Physics with accelerator neutrinos

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Neutrino oscillations and mixing

Standard Model: neutrinos are *massless* particles

3 families

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \qquad U = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}$$

***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

$\theta_{23} \sim 45^0$

$$|\Delta m^2_{32}| \cong |\Delta m^2_{31}| = |\Delta m^2_{atm}| \approx 2.4\times10^{-3}\,\mathrm{eV}^2$$

T2K; Daya Bay, RENO, Double Chooz

$\theta_{13} \approx 8.5^0$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

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

Solar experiments, SuperK, KamLAND

$\theta_{12} \approx 34^0$

$$\Delta m^2_{21} = \Delta m^2_{sol} \approx 7.5\times10^{-5}\,\mathrm{eV}^2$$

two independent Δm^2

Neutrino physics: open questions

Parameter/Feature	**Instrument/Method**
CP violation	**accelerator neutrinos**
Neutrino mass ordering	**atmospheric, reactor, accelerator neutrinos, cosmology**
Absolute scale of neutrino mass	**β decay, $0\nu2\beta$ decay, cosmology**
Neutrino nature: Dirac or Majorana	**$0\nu2\beta$ decay**
Sterile neutrinos	**β decay, $0\nu2\beta$ 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

$$J_{CP} = \mathrm{Im}(U_{e1}U_{\mu2}U^*_{e2}U^*_{\mu1}) = \mathrm{Im}(U_{e2}U_{\mu3}U^*_{e3}U^*_{\mu2})$$
$$= \cos\theta_{12}\sin\theta_{12}\cos^2\theta_{13}\sin\theta_{13}\cos\theta_{23}\sin\theta_{23}\sin\delta_{CP}$$

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

Mixing matrix

neutrinos

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

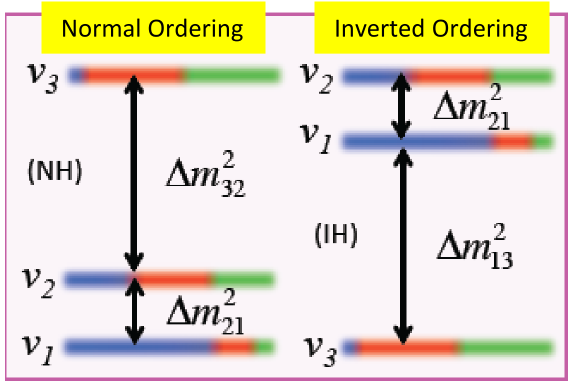
quarks

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

Quark sector: $J_{CP} \approx 3\times10^{-5}$

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

- Neutrino mass ordering (NMO)



IO: $\Sigma m_i \approx 100\ meV$
NO: $\Sigma m_i \approx 60\ meV$

CPV and Mass Ordering

New source of CP violation in lepton sector:

→ will open a new path to explain BaU through leptogenesis ?

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

Type I See-saw model

SM + 3 heavy (RH) Majorana neutrinos N_1, N_2, N_3
with masses $M_1 << M_2 < M_3$
Leptogenesis takes place at temperatures $10^9\ GeV < T < M_1$

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

M_1 = (3-5)x10^{11} GeV

BAU can be reproduced, if

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

Daya Bay: $\sin\theta_{13} = 0.15$, if $\sin\delta_{CP} > 0.75$ → **$|J_{CP}| > 0.024$**

Mass Ordering

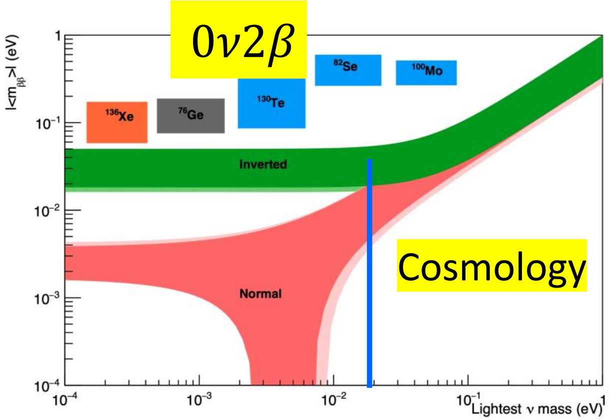
NO or IO ?

Impact on

- Cosmology
- $0\nu2\beta$ decay
- Direct mass measurement
- Cosmic neutrino background (CνB)

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

$0\nu2\beta$
Experiment: $m_{\beta\beta}$ < 28-122 meV (90%CL)
Theory **IO**: $m_{\beta\beta} \simeq$ 20-50 meV



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

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

$$P(\nu_\mu \rightarrow \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\frac{\Delta m_{13}^2 L}{4E_\nu} \times \left[1 + \frac{2a}{\Delta m_{13}^2}(1 - 2s_{13}^2)\right]$$
$$+ 8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\frac{\Delta m_{23}^2 L}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}\sin\frac{\Delta m_{12}^2 L}{4E_\nu}$$
$$- 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\frac{\Delta m_{23}^2 L}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}\sin\frac{\Delta m_{12}^2 L}{4E_\nu}$$
$$+ 4s_{12}^2 c_{13}^2(c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\frac{\Delta m_{12}^2 L}{4E_\nu}$$
$$- 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E_\nu}\frac{aL}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}(1 - 2s_{13}^2),$$

leading term

- θ_{13}
- **CP-even**
- **CP-odd**
- **Solar**
- **Matter**

$$s_{ij} = \sin\theta_{ij} \qquad c_{ij} = \cos\theta_{ij}$$

Matter effect

$$a[eV^2] = 2\sqrt{2}G_F n_e E_\nu = 7.6\times10^{-5}\rho\left[g/cm^3\right]E_\nu[GeV]$$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \Rightarrow a \rightarrow -a \qquad \delta \rightarrow -\delta$$

change sign for NH → 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 →

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

Matter →

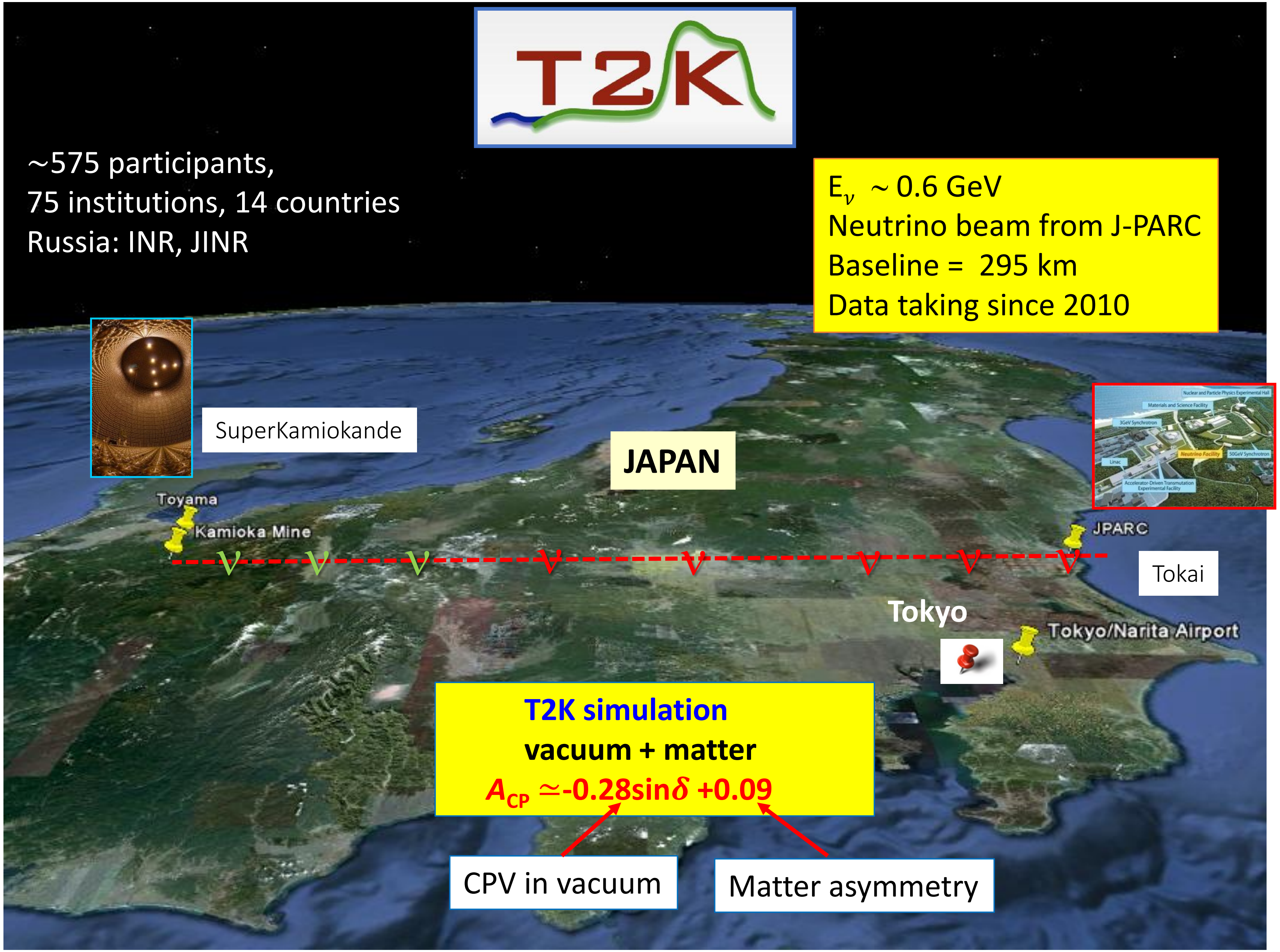
Neutrino energy tuned to oscillation maximum with atm parameters

$$A_{CP} \equiv \left. \frac{P_{(\nu_\mu \to \nu_e)} - P_{(\bar{\nu}_\mu \to \bar{\nu}_e)}}{P_{(\nu_\mu \to \nu_e)} + P_{(\bar{\nu}_\mu \to \bar{\nu}_e)}} \right|_{\frac{|\Delta m^2_{31}| L}{4E_\nu} \approx \pi/2} \sim -\frac{\pi \sin 2\theta_{12}}{\tan \theta_{23} \sin 2\theta_{13}} \frac{\Delta m^2_{21}}{|\Delta m^2_{31}|} \sin \delta_{CP} \pm \frac{L}{2800\ \mathrm{km}}$$

Matter effect
"+" - NO
"-" - IO

$A_{CP} \neq 0$ → $\delta_{CP} \neq 0$ → CP violation

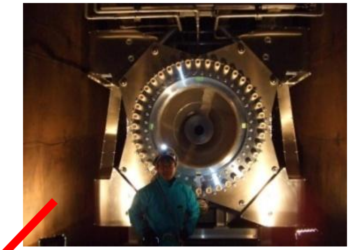
Sensitivity to CP phase increases using the value of θ_{13} obtained in reactor experiments

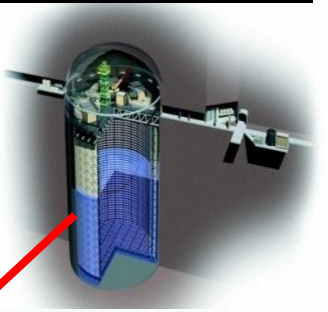

T2K
~575 participants,
75 institutions, 14 countries
Russia: INR, JINR
E_ν ~ 0.6 GeV
Neutrino beam from J-PARC
Baseline = 295 km
Data taking since 2010
SuperKamiokande
JAPAN
Toyama
Kamioka Mine
JPARC
Tokai
Tokyo
Tokyo/Narita Airport
T2K simulation
vacuum + matter
$A_{CP} \simeq -0.28\sin\delta + 0.09$
CPV in vacuum
Matter asymmetry

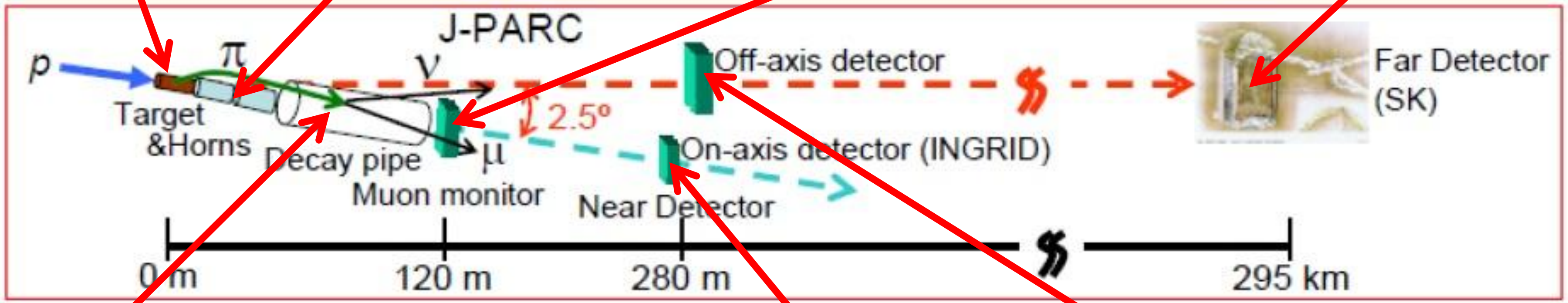
Experiment T2K

LBL accelerator experiment

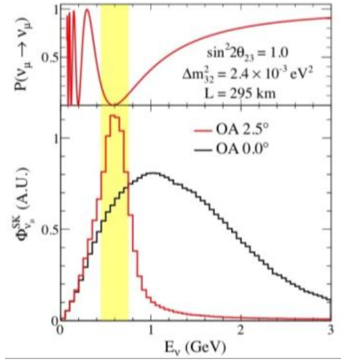
Far neutrino detector
SuperKamiokande



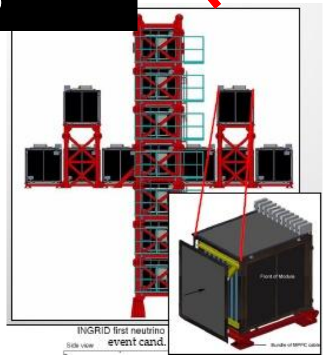




Off-axis neutrino
beam

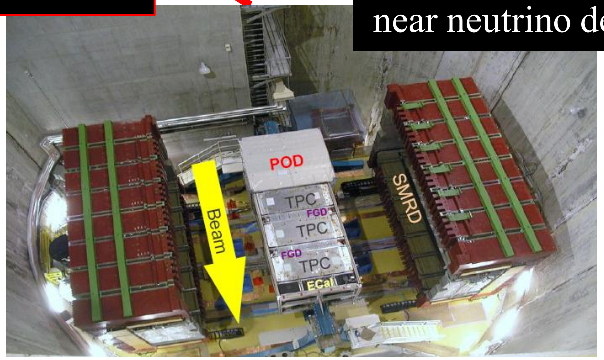


Neutrino monitor
INGRID



ND280

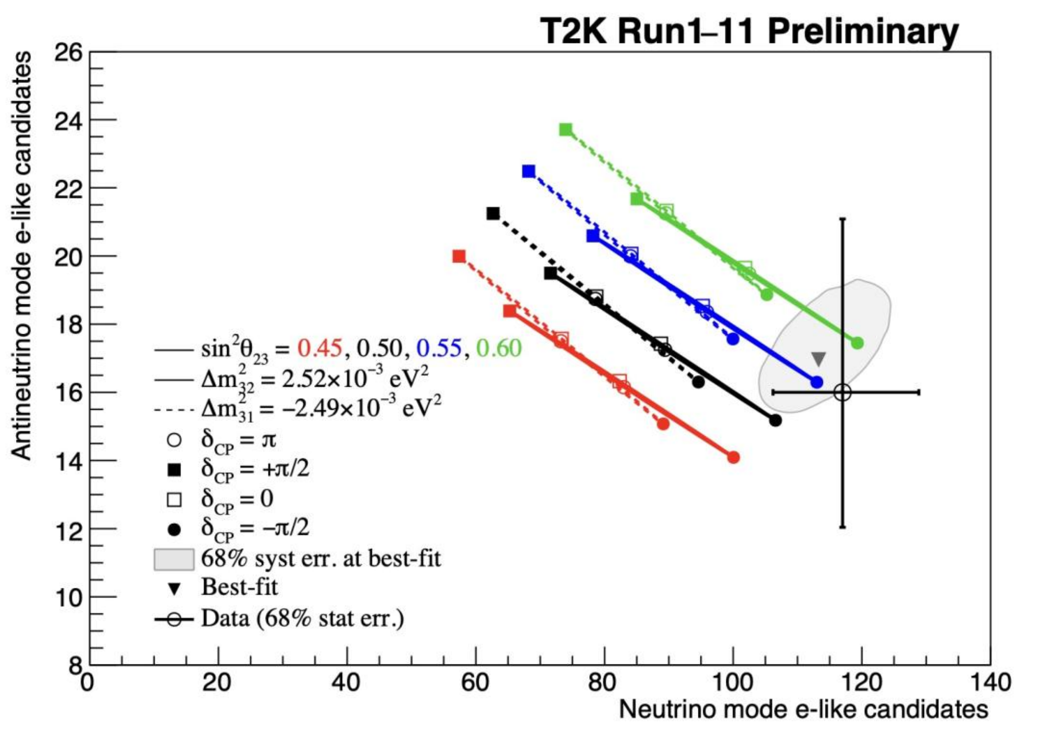
Off-axis
near neutrino detector

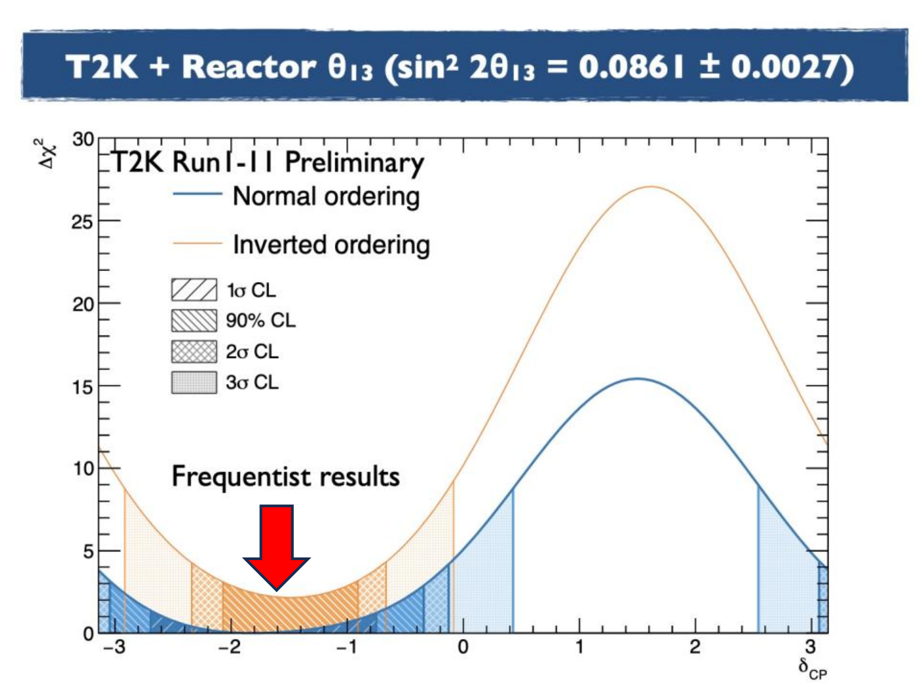


T2K: hint of CP violation

ν- mode: 21.4x10^{20} POT
$\bar{\nu}$- mode: 16.3x10^{20} POT

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



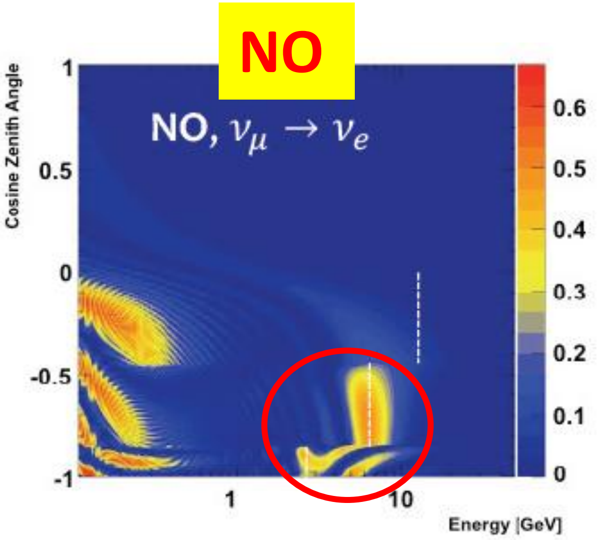


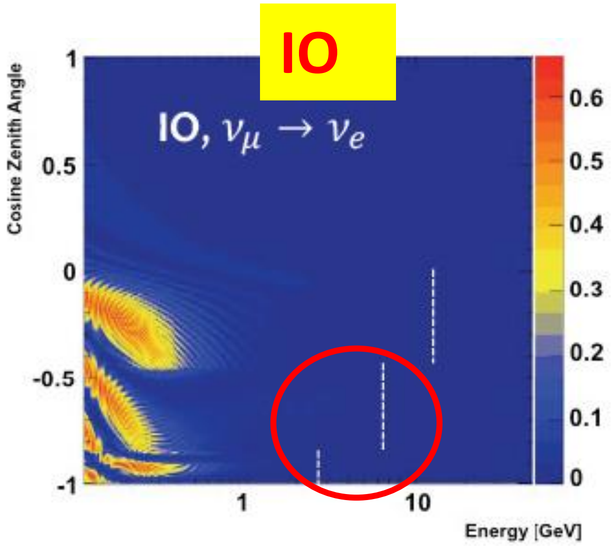
Best fit: $\delta_{CP} \sim -\pi/2$ → close to maximum CP violation

Normal mass ordering is preferred at 80% CL

CP and MO: SuperKamiokande + T2K

SuperKamiokande: enhancement of ν_e in NO; enhancement of $\bar{\nu}_e$ in IO

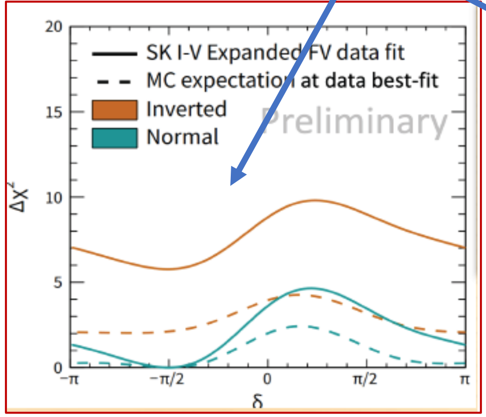


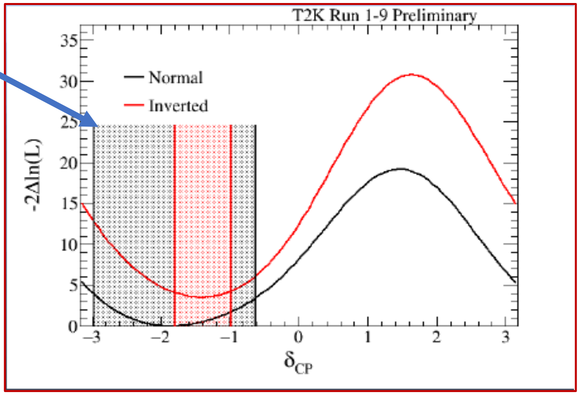


SuperKamiokande
- Atmospheric neutrino sensitive to mass ordering due to matter effect
- MSW resonance at ~ 10 GeV

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

SuperK is sensitive to **MO**
T2K is sensitive to **CP**





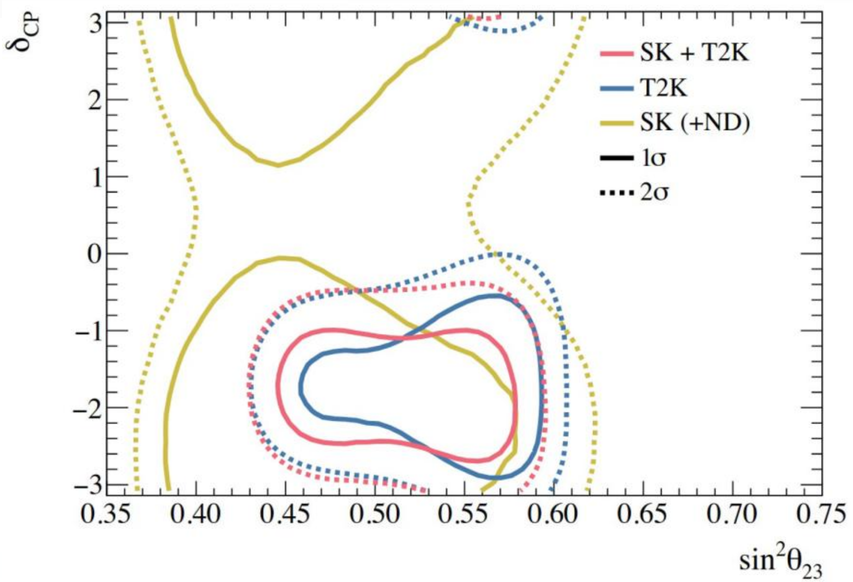
Joint analysis SuperK+T2K
- increases sensitivity to MO
- slightly increases sensitivity to CPV

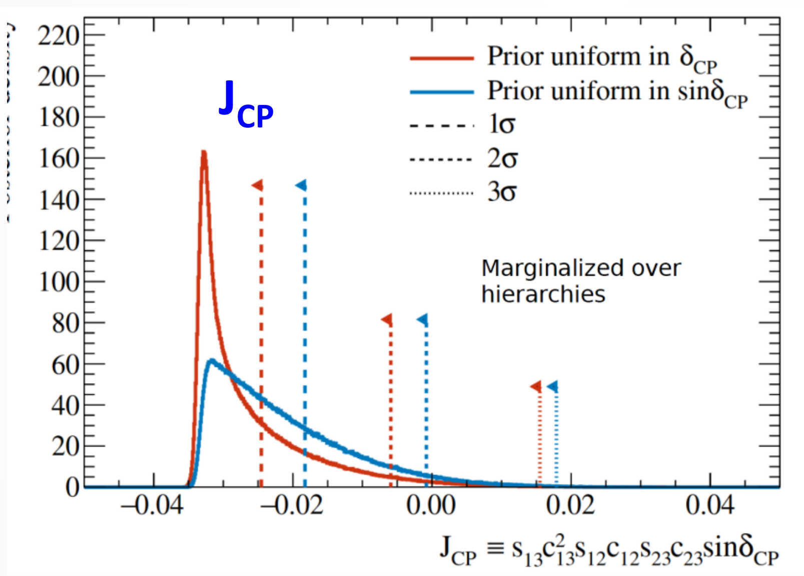
CP: Joint SuperK/T2K analysis

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



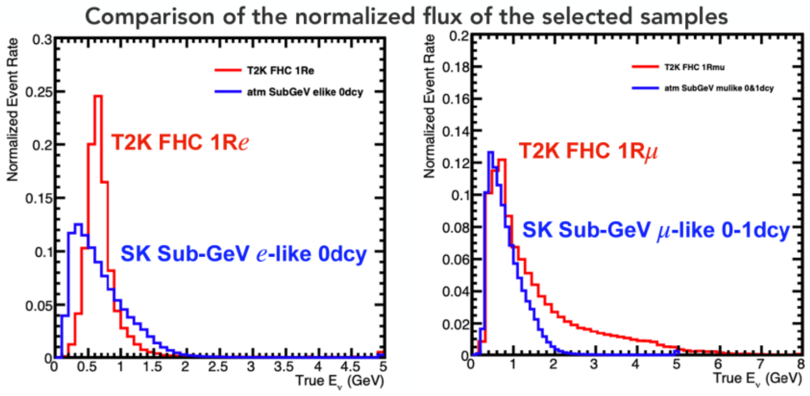


Two experiments share the same detector (SK)

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 and SuperK have different preference for θ_{23} and no preference in joint fit

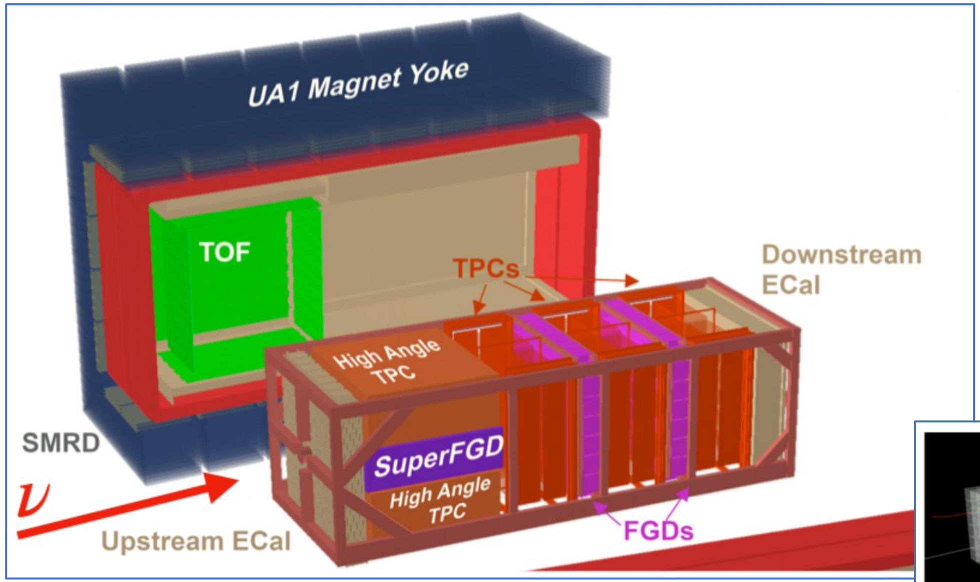
T2K: ND280 upgrade

Current ND280 ⇒ *Upgraded ND280*

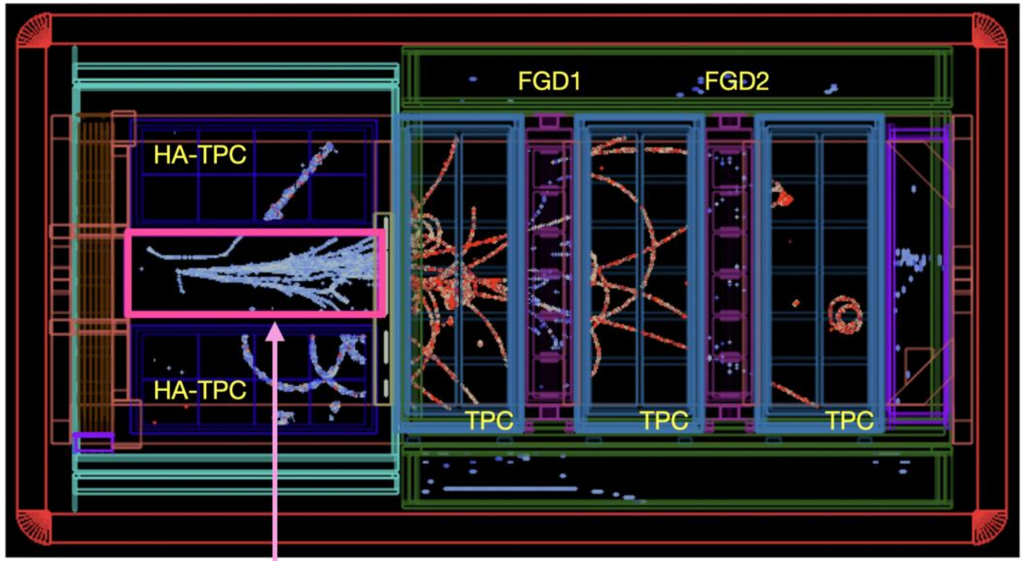
- **Improve acceptance for high angle and backward tracks**
- **High precision probe of the nuclear effects → reduced systematics**
- **Detection of short proton tracks which is very important for T2K analysis**
- **Reconstruction of the neutrino energy by time-of-flight**
- **TOF Detector separates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

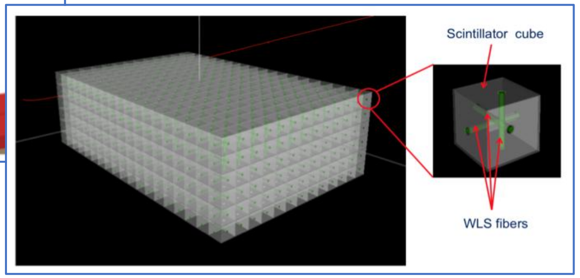
All new elements installed and commissioned with neutrino beam. Data taking started in 2024

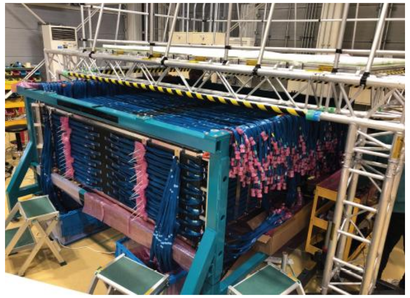
SuperFGD:
~100 participants from Russia, Japan, US, Switzerland, France, Spain
~35 from **INR, JINR, LPI**



3D highly segmented neutrino detector
- mass 2 t
- 2x10^6 optically isolated 1cm^3 scintillators
- WLS readout

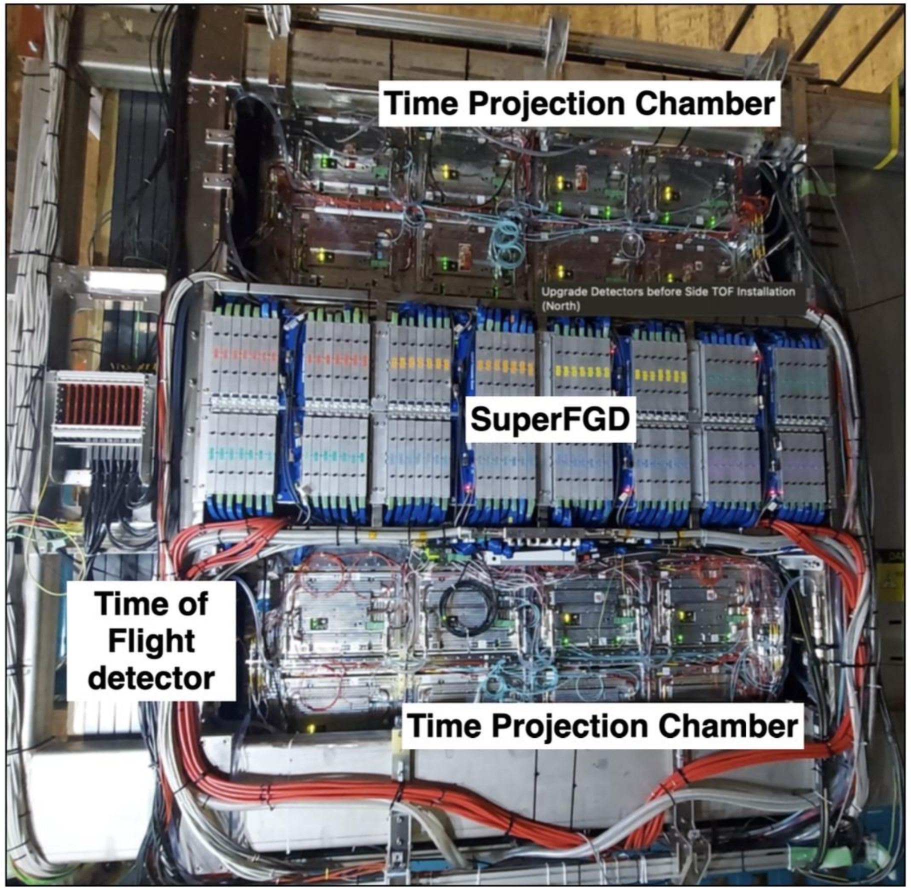






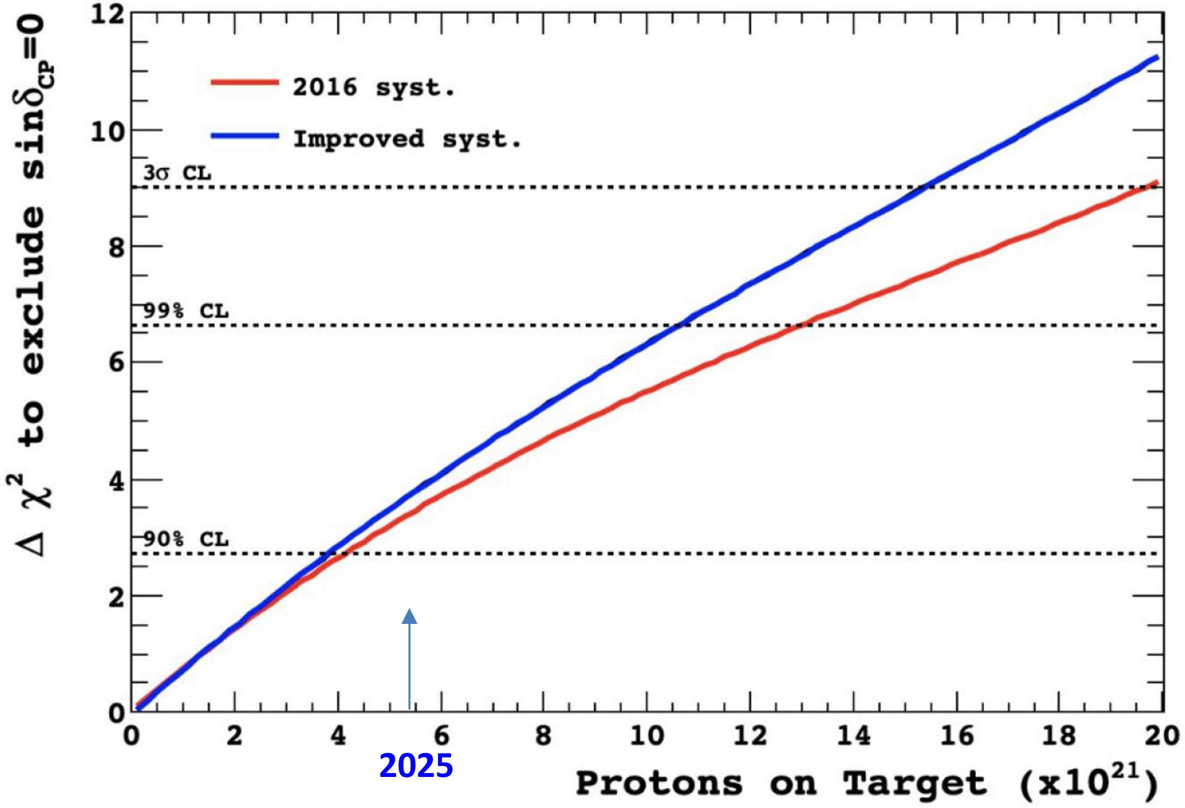
T2K perspectives

Upgraded ND280



Goal to reduce systematics
in oscillations to ~3% level

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

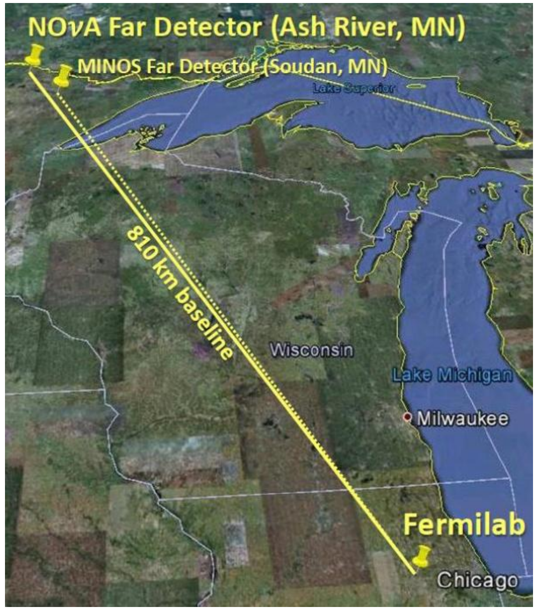


Experiment NOvA

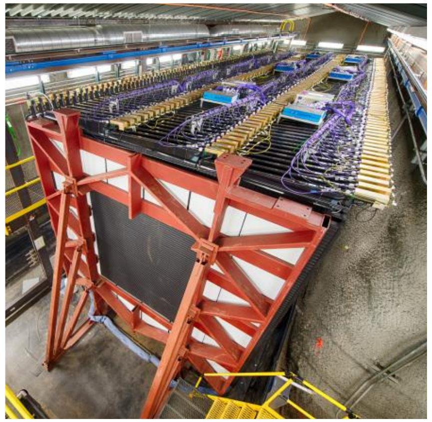
NOvA (USA)

Taking data since 2014

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



Near Detector



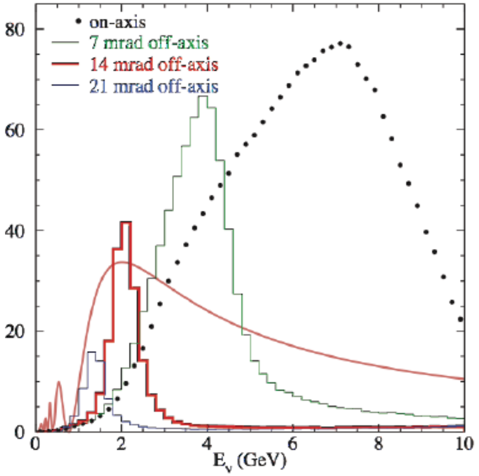
Neutrino beam from FNAL to Ash River
Baseline 810 km
Neutrino beam 14 mrad off-axis
Far detector : 14 kt fine-grained calorimeter
65% active mass
Near Detector: 0.3 kt fine-grained calorimeter

Protons on target

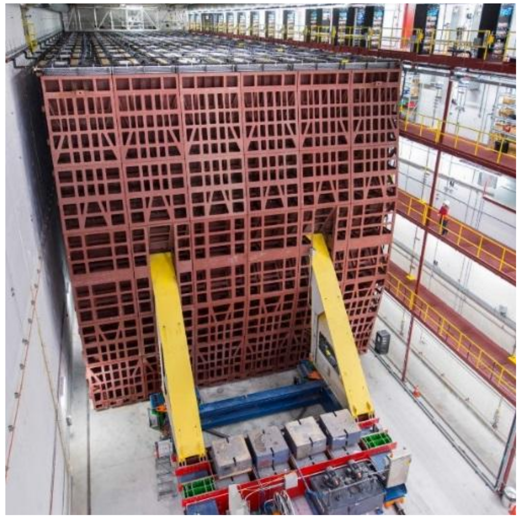
ν: $26.6\text{x}10^{20}$ POT

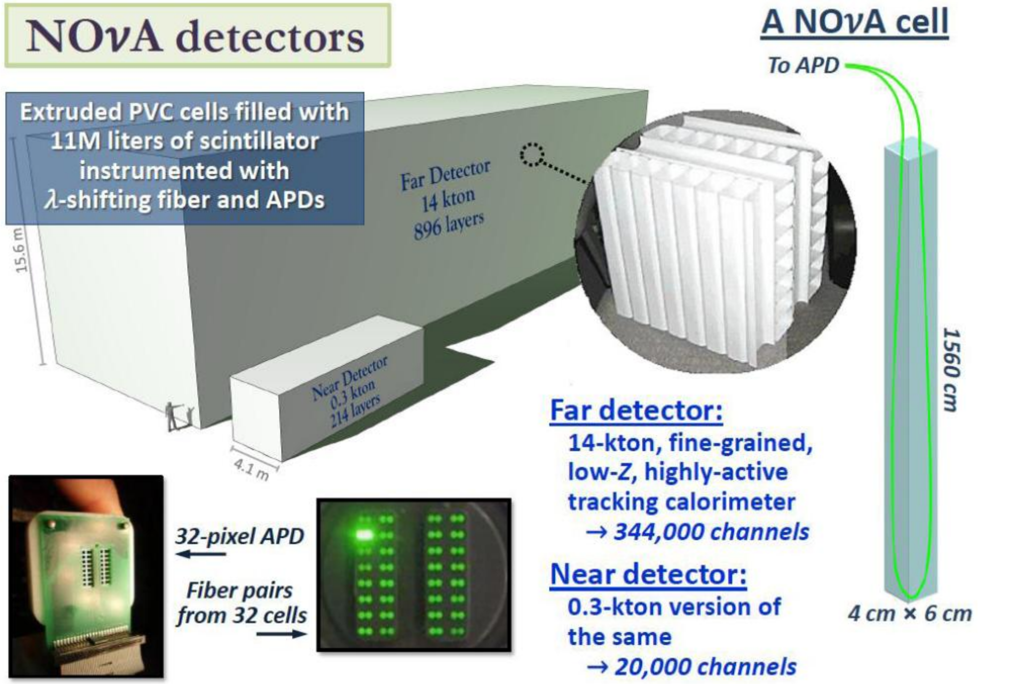
$\bar{\nu}$: $12.5\text{x}10^{20}$ POT

Neutrino beam



Far Detector



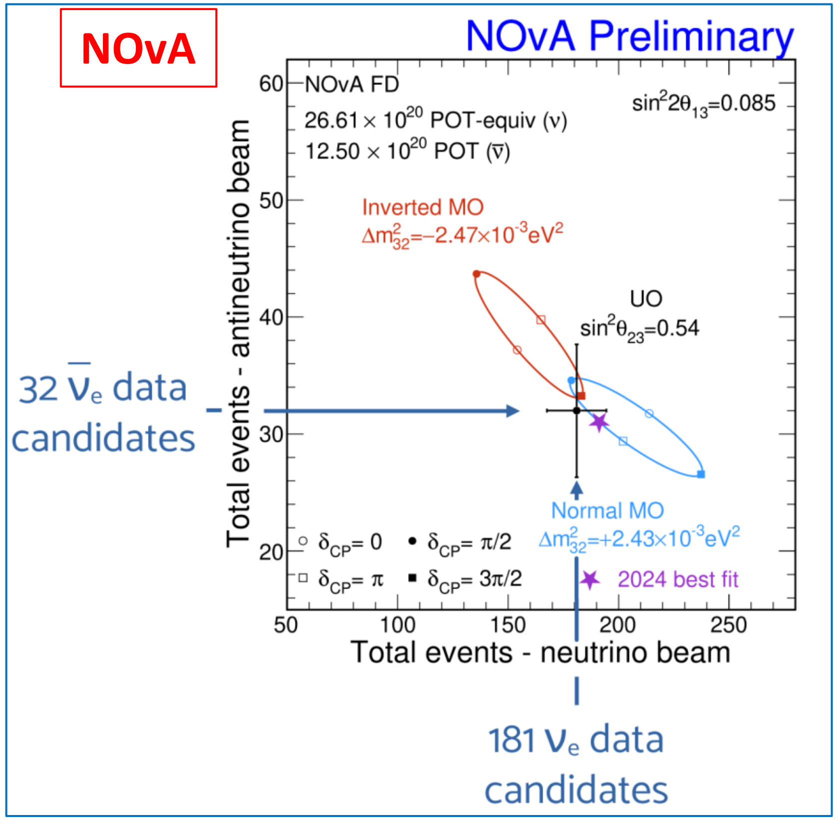


NOvA CPV result

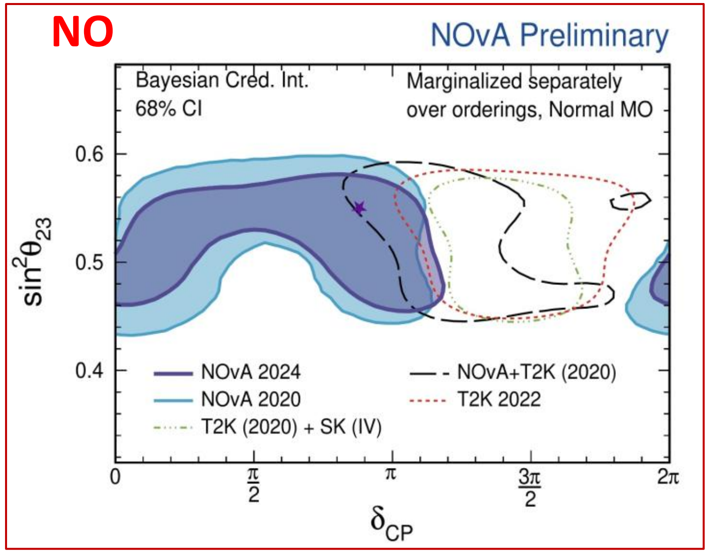
J.Wolcott, Neutrino2024

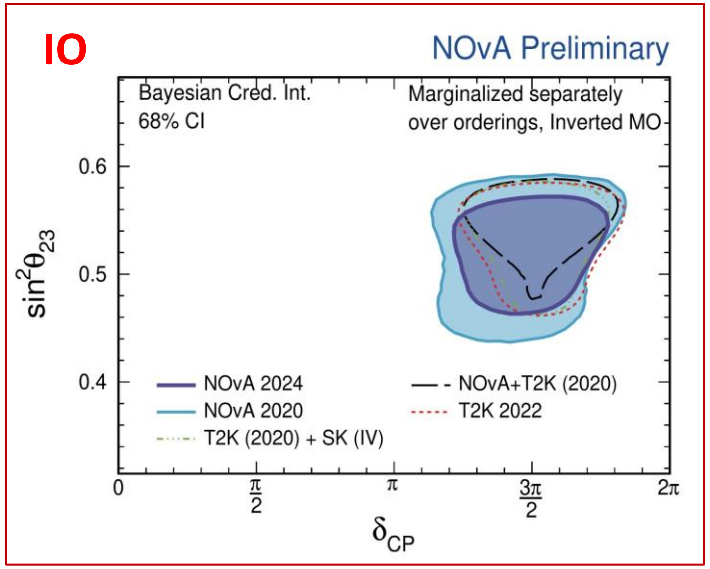
Protons on target
in 2014-2023
ν: 26.61x10^{20} POT
$\bar{\nu}$: 12.5x10^{20} POT

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**



NOvA data are in the region where
CP violation and matter effect degenerate





T2K and NOvA: CP and MO

T2K →

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

NOvA →

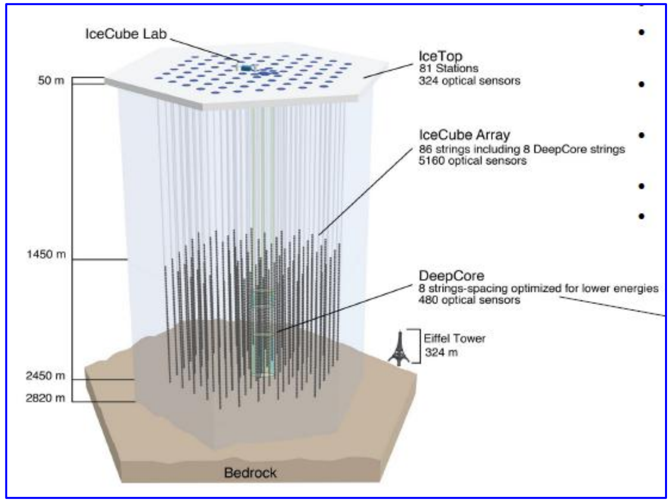
Best fit $\delta = 0.82\pi$
Exclude IH $\delta = \pi/2$ at > 3σ
Disfavor NH $\delta = 3\pi/2$ at $\sim 2\sigma$

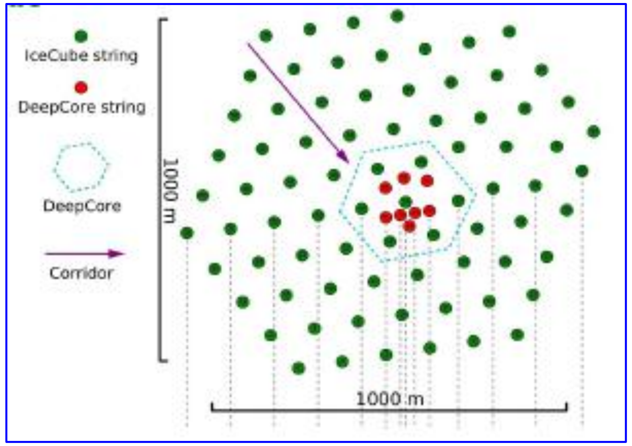
NOvA ($\nu + \overline{\nu}$) prefers:
Normal Ordering
CP conservation
Octants ~degenerate

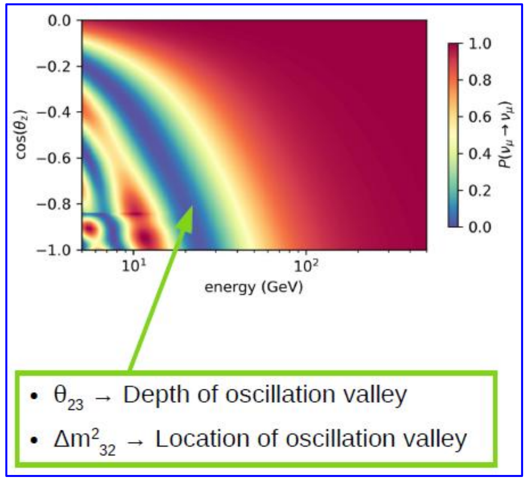
T2K ($\nu + \overline{\nu}$) prefers:
Normal Ordering
$\delta \sim -\pi/2 (\frac{3\pi}{2})$ **(max CPV)**
2nd octant

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

IceCube DeepCore: $\nu_\mu \to \nu_\mu$

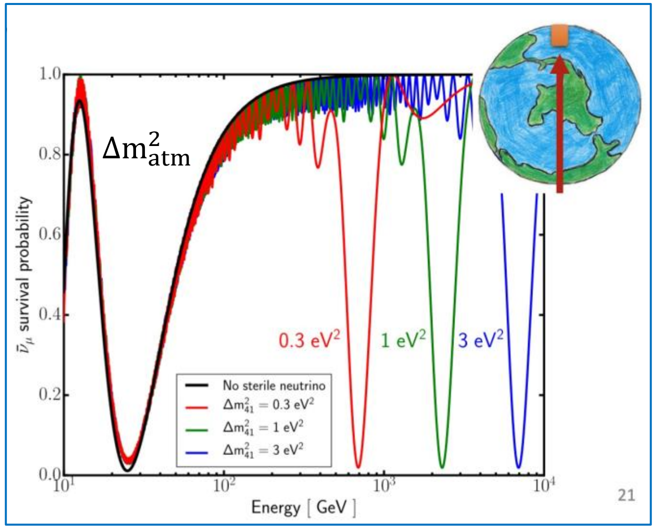


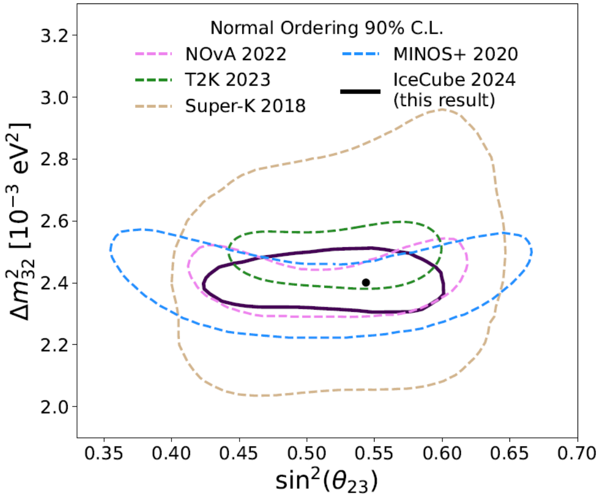




J.P. Yanez, Neutrino2024

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

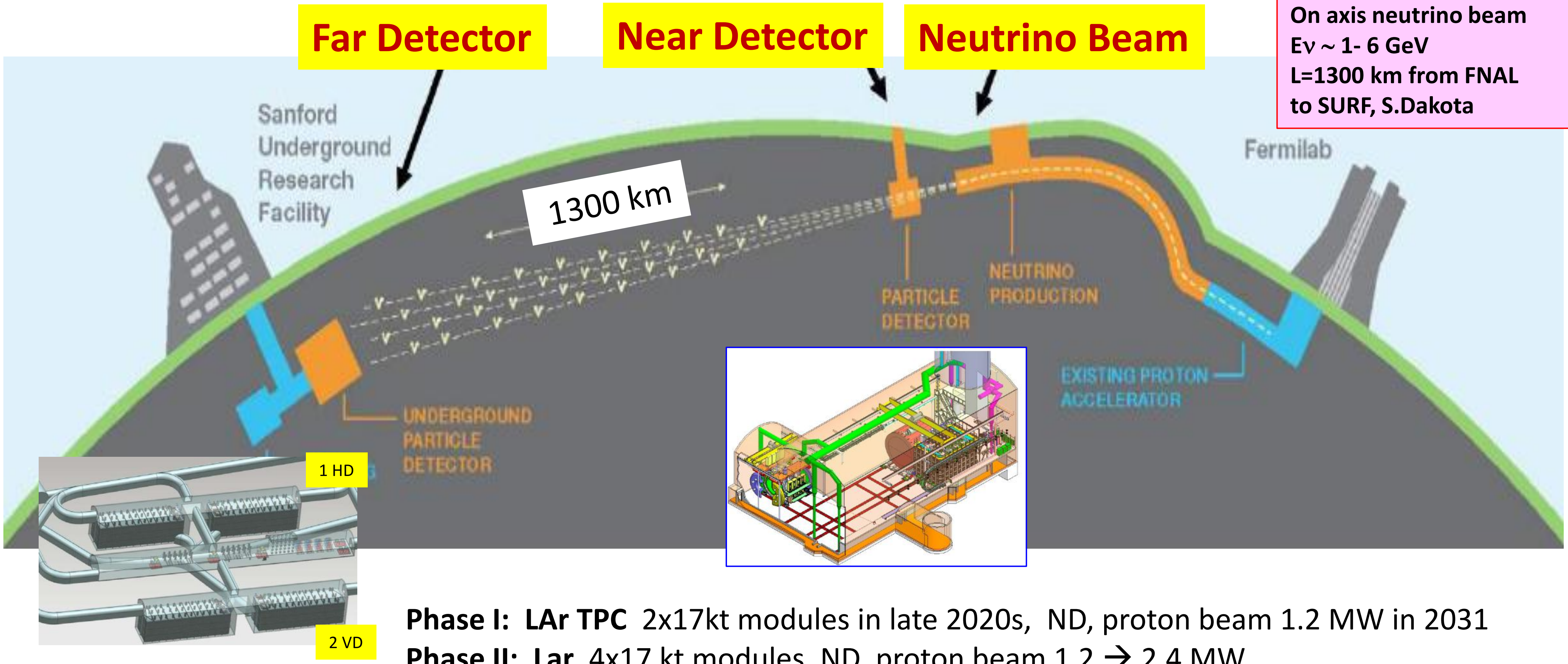
Future accelerator projects DUNE and Hyper-Kamiokande

LBNF/DUNE

USA, Fermilab

>1400 collaborators from ~200 institutions

E_p = 60-120 GeV
Beam power 1.2 -> 2.4 MW
On axis neutrino beam
Eν ~ 1- 6 GeV
L=1300 km from FNAL
to SURF, S.Dakota

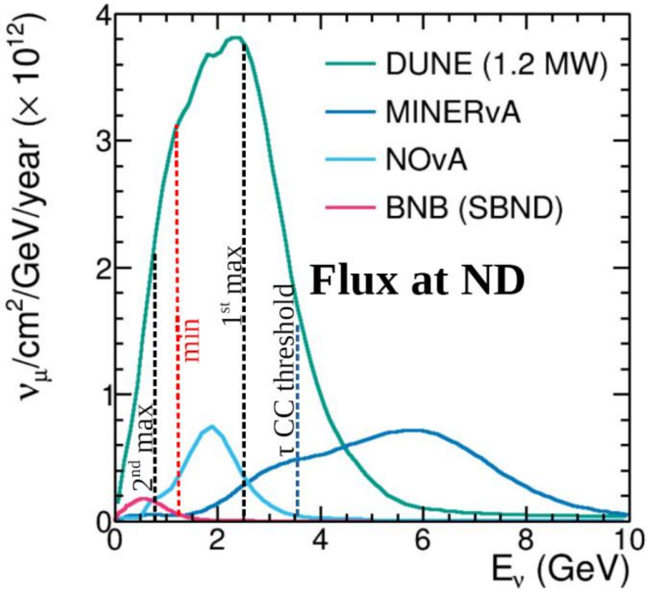


Phase I: LAr TPC 2x17kt modules in late 2020s, ND, proton beam 1.2 MW in 2031
Phase II: Lar 4x17 kt modules, ND, proton beam 1.2 → 2.4 MW

DUNE: beam and detectors

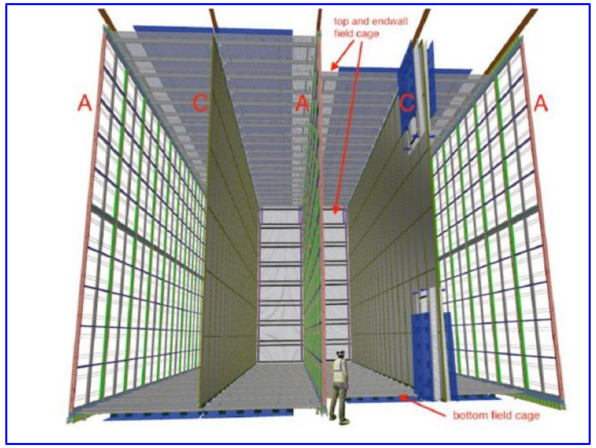
DUNE Far Detector LAr TPC's

On-axis neutrino beam

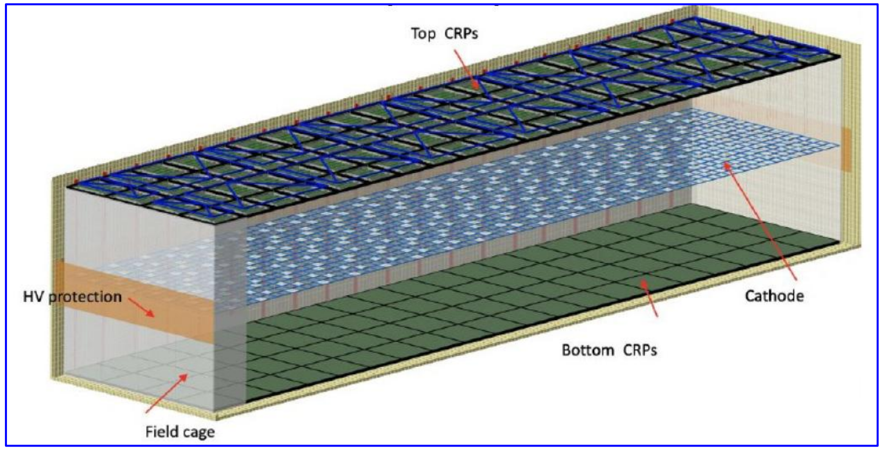


- neutrino flux at 0.5-3.5 GeV
- measurements at 1st (2.54 GeV) and 2nd (0.8 GeV) oscillation maxima are possible

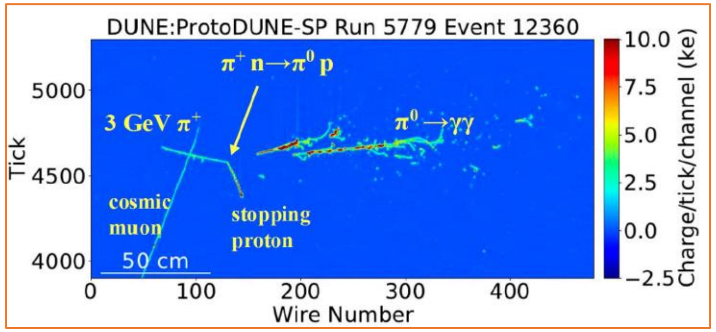
Horizontal drift with 2 central cathodes

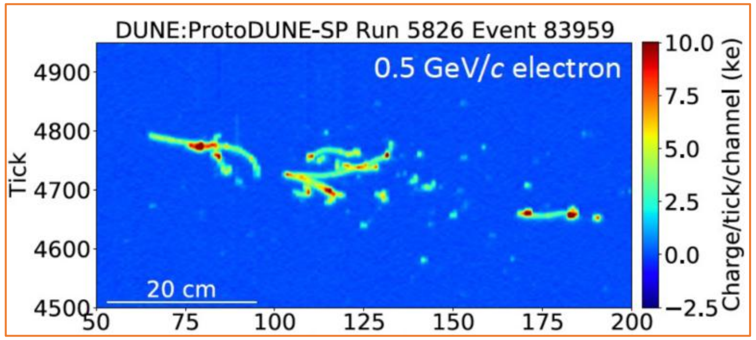


Vertical drift with 1 central cathode



ProtoDUNE data at CERN





DUNE: CP sensitivity

DUNE Collaboration, 2006.16043

Staging approach

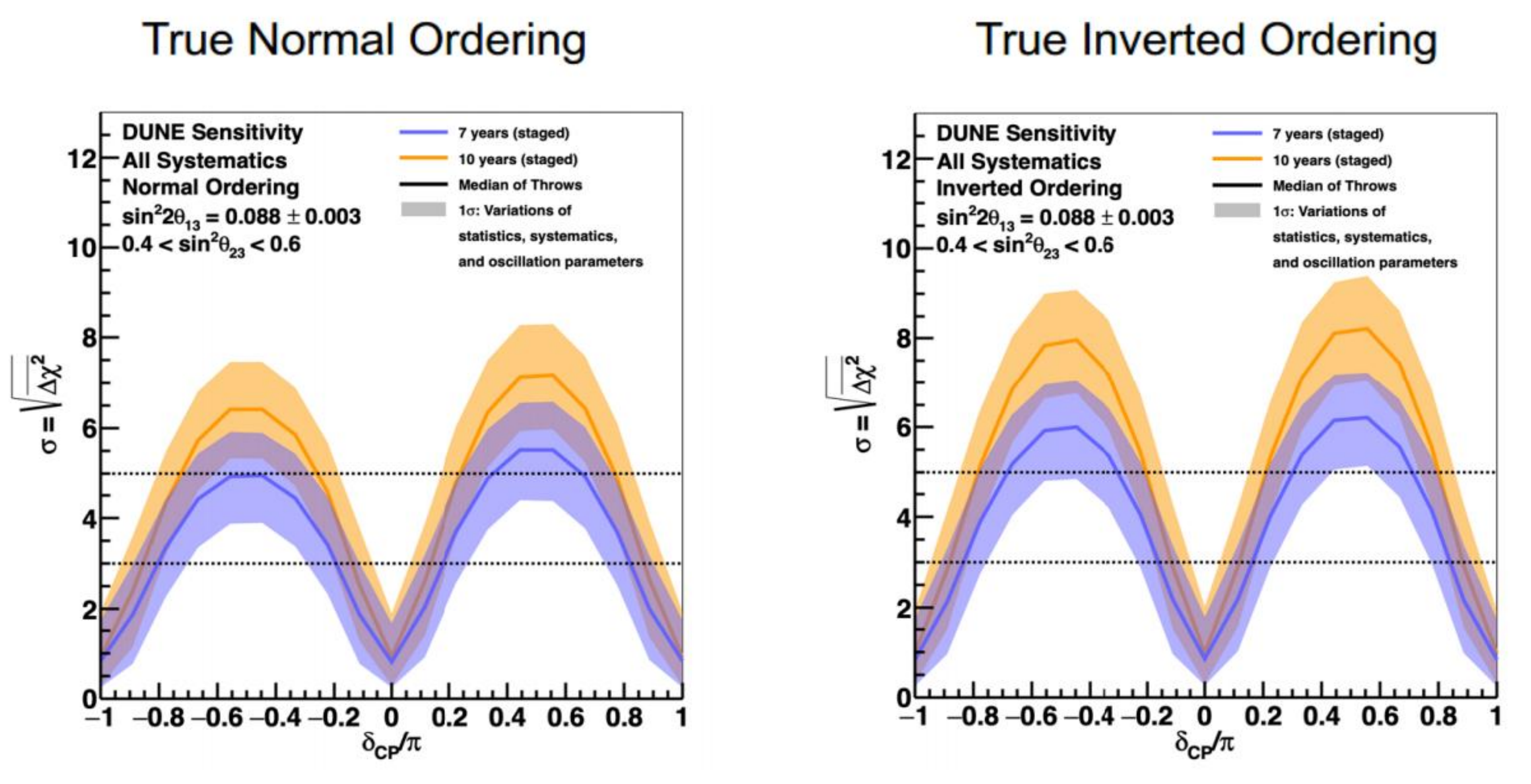
Sensitivity to δ_{CP}

- 7 years data taking
- 10 years data taking

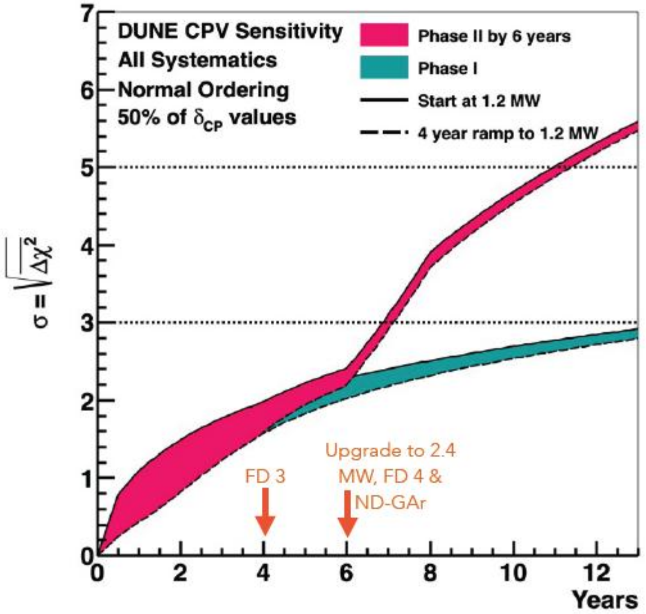
ν : $\bar{\nu}$ = 50% : 50%

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



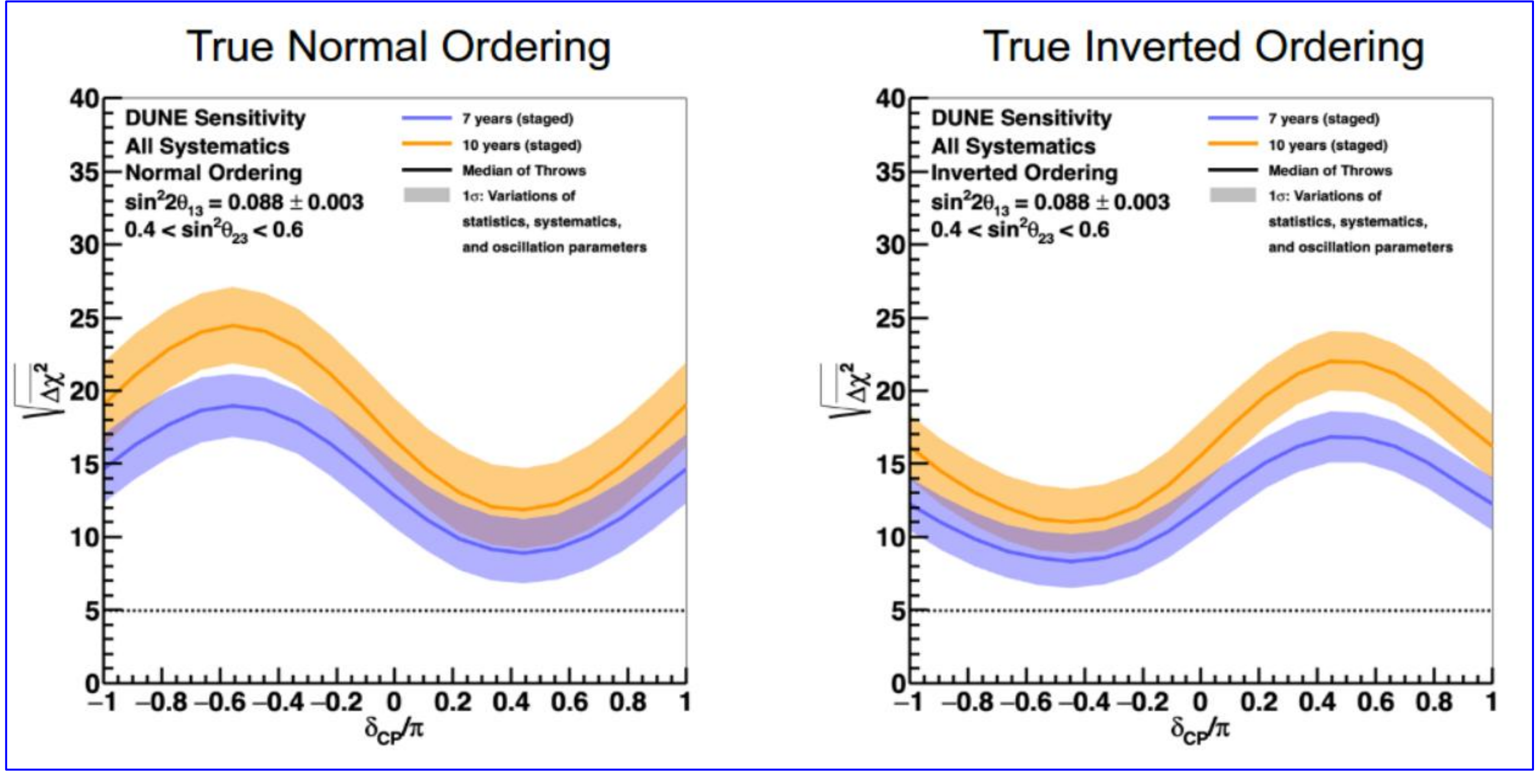
A.Booth, ICHEP2022



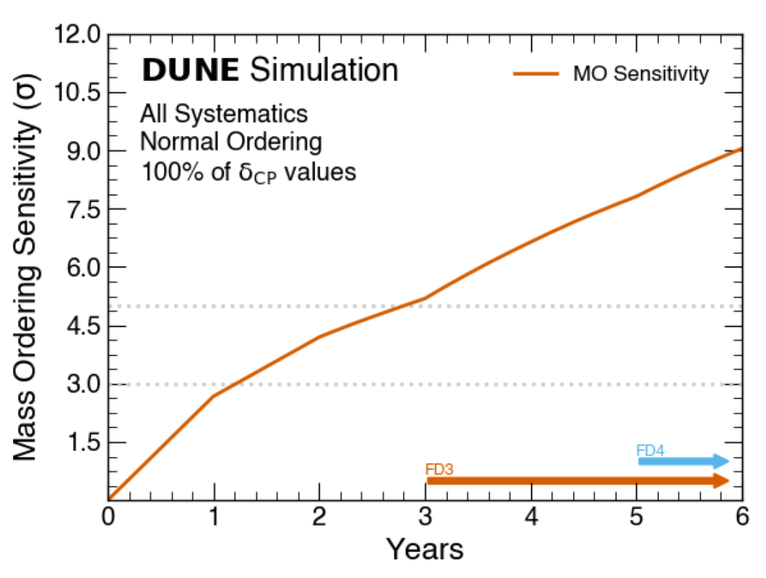
DUNE: Mass Ordering

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

DUNE Collaboration, 2006.16043

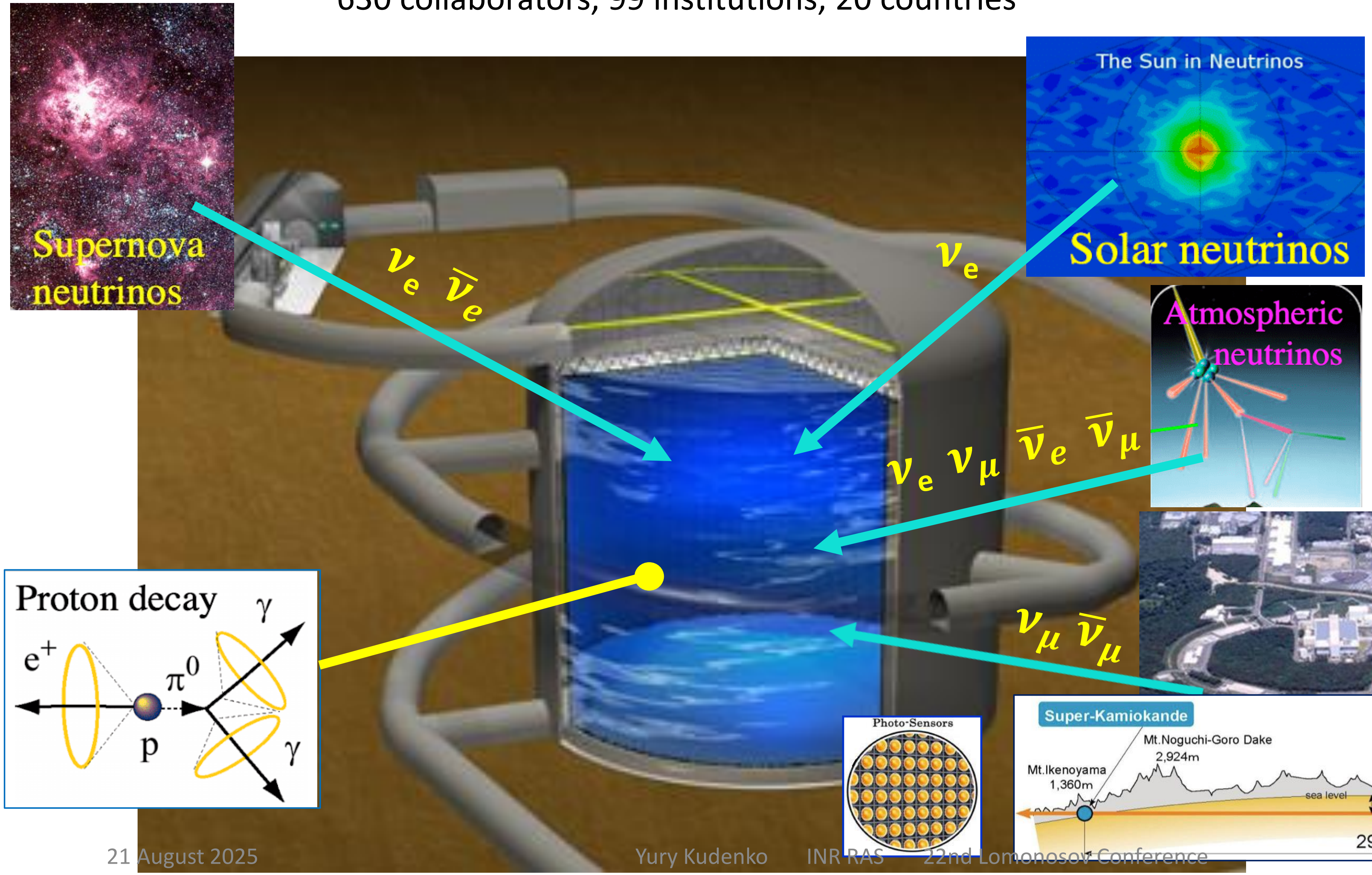


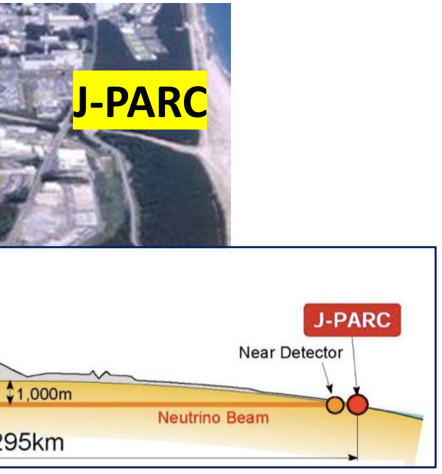
> 5σ discovery
for all possible δ_{CP} values
after 3 years of data taking



Hyper-Kamiokande

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





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

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**

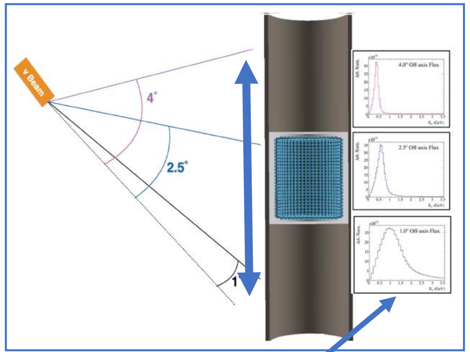
Existing (T2K+upgrade) ND **at 280 m from target**

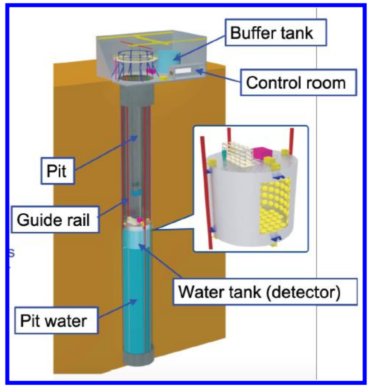
IWCD: Movable water Cherenkov detector

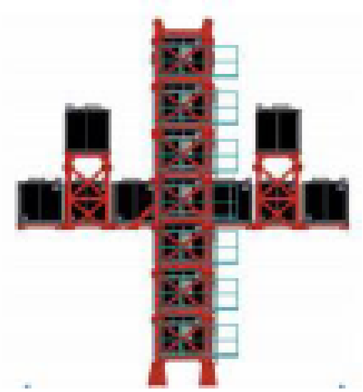
IWCD

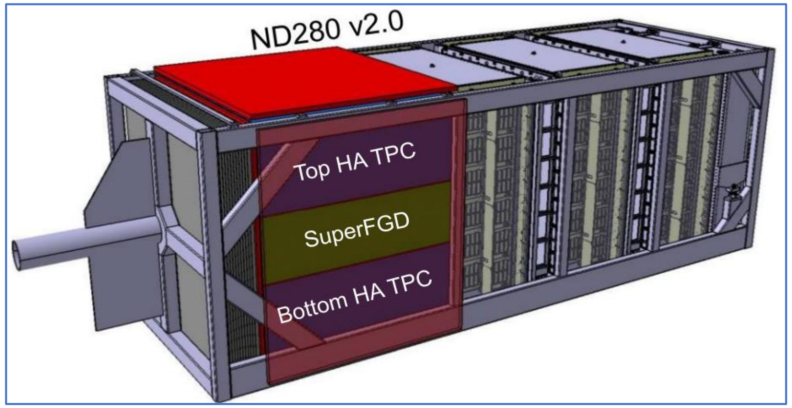
INGRID

ND280 upgraded









Neutrino spectra

~1 kt water Cherenkov detector
Photocesors: muli-PMT modules

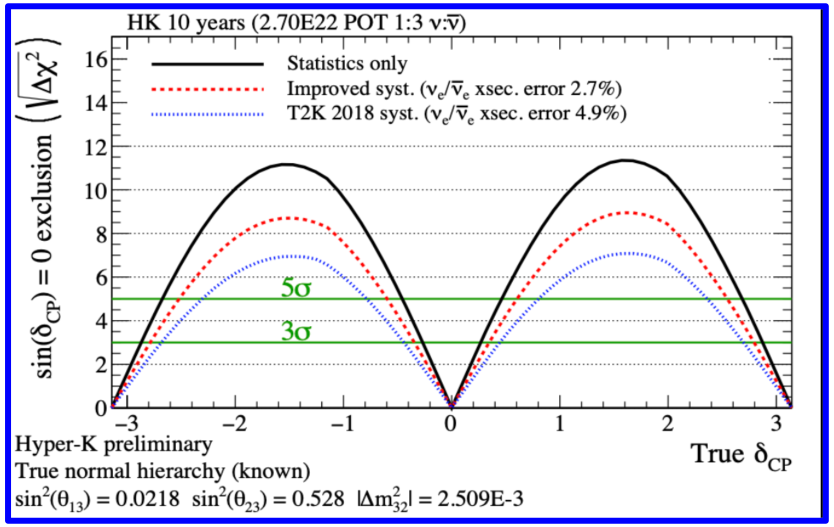
Neutrino on/off axis beam monitor

Magnetized off-axis near detector

Sensitivity to CP violation (I)

Hyper-Kamiokande, arXiv:1805.04163

Projected HyperK sensitivity to CP violation

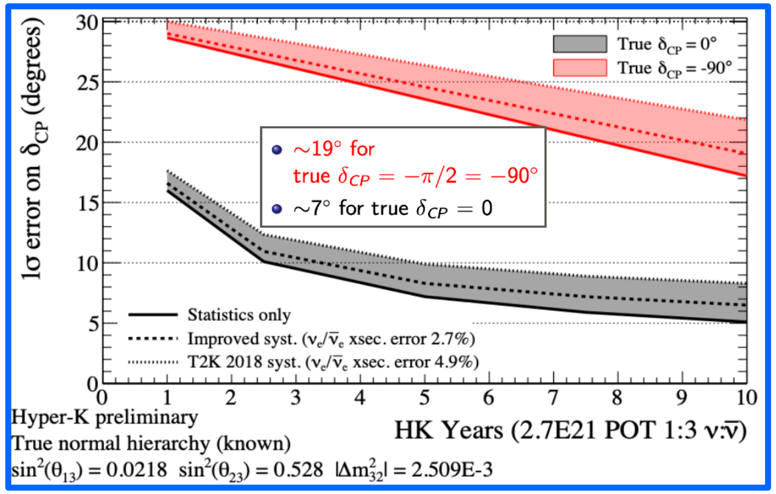


- 10 years of data taking,
- 1.3 MW beam power → 2.7x10^{22} POT

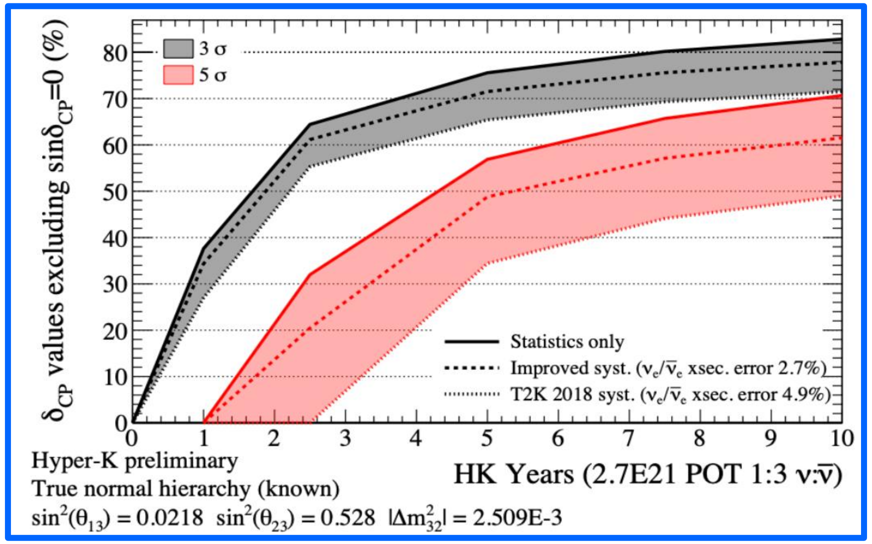
Expected number of events at HyperK for $\nu_e : \bar{\nu}_e = 1:3$ and $\sin\delta_{CP} = 0$

2300 ν_e 1300 $\bar{\nu}_e$

Measurement of δ_{CP}



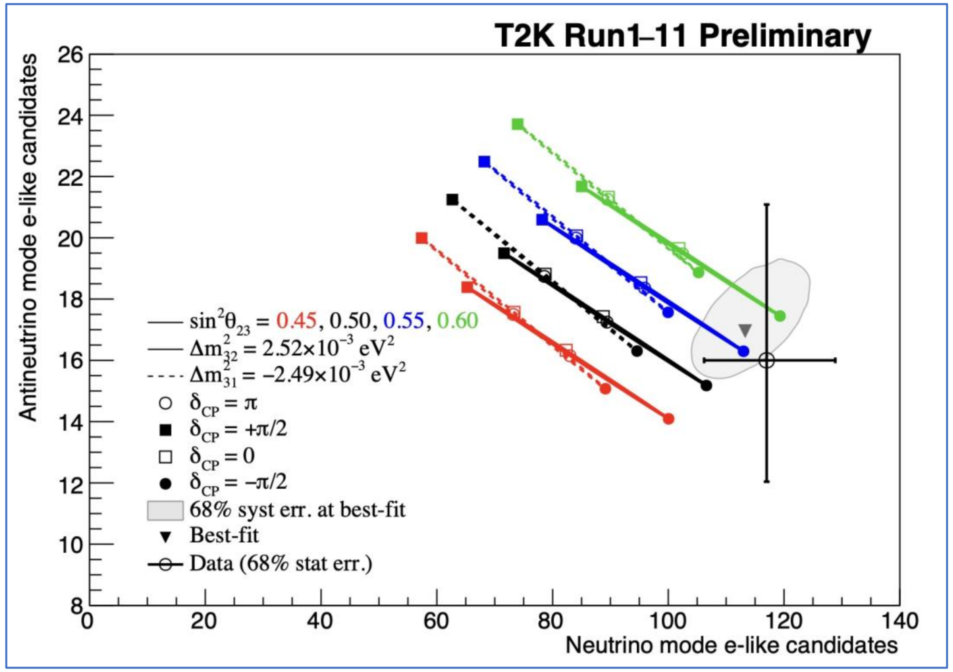
Exclusion of CP conservation



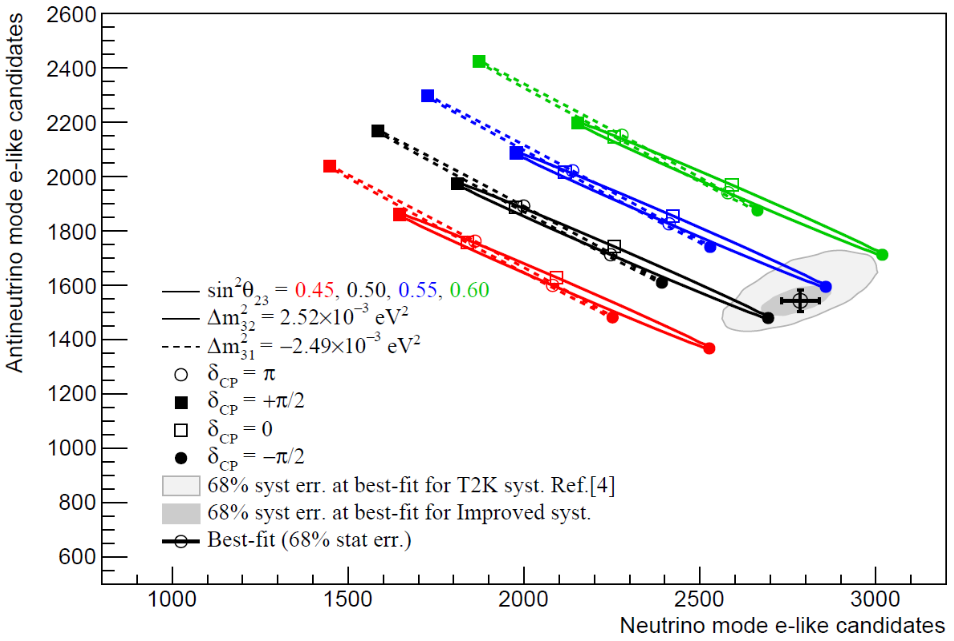
Sensitivity to CP violation (II)

Hyper-Kamiokande, arXiv:2505.15019

Current T2K result



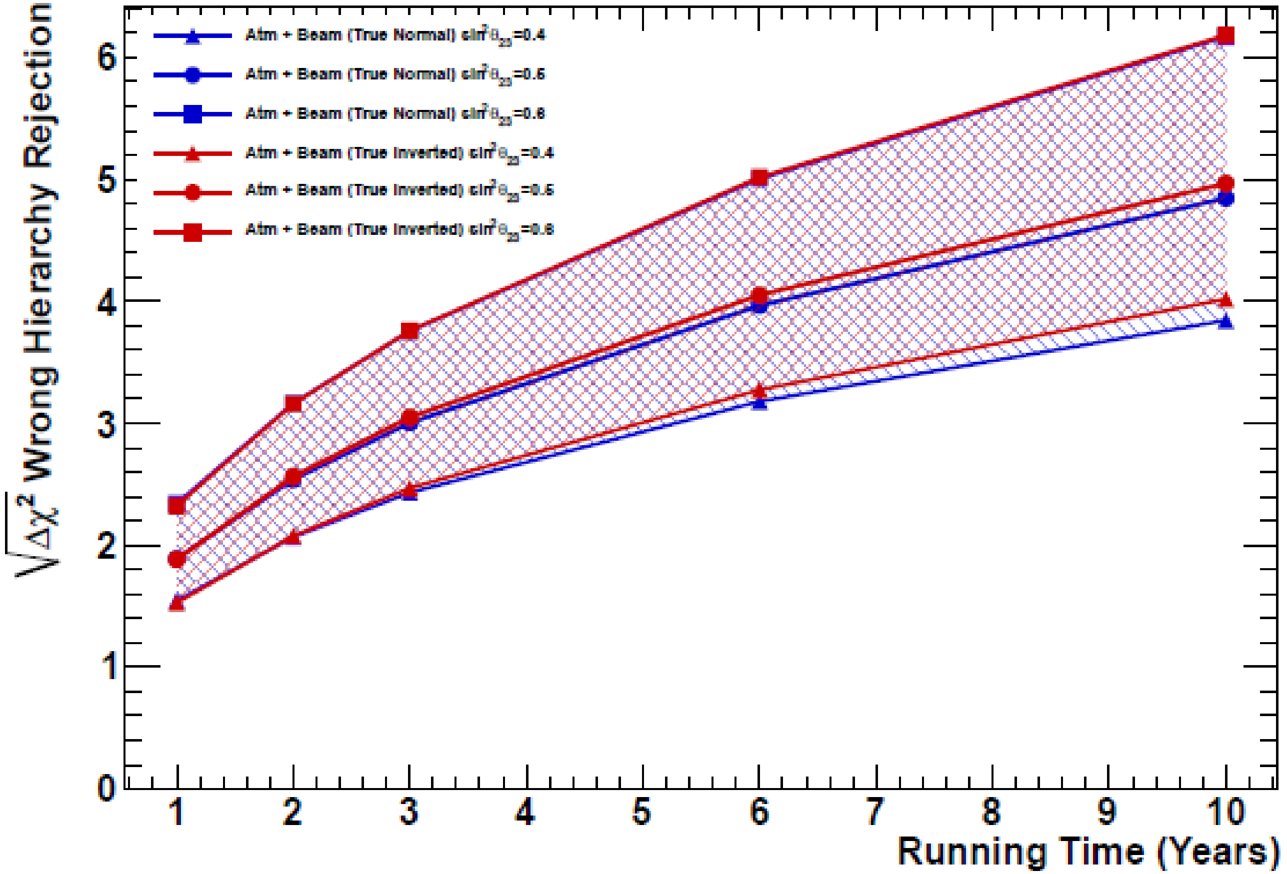
Projected Hyper-K result after 10 years data taking



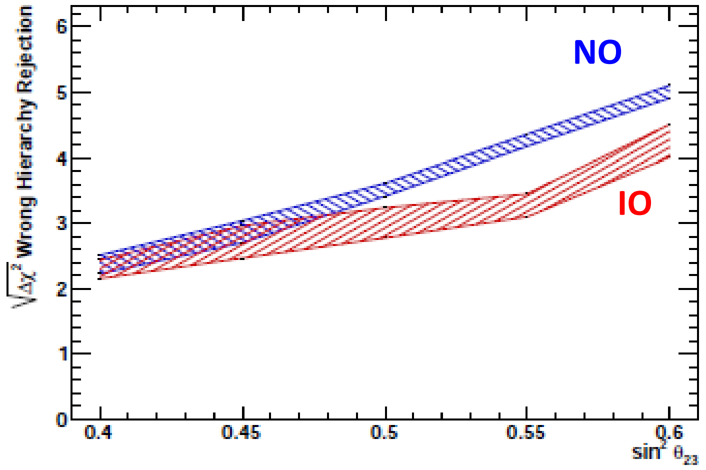
Hyper-Kamiokande: Mass Ordering

HyperKamiokande 10 years of data taking

Hyper-Kamiokande, arXiv:1805.04163



HyperKamiokande, atm neutrinos



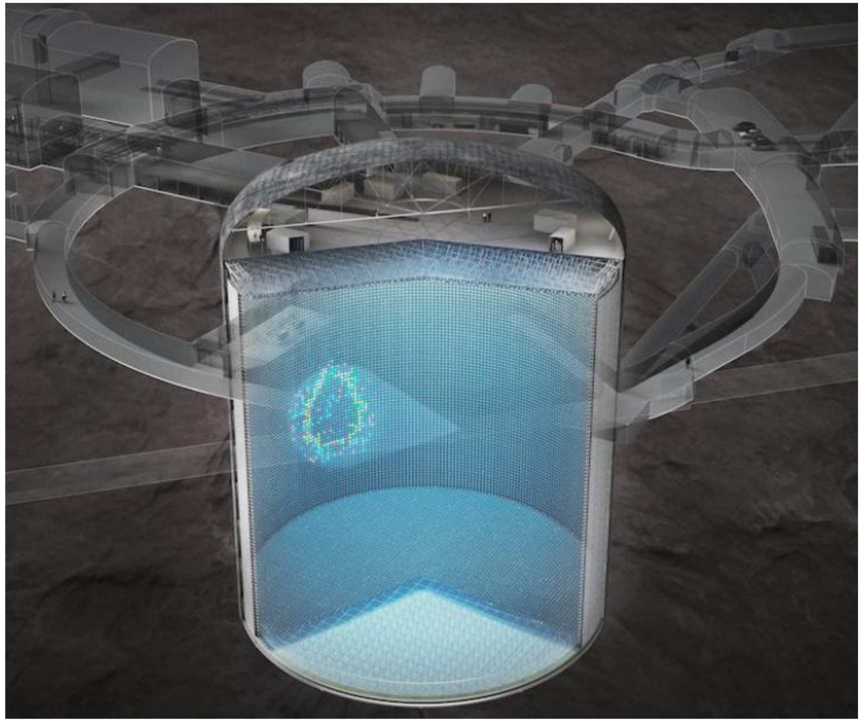
	$\sin^2\theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	2.2 σ →	3.8 σ
	0.60	4.9 σ →	6.2 σ
θ_{23} octant	0.45	2.2 σ →	6.2 σ
	0.55	1.6 σ →	3.6 σ

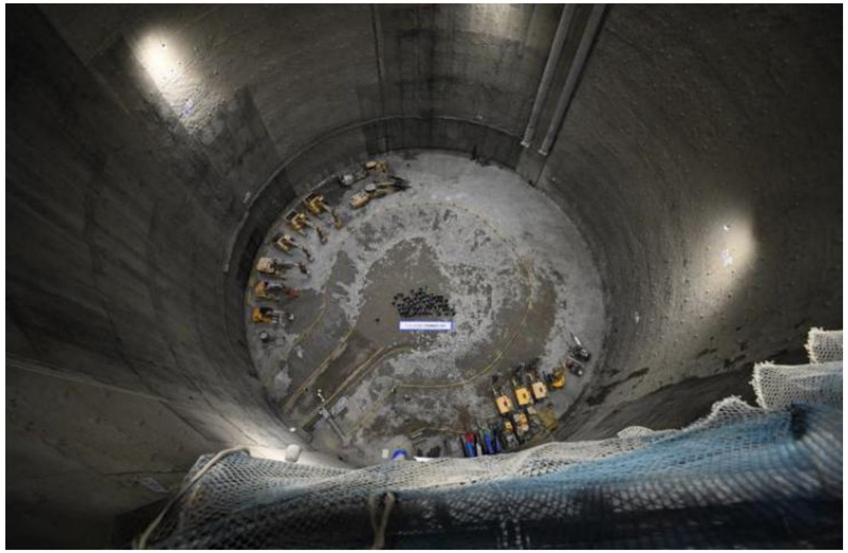
HyperK cavern

Excavation of world's largest man-made cavern
94 m total height
69 m diameter
completed in July 2025

https://www-sk.icrr.u-tokyo.ac.jp/en/hk/

600 m underground





Neutrino anomalies

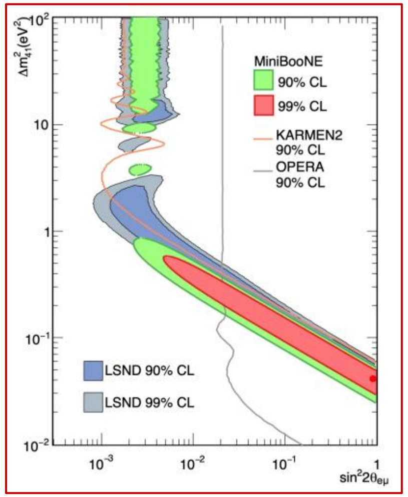
Light sterile neutrino ?

LSND/MiniBooNe anomaly

$\bar{\nu}_\mu \to \bar{\nu}_e$

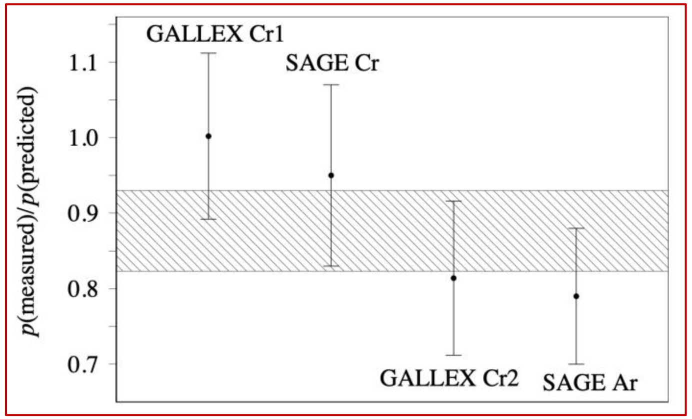
87.9 ± 22.4 ± 6.0 events

Excess 3.8σ



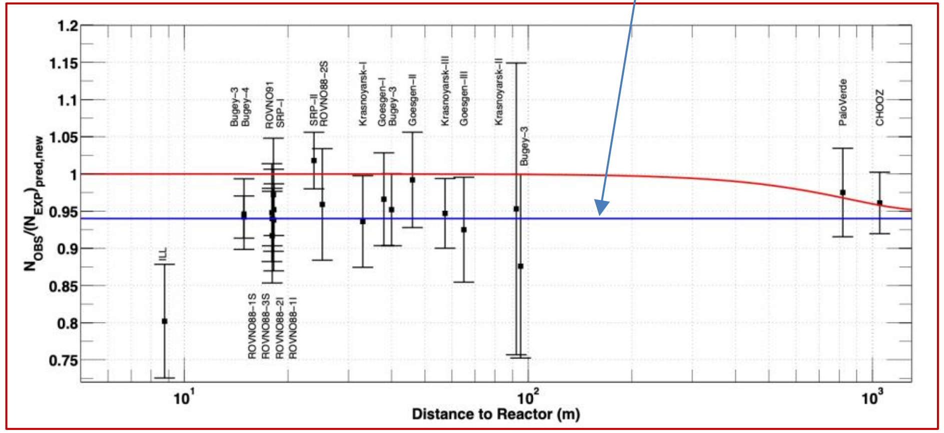
Ga anomaly

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

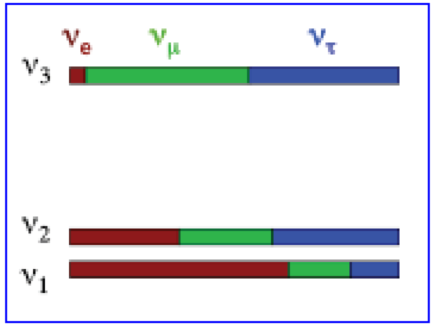


Reactor anomaly

0.937 ± 0.027

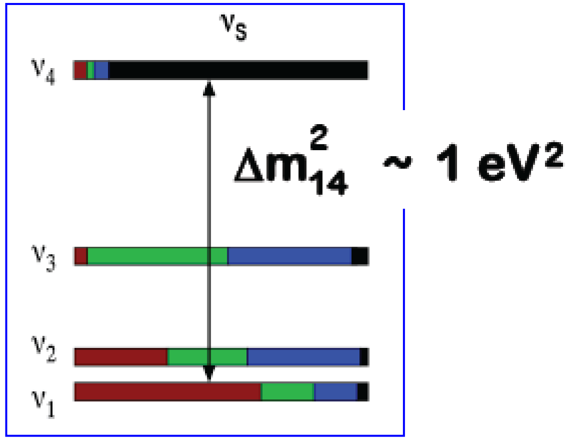


3ν, NO



?

$3\nu + 1\nu_s$



PMNS matrix

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

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

Connection between **Appearance** and **Disappearance** channels

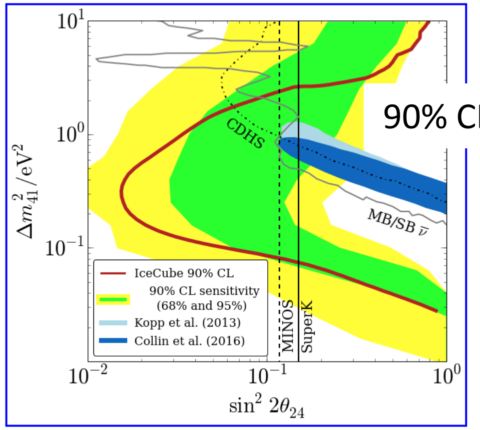
$$P_{\nu_e\to\nu_e} \simeq 1 - 2|U_{e4}|^2(1-|U_{e4}|^2)$$
$$P_{\nu_\mu\to\nu_\mu} \simeq 1 - 2|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)$$
$$P_{\nu_\mu\to\nu_e} \simeq 2|U_{e4}|^2|U_{\mu 4}|^2$$

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

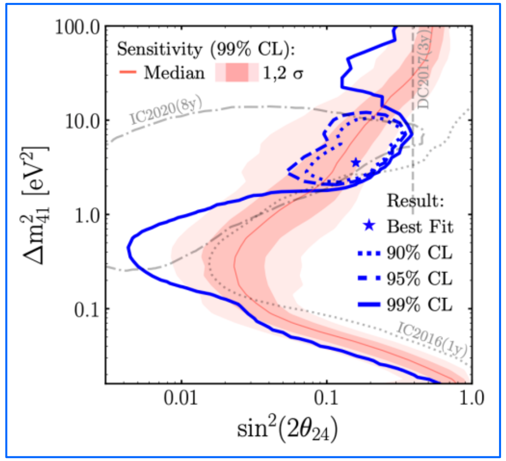
LSND/MiniBooNE anomaly

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

PRL 117 (2016) 071801



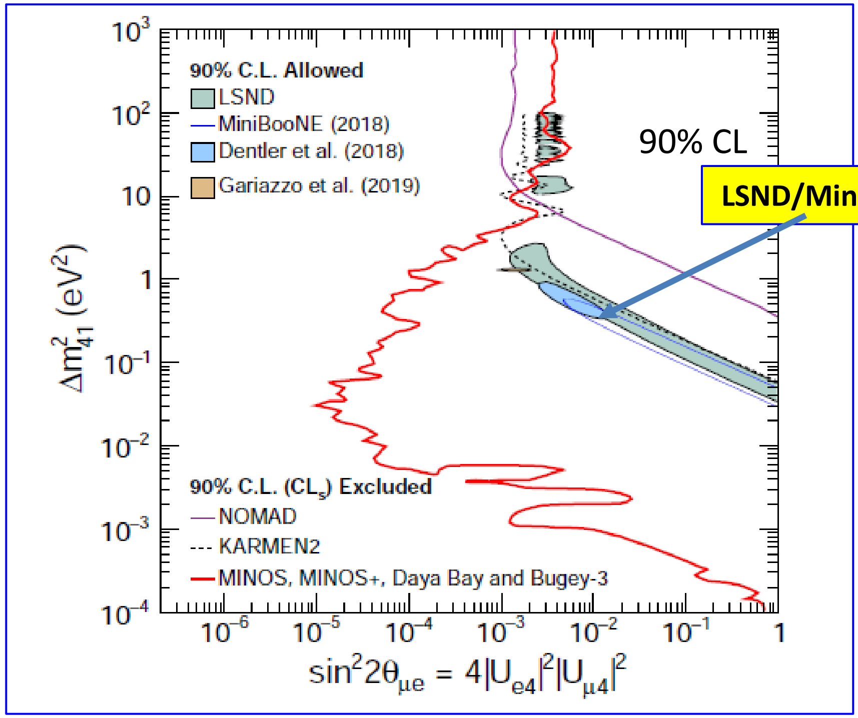
11 years of data taking, PRL 133 (2024) 201804



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

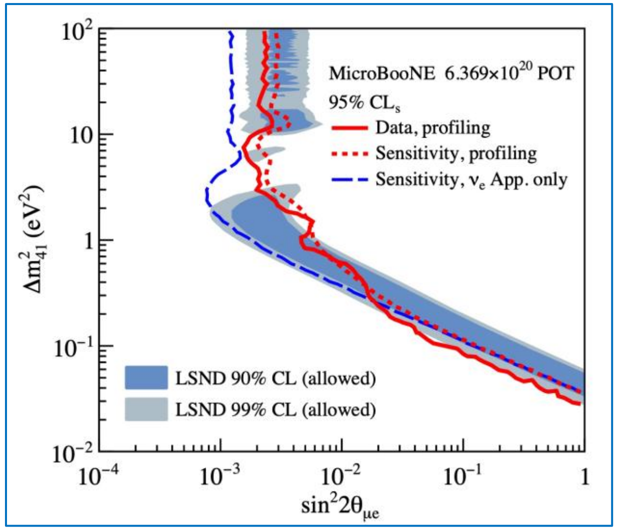
PRL 125 (2020) 131802

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



PRL 130 (2023) 011801

MicroBooNE, , LAr TPC



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

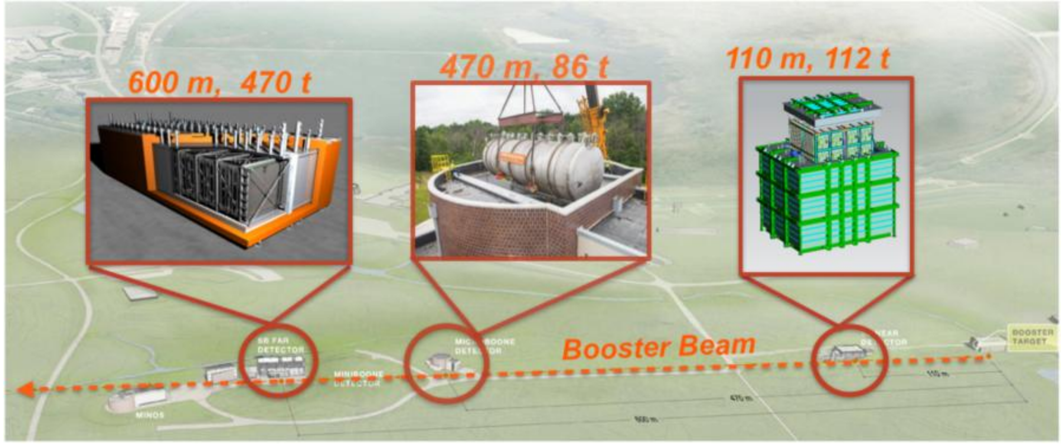
Positive signal:
LSND/MiniBooNE
Negative:
MINOS, Daya Bay/Bugey-3
IceCube, MicroBooNE

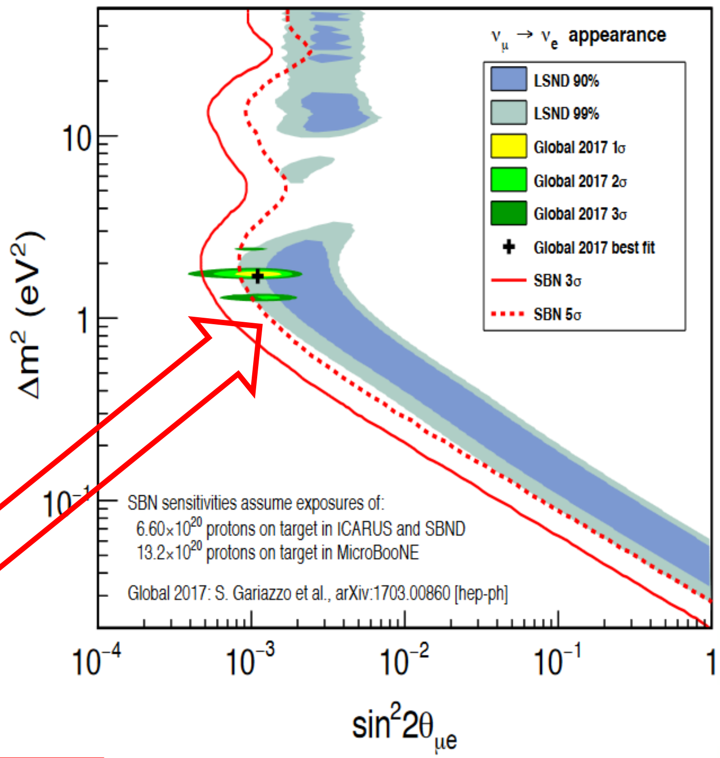
SBL experiments at FNAL

Short baseline neutrino program at FNAL

arXiv:1503.01520

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





ICARUS: commissioning in 2022,
took data from Booster and NuMI beams in 2023
LAr1-ND (SBND) collecting data since 2024

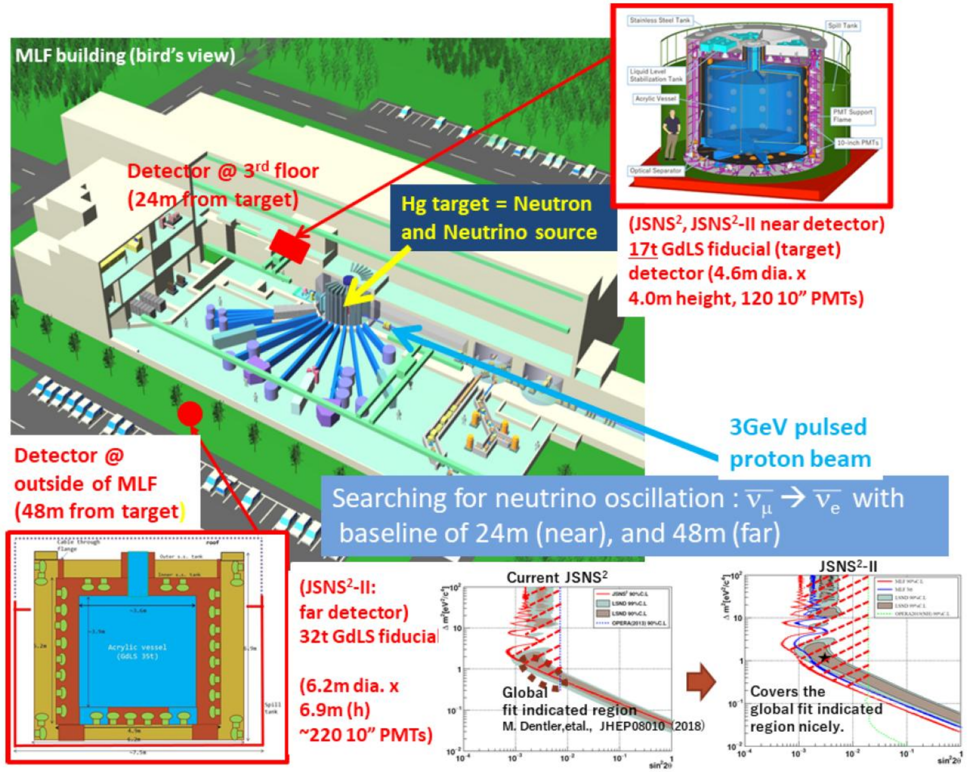
Crucial (final) direct test of LSND/MiniBooNE anomaly?

JSNS^2-JSNS^2-II at J-PARC

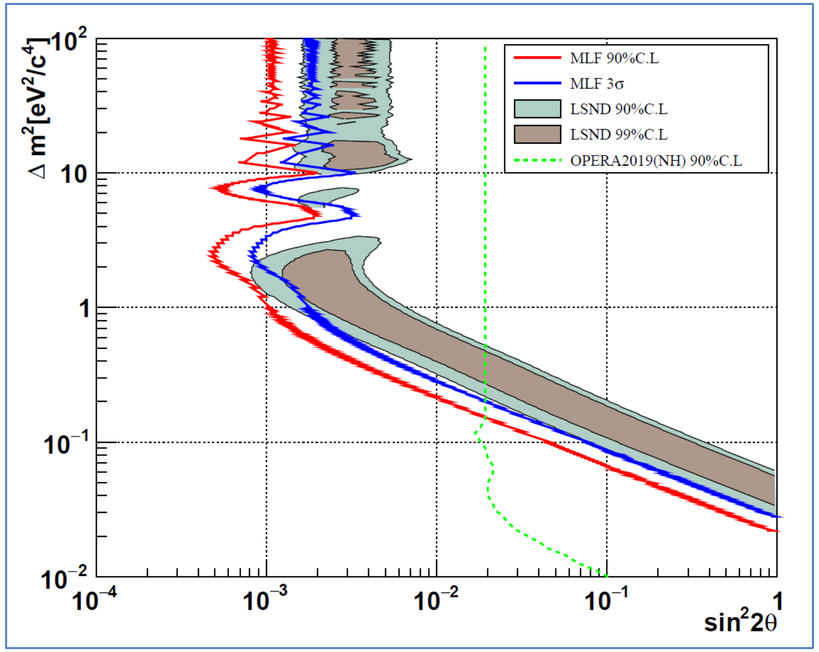
arXiv:2012.10807

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).



JSNS^2/JSNS^2-II will be able cover the full LSND parameter range in coming years



Conclusion/Perspectives

Neutrino is a unique laboratory to study Physics Beyond SM

CP violation and Mass Ordering – primarily targets of current and near future LBL accelerator experiments

Current CPV status:
T2K - hint on maximal CP violation
NOvA - CP conservation (NMO) maximal CP violation (IMO)

Individual experiments tend to favor Normal MO

Hyper-Kamiokande and DUNE will start exiting measurements of CP and MO in a few years

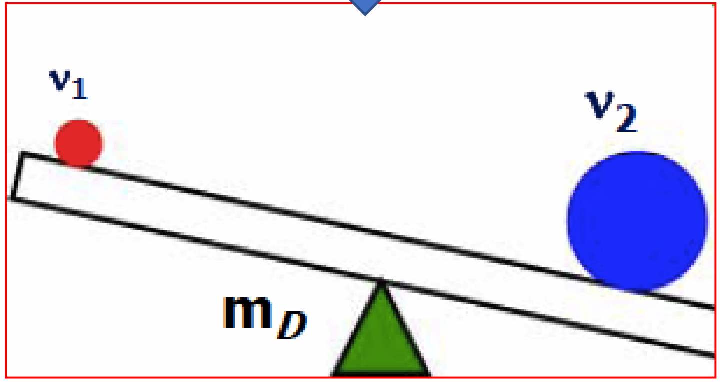
Sterile neutrinos (LSND anomaly) will be probed at FNAL and J-PARC in near future

Thank you for your attention

Backup slides

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 ~ 100 GeV

$\nu_2 \rightarrow M_R \le 10^{14}$ GeV

Baryon Asymmetry of Universe (BAU)

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

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

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

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

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 ??

CPV in PMNS ⟺ CPV in Leptogenesis ?

Type I See-saw model

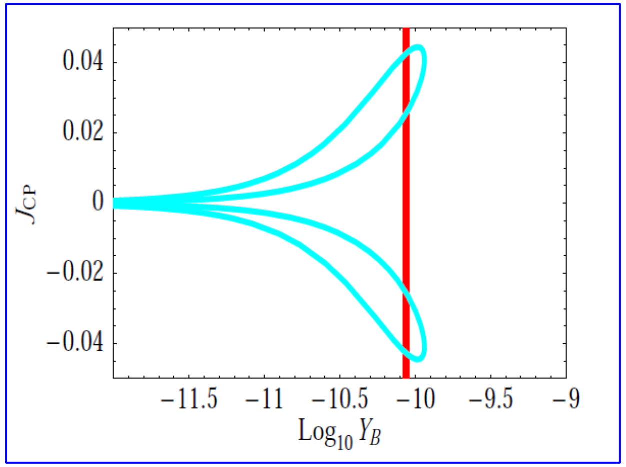
SM + 3 heavy (RH) Majorana neutrinos N_1, N_2, N_3
with masses $M_1 << M_2 < M_3$
Leptogenesis takes place at temperatures $10^9\, GeV < T < M_1$

S.Petcov et al. Nucl.Phys. B774,2007, 1
S.Petcov et al. Phys.Rev. D75, 2007, 083511

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

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

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



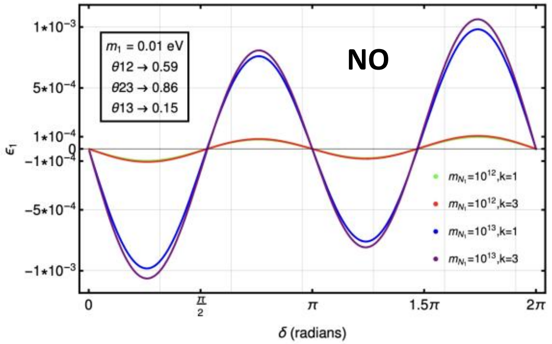
BAU can be reproduced, if $|\sin\theta_{13}\sin\delta_{CP}| > 0.11$

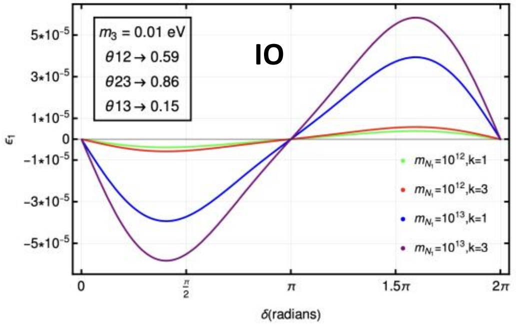
Daya Bay: $\sin\theta_{13} = 0.15$, if $\sin\delta_{CP} > 0.75$ ⇒ **$|J_{CP}| > 0.024$**

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

Left-Right Symmetric Model with double seesaw ⇒

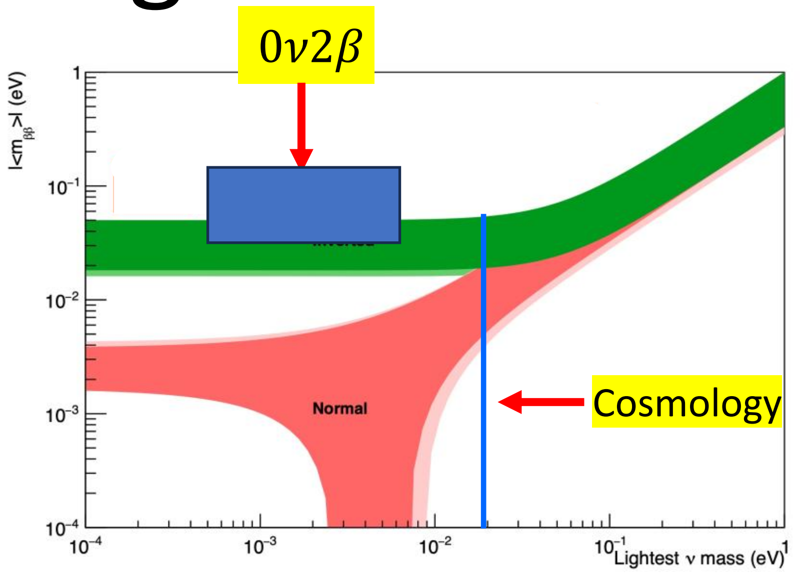
- m_D depends on δ_{CP}
- δ_{CP} is the prime source of lepton asymmetry ε_1 and Y_B





Neutrino Mass Ordering

Mass Ordering
NO or IO ?
Impact on
- Cosmology
- $0\nu2\beta$ decay
- Direct mass measurement
- Cosmic neutrino background ($C\nu B$)

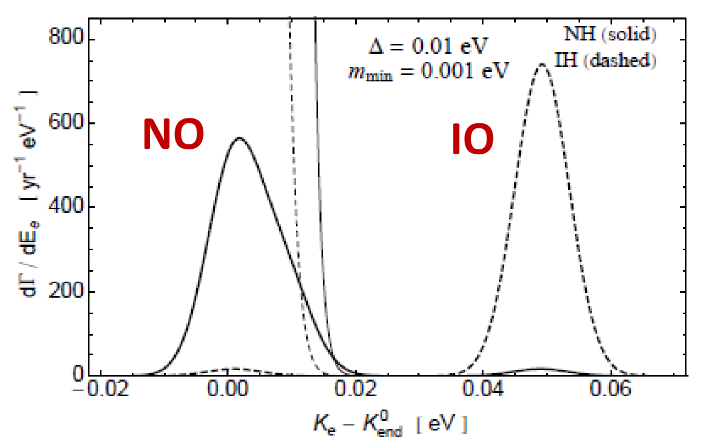


Cosmology (model dependent):
$\sum m_i < 0.12$ eV (CMB + BAO) → close to **IO**: $\sum m_i \sim 100$ meV

$0\nu2\beta$
Experiment: $m_{\beta\beta} < 28\text{-}122$ meV (90%CL)
Theory **IO**: $m_{\beta\beta} \simeq 20\text{-}50$ meV

Detection of $C\nu B$ $\nu + {}^3H \rightarrow {}^3He + e^-$

A.J.Long et al. 1405.7654

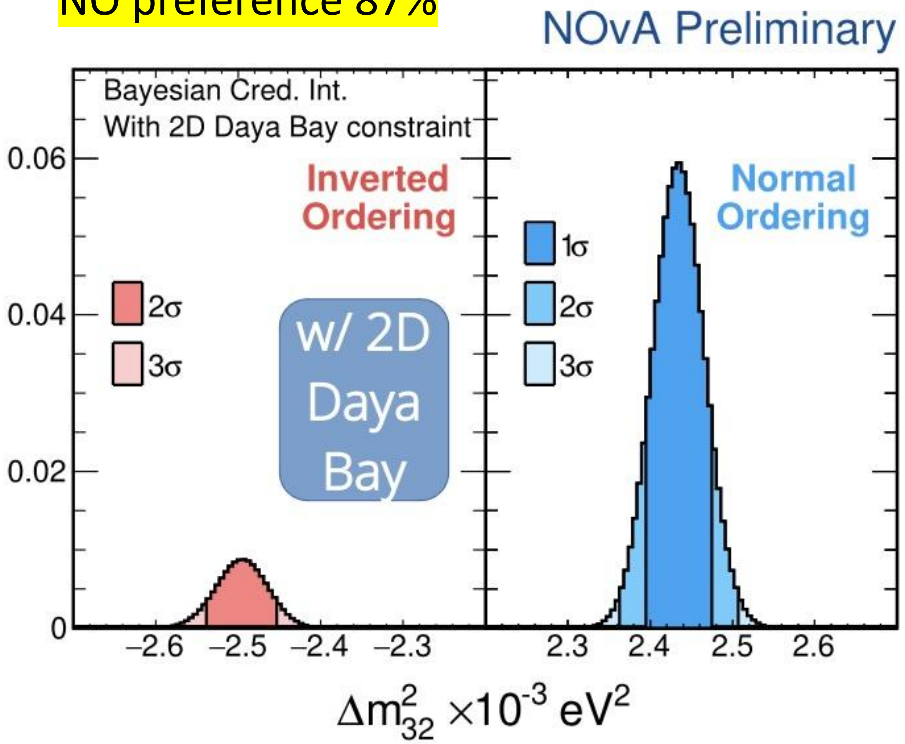


Project **PTOLEMY:**
- 100 g (1 Mci) of Tritium
- Detection of relic neutrinos
- 10 event/year

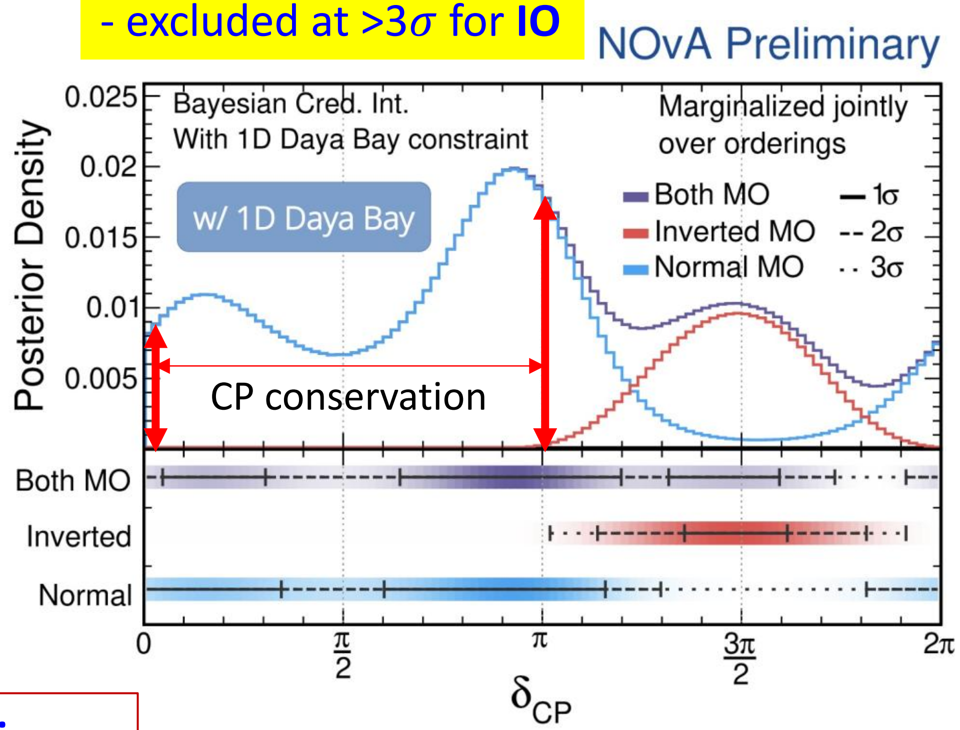
NOvA   MO and CPV

J.Wolcott, Neutrino2024

NO preference 87%



CP conservation:
- favored for **NO**
- excluded at $>3\sigma$ for **IO**



NOvA →

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