ICPPA 2024

Status and future prospects of combining the results of three-flavour neutrino oscillation experiments

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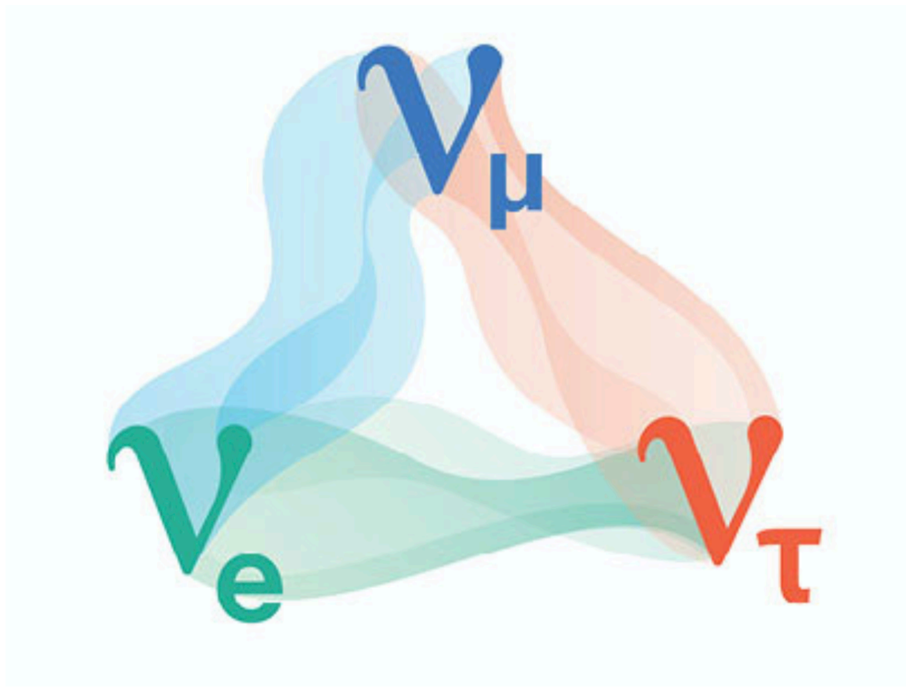


Neutrino oscillations and mixing

atmospheric accelerator	short baseline reactor accelerator	solar long baseline reactor

$$\left|\begin{array}{c}\nu_e\\ \nu_\mu\\ \nu_\tau\end{array}\right\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13}\end{pmatrix}\begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\left|\begin{array}{c}\nu_1\\ \nu_2\\ \nu_3\end{array}\right\rangle$$

Oscillation parameters and how precisely do we know them:

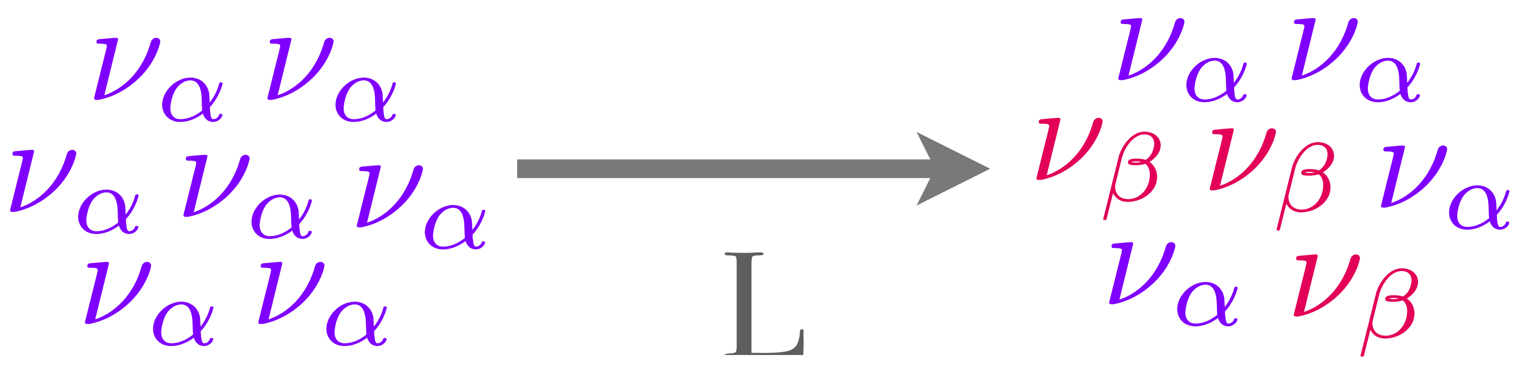
$\theta_{12} \approx 34^\circ$ (4.4%)

$\theta_{23} \approx 49^\circ$ (5.2%)

$\theta_{13} \approx 9^\circ$ (3.8%)

$\Delta m^2_{21} \approx 7.4 \times 10^{-5}\ \mathrm{eV}^2$ (2.2%)

$\Delta m^2_{32} \approx +2.5 \times 10^{-3}\ \mathrm{eV}^2$ (1.4%)

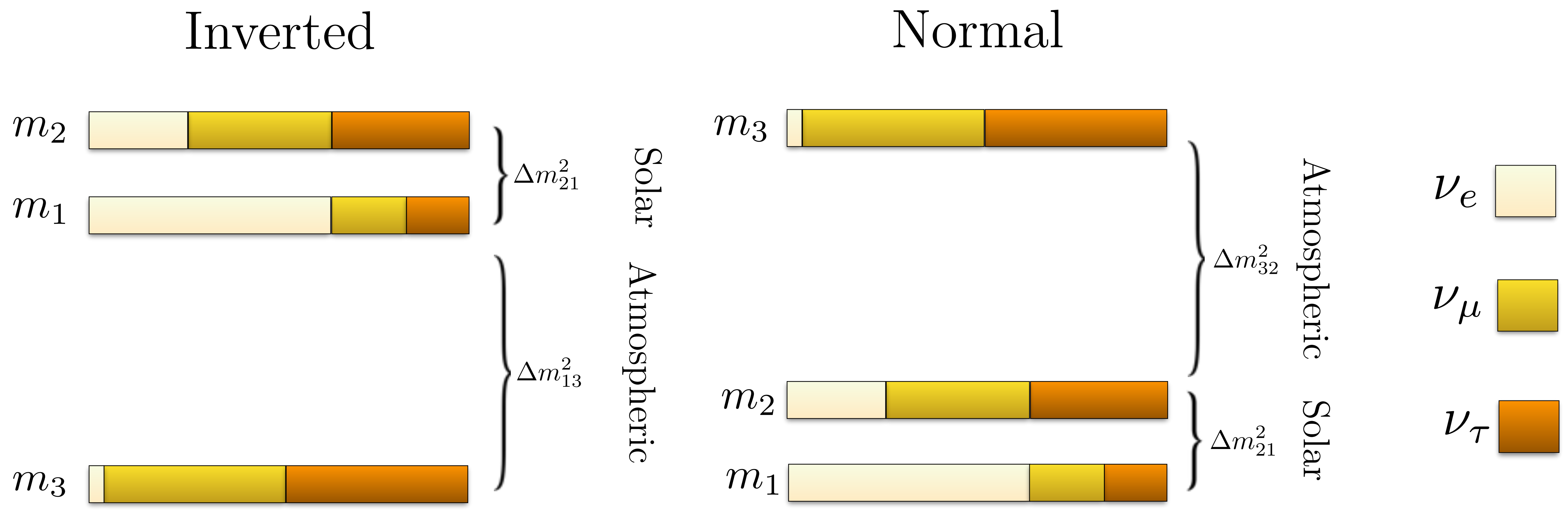


Open questions:

Is θ_{23} 45° ?

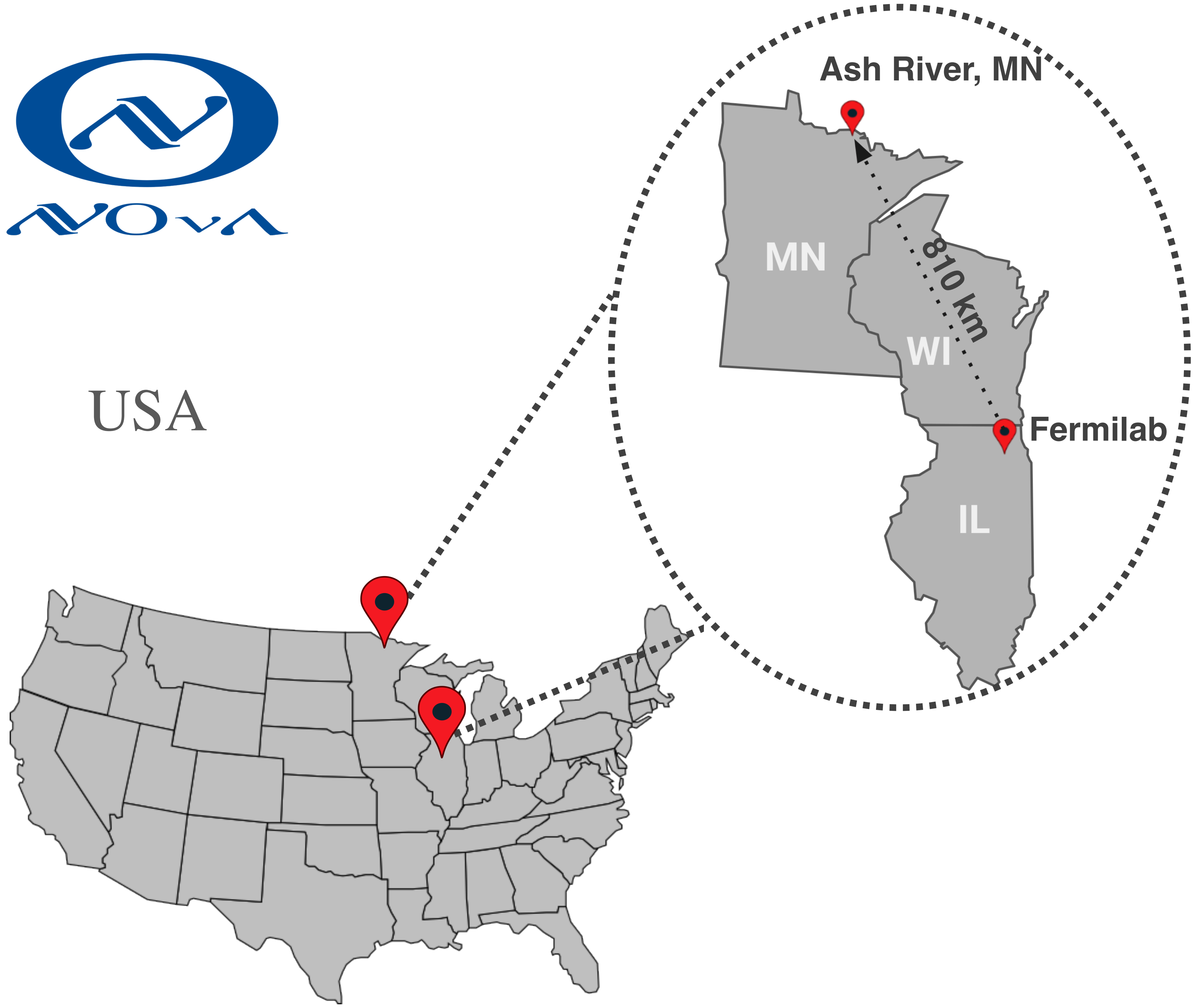
Is there CP violation in lepton sector?

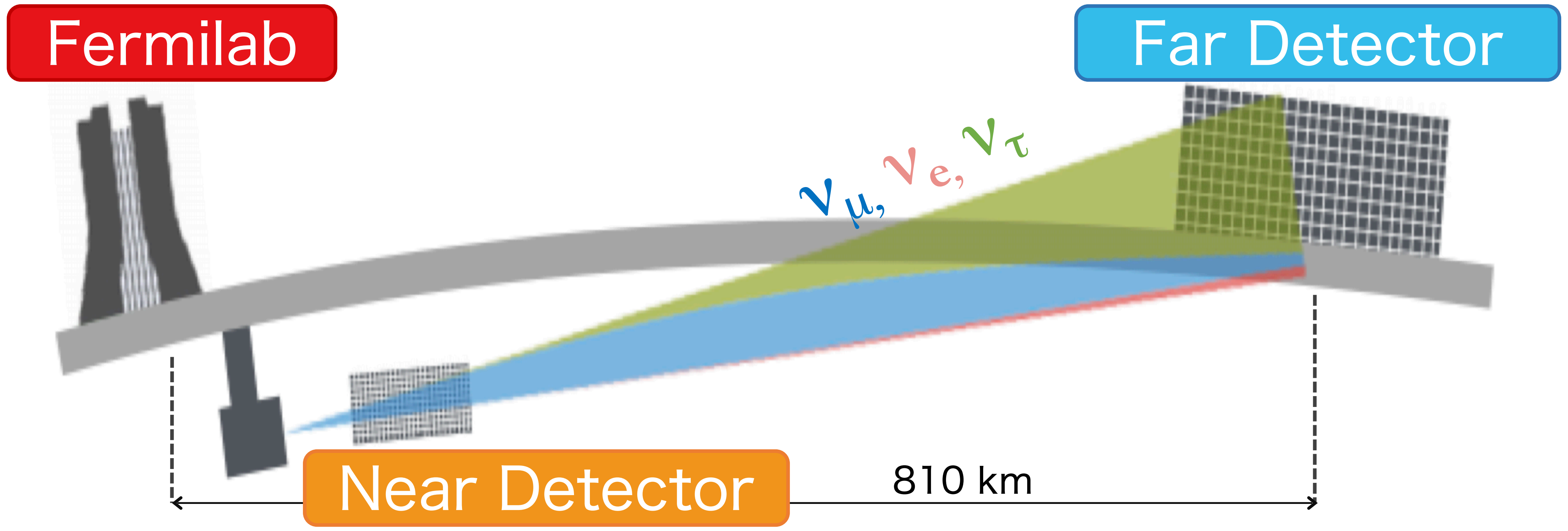
Neutrino mass hierarchy (ordering) is Normal or Inverted?



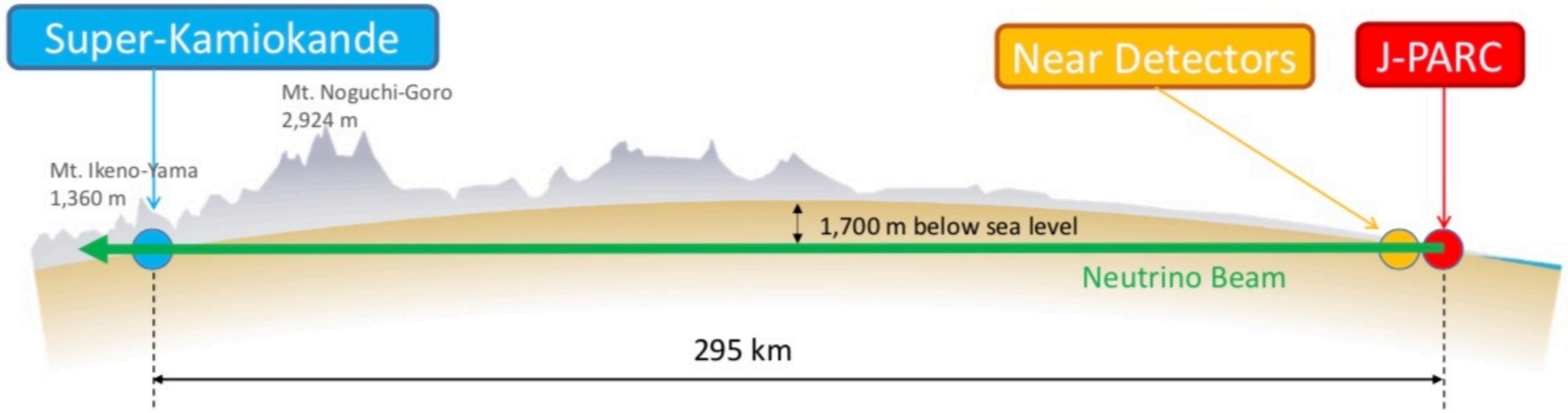
NOvA and T2K

USA





Japan



The experiments

Both experiments are located off-axis to receive a narrow-band, highly pure muon (anti-)neutrino beam:

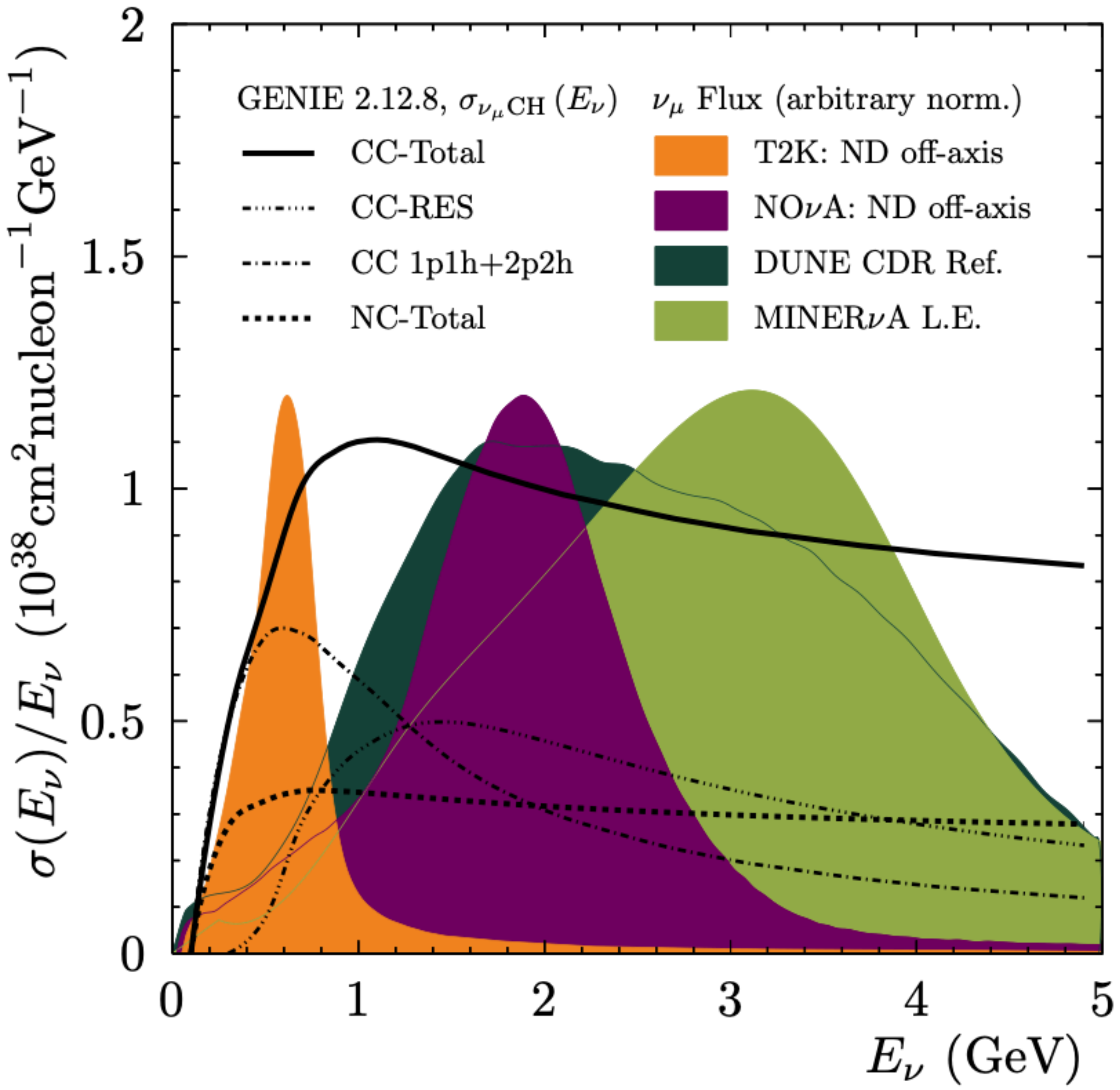
- T2K: beam peaks at 0.6 GeV neutrino energy,
- NOvA: beam peaks at 2 GeV.

The difference in neutrino beam energy leads to different neutrino interactions:

- T2K: primarily Quasi-Elastic and 2p2h interactions,
- NOvA: mix of Quasi-Elastic, 2p2h, Resonant and DIS interactions.

Experiments have very different experimental approach:

- T2K: different detector technologies for Near (magnetized plastic scintillator and gas TPC tracking detector) and Far (water Cherenkov) detectors.
- NOvA: identical detectors are active scintillator calorimeters.



Why joint analysis?

The complementarity between the experiments provides the power to break degeneracies.

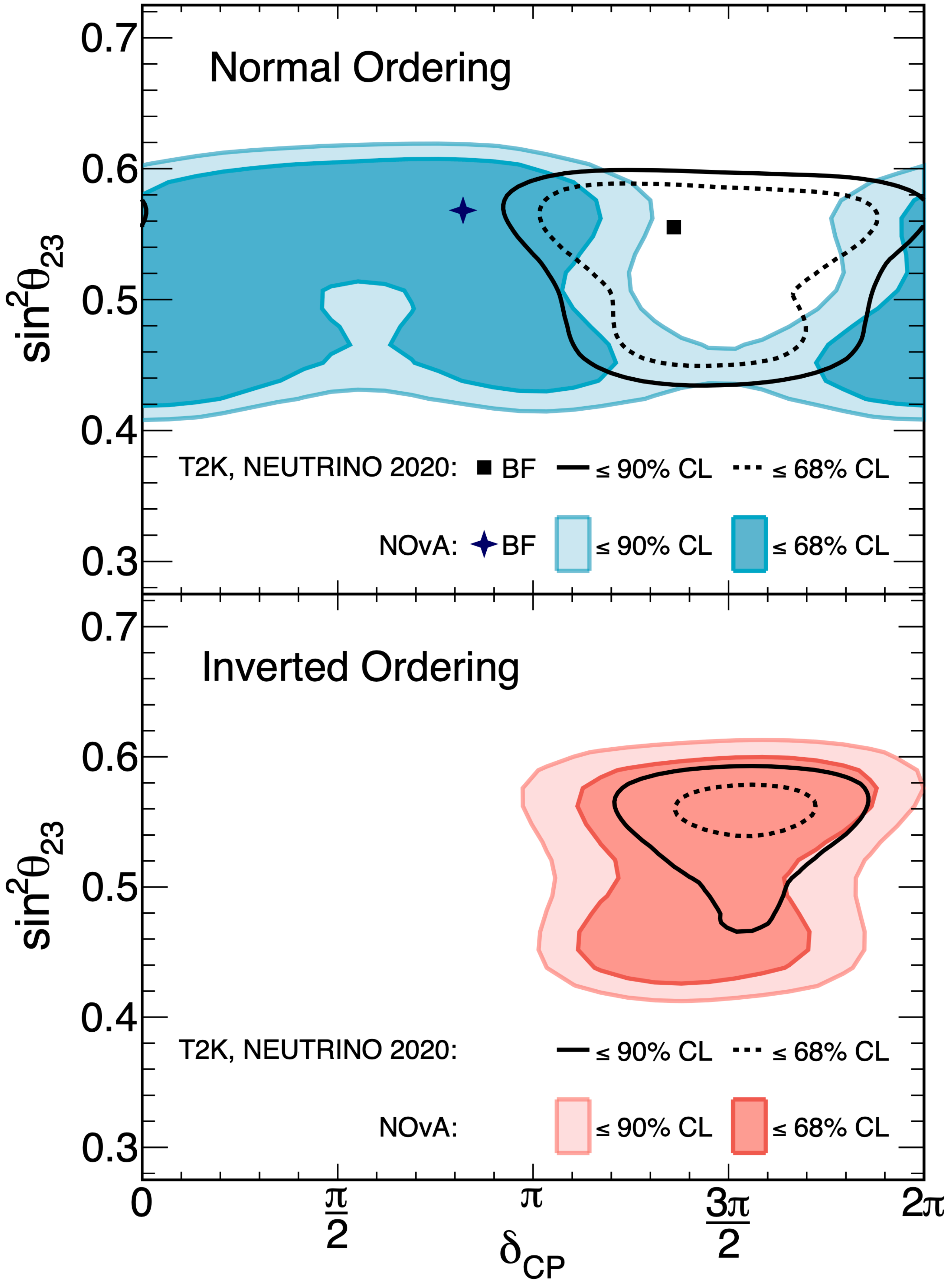
- T2K measurements isolate impact of CP violation while NOvA has significant sensitivity to mass ordering.

Full implementation of:

- energy reconstruction and detector response;
- detailed likelihood from each experiment;
- consistent statistical inference across the full dimensionality.

In-depth review of:

- models, systematic uncertainties and possible correlations;
- different analysis approaches driven by contrasting detector designs;
  - as a by-product: cross-check and review of each other analyses.



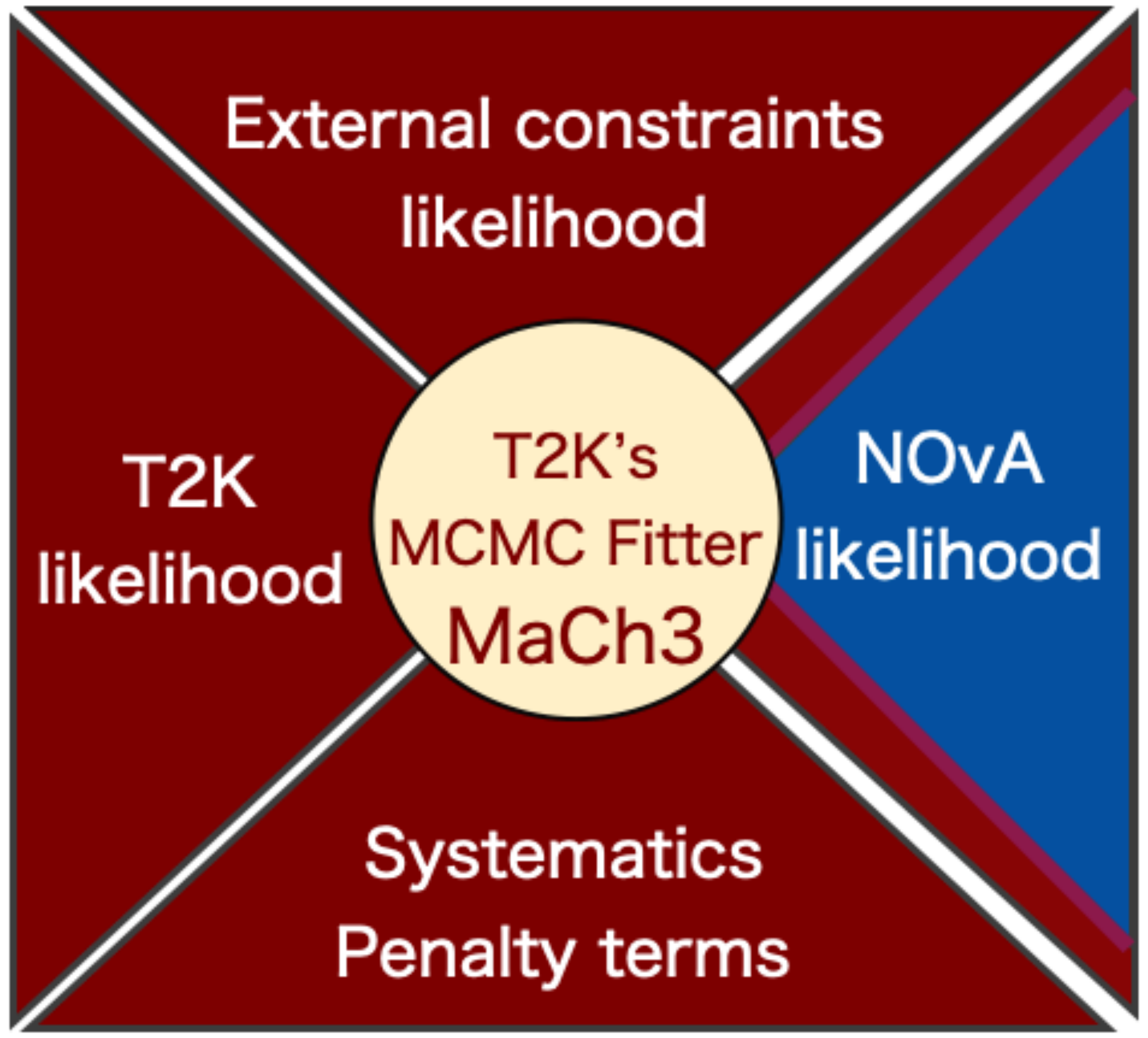
Technical implementation

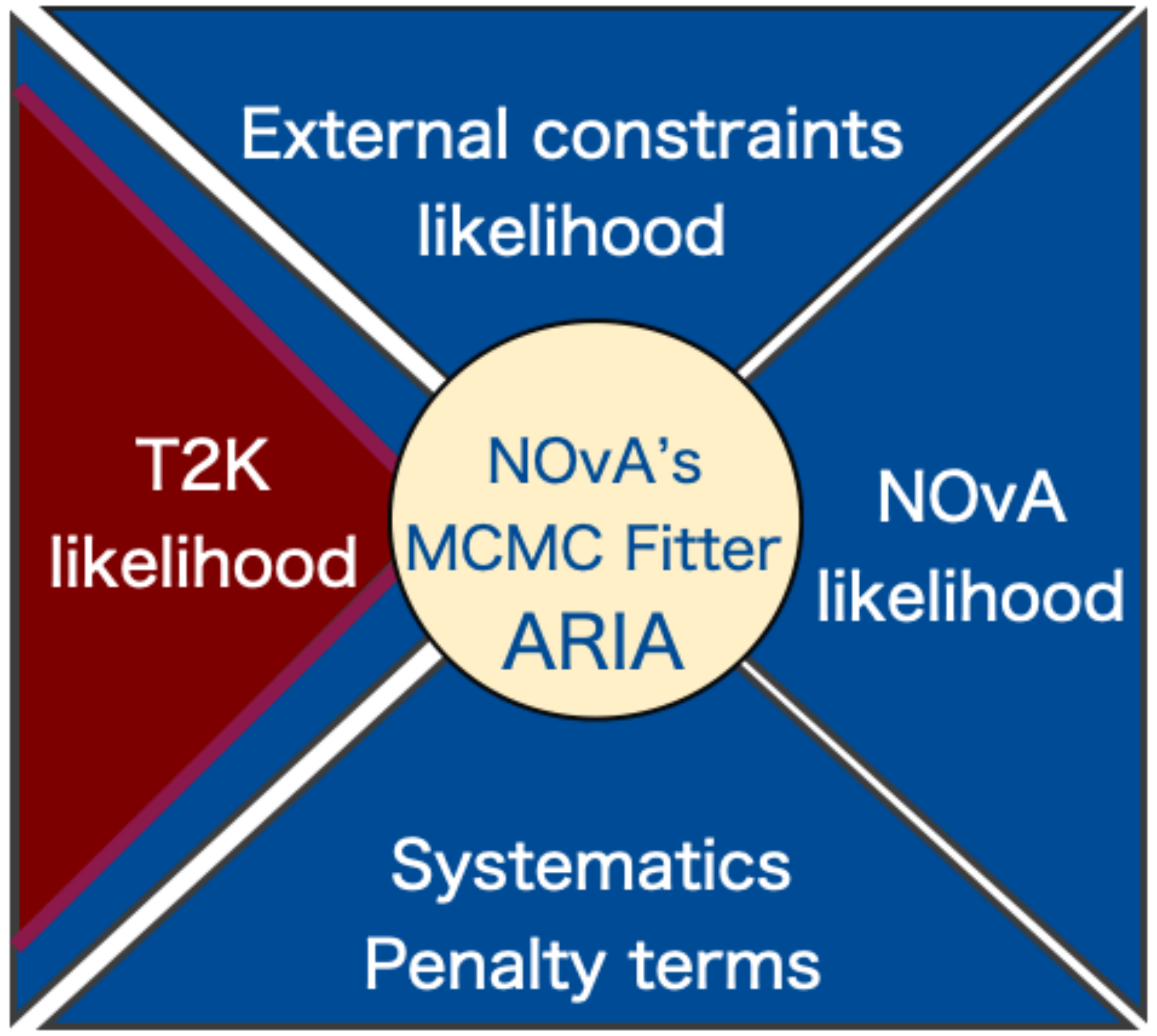
The joint-fit is constructed using:

- ✳ Poisson likelihood from each experiment;
- ✳ penalty terms from the systematics pull;
- ✳ external constraints on $\theta_{13}, \theta_{12}, \Delta m^2_{21}$ from solar and reactor neutrino experiments.

The other experiment's likelihoods are integrated via a containerized environment:

- ✳ both experiments can run each other's analysis through these containers;
- ✳ full access to Monte Carlo and data;
- ✳ safe alternative with full sensitivity to the shared events per bin + systematics details;
- ✳ containers help to avoid making changes to each experiment's software to resolve dependencies.





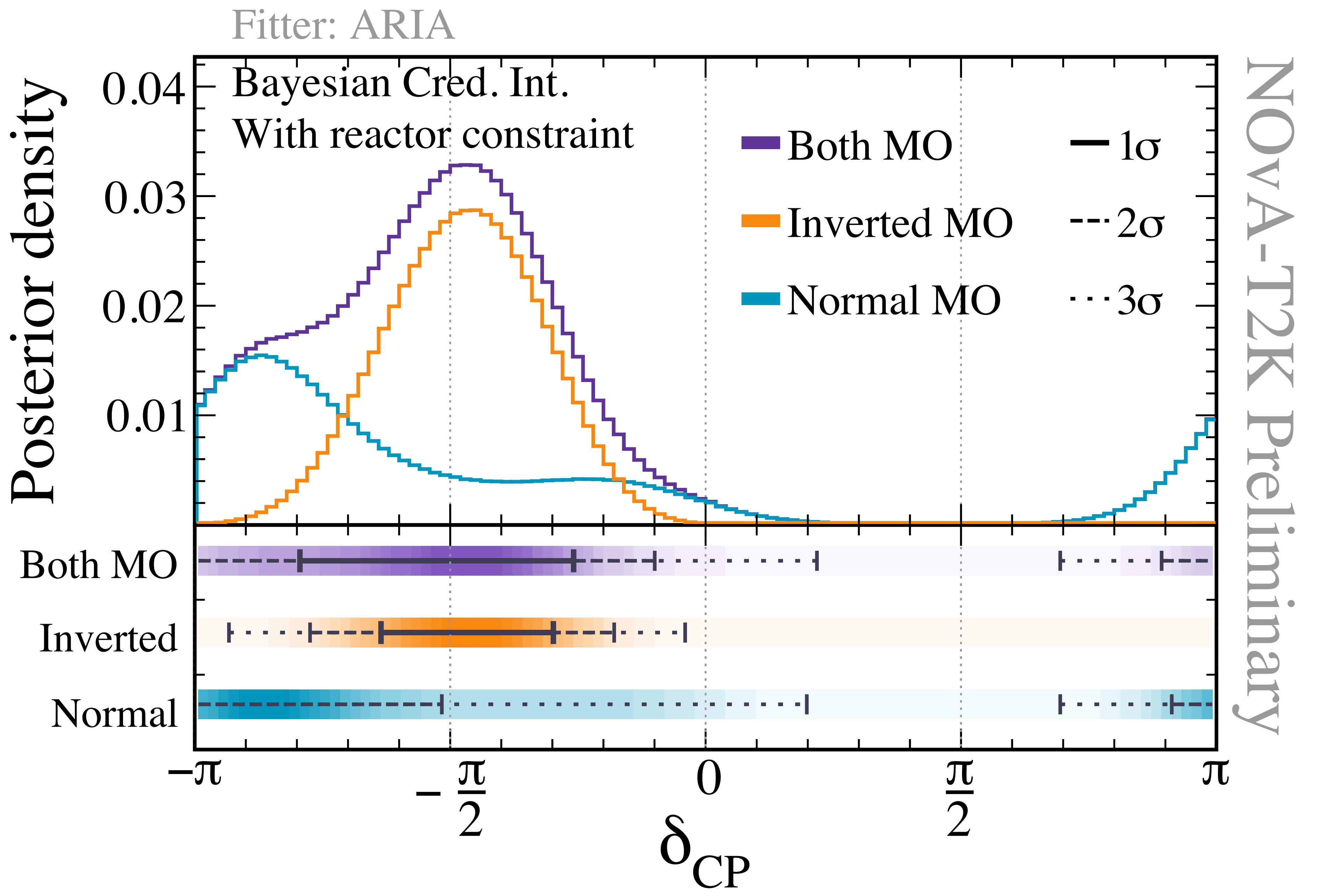
Fit results

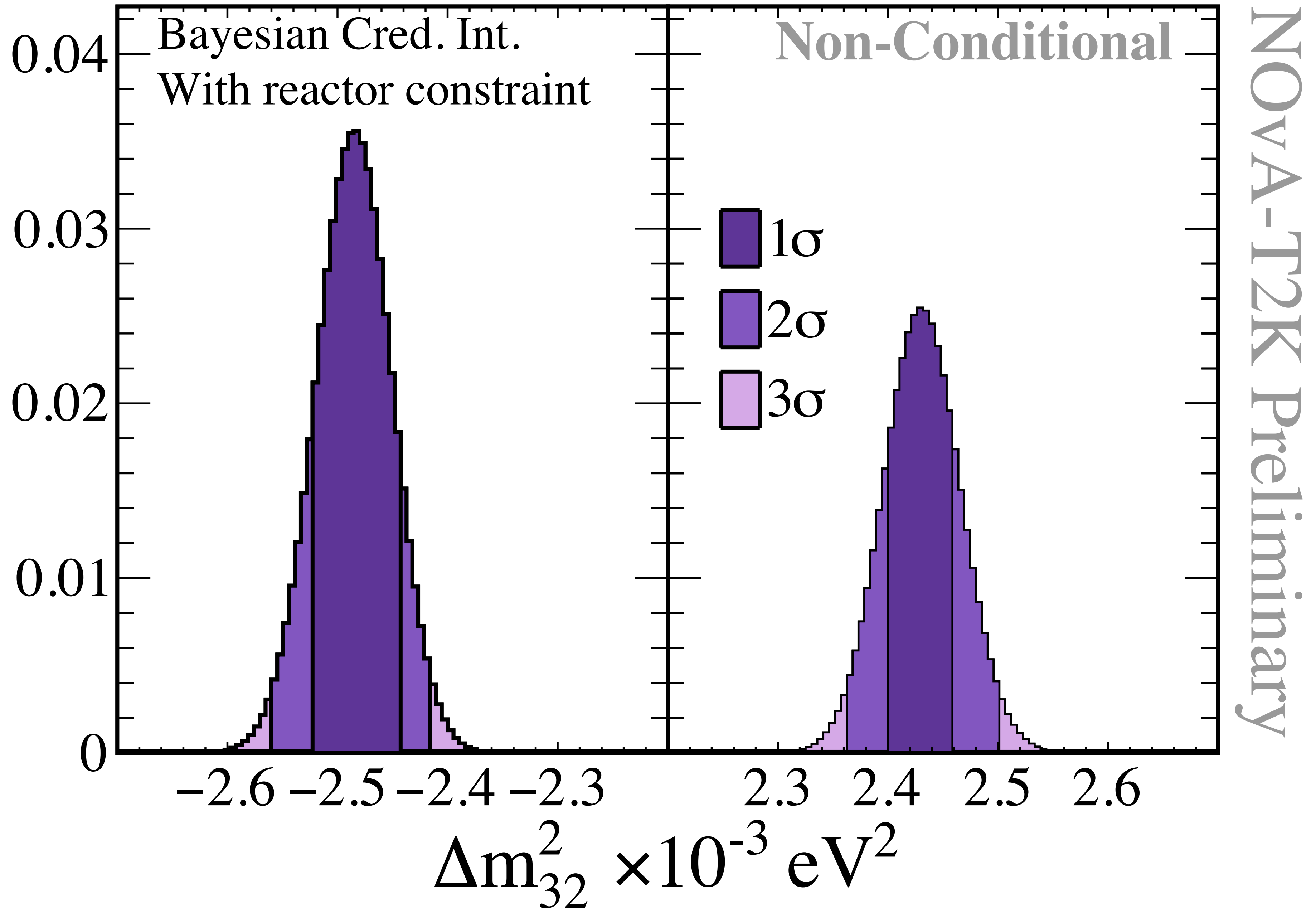
Mass ordering and δ_{CP}

- For both mass orderings, $\delta_{CP} = \pi/2$ lies outside 3σ credible interval.
- Normal Ordering allows for a broad range of permissible δ_{CP}.
- For the Inverted Ordering, CP conserving values of δ_{CP} $(0, \pi)$ lie outside the 3σ credible interval.

- Comparing the posterior density in each mass ordering, it is evident that the NOvA-T2K joint fit has a modest preference for the Inverted Ordering.

	NOvA – T2K – w/ reactor
Bayes factor	1.36 Inverted Ordering/Normal Ordering ~58% : ~42% posterior

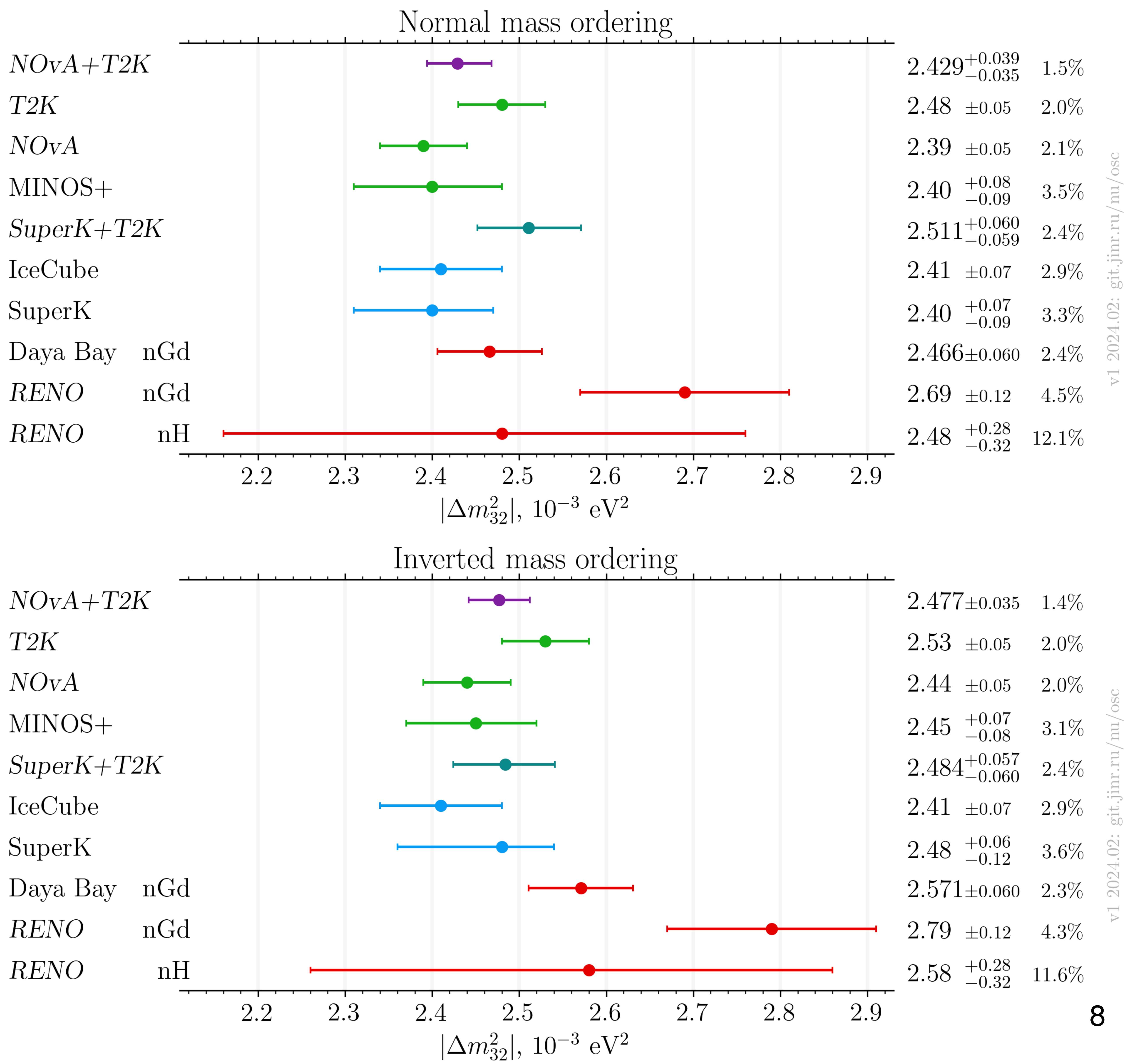




Comparisons w/ other experiments

- This analysis has the smallest uncertainty on $|\Delta m^2_{32}|$ as compared to other previous measurements.

- Same level of precision with and without reactor constraint.
- First oscillation parameter measured <2% precision.



SuperK and T2K

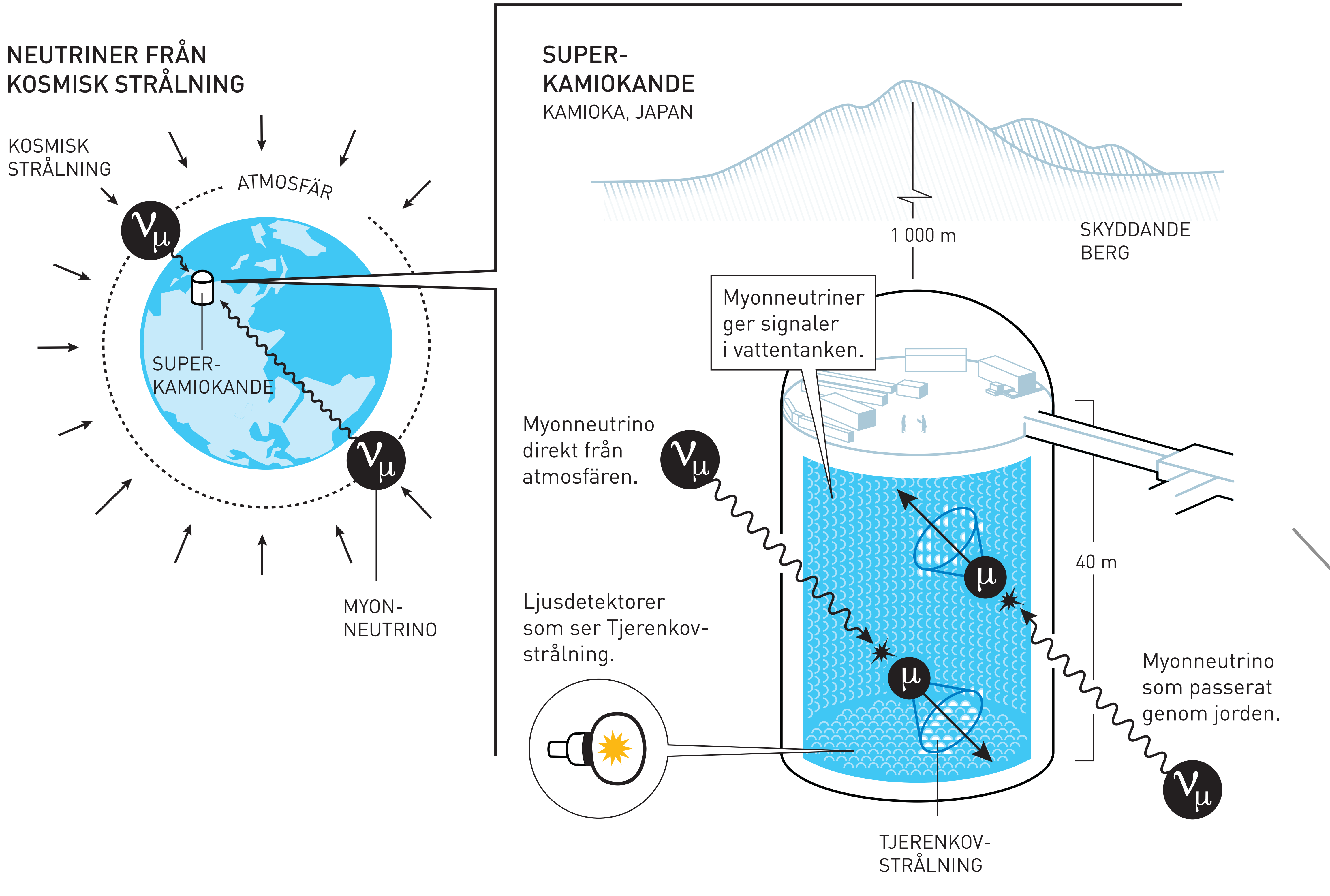
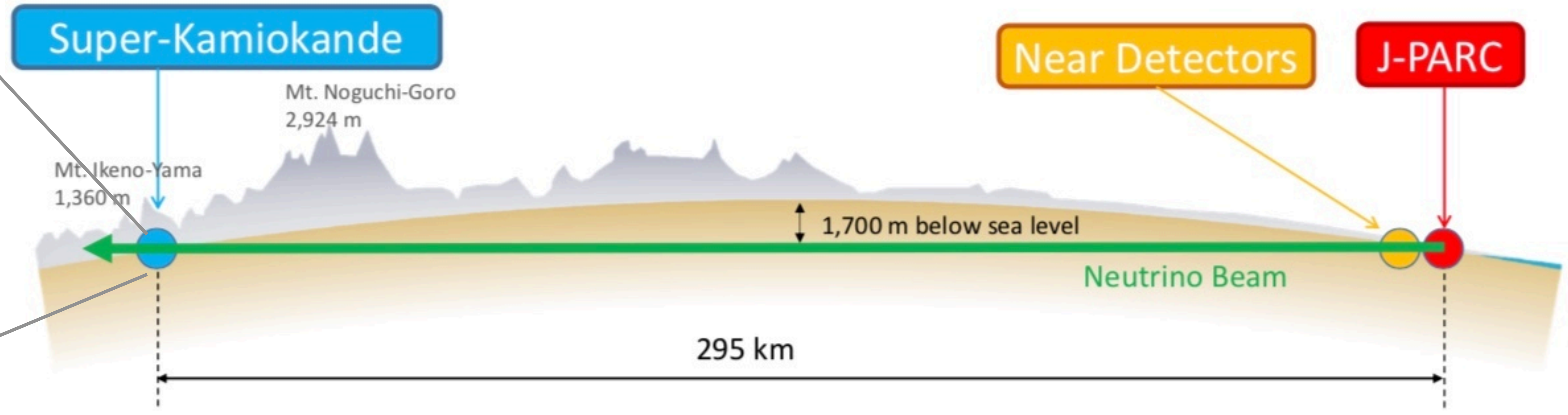
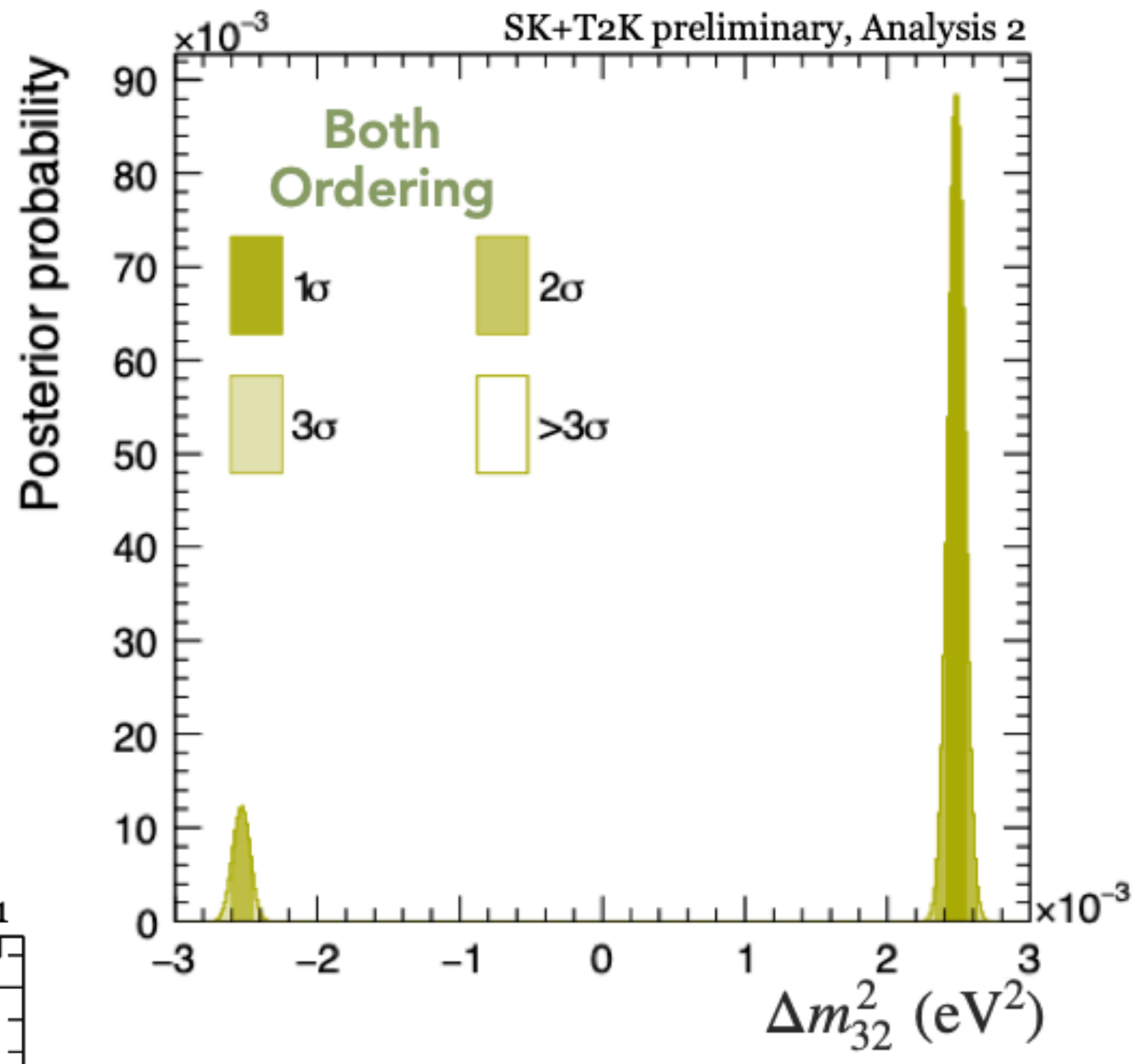


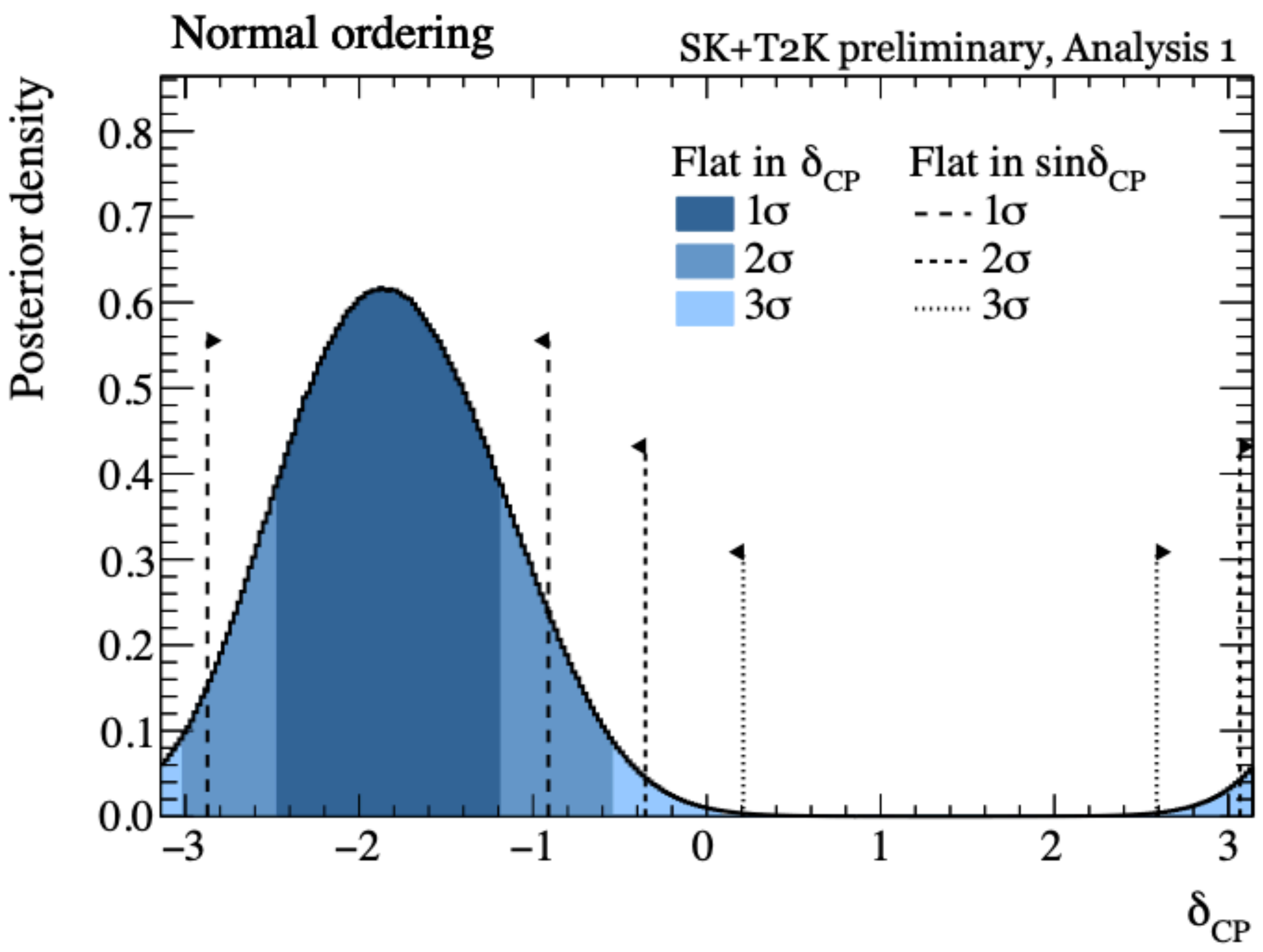
Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

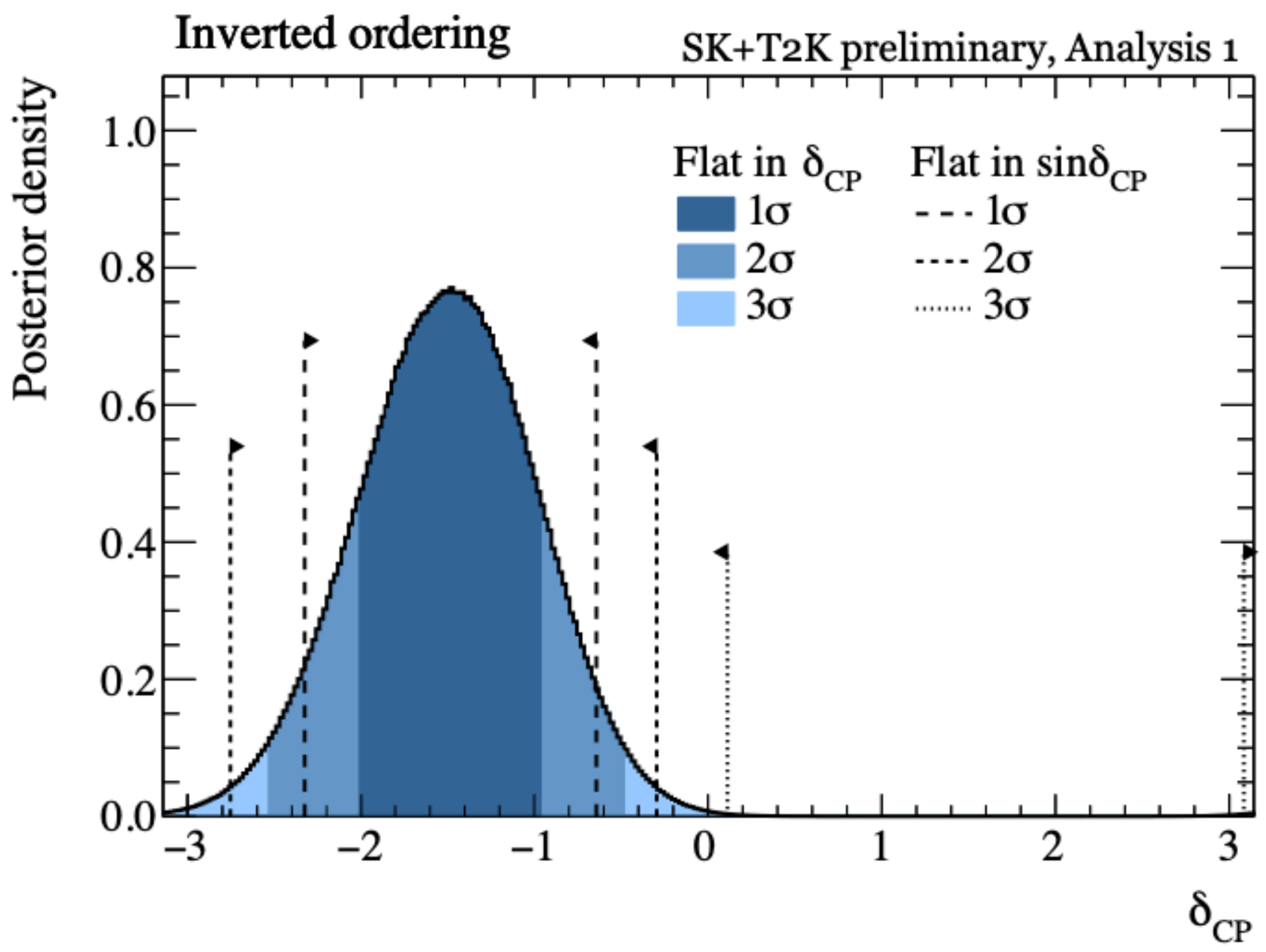


SuperK+T2K results

- ✳ The same detector, similar infrastructure for analysis.
  - ✳ Not so straight forward anyway.
- ✳ Slight preference for normal ordering:
  - ✳ Bayes factor B(NO/IO) = 8.98 ;
  - ✳ p-value for IO = 0.08 (1.2σ deviation, using one-sided test).
- ✳ Between 1.9σ and 2.0σ exclusion of CP symmetry.
  - ✳ Joint fit prefers values close to $-\pi/2$ for both MO cases with $\pi/2$ outside 3σ.







Summary of current joint fit experience

Caveat: I was involved in NOvA+T2K on NOvA side

- For both NOvA+T2K and SK+T2K it took years. Both started in ∼2016.
- Combining experiment analyses is hard:
  - T2K + NOvA: similar physics, but very different detectors and analysis methods;
  - T2K + SK: combined same detector (SK) but using different physics samples and different analysis methods.
- Overall it was a good experience for both efforts with nice physics outcome, but:
  - the data and analysis techniques used for combination are not the most up-to-date → desynchronisation w/ own analyses due to long process;
  - most likely good fraction of work will need to be re-done for the next cycle;
  - lot's of politics is hidden behind these results.
- In general, there is a common feeling that both efforts should be continued.
  - Lot's of new physics can be done: new 3F, sterile, NSI, cross-section measurement analyses etc.

General thoughts on cross-exp. joint fits - I

- If next gen. experiments start preparations for joint fits ~today many things can be done better.
- On decision to use containers:
  - was the only possible solution for NOvA+T2K (experiments had been running for years);
  - internals are hidden (easing political issues around data sharing) but validation is harder;
  - overall nice idea: let you simultaneously call code that isn't compatible;
    - if code it compatible it's better to use common infrastructure, like SuperK+T2K did.

General thoughts on cross-exp. joint fits - II

On neutrino interaction generators:

- ✳ There are GENIE, NEUT, ACHILLES, NuWro, GiBuu etc.
  - ✳ Good for cross-check, bad for compatibility.
  - ✳ Each experiment's analysis and simulation toolchain cannot easily take input from the other's generator.
- ✳ NOvA uses GENIE, T2K uses NEUT: different model description for the same processes → different systematic uncertainties with no direct mapping, not trivial to correlate.
- ✳ SK uses NEUT, but model choices can be different even for the same generator (LFG vs SF for QE).

Ideal would be to have a unified approach to describe neutrino interactions.

- ✳ Most likely not possible but there are some attempts.
- ✳ At least, like in collider experiments a unified format for generator output/analysis simulation input will be a big help (e.g. LHE files/HEPMC3 → NuHEPMC).
  - ✳ Lot's to learn from LEP and LHC experiments that are (had been) doing joint fits for decades.

Future experiment unifications

DUNE, HyperK, JUNO, IceCube-Upgrade, ORCA are coming and aim for precise neutrino physics.

- ✴ Independent experimental results necessary to confirm discoveries but join analysis provides many benefits and increase in sensitivity.
- ✴ Direct searches for new physics, non-standard interaction searches, unitarity of PMNS etc.
  - ✴ Need all of them (reactor, atmospheric, beam, solar).
- ✴ Not clear whether there will be any next-to-next gen. experiments.
  - ✴ Nonzero chance that data collected by next gen. experiments will be used for decades with goal to extract as much physics as possible.

These experiments will be systematics limited, some decisions made by current joint fits will not be applicable.

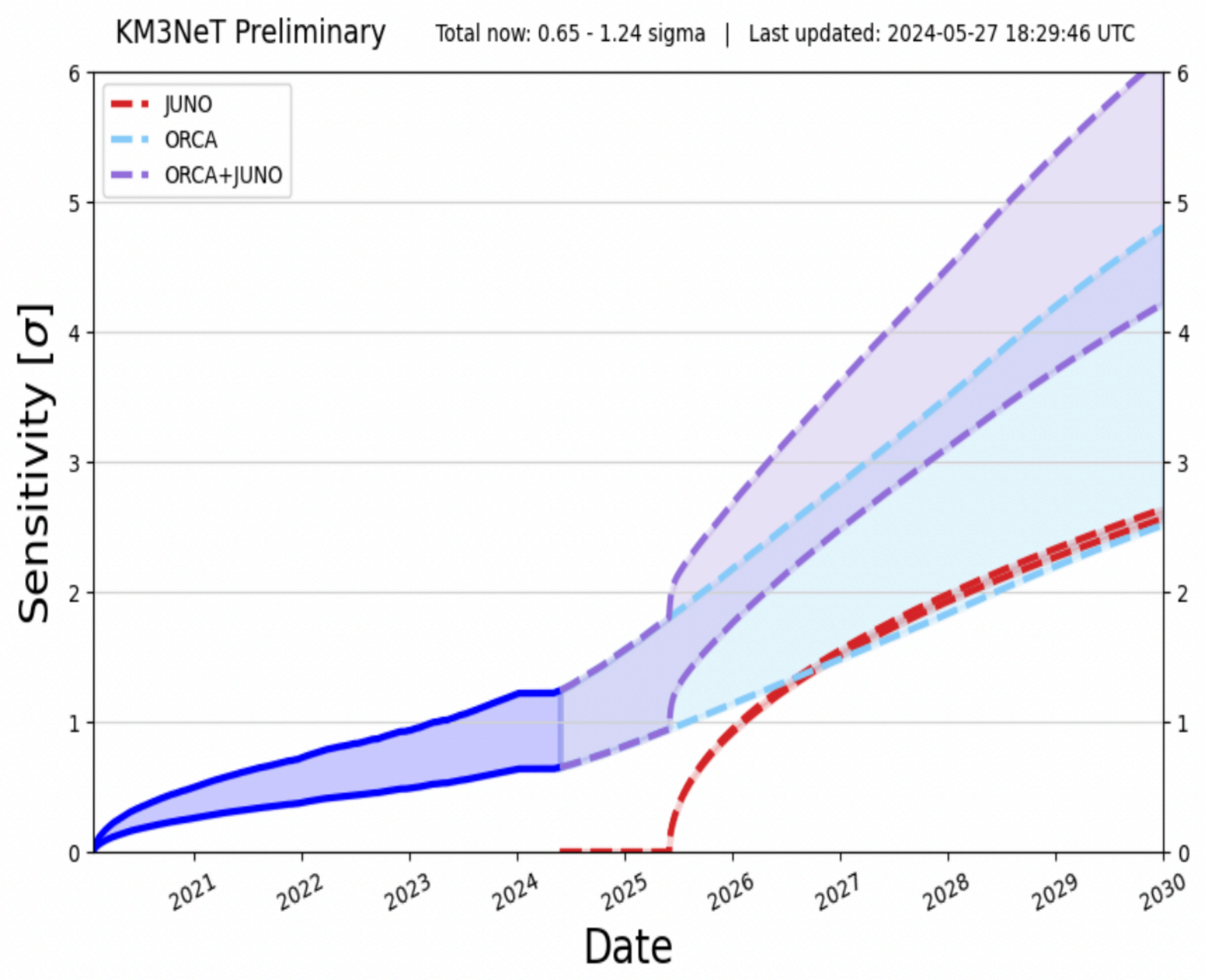
- ✴ e.g. even the tiniest effects have to be taken into account like correlations in flux systematics for beam and atm. fluxes.

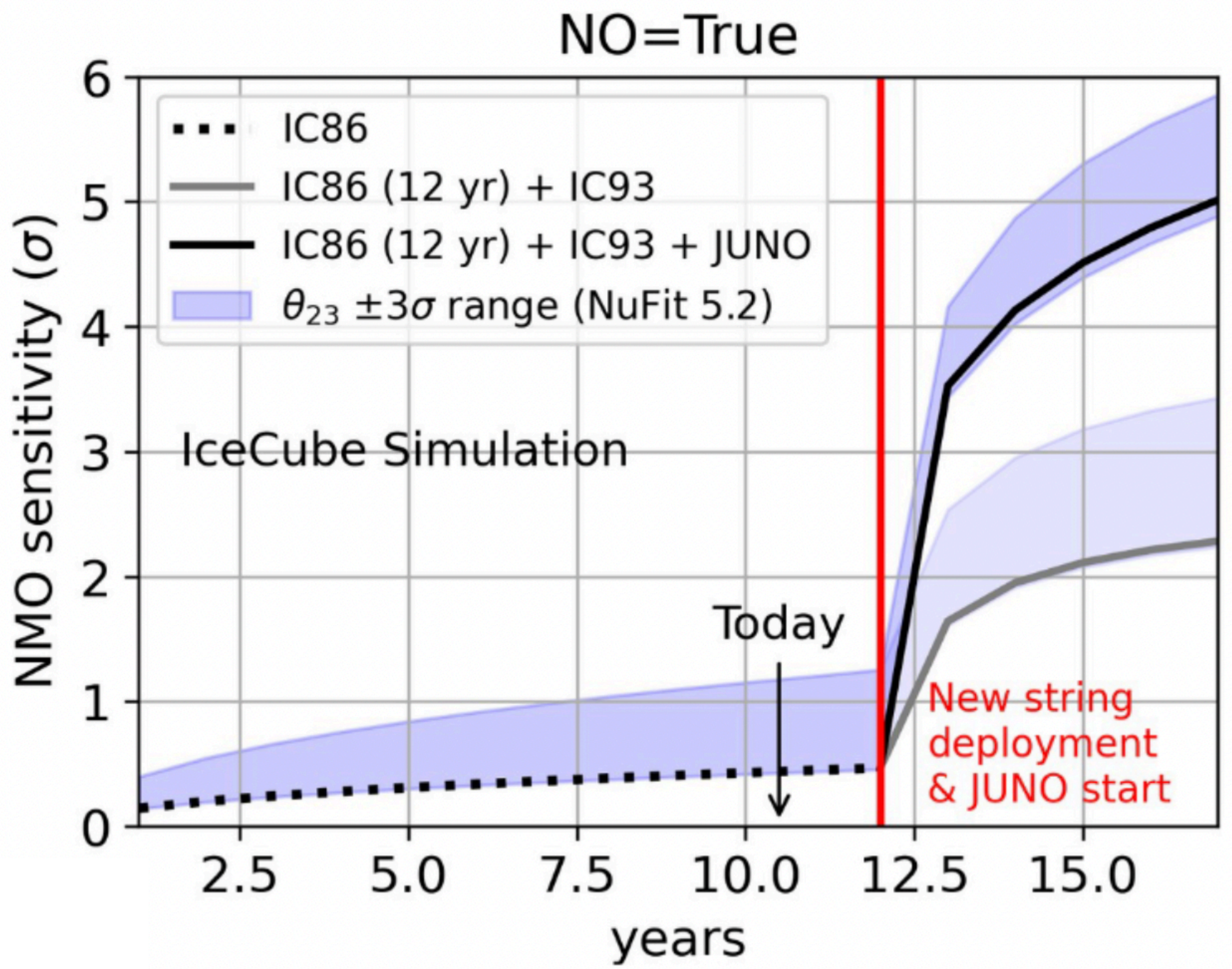
Ideas in the air these days

Joint fits w/ JUNO

IceCube and ORCA express interest in cooperation with JUNO that will start data taking soon:

- ✴ ORCA + JUNO can reach 3σ in ∼2028;
- ✴ IC + JUNO can reach the same in ∼2027.





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- ✳ IC + JUNO can reach the same in ∼2027.

There is similar idea and timelines with accelerator experiments (NOvA, T2K).

In JUNO + accel. and JUNO + atm.:

- ✳ In the true MO reactor and LBL measurements of Δm^2_{32} would be consistent but in incorrect MO would be wrong by different amounts.

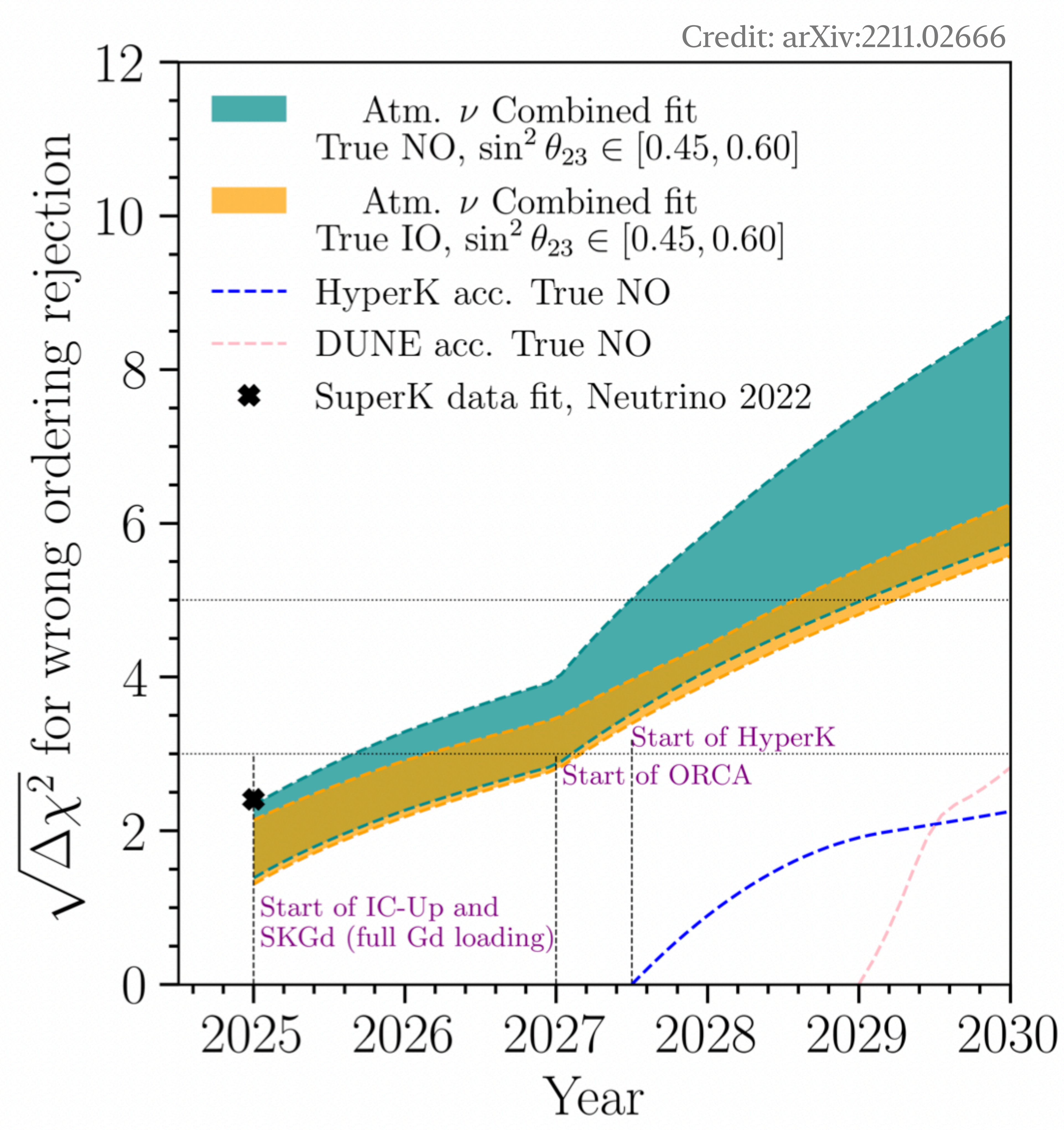
Ideas in the air these days

All atm. experiments together

- There are ideas on making a joint fit of all atmospheric experiments:
  - future atmospheric experiments ORCA (full scale in ~2028), HyperK (start in ~2027), IceCube upgrade (start in ~2026);
  - currently running SuperK.

- Physics output is very inspiring:
  - by 2030: 6σ MO, θ_{23} octant determination at 3σ, increased precision of all parameters.

- On practice such an effort will be very difficult both technically and politically.



Another approach: global fits

This effort exists for decades.

- ✴ First global analysis was published in 1994.
- ✴ Main players in the field today are NuFIT, Bari and Valencia groups that produce results on:
  - ✴ three-flavour oscillation parameters,
  - ✴ 3+1, 3+2 oscillation parameters,
  - ✴ NSI parameters.

- ✴ Newcomers: Gambit, GNA (JINR).
  - ✴ Very long way ahead.

PHYSICAL REVIEW D

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Comprehensive analysis of solar, atmospheric, accelerator, and reactor neutrino experiments in a hierarchical three-generation scheme

G. L. Fogli, E. Lisi, and D. Montanino

Phys. Rev. D **49**, 3626 – Published 1 April 1994

Article | References | Citing Articles (97) | PDF | Export Citation

ABSTRACT

We consider the possible evidence of neutrino oscillations by analyzing simultaneously, in a well-defined hierarchical three-generation scheme, all the solar and atmospheric neutrino data (except for upward-going muons) together with the constraints imposed by accelerator and reactor neutrino experiments. The analysis includes the Earth regeneration effect on solar neutrinos and the present theoretical uncertainties on solar and atmospheric neutrino fluxes. We find solutions and combined bounds in the parameter space of the neutrino masses and mixing angles, which are compatible with the whole set of experimental data and with our hierarchical assumption. We also discuss possible refinements of the analysis and the perspectives offered by the next generation of neutrino oscillation experiments.

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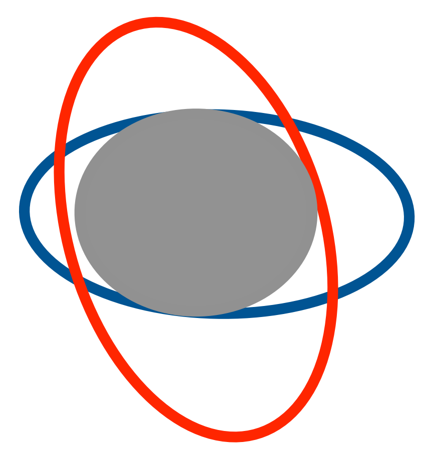
Global fits

General approach

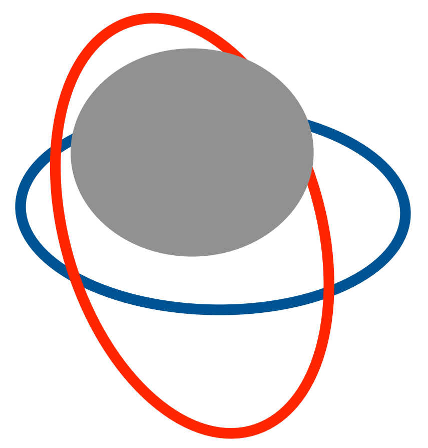
Have to use lots of approximations to make basic predictions that are used to apply oscillations.

- Impossible to repeat gigantic work on experiment simulation performed by collaborations.
  - Details of simulations (and other analysis details) most often are not shared outside collaboration.
- There is no "universal" fit output that can be used for global fit to repeat the experiment fit.
  - Some experiments are making public χ^2 maps, but that's not enough for proper joint fit.
- Interexperiment correlations:
  - the only correlations taken into account are the oscillation parameters;
  - systematic parameter correlations are non-trivial, thus excluded.
  - Of course, correlations matter.

$$\chi^2 = \chi_1^2 + \chi_2^2$$



$$\chi^2 = \chi_1^2 + \chi_2^2 + \Delta_{12}$$



Global fits

General approach

Have to use lots of approximations to make basic predictions that are used to apply oscillations

- ✳ Impossible to repeat gigantic work on experiment simulation performed by collaborations.
- ✳ Details of simulations (and others) are not shared outside collaboration.
- ✳ There is no "universal" output that can be used for global fit.
    - ✳ Some experiments are making public χ^2 maps, but that's not enough for joint fit.
- ✳ Interexperiment correlations of systematics excluded, but of course, they matter.
- ✳ With current experiments this approach works.
    - ✳ Most likely in the next decade it will be still valid.
- ✳ Given sensitivity of future experiments, hints on MO will be obtained by global fits by $\sim$2030 and this is the only way to perform the world measurement of parameters these days.
    - ✳ Neutrino experiments have just started to make joint fits.
- ✳ These days joint fits are very comprehensive and include also cosmology $\sum m_i$, $0\nu\beta\beta$, β- decay m_β.

Recent physics highlights from NuFIT 6.0

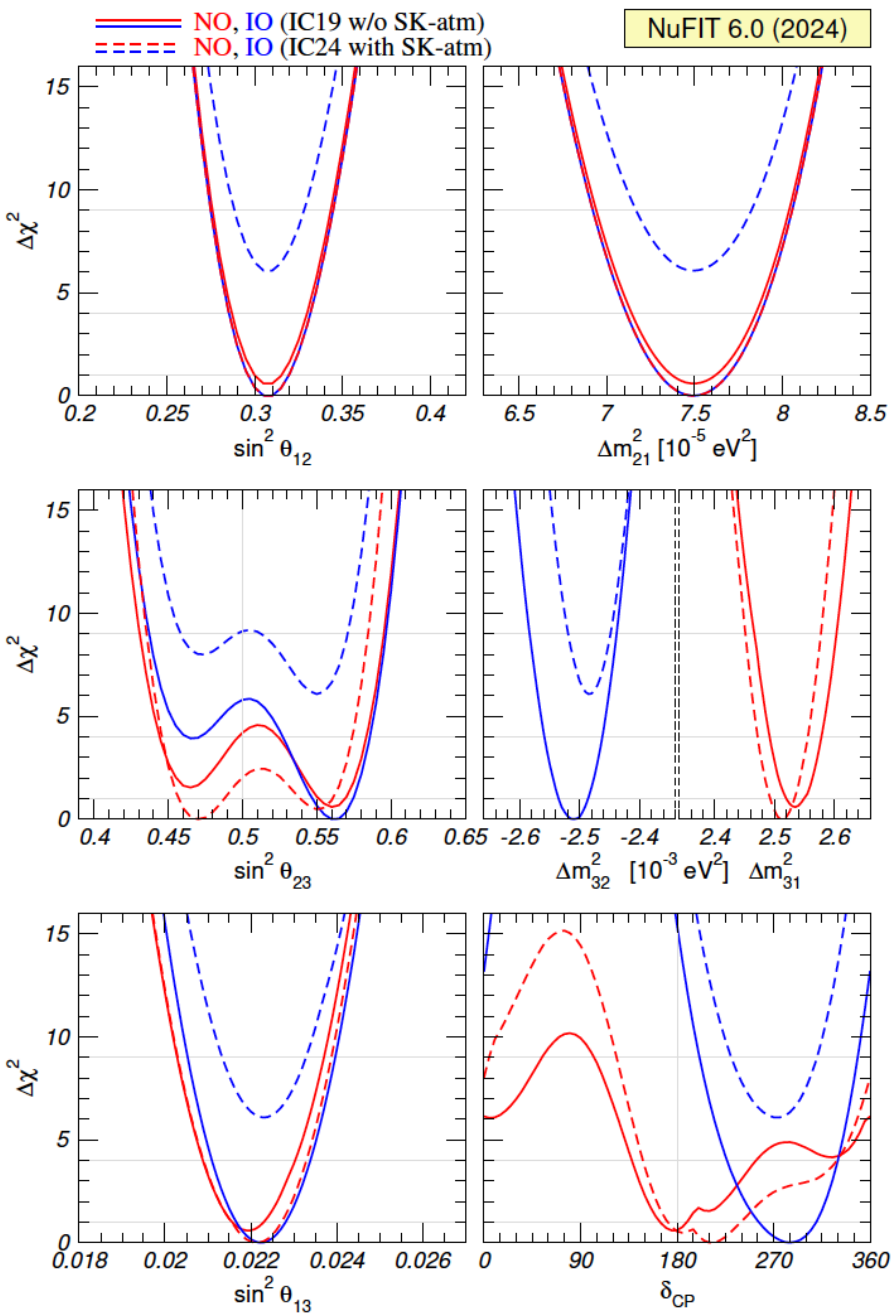
Credits: NuFIT team arXiv:2410.05380

Summary plots:

- Split results by:
  - MO: NO and IO;
  - IC19 w/o SK vs IC 24 w/ SK;
    - in case of IC19 w/o SK NuFIT team perform simulation of IC;
    - in case of IC24 w/ SK NuFIT team includes χ^2 official maps from these experiments.

- Changes in comparison with NuFIT 5.0:
  - new results from: NOvA, T2K, SuperK, IceCube, SNO+ etc;
  - new inputs: solar, reactor fluxes.

- General conclusions are similar to NuFIT 5.0.
- Still inconclusive results on
  - MO, δ_{CP}, $\sin^2\theta_{23}$ (too many correlations for these three);
  - Δm^2_{21} (new SNO+ results is not precise to change situation).



Recent physics highlights from NuFIT 6.0

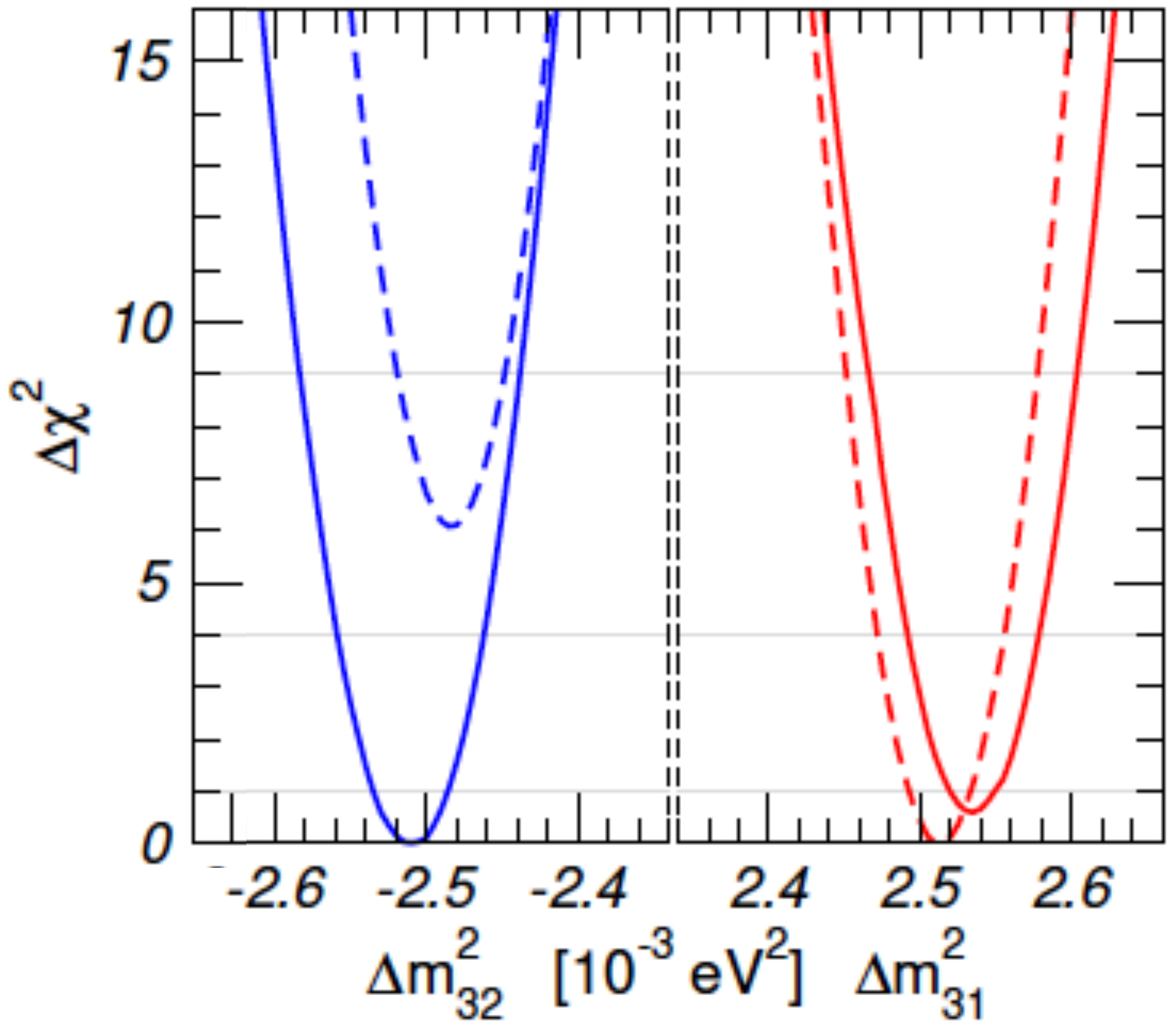
Mass ordering and δ_{CP}

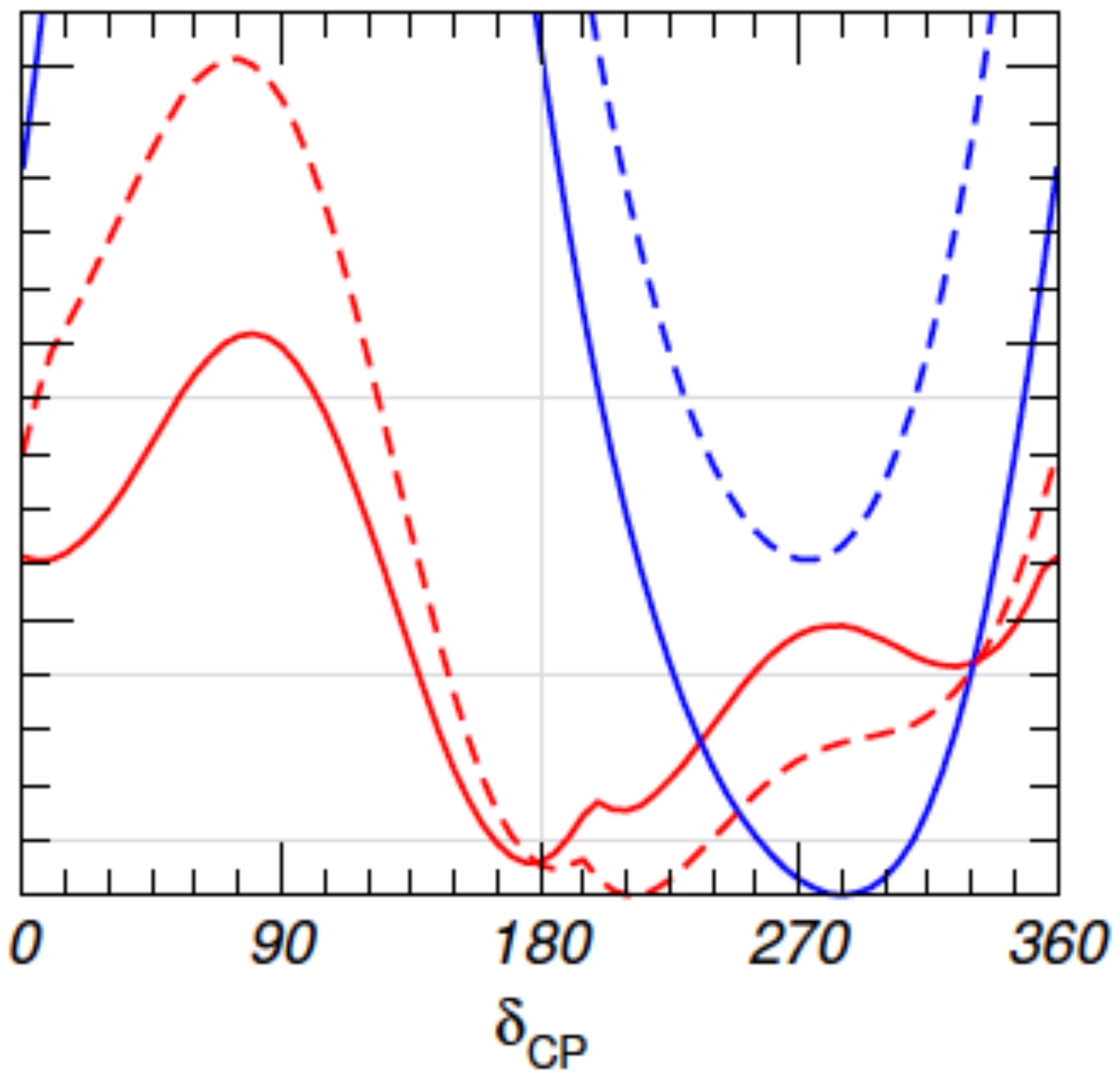
Mass ordering:

- In case of **IC19 w/o SK** IO is weakly preferred;
- In case of **IC24 w/ SK** NO is preferred at $\Delta\chi^2 \sim 6$ (due to precise Δm^2_{32});
- Some role here is played by NOvA vs T2K disagreement.
  - With new NOvA data it's a little higher than 4 year ago, but still $\sim 2\sigma$.

δ_{CP}:

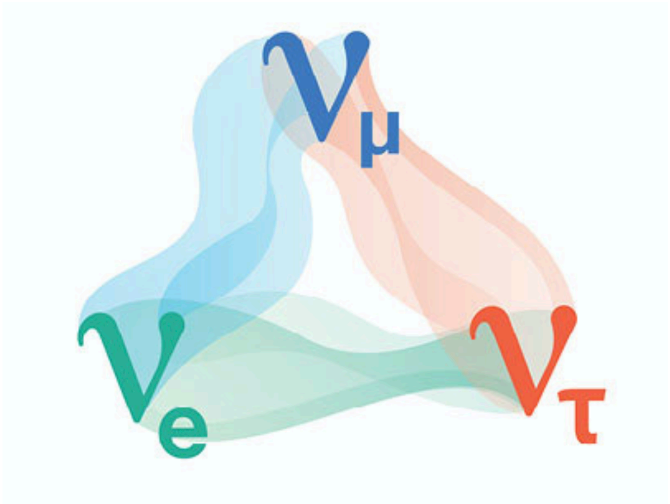
- Largest role here is played by NOvA and T2K.
- IC and SK doesn't change best fit much:
  - in NO it's close to 180°;
  - in IO is's 270°.





Summary

- ✳ Neutrinos oscillate and over the last ∼25 years that process was studied quite well.
- ✳ There are still some not yet measured parameters (mass ordering, CP violation) that are the goal of current and future experiments.
- ✳ In 2023-2024 NOvA+T2K and SuperK+T2K presented their first joint fit results.
  - ✳ Besides physics output and creation of all infrastructure and ground base that will be used for future analyses this is a wonderful example of cooperation.
    - ✳ This is the first such kind of effort for neutrino physics.
- ✳ The next 10-15 years will be quite interesting in neutrino physics especially due to the start of the next generation experiments.
  - ✳ Global analysis will still be important source of information.
  - ✳ There are some joint analyses expected, especially DUNE and HyperK that should be also very challenging.



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