Исследование осцилляций нейтрино в ускорительных и реакторных экспериментах

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Сессия-конференция «Физика фундаментальных взаимодействий»
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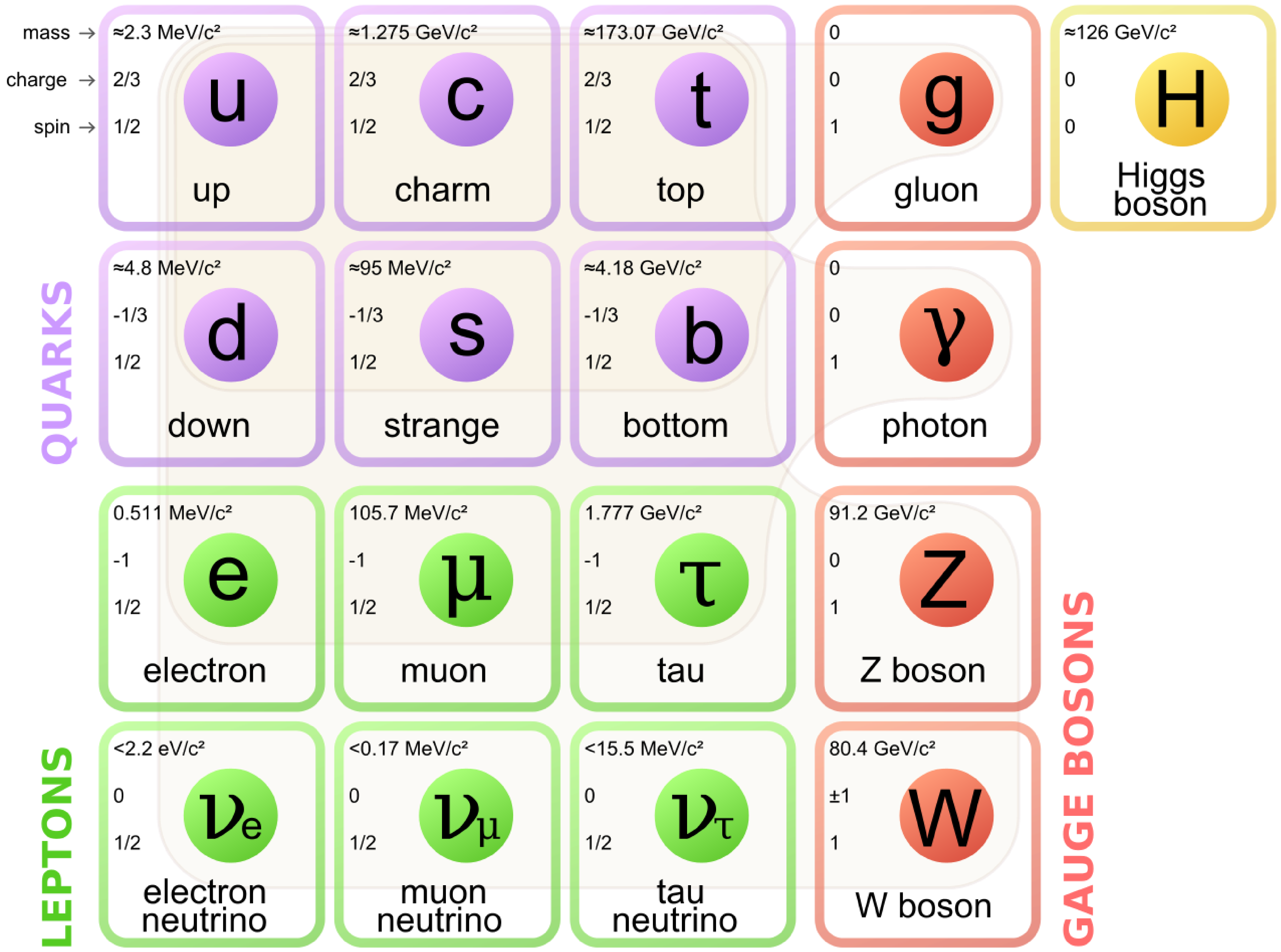
Особая благодарность коллегам: Людмиле Колупаевой и Максиму Гончару за помощь в подборе материала, в частности, поддержку базы данных осцилляционных результатов
https://git.jinr.ru/nu/osc

Neutrino physics

- ✶ Standard Model particle.
- ✶ Small but non zero mass.
- ✶ Neutrino interactions conserve flavor.
- ✶ Interact only via weak (and gravity) force.



Modern hot topics:

- ✶ Study neutrino properties, incl. three-flavor oscillation parameters;
- ✶ search for sterile neutrinos;
- ✶ measurement of absolute neutrino masses,
- ✶ search for neutrinoless double beta-decay (are neutrinos Dirac or Majorana particles);
- ✶ detection of relic neutrinos;
- ✶ detection of high energy astrophysical neutrinos and spotting their sources;
- ✶ …

Neutrino oscillations and mixing

PMNS matrix

atmospheric accelerator	short baseline reactor accelerator	solar long baseline reactor

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

Oscillation parameters and how precisely do we know them:

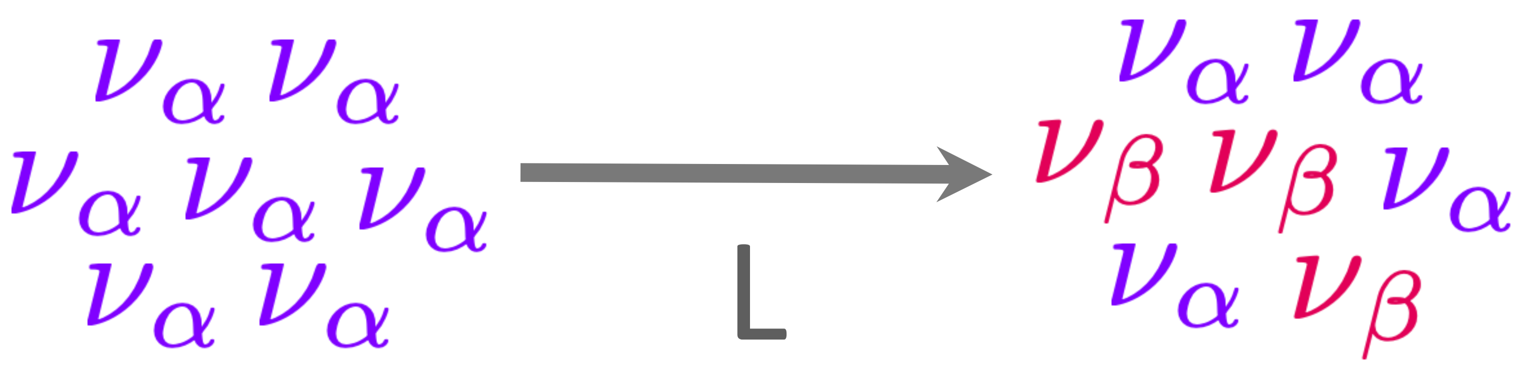
$\theta_{12} \approx 34°$ (4.4%)

$\theta_{23} \approx 49°$ (5.2%)

$\theta_{13} \approx 9°$ (3.8%)

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

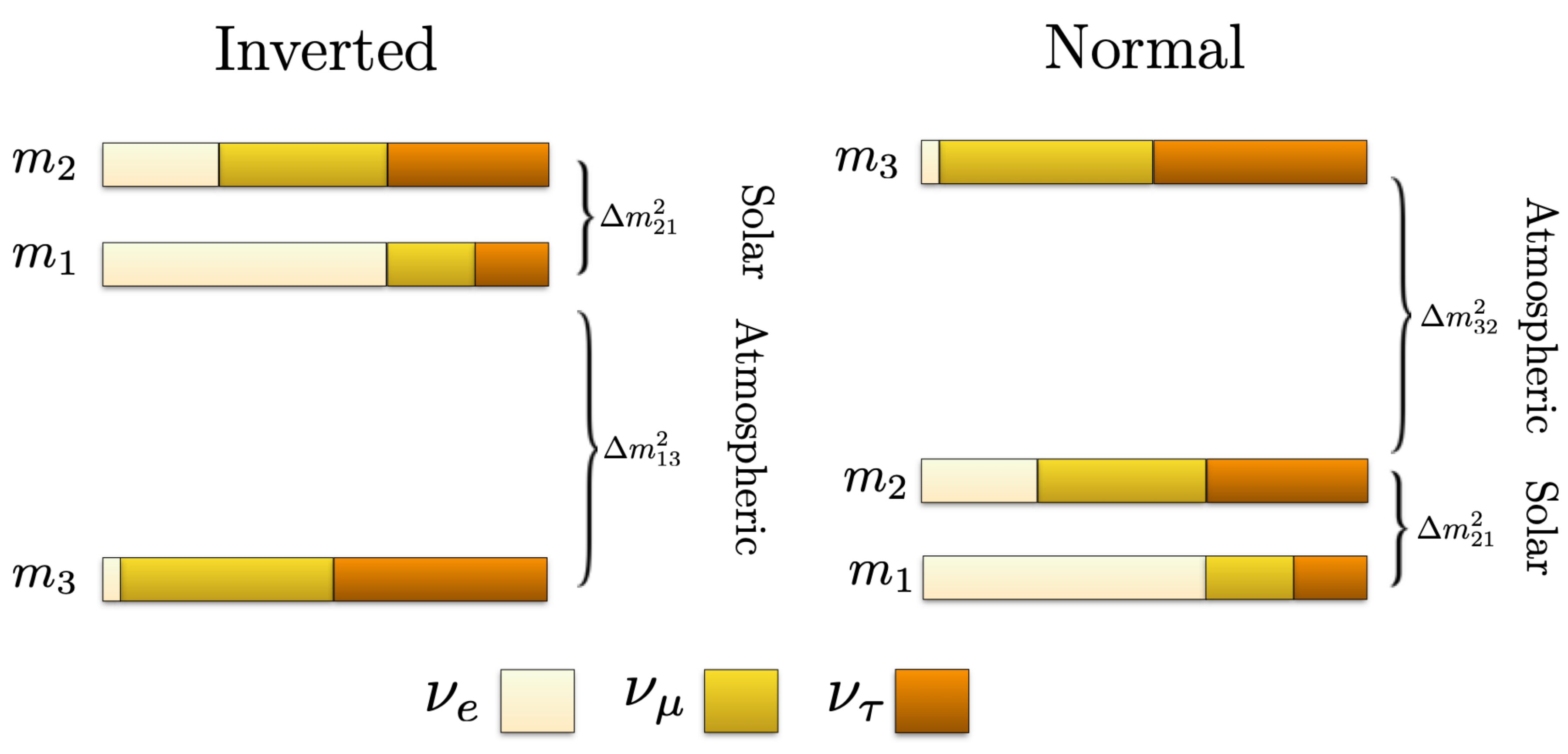
$\Delta m^2_{32} \approx +2.5 \times 10^{-3}\ \mathrm{eV}^2$ (1.4%)



Open questions:

✴ Is θ_{23} $45°$? (possible ν_μ ν_τ symmetry in ν_3)

✴ Is there CP violation in lepton sector? (matter-antimatter asymmetry of the Universe (leptogenisis)

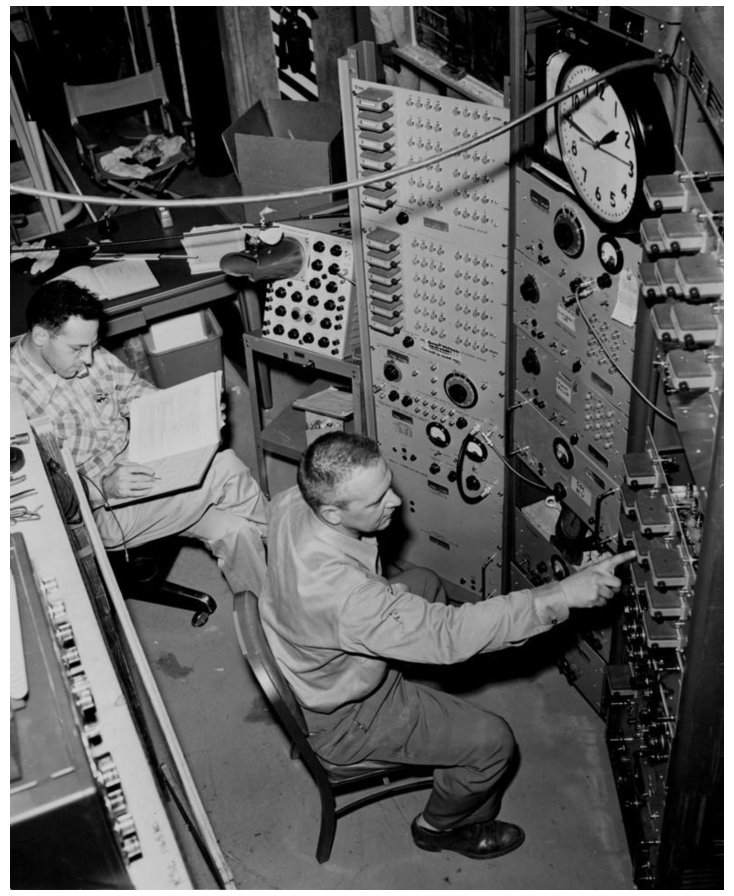


✴ Neutrino mass hierarchy (ordering) is Normal or Inverted? (neutrinoless double beta-decay searches, supernova simulations, relic neutrinos searches, absolute ν mass measurements etc)

Reactor and Accelerator experiments

✴ Both are artificial sources, very much deserved historically:

- ✴ Discovery of Neutrino
  by F.Reines and C.Cowan
  in the reactor Savannah River
  experiment in1956



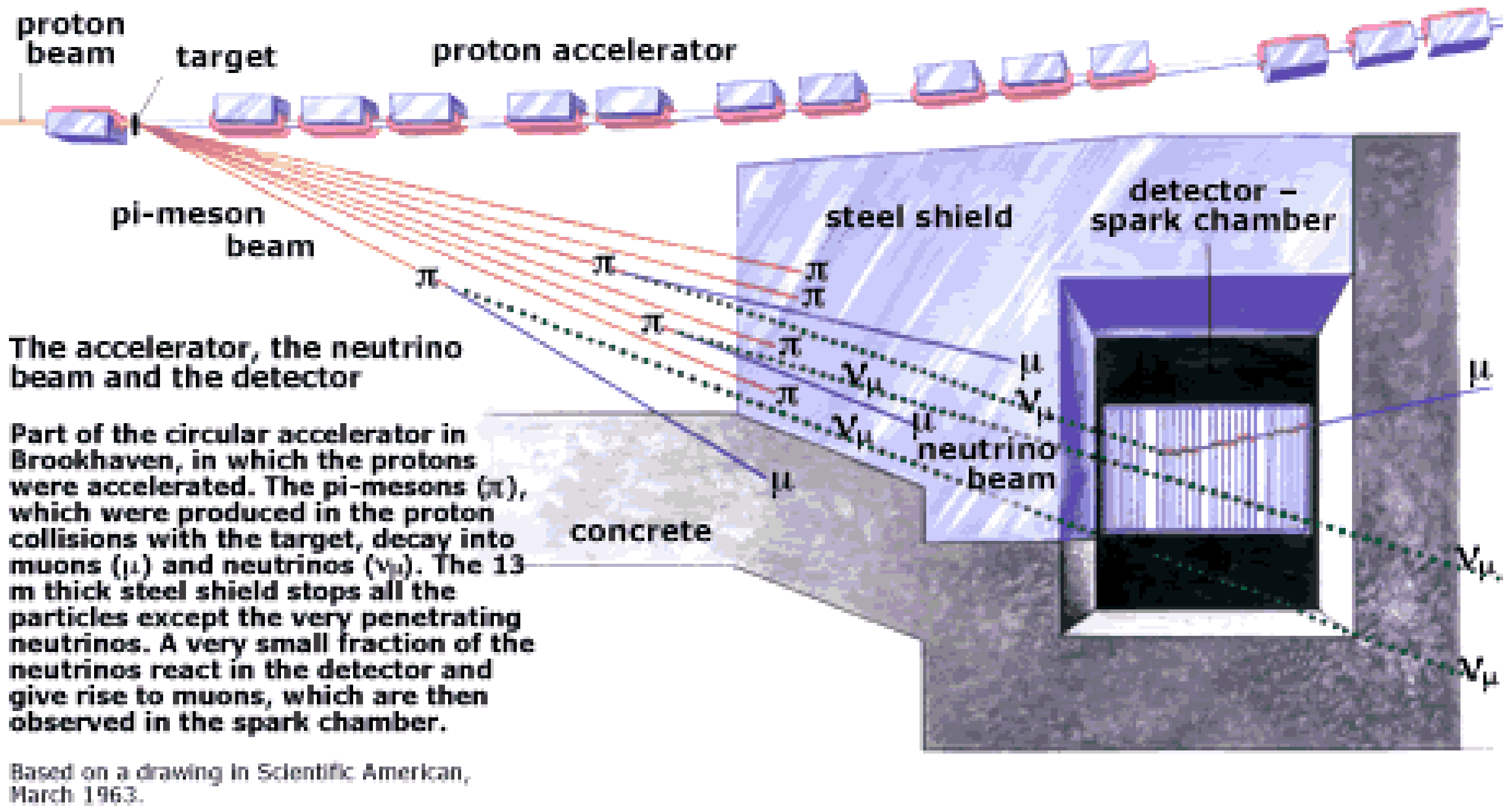
Detection of inverse beta-decay:

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

$$\hookrightarrow + {}^{108}Cd \to {}^{109m}Cd \to {}^{109}Cd + \gamma$$

Marked the beginning of experimental neutrino physics

- ✴ Discovery of the Muon Neutrino
  by L.Lederman, M.Schwartz and J.Steinberger
  at BNL accelerator in 1962 established neutrino flavor quantum number

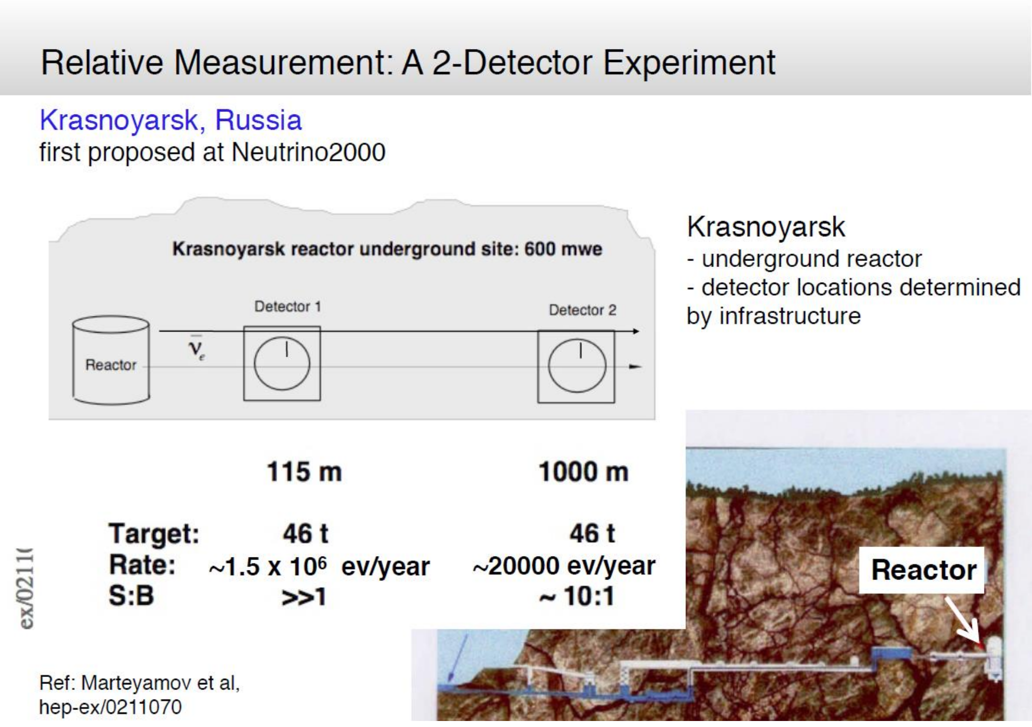


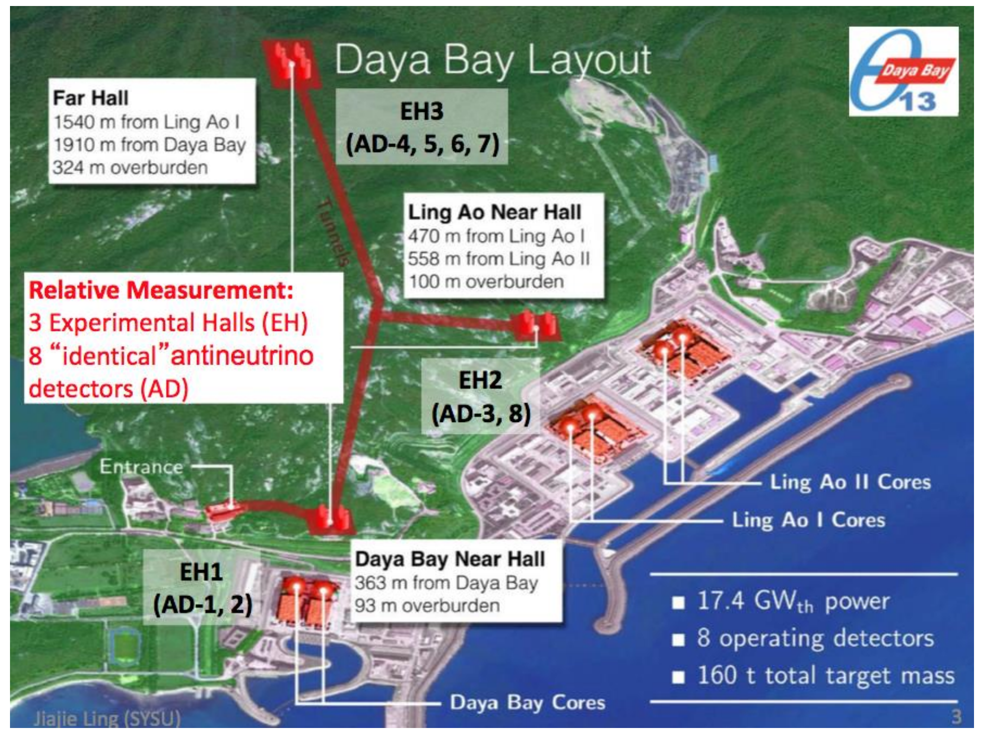
It is worth mentioning that in both cases there was contribution from Bruno Pontecorvo to those ideas

Reactor experiments

Using fission reactions:

=> Flavor: Electron antineutrino ($\bar{\nu}_e$)
=> Energy < 10 MeV
=> Tens of GW power available (for free)
=> Rate ~ 2 · 10^{20} /GW
=> Distances available from several meters to hundreds of kilometers
=> Flux uncertainties solved by two-detector scheme

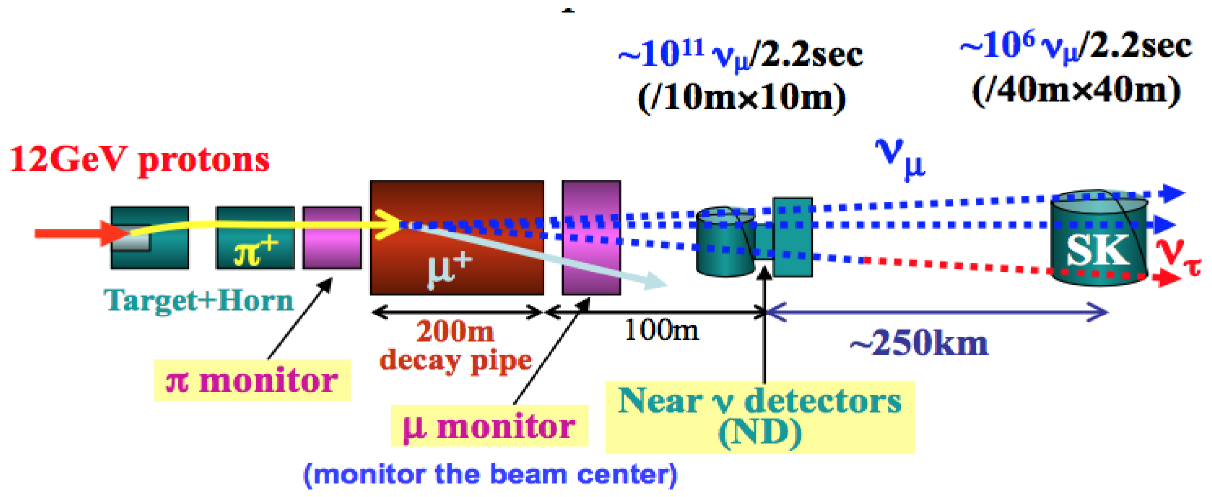


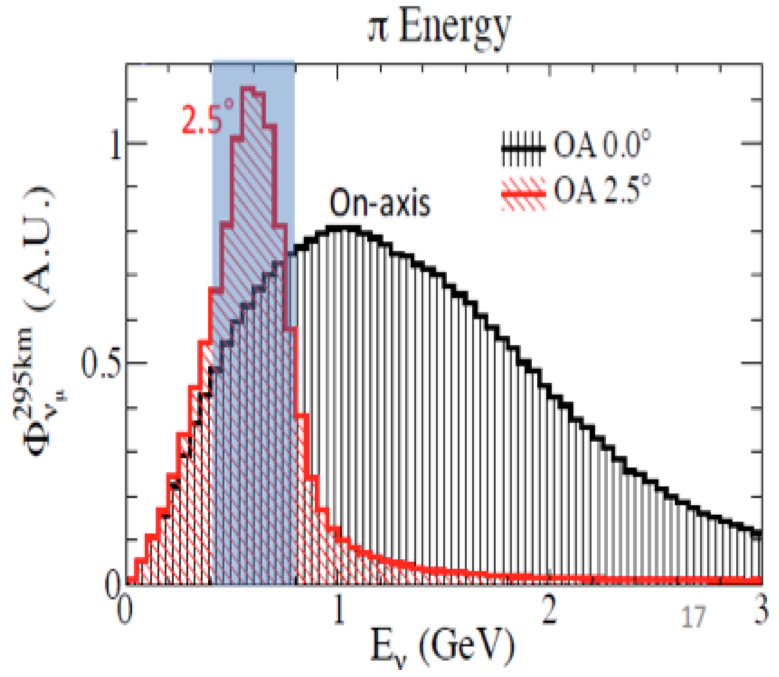


Accelerator experiments

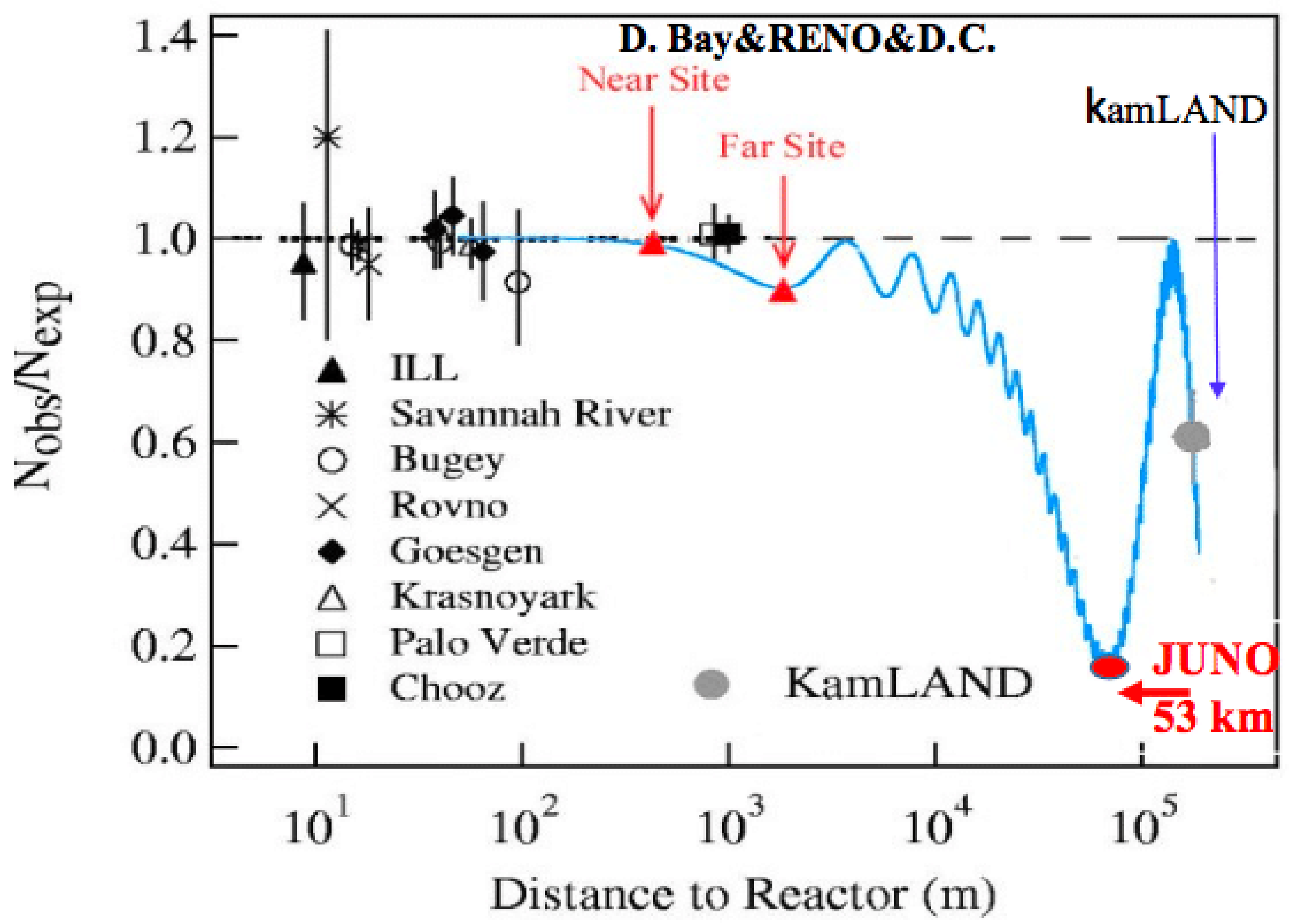
Using meson decays on flight:
=> Produced by proton beams on a target
=> ~ MW beam power available
=> Flavor: Muon (anti)neutrino ($\bar{\nu}_\mu$ and ν_μ)
=> Energy tunable
=> Exposure in Protons On Target (POT)
=> Distances available from several meters to thousand of kilometers
=> Flux uncertainties solved by two-detector scheme

=> Off-axis concept allows to ”monochromatize” neutrino energy (i.e., reduce background from high energy tail)





Reactor experiments



Depending on baseline can measure:

- short baseline (5 - 30 m) - search for sterile neutrinos and measurement of Δm^2_{41} and $\sin^2 2\theta_{14}$
- medium baseline (1 - 2 km) - measurement of $\sin^2 2\theta_{13}$ and Δm^2_{32}
- long baseline (>10 km) - measurement of Δm^2_{32} , neutrino mass ordering, Δm^2_{21}, $\sin^2 2\theta_{12}$, and $\sin^2 2\theta_{13}$ (with less precision than medium baseline experiments)

Precise measurement of $\sin^2 2\theta_{13}$ and Δm^2_{32} plays utmost important role:

- Disappearance experiments to measure $\bar{\nu}_e$ survival probabilities: $P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2(1.267\Delta m^2_{31} L/E)$
- No ambiguity, independent of matter effect (at this baseline) and δ_{CP}
- Place two detectors for a relative measurement, <1% systematics, big statistics

Reminder of the first non-zero θ_{13} reactor measurements:

- Daya Bay (March 2012, 5.2σ) Phys.Rev.Lett. 108 (2012) 171803
- RENO (April 2012, 4.9σ) Phys.Rev.Lett. 108 (2012) 191802
- Double Chooz far detector (Nov. 2011, 94.6% C.L.) Phys.Rev.Lett. 108 (2012) 131801

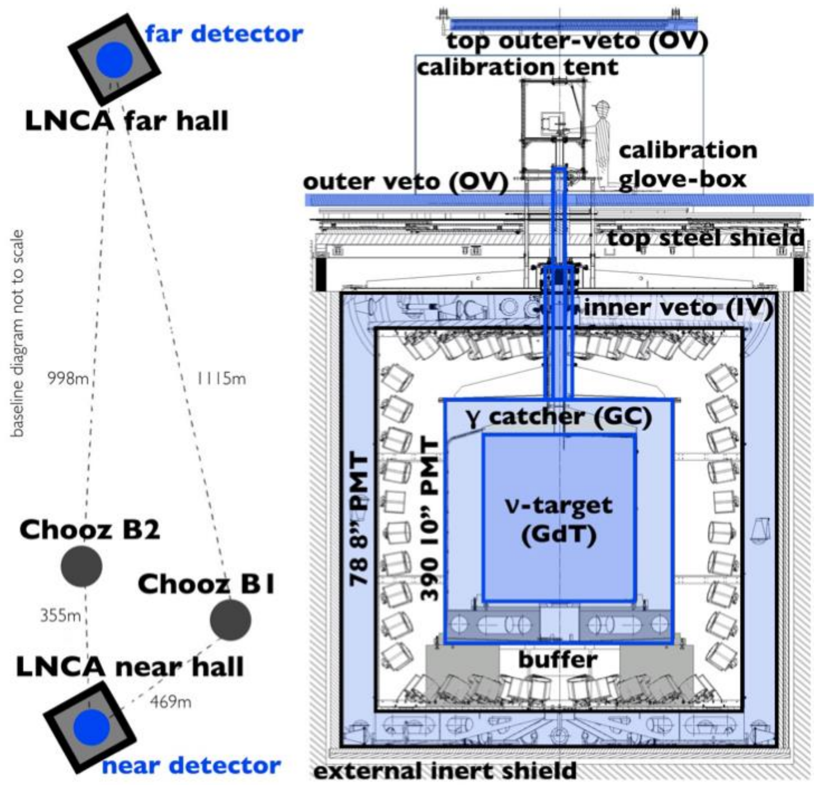
Also hints from T2K and global fits for non-zero θ_{13}.

This allowed measuring leptonic δ_{CP} via oscillations:

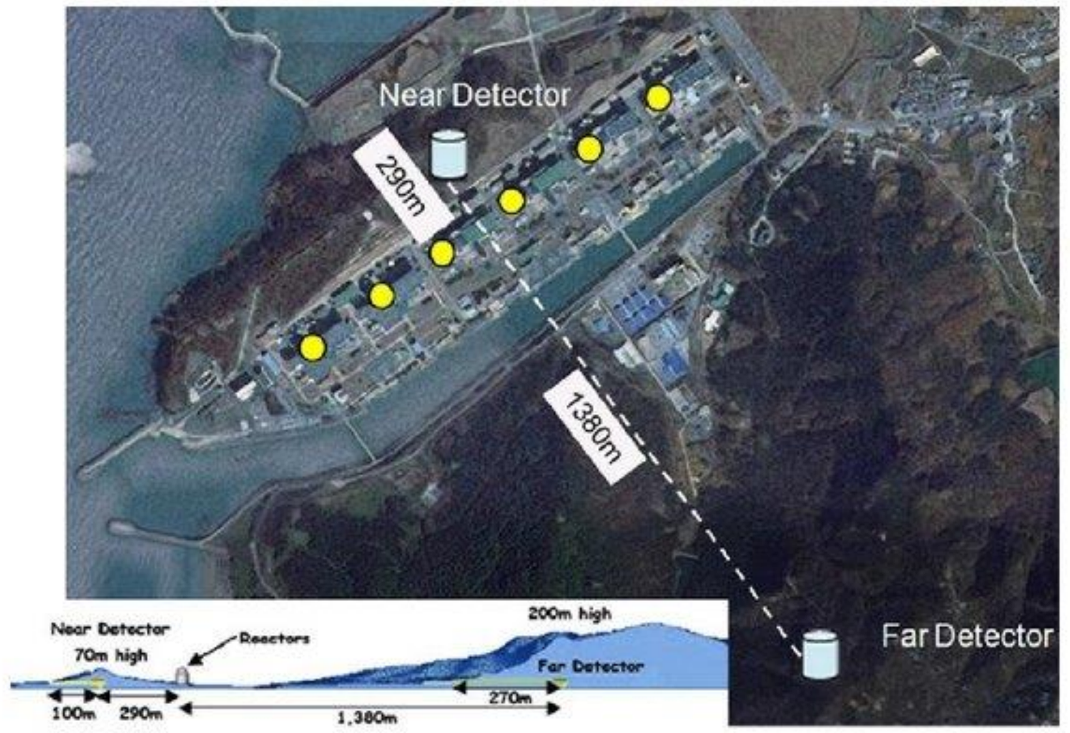
$$P(\nu_\mu \to \nu_e) \sim \frac{\sin^2\theta_{23}\sin^2 2\theta_{13}}{(1-\rho_m L)^2} - 0.04\frac{\sin 2\theta_{13}}{(1-\rho_m L)}\sin\delta_{CP}$$

Reactor experiments measuring θ_{13} :

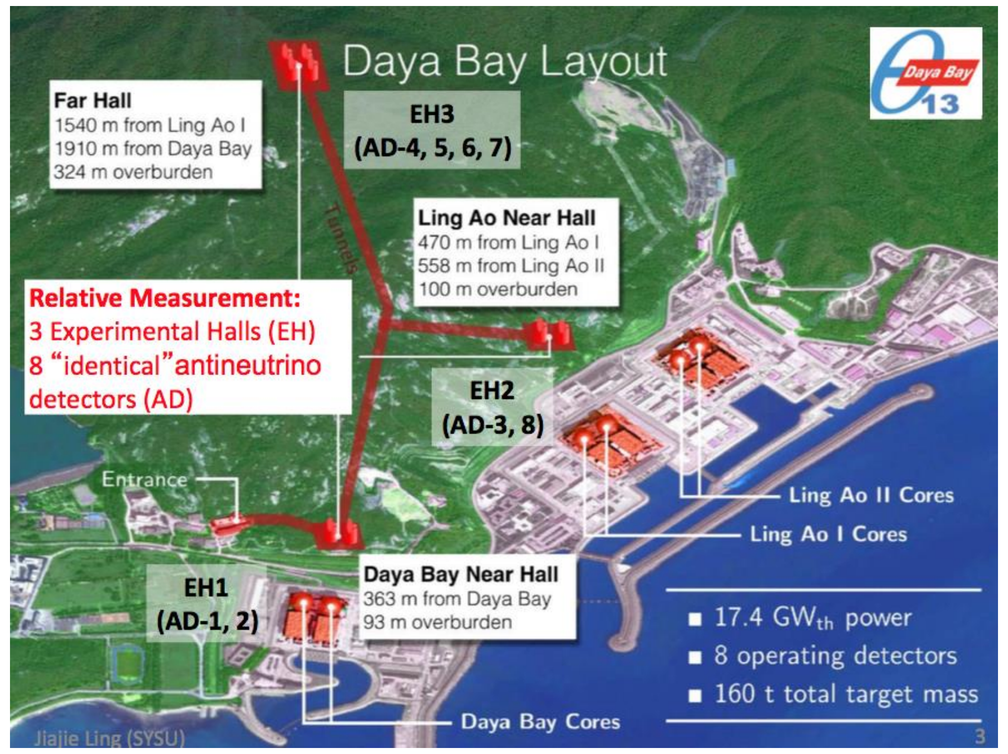
Double Chooz



Reno



Daya Bay



- Double Chooz Apr. 2011 to Dec. 2017, ~1350 days
- RENO Aug. 2011 to Mar. 2023, ~3800 days
- Daya Bay, Dec. 2011 to Dec. 2020, 3158 days

All captures (nGd + nH + nC), full dataset

Neutrino 2020 results (new analysis in progress):

$\sin^2 2\theta_{13} = 0.102 \pm 0.004(\text{stat.}) \pm 0.011(\text{syst.})$
(precision 11.8%)

nGd, full dataset
Neutrino 2024
$\sin^2 2\theta_{13} = 0.0920 \pm 0.0044(\text{stat.}) \pm 0.0041(\text{syst.})$
(precision 6.5%)

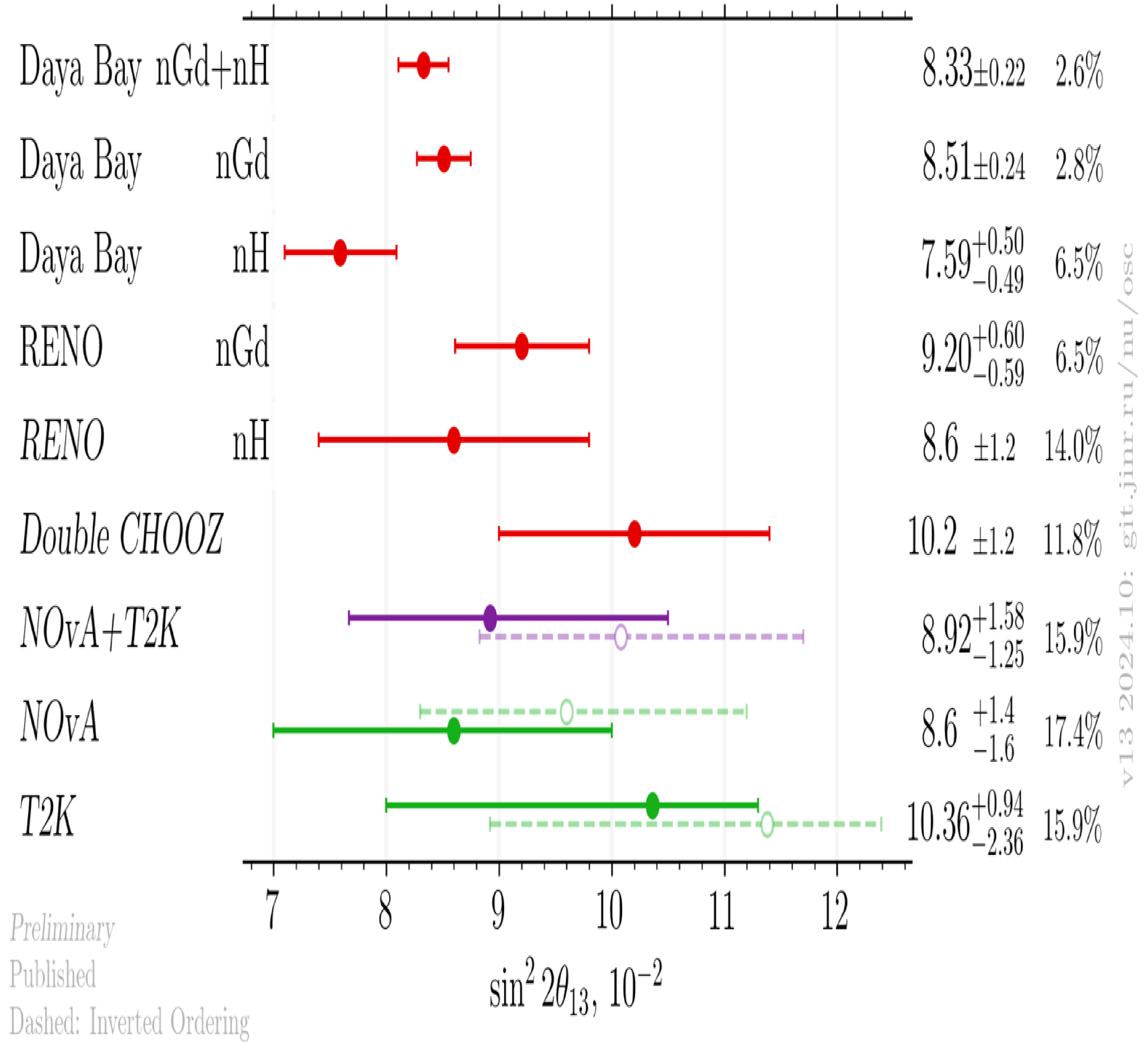
nH, ~2800 days
New results at Neutrino 2024:
$\sin^2 2\theta_{13} = 0.082 \pm 0.007(\text{stat.}) \pm 0.011(\text{syst})$
(precision 15.9%)

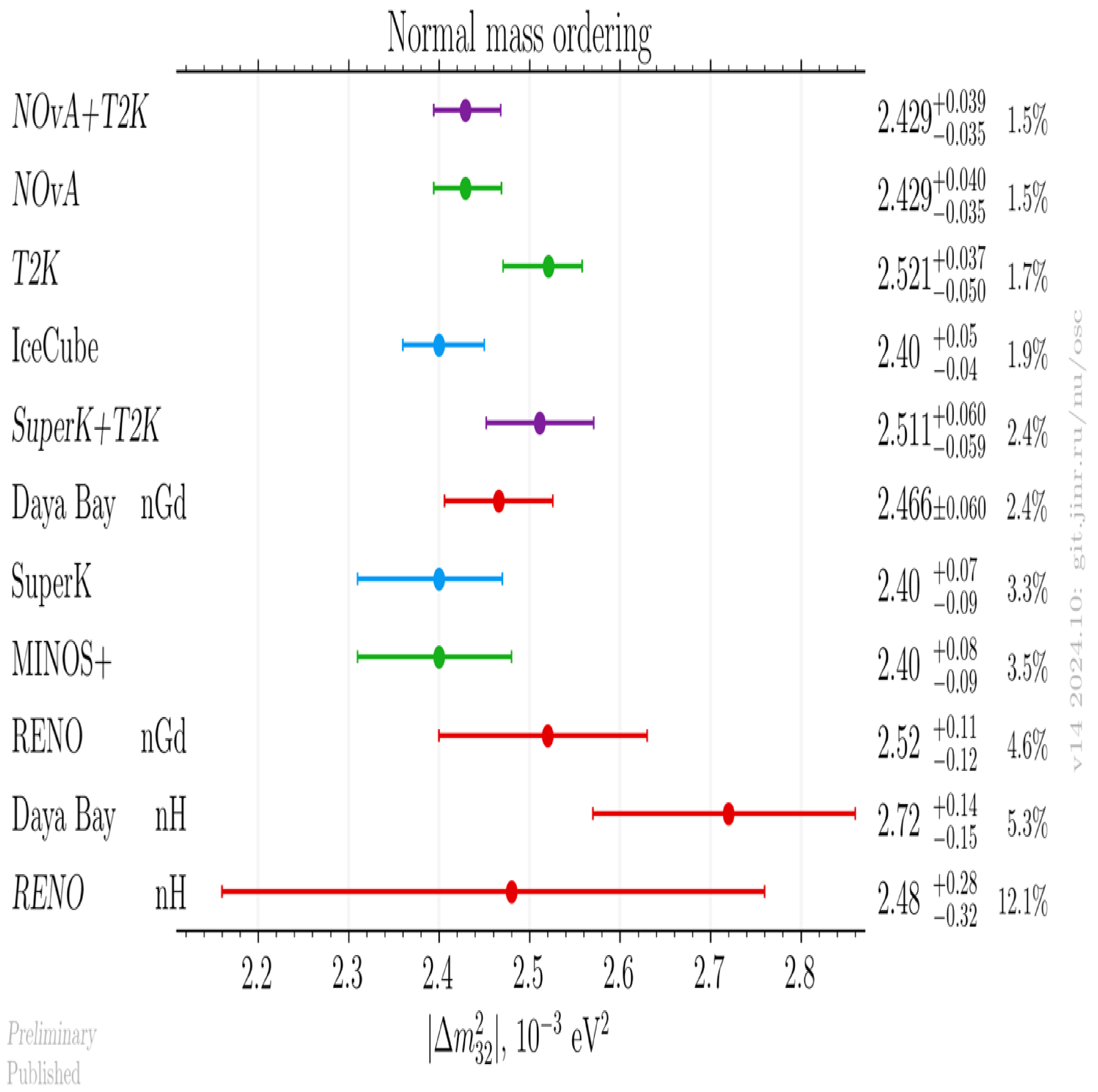
nGd, full dataset
PhysRevLett. 130 161802
$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$
(precision 2.8%)

nH, ~1958 days

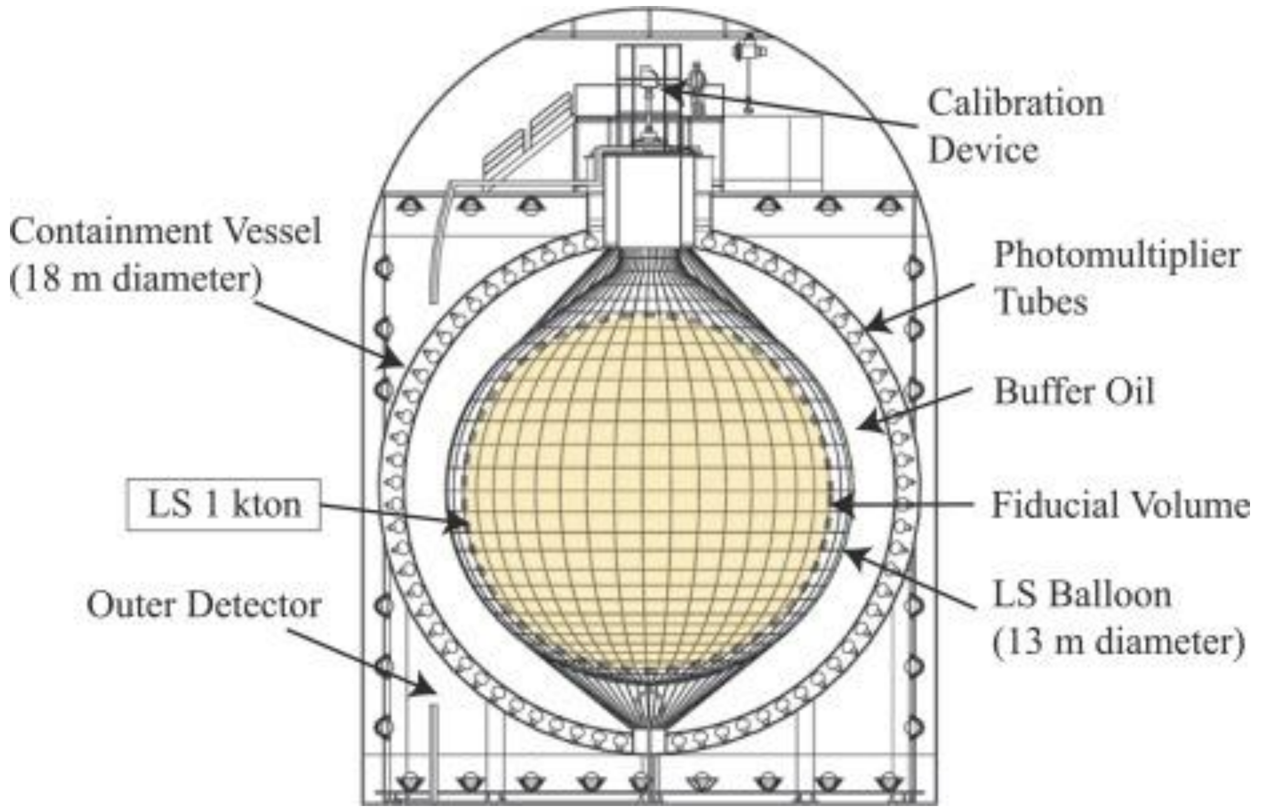
$\sin^2 2\theta_{13} = 0.0759 \pm 0.005$
(precision 5.3%)

Reactor experiments measuring θ_{13} and Δm^2_{32}:

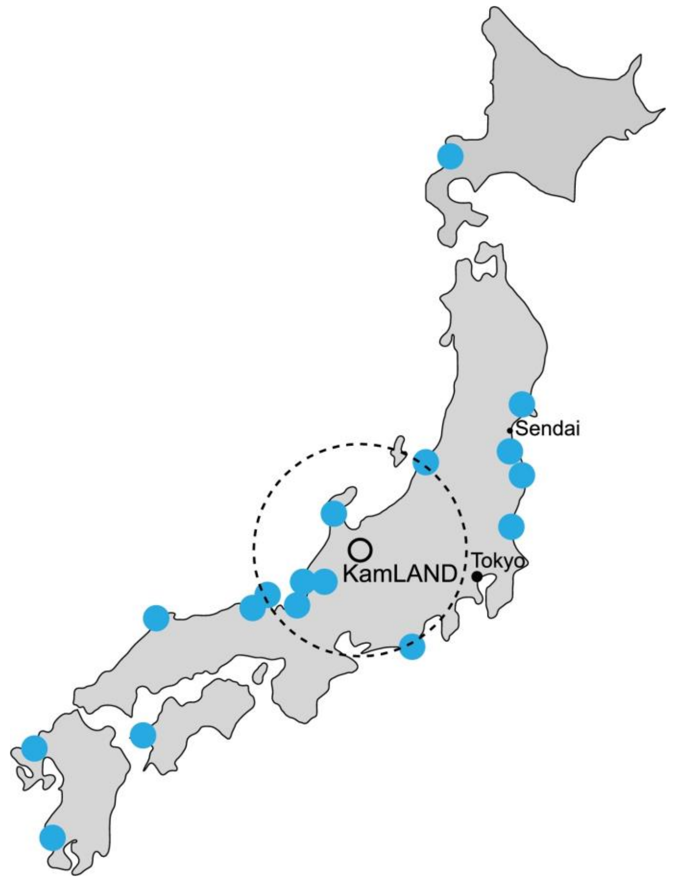


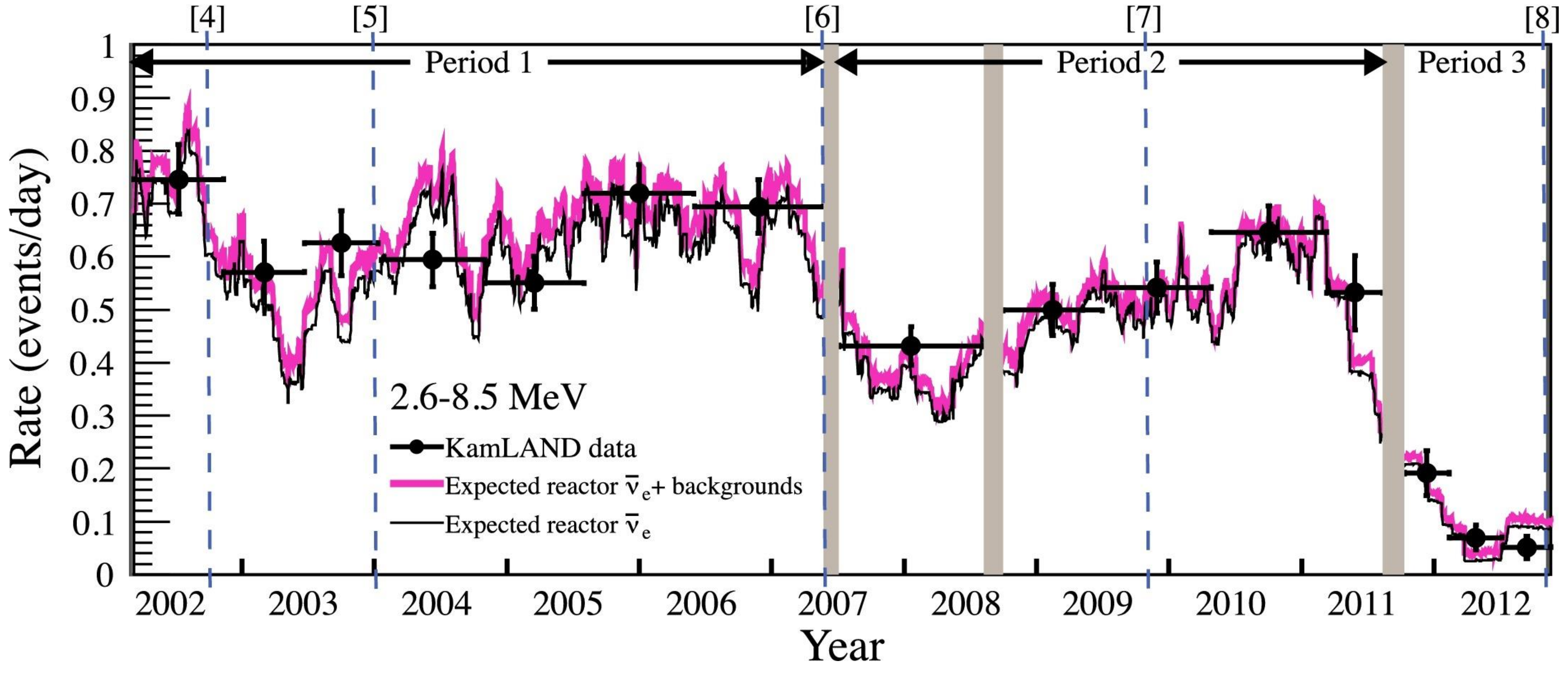


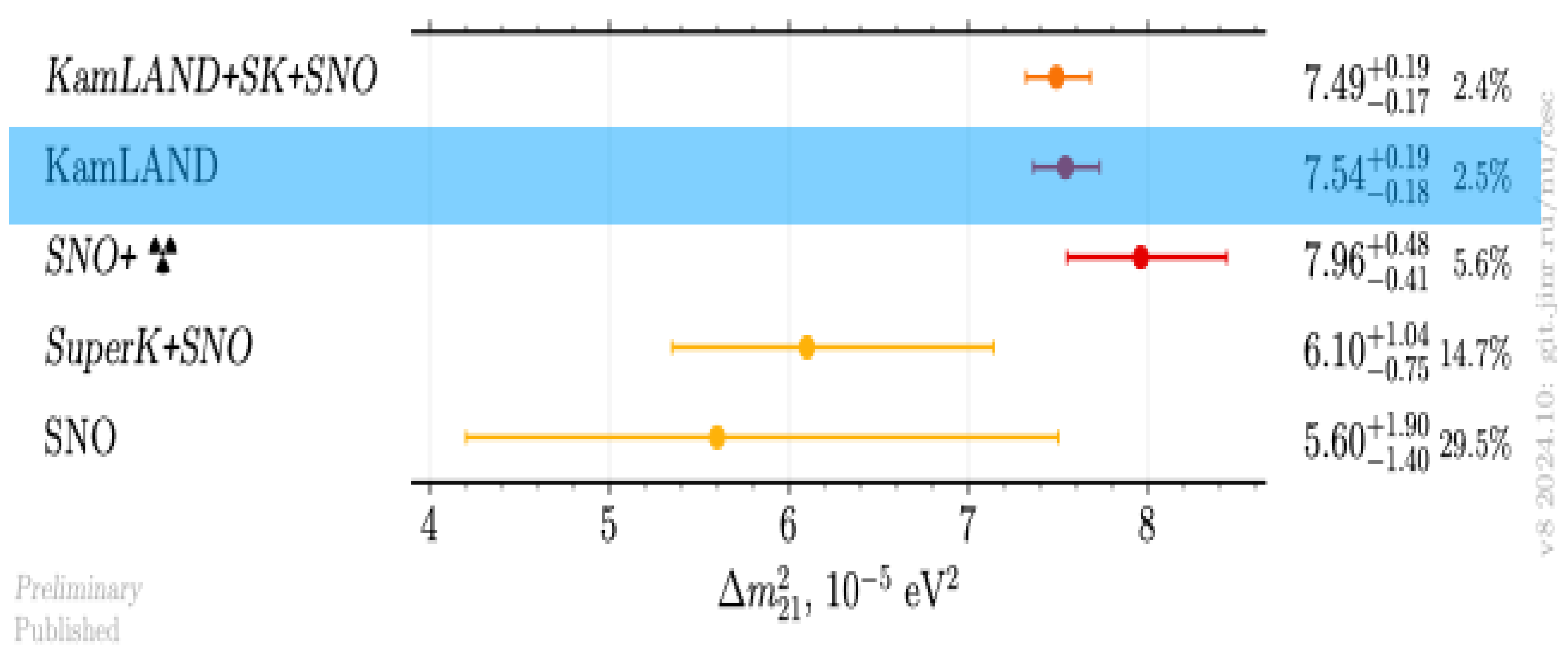
KAMLAND experiment



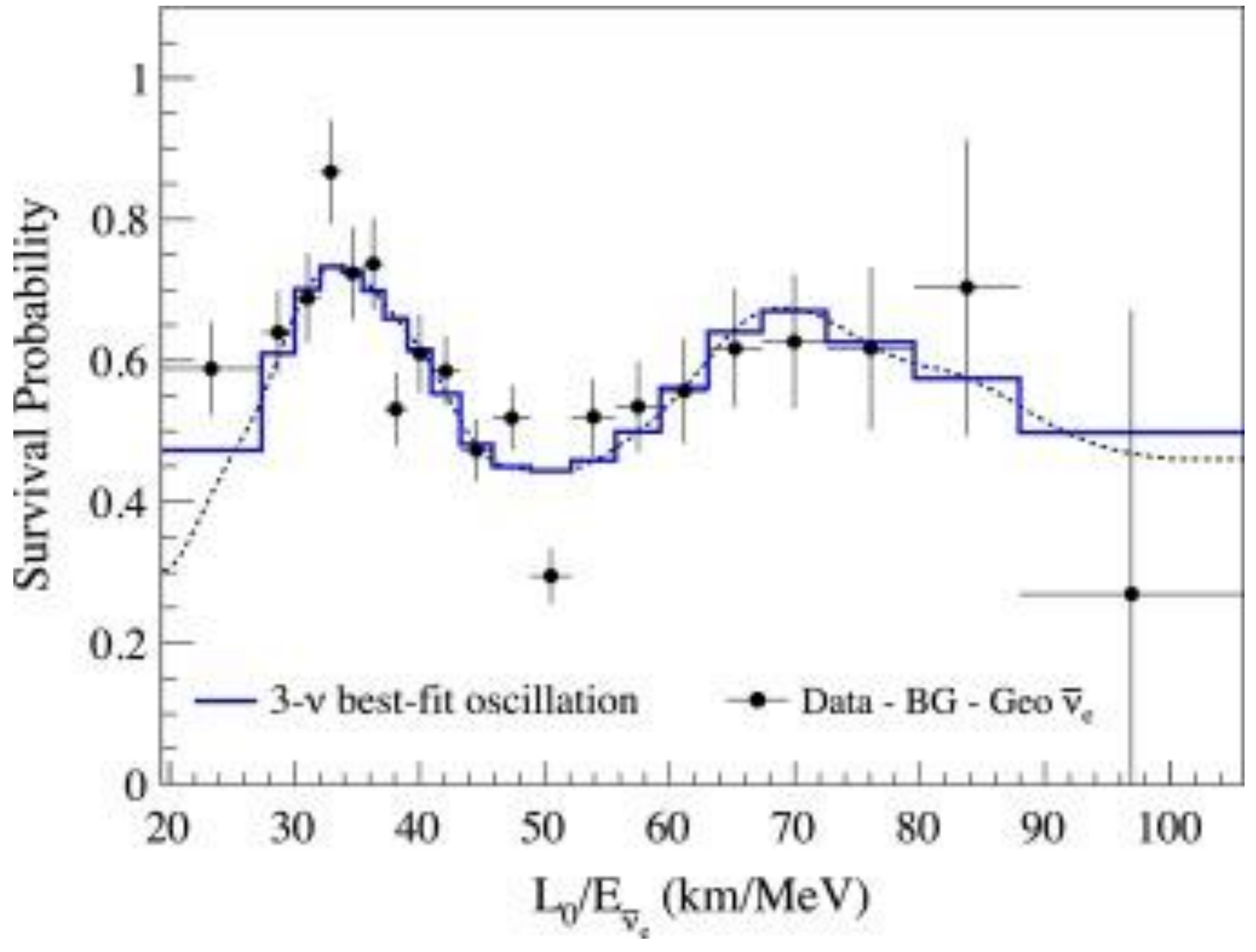
1 kton LS detector in the mine with ~2700 m water-equivalent







- Monitored over more than a decade the flux from more than 50 Japanese nuclear reactors situated at an average flux-weighted distance of ~ 180 km.
- Enable a precise determination of the Δm^2_{21} neutrino oscillation parameter and complement solar neutrino experiments which best measure θ_{12} .
- Allowed to establish the LMA-MSW neutrino oscillation mechanism as the solution to the solar neutrino flavor transformation.

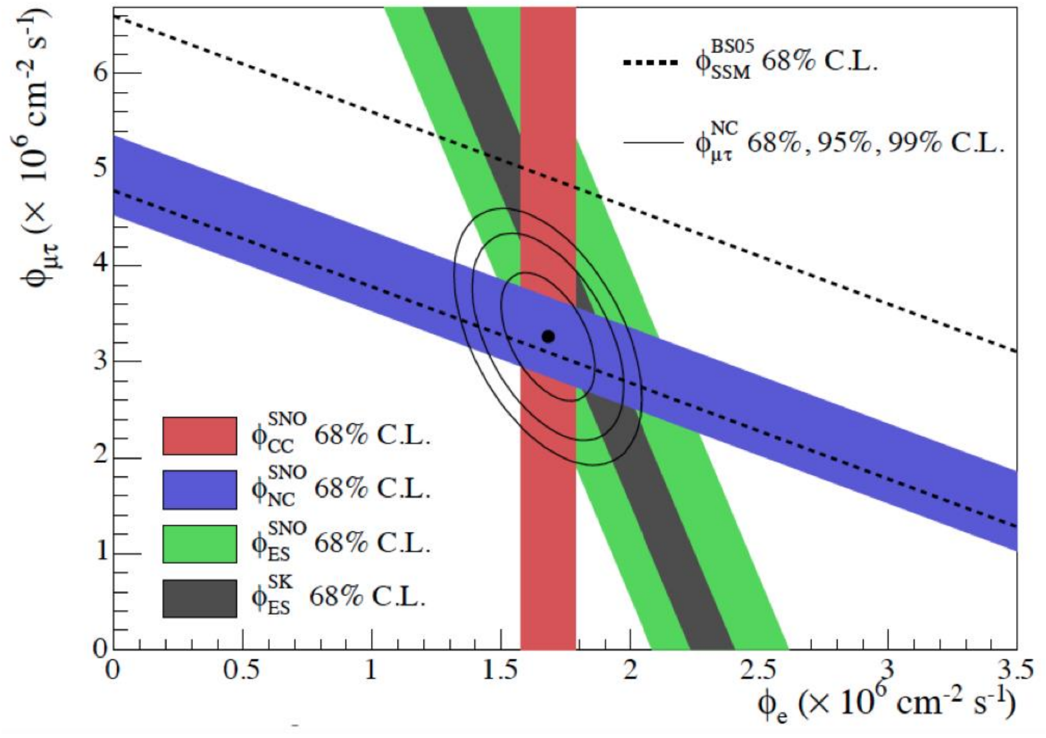


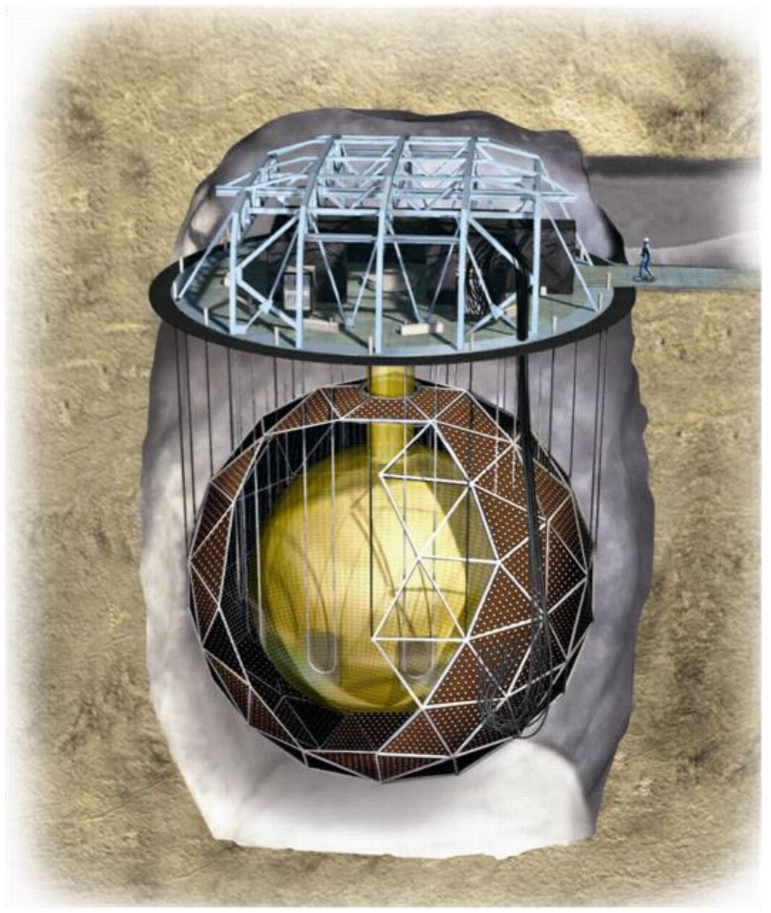
SNO+ Experiment

$$\nu_e + {}^2H \rightarrow e^- + p + p \quad \text{(CC)}$$

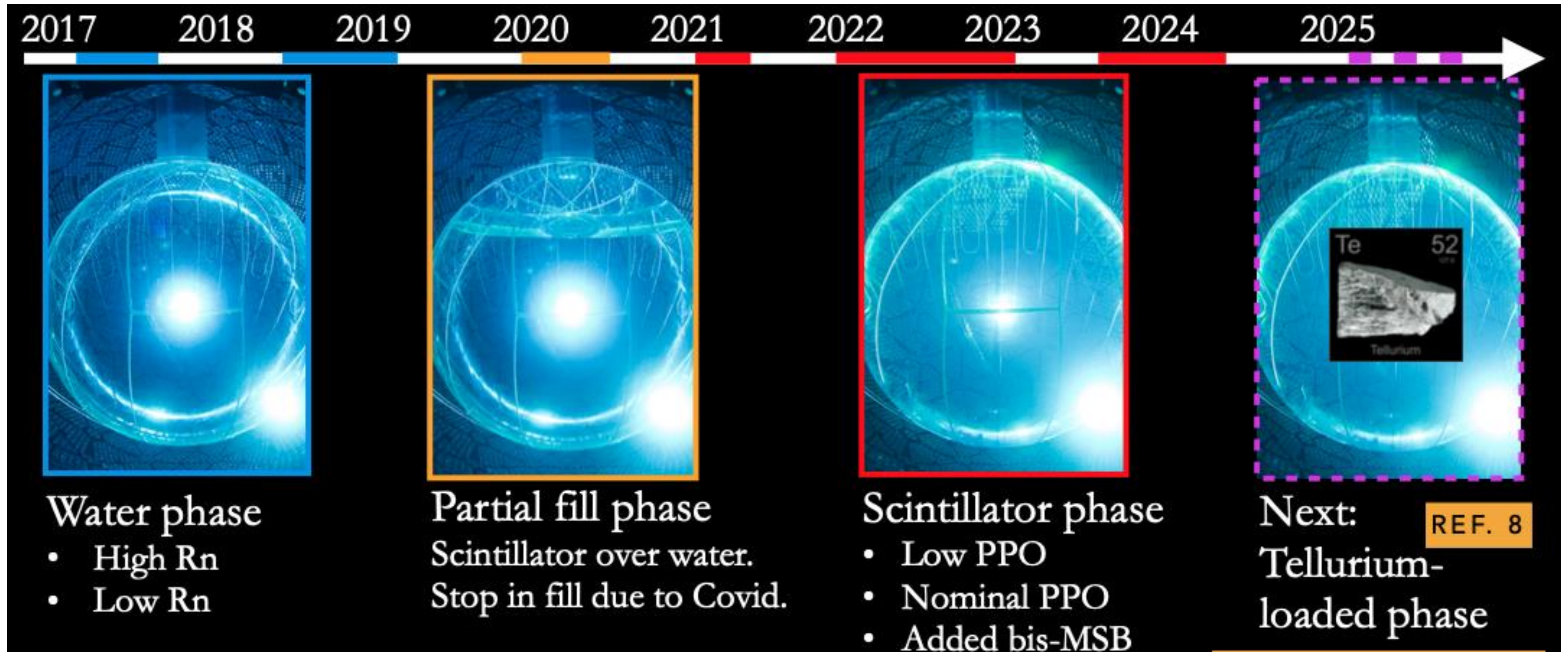
$$\nu_x + {}^2H \rightarrow \nu_x + p + n \quad \text{(NC)}$$

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{(ES)}$$

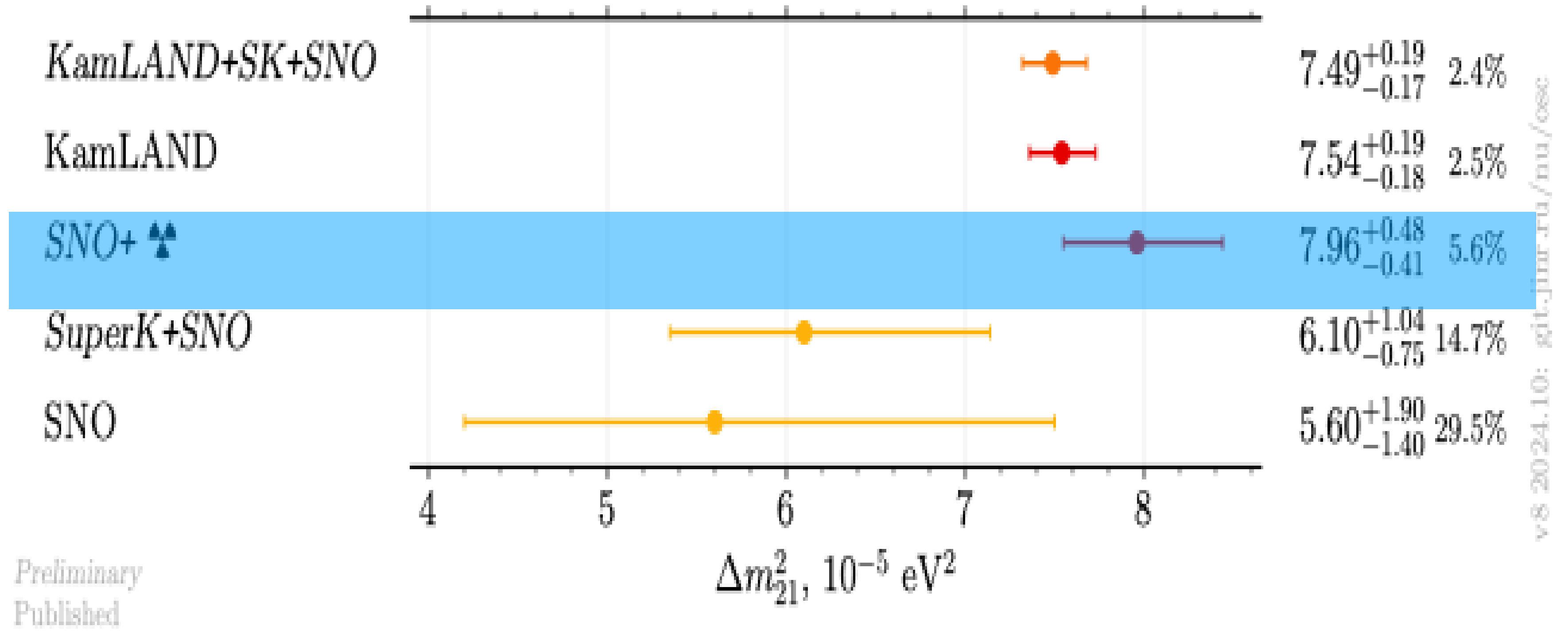




1 kton D_2O Cherenkov detector at ~6000 mwe

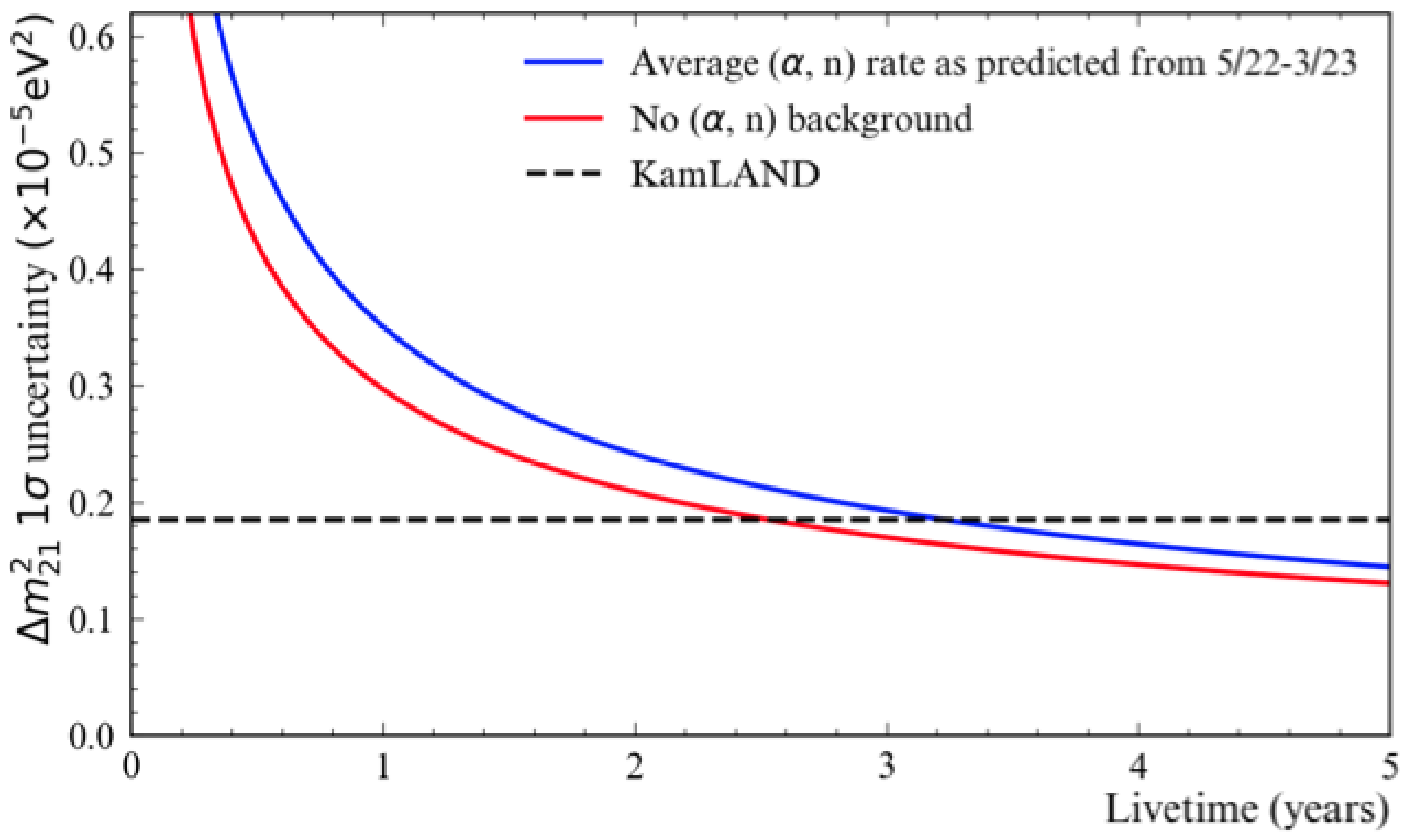


LS loading and $\bar{\nu}_e$ flux detection from 3 CANDU reactors at distances of 240, 340, 350 km (60%) and ~ 100 cores in the USA (40%)

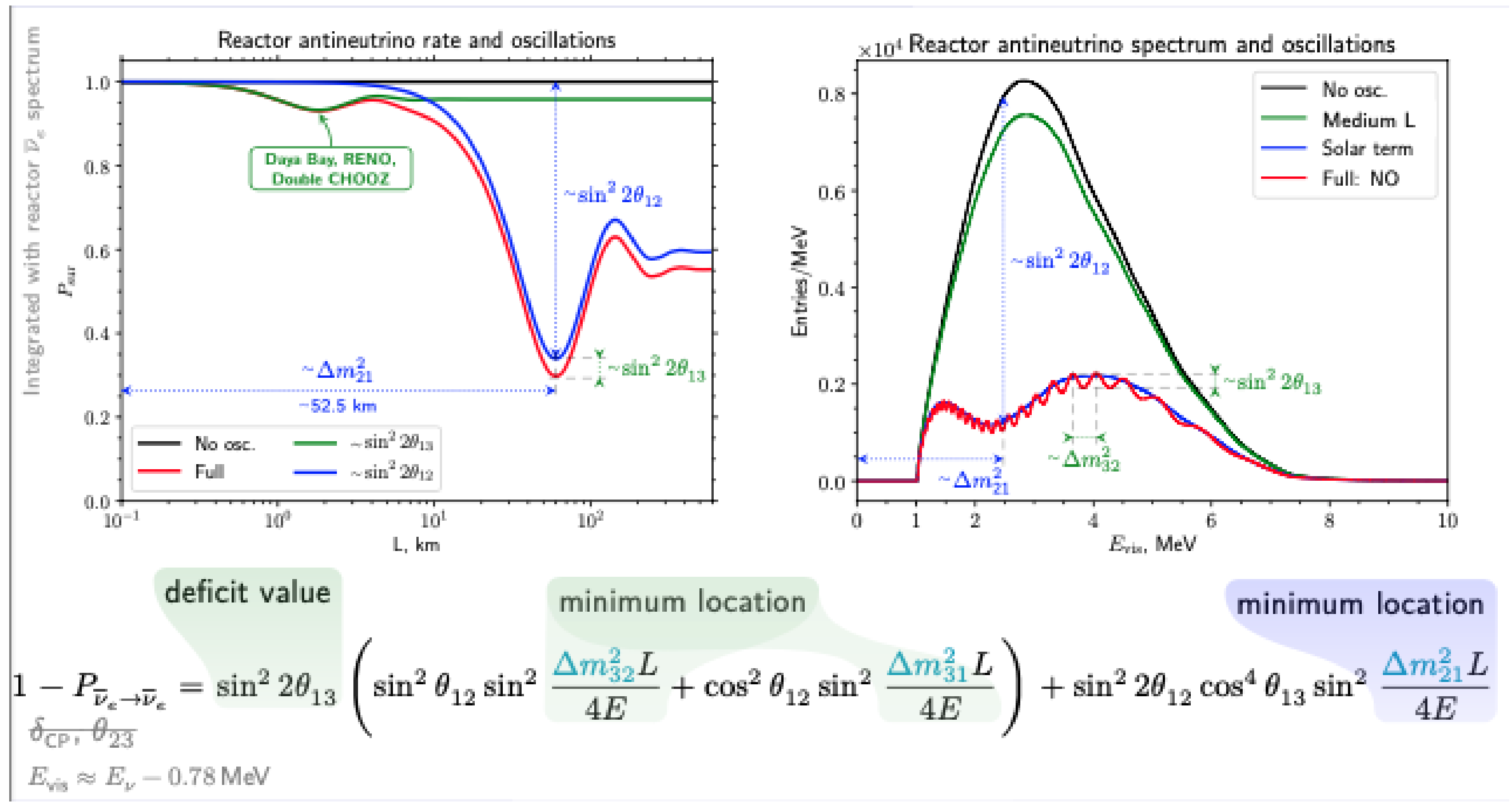


- Following first detection in a water Cherenkov detector, new results from partial and scintillation phases were presented
- Stable data taking from March to October 2020 with scintillator at a height of about 75cm above the AV equator, allowed 114 ton*years (and 85 Hz ^{210}Po) exposure
- Preliminary result of Scintillation phase with 286 ton*years (and 85 Hz ^{210}Po) exposure was presented at Neutrino 2024:

  $\Delta m^2_{21} = (7.96+0.48–0.41) \times 10^{-5}$eV^2



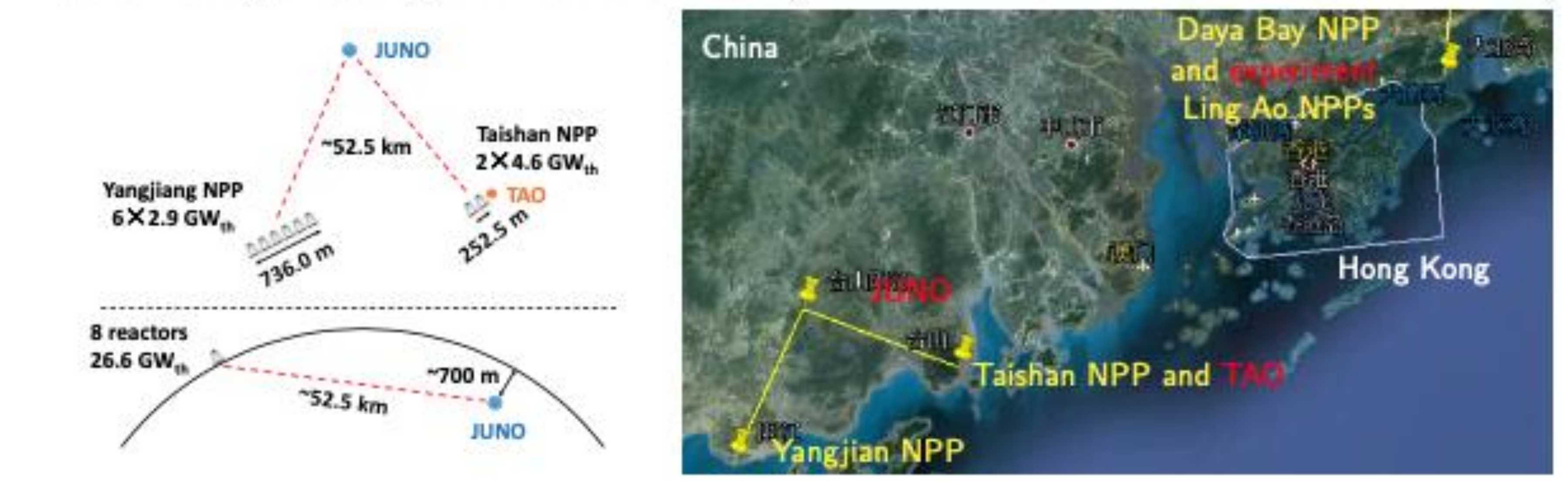
NMO measurement at reactors



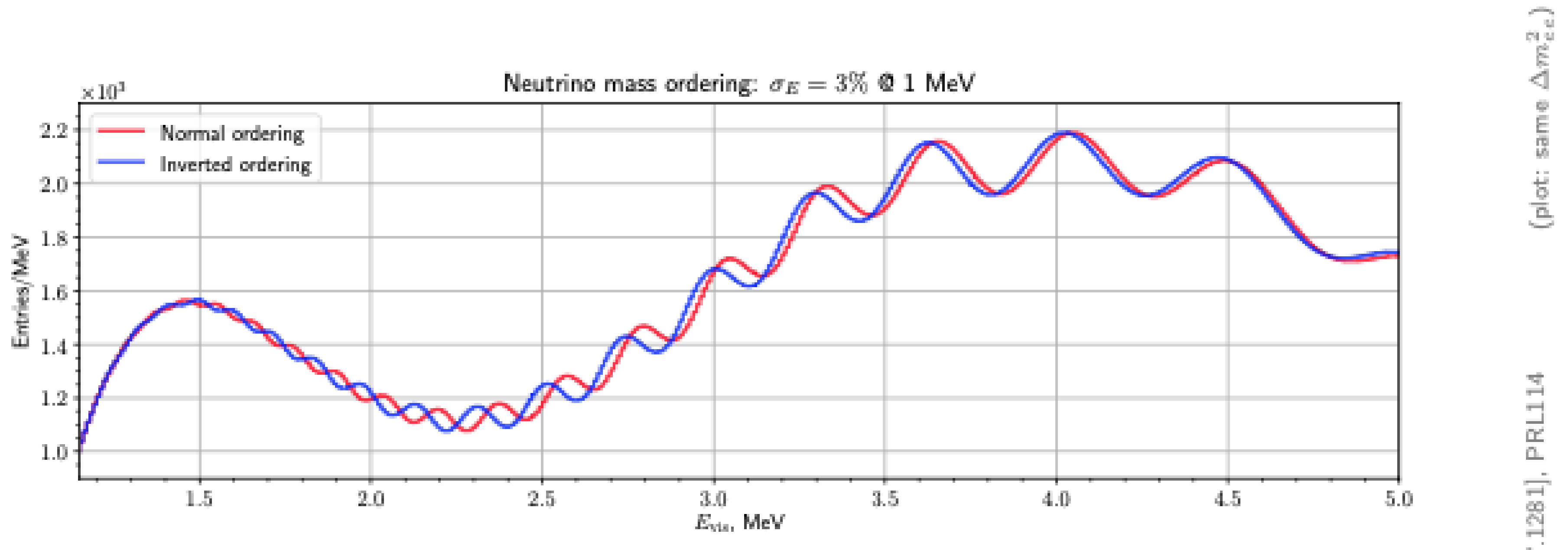
JUNO/TAO

- High statistics (power)
- Optimized baseline
- Unique energy resolution
- Significant overburden
- Radiopure materials
- Reactor spectrum measurement

- JUNO — Jiangmen Underground Neutrino Observatory
- TAO — Taishan Antineutrino Observatory

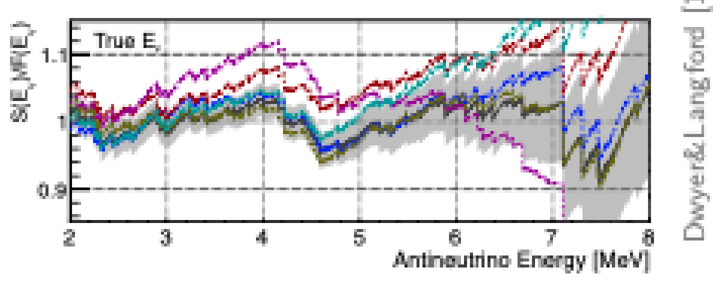


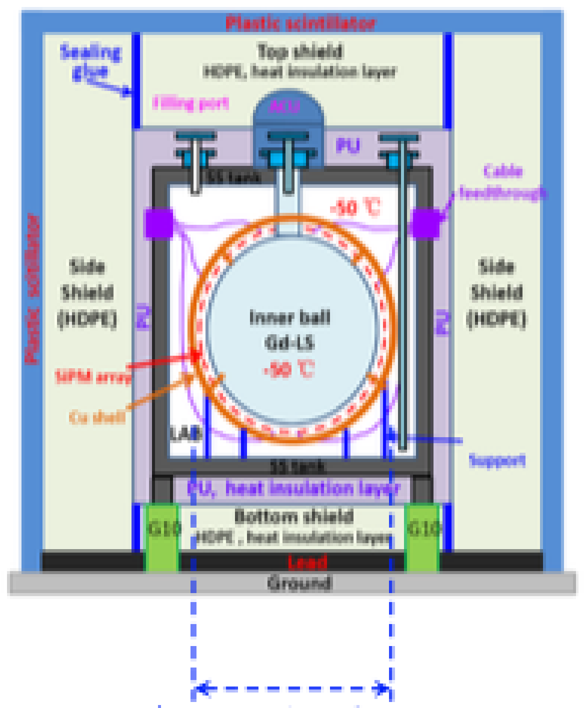
	Yangjian (YJ)	Taishan (TS)	Daya Bay/Ling Ao	World
Thermal power, GW	2.9×6	4.6×2	2.9×6	
Total, GW	26.6		17.4	...
	signal		background	



- Change of oscillation period with ordering ≪ energy resolution
- Cumulative effect across most of the energy range
- Possible impact: fine structure in reactor $\bar{\nu}_e$ spectrum need a reference measurement!

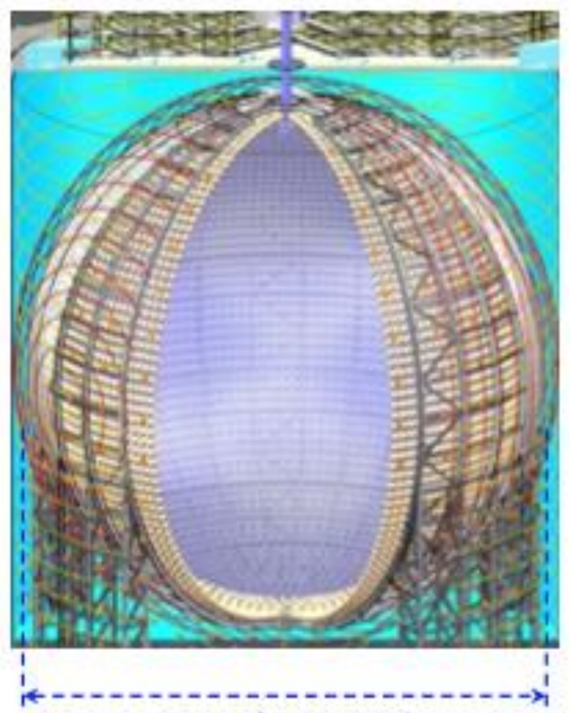
$E_{vis} \approx E_\nu - 0.78$ MeV





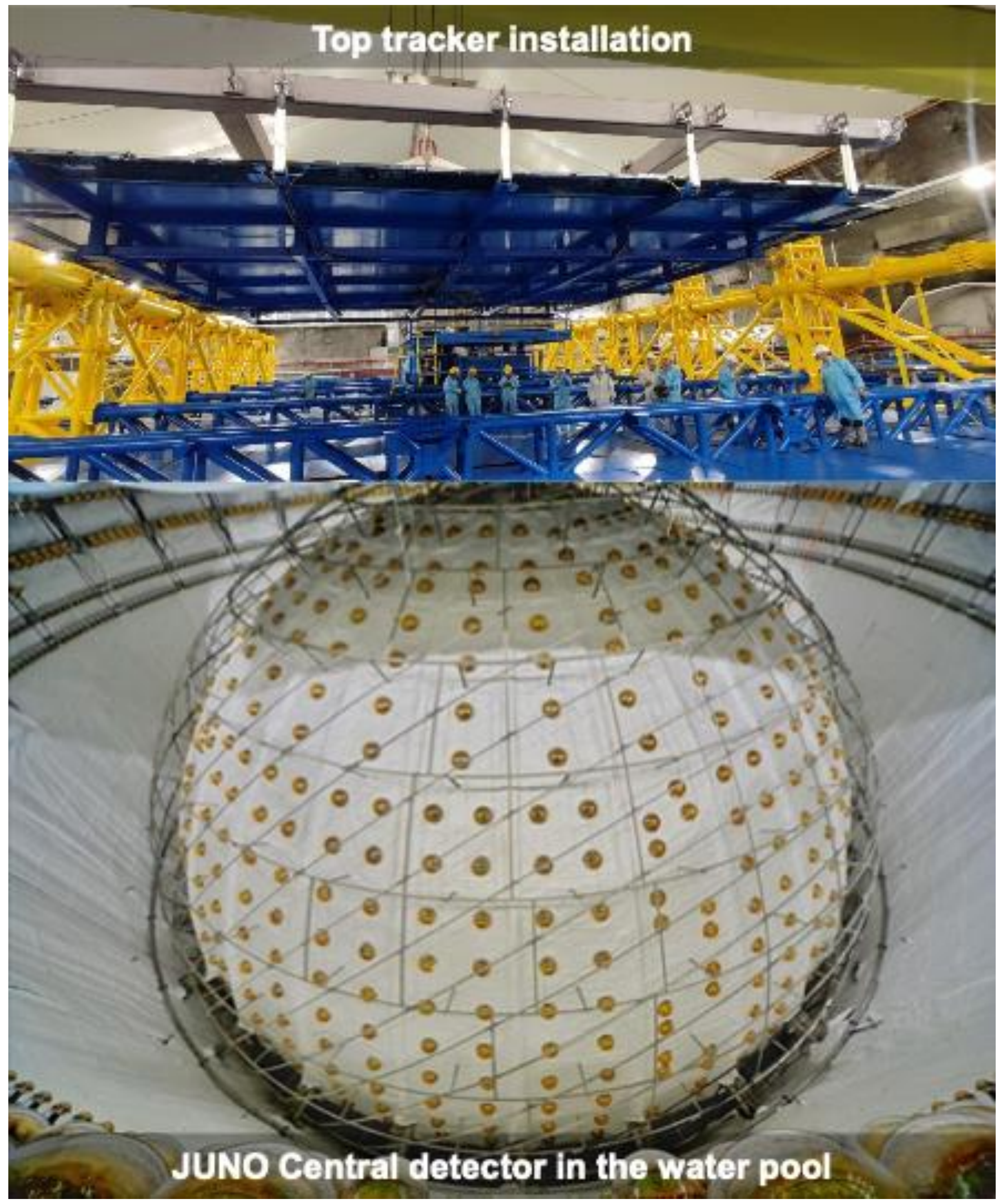
1.8 m / 2.8 t GdLS, 1 t in FV

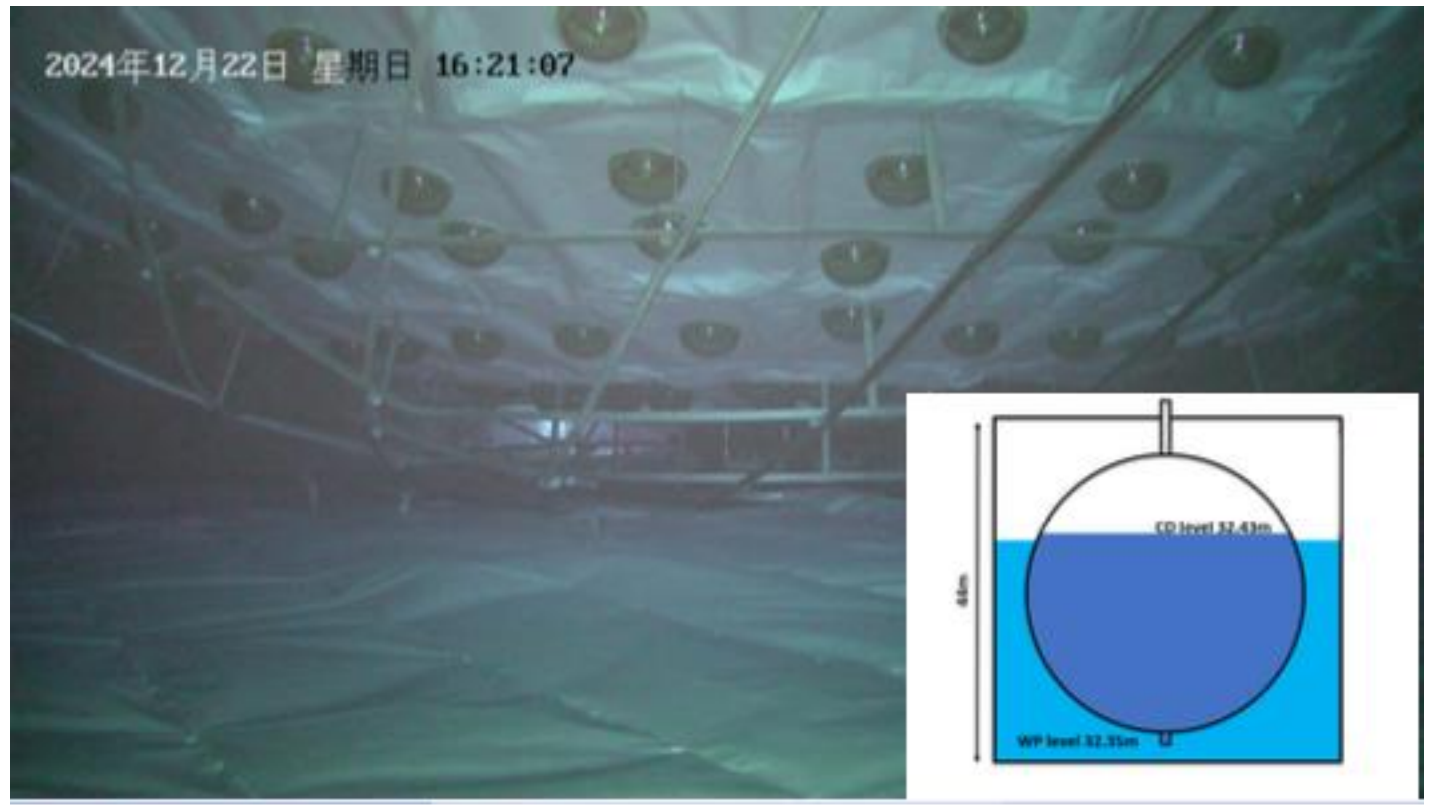
	TAO	JUNO
Attention	Energy resolution σ ↘	
Method	Light collection ↗ Dark noise ↘	
Scintillator	GdLS @ -50°C	LS
PMTs	SiPM 1.5M 5 mm	18k 20" +26k 3"
Coverage, %	94	78
Light col. p.e./MeV	4500	1665
σ_E at 1 MeV, %	2	2.9
Thermal power, GW	4.6	26.6
Baseline	44 m	52.5 km
IBD/day	1000	47



35 m / 20 kt LS

JUNO status



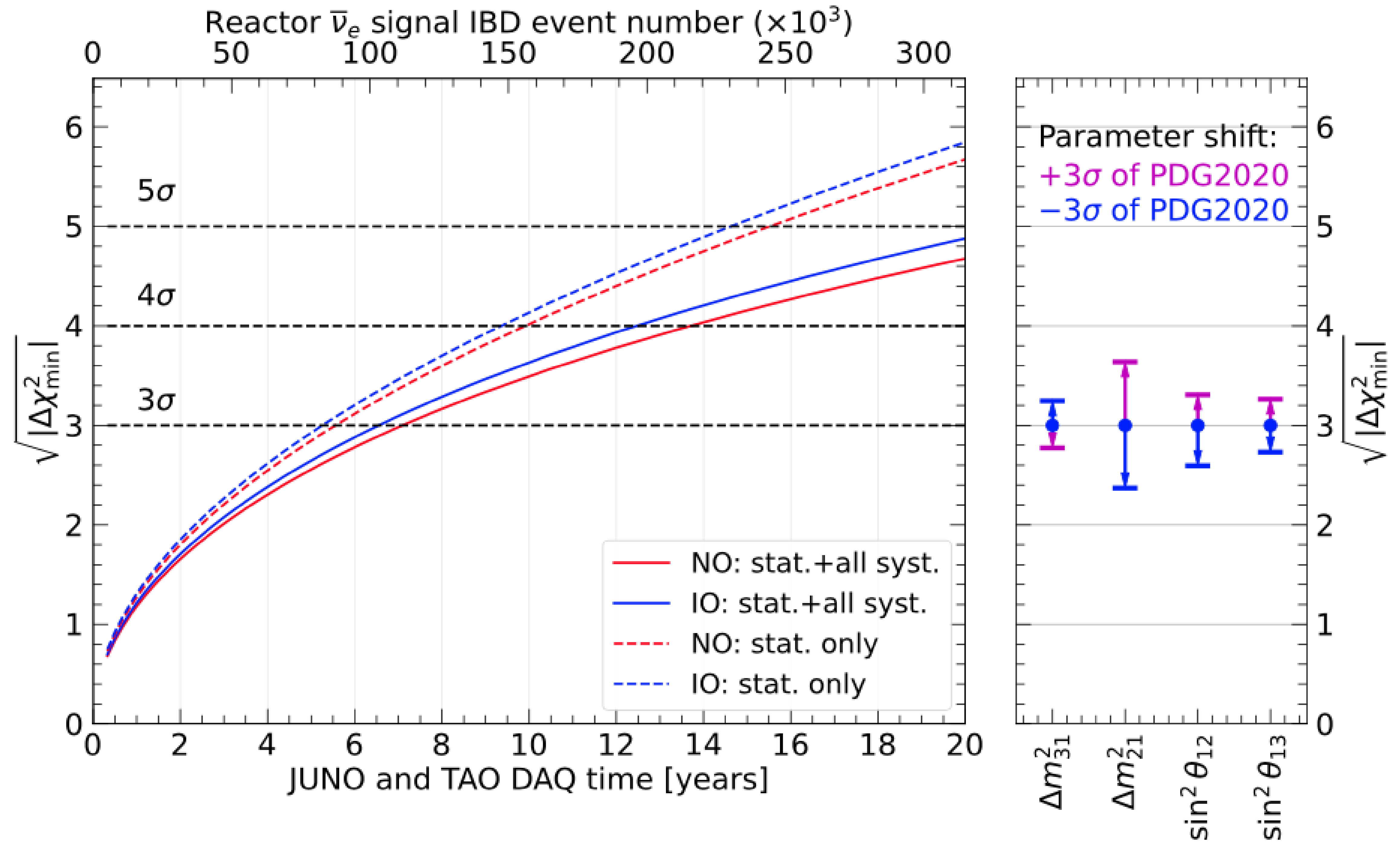


20 kt liquid scintillator detector, 26.6 GW_{th} reactors,
52.5 km baseline: 47 $\bar{\nu}_e$/day.
Neutrino Mass Ordering (NMO): 3σ in 7.1 years.

TAO status

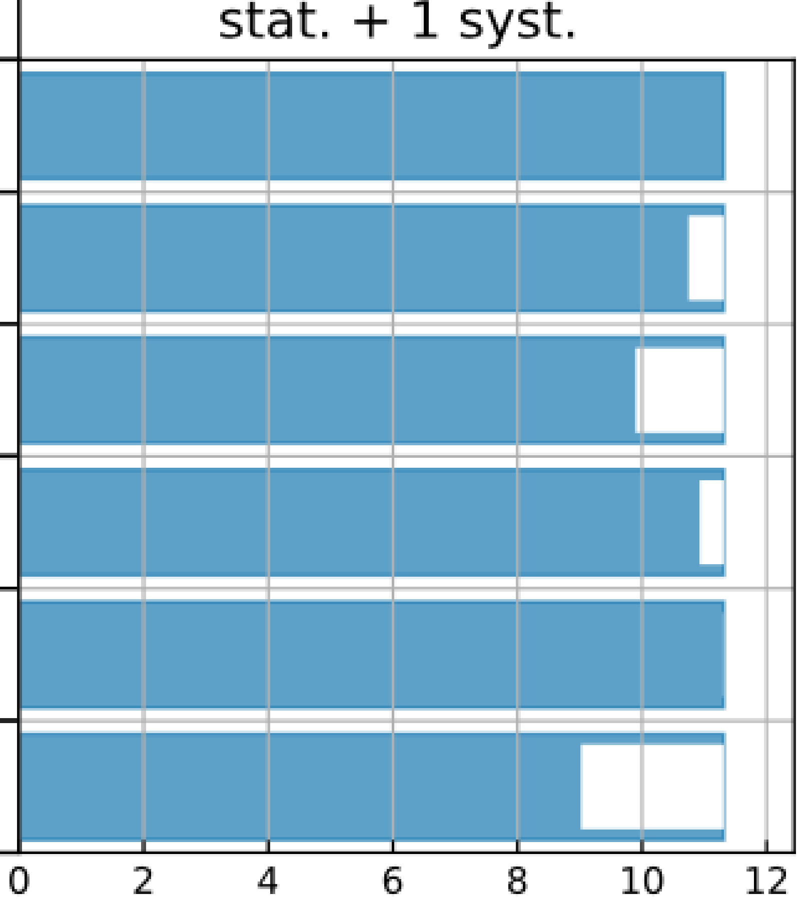
- JUNO filling goes full speed and will finish by Sep 2025
- Part of the detector already in operation
- First physics results in early 2026

Sensitivity to Neutrino Mass Ordering



Impact of systematics:

	$\Delta\chi^2_{min}$
Statistics	11.3
Stat.+Flux error	-0.6
Stat.+Backgrounds	-1.4
Stat.+Nonlinearity	-0.4
Stat.+Others	< -0.05
Total	9.0



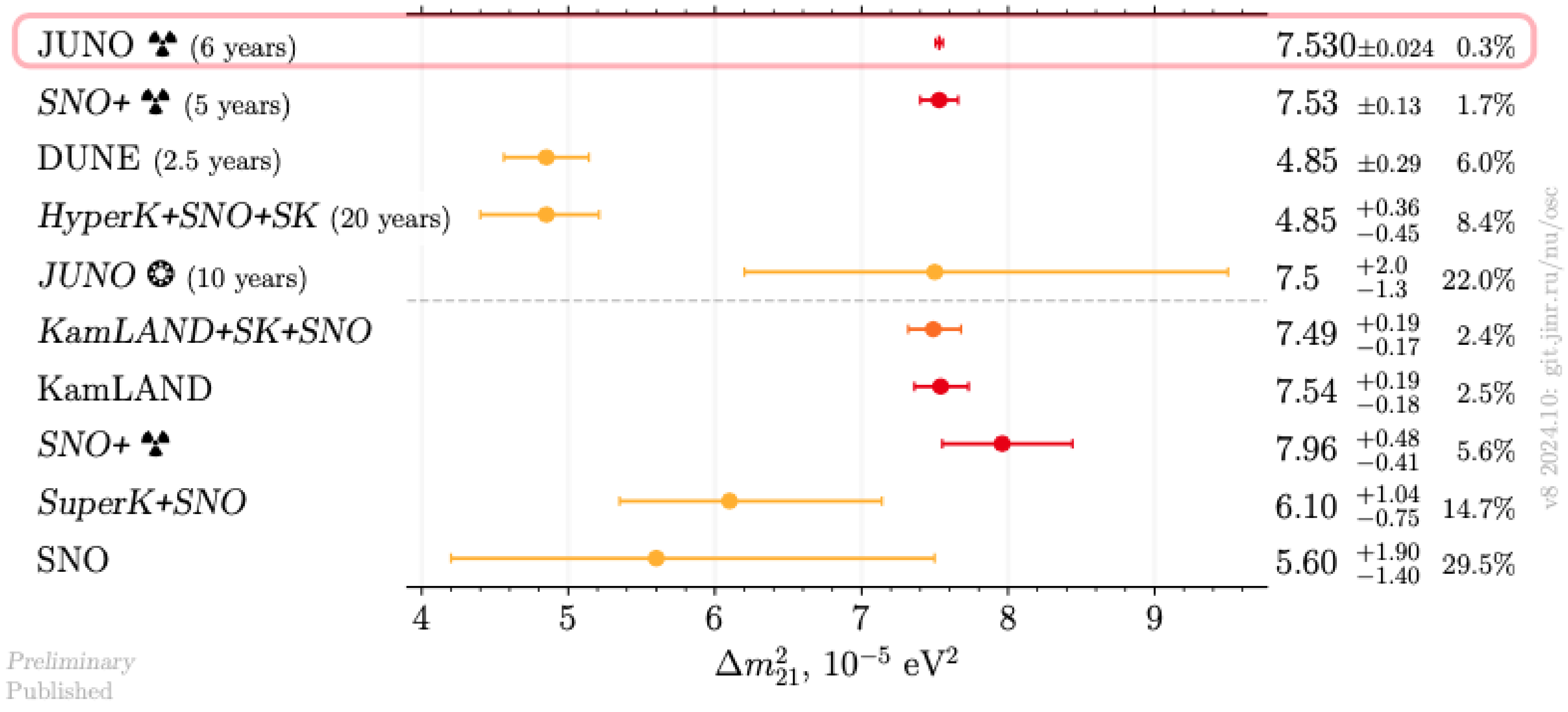
JUNO Simulation Preliminary

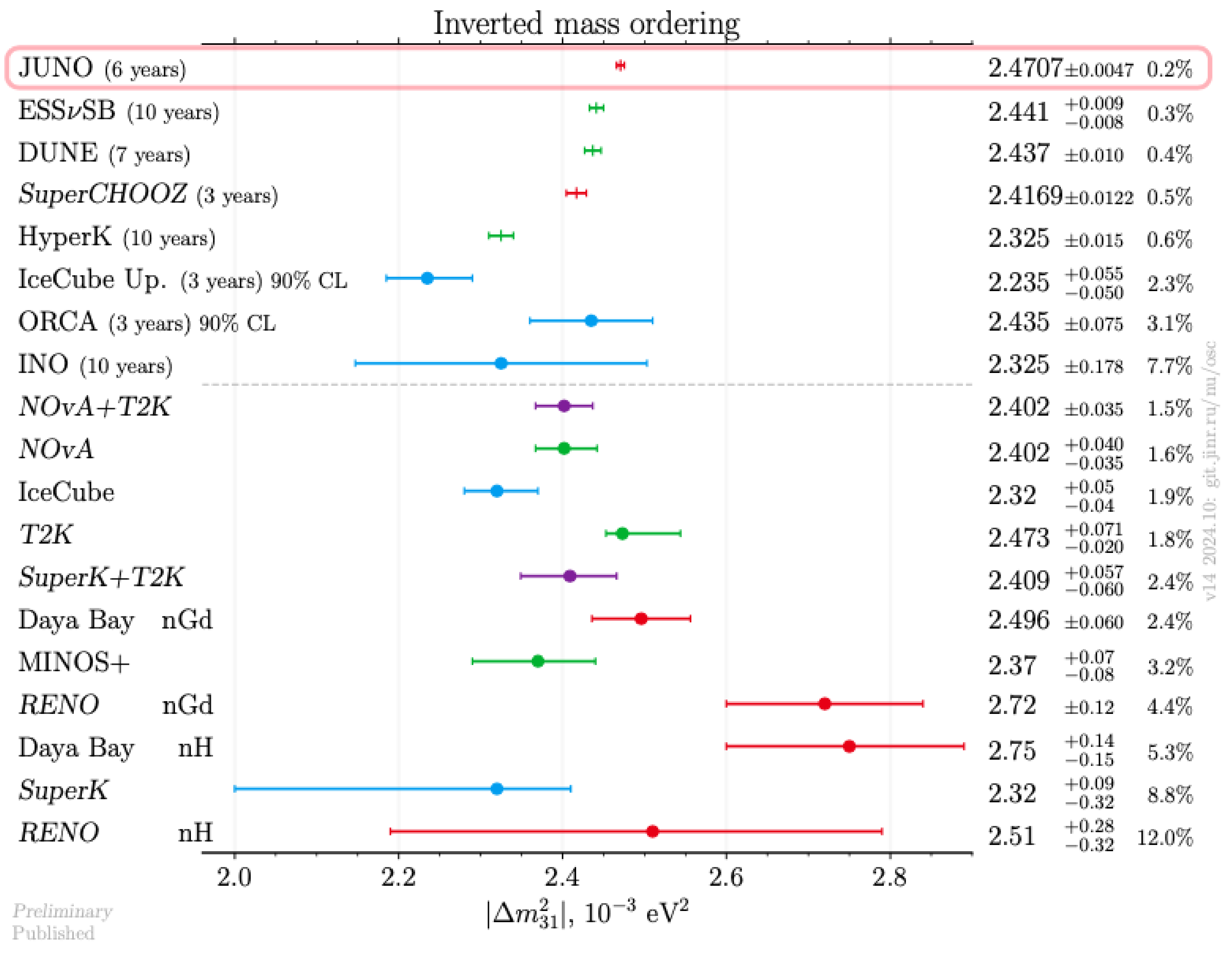
✓ JUNO+TAO, 7.1 years×26.6 GW exposure: $\sim 3\sigma$

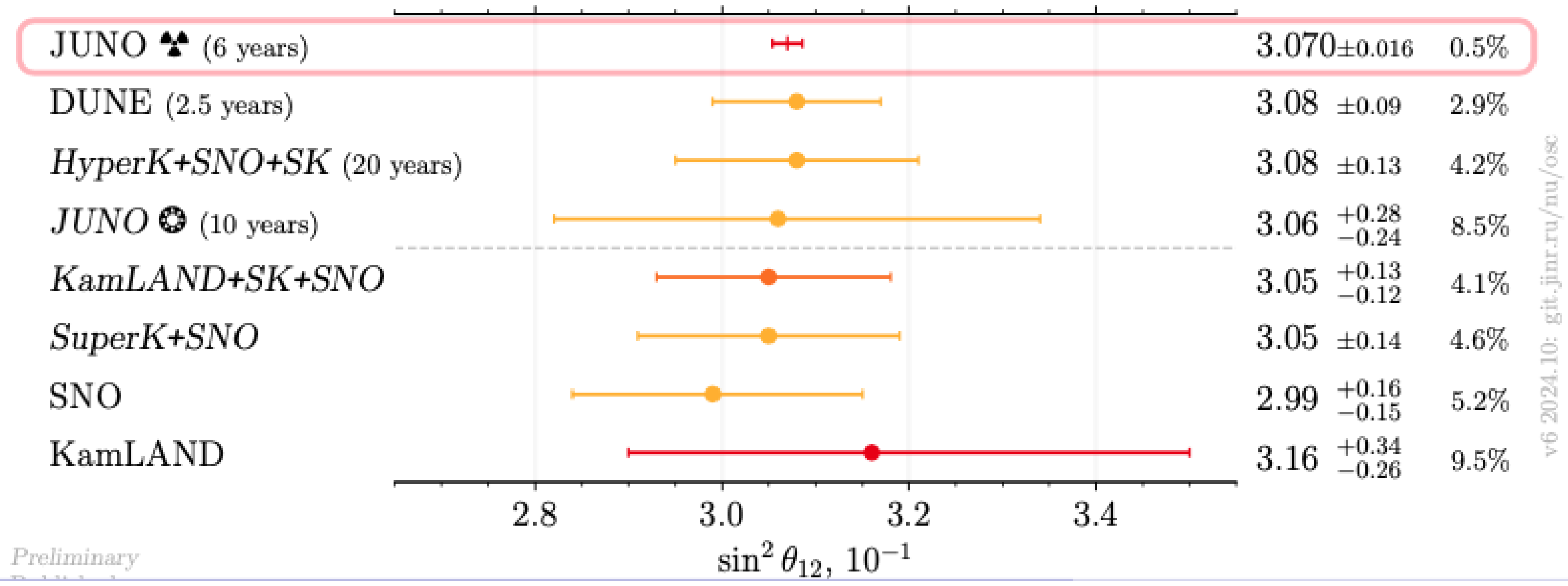
JUNO and neutrino oscillation parameters

- Percent precision for $\Delta m^2_{21}/\Delta m^2_{31}$: 100 days
- Few permille level for $\Delta m^2_{21}/\Delta m^2_{31}/\sin^2 2\theta_{12}$: 6 years

✓ Order of magnitude improvement over existing constraints.





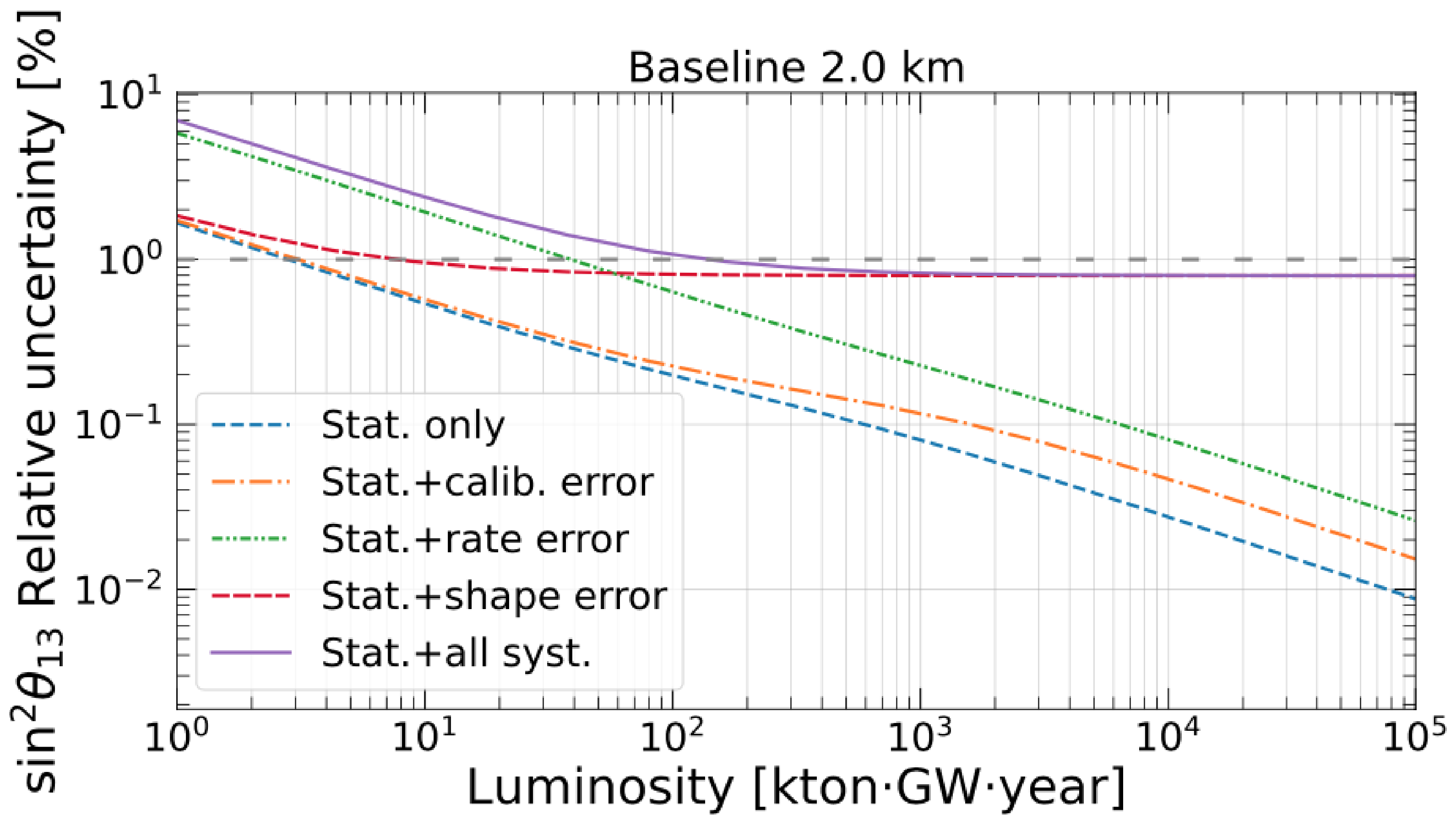


✓ Negligible correlation between measured parameters.

+ many other subjects: sterile, supernova, light dark matter, solar, geo, atmospheric, etc.

Future reactor experiments and their sensitivities

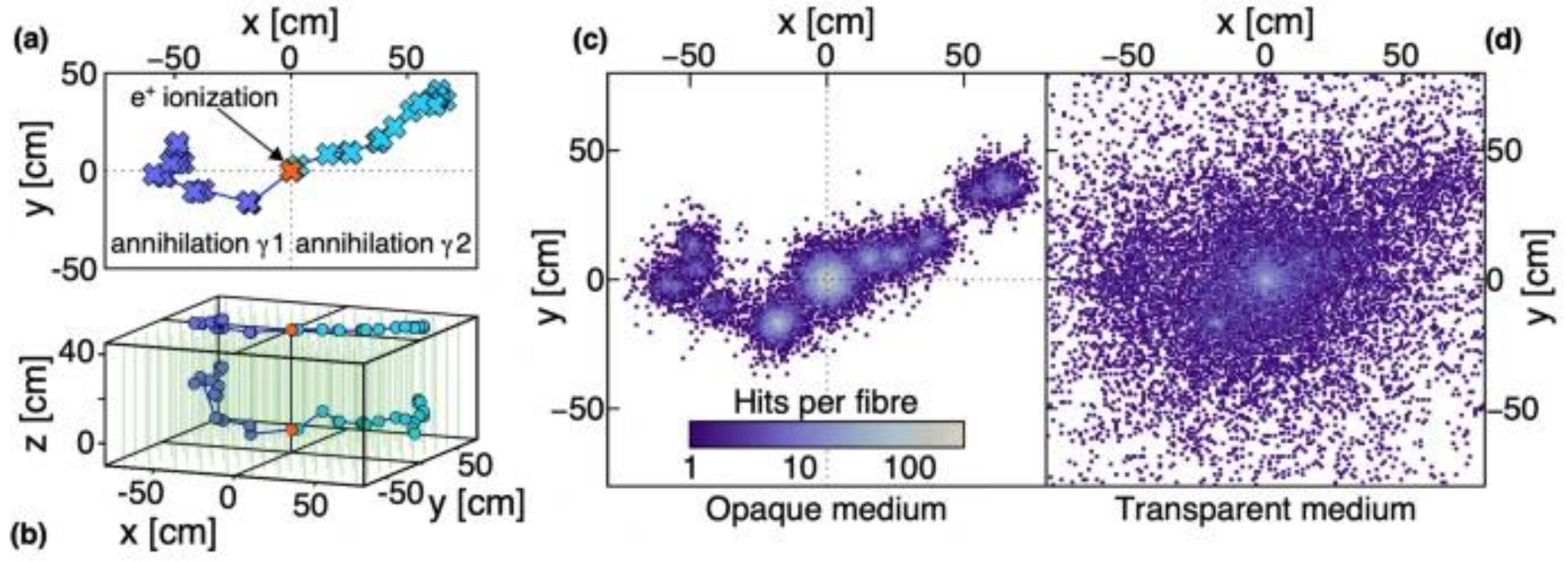
Motivation: sub-percent precision on θ_{13} can be helpful in unitarity test of PMNS, which in turn is important for various research fields, including particle physics, astrophysics, and cosmology.



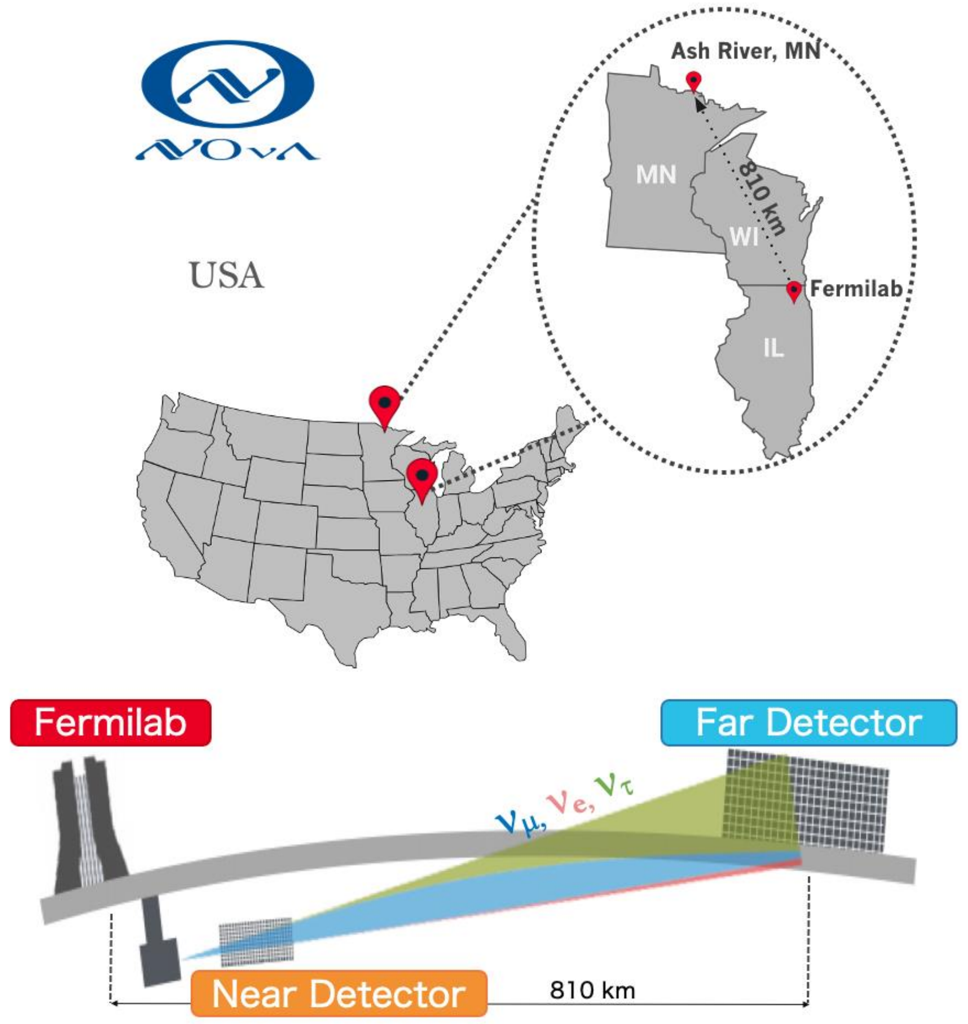
Two interesting proposals exist:

- the statistics, the baseline, and the control of the spectral shape uncertainty were studied numerically in *JHEP03(2023)072* and it was shown that a single detector with an exposure of about 150ktons·GW·year (~4kton·4years·9.2GW(Taishan)) at optimal 2.0 km baseline can provide sub-percent measurement of θ_{13}

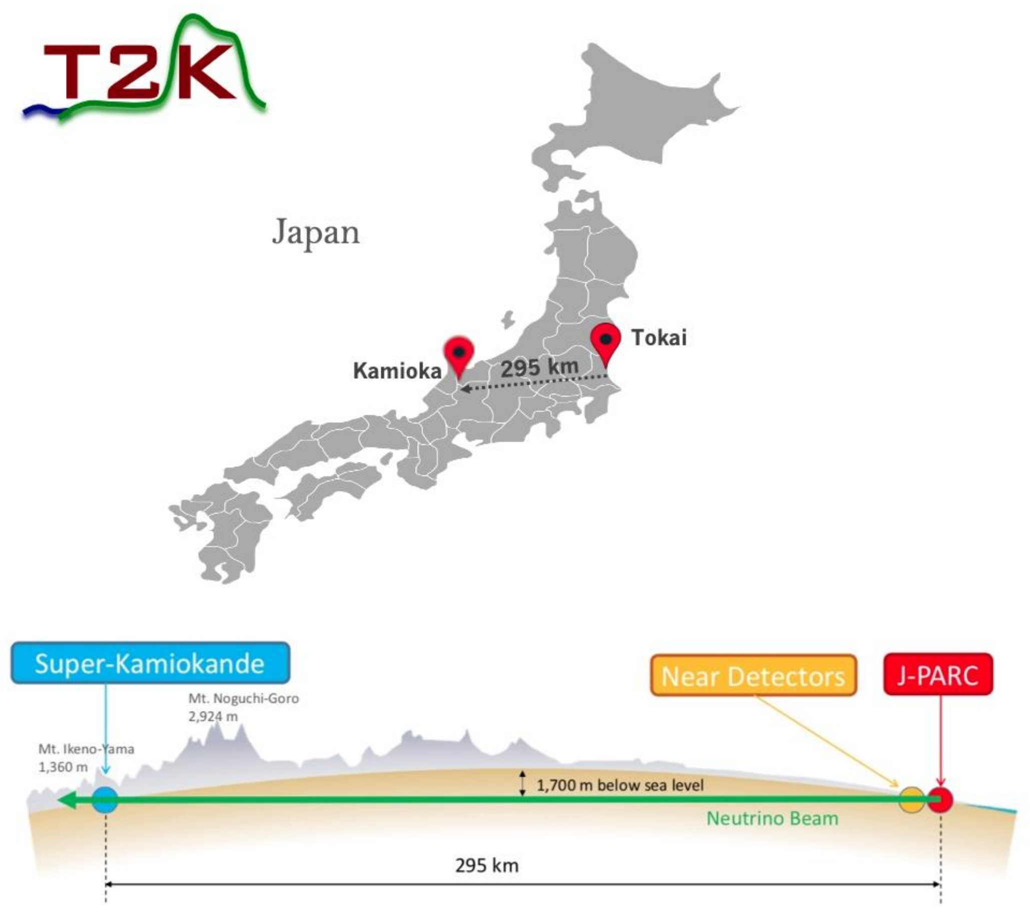
- SuperCHOOZ experiment proposal at Chooz-B reactors with 8.4GW thermal power is expected to provide 0.5% precision on $\sin^2 2\theta_{13}$
Near (5 tons, baseline ~30 m, overburden ~5 m, rate ~30 M/year) and Far (10 ktons, baseline ~1km , overburden ~300 mwe, ~20 M/year) both will be using LiquidO detector technique: opaque scintillator and a lattice of 1 cm pitch optical fibers readout by SiPM with high quantum efficiency (50%) and good time resolution (100ps)



Accelerator long baseline experiments

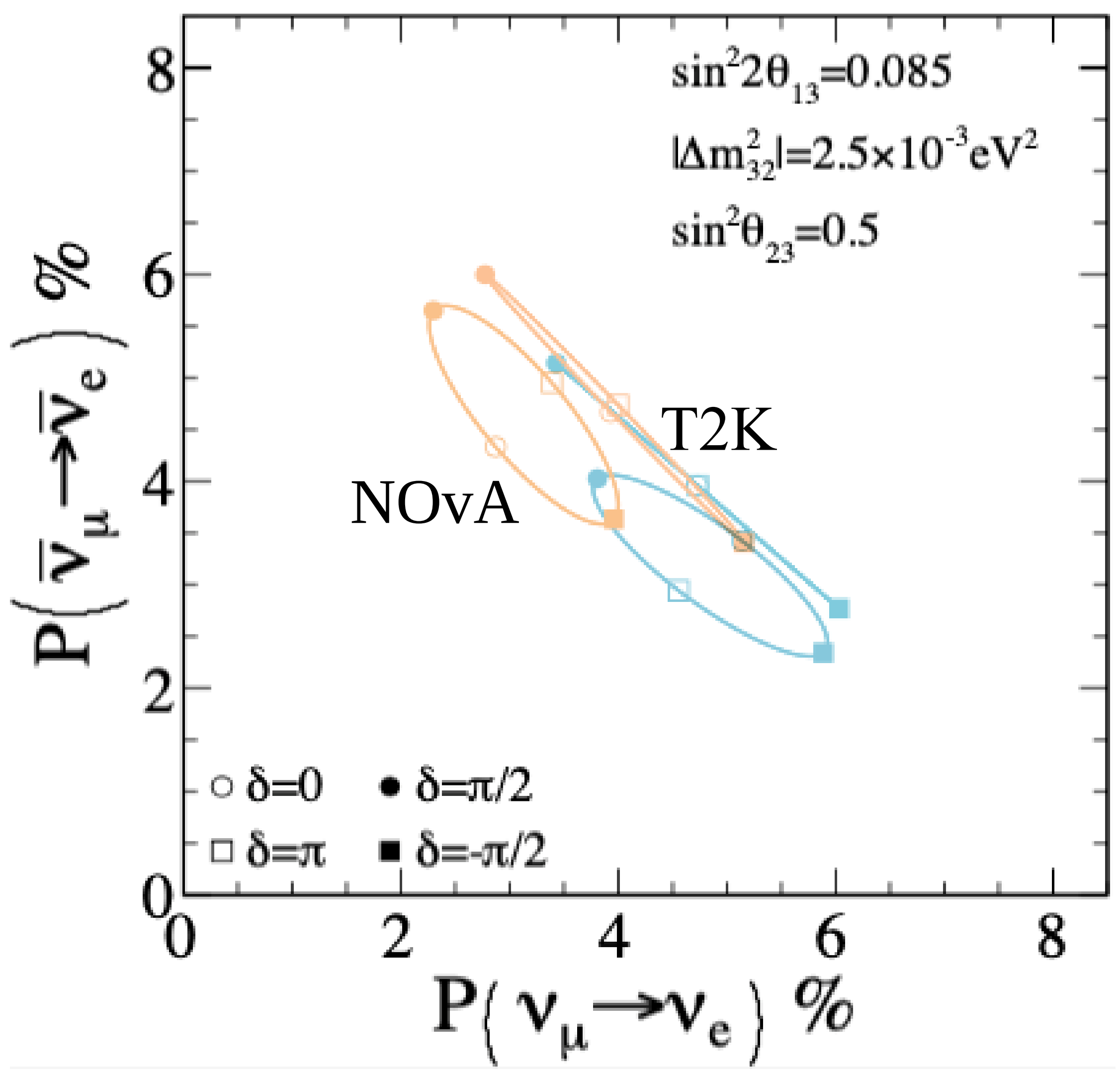


- ✴ Allows control of beam characteristics to emphasize sensitivity
- ✴ Focused and intense beam with timing information to reduce backgrounds
- ✴ Exposure measured in Protons On Target (POT) and beam power of ~ MW
- ✴ Can choose energy to work with and switch between neutrinos and antineutrinos
- ✴ Distances available from several meters to thousand of kilometers
- ✴ Flux uncertainties solved by two-detector scheme
- ✴ Additional physics at near detectors



NOvA at Fermilab

- ➢ Typically run at ~900 kW (record 1018 kW)
- ➢ Exposure ~ 40 ･ 10^{20} POT shared between $\nu/\bar{\nu}$
- ➢ Technologically identical Near and Far detectors
- ➢ E ~ 2 GeV
- ➢ L = 810 km
- ➢ 14 mrad off-axis

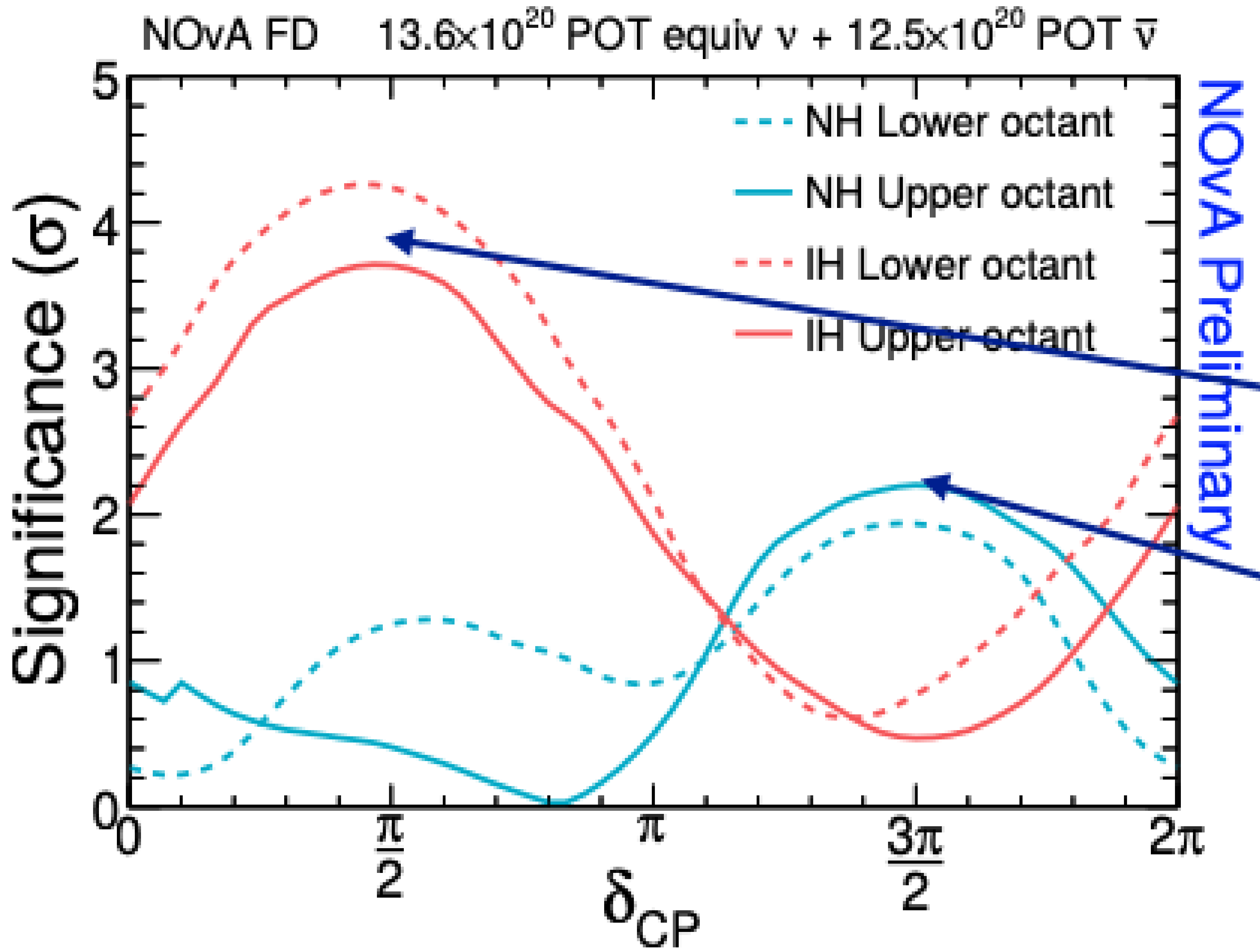


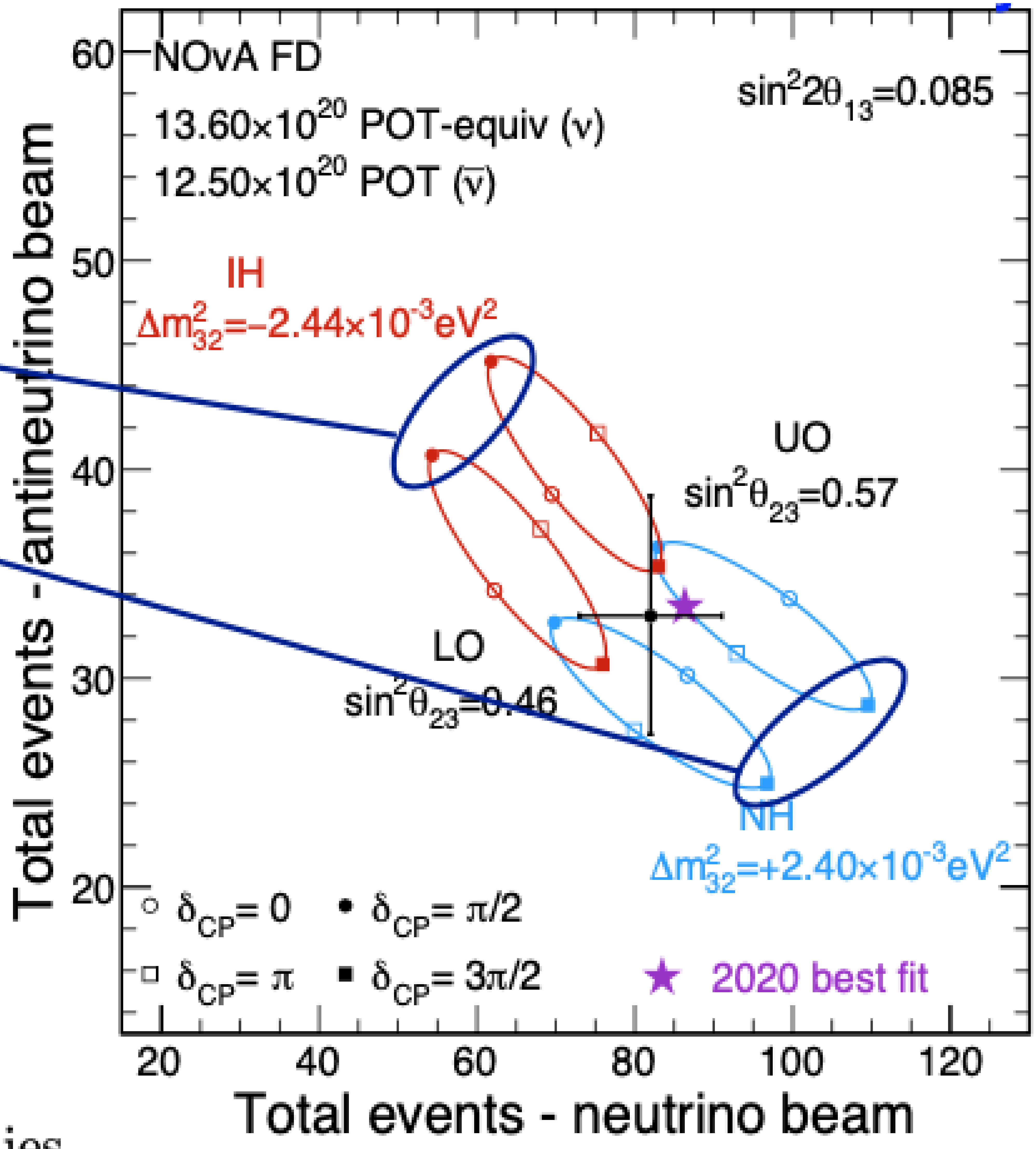
T2K at JPARC

- ➢ Beam power reached 800 kW
- ➢ Exposure ~ 40 ･ 10^{20} POT shared between $\nu/\bar{\nu}$
- ➢ ND280 and SK as Near and Far detectors
- ➢ E ~ 0.6 GeV
- ➢ L = 295 km
- ➢ 2.5^{o} off-axis

NOvA results: 2020 ana

Phys. Rev D 106, 032004 (2022) (Frequentist)
and arXiv:2311.07835 (Bayesian)

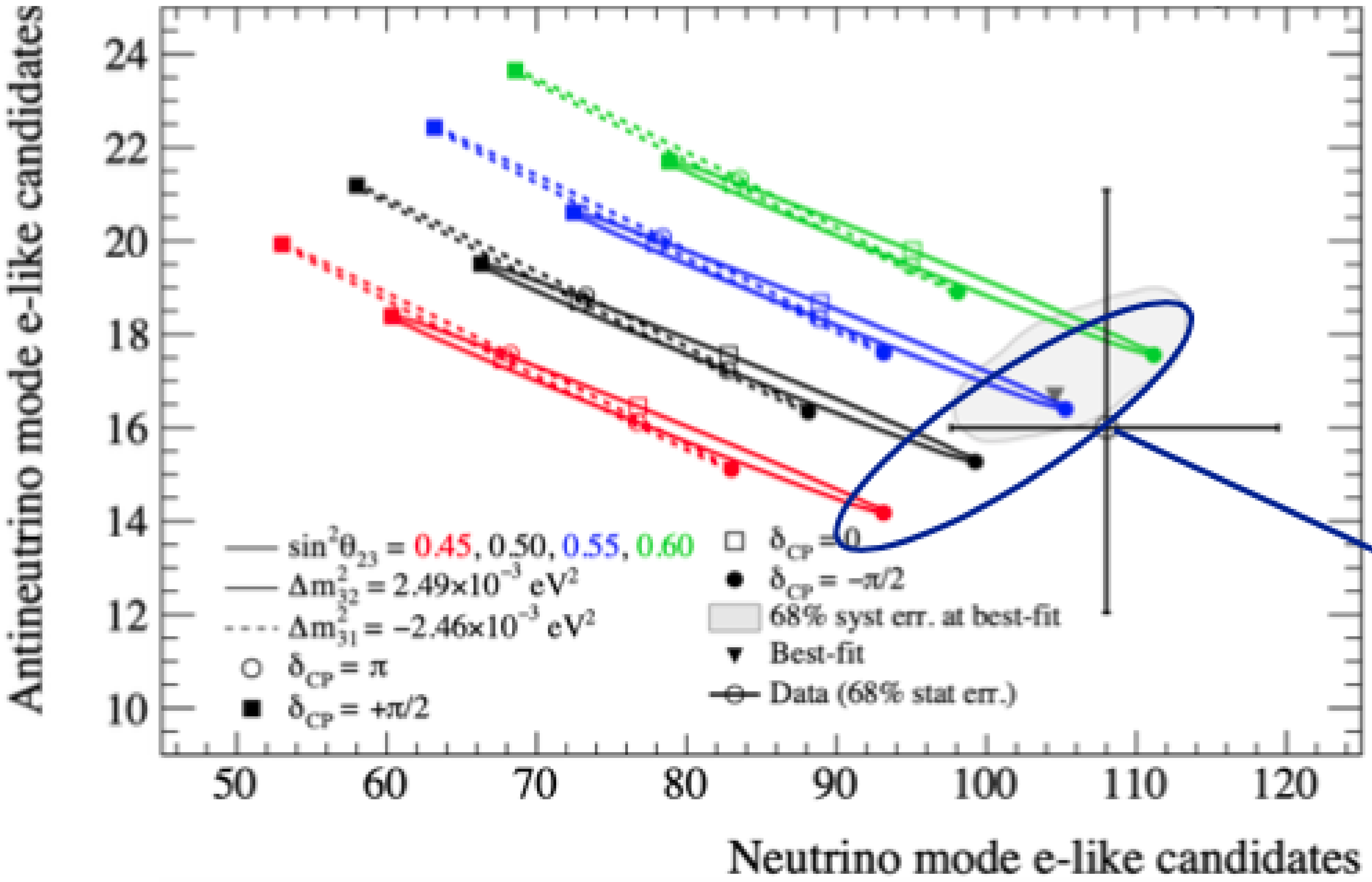


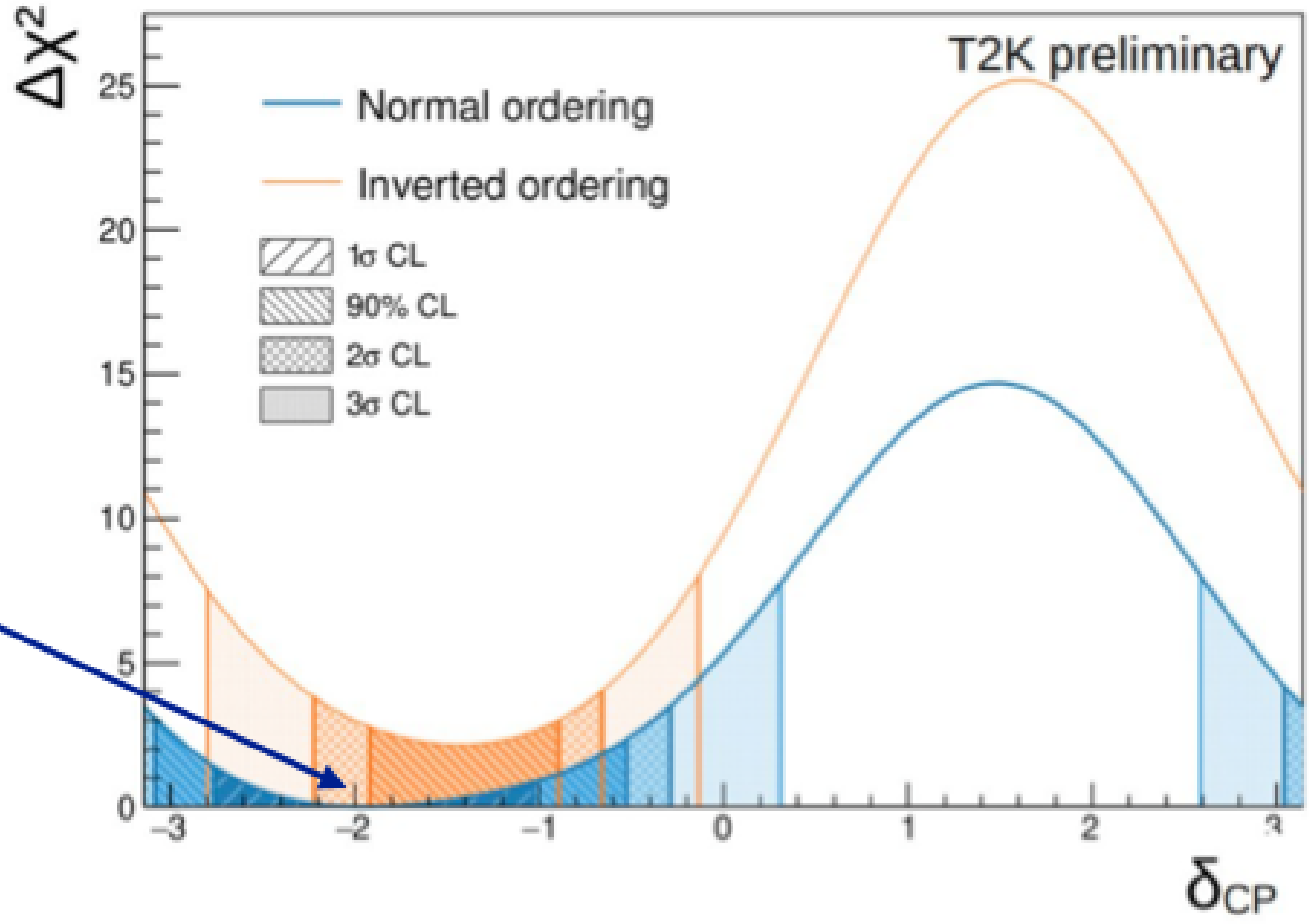


- ✶Disfavor NO, $\delta = 3\pi/2$ at $\sim 2\sigma$.
- ✶Exclude IO, $\delta = \pi/2$ at $> 3\sigma$.
- ✶Combinations that include effect “cancellation” are preferred:
  - ✶ since such options exist for both octants and hierarchies, results show no strong preferences.

T2K results: 2020 ana

Eur. Phys. J. C (2023) 83:782 (2023)



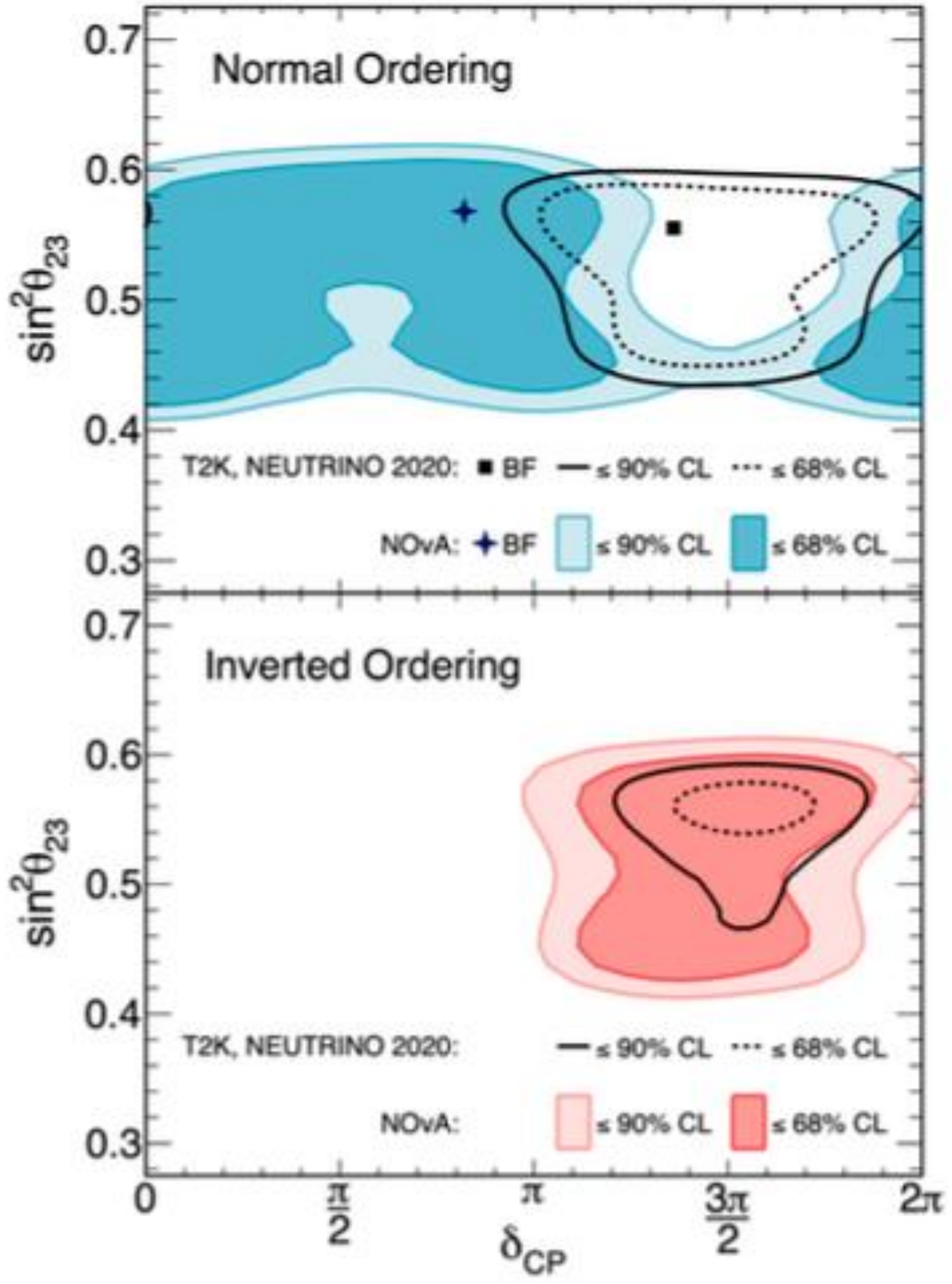


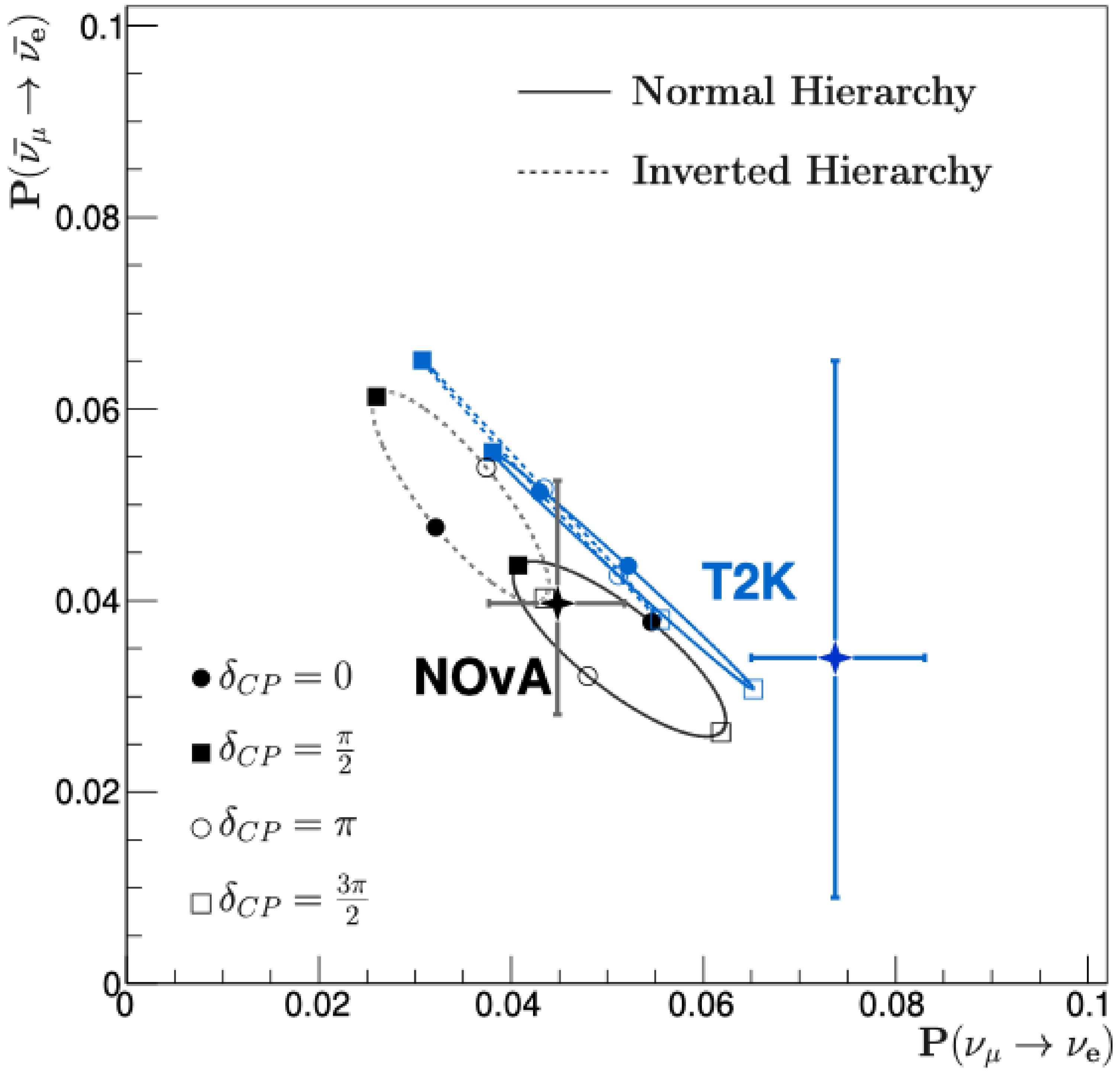
✷Preference of $3\pi/2$ value and normal MO.

✷No CP violation disfavored at $>2\sigma$.

✷Disfavour wide range of δ_{CP} values at $>3\sigma$.

T2K sees asymmetry in ν_e and $\bar{\nu}_e$ rate, while NOvA doesn't.





Tension

- ✷ Huge excitement due to this tension.
- ✷ Two main hypothesis about the reasons:
  - ✷ true inverted hierarchy in Nature;
  - ✷ non-standard interactions (NSI):

$$H = \frac{1}{2E}\left[UM^2U^\dagger + a\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau}\end{pmatrix}\right]$$

- ✷ $\epsilon_{\alpha\beta}$ - the size of the new interaction relative to the weak interaction.
- ✷ Longer baseline = larger NSI effect.
- ✷ Could be due to new heavy states or light mediators.
- ✷ But significance is small, both experiments will keep taking data.

NOvA + T2K

Based on latest published analyses

Full-fledged joint fit produced by both collaborations:

- unique effort for neutrino physics
- use complementary features of both experiments

Full implementation of:

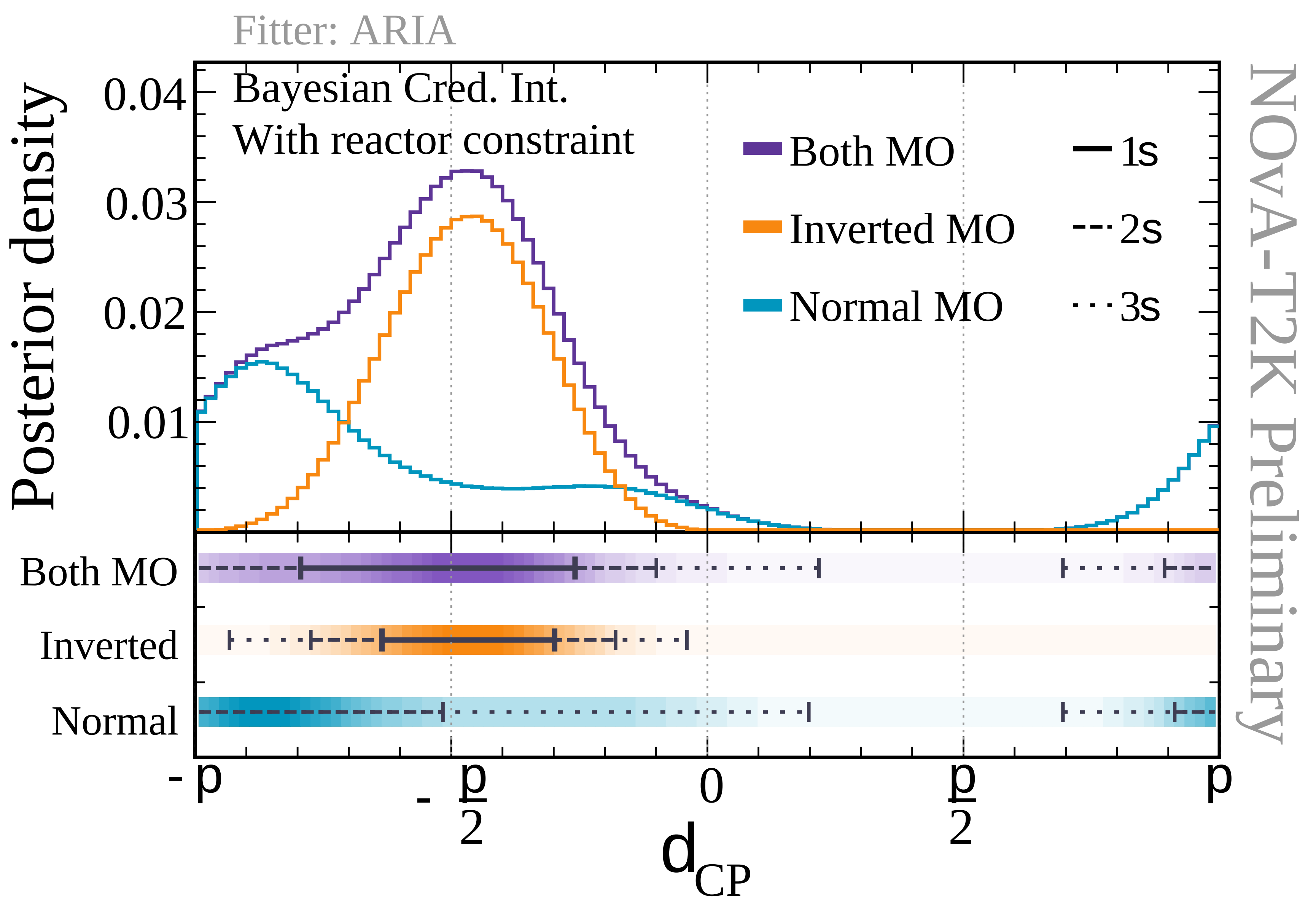
- energy reconstruction and detector response
- detailed likelihood from each experiment
- consistent statistical inference across the full dimensionality

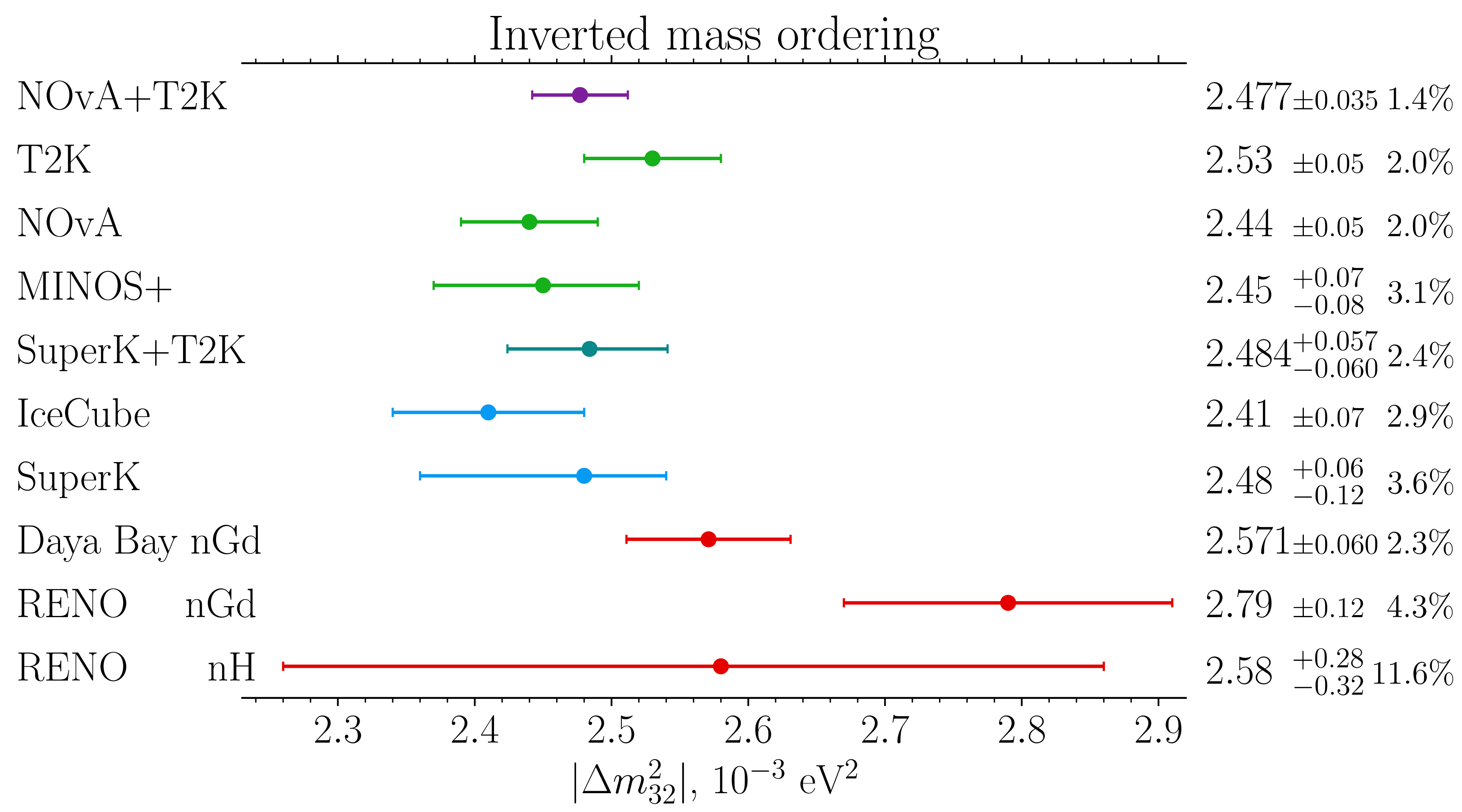
In-depth review of:

- 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

Results:

- More precise measurement of oscillation parameters compared to individual results
- Stronger constraint on Δm^2_{32} (for the first time was better than 2.0%)
- Disfavor CP conservation in Inverted neutrino mass ordering at >3σ
- Firm foundation for future NOvA+T2K analyses





Common publication is prepared

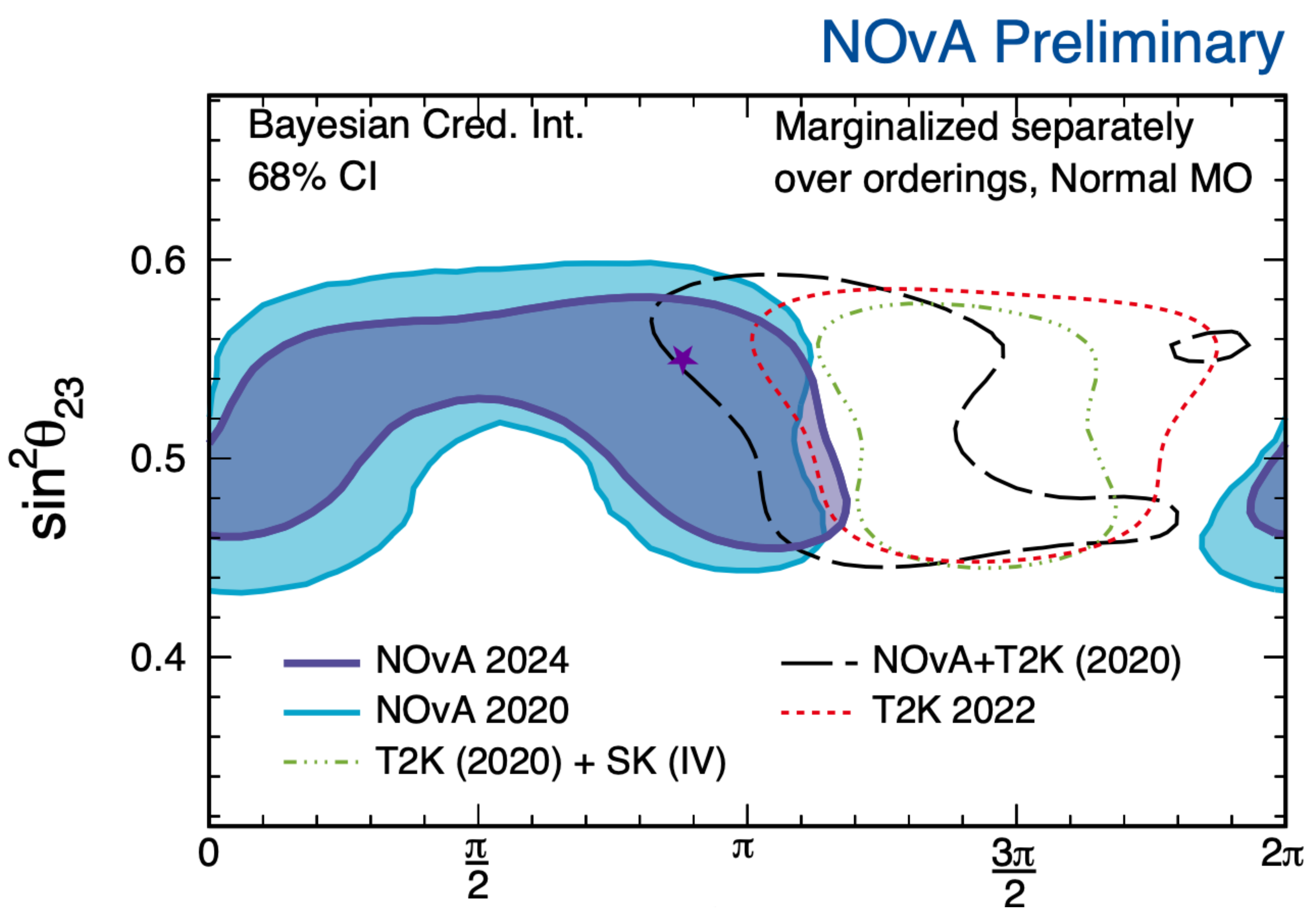
NOvA results

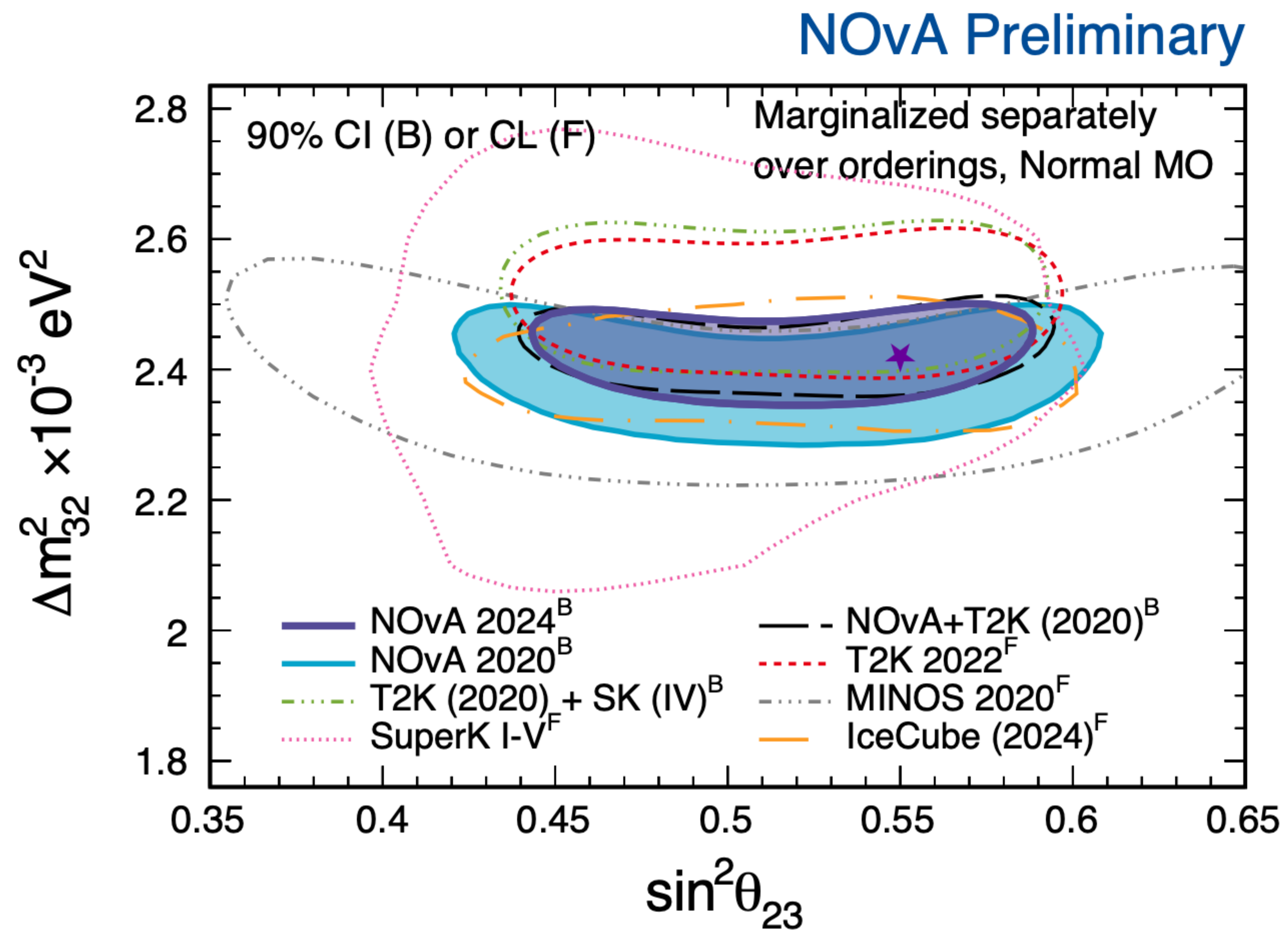
Recent 2024 results

NOvA's first large update since 2020

- Doubled neutrino-mode dataset with 10 years of neutrino & antineutrino data (26.61×10^{20} POT neutrino + 12.5×10^{20} POT antineutrino)
- World's largest accelerator ν sample
- Various remarkable updates to the analysis procedures (larger analysis phase space, improved simulation and systematics)

- As a result:
  - Most precise single-experiment measurement of Δm^2_{32} (1.5%).
  - Results are consistent with previous analysis.
  - Data favors region where matter, CP violation effects are degenerate.
  - Reactor constraint on Δm^2_{32} enhances Normal Ordering preference.





T2K results

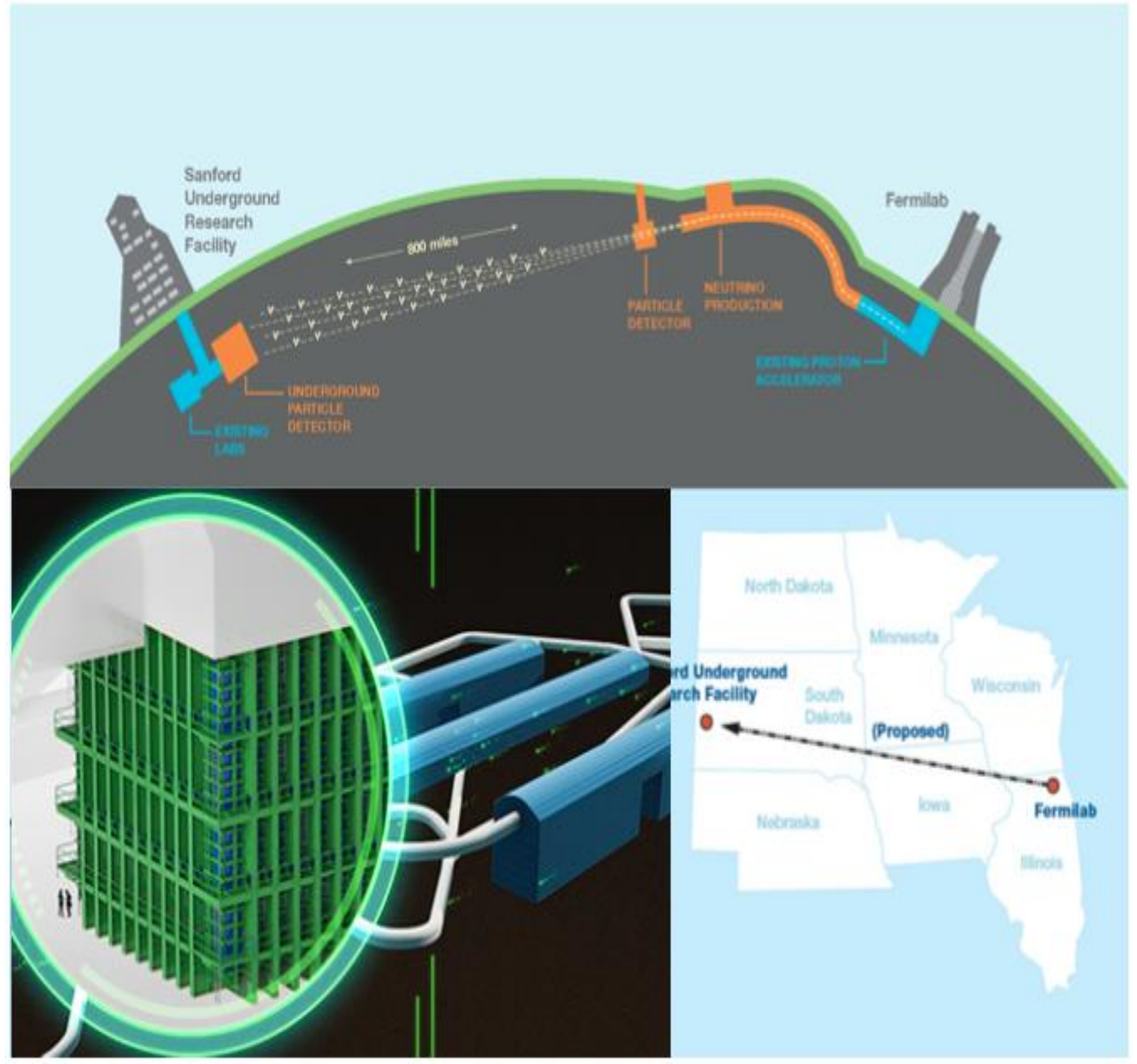
Recent 2024 results

Improved SK detector systematics evaluation

- Neutrino-mode dataset (+10%), first data after Gd loading to SK (0.01%) (21.4×10^{20} POT neutrino + 16.4×10^{20} POT antineutrino)
- Same ND280 analysis and neutrino interaction model
- Improved SK detector systematics evaluation

- As a result:
  - Small improvements in the precision of results, which are consistent with previous analysis.
  - $\delta_{CP} = -2.08{+1.33}{-0.61}$, CP conservation is excluded with 90% CL
  - IO slightly disfavored (1.69σ)
  - Weak preference of upper octant for θ_{23}, compatible with maximal mixing
  - $|\Delta m^2_{32}| = 2.521{+0.037}{-0.050} \times 10^{-2}\mathrm{eV}^2$ (1.7%)

Future accelerator experiments: DUNE



∗1400 collaborators from ~200 institutions and over 30 countries.

∗DUNE will start "in late 2020s" (this is official statement).

∗Baseline 1300 km,

∗ δ_{CP} sensitivity, MO and all PMNS parameters.

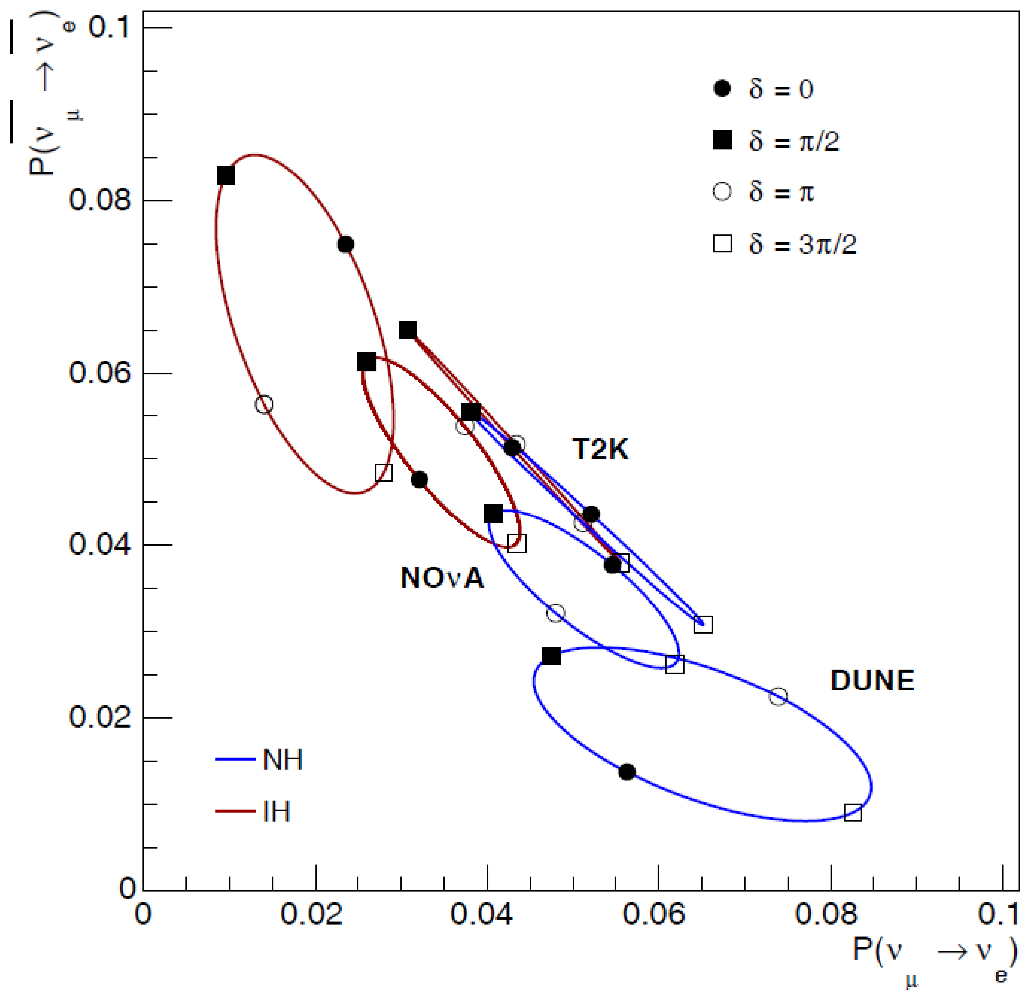
∗On-axis experiment;

∗E at peak ~2.5 GeV;

∗70 kt FD LArTPC with single/dual phase under consideration;

∗Start with 1.2 MW proton beam at 60-120 GeV (10^{20} POT/ year),

∗up to 2.4 MW beam power by ~2035.



Future accelerator experiments: HyperK

∗ 3rd generation of water Cherenkov underground detectors in Kamioka:

Kamiokande (3kt) → Super-Kamiokande (50 kt) → Hyper-Kamiokande (260 kt)

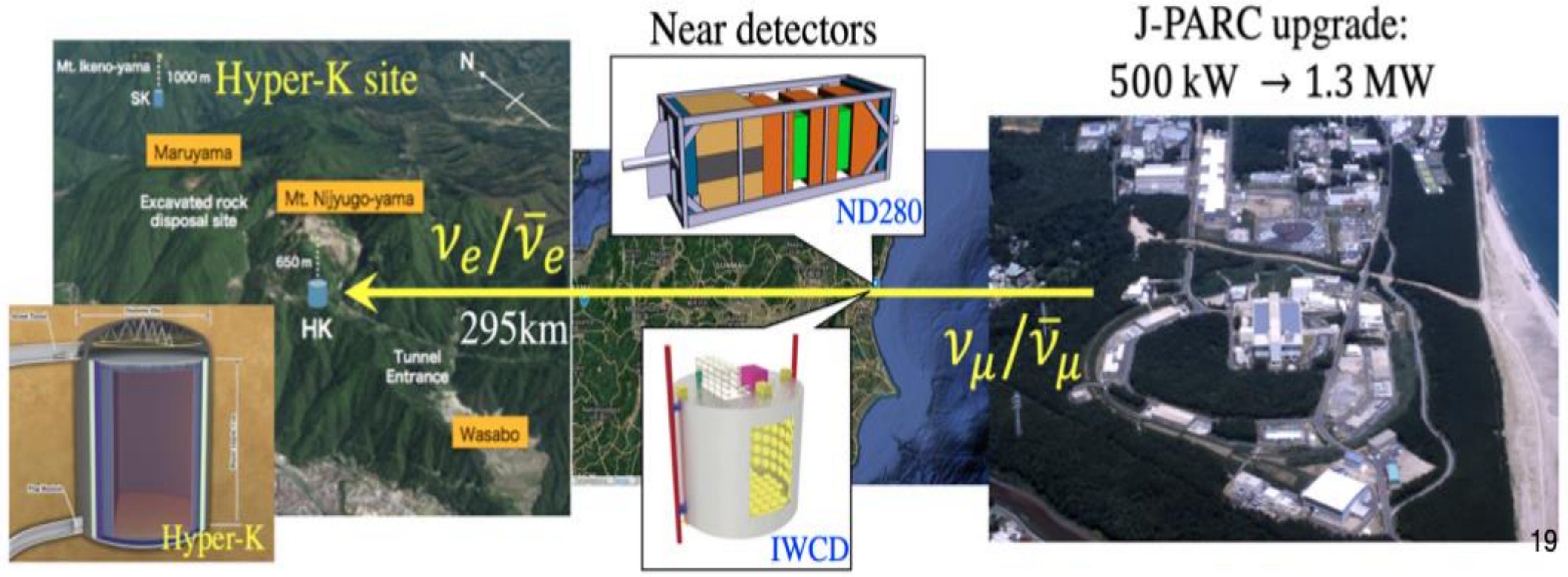
∗ Operation should begin in 2027.

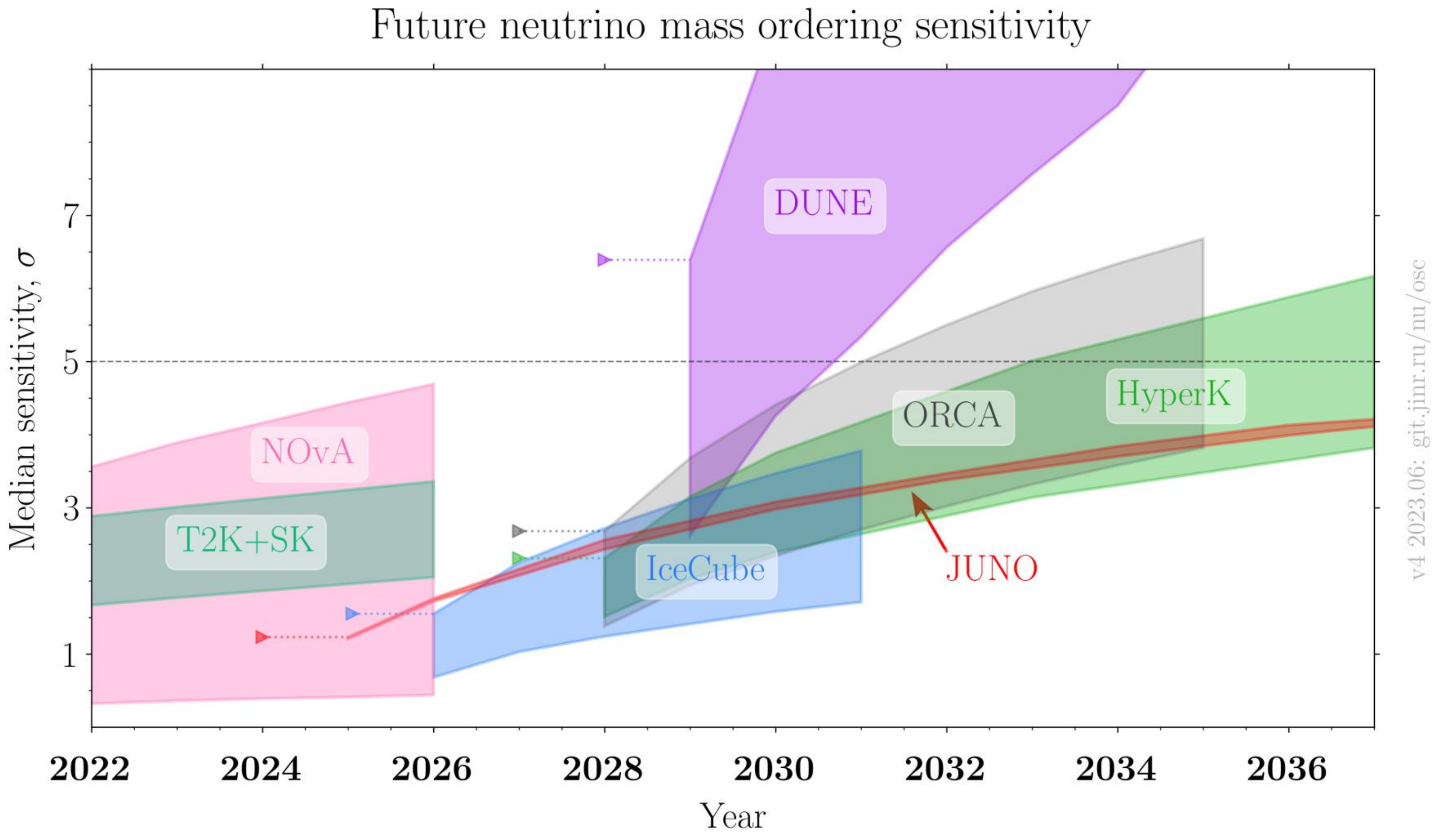
∗ 1.3 MW beam power + larger detector → high statistics.

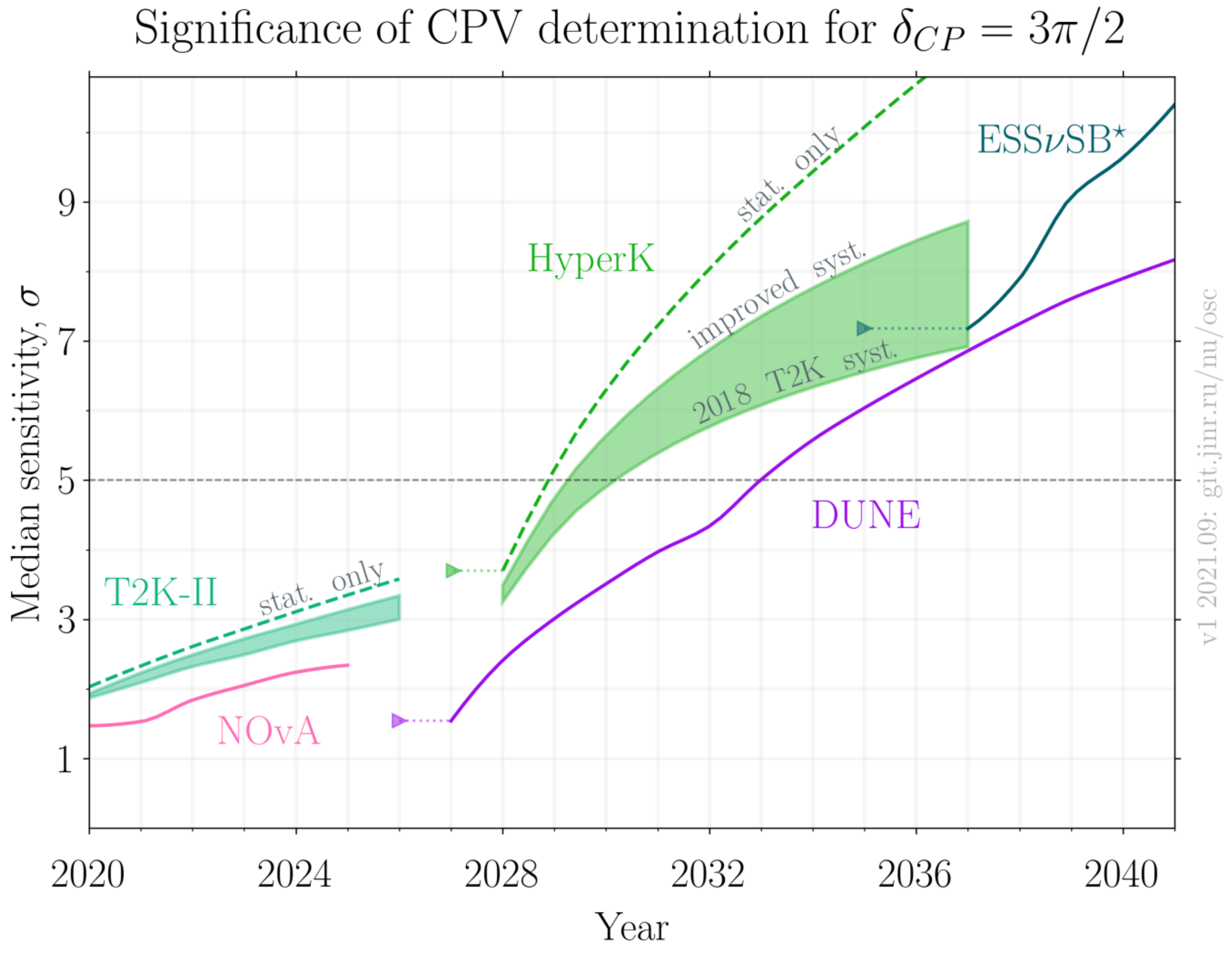
∗ Besides oscillations: supernova, proton decay etc.

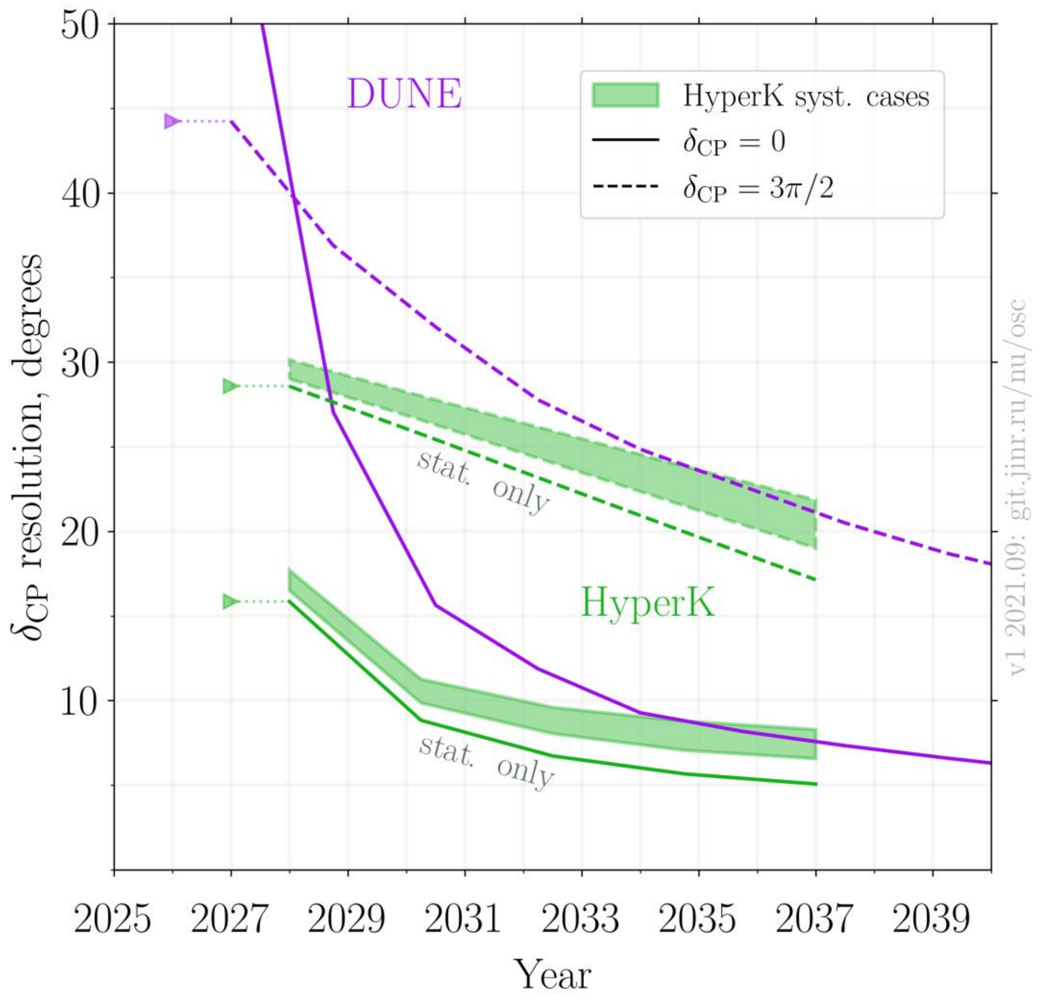
∗ Additional intermediate water Cherenkov detector at 1 km.

∗ ND280 complex inherited from T2K.









Future accelerator experiments:

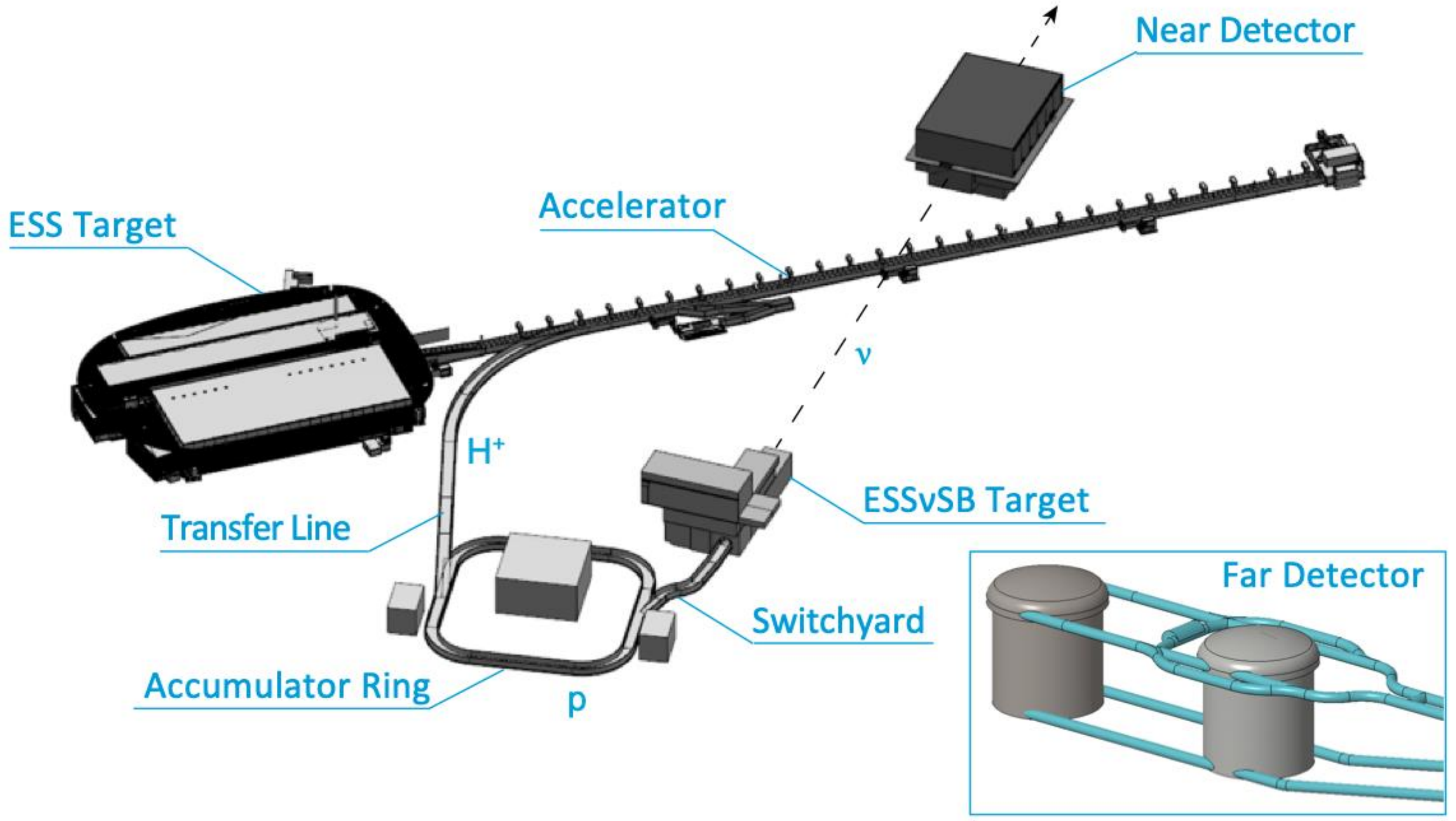
ESSnuSB

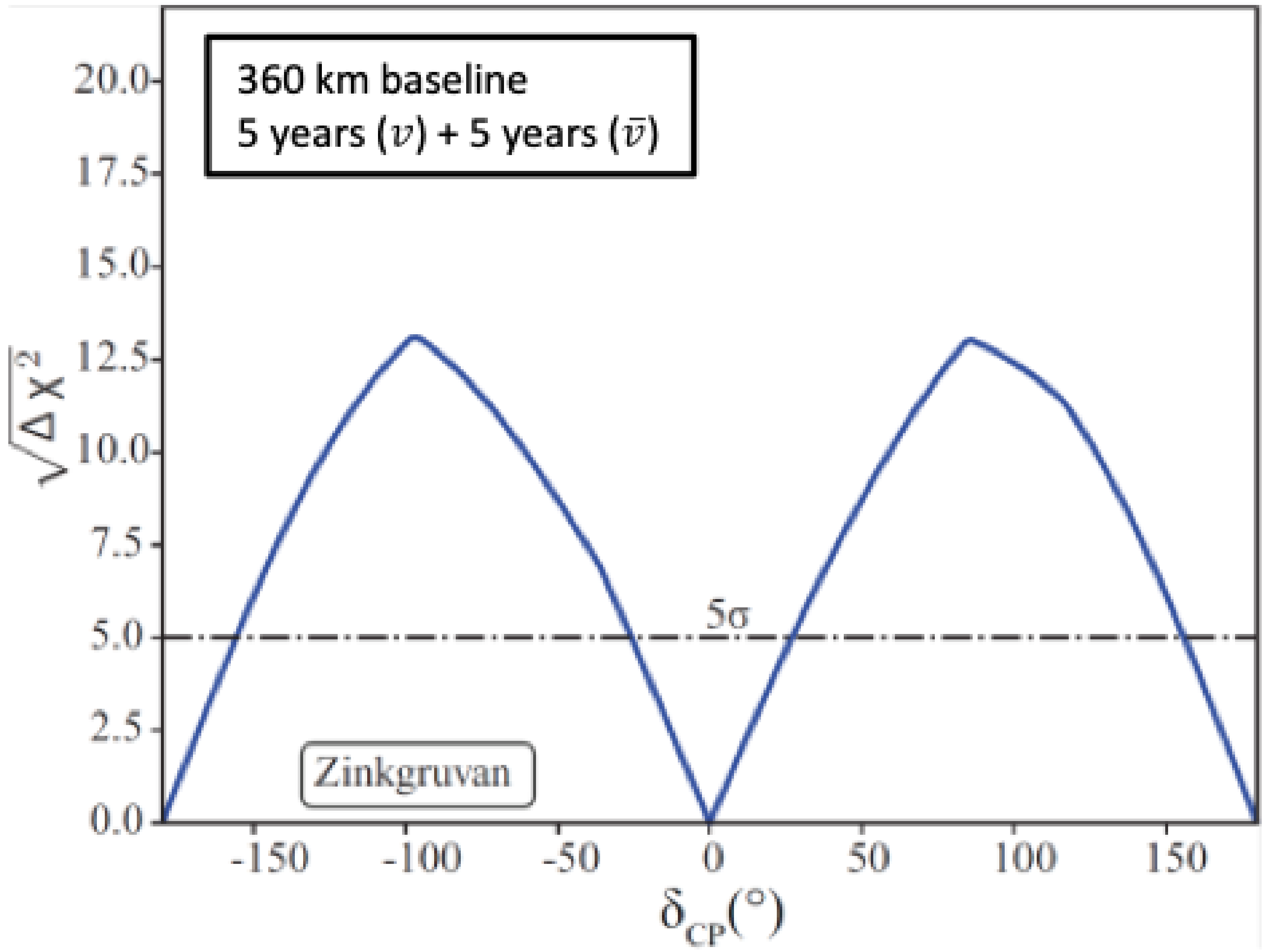
Proposed addition to the ESS project (neutron facility)

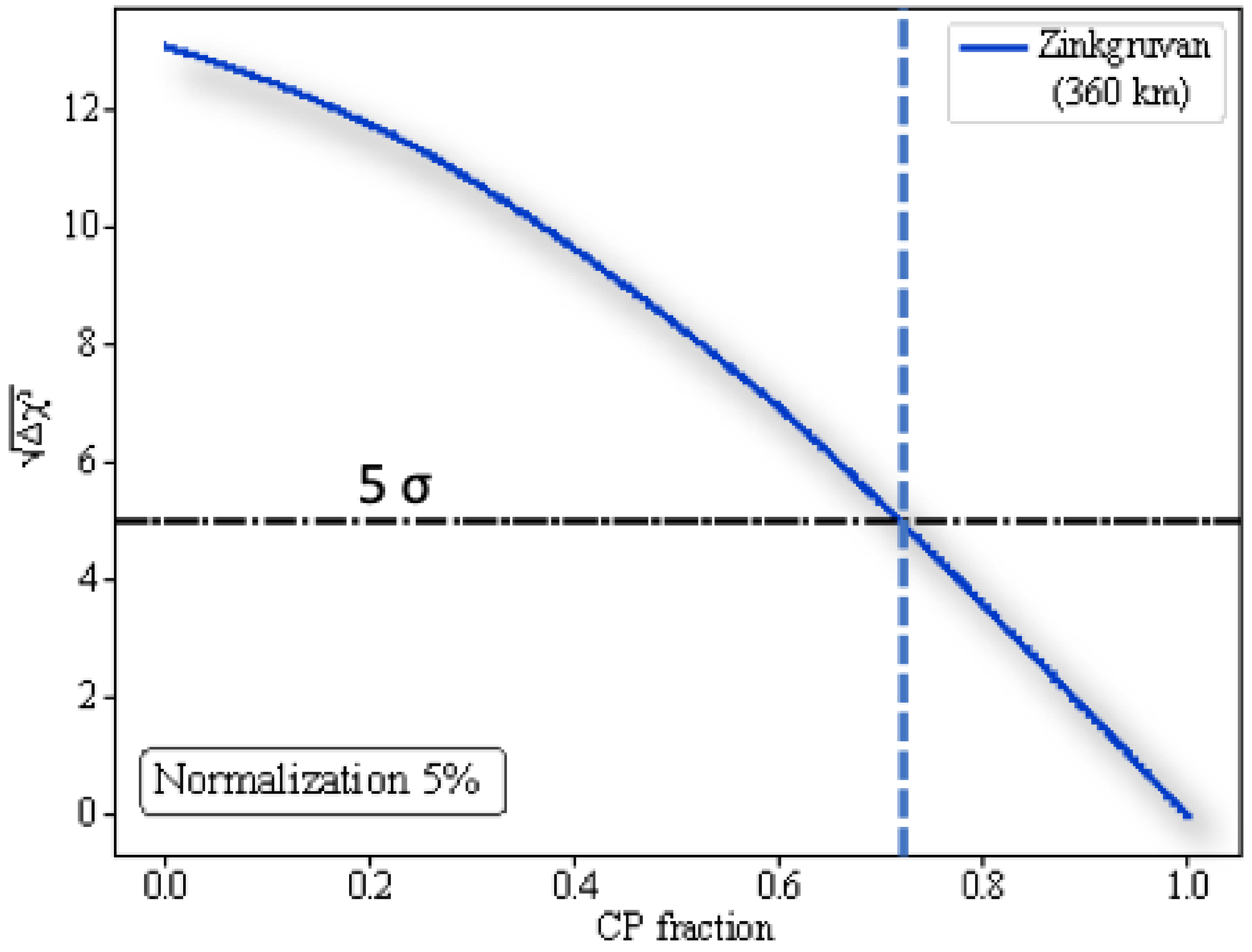
Extremely high power (5 MW) 2 GeV proton beam

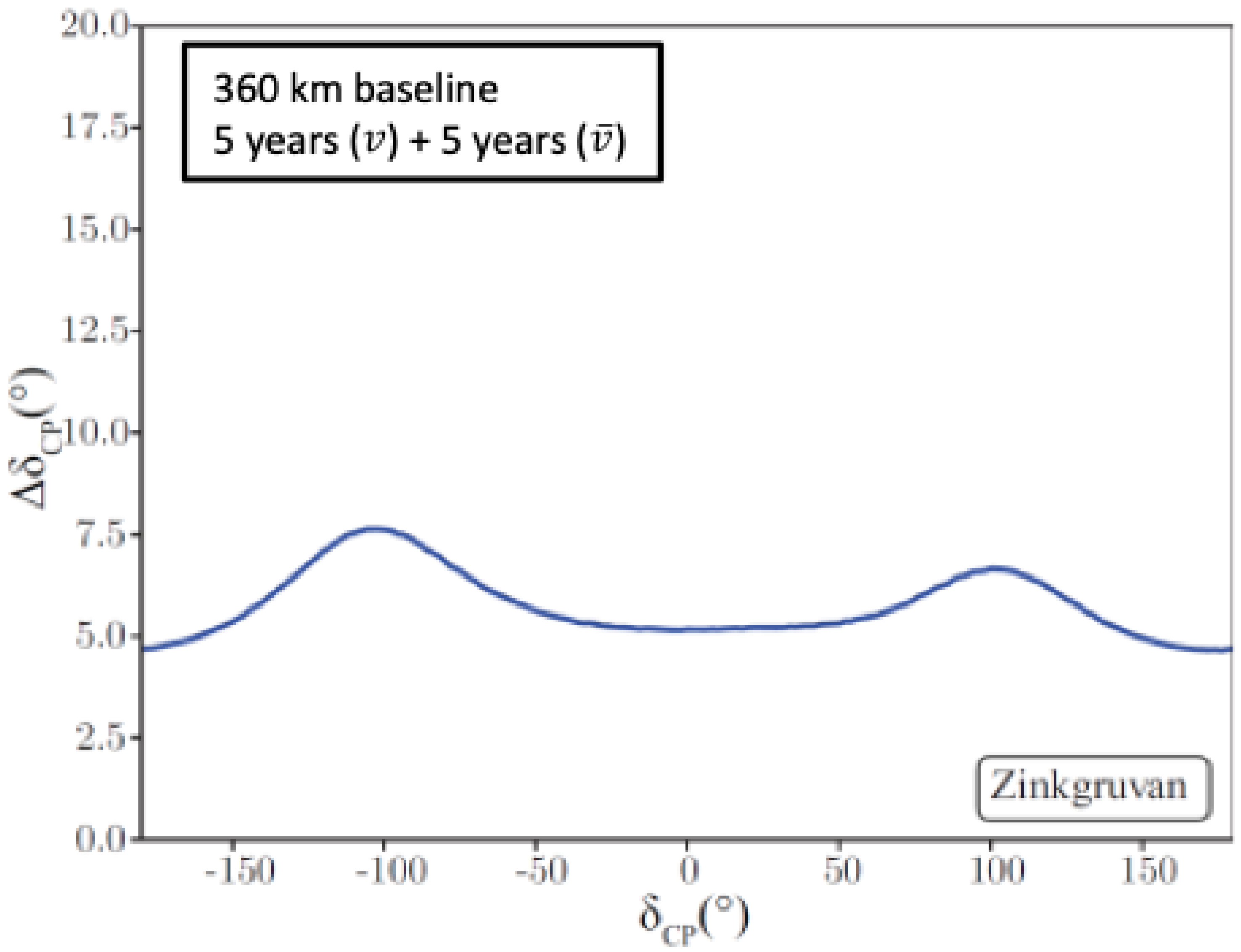
Neutrino beam energy in the range 200-600 MeV

ND/FD setup tuned to measure CPV precisely









Future accelerator experiments:

THEIA

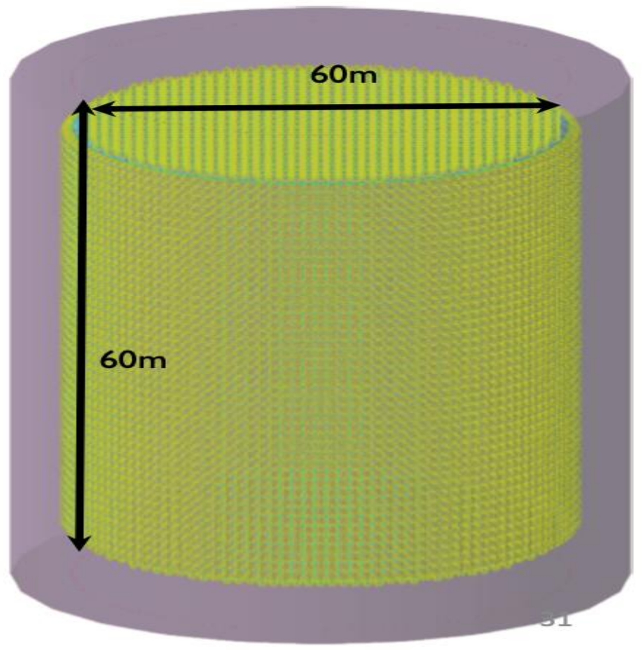
Additional detector at the location of DUNE

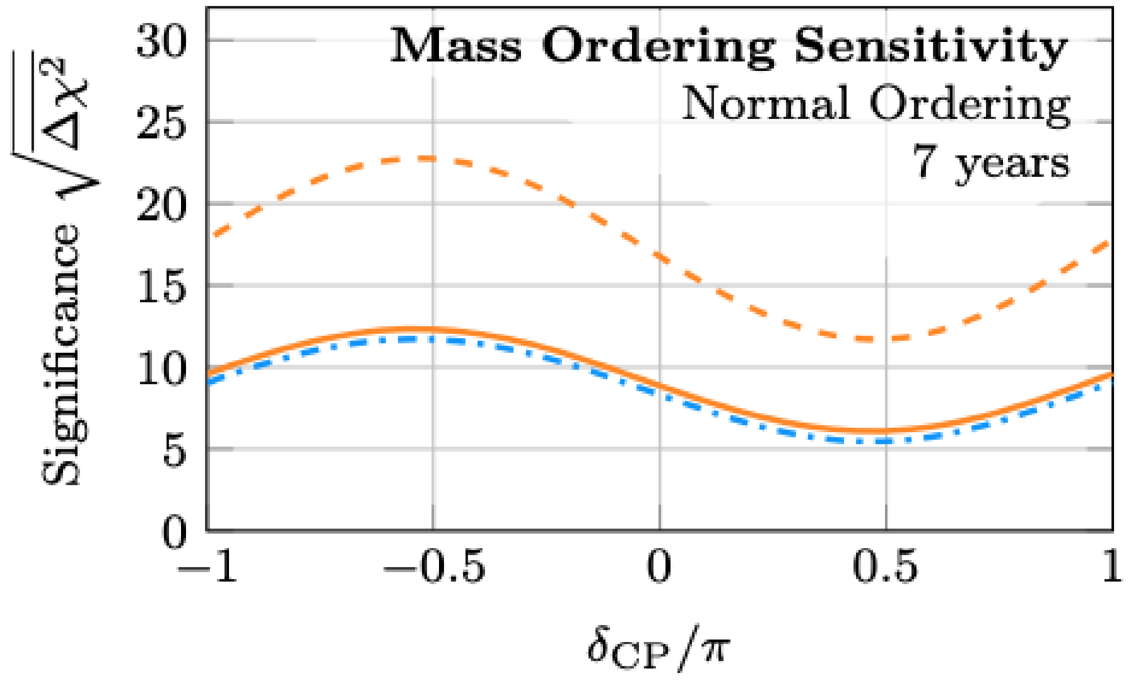
Complements DUNE measurement by different technique

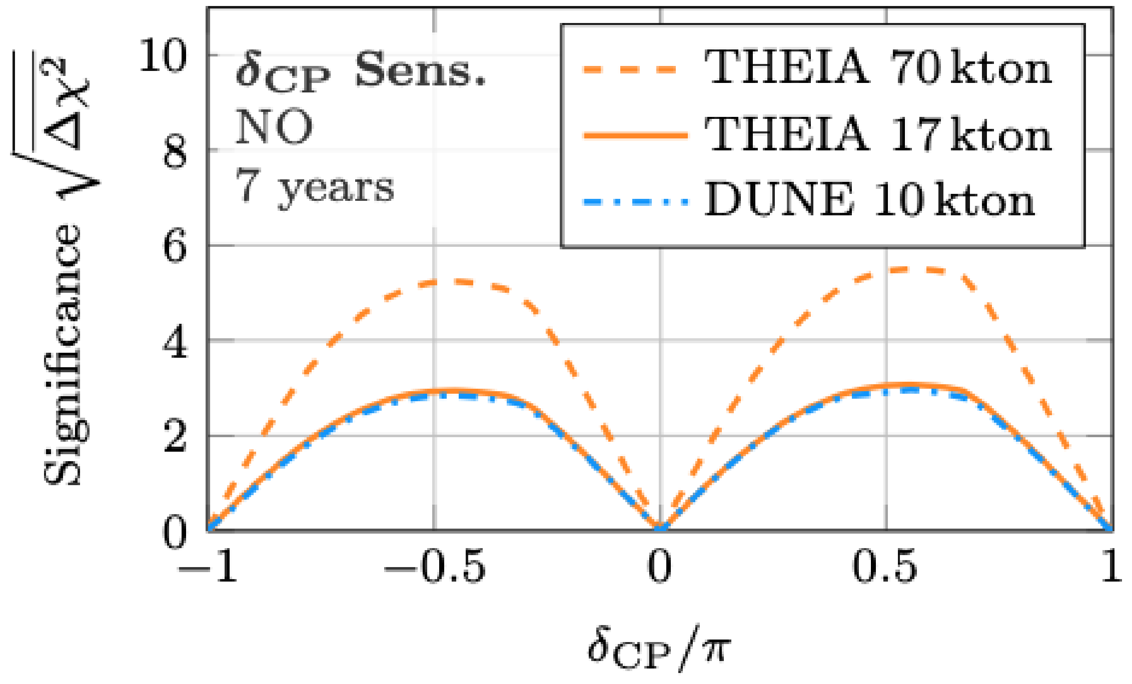
Simultaneous WC and LS detector combines advantages:

Large mass, direction reconstruction, low cost & high light yield, low threshold

R&D on Water based Liquid Scintillator detector and fast high-efficiency photon detection







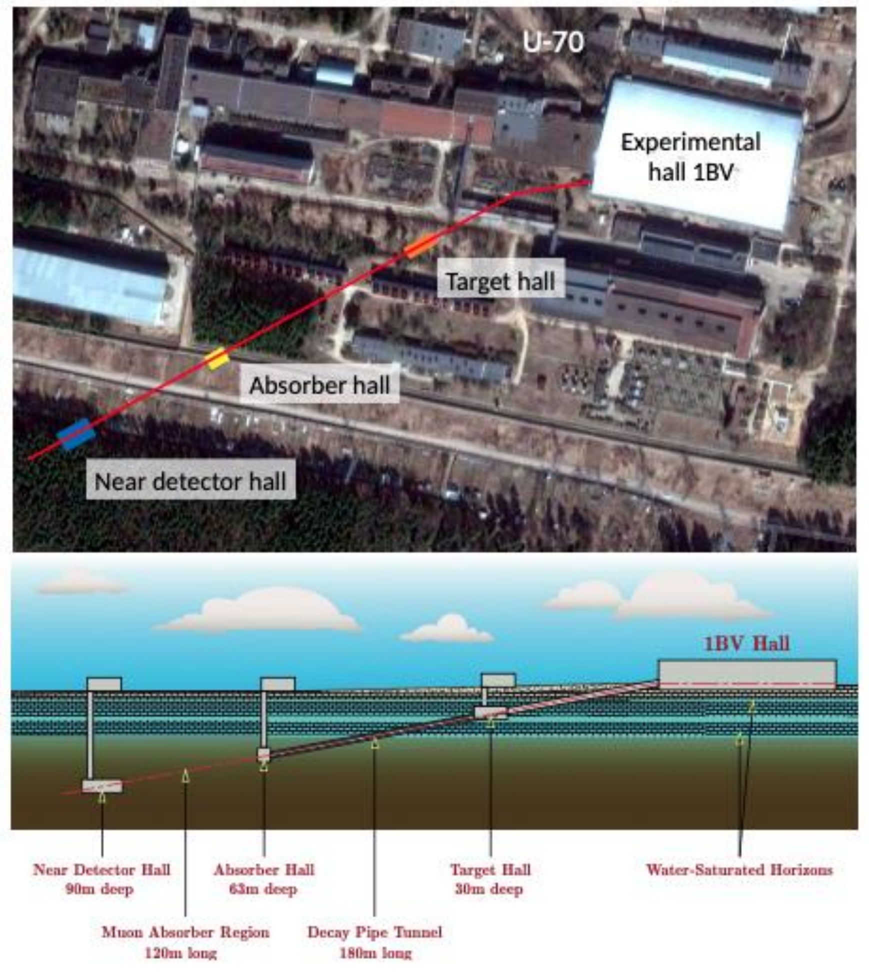
P2O

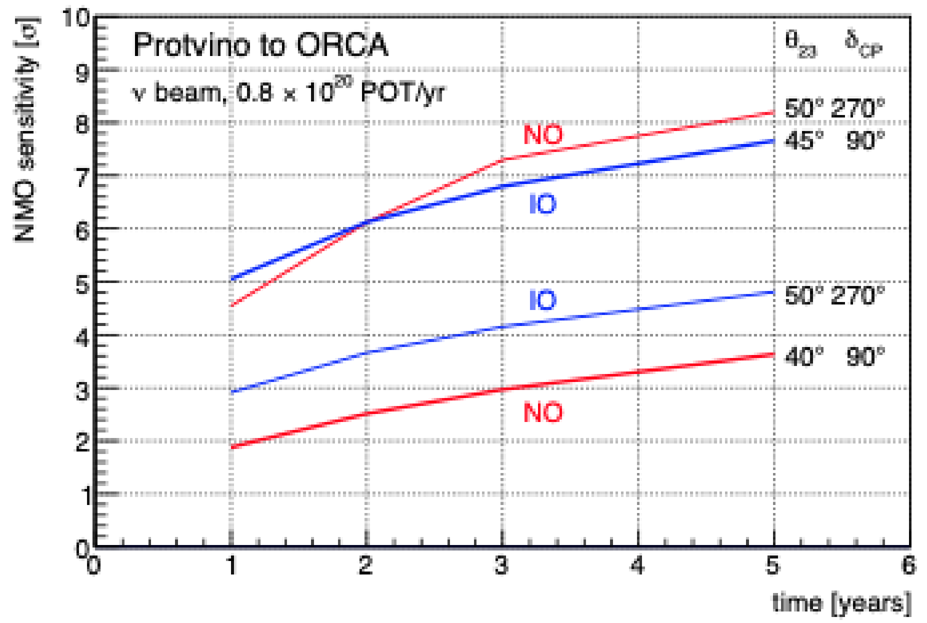
Neutrino beam from U-70 to ORCA (8Mton)

Very long baseline = 2595 km , Enu = 5 GeV

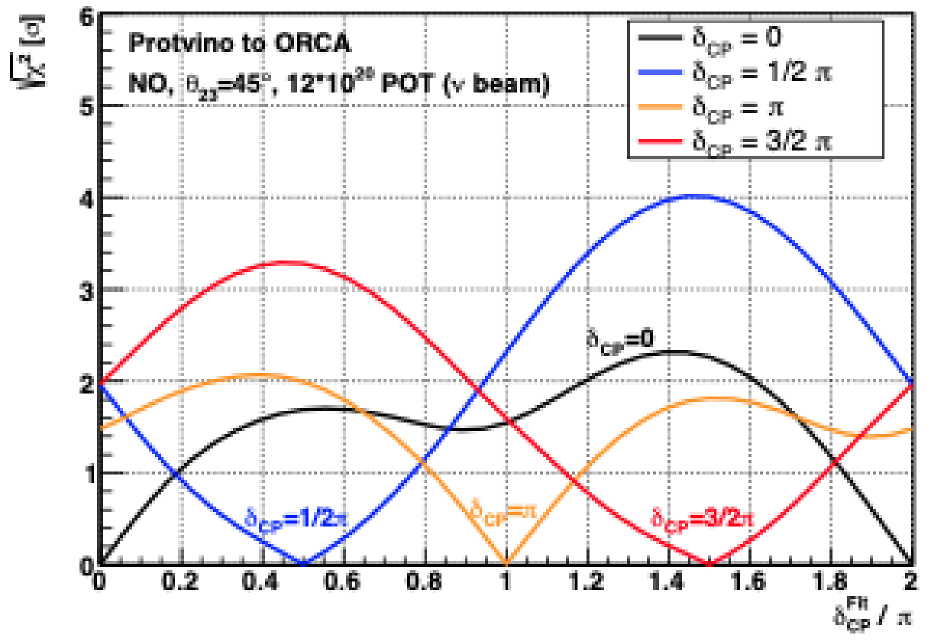
Beam power: 15 kW -> 90 kW -> 450 kW

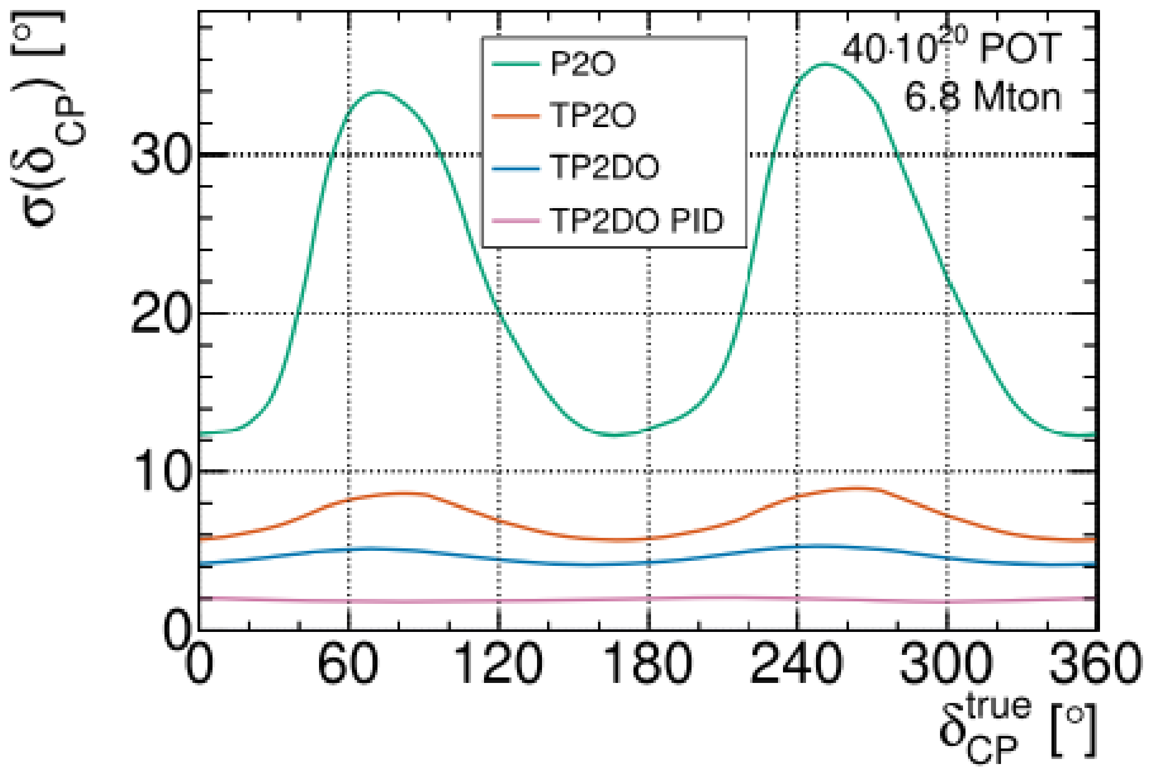
90 kW*year = 0.8 10^{20} POT





Tagging provides Enu and modest energy resolution detector provides identification

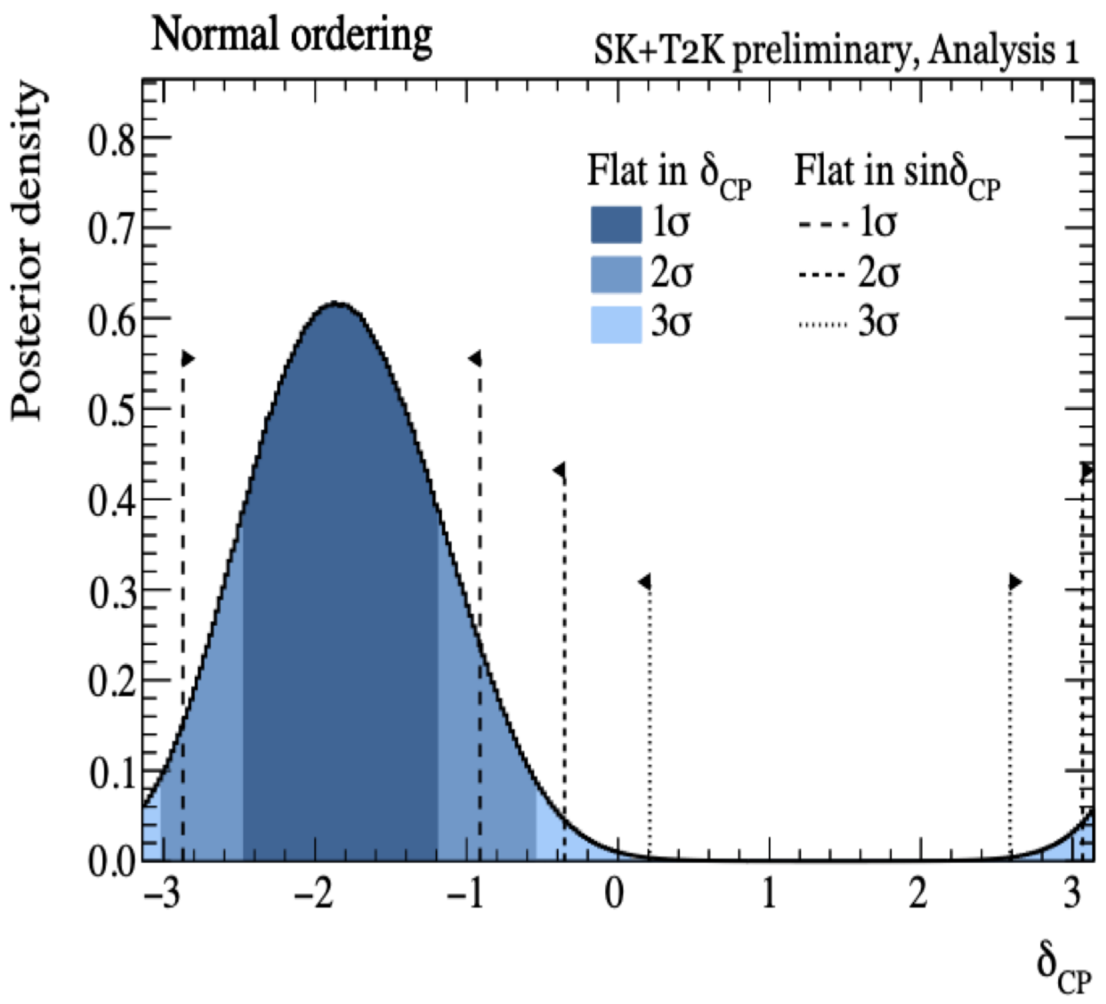


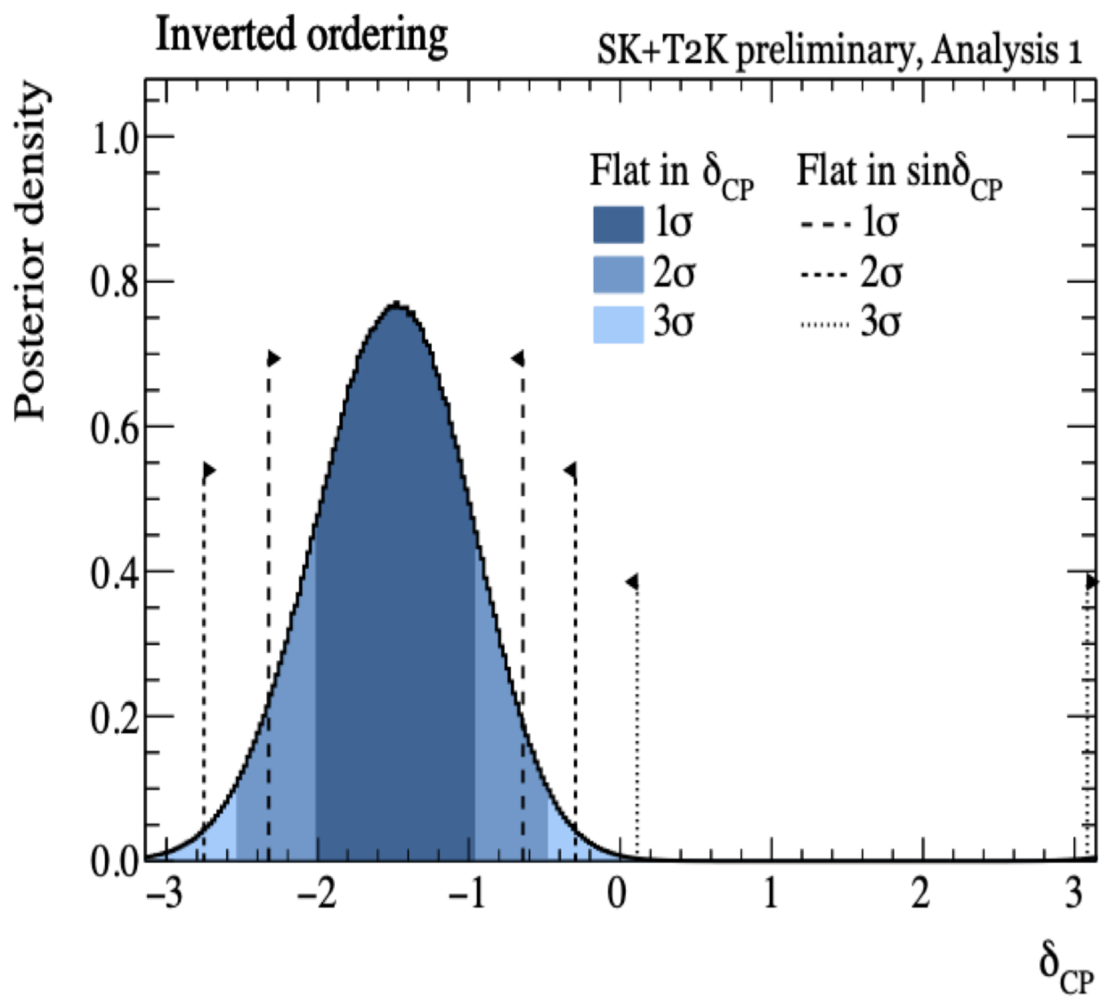


Combining experiments results

SuperK + T2K

- 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.

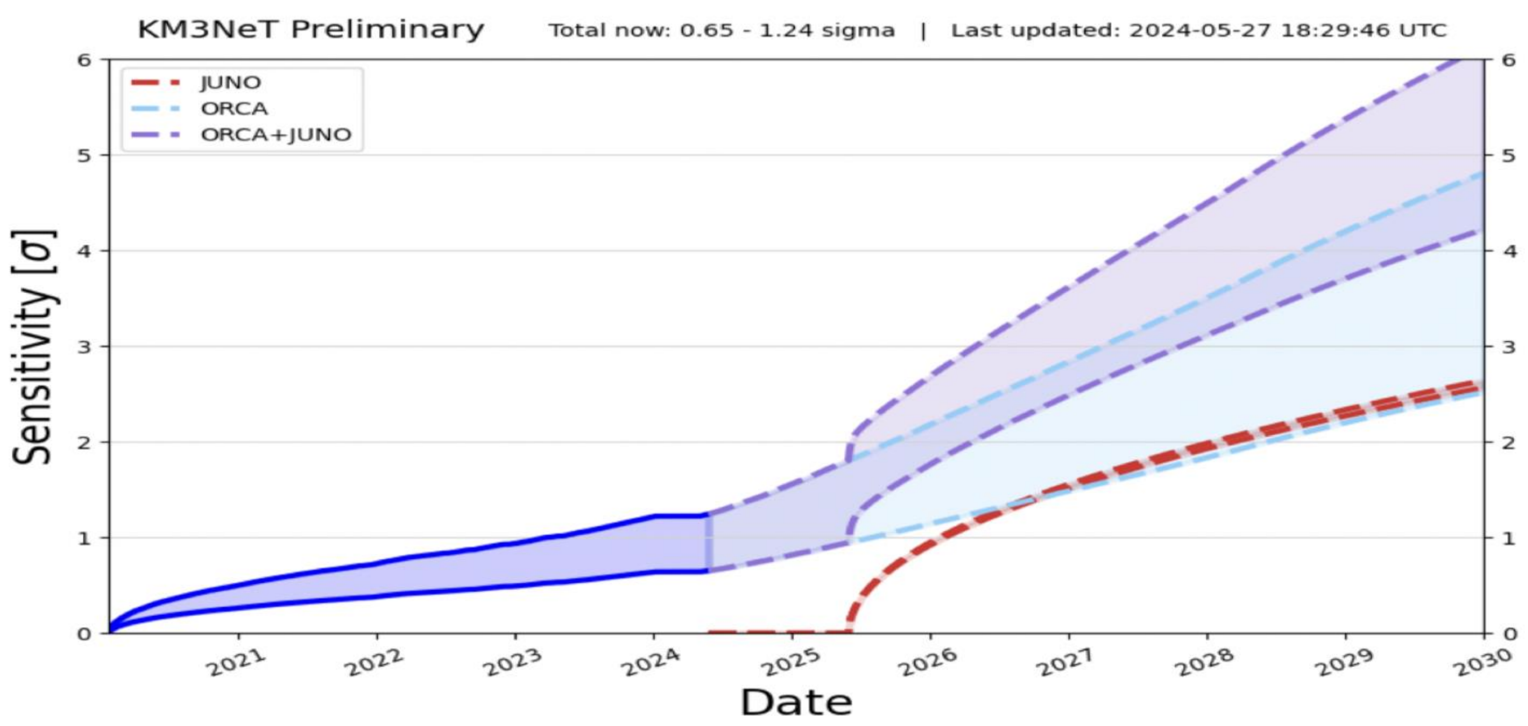


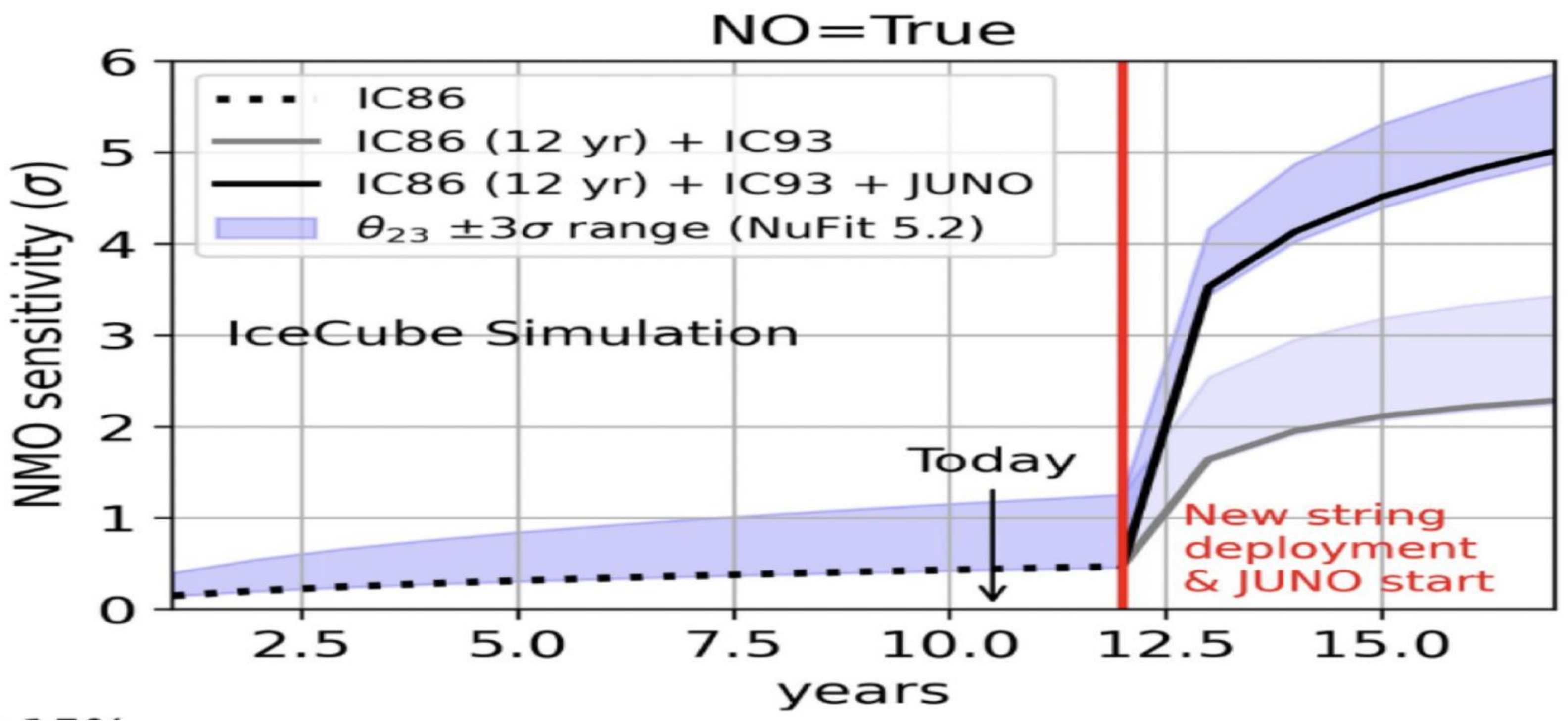


JUNO + Accelerator + Atmospheric

- ✓ JUNO+TAO, 7.1 years×26.6 GW exposure: $\sim 3\sigma$
- ✓ +1% external constrain on Δm^2_{32}: $> 4\sigma$
- ✓ combined with accelerator/atmospheric experiment: $> 5\sigma$
  - ↪ sensitivity boost due to tension for wrong ordering

JUNO NMO, CPC (2025) [2405.18008]
JUNO+accelerator [2008.11280]
JUNO+IceCube [1911.06745]





Another approach: global fits

Exist already 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.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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.

Received 13 September 1993

DOI: https://doi.org/10.1103/PhysRevD.49.3626

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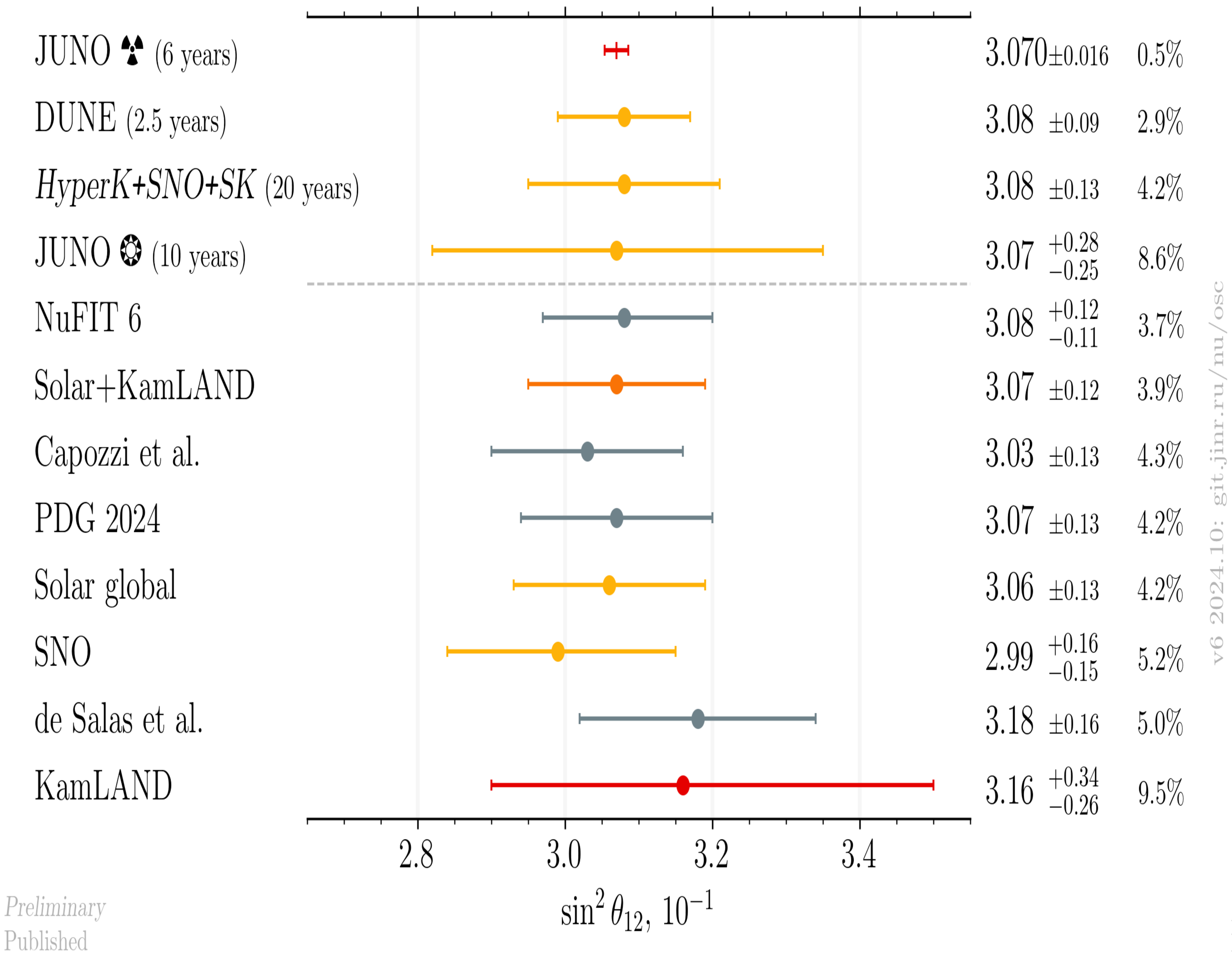
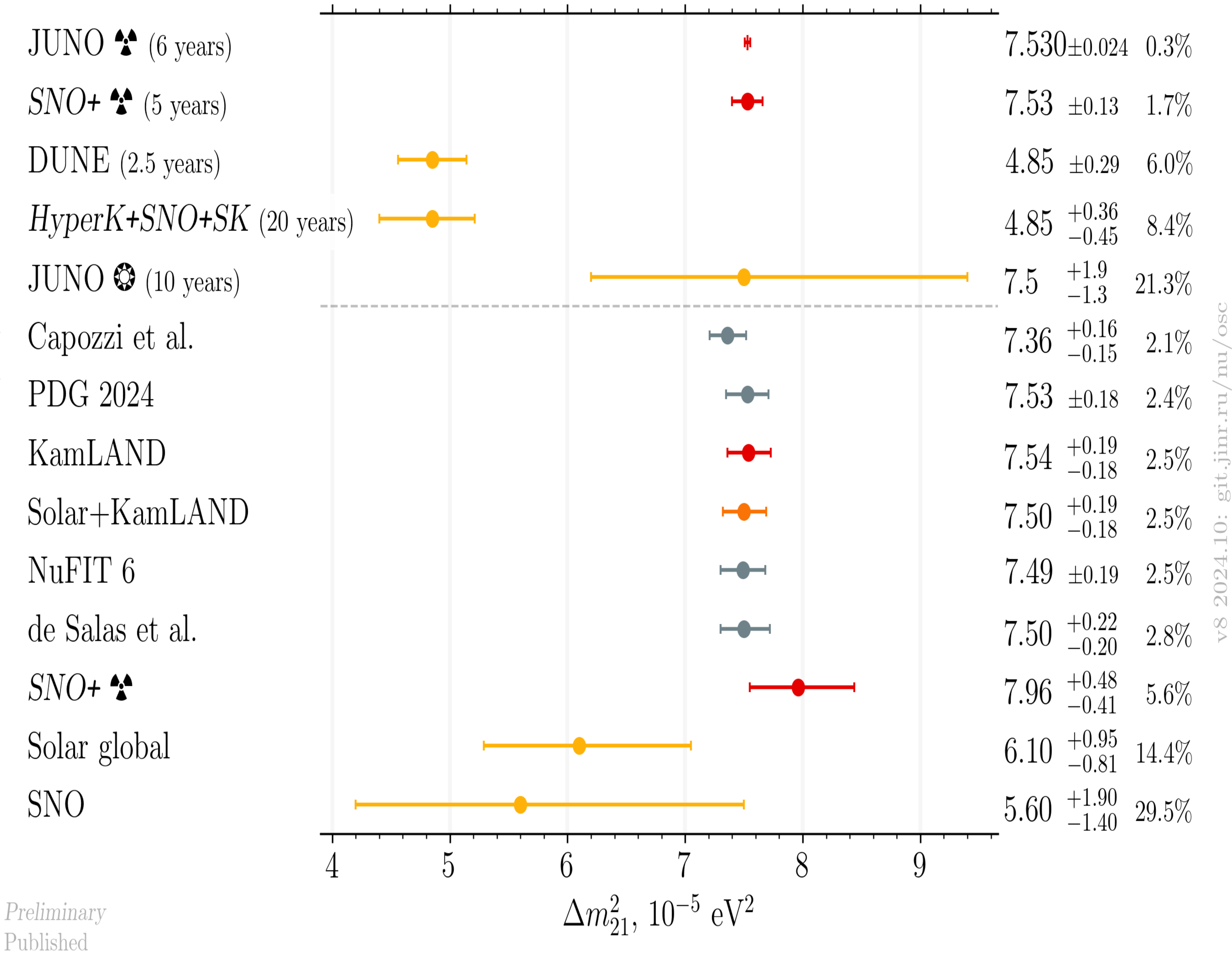
General approach

- 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 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 and 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 2030 and this seems to be the best practical way to perform the world measurement
- 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

Present and Future Accuracy on Oscillation Parameters:

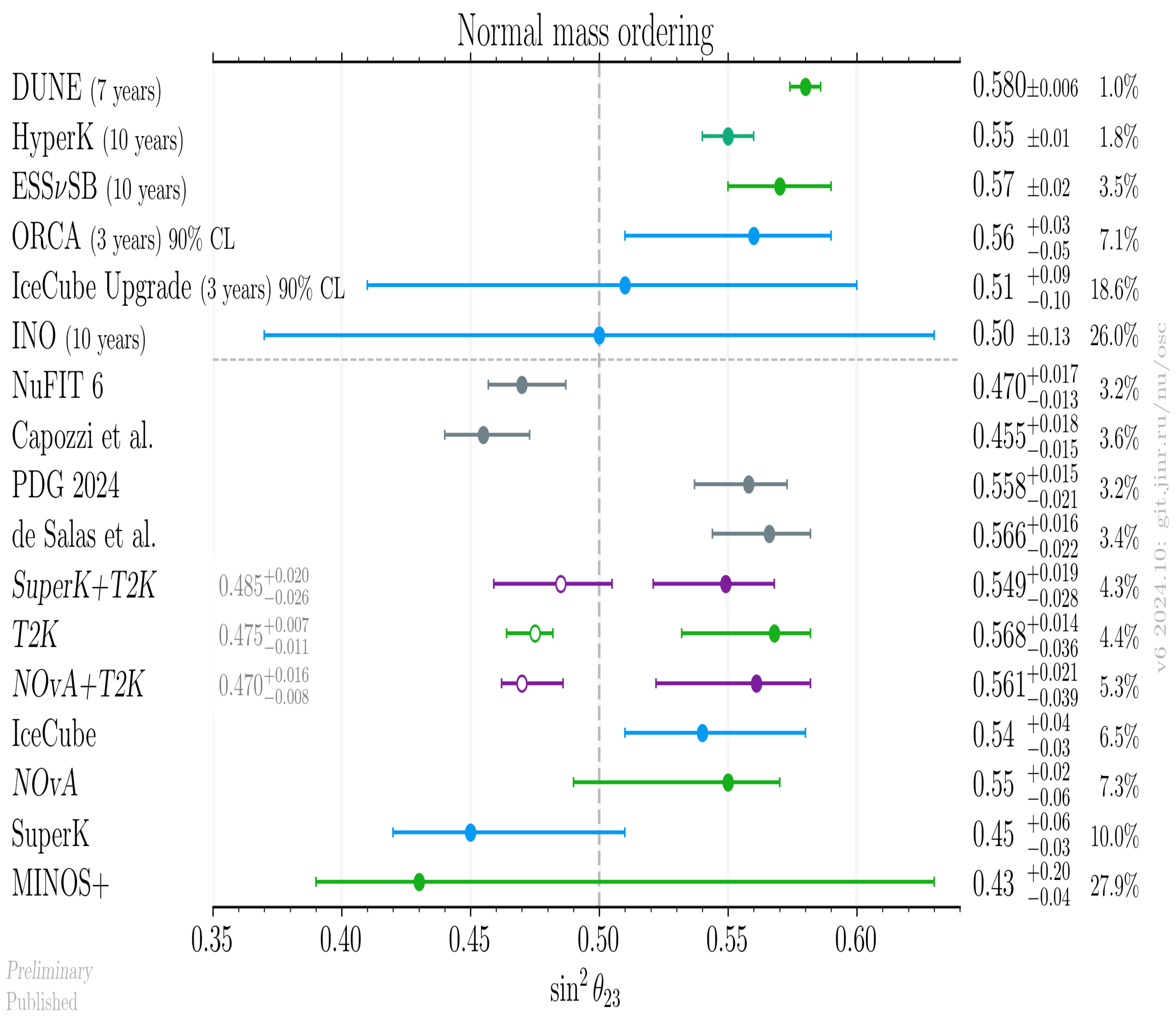
$sin^2\theta_{12}, \Delta m^2_{21}$

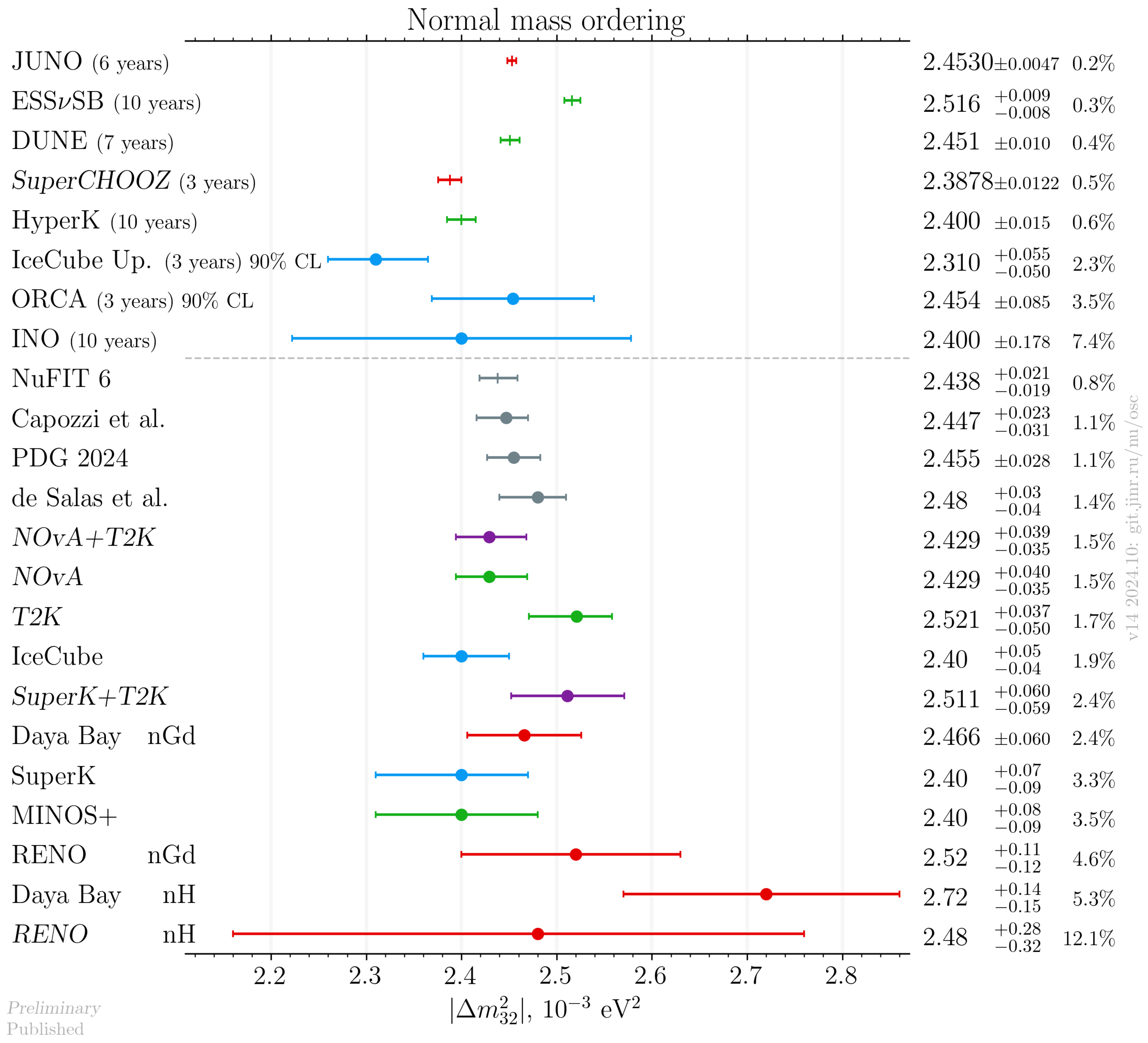




Present and Future Accuracy on Oscillation Parameters:

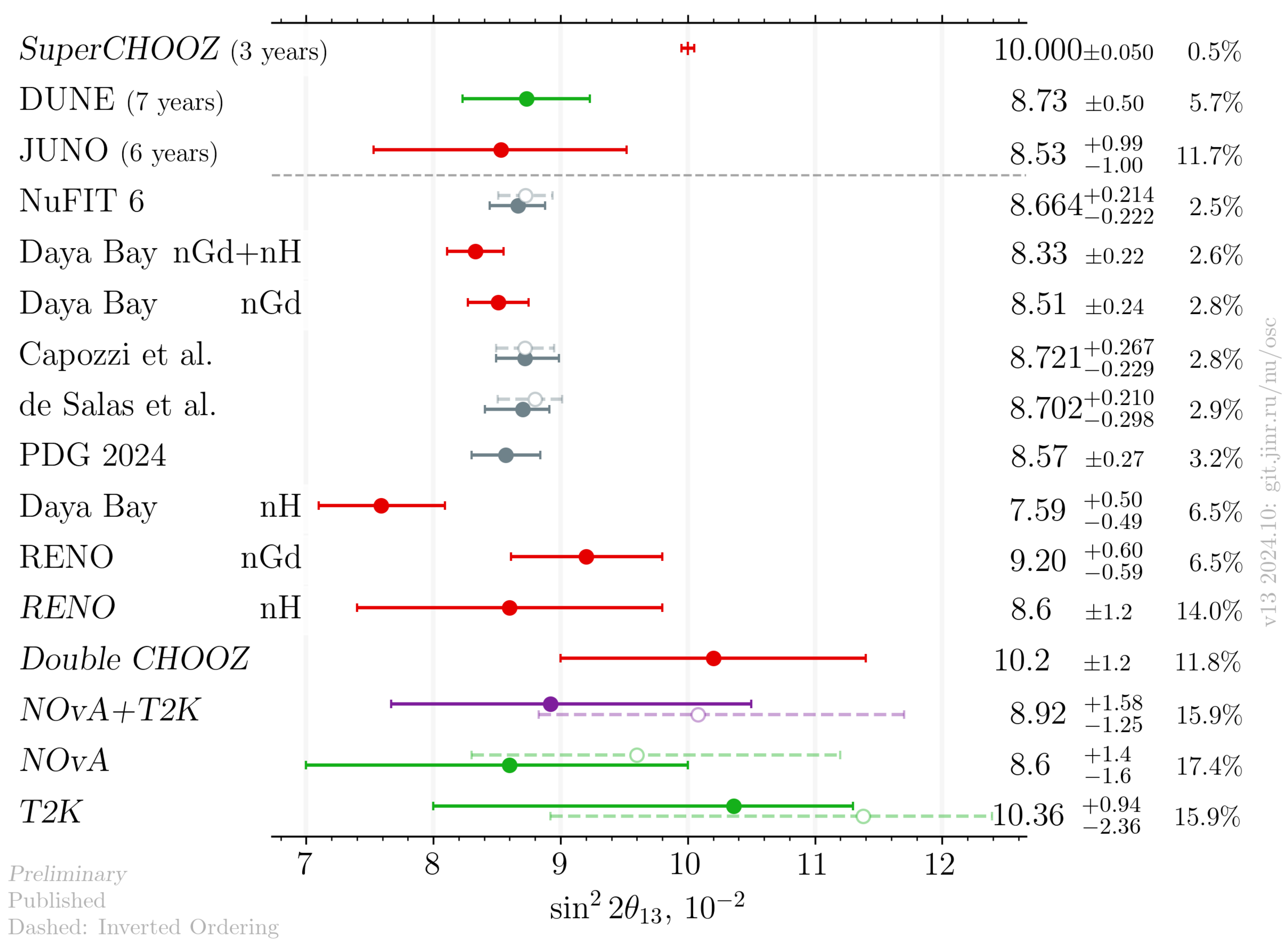
$sin^2\theta_{23}$, $|\Delta m^2{}_{32}|$

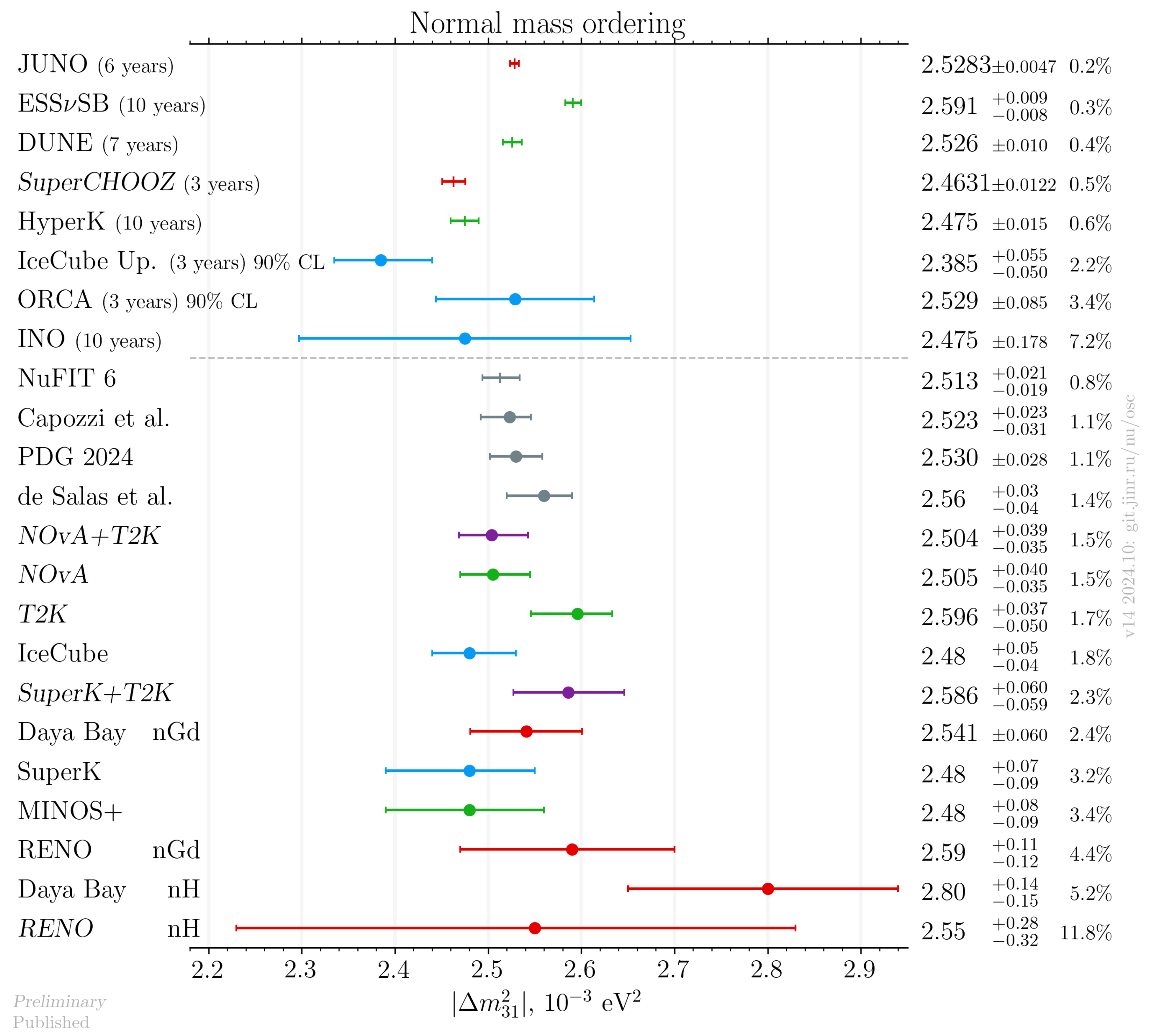




Present and Future Accuracy on Oscillation Parameters:

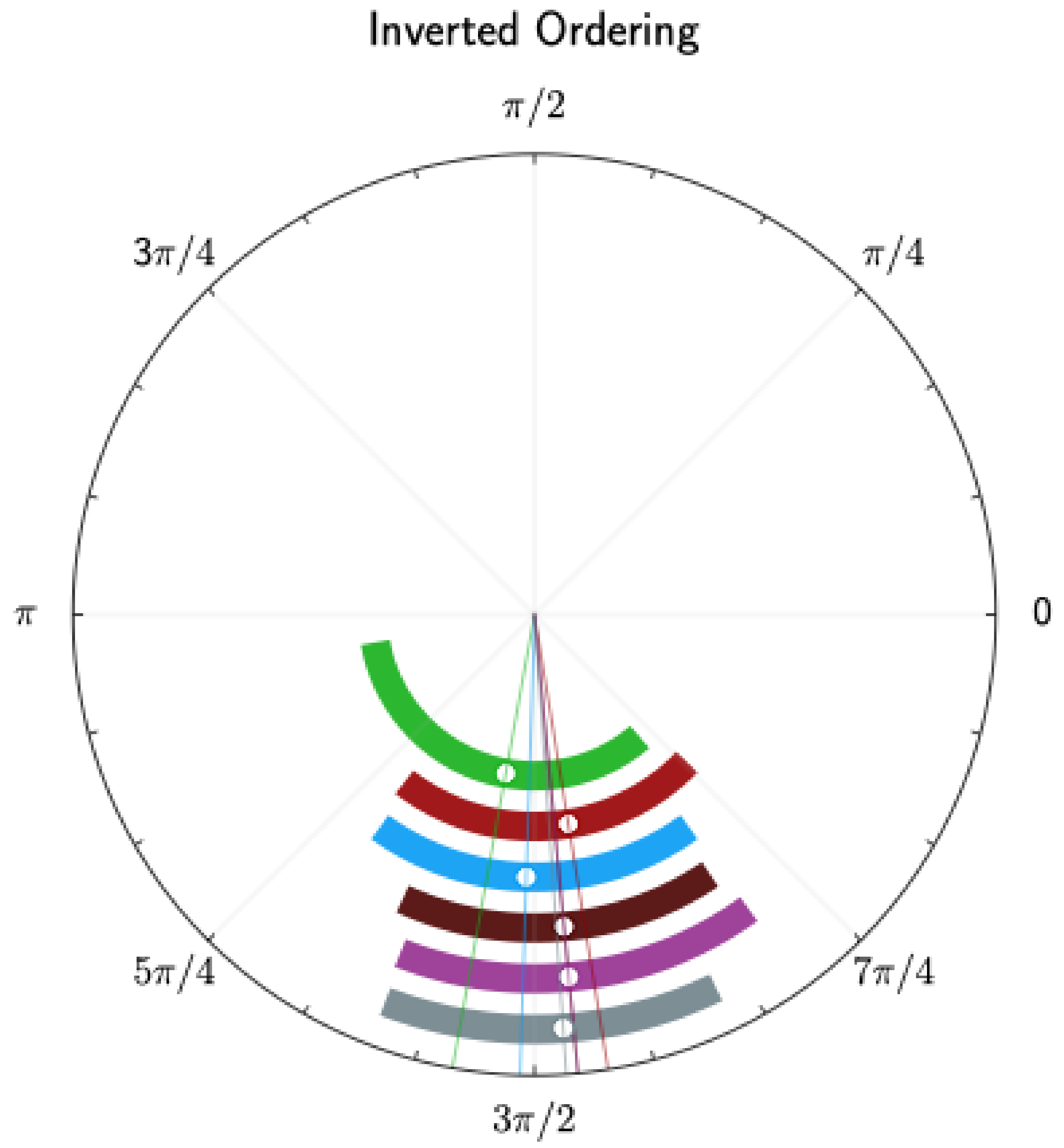
$sin^2 2\theta_{13}$, $|\Delta m^2{}_{31}|$



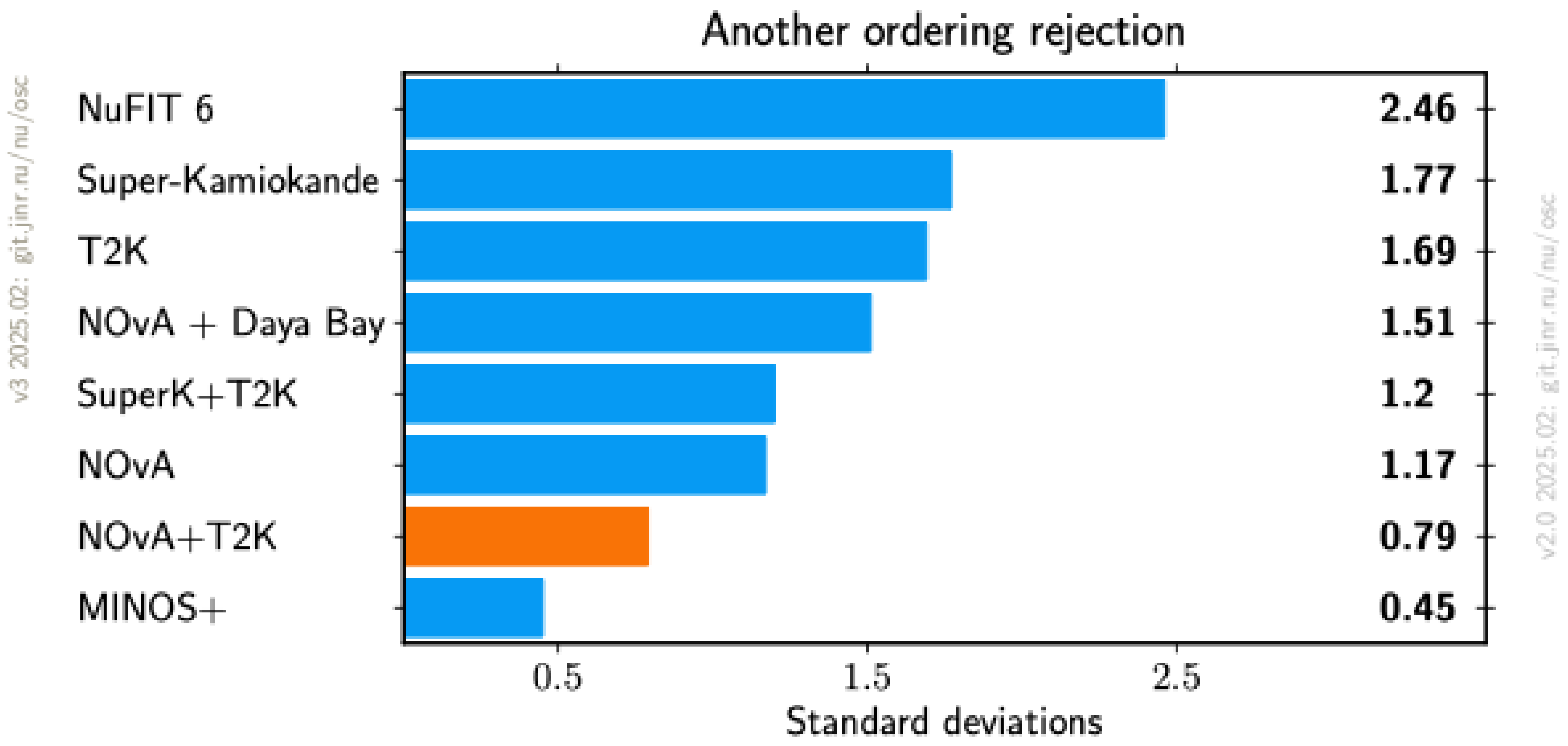


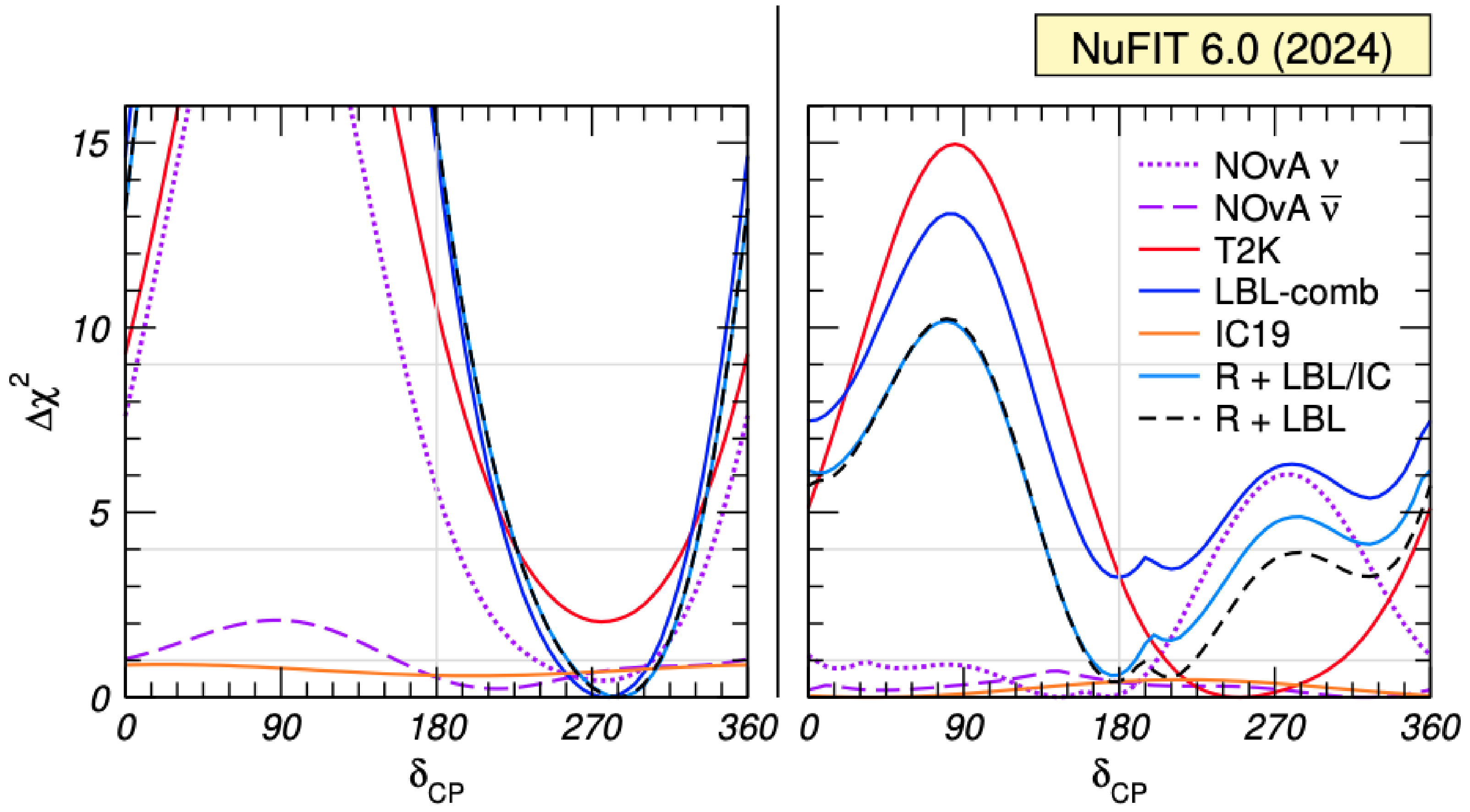
Present Accuracy on Oscillation Parameters:

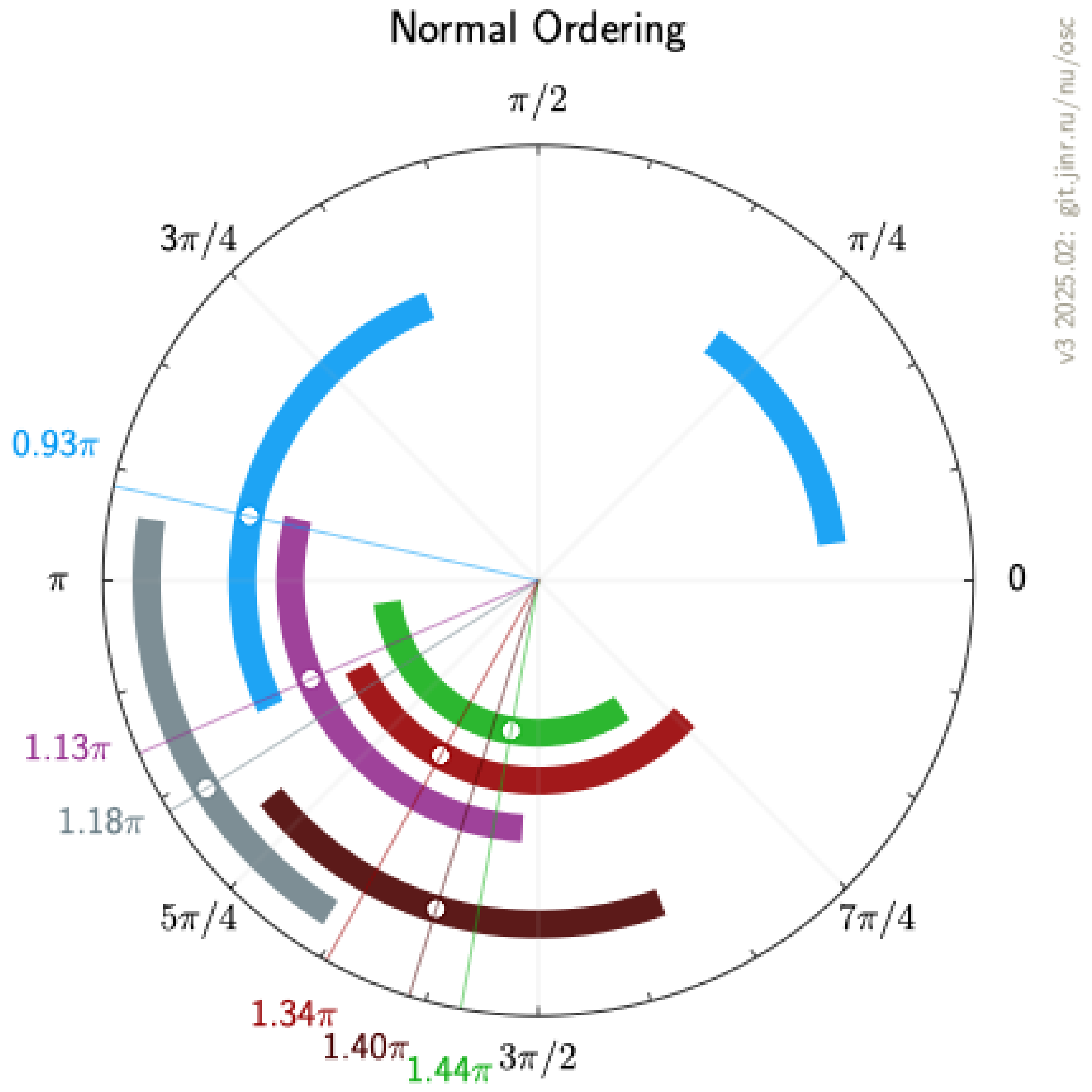
$NMO\ ,\ \delta_{CP}$



Experiment	δ_{CP}/π, CV	and 1σ range
Super-Kamiokande	1.44	[1.06, 1.73]
T2K	1.55	[1.29, 1.75]
NOvA	1.49	[1.30, 1.70]
SuperK+T2K	1.53	[1.36, 1.69]
NOvA+T2K	1.53	[1.38, 1.70]
NuFIT 6	1.52	[1.38, 1.64]







Experiment	δ_{CP}/π, CV	and 1σ range
Super-Kamiokande	1.44	[1.04, 1.69]
T2K	1.34	[1.14, 1.76]
NOvA+T2K	1.13	[0.92, 1.48]
NOvA	0.93	[0.62, 1.14], [0.04, 0.30]
SuperK+T2K	1.40	[1.22, 1.62]
NuFIT 6	1.18	[0.95, 1.32]

Summary

- Neutrino physics, in general, is an exciting and rapidly developing field with a good chance for fundamental discoveries in the era of precision measurements that has just begun.

- Accelerator and reactor neutrino experiments have played and continue to play a fundamentally important role in neutrino physics and oscillation studies.

- At present, most of the parameters in the 3-flavor oscillation picture have been established with good accuracy, while poorly determined (NMO, δ_{CP} and θ_{23}) are planned to be measured in the near future in the JUNO, NOvA/DUNE, and T2K/T2HK experiments, as well as in others, including atmospheric and solar neutrino experiments.

- Joint analyses and combining results from different experiments will play an important role in achieving accuracy. This work will require serious efforts of collaborations and joint working groups and, besides the main result of increasing the accuracy of measurements, will be a good mutual verification of individual results.

- The first experience of full-fledged joint analysis obtained in the NOvA/T2K group, combined SuperK/T2K results and proposals for combining JUNO with other experiments, as well as interpreting results using "global" analysis (NUFIT, GAMBIT, GNA and others), are complementary approaches and will require further development.

Заключение

- Физика нейтрино, увлекательная и быстро развивающаяся область, имеет хорошие шансы на фундаментальные открытия в начавшейся недавно эре прецизионных измерений.

- Ускорительные и реакторные нейтринные эксперименты сыграли и продолжают играть принципиально важную роль в физике нейтрино и изучении осцилляций.

- В настоящий момент большинство параметров в картине 3-флейворных осцилляций установлены с хорошей точностью, а плохо пока определенные (NMO, δ_{CP} и θ_{23}) планируется измерить в ближайшее время в экспериментах JUNO, NOvA/DUNE и T2K/T2HK, а также в других, в том числе, с атмосферными и солнечными нейтрино.

- Важная роль в достижении точности отводится совместным анализам и объединению результатов различных экспериментов. Эта работа требует серьезных усилий, как самих коллабораций, так и совместных рабочих групп и, кроме основного результата по увеличению точности измерений, будет хорошей взаимной проверкой индивидуальных результатов.

- Первый опыт полноценного совместного анализа, полученный в группе NOvA/T2K, комбинированные результаты SuperK/T2K и предложения по объединению JUNO с другими экспериментами, а также интерпретация результатов с помощью «глобального» анализа (NUFIT, GAMBIT, GNA и другие), являются дополняющими друг друга подходами и требуют дальнейшего развития.