



Study of neutrino oscillations with accelerator and atmospheric neutrinos

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LXXV International Conference «NUCLEUS – 2025. Nuclear
physics, elementary particle physics and nuclear technologies»
July 1 – 6, 2025, St. Petersburg State University, Russia

Supported by the RSF grant # 24-12-00271



Neutrino oscillations and mixing

Standard Model: neutrinos are *massless* particles

3 families

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

U parameterization:

three mixing angles θ_{12} θ_{23} θ_{13}
CP violating phase δ_{CP}

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

atmospheric

link between
atmospheric and solar

solar

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

SuperK, K2K,
MINOS, T2K, NOvA

T2K

Daya Bay, RENO
Double Chooz

Solar experiments, SuperK
KamLAND

$$\theta_{23} \sim 45^\circ$$

$$|\Delta m_{32}^2| \cong |\Delta m_{31}^2| =$$

$$|\Delta m_{atm}^2| \approx 2.4 \times 10^{-3} \text{ eV}^2$$

$$\theta_{13} \approx 8.5^\circ$$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

$$\Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{31}^2 = 0$$

$$\theta_{12} \approx 34^\circ$$

$$\Delta m_{21}^2 = \Delta m_{sol}^2 \approx 7.5 \times 10^{-5} \text{ eV}^2$$

two independent Δm^2



Neutrino physics: fundamental questions

Parameter/Feature

Instrument/Method

CP violation

accelerator neutrinos

Neutrino mass ordering

atmospheric, reactor, **accelerator**
neutrinos, cosmology

Absolute scale of neutrino mass

β decay, $0\nu 2\beta$ decay, cosmology

Neutrino nature: Dirac or Majorana

$0\nu 2\beta$ decay

Sterile neutrinos

β decay, $0\nu 2\beta$ decay, **atmospheric**, reactor,
accelerator neutrinos, cosmology

- Search for CP violation
- Measurement of Mass Ordering



Neutrino: CPV and Mass Ordering

- CP violation in lepton sector

Strength of CP violation in neutrino oscillations

$$J_{CP} = \text{Im}(U_{e1}U_{\mu 2}U_{e2}^*U_{\mu 1}^*) = \text{Im}(U_{e2}U_{\mu 3}U_{e3}^*U_{\mu 2}^*) \\ = \cos\theta_{12}\sin\theta_{12}\cos^2\theta_{13}\sin\theta_{13}\cos\theta_{23}\sin\theta_{23}\sin\delta_{CP}$$

all mixing angles $\neq 0 \rightarrow J_{CP} \neq 0$ if $\delta_{CP} \neq 0$

Mixing
matrix

neutrinos

quarks

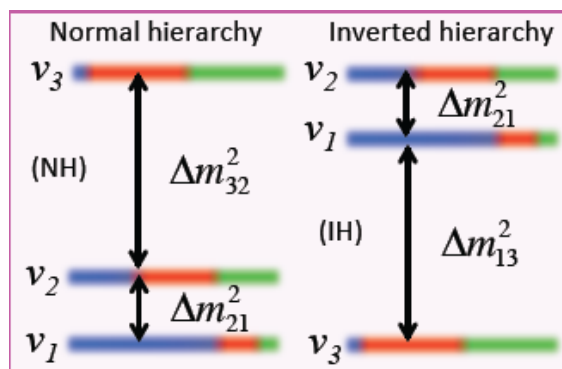
$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

Quark sector: $J_{CP} \approx 3 \times 10^{-5}$

Lepton sector: $J_{CP} \sim 0.04 \times \sin\delta_{CP}$

- Neutrino mass ordering (NMO)



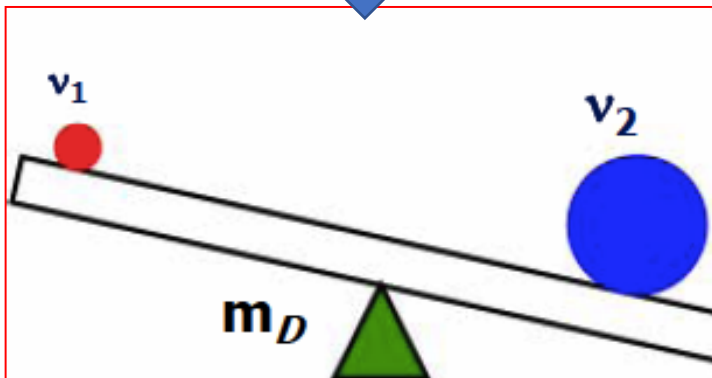
IO: $\Sigma m_i \approx 100 \text{ meV}$
NO: $\Sigma m_i \approx 60 \text{ meV}$



CP violation in lepton sector → BAU?

SM cannot explain non-zero neutrino mass

See-saw model



$$m_\nu \approx \frac{m_D^2}{M_R}$$

$$m_D \sim 100 \text{ GeV}$$
$$\nu_2 \rightarrow M_R \leq 10^{14} \text{ GeV}$$

N_R decays



lepton asymmetry ε_1



partially transformed into BAU

lepton asymmetry from N_R decays ε_1 must be $> 10^{-6}$

Baryon Asymmetry ↔ Neutrino Physics ??

Baryon Asymmetry of Universe (BAU)

CP violation in quark sector (K, B, D decays) too small to generate BAU

$$Y_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10}$$

$$\frac{n_{\bar{B}}}{n_B} < 10^{-6}$$

M. Gavela et al. Mod. Phys. Lett. 9 (1994) 795

$$Y_B \sim J \frac{(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)}{M_W^6} \frac{(m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_b^2 - m_d^2)}{(2\gamma)^9}$$

~10 orders below BAU value

See-saw model produces BAU by leptogenesis mechanism

M. Fukugita, T. Yanagida, 1986



CPV in PMNS $\longleftrightarrow$ CPV in Leptogenesis ?

Type I See-saw model

SM + 3 heavy (RH) Majorana neutrinos N_1, N_2, N_3

with masses $M_1 \ll M_2 < M_3$

Leptogenesis takes place at temperatures $10^9 \text{ GeV} < T < M_1$

S.Petcov et al. Nucl.Phys. B774,2007, 1

S.Petcov et al. Phys.Rev. D75, 2007, 083511

$$Y_B \simeq 3 \times 10^{-13} |\sin \delta_{CP}| \left(\frac{\sin \theta_{13}}{0.2} \right) \left(\frac{M_1}{10^9 \text{ GeV}} \right)$$

$$M_1 = (3-5) \times 10^{11} \text{ GeV}$$

BAU can be reproduced, if

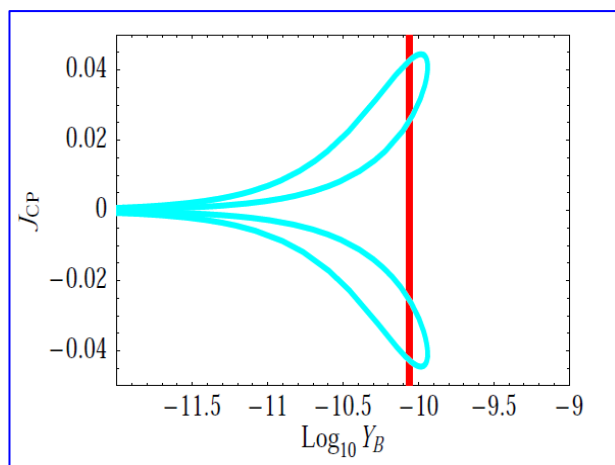
$$|\sin \theta_{13} \sin \delta_{CP}| > 0.11$$

Daya Bay: $\sin \theta_{13} = 0.15$, if $\sin \delta_{CP} > 0.75$



$$|J_{CP}| > 0.024$$

Normal Ordering
 $\sin \theta_{13} = 0.2$

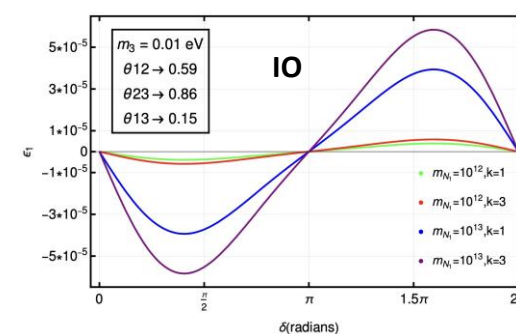
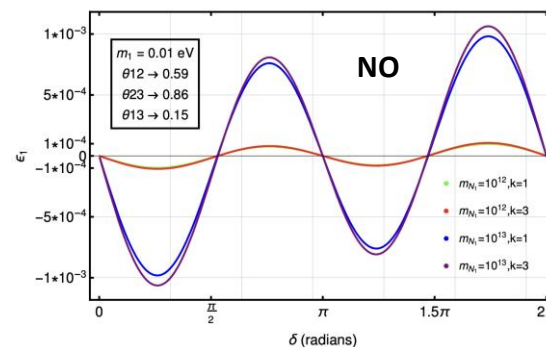


U.Patel et al. JHEP 03 (2024) 029

Left-Right Symmetric
Model with double seesaw



- m_D depends on δ_{CP}
- δ_{CP} is the prime source of lepton asymmetry ε_1 and Y_B





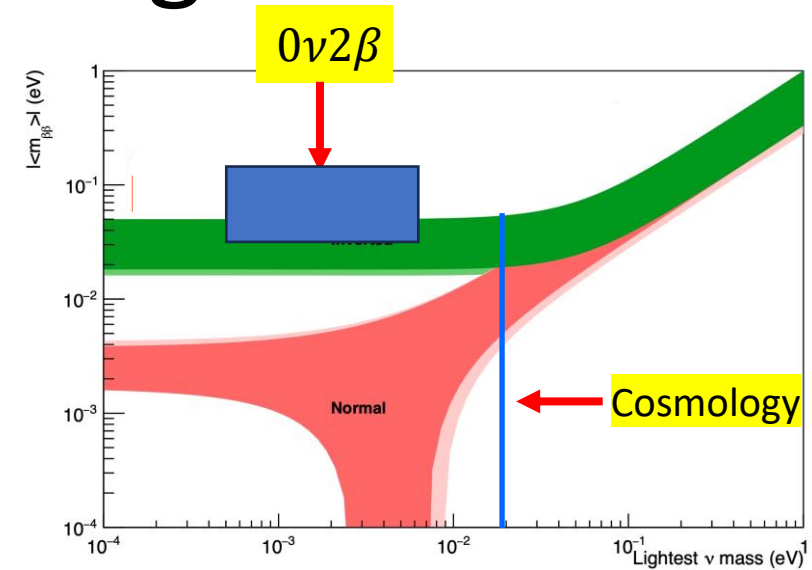
Neutrino Mass Ordering

Mass Ordering

NO or IO ?

Impact on

- Cosmology
- $0\nu 2\beta$ decay
- Direct mass measurement
- Cosmic neutrino background (CvB)



Cosmology (model dependent):

$\sum m_i < 0.12$ eV (CMB + BAO) $\rightarrow$ close to **IO**: $\sum m_i \sim 100$ meV

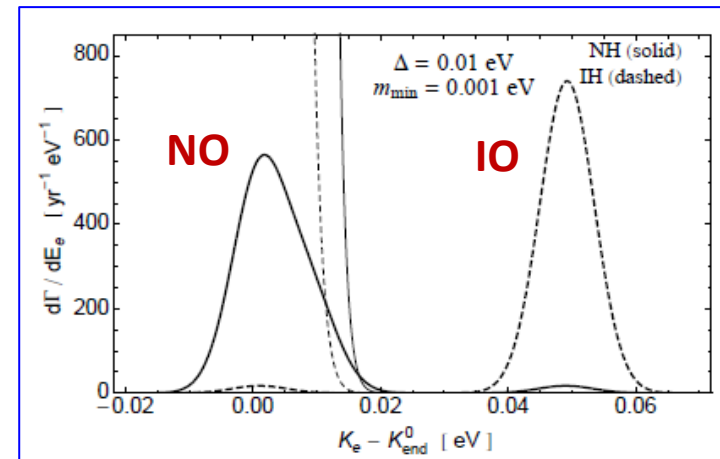
$0\nu 2\beta$

Experiment: $m_{\beta\beta} < 28-122$ meV (90%CL)

Theory **IO**: $m_{\beta\beta} \simeq 20-50$ meV

Detection of CvB $\nu + {}^3\text{H} \rightarrow {}^3\text{He} + e^-$

A.J.Long et al. 1405.7654



Project PTOLEMY:

- 100 g (1 Mci) of Tritium
- Detection of relic neutrinos
- 10 event/year



Golden channel for CPV search: $\nu_\mu \rightarrow \nu_e$

Probability of $\nu_\mu \rightarrow \nu_e$ oscillation in matter

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) = & 4c_{13}^2 \boxed{s_{13}^2} s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E_\nu} \times \left[1 + \frac{2a}{\Delta m_{13}^2} (1 - 2s_{13}^2) \right] & \text{leading term} \\
 & + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos \delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E_\nu} \sin \frac{\Delta m_{13}^2 L}{4E_\nu} \sin \frac{\Delta m_{12}^2 L}{4E_\nu} & \text{CP-even} \\
 & - 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin \delta \sin \frac{\Delta m_{23}^2 L}{4E_\nu} \sin \frac{\Delta m_{13}^2 L}{4E_\nu} \sin \frac{\Delta m_{12}^2 L}{4E_\nu} & \text{CP-odd} \\
 & + 4s_{12}^2 c_{13}^2 (c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta) \sin^2 \frac{\Delta m_{12}^2 L}{4E_\nu} & \text{Solar} \\
 & - 8c_{13}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E_\nu} \frac{aL}{4E_\nu} \sin \frac{\Delta m_{13}^2 L}{4E_\nu} (1 - 2s_{13}^2), & \text{Matter}
 \end{aligned}$$

$$s_{ij} = \sin \theta_{ij}$$

$$c_{ij} = \cos \theta_{ij}$$

Matter effect

$$a [eV^2] = 2\sqrt{2} G_F n_e E_\nu = 7.6 \times 10^{-5} \rho \left[\frac{g}{cm^3} \right] E_\nu [GeV]$$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$



$$a \rightarrow -a \quad \delta \rightarrow -\delta$$

change sign for NH $\rightarrow$ IH



Search/measurement of CP violation

Long baseline accelerator experiments

Direct search: compare oscillation probabilities
muon neutrino → **electron neutrino**
and
muon antineutrino → **electron antineutrino**

CP asymmetry A_{CP}

Vacuum

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \cong \frac{\Delta m_{12}^2 L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta$$

Matter

Neutrino energy
tuned to oscillation
maximum with atm
parameters

$$A_{CP} \equiv \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \bigg|_{\frac{|\Delta m_{31}^2| L}{4E_\nu} \approx \pi/2} \sim -\frac{\pi \sin 2\theta_{12}}{\tan \theta_{23} \sin 2\theta_{13}} \frac{\Delta m_{21}^2}{|\Delta m_{31}^2|} \sin \delta_{CP} \pm \frac{L}{2800 \text{ km}}$$

Matter effect
“+” - NO
“-” - IO

$A_{CP} \neq 0 \rightarrow \delta_{CP} \neq 0 \rightarrow \text{CP violation}$

Sensitivity to CP phase increases using the value of θ_{13} obtained in reactor experiments



~575 participants,
75 institutions, 14 countries
Russia: INR, JINR

$E_\nu \sim 0.6 \text{ GeV}$
Neutrino beam from J-PARC
Baseline = 295 km
Data taking since 2010



SuperKamiokande

JAPAN



Toyama

Kamioka Mine

J-PARC

Tokai

Tokyo

Tokyo/Narita Airport

T2K simulation
vacuum + matter
 $A_{CP} \simeq -0.28\sin\delta + 0.09$

CP in vacuum

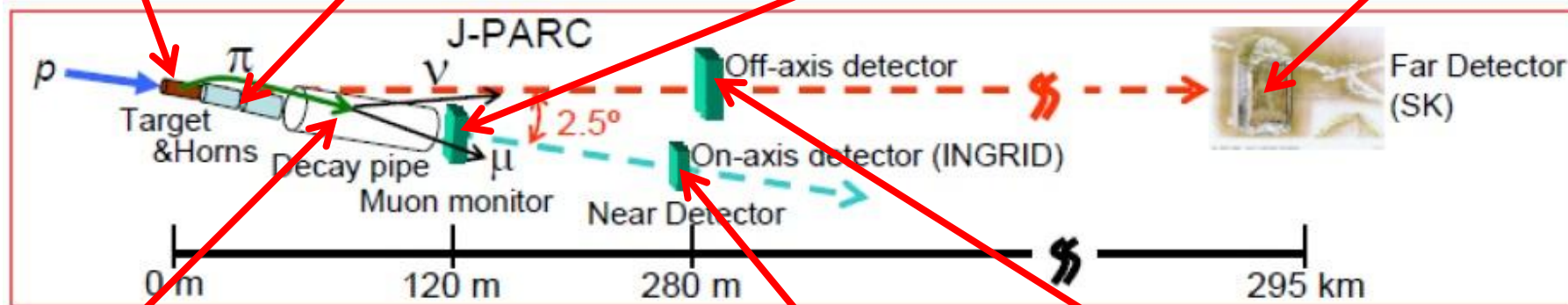
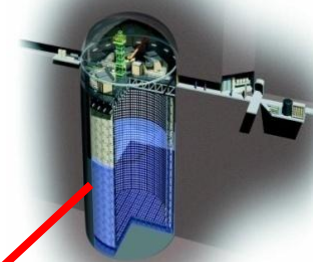
Matter asymmetry



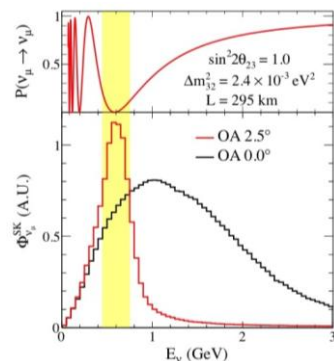
Experiment T2K

LBL accelerator experiment

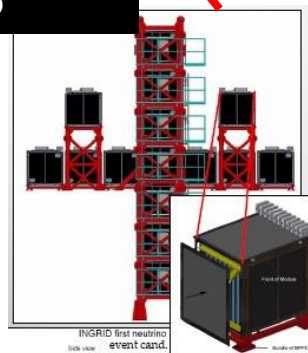
Far neutrino detector
SuperKamiokande



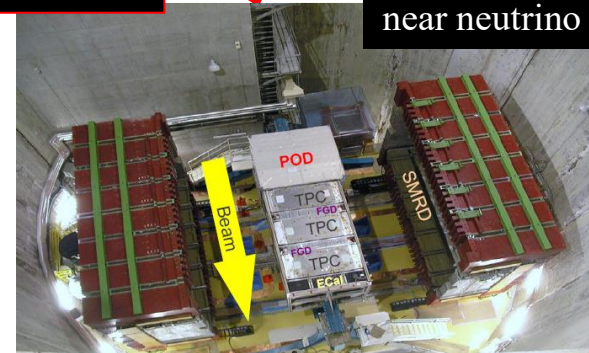
Off-axis neutrino beam



Neutrino monitor
INGRID



ND280



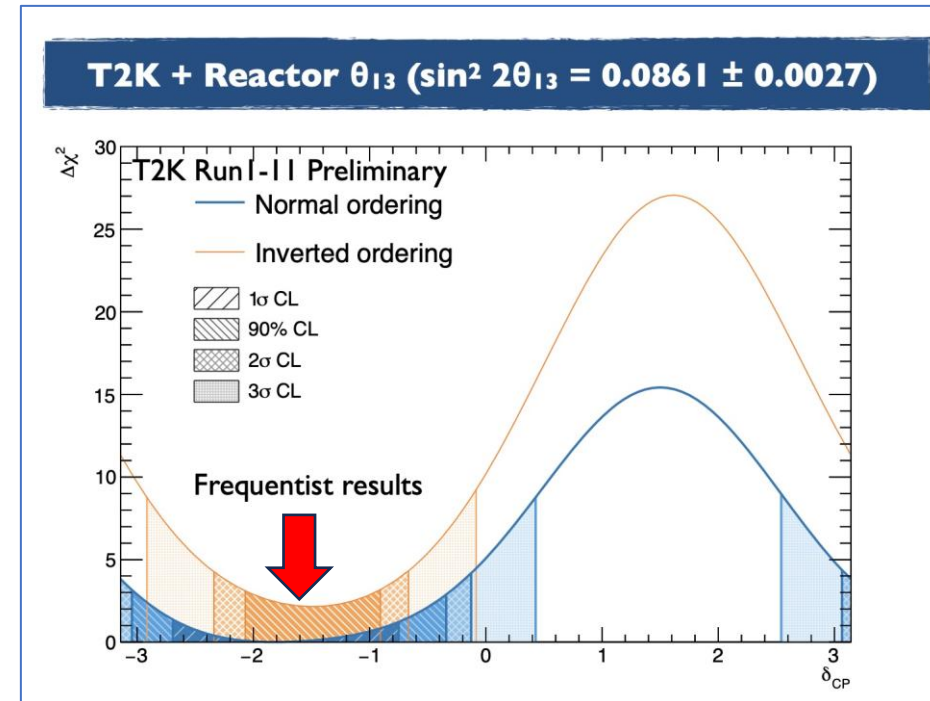
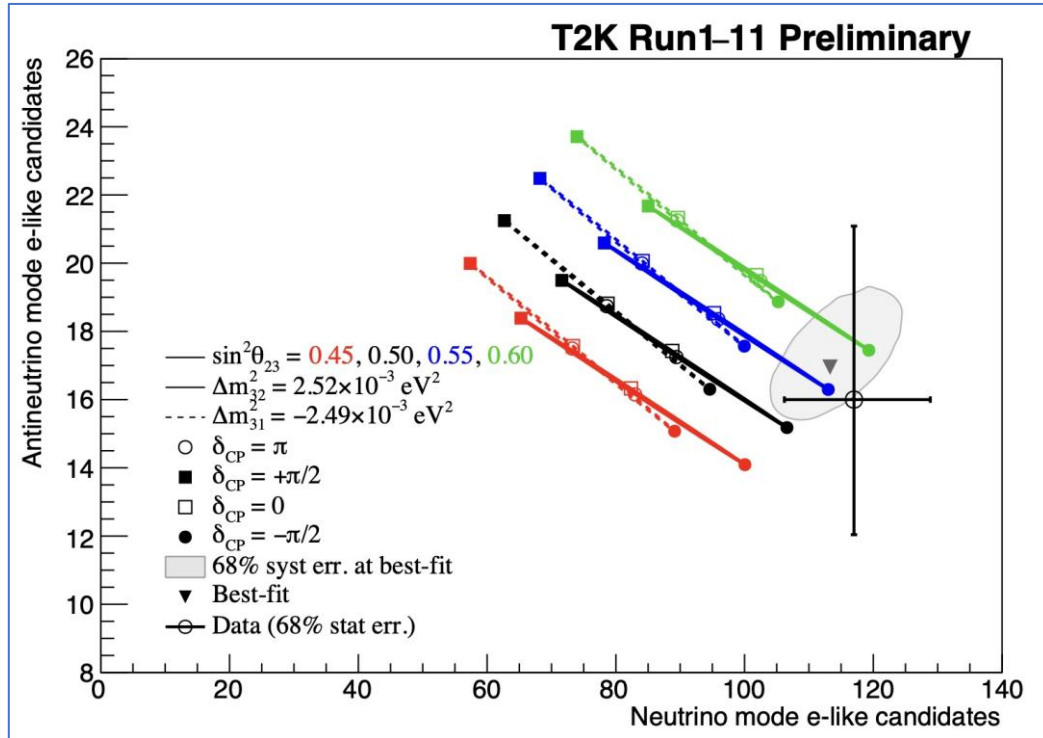
Off-axis near neutrino detector



T2K: hint of CP violation

ν - mode: 21.4×10^{20} POT
 $\bar{\nu}$ - mode: 16.3×10^{20} POT

35% of δ_{CP} values excluded at 3σ marginalized over hierarchies
CP conserving values ($\delta_{CP} = 0, \pi$) excluded at $>90\%$



Best fit: $\delta_{CP} \sim -\pi/2 \rightarrow$ close to maximum CP violation

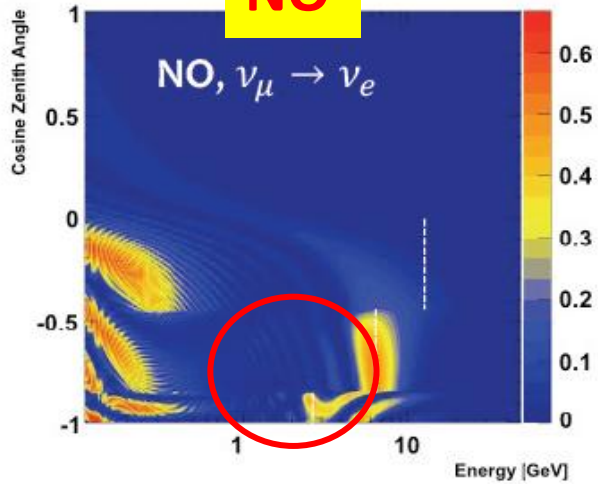
Normal mass ordering is preferred at 80% CL



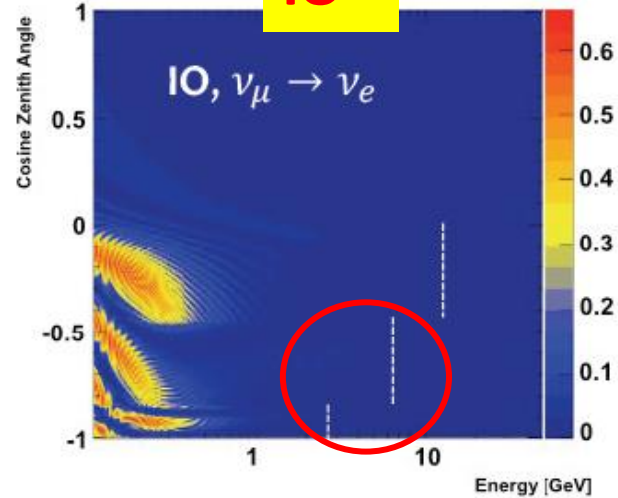
Mass ordering: SuperKamiokande + T2K

SuperKamiokande

NO



IO



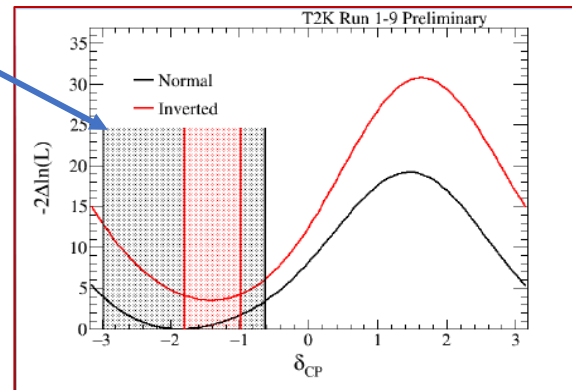
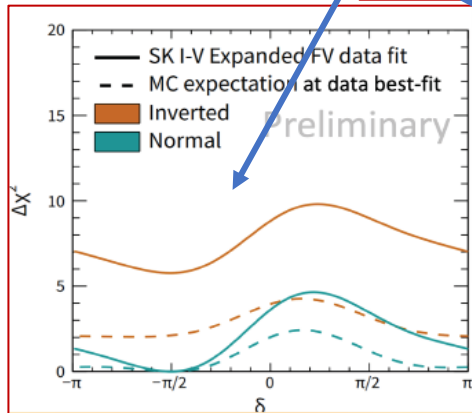
SuperKamiokande

- Atmospheric neutrino sensitive to mass ordering due to matter effect
- MSW resonance at ~ 10 GeV

$$2\sqrt{2}G_F N_e E_\nu = \Delta m_{31}^2 \cos 2\theta_{13}$$

SuperK is sensitive to MO

T2K is sensitive to CP



Joint analysis SuperK+T2K

- increases sensitivity to MO
- slightly increases sensitivity to CPV



CP: Joint SuperK/T2K analysis

Data corresponding to Super-K 2019 analysis (prior to Gd doping) and T2K 2020 oscillation analysis (no multi-ring far detector sample, older systematics implementation).

T2K: 3.6×10^{21} POT

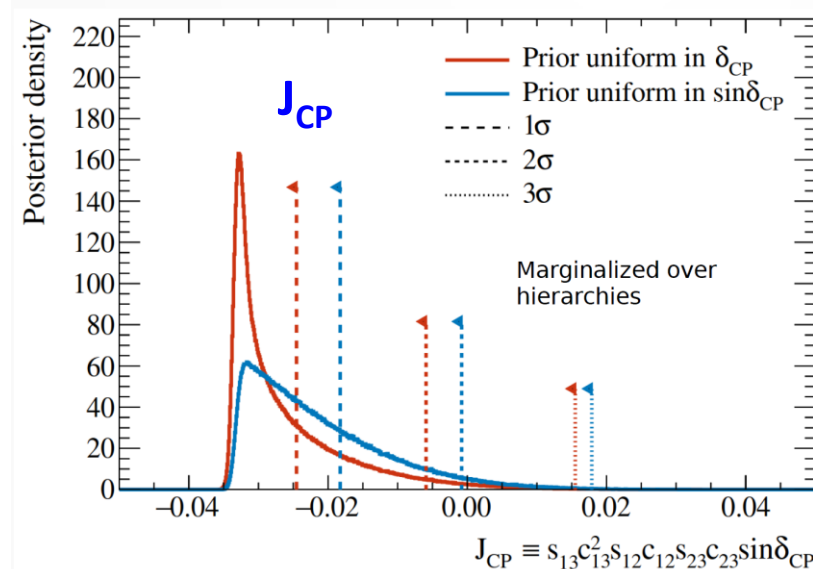
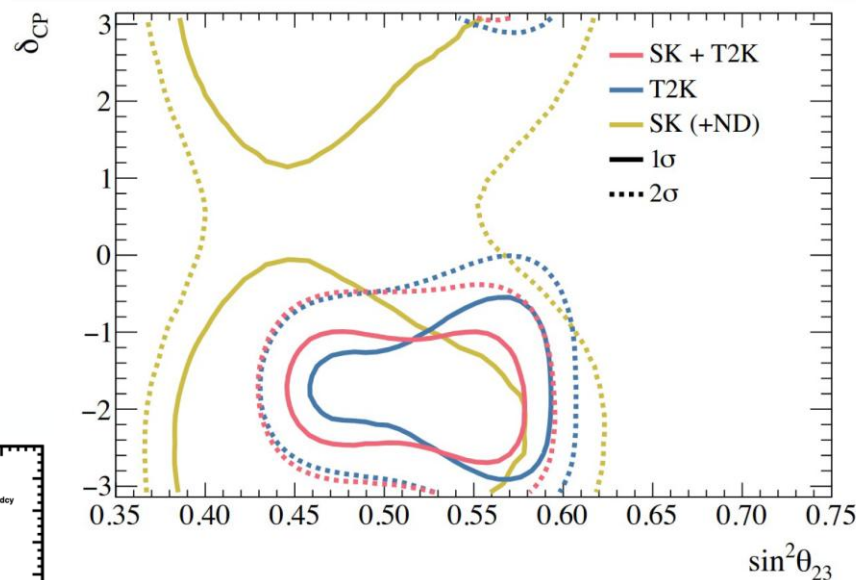
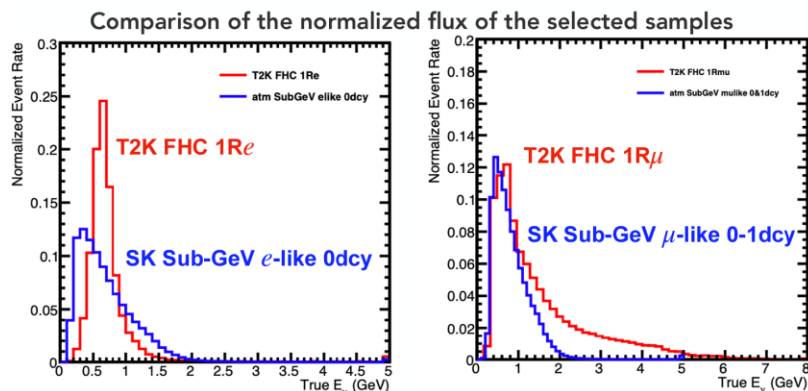
Phys.Rev.Lett. 134 (2025) 1, 011801

Two experiments share the same detector (SK)

Samples from the two sources have overlap energy range and among which, share similar selection cuts

- T2K ND can be utilized to constrain the xsec uncertainties for samples of the same energy range

Increase of statistics



SuperK+T2K analysis:

- excludes **CP conservation at 2.0σ CL**
- prefers **maximal CP violation, $\delta_{CP} \sim -\pi/2$**
- preferred **NO at 1.2σ CL (about 90%)**

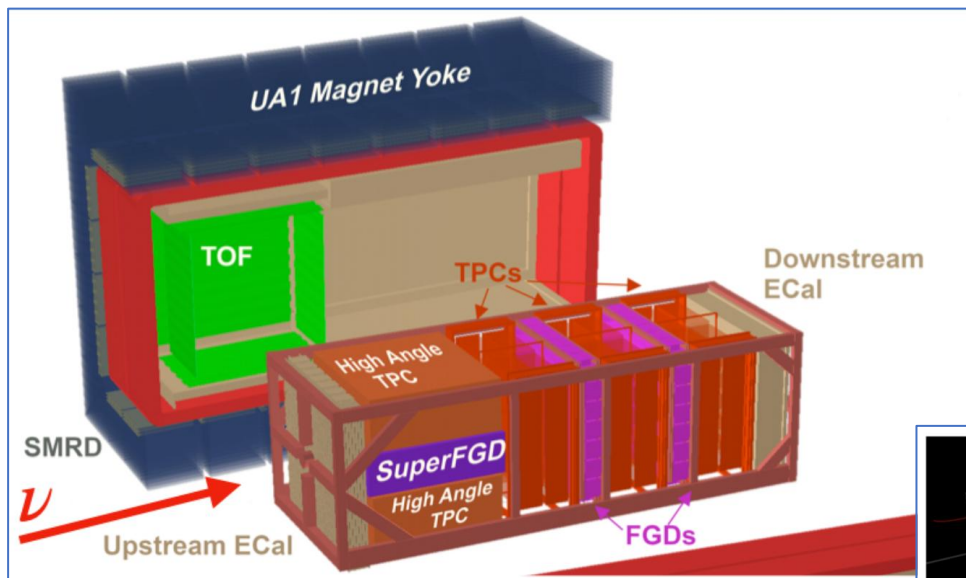


T2K: ND280 upgrade

Current ND280 ⇒ *Upgraded ND280*

- Improve acceptance for high angle and backward tracks
- High precision probe of the nuclear effects → reduced systematics
- Detection of short proton tracks which is very important for T2K analysis
- Reconstruction of the neutrino energy by time-of-flight
- TOF Detector separates background from outside SuperFGD and HA-TPC

All new elements installed and commissioned with neutrino beam. Data taking started in 2024

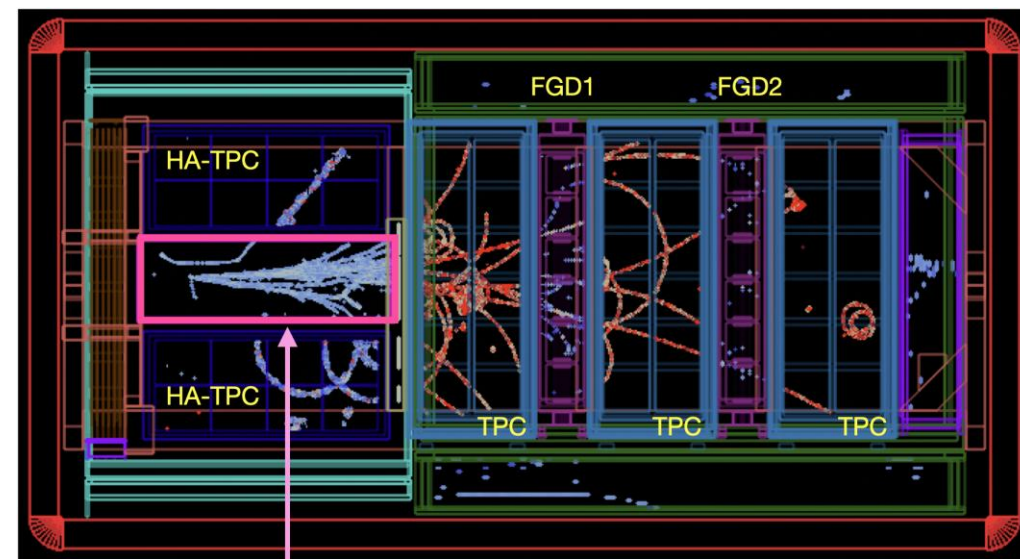
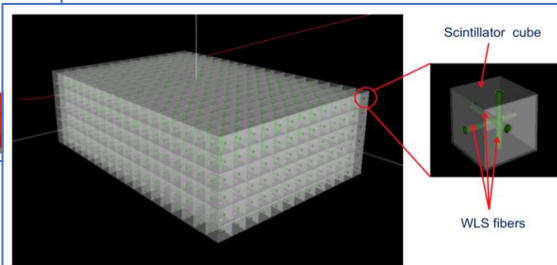


SuperFGD:

~100 participants from
Russia, Japan, US,
Switzerland, France, Spain
~35 from INR, JINR, LPI

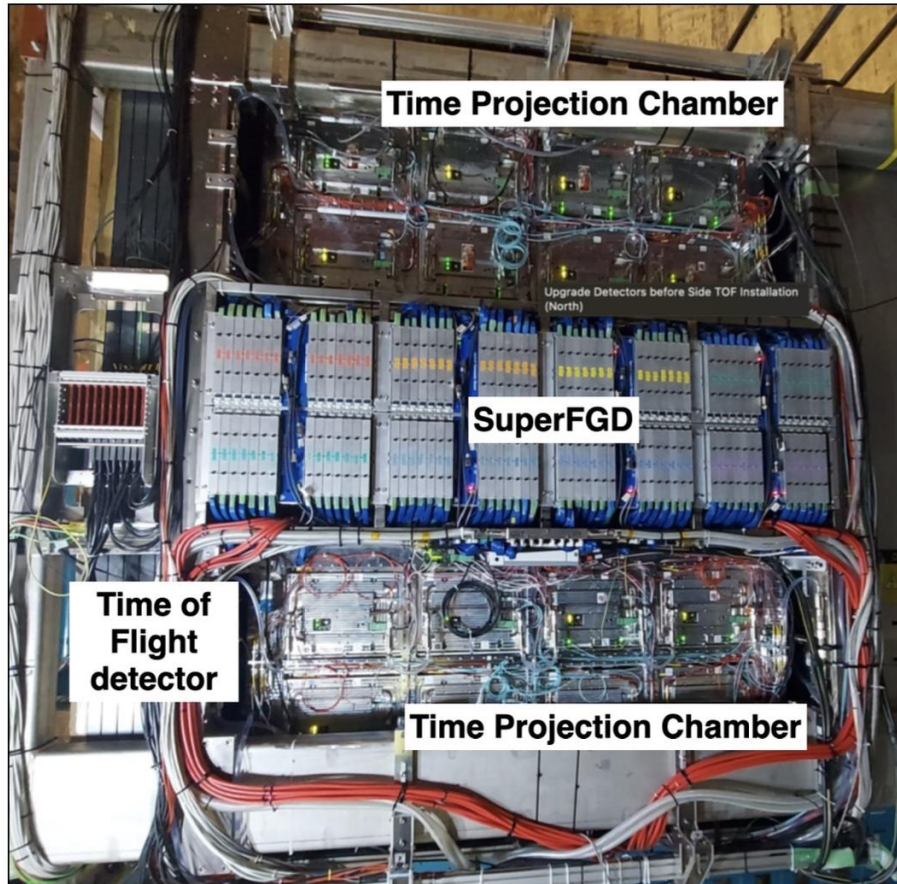
3D highly segmented
neutrino detector

- mass 2 t
- 2×10^6 optically isolated 1cm^3 scintillators
- WLS readout



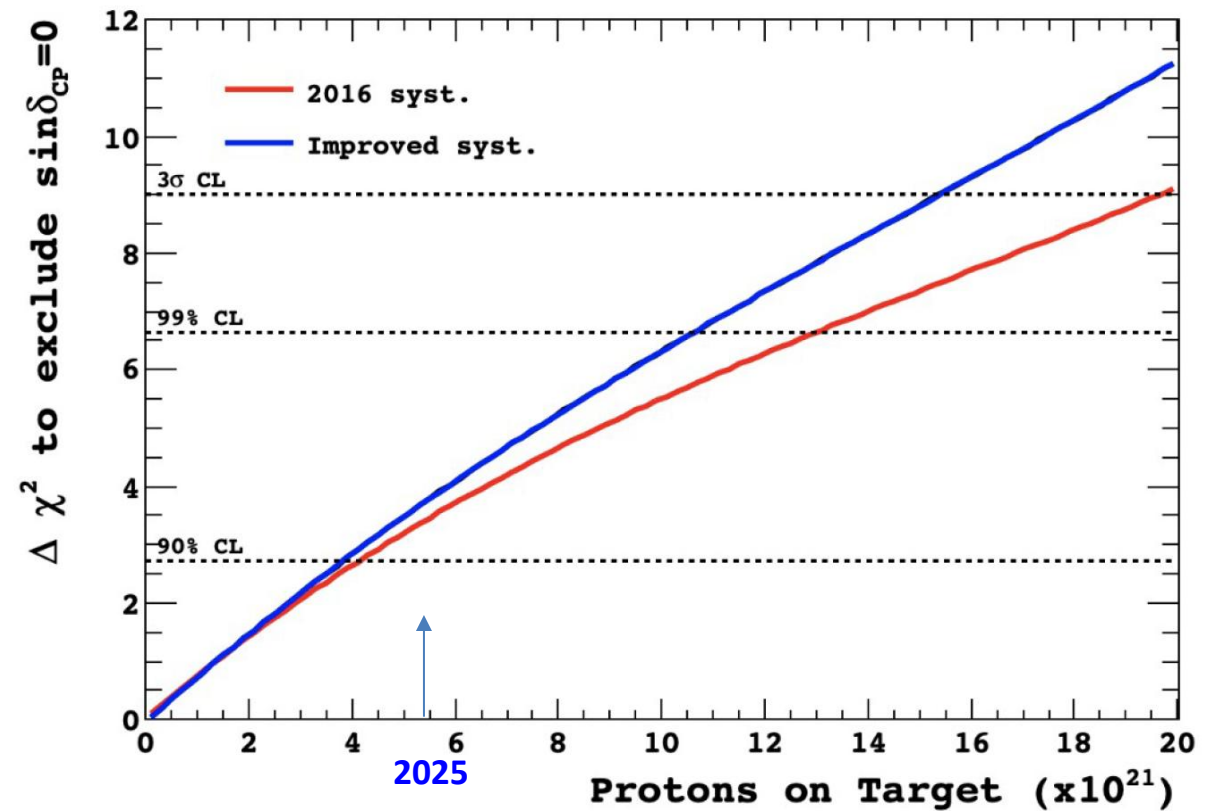
T2K perspectives

Upgraded ND280



Goal to reduce systematics in oscillations to $\sim 3\%$ level

T2K will continue data taking until ~ 2028 using >800 kW proton beam with improved systematics due to **SuperFGD**





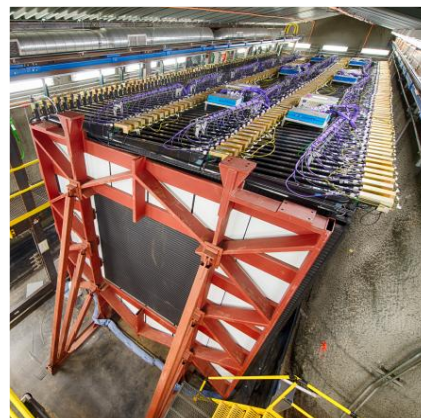
Experiment NOvA

NOvA (USA)

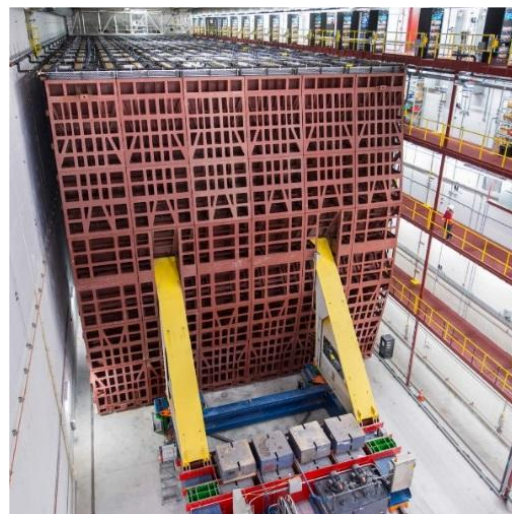
Near Detector

Taking data since 2014

Study of $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ oscillations



Far Detector



Neutrino beam from FNAL to Ash River

Baseline 810 km

Neutrino beam 14 mrad off-axis

Far detector : 14 kt fine-grained calorimeter

65% active mass

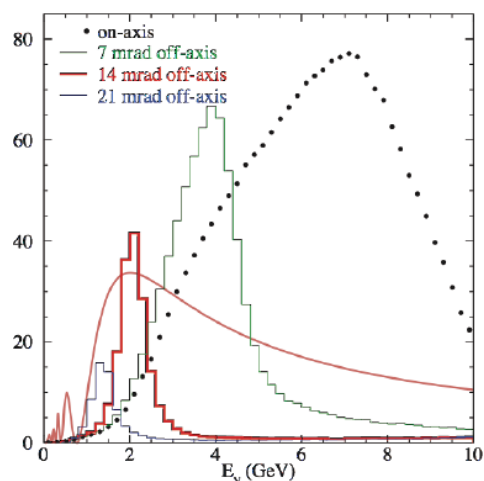
Near Detector: 0.3 kt fine-grained calorimeter

Protons on target

ν : 26.6×10^{20} POT

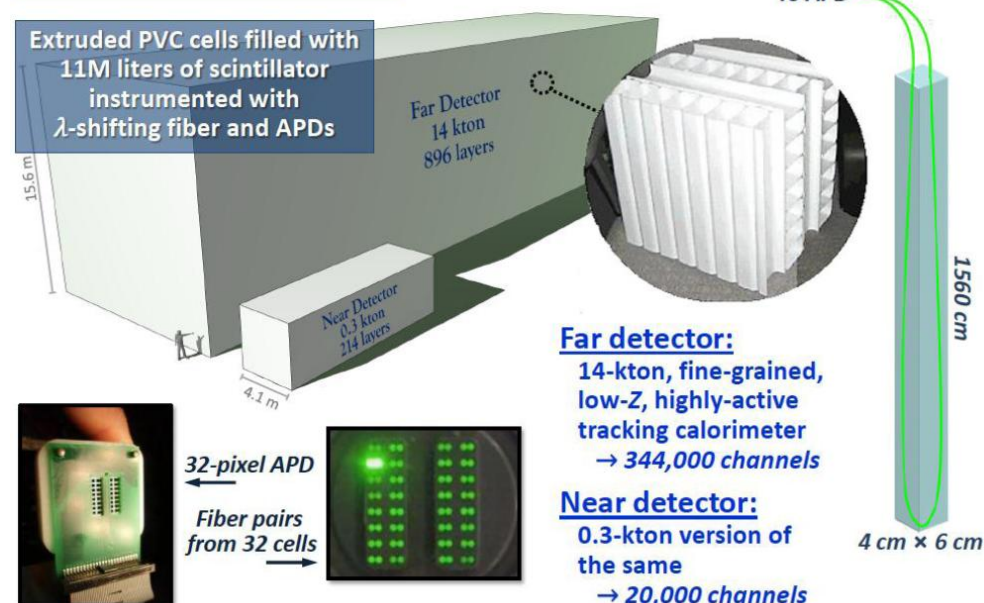
$\bar{\nu}$: 12.5×10^{20} POT

Neutrino beam



NOvA detectors

Extruded PVC cells filled with 11M liters of scintillator instrumented with λ -shifting fiber and APDs



Far detector:

14-kton, fine-grained, low-Z, highly-active tracking calorimeter
→ 344,000 channels

Near detector:

0.3-kton version of the same
→ 20,000 channels



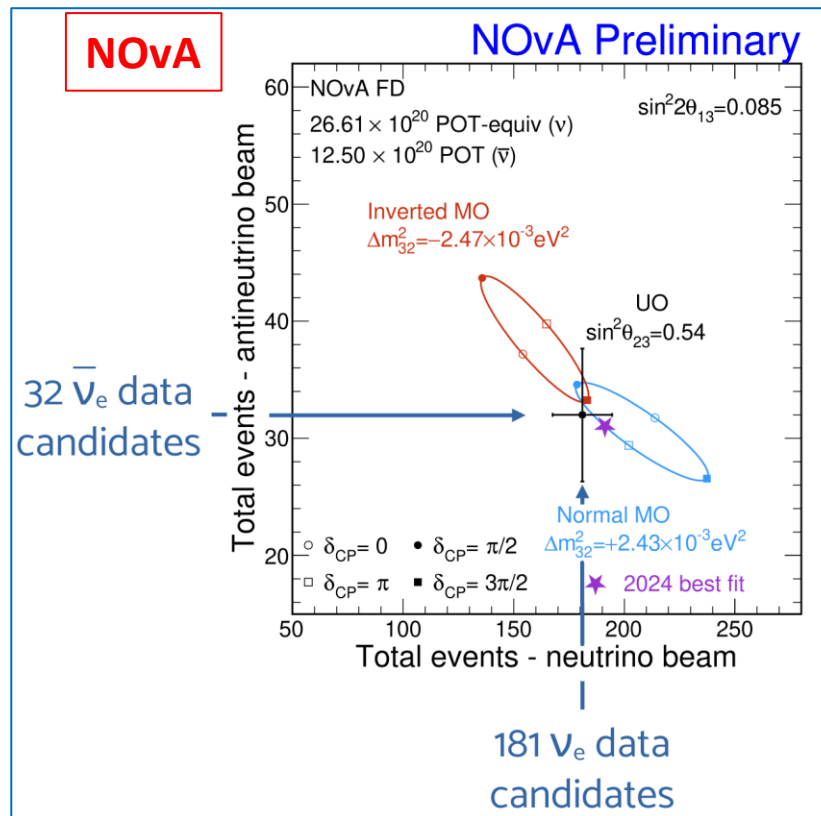
NOvA CPV result

J.Wolcott, Neutrino2024

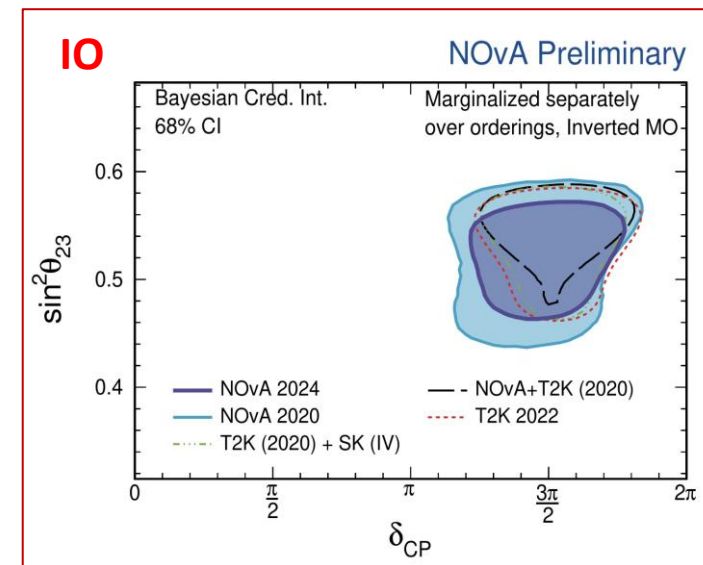
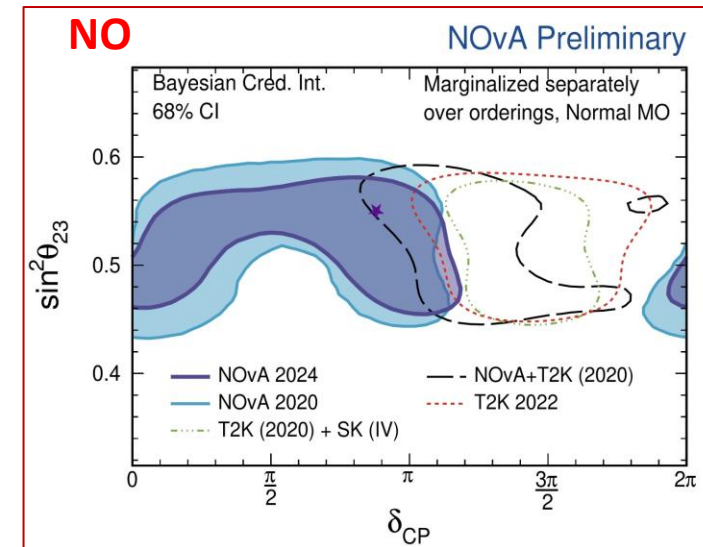
Protons on target
in 2014-2023
 ν : 26.61×10^{20} POT
 $\bar{\nu}$: 12.5×10^{20} POT



384 ν_μ	11.3 background
106 $\bar{\nu}_\mu$	1.7 background
181 ν_e	61.7 background
32 $\bar{\nu}_e$	12.2 background



Data are in the region where
CP violation and matter effect degenerate



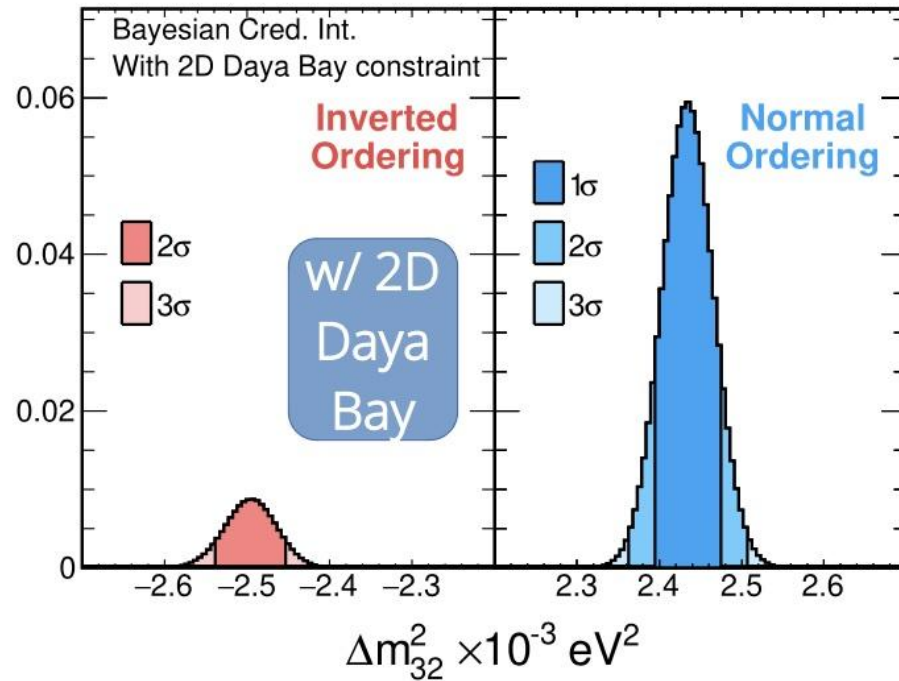


NOvA MO and CPV

J.Wolcott, Neutrino2024

NO preference 87%

NOvA Preliminary

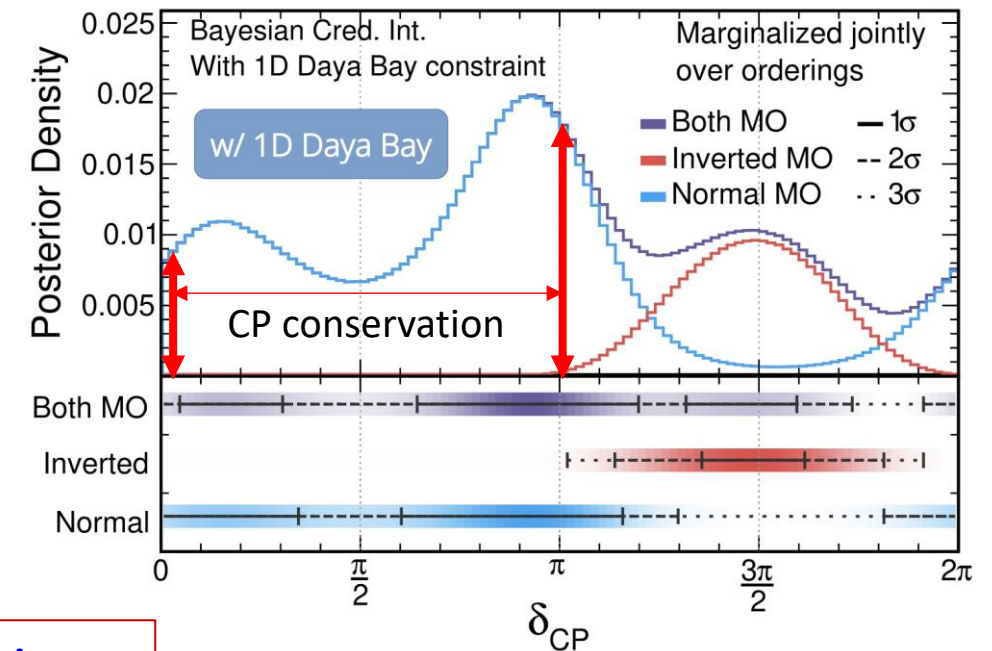


CP conservation:

- favored for NO

- excluded at $>3\sigma$ for IO

NOvA Preliminary



NOvA →

- Weak preference for normal ordering
- No CP asymmetry observed for NO
- CP conservation excluded at $>3\sigma$ for IO



CP: T2K and NOvA

T2K →

$\delta = -\pi/2$ favored

Large range of values of δ
around $+\pi/2$ excluded at 99.7%

NOvA →

Best fit $\delta = 0.82\pi$

Exclude IH $\delta = \pi/2$ at $> 3\sigma$

Disfavor NH $\delta = 3\pi/2$ at $\sim 2\sigma$

NOvA ($\nu + \bar{\nu}$) prefers:
Normal Ordering
CP conservation
Octants $\sim$ degenerate

T2K ($\nu + \bar{\nu}$) prefers:
Normal Ordering

$\delta \sim -\pi/2(\frac{3\pi}{2})$ (max CPV)

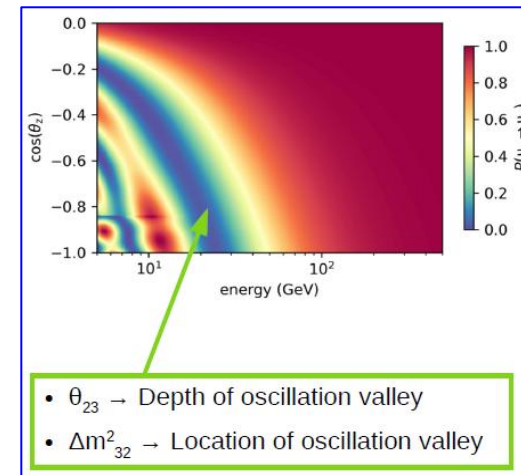
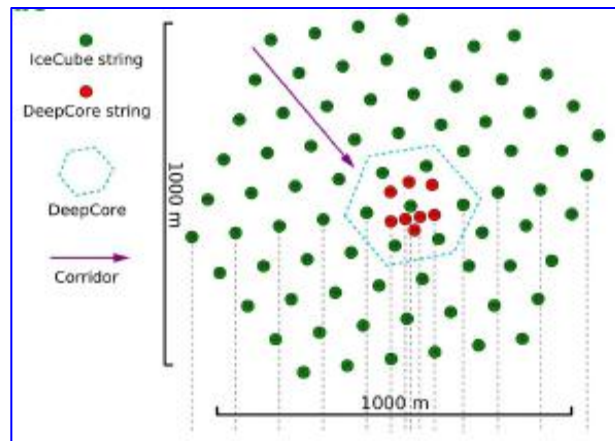
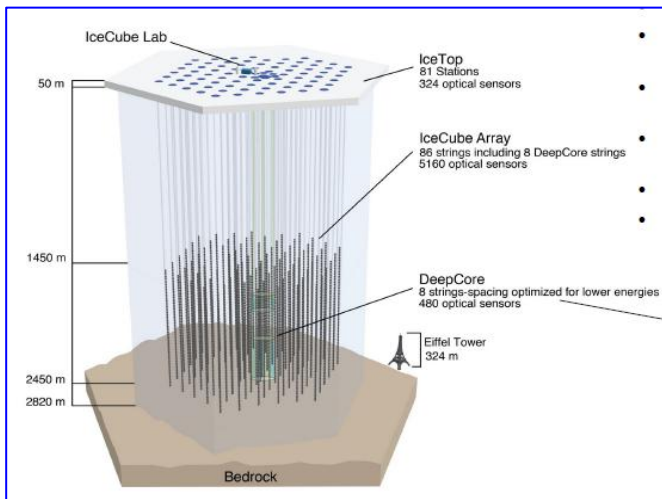
2nd octant

- T2K and NOvA continue data taking
- 3 times more statistics is expected



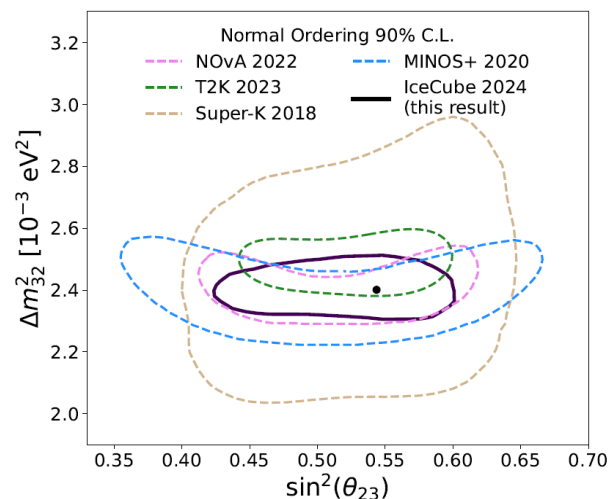
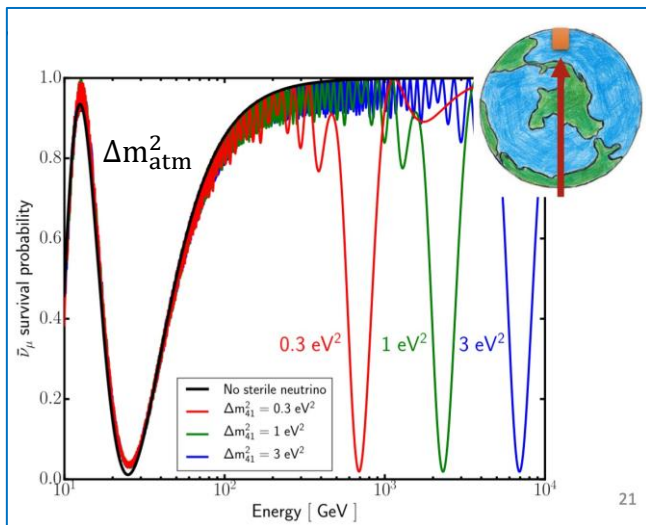
IceCube DeepCore: $\nu_\mu \rightarrow \nu_\mu$

A.Kumar, EPS-HEP 2023



J.P. Yanez, Neutrino2024

Convolutional Neural Network (CNN), 9.3 years: about 150k events



Phys.Rev.Lett. 134 (2025) 9, 091801

Consistent results
in disappearance on
 $\sin^2 \theta_{23}$ and Δm^2_{32}
in NOvA, T2K, SuperK,
MINOS, IceCube

Future accelerator projects DUNE and Hyper-Kamiokande



LBNF/DUNE

USA, Fermilab

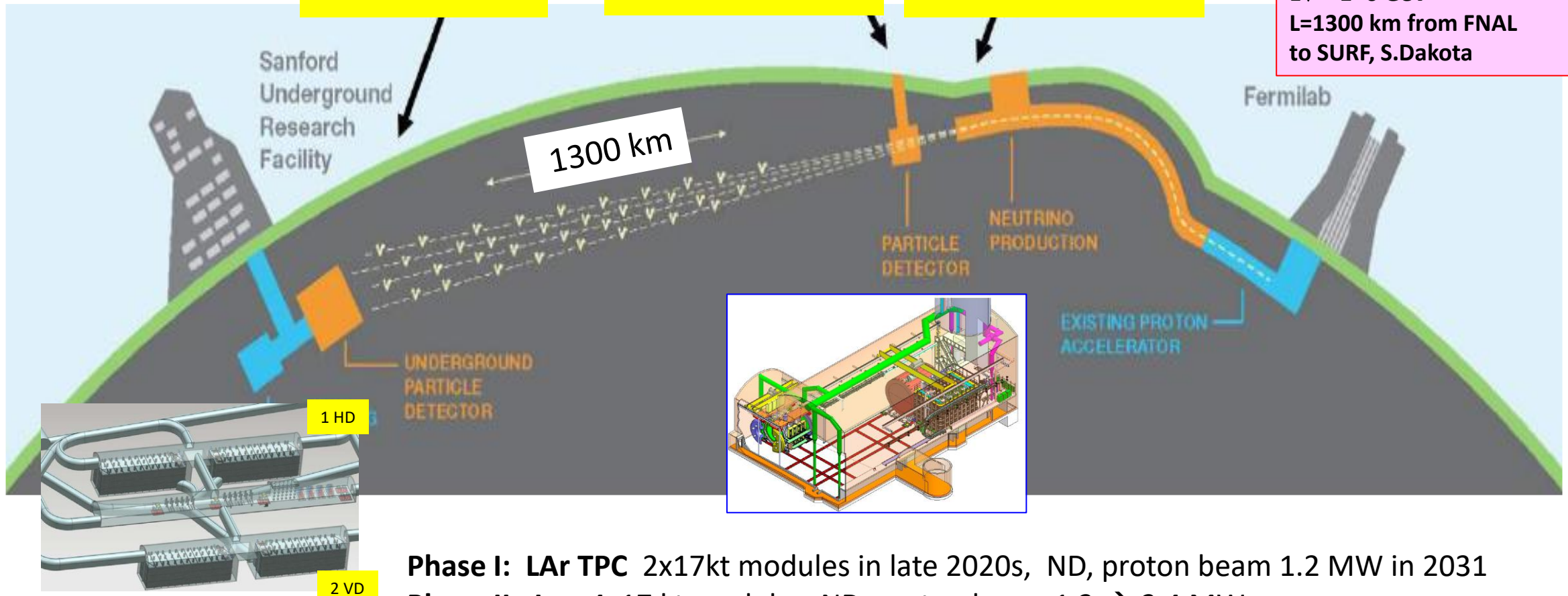
>1400 collaborators from ~200 institutions

$E_p = 60-120$ GeV
Beam power 1.2 $\rightarrow$ 2.4 MW
On axis neutrino beam
 $E_\nu \sim 1-6$ GeV
 $L=1300$ km from FNAL
to SURF, S.Dakota

Far Detector

Near Detector

Neutrino Beam



Phase I: LAr TPC 2x17kt modules in late 2020s, ND, proton beam 1.2 MW in 2031

Phase II: Lar 4x17 kt modules, ND, proton beam 1.2 $\rightarrow$ 2.4 MW



DUNE: CP sensitivity

DUNE Collaboration, 2006.16043

Staging approach

Sensitivity to δ_{CP}

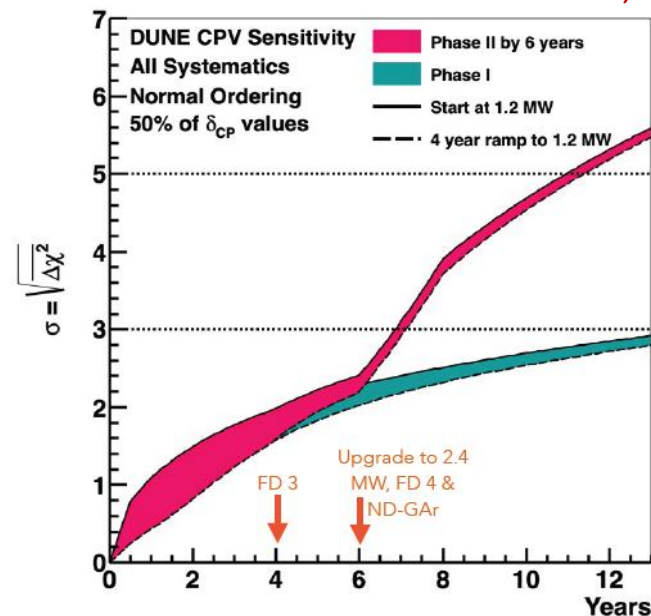
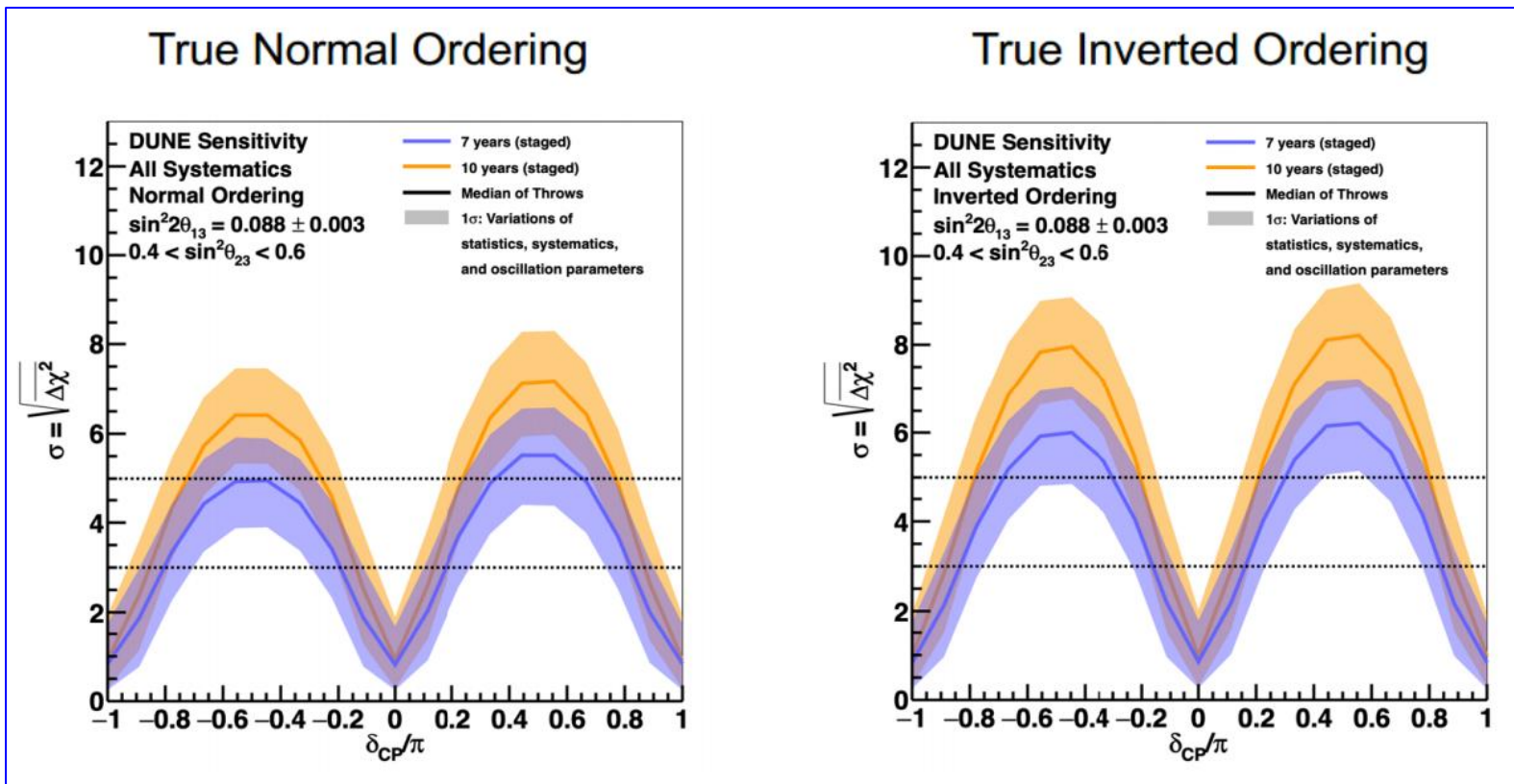
- 7 years data taking
- 10 years data taking

$$\nu : \bar{\nu} = 50\% : 50\%$$

3.5 years, staged exposure

Sample	Expected Events			
	$\delta_{CP} = 0$	$\delta_{CP} = -\frac{\pi}{2}$		
	NH	IH	NH	IH
ν mode				
Oscillated ν_e	1155	526	1395	707
$\bar{\nu}$ mode				
Oscillated ν_e	81	39	95	53
Oscillated $\bar{\nu}_e$	236	492	164	396

A.Booth, ICHEP2022

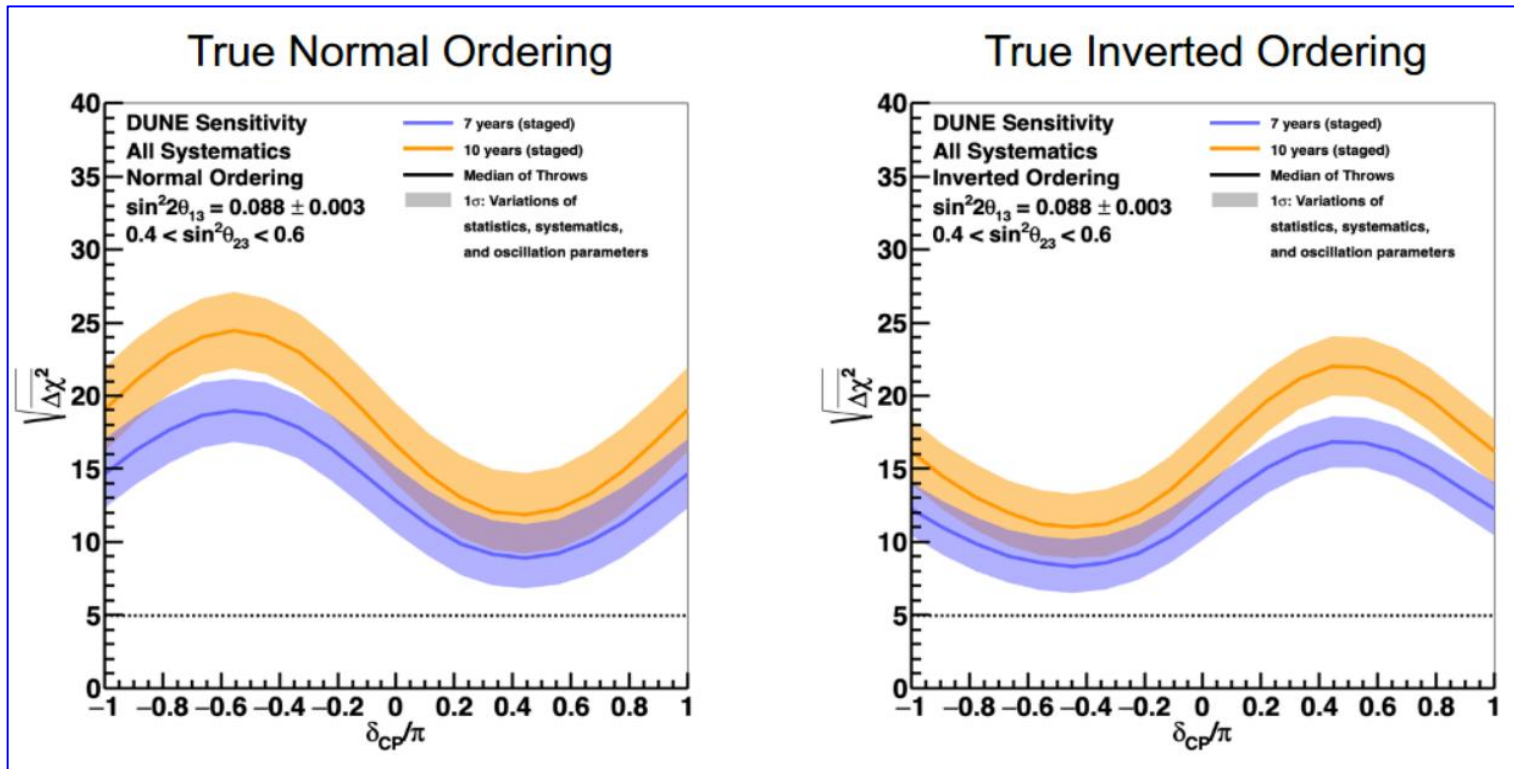




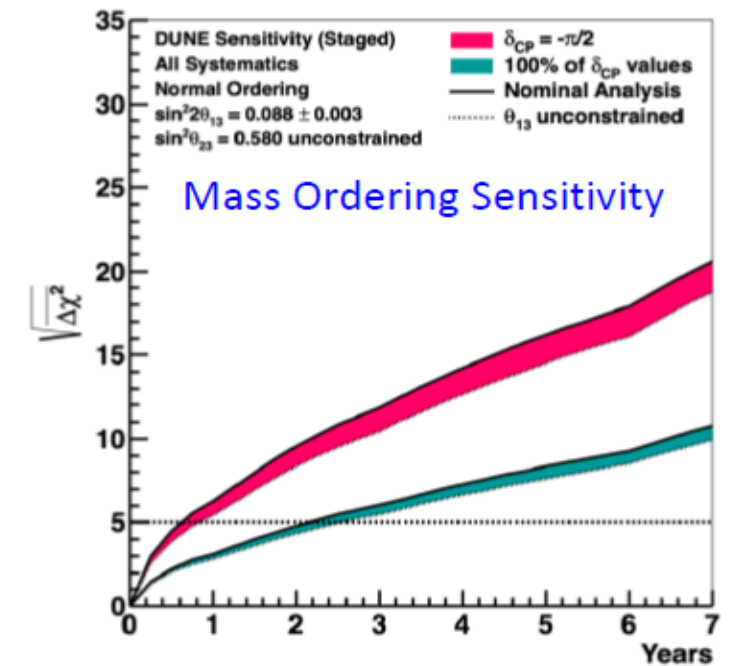
DUNE: Mass Ordering

$$\nu : \bar{\nu} = 1:1$$

DUNE Collaboration, 2006.16043



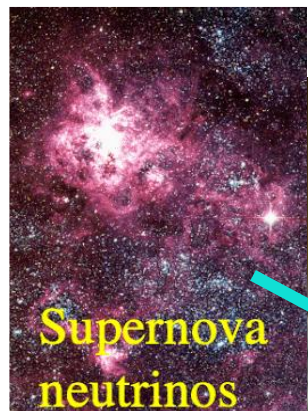
> 5 σ discovery
for all possible δ_{CP} values
after 7 years of data taking



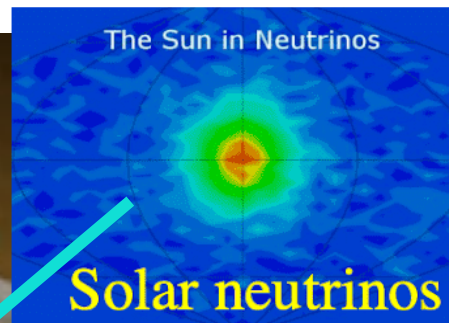


Hyper-Kamiokande

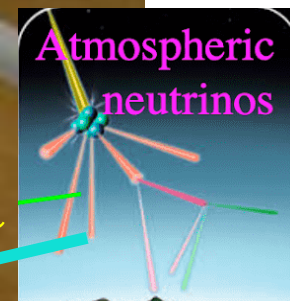
Japan. Project approved in 2020, construction begun in 2021, operation will start in 2028
> 500 collaborators, 99 institutions, 20 countries



Supernova
neutrinos



Solar neutrinos



Atmospheric
neutrinos

Physics program:

- Search for CP violation
- Neutrino oscillations
- Proton decay
- Neutrino astrophysics

Water Cherenkov detector

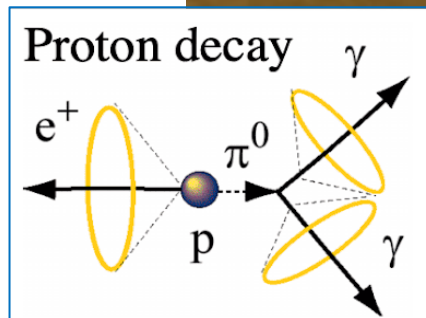
71 m (height) x 68 m (diameter)
Total mass about 260 kt

Inner Detector:

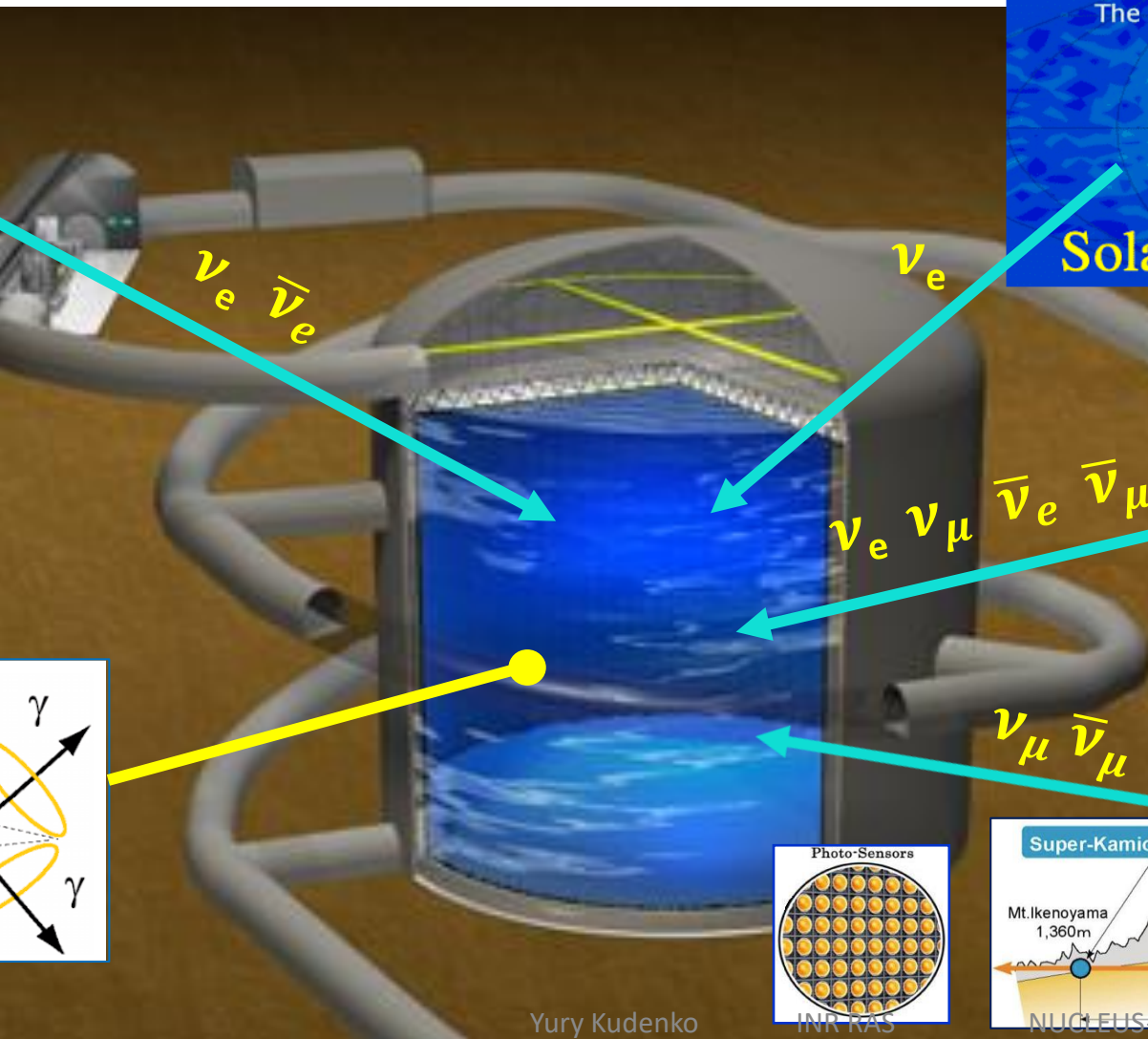
20000 50 cm PMTs + mPMTs

Outer Detector:

~4000 7.5 cm PMTs + WLS plates



Proton decay



J-PARC

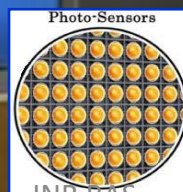
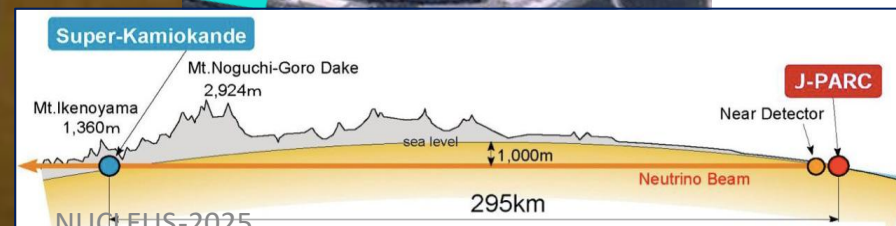


Photo-Sensors



Super-Kamiokande

J-PARC



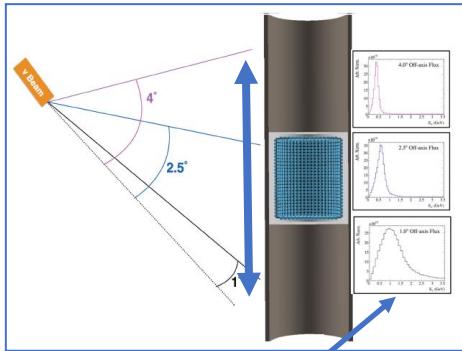
Near Detectors

- measure and control neutrino beam before oscillations
- neutrino cross sections
- systematics

J-RARC beam
30 GeV
1.3 MW

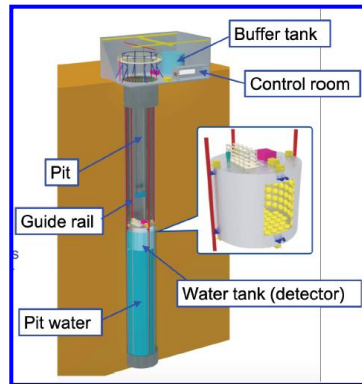
New ND ~1 km from target

**IWCD: Movable water
Cherenkov detector**



Neutrino
spectra

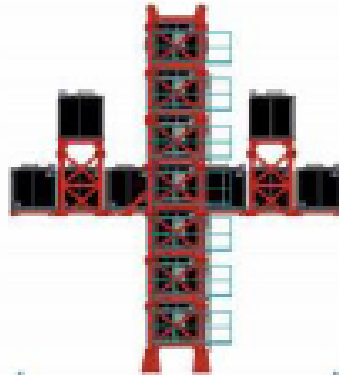
IWCD



~1 kt water
Cherenkov detector
Photocensors:
multi-PMT modules

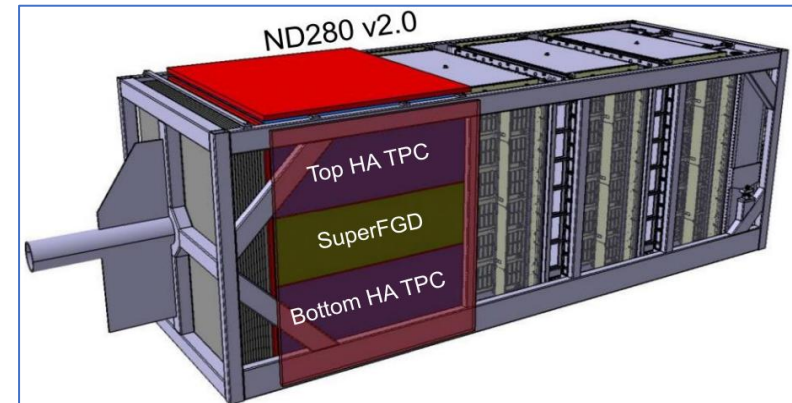
Existing (T2K+upgrade) ND at 280 m from target

INGRID



Neutrino on/off axis
beam monitor

ND280 upgraded



Magnetized off-axis near detector



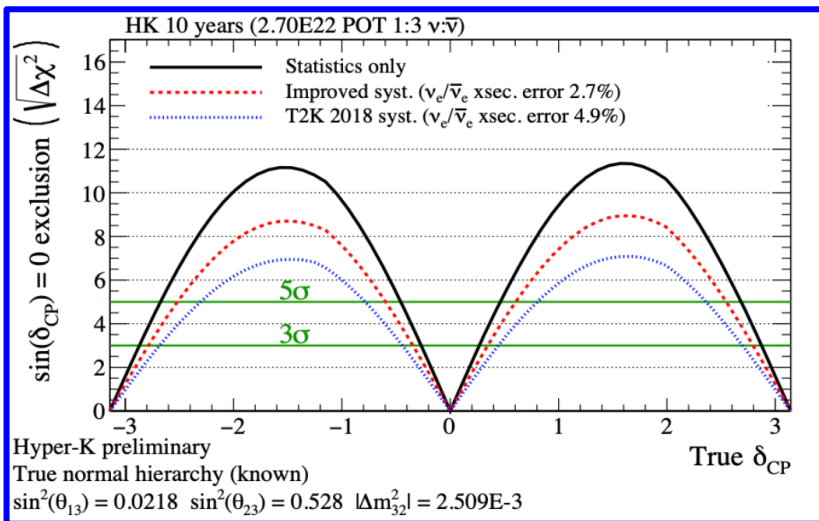
Sensitivity to CP violation (I)

Projected HyperK sensitivity to CP violation

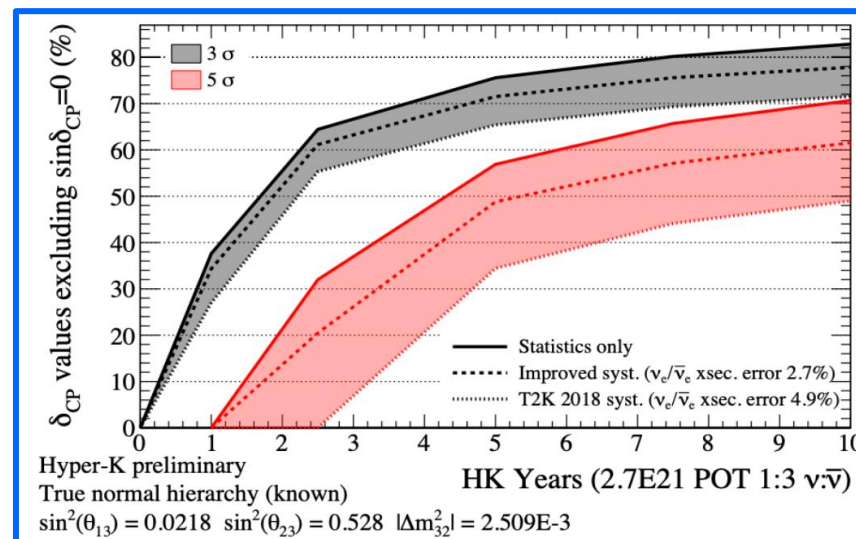
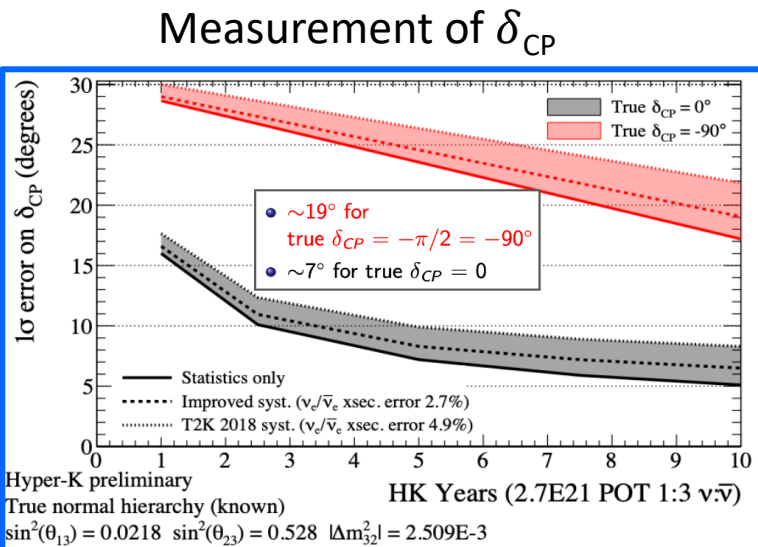
Hyper-Kamiokande, arXiv:1805.04163

- 10 years of data taking,
- 1.3 MW beam power $\rightarrow 2.7 \times 10^{22}$ POT

Expected number of events at HyperK
for $\nu_e : \bar{\nu}_e = 1:3$ and $\sin \delta_{CP} = 0$
2300 ν_e **1300 $\bar{\nu}_e$**



Exclusion of CP conservation

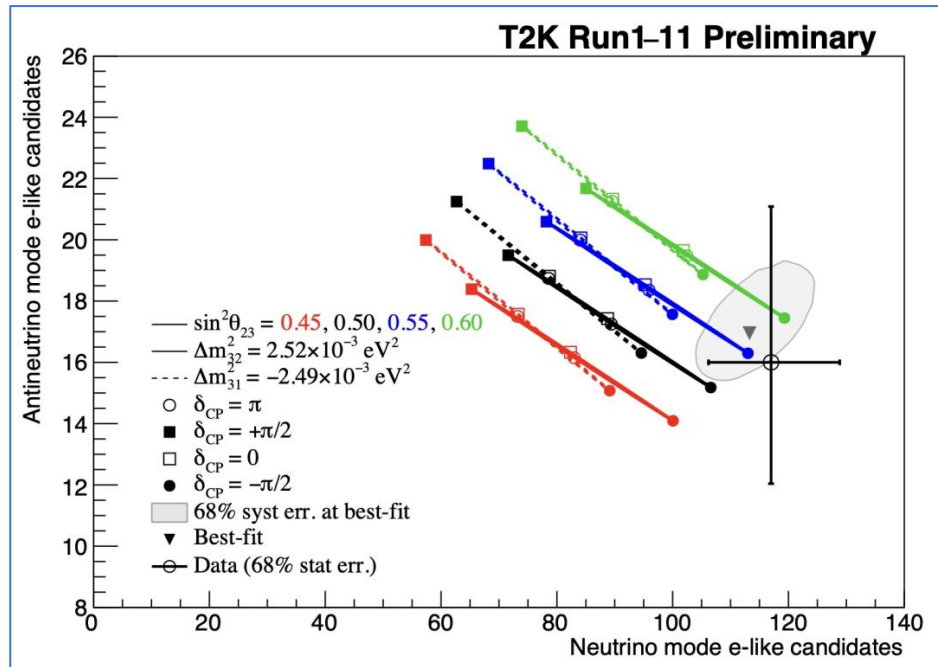




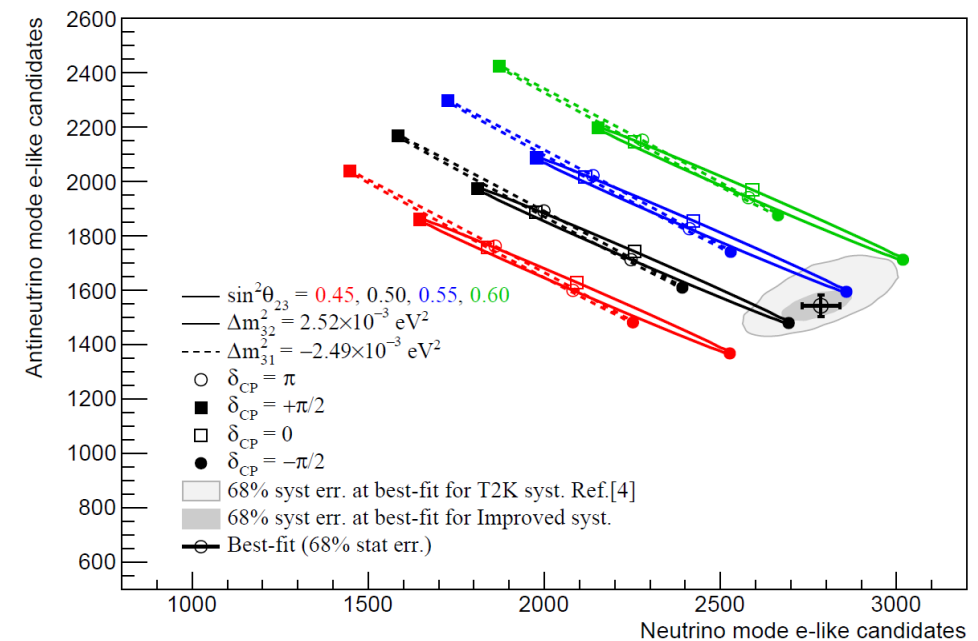
Sensitivity to CP violation (II)

Hyper-Kamiokande, arXiv:2505.15019

Current T2K result



Projected Hyper-K result after 10 years data taking

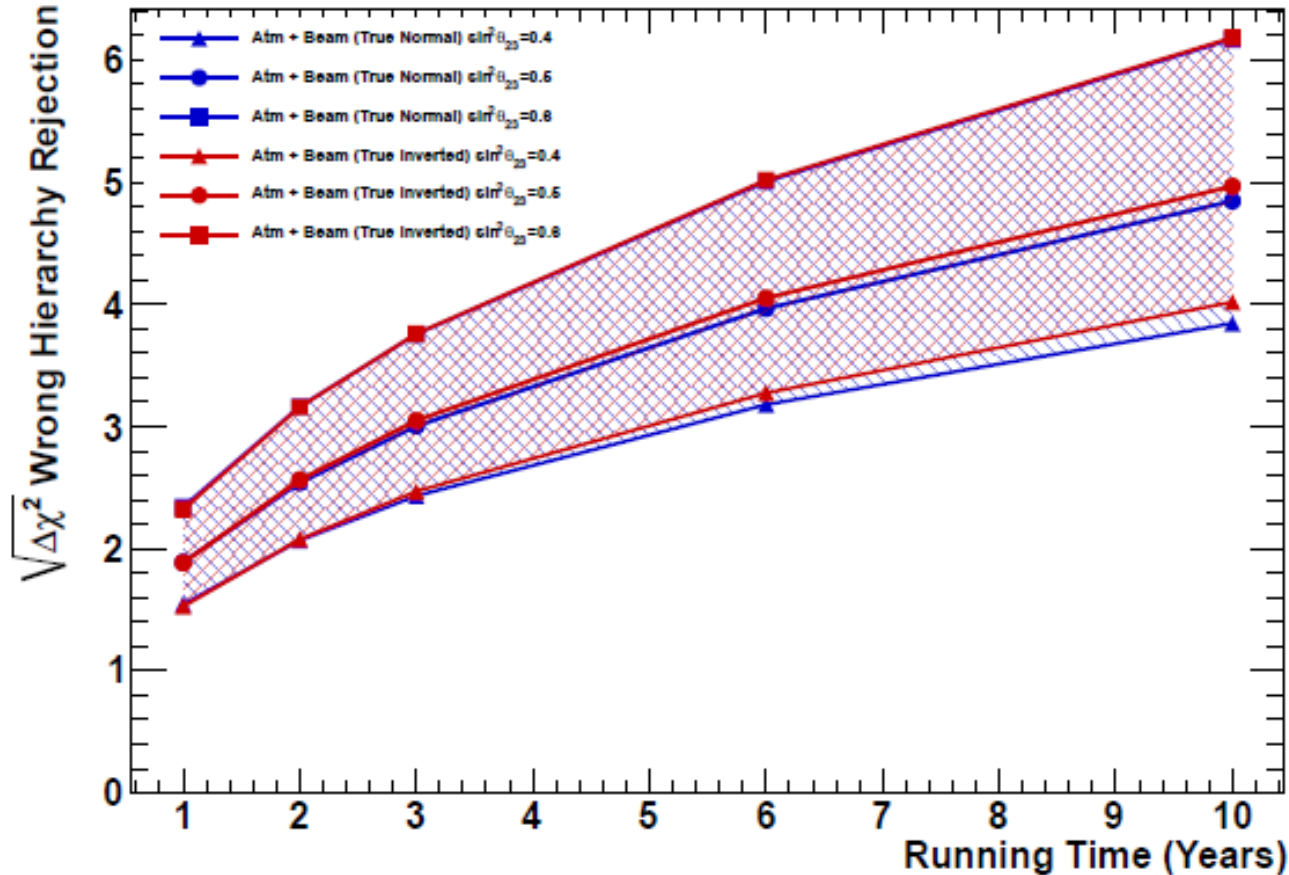




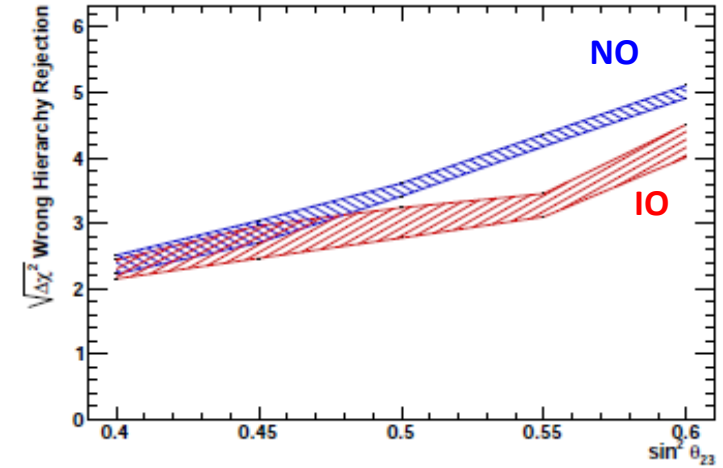
Hyper-Kamiokande: Mass Ordering

HyperKamiokande 10 years of data taking

Hyper-Kamiokande, arXiv:1805.04163



HyperKamiokande, atm neutrinos



	$\sin^2 \theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	2.2σ	$\rightarrow 3.8 \sigma$
	0.60	4.9σ	$\rightarrow 6.2 \sigma$
θ_{23} octant	0.45	2.2σ	$\rightarrow 6.2 \sigma$
	0.55	1.6σ	$\rightarrow 3.6 \sigma$

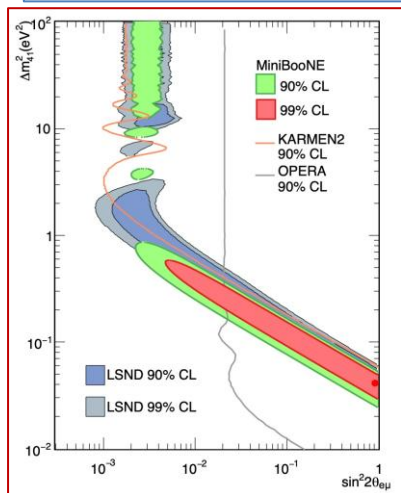
Neutrino anomalies



Light sterile neutrino ?

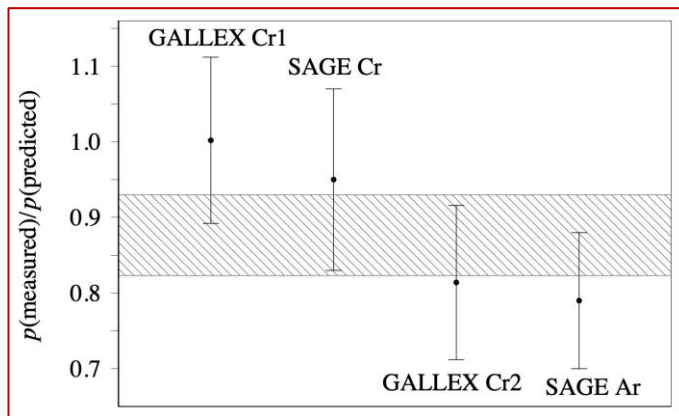
LSND/MiniBooNe anomaly

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
 $87.9 \pm 22.4 \pm 6.0$ events
 Excess 3.8σ



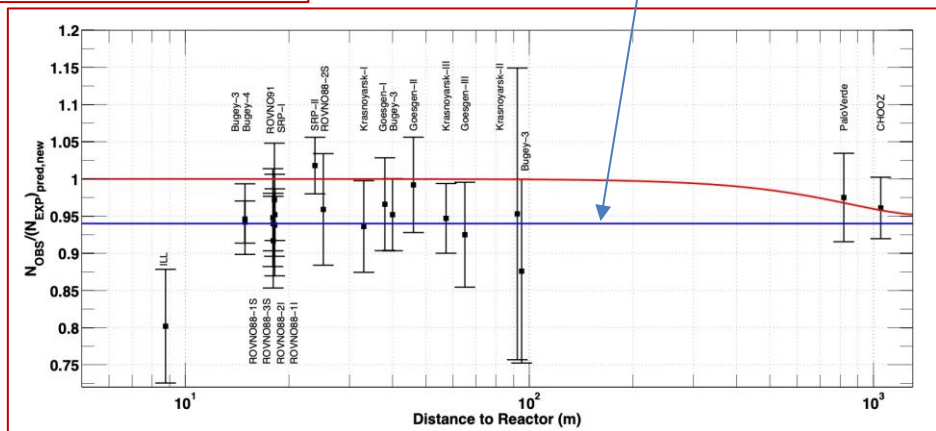
Ga anomaly

$$R = p_{exp}/p_{theory} = 0.87 \pm 0.05$$

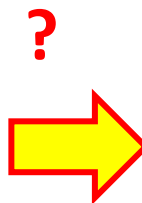
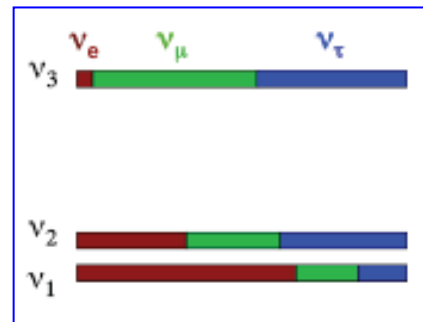


Reactor anomaly

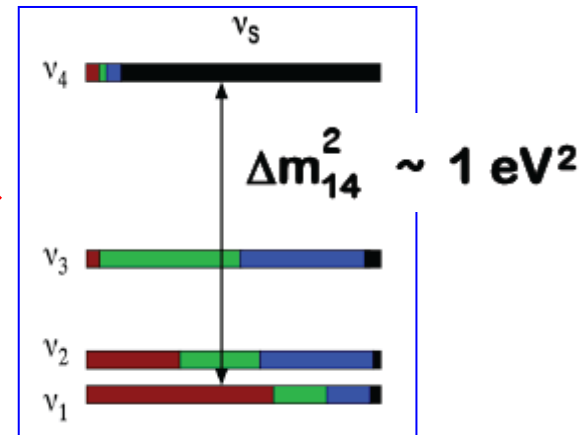
$$0.937 \pm 0.027$$



3ν, NO



3ν + 1ν_s



PMNS matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

$$\begin{aligned} |U_{e4}|^2 &= \sin^2 \theta_{14} \\ |U_{\mu 4}|^2 &= \sin^2 \theta_{24} \cdot \cos^2 \theta_{14} \\ |U_{\tau 4}|^2 &= \sin^2 \theta_{34} \cdot \cos^2 \theta_{24} \cdot \cos^2 \theta_{14} \end{aligned}$$

Connection between Appearance and Disappearance channels

$$\begin{aligned} P_{\nu_e \rightarrow \nu_e} &\simeq 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2) \\ P_{\nu_\mu \rightarrow \nu_\mu} &\simeq 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2) \\ P_{\nu_\mu \rightarrow \nu_e} &\simeq 2|U_{e4}|^2|U_{\mu 4}|^2 \end{aligned}$$

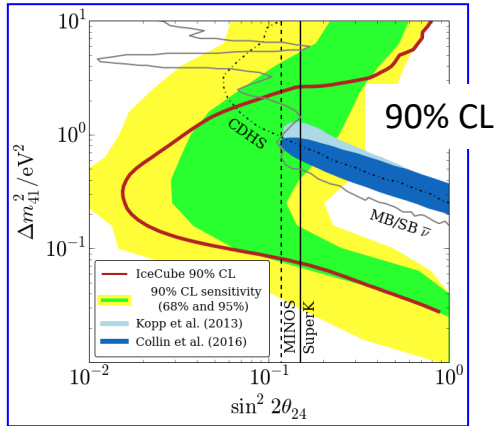
$$\sin^2 2\theta_{e\mu} \simeq \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$



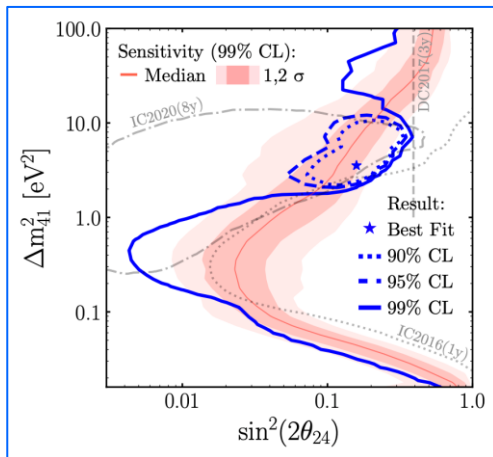
LSND/MiniBooNE anomaly

IceCube: $\nu_\mu \rightarrow \nu_\mu$ disappearance

PRL 117 (2016) 071801



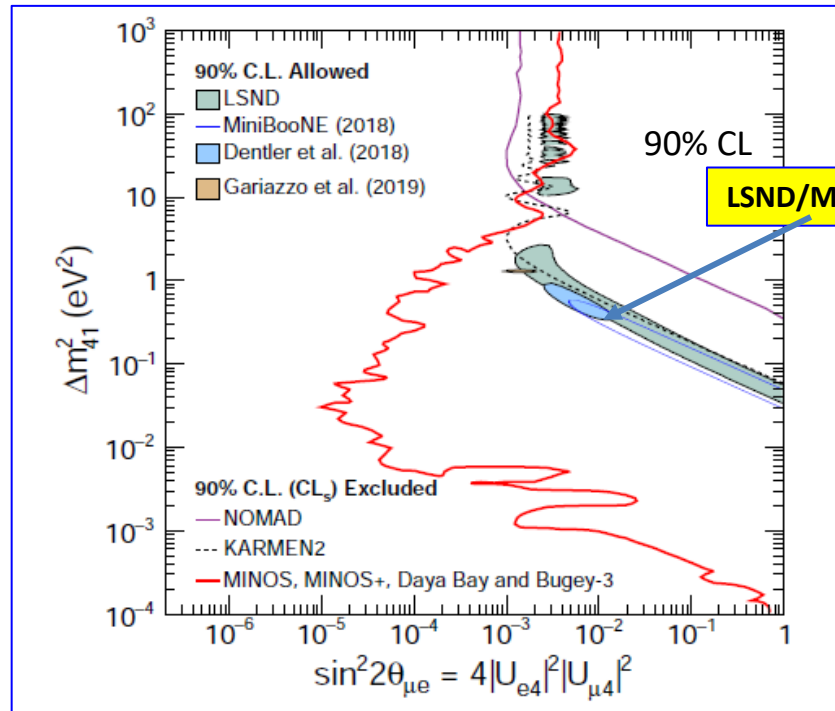
11 years of data taking, PRL 133 (2024) 201804



absence of sterile neutrino: $p=3.1\%$, no-zero fit significance: 2σ

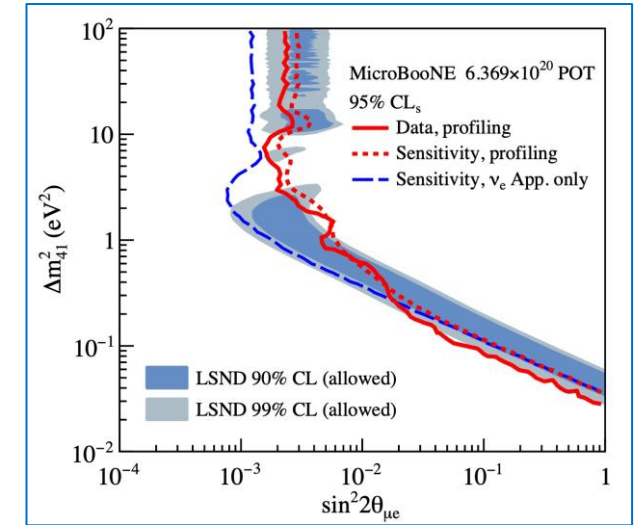
PRL 125 (2020) 131802

MINOS: $\nu_\mu \rightarrow \nu_\mu$ Daya Bay, Bugey-3: $\nu_e \rightarrow \nu_e$



PRL 130 (2023) 011801

MicroBooNE, , LAr TPC



$$\sin^2 2\theta_{e\mu} \simeq \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

Positive signal:

LSND/MiniBooNE

Negative:

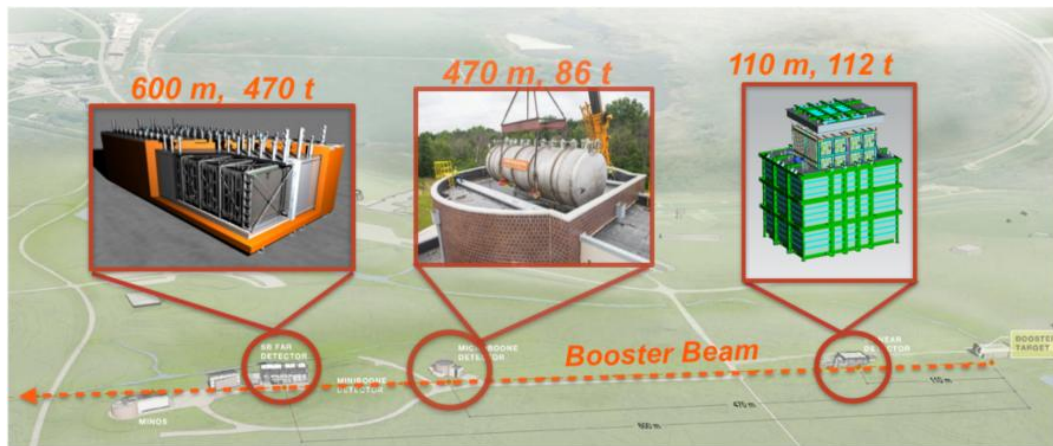
MINOS, Daya Bay/Bugey-3
IceCube



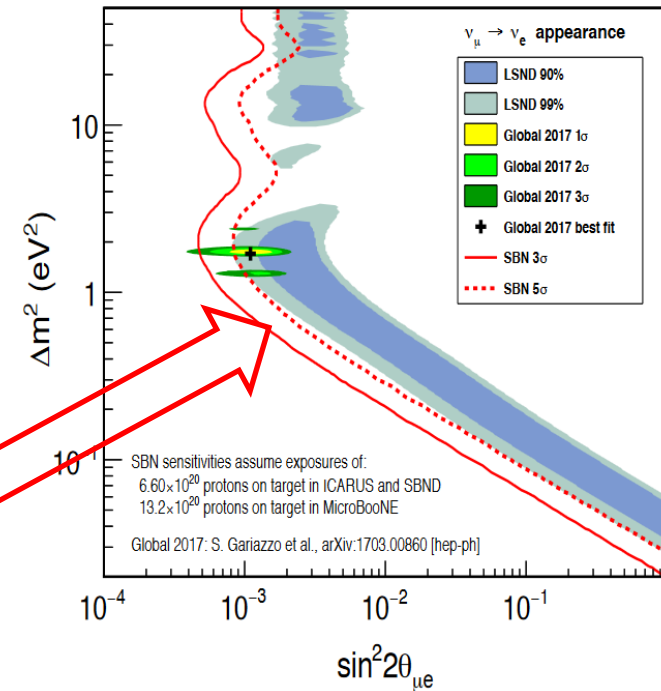
SBL experiments at FNAL

Detector	Distance from BNB Target	LAr Total Mass	LAr Active Mass
LAr1-ND	110 m	220 t	112 t
MicroBooNE	470 m	170 t	89 t
ICARUS-T600	600 m	760 t	476 t

arXiv:1503.01520



**Crucial (final) direct test
of LSND/MiniBooNE
anomaly?**



ICARUS: commissioning in 2022,
took data from Booster and NuMI beams in 2023

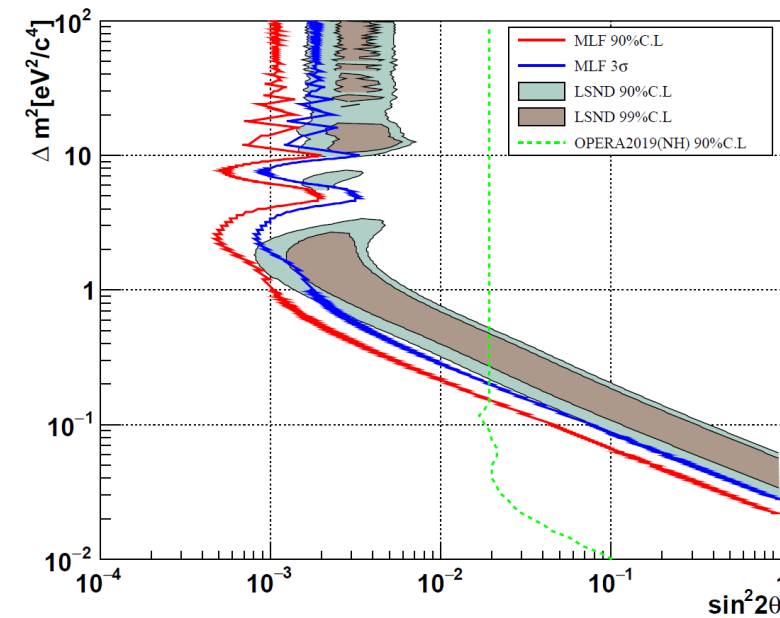
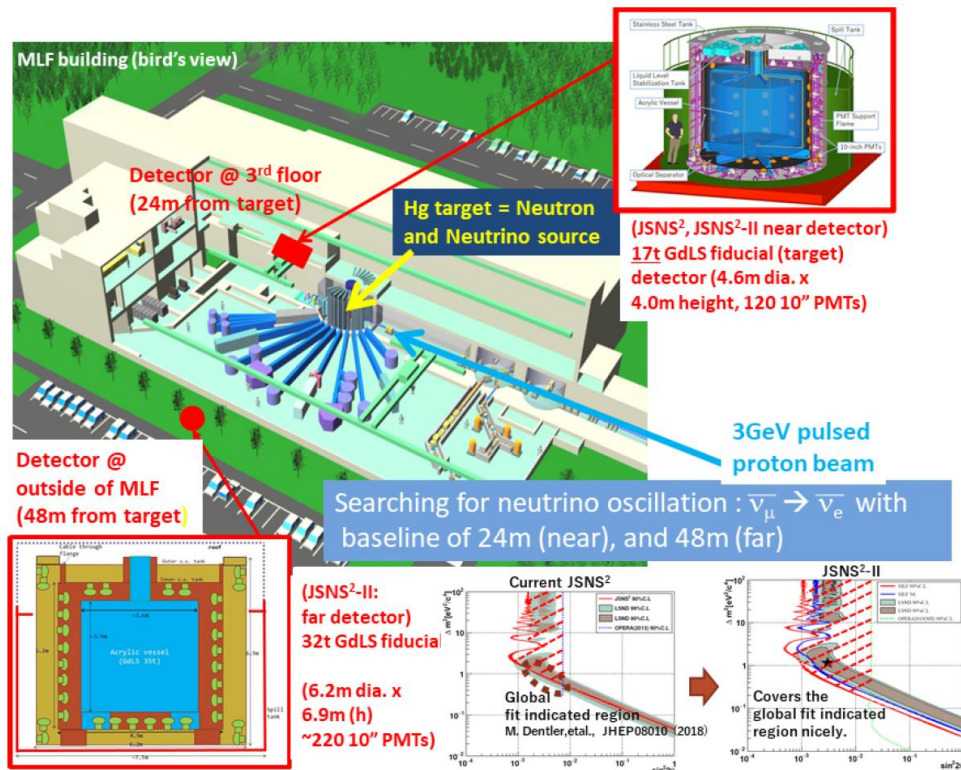
JSNS² at J-PARC

arXiv:2012.10807

Proposed in 2013, data taking begun in 2020

Short-pulsed 3GeV, 1 MW 3 GeV proton beam, 25 Hz repetition rate at J-PARC

Detector: gadolinium (Gd) loaded liquid scintillator (LS).





Conclusion/Perspectives

Neutrino is a unique laboratory to study Physics Beyond SM

CP violation and **Mass Ordering** – primarily targets of current (**T2K**, **NOvA**), and near future (**DUNE**, **HyperKamiokande**) long baseline accelerator experiments

Hint on **maximal CP** violation in **T2K**

CP conservation for NO and maximal CP violation for IO in **NOvA**

SuperKamiokande, **T2K** and **NOvA** prever **NO** of neutrino mass

Sterile neutrinos (LSND anomaly) will be probed at **FNAL** and **J-PARC**

Thank you for your attention