Нейтринная физика: последние результаты и перспективы

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Neutrino physics: fundamental questions

CP violation

Neutrino mass ordering

Absolute scale of neutrino mass

Neutrino nature: Dirac or Majorana

Sterile neutrinos

- 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

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

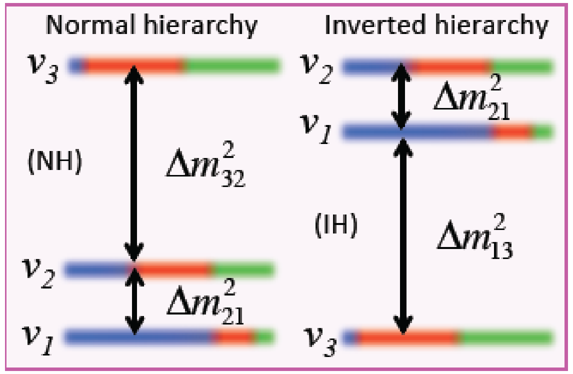
quarks

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

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

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

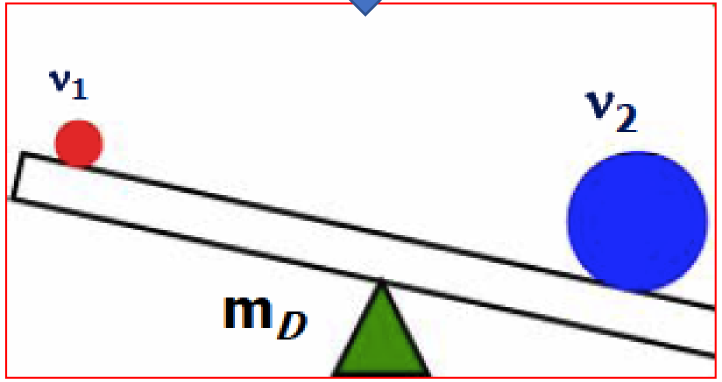
- Neutrino mass ordering (NMO)



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

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

$\nu_2 \to M_R \leq 10^{14}$ 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

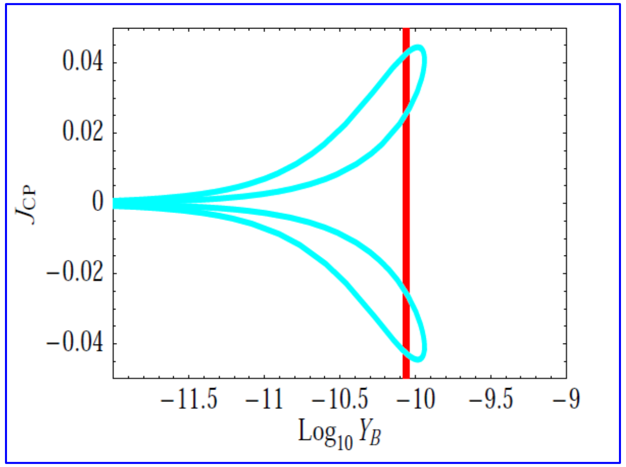
SM + 3 heavy (RH) Majorana neutrinos N_1, N_2, N_3
with masses $M_1 << M_2 < M_3$
Leptogenesis takes place at temperatures $10^9\, GeV < T < M_1$

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

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

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

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



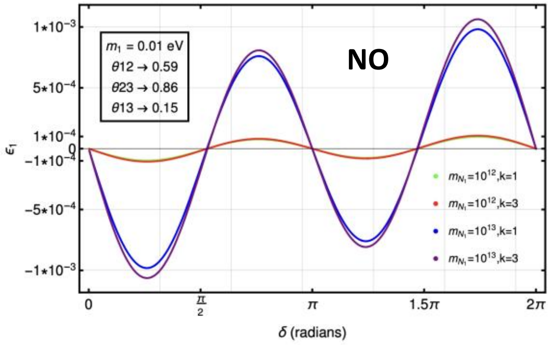
BAU can be reproduced, if $|\sin\theta_{13} \sin\delta_{CP}| > 0.11$

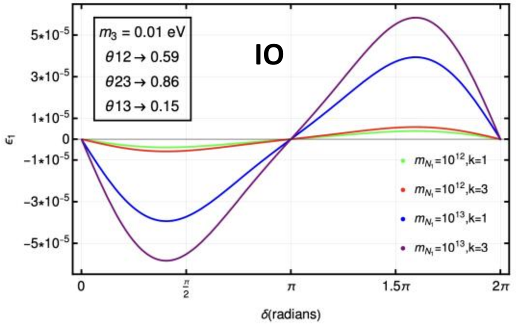
Daya Bay: $\sin\theta_{13} = 0.15$, if $\sin\delta_{CP} > 0.75$ ⟹ **$|J_{CP}| > 0.024$**

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





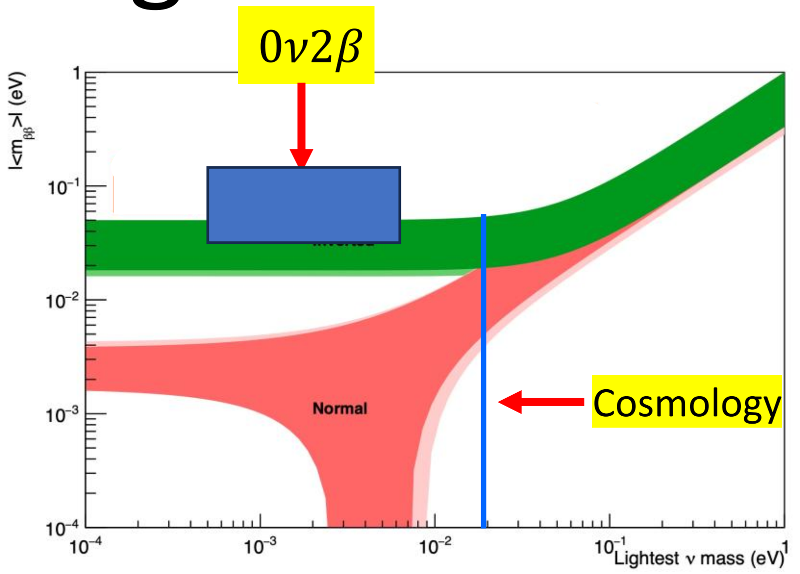
Neutrino Mass Ordering

Mass Ordering

NO or IO ?

Impact on

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

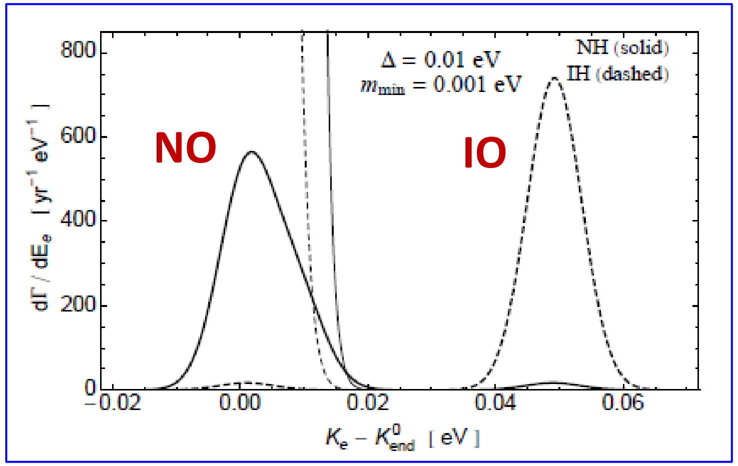


Cosmology (model dependent):
Limit/determination of $\sum m_i$ = **60 meV (NO) or 100 meV (IO)**

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

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

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

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

leading term

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

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

Matter effect

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

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

change sign for NH $\to$ 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 →

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

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

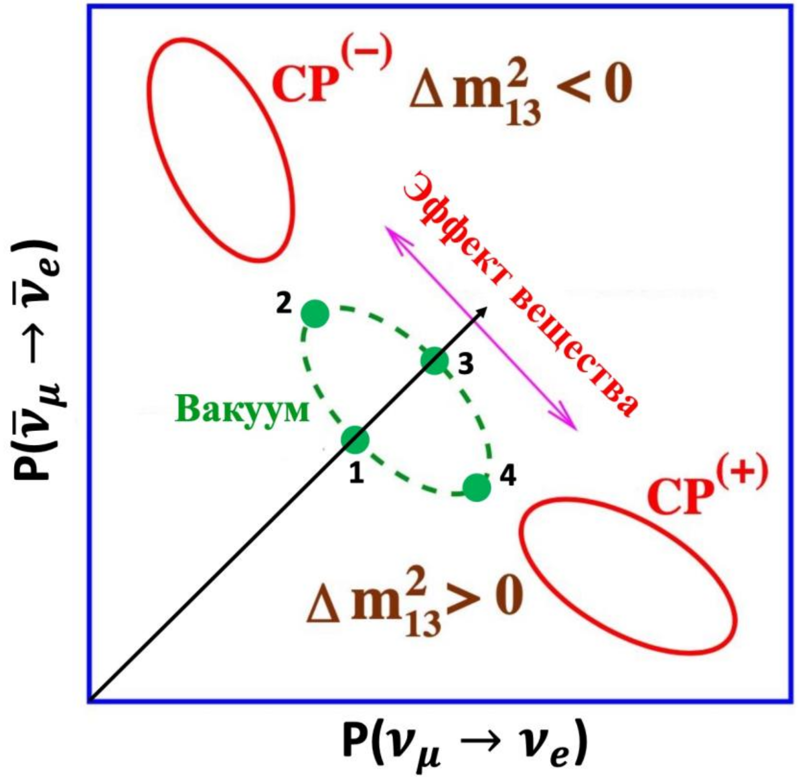
Matter →

Neutrino energy tuned to oscillation maximum with atm parameters

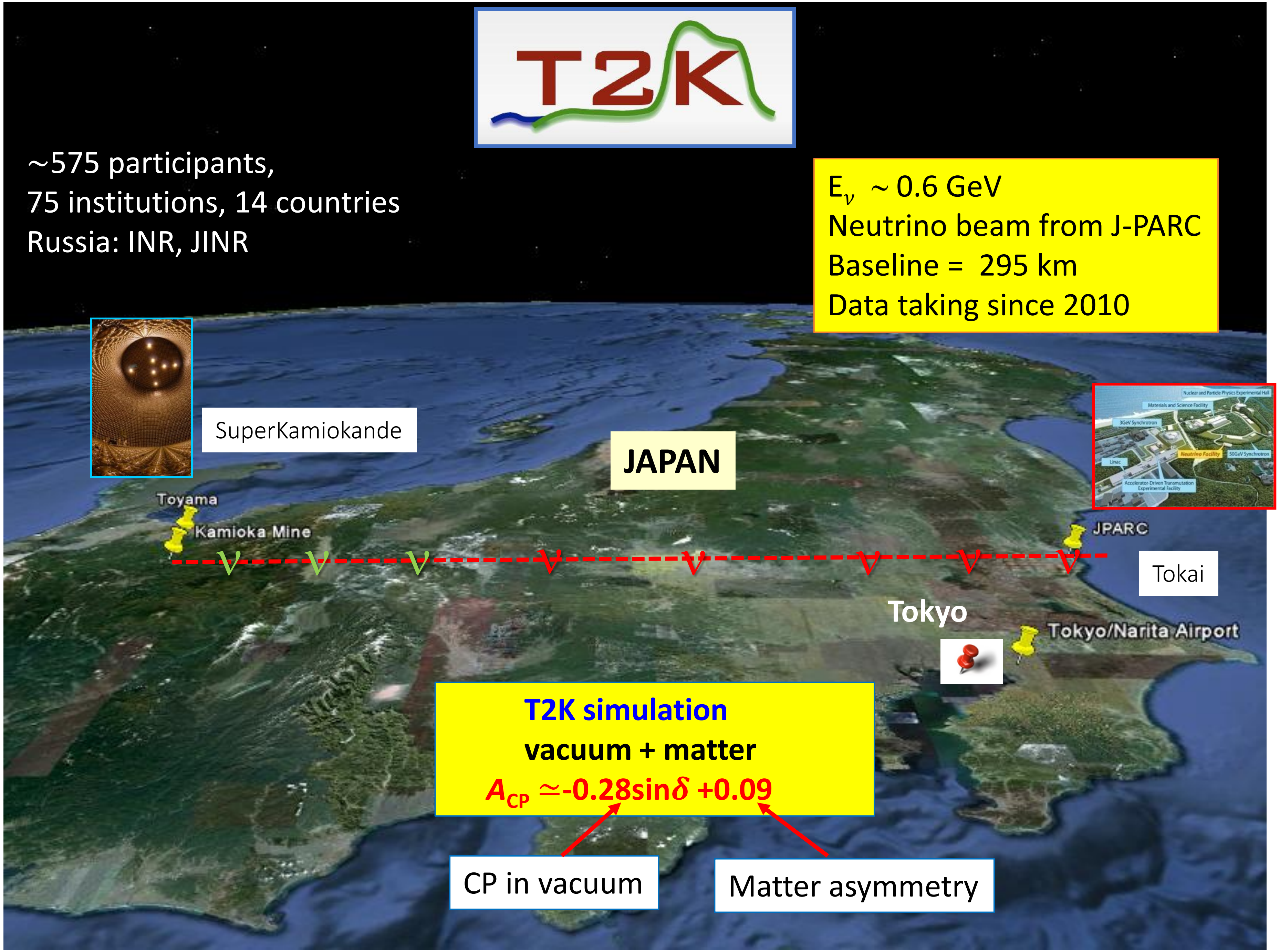
$$A_{\rm CP} \equiv \left. \frac{P_{(\nu_\mu \to \nu_e)} - P_{(\bar{\nu}_\mu \to \bar{\nu}_e)}}{P_{(\nu_\mu \to \nu_e)} + P_{(\bar{\nu}_\mu \to \bar{\nu}_e)}} \right|_{\frac{|\Delta m_{31}^2| L}{4E_\nu} \approx \pi/2} \sim -\frac{\pi \sin 2\theta_{12}}{\tan\theta_{23} \sin 2\theta_{13}} \frac{\Delta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

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

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



δ_{CP} : 1 - 0, 2 - π/2, 3 - π, 4 - 3/2π

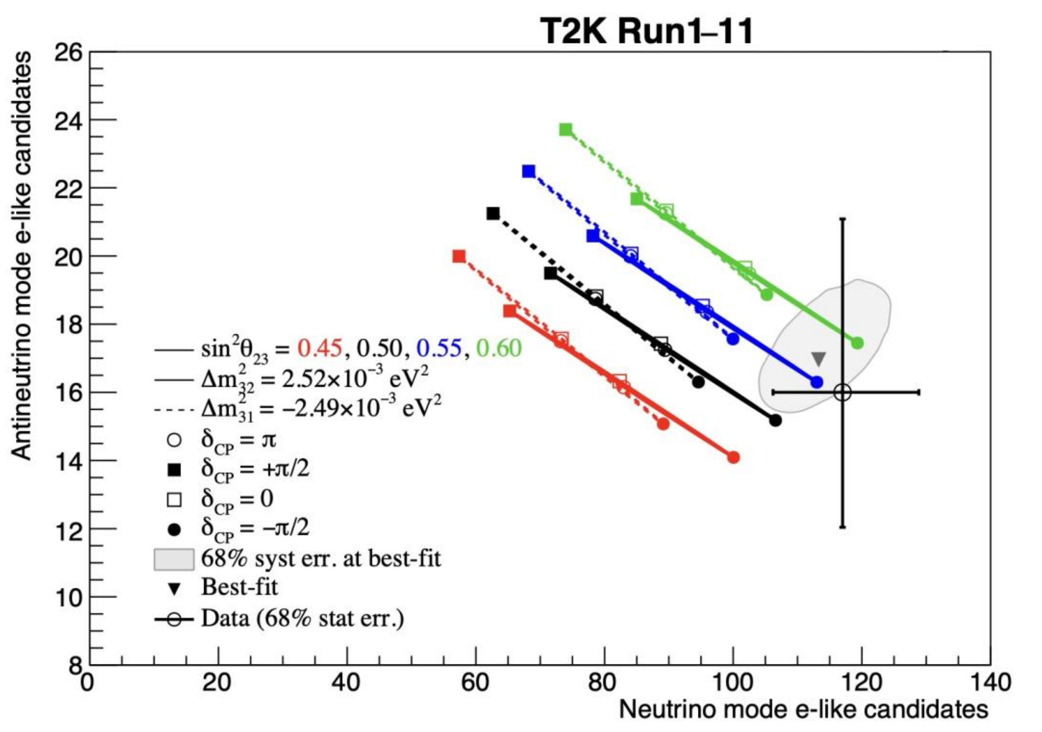

T2K
~575 participants,
75 institutions, 14 countries
Russia: INR, JINR
E_ν ~ 0.6 GeV
Neutrino beam from J-PARC
Baseline = 295 km
Data taking since 2010
SuperKamiokande
JAPAN
Toyama
Kamioka Mine
JPARC
Tokai
Tokyo
Tokyo/Narita Airport
T2K simulation
vacuum + matter
$A_{CP} \simeq -0.28\sin\delta + 0.09$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

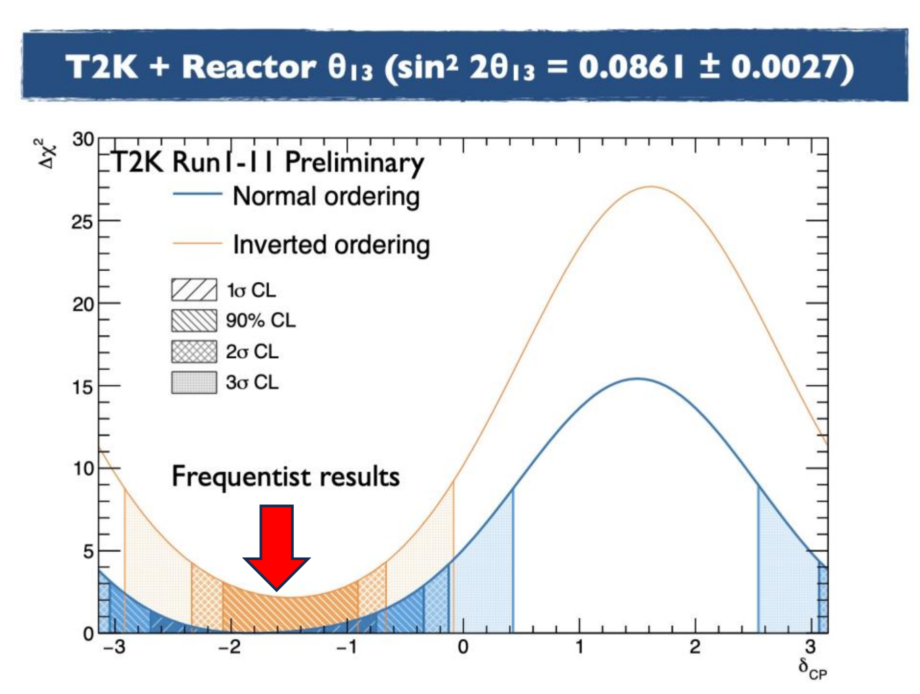
T2K: hint of CP violation

Eur.Phys.J.C 83 (2023) 9, 782

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%



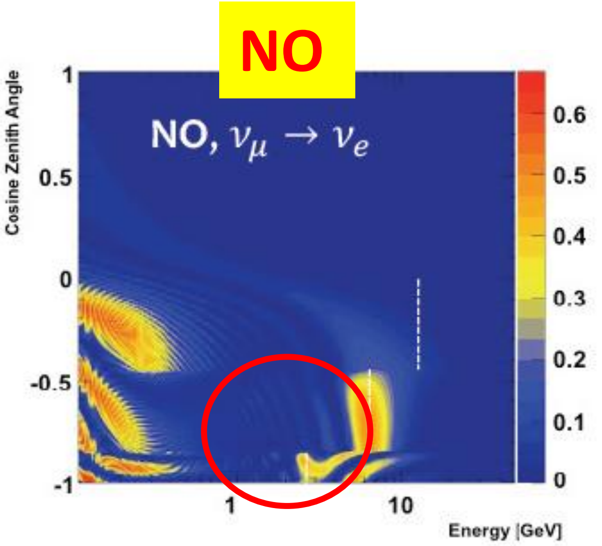


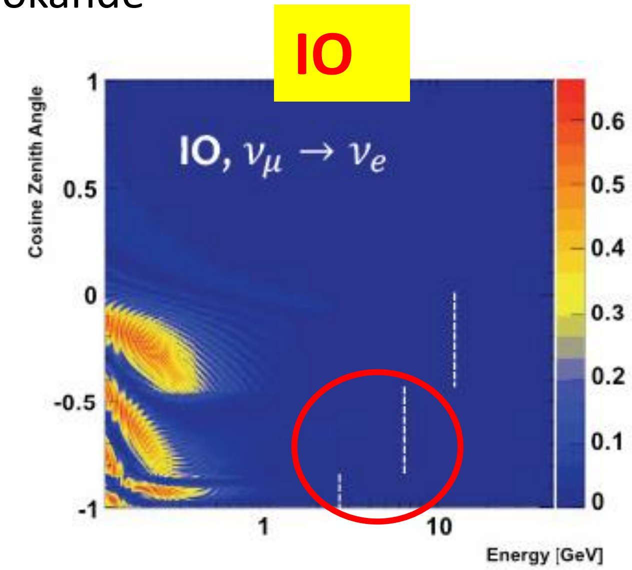
Best fit: $\delta_{CP} \sim -\pi/2$ → close to maximum CP violation

Normal mass ordering is preferred at 80% CL

Mass ordering: SuperKamiokande + T2K

SuperKamiokande

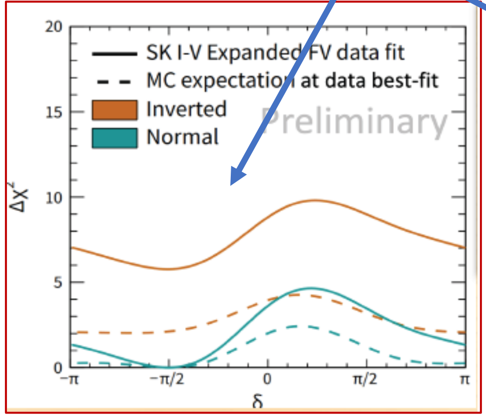


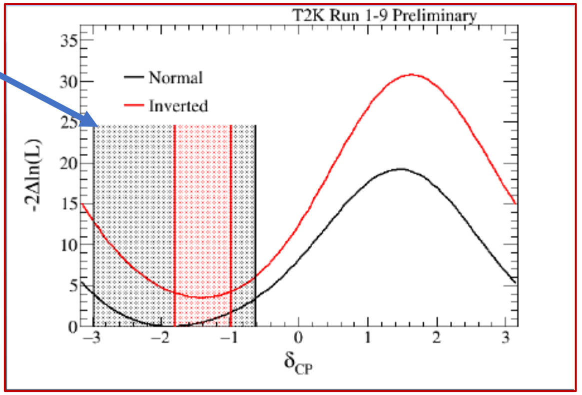


SuperKamiokande
- Atmospheric neutrino sensitive to mass ordering due to matter effect
- MSW resonance at ~ 10 GeV

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

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





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

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

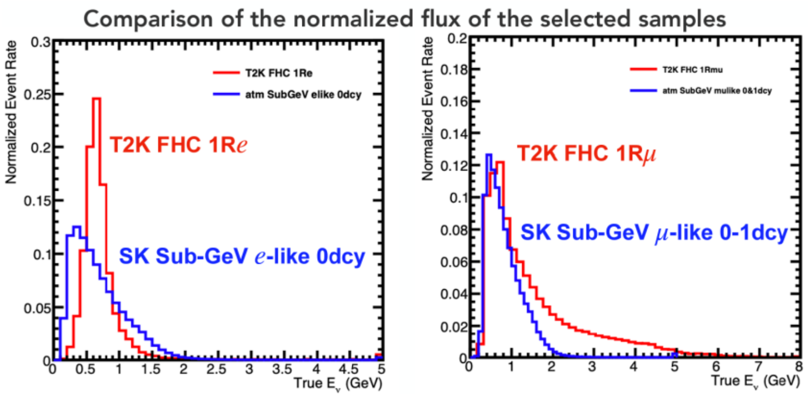
Phys.Rev.Lett. 134 (2025) 1, 011801

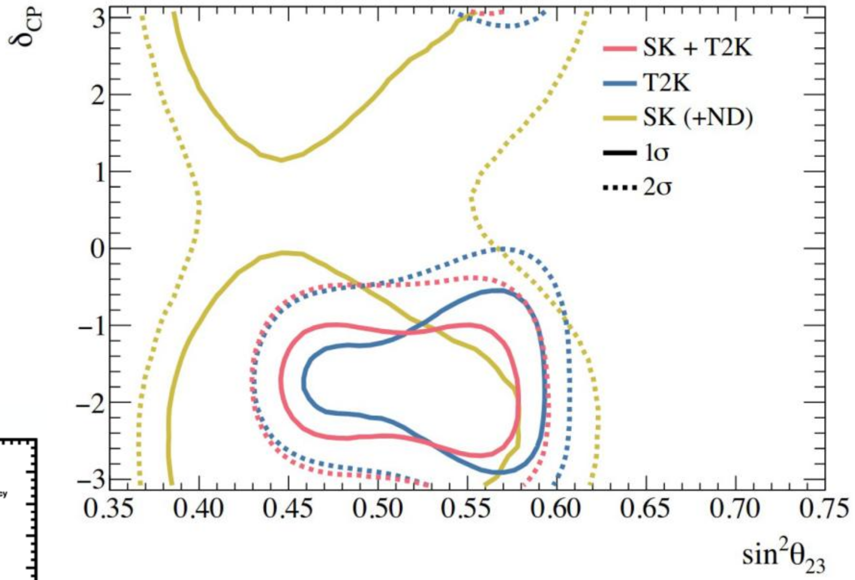
Two experiments share the same detector (SK)

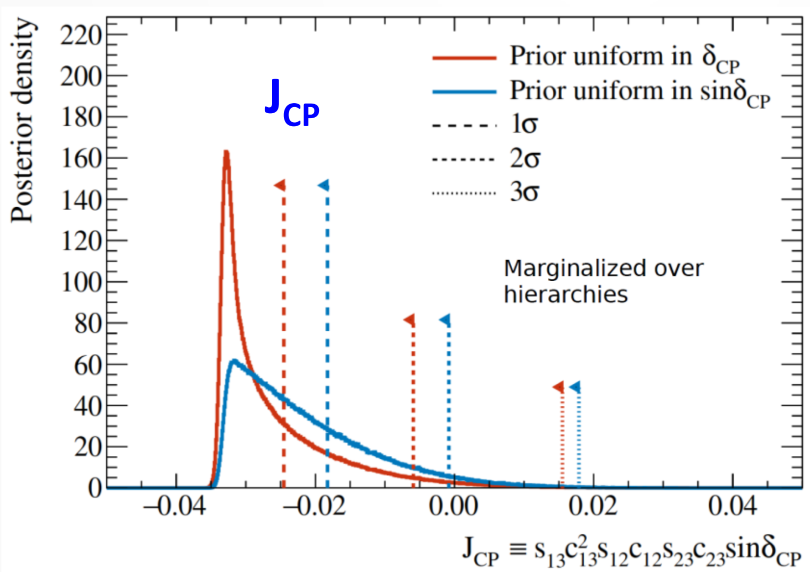
Samples from the two sources have overlap energy range and among which, share similar selection cuts

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

Increase of statistics





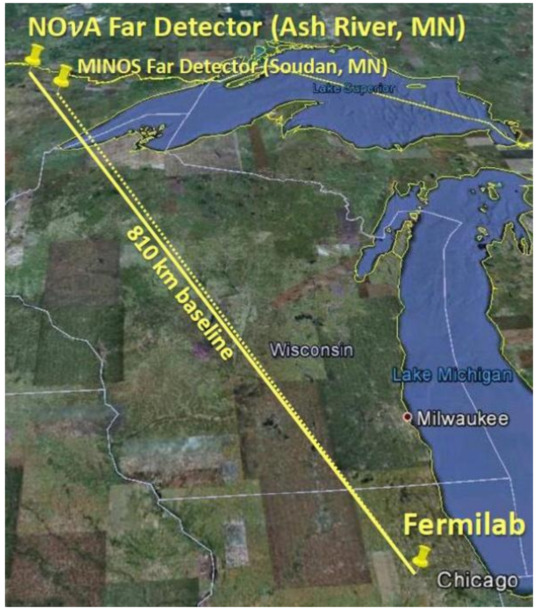


SuperK+T2K analysis:

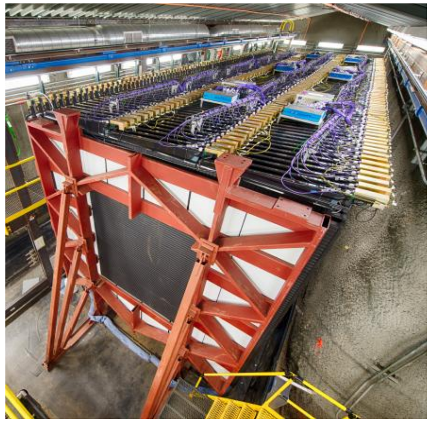
- excludes **CP conservation at 2.0σ CL**
- prefers **maximal CP violation, $\delta_{CP} \sim -\pi/2$**
- preferred **NO at 1.2σ CL (about 90%)**

Experiment NOvA

NOvA (USA)



Near Detector



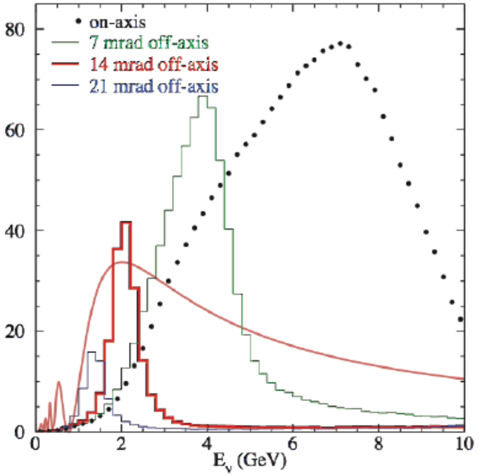
Taking data since 2014

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

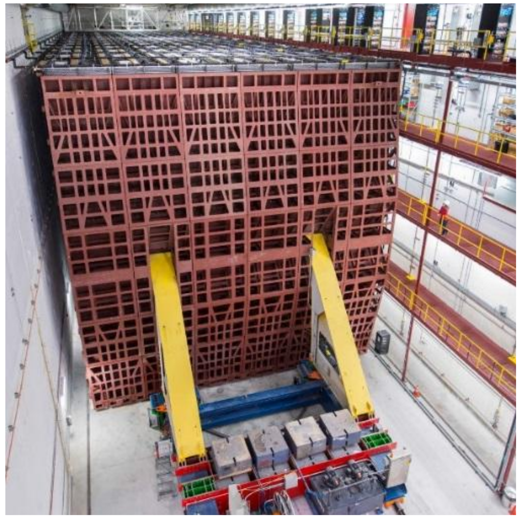
Neutrino beam from FNAL to Ash River
Baseline 810 km
Neutrino beam 14 mrad off-axis
Far detector : 14 kt fine-grained calorimeter
65% active mass
Near Detector: 0.3 kt fine-grained calorimeter

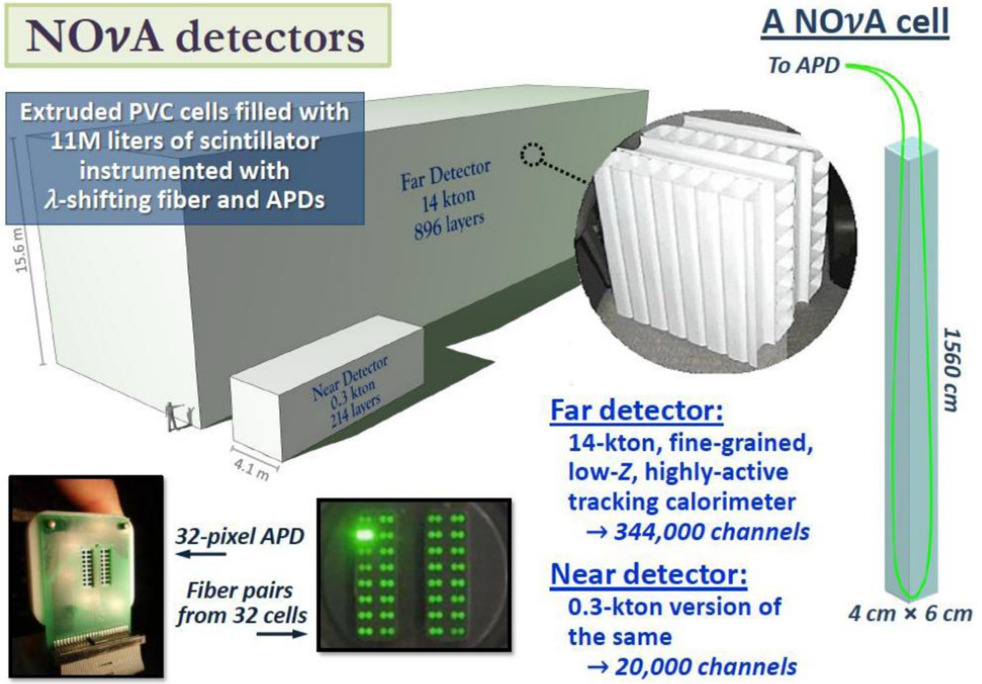
Protons on target
ν: 26.6x10^{20} POT
$\bar{\nu}$: 12.5x10^{20} POT

Neutrino beam



Far Detector





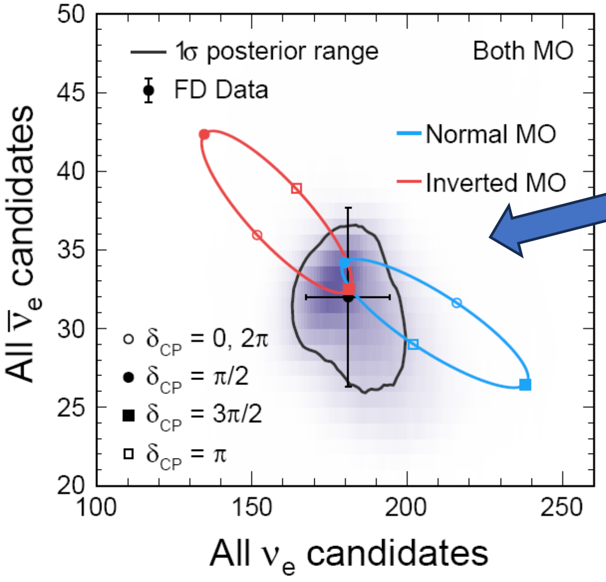
NOvA: CPV result

Phys.Rev.Lett. 136 (2026) 1, 011802

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**

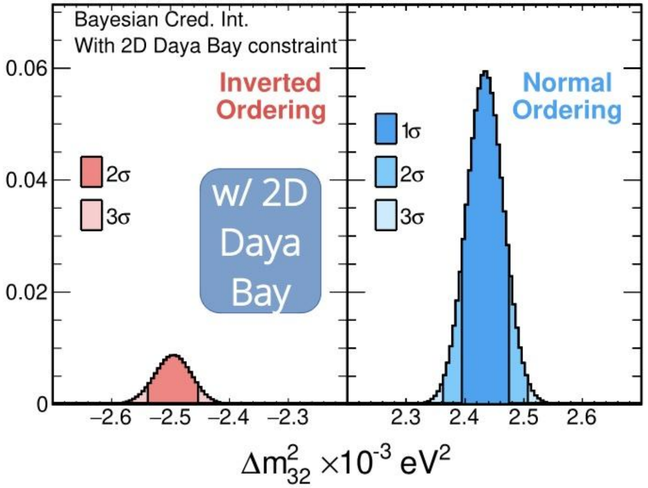
NOvA



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

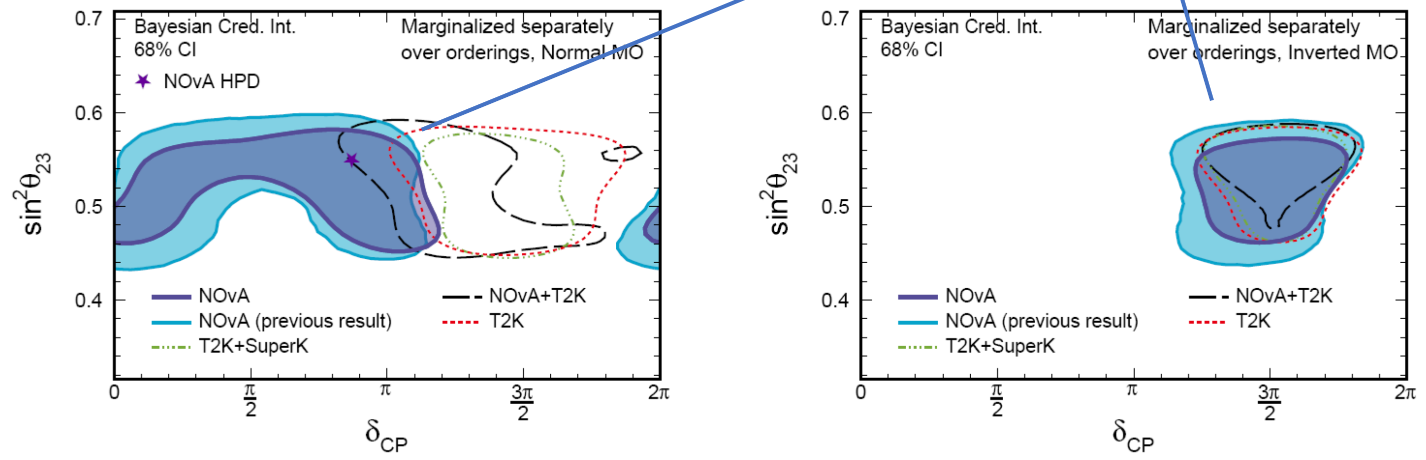
- Preference for NO
- No   CP asymmetry observed for NO
- CP conservation excluded at >3σ for IO

NO preference 87%



NO

IO



CP and MO: T2K and NOvA

T2K →

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

NOvA →

Best fit δ = 0.82π
Exclude IO δ = $\pi/2$ at > 3σ
Disfavor NO δ = 3$\pi/2$ at $\sim 2\sigma$

Features/sensitivities	T2K	NOvA
Proton beam	30 GeV	120 GeV
	295 km	810 km
Peak neutrino energy	0.6 GeV	2 GeV
Detection tech	FGD and Water Cherenkov	Segmented Liq scin. bars
CP effect	32%	22%
Matter effect	9%	29%

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

T2K-NOvA joint analysis
Nature 646 (2025) 8086, 818

No strong preference for either **MO**, however if **IO** is true within 3-ν mixing paradigm, then T2K-NOvA joint result provides evidence of **CP violation** in the lepton sector ($\boldsymbol{\delta = 0, \pi}$ **outside 3σ interval**).

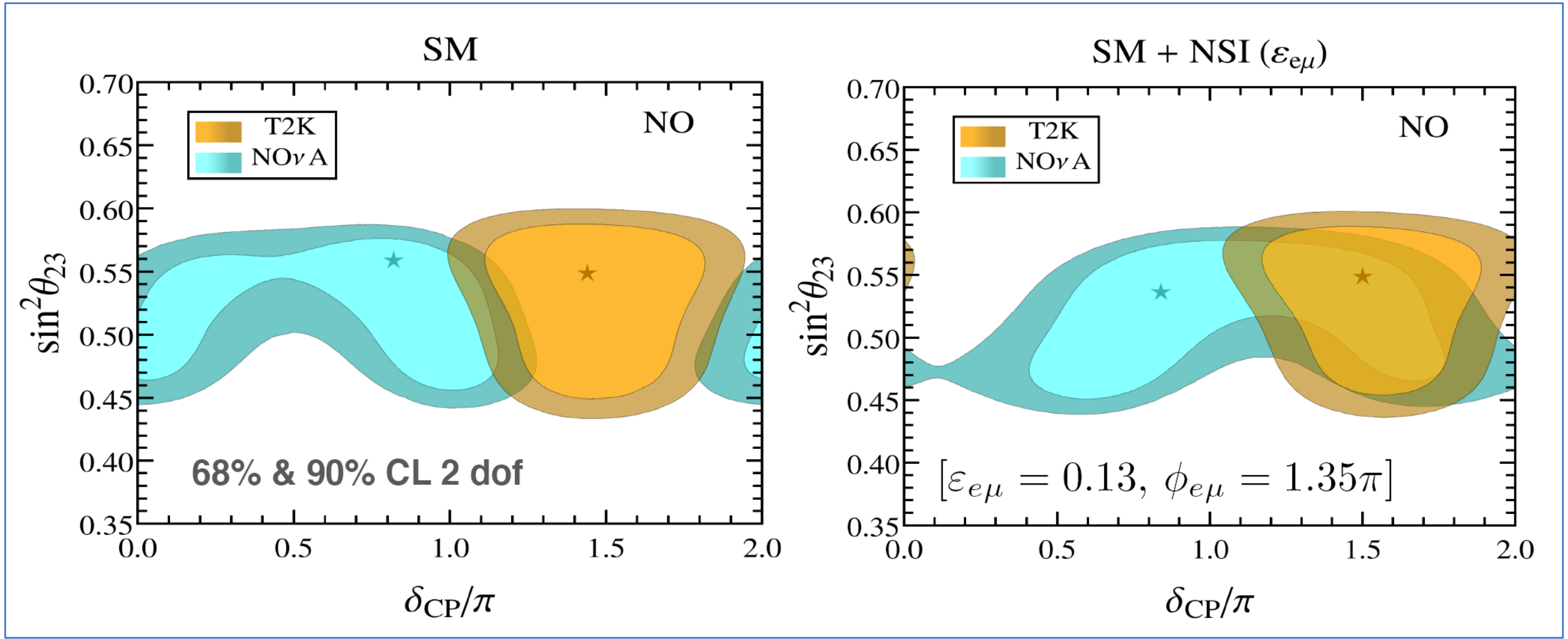
T2K - NOvA tension

Chatterjee and Palazzo, PRL 126, 051802 (2021)

Possible explanation: matter non-standard interactions (NSI)

T2K: short baseline,
δ_{CP} is independent on NSI

NOvA: larger matter effect,
δ_{CP} is affected by NSI

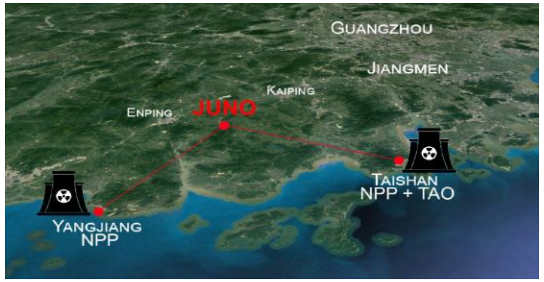


No change in T2K allowed region ⟷ **NSI** ⟷ **Strongly modified NOvA regions**

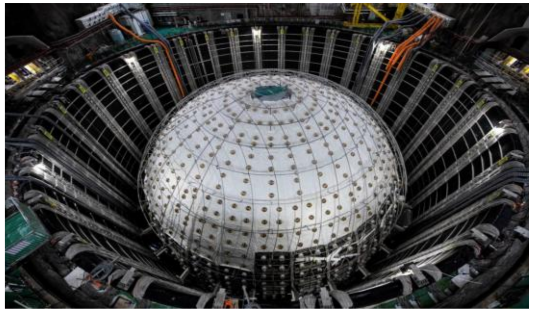
Near future CP and MO:
JUNO, DUNE and Hyper-Kamiokande

JUNO: MO

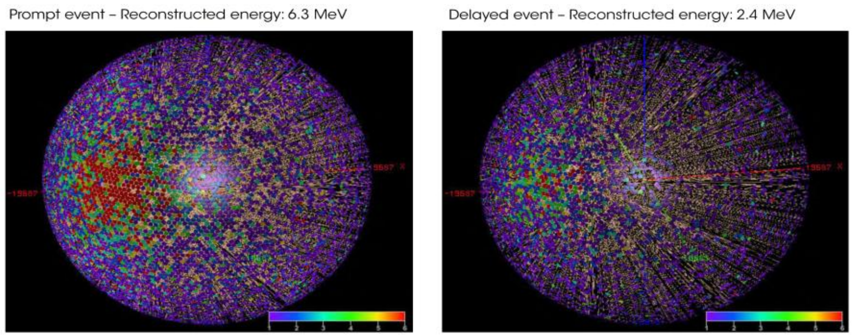
JUNO (China),
reactor experiment,
begun data taking
in August 2025

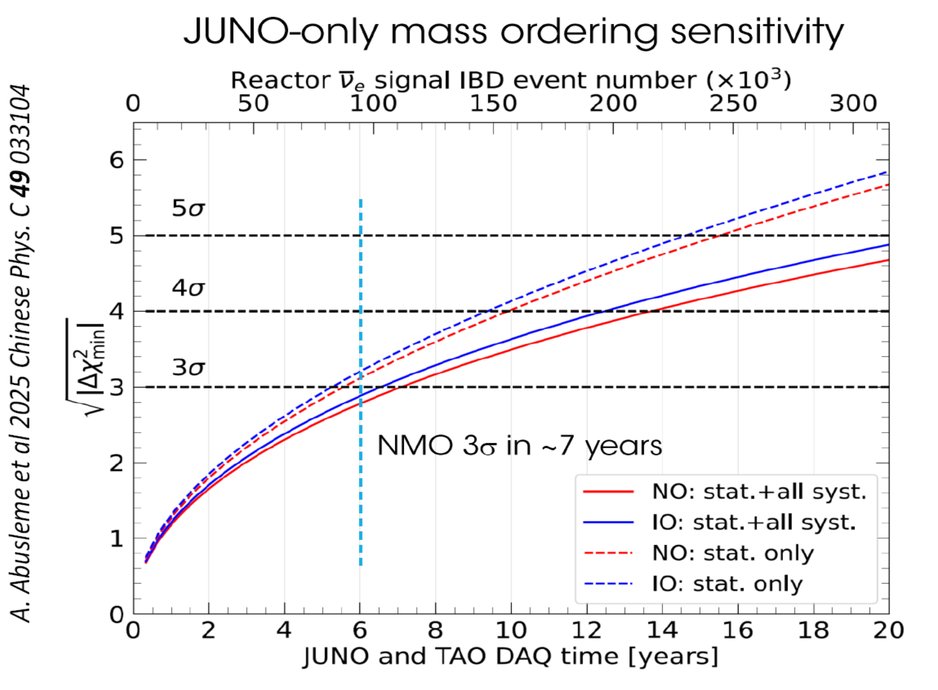


20 kT LS-based
neutrino detector



JUNO first events

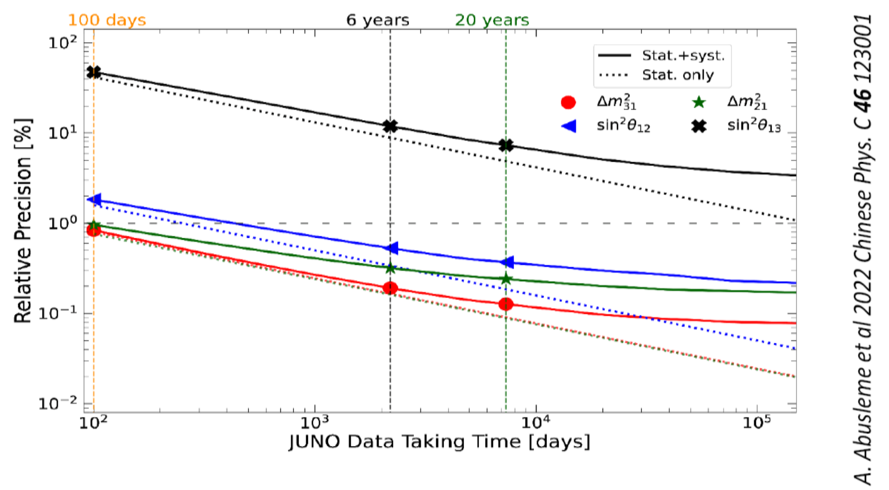




Most precise measurement of "solar" oscillation parameters after 59 days of data taking

$$\sin^2\theta_{12} = 0.3092 \pm 0.0087$$
$$\Delta m^2_{21} = (7.50 \pm 0.12) \cdot 10^{-5}\text{eV}^2$$

	$\sin^2\theta_{12}$	Δm^2_{21}
PDG 2025	3.9%	2.5%
JUNO 59.1 days	2.8%	1.6%



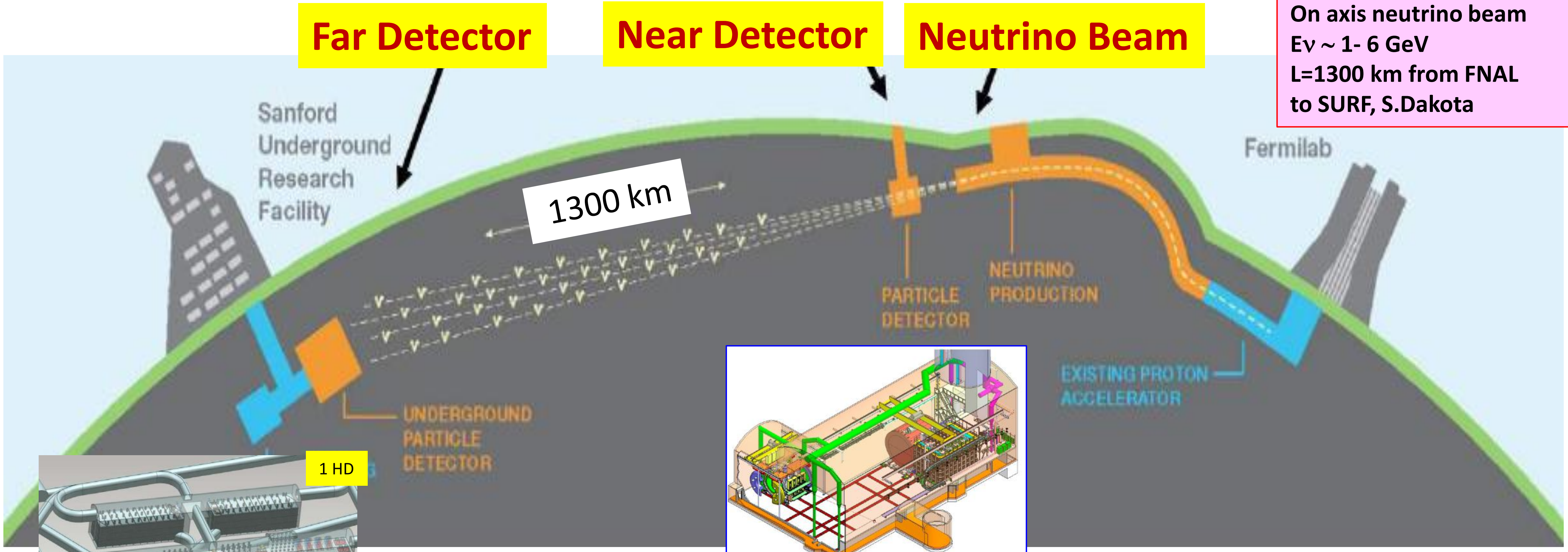
	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	Δm^2_{21}	Δm^2_{31}
PDG 2025	3.9%	2.8%	2.5%	1.3%
JUNO 6 years	0.5%	12.1%	0.3%	0.2%

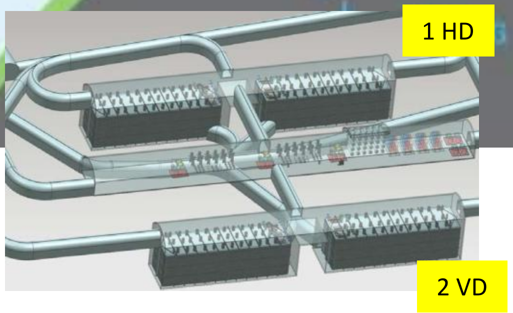
DUNE

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 2030

Phase II: Lar 4x17 kt modules, ND, proton beam 1.2 → 2.4 MW

DUNE: CP and MO sensitivity

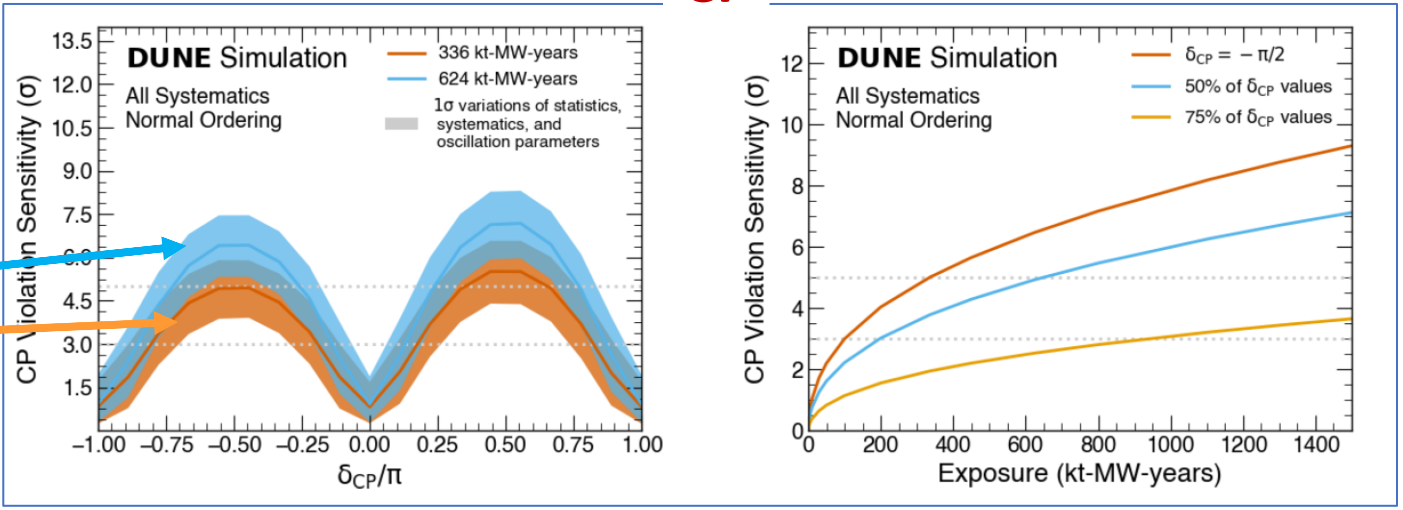
L.Perez-Molina, EPS-HEP 2025

Staging approach

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

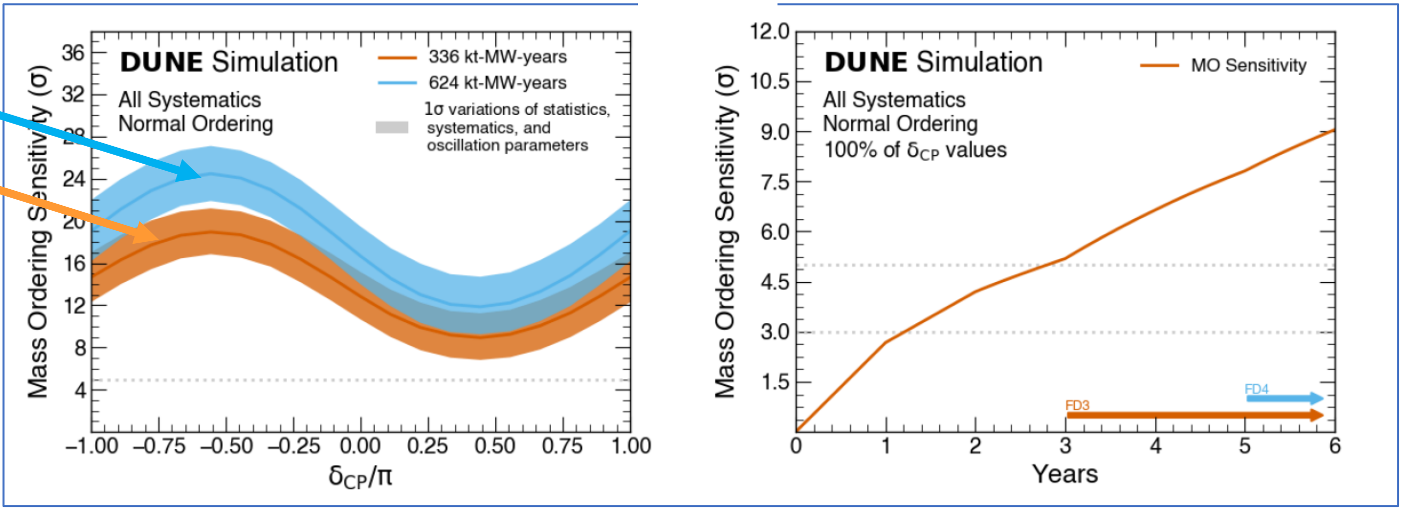
Sensitivity to δ_{CP}
- 10 years data taking
- 7 years data taking

CP



Sensitivity to δ_{CP}
- 10 years data taking
- 7 years data taking

MO

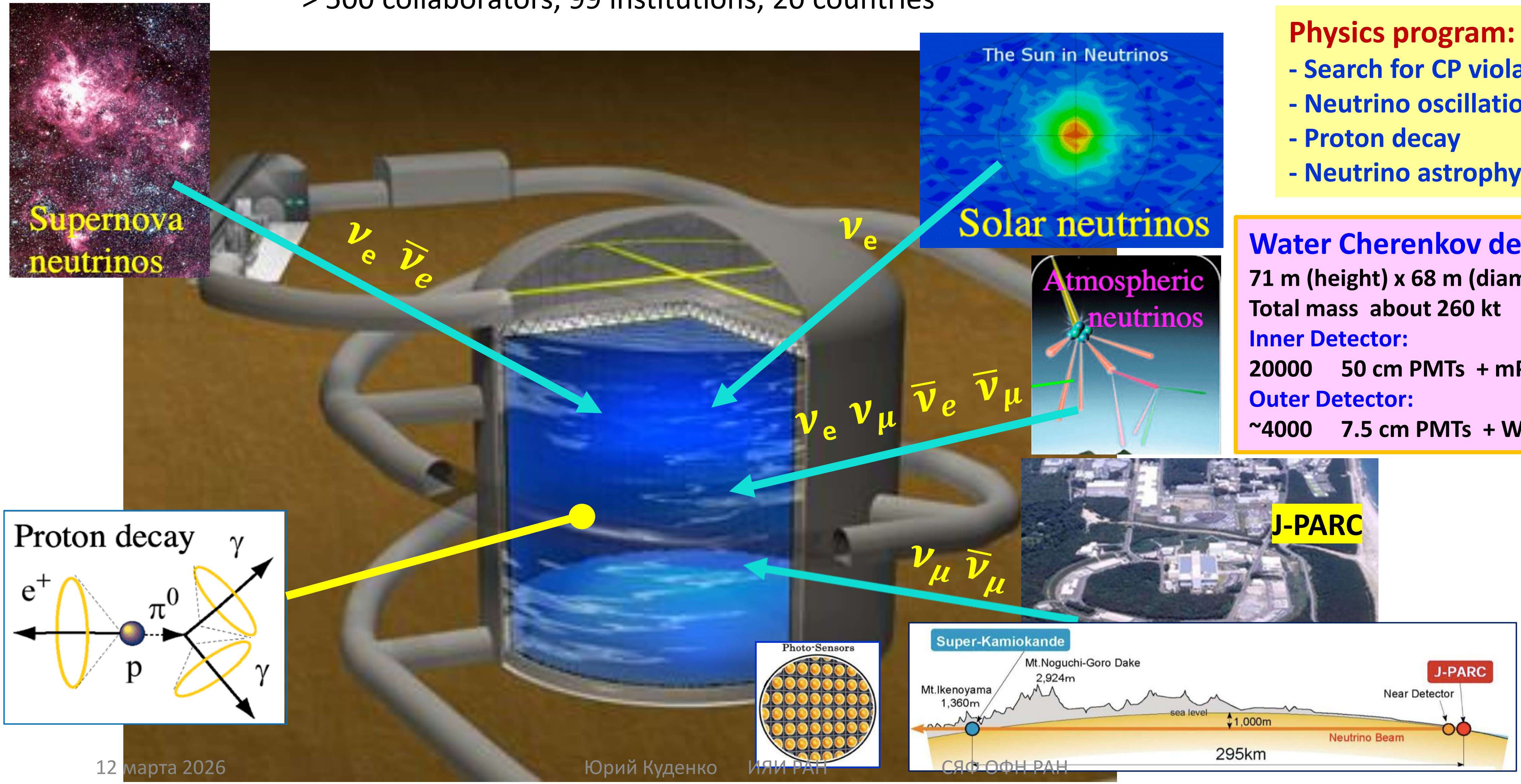


- Solar and atmospheric neutrino in 2029
- First neutrino beam data are expected in 2030

Hyper-Kamiokande

Japan. Project approved in 2020, construction begun in 2021, operation will start in 2028

> 500 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

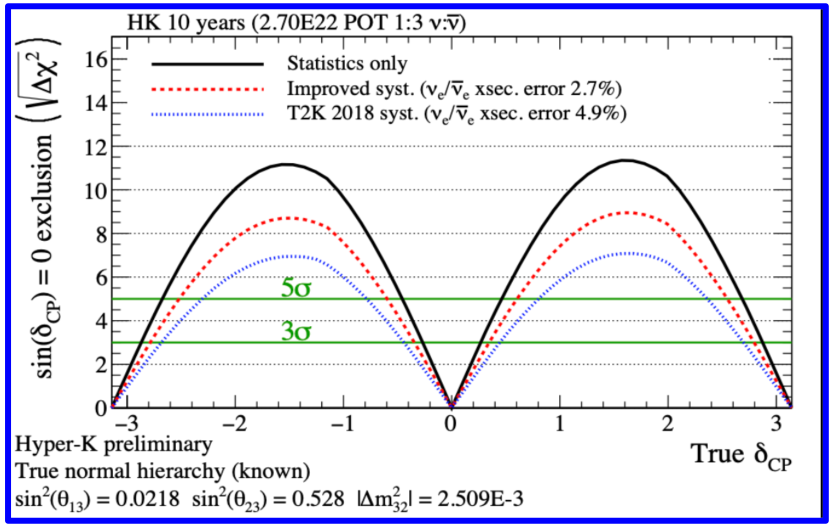
Outer Detector:

~4000 7.5 cm PMTs + WLS plates

Sensitivity to CP violation (I)

Hyper-Kamiokande, arXiv:1805.04163

Projected HyperK sensitivity to CP violation

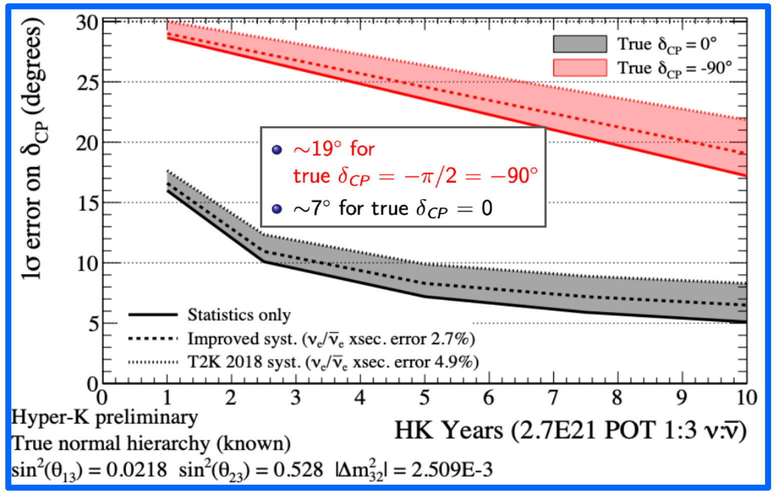


- 10 years of data taking,
- 1.3 MW beam power → 2.7×10^{22} POT

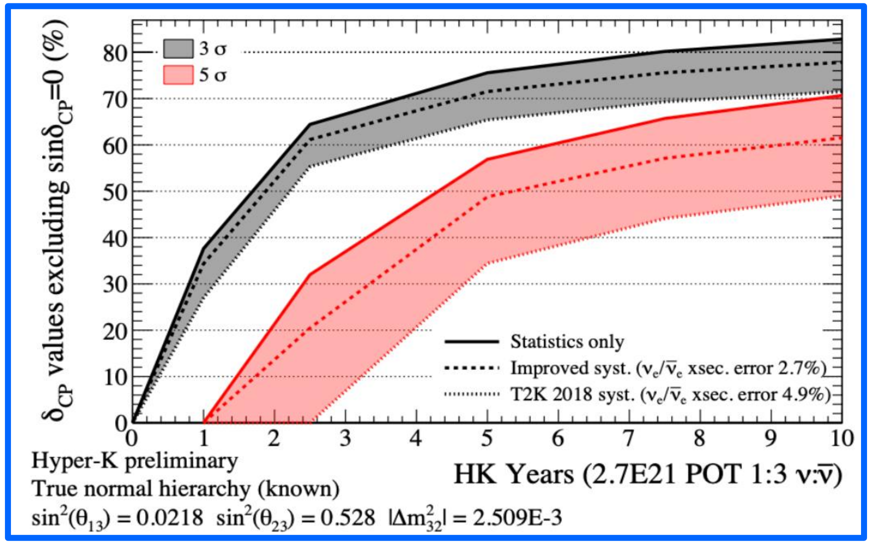
Expected number of events at HyperK for $\nu_e : \bar{\nu}_e = 1:3$ and $\sin\delta_{CP} = 0$

2300 ν_e 1300 $\bar{\nu}_e$

Measurement of δ_{CP}



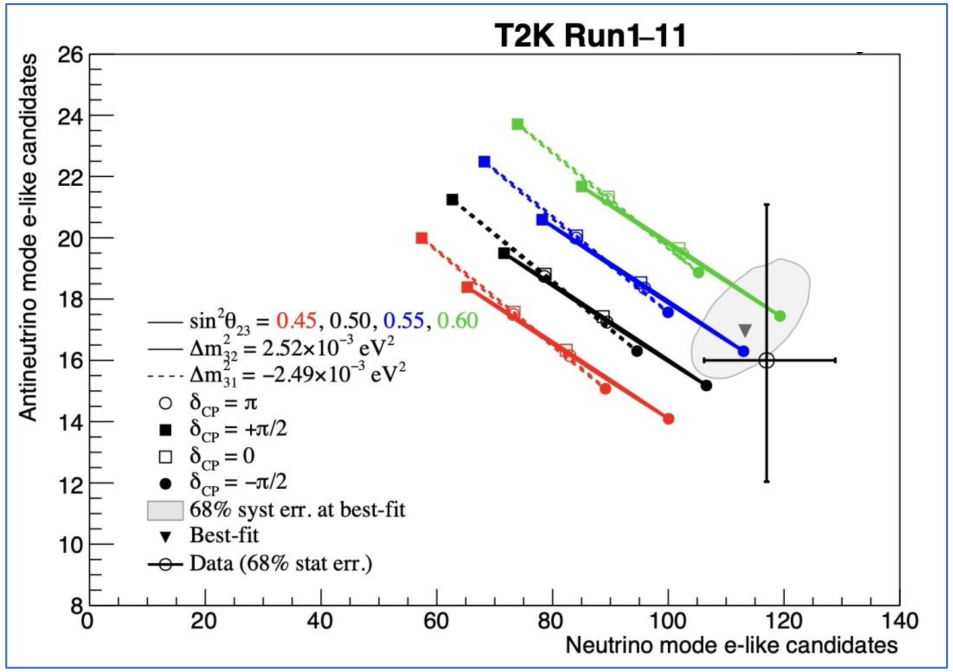
Exclusion of CP conservation



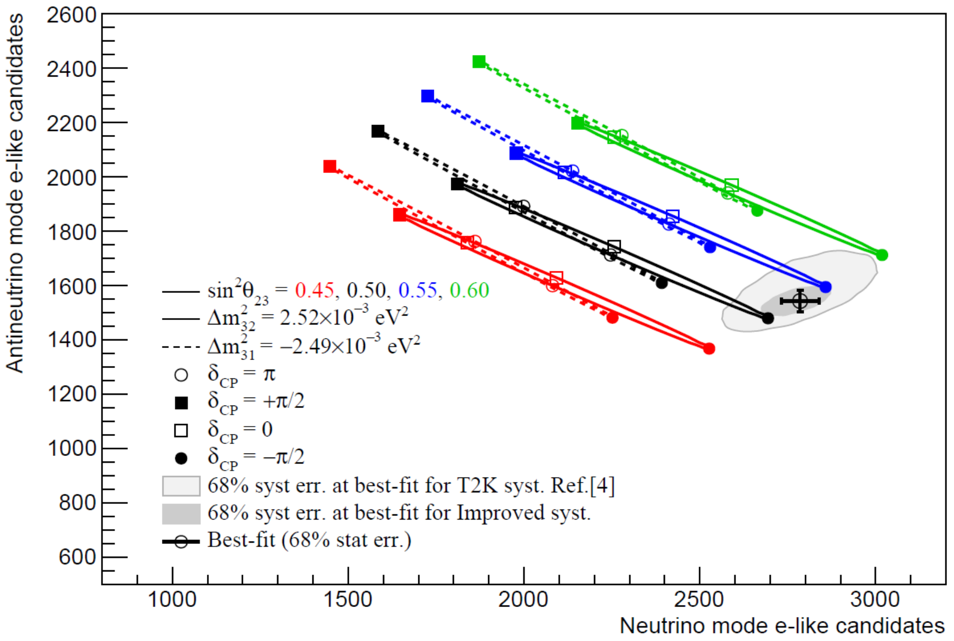
Sensitivity to CP violation (II)

Hyper-Kamiokande, arXiv:2505.15019

Current T2K result



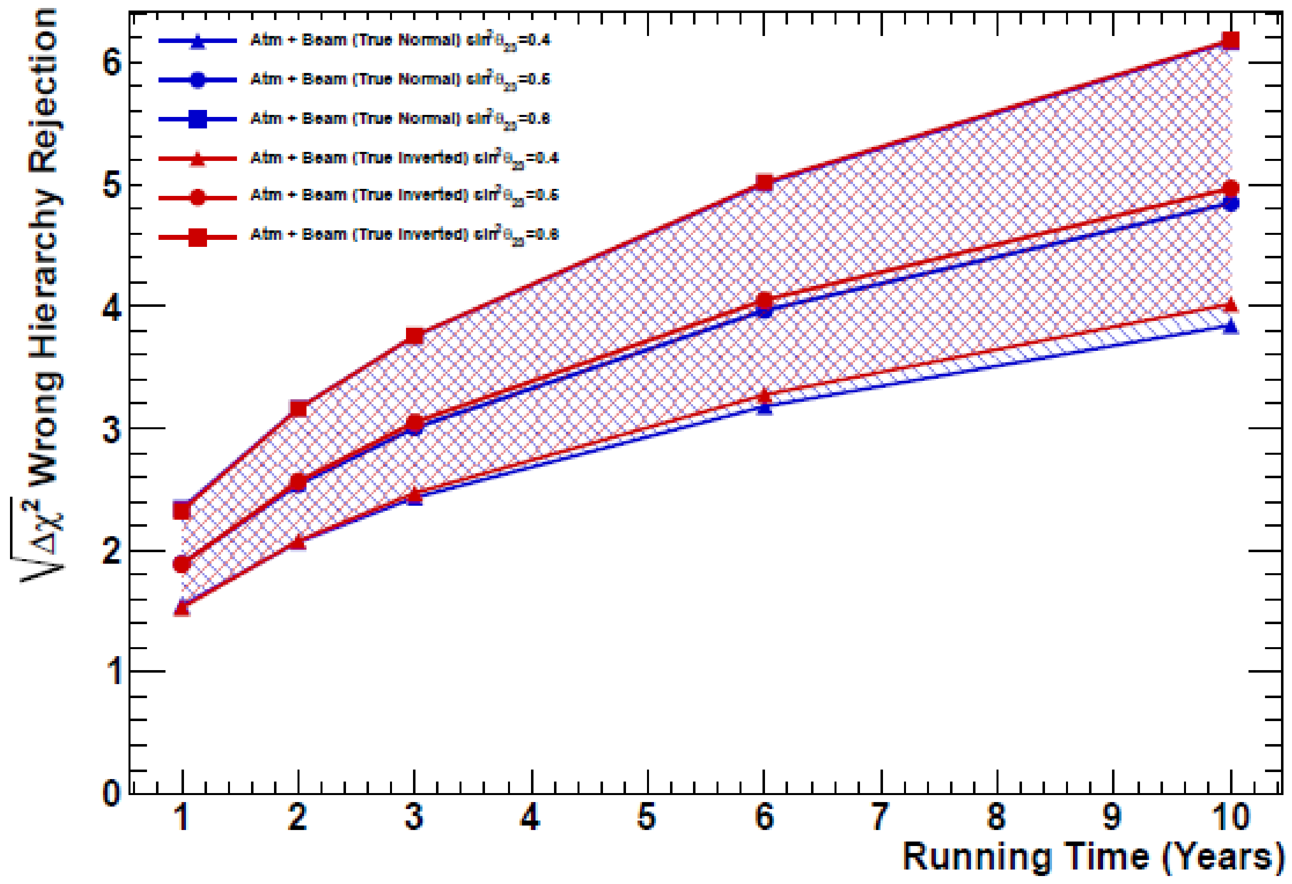
Projected Hyper-K result after 10 years data taking



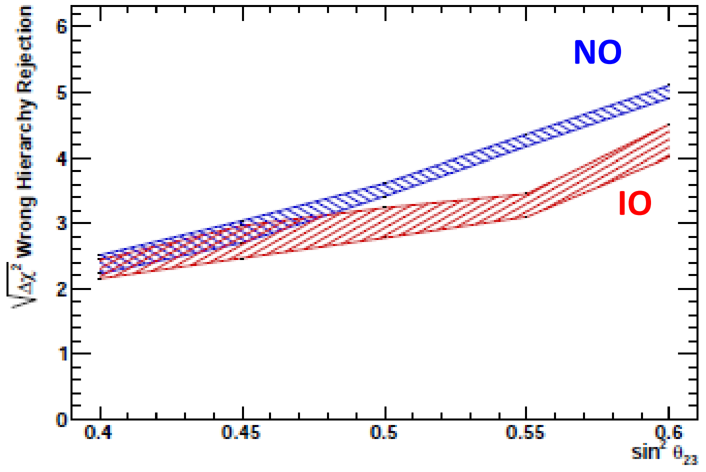
Hyper-Kamiokande: Mass Ordering

HyperKamiokande 10 years of data taking

Hyper-Kamiokande, arXiv:1805.04163



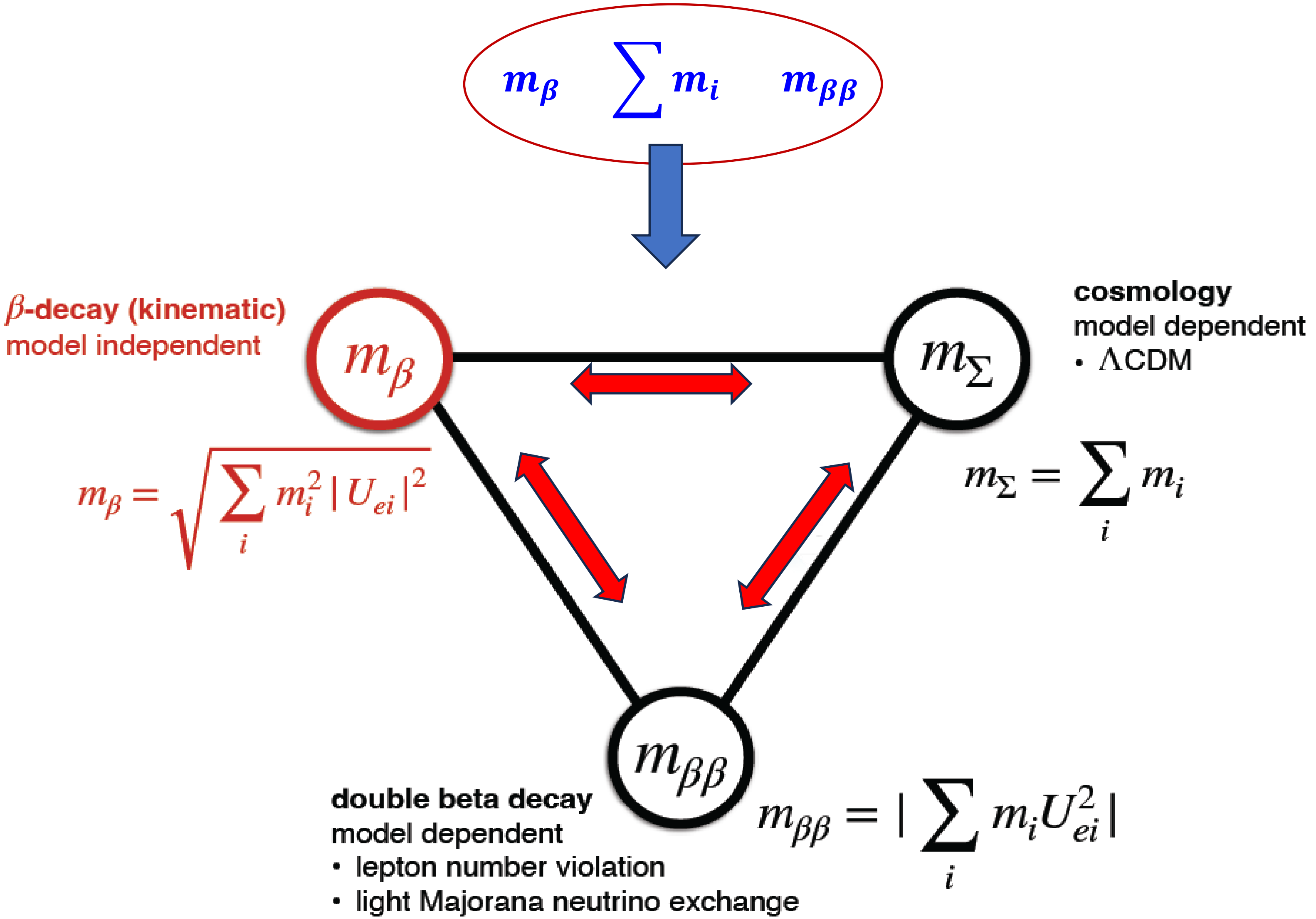
HyperKamiokande, atm neutrinos



	$\sin^2\theta_{23}$	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

Absolute scale of neutrino mass

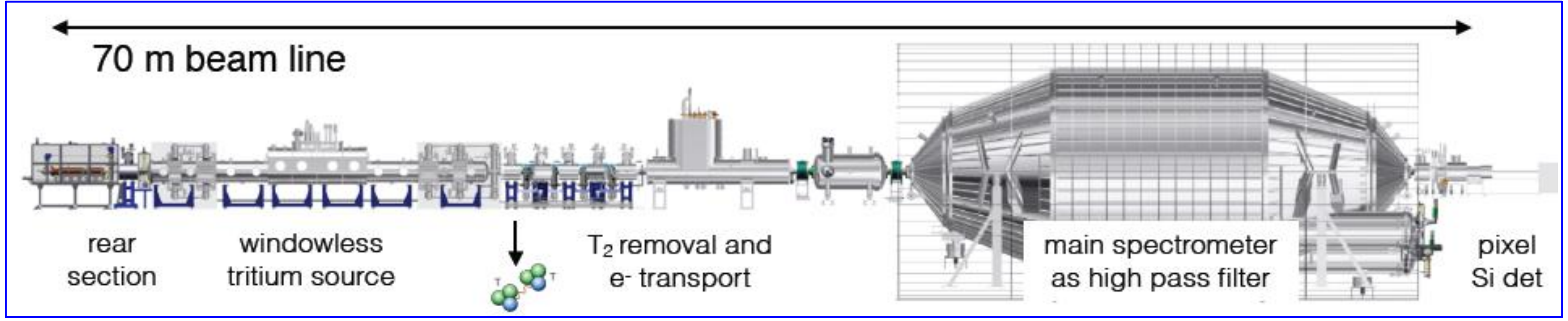
Neutrino mass observables

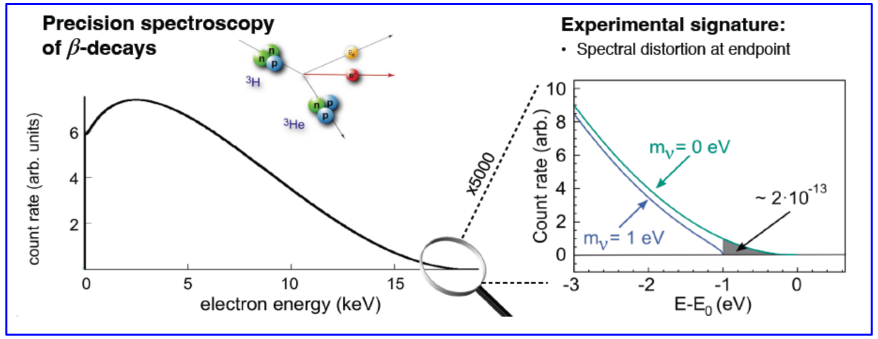


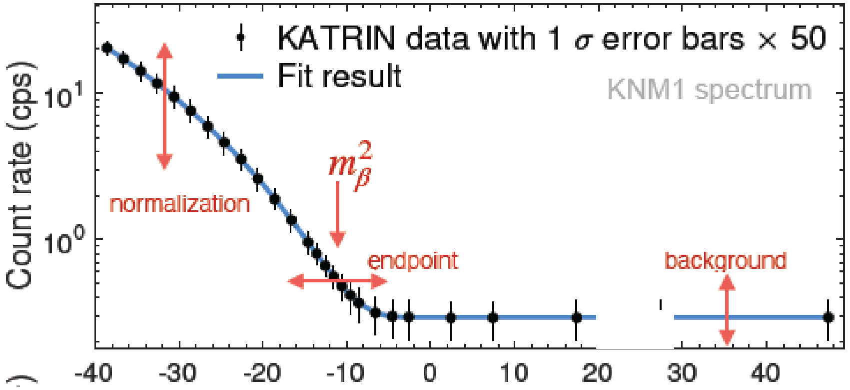
Direct measurement of neutrino mass

KATRIN: measurement of the beta decay end-point of tritium (^3H)

KATRIN, Science **388** (2025) 180







$$m_\nu^2 = -0.14^{+0.13}_{-0.15}\,\mathrm{eV}^2$$

$$m_\nu < 0.45\,\mathrm{eV}\ \ (90\,\%\ \mathrm{CL})$$

October 2025: KATRIN Completed **1000 days of data** at endpoint for projected sensitivity m_ν< 0.3 eV (90% C.L.)

Expected final KATRIN sensitivity < 0.3 eV (90% CL)

$0\nu2\beta$ decay: experimental status

C. None, talk at Nuphys 2026

KamLAND-Zen

750 kg of 91% ^{136}Xe

$T_{1/2}(^{136}Xe)$ > **$3.8 \cdot 10^{26}$ yr** (90% CL)

→ $m_{\beta\beta}$ < **[28, 122] meV** (90% CL)

Upgrade

After 5 years: $T_{1/2}^{0\nu} > 2 \times 10^{27}$ yr

SNO+

760 t liquid scintillator

1.3 ton of ^{130}Te for 0.5% loading

Projected sensitivity

$T_{1/2}(^{130}Te)$ > **$1.8 \cdot 10^{26}$ yr** (90% CL), 3 yr with 0.5%

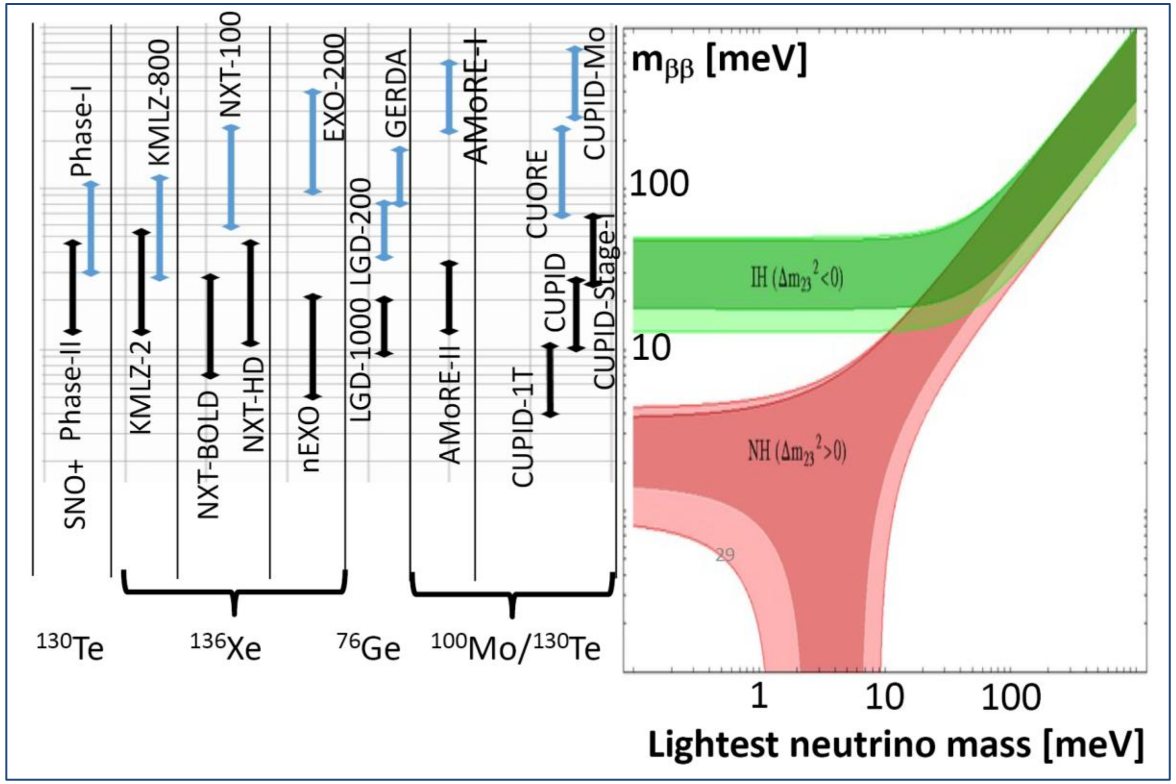
$T_{1/2}(^{130}Te)$ > **$7.4 \cdot 10^{26}$ yr** (90% CL), 5 yr with 1.5 %

LEGEND-200

200 kg og 90% Ge-76 in GERDA infrastructure

Projected sensitivity

$T_{1/2}(^{76}Ge)$ = **$1.5 \cdot 10^{27}$ yr** (3σ)



Full CUPID ⇨ (10 y livetime - 240 kg ^{100}Mo + 5 keV FWHM)

$T^{0\nu}_{1/2}$ > 1.4×10^{27} yr

$m_{\beta\beta}$ < (9.6-16) meV

CUPID-1T ⇨ 10 y livetime - 1000 kg ^{100}Mo + 5 keV FWHM

$T^{0\nu}_{1/2}$ > 1×10^{28} yr

$m_{\beta\beta}$ < (3.8-6.3) meV

Cosmology, DESI: Σm_ν

Oscillation data, assuming mass of lightest neutrino = 0

$$\left(\sum m_\nu\right)^{NO} > (58.980 \pm 0.304) \times 10^{-3}\,\text{eV}, \quad \left(\sum m_\nu\right)^{IO} > (99.824 \pm 0.581) \times 10^{-3}\,\text{eV}.$$

KATRIN + oscillation data

$$\Sigma m_\nu < 1.35\ \text{eV}$$

Cosmology

Planck 1807.06209 $\quad$ *Planck* 2018 + BAO $< 0.12\text{eV}$

Dark Energy Spectroscopic Instrument (DESI) (Mayall 4-meter Telescope in Arizona):
3 year measurements of BAO from $14\text{x}10^6$ galaxies and quasars
Combining these data with CMB + Atacama Cosmology Telescope, assuming **ΛCDM model**

$$\Sigma m_\nu < 61\ \text{meV (95\% CL)}$$

arXiv:2504.18464

Planck 2018 + ACT + DESI DR1 $\quad N_{\text{eff}} = 2.86 \pm 0.13$

arXiv:2503.14454

Evolving (dynamical) dark energy

$$\Sigma m_\nu < 152\ \text{meV (95\% CL)}$$

Neutrino anomalies

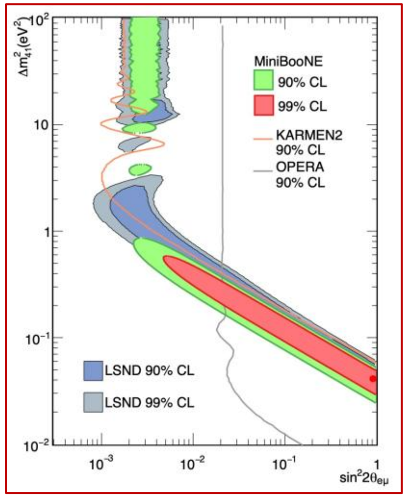
Light sterile neutrino ?

LSND/MiniBooNe anomaly

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

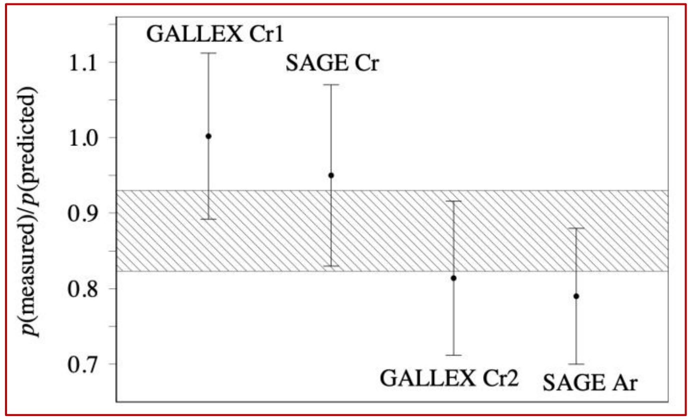
87.9 ± 22.4 ± 6.0 events

Excess 3.8σ



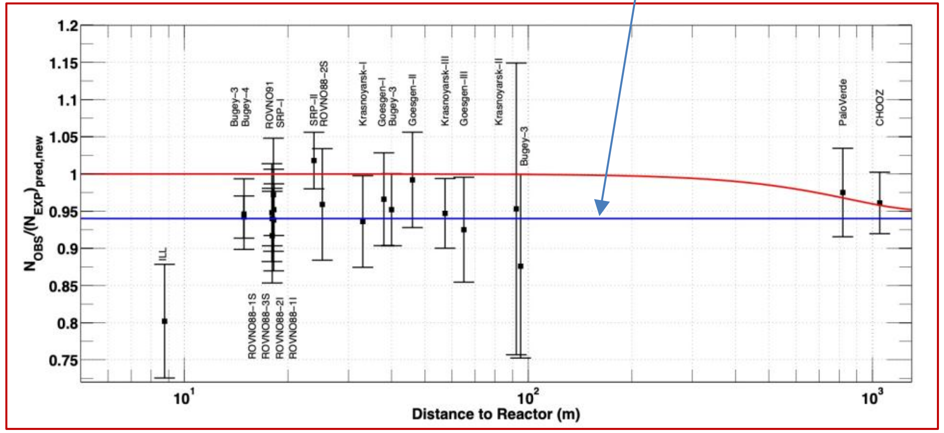
Ga anomaly

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

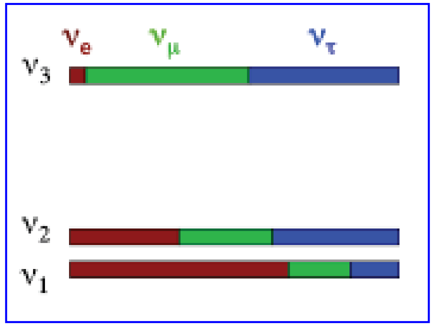


Reactor anomaly

0.937 ± 0.027

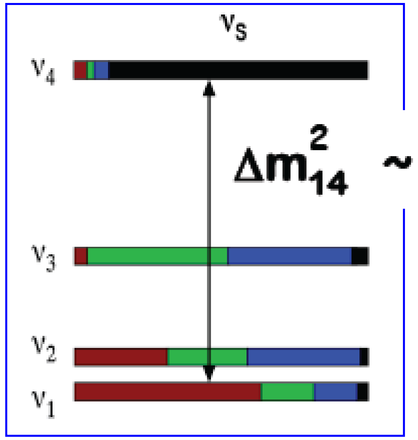


3ν, NO



?

$3\nu + 1\nu_s$



Δm^2_{14} ~ 1 eV²

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

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

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

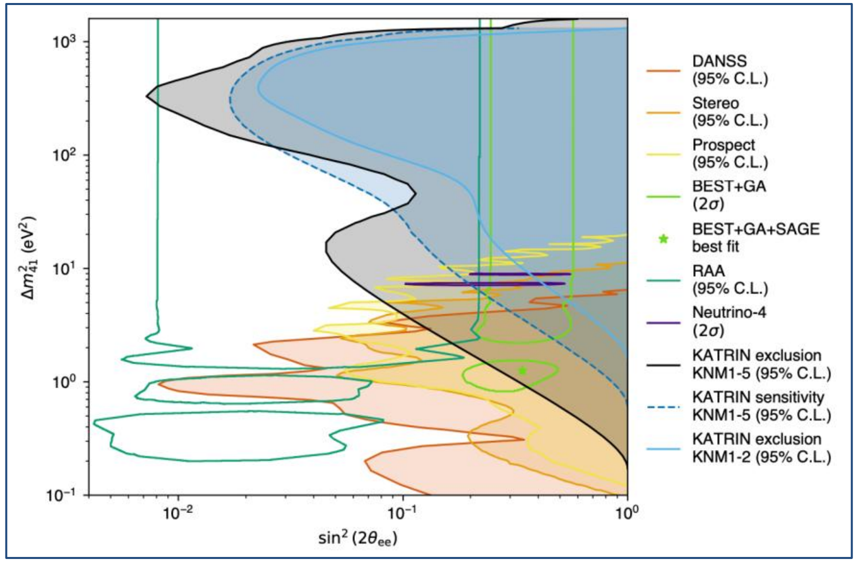
$$P_{\nu_\mu \to \nu_e} \simeq 2|U_{e4}|^2|U_{\mu 4}|^2$$

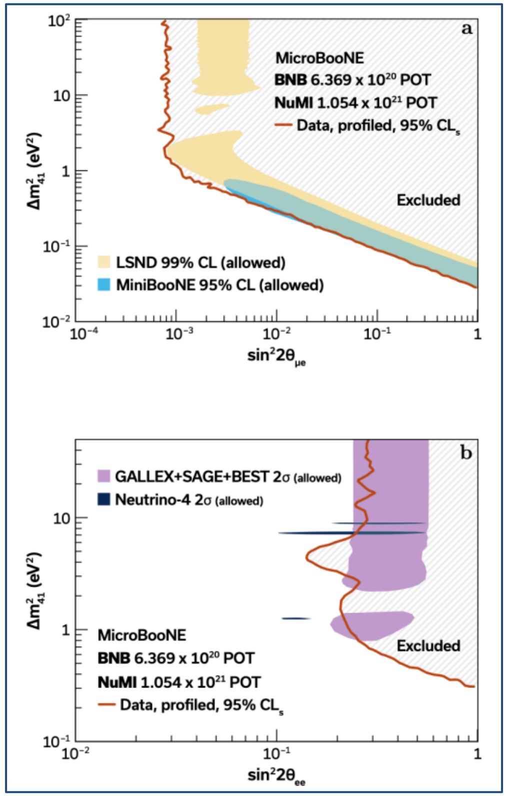
$$\sin^2 2\theta_{e\mu} \simeq \frac{1}{4}\sin^2 2\theta_{ee} \ \sin^2 2\theta_{\mu\mu}$$

KATRIN and MicroBooNE: ν_s search

MicroBooNE, Nature 648 (2025) 8092, 64-69

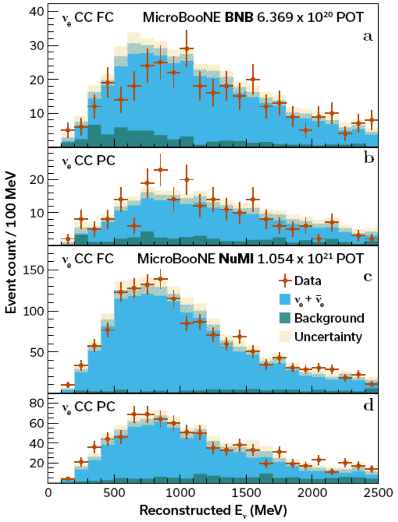
KATRIN, Nature 648 (2025) 8092, 70-75





Two ν_μ beams at FNAL:
- Booster neutrino beam (**0.57% ν_e**)
- NuMI beam (**4.6% ν_e**)

Break the degeneracy between ν_e appearance and disappearance



Results of five measurement campaigns with 36 x 10^6 electrons near the tritium β-decay endpoint:

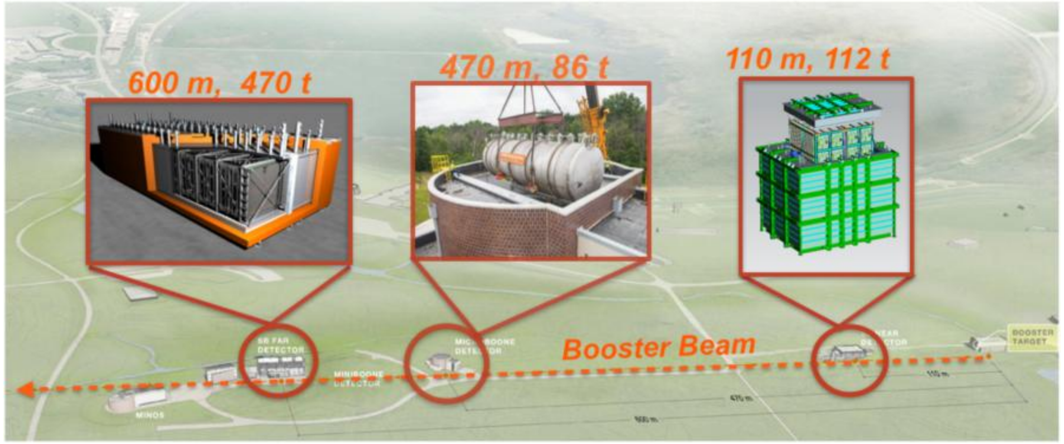
- 95% CL contour of Neutrino-4 is fully excluded, best-fit point is rejected at 99.99% CL;
- a large portion of parameter space of the reactor anomaly is excluded;
- most of the parameter space favoured by the Gallium anomaly is excluded

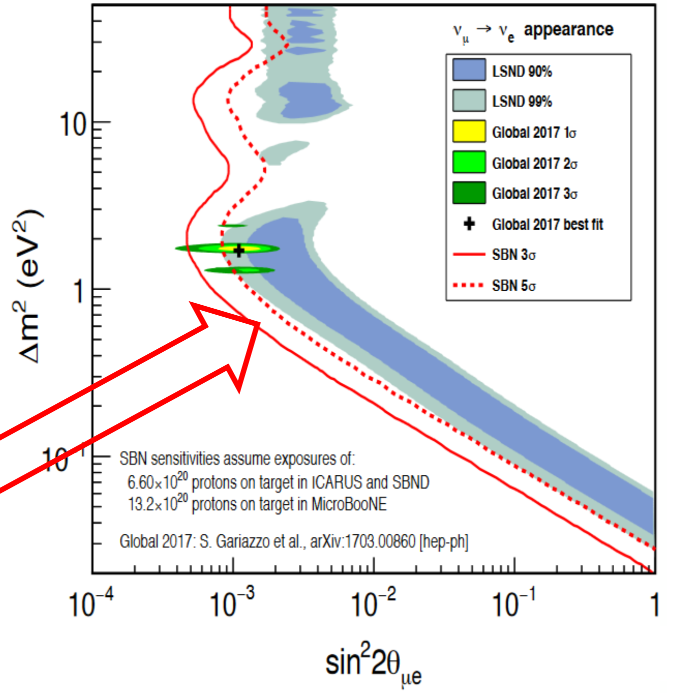
- Single ν_s interpretation of the LSND/MiniBooNE anomalies is excluded at 95% CL.
- A notable portion of parameter space that could explain the Gallium anomaly is ruled out

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





Test of LSND/MiniBooNE anomaly

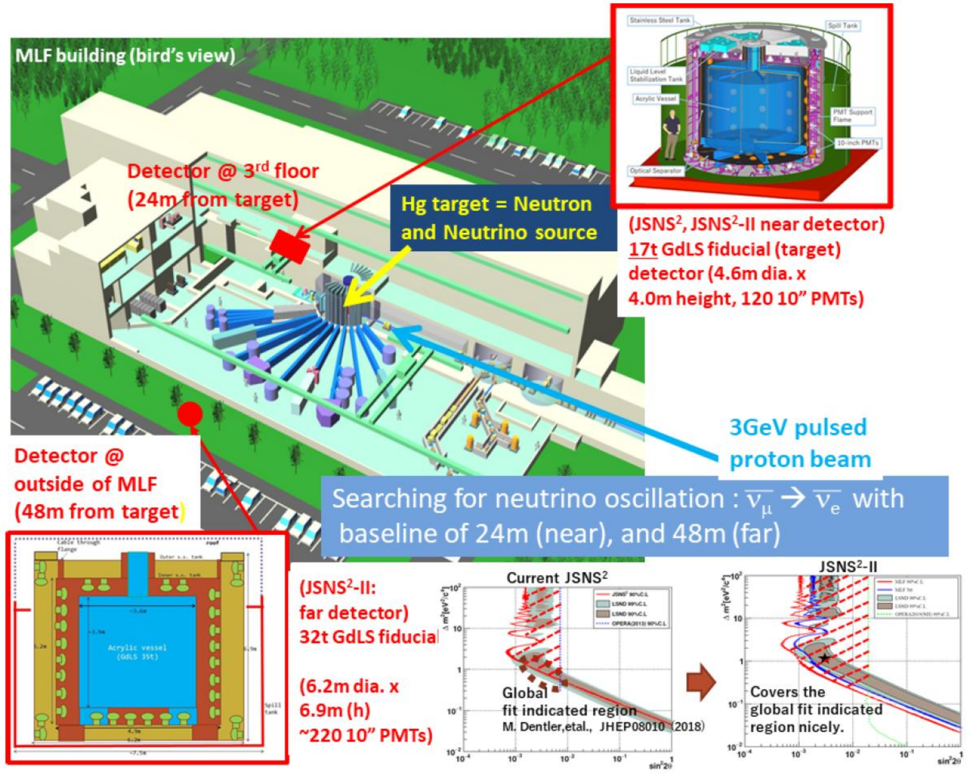
ICARUS: commissioning in 2022,
took data from Booster and NuMI beams in 2023

JSNS^2 at J-PARC

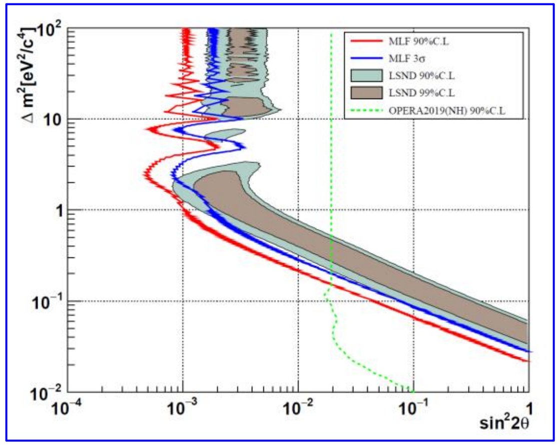
Proposed in 2013, data taking begun in 2020

Short-pulsed 3GeV, 1 MW 3 GeV proton beam, 25 Hz repetition rate at J-PARC
Detector: gadolinium (Gd) loaded liquid scintillator (LS).

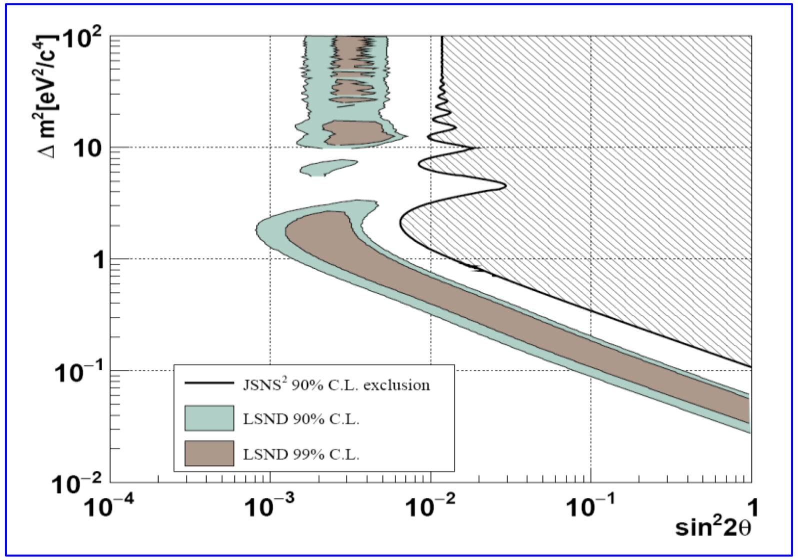
arXiv:2602.06274



Expected sensitivity



Data collected in 2022,
about 7% of POT approved
for experiment



Conclusion

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) accelerator experiments.
Mass Ordering is the main goal of JUNO which begun data taking in 2025

Hint on maximal CP violation in T2K for both, NO and IO

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

SuperKamiokande, T2K and NOvA prever NO of neutrino mass

Cosmology prefers NO? Extension of ΛCDM ?

Interpretation of LSND, reactor and Ga anomalies in 3+1 scheme with a single ν_s is mostly excluded

Спасибо за внимание

Backup slides

Neutrino oscillations and mixing

Standard Model: neutrinos are *massless* particles

3 families

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \qquad U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}$$

***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

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

$$|\Delta m^2_{32}| \cong |\Delta m^2_{31}| = |\Delta m^2_{atm}| \approx 2.4\times 10^{-3}\,\mathrm{eV}^2$$

T2K — Daya Bay, RENO, Double Chooz

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

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

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

Solar experiments, SuperK, KamLAND

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

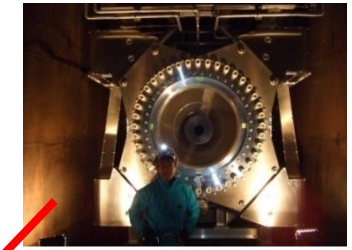
$$\Delta m^2_{21} = \Delta m^2_{sol} \approx 7.5\times 10^{-5}\,\mathrm{eV}^2$$

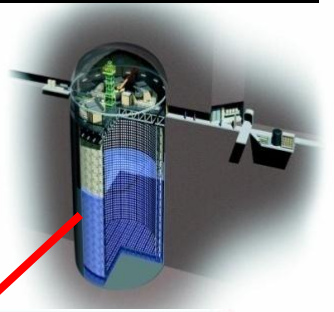
two independent Δm^2

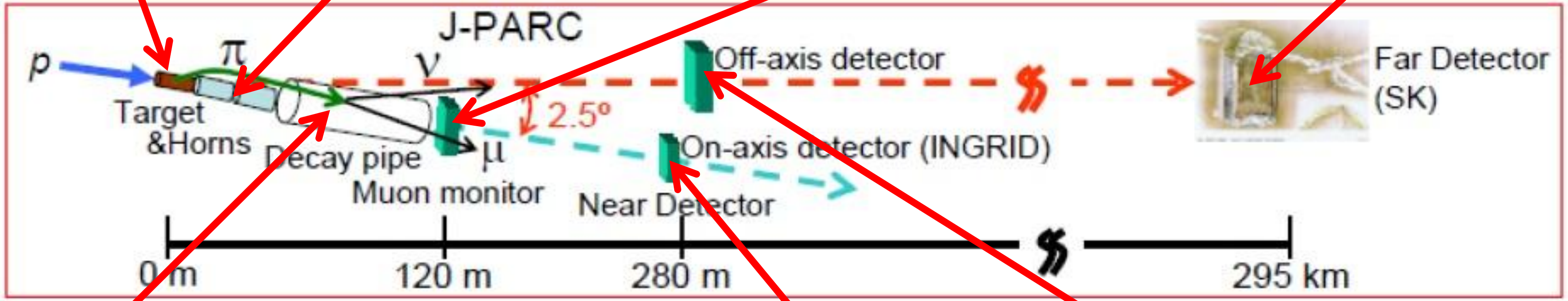
Experiment T2K

LBL accelerator experiment

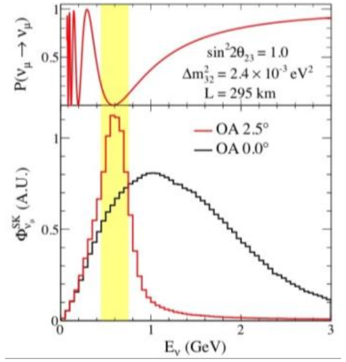
Far neutrino detector
SuperKamiokande



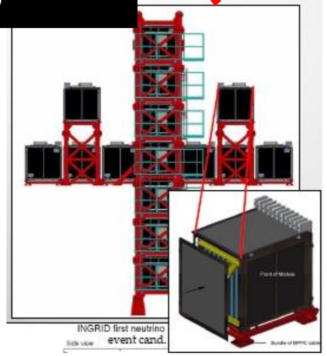




Off-axis neutrino beam

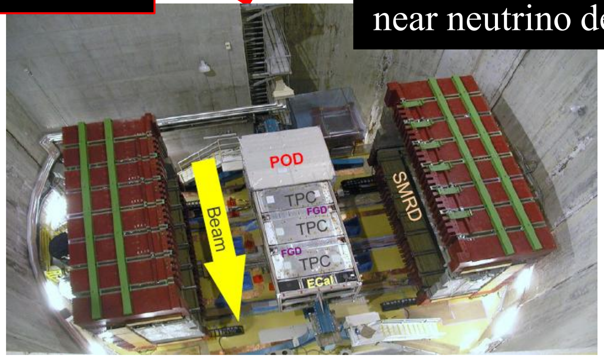


Neutrino monitor
INGRID

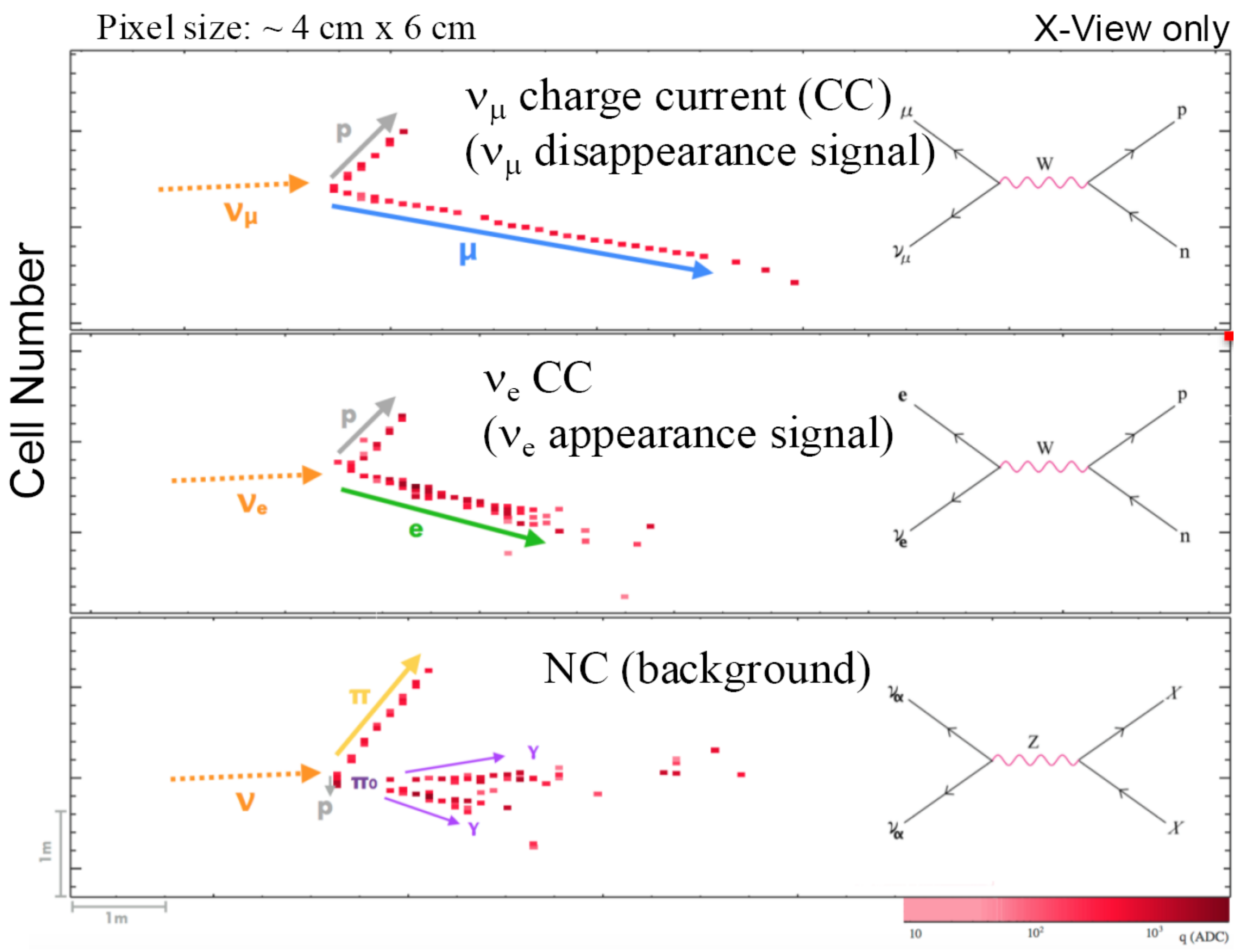


ND280

Off-axis
near neutrino detector



NOvA: event display



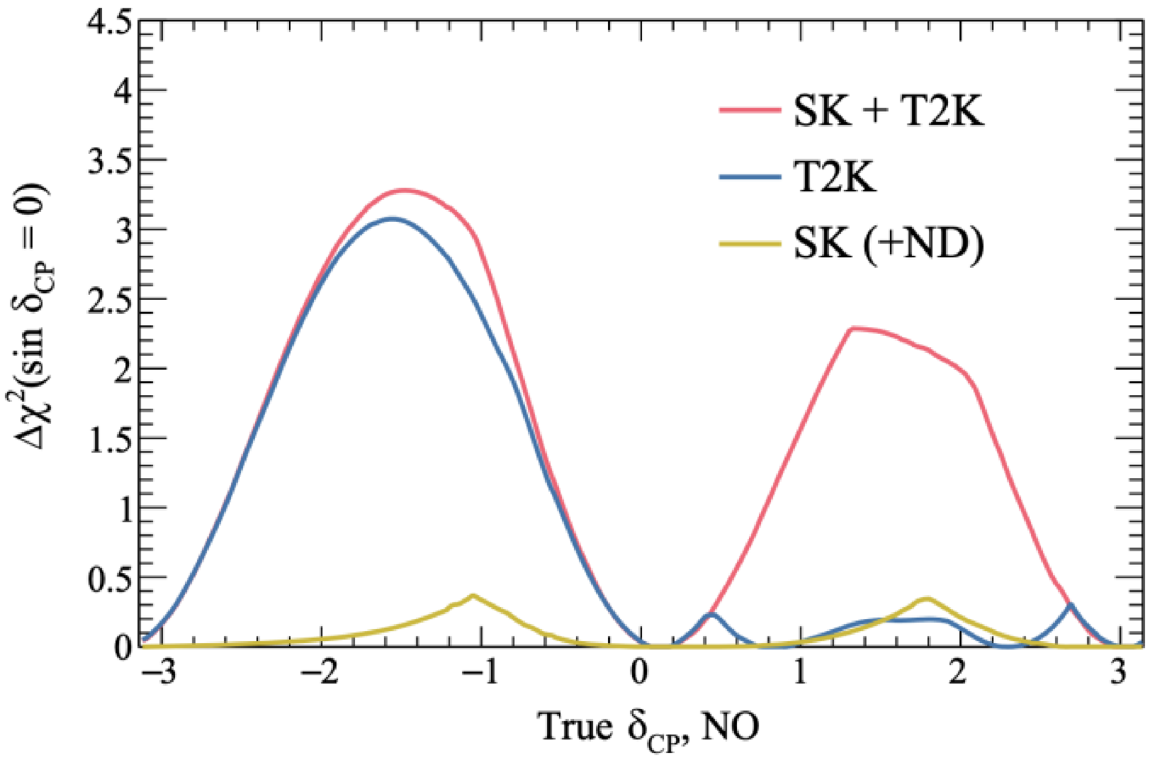
SuperK/T2K analysis

SK atmospheric and T2K beam neutrinos have different oscillation baselines and energy ranges, but both experiments use the Super-K detector

Overlapping systematic uncertainties! (detector model + sub-GeV cross-section model)

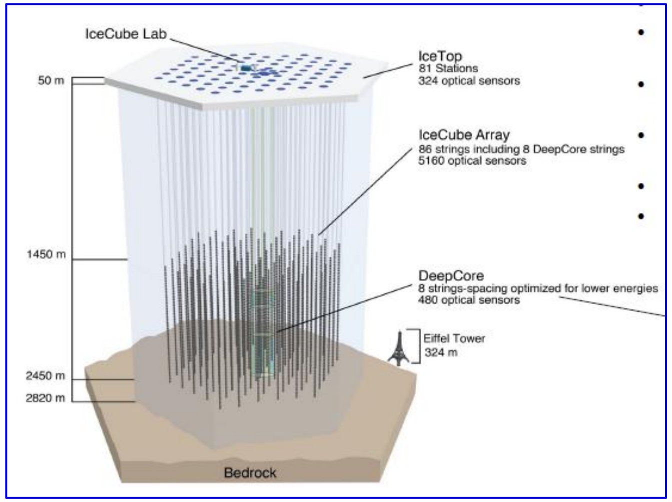
T2K has good δ_{CP} sensitivity, but mild mass ordering sensitivity

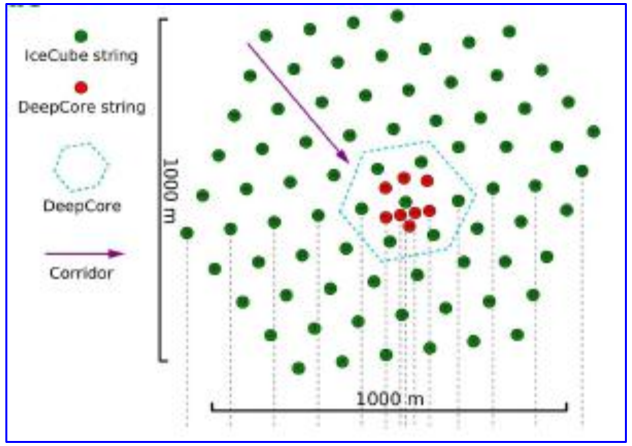
SK has good mass ordering sensitivity, but limited δ_{CP} sensitivity

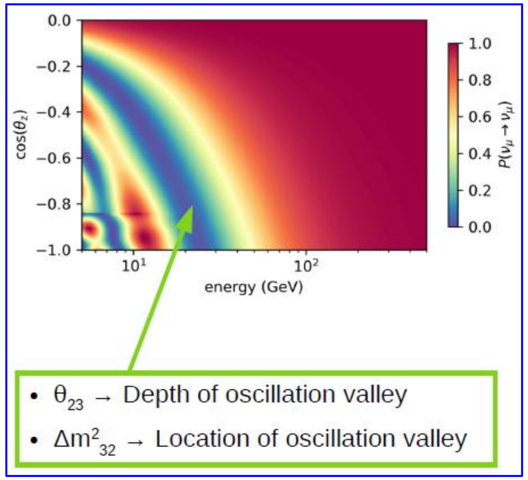


IceCube DeepCore: $\nu_\mu \rightarrow \nu_\mu$

A.Kumar, EPS-HEP 2023

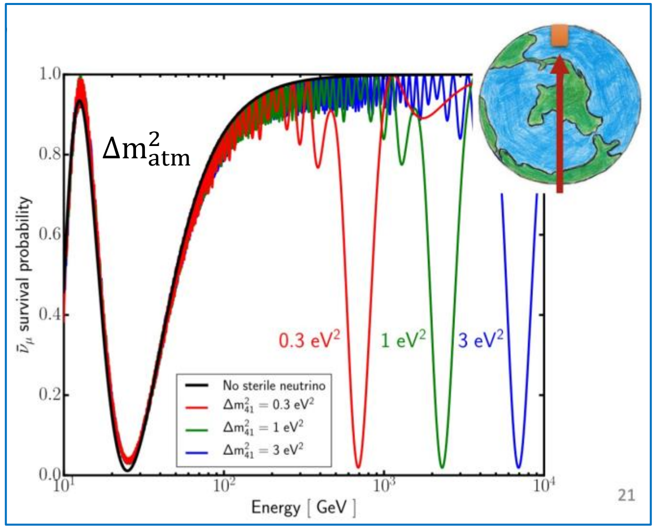


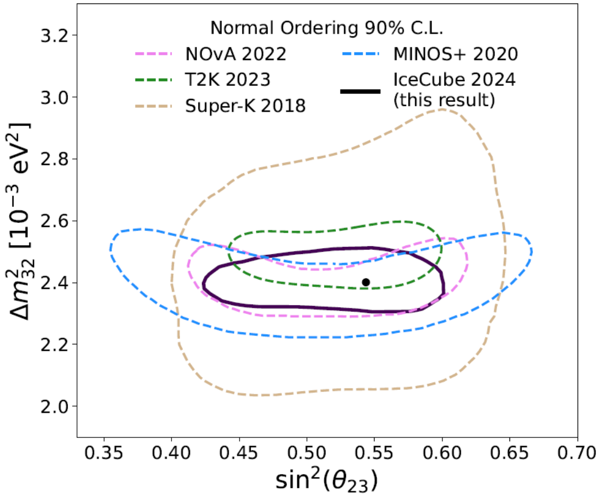




J.P. Yanez, Neutrino2024

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



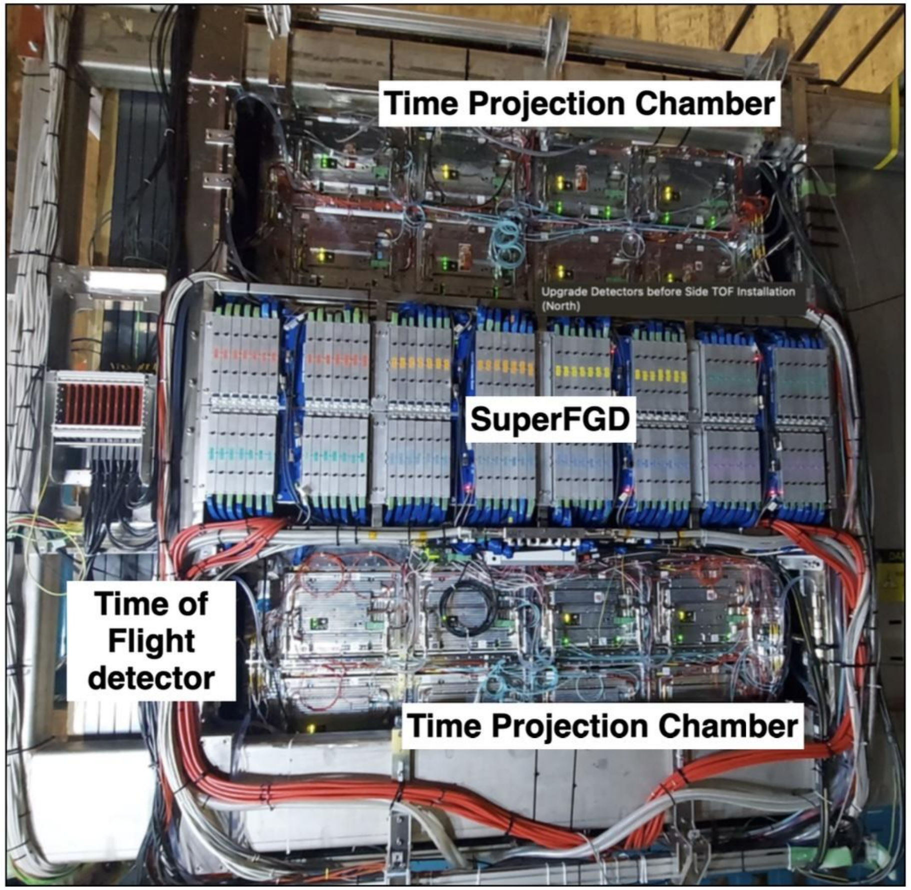


Phys.Rev.Lett. 134 (2025) 9, 091801

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

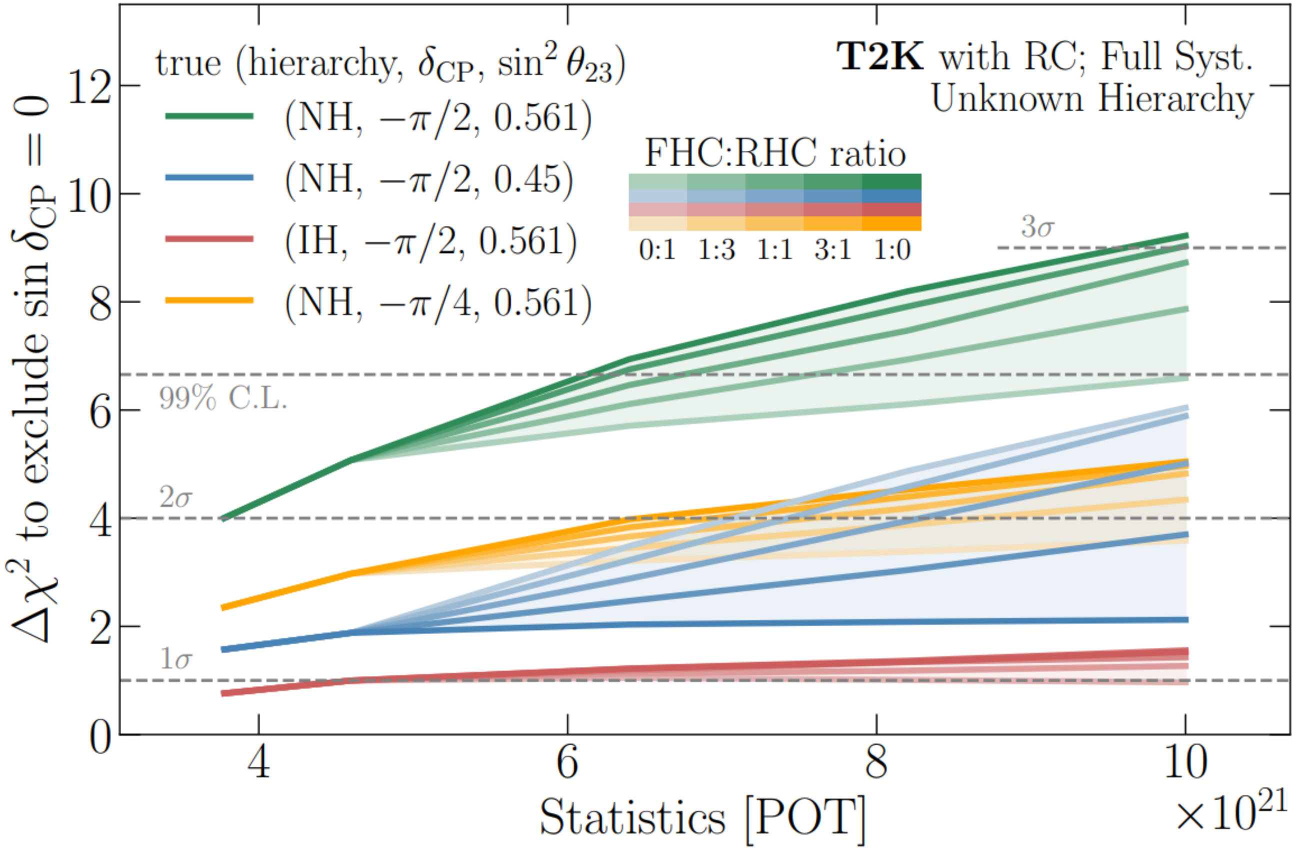
T2K perspectives

Upgraded ND280



Goal to reduce systematics in oscillations to ~3% level

T2K will continue data taking until ~2028 using >900 kW proton beam with improved systematics due to **SuperFGD**



T2K: ND280 upgrade

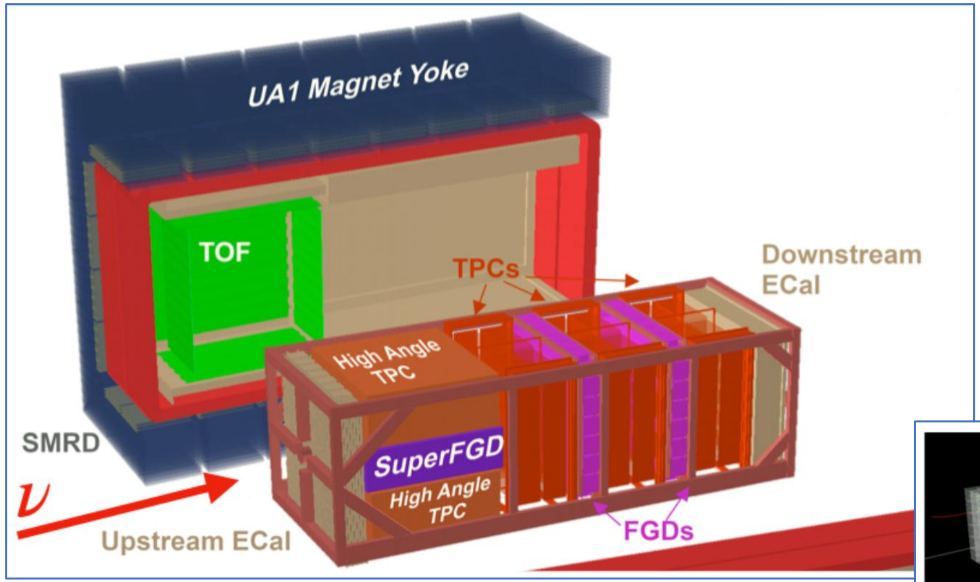
Current ND280 ⇒ *Upgraded ND280*

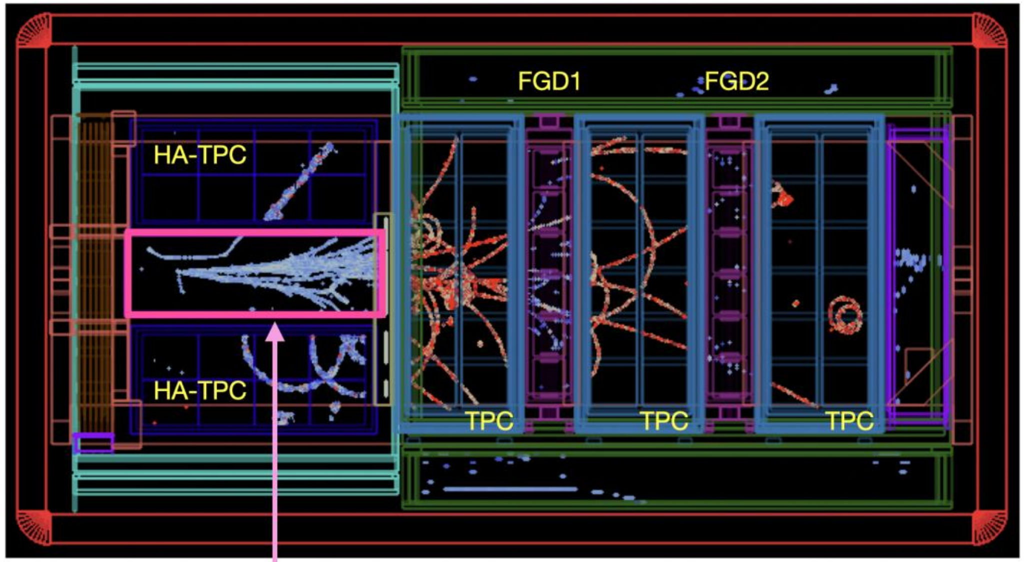
- Improve acceptance for high angle and backward tracks
- High precision probe of the nuclear effects → reduced systematics
- Detection of short proton tracks which is very important for T2K analysis
- Reconstruction of the neutrino energy by time-of-flight
- TOF Detector separates background from outside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

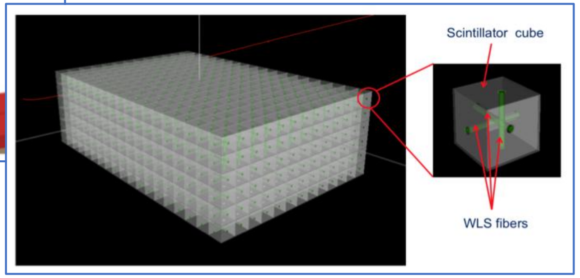
All new elements installed and commissioned with neutrino beam. Data taking started in 2024

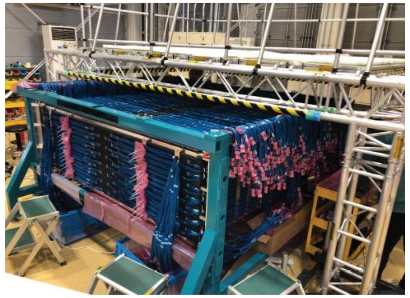
SuperFGD:
~100 participants from Russia, Japan, US, Switzerland, France, Spain
~35 from **INR, JINR, LPI**

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









HyperK 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**

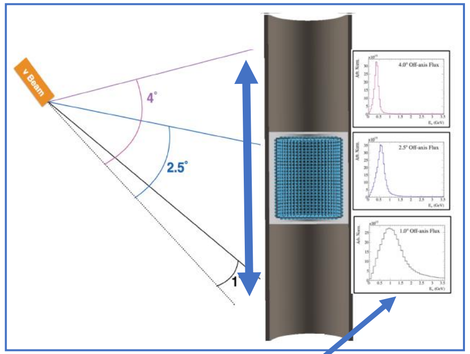
Existing (T2K+upgrade) ND **at 280 m from target**

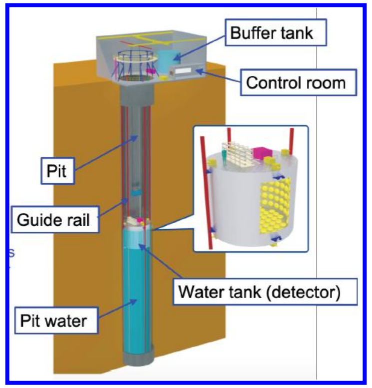
IWCD: Movable water Cherenkov detector

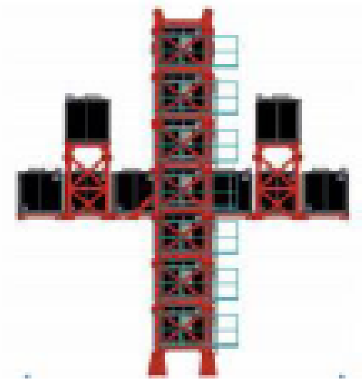
IWCD

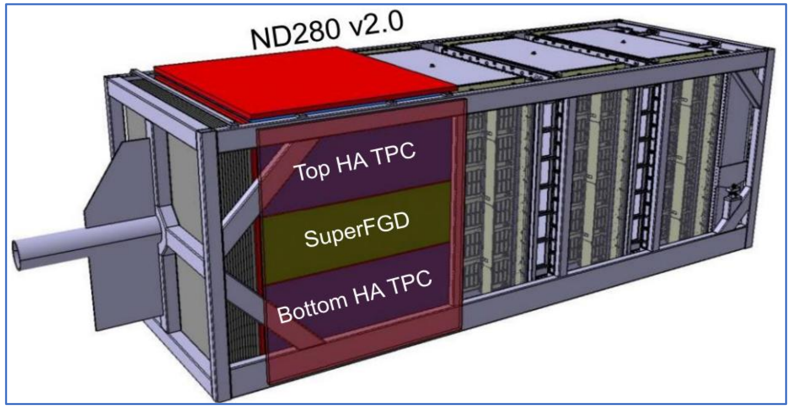
INGRID

ND280 upgraded









Neutrino spectra

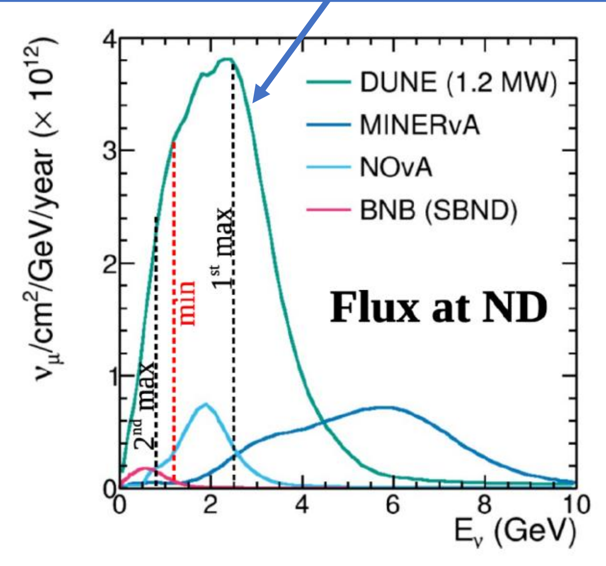
~1 kt water Cherenkov detector
Photocesors:
muli-PMT modules

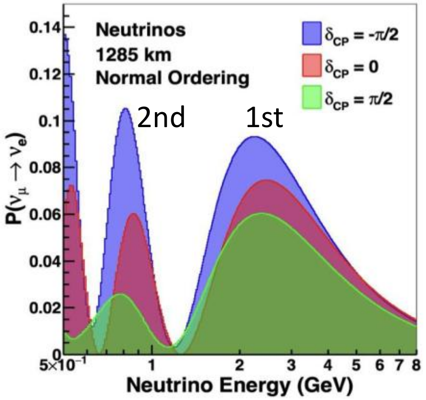
Neutrino on/off axis beam monitor

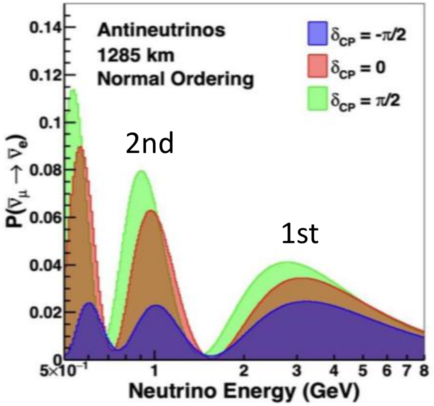
Magnetized off-axis near detector

DUNE features

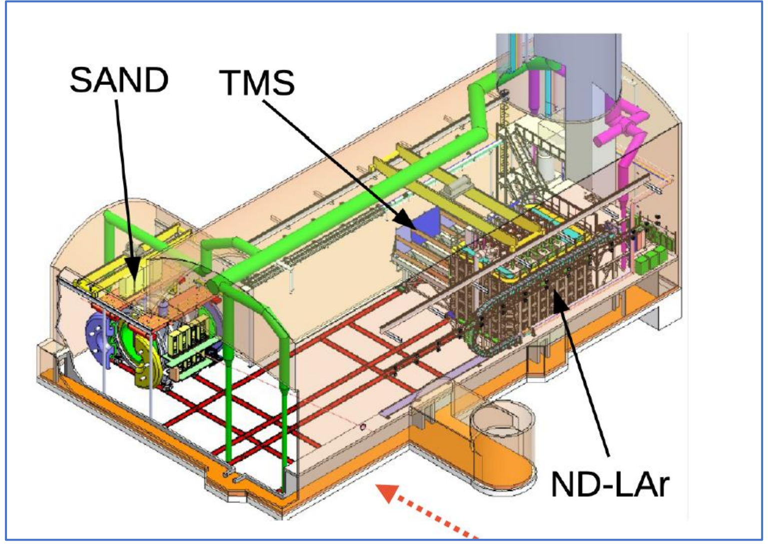
DUNE flux at ND





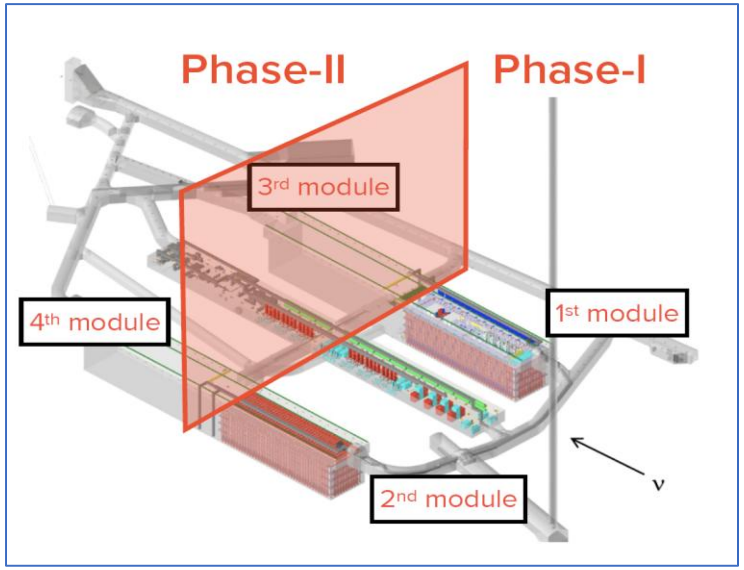


Near Detector



Near Detector:
- ND-LAr
- Movable Temporary Muon Spectrometer (TMS)
- On-axis monitor: SAND

Far Detector



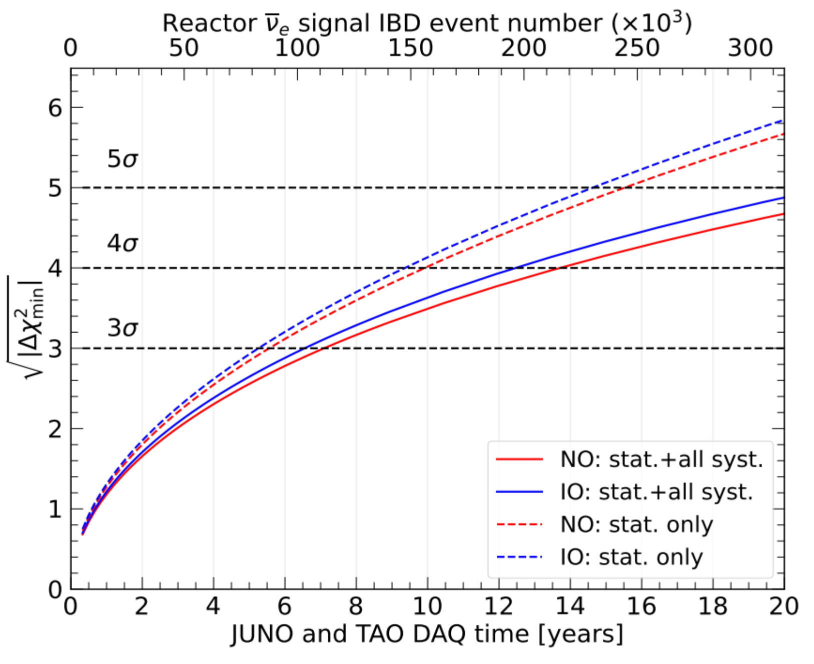
Phase I:
Two 17 kt (10 kt fiducial) LAr TPC FD modules:
one Vertical Drift + one Horizontal Drift
Phase II:
Four 17 kt (10 kt fiducial) LAr TPC FD modules

Sensitivity to MO

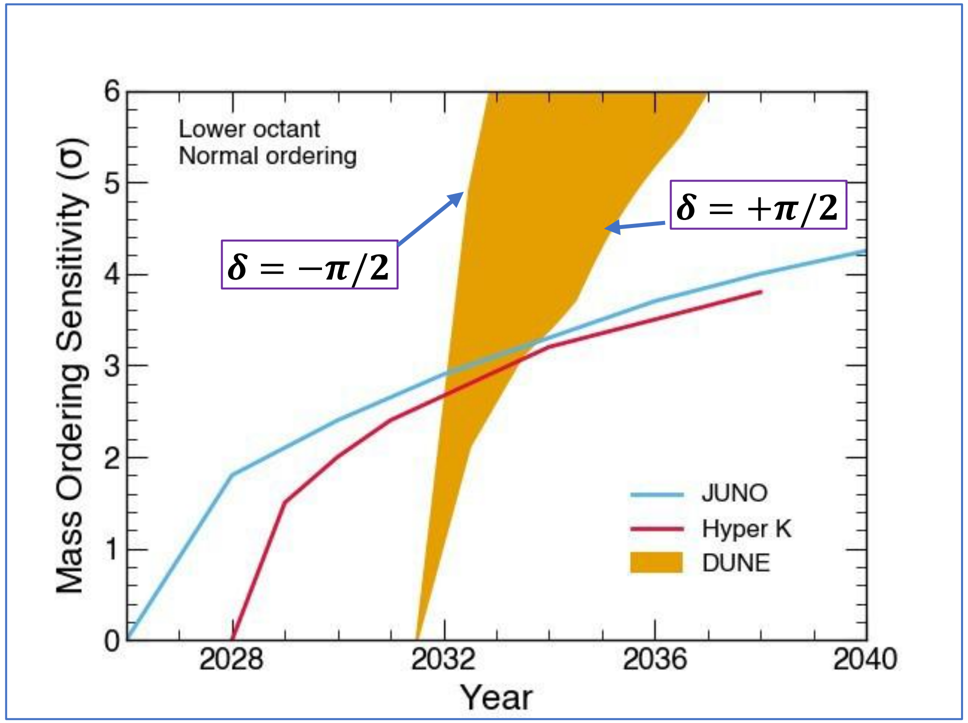
D. Rivera, talk at NeuTel 2025

Chinese Phys. C 49 033104 (2025)

JUNO



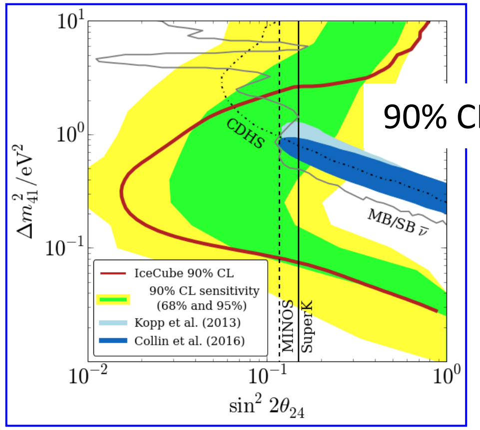
JUNO, HyperK, DUNE



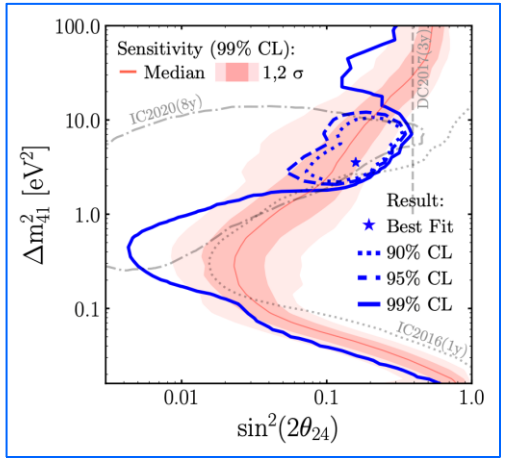
LSND/MiniBooNE anomaly

IceCube: $\nu_\mu \to \nu_\mu$ disappearance

PRL 117 (2016) 071801



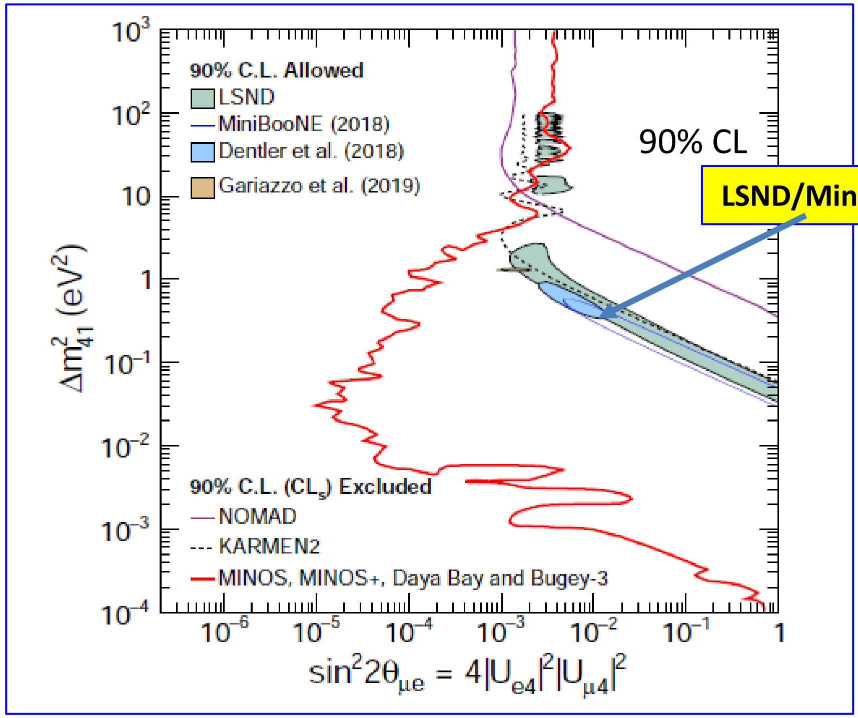
11 years of data taking, PRL 133 (2024) 201804



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

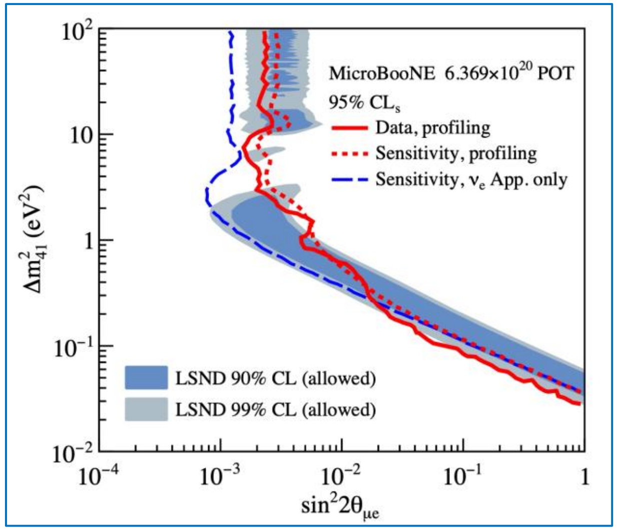
PRL 125 (2020) 131802

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



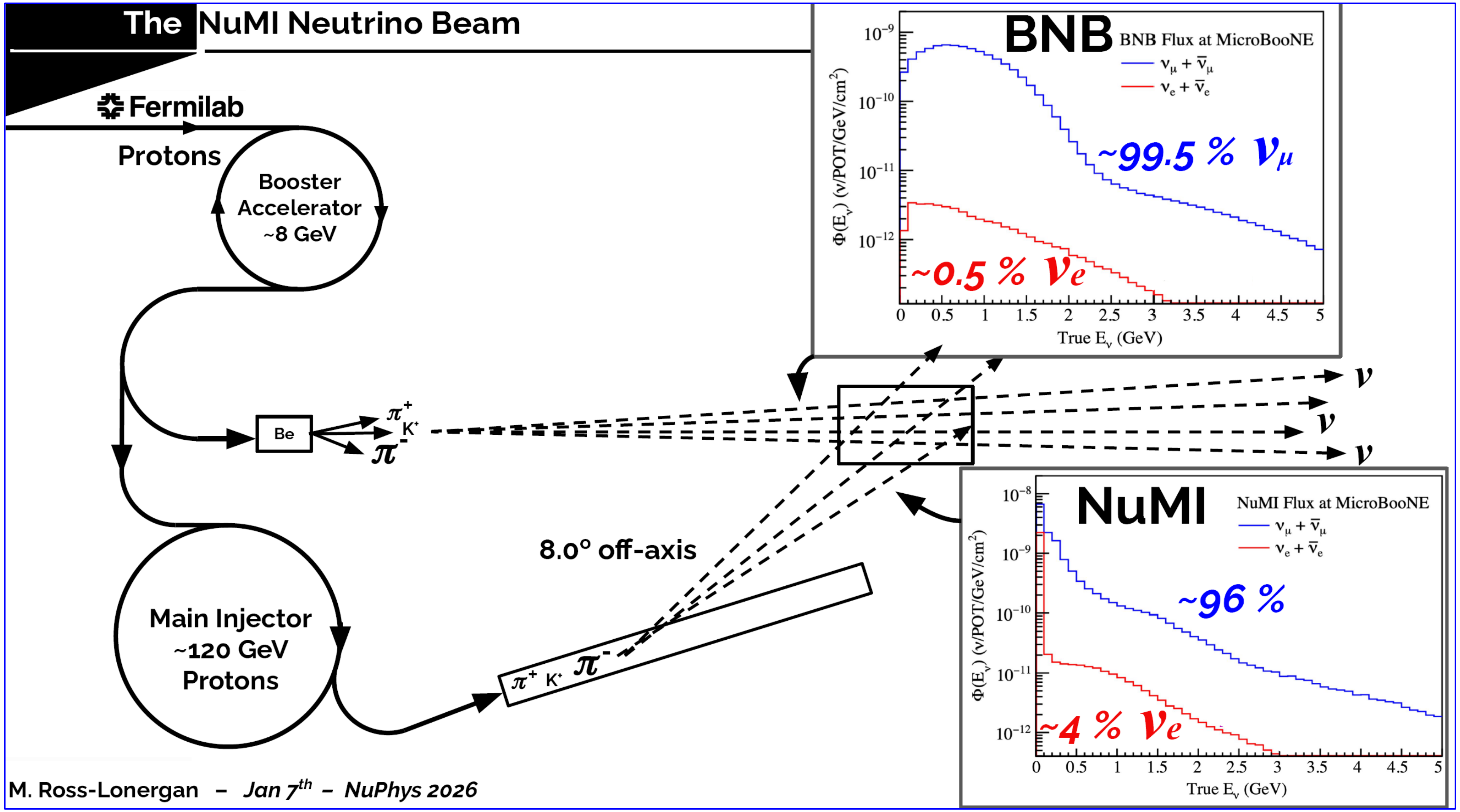
PRL 130 (2023) 011801

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


The NuMI Neutrino Beam
Fermilab
Protons
Booster Accelerator ~8 GeV
Be
π+ K+ π-
8.0° off-axis
Main Injector ~120 GeV Protons
π+ K+ π-
ν
ν
ν
BNB
BNB Flux at MicroBooNE
νμ + ν̄μ
νe + ν̄e
~99.5 % νμ
~0.5 % νe
Φ(Eν) (ν/POT/GeV/cm2)
True Eν (GeV)
NuMI
NuMI Flux at MicroBooNE
νμ + ν̄μ
νe + ν̄e
~96 %
~4 % νe
Φ(Eν) (ν/POT/GeV/cm2)
True Eν (GeV)
M. Ross-Lonergan – Jan 7th – NuPhys 2026