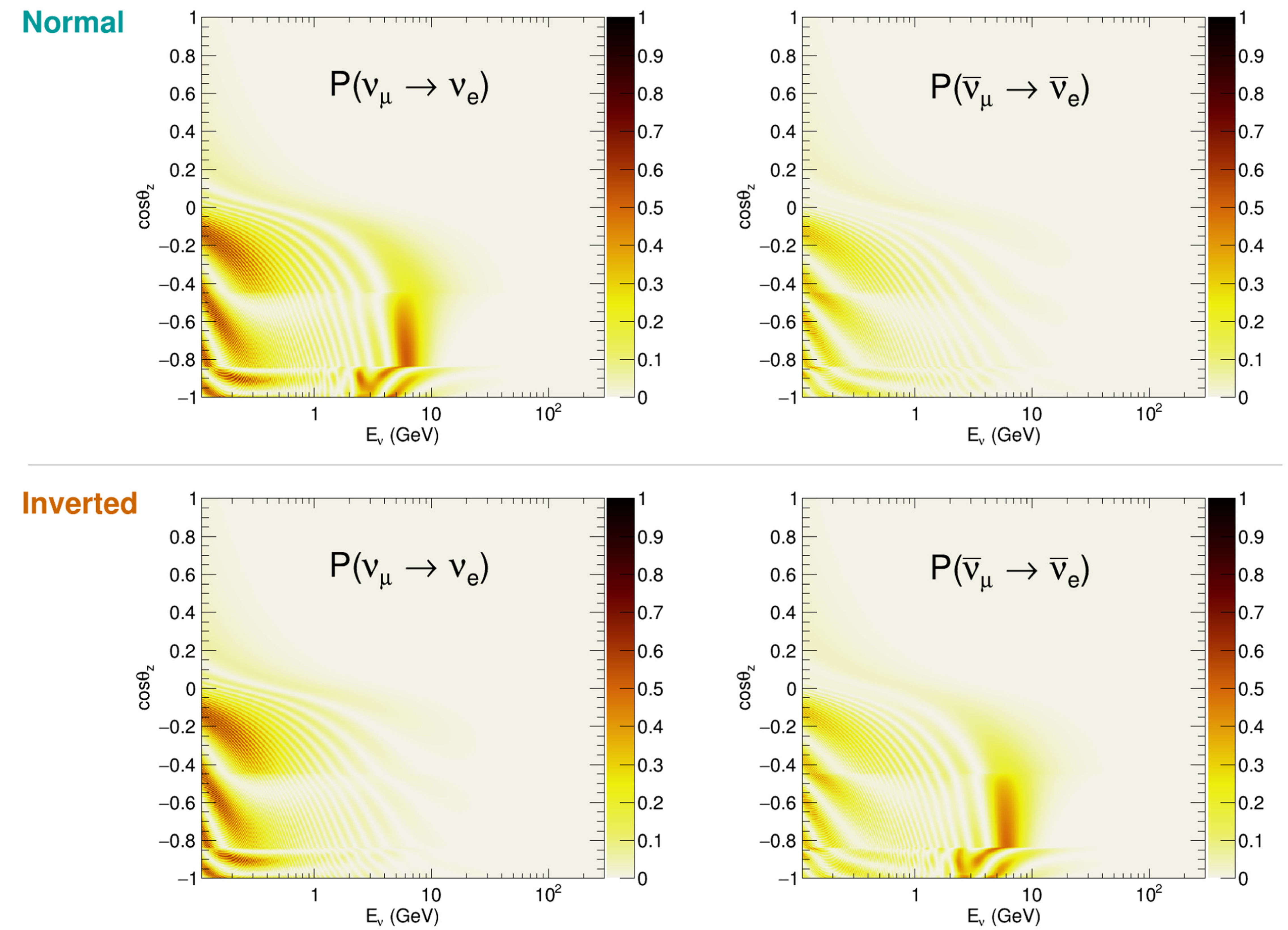
Reactor neutrinos

- Maximized sensitivity by joint-analysis of different experiments with synergies.
- Note: core-collapse supernova neutrinos not included in this talk given the time limit.

How to Determine MH: Atmospheric Neutrinos



- Wide range of baseline lengths, $\nu_\mu/\bar{\nu}_\mu/\nu_e/\bar{\nu}_e$
- Matter effect: e neutrinos experience an additional potential while propagating through the earth though CC interaction with e$^-$
  - Opposite for $\nu/\bar{\nu}$ oscillations.

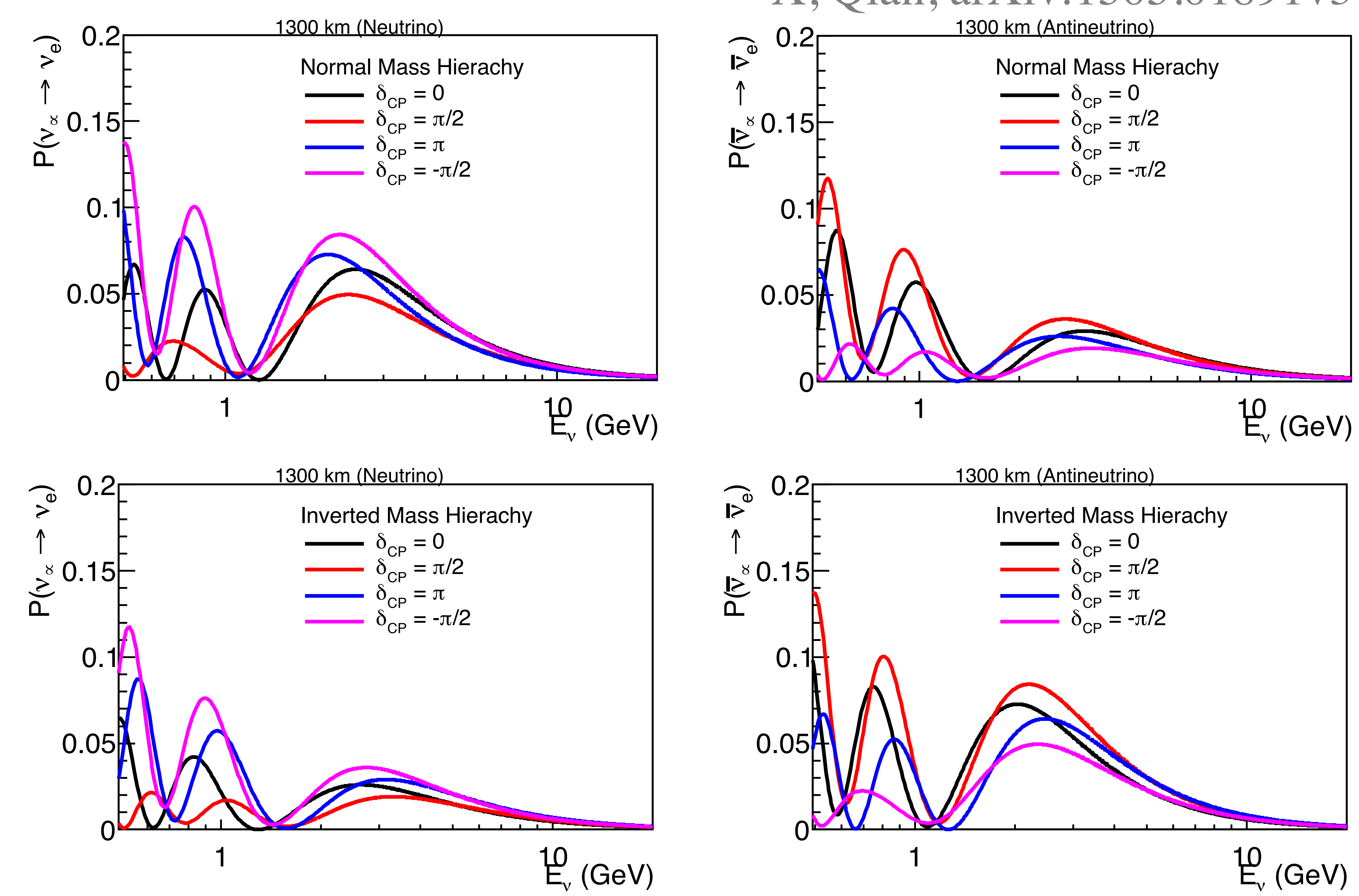


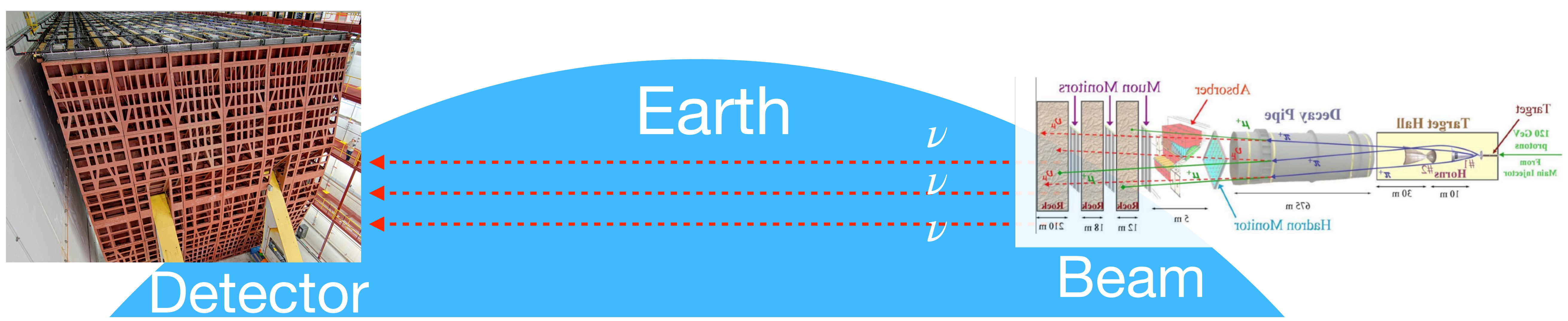
Sensitivity benchmarked by $\Delta\chi^2 = |\chi^2_{NO} - \chi^2_{IO}|$

- Degeneracies between MH, θ_{23} octant, and δ_{CP} .
- Better to be able to separate neutrinos and anti-neutrinos.
  - Difficult given the massive detectors.
  - Still sensitivity without $\nu/\bar{\nu}$ separation since two have different flux and cross sections

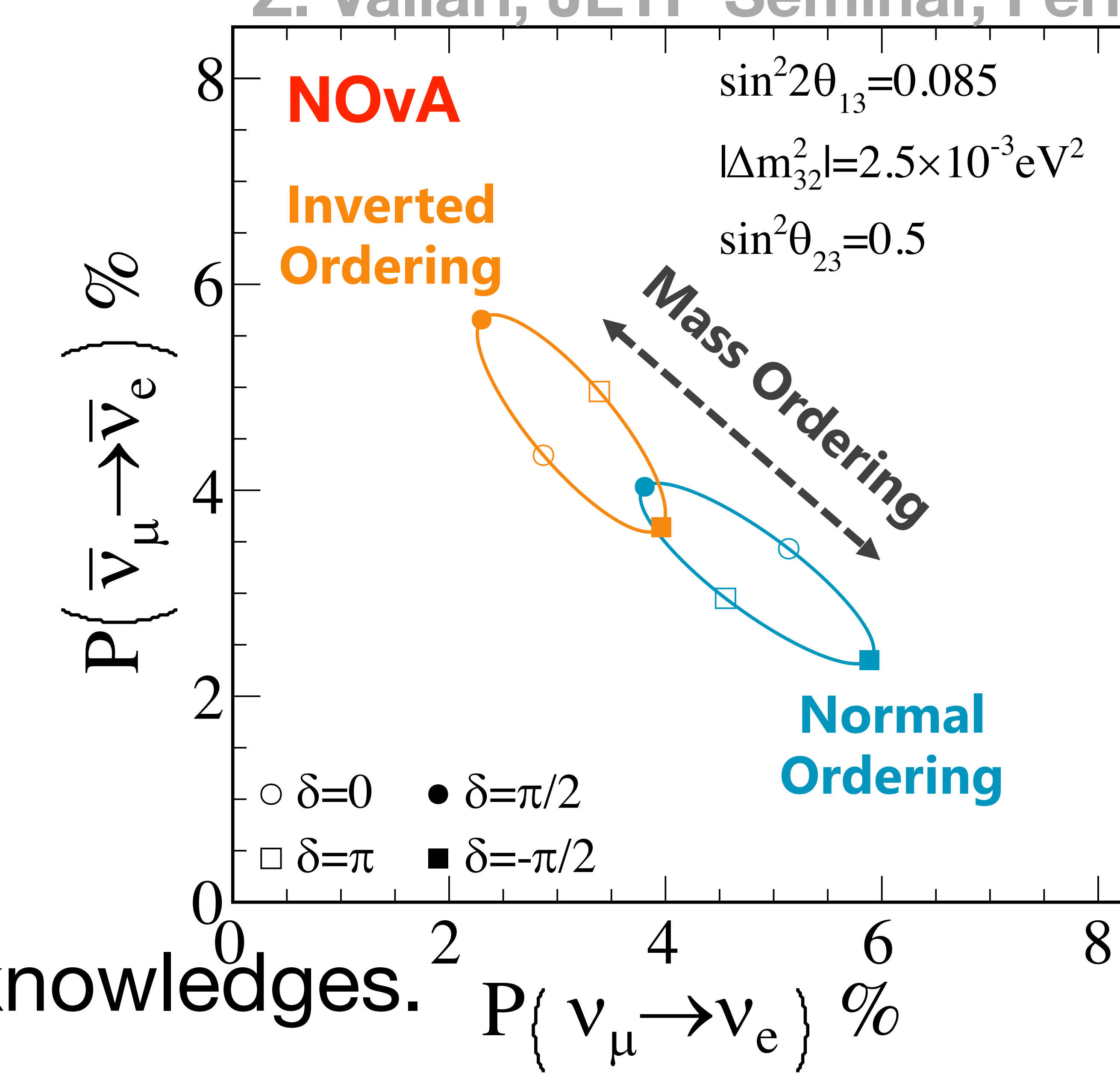
How to Determine MH: Accelerator Neutrinos

X, Qian, arXiv:1505.01891v3



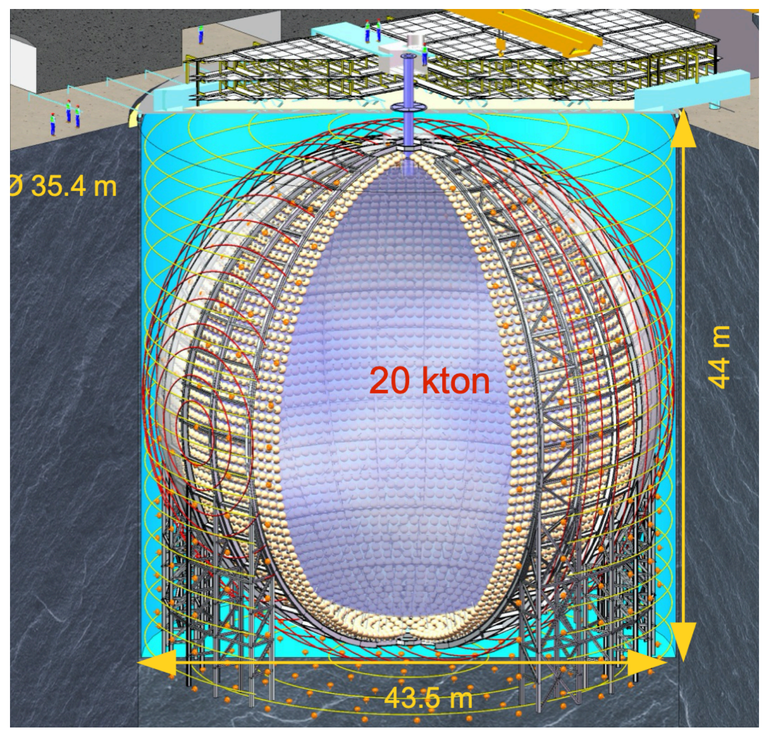


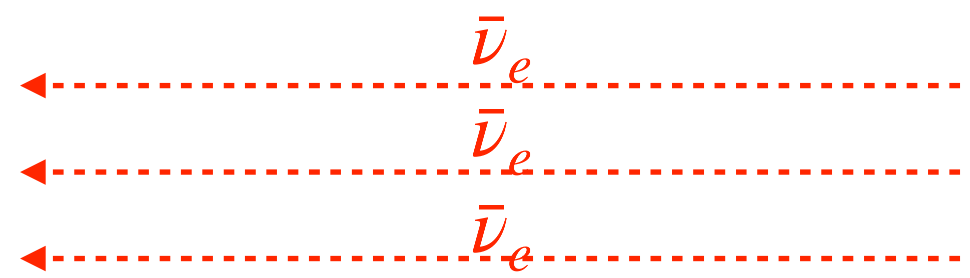
Z. Vallari, JETP Seminar, Fermilab



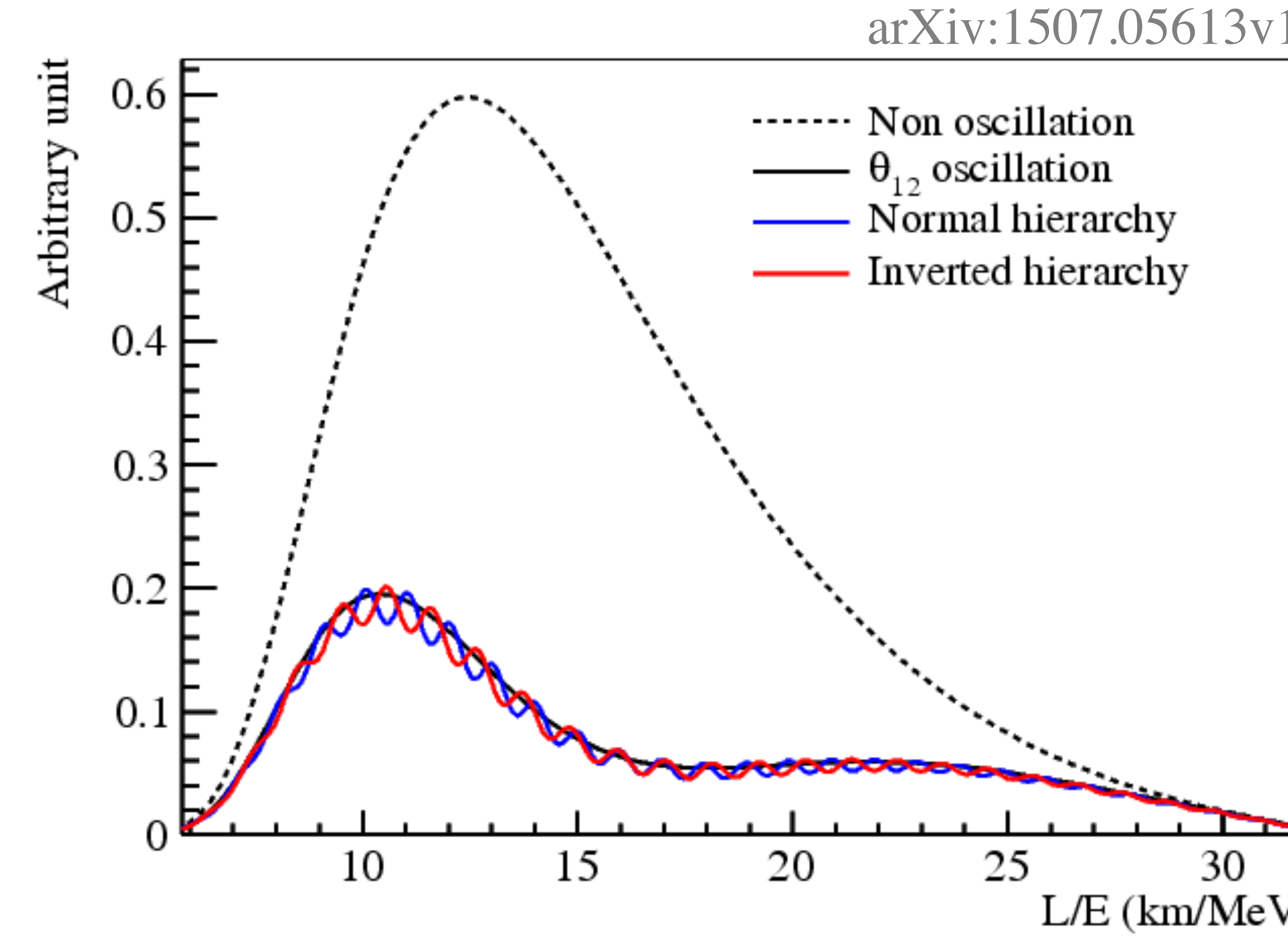
- Matter effect: e neutrinos experience an additional potential while propagating through the earth though CC interaction with e^-
  - Opposite for $\nu/\bar{\nu}$ oscillations.
- Need long baseline length to be sensitive to MH.
- Both neutrino (ν_μ) and anti-neutrino ($\bar{\nu}_\mu$) modes.
  - MH and δ_{CP} can be disentangled to some level with mixing angle knowledges.
- See talk by Veera Matilda Mikola tomorrow.

How to Determine MH: Reactor Neutrinos





Medium baseline maximizing the interference amplitude.

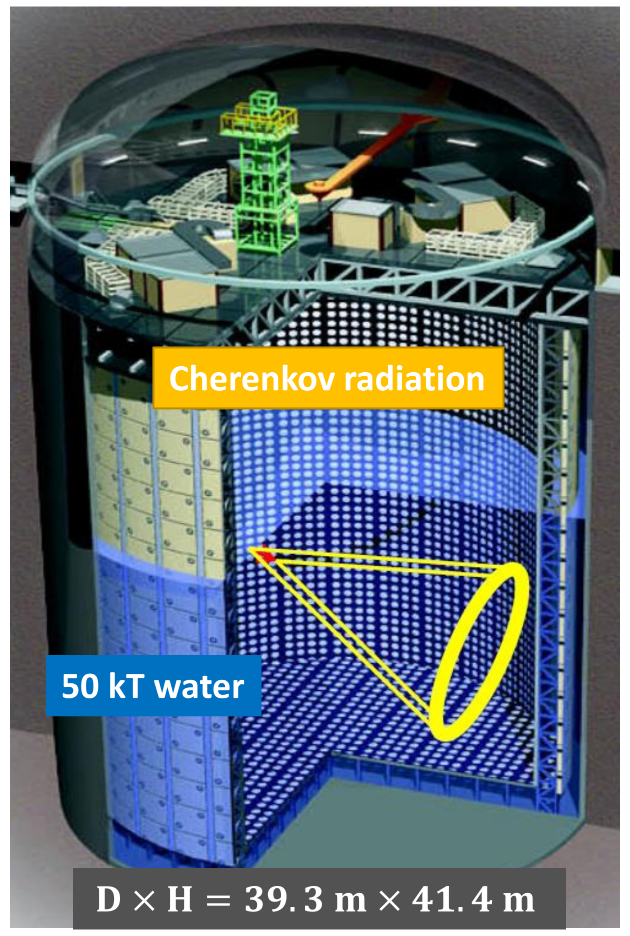


$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4 \sin^2 2\theta_{12}\sin^2\Delta_{21}$$

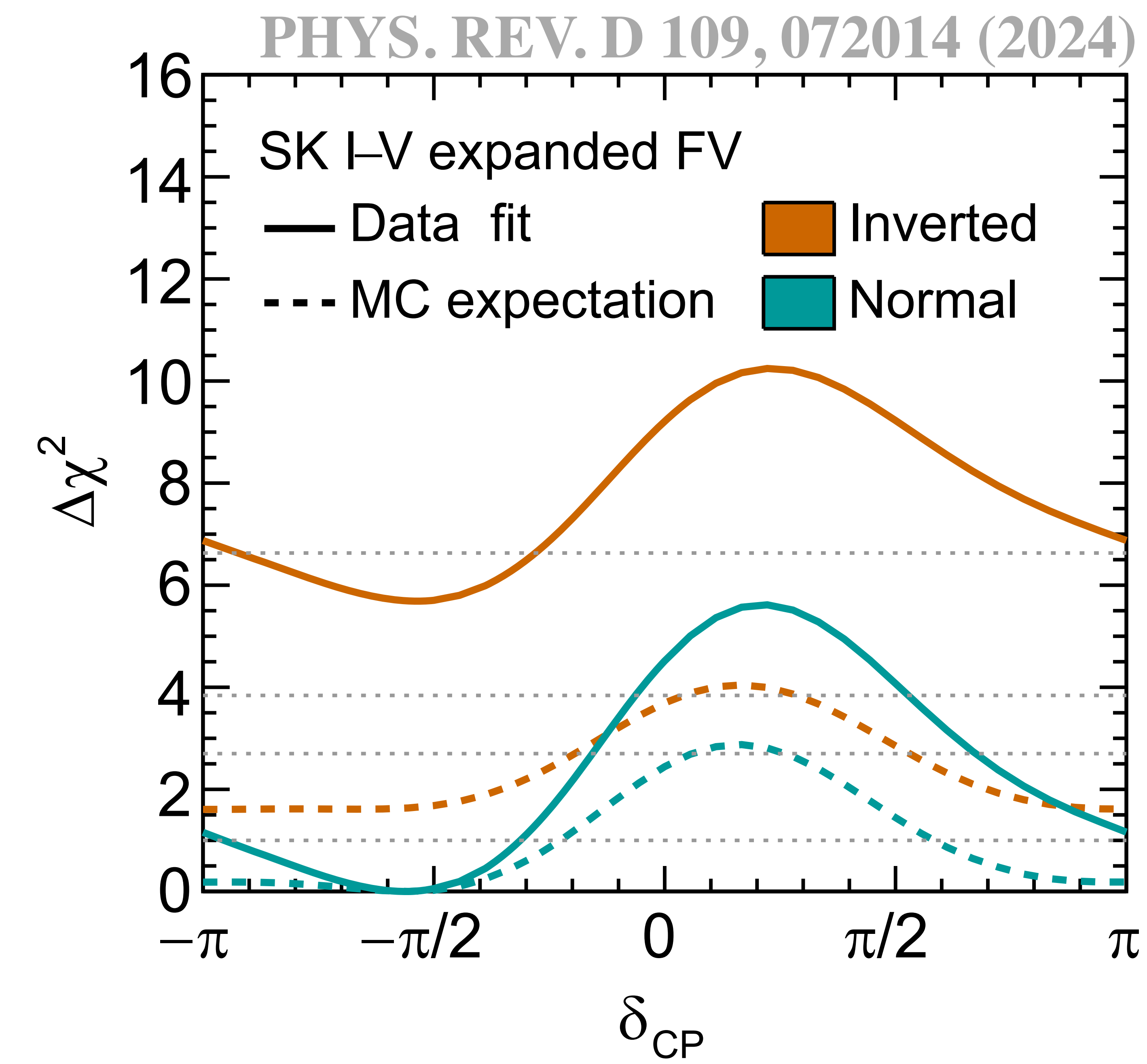
- Vacuum oscillation utilizing small differences in $|\Delta m^2_{31}|$ and $|\Delta m^2_{32}|$ for different MH.
- Independent from θ_{23} octant and δ_{CP}.
- Made possible by the relatively large θ_{13} value.
- Need really good energy resolution and statistics.

Experiments’ Status

Atmospheric Neutrino Experiments: Super-Kamiokande



- Water Cherenkov detector, 22.5 kton fiducial mass.
- Updated analysis with neutron tagging (26% efficiency) for $\nu/\bar{\nu}$ separation

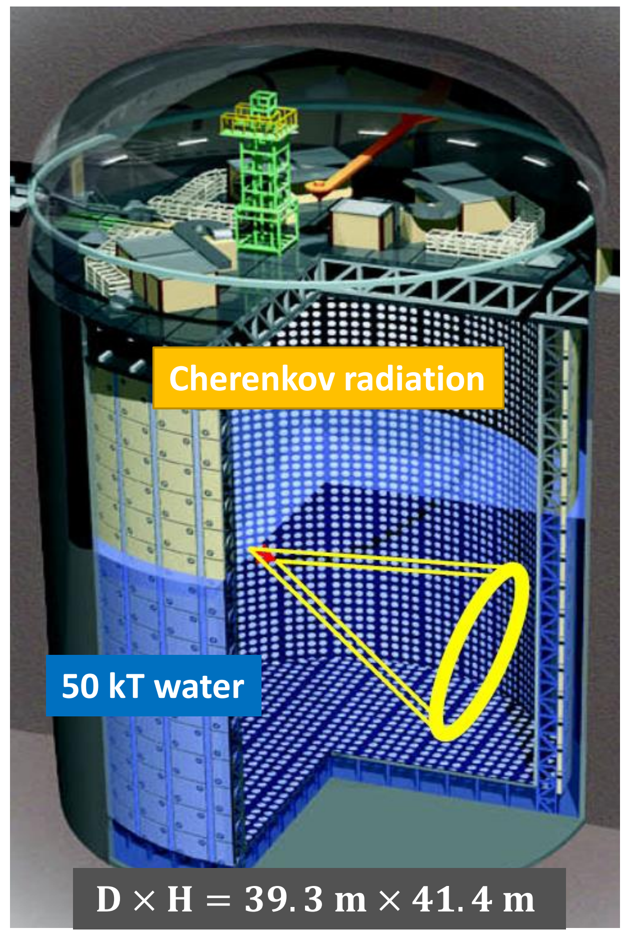


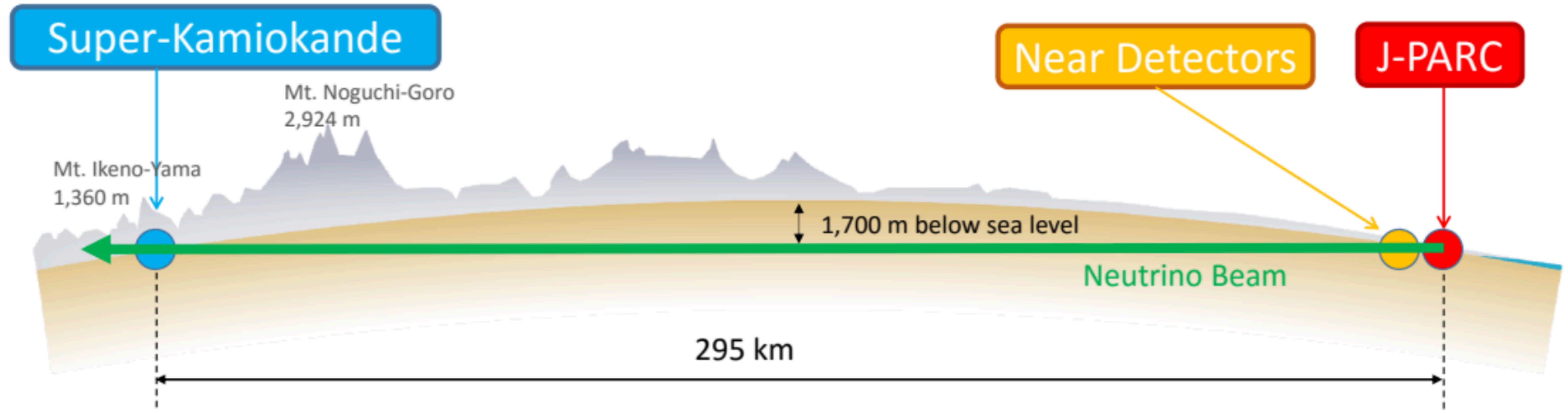
Phase	Dates	Live time (Days)	Photo-coverage (%)	Neutron tagging
SK I	1996–2001	1489.2	40	···
SK II	2002–2005	798.6	19	···
SK III	2006–2008	518.1	40	···
SK IV	2008–2018	3244.4	40	H
SK V	2019–2020	461.0	40	H
SK Gd	2020–Present	···	40	H + Gd

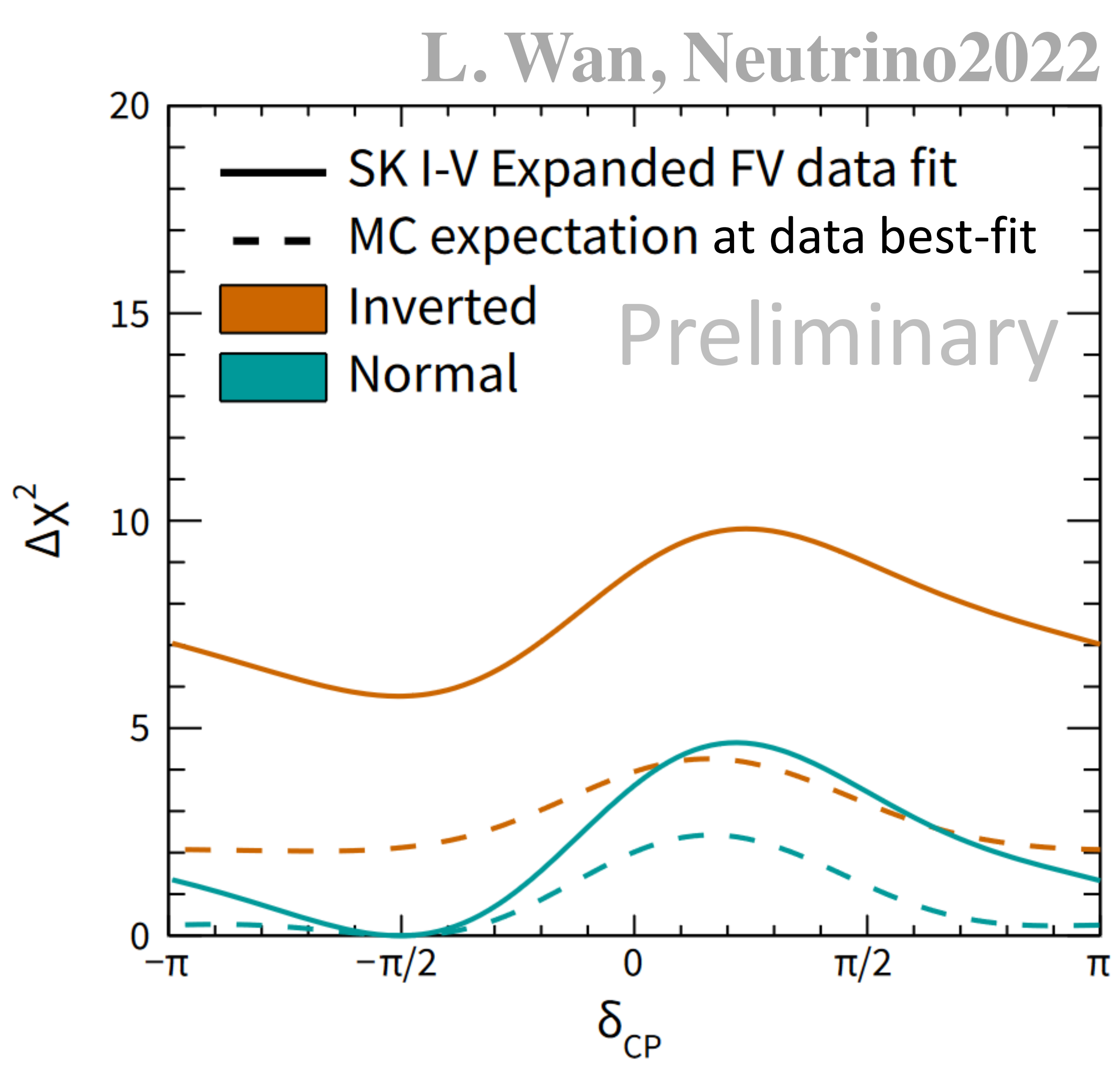
Fit result	Ordering	χ^2	$\Delta\chi^2_{\mathrm{I.O.-N.O.}}$
SK, Atmospheric only	Normal	1022.06	5.23
	Inverted	1027.29	
SK, $\sin^2\theta_{13}$ Constrained	Normal	1022.06	5.69
	Inverted	1027.75	

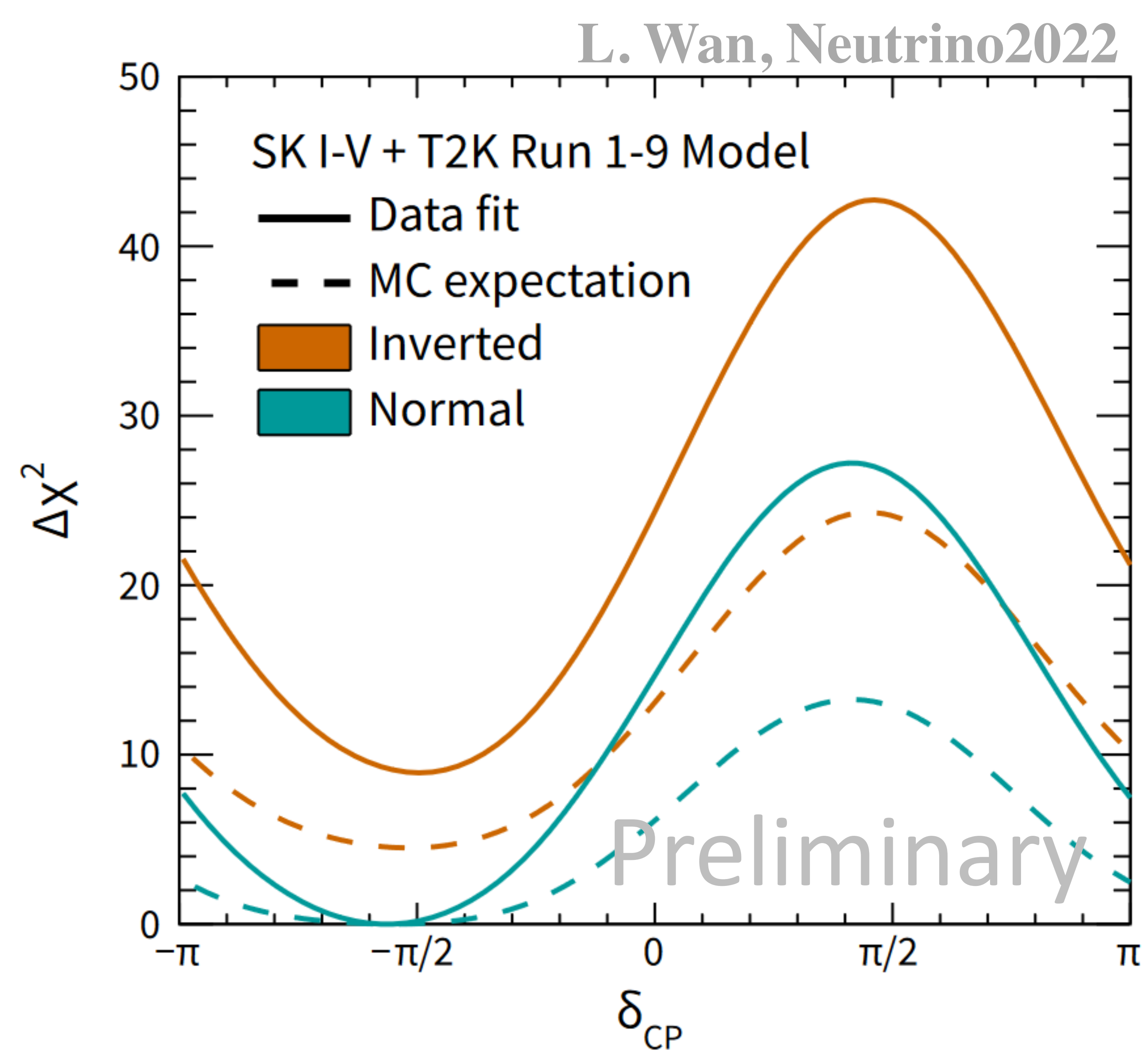
- Most of the current sensitivity if from SuperK.
- Rejection of IH by 92.3% confidence level.

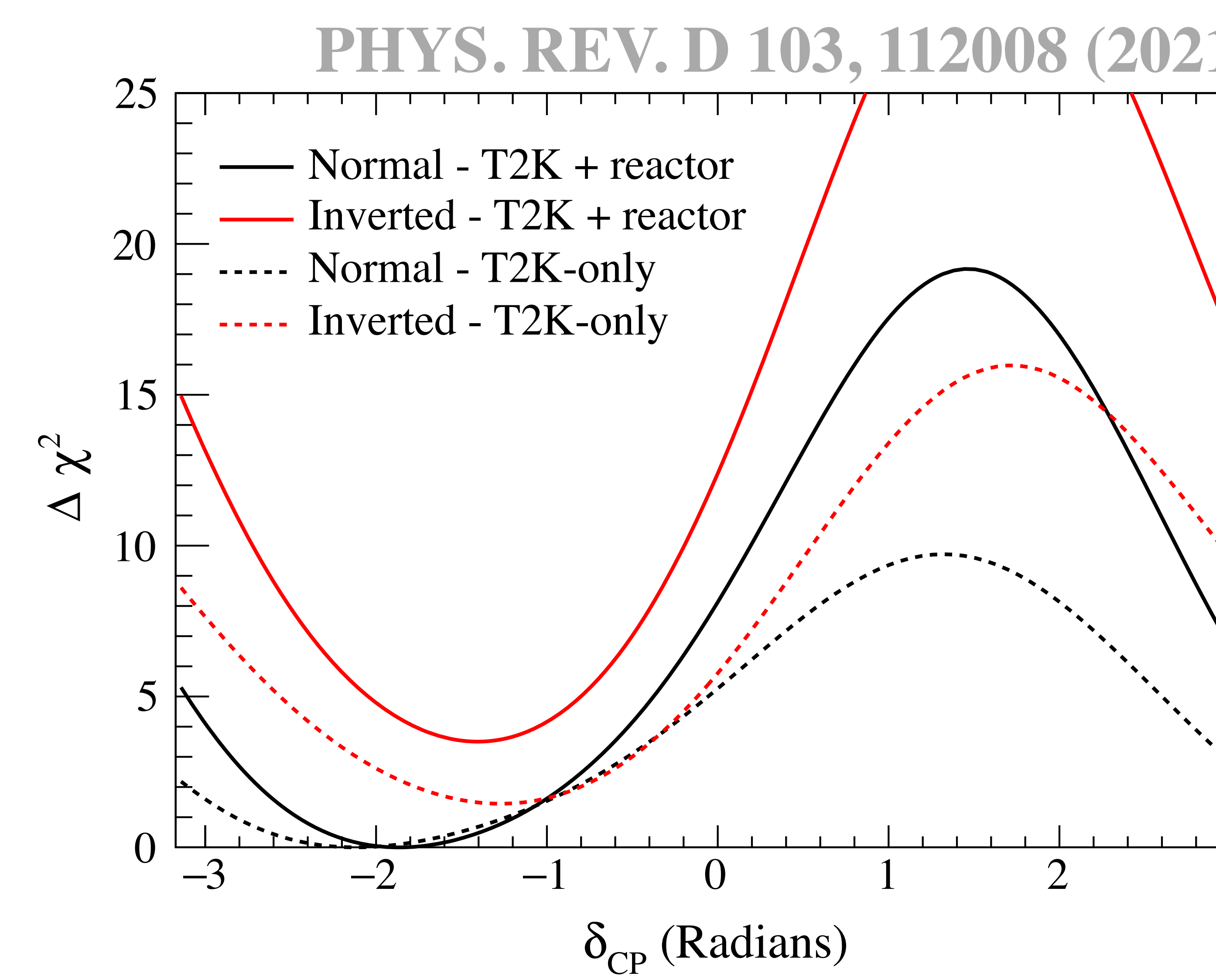
Super-K + T2K





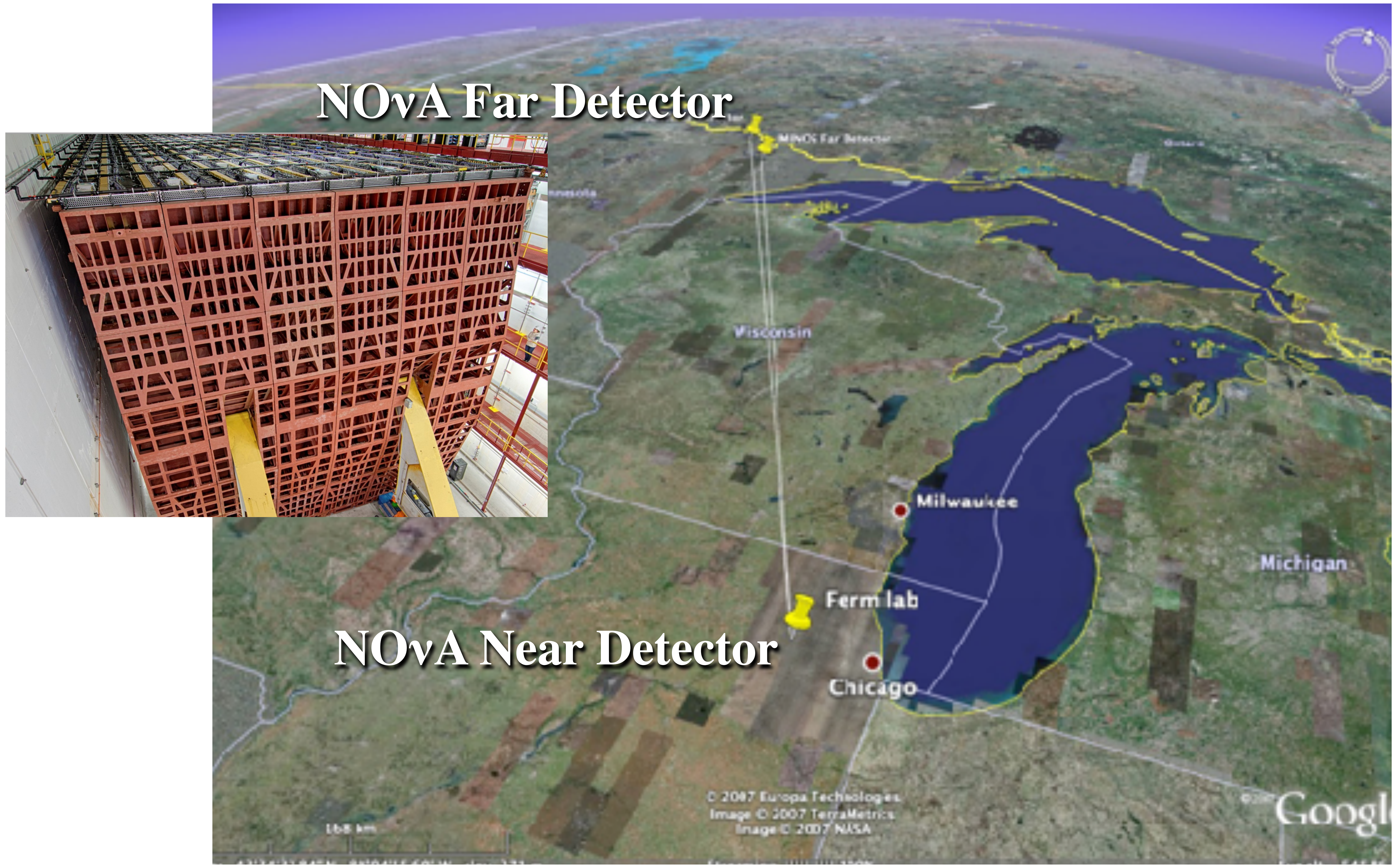


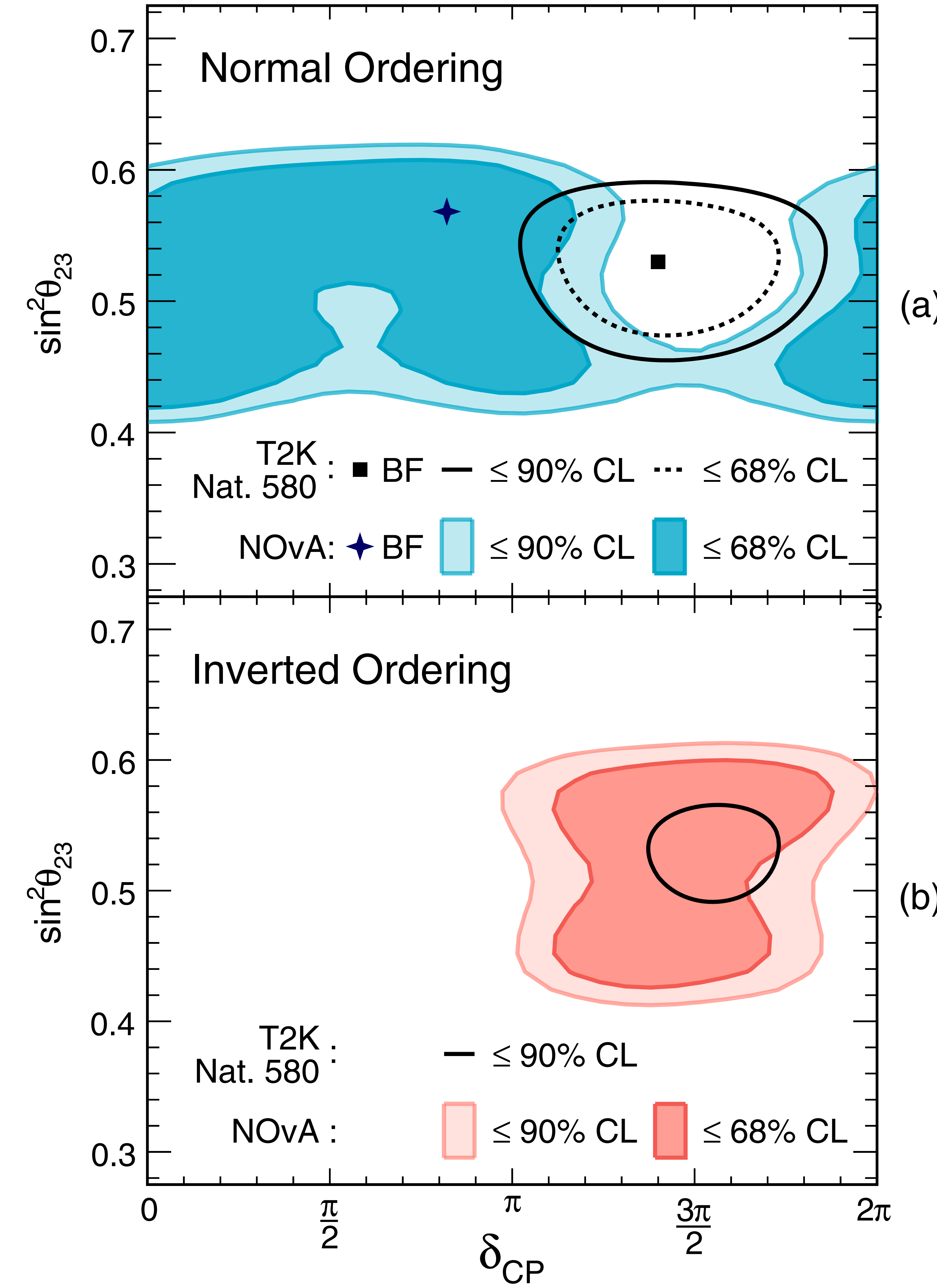




- Simultaneous fit of Super-K and T2K published data.
  - Correlated systematic uncertainties.
- Prefer NH with $\Delta\chi^2 = 8.9$

Accelerator-based Experiments: NOvA

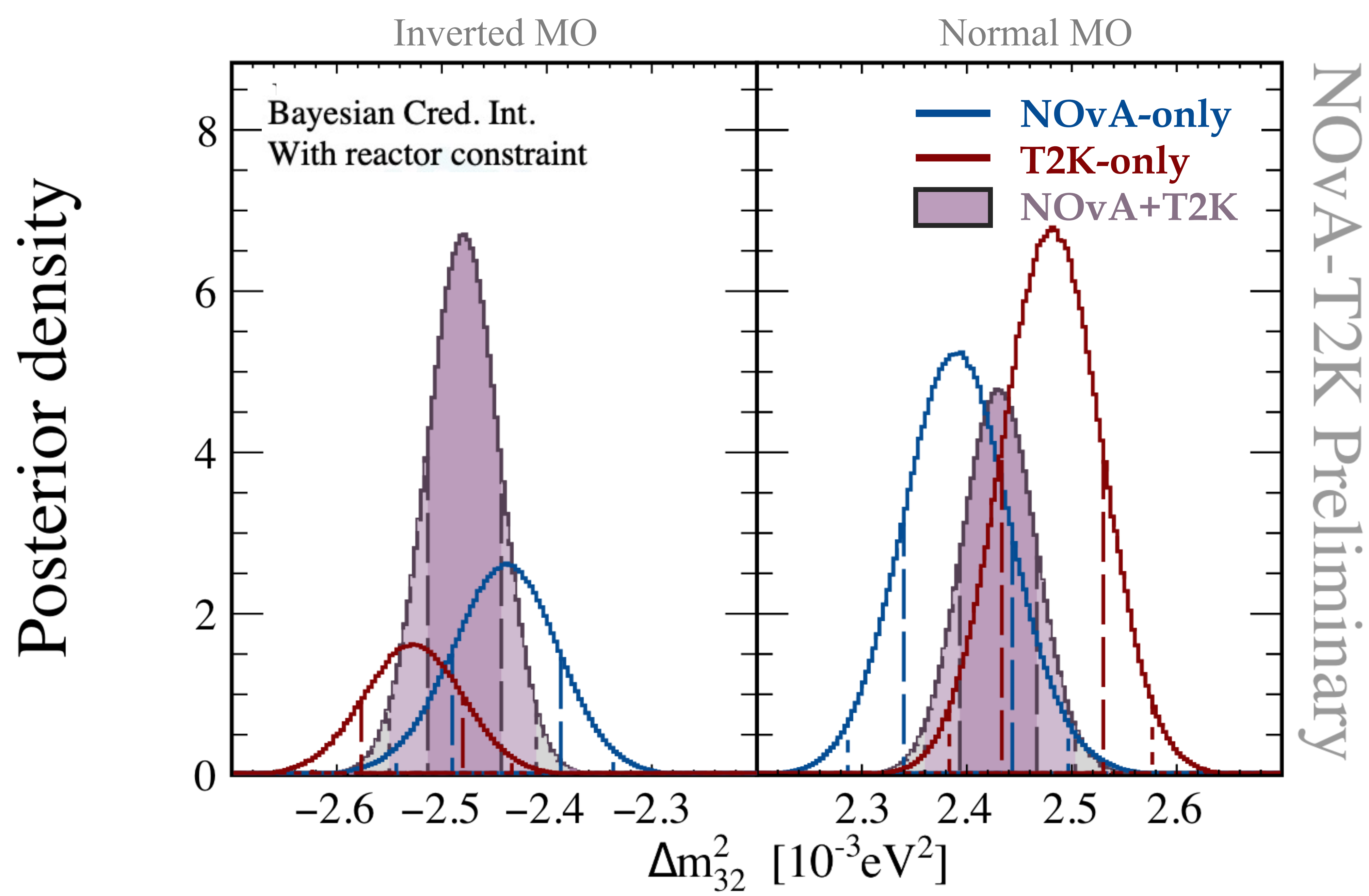




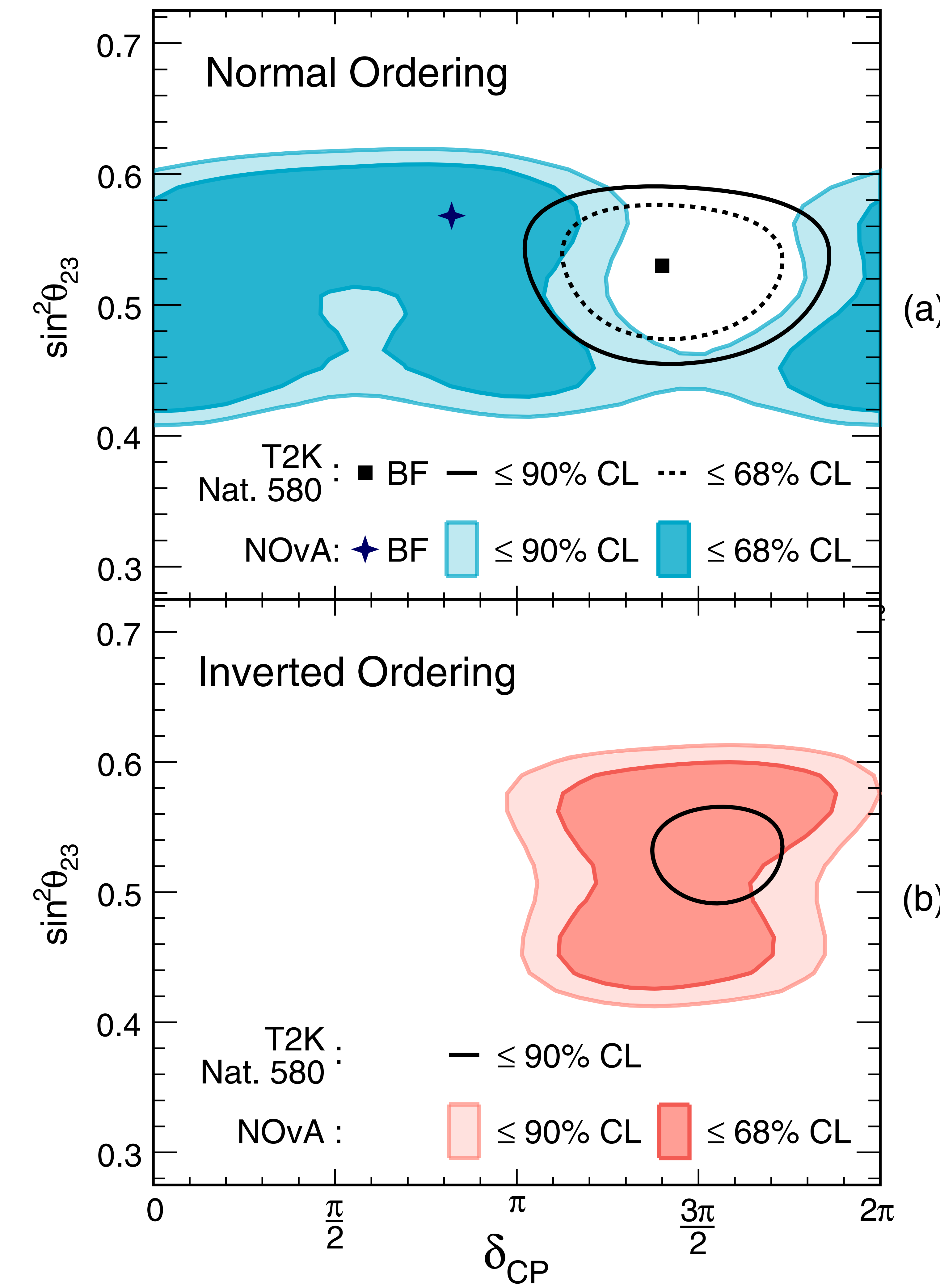
PHYS. REV. D 106, 032004 (2022)

- 14 kton segmented LS detector.
- 810 km baseline.
- 290 ton ND for systematic cancellation.
- **Favors NH by 1.0 σ.**

Joint NOvA-T2K Analysis



Z. Vallari, JETP Seminar, Fermilab



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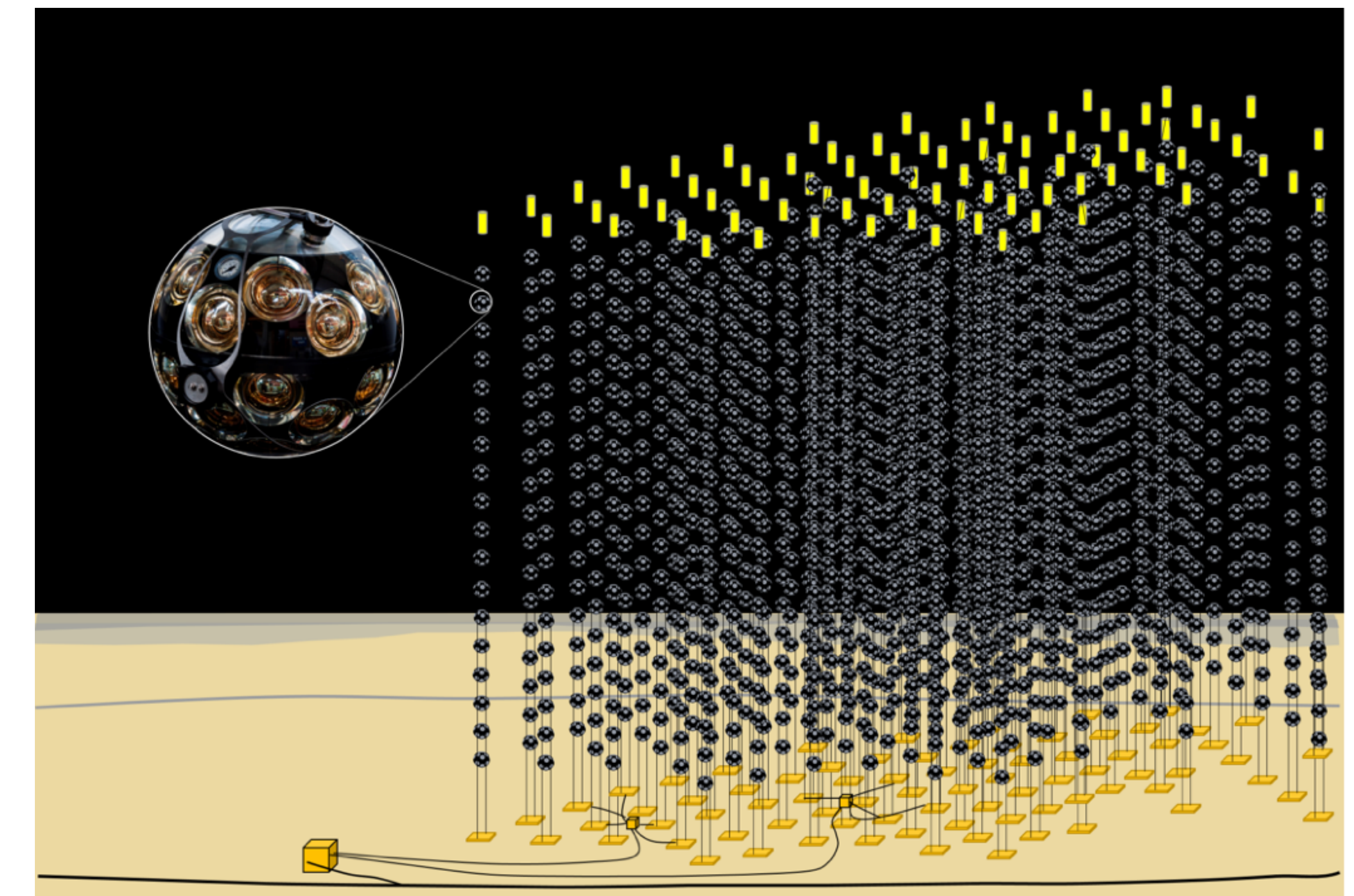
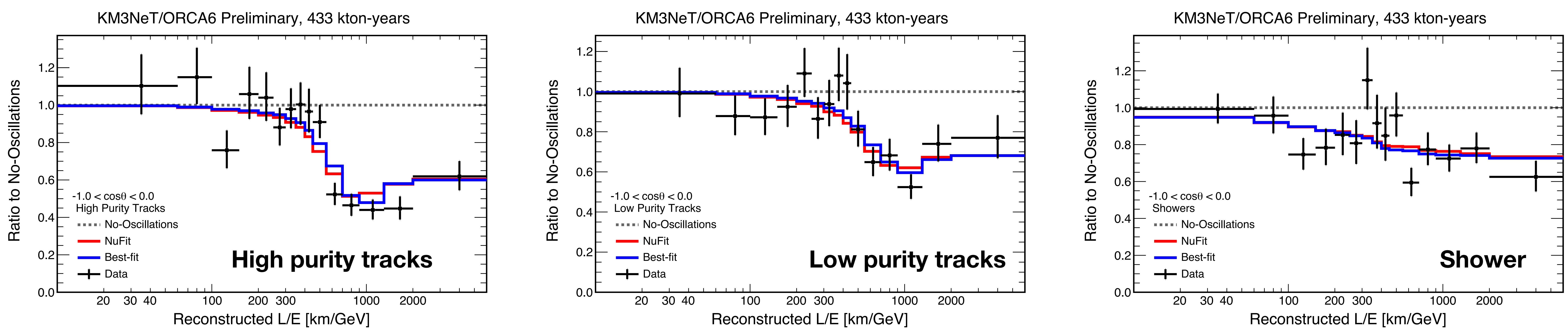
- Different baseline length helps to disentangle MH from δ_{CP}
- Correlated systematics taken into account.
- Challenging analysis: different ND-FD extrapolation strategies.
- The joint analysis show modest preference for IH (IH/NH = 58%:42%), although each experiment favors NH by itself.

KM3NeT/ORCA

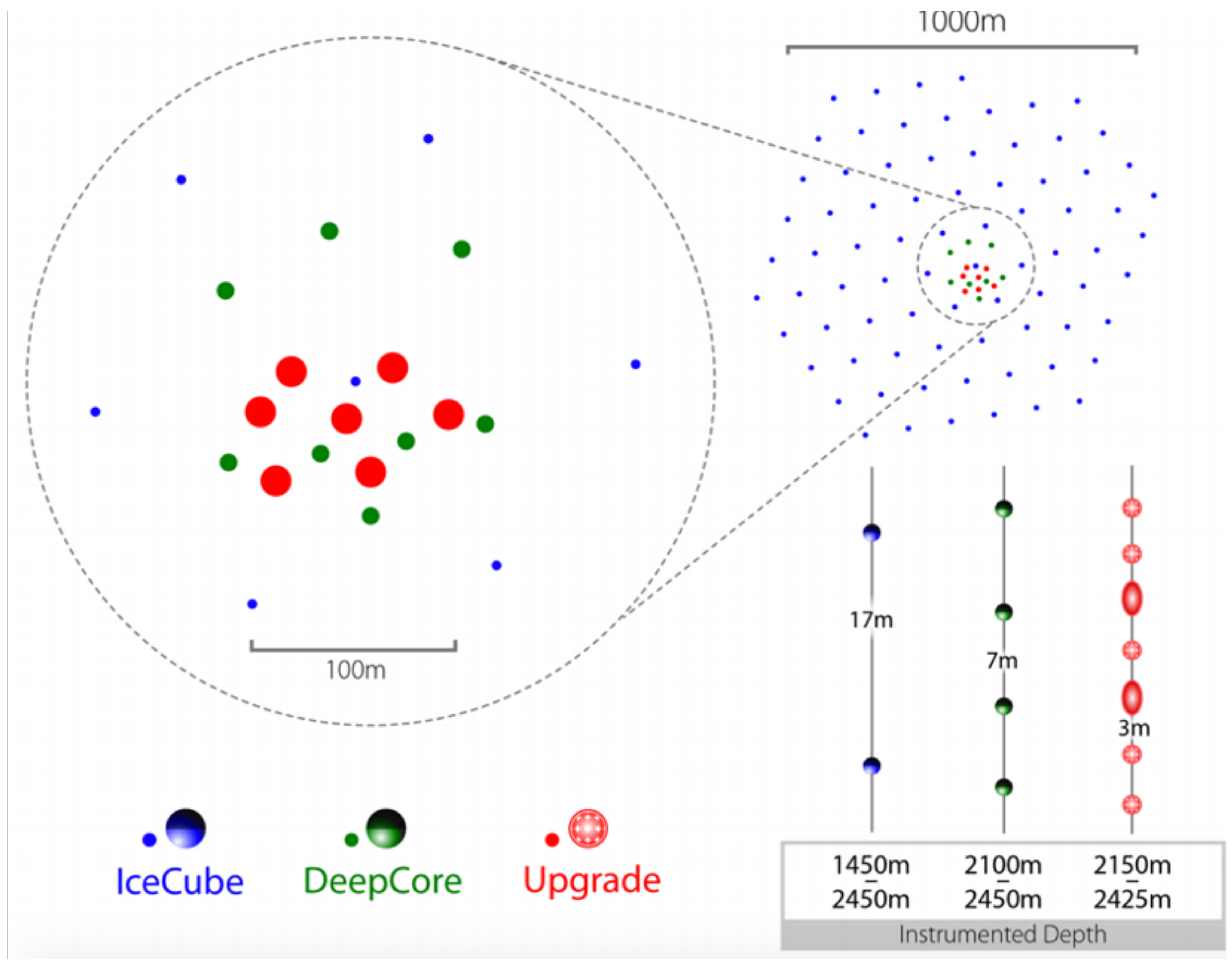


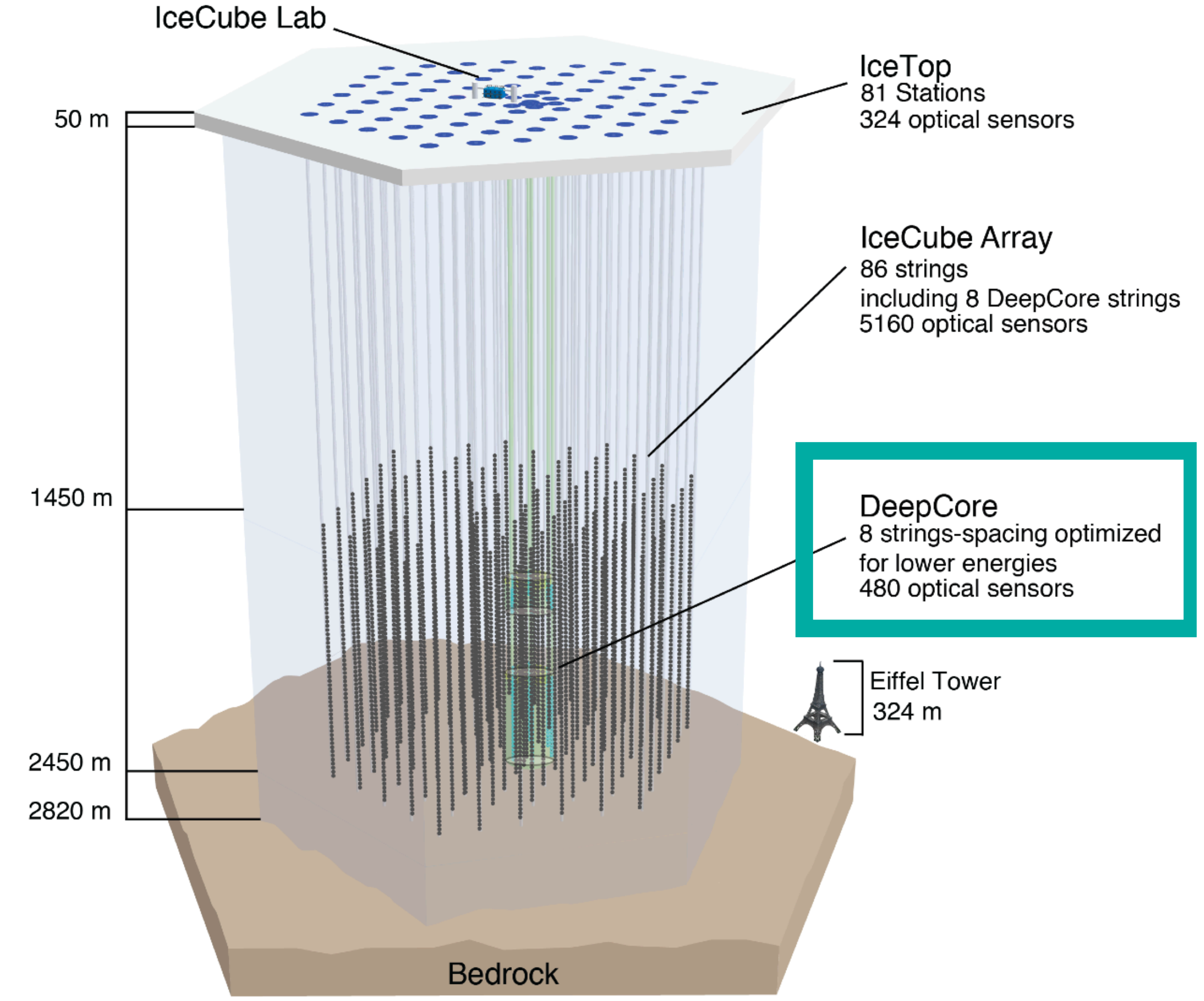


PoS(ICRC2023)996

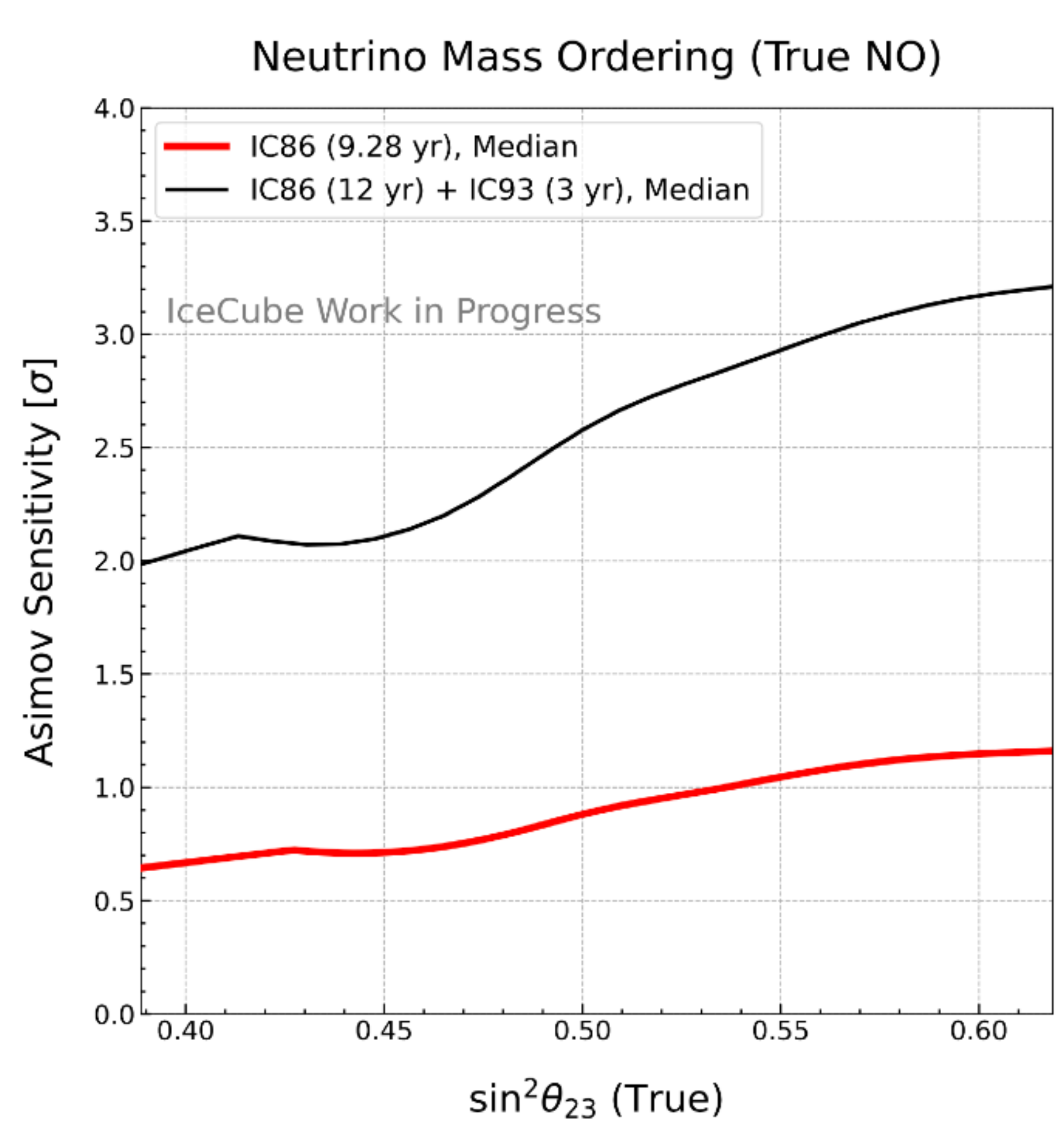
- 7 Mton water-Cherenkov detector at the bottom of the Mediterranean Sea with 115 strings.
- During 2020 and 2021, an early configuration of the detector with six lines was in operation
  - Analysis with 433 kton-years of exposure
- NH is prefered -2 log(LNO/LIO) = 0.9. (**PoS(ICRC2023)996**)
- For more details see the talk by Ekaterini Tzamariudaki.

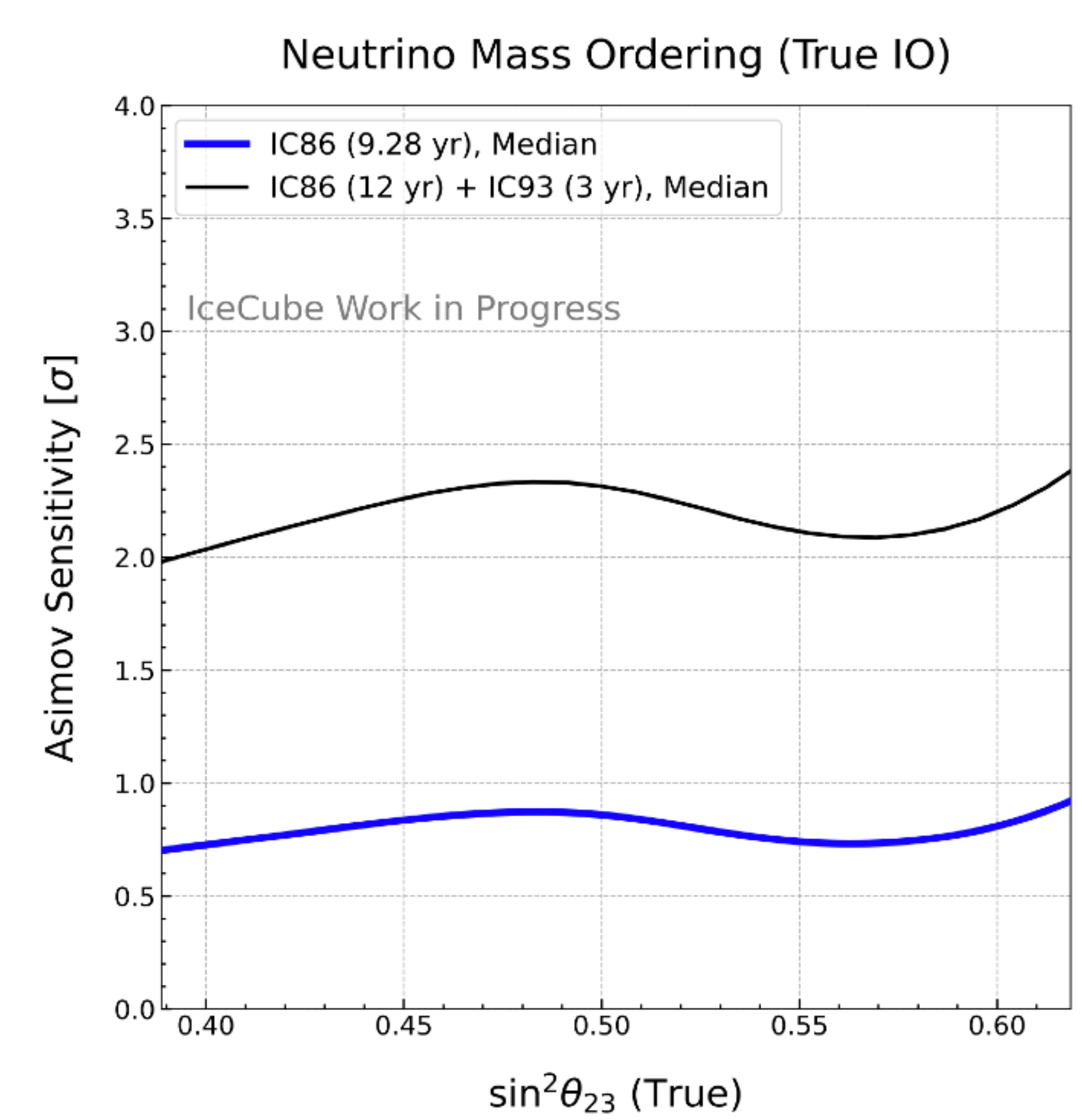
IceCube DeepCore/Upgrade





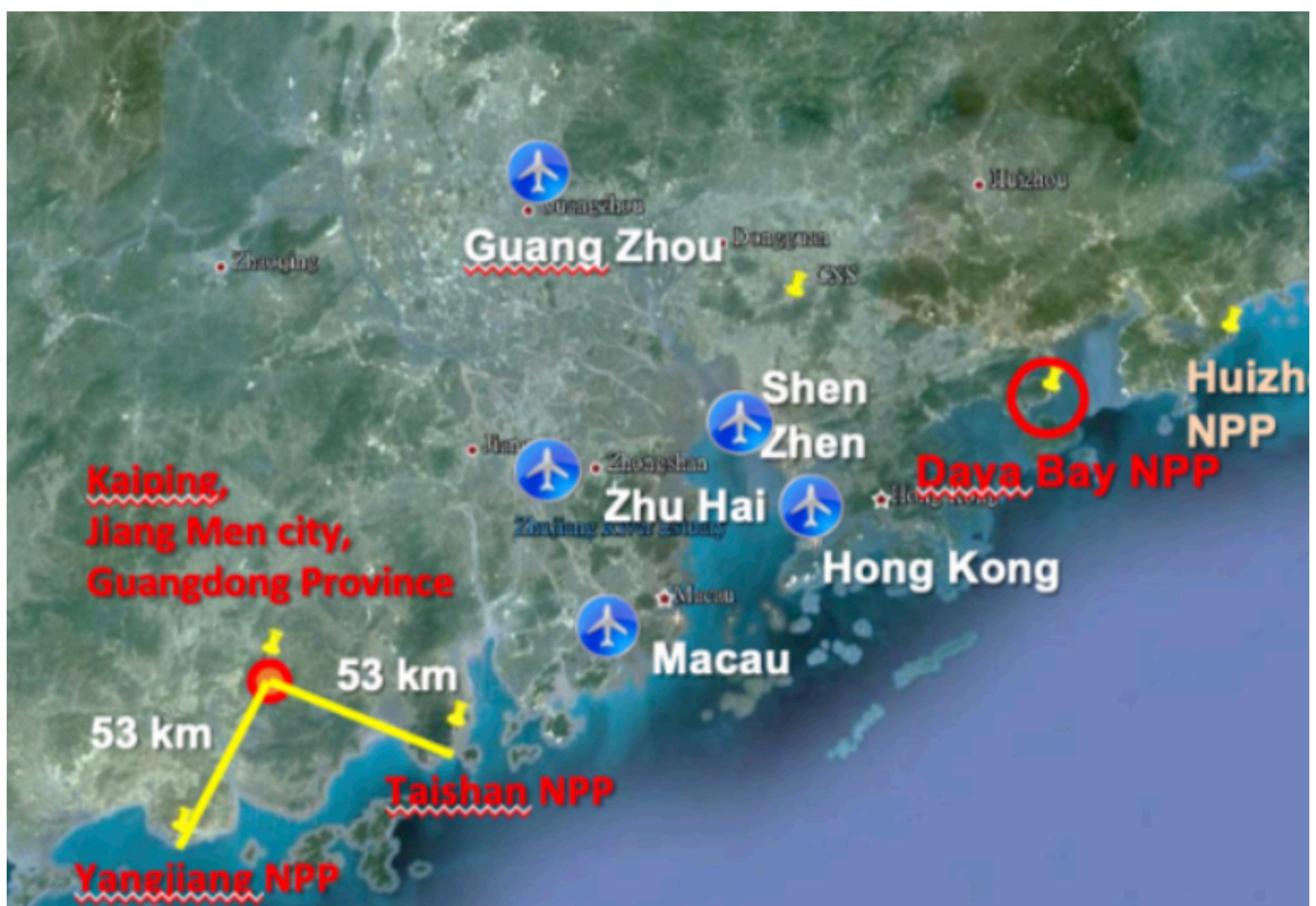
- DeepCore: 8 more strings with more PMTs.
  - 10 Mton mass.
  - Lower threshold (3 - 100 GeV)
- Upgrade: 7 more strings
  - 2025/2026

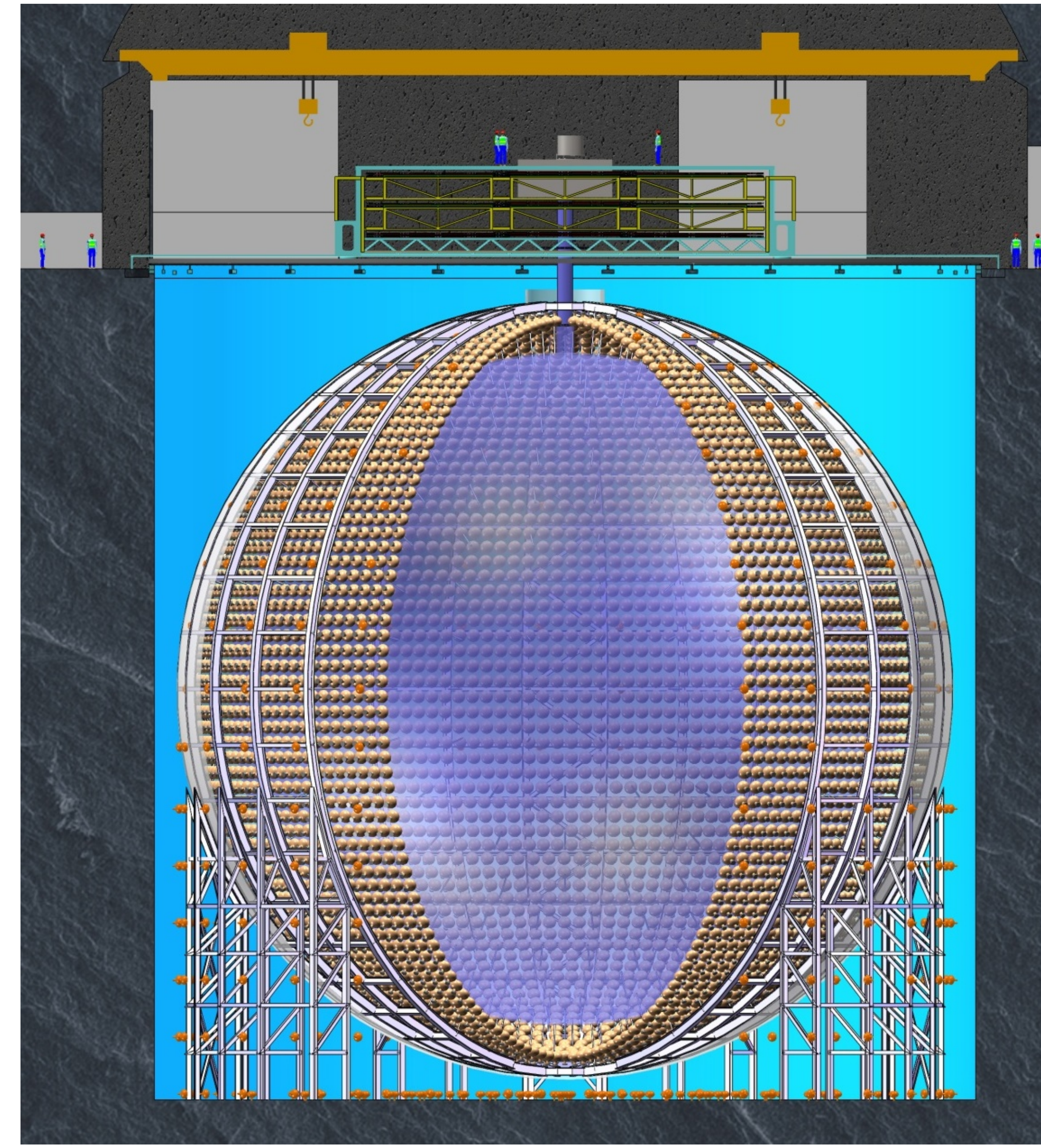




Reactor Neutrino Experiment: JUNO

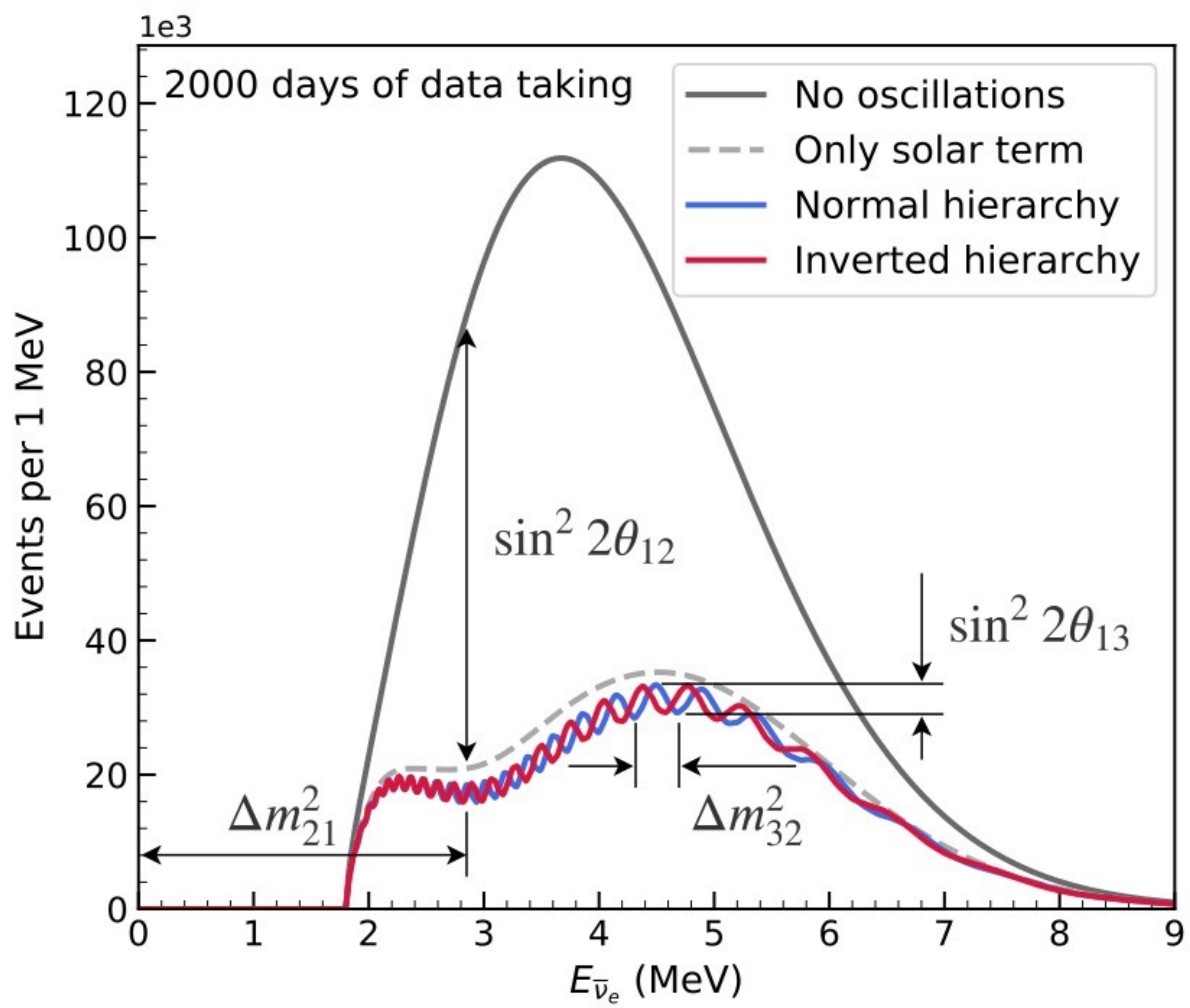
- Jiangmen Underground Neutrino Observatory (JUNO).
- 20kton homogeneous LS detector with 78% PMT coverage.
- Taishan Neutrino Observatory (TAO) for flux measurement.
- Currently under construction. Physics run to start in 2025.

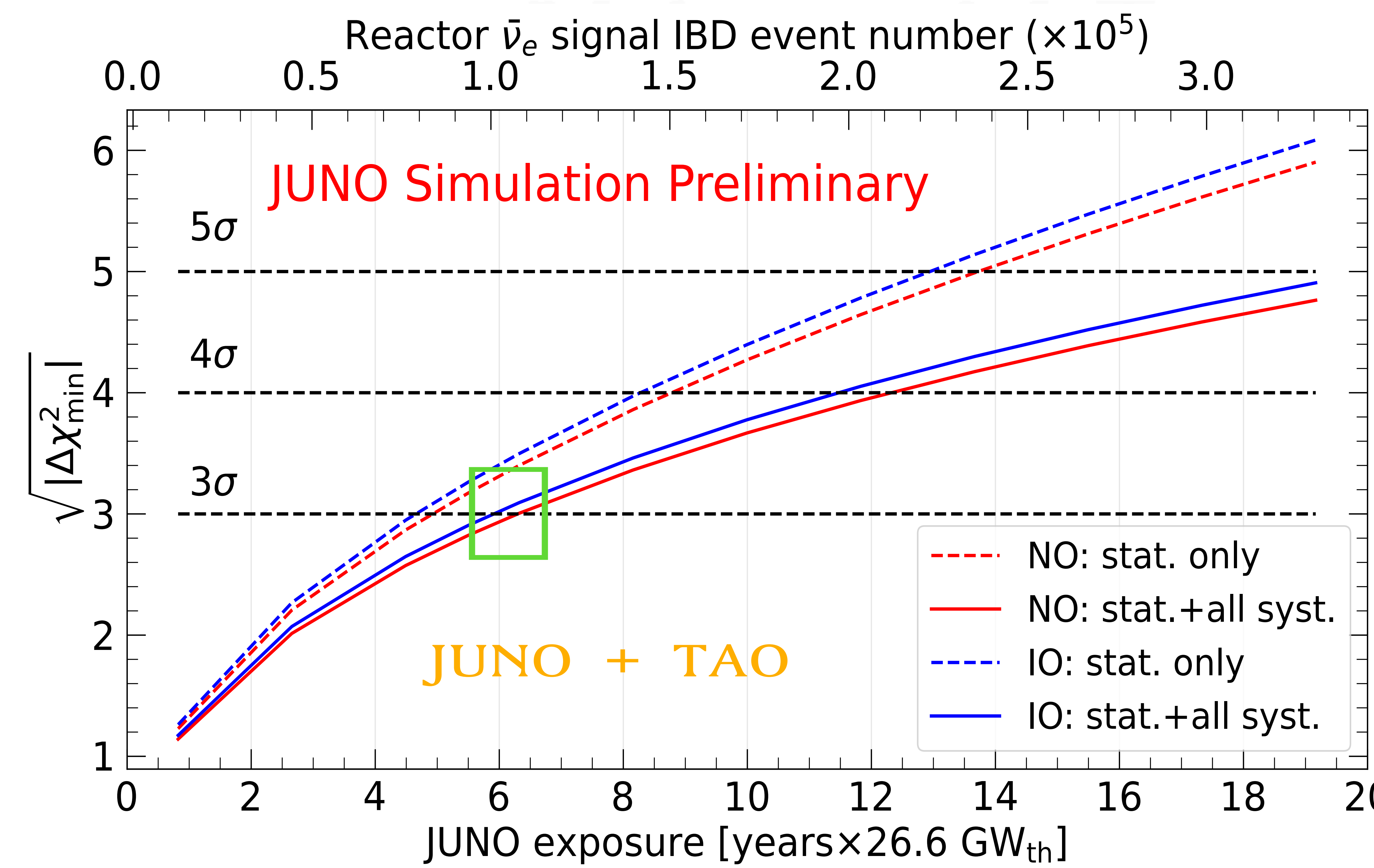




The largest liquid scintillator detector ever built.

Reactor ν Experiment for the MH problem: JUNO

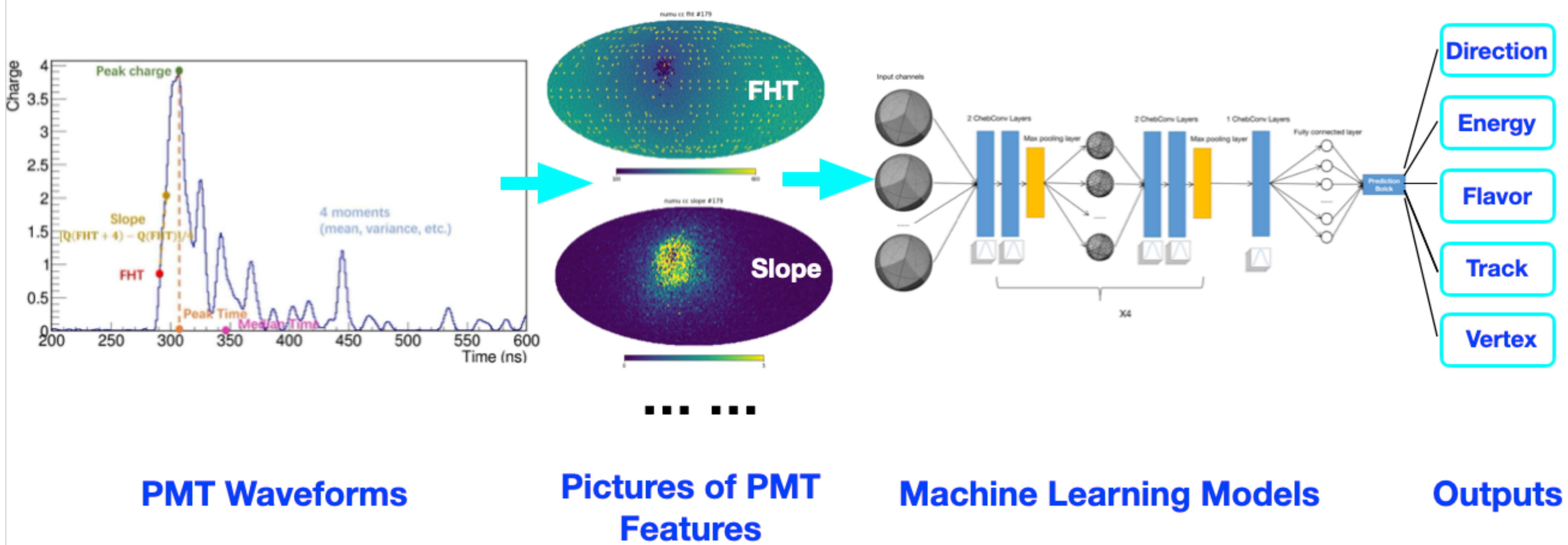




$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4 \sin^2 2\theta_{12}\sin^2\Delta_{21}$$

- 2.9% @ 1 MeV energy resolution
- 3σ sensitivity by itself expected after 6 years data-taking.

JUNO Atmospheric Neutrino Measurement



- JUNO is also able to measure atmospheric neutrino oscillations
  - Good directional resolution using a ML approach.
  - Capable of ν vs $\bar{\nu}$ statistically with help from neutron captures on hydrogen.
- Sensitivity study on-going.

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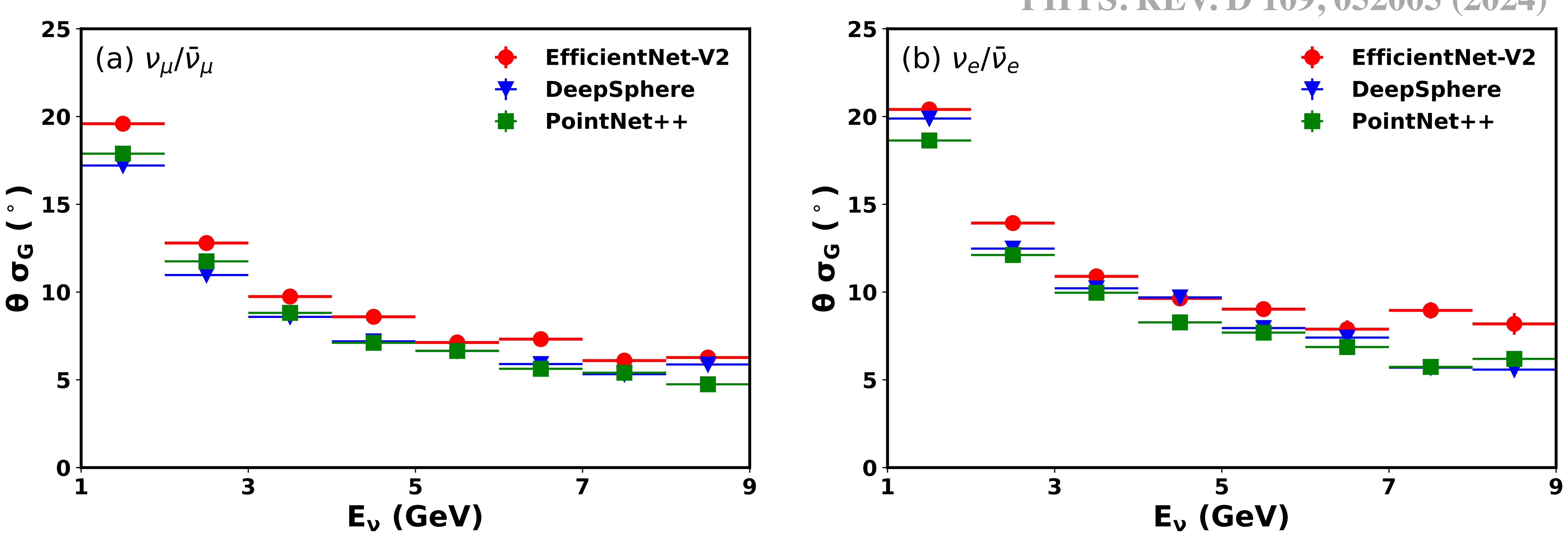
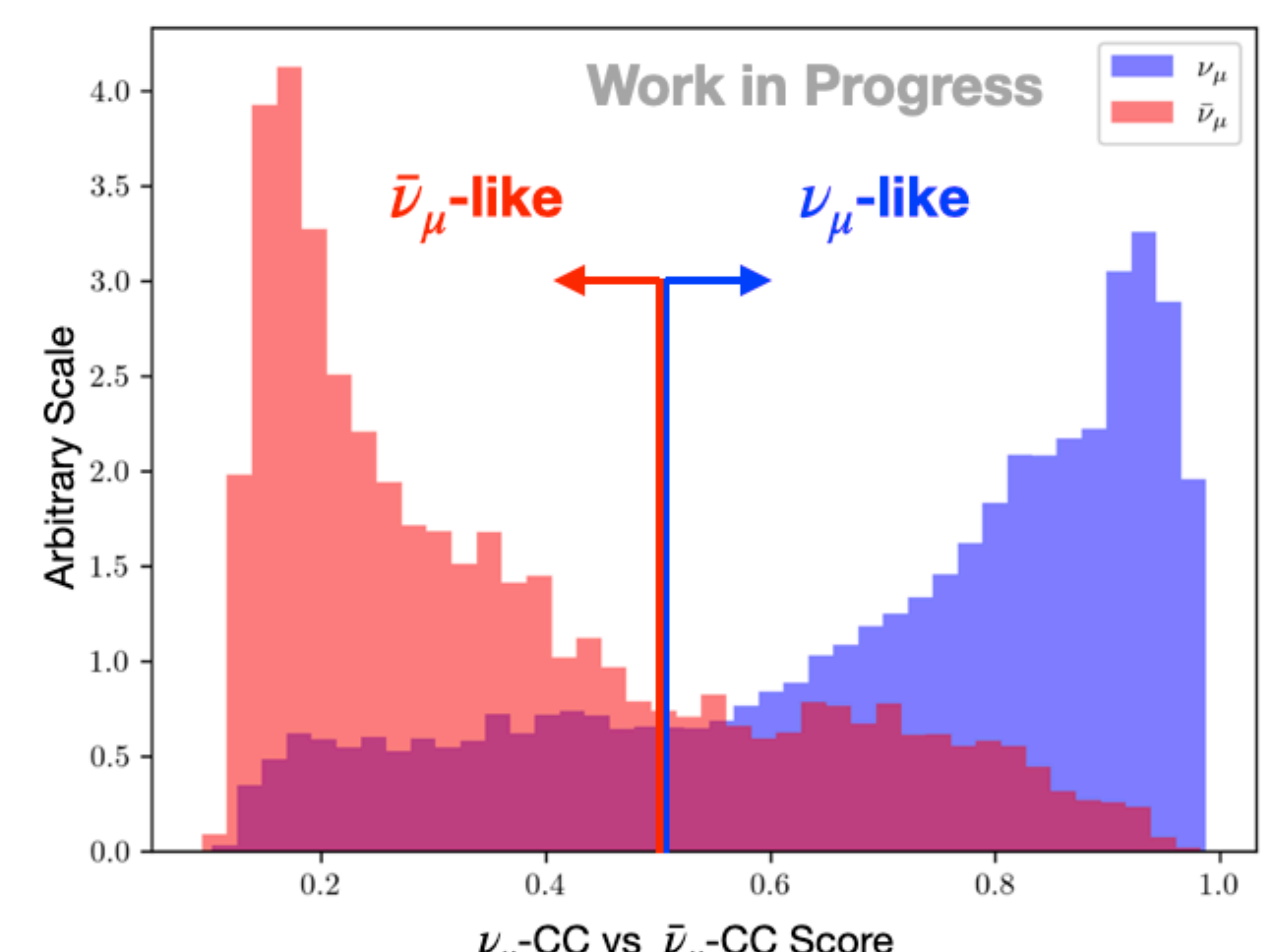
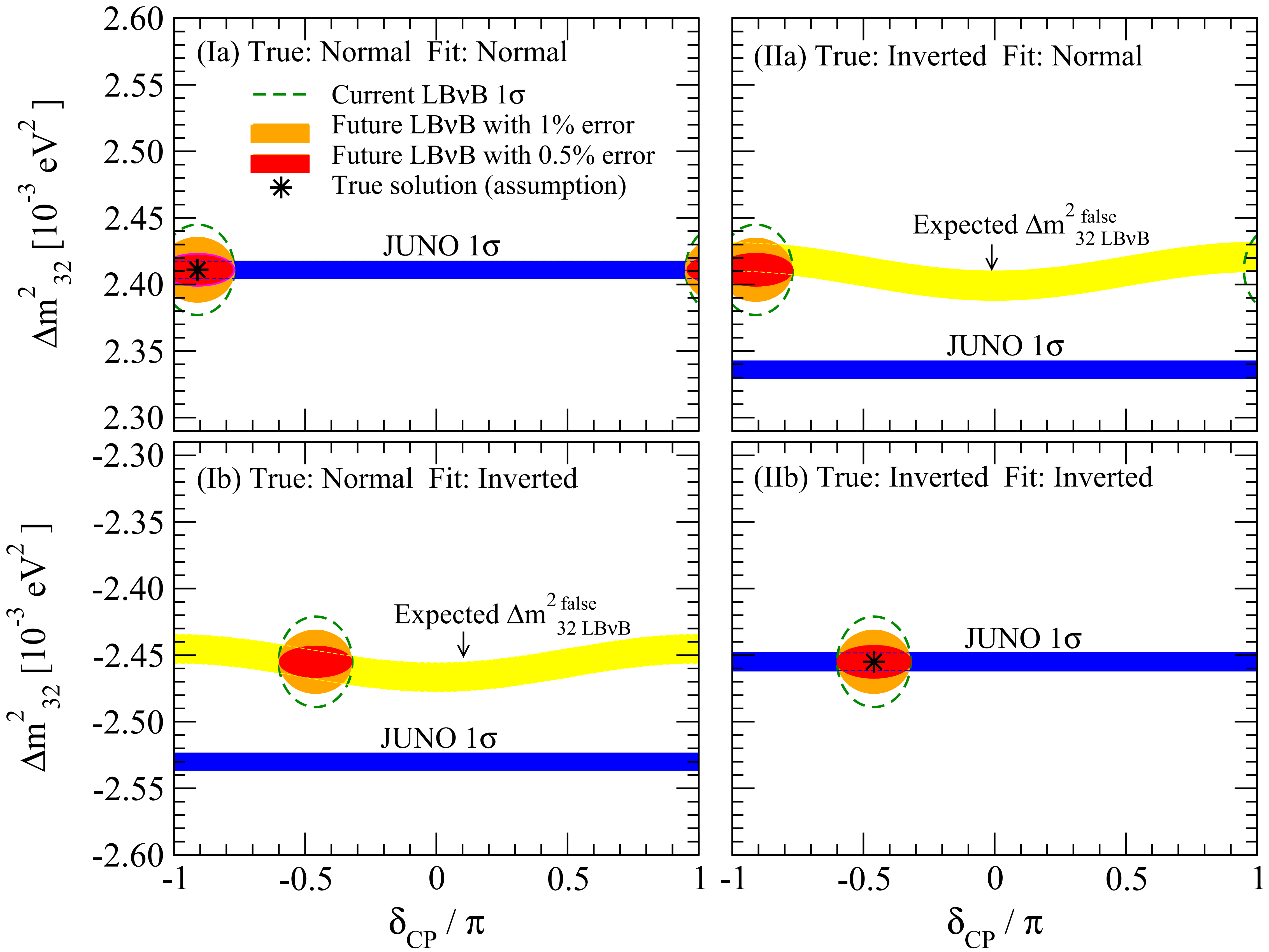


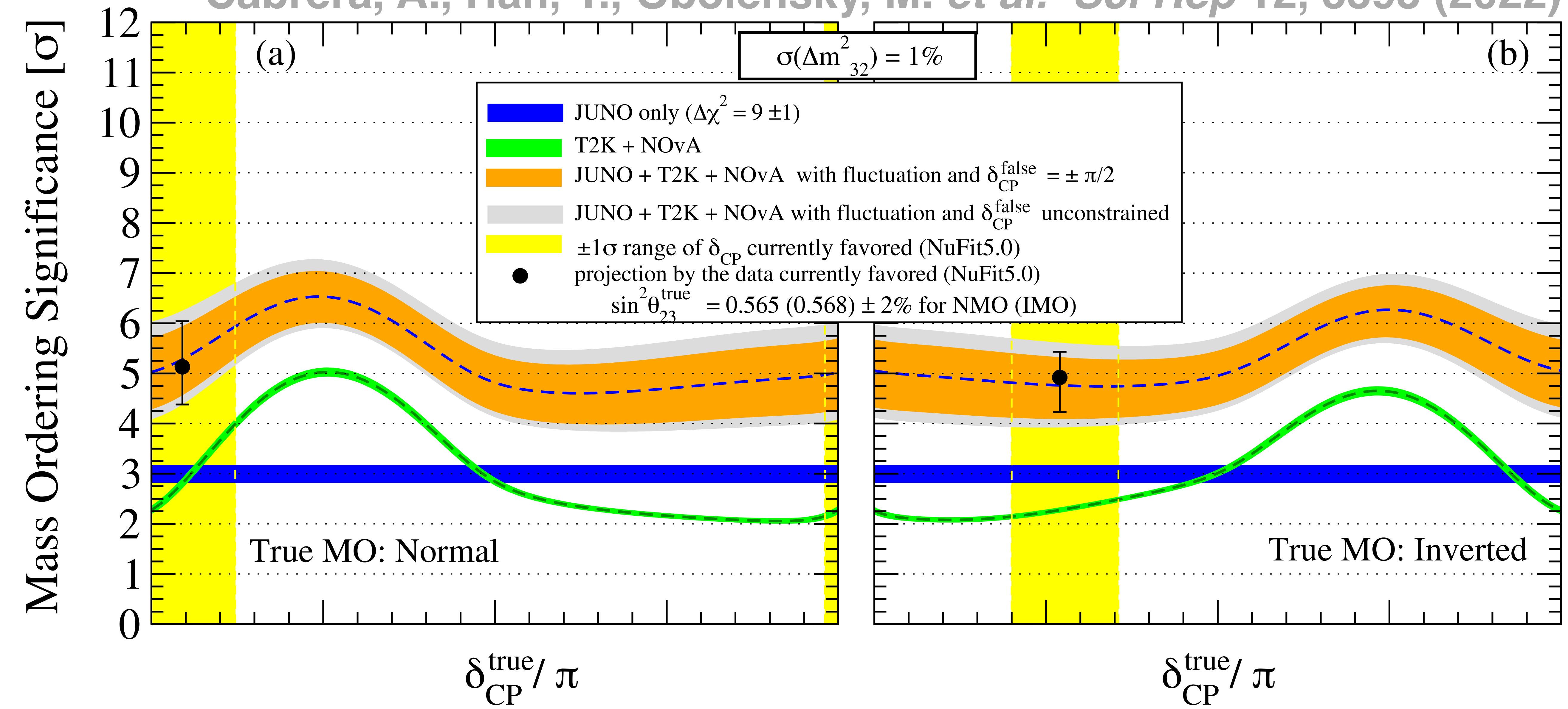
JUNO's directional reconstruction performance for atmospheric neutrinos



Synergy between Reactor/Accelerator/Atmospheric Neutrino Experiments



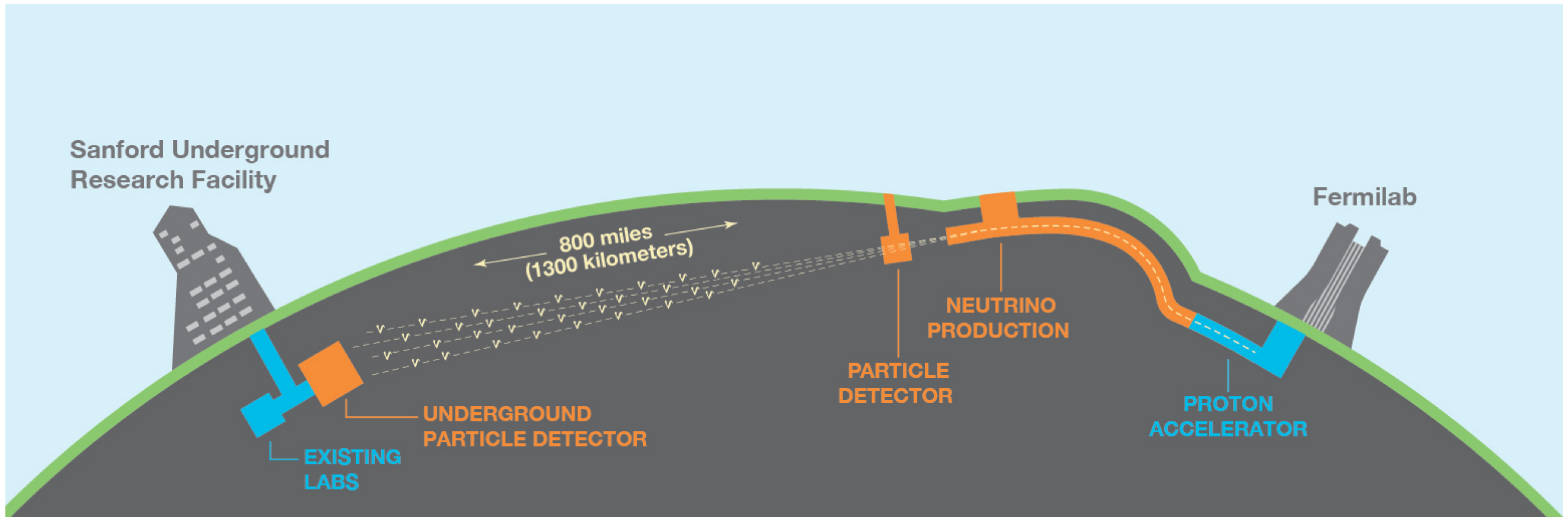
Cabrera, A., Han, Y., Obolensky, M. *et al.* *Sci Rep* 12, 5393 (2022)

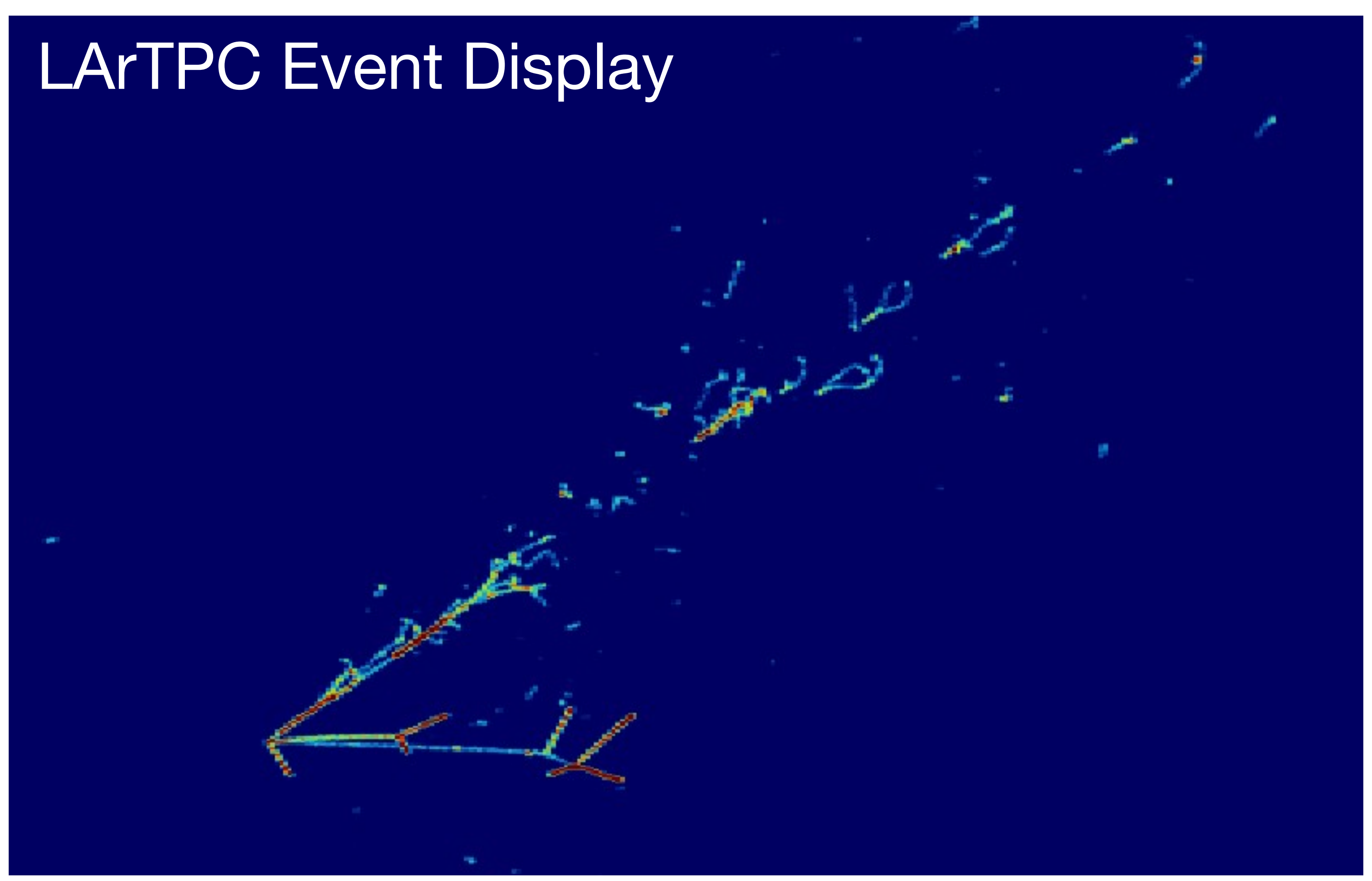


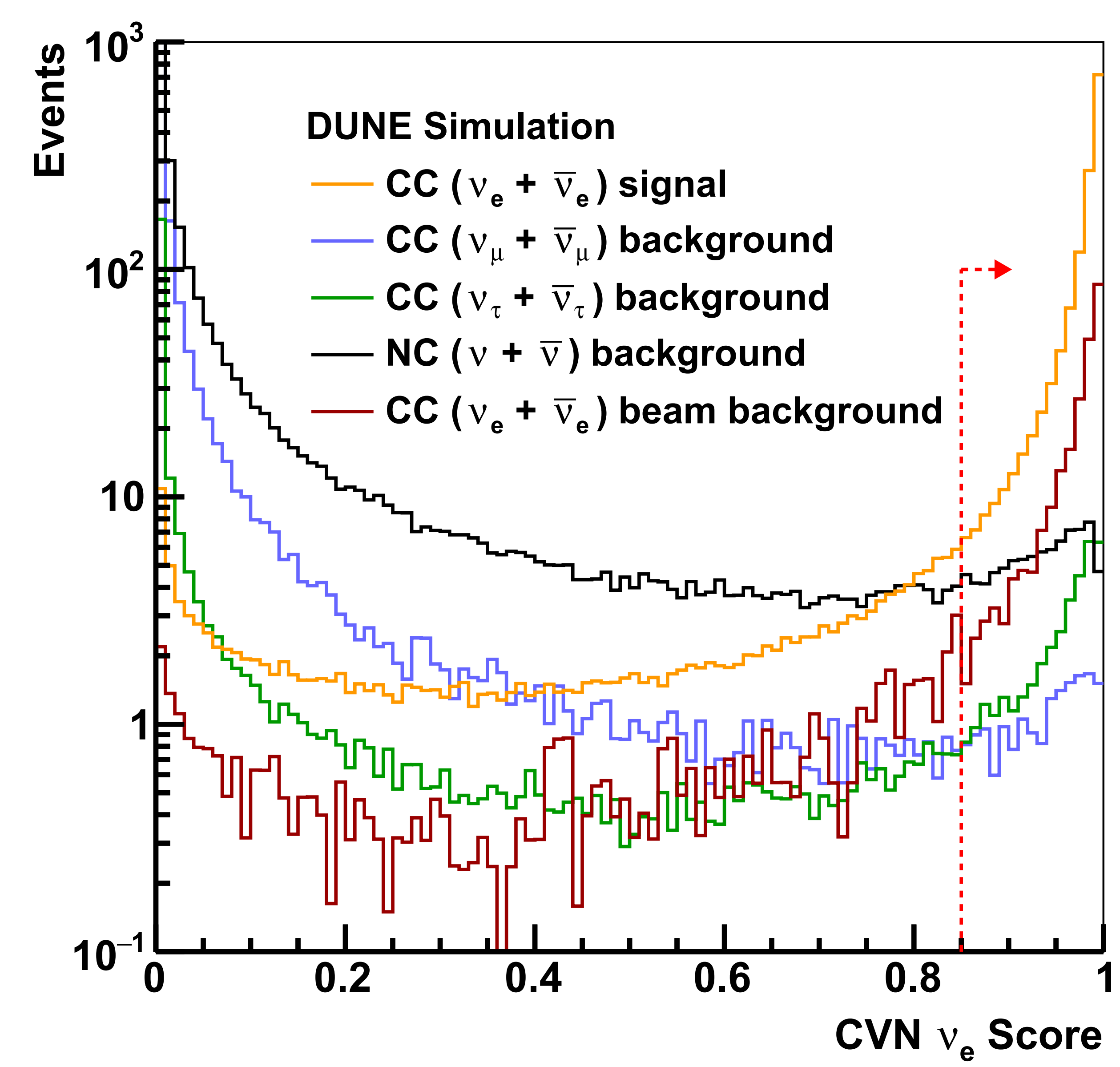
- Reactor and accelerator/atmospheric experiments get different Δm^2_{32} values for the wrong NH since they use different oscillation modes. (Vacuum oscillation vs matter effects)
  - An extra $\Delta\chi^2$ for the determination of MH.
  - Larger joint sensitivity than simple sum of experiments.
  - Plot showing JUNO + NOvA + T2K sensitivity via NuFit5.0 after ~6 year of JUNO data-taking.

Next Generation Experiments

DUNE







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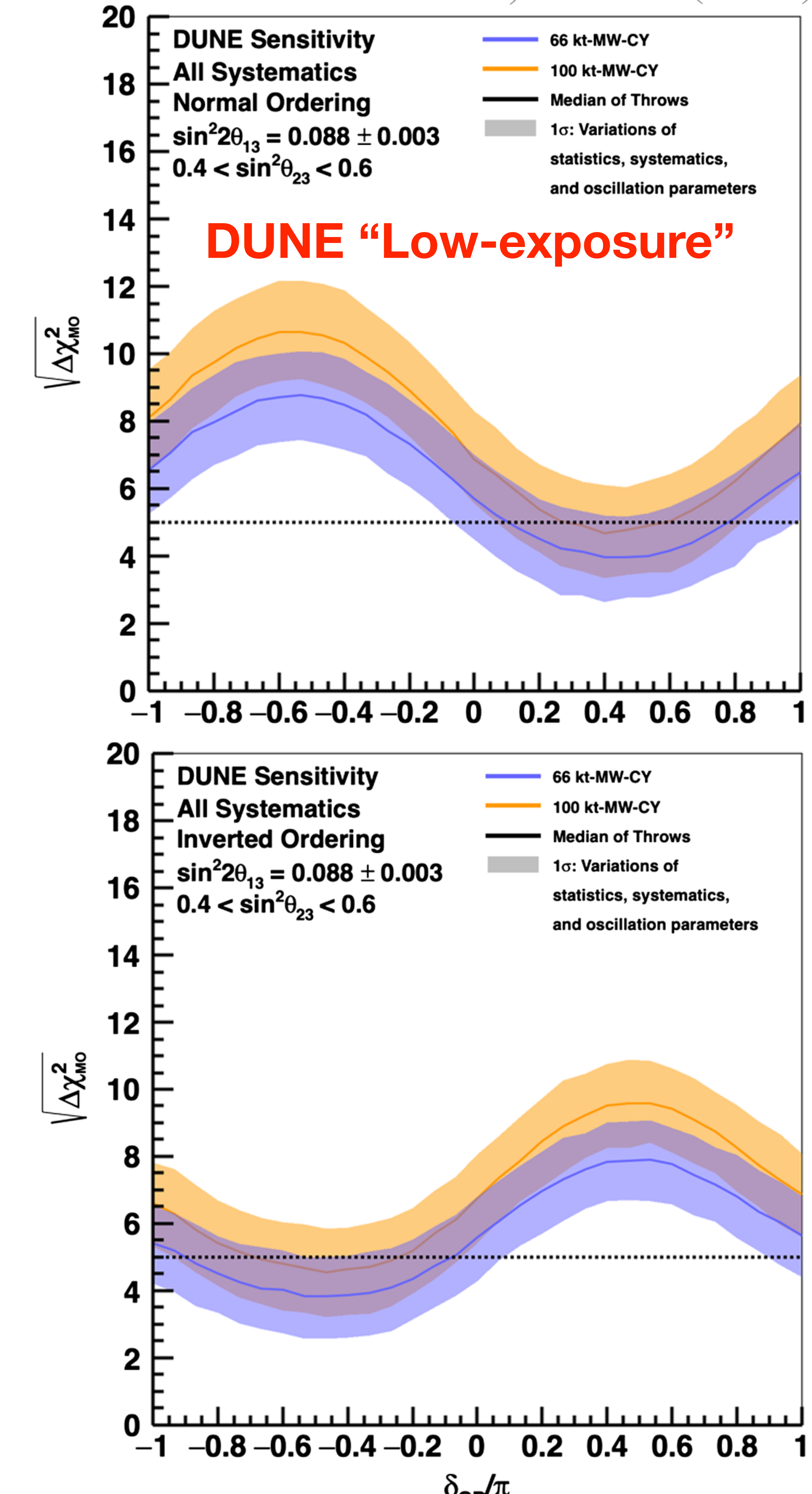
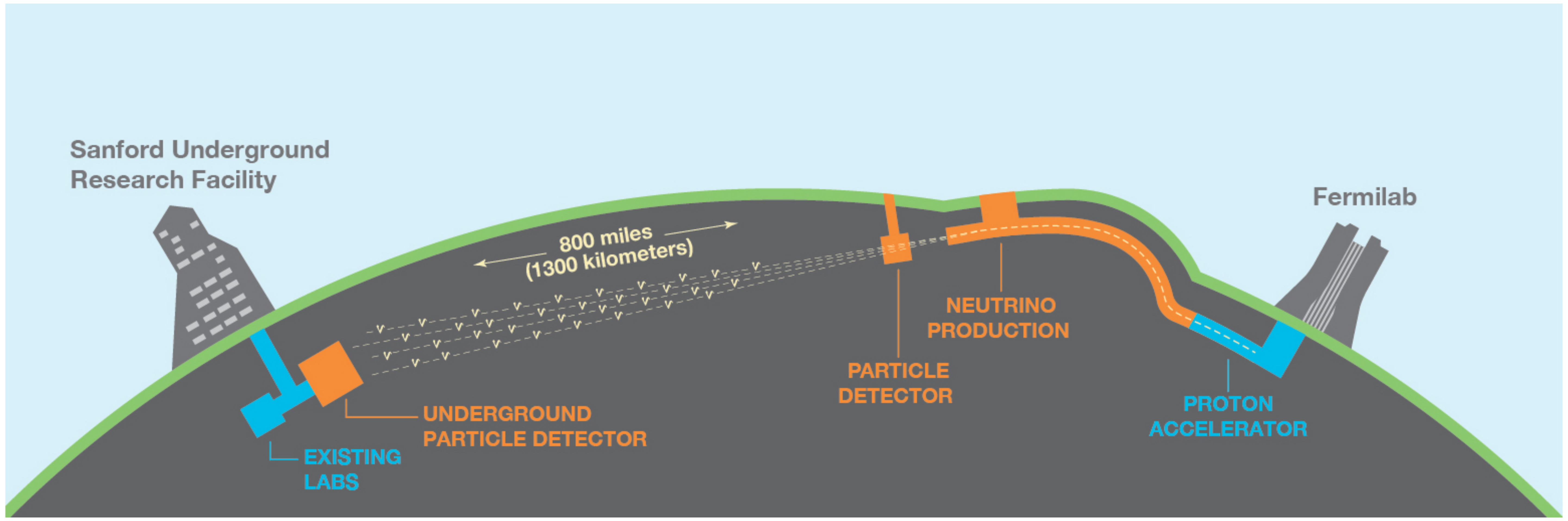
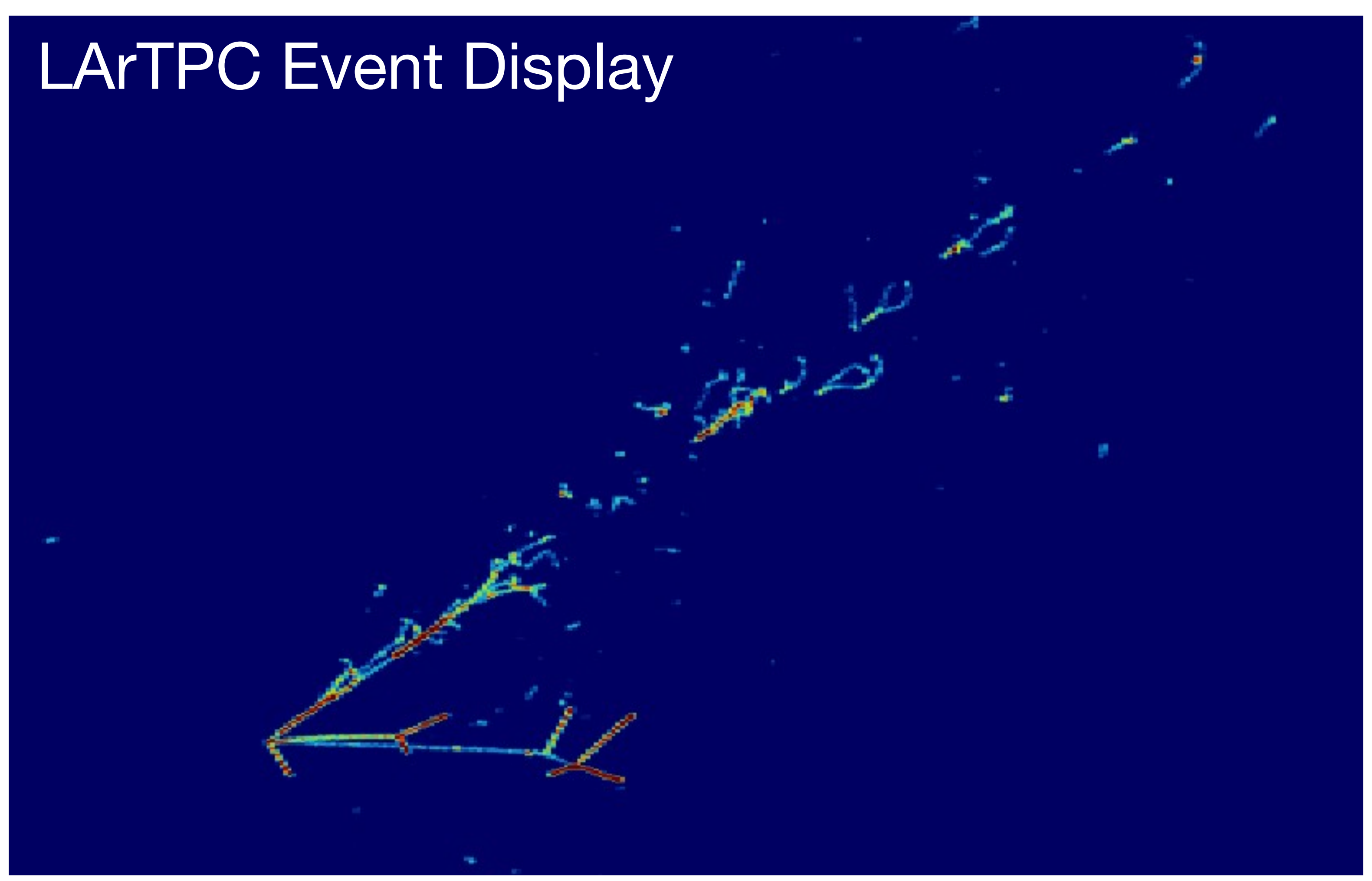
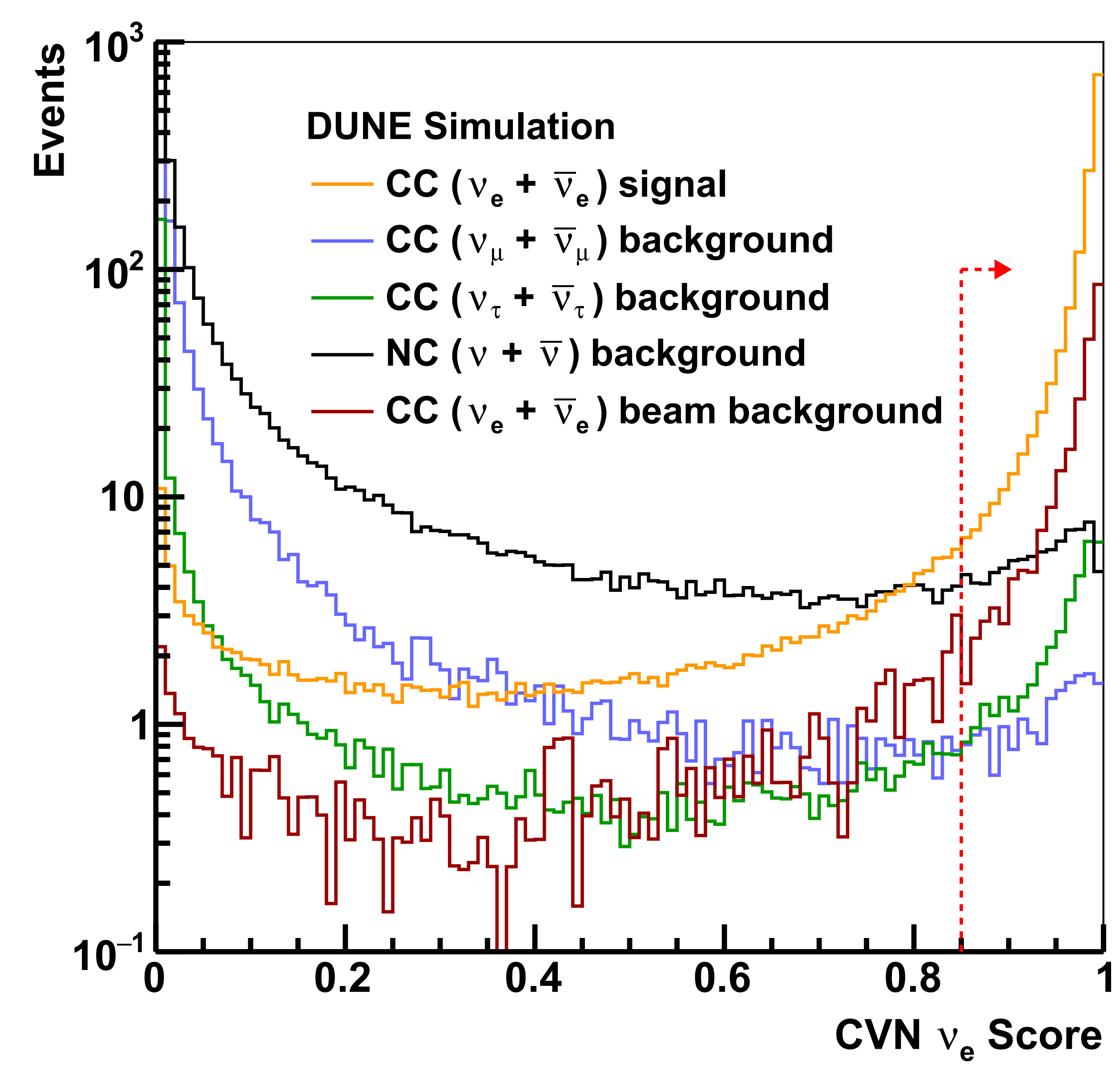


- Phased construction:
  - Phase I: 2 LArTPC modules (10 kton fiducial mass each, 1300 km from ν source), 1.2 MW beam, finish by 2031;
  - Phase II: 2 additional modules, > 2 MW beam.
- "Low-exposure": 3-5 years of phase I (two 10 kton LArTPC modules)
- Ultimate sensitivity with full 40 kton far detector can resolve MH (>5σ) regardless of δ_{CP} or other parameters.

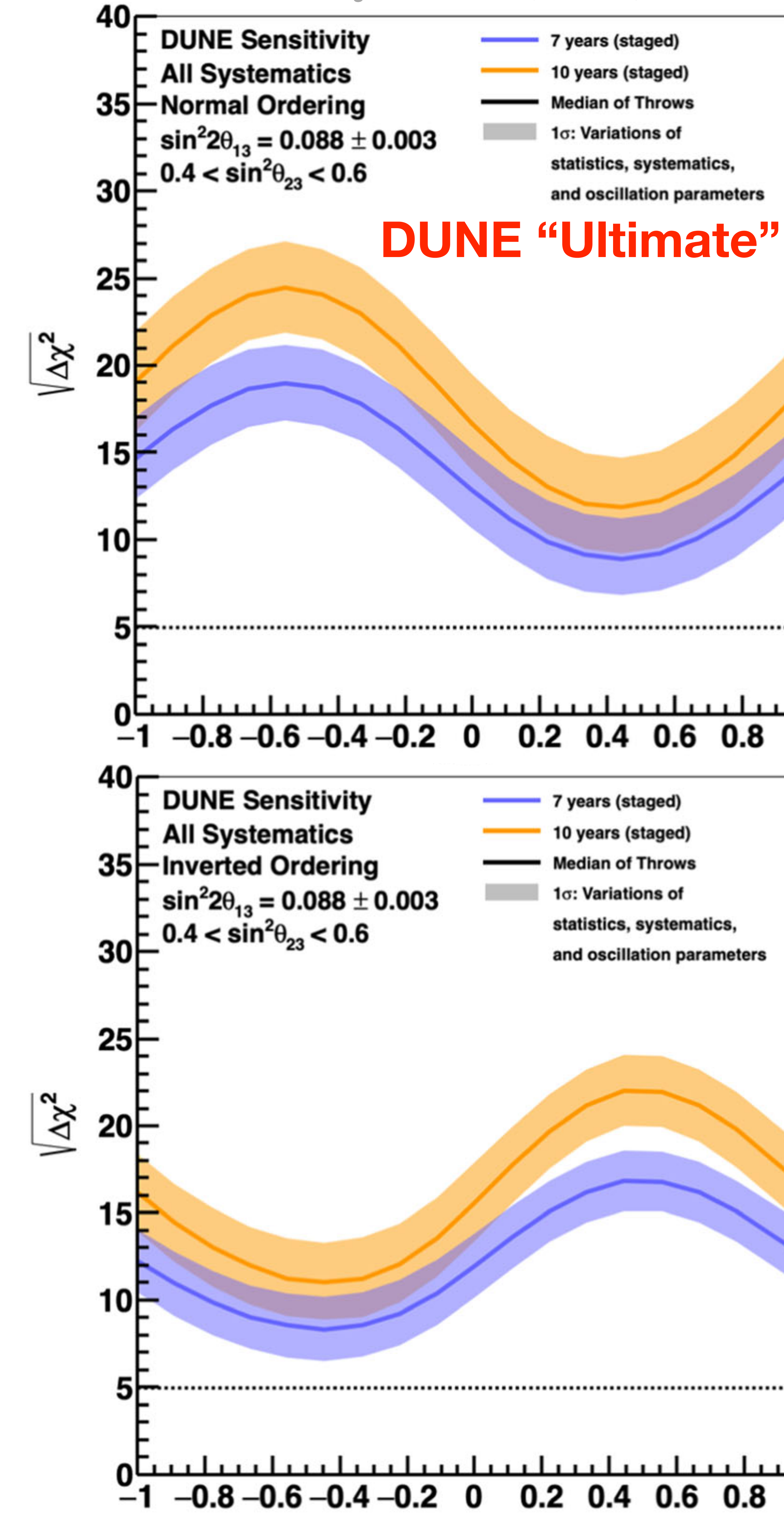
DUNE







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



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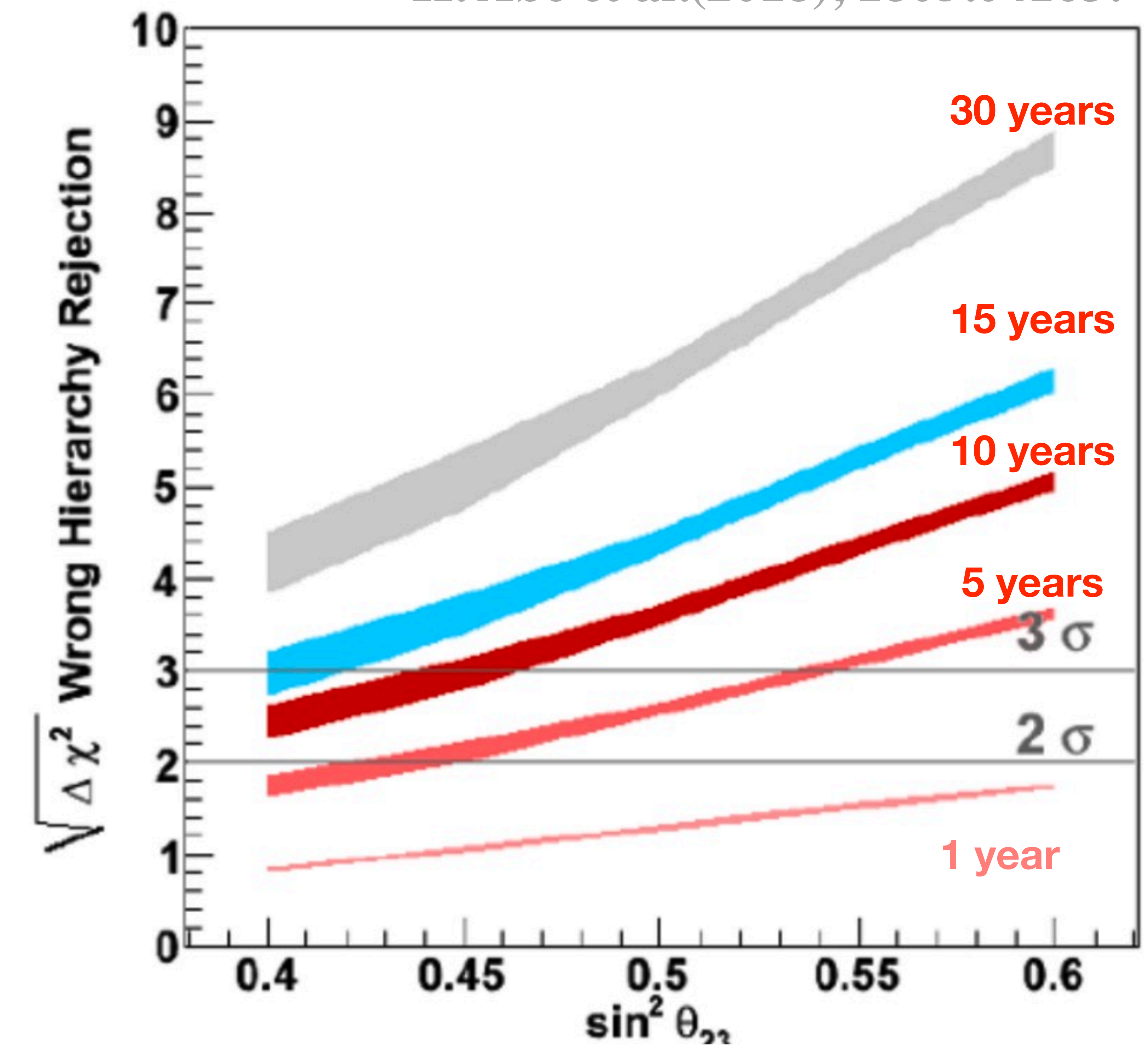
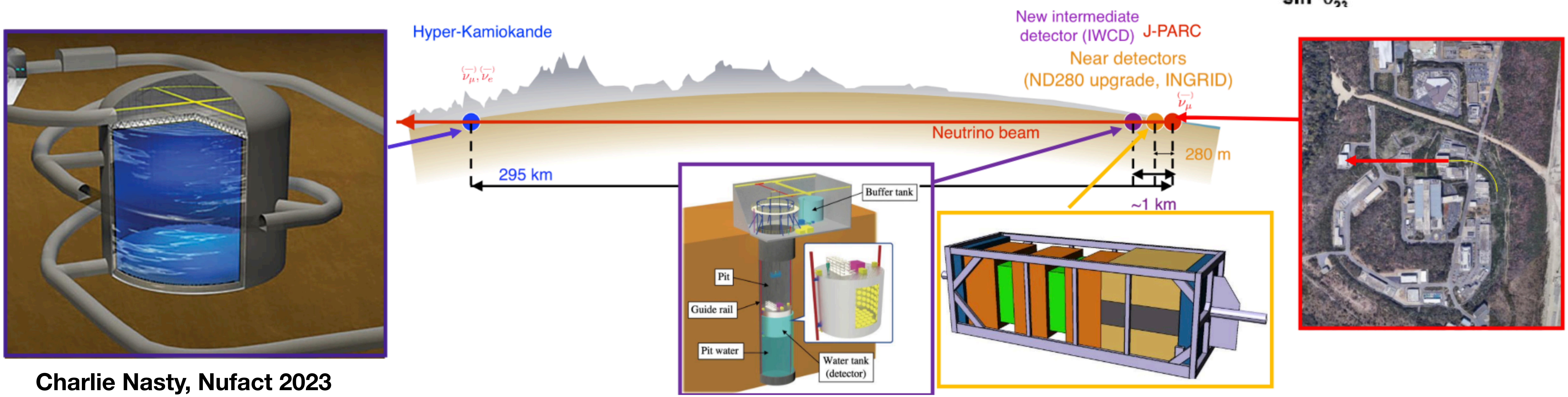
HyperK

- 258 kton water-Cherenkov detector (8 X Super-K)
- Sensitivity to MH from atmospheric neutrinos.
- Accelerator neutrinos may boost MH sensitivity in a joint analysis.
    - For more details see the talk by César Jesús-Valls

K. Abe et al.(2018), 1805.04163.

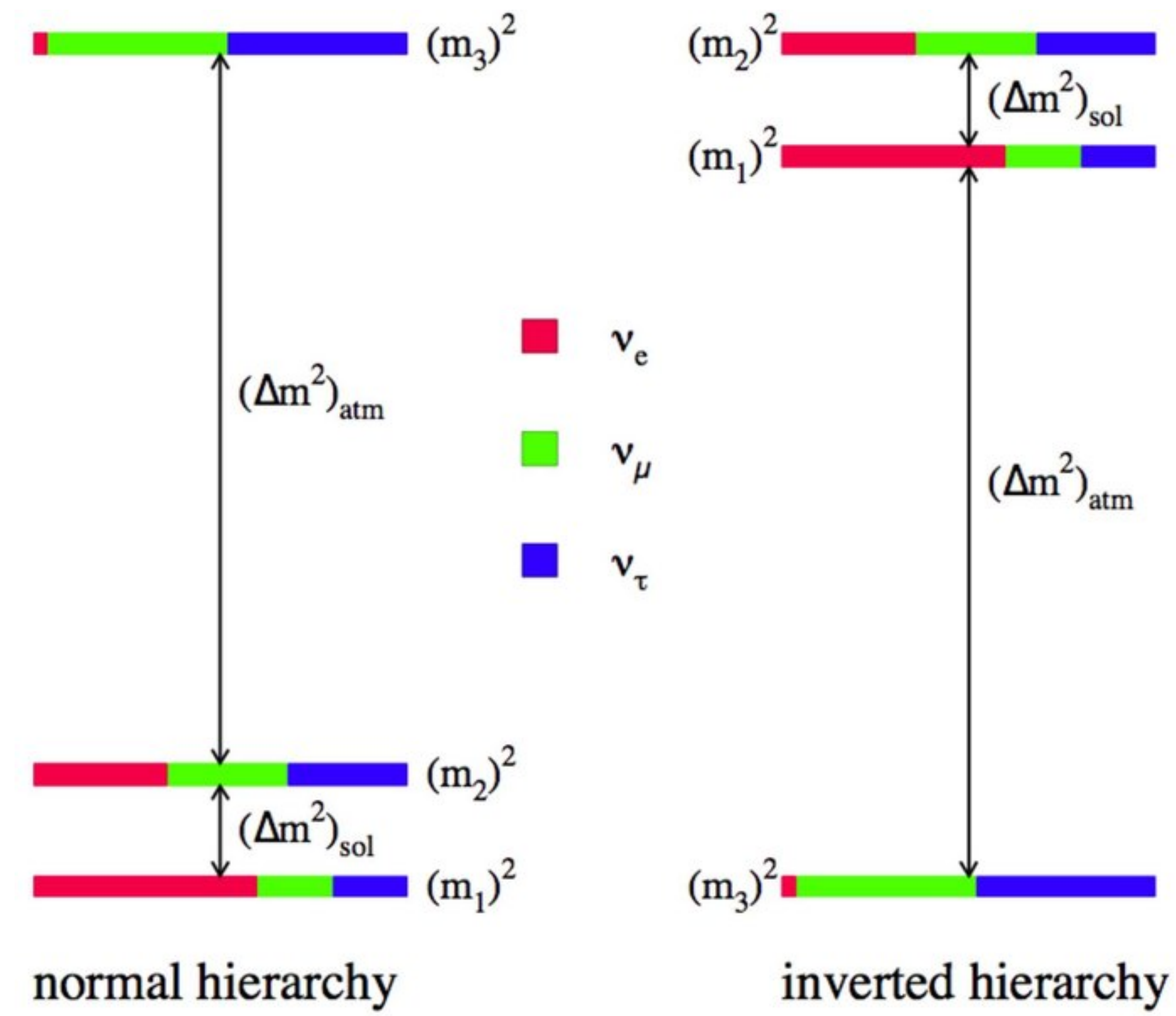




Charlie Nasty, Nufact 2023

Summary

- Neutrino hierarchy is important.
- Current experiments favor normal hierarchy (by ~3σ according to NuFit5.3).
  - Still tensions between data.
- Very exciting time ahead:
  - Likely that MH will be solved by joint analysis from multiple experiments in the next 5-6 years.
    - Reactor + accelerator/atmospheric with synergy.
  - DUNE will give a final answer.



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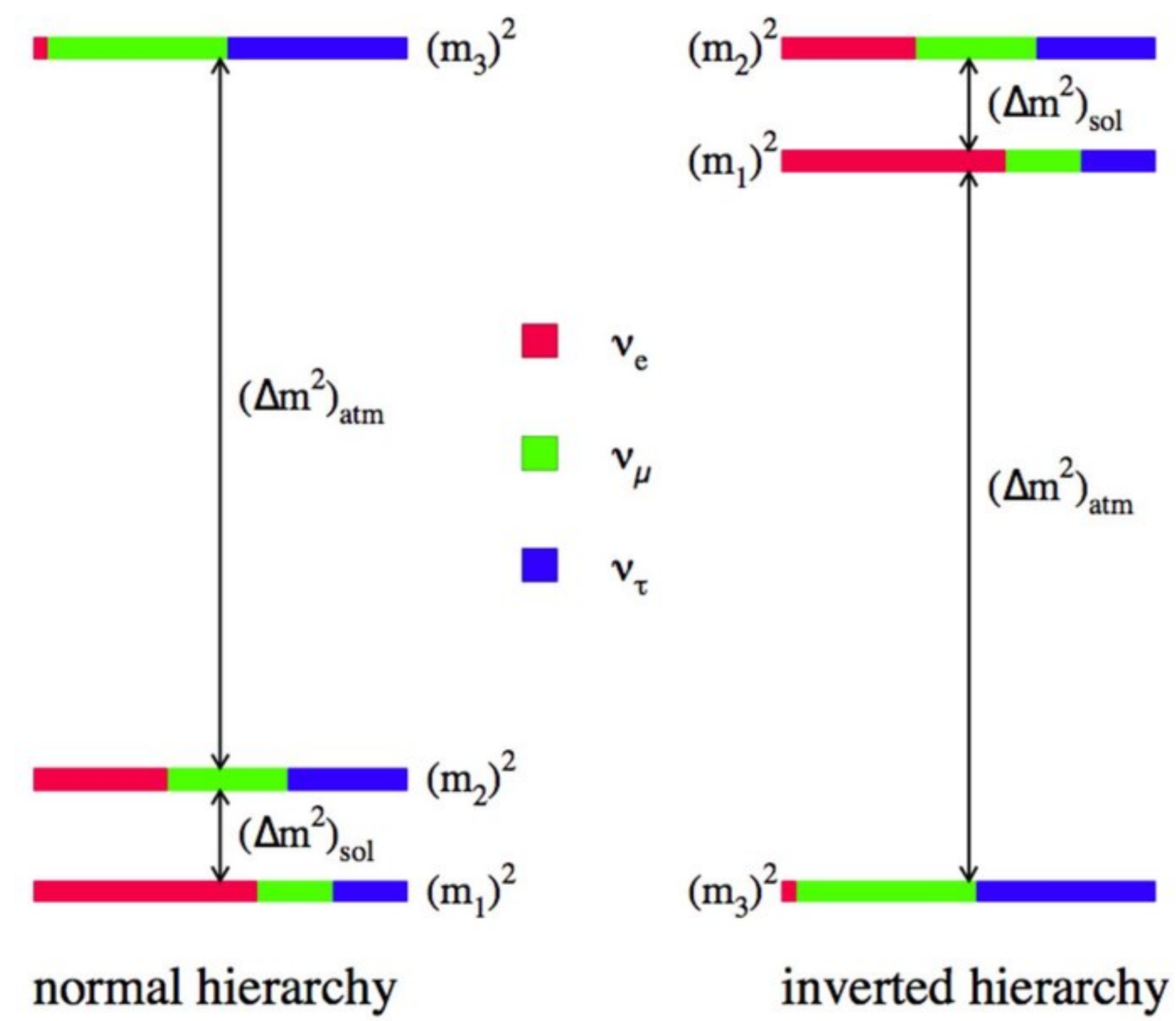

Thank you!

Back up slides

Global Fitting

- Latest global fitting (NuFIT5.3) favors NH by ~3σ, driving by Super-K.

NuFIT 5.3 (2024)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
	$\theta_{12}/^\circ$	$33.66^{+0.73}_{-0.70}$	$31.60 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.407 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00058}$	$0.02029 \to 0.02391$	$0.02219^{+0.00059}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.90$
	$\delta_{CP}/^\circ$	197^{+41}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.511^{+0.027}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.024}$	$-2.581 \to -2.409$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
	$\theta_{12}/^\circ$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
	$\sin^2\theta_{23}$	$0.454^{+0.019}_{-0.016}$	$0.411 \to 0.606$	$0.568^{+0.016}_{-0.021}$	$0.412 \to 0.611$
	$\theta_{23}/^\circ$	$42.3^{+1.1}_{-0.9}$	$39.9 \to 51.1$	$48.9^{+0.9}_{-1.2}$	$39.9 \to 51.4$
	$\sin^2\theta_{13}$	$0.02224^{+0.00056}_{-0.00057}$	$0.02047 \to 0.02397$	$0.02222^{+0.00069}_{-0.00057}$	$0.02049 \to 0.02420$
	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.13}_{-0.11}$	$8.23 \to 8.95$
	$\delta_{CP}/^\circ$	232^{+39}_{-25}	$139 \to 350$	273^{+24}_{-26}	$195 \to 342$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.505^{+0.024}_{-0.026}$	$+2.426 \to +2.586$	$-2.487^{+0.027}_{-0.024}$	$-2.566 \to -2.407$

Advertisement

- I am looking for postdoc candidates to work on the JUNO experiment, especially the reconstruction with machine learning and analysis of reactor and atmospheric oscillations. If you are interested please contact me at duyang@sdu.edu.cn

Thank you!