XXI Lomonosov Conference on Elementary Particle Physics
Moscow State University

Current status and future prospects of three-flavor oscillations with accelerator neutrino beams

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Neutrino oscillations and mixing

	ATMOSPHERIC	SHORT BASELINE REACTOR	SOLAR
	ACCELERATOR	ACCELERATOR	LONG BASELINE REACTOR

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

Oscillation parameters and how precisely do we know them:

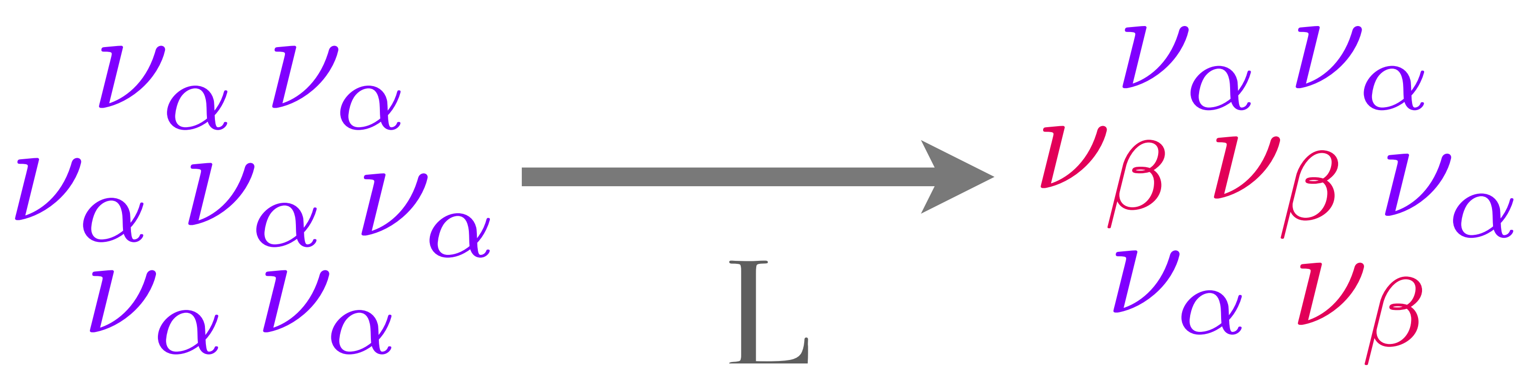
$\theta_{12} \approx 34^\circ$ (4.4%)

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

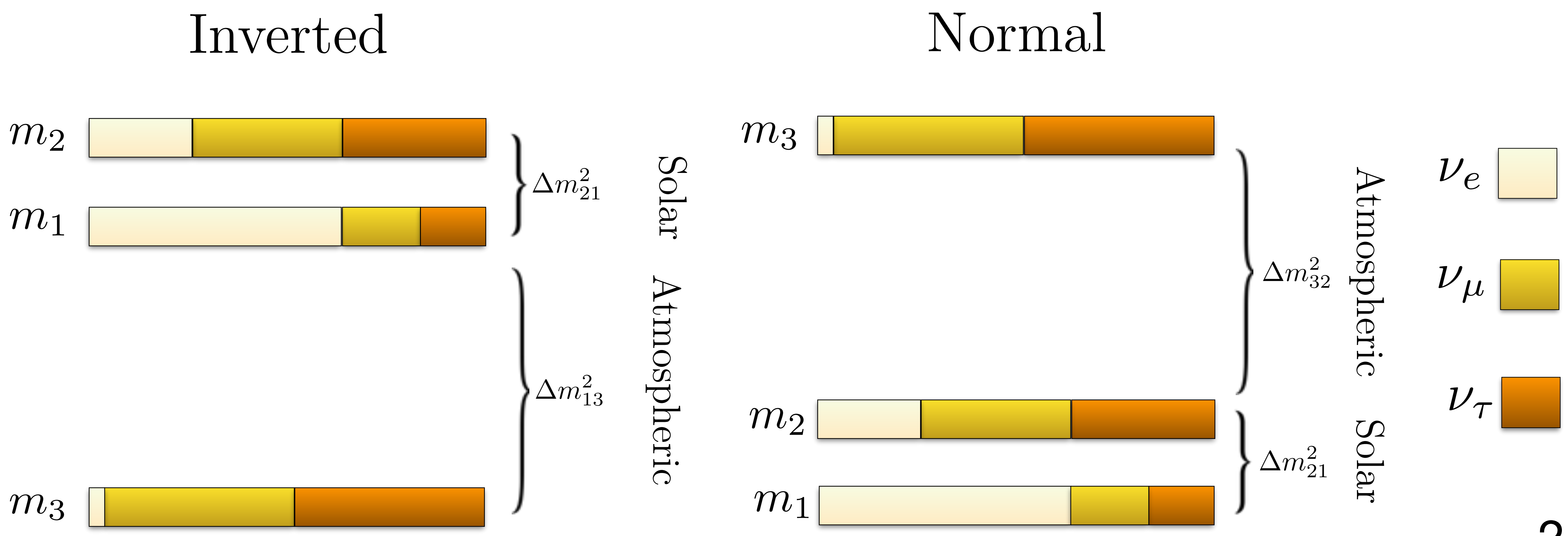


Open questions:

Is θ_{23} 45°?

Is there CP violation in lepton sector?

Neutrino mass hierarchy (ordering) is Normal or Inverted?



Motivation - I

Mass hierarchy plays important role for:

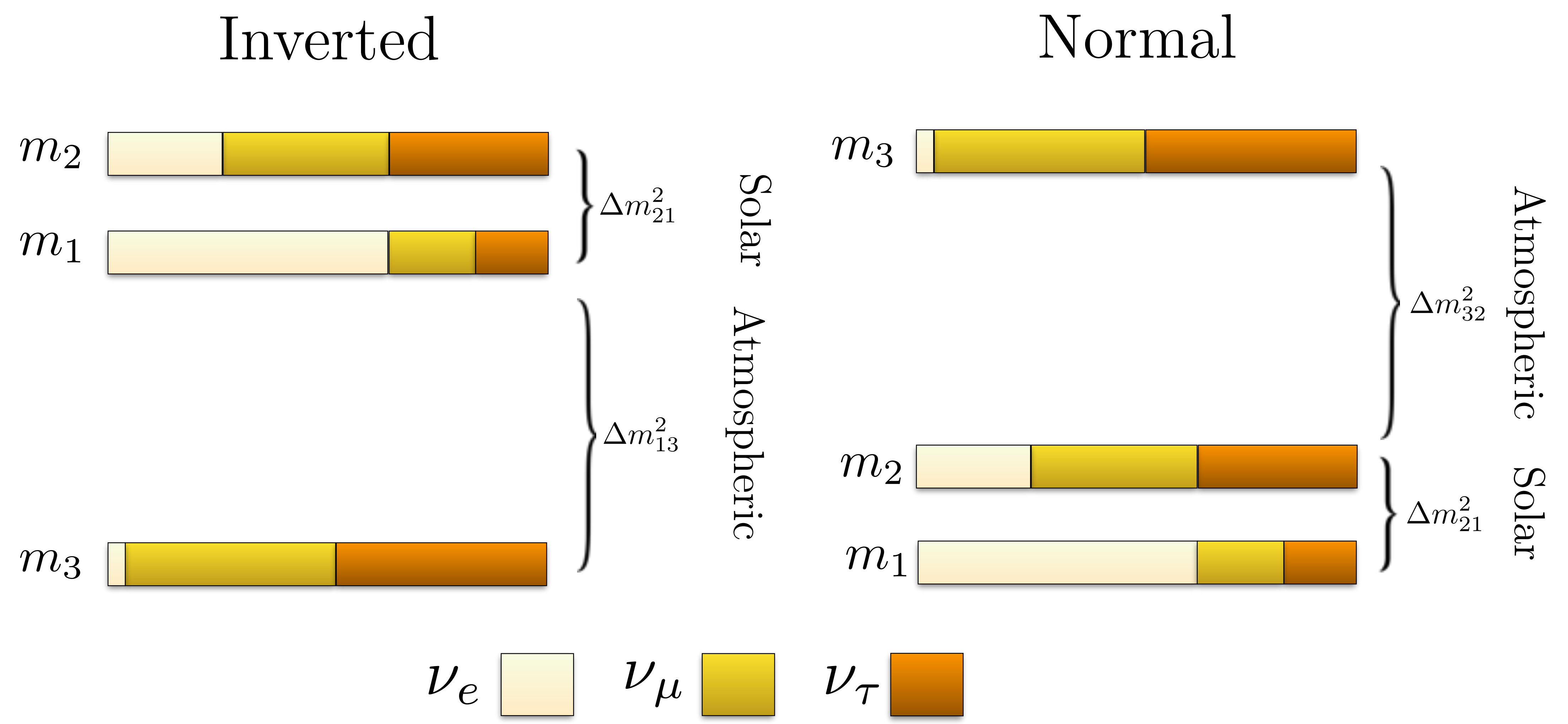
∗ neutrinoless double beta-decay searches,

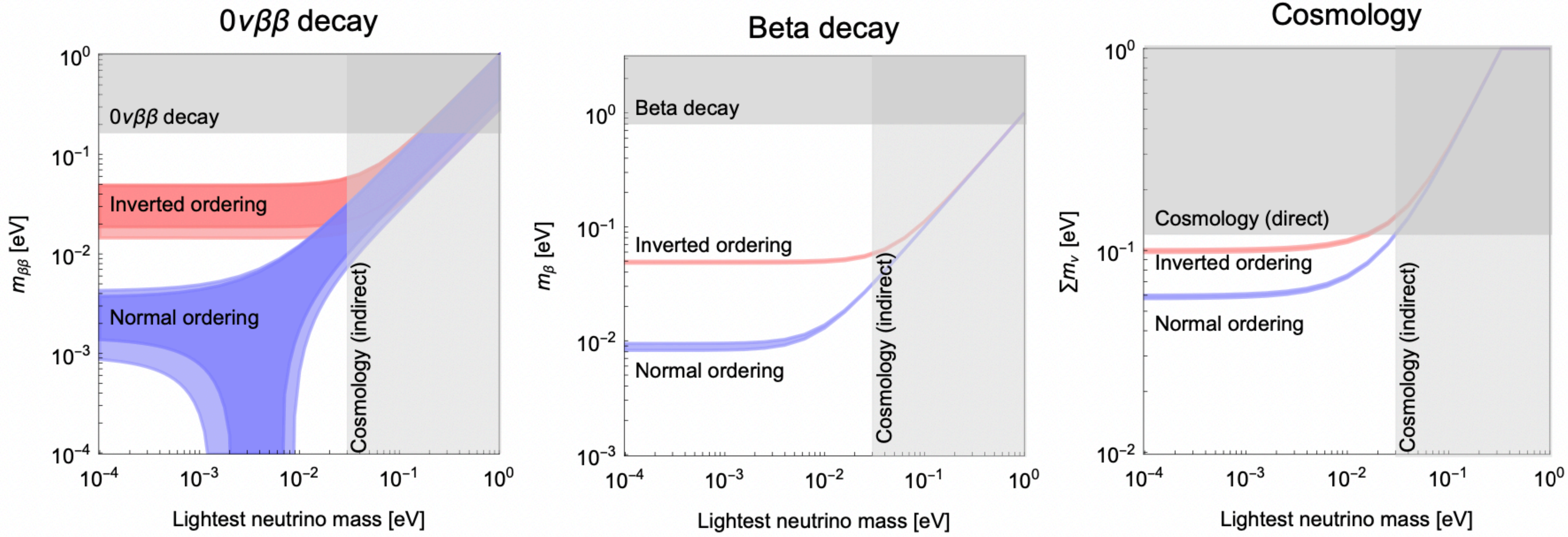
∗ supernova simulations,

∗ relic neutrinos searches,

∗ absolute ν mass measurements etc.

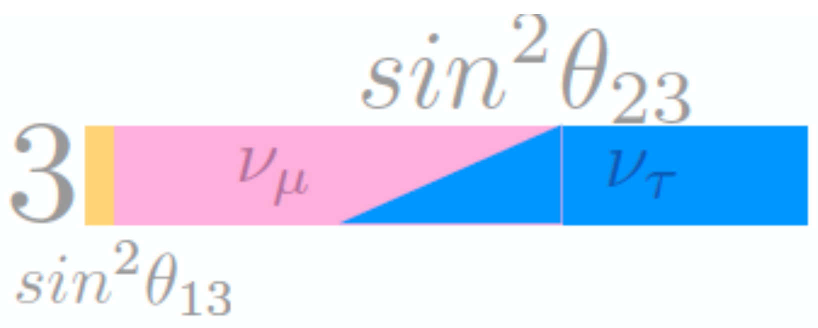
So it affects everything connected with ν masses





Motivation - II

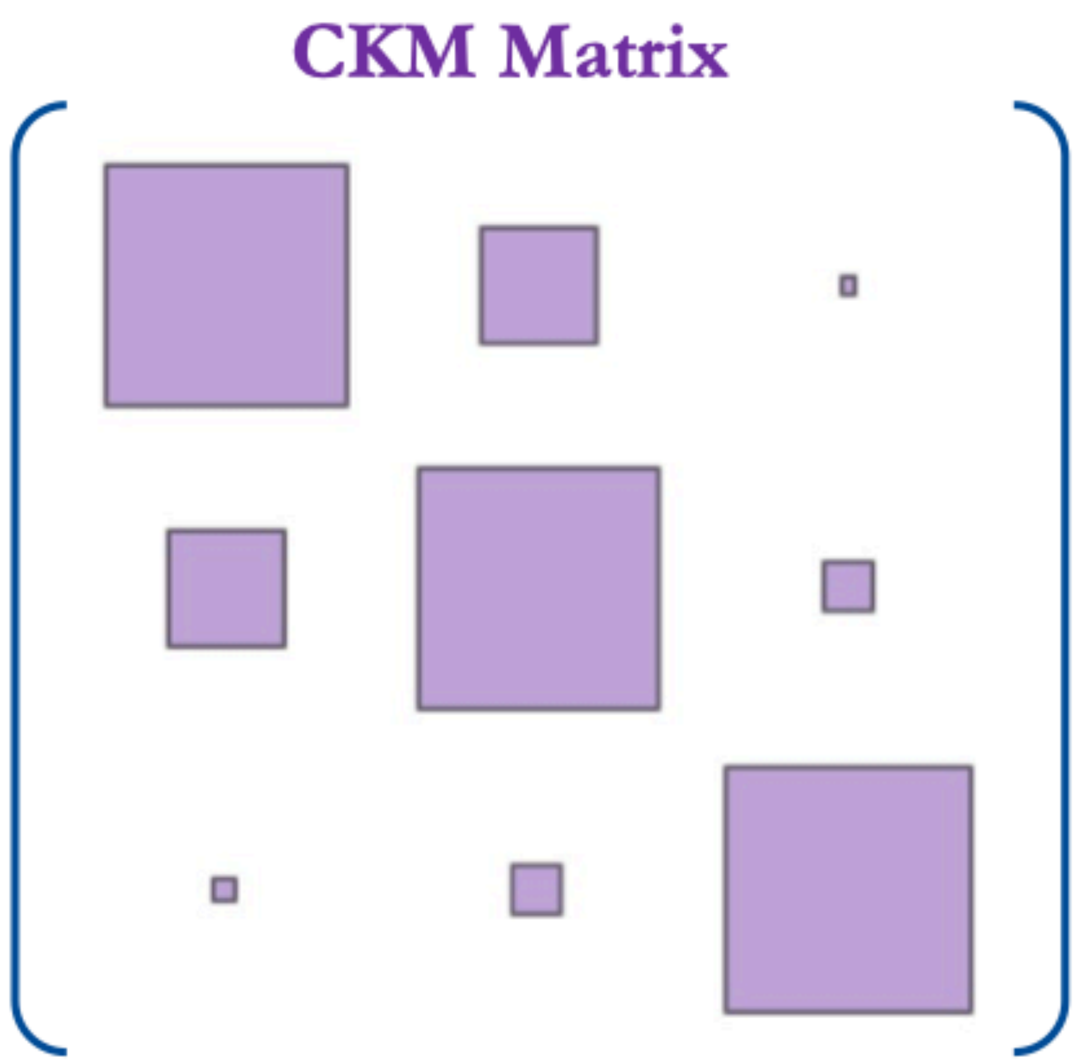
θ_{23} is responsible for possible ν_μ and ν_τ symmetry in ν_3



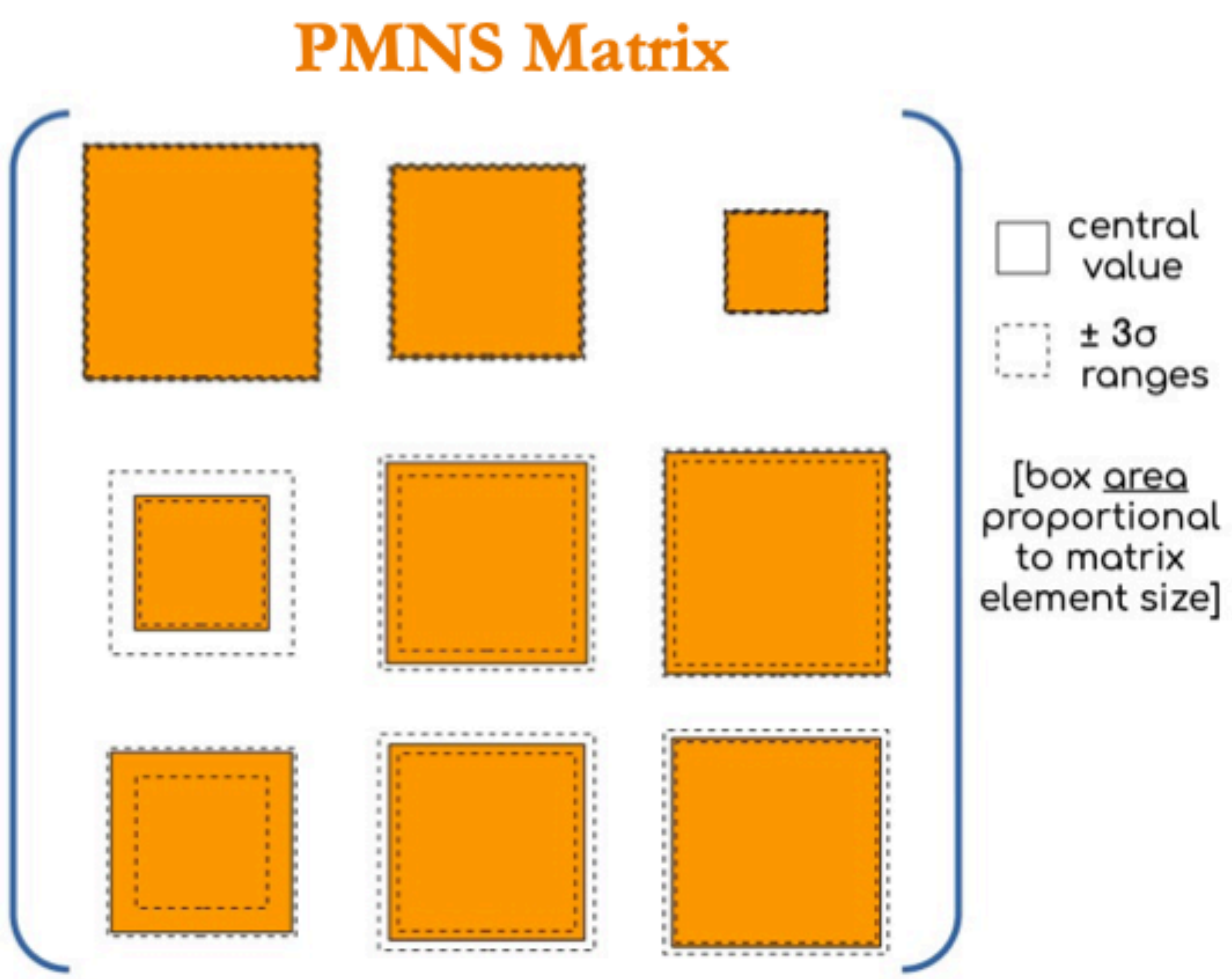
δ_{CP} may be connected with matter-antimatter asymmetry of the Universe (leptogenisis)

$$\frac{J_{\rm PMNS}}{J_{\rm CKM}} = \frac{3\times10^{-2}}{3\times10^{-5}}\sin(\delta_{\rm PMNS}), \quad J \equiv s_{12}c_{12}s_{13}c_{13}^2 s_{23}c_{23}\sin\delta$$

The very final goal of all these measurements is the creation of theory that can also explain the smallness of neutrino masses and mixing, and its unification with SM.
Neutrino parameters as test for theories (check sums)



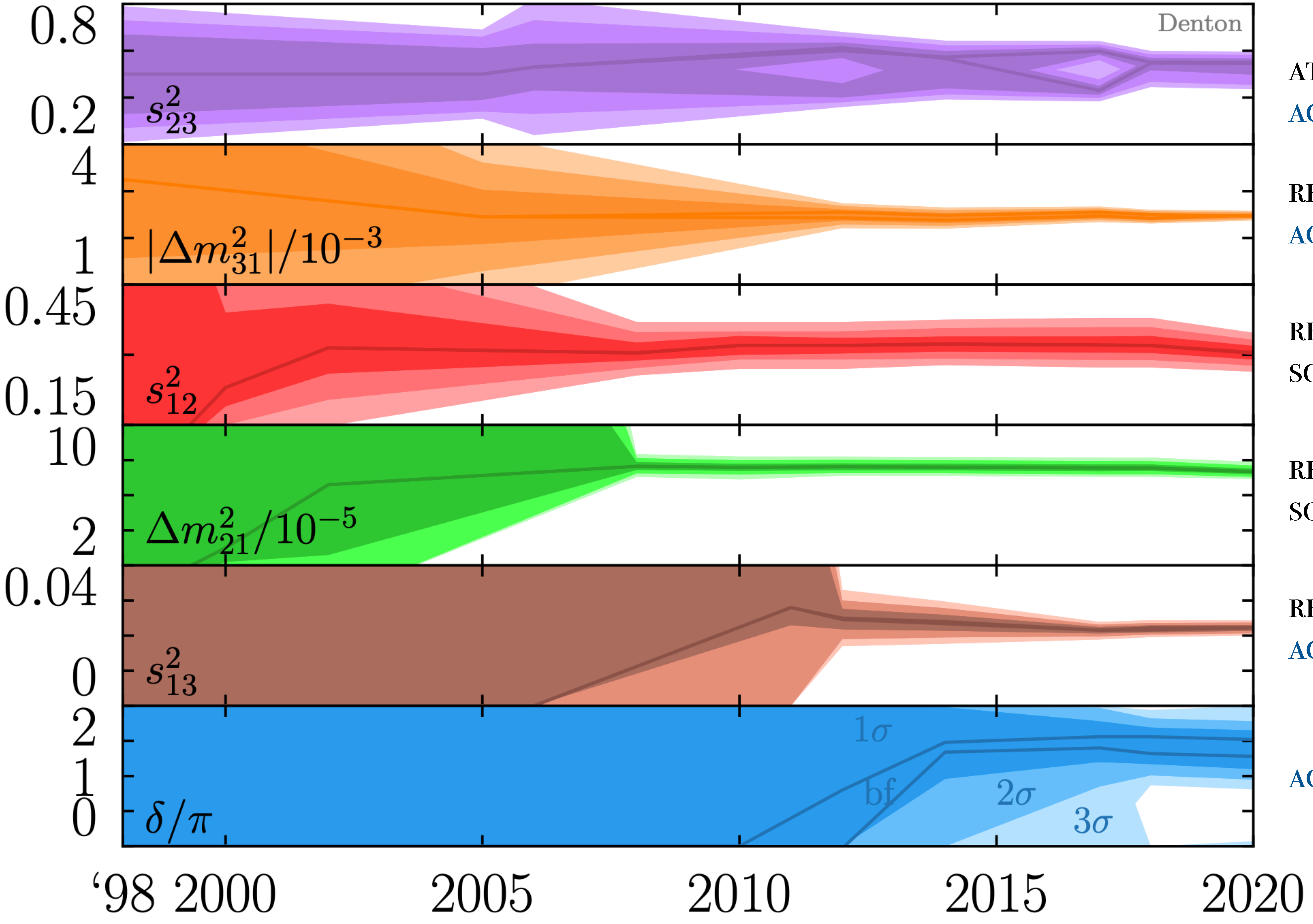
- Values from PDG 2020



- Values from NuFIT 5.0, arXiV:2007.14792

Three-flavor oscillations. Full picture.

25 years of experimental history are concentrated in this plot:



The most sensitive types of experiments:

ATMOSPHERIC
ACCELERATOR

REACTOR (MEDIUM BL)
ACCELERATOR

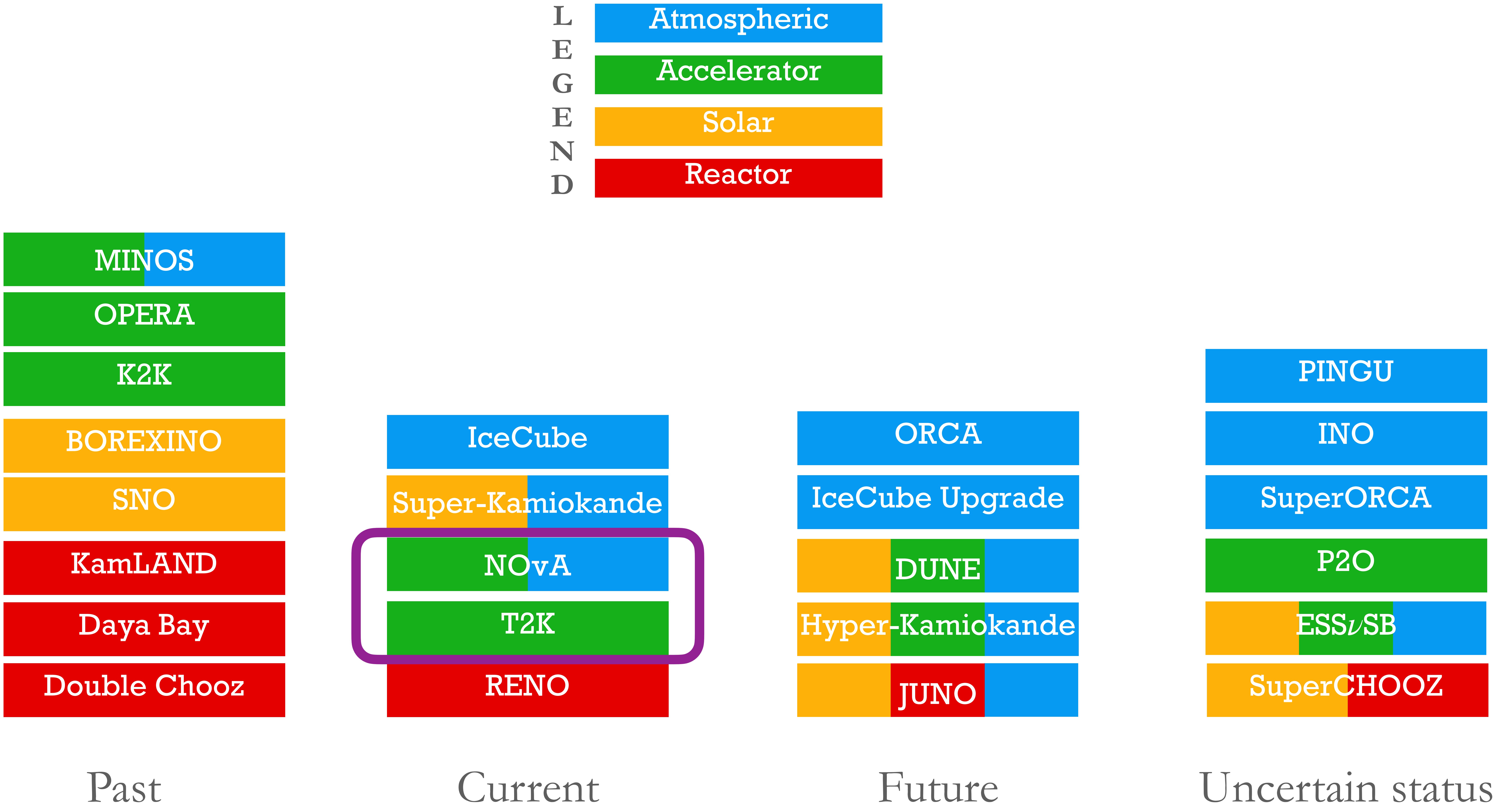
REACTOR (LONG BL)
SOLAR

REACTOR (LONG BL)
SOLAR

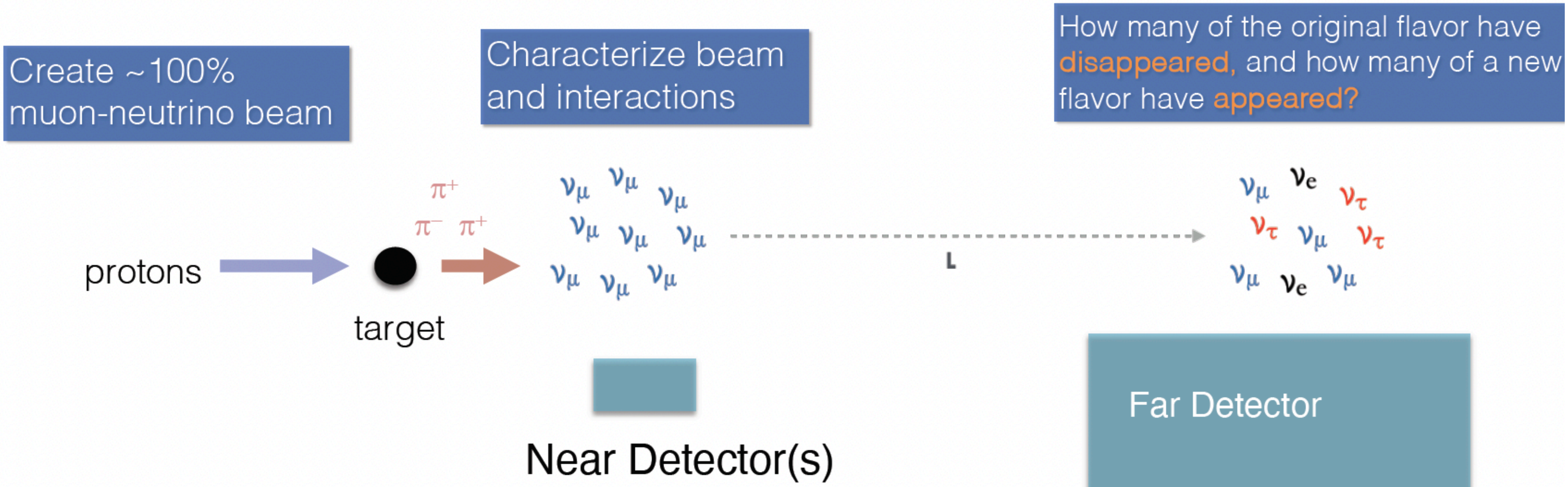
REACTOR (MEDIUM BL)
ACCELERATOR

ACCELERATOR

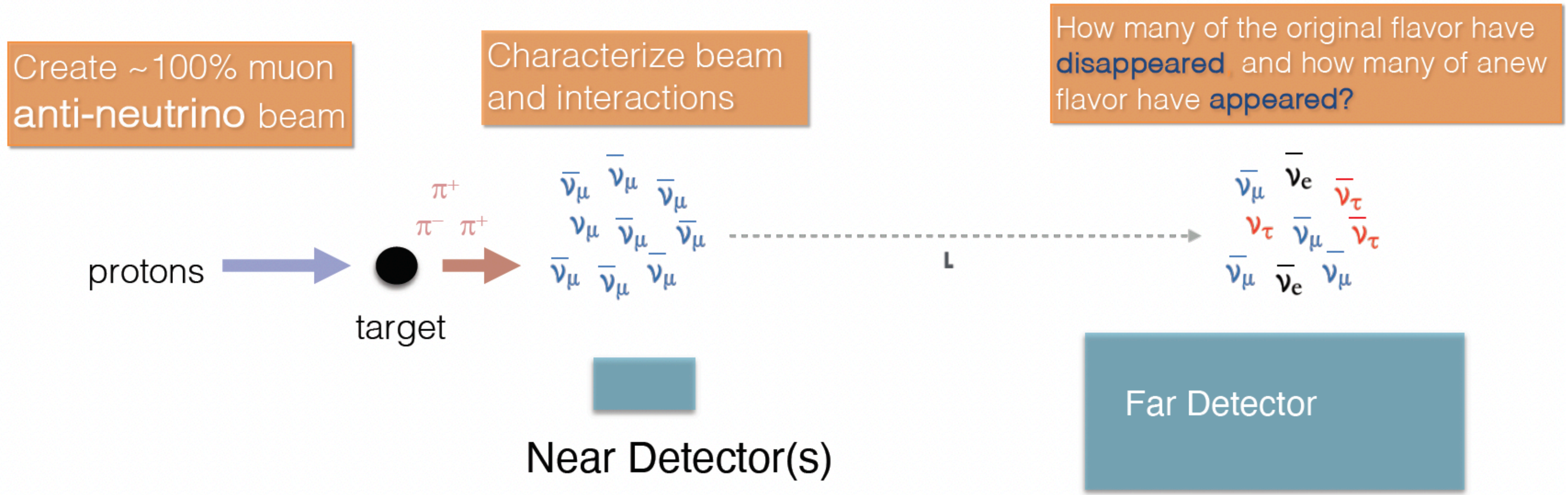
All three-flavour oscillation experiments



Three-flavor oscillations with accelerator neutrinos

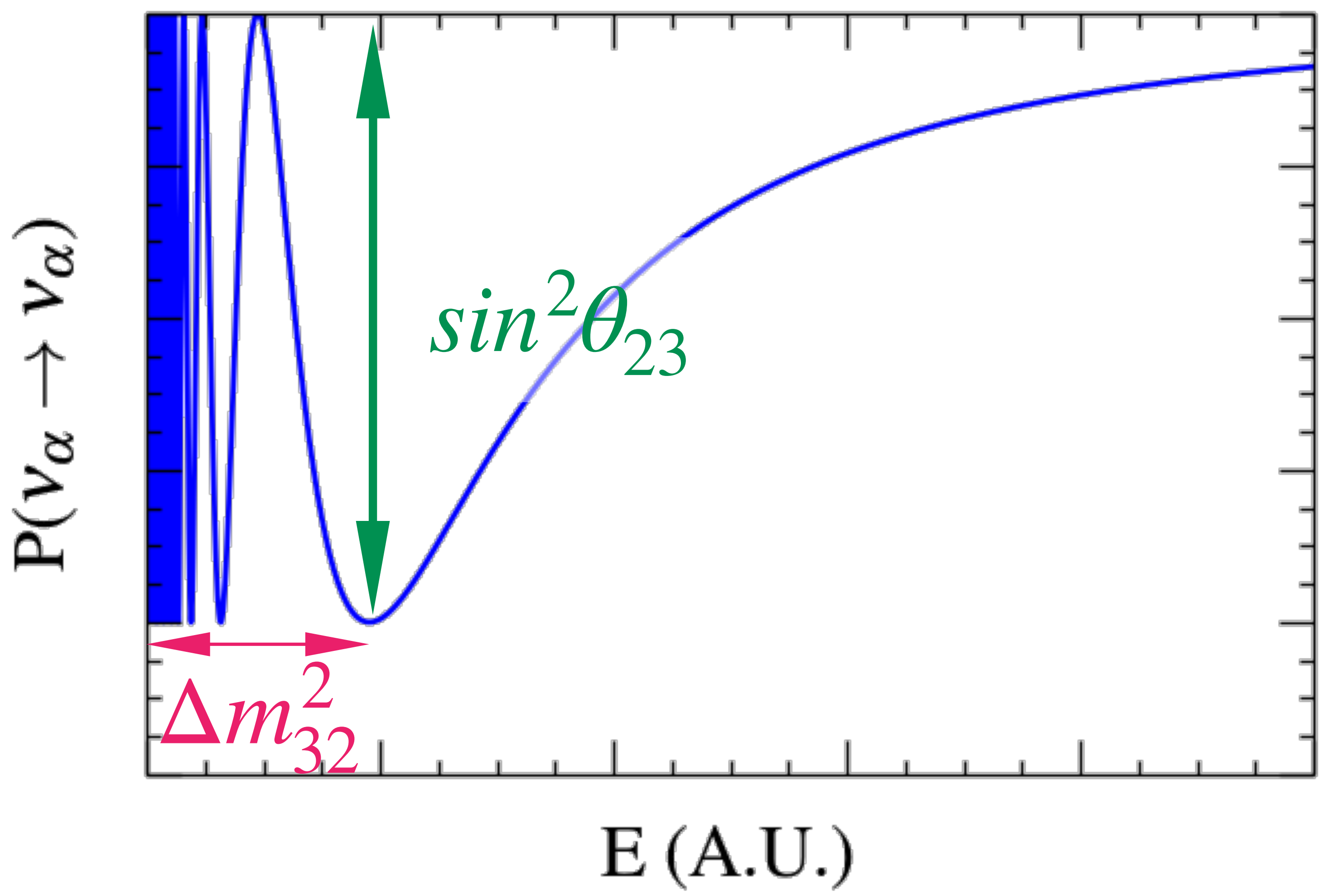


Three-flavor oscillations with accelerator neutrinos



Strategy

Disappearance $P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu) \approx 1 - sin^2(2\theta_{23})sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$



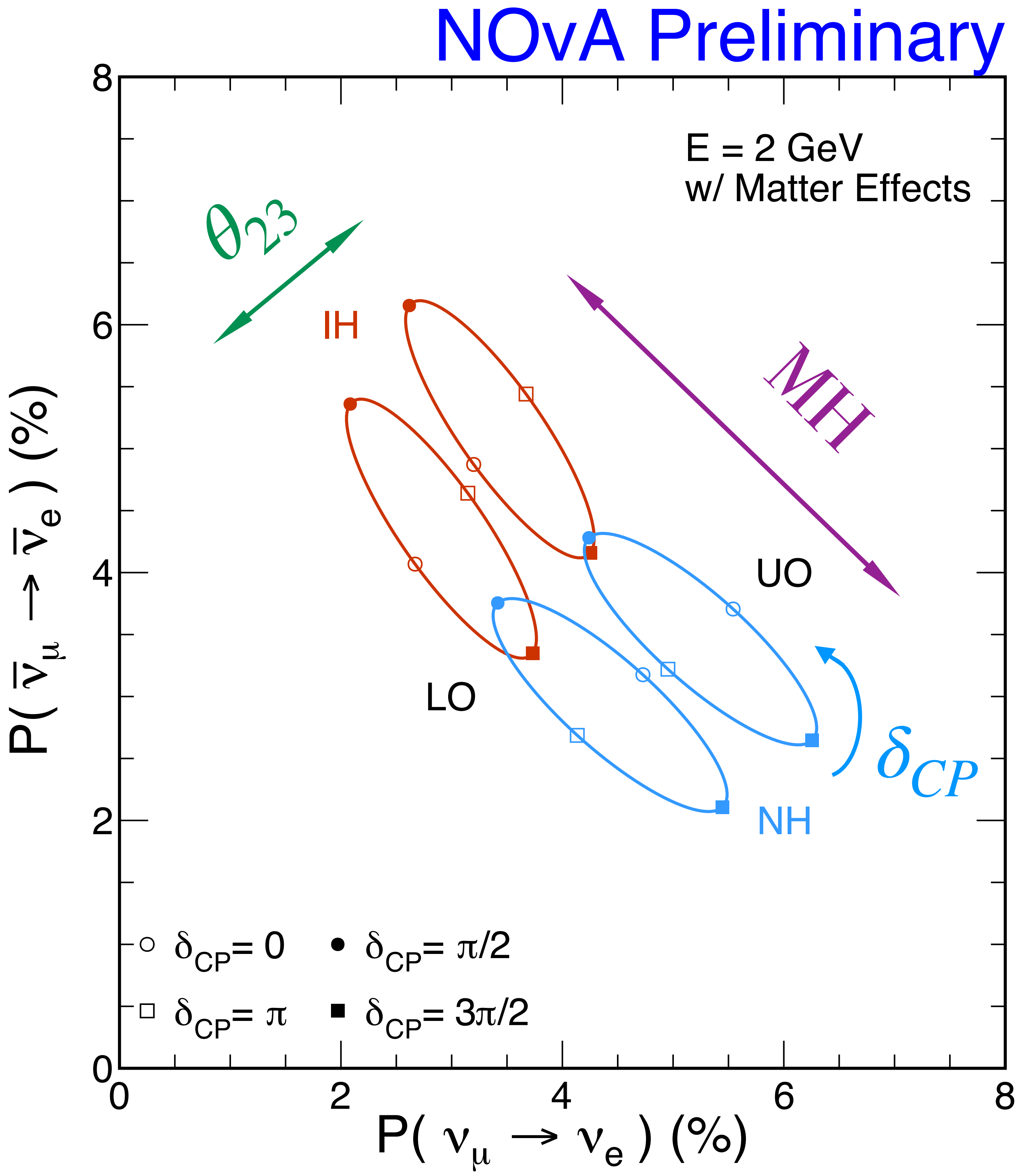
$\Delta P_{\nu\bar{\nu}} \sim sin\ \delta_{CP}$

Appearance $P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx P_{atm} + P_{sol} +$

ν vs $\bar{\nu}$

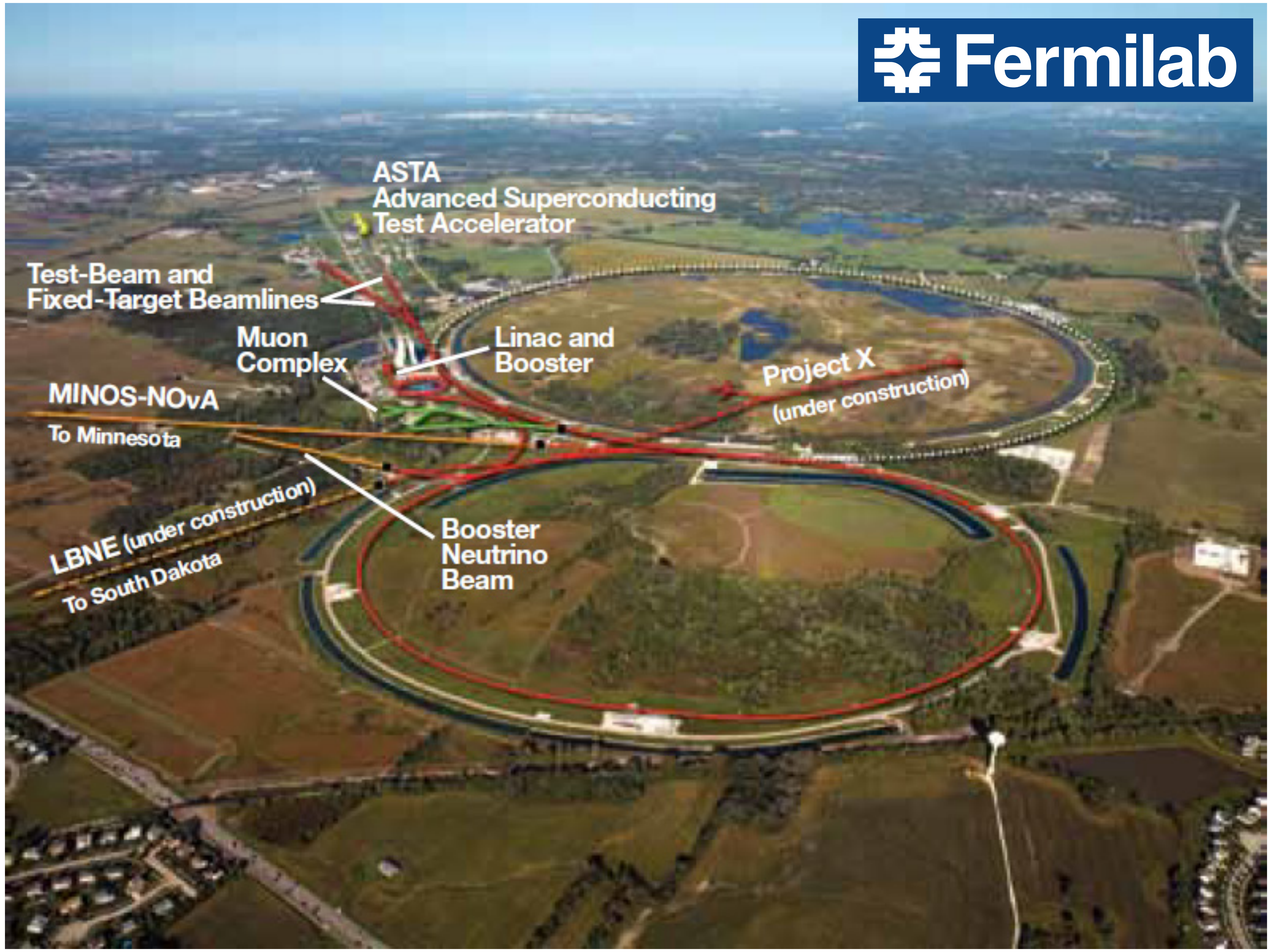
$$+ 2\sqrt{P_{atm}P_{sol}}(cos\Delta_{32}cos\delta_{CP} \mp sin\Delta_{32}sin\delta_{CP})$$

$$\sqrt{P_{atm}} = sin(\theta_{23})sin(2\theta_{13})\frac{sin(\Delta_{31} - aL)}{\Delta_{31} - aL}\Delta_{31}$$



Obtain sensitivity to the mass hierarchy due to matter effects. In order to avoid degeneracy "θ_{23} - mass hierarchy - δ_{CP}" need both neutrino and antineutrino beams.

Modern accelerator neutrino experiments



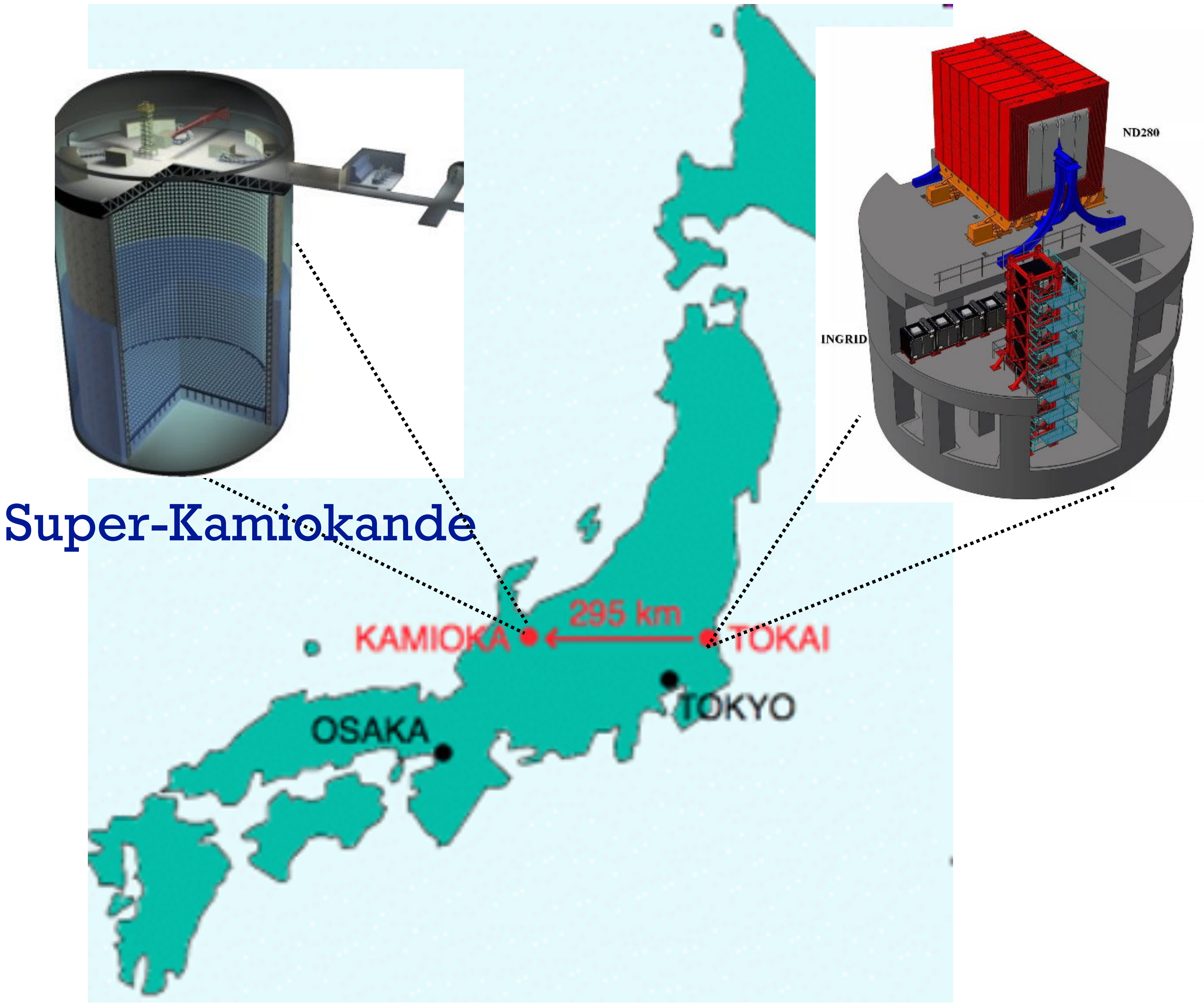
T2K and NOvA

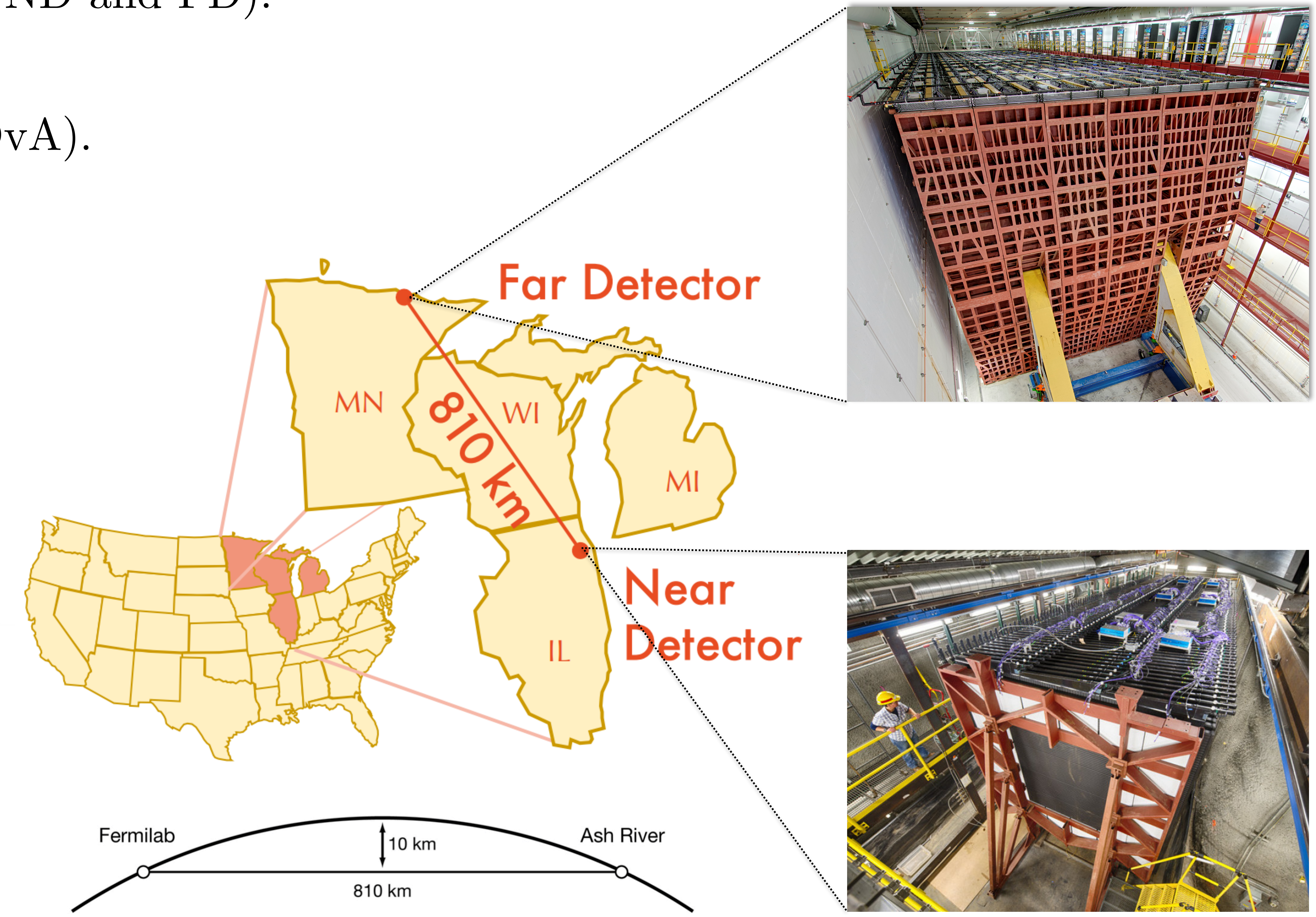
Very similar idea: two-detector scheme with off-axis position (narrow peak, suppress high energy bkg).

∗ T2K started data taking in 2010 (different ND and FD).

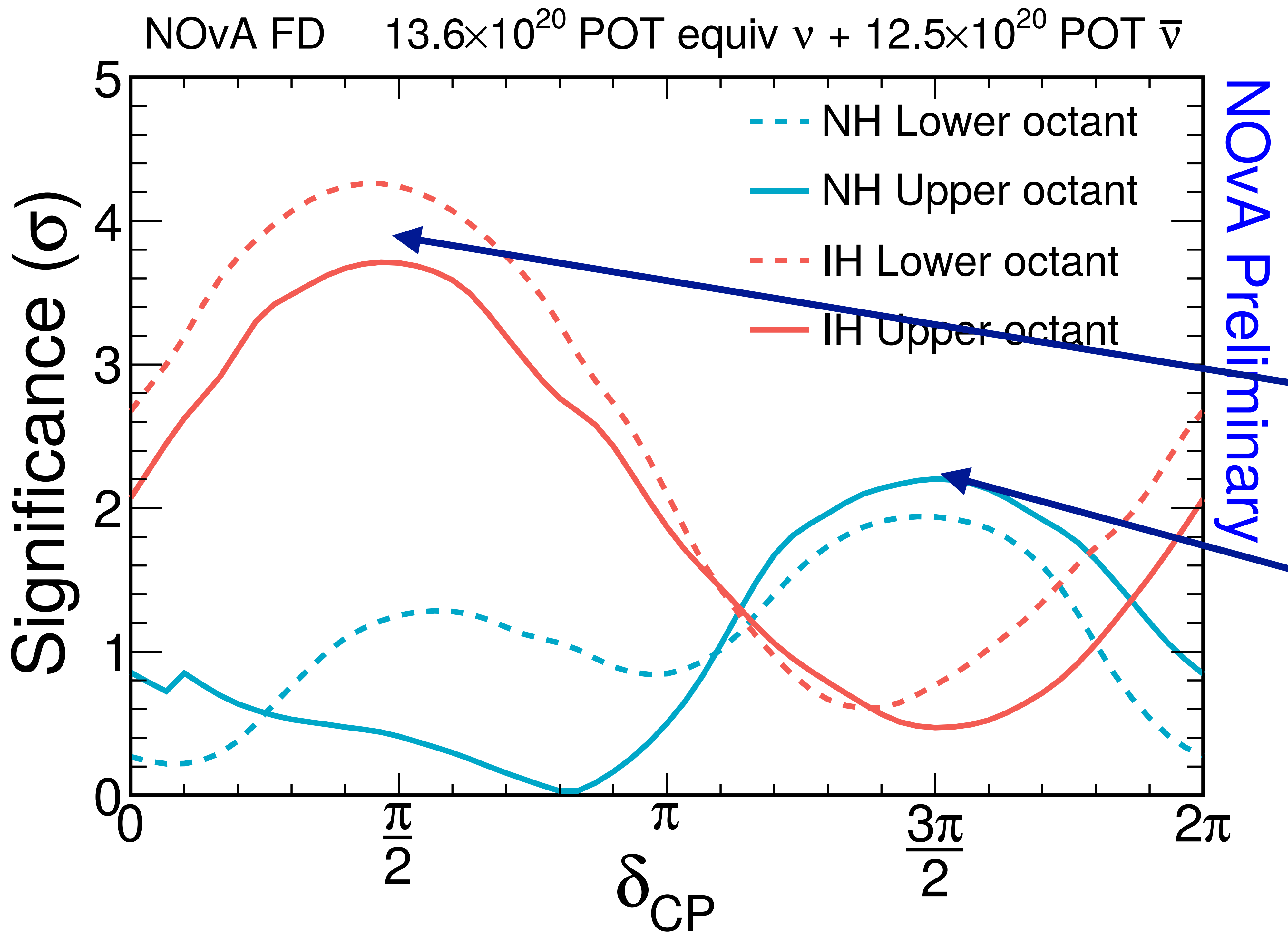
∗ NOvA run since 2014 (same ND and FD).

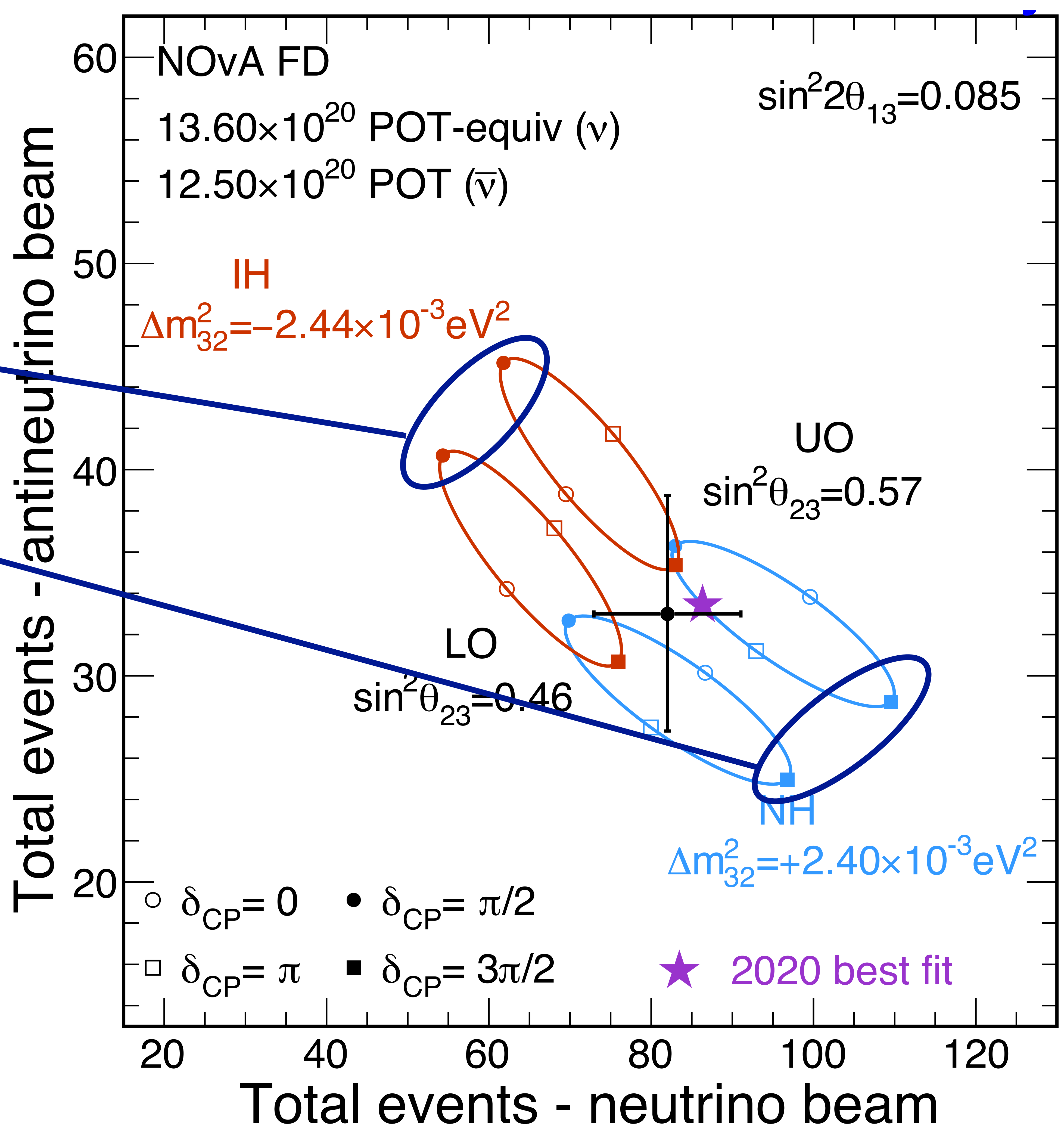
∗ E = 0.6 GeV (T2K) and E = 1.8 GeV (NOvA).





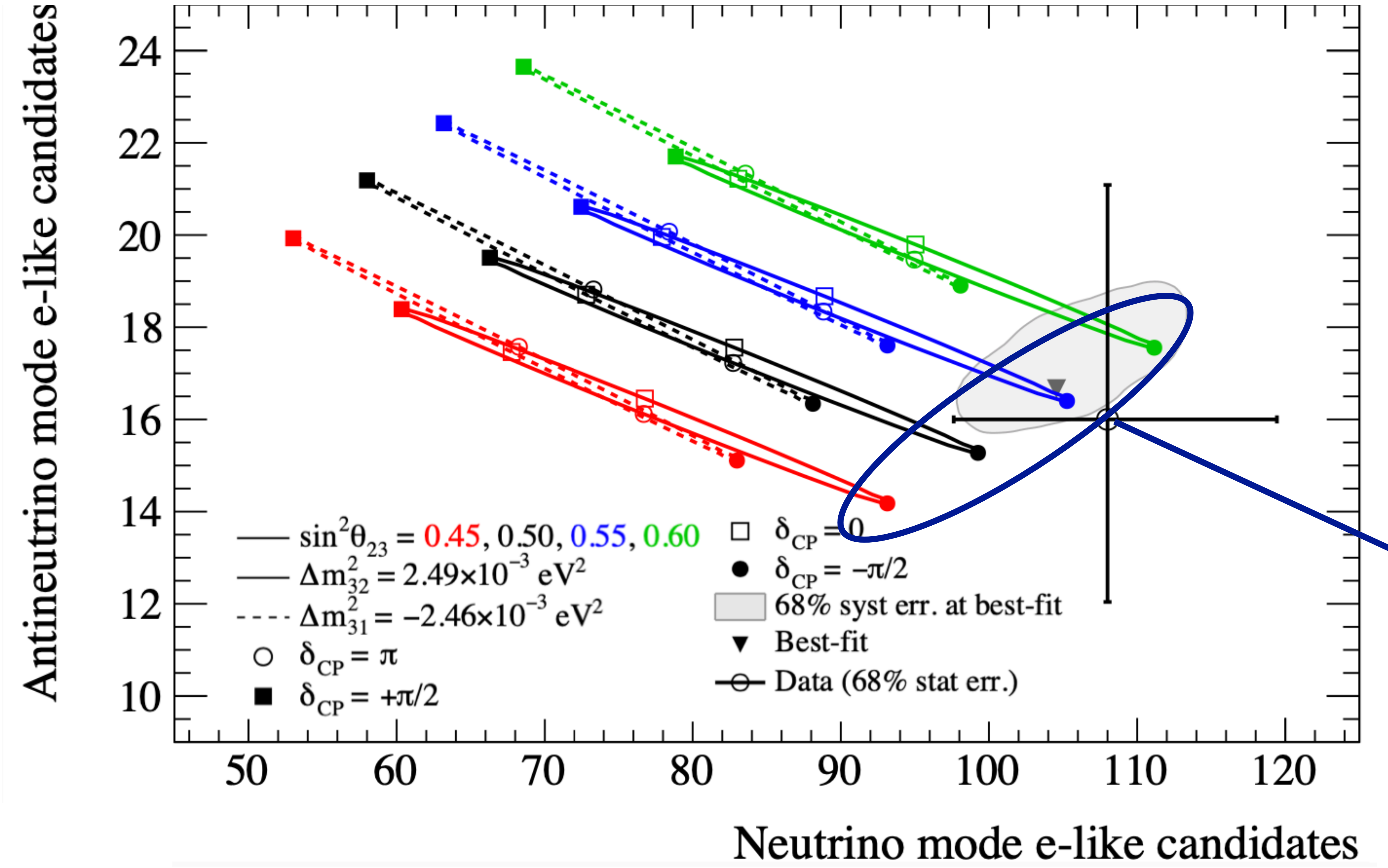
NOvA results

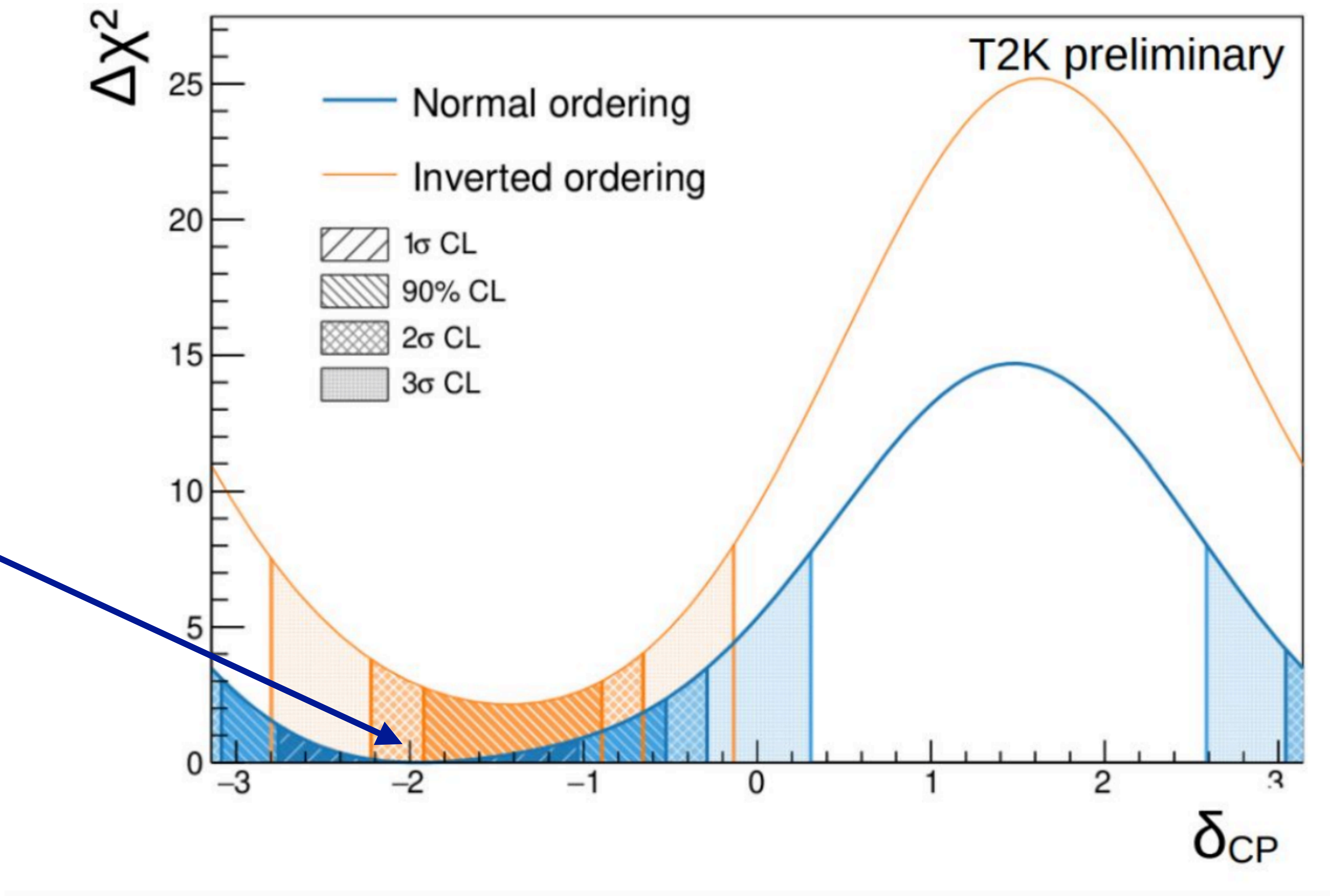




- ✳Disfavor NO, $\delta = 3\pi/2$ at $\sim 2\sigma$.
- ✳Exclude IO, $\delta = \pi/2$ at $> 3\sigma$.
- ✳Combinations that include effect “cancellation” are preferred:
  - ✳ since such options exist for both octants and hierarchies, results show no strong preferences.

T2K results



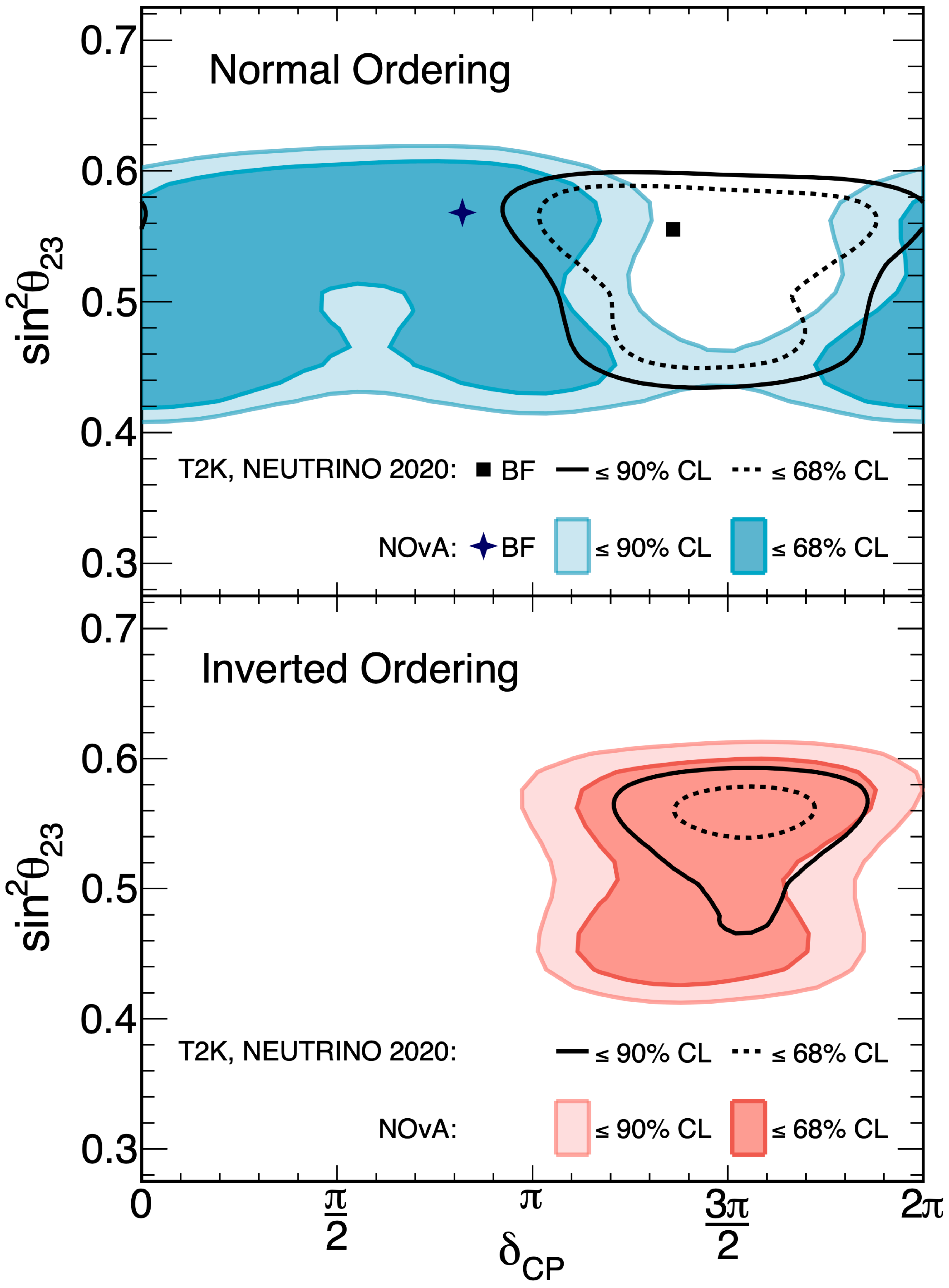


✴Preference of $3\pi/2$ value and normal MO.

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

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

T2K and NOvA: result comparisons



- $\sim 2\sigma$ tension for preferred value of δ_{CP},
  - T2K sees asymmetry in ν_e and $\bar{\nu}_e$ rate, while NOvA doesn't.

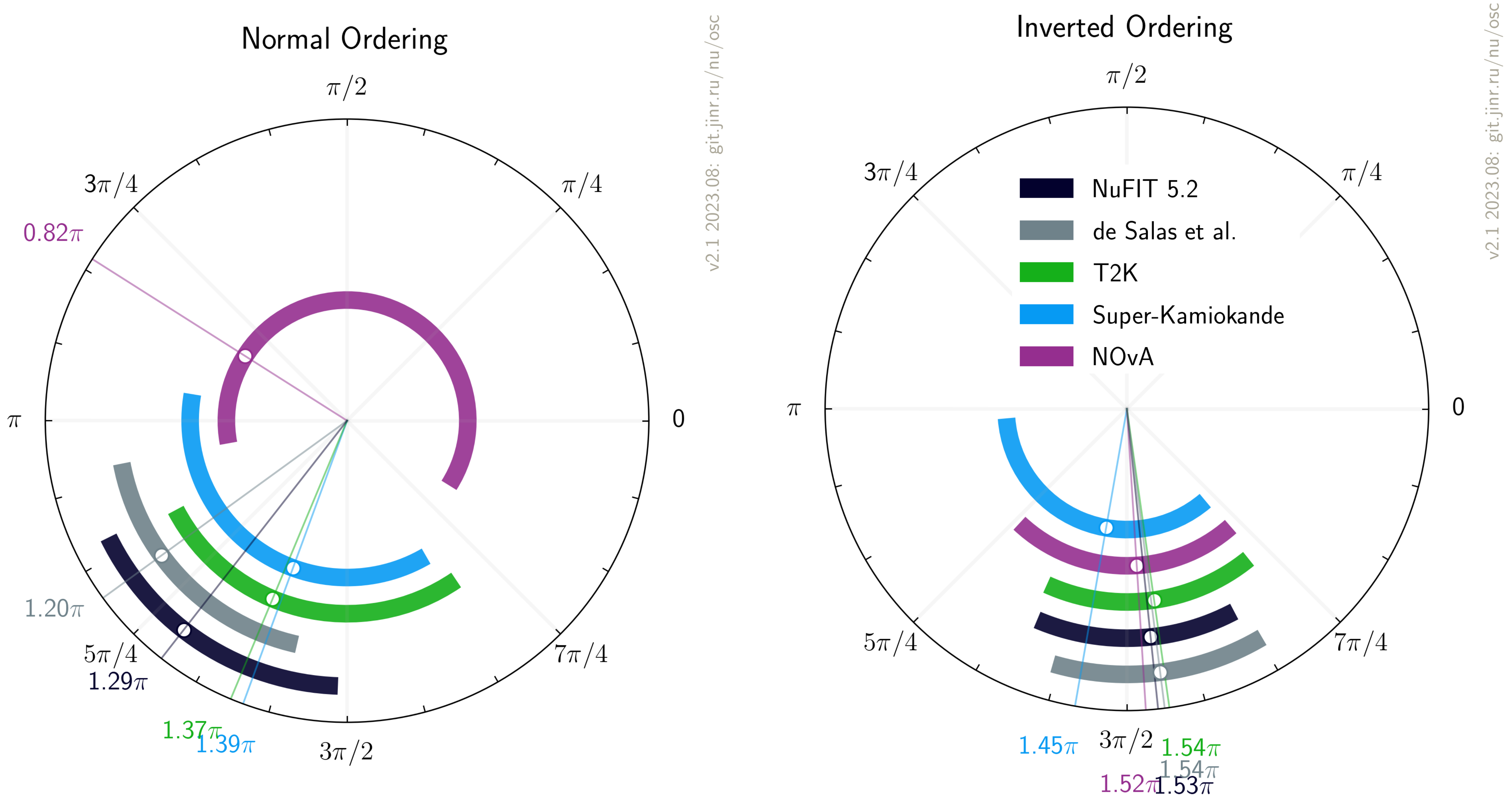
- NOvA and T2K are preparing joint analysis with shared data and proper systematics correlations:
  - Experiments are complementarity, have different baselines, energy ranges and detector technologies
  - As a result:
    - Increased sensitivity
    - Ability to break the degeneracy between mass ordering and δ_{CP}

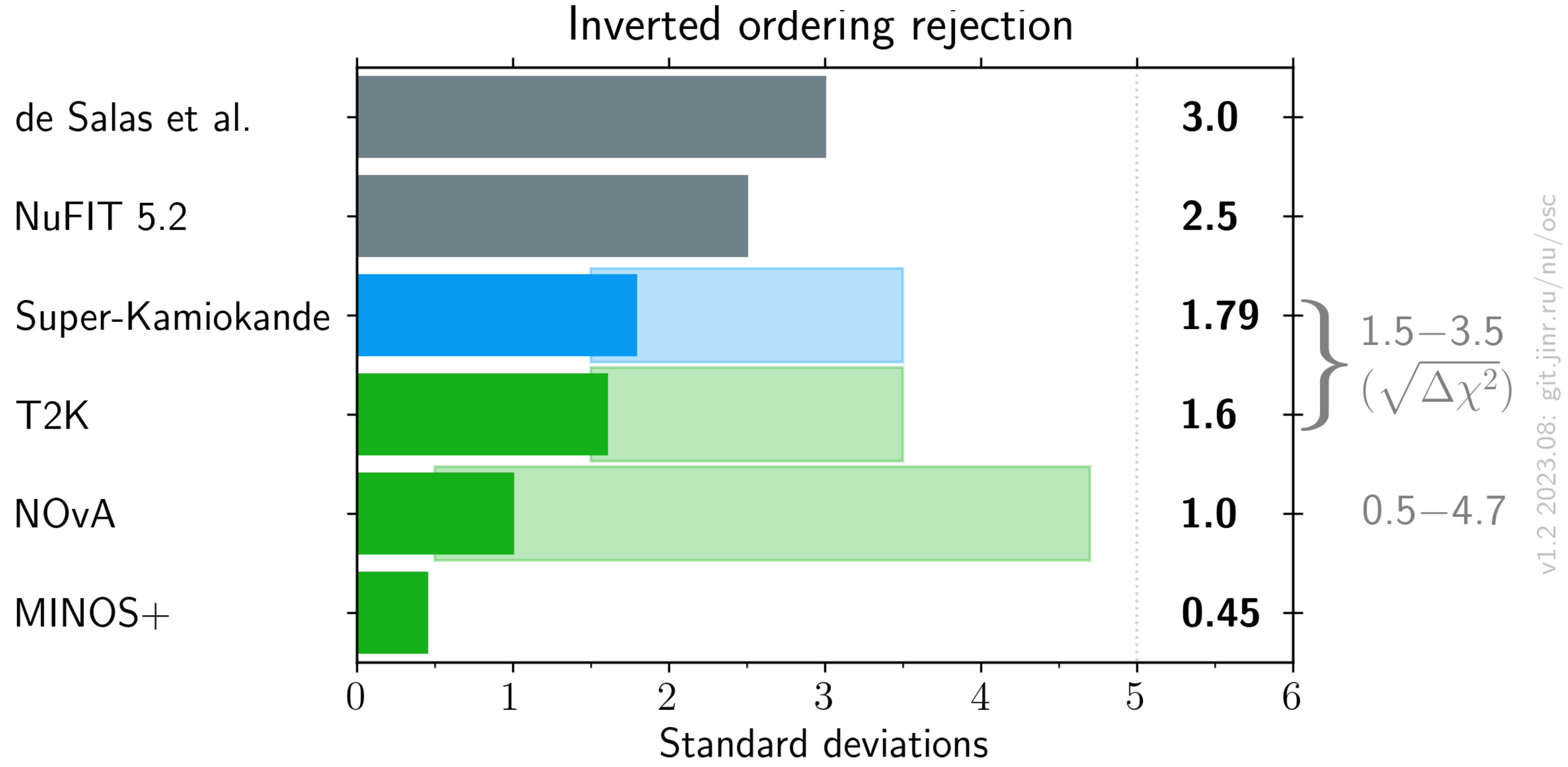
Tension

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

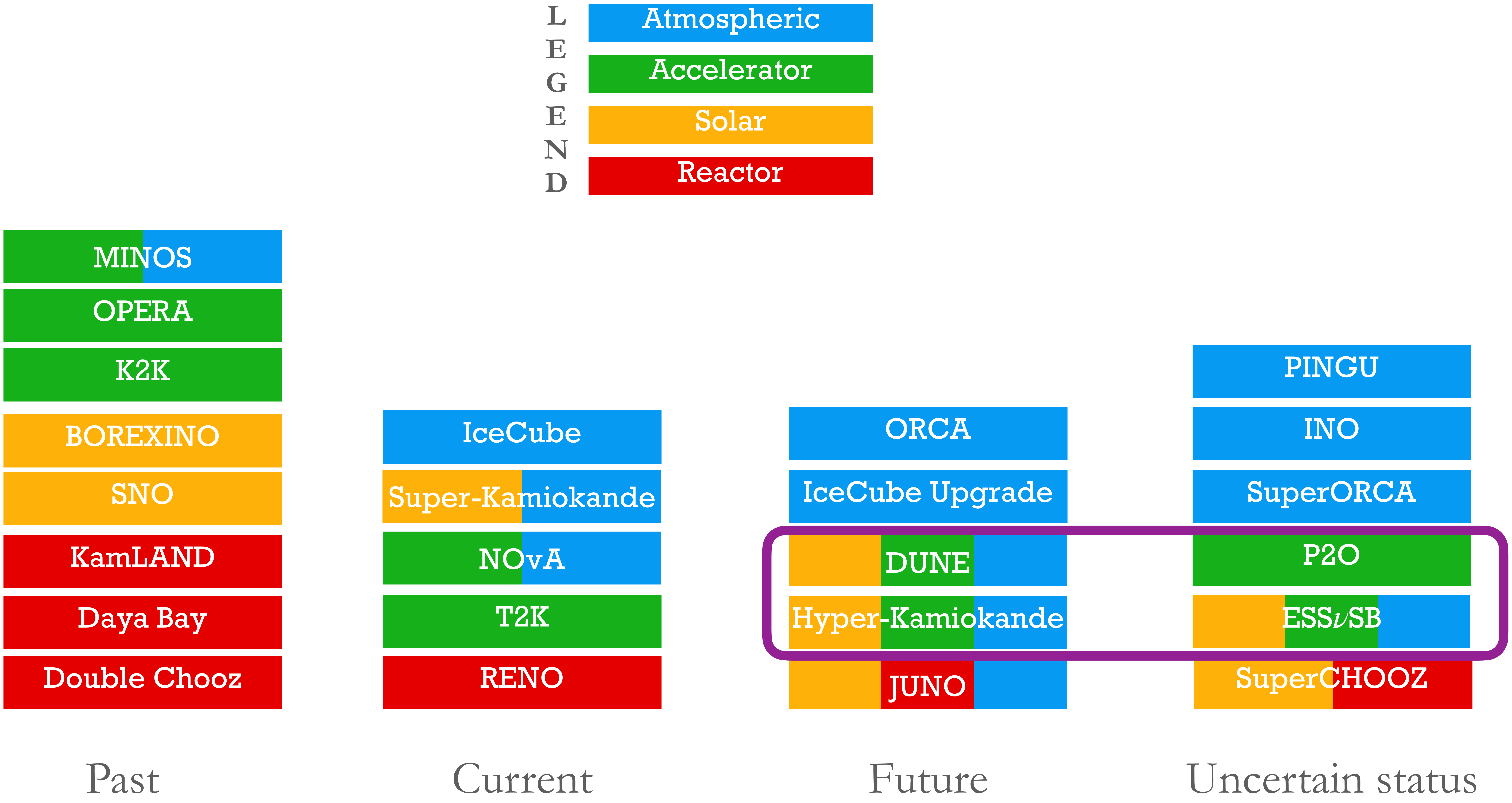
$$H = \frac{1}{2E}\left[UM^2U^\dagger + a\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}\right]$$

- $\epsilon_{\alpha\beta}$ - 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.

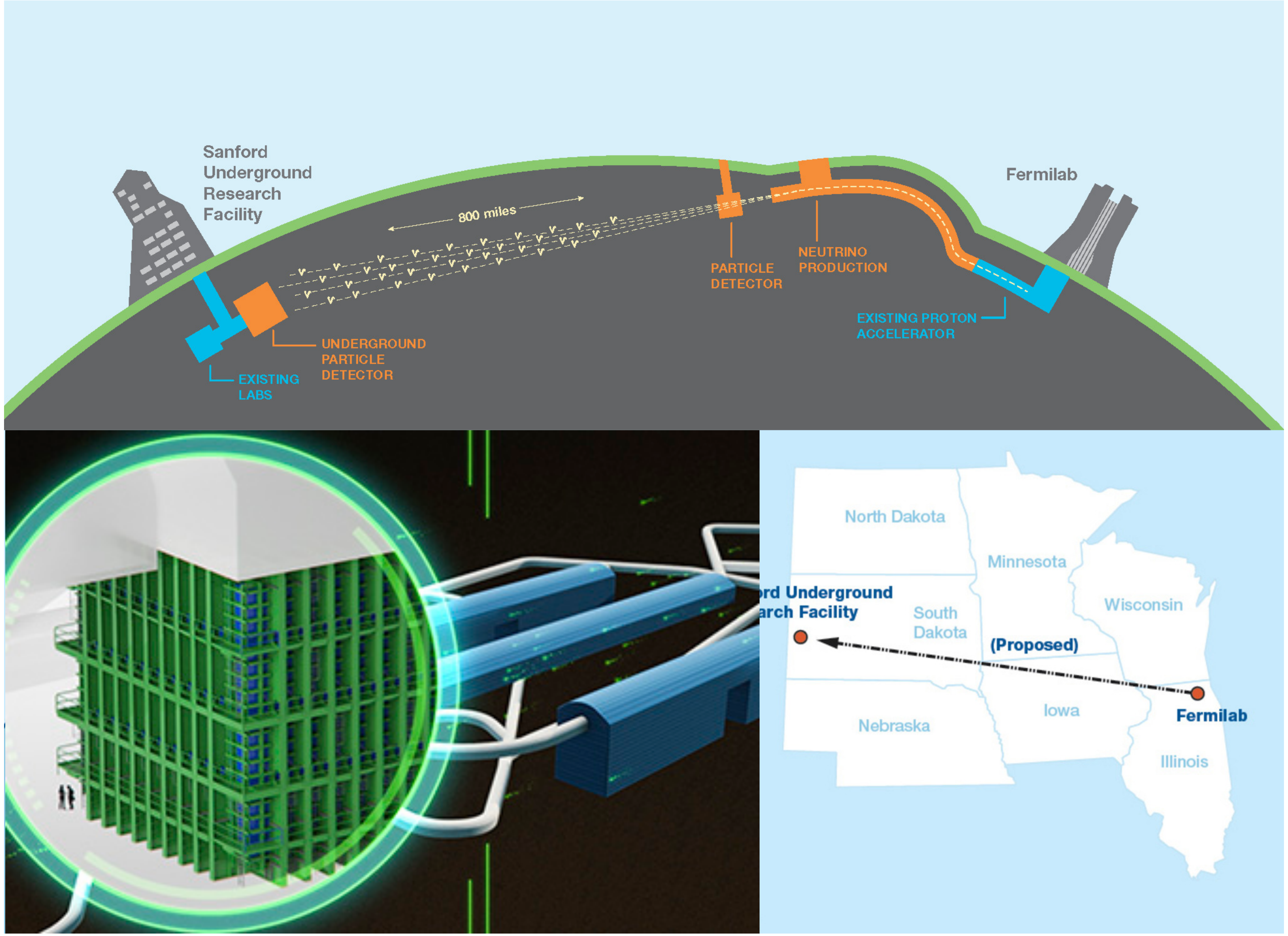




Oscillations: Next generation



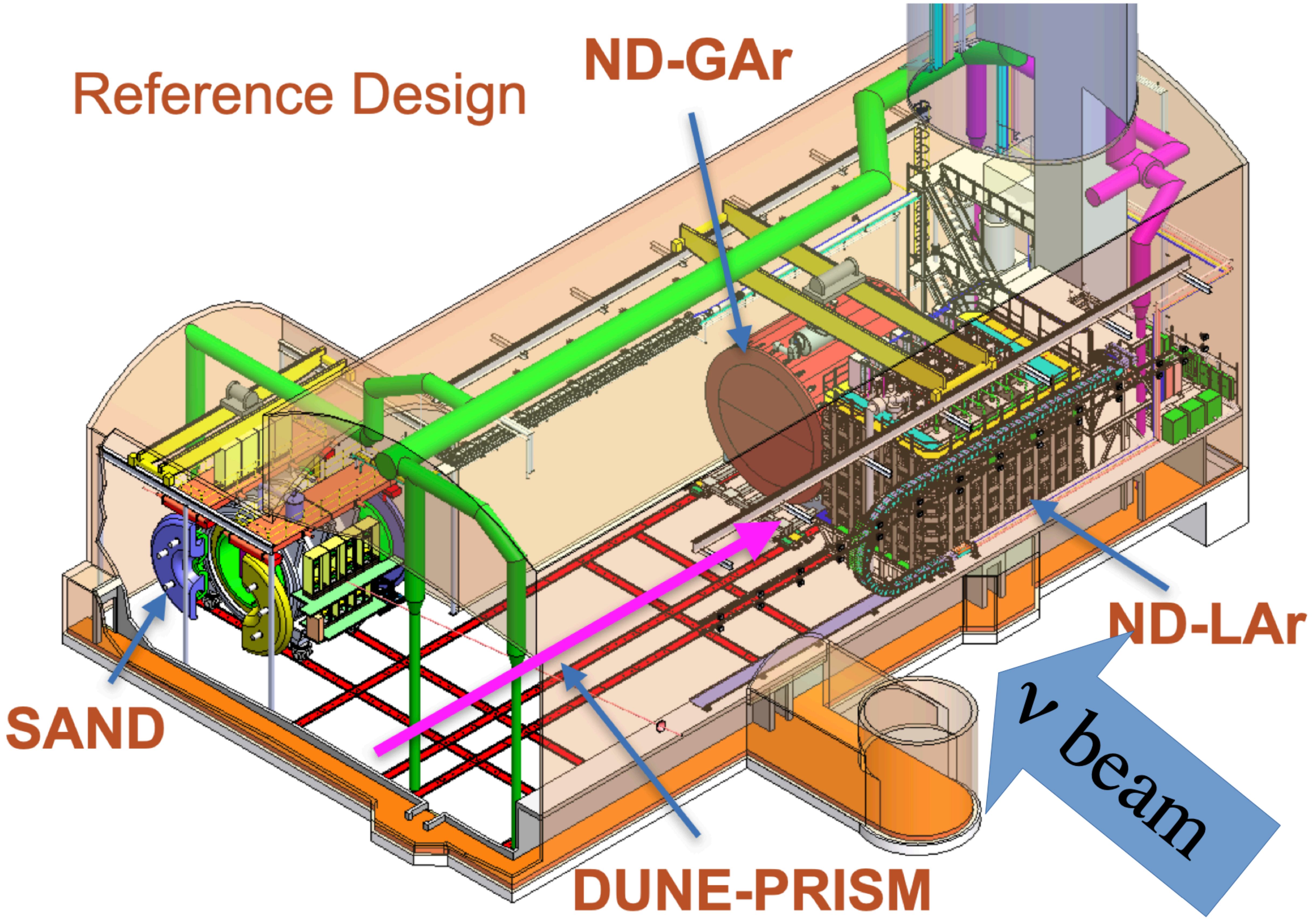
DUNE



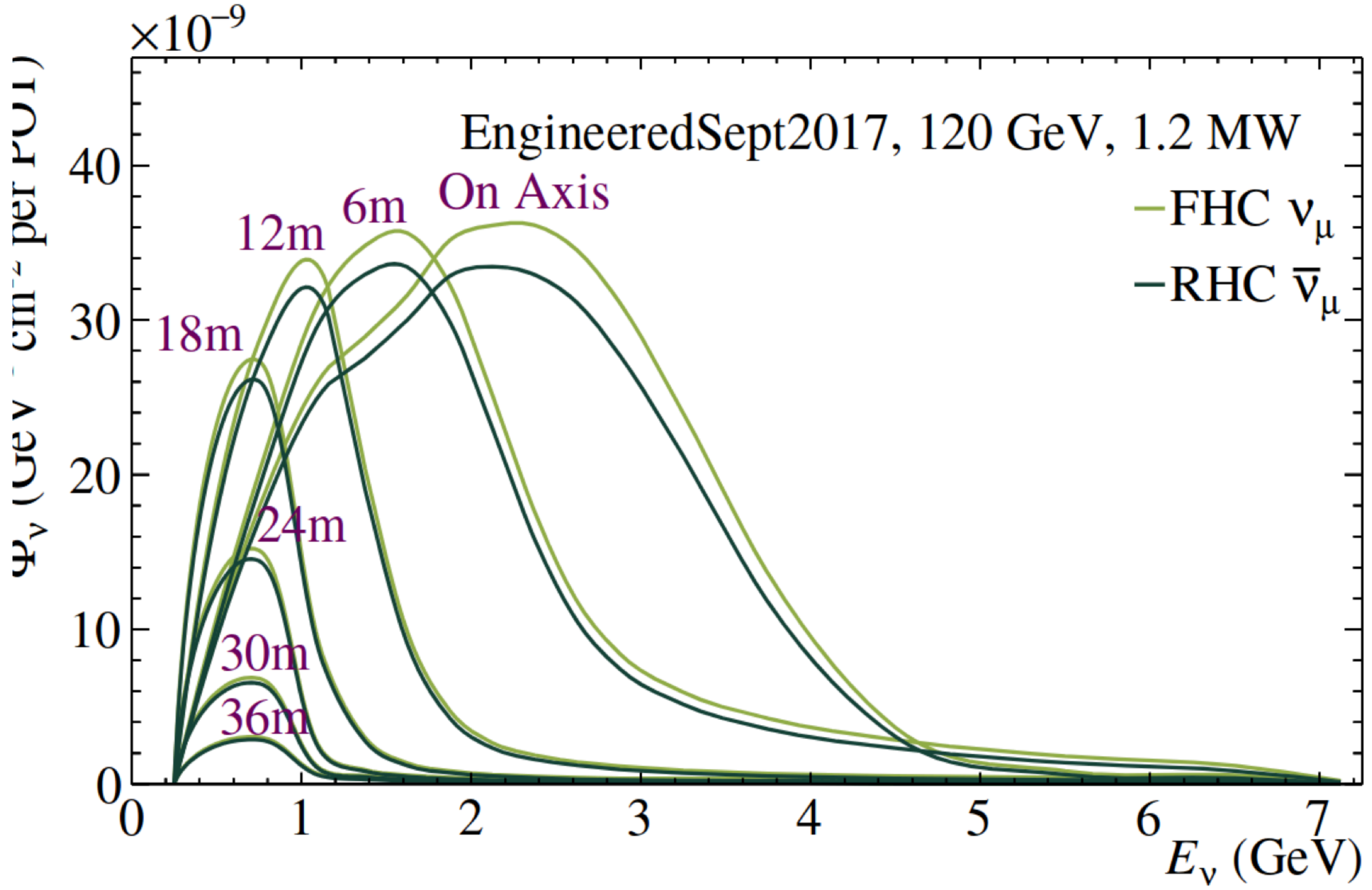
- ∗1400 collaborators from ∼200 institutions and over 30 countries.
- ∗DUNE will start ”in late 2020s” (this is official statement).
- ∗Baseline 1300 km,
- ∗ δ_{CP} sensitivity, MO and all PMNS parameters.
- ∗On-axis experiment;
- ∗E at peak ∼2.5 GeV;
- ∗70 kt FD LArTPC with single/dual phase under consideration;
- ∗Start with 1.2 MW proton beam at 60-120 GeV (10^{20} POT/ year),
- ∗up to 2.4 MW beam power by ∼2035.

DUNE ND complex and DUNE-PRISM

- ✶We only ever measure a combination of flux and cross-section.
- ✶The goal of DUNE-PRISM is to use the flux model to predict far detector event rates with minimal cross-section model dependence.
- ✶Achieve this by collecting data at several off-axis angles, exposing the detector to different fluxes.



- ✶Spend half of year on axis and half at several points outside.

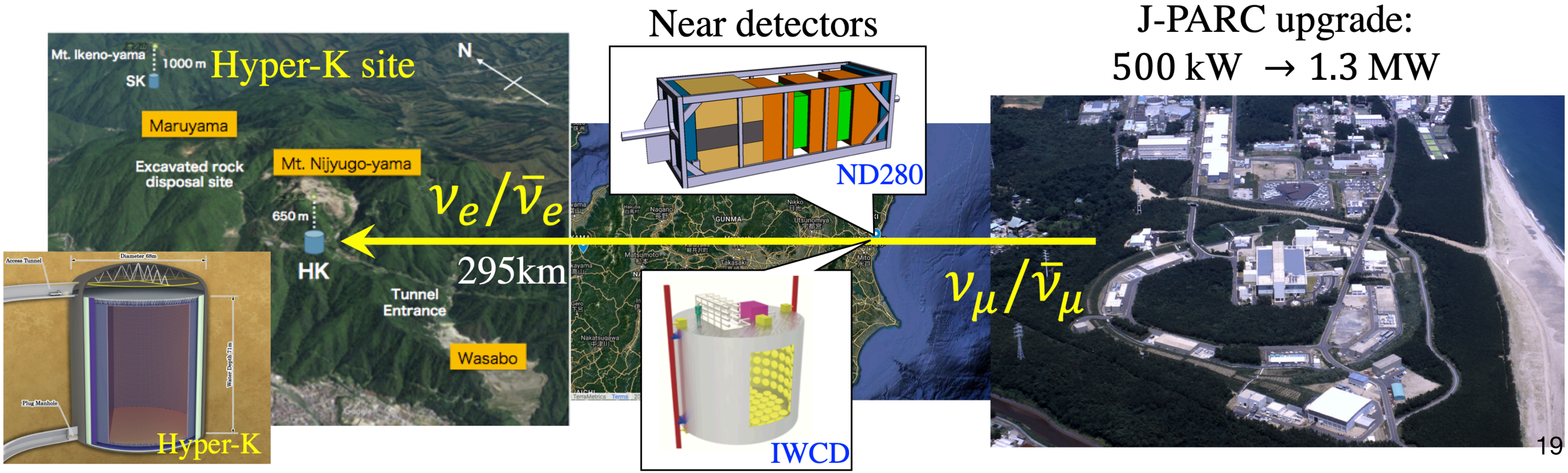


HyperK

- ✳ 3rd generation of water Cherenkov underground detectors in Kamioka:

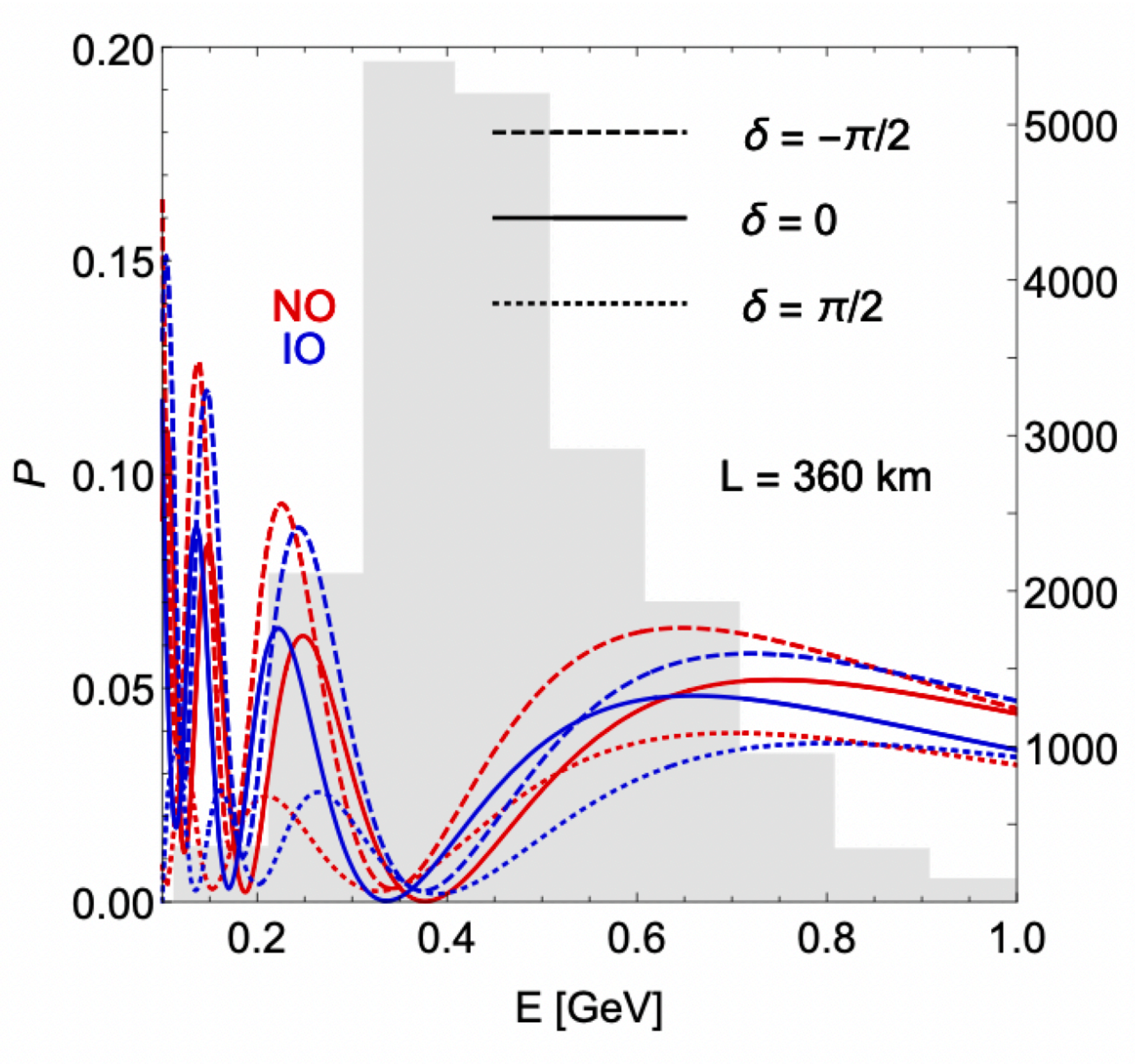
Kamiokande (3kt) → Super-Kamiokande (50 kt) → Hyper-Kamiokande (260 kt)

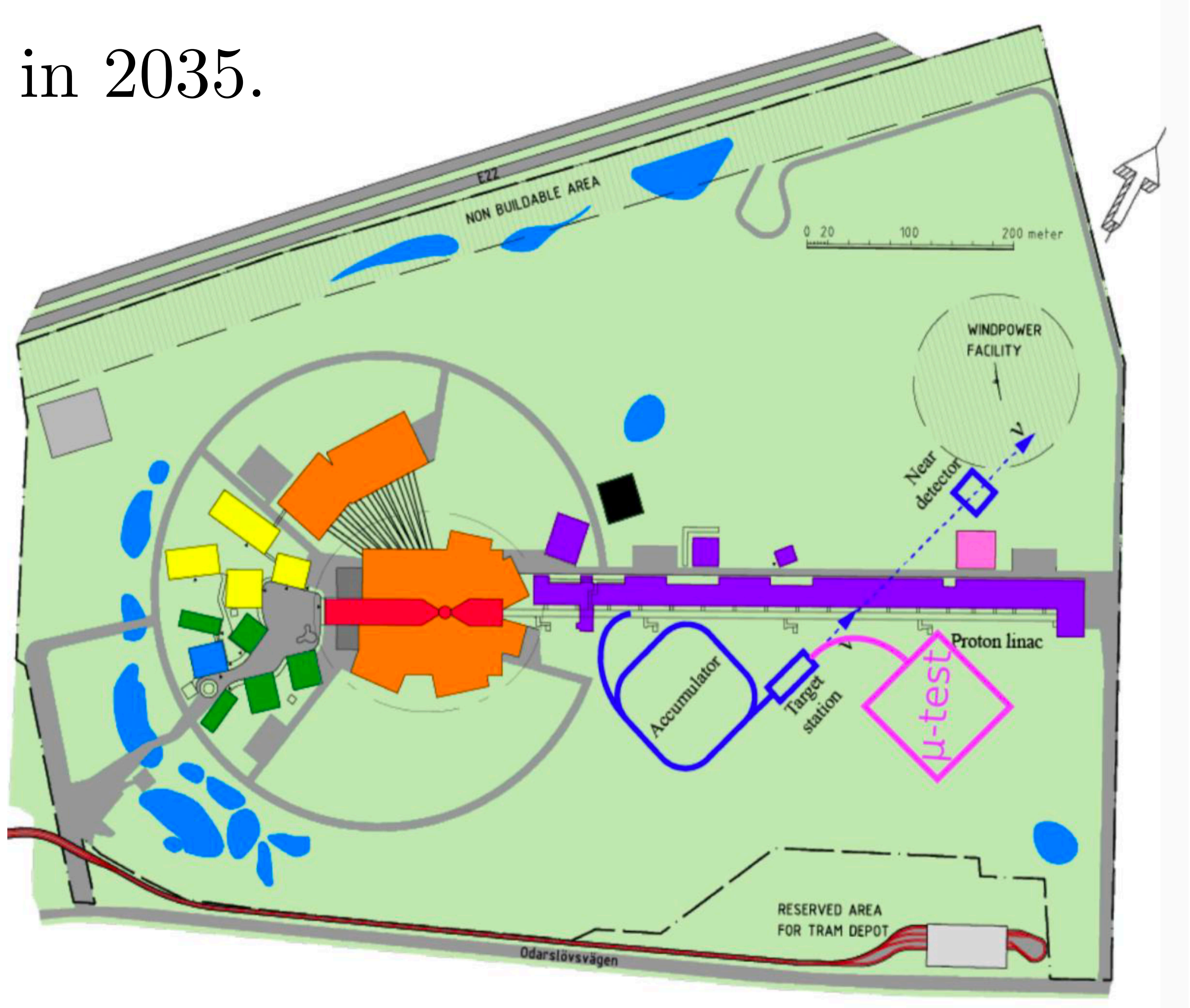
- ✳ Operation should begin in 2027.
- ✳ 1.3 MW beam power + larger detector → high statistics.
- ✳ Besides oscillations: supernova, proton decay etc.
- ✳ Additional intermediate water Cherenkov detector at 1 km.
- ✳ ND280 complex inherited from T2K.

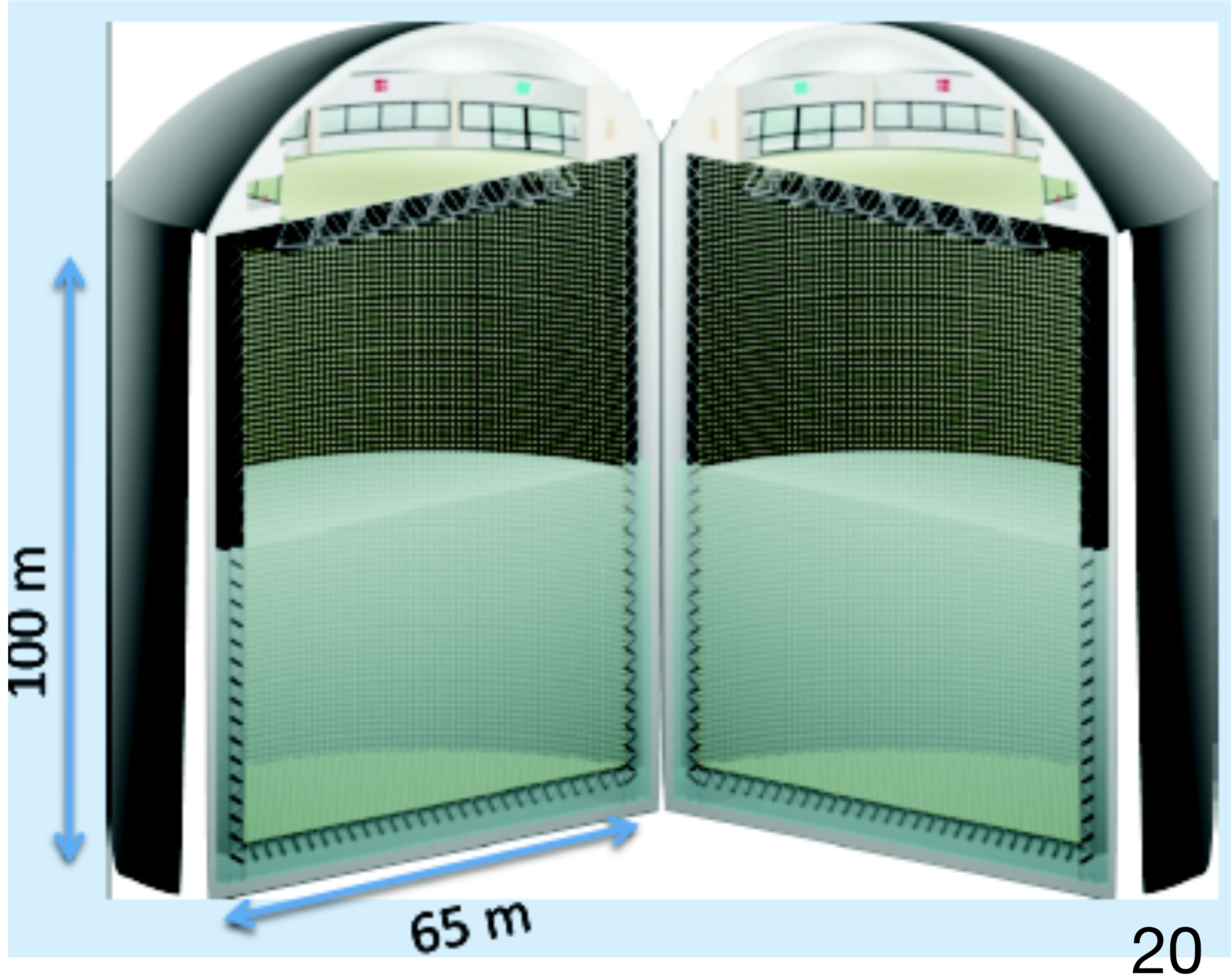


Projects with unclear status: ESSνSB

- ✶ Proposed experiment at European Spallation Source.
- ✶ 5 MW accelerator beam, neutrino E = $\sim$ 300 MeV
- ✶ FD location is at a distance of 360 km in the mine.
- ✶ FD is water Cherenkov detectors with 540 kt total weight. ND is also inspired by HK.
- ✶ Similar physics performance to HK, the largest sensitivity to δ_{CP} among all LBL experiments.
- ✶ If approved, data taking will start in 2035.



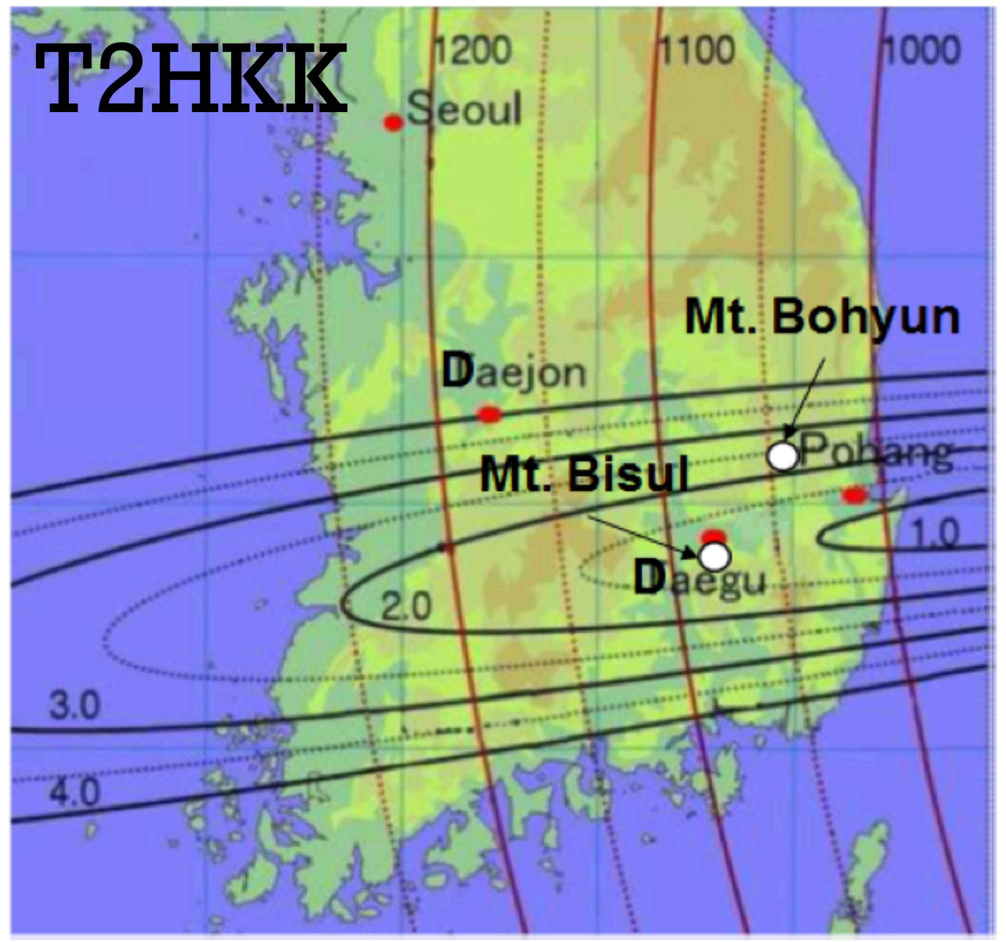




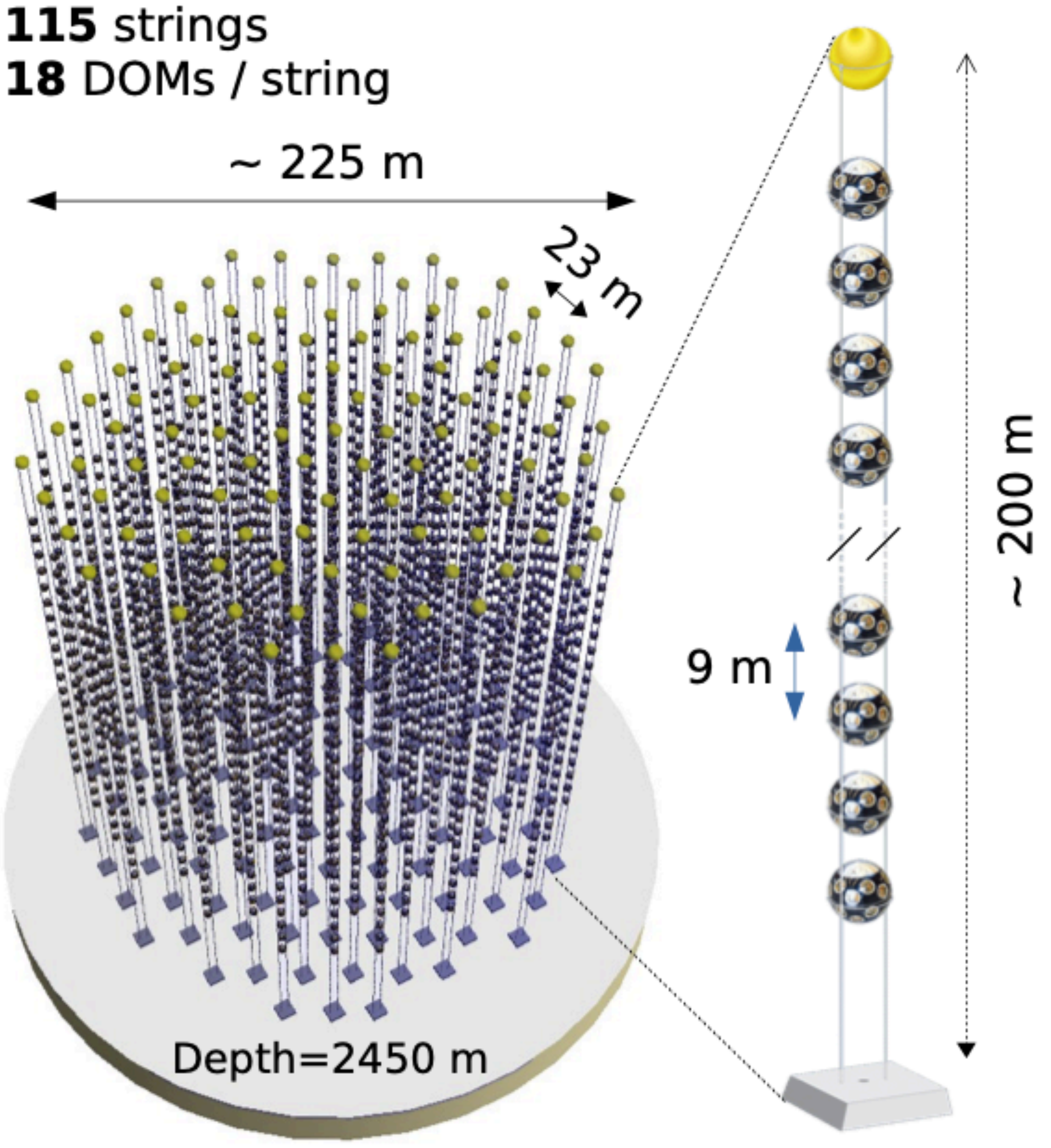
Projects with unclear status

- P2O:
  - Accelerator beam from Protvino (Russia) to ORCA → 2595 km baseline
  - Flavor identification is impossible with ORCA
  - Requires significant improvement in beam intensity (from 15 kW to 90kW, 450 kW)
  - SuperORCA is 10 times more dense ORCA.
  - P2O + SuperORCA can do the same as DUNE and HyperK for δ_{CP} measurement after 10 years of running.

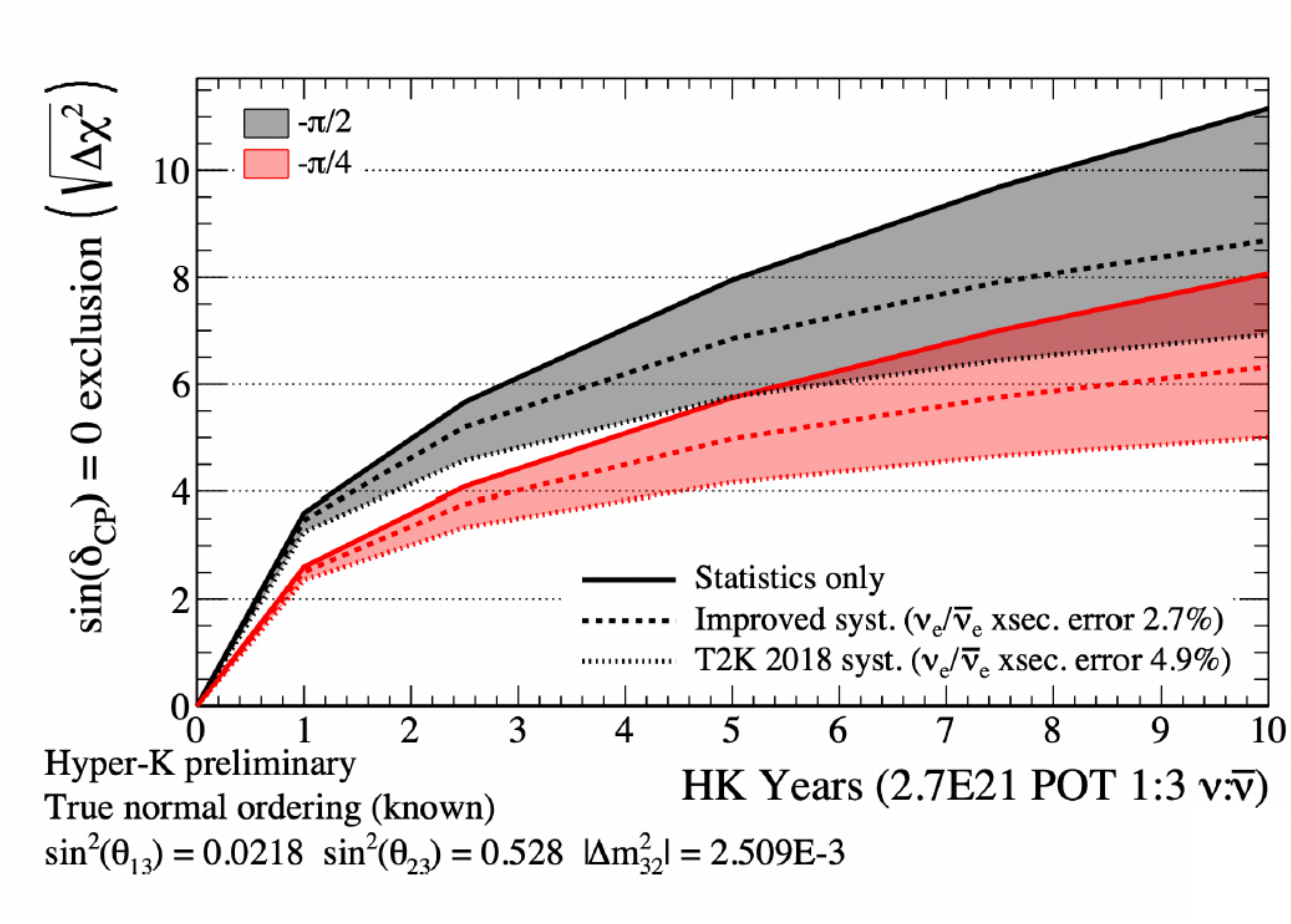
- HyperK - additional tank in Korea:
  - Baseline ~1000 km

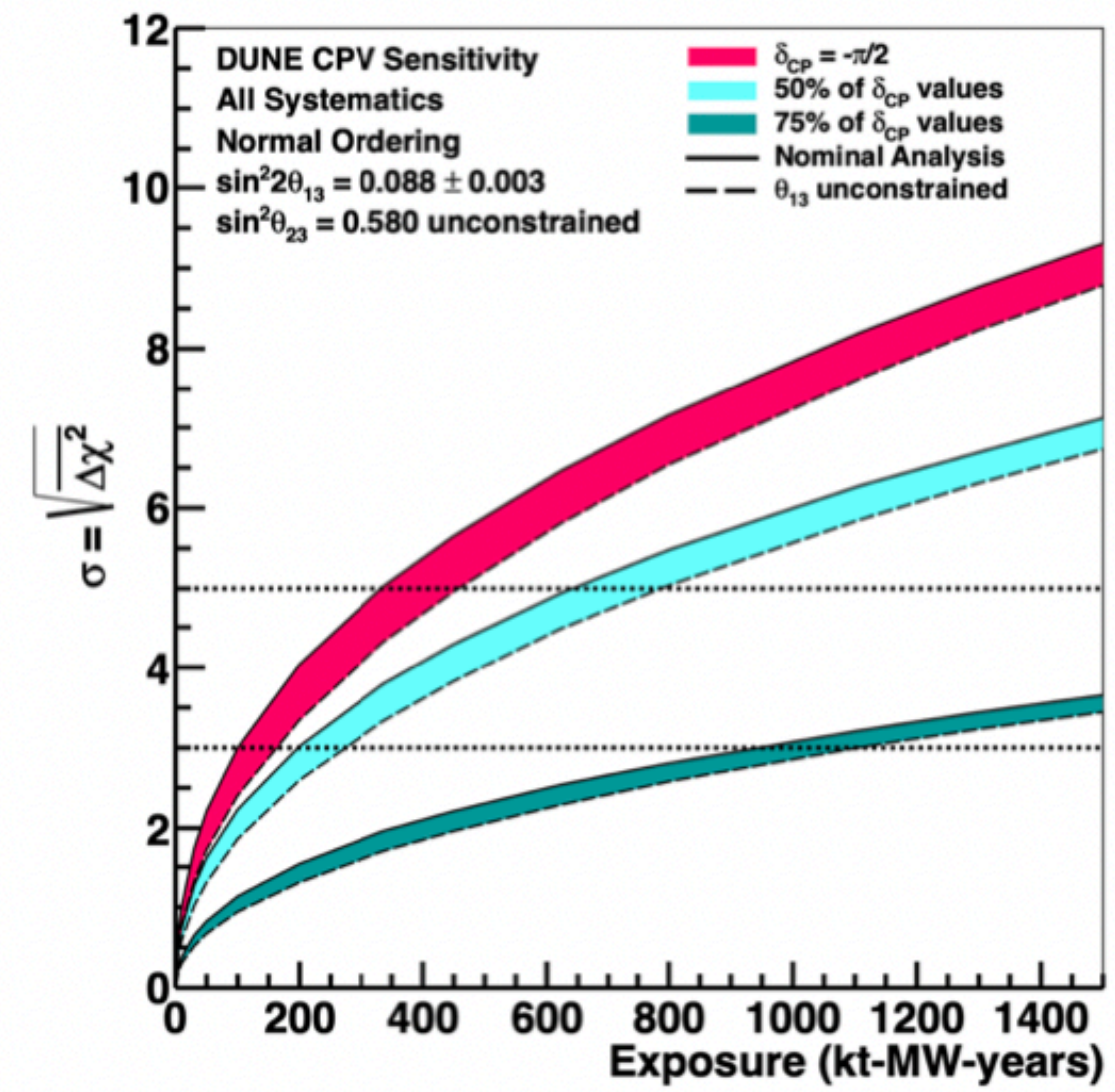


KM3NeT/ORCA



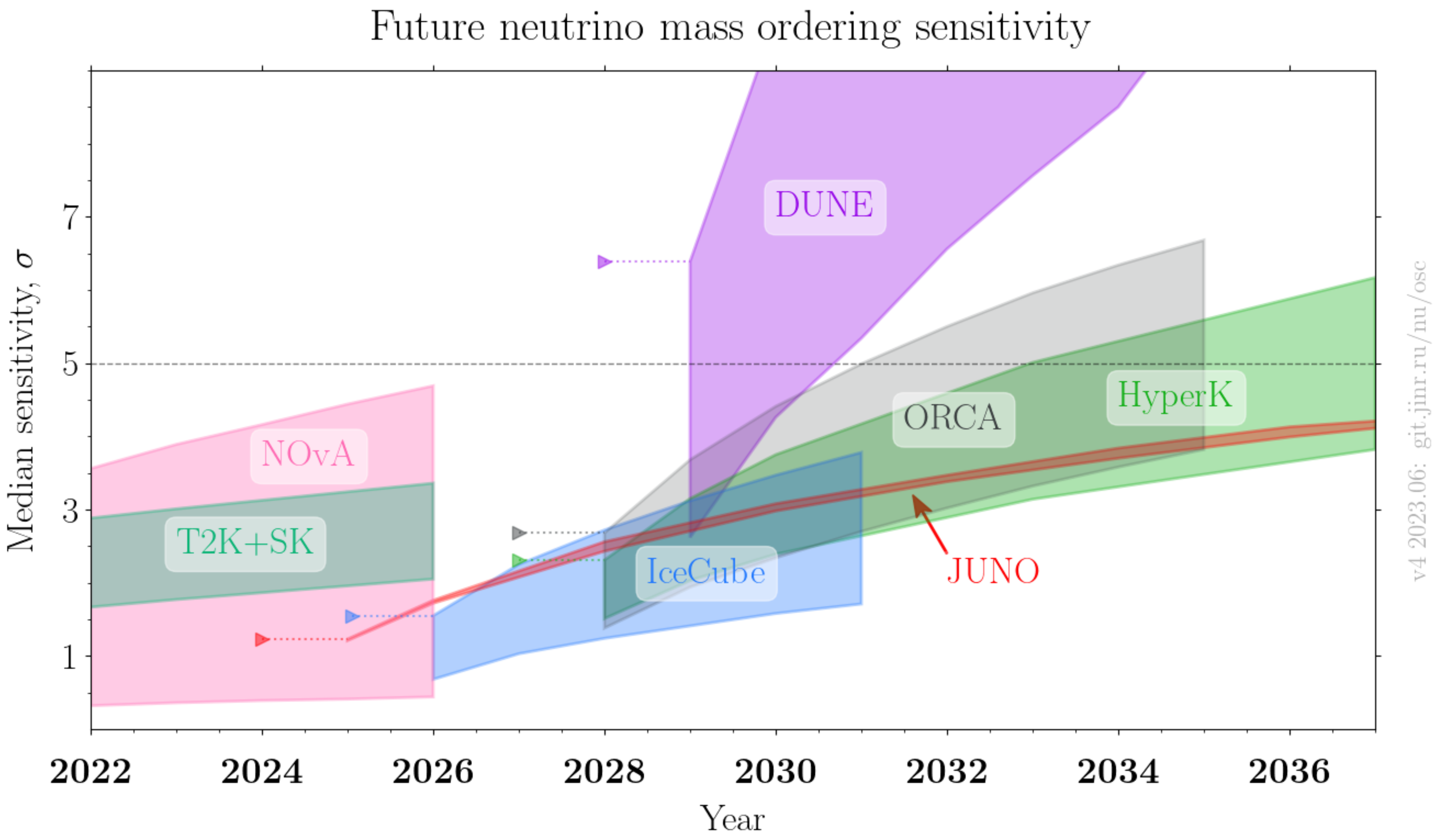
HyperK and DUNE sensitivities to CPV



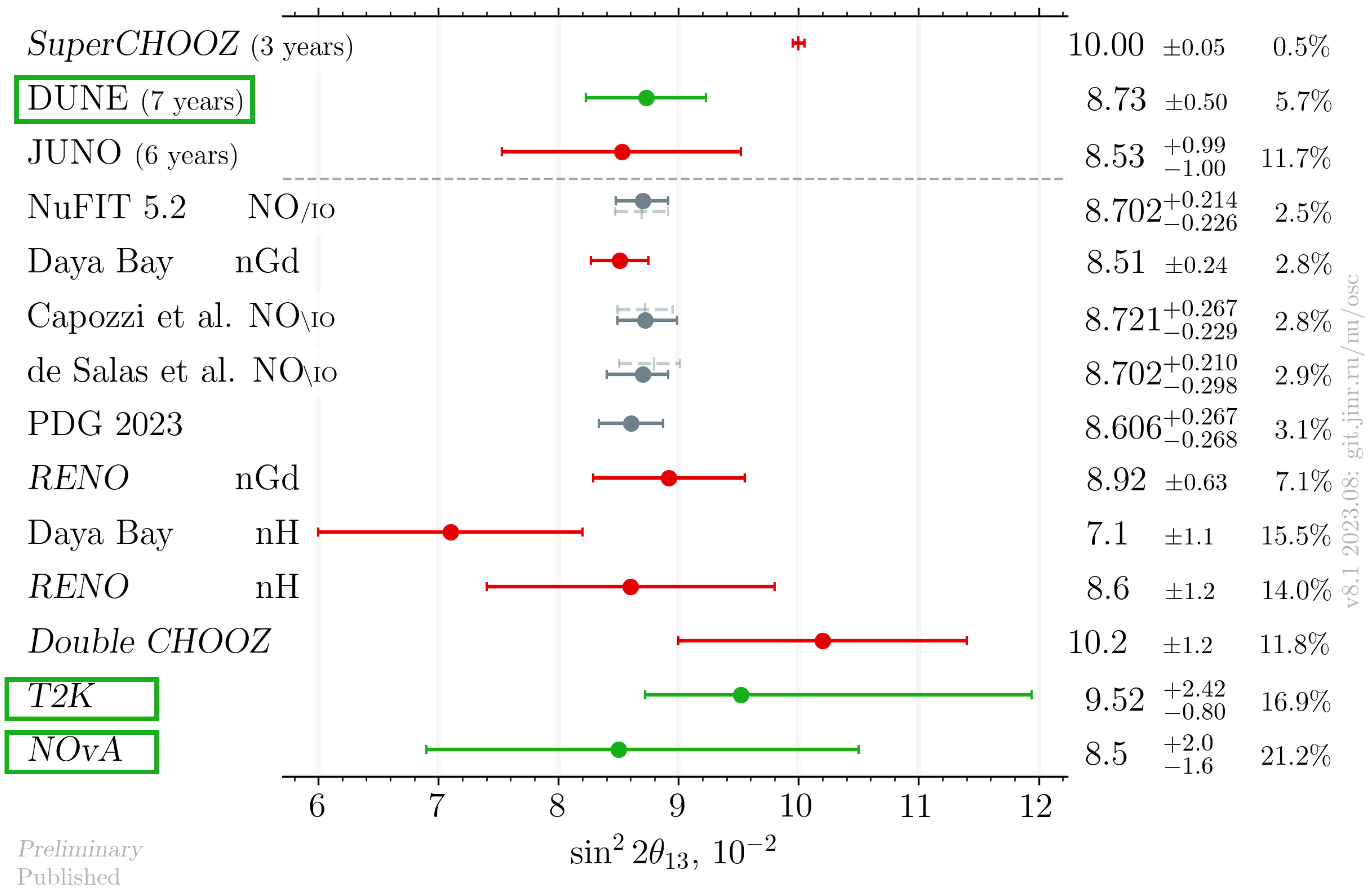


- ✳ The only experiments that can measure it
- ✳ HK is focused on δ_{CP} (shorter L, need hierarchy to be known) while DUEN is going to measure both.

Expected sensitivities: mass hierarchy



Expected sensitivities: θ_{13}

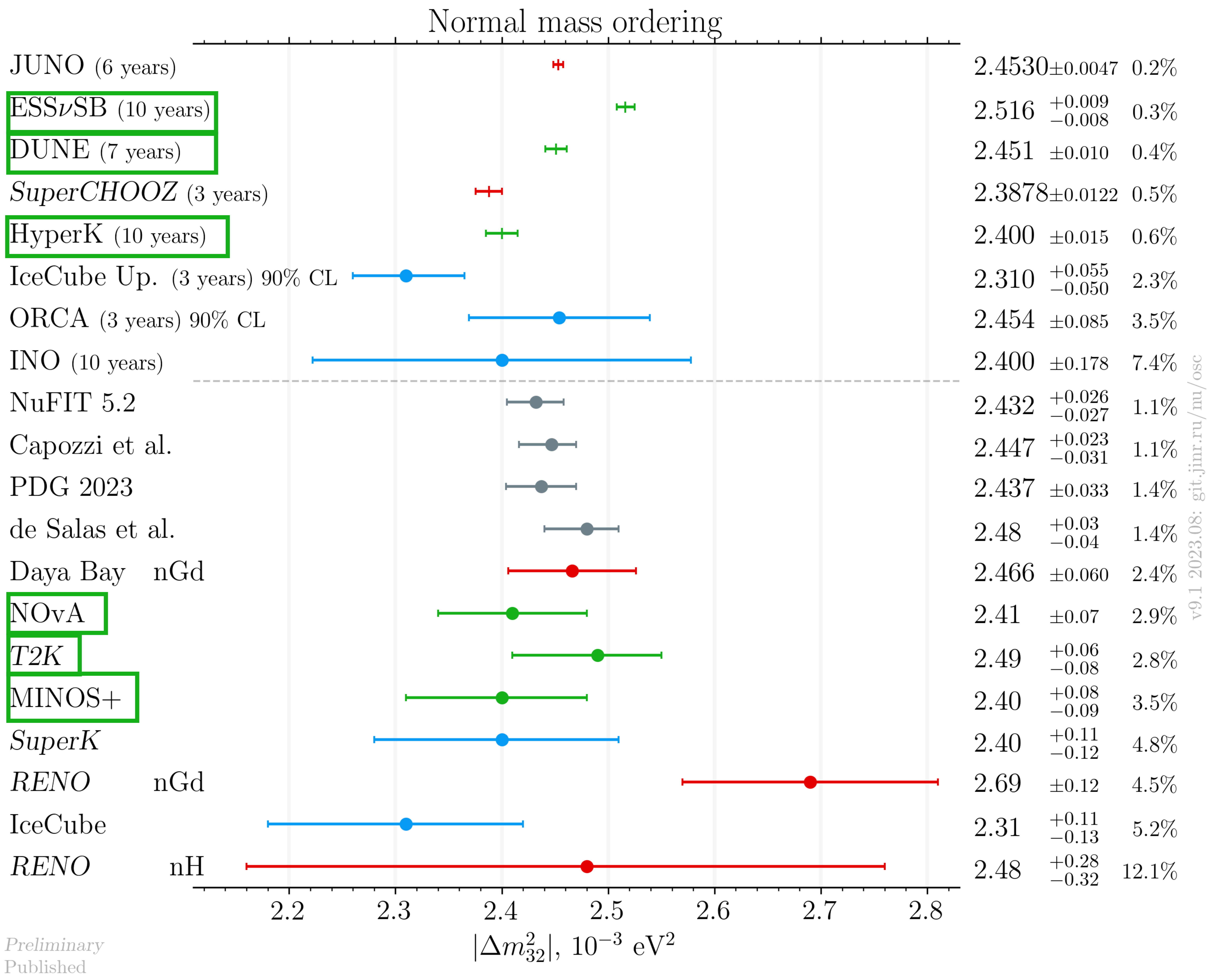


Current results, central values with 1σ errors and future sensitivities.

✳ Not so much room for improvement.

NB: future c.v. depends on initial assumption of parameter value.

Expected sensitivities: Δm^2_{32}

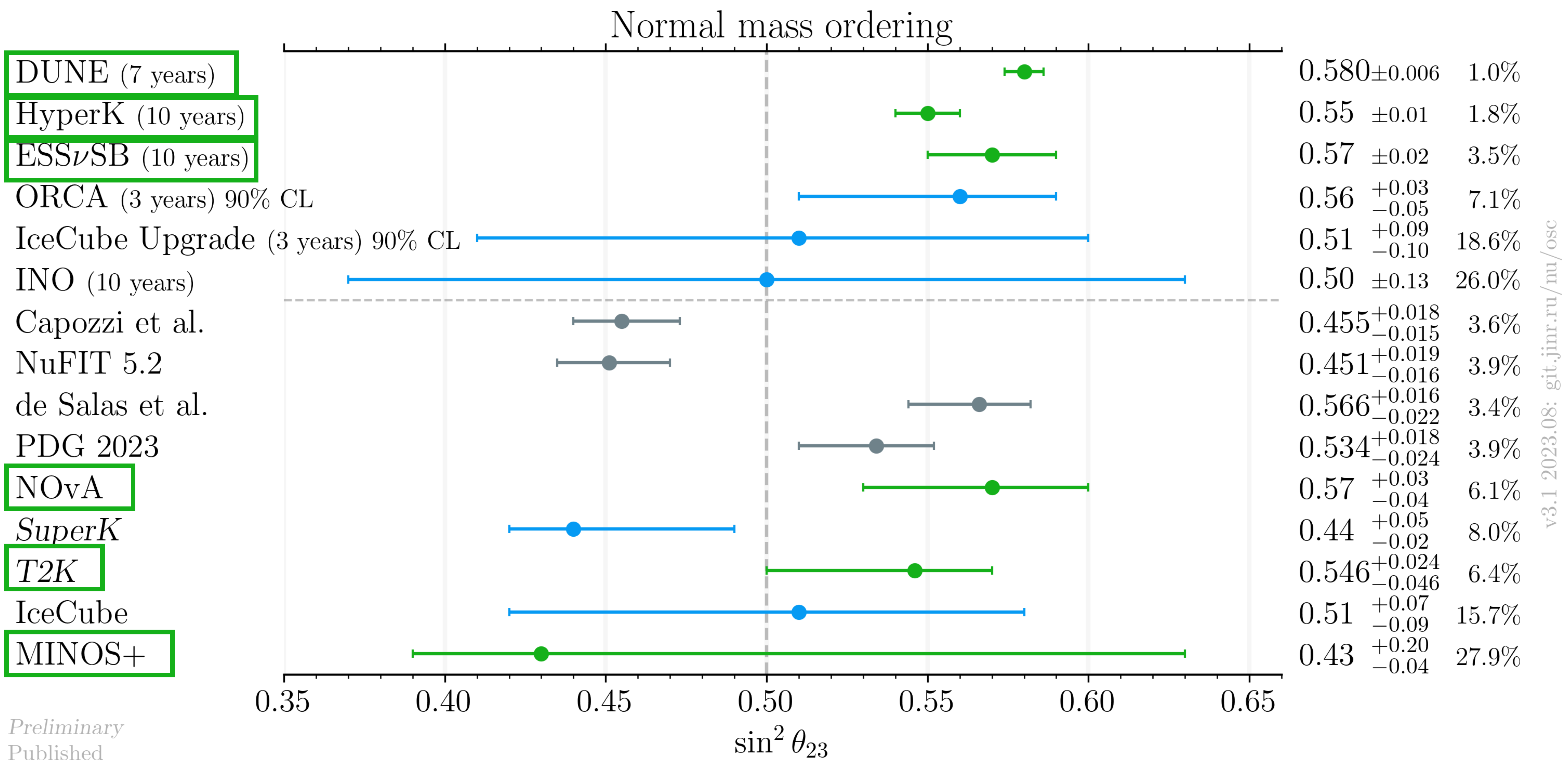


Current results, central values with 1σ errors and future sensitivities.

* LBL accelerator experiments and JUNO will improve Δm^2_{32} up to sub-percent level.

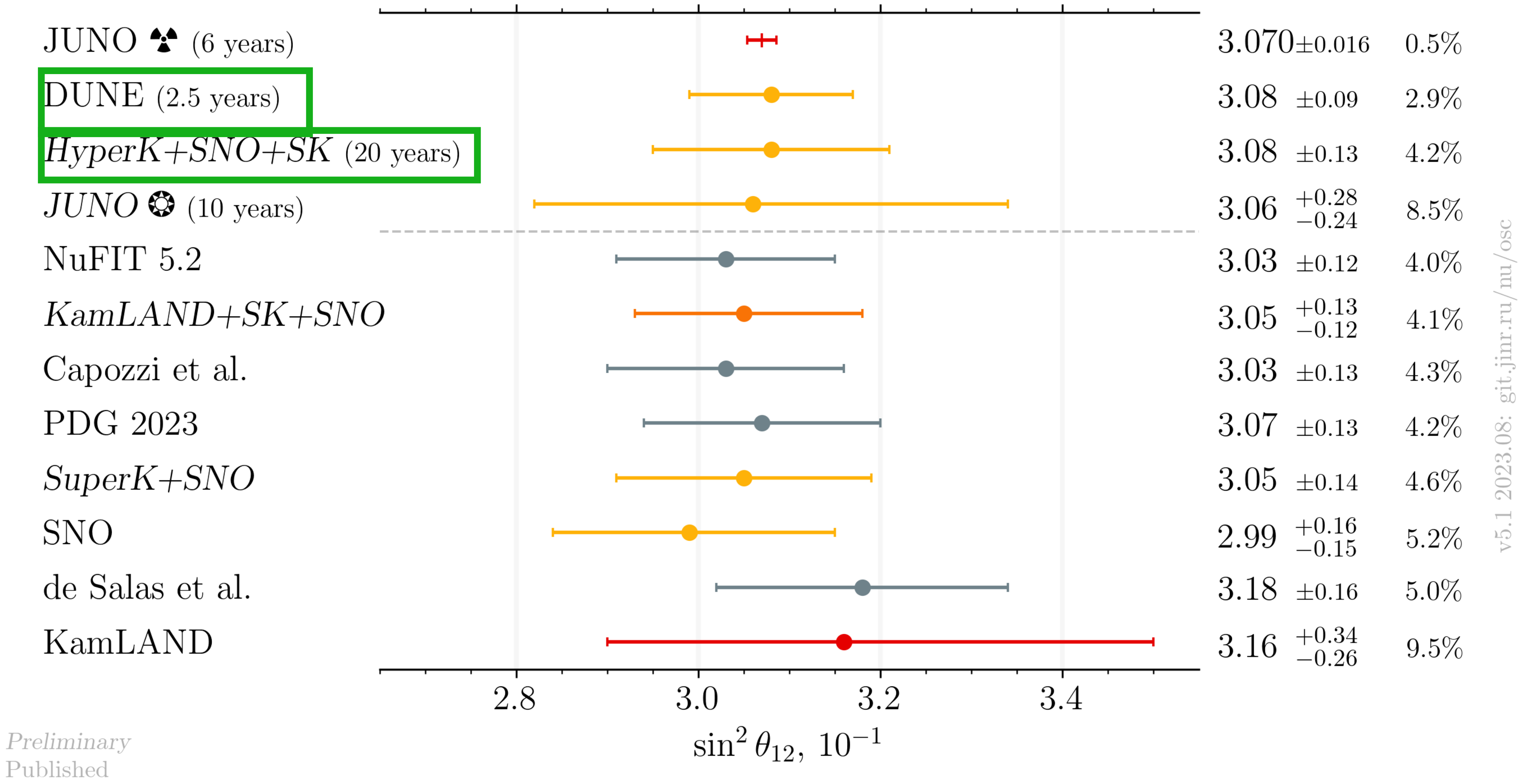
NB: future c.v. depends on initial assumption of parameter value.

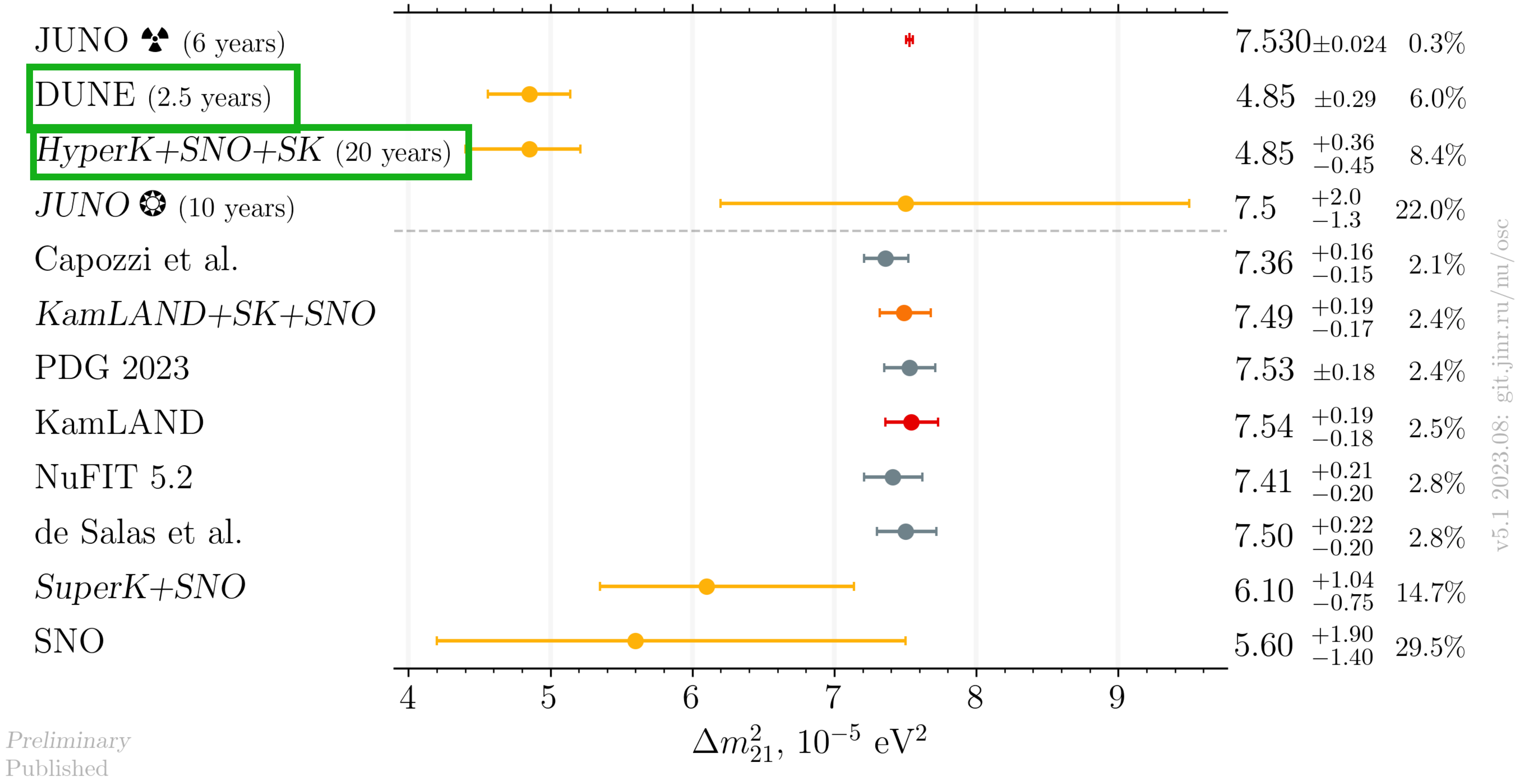
Expected sensitivities: θ_{23}



✳ LBL accelerator experiments will improve θ_{23} up to percent level.

Expected sensitivities: solar sector





Current results, central values with 1σ errors and future sensitivities.

- ✳ SK + SNO vs KamLAND weak tension.
- ✳ JUNO will have an opportunity to check this with both sources: solar and reactor.
- ✳ Extremely high JUNO sensitivity to these parameters.
- ✳ Expected resolution is $< 1\%$.
- ✳ Accelerator DUNE and HK will have chance contribute with solar neutrino measurements

NB: future c.v. depends on initial assumption of parameter value.

Summary

∗Neutrinos oscillate and over the last ∼25 years this process was studied pretty well.

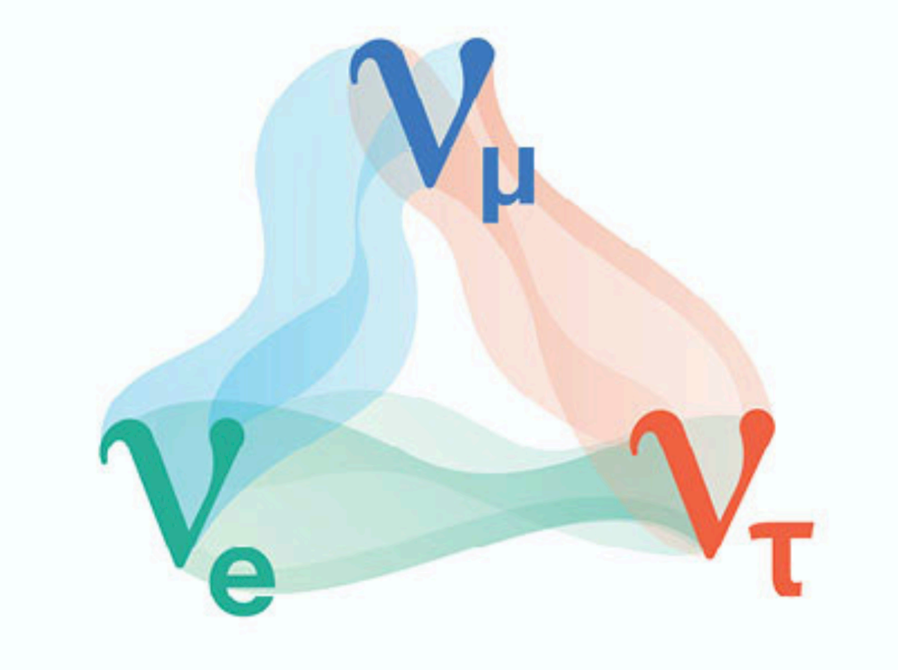
∗But there are still some parameters with pure knowledge (NMO, CP violation in lepton sector).

- ∗ LBL accelerator experiments are one of the main players in this area.

∗The following $10 - 15$ years will be extremely exciting in neutrino oscillation physics especially due to start of next-generation experiments.

∗As for LBL accelerator experiments:

- ∗NOvA and T2K already produce interesting physics and will keep taking data for several more years.
- ∗We're looking forward to seeing first DUNE and HyperK results.



Thank you!

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