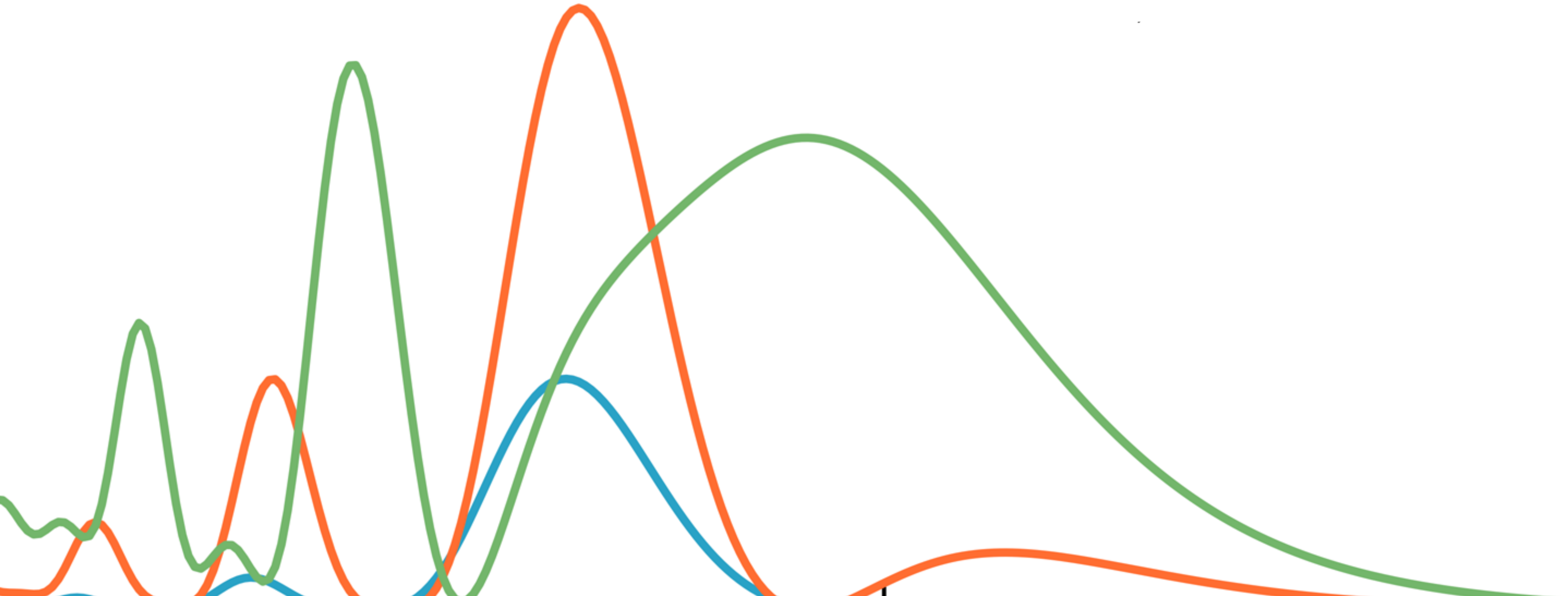
Review of neutrino oscillation experiments

Reactor / Accelerator / Atmospheric

TAUP 2025, Lukas Berns, Tohoku U



Lower left oscillogram from PRX 13, 041055 (2023)

ν-oscillation

For neutrinos flavor basis (interaction) $\neq$ Hamiltonian basis (propagation).

↓

Flavor (ν_e | ν_μ | ν_τ) oscillates over $L \times \Delta m^2 / E$, amplitude controlled by (PMNS) mixing matrix U:

θ_{23} atmospheric — $\theta_{13}, \delta_{\text{CP}}$ reactor, accelerator — θ_{12} solar

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$
$s_{ij} \equiv \sin\theta_{ij}$

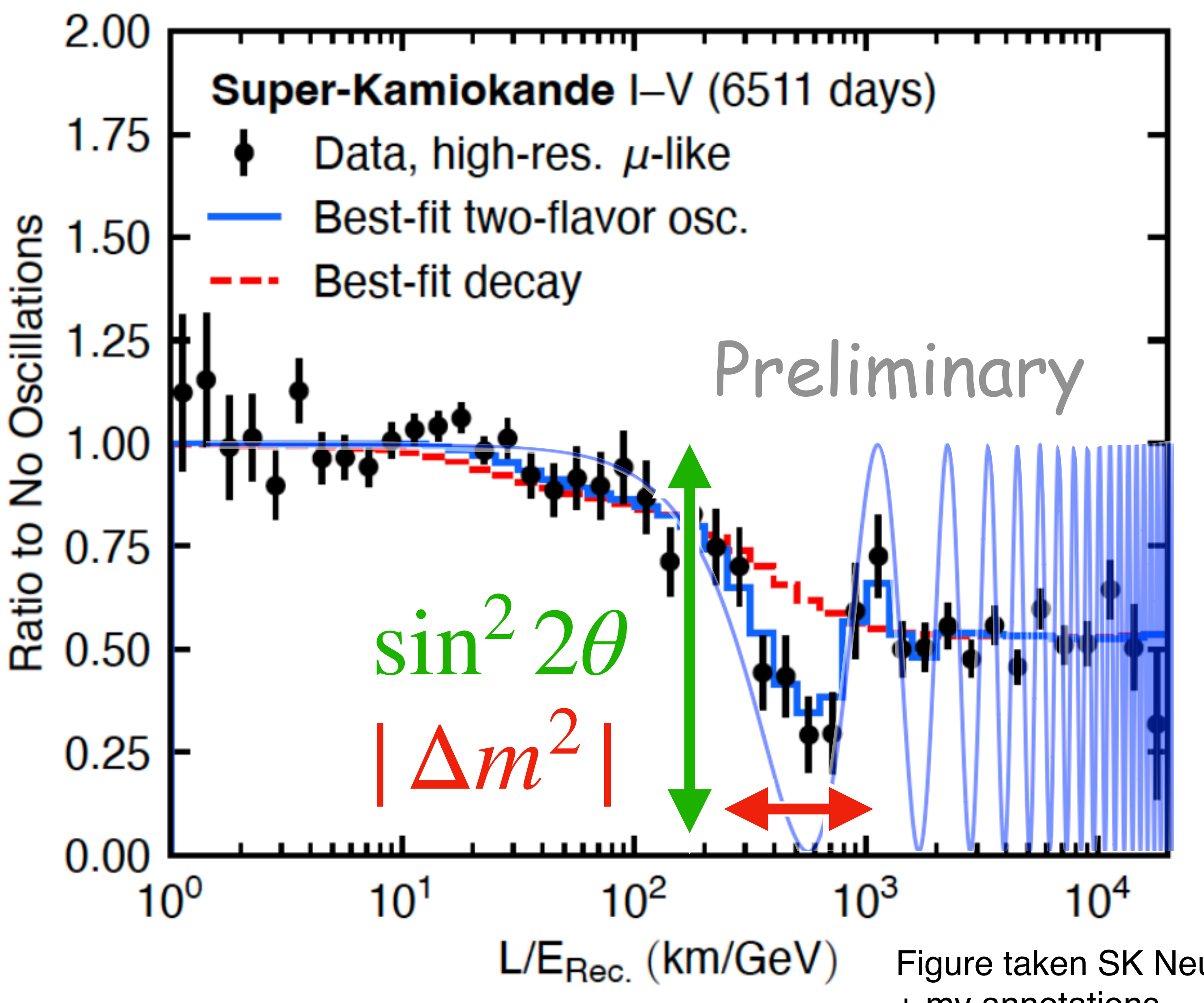
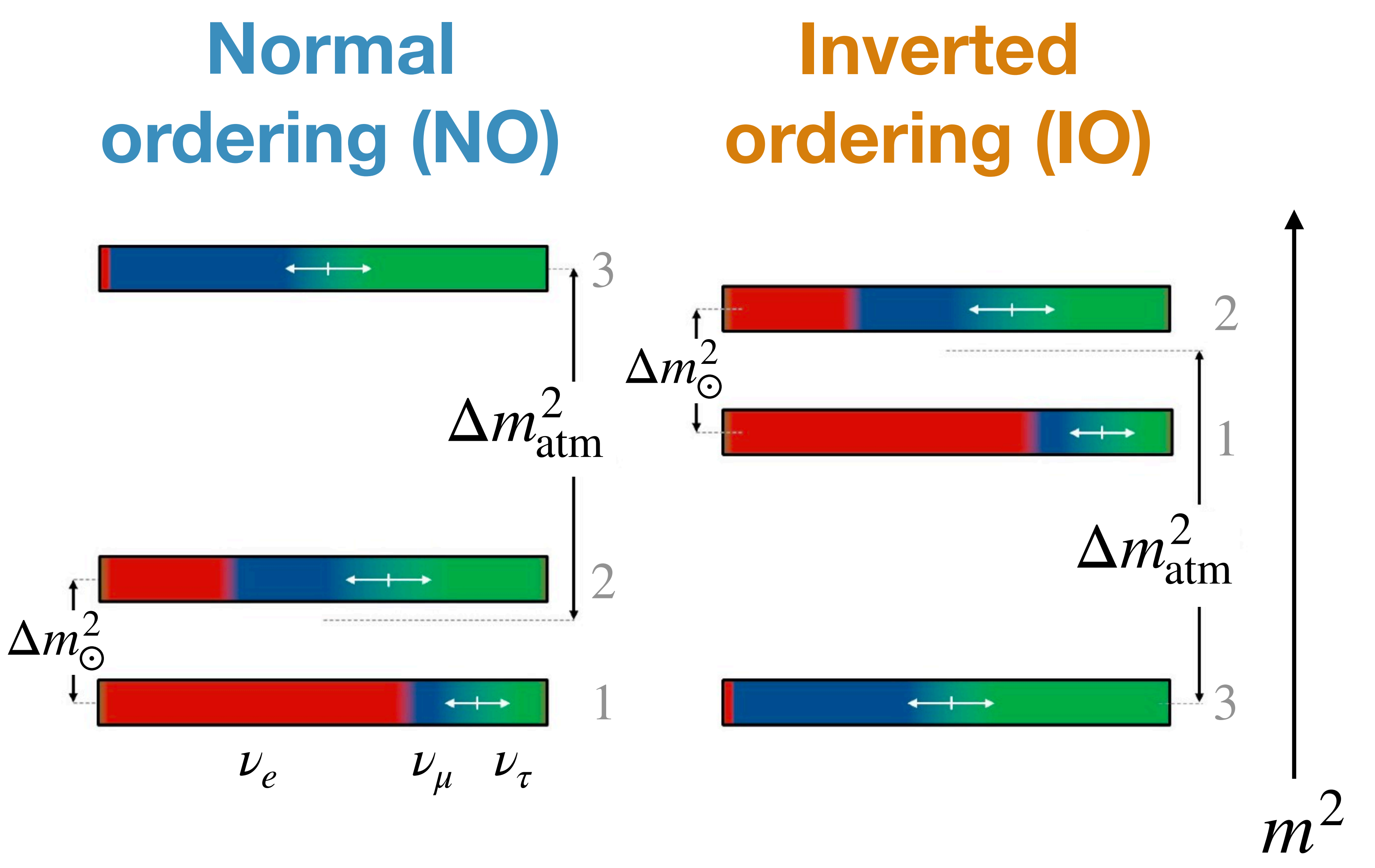


Figure taken SK Neutrino 2024 + my annotations

Mass ordering (MO)



ν-oscillation

θ_{23}	θ_{13}, δ_{CP}	θ_{12}
atmospheric	reactor, accelerator	solar

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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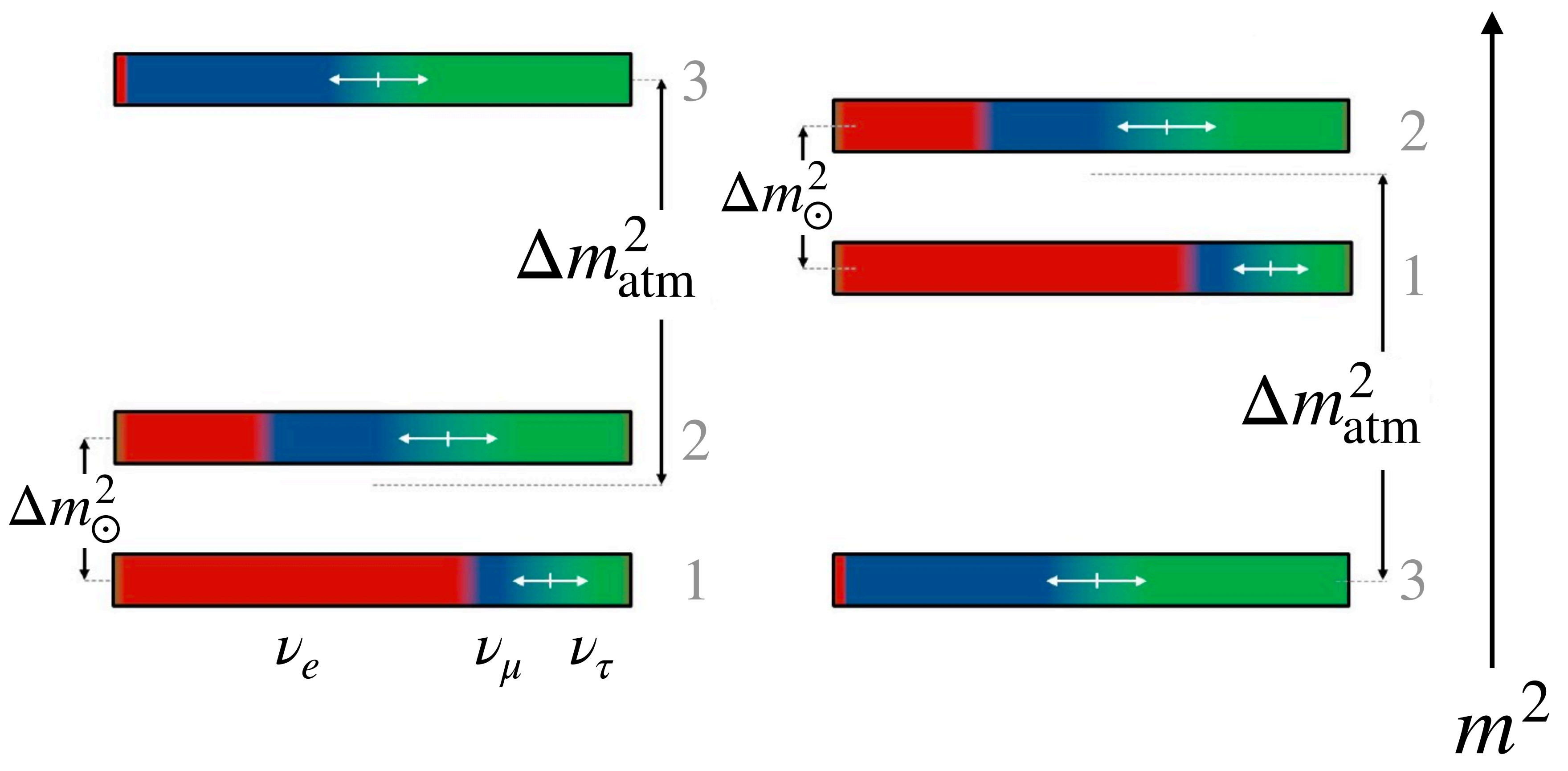
?

Mass ordering (MO)

Normal ordering (NO) **Inverted ordering (IO)**



Open questions:

- value of δ_{CP} → if $\sin\delta_{\mathrm{CP}} \neq 0$, CP violation

ν-oscillation

θ_{23} — **atmospheric** | θ_{13}, δ_{CP} — **reactor, accelerator** | θ_{12} — **solar**

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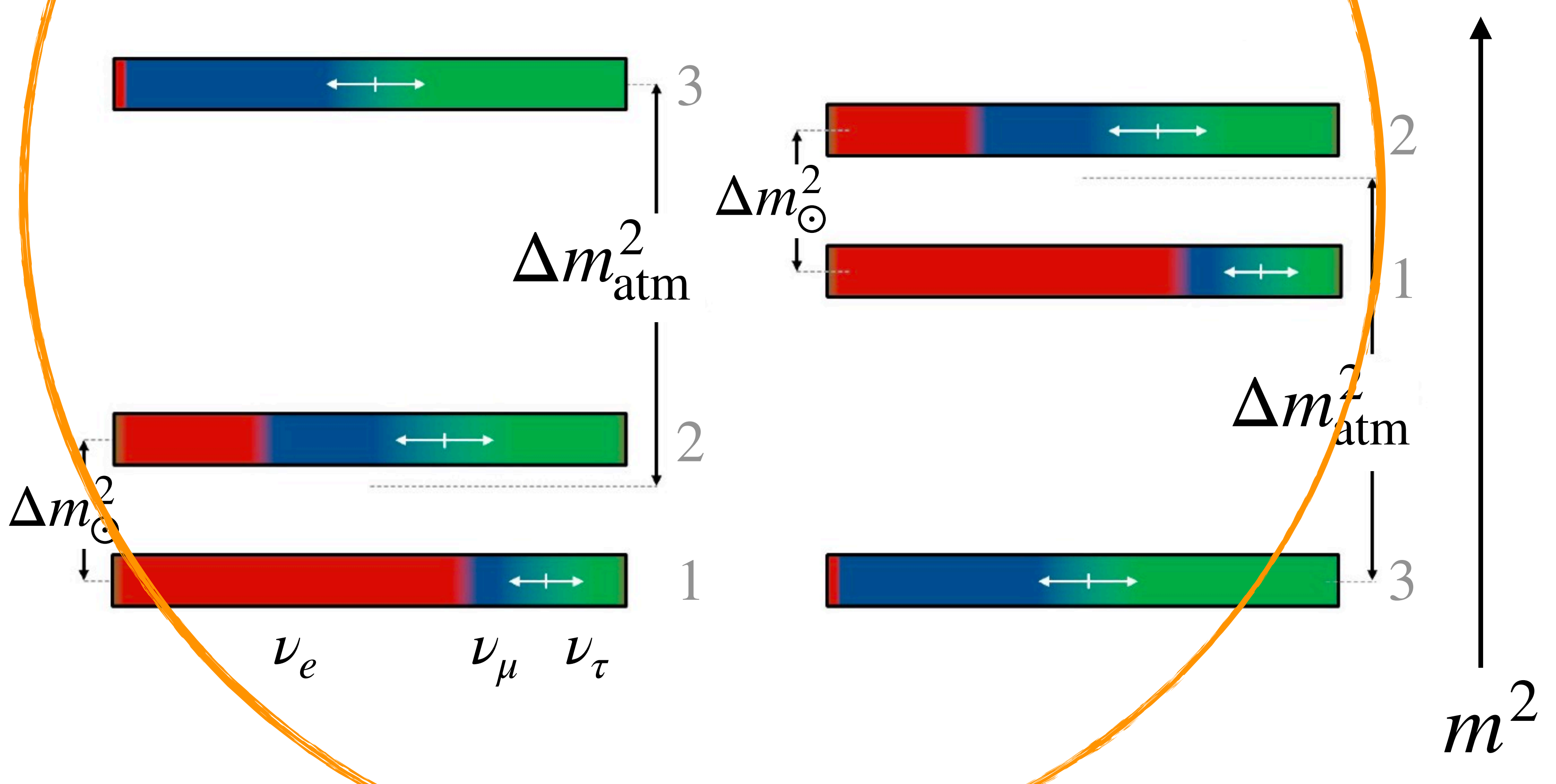

Open questions:

- value of δ_{CP} → if $\sin\delta_{\text{CP}} \neq 0$, CP violation
- sign of Δm^2_{32} (mass ordering)

Important for cosmology (leptogenesis...), 0ν2β searches

ν-oscillation

θ_{23} atmospheric — θ_{13}, δ_{CP} reactor, accelerator — θ_{12} solar

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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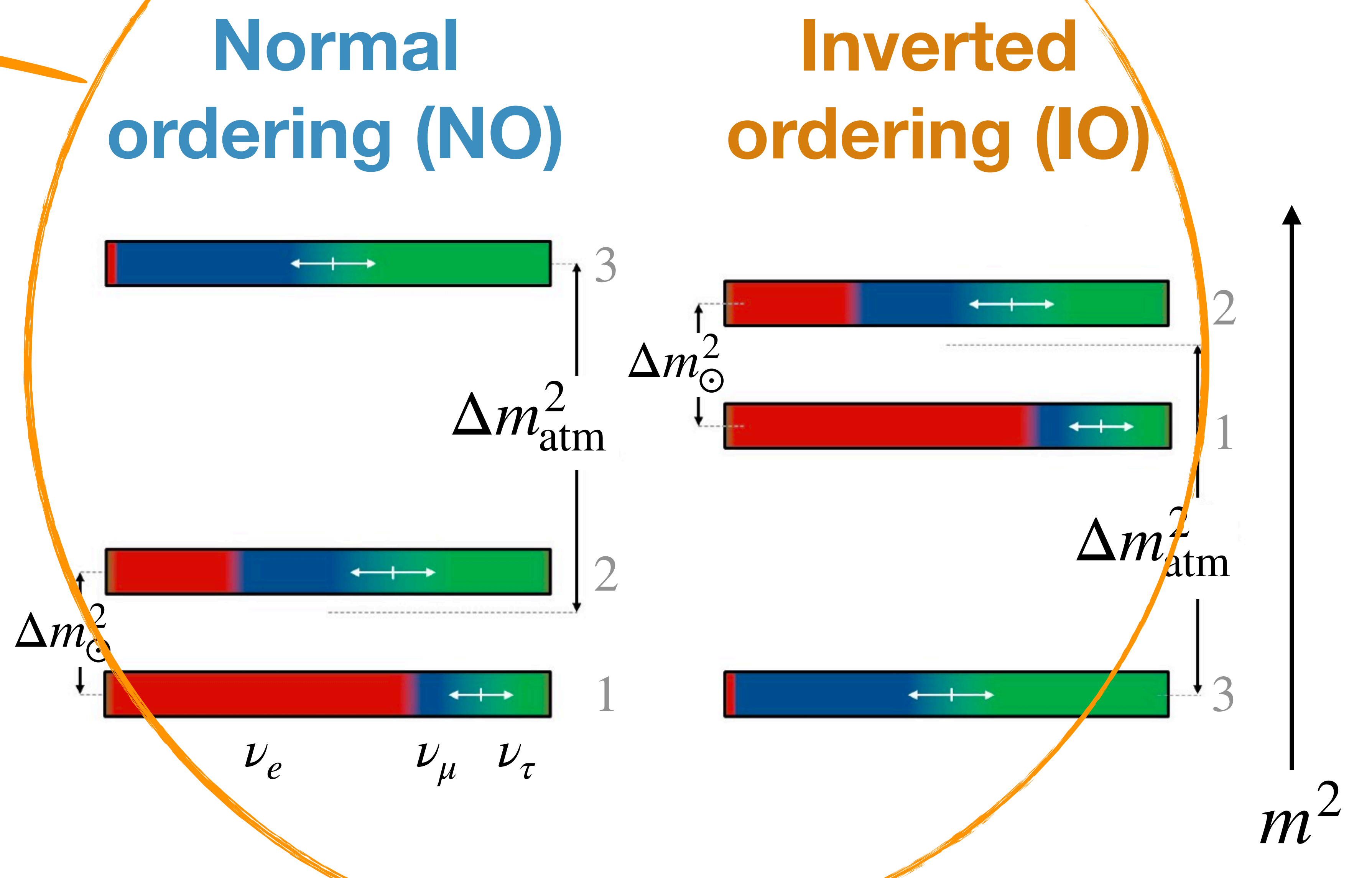
Mass ordering (MO)



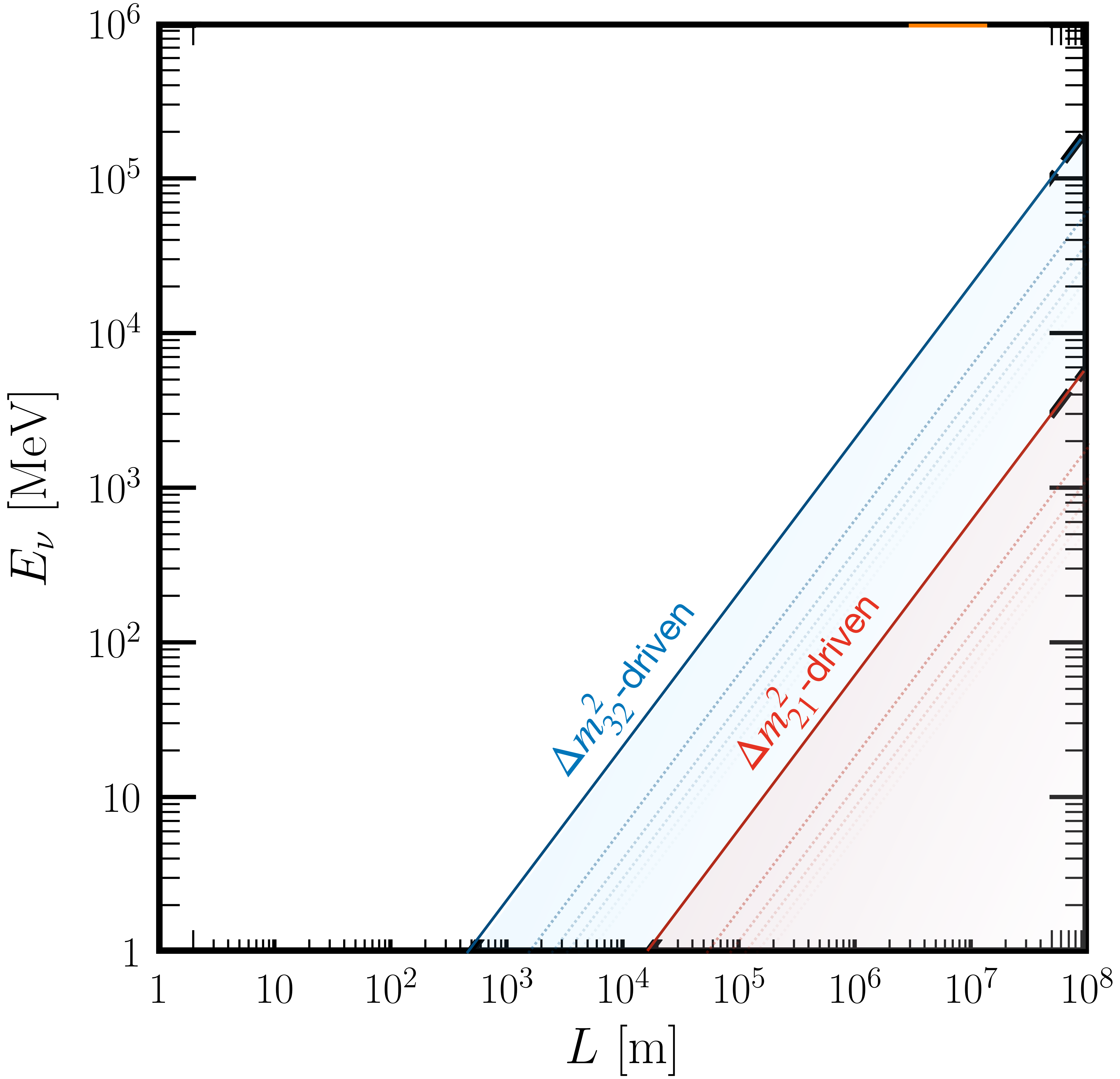
Open questions:

- value of δ_{CP} → if $\sin\delta_{\text{CP}} \neq 0$, CP violation
- sign of Δm^2_{32} (mass ordering)
- Is $\theta_{23} = \frac{\pi}{4}$? $< \frac{\pi}{4}$? $> \frac{\pi}{4}$? (octant)

Important for cosmology (leptogenesis...), 0ν2β searches

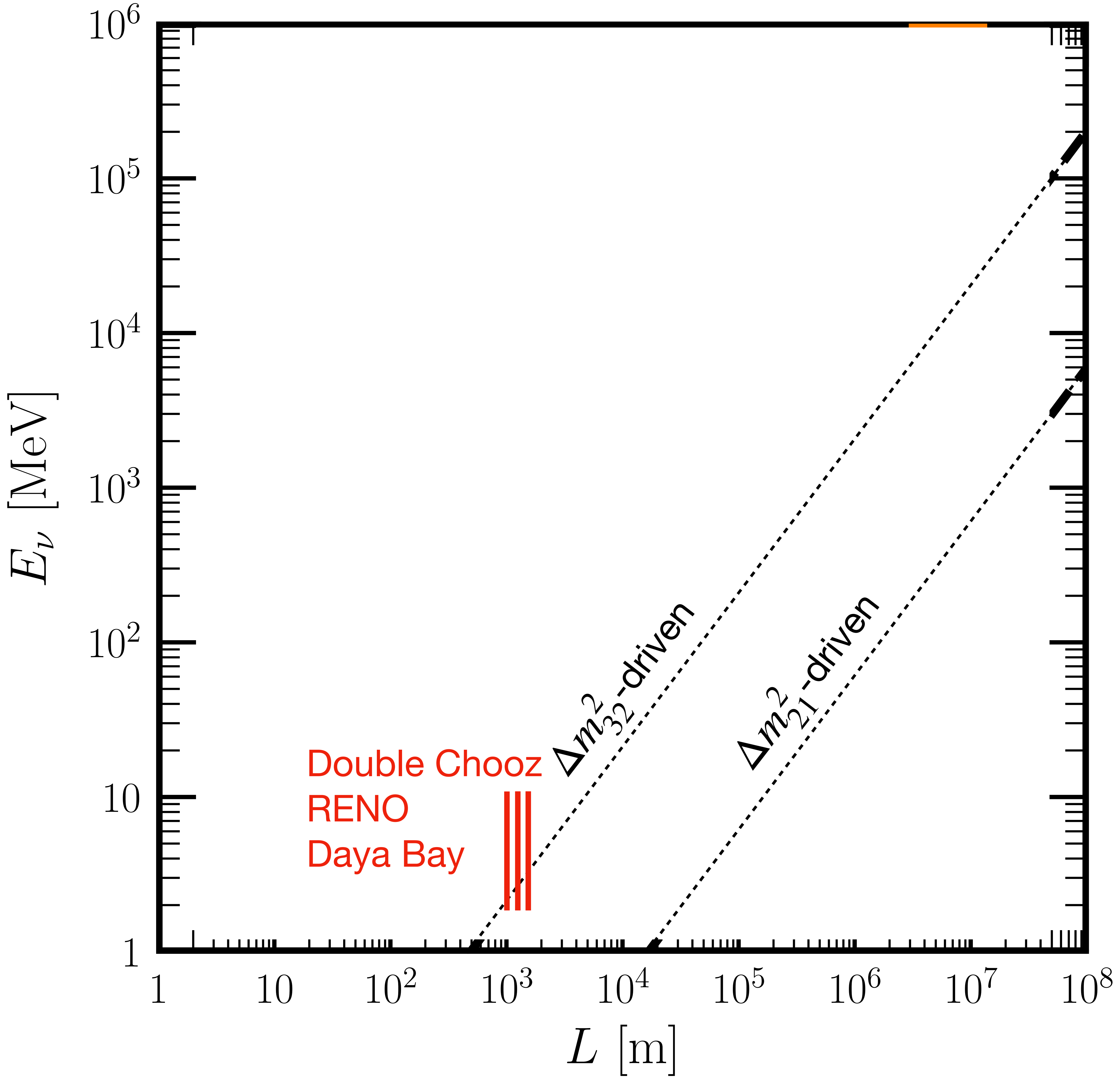
Flavor symmetries?

Current (3-flavor) oscillation experiments



Plot inspired by PRD 101, 033008 (2020)

Current (3-flavor) oscillation experiments



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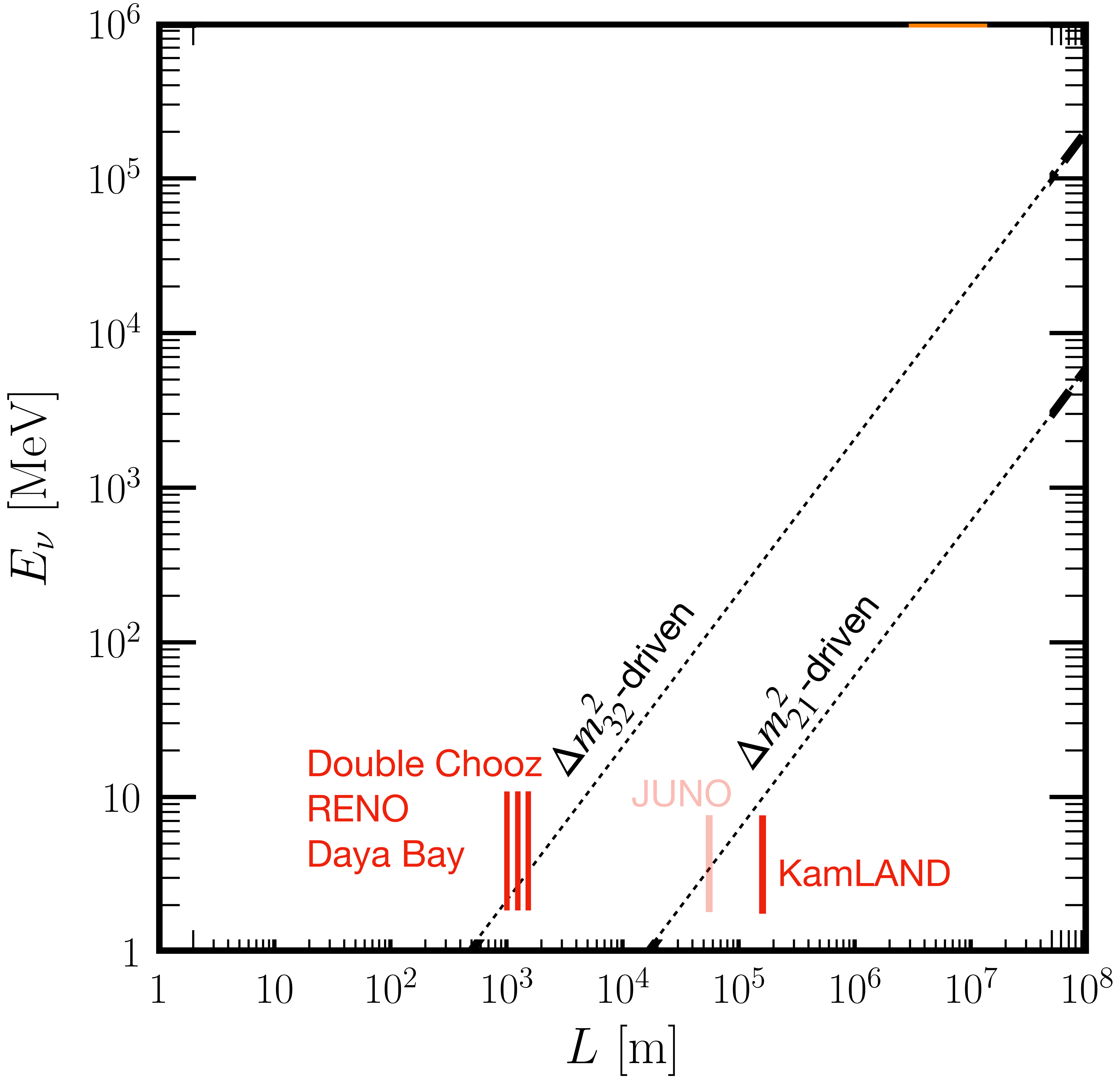

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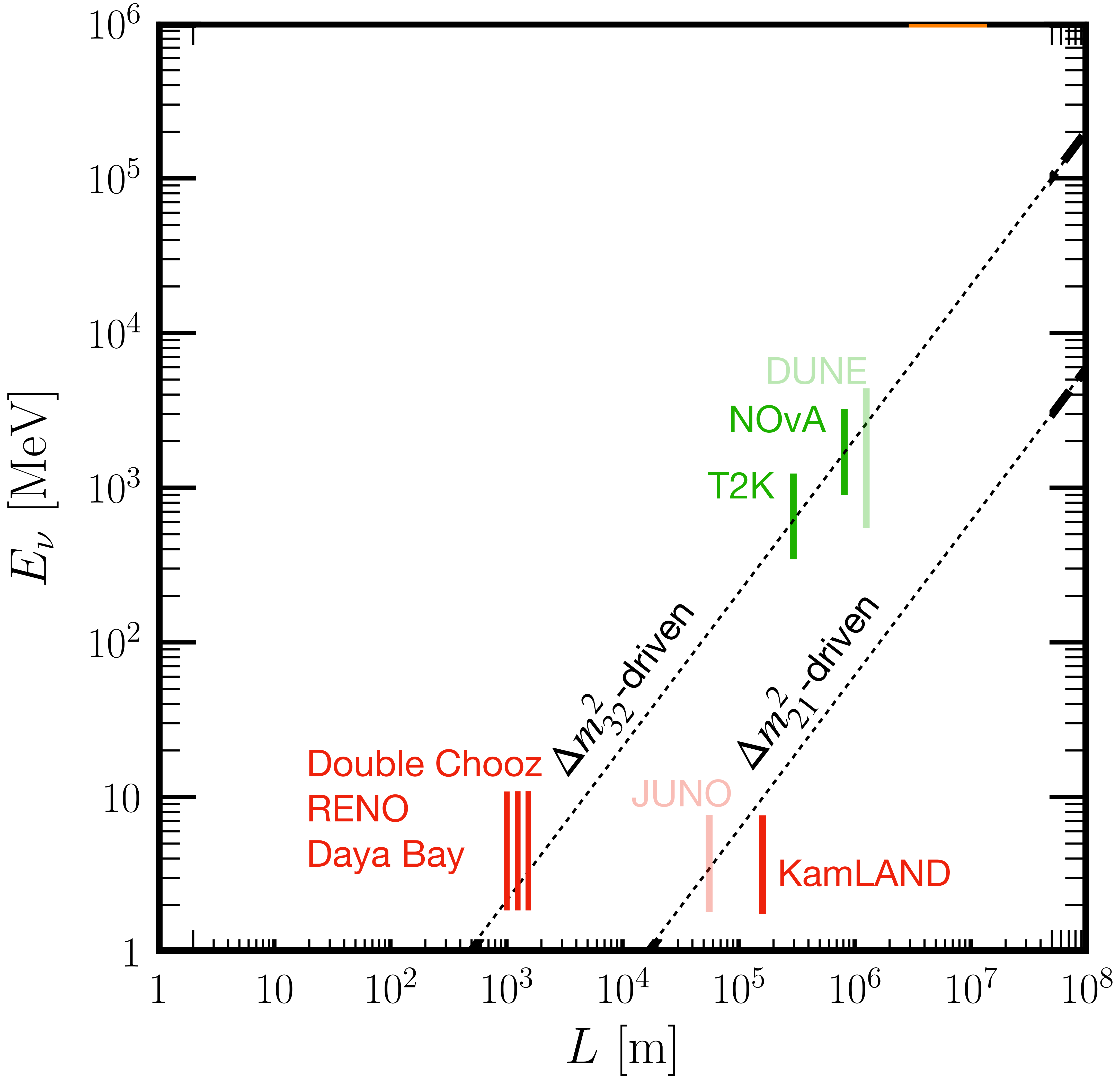

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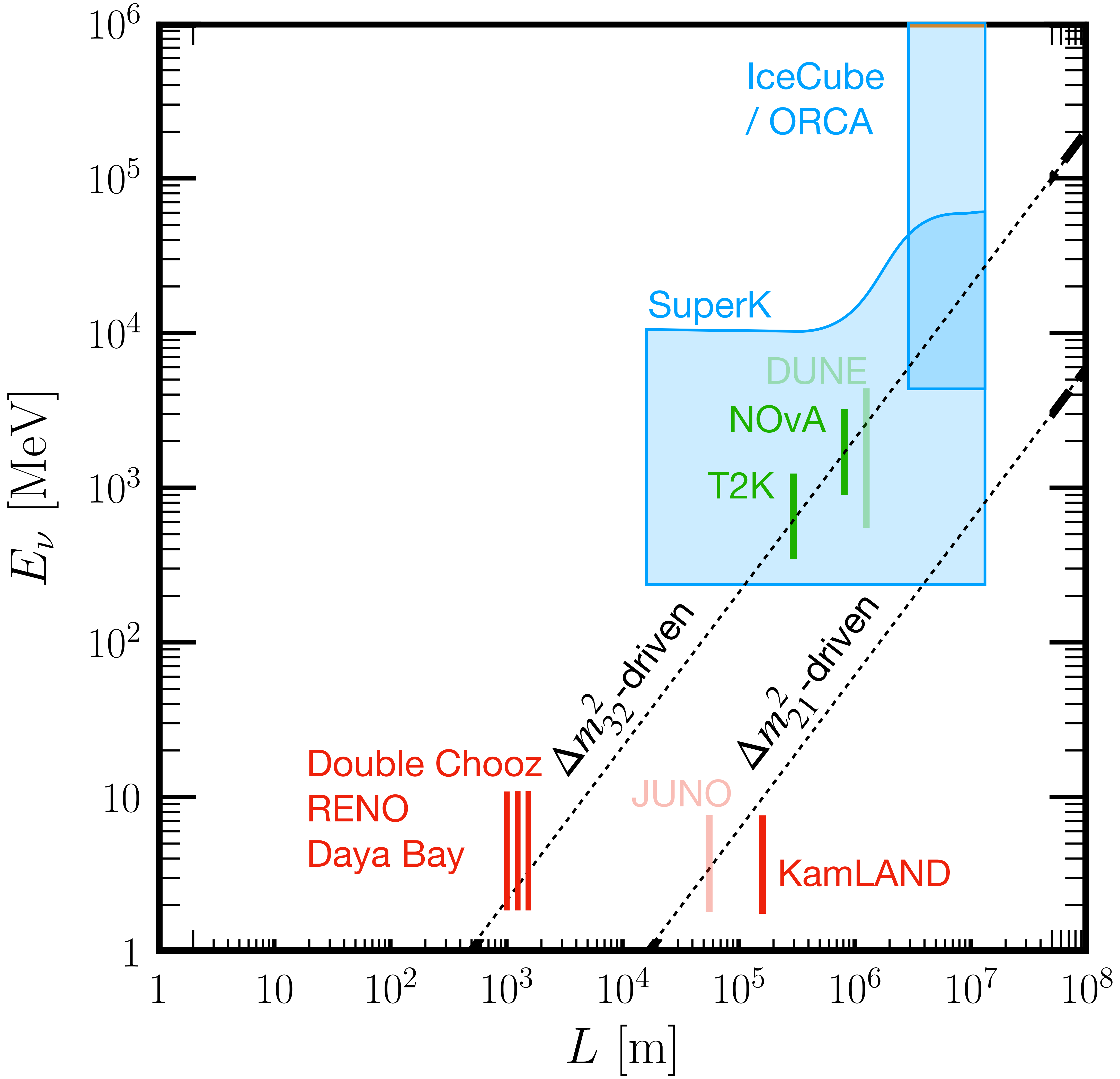
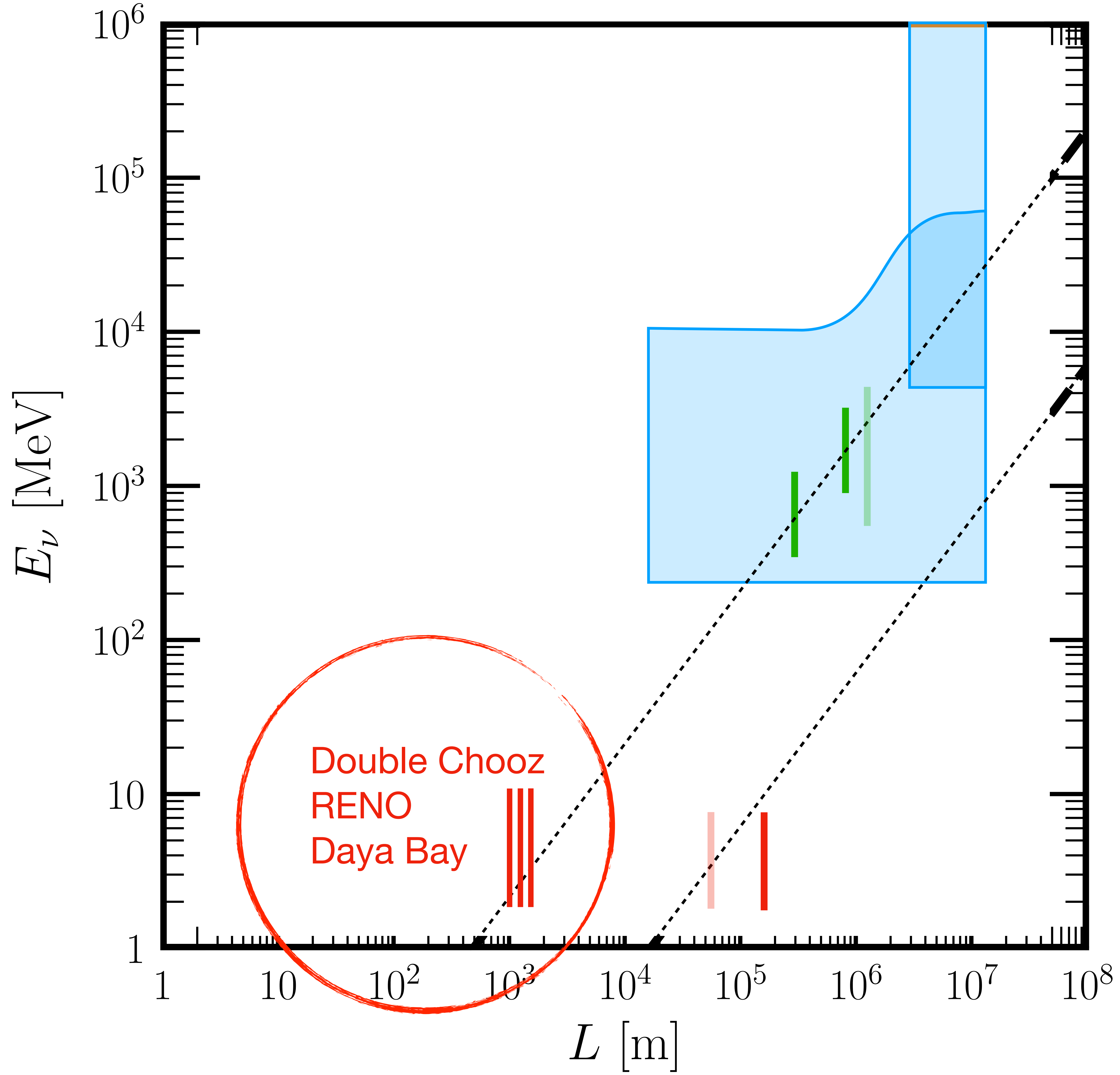
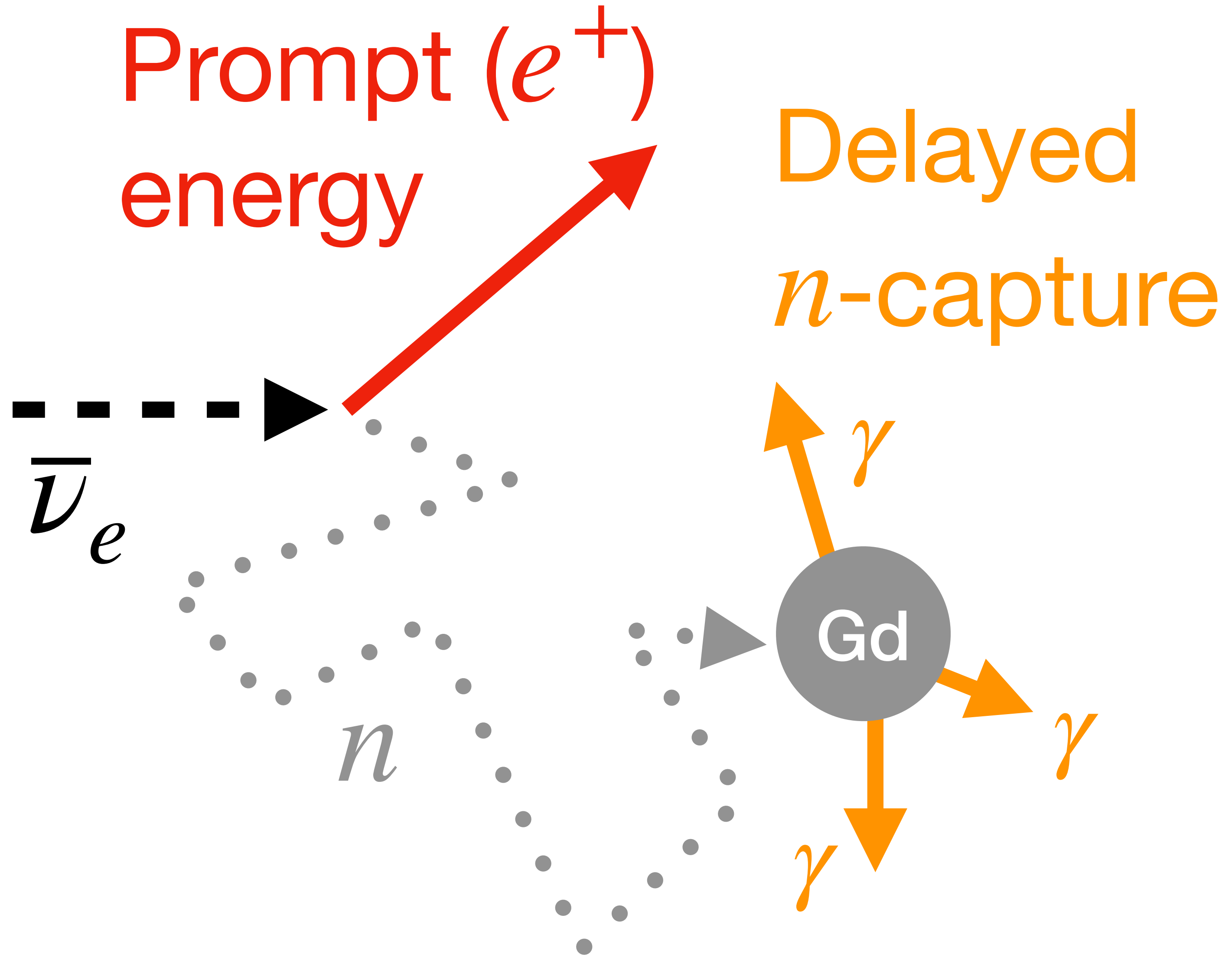


Plot inspired by PRD 101, 033008 (2020)

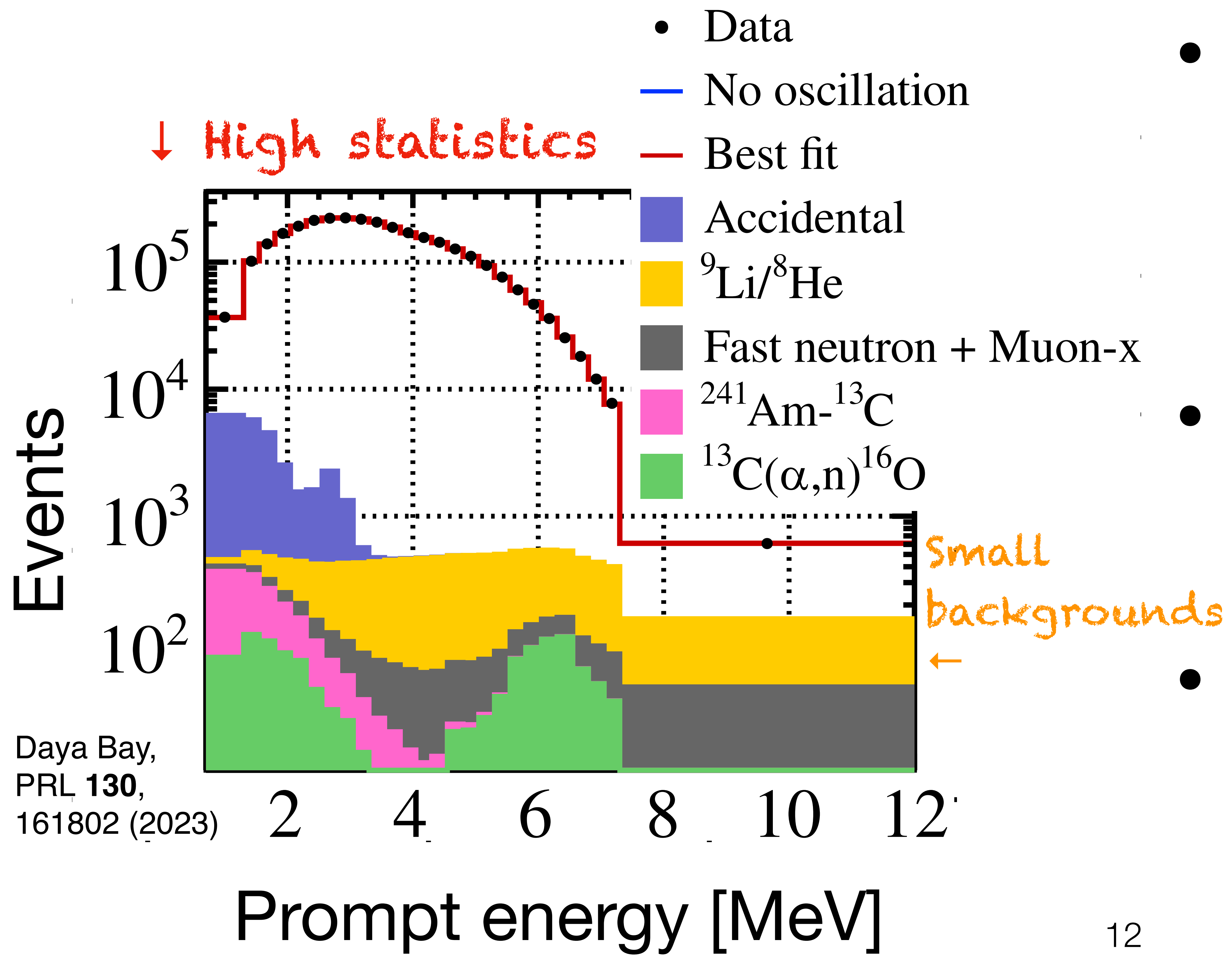
Medium Baseline (km)
Reactor Experiments



Assuming typical densities for terrestial exp.
Plot inspired by PRD 101, 033008 (2020)



Medium Baseline (km) Reactor Experiments



Daya Bay, PRL **130**, 161802 (2023)

- Intense anti-neutrino flux from reactor beta decay chain
- Detection in liquid scintillator via inverse-beta decay with delayed coincidence $\bar{\nu}_e + p \to e^+ + n$
- Neutrino energy inferred from e^+ energy deposit in LS
- Delayed γ from neutron capture on Gd (main) or H (sub) for significant background reduction

Medium Baseline (km) Reactor Experiments

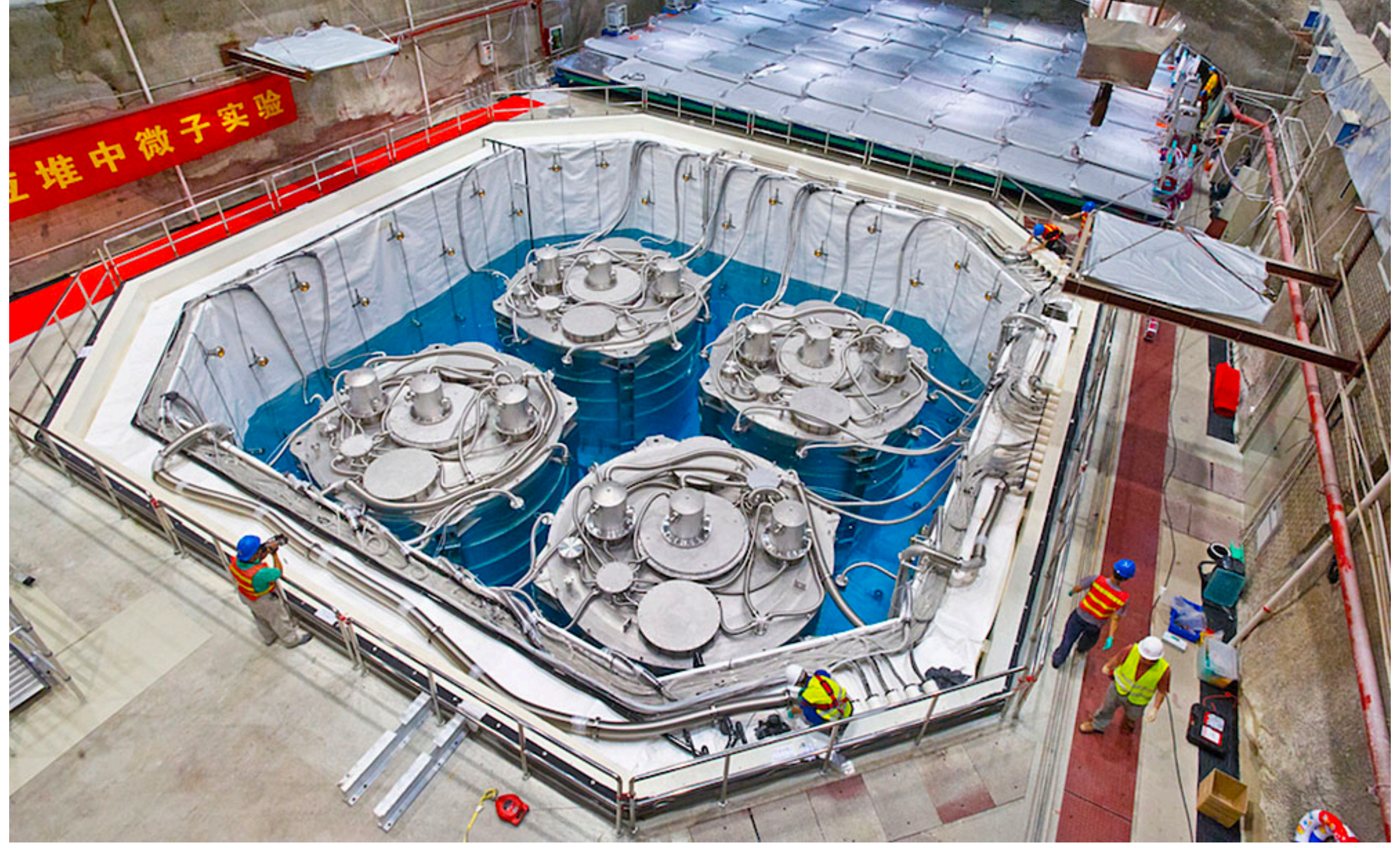
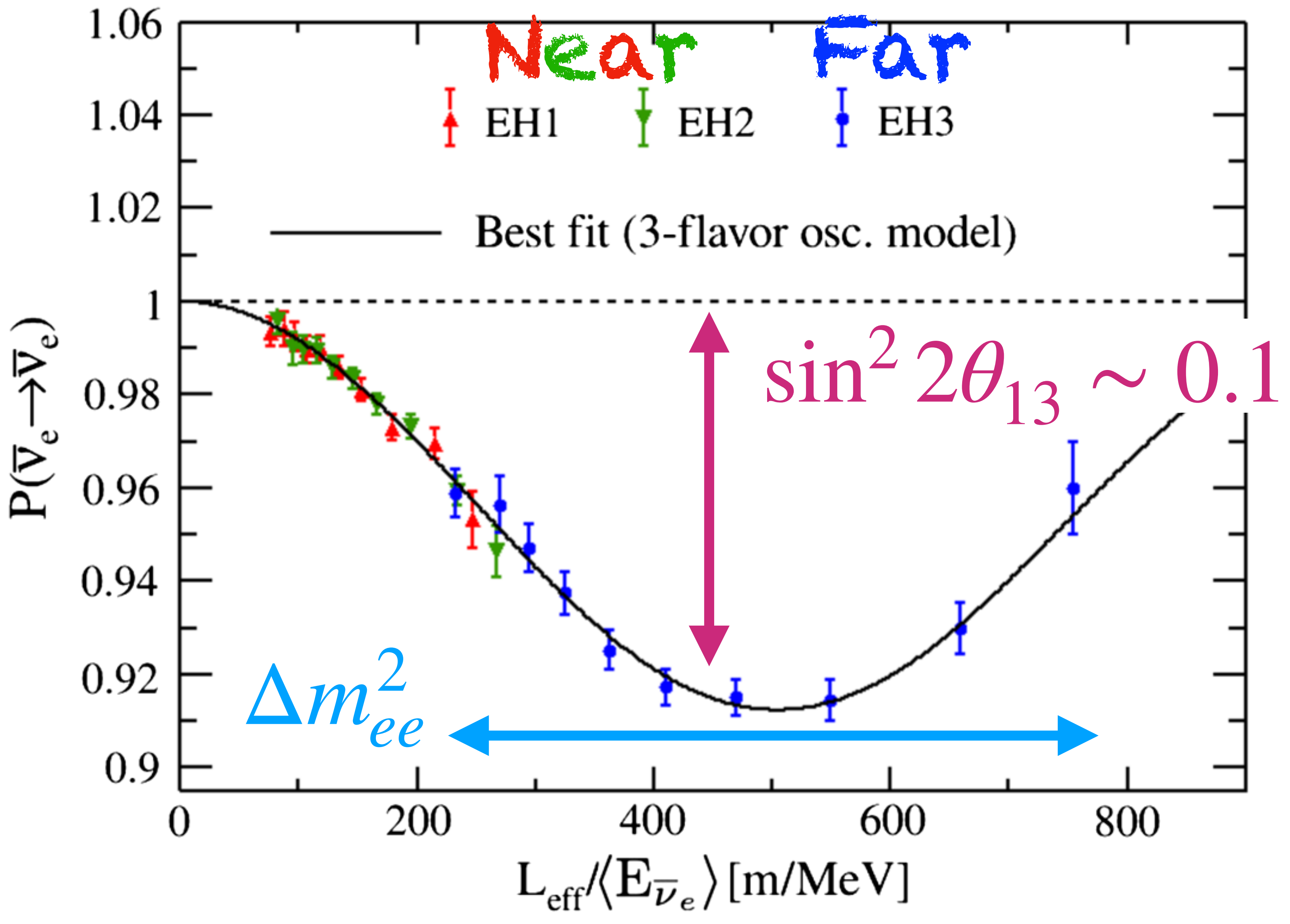


Photo: Roy Kaltschmidt, Berkeley Lab

DayaBay (PRL.130.161802)



Very clear oscillation signature

- 3 experiments with similar design
  Double Chooz (France),
  Daya Bay (China),
  RENO (Korea)

  All have completed data taking

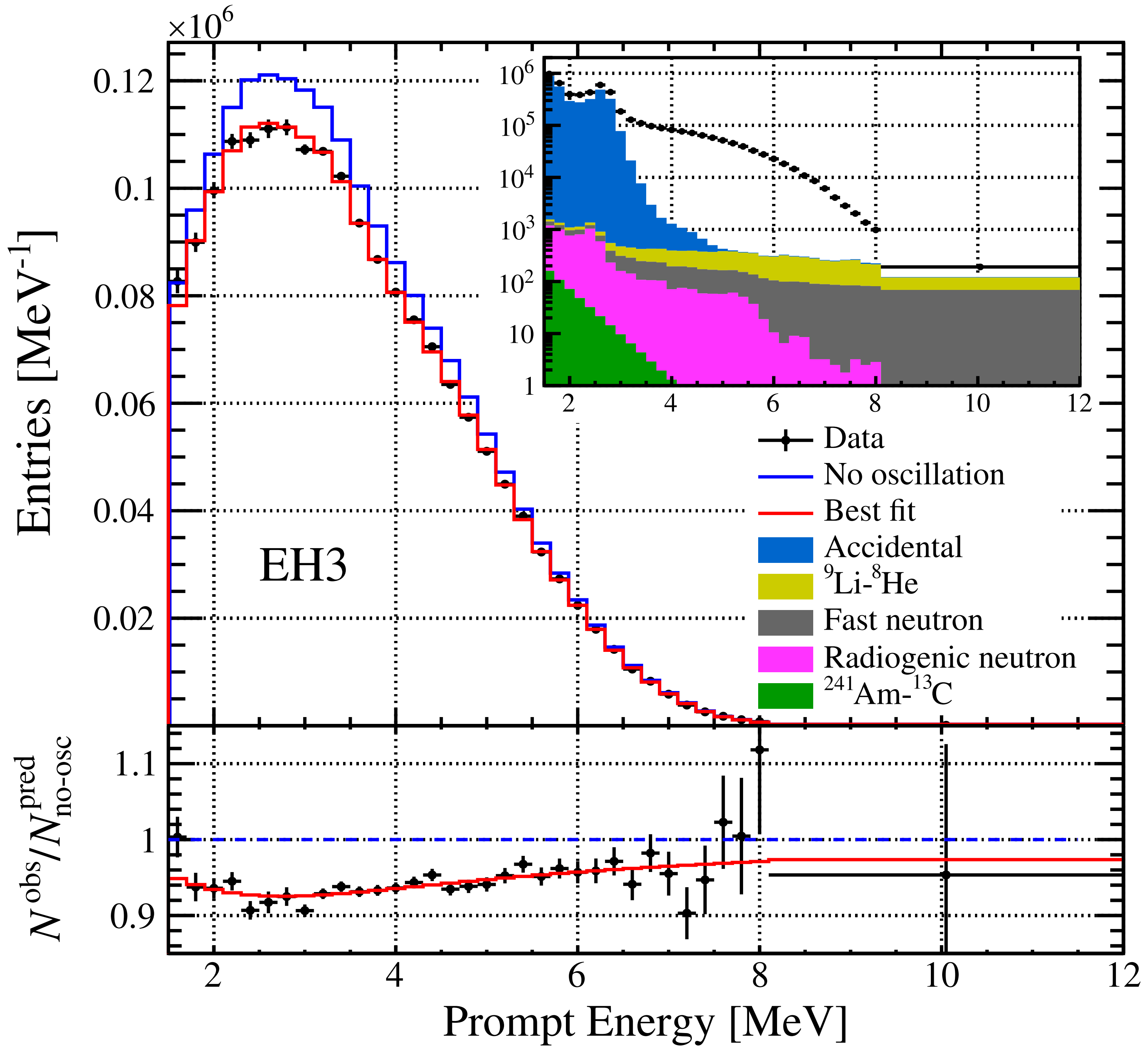
- Identical detectors near and far (~ 1 km) from reactor allows cancellation of many systematic effects

- Oscillation of $\bar{\nu}_e \to \bar{\nu}_e$ at first osc. max.

  Approximately 2-flavor osc. with amplitude $\sin^2 2\theta_{13}$ and frequency $|\Delta m^2_{ee}| \approx |\Delta m^2_{31}|$

θ_{13} constraints

Daya Bay nH analysis
PRL **133**, 151801 (2024)



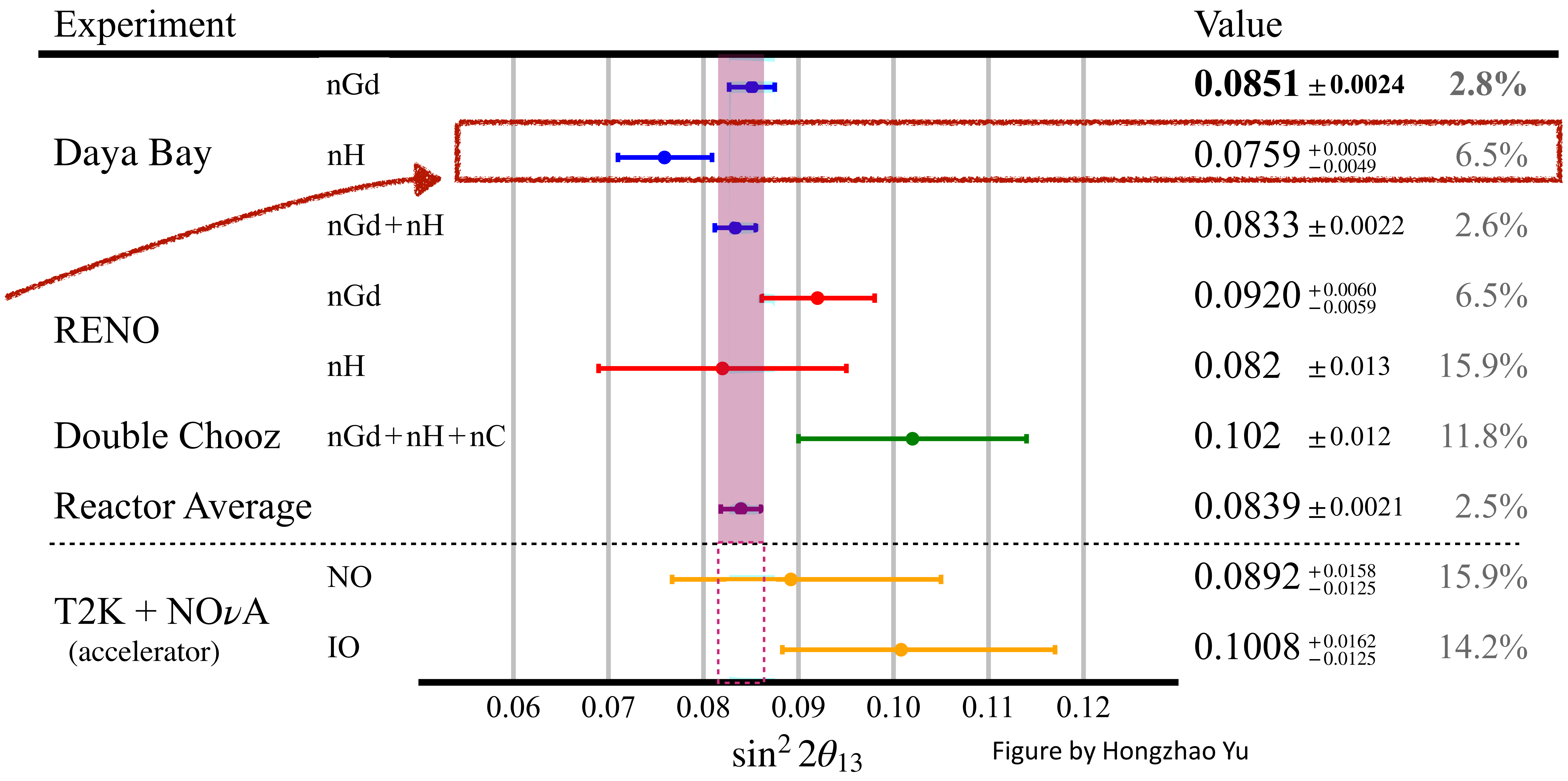


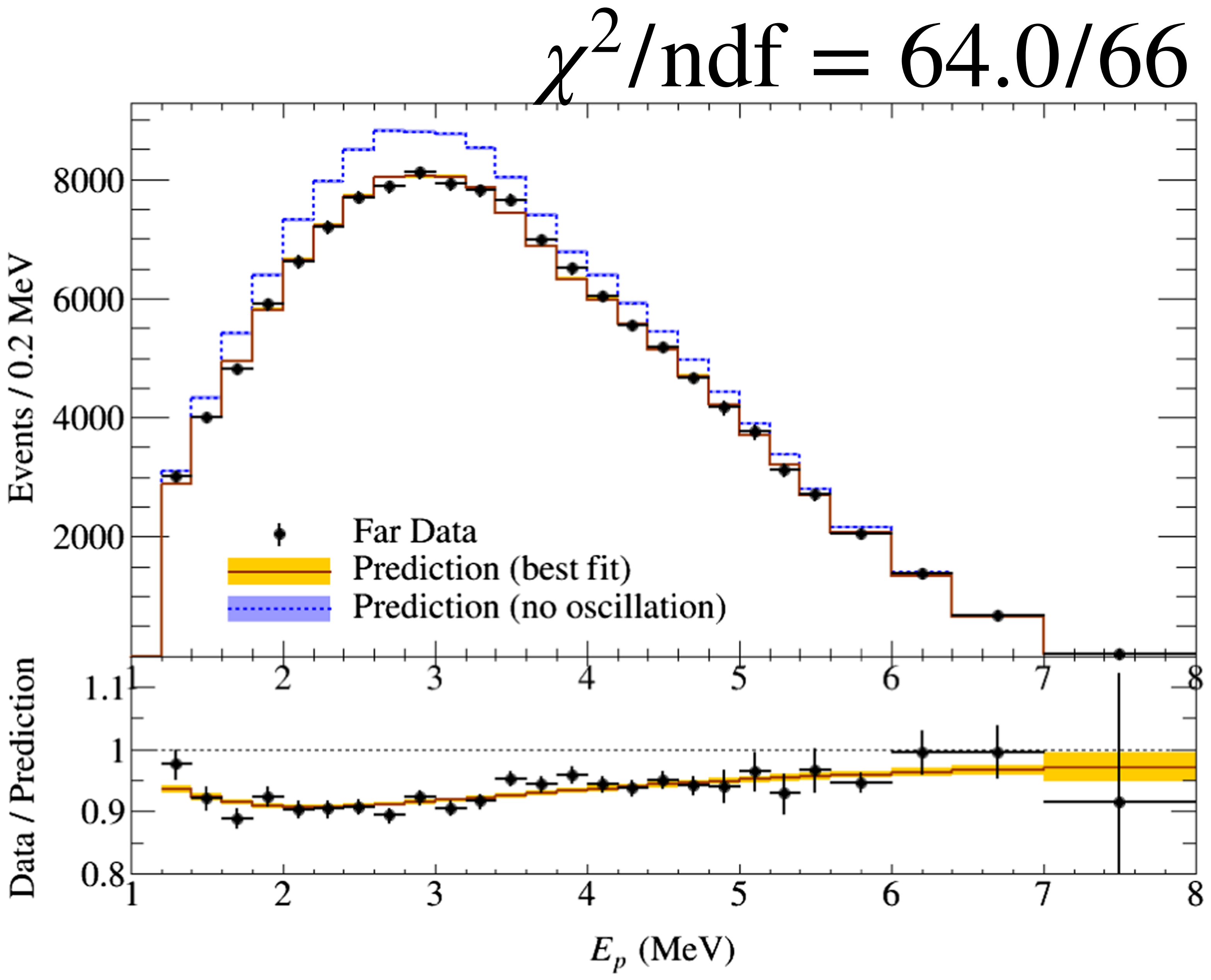
Figure by Hongzhao Yu

Slightly modified emphasis

Note: average is error weighted average assuming no correlation

θ_{13} constraints

RENO final
PRD **111**, 112006 (2025)



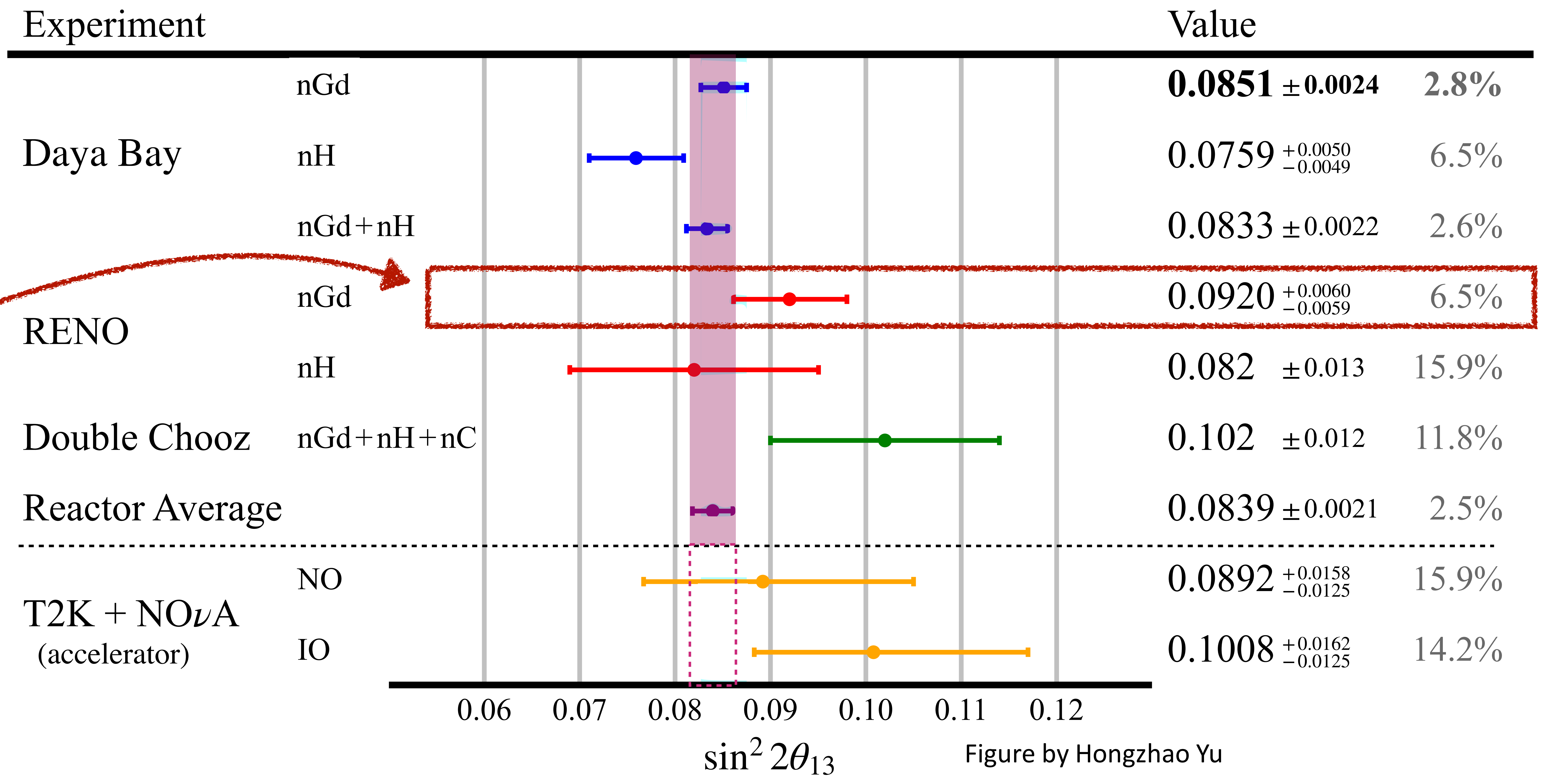


Figure by Hongzhao Yu

Slightly modified emphasis

Note: average is error weighted average assuming no correlation

θ_{13} constraints

Double Chooz

Final results will be presented this afternoon by Philipp Soldin

Neutrino Physics and Astrophysics Parallel 1B

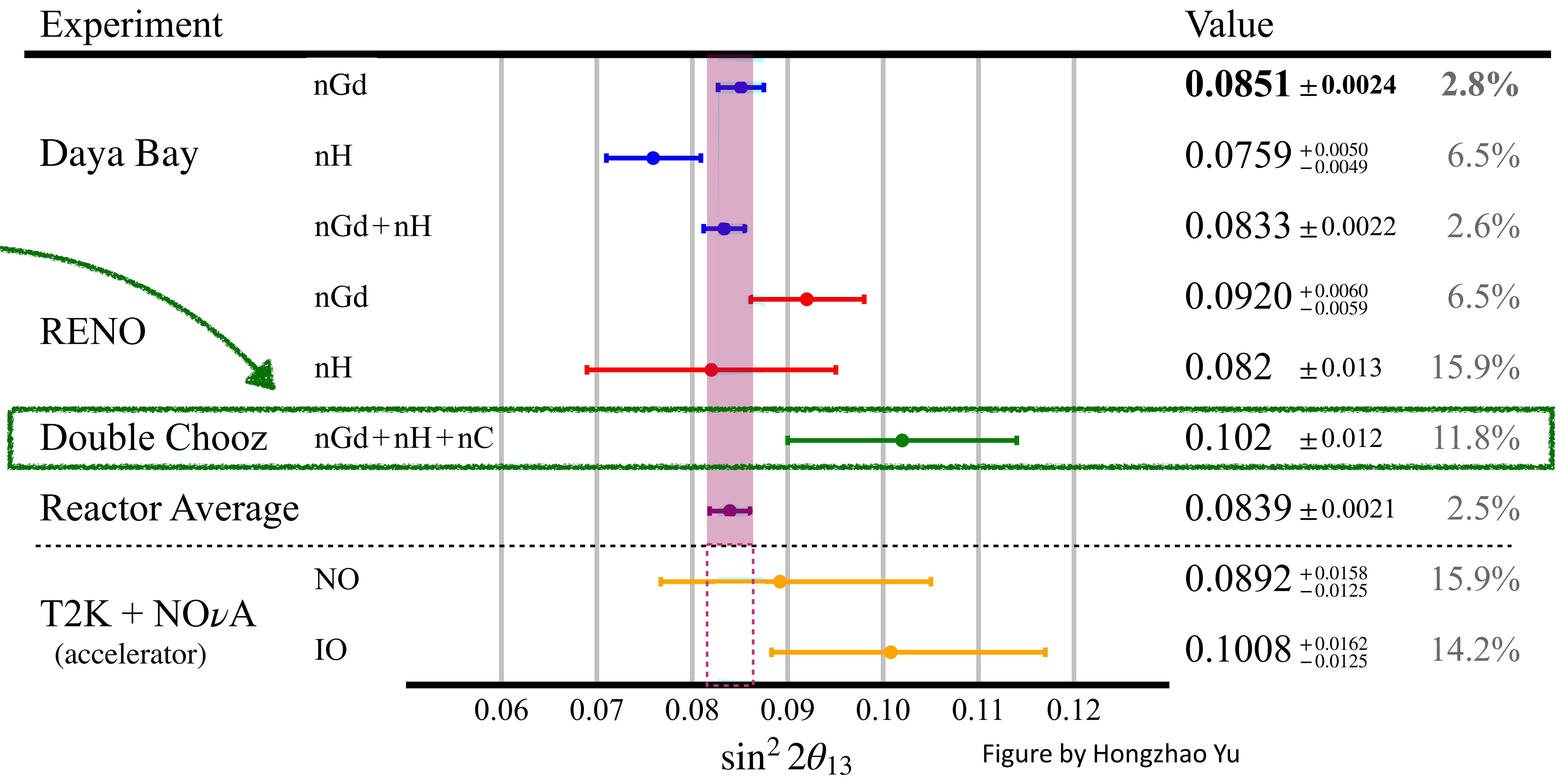


Figure by Hongzhao Yu

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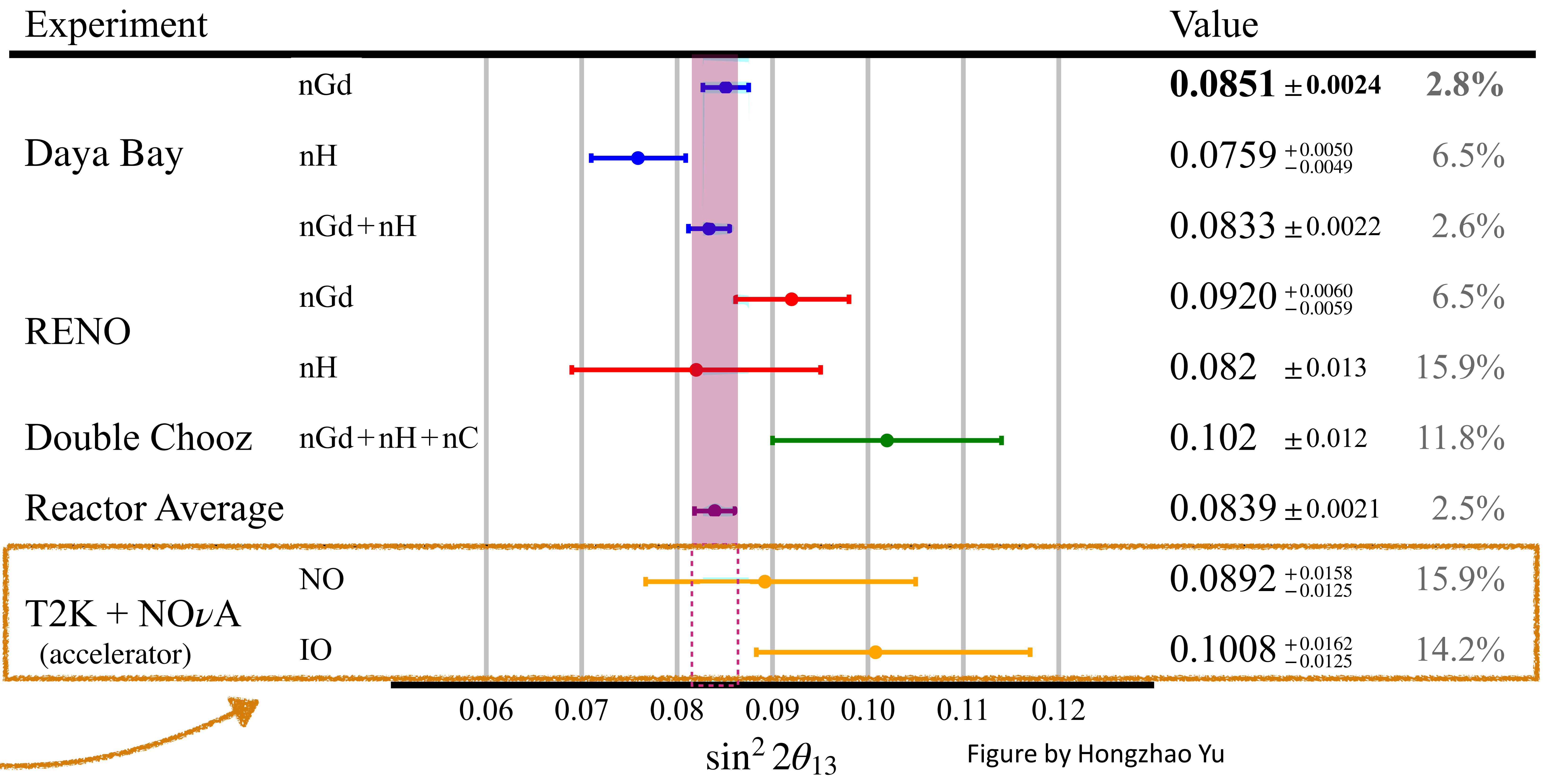


Figure by Hongzhao Yu

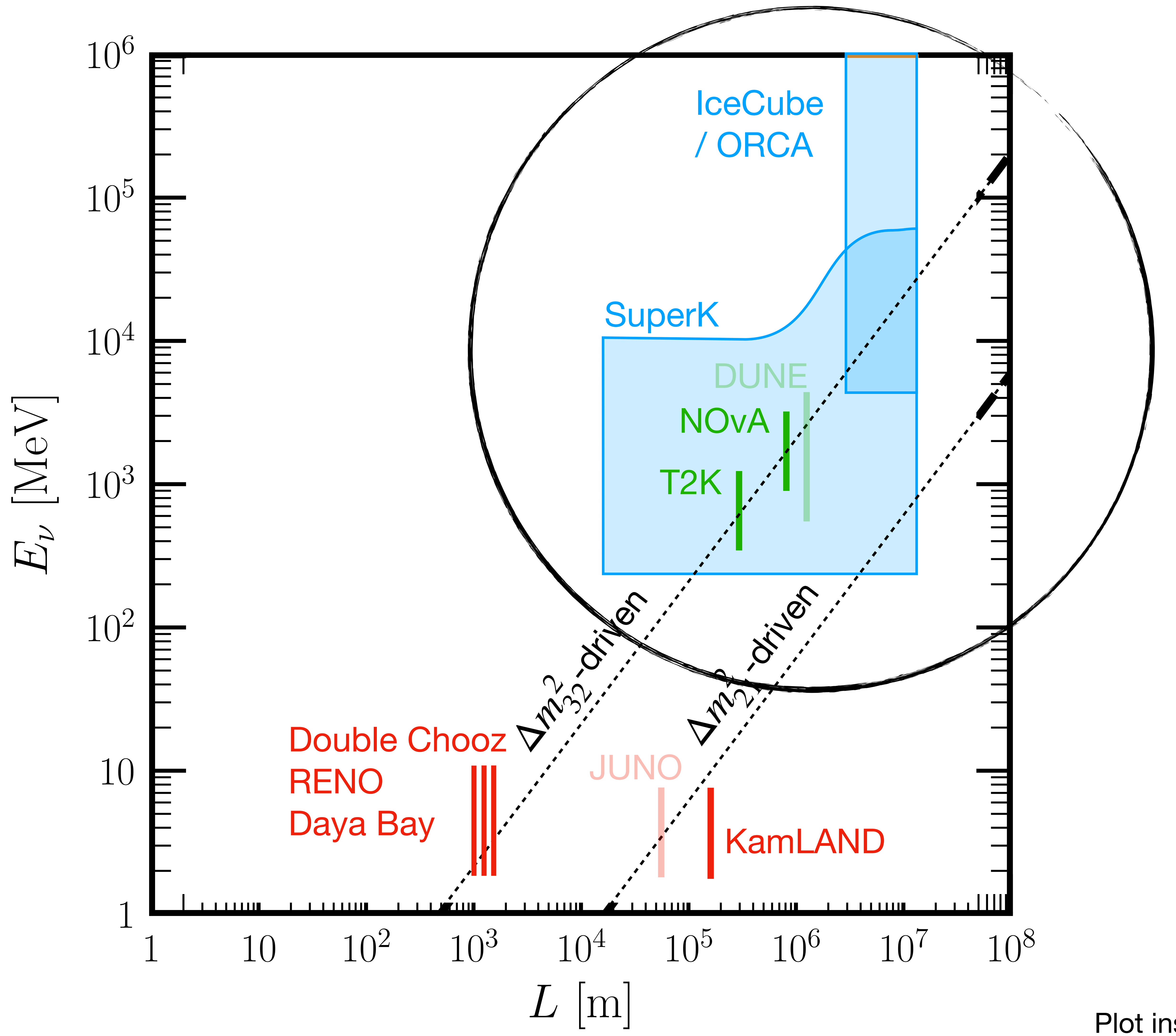
Slightly modified emphasis

Consistent results also from $\nu_\mu \to \nu_e$ appearance at accelerators (some implication on MO)

Nice check of 3ν paradigm

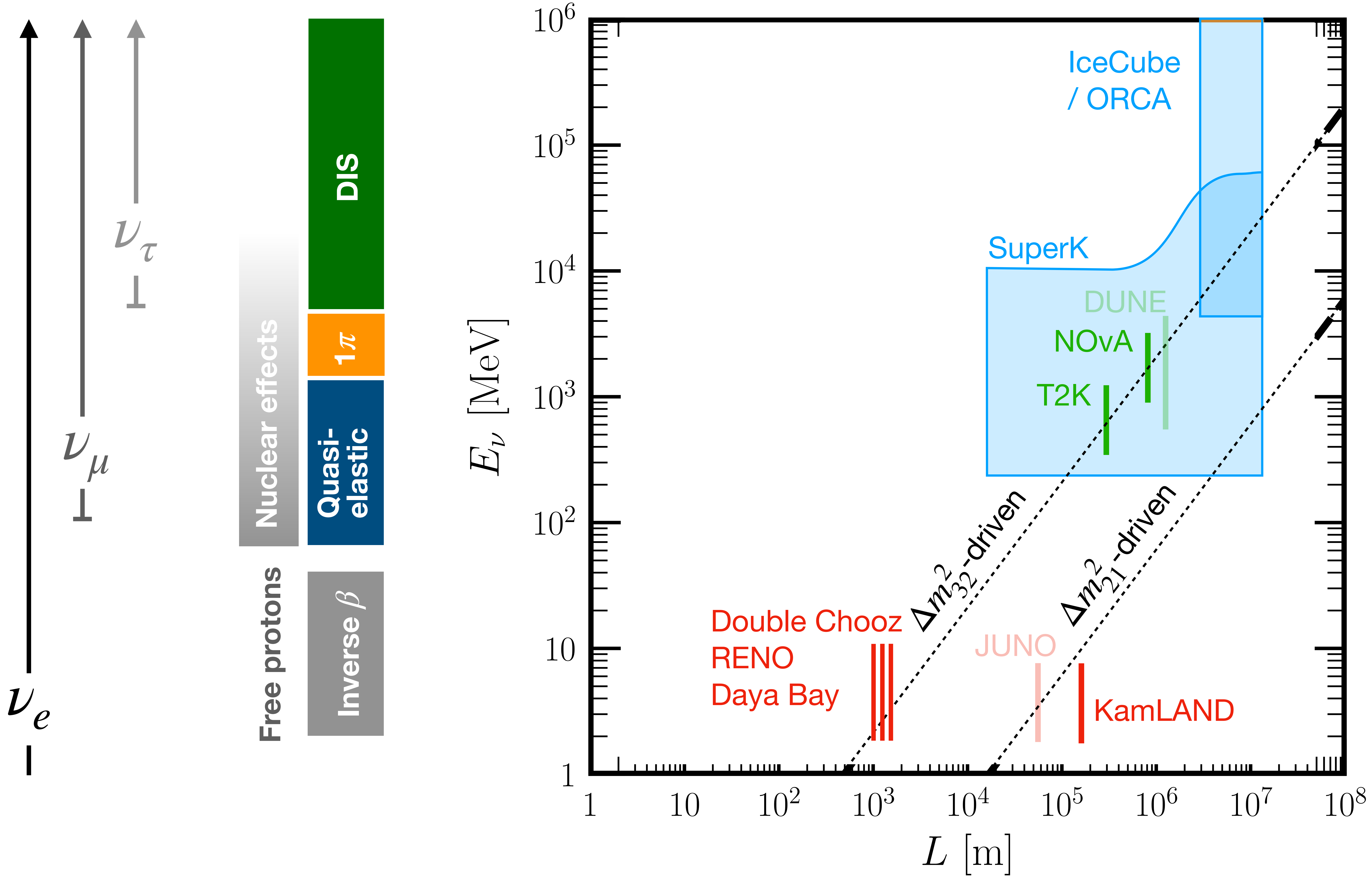
Note: average is error weighted average assuming no correlation

Long-baseline experiments



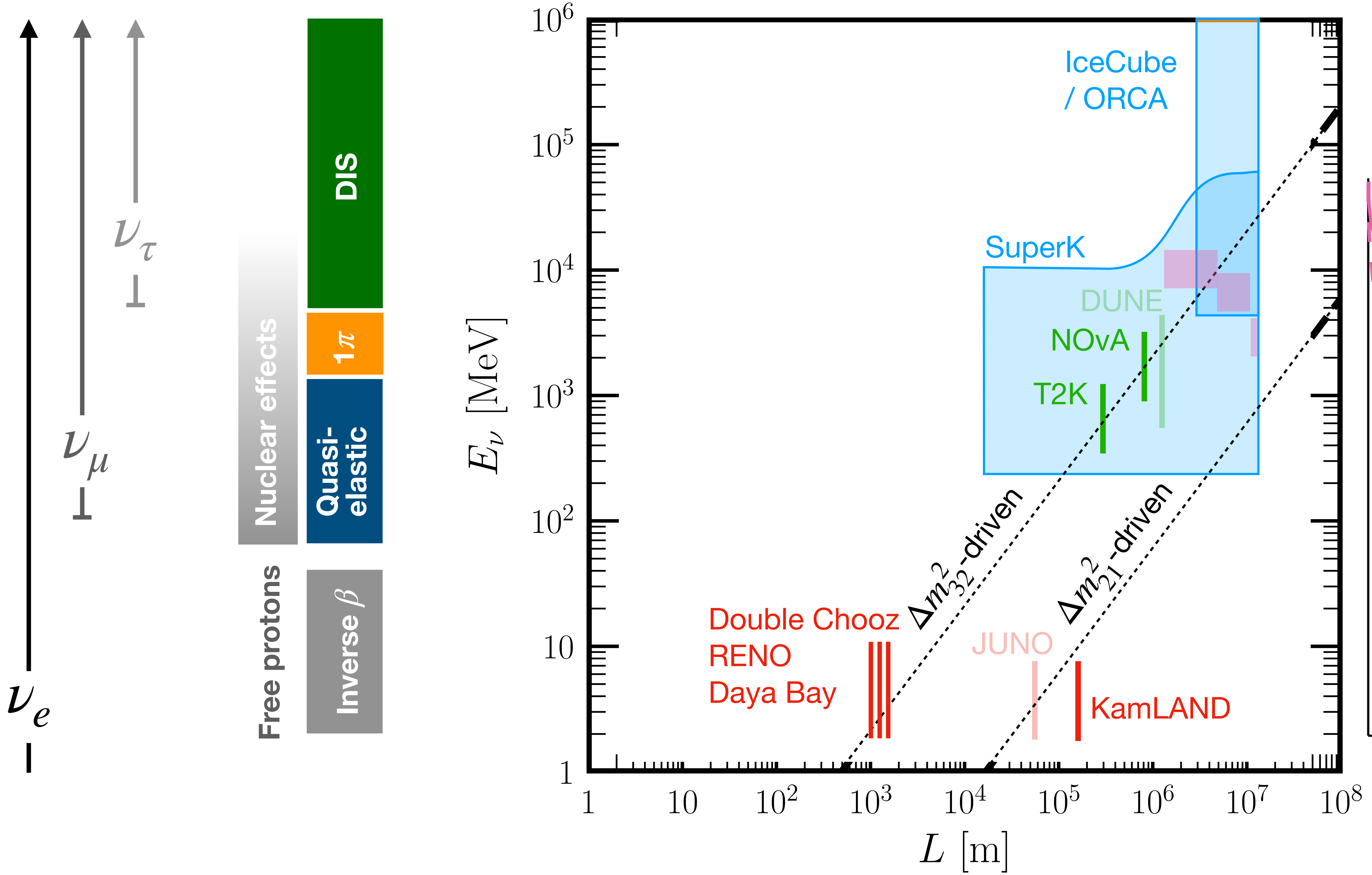
Plot inspired by PRD 101, 033008 (2020)

Long-baseline experiments

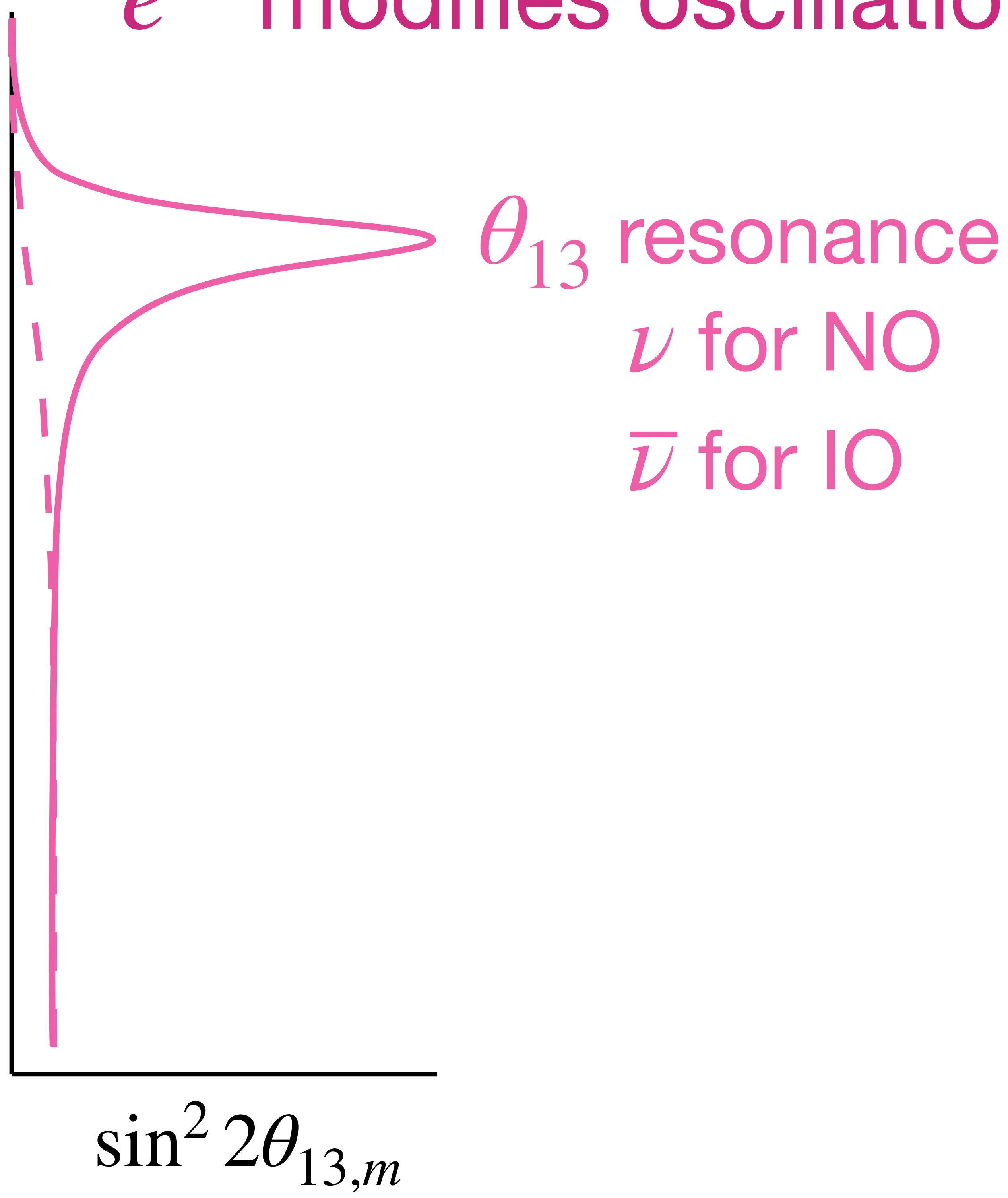


Plot inspired by PRD 101, 033008 (2020)

Long-baseline experiments

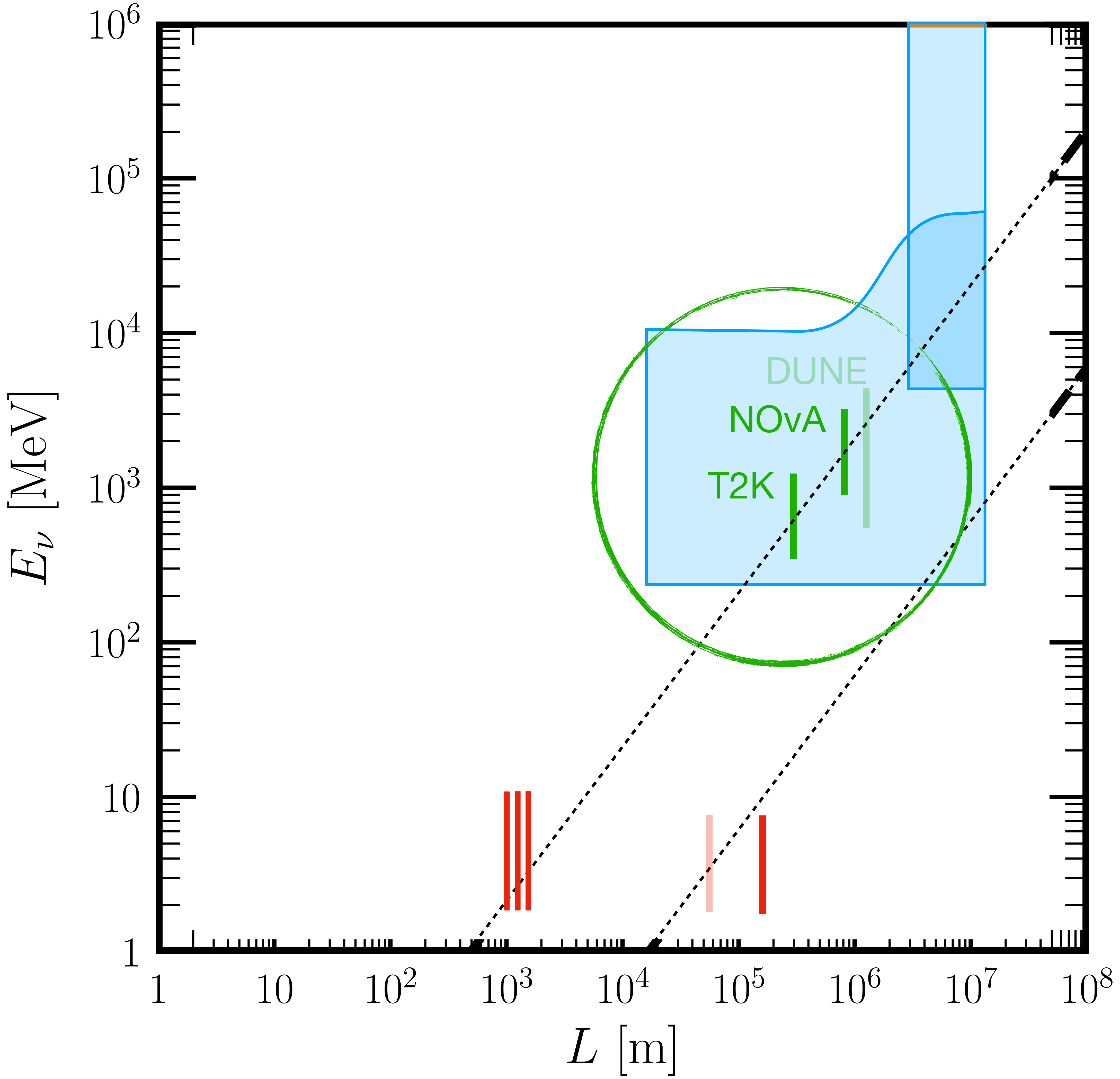


In matter, coherent forward-scattering with e^- modifies oscillations



Assuming typical densities for terrestial exp.
Plot inspired by PRD 101, 033008 (2020)

Accelerator experiments

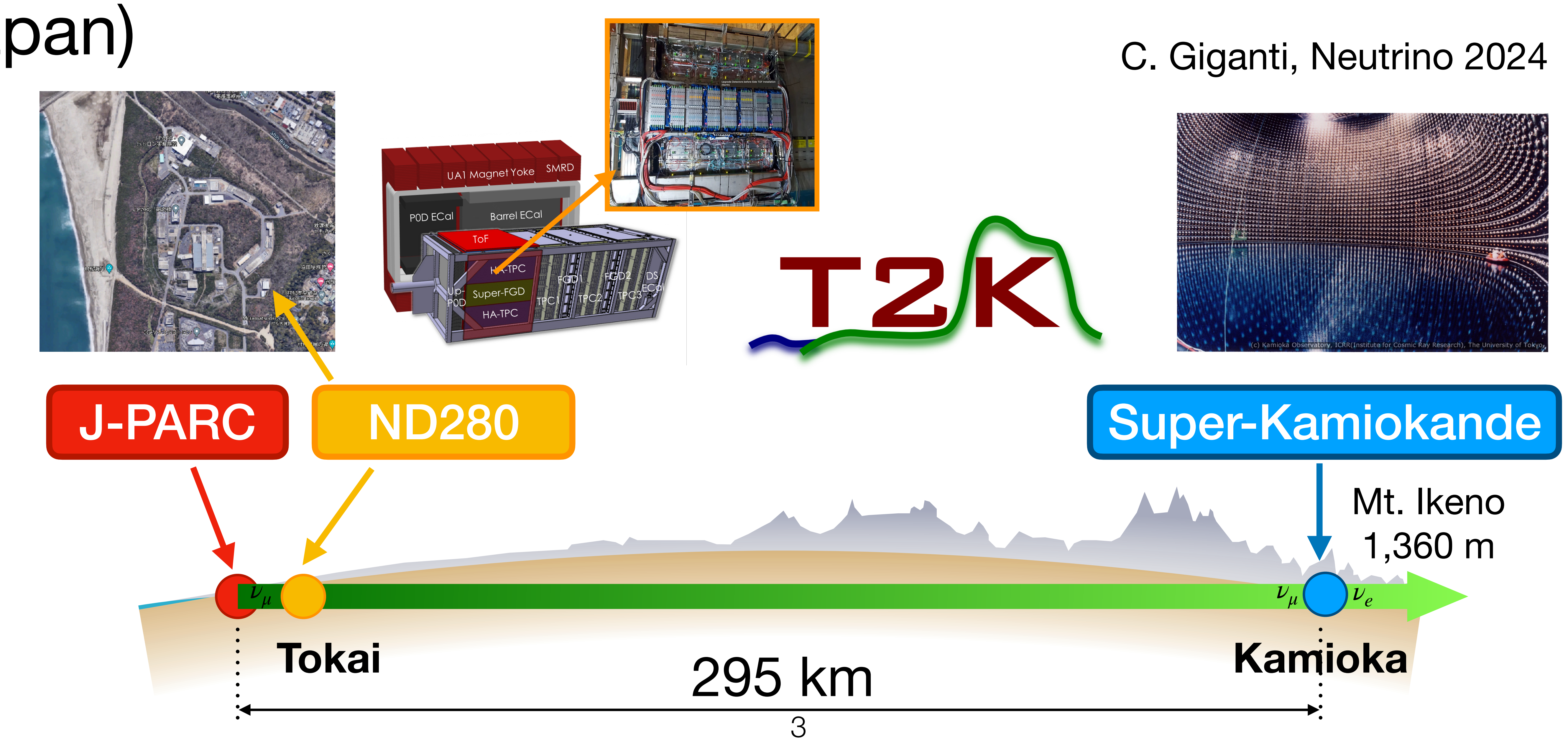


Assuming typical densities for terrestial exp.
Plot inspired by PRD 101, 033008 (2020)

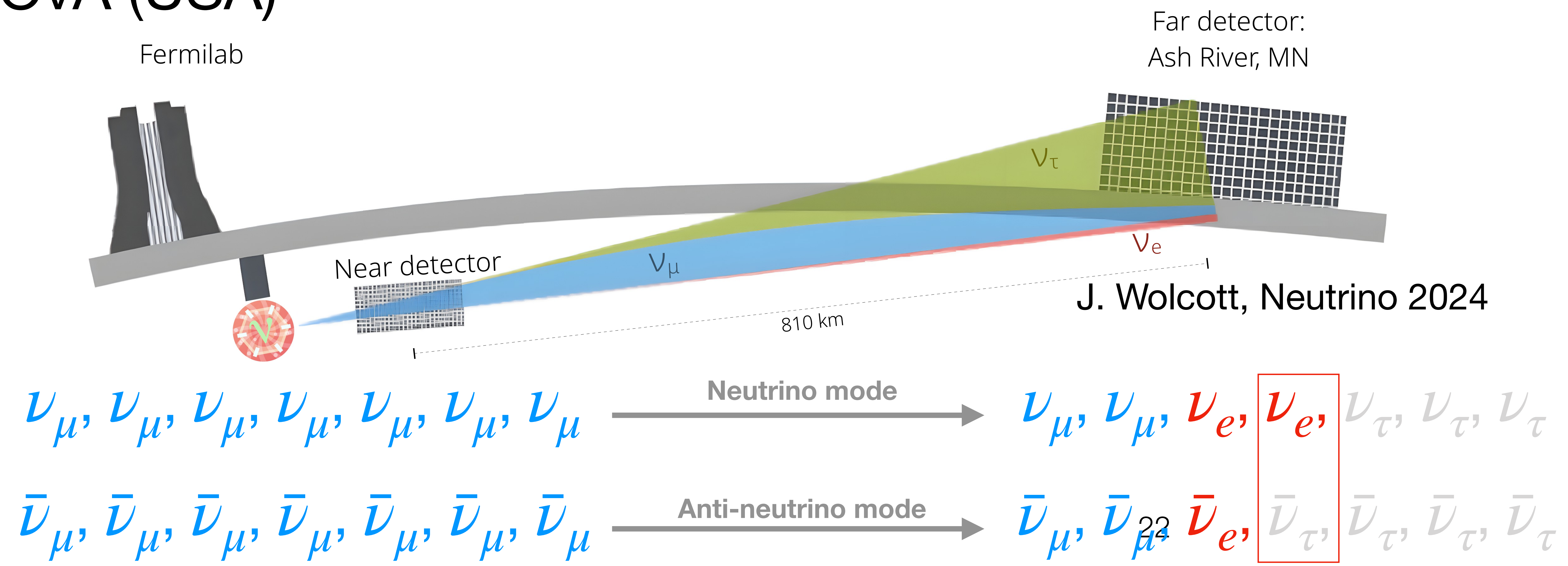
Accelerator neutrinos

T2K (Japan)

C. Giganti, Neutrino 2024



NOvA (USA)

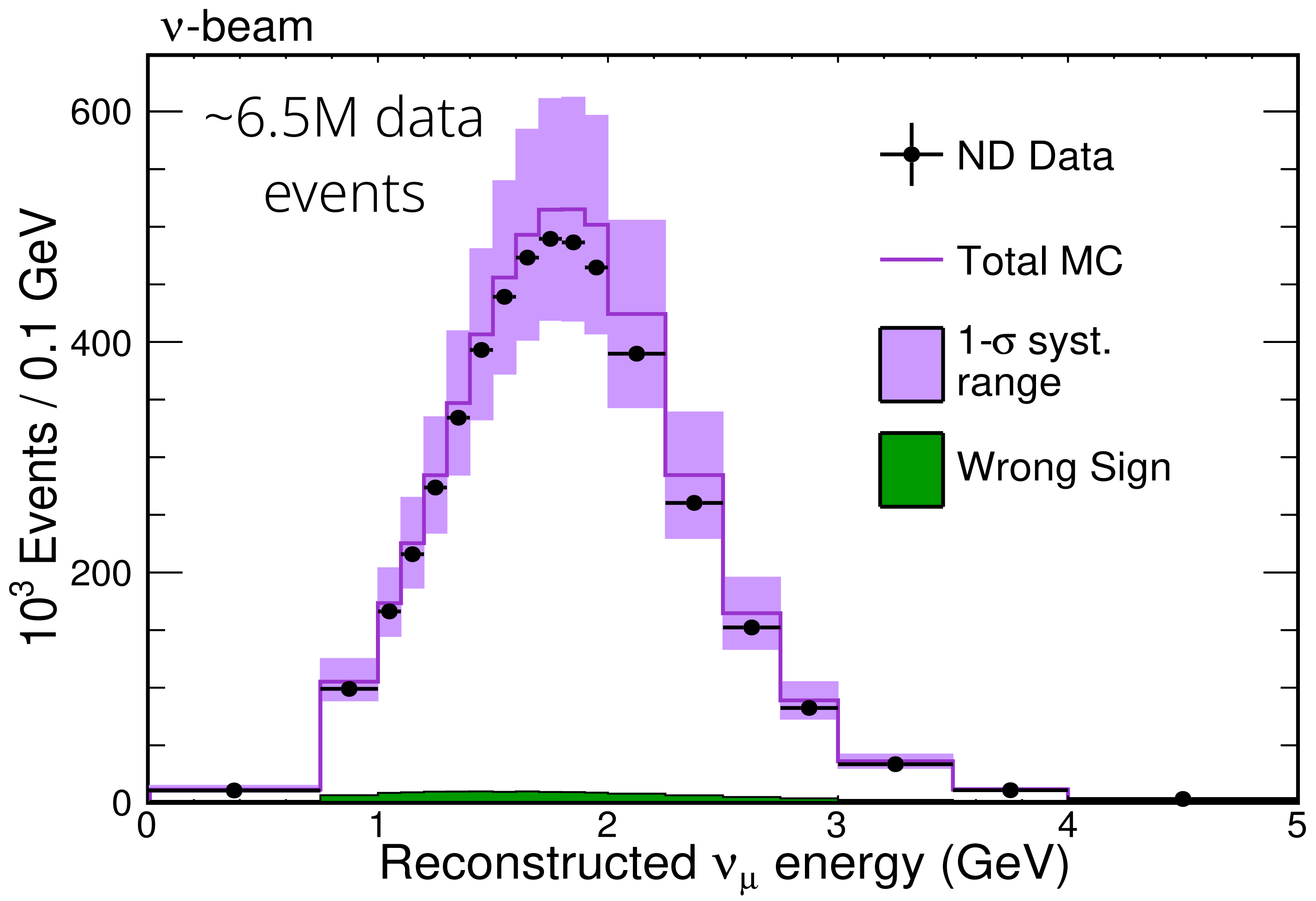


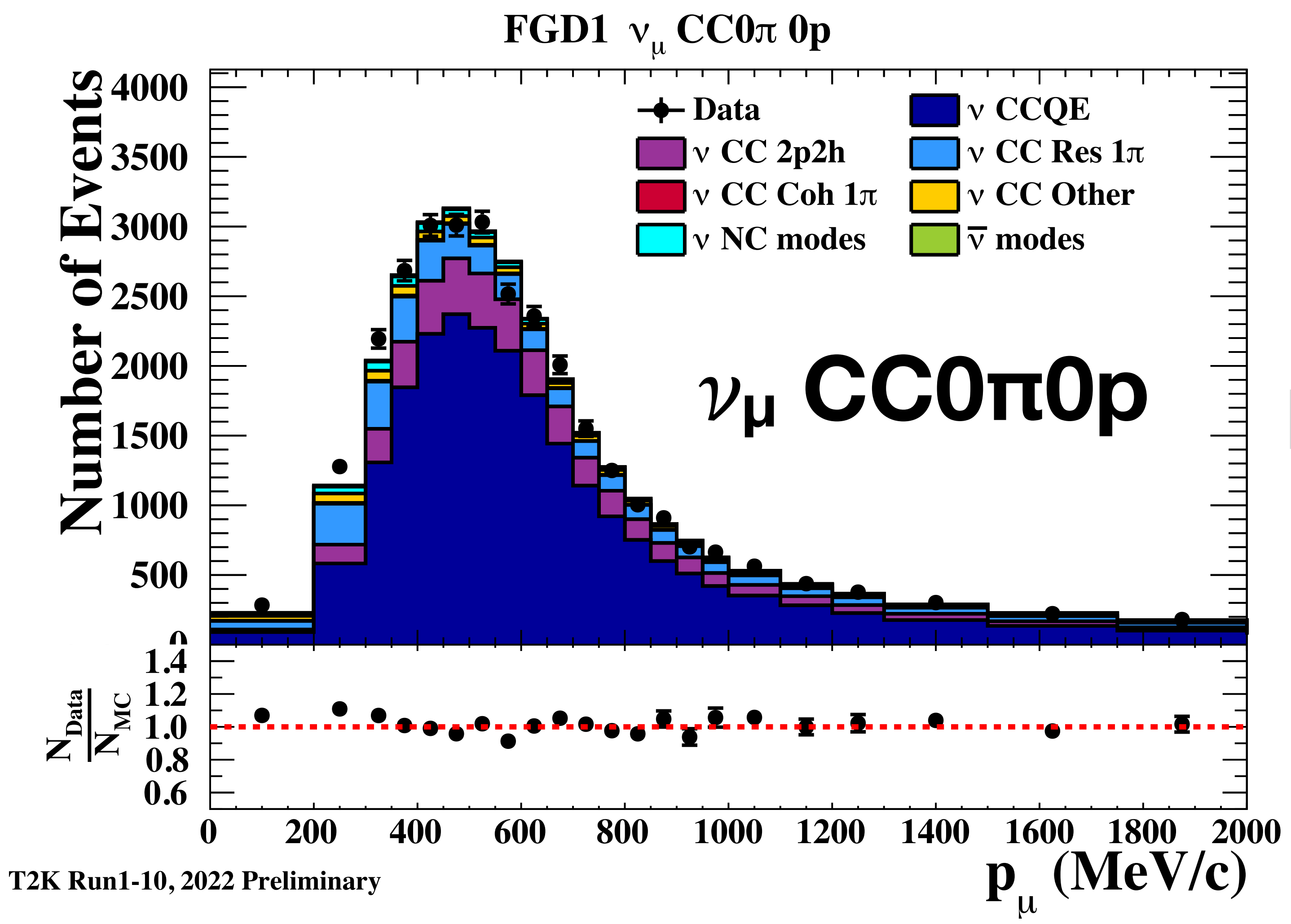
- Selectable ν_μ or $\bar{\nu}_\mu$ beams by focusing $\pi^\pm$ produced by p beam on fixed target
- Precision study of $\nu_\mu \to \nu_{e,\mu}$ oscillations near first oscillation maximum
- Low $\nu_e/\bar{\nu}_e$ contamination allows study of $\nu_\mu \to \nu_e$ oscillations for both $\nu/\bar{\nu}$
- Near detectors to measure neutrinos before oscillations
  ↓
  constrain flux × interaction systematics

ν_μ disappearance

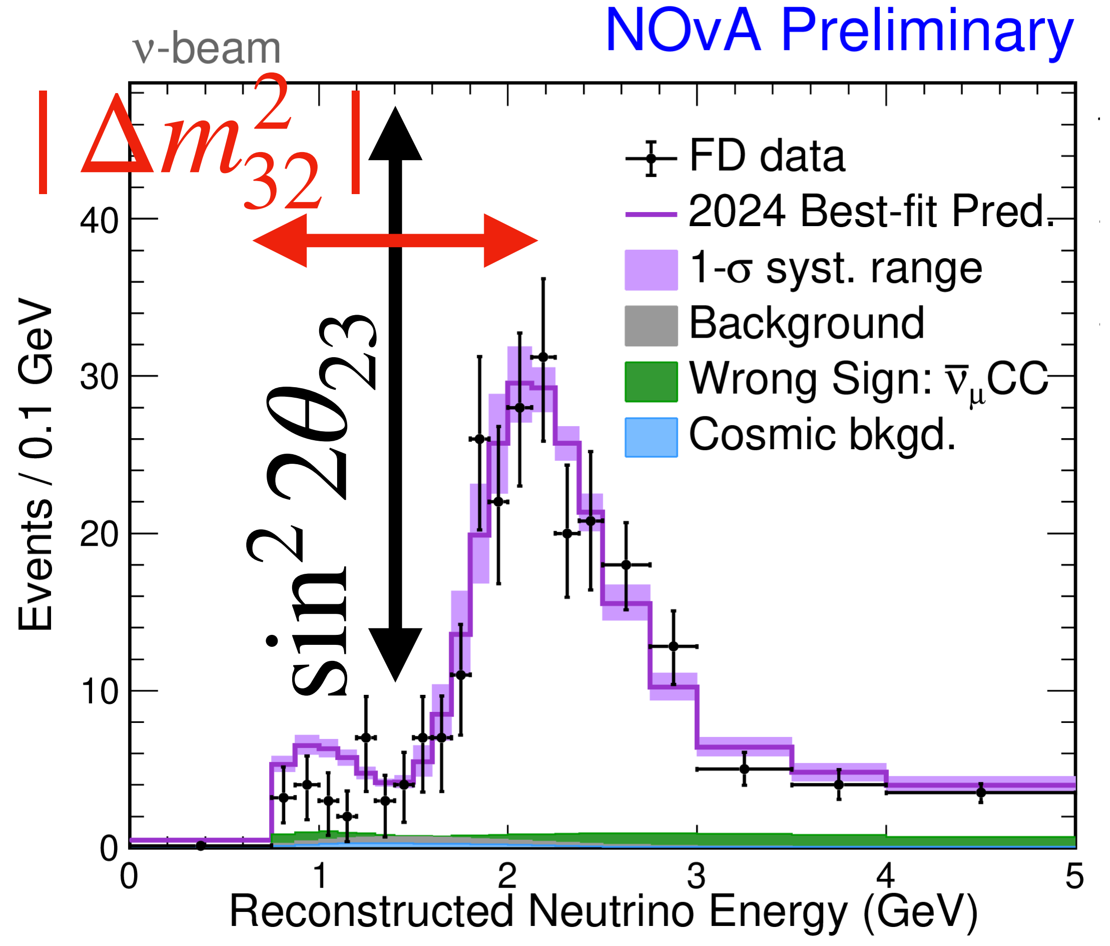
Neutrino 2024 Preliminary

ND

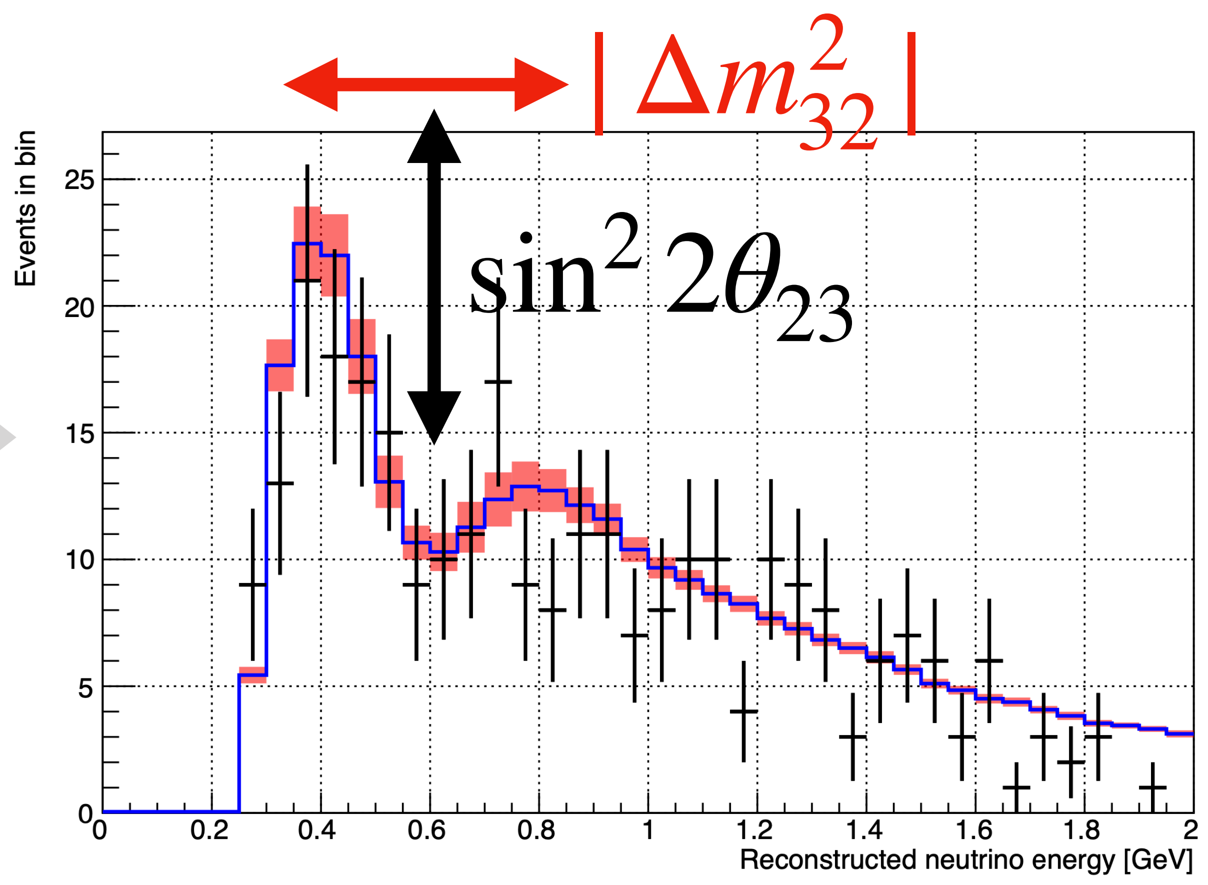




FD

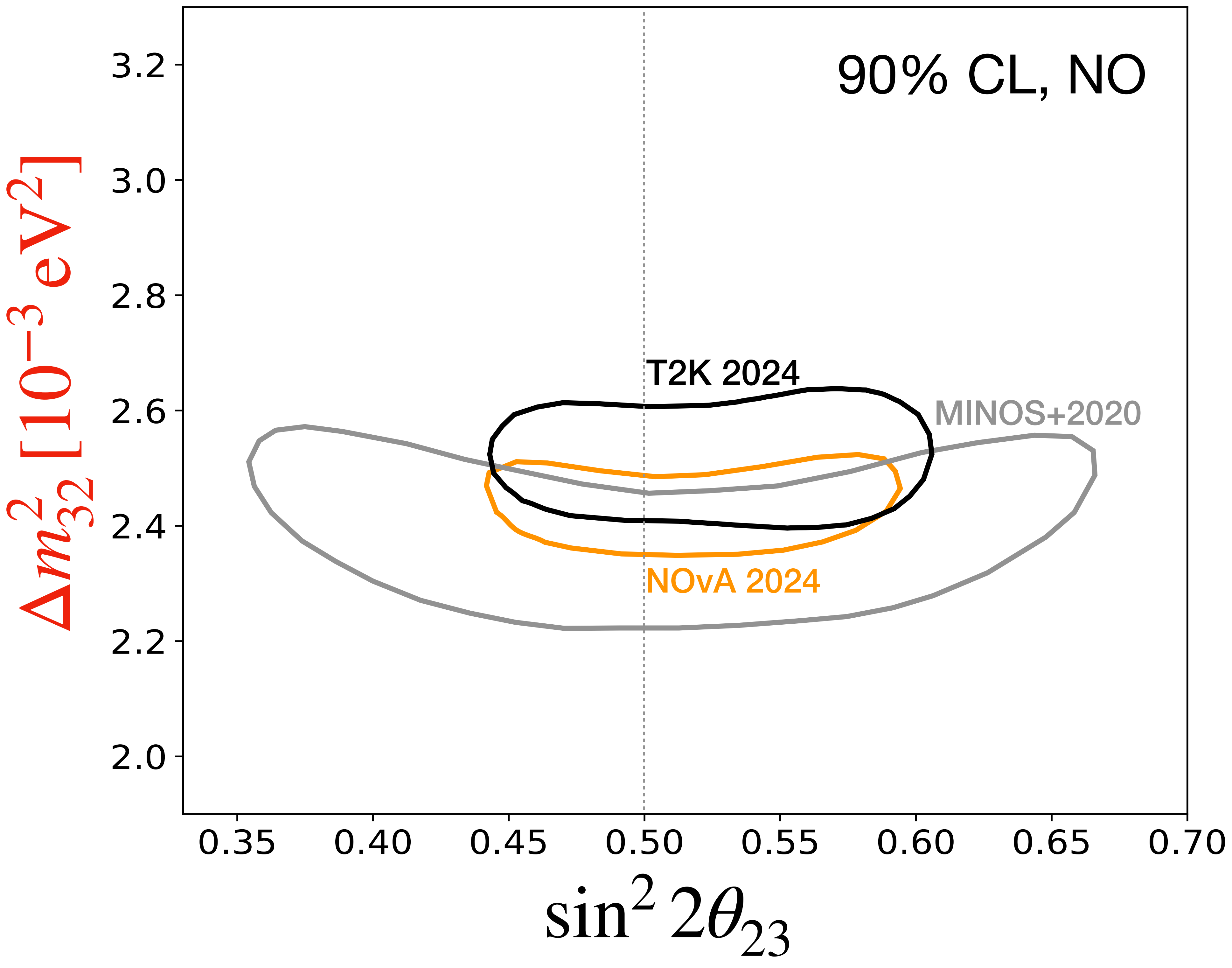


384 ν_μ data candidates
(11.3 background)



NOvA doubled ν-mode statistics → leading

T2K 10% more ν-mode compared to 2022 and reduced FD detector systematics



Consistent with maximal mixing

T2K has been upgrading beam-line and ND.
→ expect improvement in future.

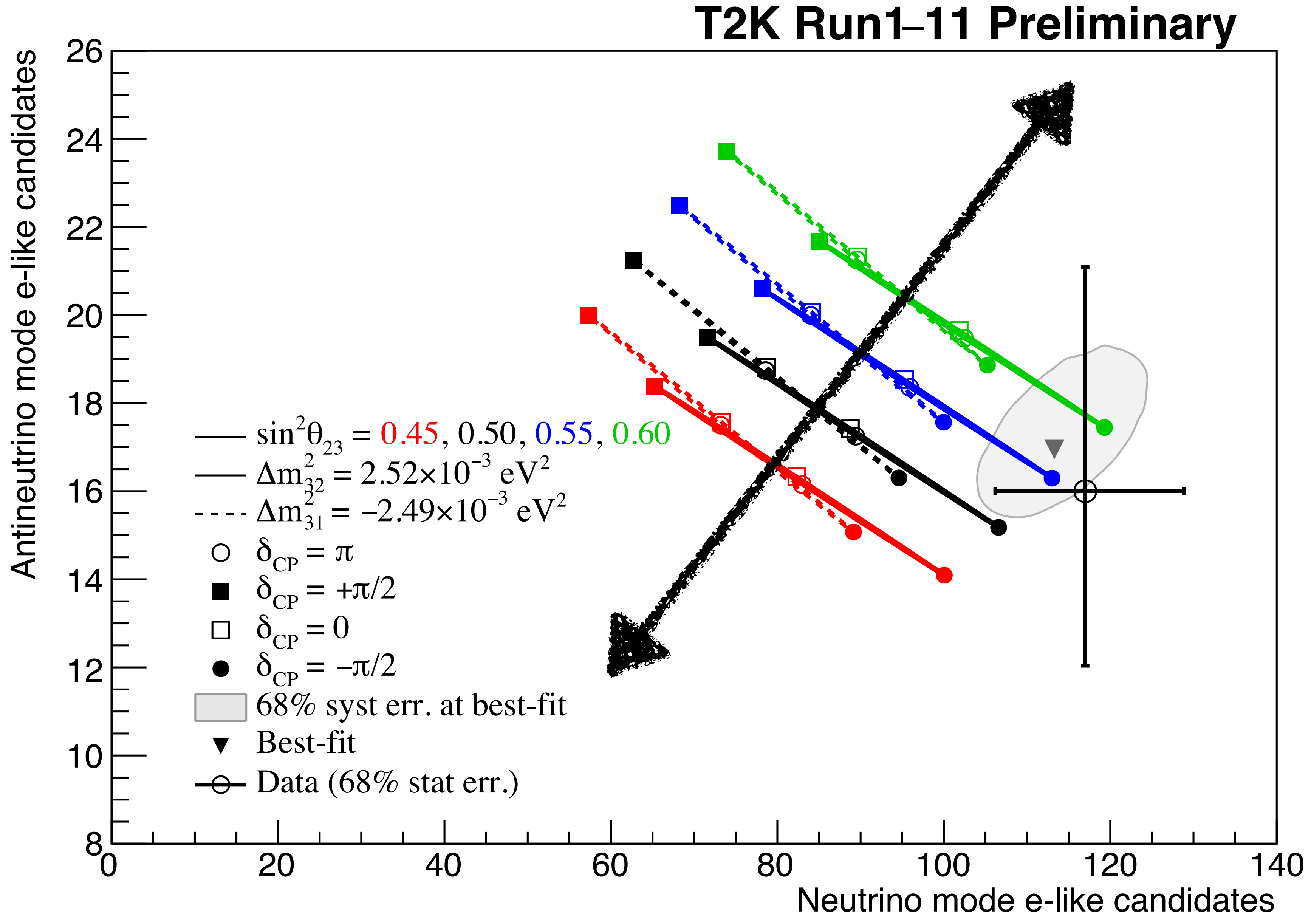
$\nu_e/\overline{\nu}_e$ appearance

Currently mostly a rate measurement

T2K

NOvA

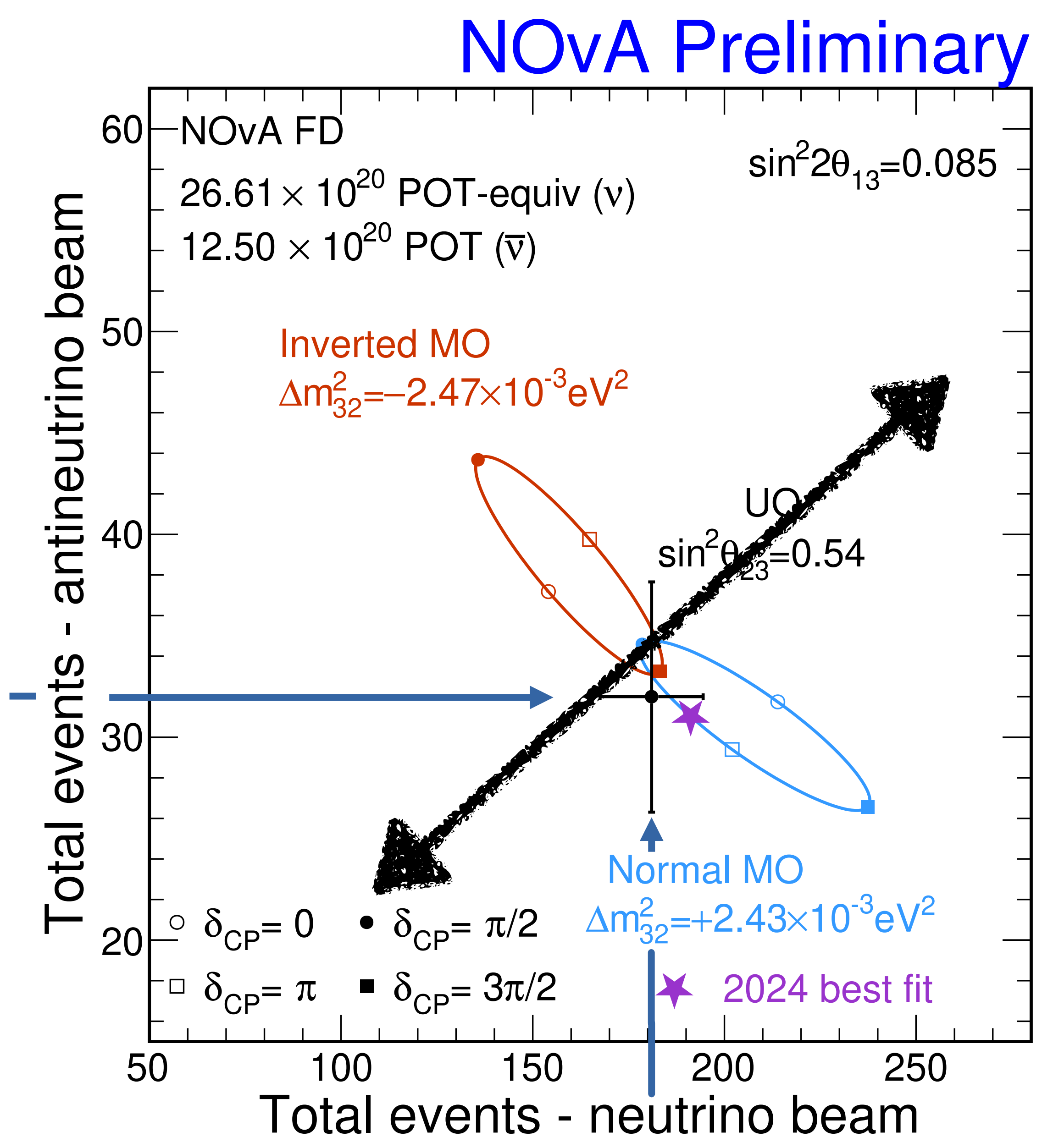
$\#\overline{\nu}_e$



$\#\nu_e$

$\#\overline{\nu}_e$

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



181 ν_e data candidates

$\#\nu_e$

Correlated change

Accelerator only: θ_{13}

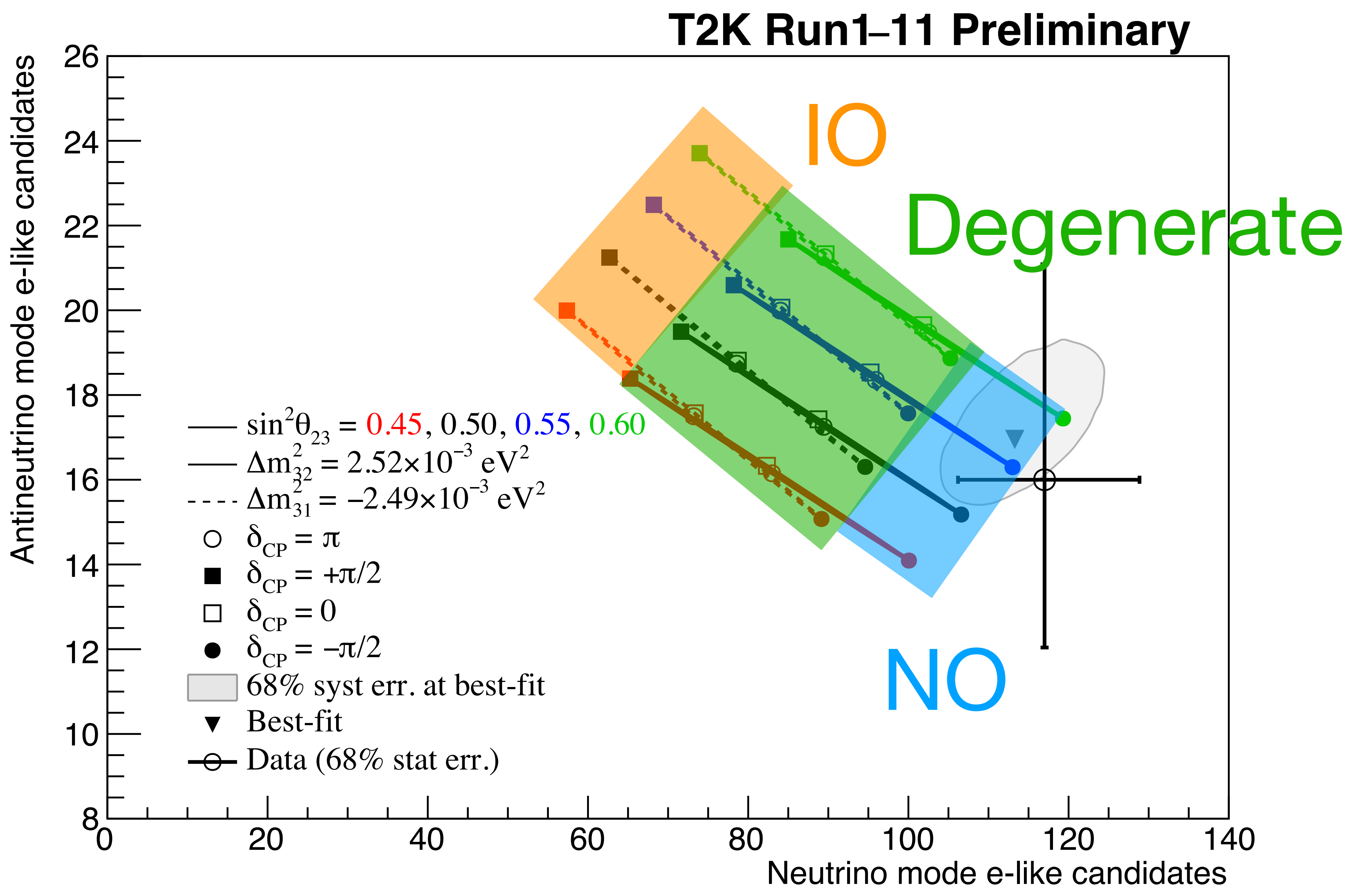
With reactor θ_{13} :

θ_{23} octant, $\cos\delta_{CP}$

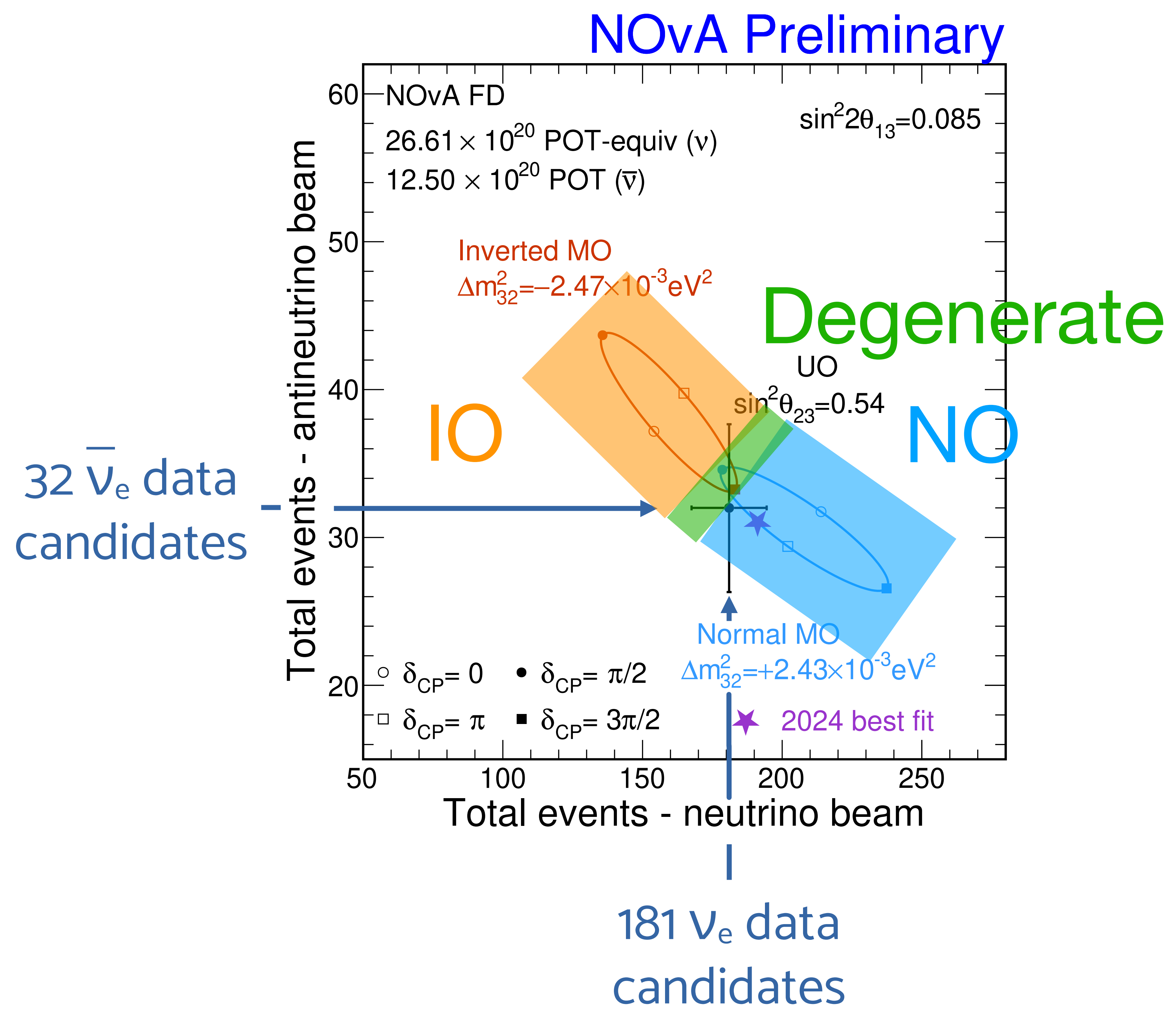
$\nu_e/\bar{\nu}_e$ appearance

Currently mostly a rate measurement

T2K



NOvA



Preference for NO

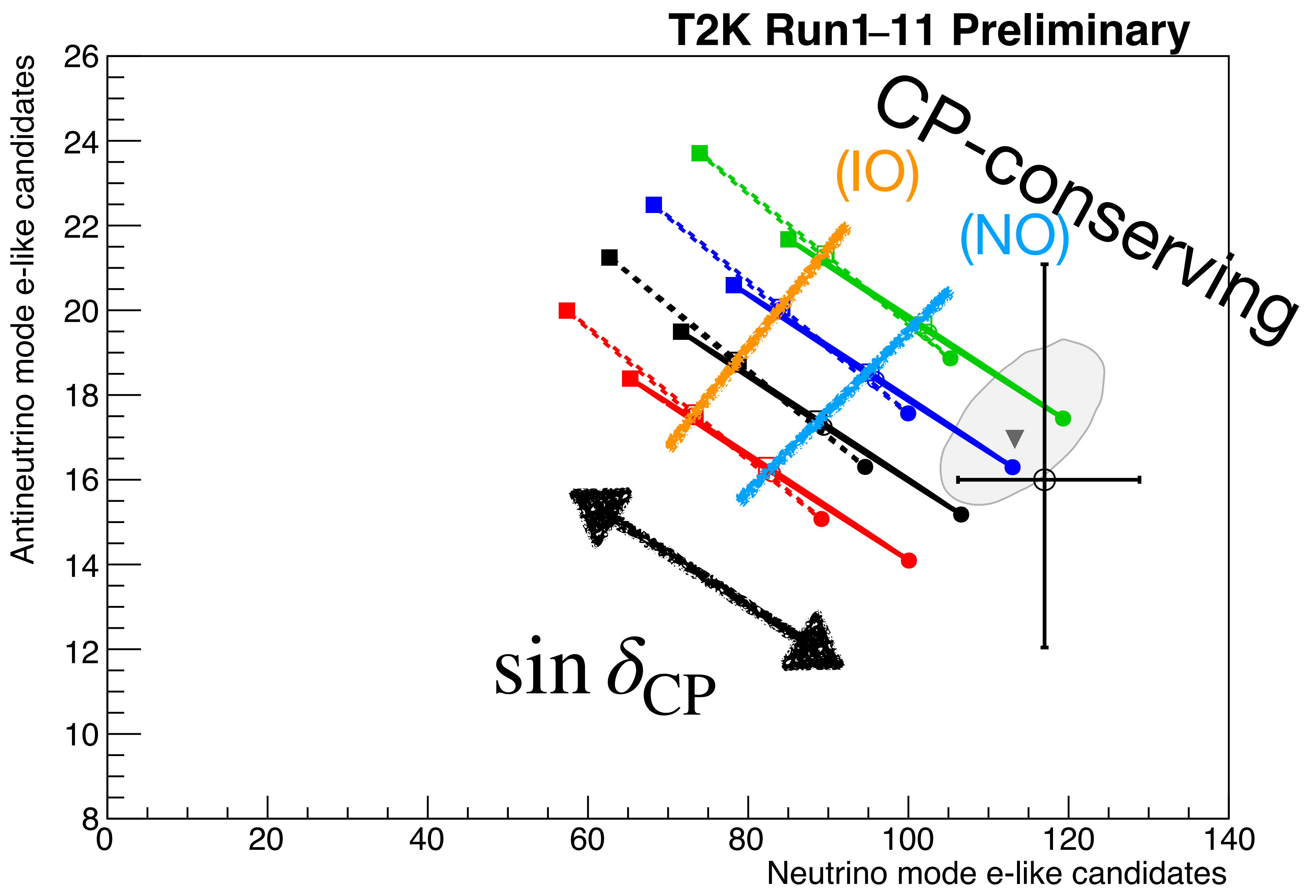
More sensitivity to MO than T2K due to higher energy (longer baseline).

But data prefers MO-degenerate region

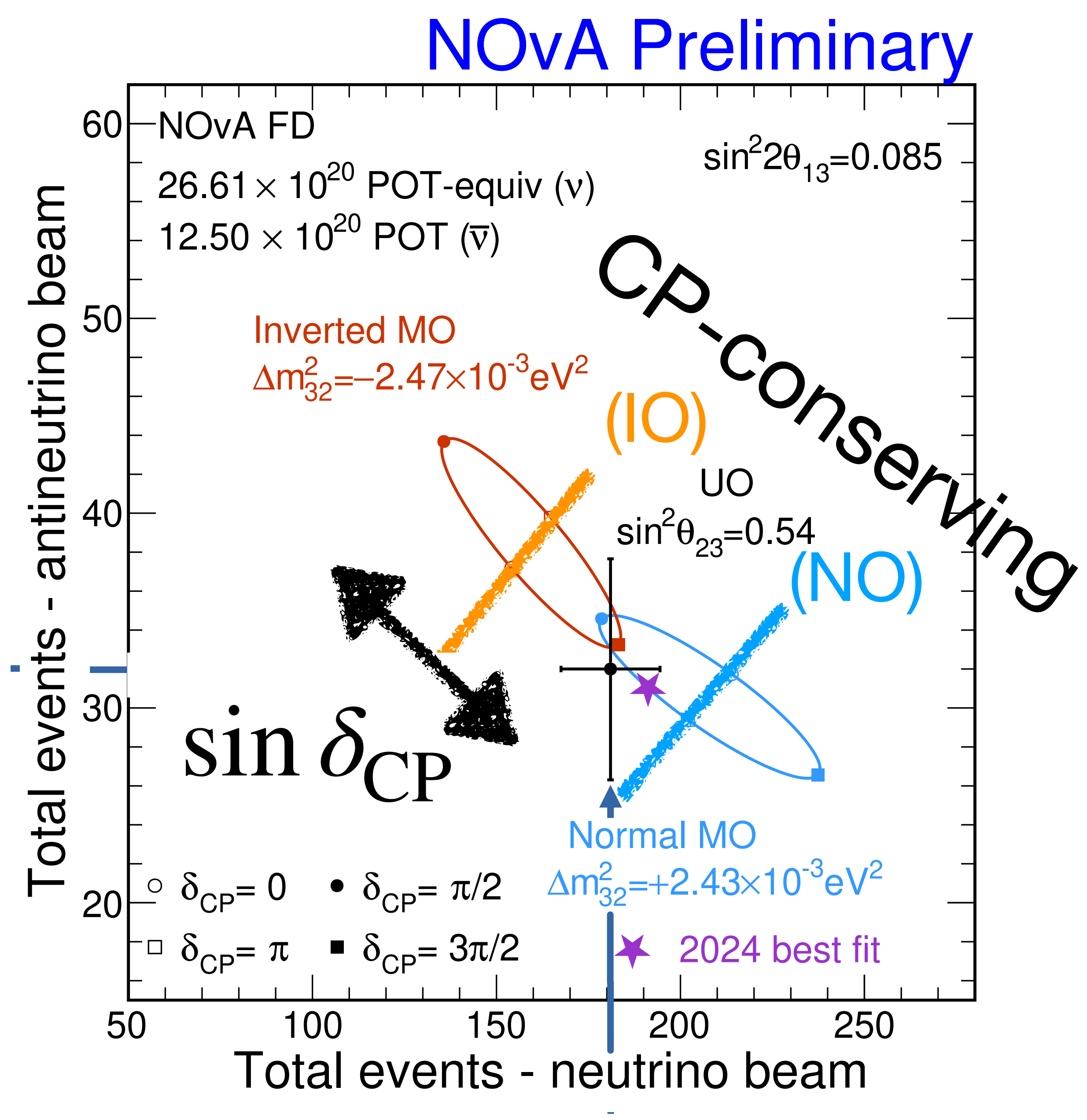
$\nu_e/\bar{\nu}_e$ appearance

Currently mostly a rate measurement

T2K



NOvA



Preference for $\delta_{CP} \approx -\pi/2$

Data outside of MO-degeneracy
= stronger CP constraint

δ_{CP} preference depends on MO

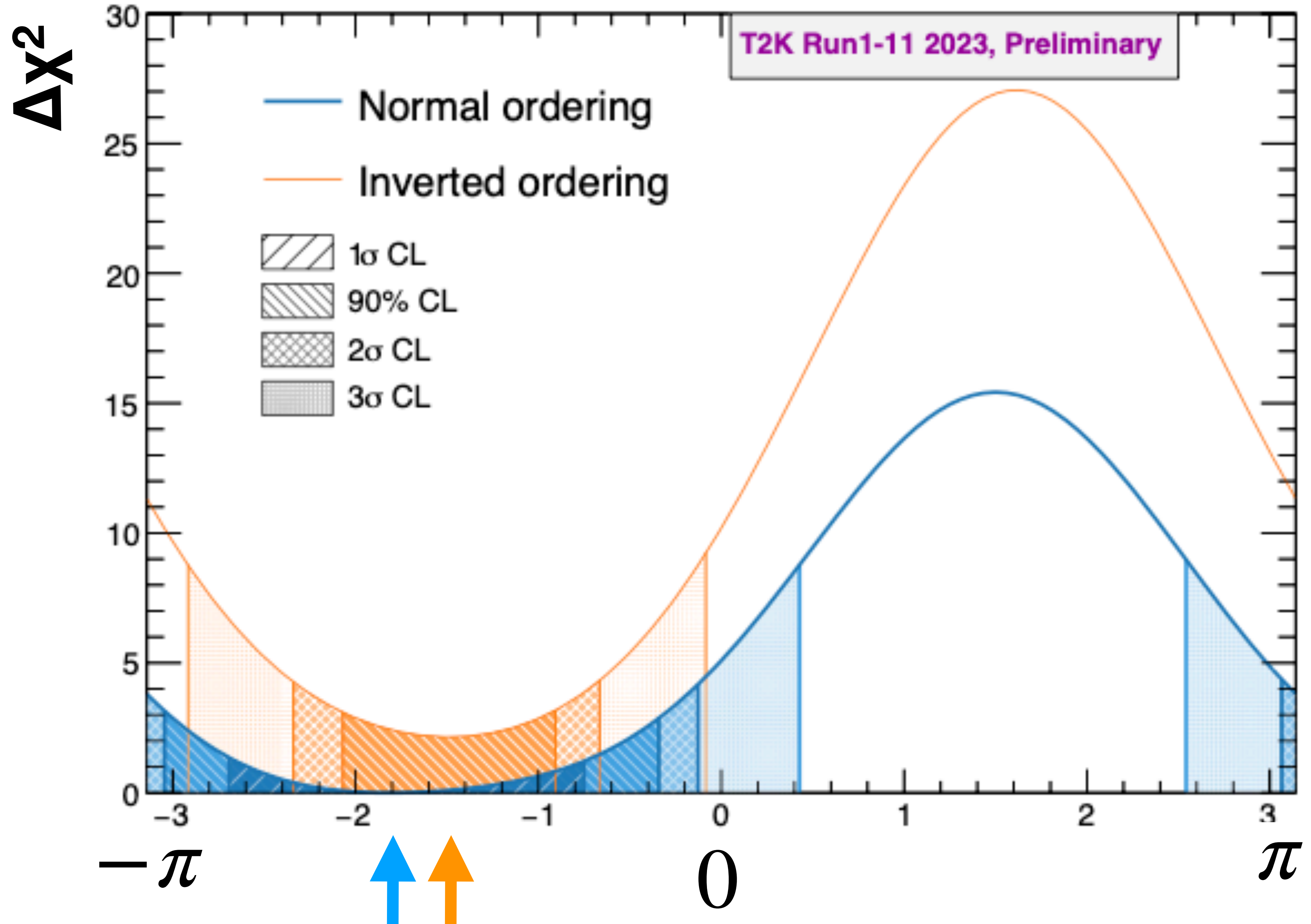
Using reactor θ_{13} constraint
(different values are used)

warn: difference in freq vs. bayesian

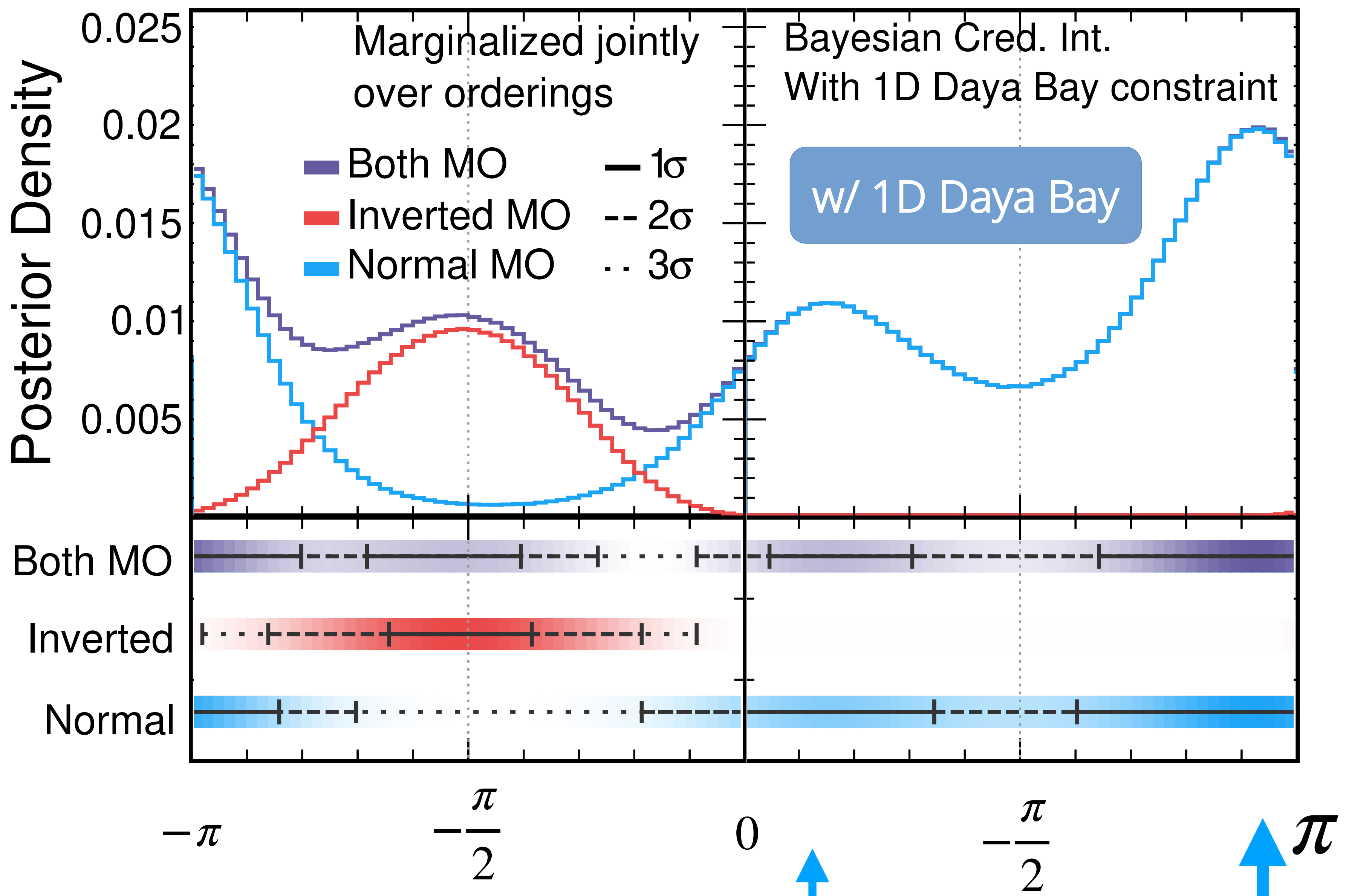
T2K

NOvA

Smaller = more favored



NOvA Preliminary (Neutrino 2024)
note: plot range modified for consistency



Larger = more favored

Preference for CP violation ($\sin\delta_{CP} < 0$)

Mild NO preference* (1.7σ_{freq})

In NO prefer CP-conserving or $\sin\delta_{CP} > 0$

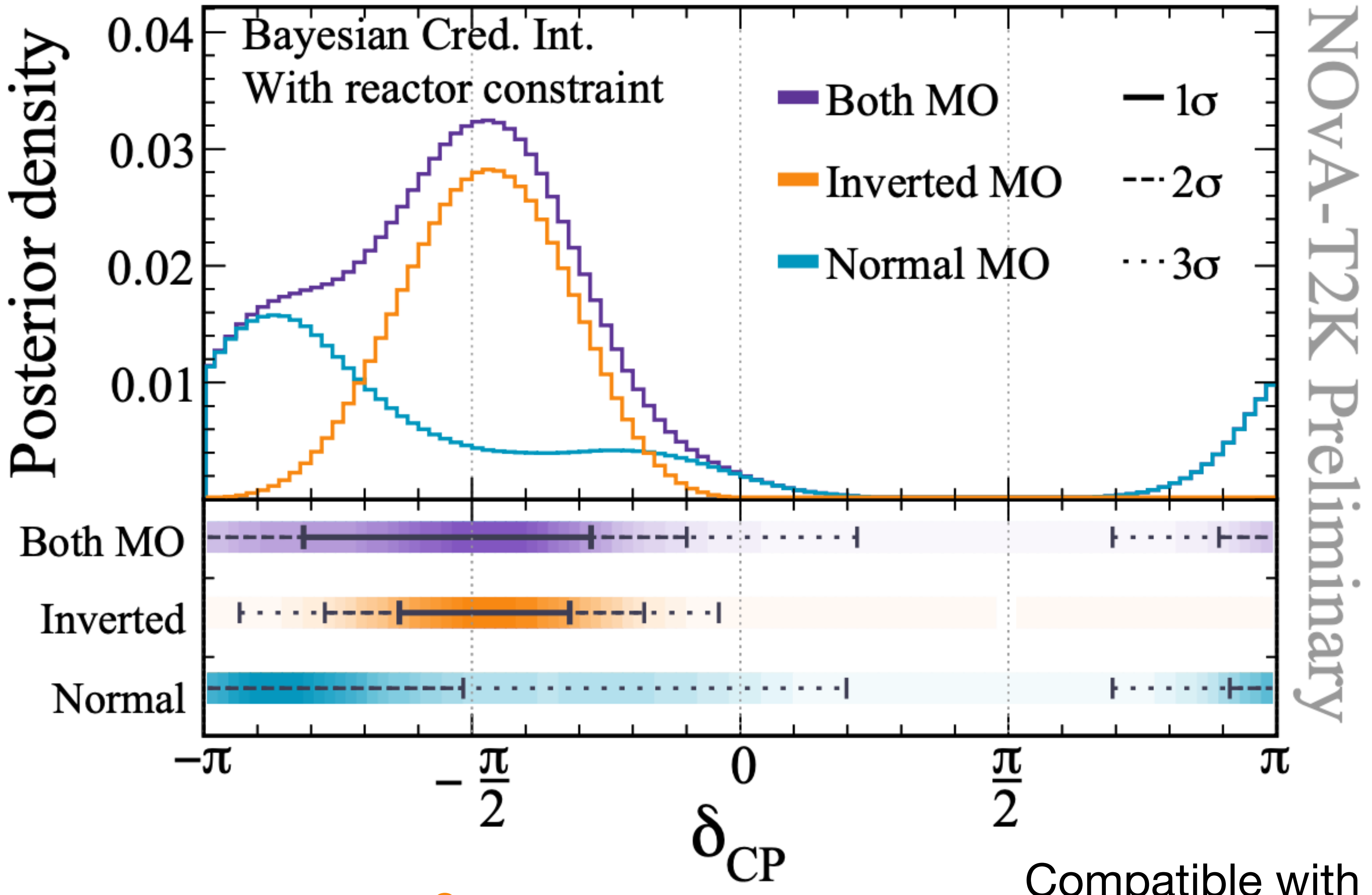
In IO prefer CP-violation ($\sin\delta_{CP} < 0$)

Mild NO preference (1.4σ_{freq})

Neutrino 2024, Preliminary
* Carabadjac Denis, ICHEP 2024, T2K Preliminary

T2K + NOvA

NOvA only: Phys. Rev. D106, 032004 (2022)
T2K only: Eur. Phys. J. C83, 782 (2023)
Input analyses are not latest results, but first shown in 2020



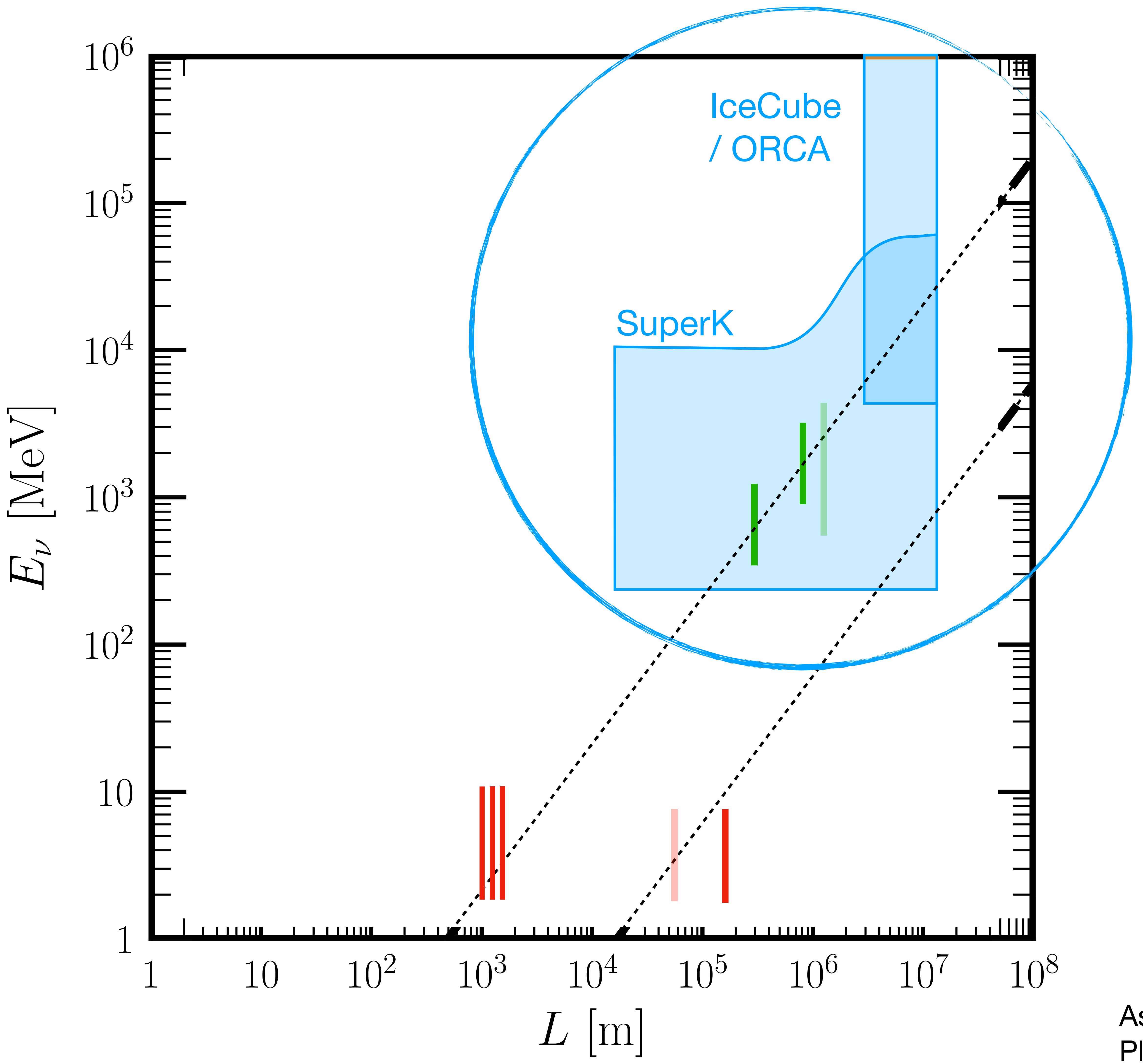
- If IO, CP violated at 3σ
  (Above plot is normalized over both MO, but conclusion also holds when conditioned on IO)
- If NO, consistent with CP conservation

Compatible with both MO, posterior influenced by reactor constraint

NOVA+T2K only : IO (71%)
+ 1D θ_{13} : IO (57%)
+ 2D $\left(\theta_{13}, \Delta m^2_{32}\right)$: NO (59%)

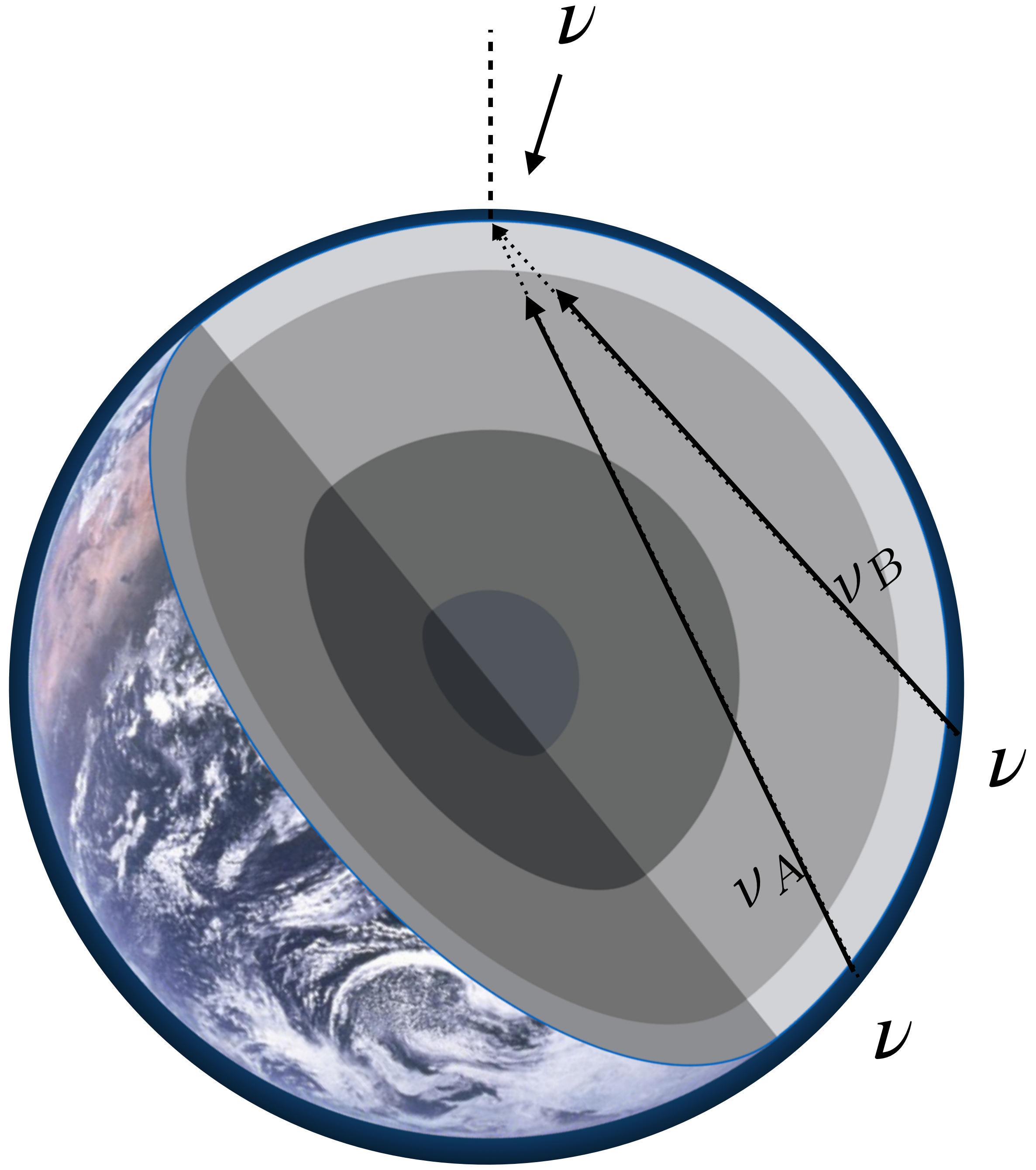
- Different degeneracy of δ_{CP}, MO, and θ_{23} octant → synergy
- A first joint fit was performed using the analyses first shown in 2020
  (publication in preparation)
- Candidate for systematic correlations:
  ν interactions
  - No trivial mapping between parameters
    (except $\nu_e/\overline{\nu}_e$ systematics which were correlated)
  - At current statistics omitting correlations found to not affect result
  - Studied impact of interaction model differences, all tests pass pre-set criteria

Atmospheric experiments



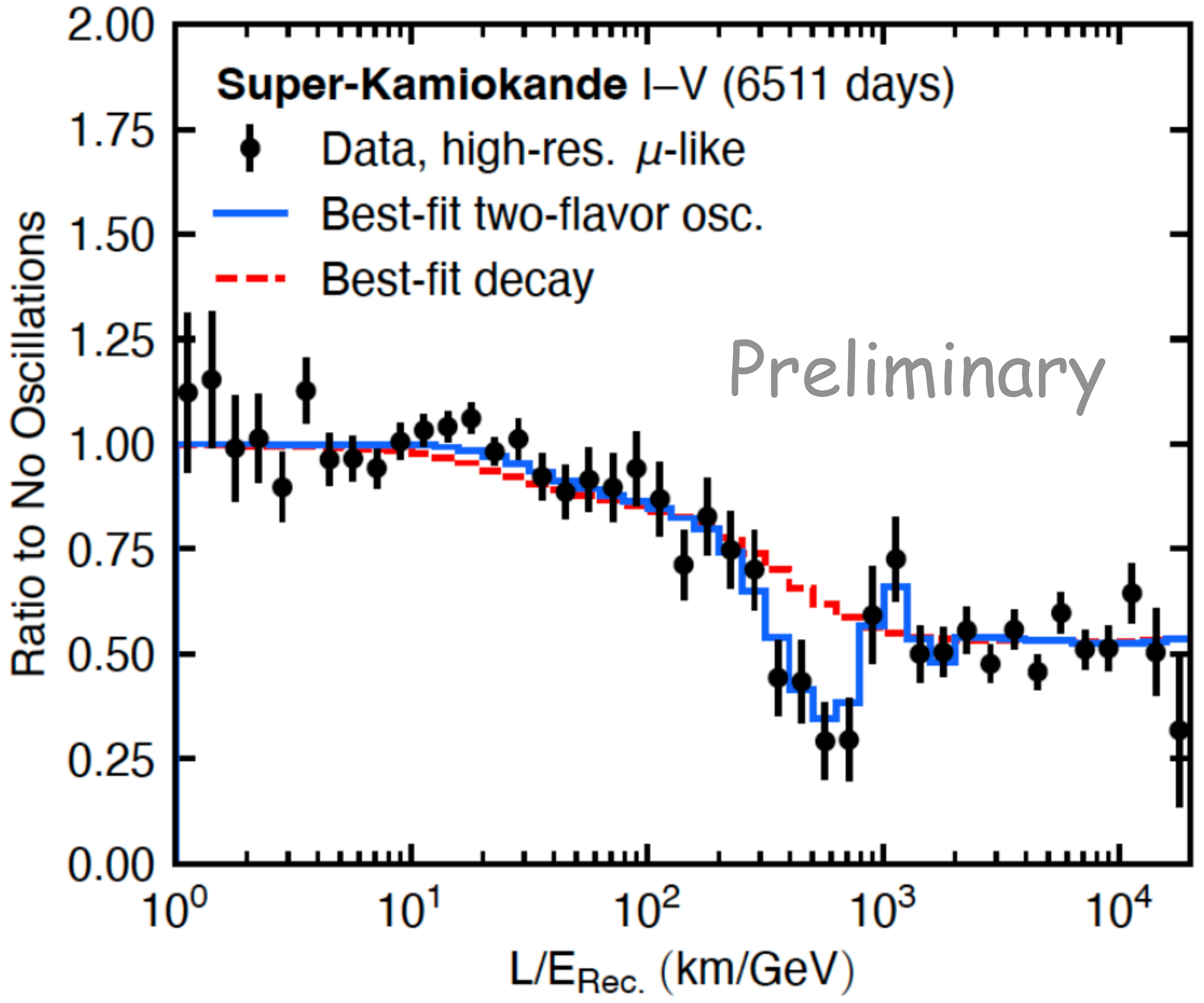
Assuming typical densities for terrestial exp.
Plot inspired by PRD 101, 033008 (2020)

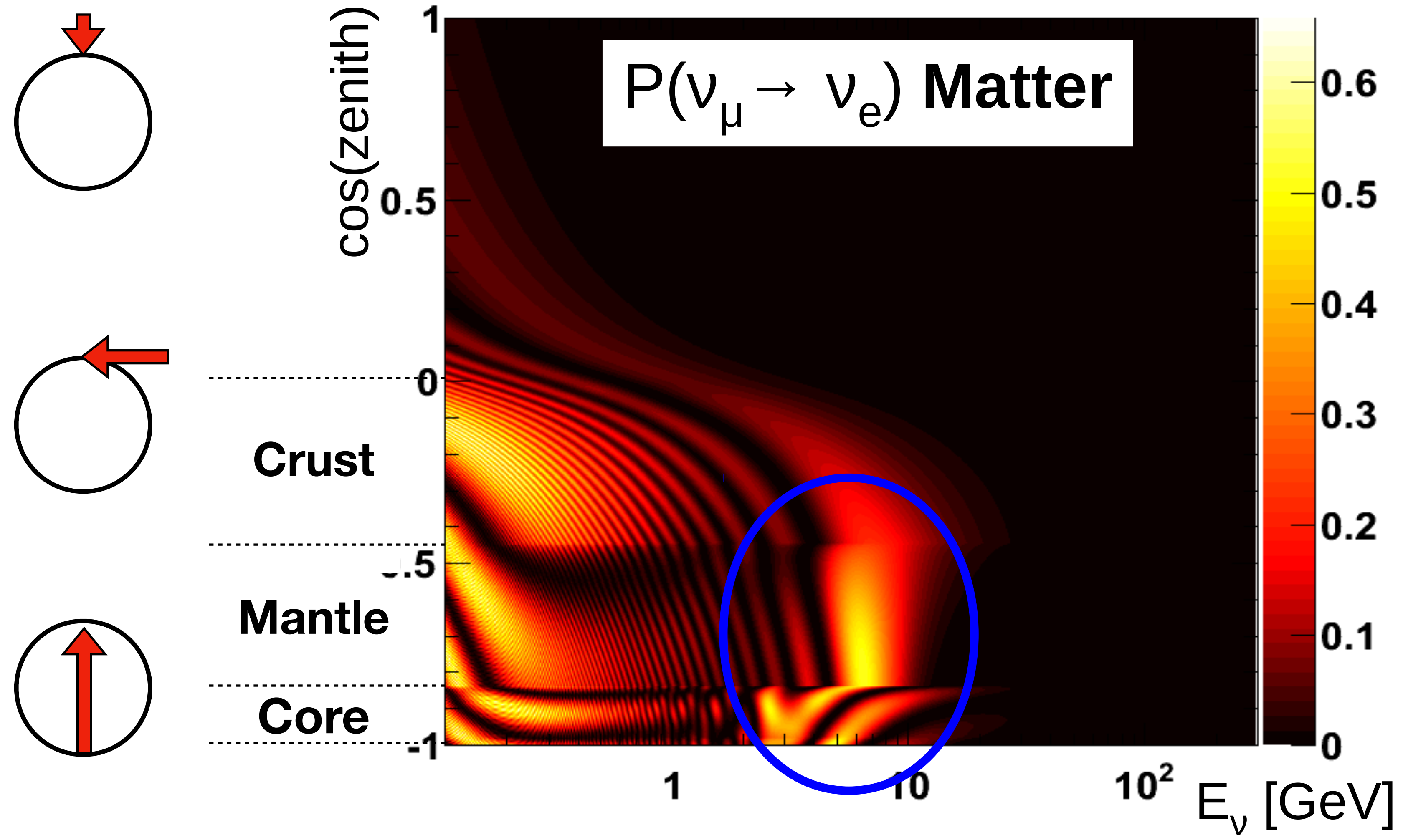
Atmospheric neutrinos



From K. Abe et al. PRD 97, 072001 (2018) + annotations

Signals at multi-GeV





Oscillograms from:
C. Bronner for SK collaboration, at ICTP Advanced Workshop on Physics of Atmospheric Neutrinos 2018

- ν_μ, ν_e produced from $\pi^\pm, \mu^\pm, K$ decay in atmosphere
- Neutrino zenith angle ($\rightarrow L$) inferred from measured charged lepton angle (better for $E_\nu \gg 1\,\mathrm{GeV}$)

- First ν_μ oscillation dip can be resolved at high-E → $|\Delta m^2_{32}|$
- Oscillation at larger L/E is smeared out to a ~0.5 reduction of ν_μ → $\sin^2 2\theta_{23} \approx 1$

- Resonant enhancement of ν_e appearance in mantle/core at few GeV

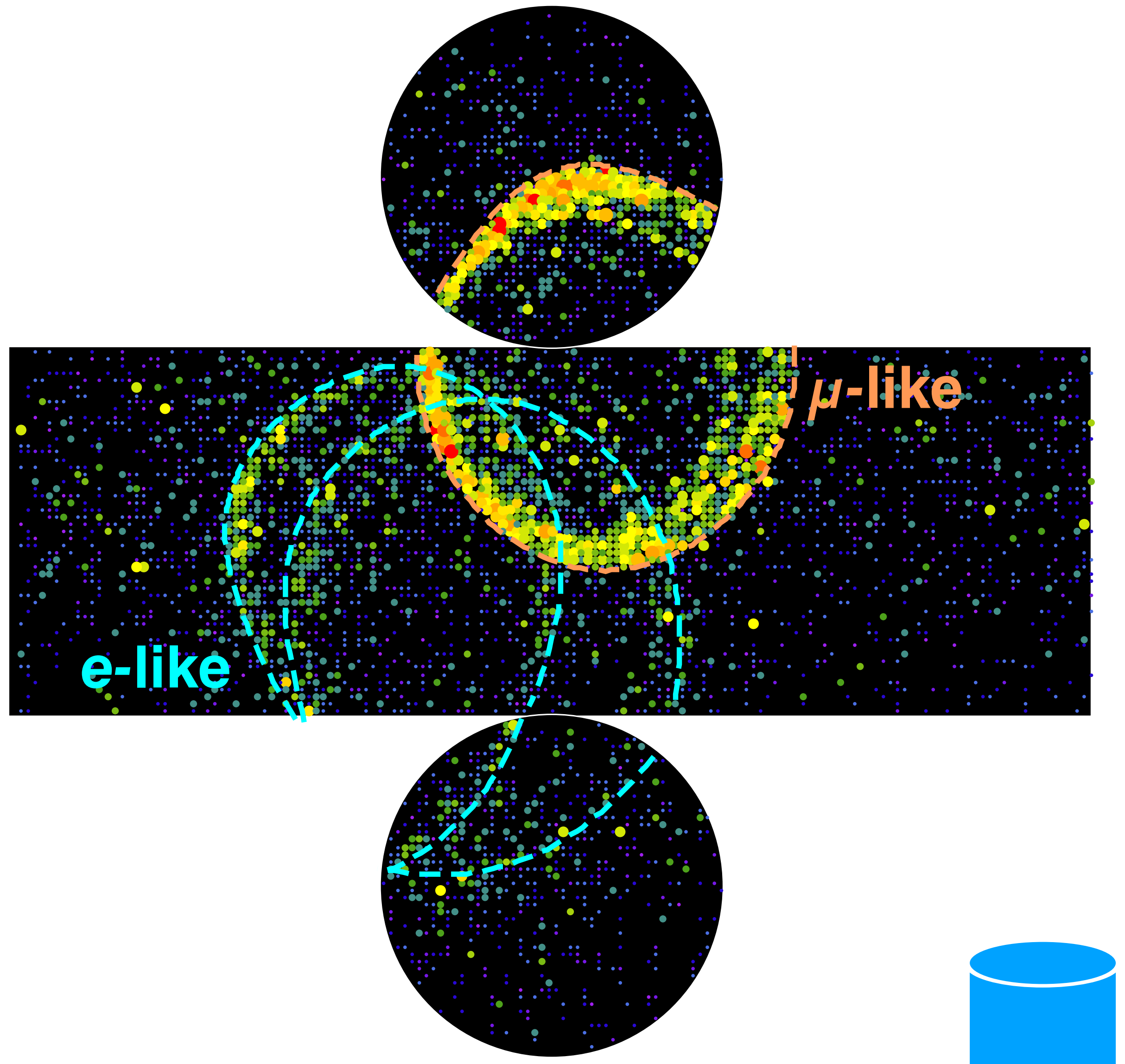
  only for ν in NO
  only for $\bar{\nu}$ in IO → MO

- For flux $\nu \approx \bar{\nu}$, but ν cross-section is ~3x larger → charge ID optional

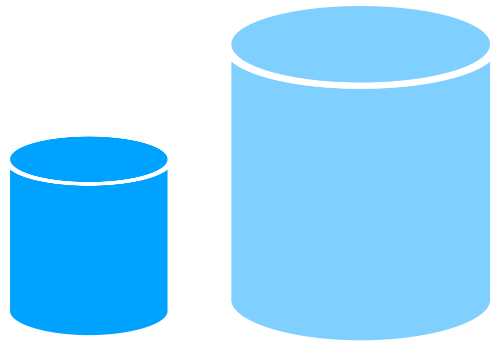
Atmospheric ν detectors

detectors drawn roughly to scale

Surface covering

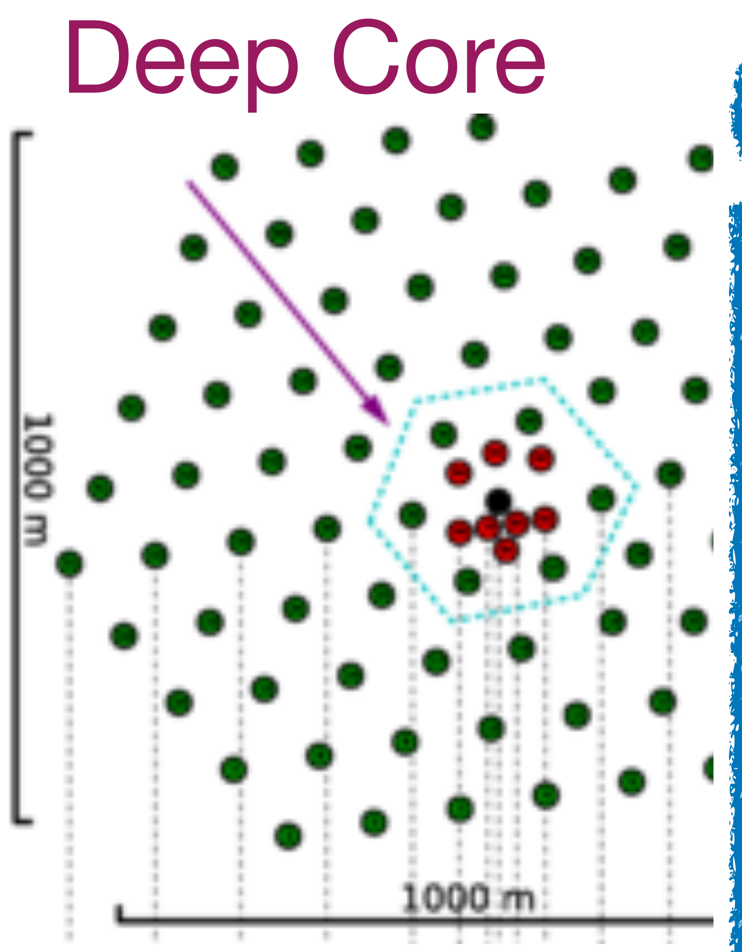


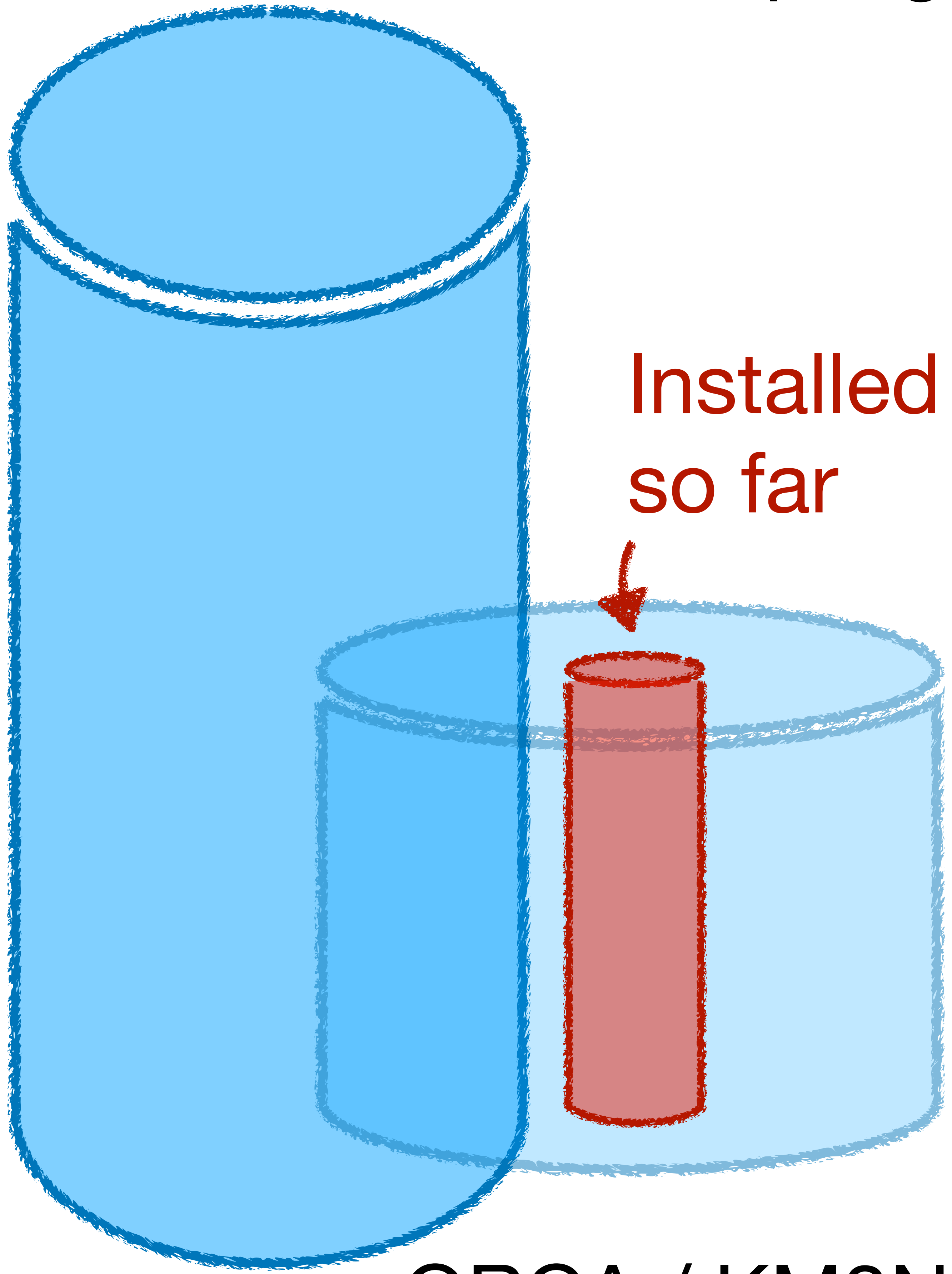
PhysRevD.109.072014



Detailed event reconstruction over wide E_ν down to sub-GeV

3D sampling



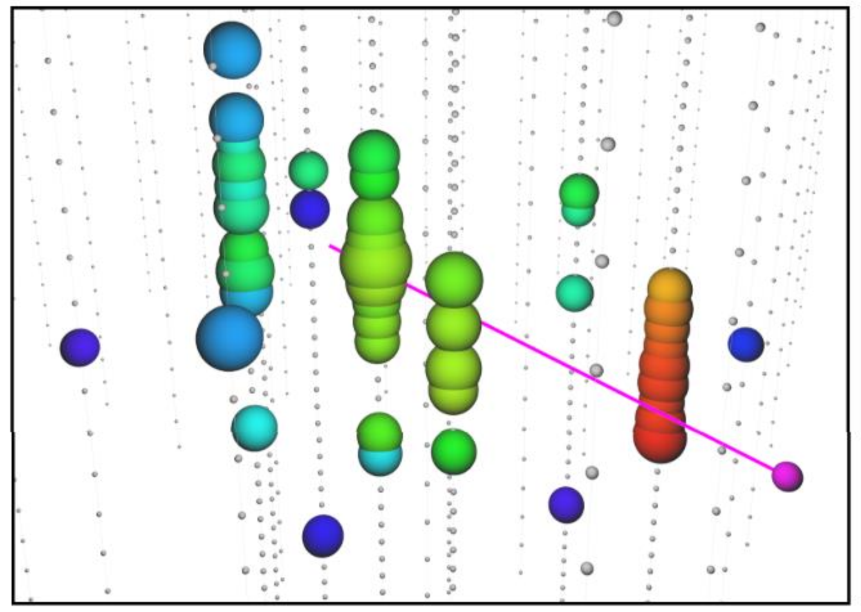


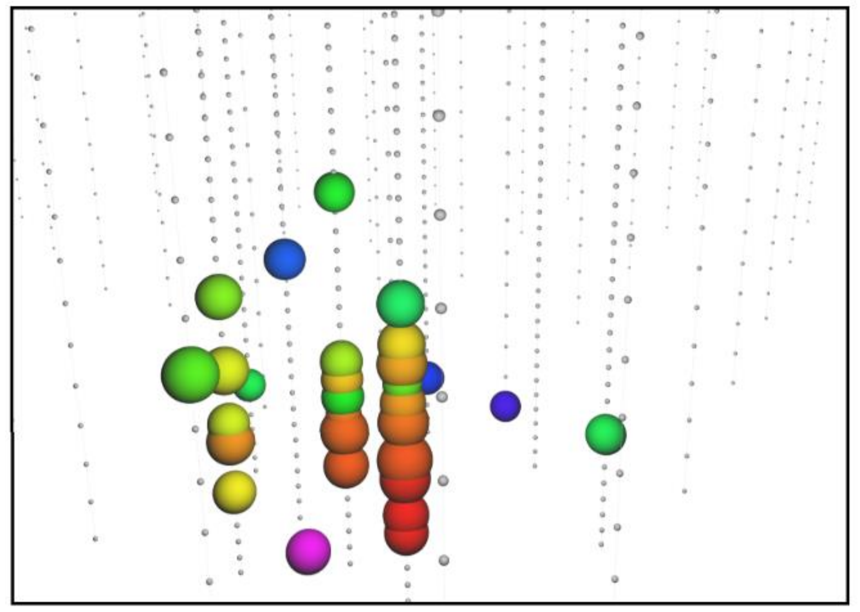
IceCube (South Pole)

DeepCore 10 Mton

ORCA / KM3Net (Mediterranean Sea) 7 Mt

Track-like (ν_μ)

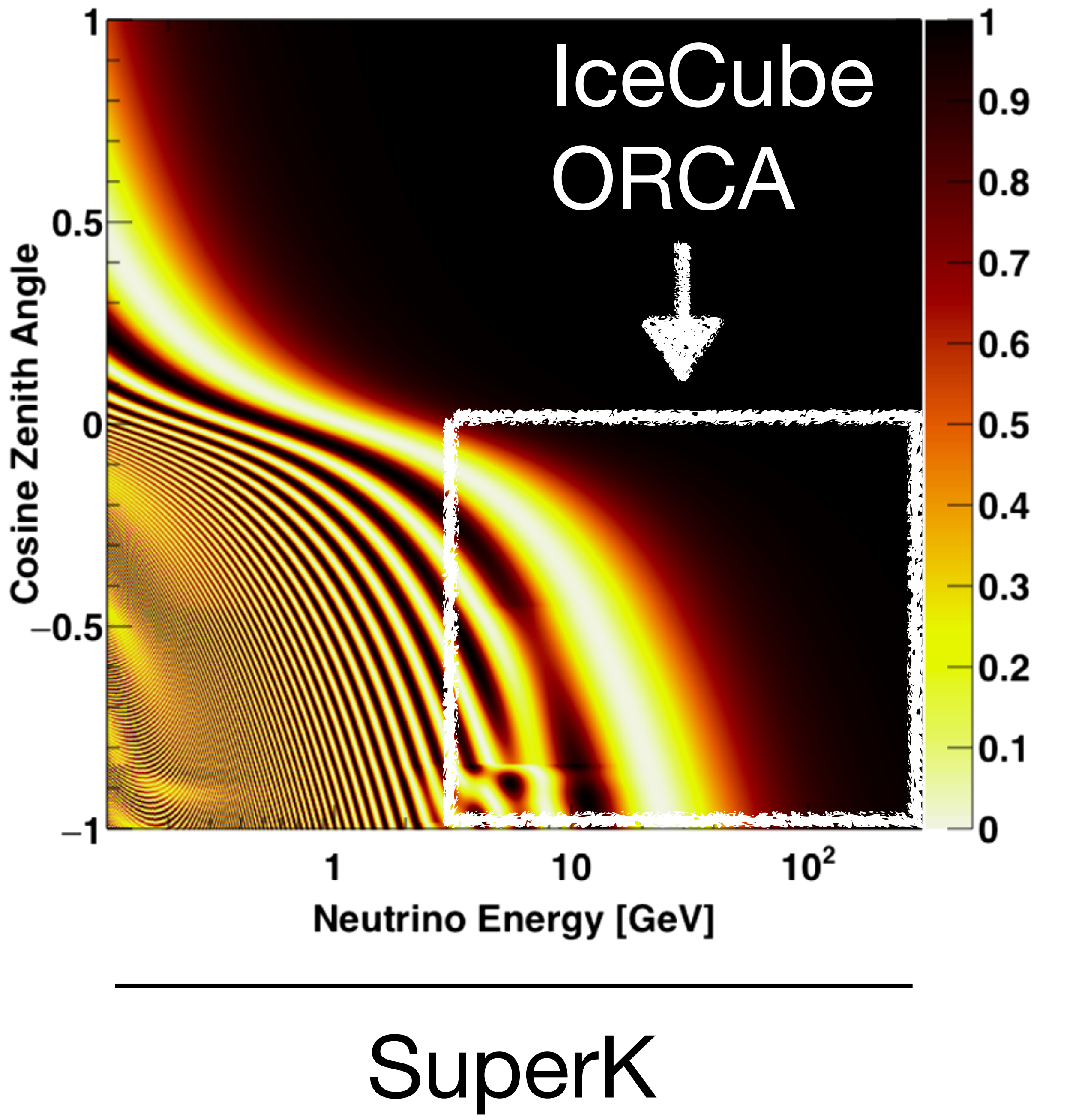


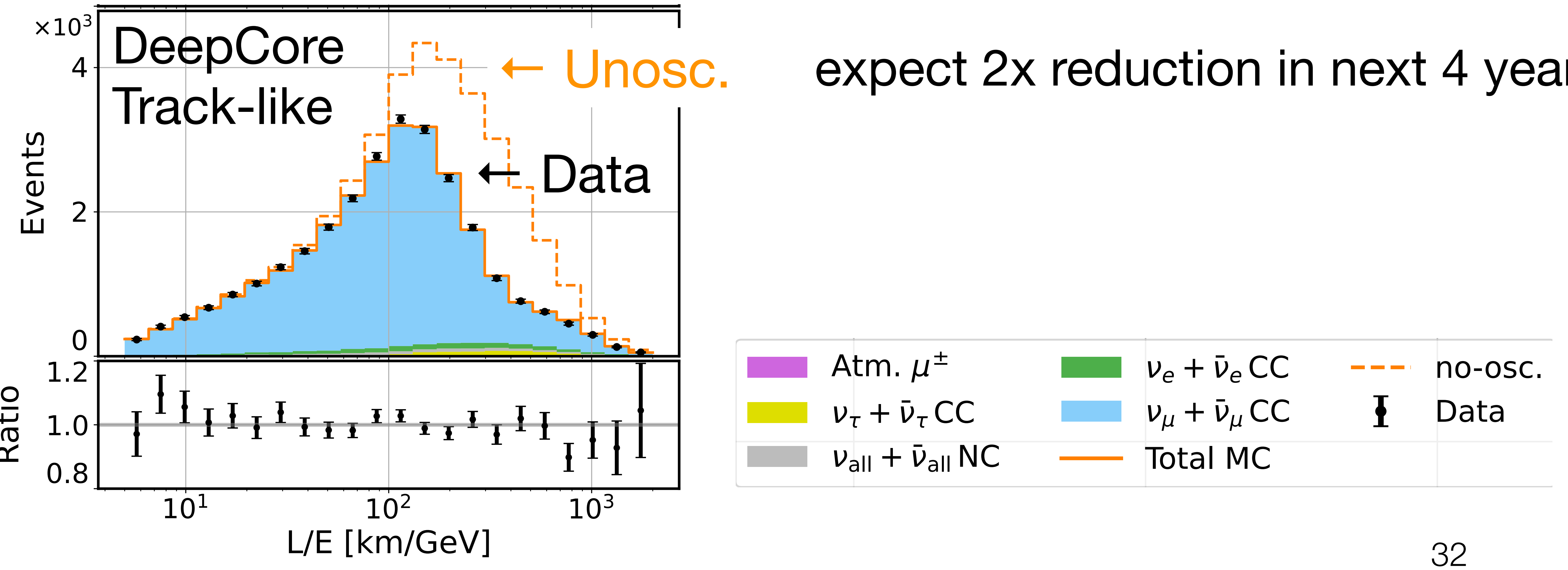


Shower-like (ν_e, NC, …)

Ice Cube, Neutrino 2024

ν_μ disappearance



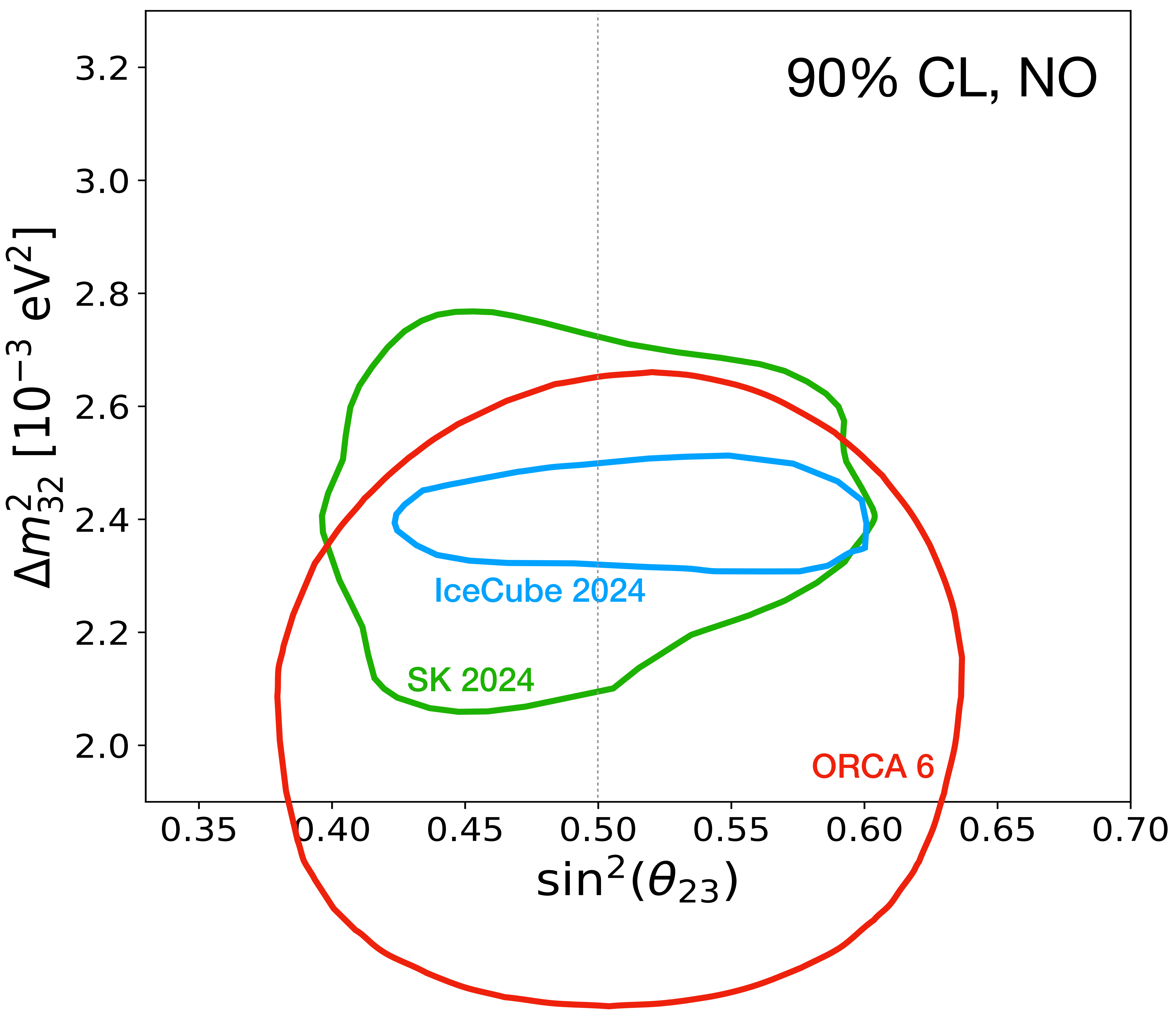


- **SuperK:** 20% expansion of fiducial volume + additional years.
  `PRD 109, 072014 (2024)`

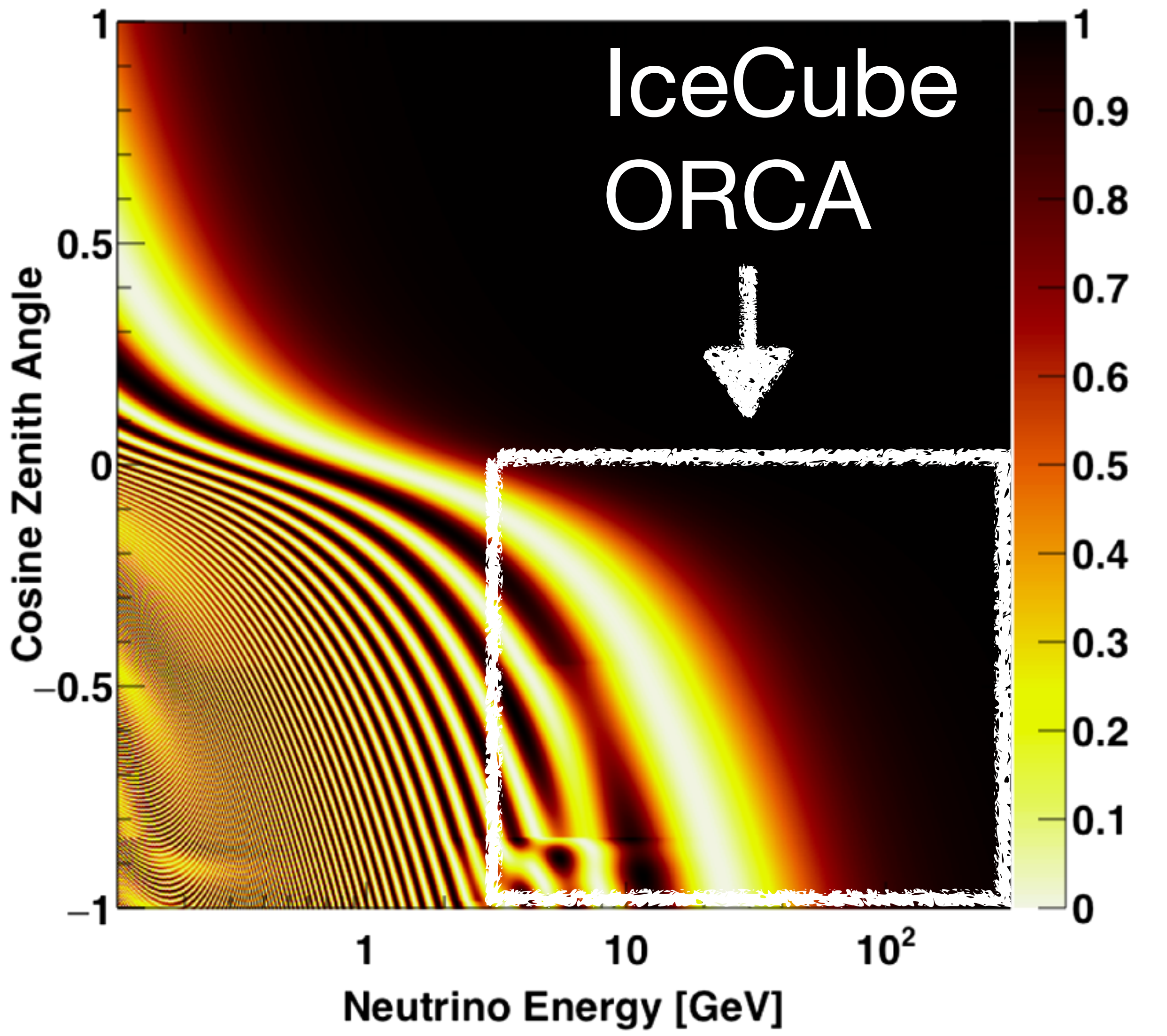
  In total 48% statistics increase over previous publication

- **DeepCore** moved to CNN-based reconstruction + 2 years
  ↓
  7x increase in statistics
  `arXiv:2405.02163`

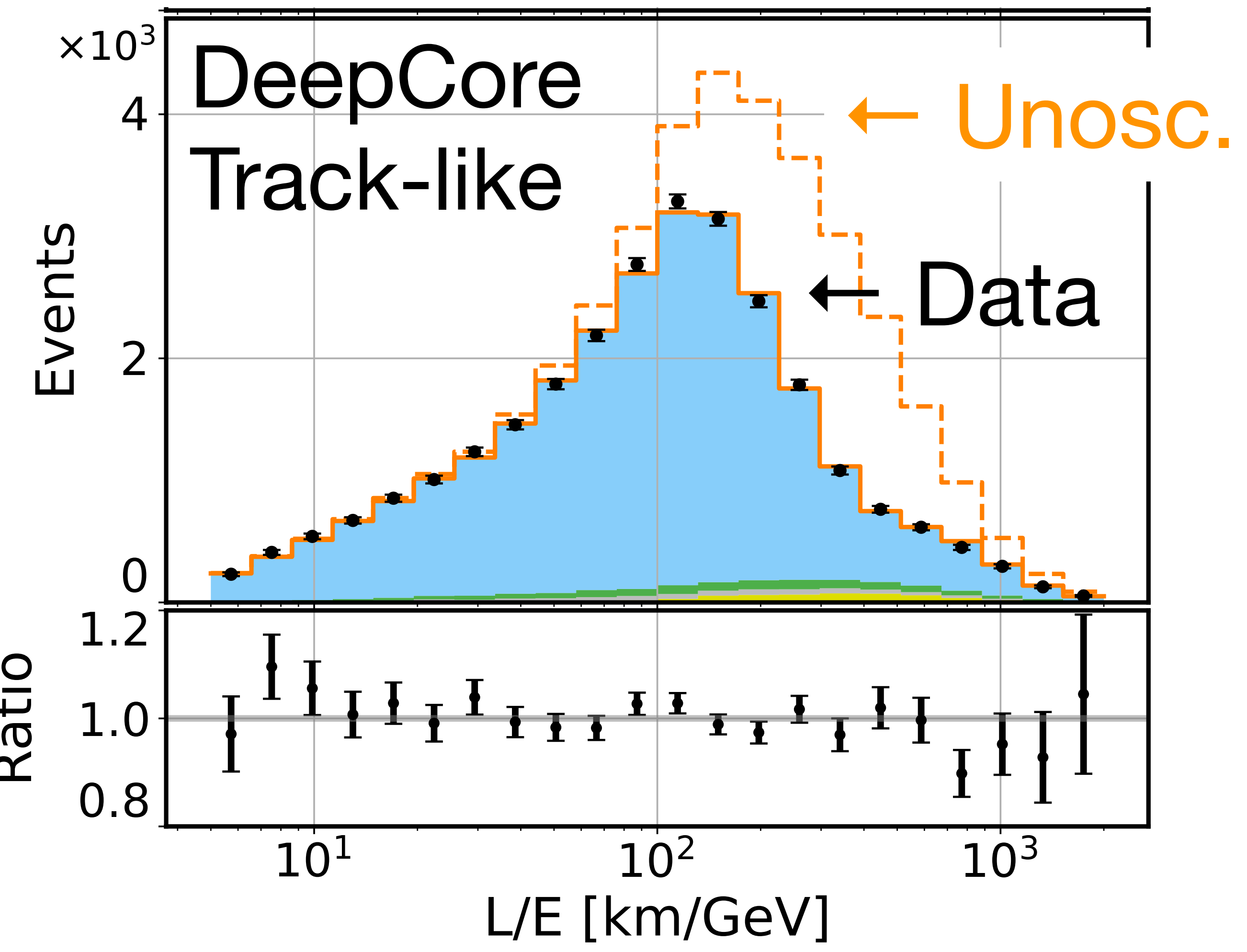
  expect 2x reduction in next 4 years



ν_μ disappearance



SuperK



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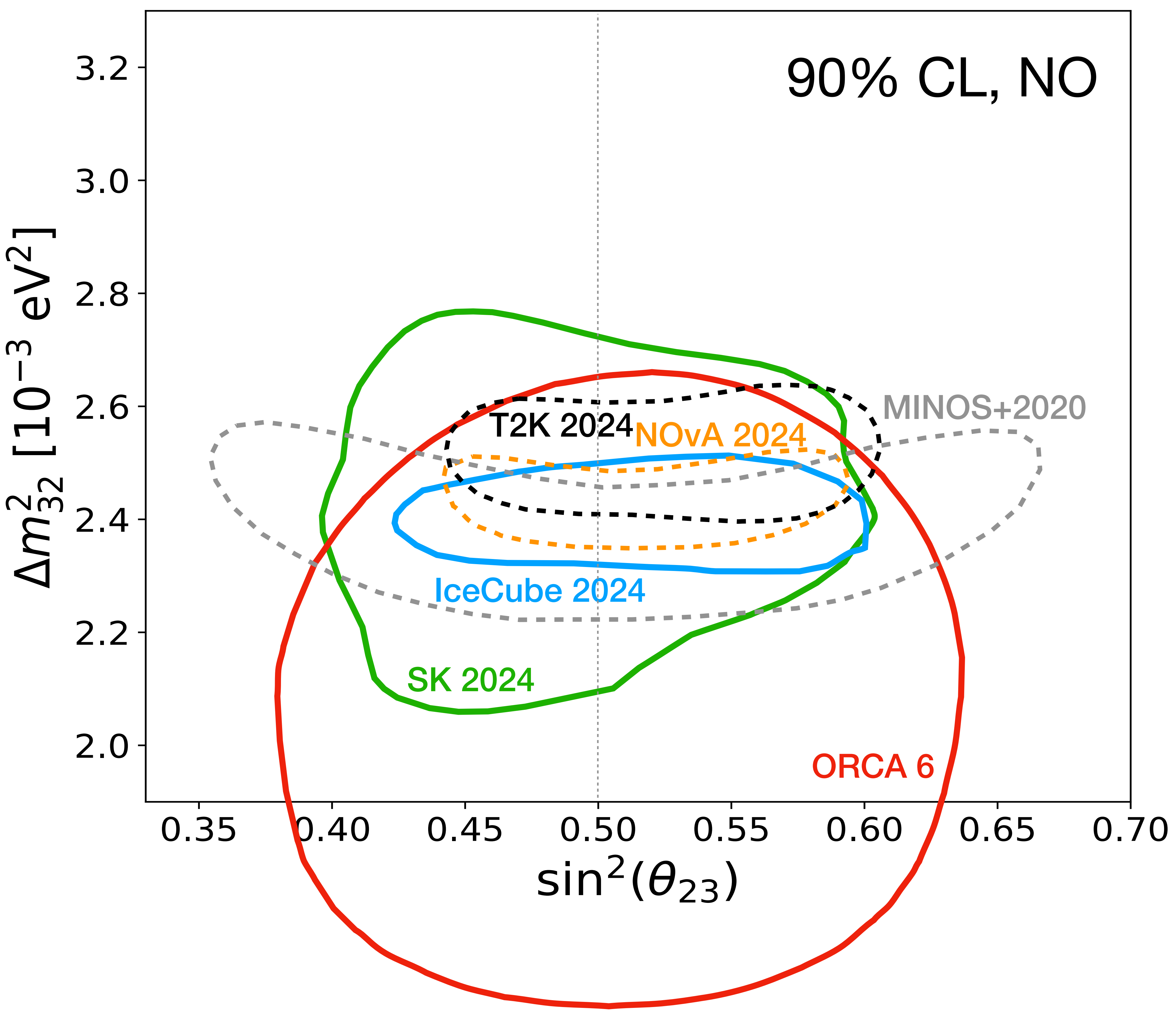
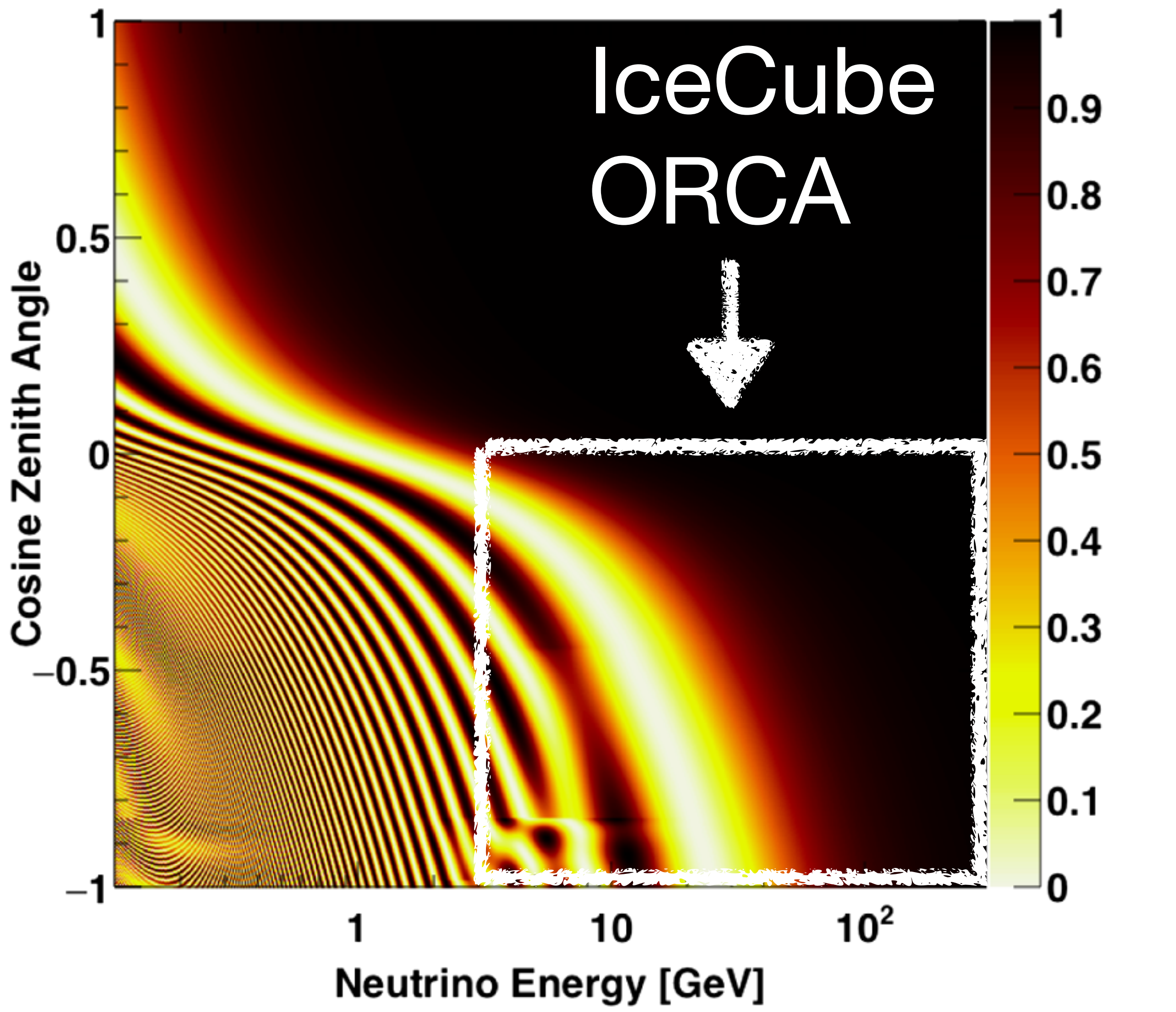


Consistent results, and now competitive (IC) with accelerator measurements

note: 20~50x longer baselines and energies

ν_μ disappearance



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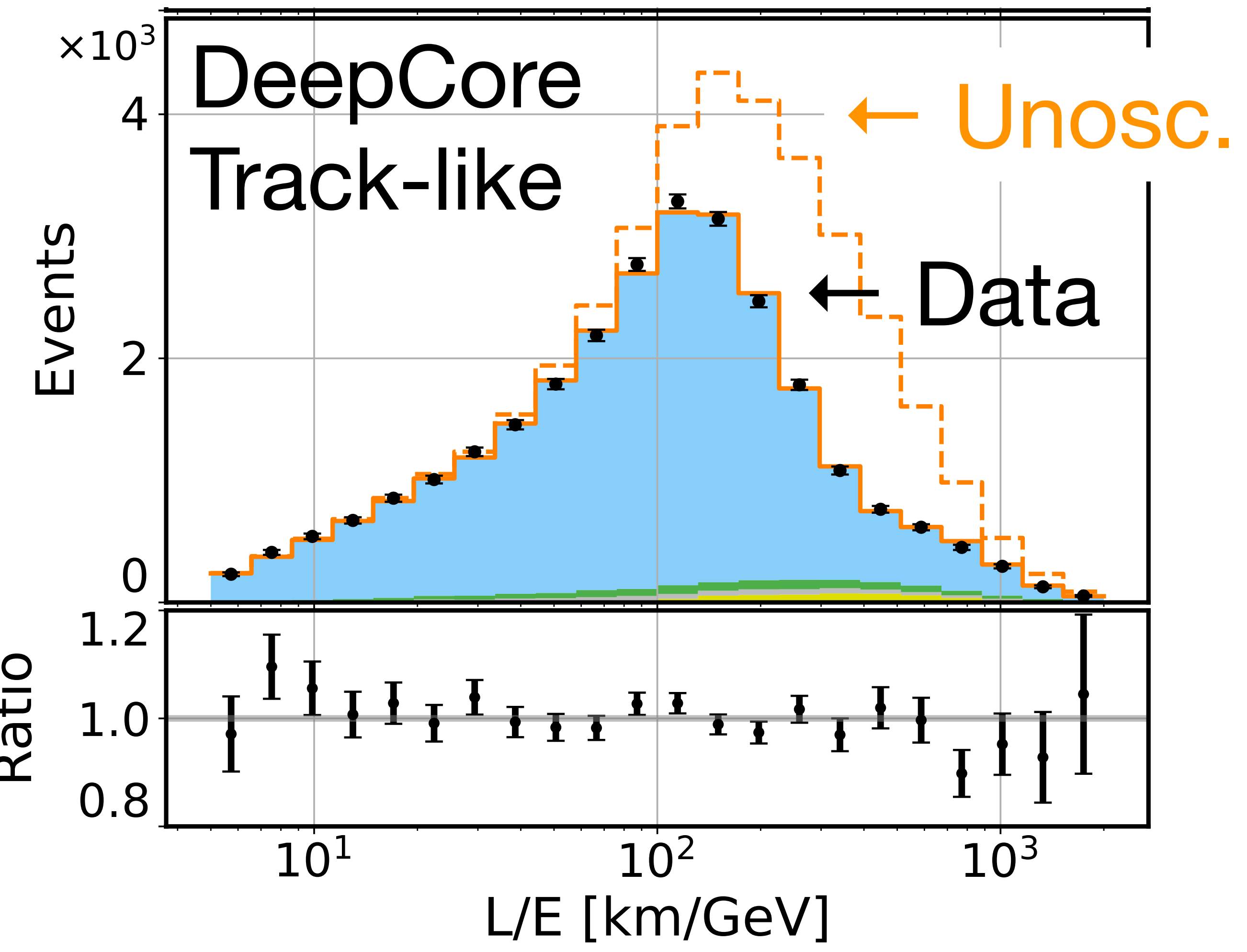

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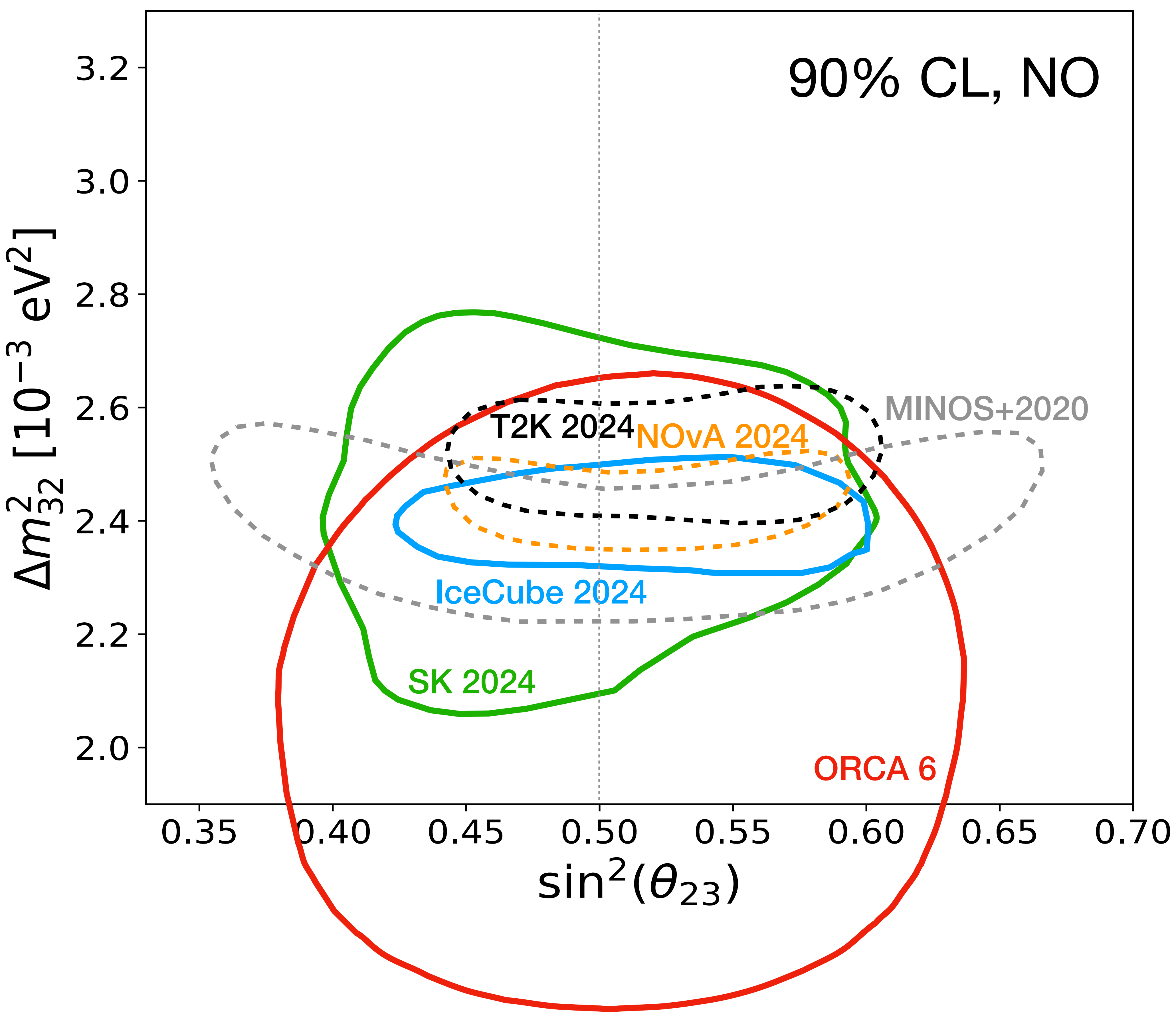
- **ORCA** first result using ~5% of final detector size. Expect improvement in statistics and systematics as more strings get installed.

  `JHEP 10 (2024) 206`



Consistent results, and now competitive (IC) with accelerator measurements

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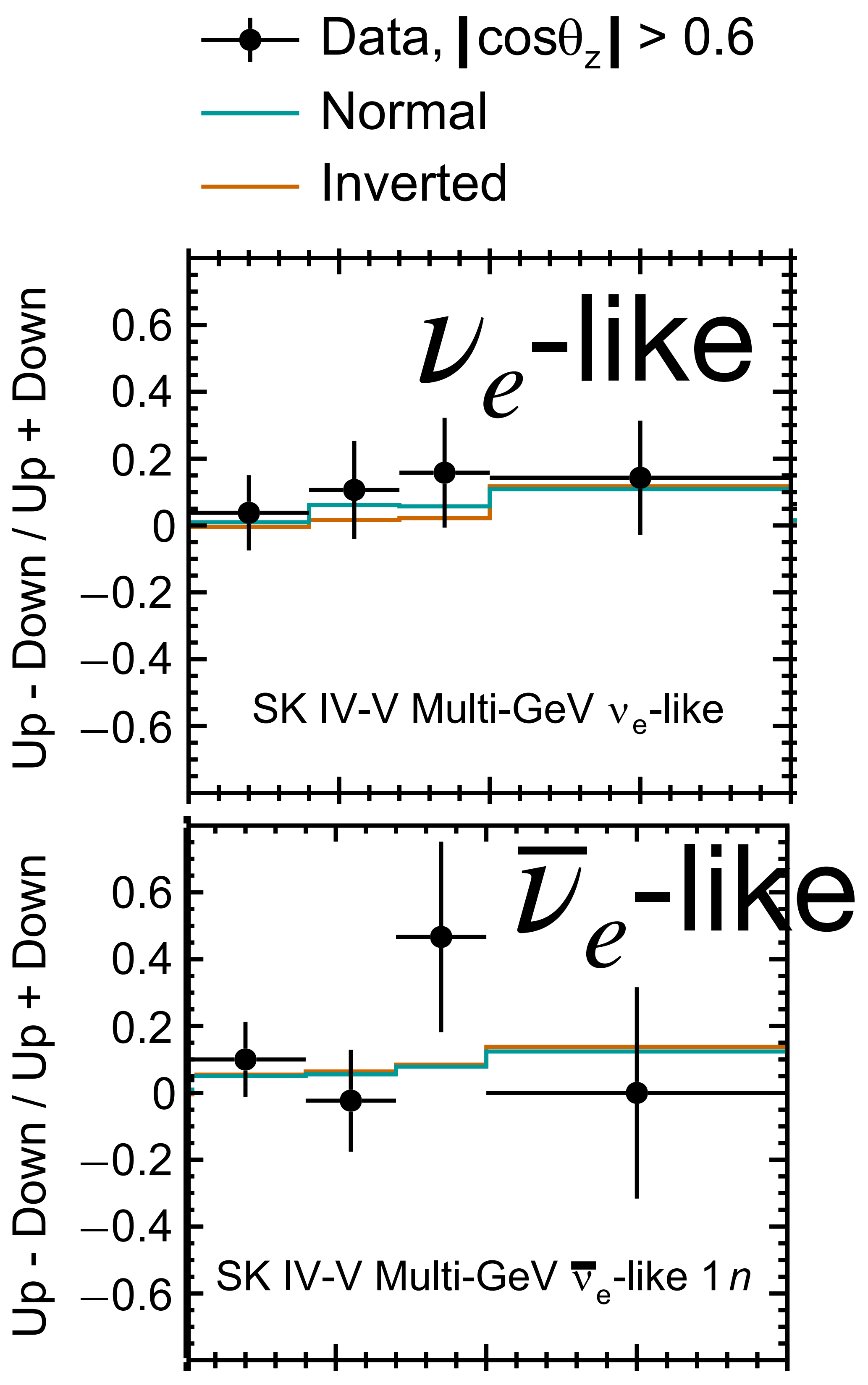
Mass ordering

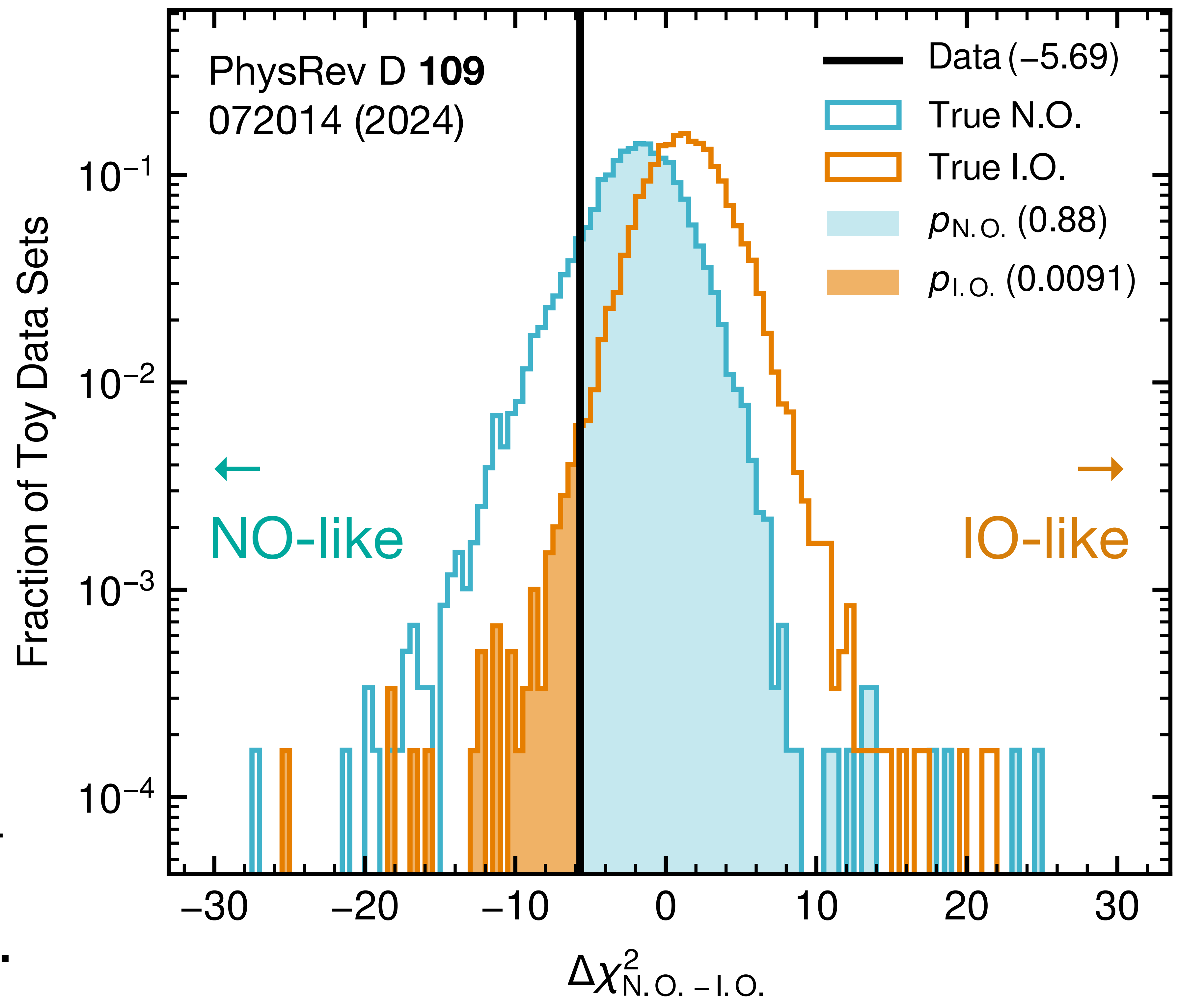
From matter resonance



(subset of sensitive samples shown)

- SK performs statistical $\nu/\bar{\nu}$ separation using # of π etc. to enhance purity
- Updates to selection
  Multi-Ring: likelihood → BDT
  Single-Ring: + neutron tag

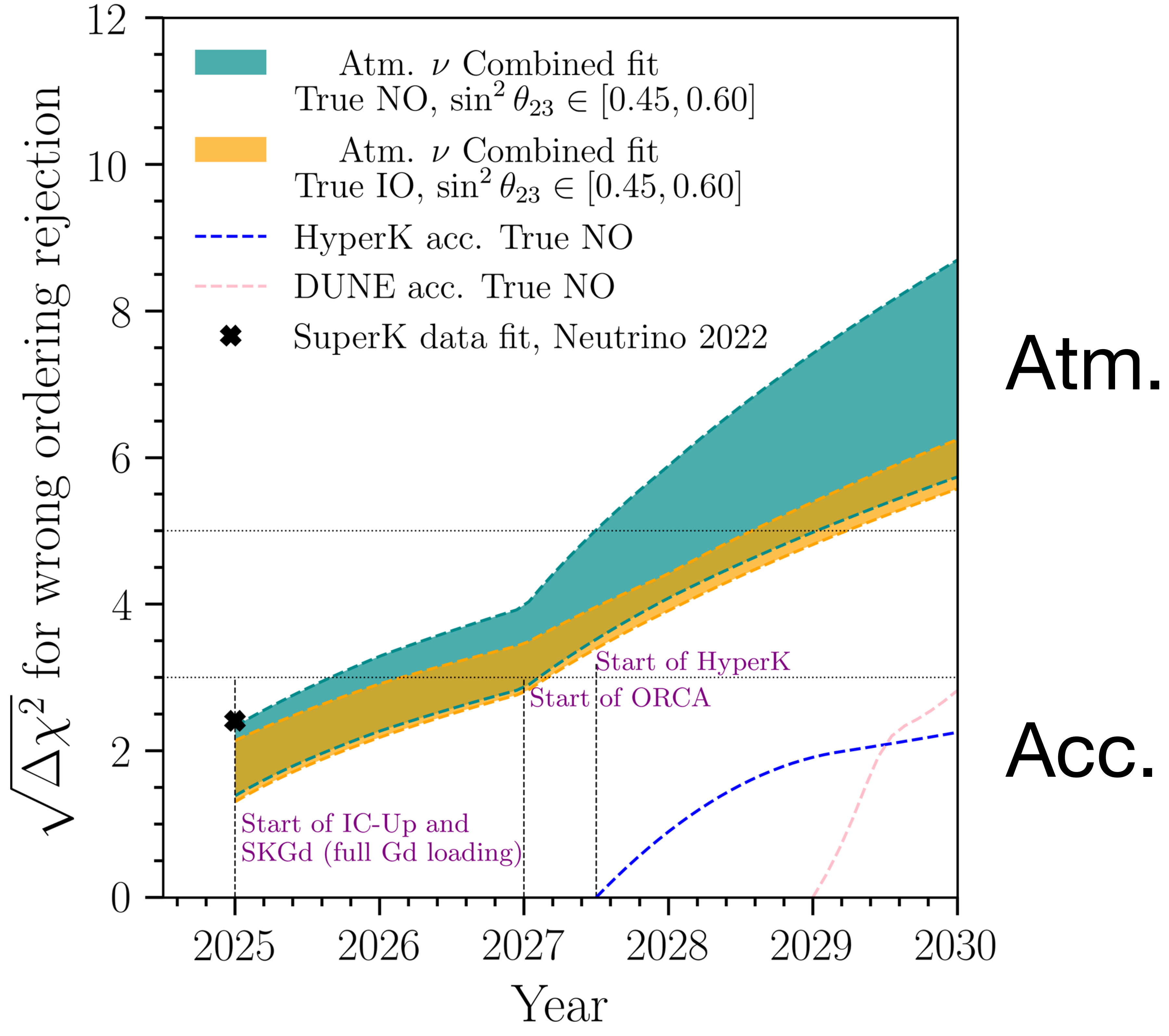
SK, 484 kt years



Indication of NO.
Rejection of IO at 92.3% CLs.

Dominated by stats, then xsec

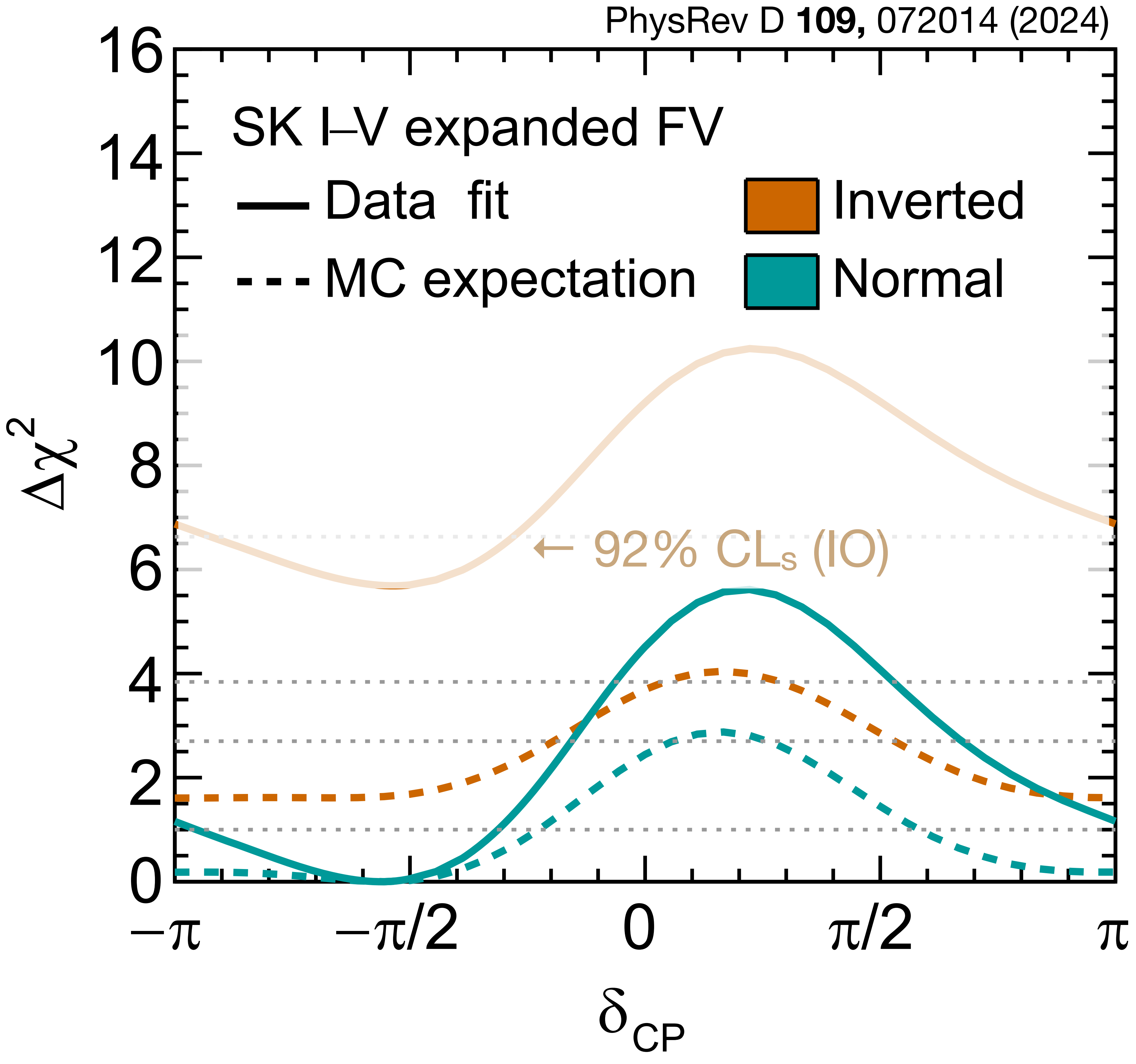
Future sensitivity

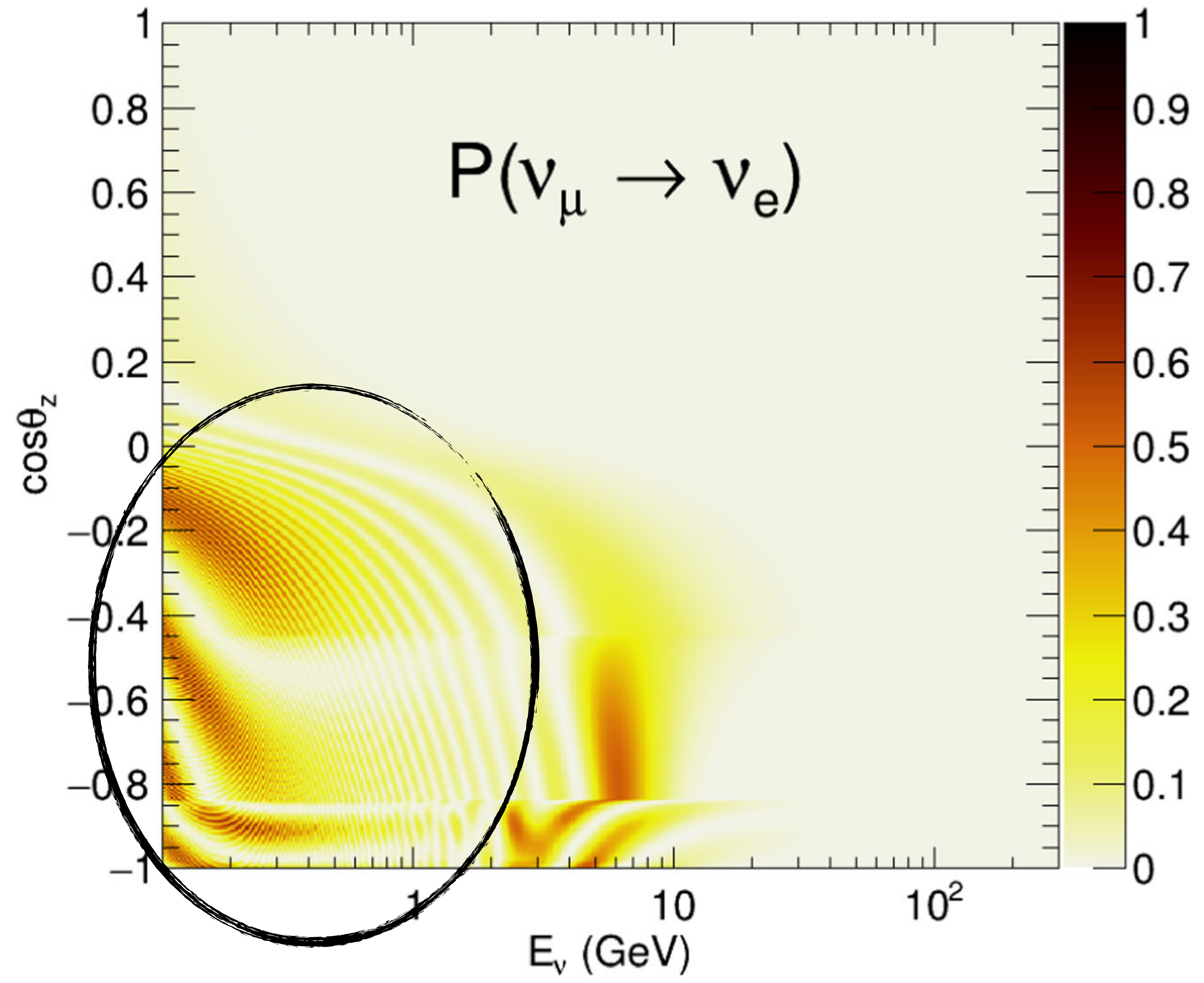


IceCube upgrade, ORCA, and HyperK expected to measure MO in the next few years. PRX 13, 041055 (2023)

Using θ_{13} constraint from reactors

CP phase





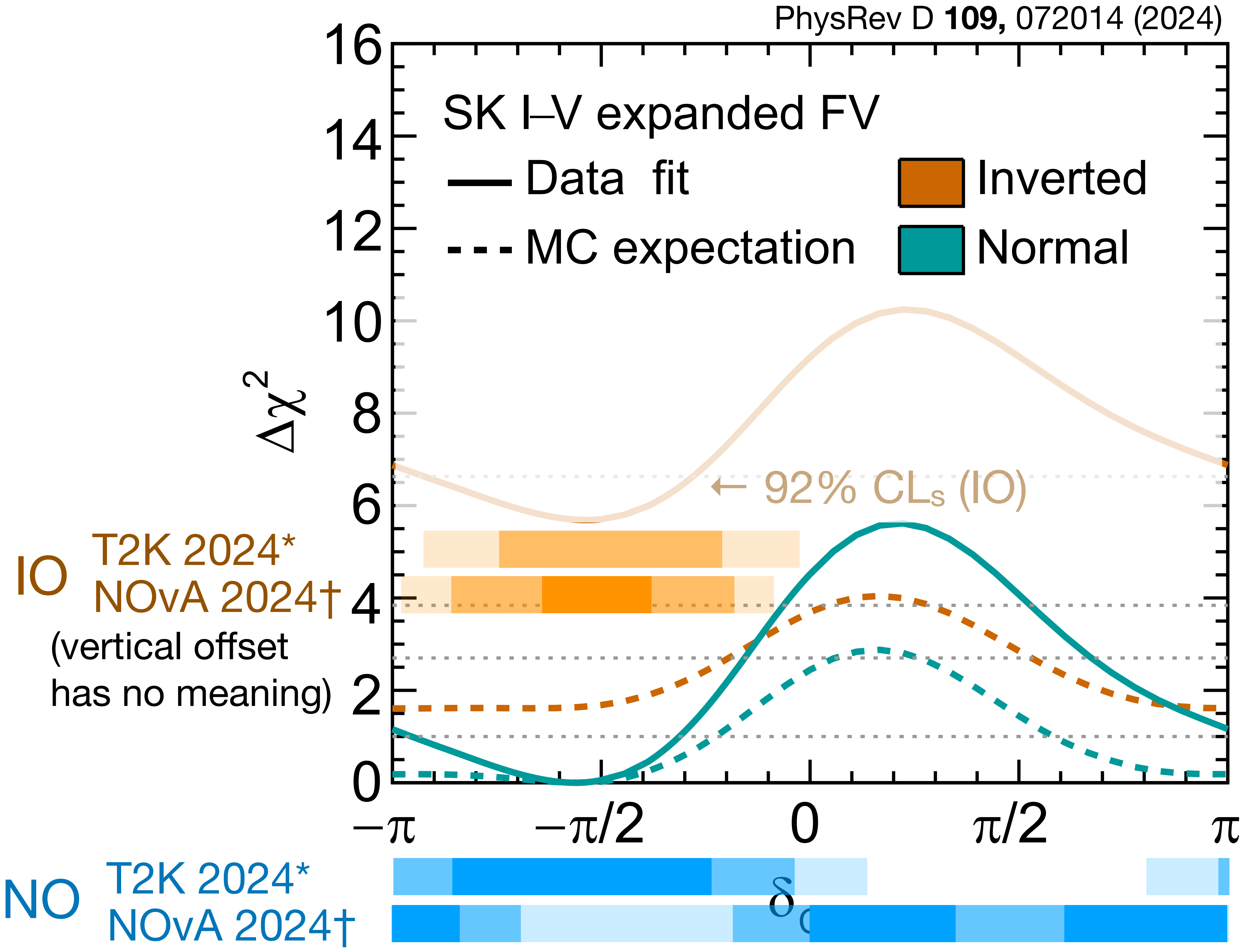
- SK also constrains δ_{CP} from normalization of sub-GeV e-like events. Unlike accelerators, decoupled from MO. Interplay of $\Delta m^2_{32} - \Delta m^2_{21}$ interference phase-shift and flux/xsec shape, fully smeared due to resolution.

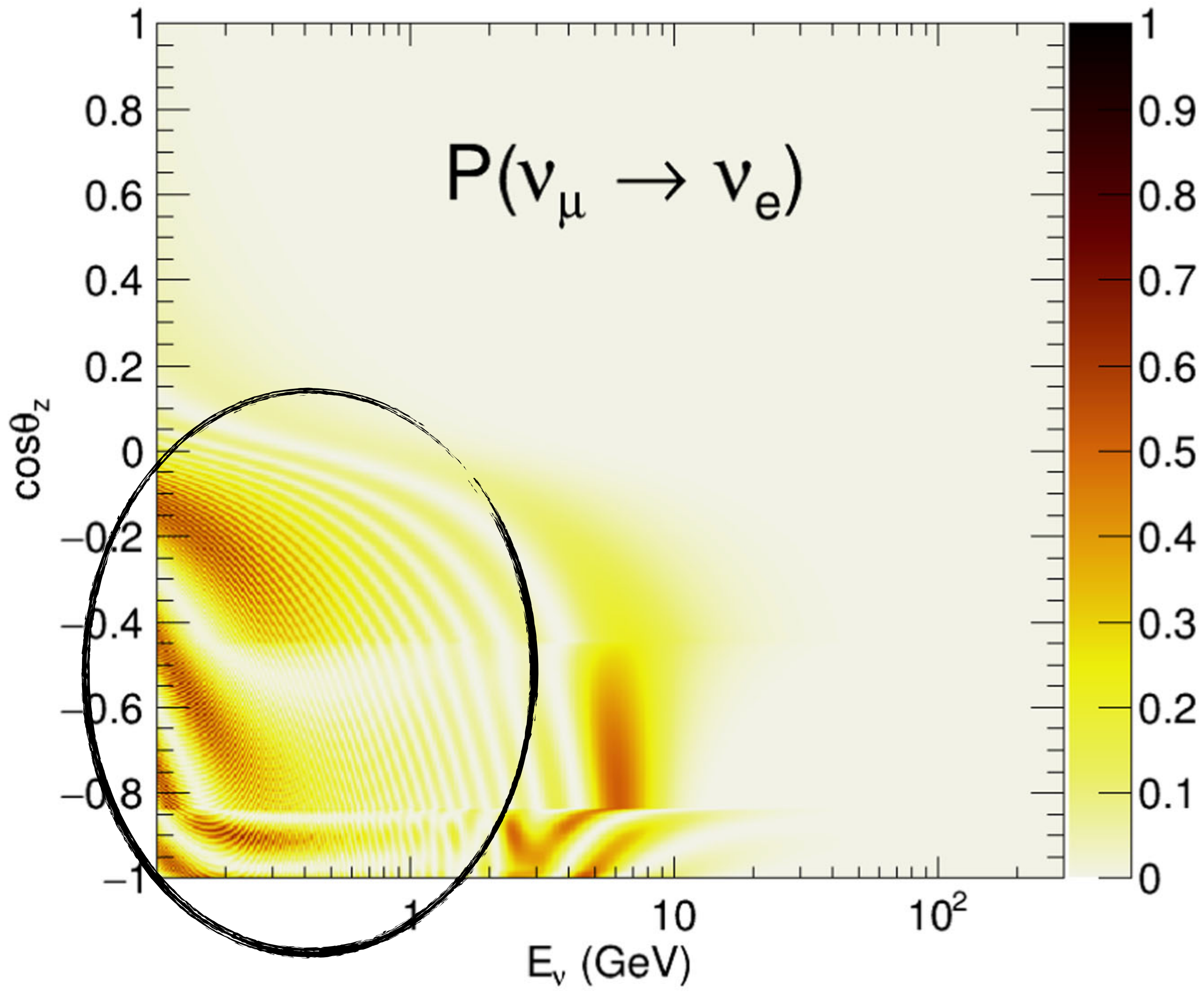
- Weak indication of maximal CP violation but CP conservation still allowed
  Caveat: somewhat stronger exclusion than sensitivity. Due to parameter boundaries and degeneracies cannot take $\sqrt{\Delta\chi^2}$ as sigmas.

Using θ_{13} constraint from reactors

* Feldman-Cousins
† Bayesian

CP phase





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  Interesting contribution to NOvA and T2K's NO constraints.

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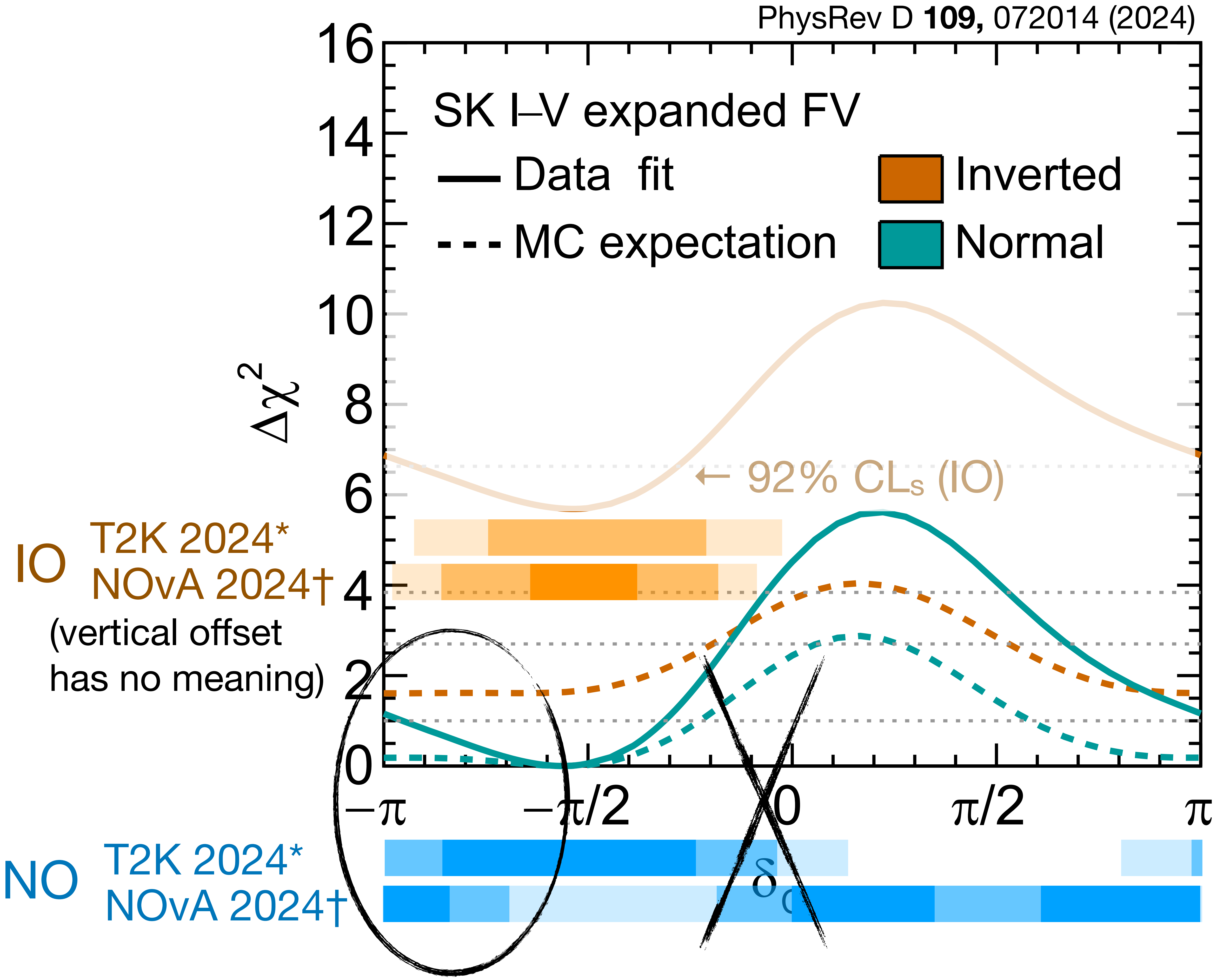

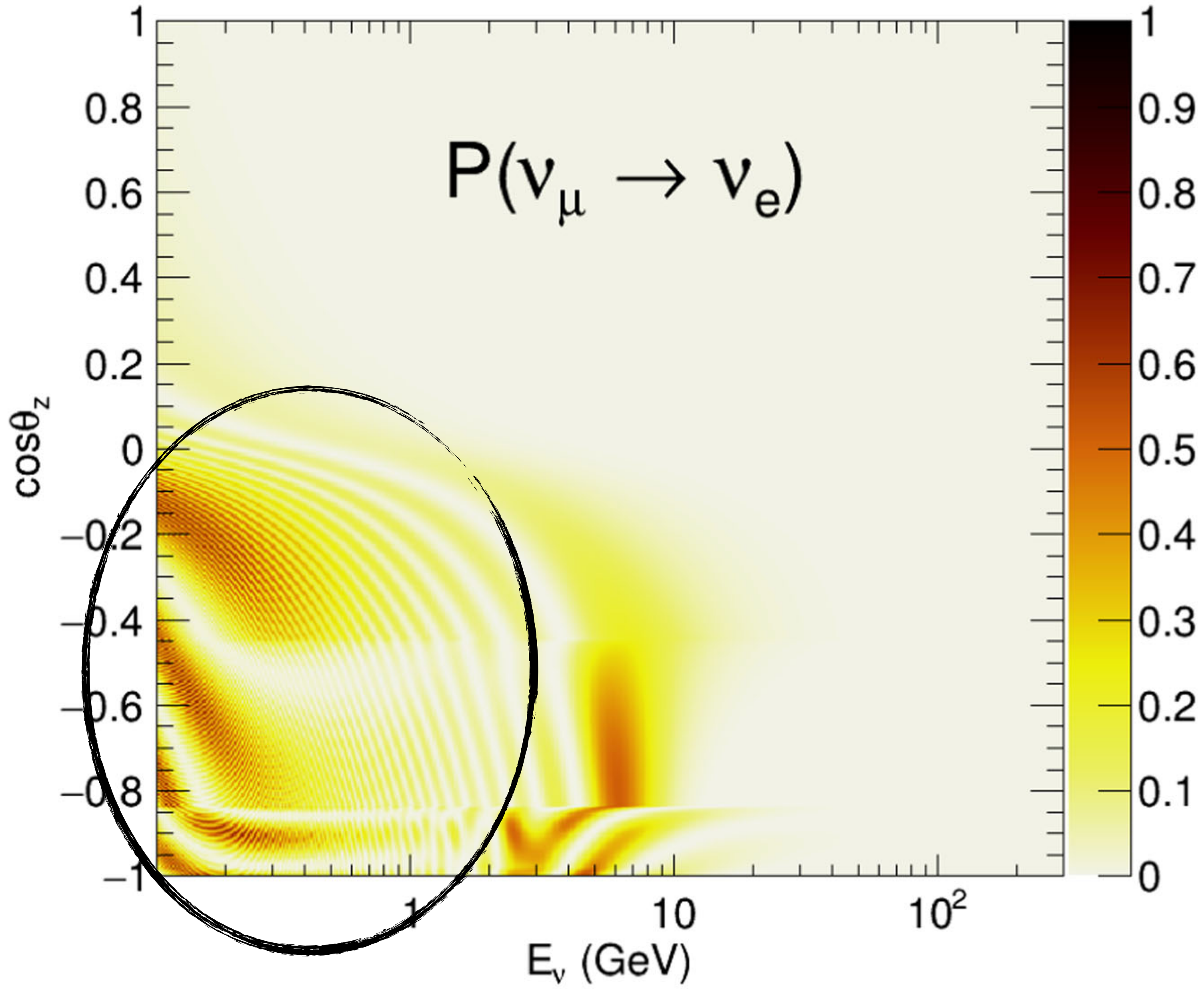

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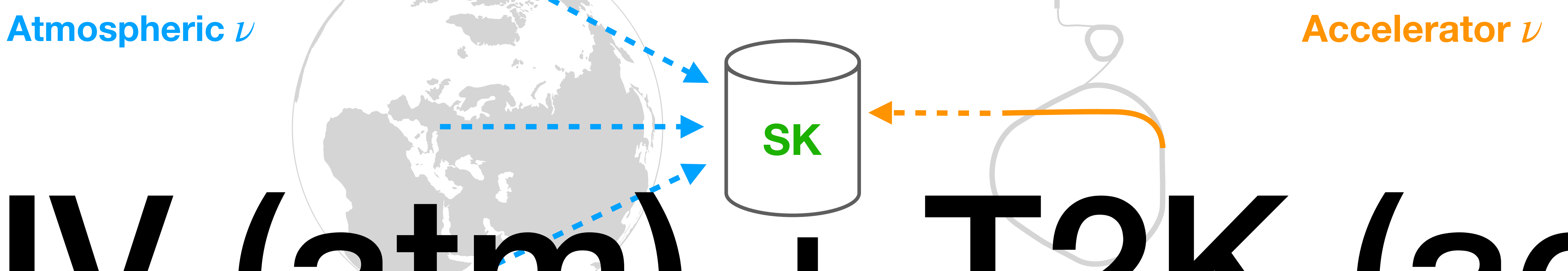
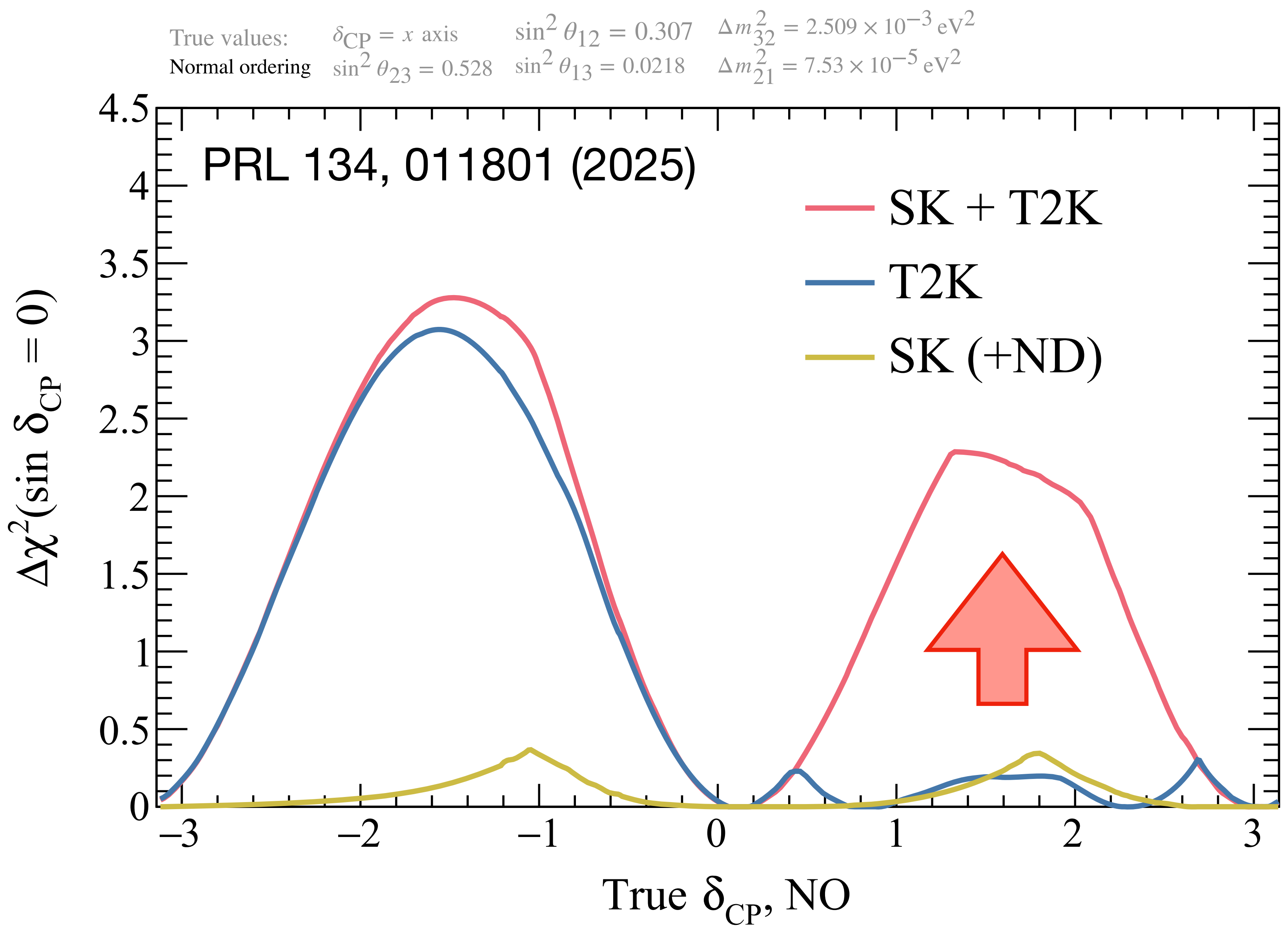
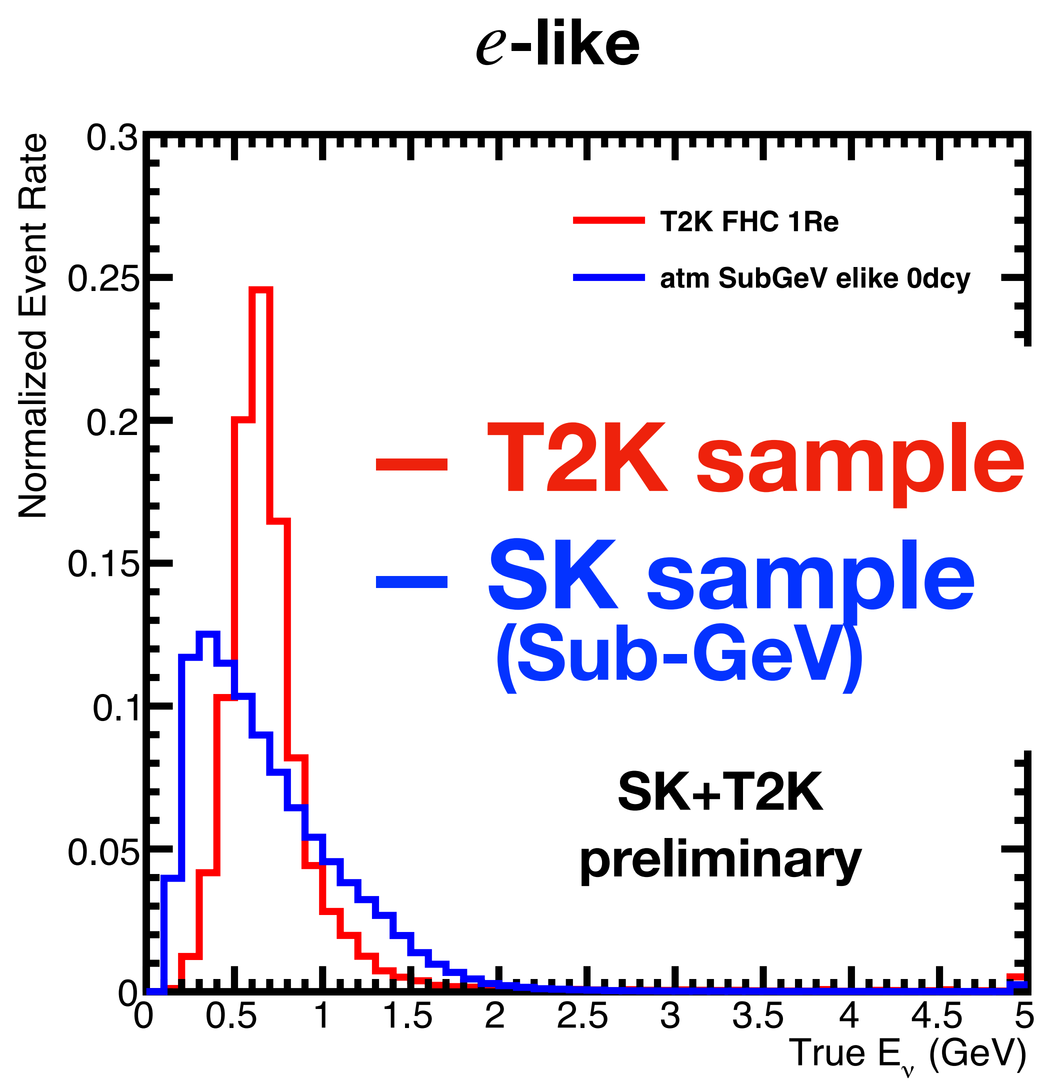
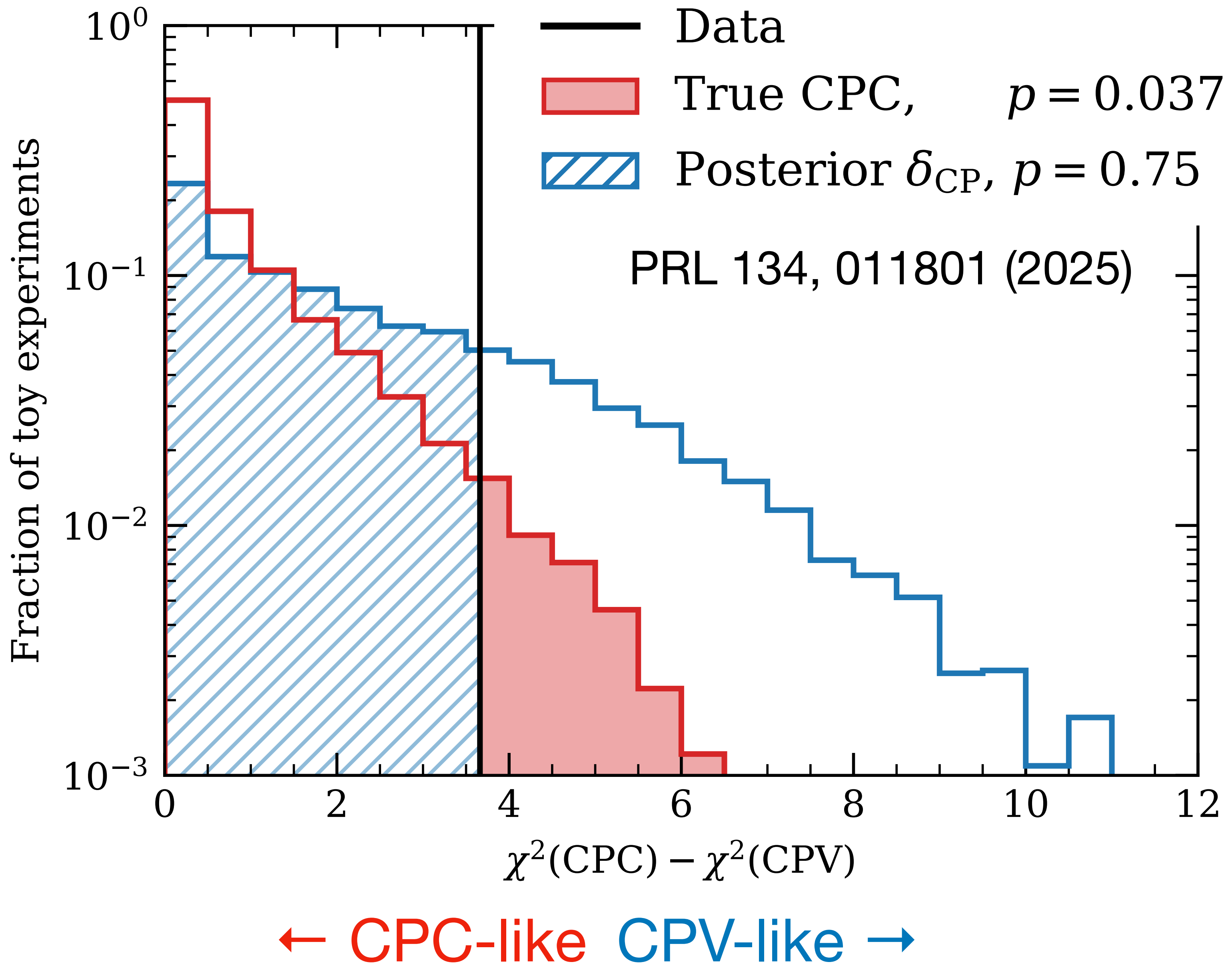
  Interesting contribution to NOvA and T2K's NO constraints.

SK IV (atm) + T2K (acc)







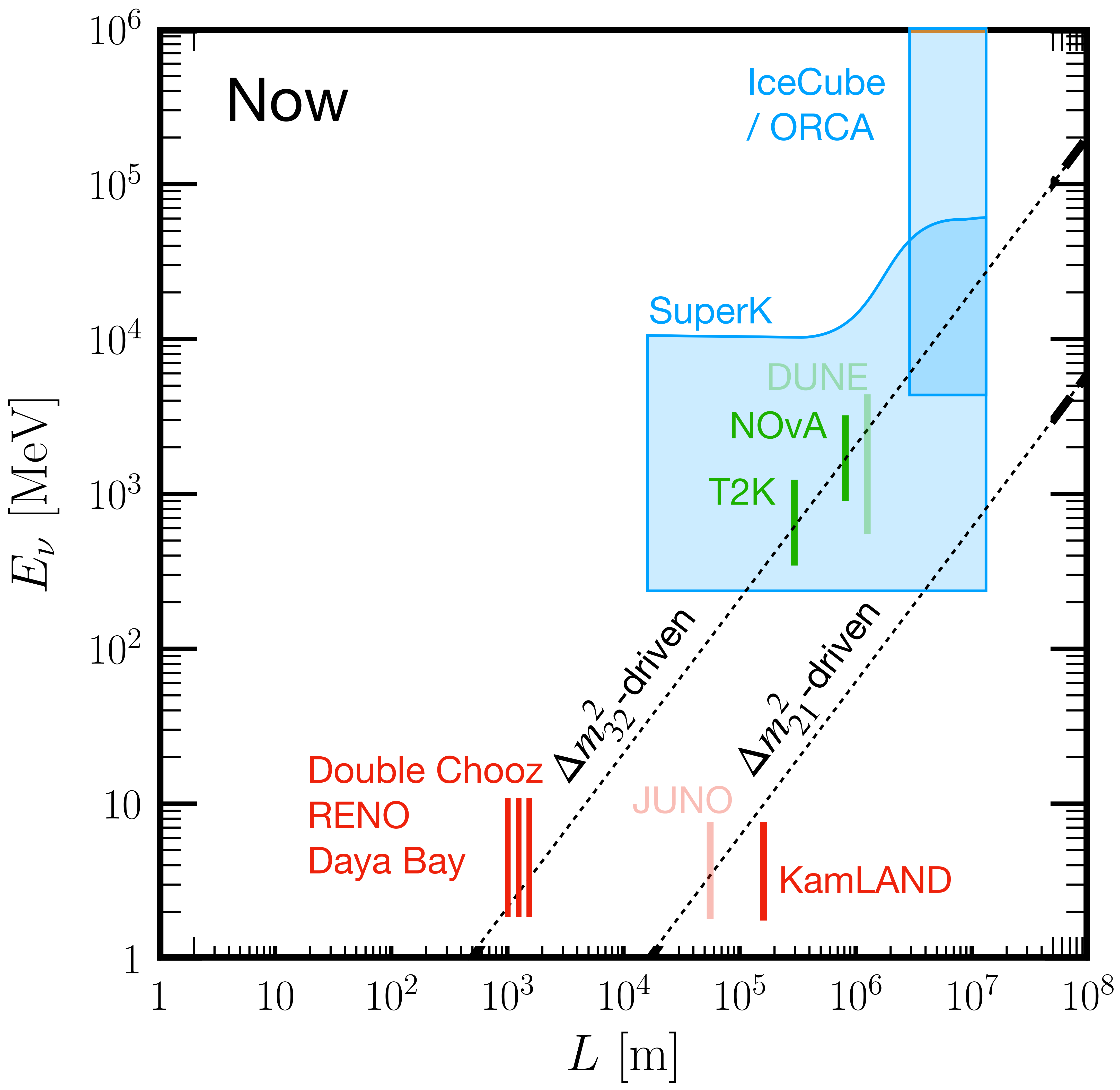


- Lifting δ_{CP}—MO degeneracy
- First joint fit based on past analyses PRL 134, 011801 (2025)
    - SK: just SK IV period, same reconstruction and baseline interaction model as T2K PTEP 2019, 053F01
    - T2K: results first shown in 2020 EPJ. C (2023) 83:782

- Correlate (sub-GeV) xsec and detector systematics
- Apply T2K ND xsec constraint to atmospheric fit
- Good fit using correlated systematics
  $p = 0.19$: Atm. vs. ND
  $p = 0.24$: Atm vs. acc (with ND)

- Reject CP-conservation at 1.9σ
  Note: T2K data not in MO-degenerate region
- New dedicated test-statistic found to be more powerful than typical $(\delta_{CP}, \mathrm{MO})$-intervals
  Profiling over discrete choices ($\delta_{CP} = 0,\pi$ and MO) helps retain calibration of confidence level, especially in joint fit.

Future / Outlook



→ talks on Friday

- Reactor
  - long-baseline JUNO → θ_{12}, Δm^2_{21}, Δm^2_{32}, MO
- Accelerator
  - HyperK → θ_{13}, δ_{CP} (if given MO)
  - DUNE → θ_{13}, δ_{CP}, MO
- Atmospheric
  - IceCube upgrade, ORCA → Δm^2_{32}, θ_{23}, MO
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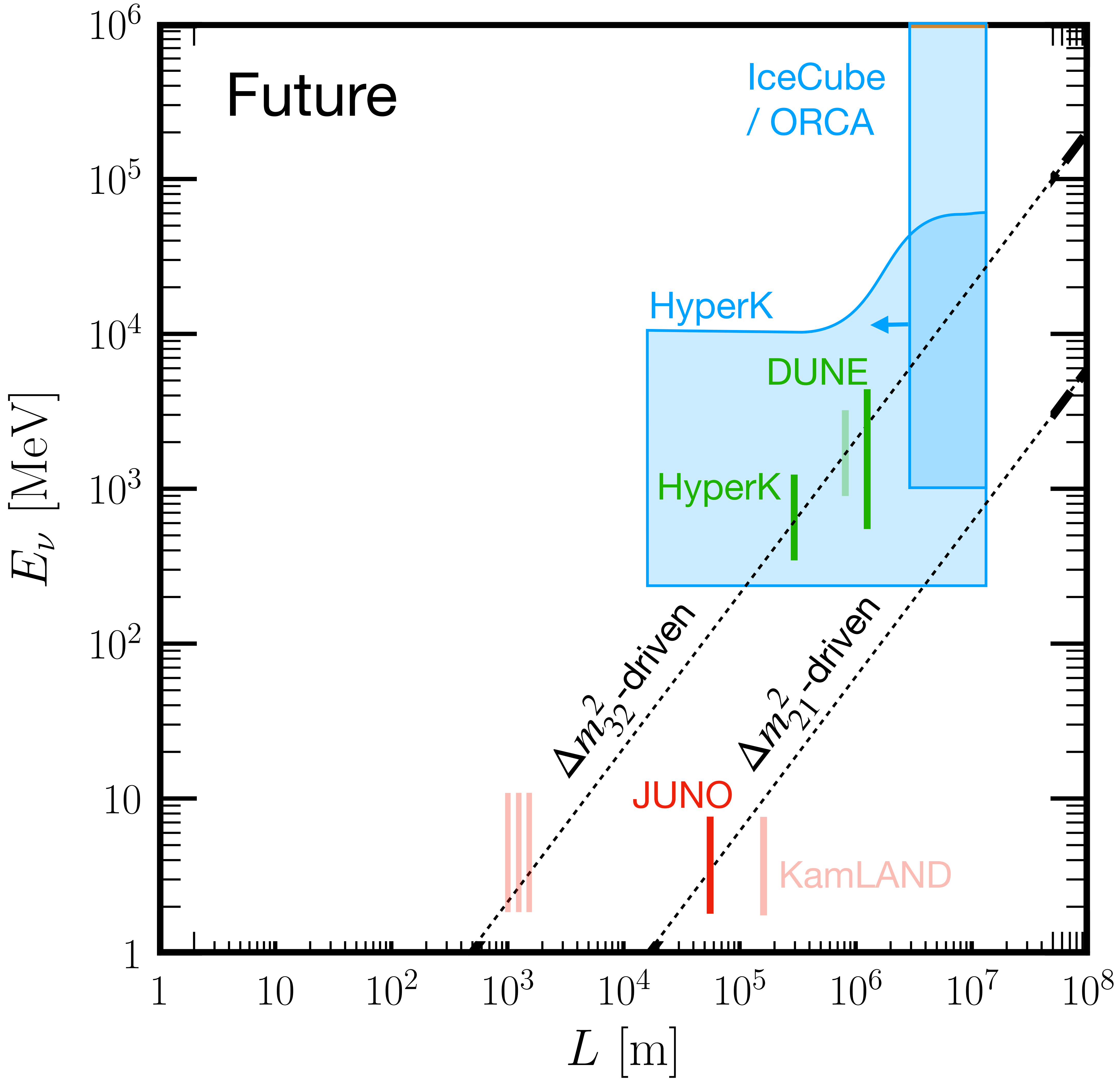
  - DUNE → δ_{CP} (see protons for sub-GeV)
- Cosmological constraints → MO from $\Sigma_i m_i$
- Some challenges
  - Precise understanding of flux, interaction (nuclear fx, ν_e, ν_τ), detector systematics
  - Effective sharing of results as analyses become more complex, but global analyses are essential if we want to stress-test 3ν-paradigm or look beyond

Projects in R&D phase are not mentioned

Future / Outlook



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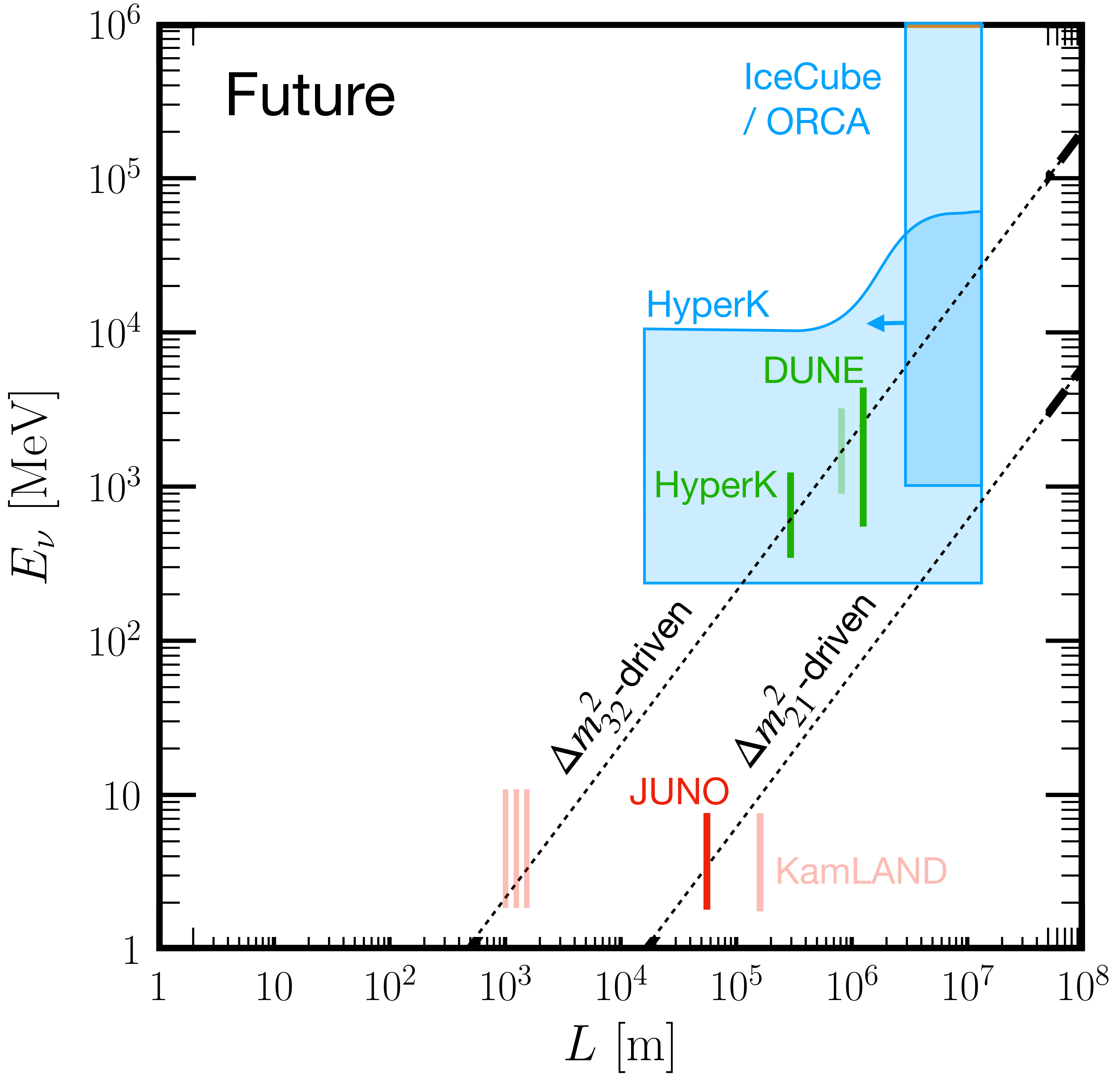

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Currently JUNO

$|\Delta m^2_{ee}|$ $\approx 2\,\% \rightarrow 0.X\,\%$

(technically value measured by medium baseline and JUNO has a slight offset, so shouldn't call Δm^2_{ee})

Already

$|\Delta m^2_{\mu\mu}|$ $< 1\,\%$

(global average)

↓

Yet another way to get MO: from $\Delta m^2_{\mu\mu}$ vs. Δm^2_{ee}

PRD 72, 013009 (2005)

PRD 111, 013008 (2025)

Many ways to measure MO!

Projects in R&D phase are not mentioned

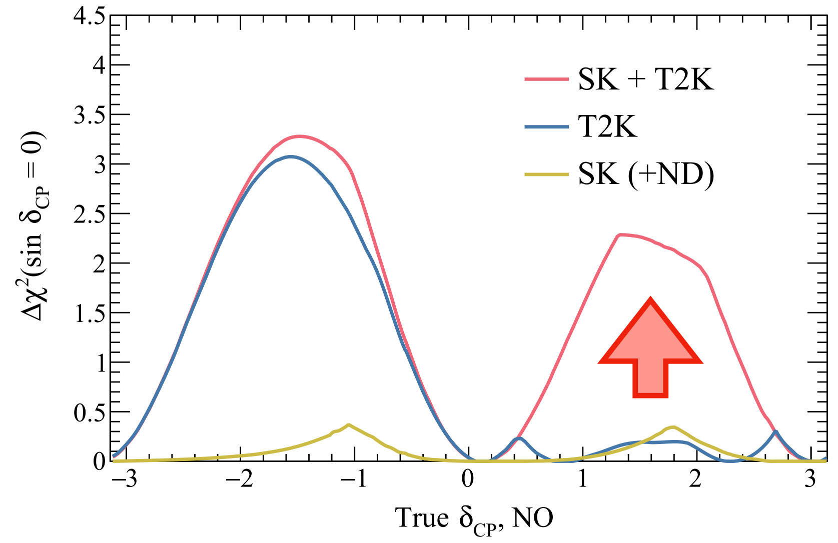
Related parallel talks

- NPA 1B: Philipp Soldin
  "Double Chooz Single-Detector Physics Results"
  (includes final Double Chooz oscillation results)
- NPA 1B: Zhe Wang
  "The latest reactor neutrino oscillation results and reactor neutrino flux and spectrum measurement results from Daya Bay"
- NPA 1B: Antonio Marrone
  "Precision Neutrino Physics: Status and Outlook in the 3ν Paradigm"
- NPA 4B: Masaki Ishitsuka
  "Latest neutrino oscillation measurements from T2K"
- NPA 7A: Denise Casazza
  "The SAND detector of the DUNE experiment"
- NPA 7A: Iwan Morton-Blake
  "Commissioning of the JUNO detector"
- NPA 7A: Ruhui Li
  "Status and Prospect of JUNO-TAO"
- NPA 7A: Akira Takenaka
  "Development of the calibration sources for the JUNO experiment"

Related posters

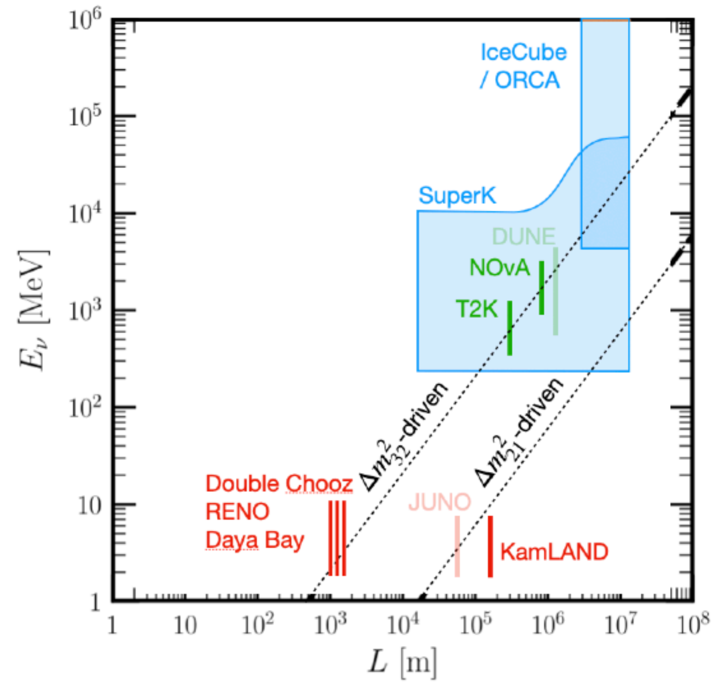
- 48 NPA Ali Murat Guler
  Results from the DsTau (NA65) experiment at the CERN-SPS
- 161 NPA Yaoguang Wang
  Calibration of 20-inch Photomultiplier Tubes in JUNO
- 175 NPA Yukine Sato
  Performance Evaluation of a New Sensor for the T2K Muon Monitor in Neutrino Beam Direction Measurements
- 313 NPA Laurence Cook
  Reducing Systematic Uncertainties in Neutrino Detection with the Water Cherenkov Test Experiment (WCTE)
- 334 NPA Qishan LIU
  Neutron Capture Information in Improving IBD Angular Resolution
- 413 NPA Rui Li
  Calibration System of the JUNO experiment
- 497 NPA Jingqin Xue
  The accelerated Reactor fitter and Oscillation analysis for JUNO

I'm sorry if I missed some, or cited an unrelated contribution…



Summary

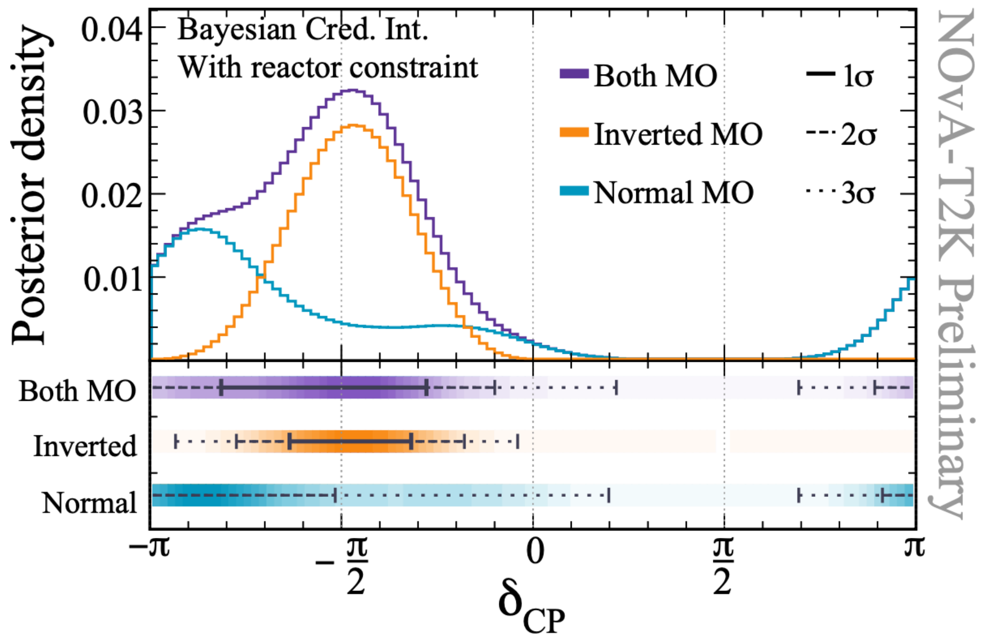
- **3ν oscillation** paradigm successfully describes many reactor/accelerator/atmospheric ν-oscillation experiments. Consistency across
  - Different oscillation channels ($\bar{\nu}_e \rightarrow \bar{\nu}_e, \nu_\mu \rightarrow \nu_\mu, \nu_\mu \rightarrow \nu_e$ etc.)
  - Different interaction mechanisms
  - Different detector technologies
  - Different contributions of matter effects



- Some parameters are entering precision era
  $|\Delta m^2_{32}|$ is now measured sub-% (global average)

  Strong contributions from recent NOvA and IceCube results

- If IO, we have evidence for CP-violation, but various weak indications of NO



- Two joint fits were done (T2K+NOvA, T2K+SK), potential for cancelling degeneracies, testing systematic correlations, stress-testing the model

  Significance of such will increase in upcoming systematic-dominant era

- New detectors are coming online:
  ORCA, IceCube upgrade,
  JUNO, HyperK, DUNE
  High statistics experiments requiring good understanding of systematics

- Especially for MO, **many ways to measure**

  Over the next 4~6 years we may not only get one, but two different measurements of MO?
  → feeds into CPV search and $0\nu\beta\beta$