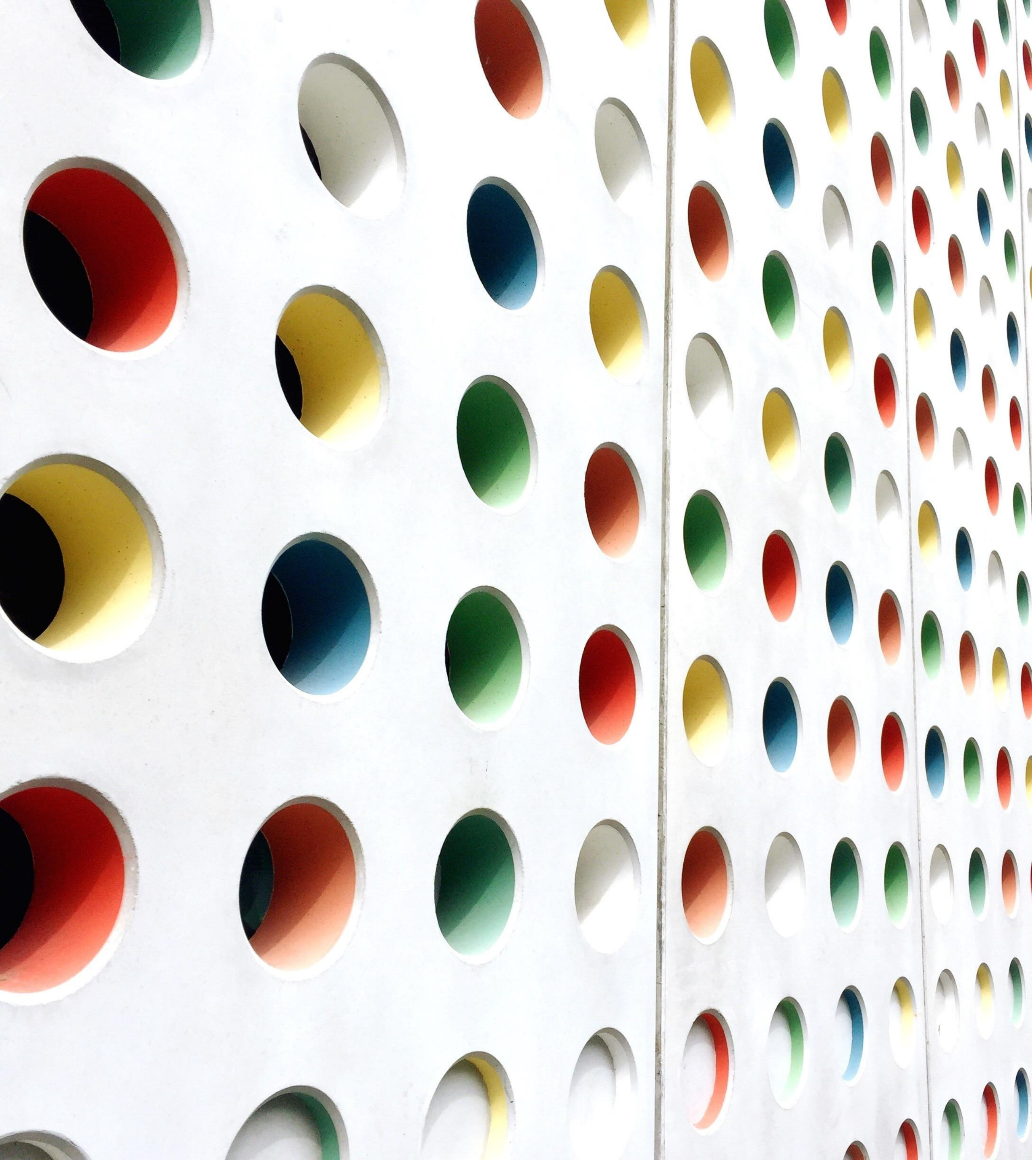
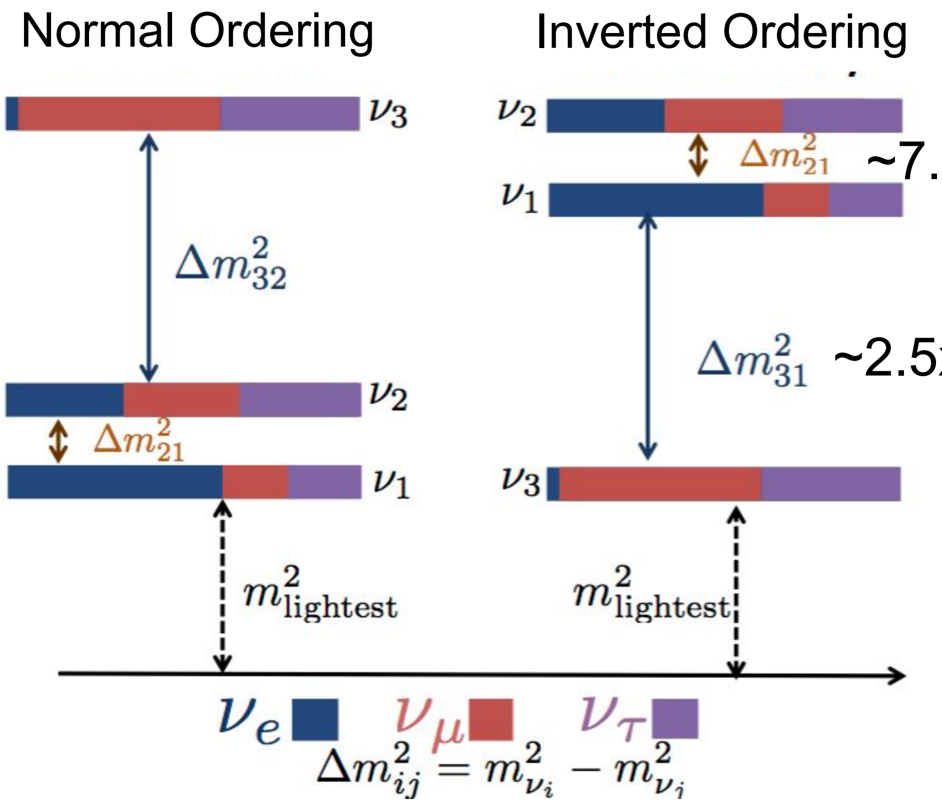


Status of neutrino oscillations (long baseline and reactor experiments)

Atsuko K. Ichikawa

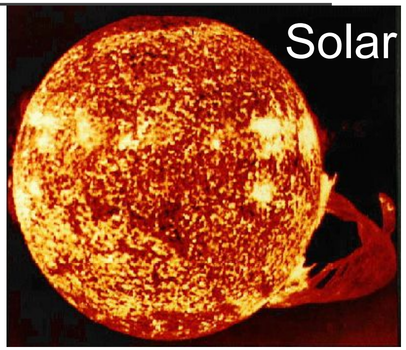
Tohoku university, Japan

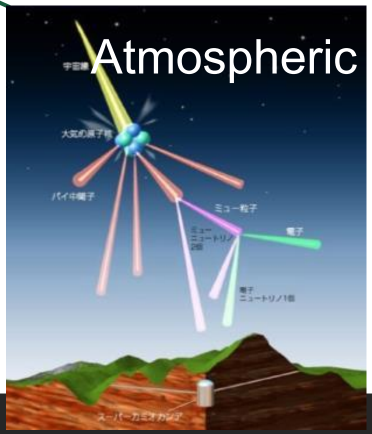
Neutrino oscillation, mixing matrix and $\Delta m's$



$\sim 7.5\text{x}10^{-5}\text{eV}^2$ ~50 km @ Eν=3 MeV

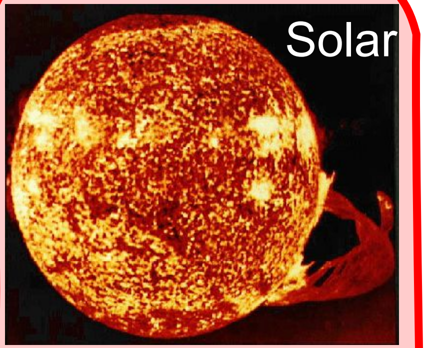
$\sim 2.5\text{x}10^{-3}\text{eV}^2$ ~500 km @ Eν=1 GeV



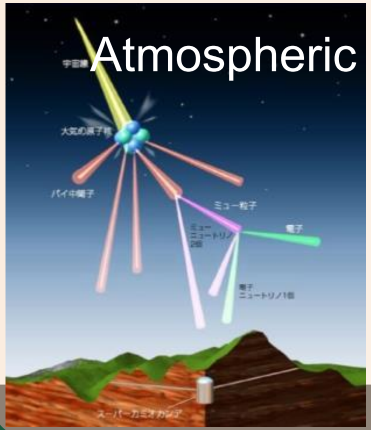


Three-flavor Mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \boldsymbol{U} \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix}$$



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



$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$

Three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
One CP-phase : δ_{CP}

Mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \boldsymbol{U} \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix}$$

$$U_{PMNS} = \begin{pmatrix} 0.823 \pm 0.008 & 0.55 \pm 0.01 & 0.148 \pm 0.002 \\ -0.47 \pm 0.01 & 0.50 \pm 0.02 & 0.73 \pm 0.01 \\ 0.33 \pm 0.01 & -0.67 \pm 0.01 & 0.67 \pm 0.02 \end{pmatrix}$$

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

Some flavor symmetry predicts.

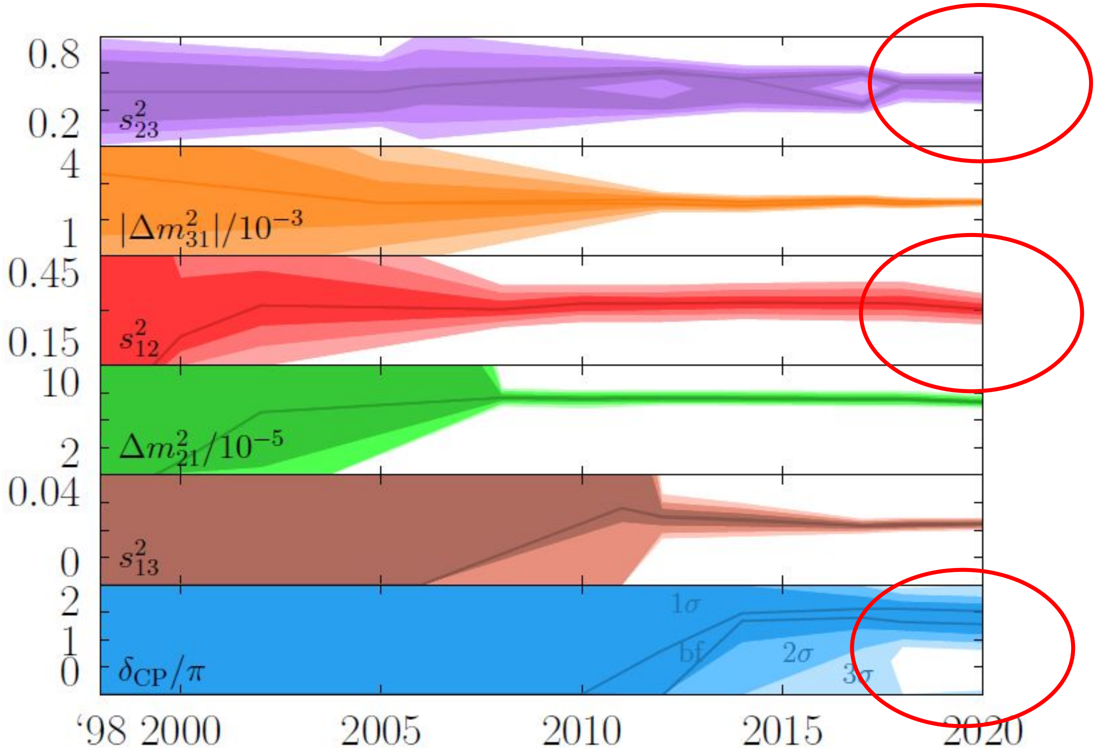
$$U_{MNS} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \\ \sqrt{1/6} & -\sqrt{1/3} & \sqrt{1/2} \end{pmatrix} = \begin{pmatrix} 0.816 & 0.577 & 0 \\ -0.408 & 0.577 & 0.707 \\ 0.408 & -0.577 & 0.707 \end{pmatrix}$$

$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$

Flavor symmetry may originate from, e.g., structure of extra-dimension.

Target of long-baseline neutrino experiments

- Determine the mixing matrix (a little more?) precisely
- Determine the size of CP-violation
- Determine the order of masses
- Search for something unknown
  - ✔ Violation of unitarity, Lorentz symmetry, CPT etc.
  - ✔ new type of interaction etc.
  - ✔ ?
  - ✔ Neutrino mass may be already suppressed by high energy physics, so new physics may happen at same order.



Snowmass NF01 arXiv:2212.00809

Reactor neutrino ($\bar{\nu}_e$)

Reactor neutrino ($\bar{\nu}_e$)

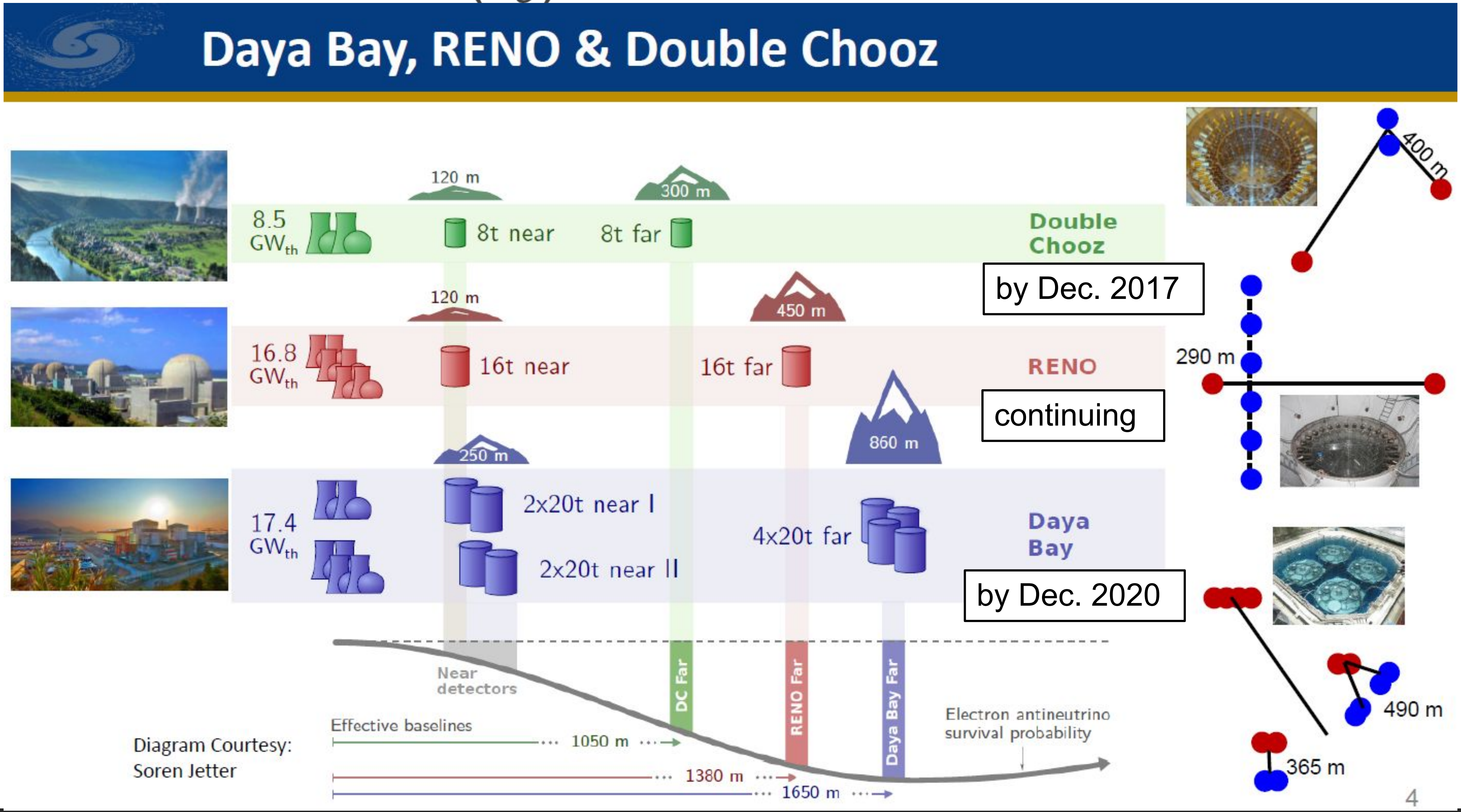
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \boldsymbol{U} \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix}$$

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

$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$

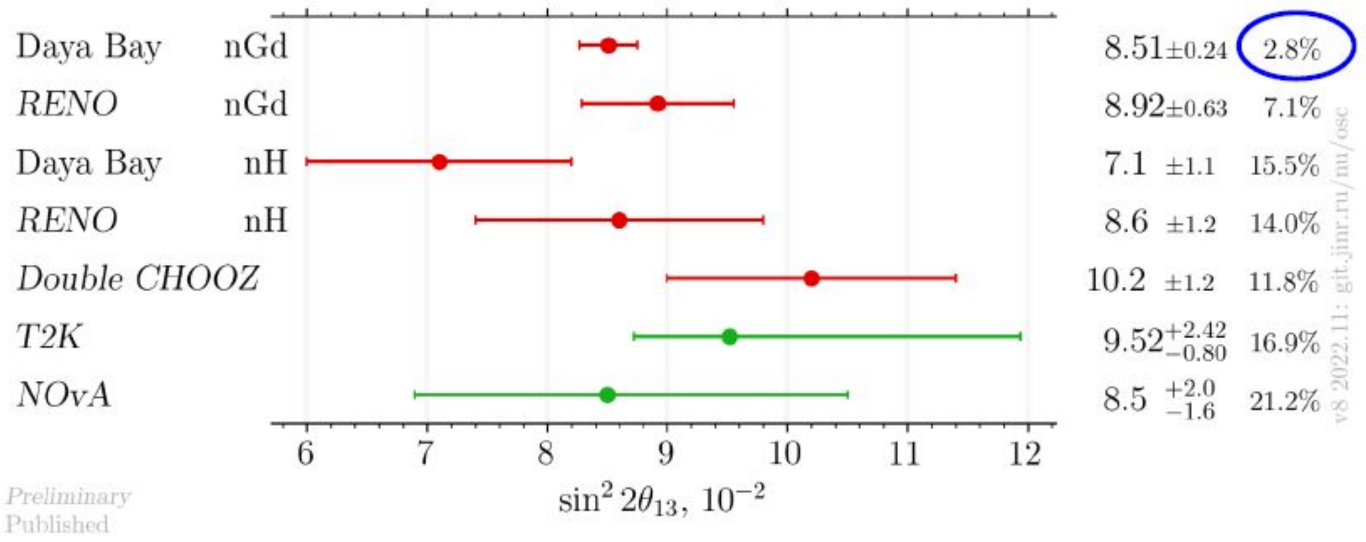
$i\delta$

Reactor neutrino ($\bar{\nu}_e$)



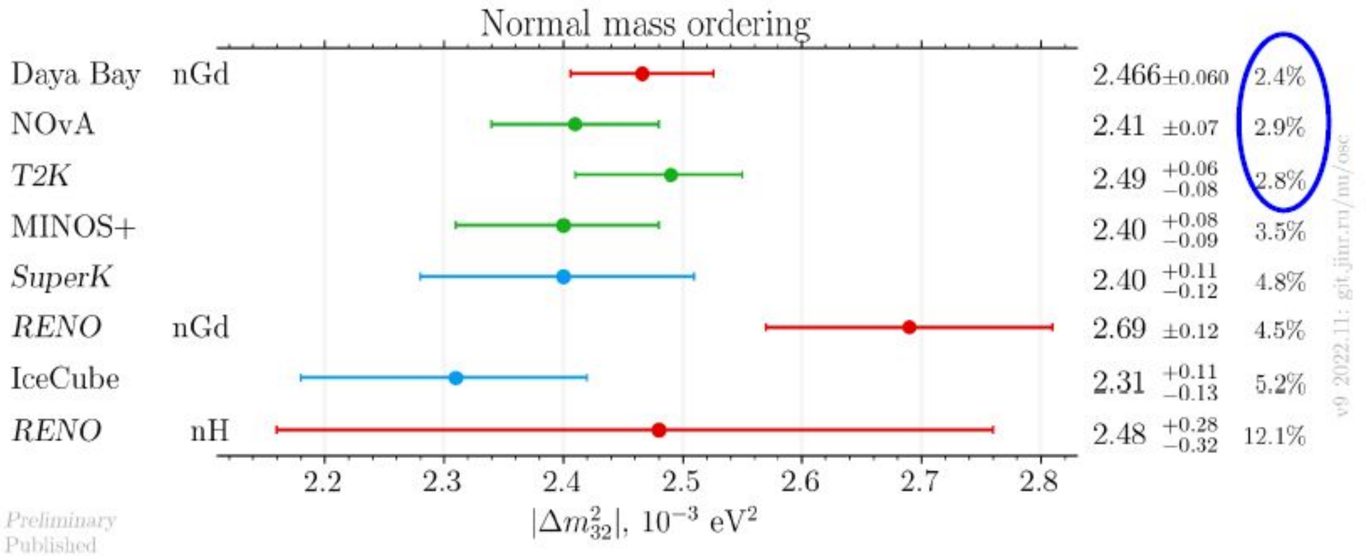
Global Picture for θ_{13}

$\sin^2 2\theta_{13}$



Will likely be the best measurement in the foreseeable future

Δm^2_{32} (NO)



Greatly consistent results from $\bar{\nu}_e$ (reactor) and ν_μ (accelerator) measurements, strongly support 3-flavor framework

7

Atmospheric neutrino ($\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$)

Atmospheric neutrino $(\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e)$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \boldsymbol{U} \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix}$$

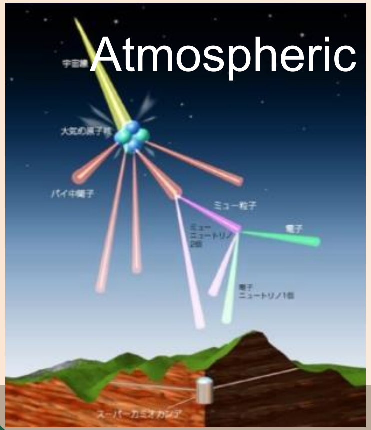
Matter effect makes a peculiar feature depending on mass order.

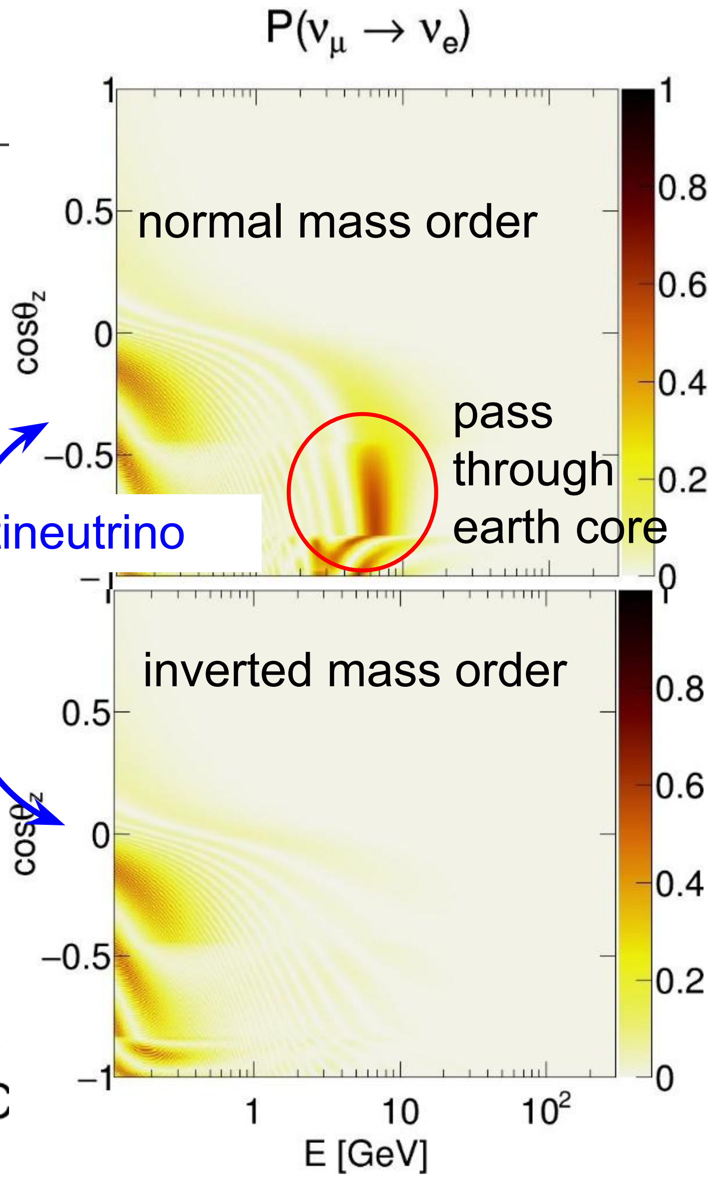
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} \\ -s_{12} \\ 0 \end{pmatrix}$$

$(c_{ij}$

Three

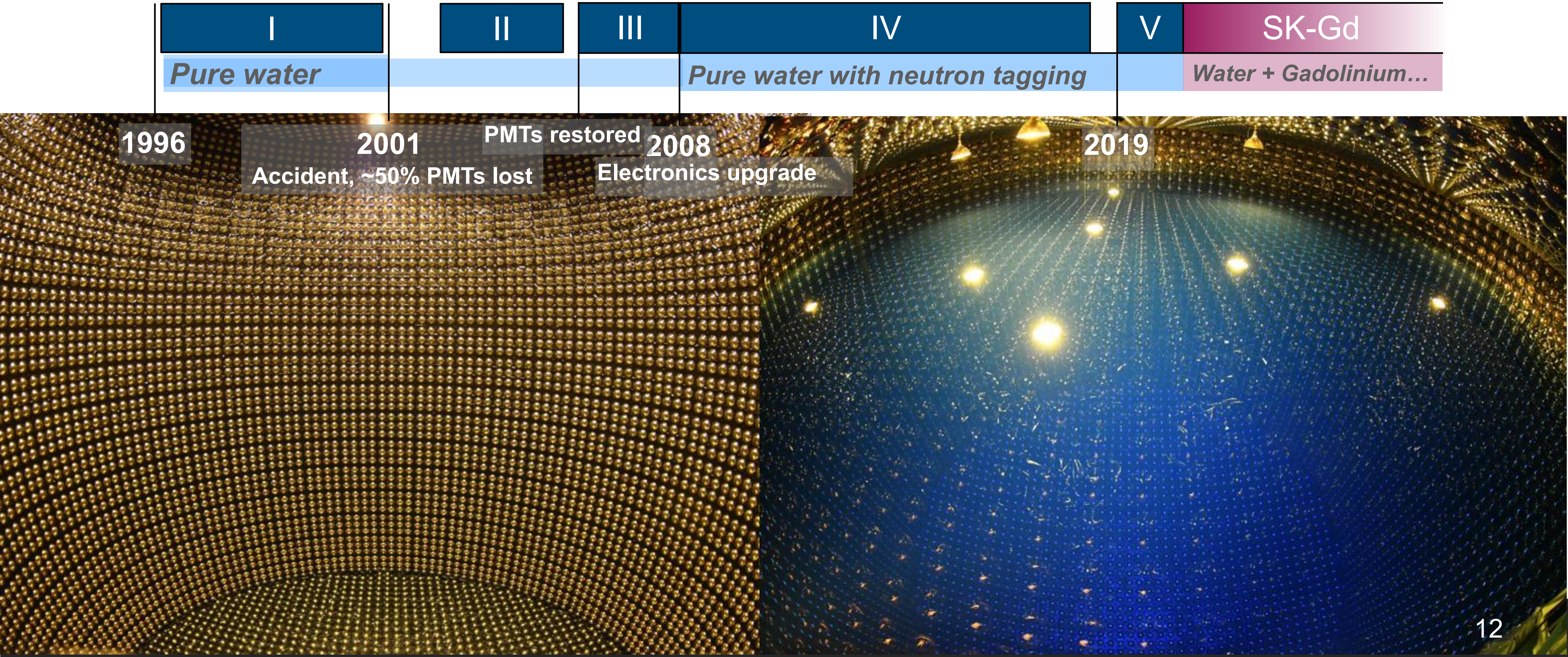
One C



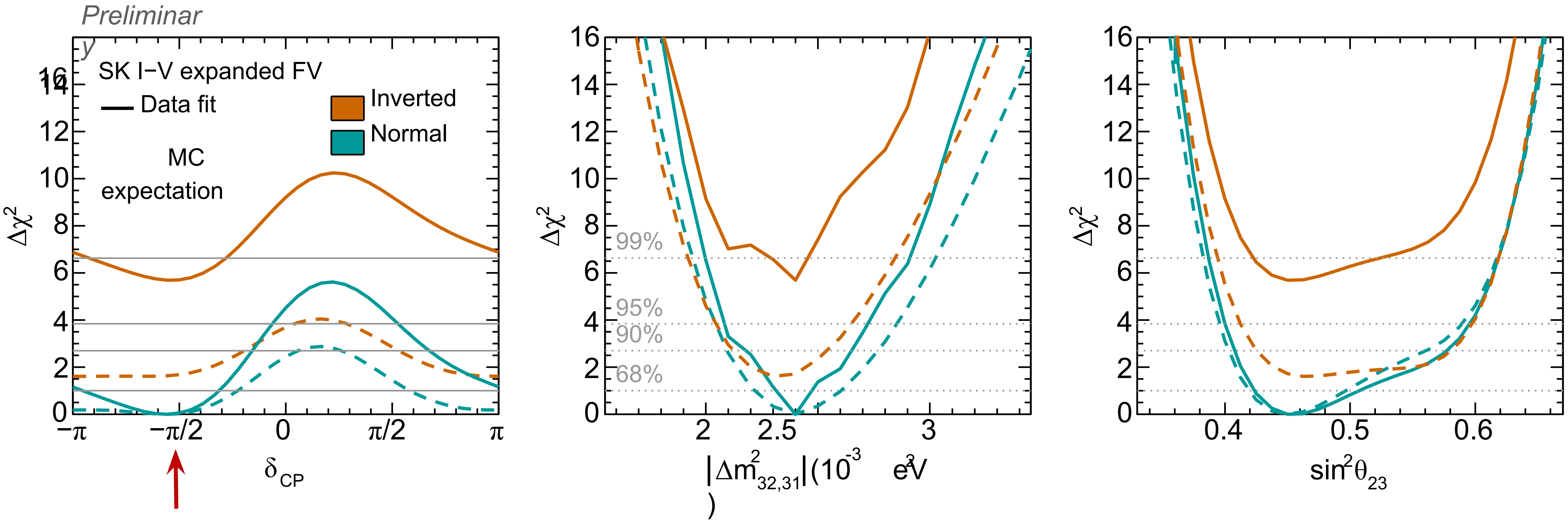


Super Kamiokande

SK I – SK V: Pure water phases
SK-Gd: Gadolinium added in 2020



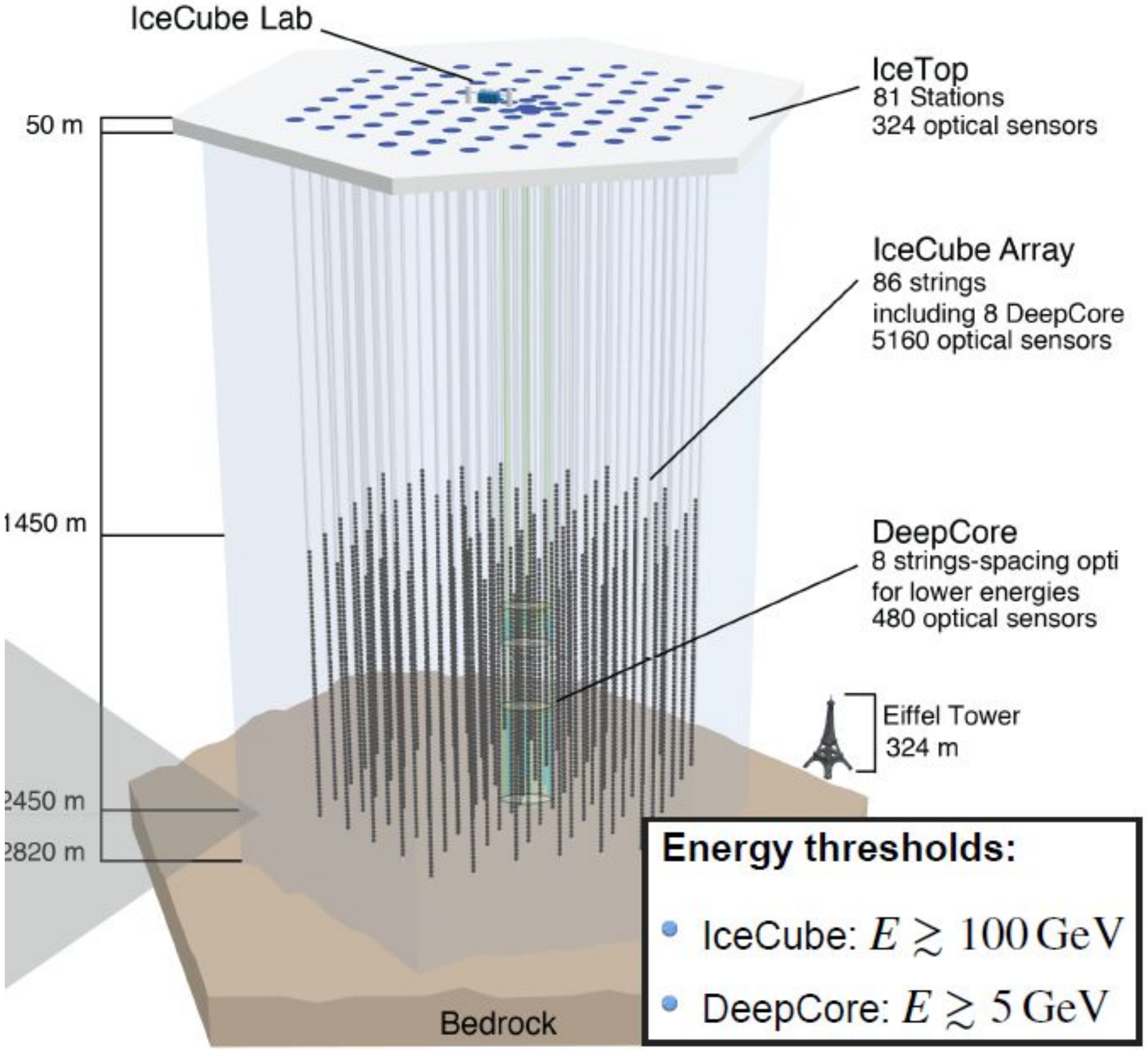
Super Kamiokande –latest result-

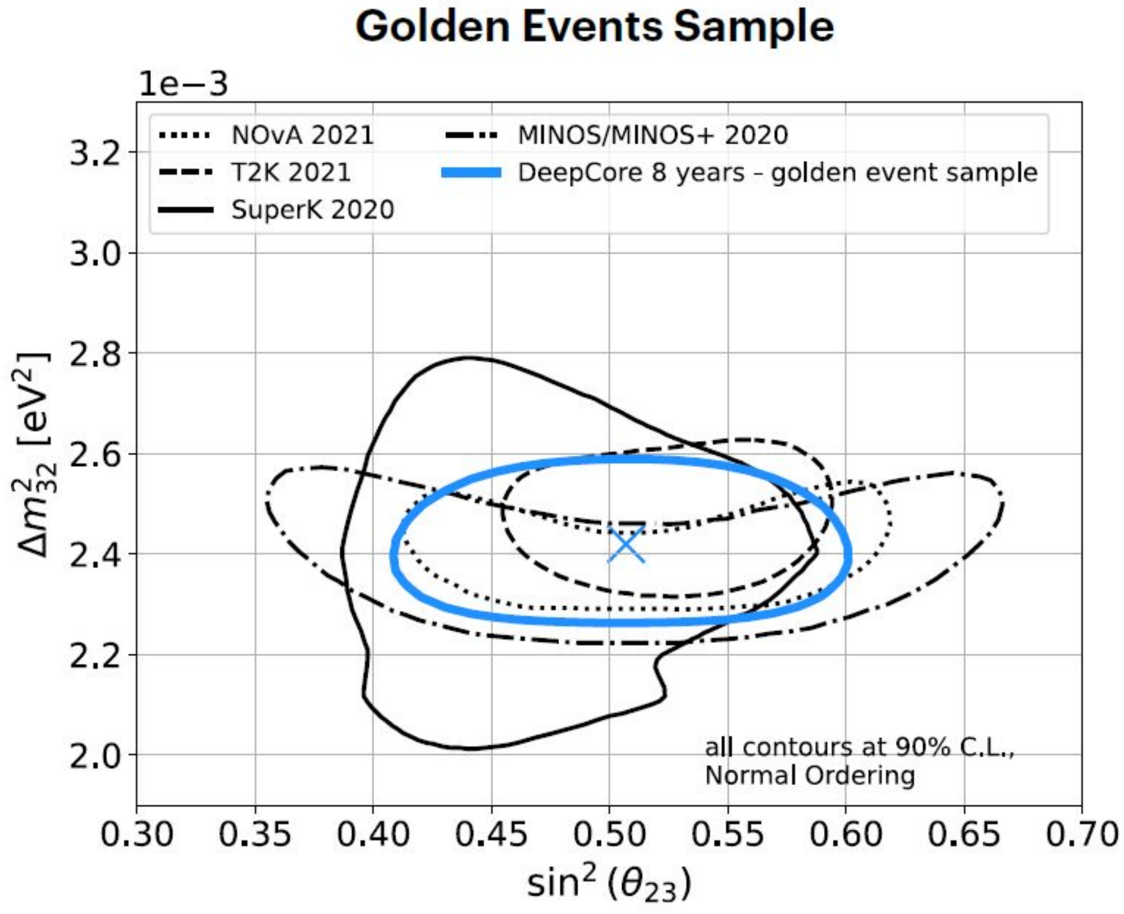


Close to T2K best fit

Reject inverted ordering at ~92% C.L.
($CL_s = \frac{p_{IO}}{1-p_{NO}} = 0.077$)

IceCube





arXiv:2304.12236

Accelerator neutrino $(\nu_\mu, \bar{\nu}_\mu)$

Accelerator neutrino $(\nu_\mu, \bar{\nu}_\mu)$

signs flip for antineutrino

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \boldsymbol{U} \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix}$$

At oscillation maximum

matter effect

$$P(\nu\mu \to \nu e) \simeq 4{C_{13}}^2{S_{13}}^2{S_{23}}^2\left(1 \pm \frac{2a}{\Delta m^2_{31}}(1-2S^2_{13})\right)$$
$$\mp 8{C_{13}}^2 C_{12}C_{23}S_{12}S_{13}S_{23} \sin\delta \times 0.047$$

CPV

$$a = 7.56 \times 10^{-5}[\mathrm{eV}^2] \cdot \rho[\mathrm{g/cm}^3] \cdot E[\mathrm{GeV}]$$

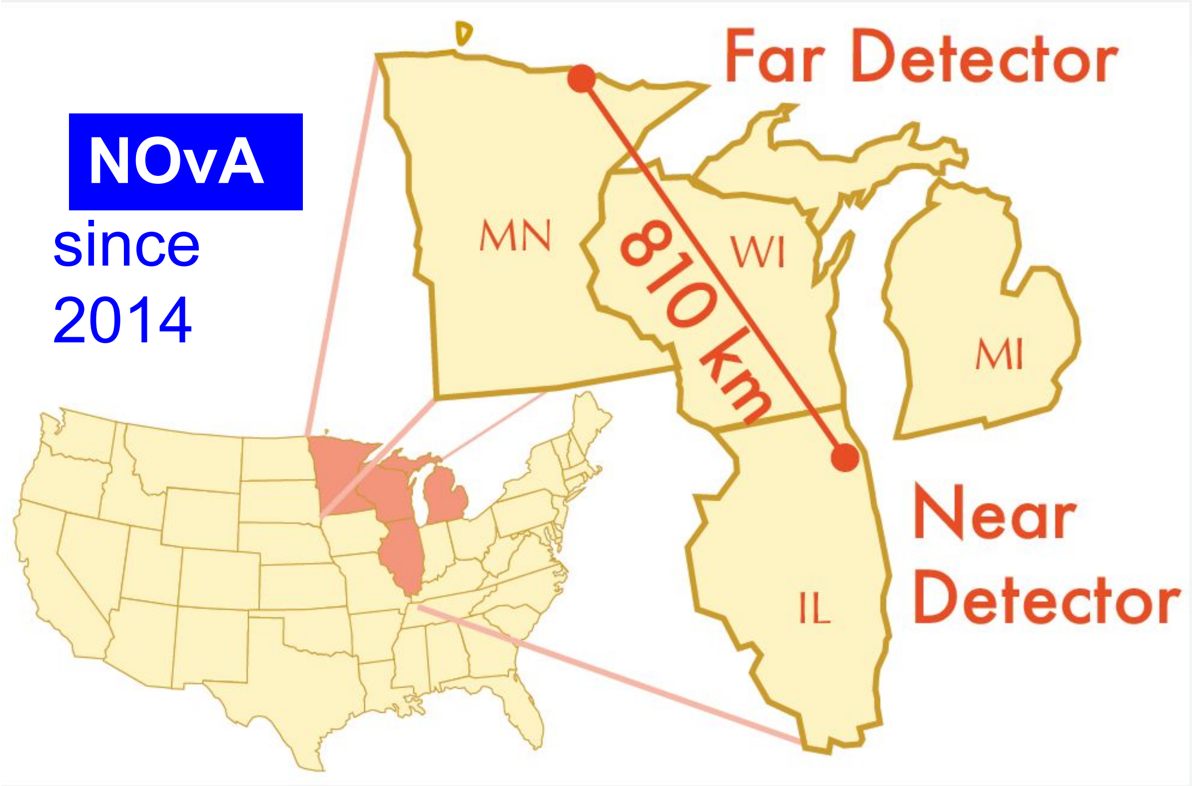
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$

Three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
One CP-phase : δ_{CP}

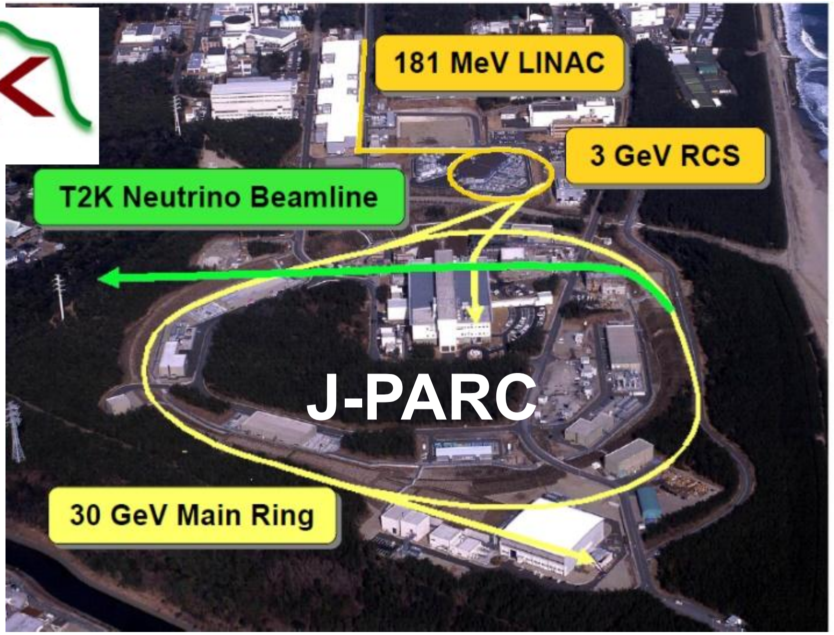
In the following slides, shown are results using the Solar and reactor constraints.

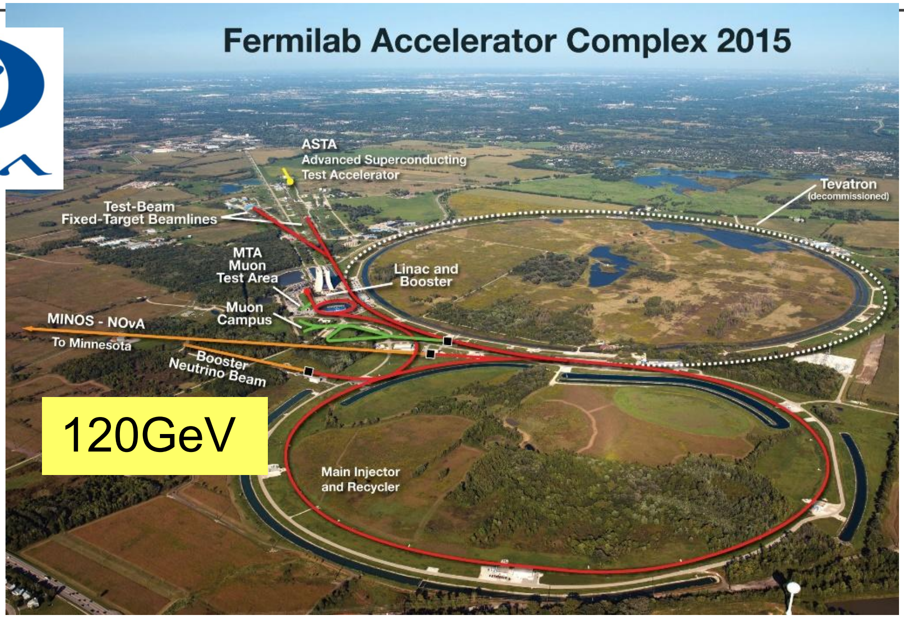
Running experiments: T2K & NOvA



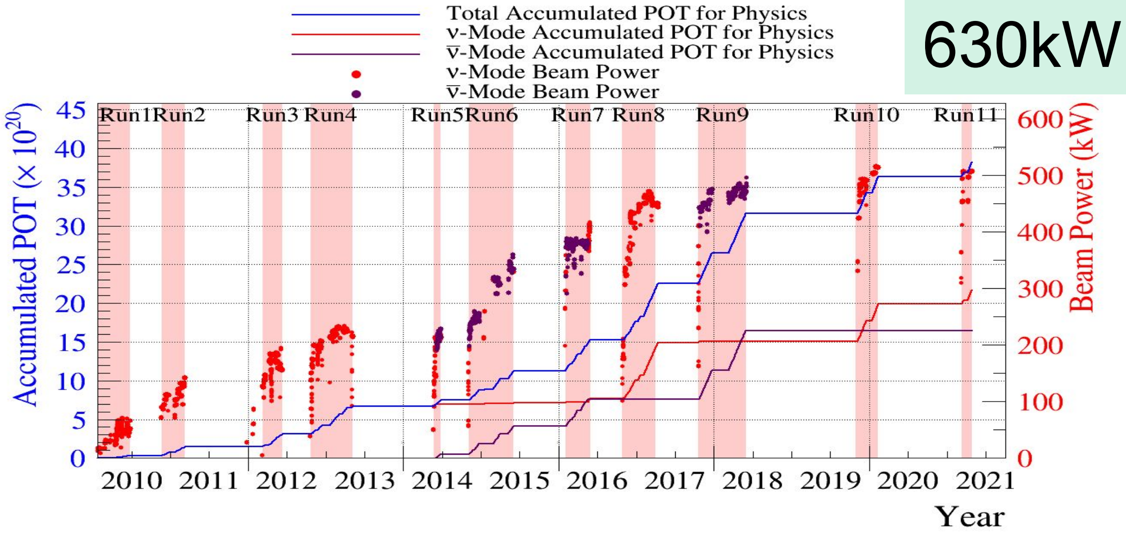
Matter effect ~10% for T2K and ~30% for NOvA
(Important to resolve degeneracies)

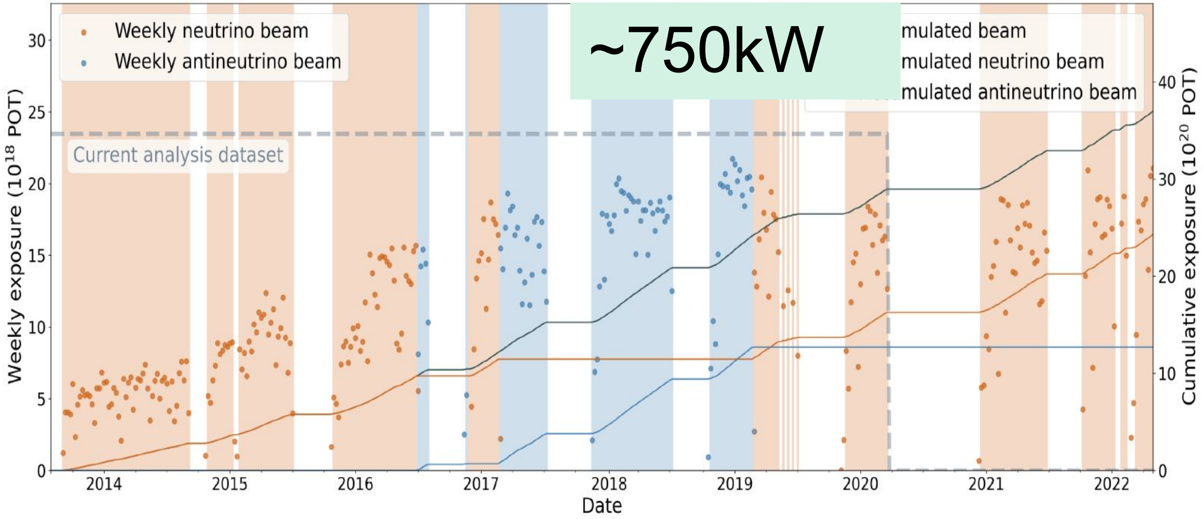
Running experiments: T2K & NOvA



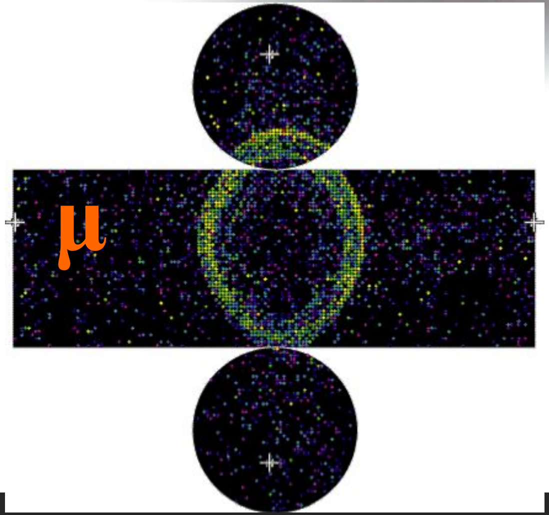


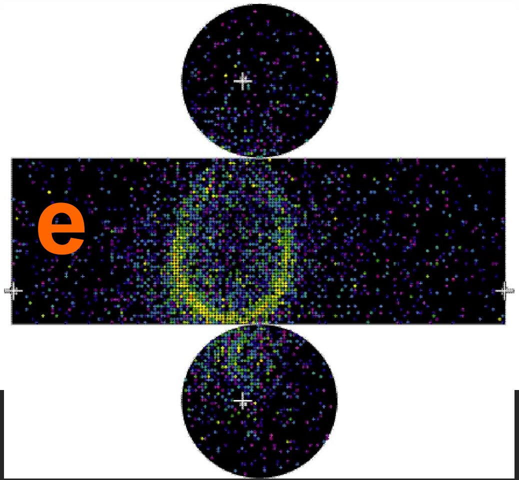
630kW

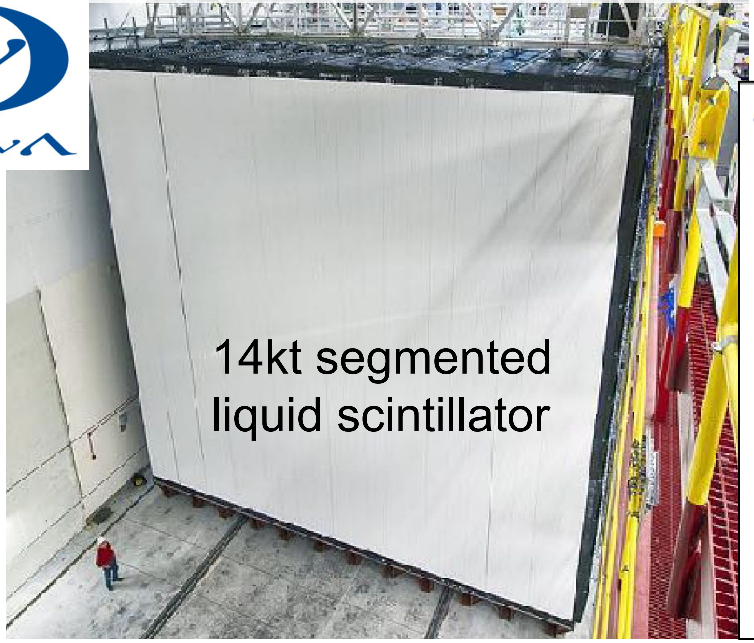


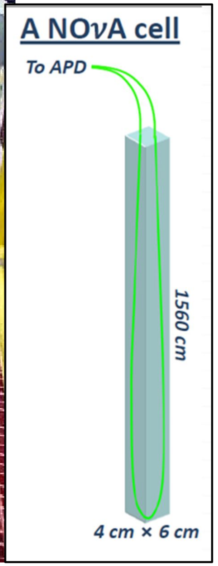


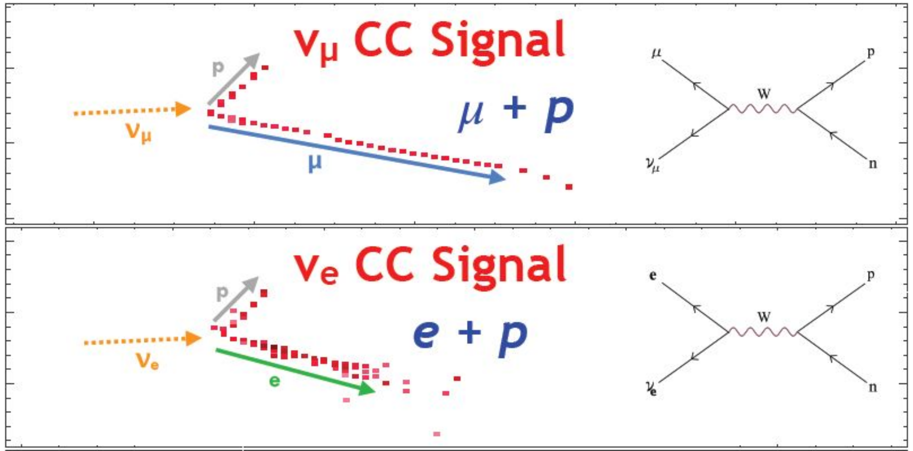
Running Accelerator long baseline experiments
T2K and NOvA



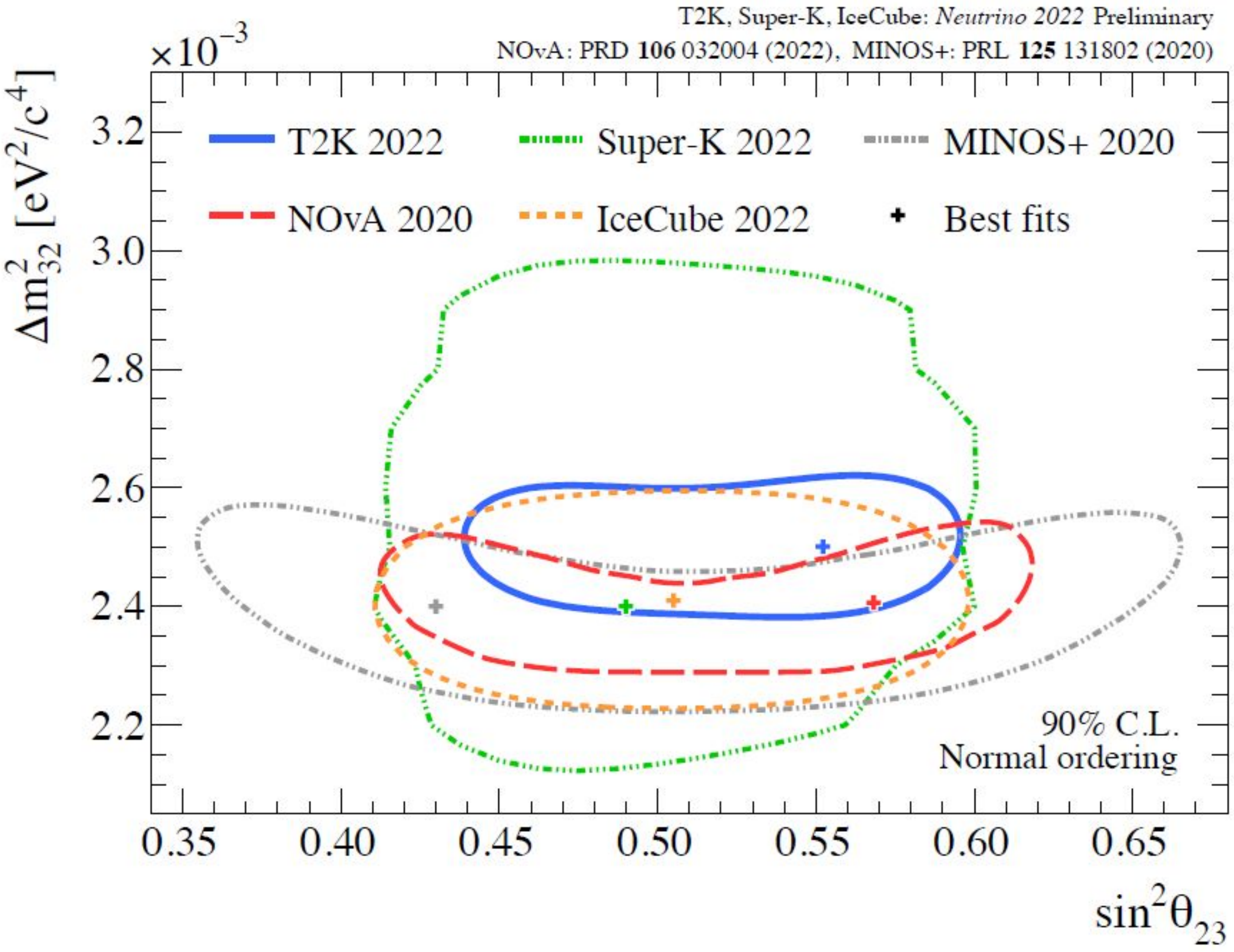






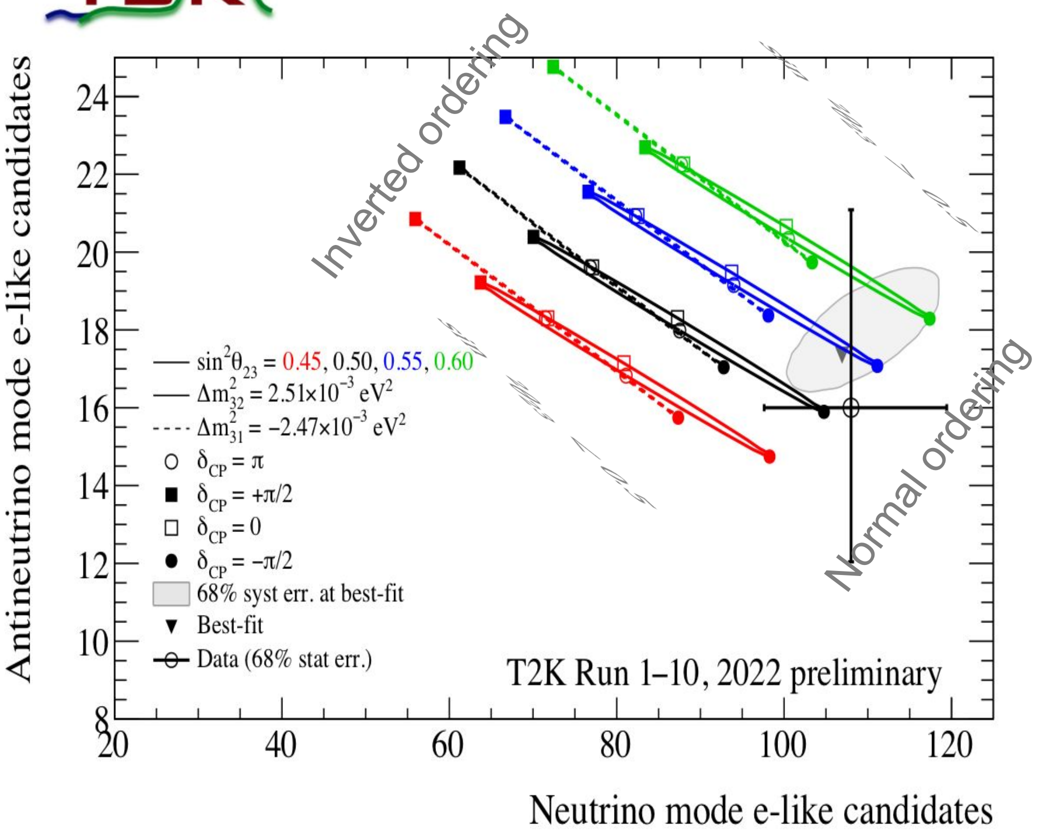


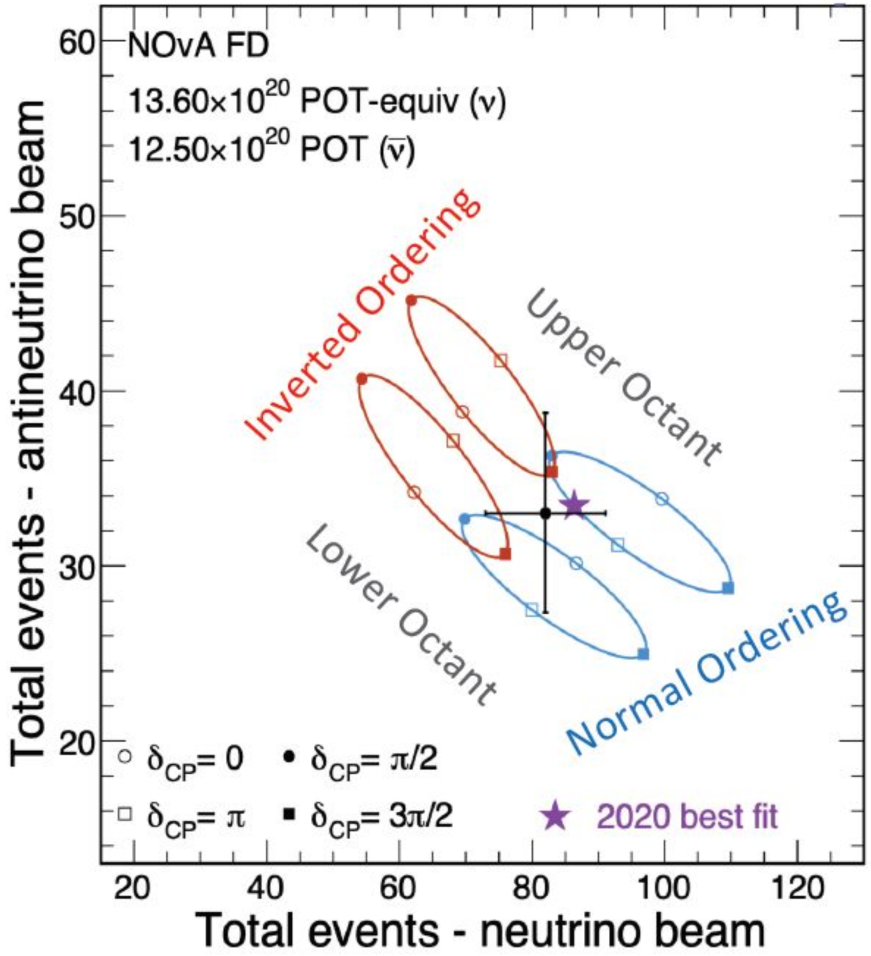
T2K and NOvA – latest results -

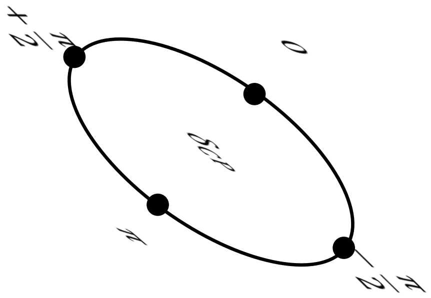


T2K and NOvA – latest results -

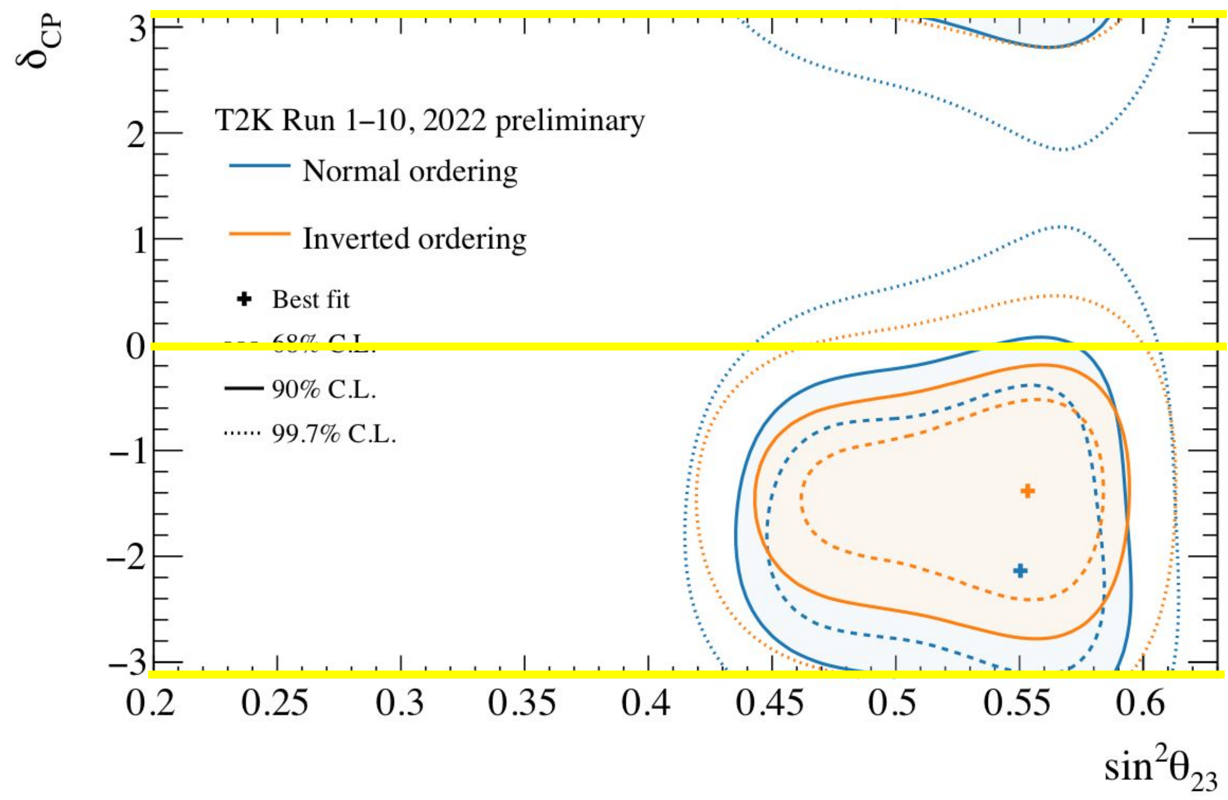
#anti-ν_e vs. # ν_e

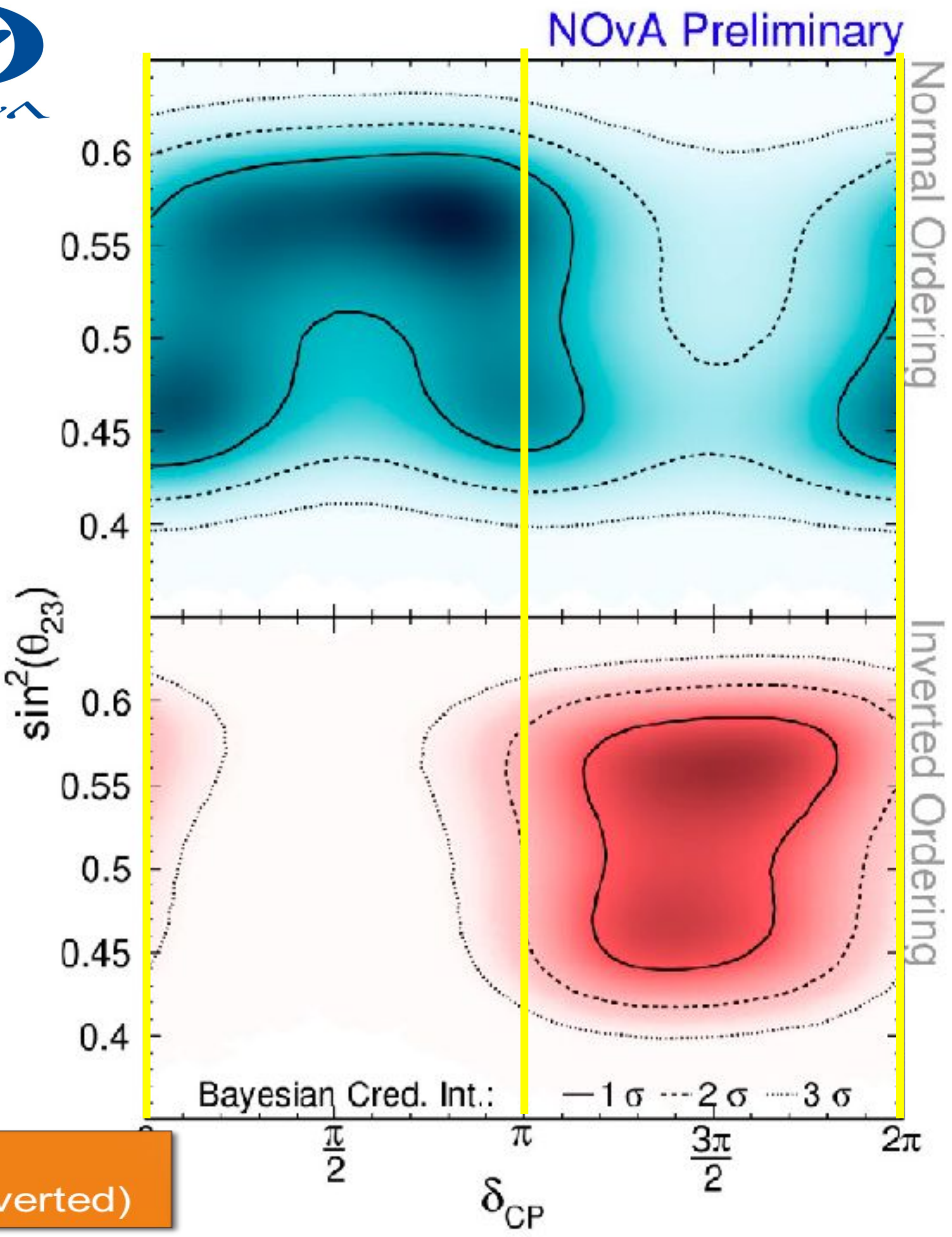






T2K and NOvA – latest results -



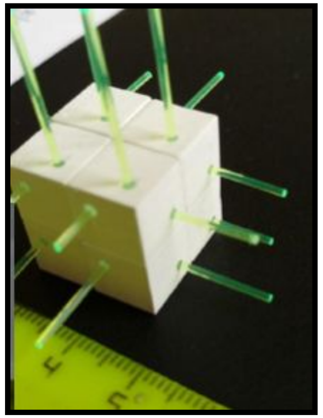


CP conserving line

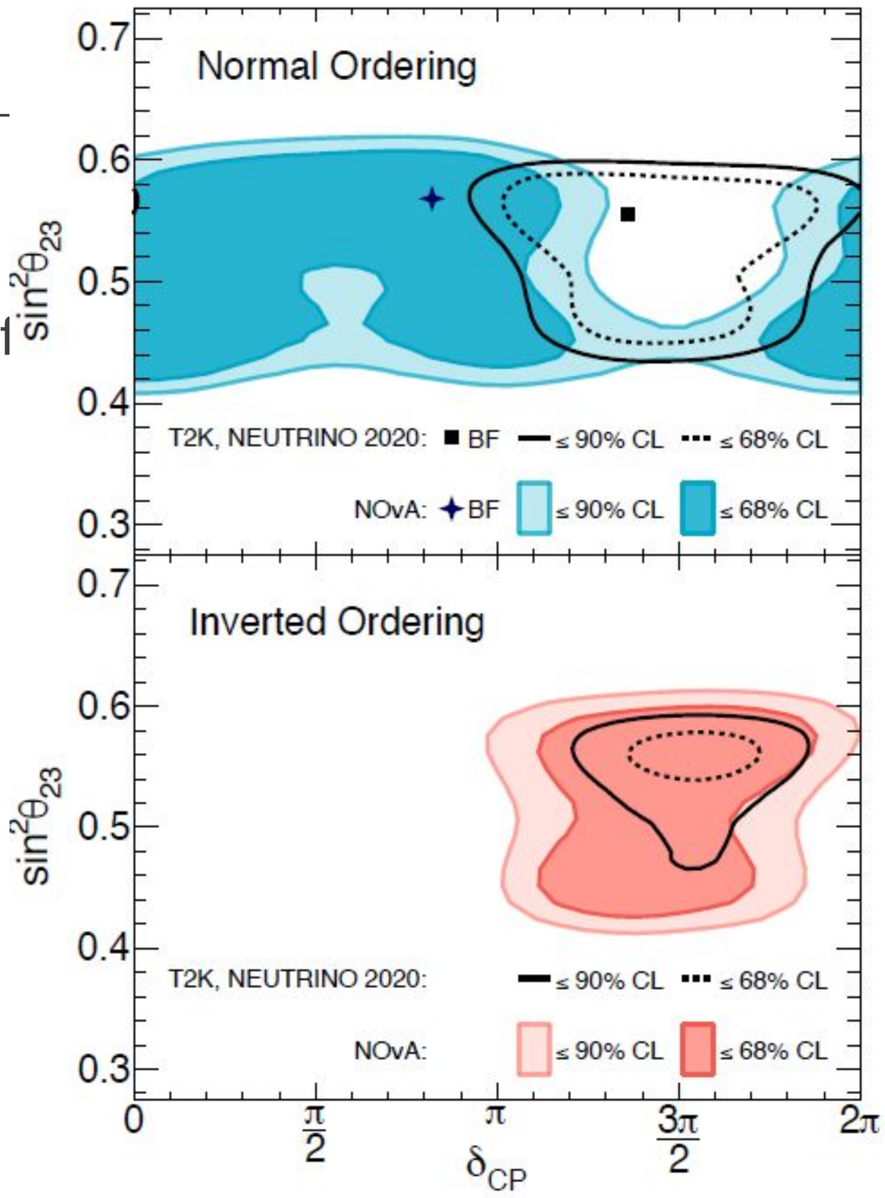
T2K C.L. for CP conservation ($\delta_{CP} = 0, \pi$) is outside 90% C.L.
Posterior probability for mass ordering is 78%(Normal) vs 22%(Inverted)

T2K and NOvA prospect

- Joint analysis by two collaborations will come soon
- Both experiments will continue running through ~2026.
- T2K is upgrading near detector for more precise study of neutrino-nucleus interaction.



1cm^3 x 200M cubes



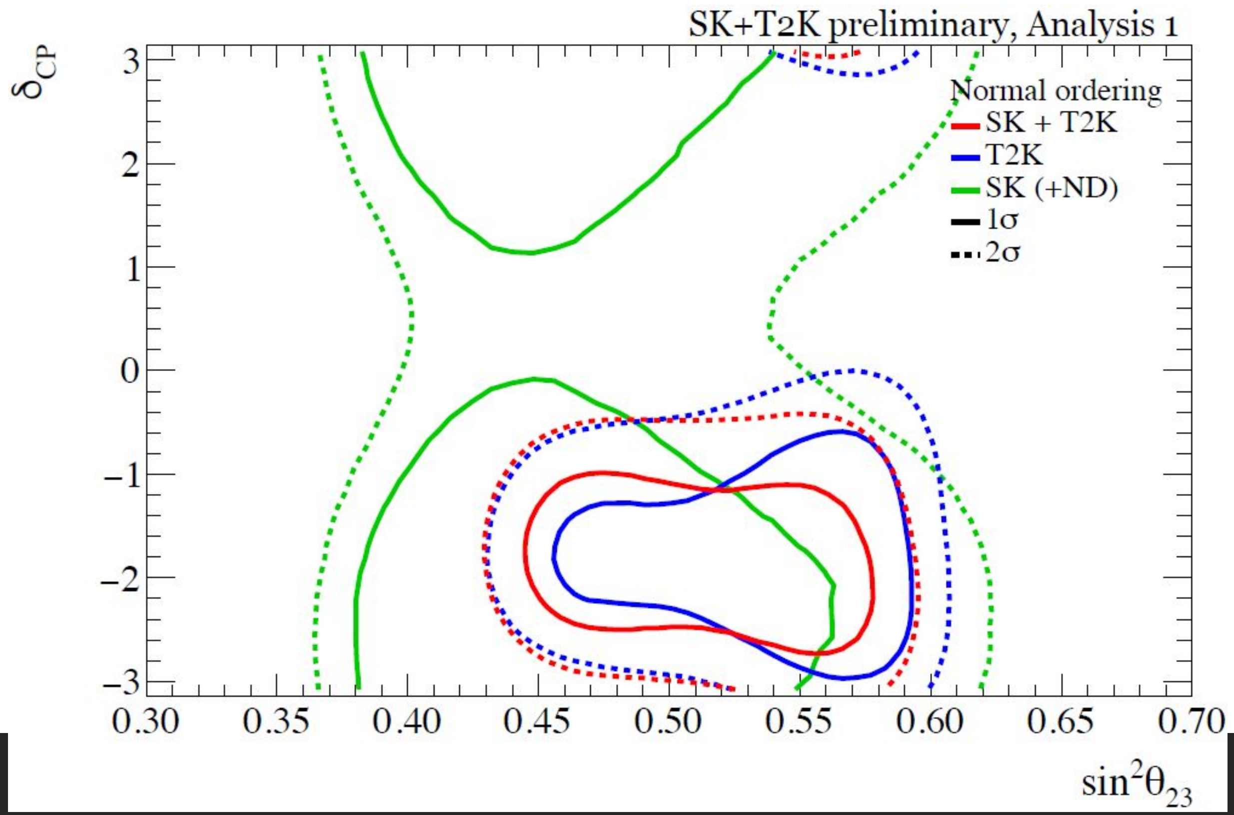
Accelerator & Atmospheric

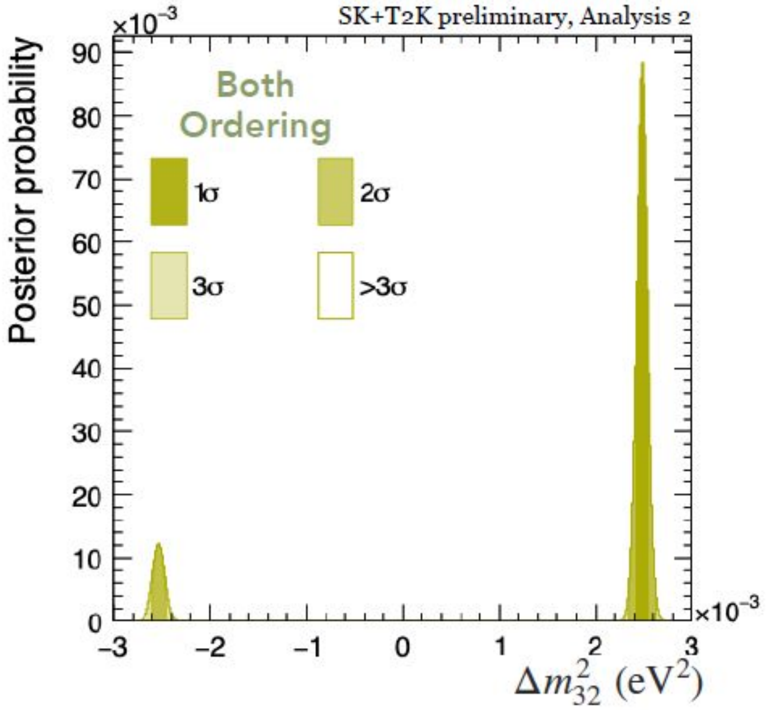
T2K&SK Joint analysis

Two collaboration conducted joint analysis and released results in November

Not yet with full data

- ✔ T2K : data till 2020
- ✔ SK : data from 2008 to 2019

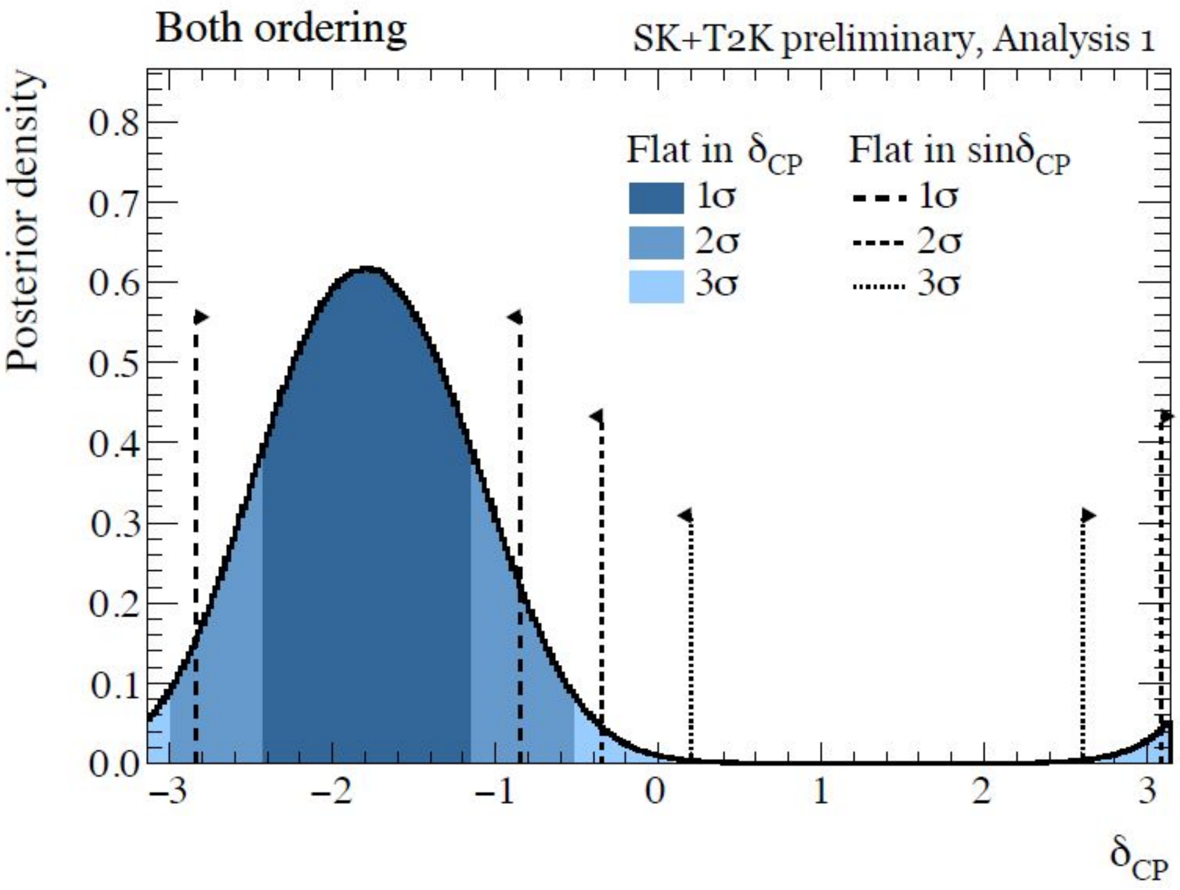


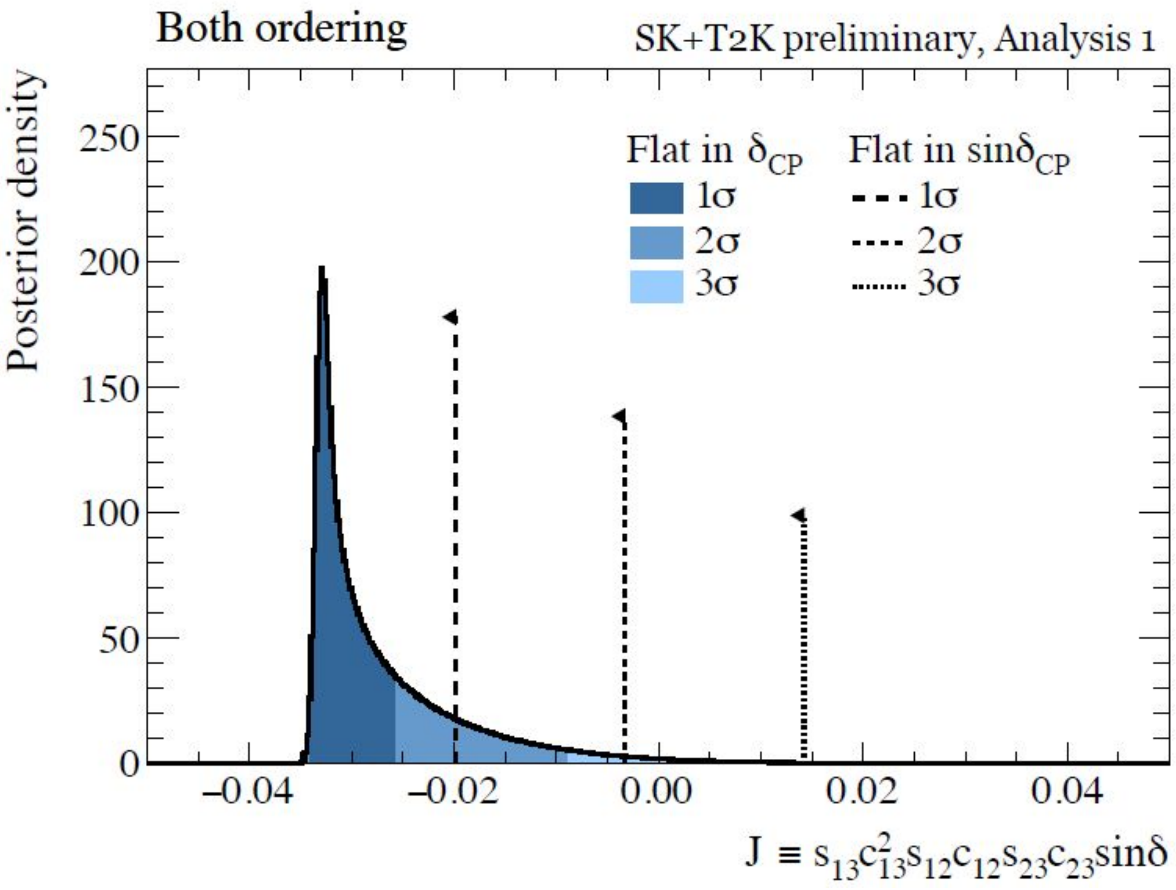


Posterior probability of mass ordering
Normal 90% vs. Inverted 10%

T2K&SK Joint analysis

δ_{CP} and J_{CP} posterior distributions with reactor constraint marginalized over both mass ordering





CP conserving values are outside 2σ credible interval.

Jarskog Invariant
= size of CPV from three-flavor mixing

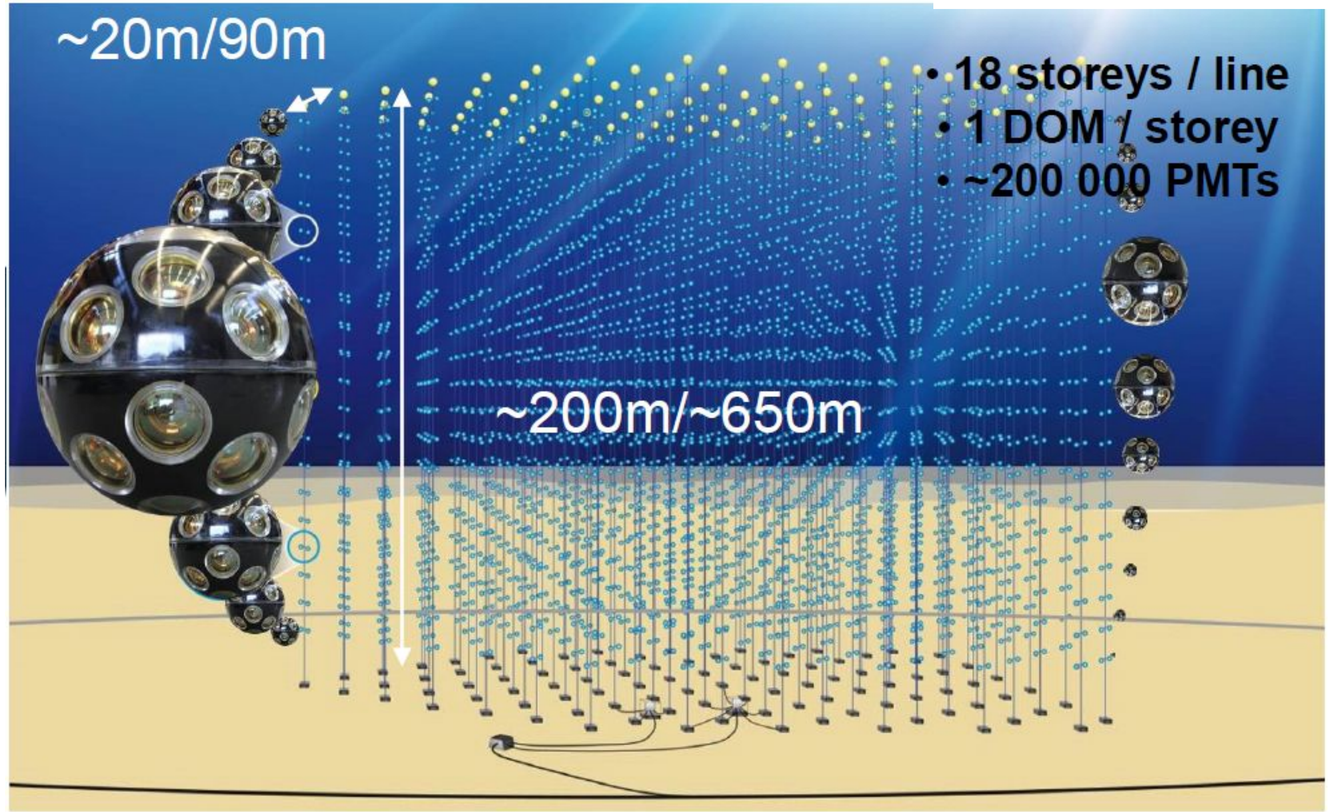
Projects under construction

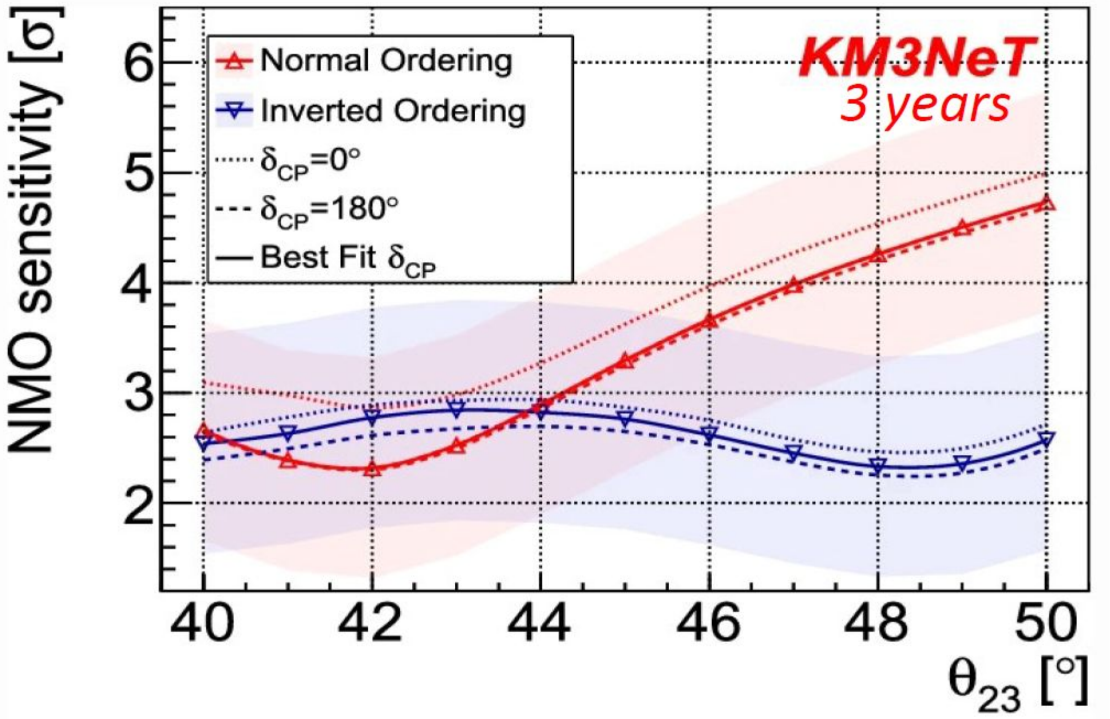
KM3NeT: neutrino telescope in Mediterranean

2020 2021 2022 2023 2024 2025 2026 2027 2028 2029

- 2022: ANTARES decommissioning
- NOW (2024): ANTARES legacy papers
- 2027–2028: ORCA ARCA completions

M. Spurio: ANTARES and KM3NeT @NNN23

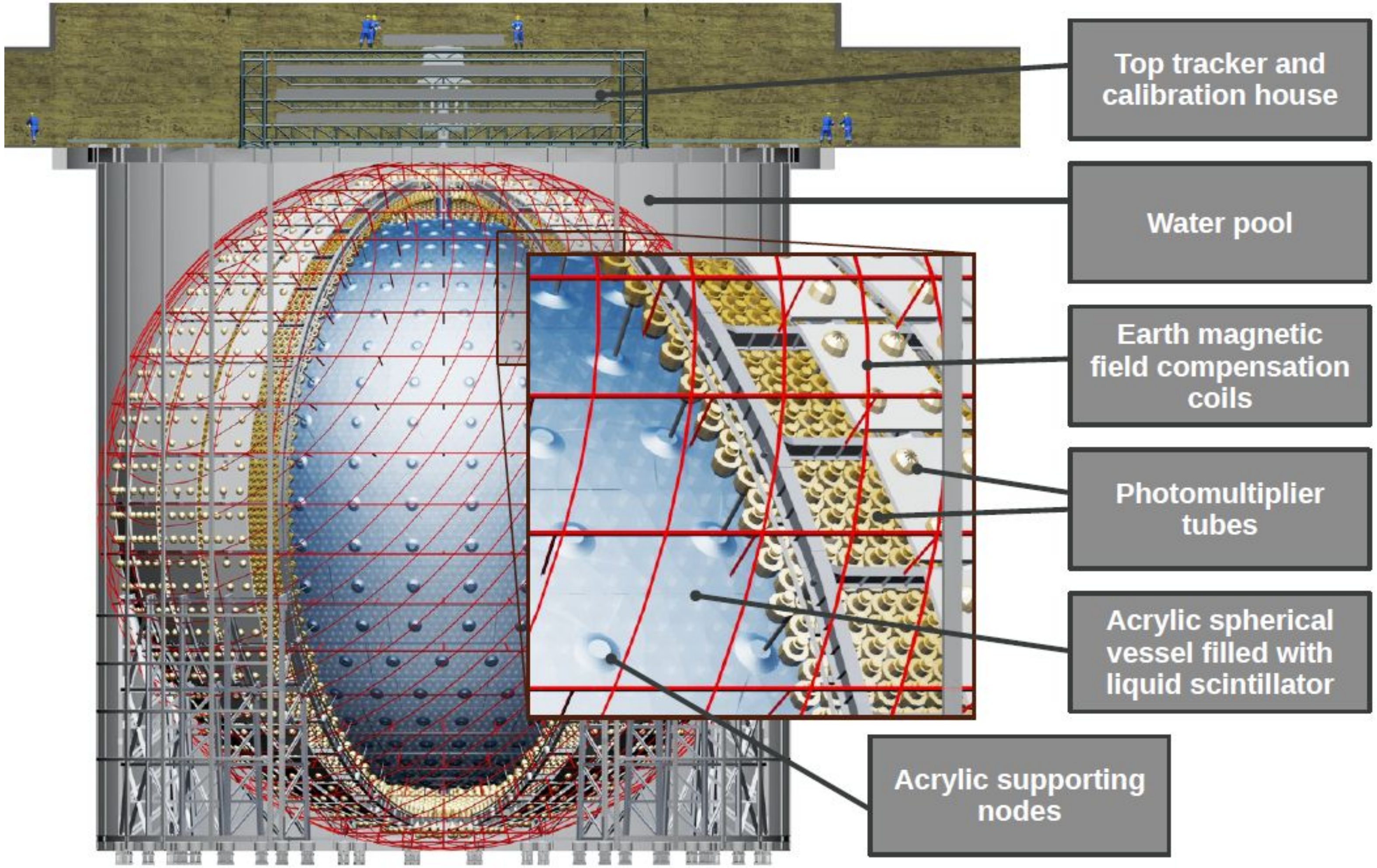


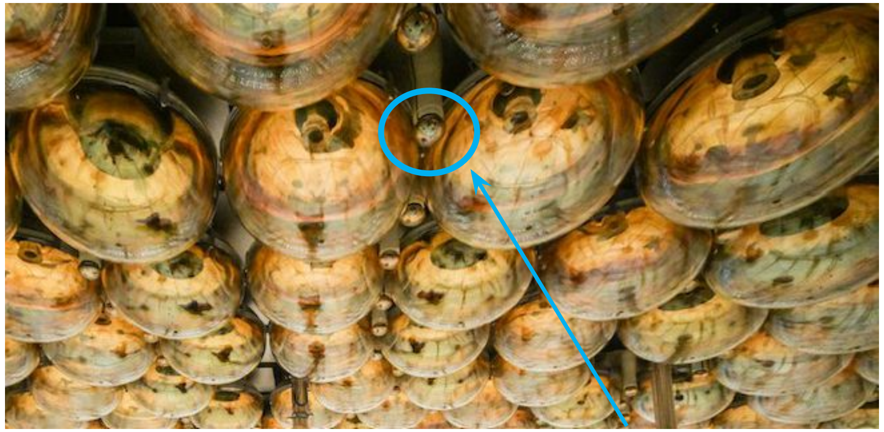


230 ARCA (Italy) + 115 ORCA (France) lines
~1 Gton ~7 Mton

20 kton

JUNO is a huge liquid scintillator detector





20012 20'' PMTs + 25600 3" PMT's

figures from slides by M. Grassi, NNN2023

MARCO GRASSI JUNO AT NNN 2023 Slide by M. Grassi, NNN2023 3

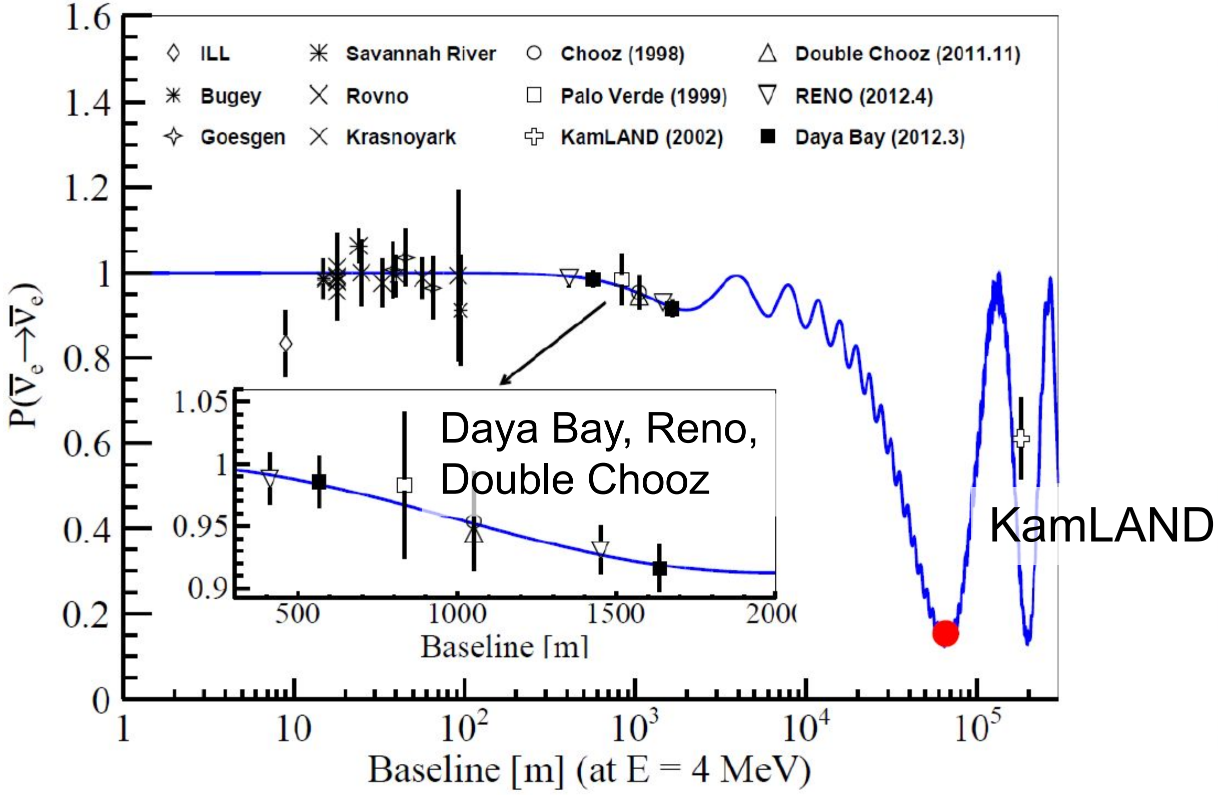
- **Supernova** ν: ~7300 of all-flavor neutrinos @ 10 kpc
- **DSNB**: **3σ** in 3 yrs (2205.08830)
- **Solar** ν:
  - ^{7}Be, pep, CNO (2303.03910)
  - ^{8}B flux (2210.08437)
- **Geo** ν: ~400 per year, 5% precision in 10 yrs
- **Nucleon Decays**: $p \to \bar{\nu} K^{+}$ 9.6×10^{33} yrs (90% C.L.) in 10 yrs (2212.08502), neutron invisible decay (ongoing)
- **Indirect DM search:** ~good sensitivity in 15-100 MeV region (2306.09567)
- **Future upgrade (2030s) : searching for 0νββ**

11

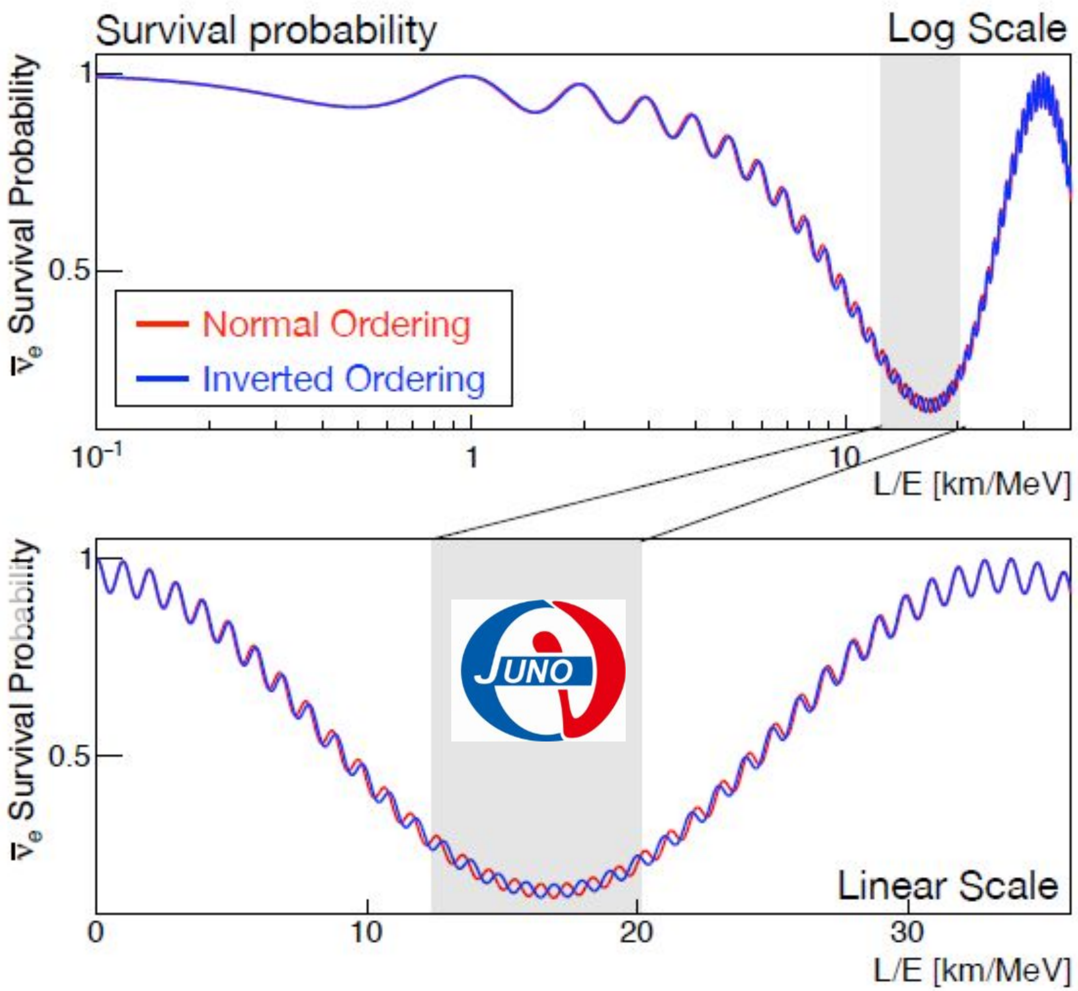
rom Slide by L. Wen, NNN2023

JUNO Detector will be ready next year (2024)

JUNO: reactor neutrino measurement



plot from Slide by L. Wen, NNN2023



plot from Slide by M. Grassi, NNN2023

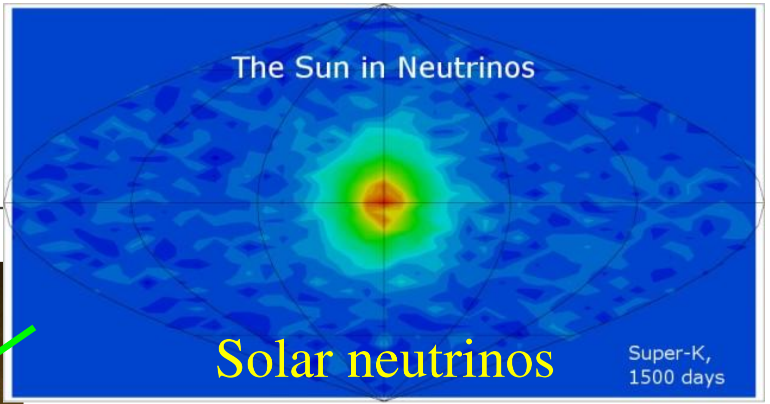
JUNO 6 years sensitivity on oscillation parameters

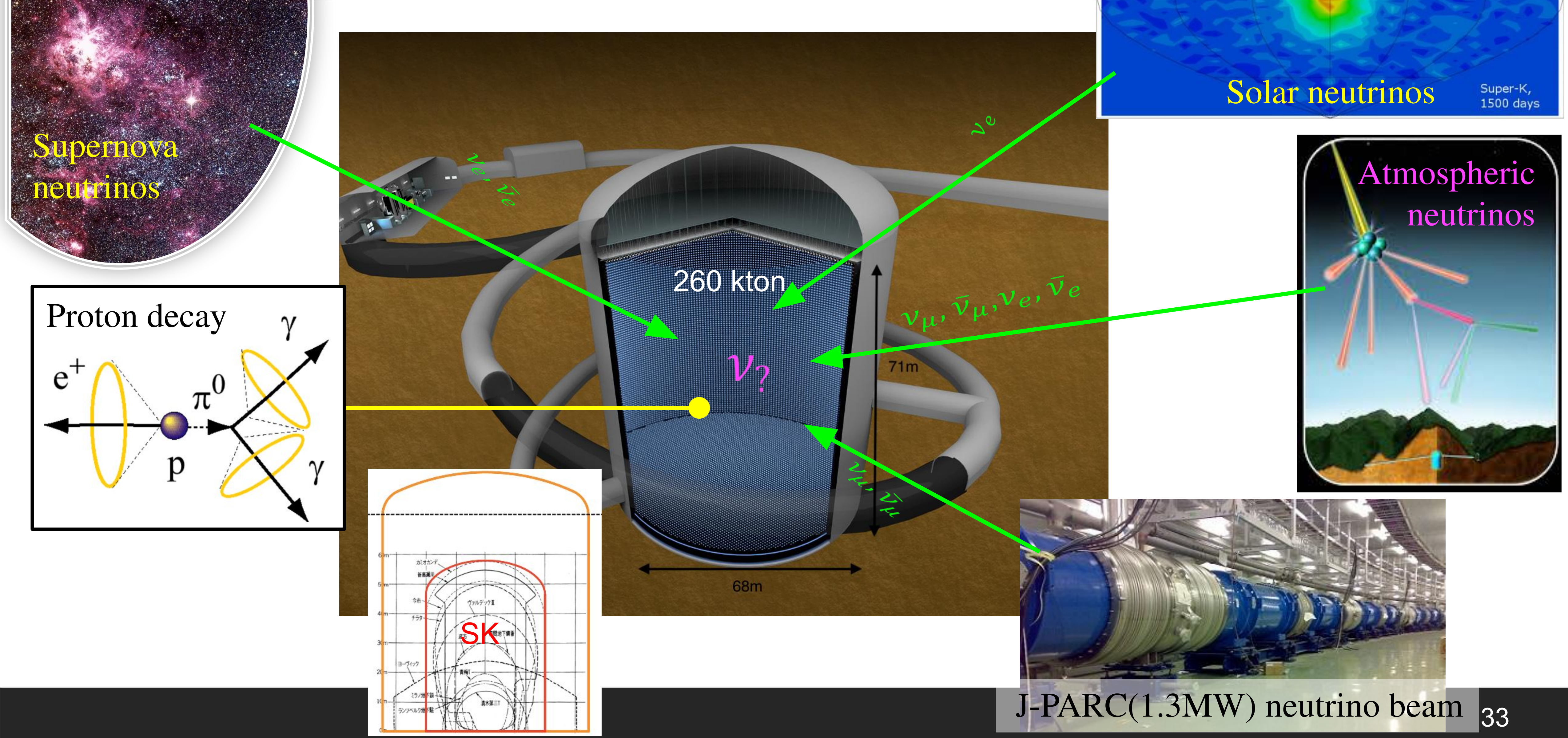
- $\sin^2\theta_{12}$, Δm^2 , $|\Delta m^2|$ < 0.5%
- 3σ determination of mass ordering

$$U_{PMNS} = \begin{pmatrix} 0.823 \pm 0.008 & 0.55 \pm 0.01 & 0.148 \pm 0.002 \\ -0.47 \pm 0.01 & 0.50 \pm 0.016 & 0.73 \pm 0.01 \\ 0.33 \pm 0.01 & -0.67 \pm 0.01 & 0.67 \pm 0.02 \end{pmatrix}$$

$$U_{PMNS} = \begin{pmatrix} 0.823 \pm 0.001 & 0.55 \pm 0.001 & 0.148 \pm 0.002 \\ -0.47 \pm 0.007 & 0.50 \pm 0.014 & 0.73 \pm 0.01 \\ 0.33 \pm 0.014 & -0.670 \pm 0.01 & 0.67 \pm 0.02 \end{pmatrix}$$

Hyper Kamiokande

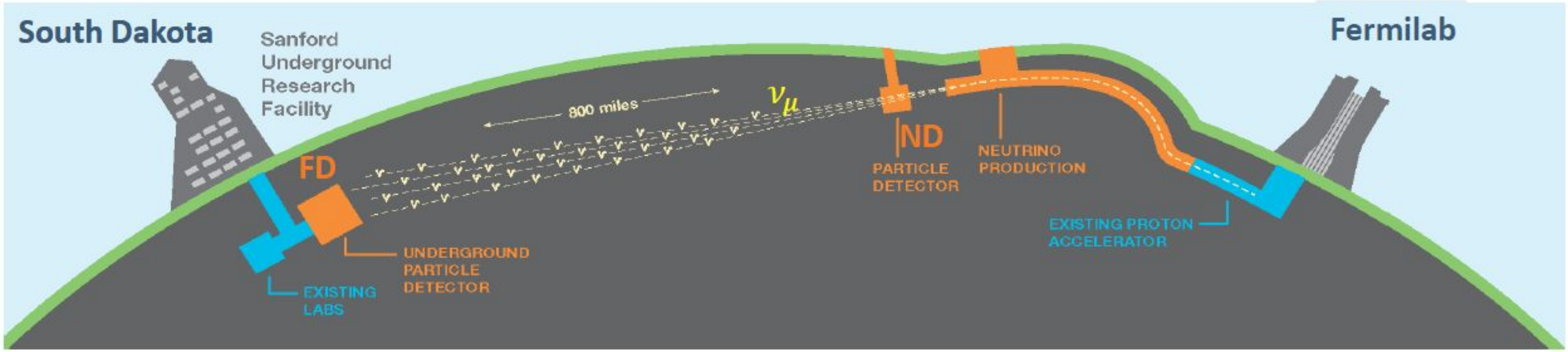




Hyper-K main cavern excavation

- **<u>October 3, 2023:</u>** Excavation of the dome section completed.
  - 69m diameter, 21m height
  - One of the largest human-made underground space.
- Now, the excavation of the barrel section is ongoing.
- Aiming to start data taking in JFY2027.

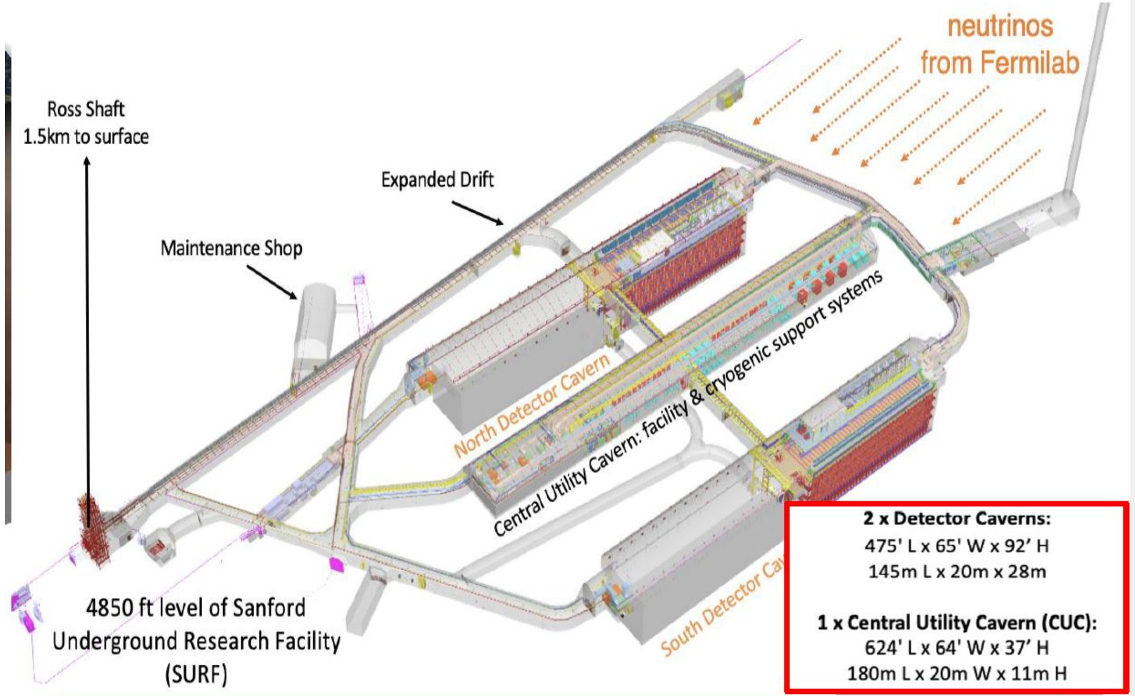
The Deep Underground Neutrino Experiment (DUNE)



A new generation Long-Baseline – 1300 km – neutrino oscillation experiment based on

- a wide band high intensity (1.2 MW upgradable to 2.4 MW) $\nu/\bar{\nu}$ neutrino beam produced at Fermilab
- a large total mass (~70 kton) Far Detector at the Sanford Underground Neutrino Facility (SURF) 1.5 km underground exploiting the Liquid Argon Time Projection Chamber (LArTPC) technology
- a Near Detector complex (ND) at Fermilab providing control of systematic uncertainties, enabling a rich physics program

DUNE cavern xcavation

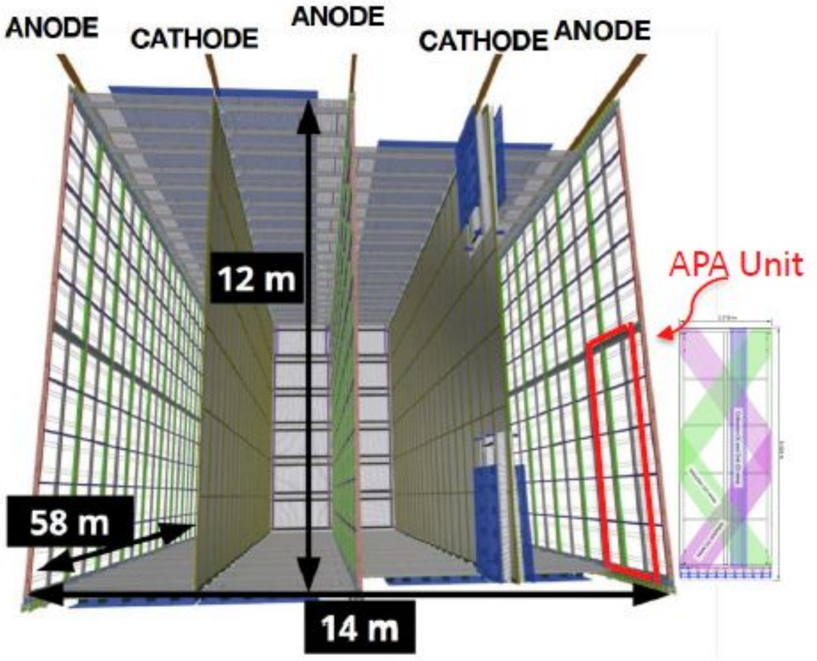


80% of excavation done as of September 2023.

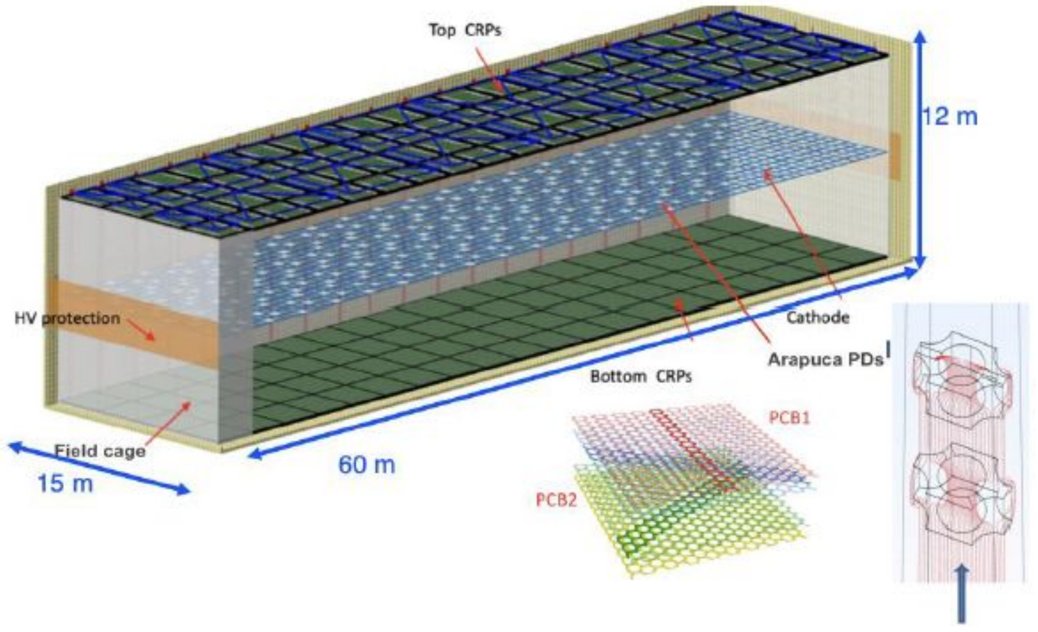
Figures from slides by M. Tenti, NNN23

DUNE far detector for phase I

FD1-HD «Horizontal drift»



FD2-VD «Vertical drift»



2029 Start Data Taking @Far Detector	2031 Start of Phase I	2037-2038 Start of Phase II
atmospheric ν, astrophysics	oscillation physics atmospheric ν, astrophysics	full physics scope

Sensitivity of neutrino oscillation measurement by Hyper Kamiokande and DUNE

Hyper-K 10 years

- δ_{CP} resolution $7°(20°)$at $\sin\delta_{\mathrm{CP}} = 0(\pm 1)$
- $\sin^2\theta_{23}$ resolution $\pm 0.017(0.009)$ at $\sin^2\theta_{23} = 0.5(0.55)$
- mass ordering $> 3.8\sigma$

DUNE

- δ_{CP} resolution $6°(16°)$ at $\sin\delta_{\mathrm{CP}} = 0(\pm 1)$ with 1104 $\mathrm{kt \cdot MW \cdot yr}$
- $\sin^2\theta_{23}$ resolution ± 0.004 at $\sin^2\theta_{23} = 0.58$ with 800 $\mathrm{kt \cdot MW \cdot yr}$
- mass ordering $3\boldsymbol{\sigma}(5\boldsymbol{\sigma})$level with a 66 (100) kt-MW-yr

* phase I(20kt 6 years)+phase II(40kt 7 years) $\sim 820\ \mathrm{kt \cdot MW \cdot yr}$

with JUNO, Hyper-K and DUNE

$$U_{PMNS} = \begin{pmatrix} 0.823 \pm 0.008 & 0.55 \pm 0.01 & 0.148 \pm 0.002 \\ -0.47 \pm 0.01 & 0.50 \pm 0.016 & 0.73 \pm 0.01 \\ 0.33 \pm 0.01 & -0.67 \pm 0.01 & 0.67 \pm 0.02 \end{pmatrix}$$

$$U_{PMNS} = \begin{pmatrix} 0.823 \pm 0.001 & 0.55 \pm 0.001 & 0.148 \pm 0.002 \\ -0.47 \pm 0.003 & 0.50 \pm 0.006 & 0.73 \pm 0.006 \\ 0.33 \pm 0.005 & -0.670 \pm 0.005 & 0.67 \pm 0.007 \end{pmatrix}$$

take $\sin^2\theta_{23} = 0.55 \pm 0.009$ as an example

Summary

- Solar neutrino observation is now checking matter effect etc.
- High precision achieved by reactor neutrino measurement (KamLAND, Daya Bay, RENO, Double Chooz) for $\Delta m^2_{21}, \Delta m^2_{32}$ and $\sin^2 2\theta_{13}$
- Precision of $\sin^2\theta_{23}$ is improving by atmospheric(SK, IceCube) and accelerator(T2K, NOvA) neutrino measurements, but the octant is not yet uncertain.
- T2K and SK(atmospheric) favors normal mass ordering and $\delta_{CP} = -\frac{\pi}{2}$, but NOvA dose not. Need more data and joint analyses.
- With JUNO, Hyper-K, DUNE and KM3Net,
  - ✓ mass ordering will be determined
  - ✓ High precision on $\sin^2\theta_{12}$, $\sin^2\theta_{23}$ $\Delta m^2_{21}, \Delta m^2_{32}$
  - ✓ CP violation and measurement of δ_{CP}
- Whole picture for three-flavor mixing (and possibly violation from it?)

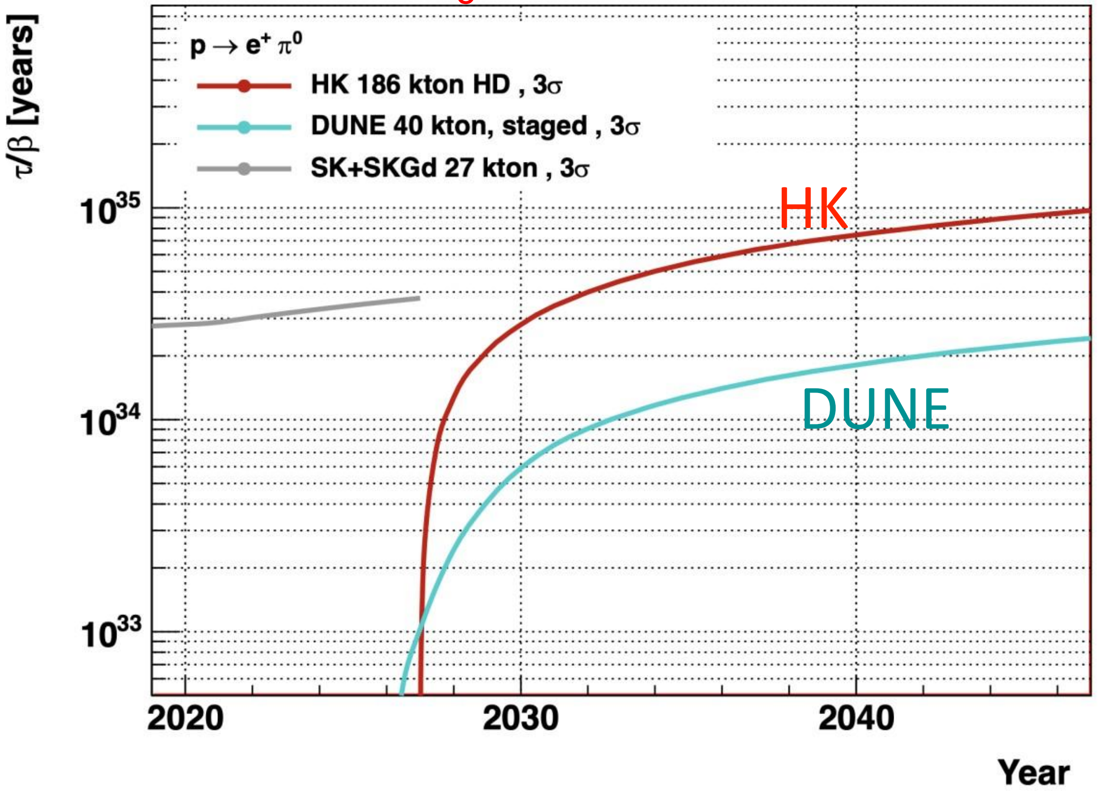
back up

Nucleon decay search

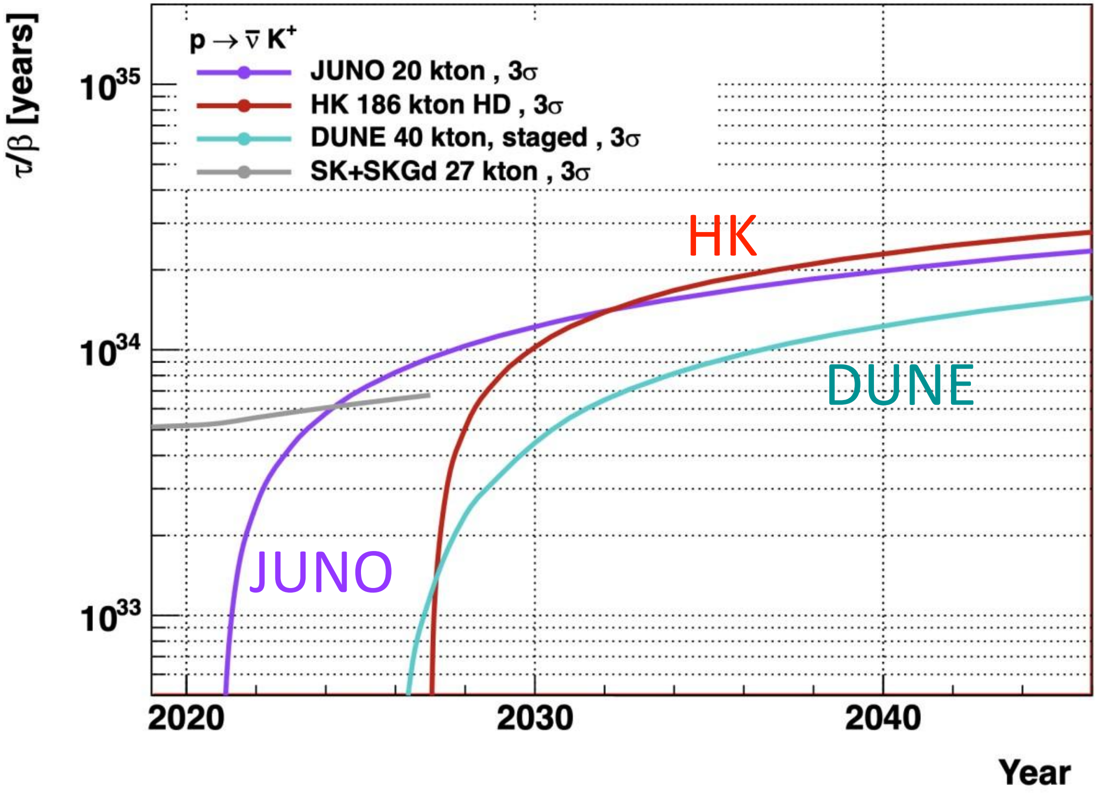
- Nucleon decay is evidence of Beyond Standard Model (BSM) and Grand Unified Theories (GUT)
- Examples of proton decay sensitivity in two modes:

[HK] arXiv:1805 04163
[DUNE] arXiv:2002.03005
[JUNO] arXiv:1508.07166

$p \rightarrow e^{+}\pi^{0}$



$p \rightarrow \bar{\nu}K^{+}$



$\tau \sim 10^{35}$ years (3σ)

$\tau \sim 3 \times 10^{34}$ years (3σ)