Исследование свойств нейтрино: новые результаты и ближайшие перспективы

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Standard Model: neutrinos are *massless* particles

However, the discovery of *neutrino oscillations*

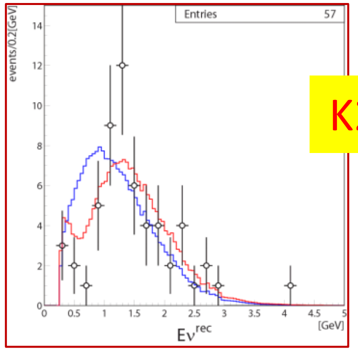
$m_\nu \neq 0$

↓

NEW PHYSICS beyond the STANDARD MODEL

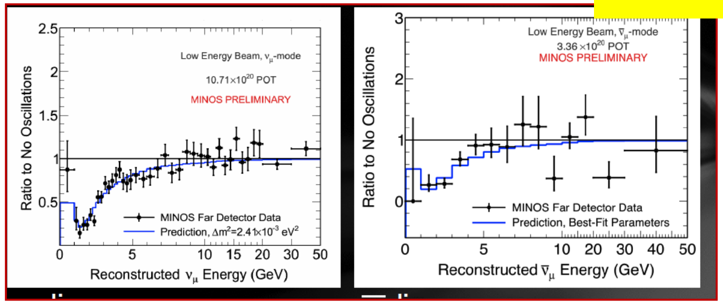
Accelerator neutrinos

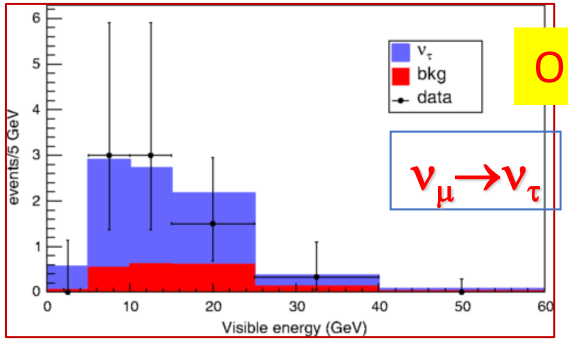
K2K, MINOS, OPERA



K2K

MINOS

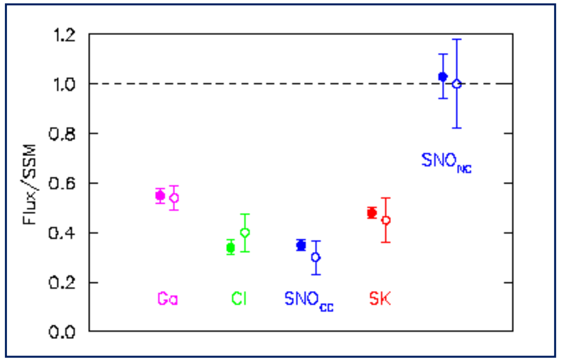


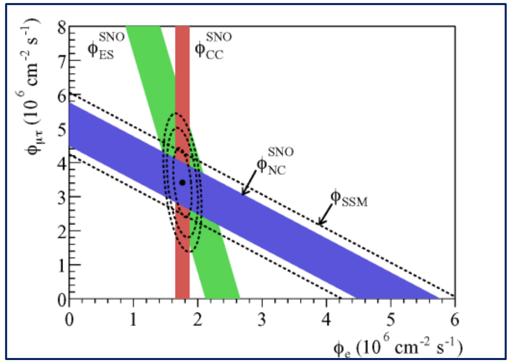


OPERA

Solar neutrinos

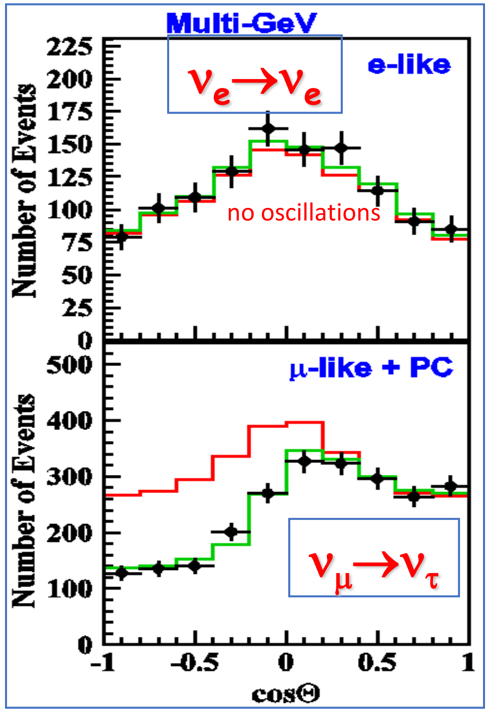
Homestake, Sage, Gallex/GNO, SuperK, SNO



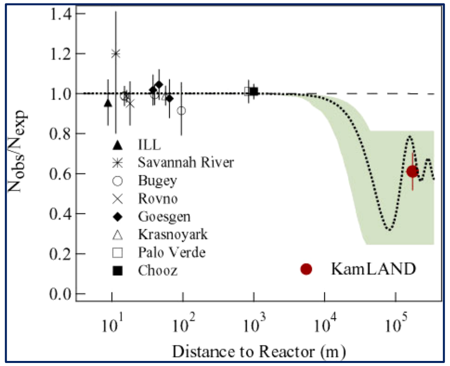


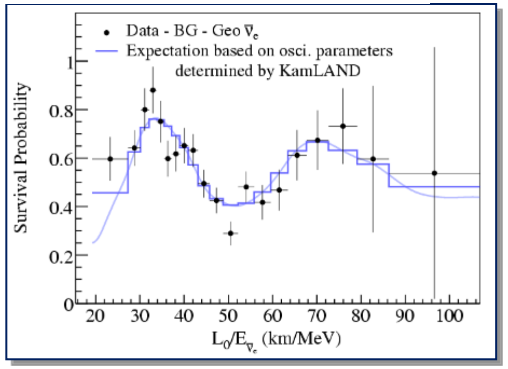
Atmospheric neutrinos

SuperKamiokande



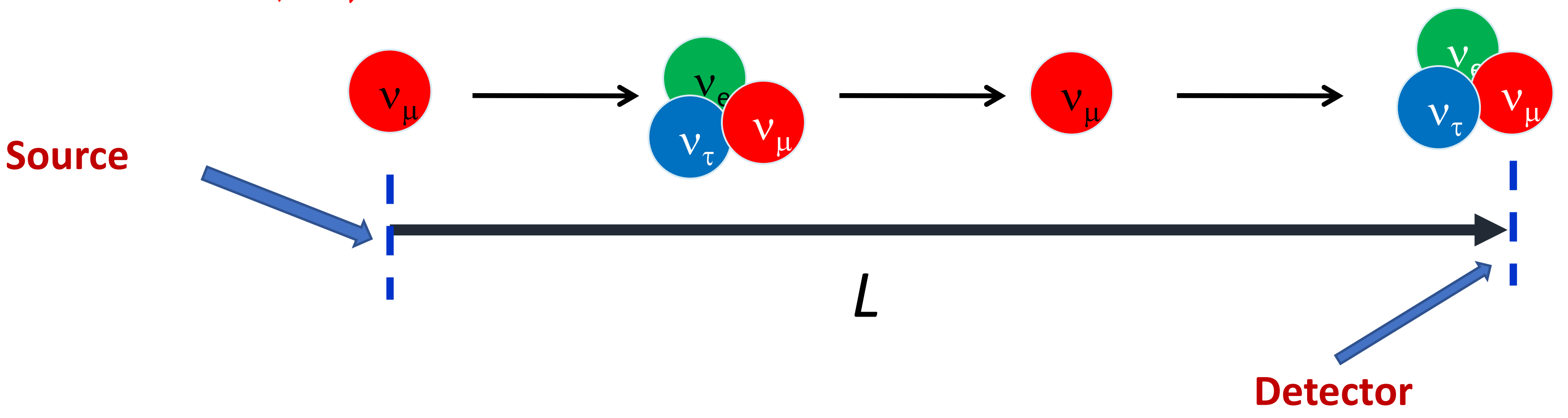
Reactor neutrinos KamLand





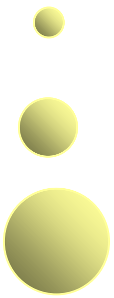
Neutrinio oscillations

- one flavor can transform into another
- neutrino should have a non-zero mass and mix
- oscillation probability depends on
  m_ν, E_ν and distance L



Weak eigenstates

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



m_1, m_2, m_3

Mass eigenstates

U is the PMNS mixing matrix

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

Weak eigenstates differ from mass eigenstates

Neutrino oscillations and mixing

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 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, IceCube

θ_{23}~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, NOvA — 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

New Physics

Main topics

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

Neutrino: CPV and Mass Ordering

- CP violation in lepton sector

Strength of CP violation in neutrino oscillations

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

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

Mixing matrix

neutrinos

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

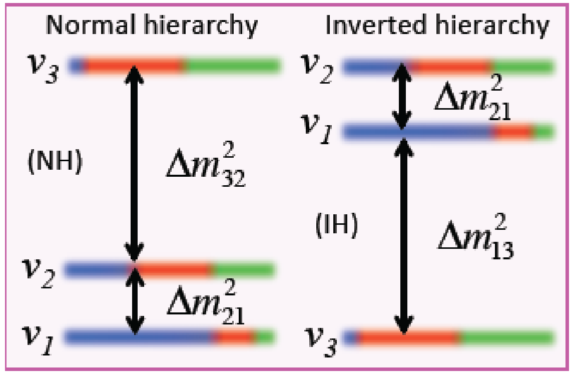
quarks

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

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

Lepton sector: $J_{CP} \sim 0.02\times\sin\delta_{CP}$

- Neutrino mass ordering (NMO)



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

Mass Ordering

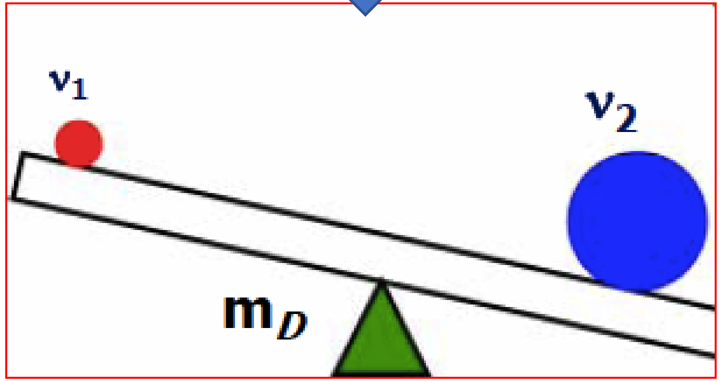
NO or IO ?

Impact on

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

Why is CPV in lepton sector important?

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 ??

- Search for CP violation
- Measurement of Mass Ordering

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

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

leading term

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\frac{\Delta m_{13}^2 L}{4E_\nu} \times \left[1 + \frac{2a}{\Delta m_{13}^2}(1 - 2s_{13}^2)\right]$$ → θ_{13}

$$+ 8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\frac{\Delta m_{23}^2 L}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}\sin\frac{\Delta m_{12}^2 L}{4E_\nu}$$ → **CP-even**

$$- 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23}\sin\delta\sin\frac{\Delta m_{23}^2 L}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}\sin\frac{\Delta m_{12}^2 L}{4E_\nu}$$ → **CP-odd**

$$+ 4s_{12}^2 c_{13}^2(c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\frac{\Delta m_{12}^2 L}{4E_\nu}$$ → **Solar**

$$- 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E_\nu}\frac{aL}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}(1 - 2s_{13}^2),$$ → **Matter**

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

Matter effect

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

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

change sign for NH → 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}

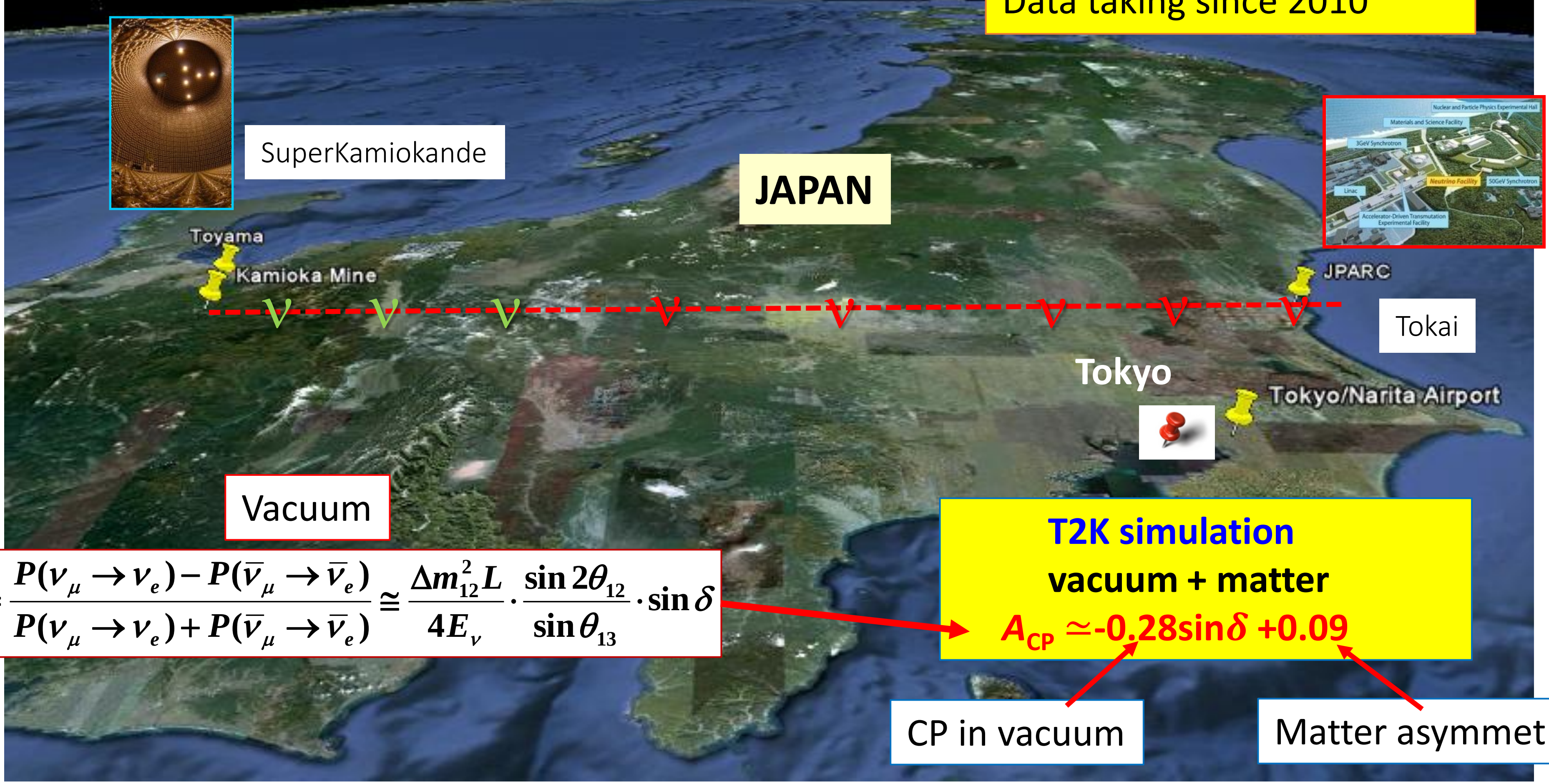
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

$A_{CP} \neq 0 \rightarrow \delta_{CP} \neq 0 \rightarrow$ **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_ν ~ 0.6 GeV
Neutrino beam from J-PARC
Baseline = 295 km
Data taking since 2010



Vacuum

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

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

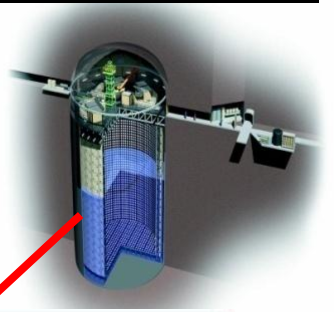
CP in vacuum

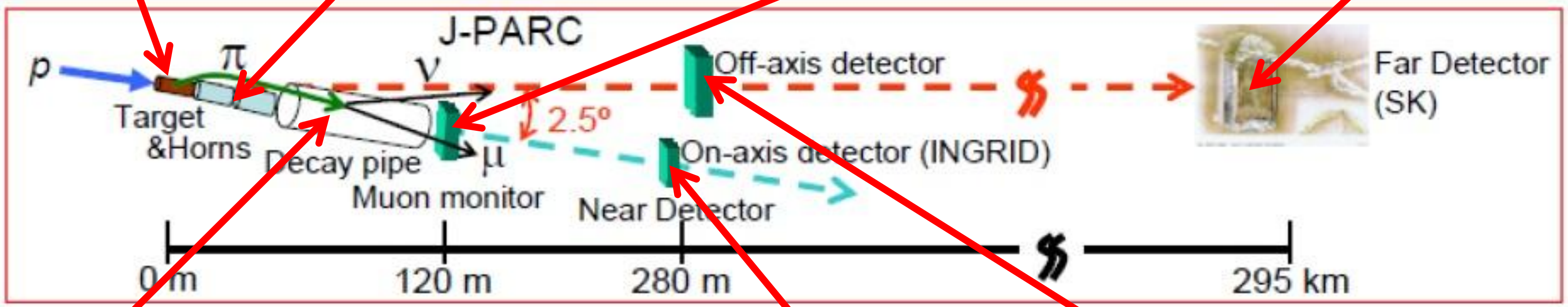
Matter asymmetry

Experiment T2K

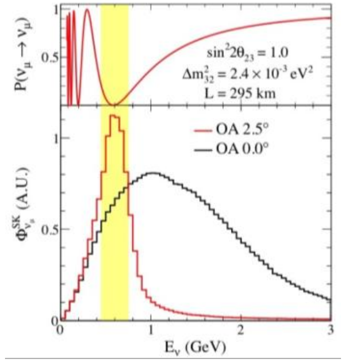
LBL accelerator experiment

Far neutrino detector
SuperKamiokande

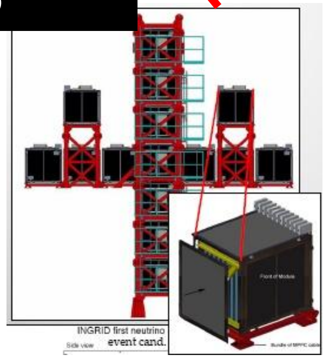




Off-axis neutrino beam

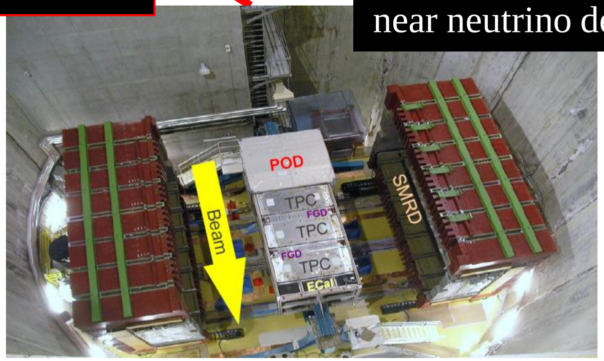


Neutrino monitor
INGRID



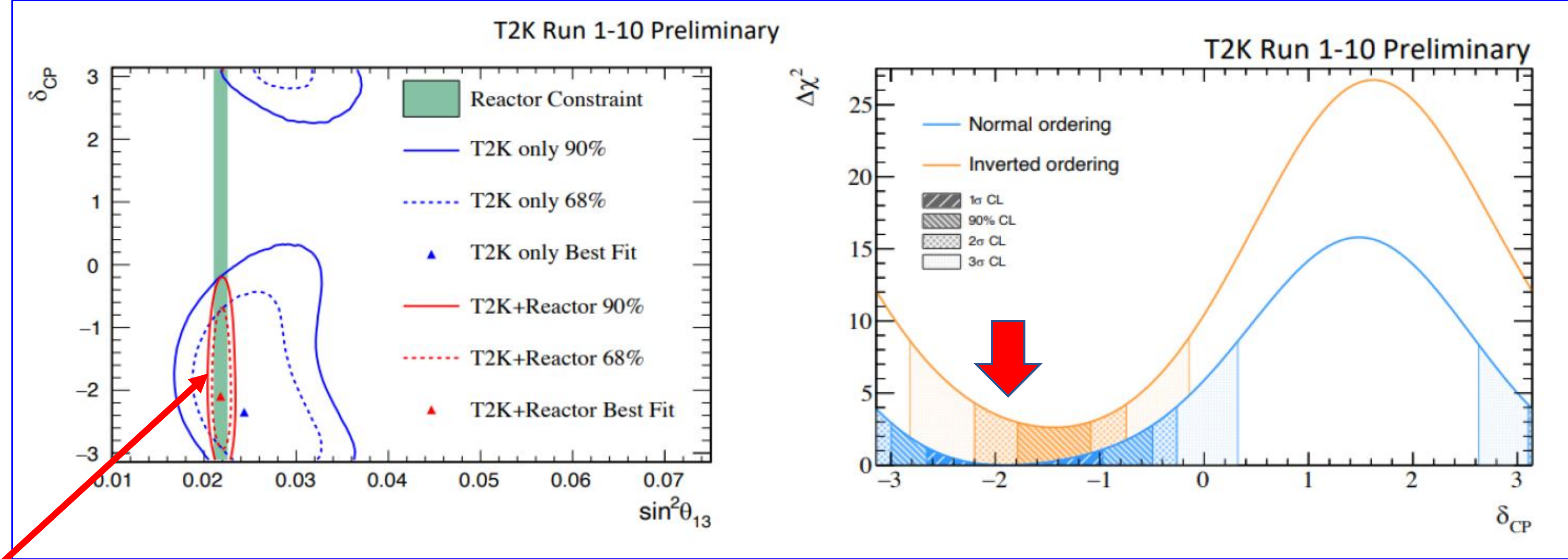
ND280

Off-axis
near neutrino detector



T2K: hint of CP violation

ν-mode: 2.17×10^{21} (56.8%)
$\bar{\nu}$-mode: 1.65×10^{21} (43.2%)



Constraint on θ_{13} from reactor experiments Daya Bay, RENO, DChooz

35% of δ_{CP} values excluded at 3σ marginalized over hierarchies

CP conserving values ($\delta_{CP} = 0,\ \pi$) excluded at >90% CL

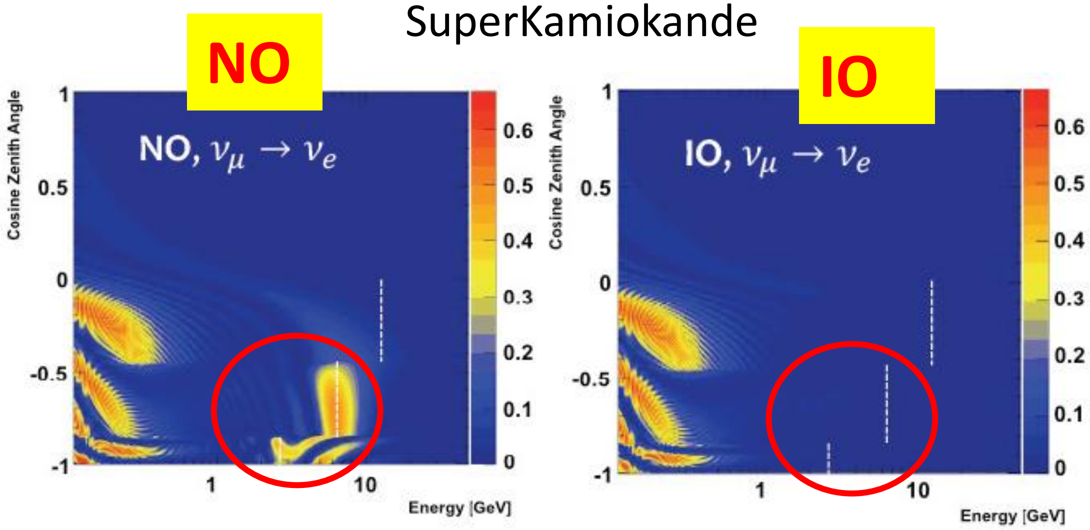
Best fit: $\delta_{CP} \sim -\pi/2$ → close to maximum CP violation

Normal mass ordering is preferred at 80% CL

Mass ordering: SuperKamiokande + T2K

SuperKamiokande

M.Pasiadala-Zezula, ICHEP2022

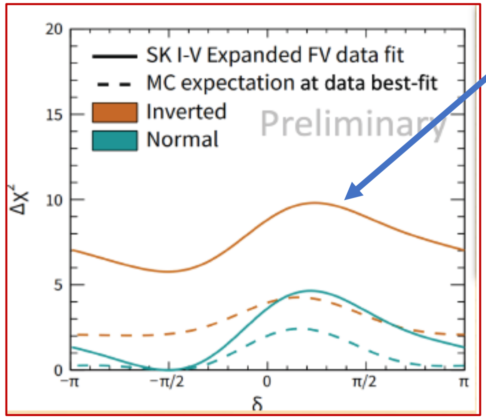


SuperKamiokande

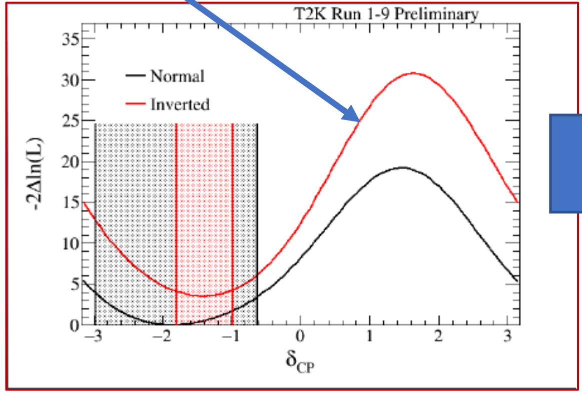
- Atmospheric neutrino sensitive to mass ordering due to matter effect
- MSW resonance at ~ 10 GeV

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

K.Sakashita, talk at NPB2024



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

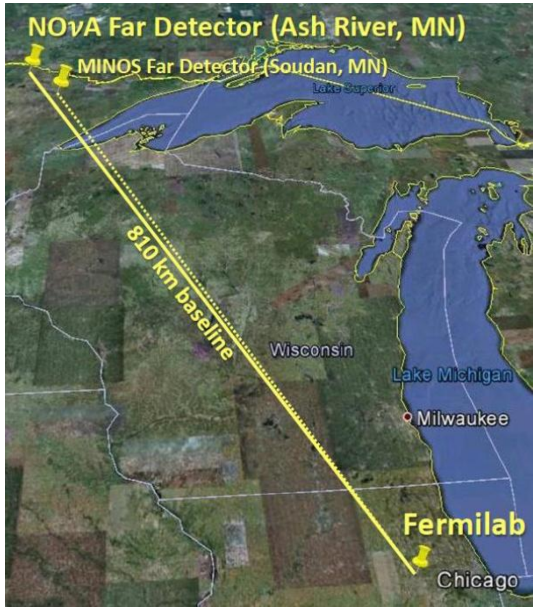


Joint analysis SuperK+T2K increases sensitivity to MO

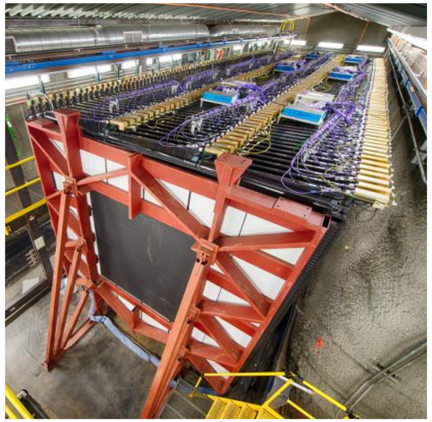
- SuperK provided an additional rejection of $\delta_{CP} = 0, \pi$
- Joint analysis prefers $\delta_{CP} \sim -\pi/2$ in both orderings with +π/2 lying outside the 3σ interval
- CP conservation $\delta_{CP} = 0, \pi$ is excluded at $\sim 2\sigma$ in IO; $\delta_{CP} = \pi$ still within 2σ in NO
- Preference of NO at 90% CL

Experiment NOvA

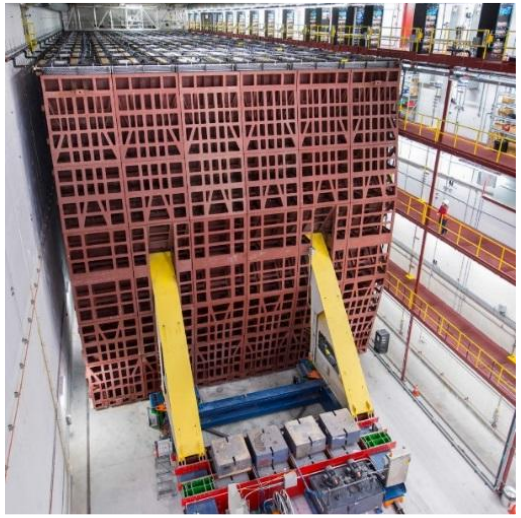
NOvA (USA)



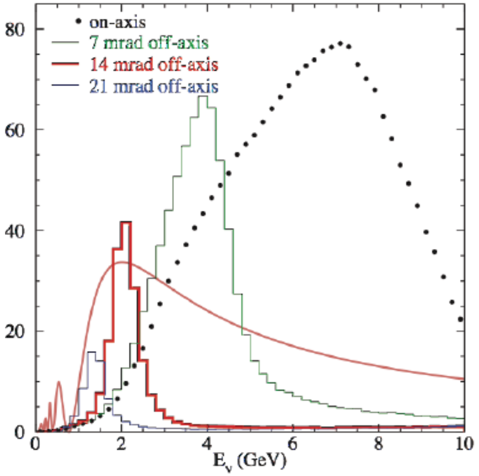
Near Detector



Far Detector



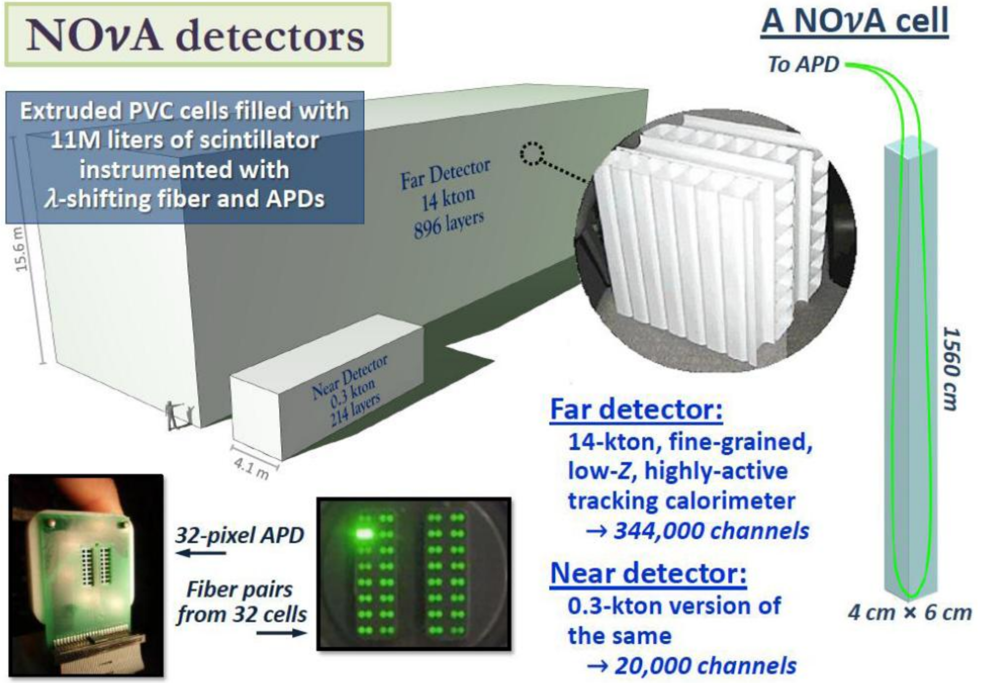
Neutrino beam



Taking data since Summer 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

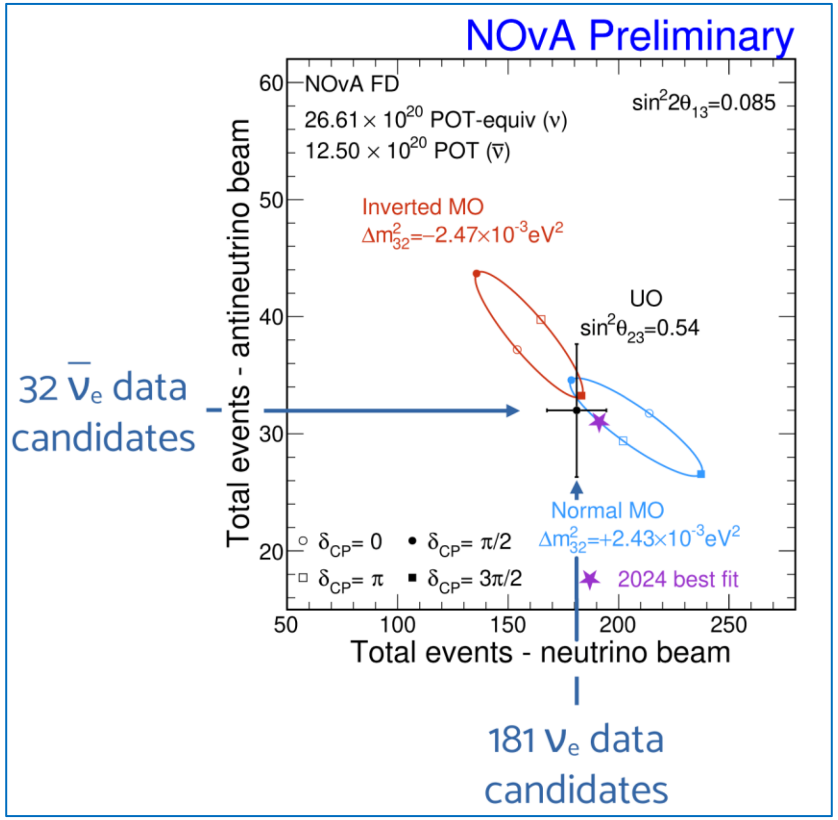


New NOvA result

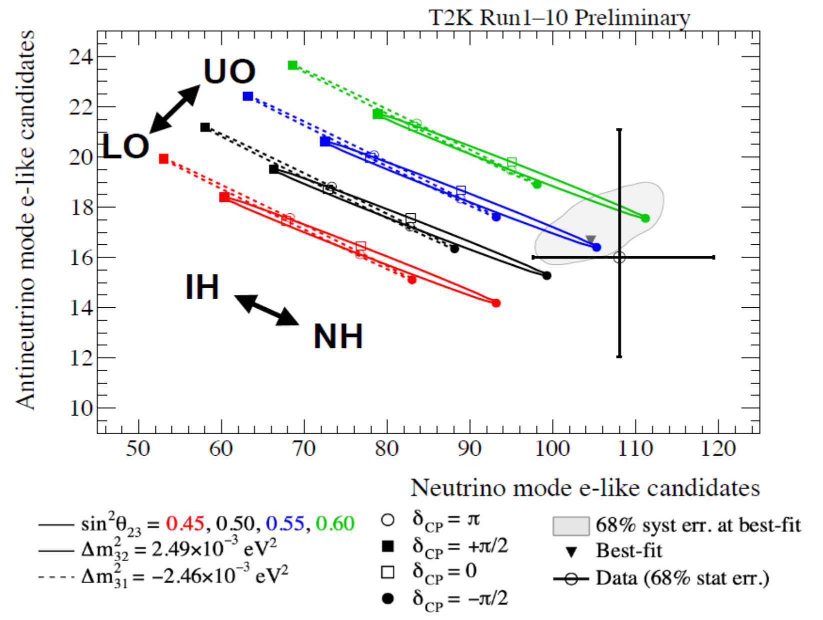
Protons on target in 2014-2023
ν: 26.61x10^{20} POT
$\bar{\nu}$: 12.5x10^{20} POT

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

NOvA J.Wolcott, Neutrino2024



T2K



NOvA mass ordering and CPV

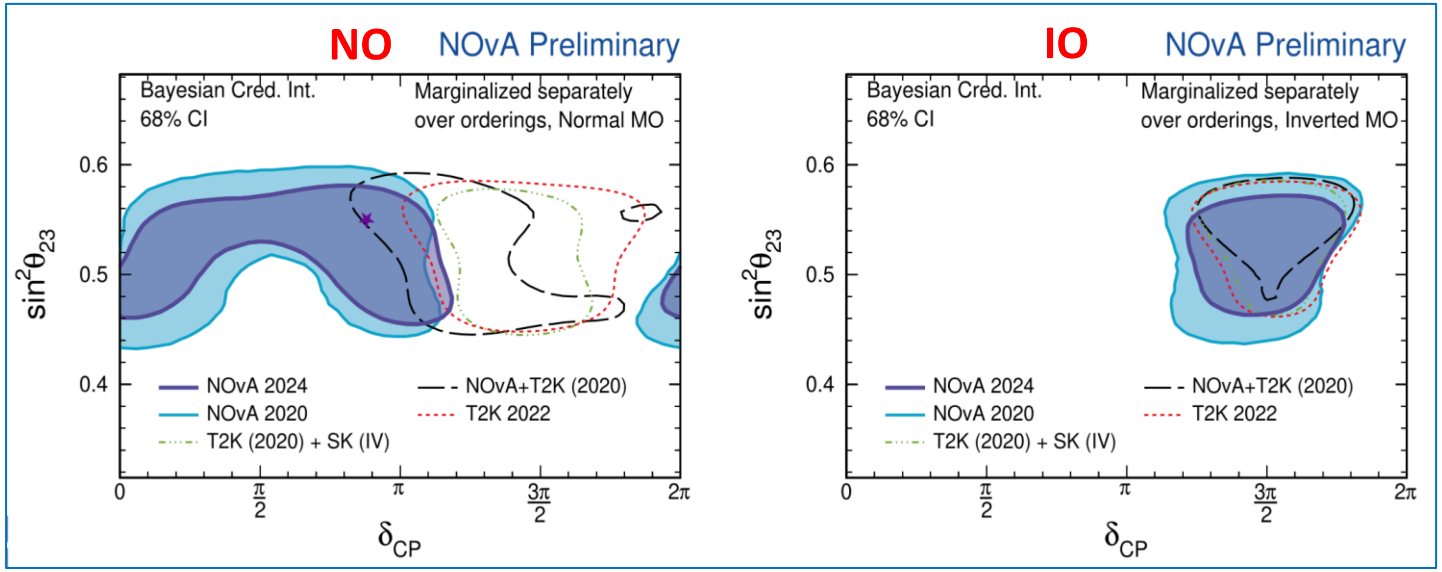
T2K and NOvA data: *mild tension*
Normal Ordering
- **1σ overlap for some regions**

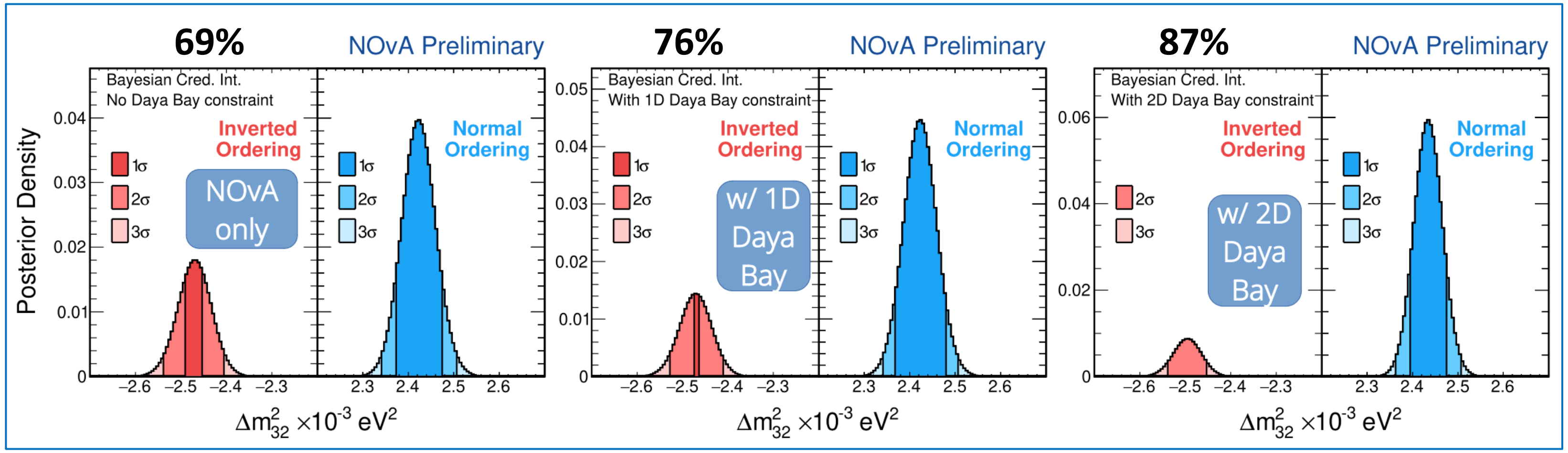
Inverted Ordering
- **very similar allowed regions**

T2K- NOvA joint analysis:
different baselines, energies, detector technologies

R.Sanchez, Moriond 2024

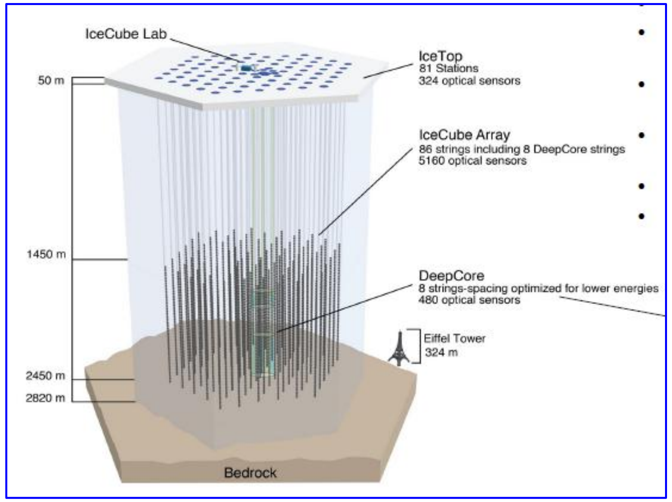
Main results of joint analysis
- Smallest uncertainty on $|m^2_{32}|$, error about 1.5%
- For both mass ordering $\delta_{CP} = \frac{\pi}{2}$ excluded at >3σ
- CP conservation excluded at >3σ for IO

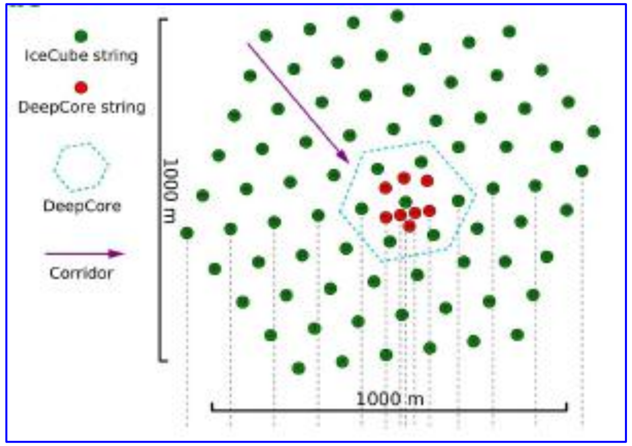


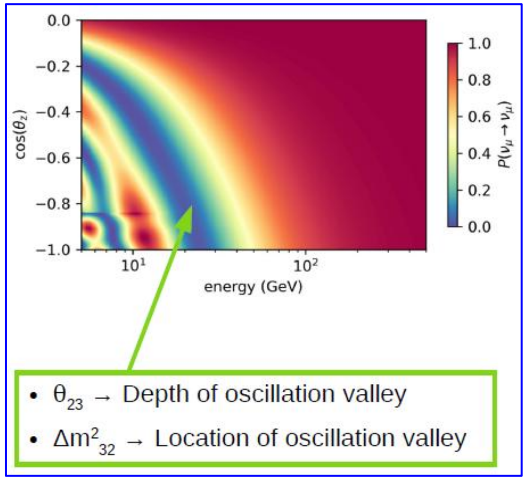


IceCube DeepCore: $\nu_\mu \to \nu_\mu$

A.Kumar, EPS-HEP 2023

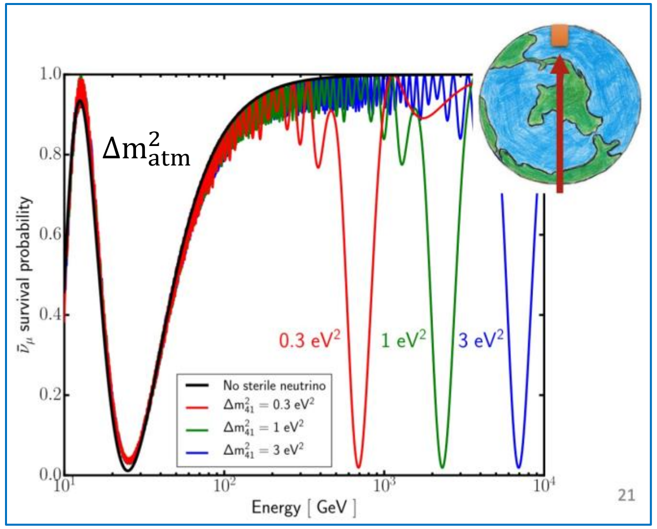


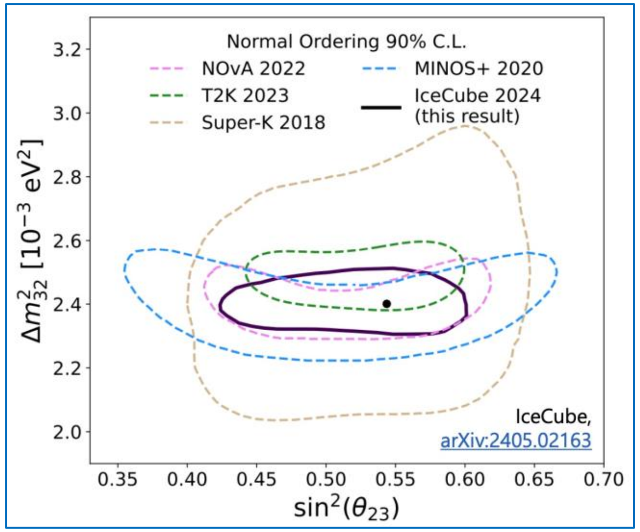




J.P. Yanez, Neutrino2024

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





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

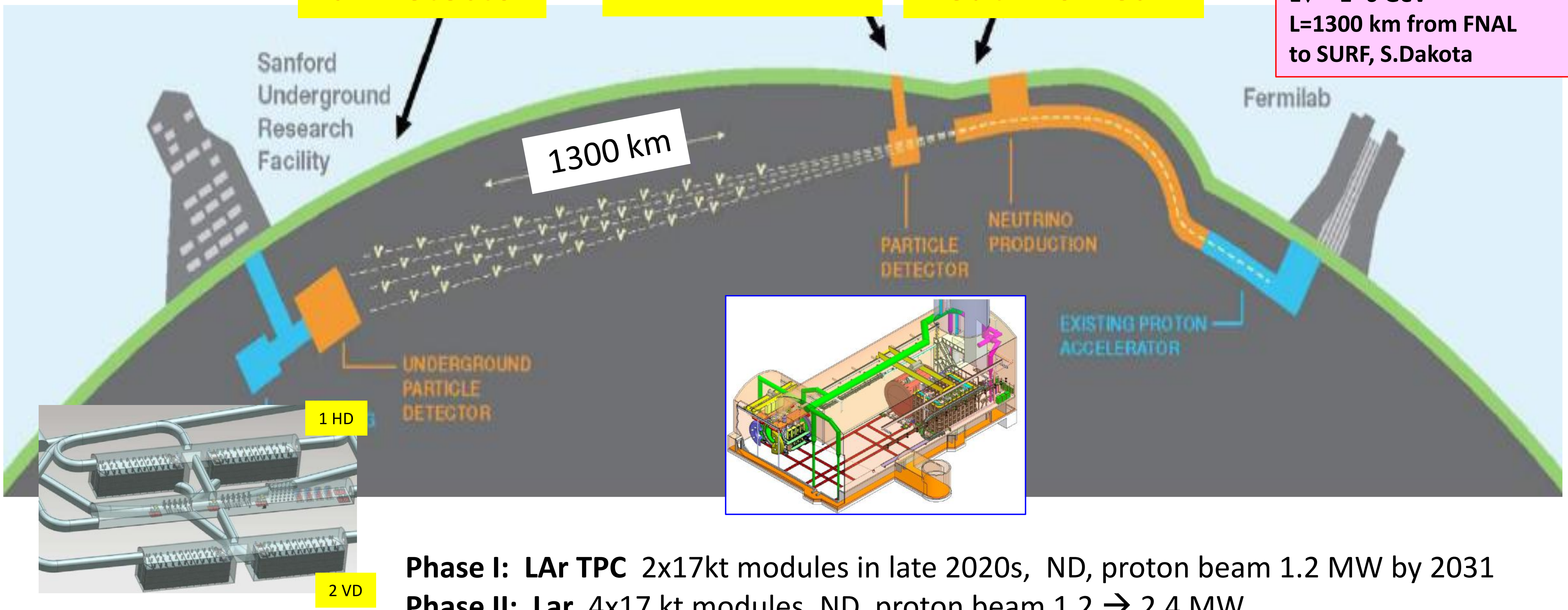
Future projects
DUNE,Hyper-Kamiokande, JUNO

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 by 2031
Phase II: Lar 4x17 kt modules, ND, proton beam 1.2 → 2.4 MW

DUNE: CP sensitivity

DUNE Collaboration, 2006.16043

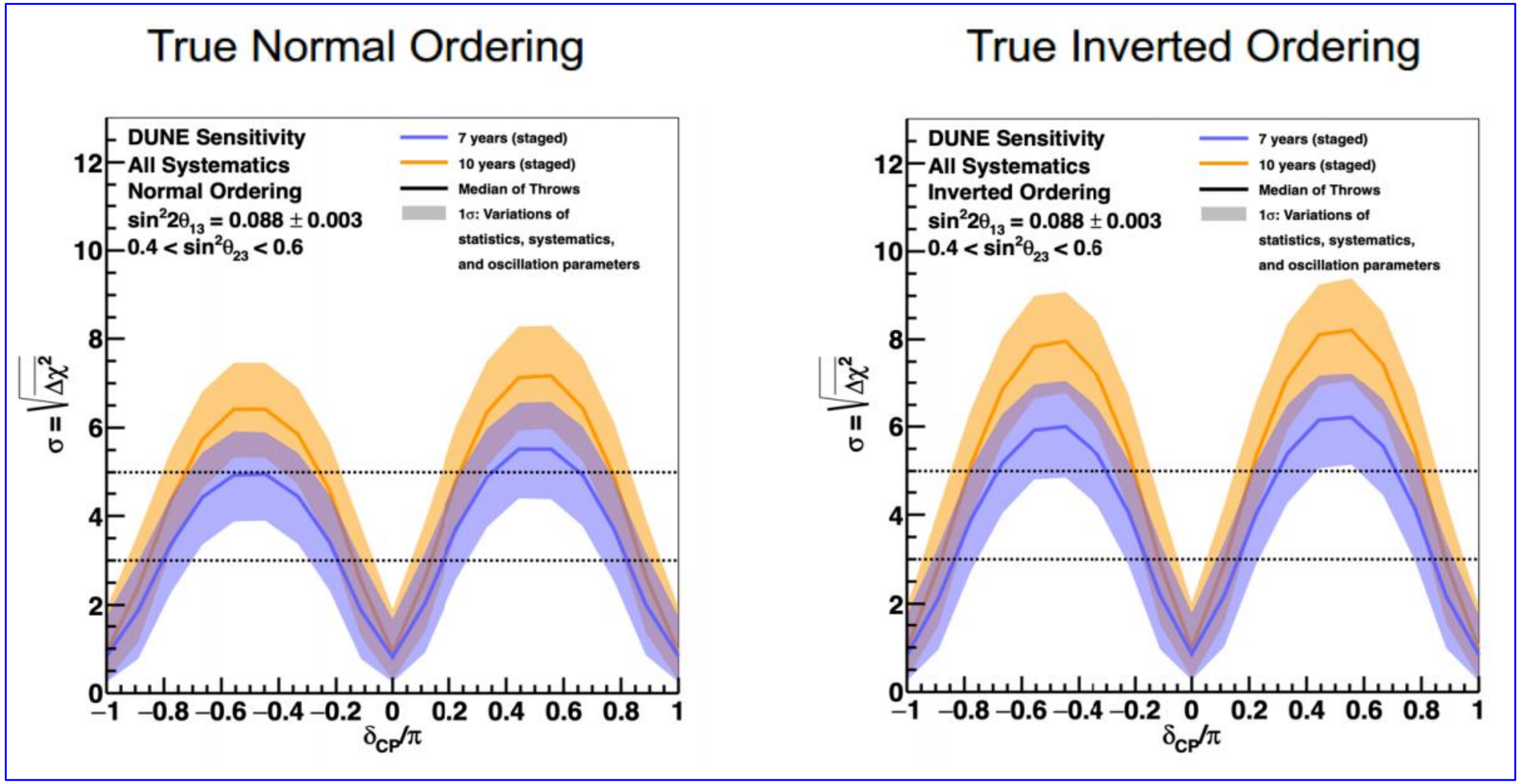
Staging approach

Sensitivity to δ_{CP}

- 7 years data taking

- 10 years data taking

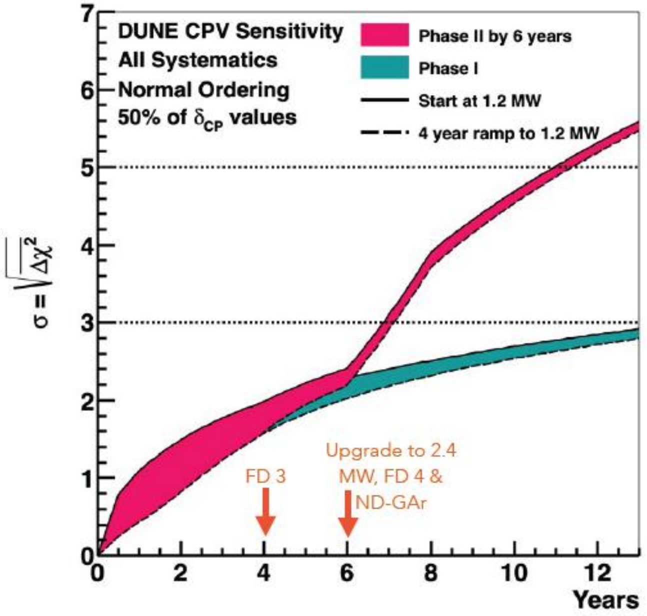
$\nu : \bar{\nu}$ = 50% : 50%



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

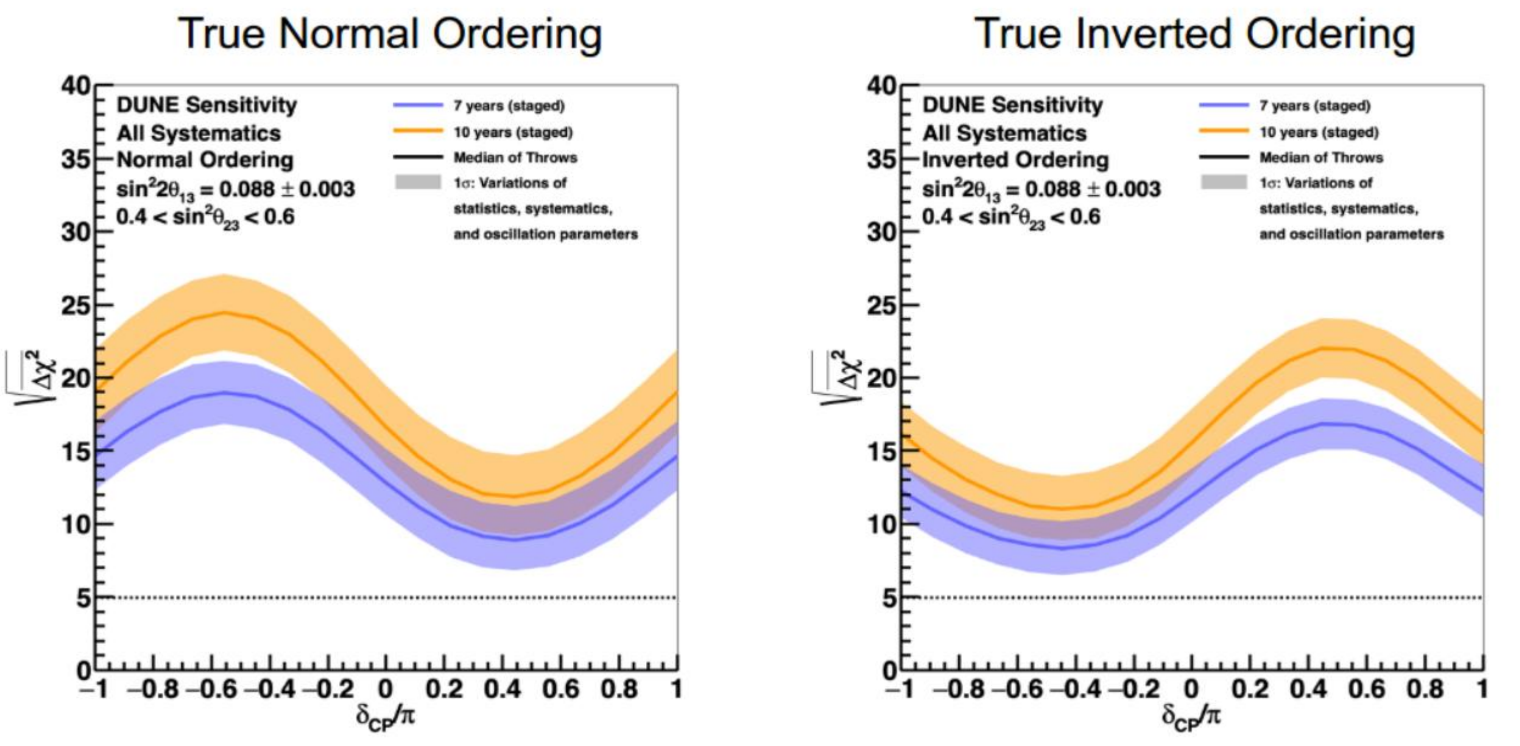
A.Booth, ICHEP2022



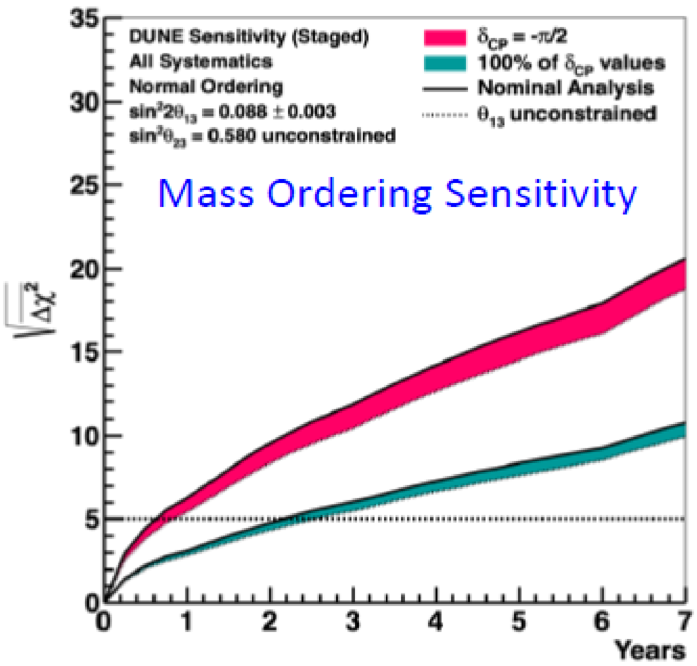
DUNE: Mass Ordering

DUNE Collaboration, 2006.16043

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

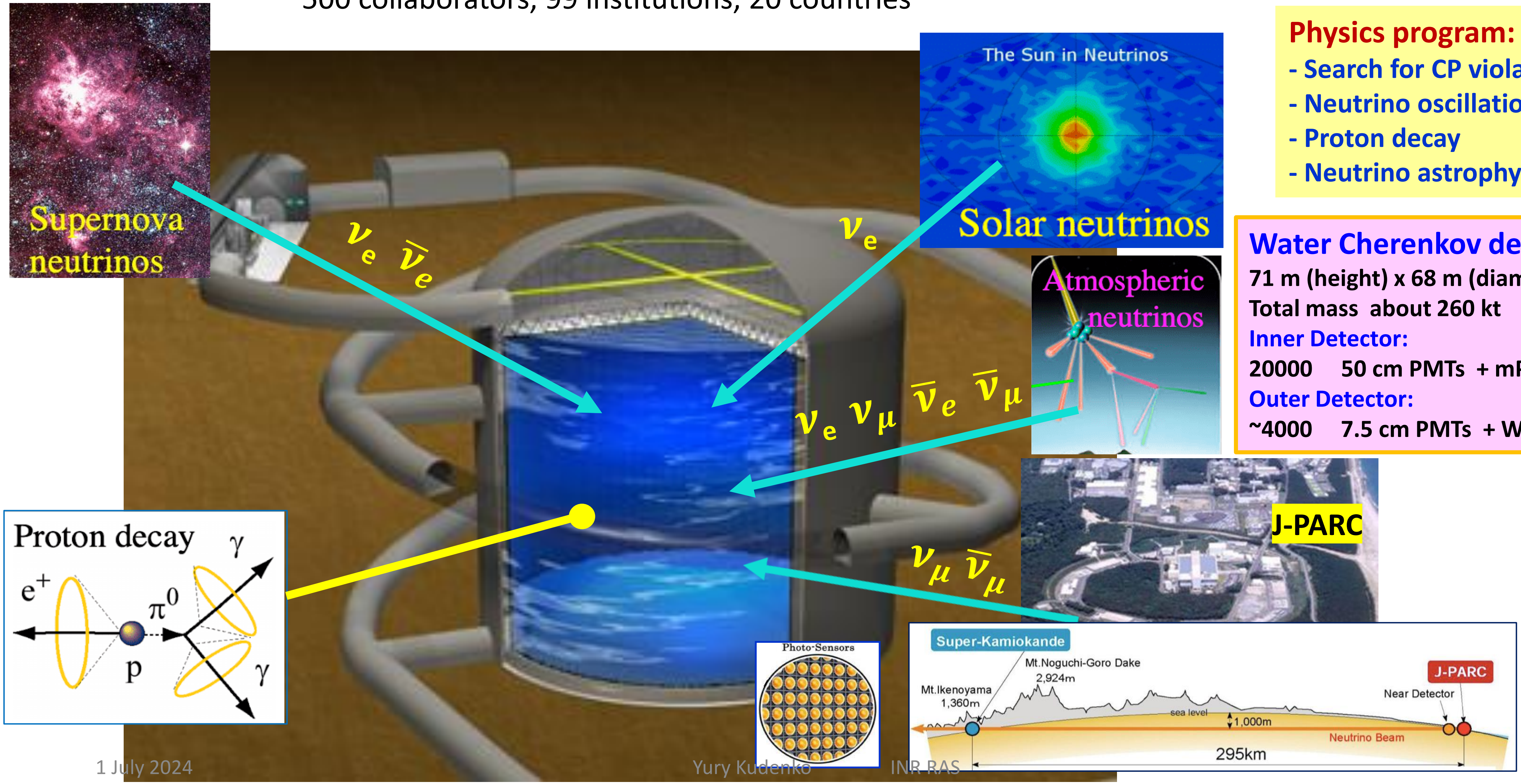


> 5σ discovery
for all possible δ_{CP} values
after 7 years of data taking



Hyper-Kamiokande

Japan. Project approved in 2020, construction begun in 2021, operation starts in 2027
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

Near Detectors

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

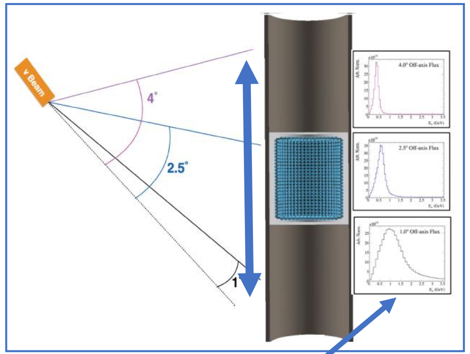
J-RARC beam
30 GeV
1.3 MW

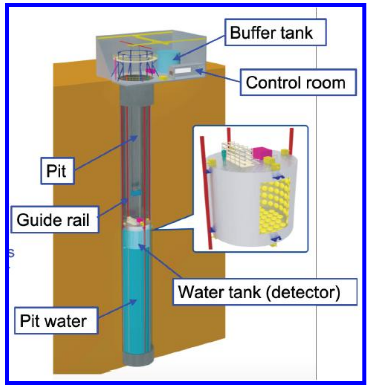
New ND **~1 km from target**

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

IWCD: Movable water Cherenkov detector

IWCD

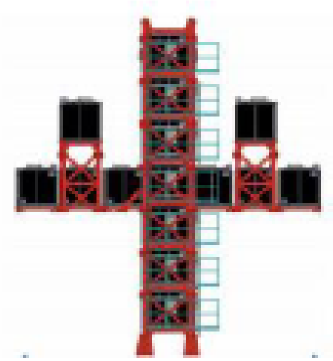




Neutrino spectra

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

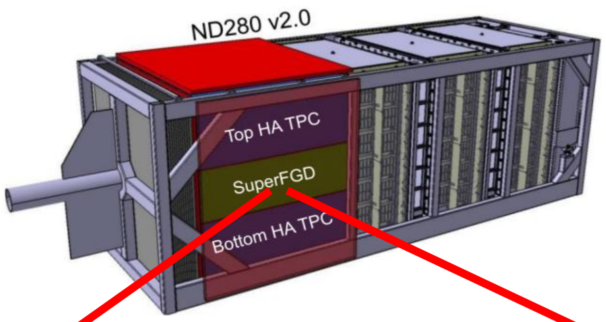
INGRID



Neutrino on/off axis beam monitor

ND280 upgraded

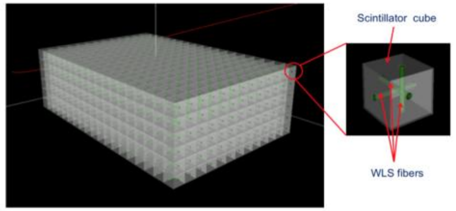
Magnetized off-axis detector

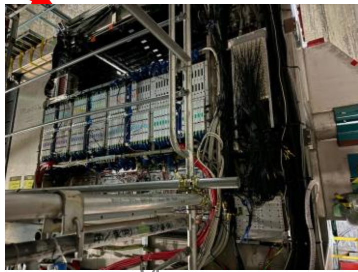


3D detector SuperFGD:
$2x10^6$ scintillator cubes each of $1cm^3$ with WLS readout

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

SuperFGD

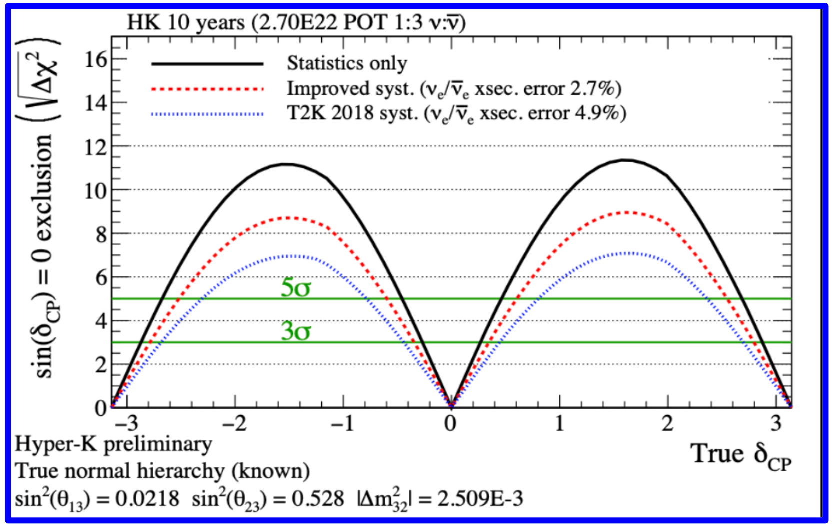




Sensitivity to CP violation

Hyper-Kamiokande, arXiv:1805.04163

Projected HyperK sensitivity to CP violation

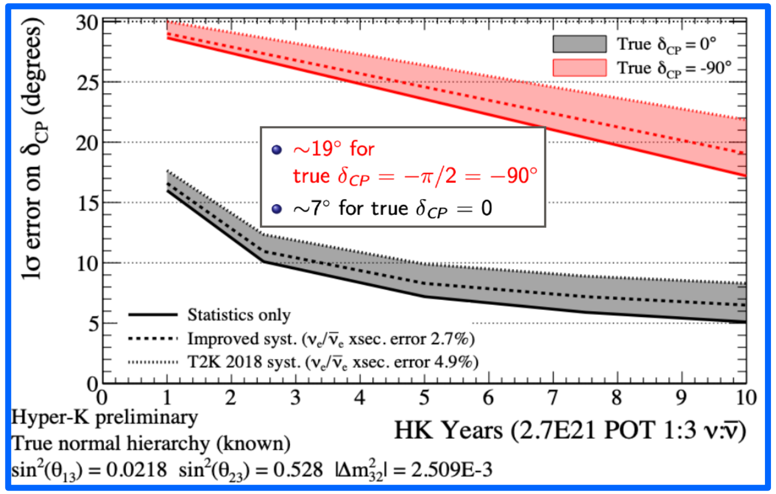


- 10 years of data taking,
- 1.3 MW beam power → 2.7x10^{22} POT

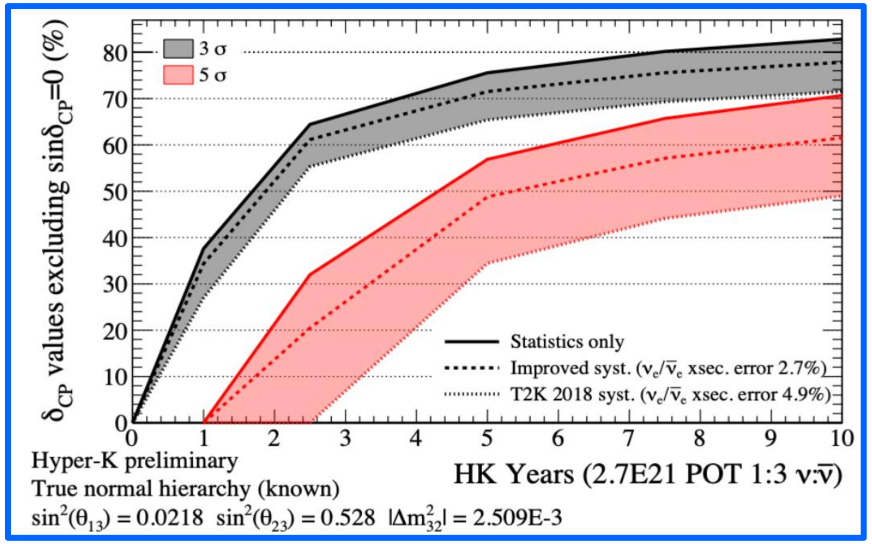
Expected number of events at HyperK for $\nu_e : \bar{\nu}_e = 1:3$ and $\sin\delta_{CP} = 0$

2300 ν_e 1300 $\bar{\nu}_e$

Measurement of δ_{CP}



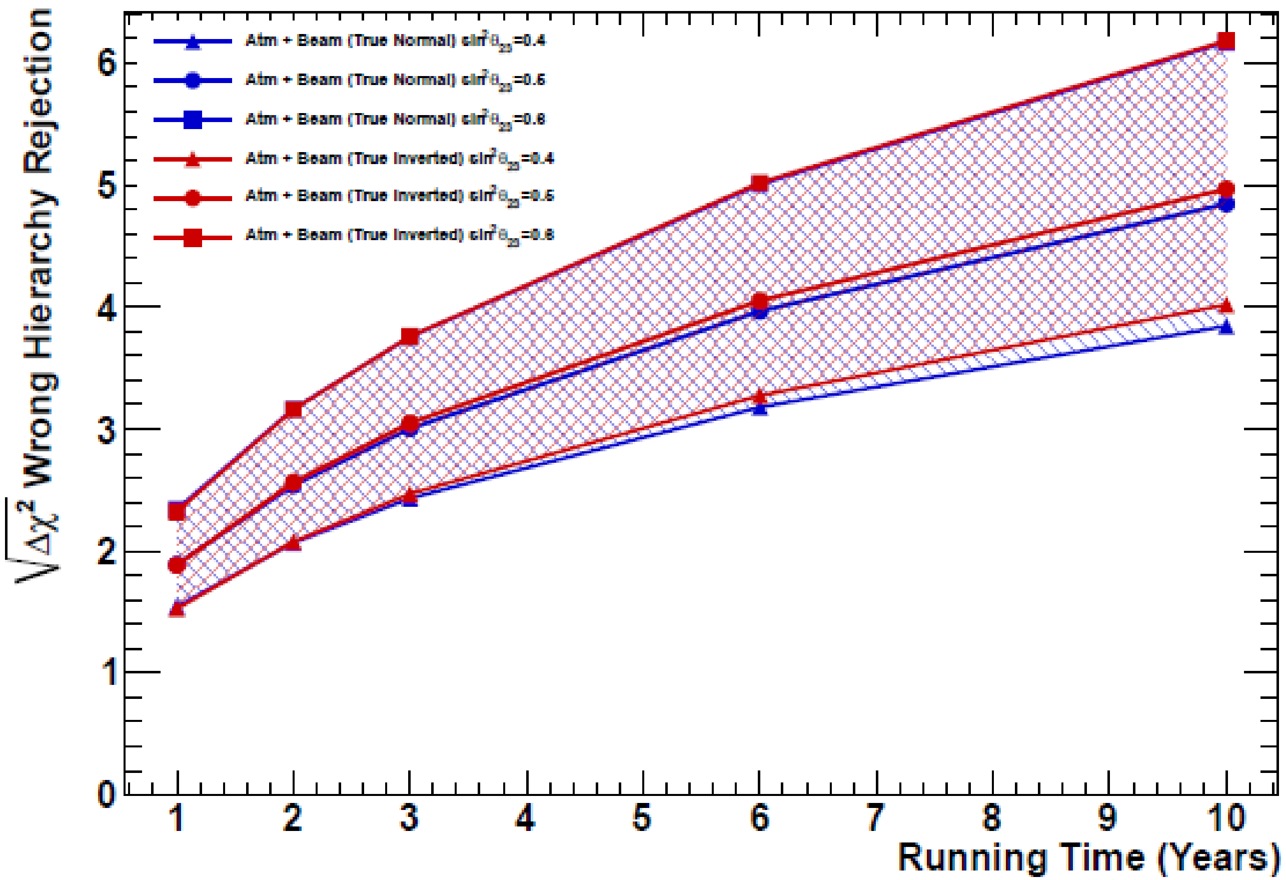
Exclusion of CP conservation



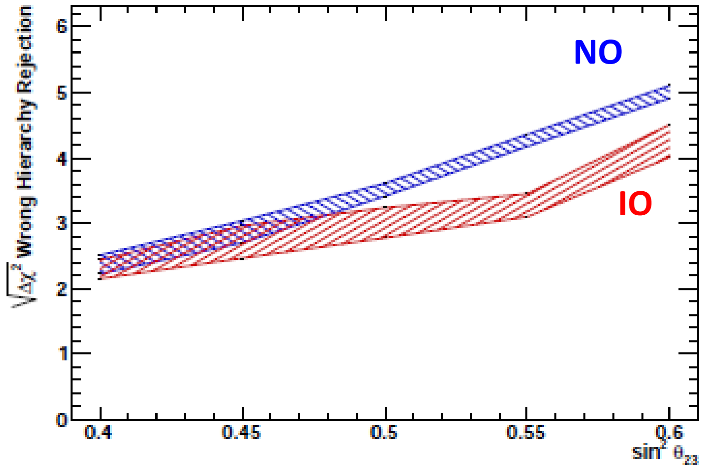
Hyper-Kamiokande: Mass Ordering

HyperKamiokande 10 years of data taking

Hyper-Kamiokande, arXiv:1805.04163



HyperKamiokande, atm neutrinos



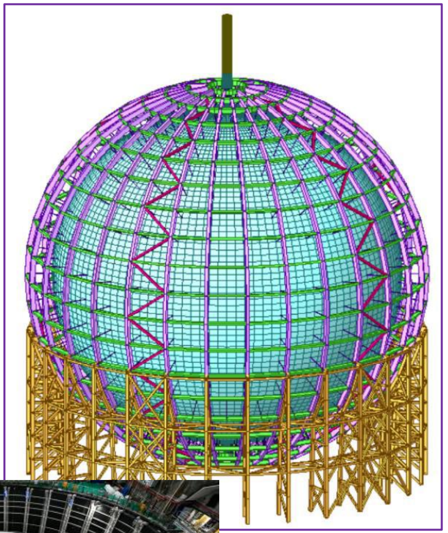
	$\sin^2\theta_{23}$	Atmospheric neutrino		Atm + Beam
Mass ordering	0.40	2.2 σ	→	3.8 σ
	0.60	4.9 σ	→	6.2 σ
θ_{23} octant	0.45	2.2 σ	→	6.2 σ
	0.55	1.6 σ	→	3.6 σ

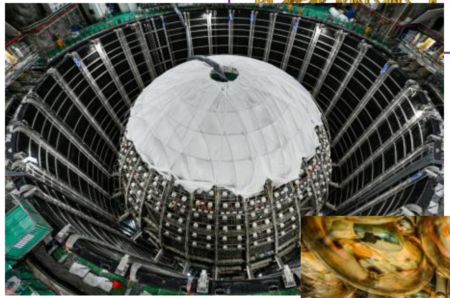
JUNO: Mass Ordering

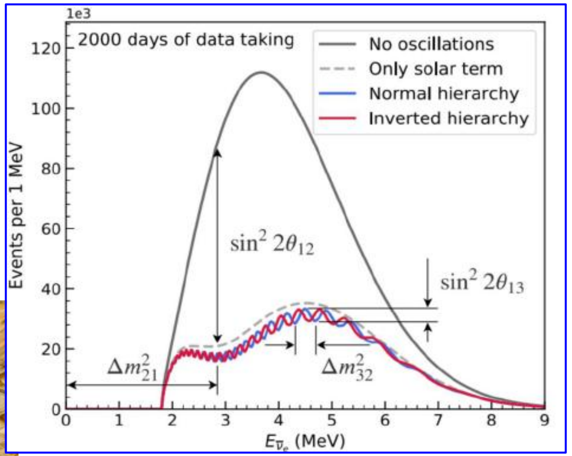
Reactor experiment JUNO, China

Chin.Phys.C 46 (2022) 12, 123001

JUNO detects the mass hierarchy directly by the phase shift in the oscillation pattern in a 20kton scintillator detector. Energy resolution is 3% at 1 MeV and nonlinearity < 1%

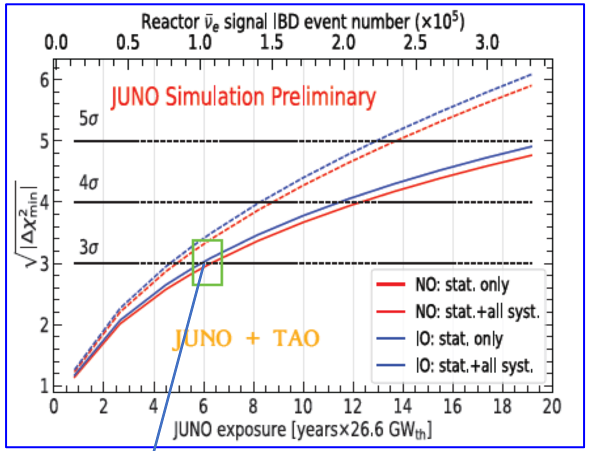






arXiv:2405.18008

	Design	Now
Thermal Power	36 GW_{th}	26.6 GW_{th} (26%↓)
Signal rate	60 /day	47.1 /day (22%↓)
Overburden	~700 m	~ 650 m
Muon flux in LS	3 Hz	4 Hz (33%↑)
Muon veto efficiency	83%	91.6% (11%↑)
Backgrounds	3.75 /day	4.11 /day (10%↑)
Energy resolution	3.0% @ 1 MeV	2.95% @ 1 MeV (2%↑)
Shape uncertainty	1%	JUNO+TAO
3σ NMO sens. Exposure	<6 yrs × 35.8 GW_{th}	~6 yrs × 26.6 GW_{th}



- Detector construction is ongoing
- Finish constructuion and start detector filling in 2024

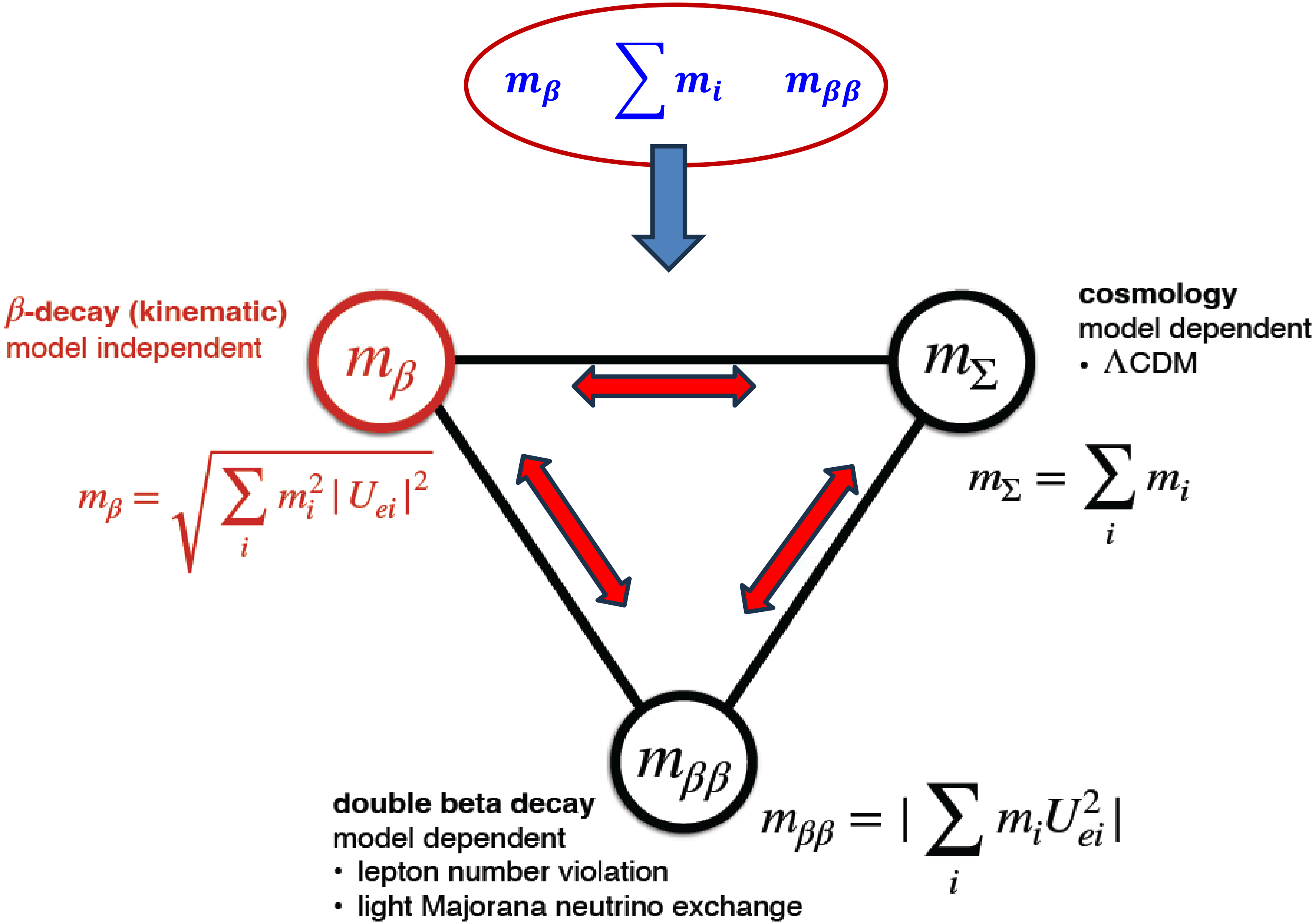
3σ within 6 years of data taking

20 kt liquid scintillator detector
20k - 50 inch PMT; 25.6k - 3 inch PMT
Baseline 53 km, 650 m overburden

Far future: JUNO-0νββ

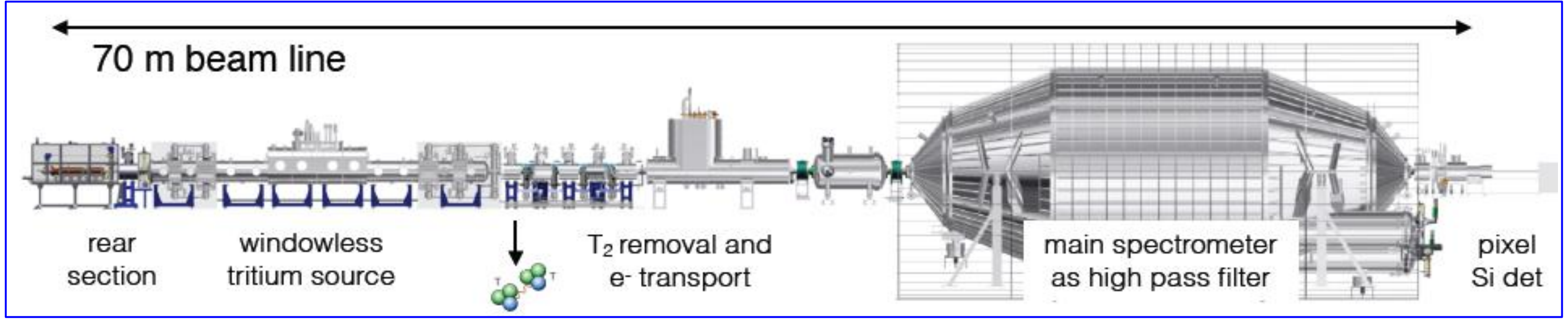
- Measurement of neutrino mass
- Neutrino nature: Dirac or Majorana

Neutrino mass observables

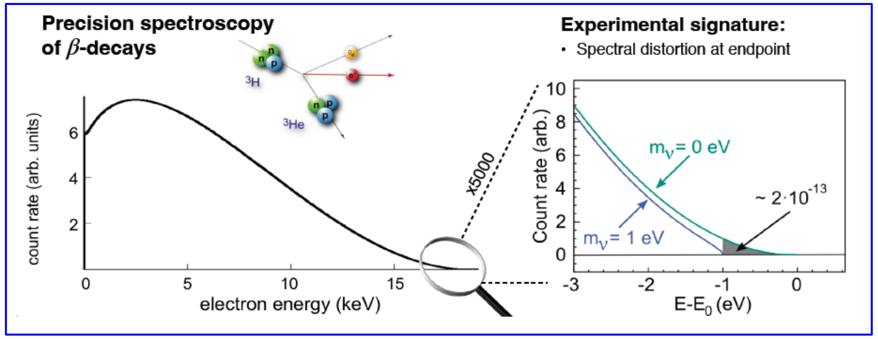


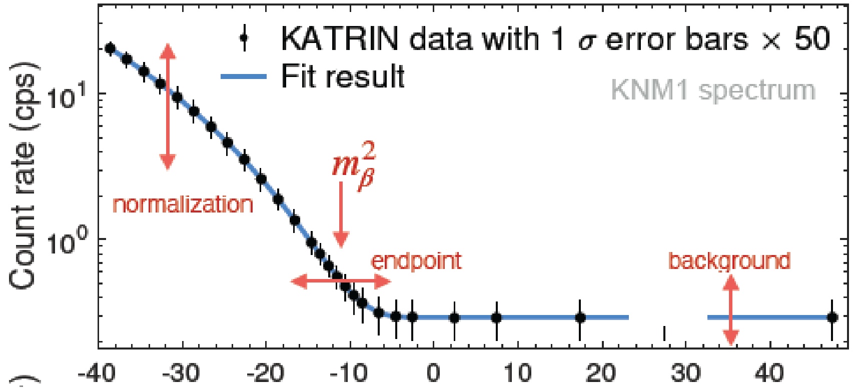
Direct measurement of neutrino mass

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



A.Lokhov, Neutrino2024





New KATRIN result

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

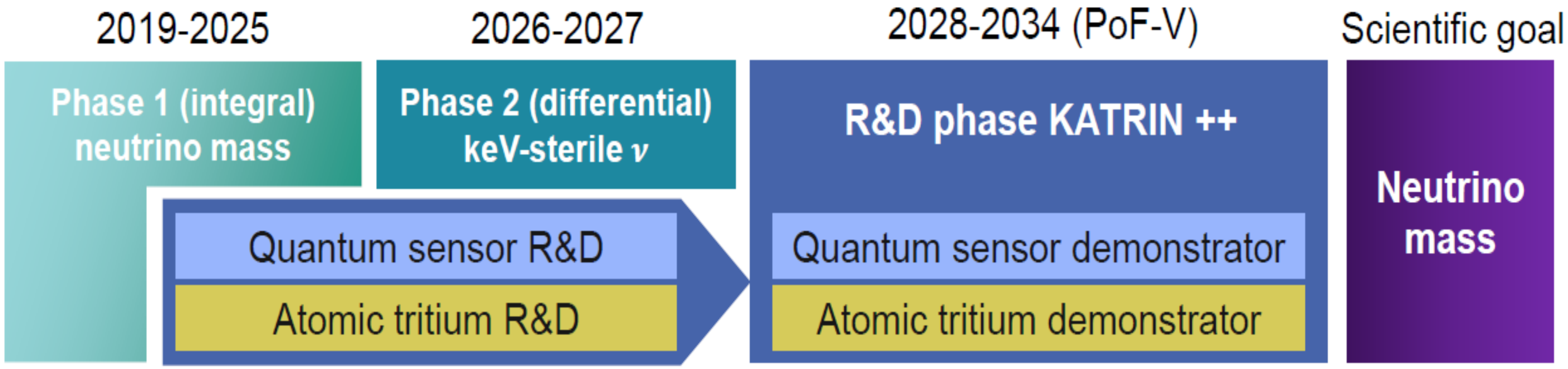
$$m_\nu < 0.45\,\mathrm{eV}\ \ (90\,\%\ \mathrm{CL})$$

Current program will continue through 2025, about 1000 days

Target KATRIN sensitivity < 0.3 eV (90% CL)

Perspectives of m_ν measurements

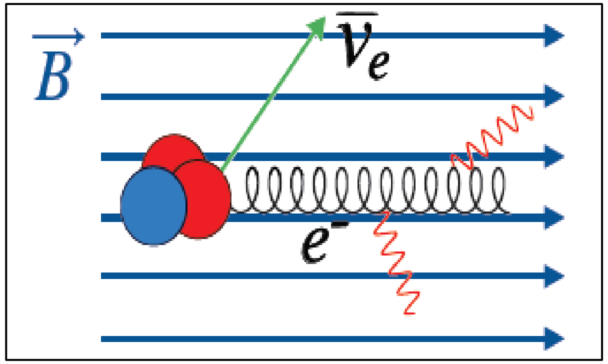
KATRIN prospects



M.Shlosser, talk at NuMass2024

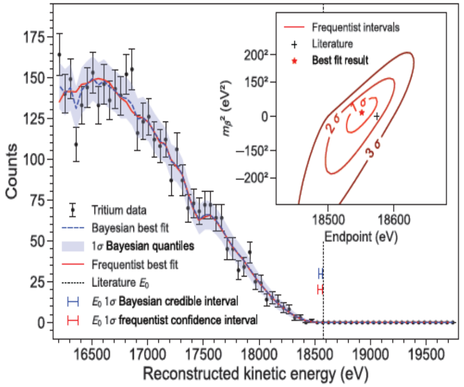
sensitivity on m_β < 40 meV

Project-8: Cyclotron Radiation Emission Spectroscopy



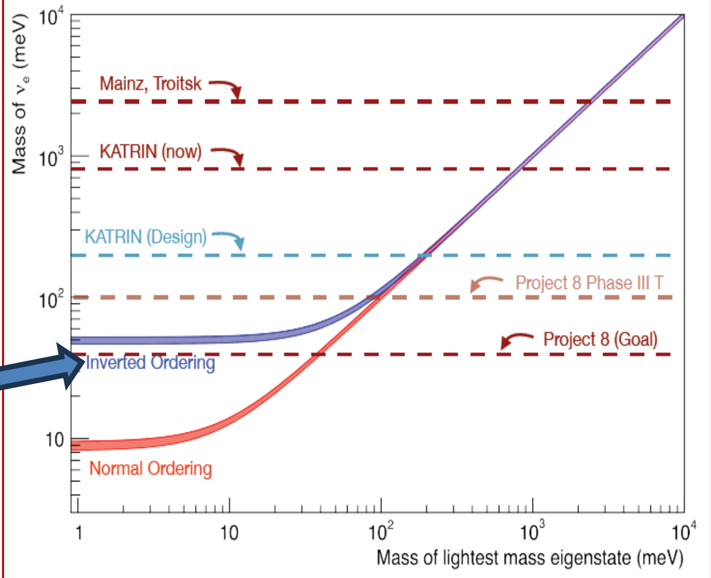
$$f_{Cyc} = \frac{1}{2\pi}\frac{qB}{m\gamma} = \frac{1}{2\pi}\frac{qB}{m_e + E_e}$$

Phys.Rev.Lett. 131 (2023) 102502

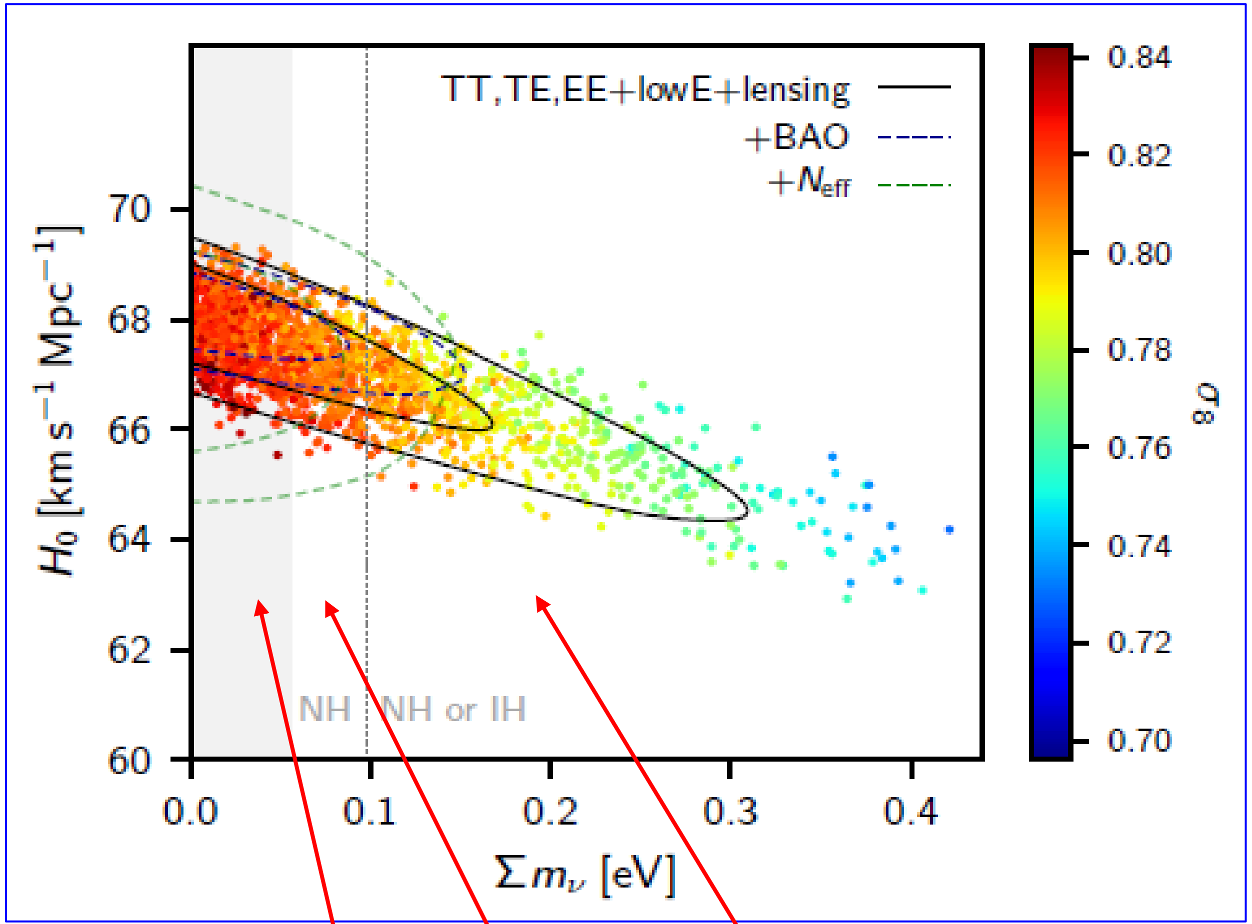


m_ν< 152 eV (90% CL)

Projected sensitivity 40 meV



Cosmology: $\sum m_i$



Oscillations: **Excluded** **Only NO** **NO or IO**

Planck, A&A 641 (2020) A6

Model dependent Λ**CDM**

$$\sum m_i < 0.12 \text{ eV } (95\backslash\% \text{ CL})$$

IO: $\Sigma m_i \approx 100\ meV$

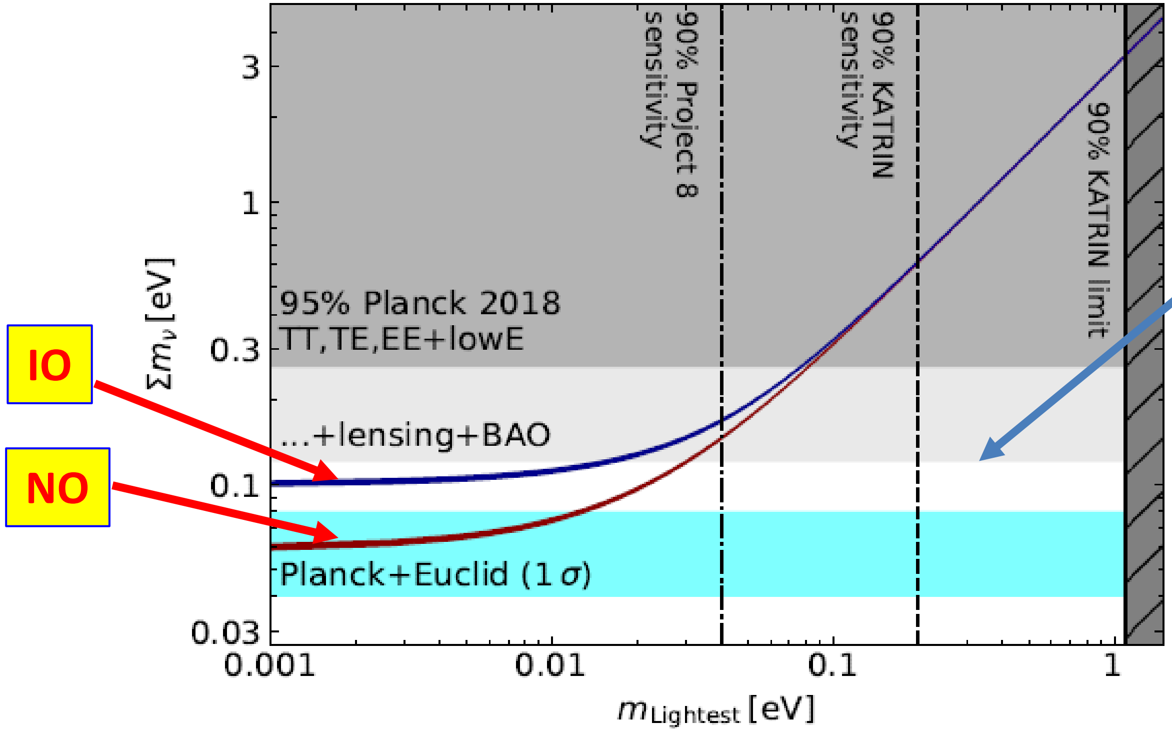
NO: $\Sigma m_i \approx 60\ meV$

Cosmology: Mass Ordering

Normal Ordering $\sum m_i^{NO} = m_{light} + \sqrt{m_{light}^2 + \Delta m_{21}^2} + \sqrt{m_{light}^2 + |\Delta m_{31}^2|} \simeq$ **0.06 eV**

Inverted Ordering $\sum m_i^{IO} = m_{light} + \sqrt{m_{light}^2 + |\Delta m_{31}^2|} + \sqrt{m_{light}^2 + |\Delta m_{31}^2| + m_{21}^2} \simeq$ **0.1 eV**

M.Archiacomo et al, arXiv:2003.03354



ΛCDM Model upper limit:

$$\sum m_i < 0.12\ eV\ \ (95\%\ CL)$$

However, the limit is model dependent

Robust $\sum m_i < 0.6\ eV\ \ (95\%\ CL)$

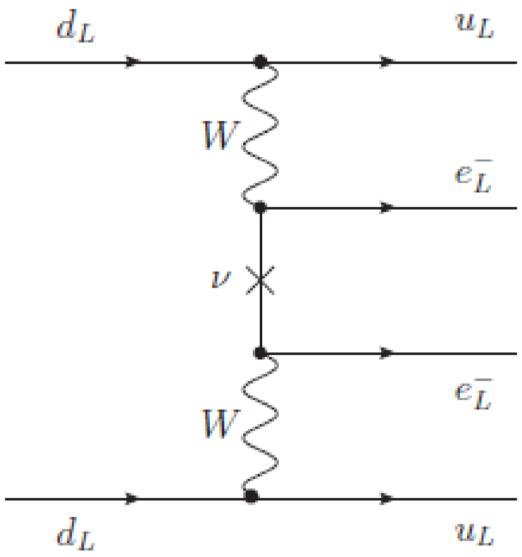
by only CMB for any extension of ΛCDM Model

ESA Euclid: **expected 1σ sensitivity** $0.011 - 0.02$ **eV**

(3-4)σ detection of $\sum m_i$ **(NO) may be possible!?**

0ν2β

$0\nu 2\beta$ decay:
Standard mechanism - exchange by light **Majorana** neutrinos



$$\frac{1}{T^{0\nu}_{1/2}} = g_A^4 G^{0\nu} |M^{'0\nu}|^2 \frac{\langle m_{ee}\rangle^2}{m_e^2}$$

$T^{0\nu}_{1/2}$ = measured experimentally
g_A = axial vector coupling, assume = 1.25
$G^{0\nu}$ = phase space factor ~ Q^5
$M^{0\nu}$ = nuclear matrix element
m_e = electron mass

m_{ee} ($m_{\beta\beta}$)

$$m_{\beta\beta} = e^{i\alpha_1} U_{e1}|^2 m_1 + e^{i\alpha_2}|U_{e2}|^2 m_2 + U_{e3}|^2 m_3$$

$$m_{\beta\beta} = \cos^2\theta_{12} e^{i(\alpha_2} \cos^2\theta_{13} m_1 + \sin^2\theta_{12} \cos^2\theta_{13} e^{i\alpha_2} m_2 + \sin^2\theta_{13} m_3$$

Normal Ordering

$$m_1 = m_0, \quad m_2 = \sqrt{m_0^2 + \Delta m_{21}^2}, \quad m_3 = \sqrt{m_0^2 + \Delta m_{31}^2},$$

Inverse Ordering

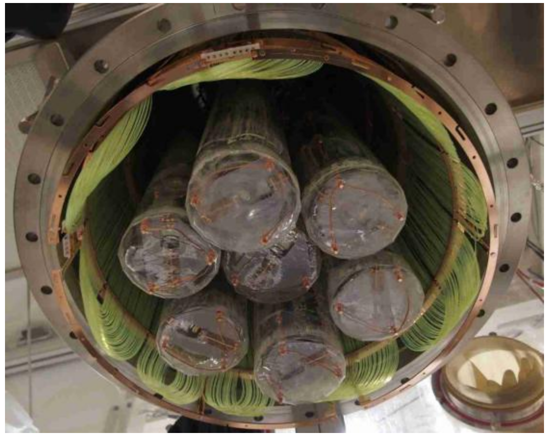
$$m_3 = m_0, \quad m_1 = \sqrt{m_0^2 - \Delta m_{31}^2}, \quad m_2 = \sqrt{m_0^2 - \Delta m_{31}^2 + \Delta m_{21}^2}$$

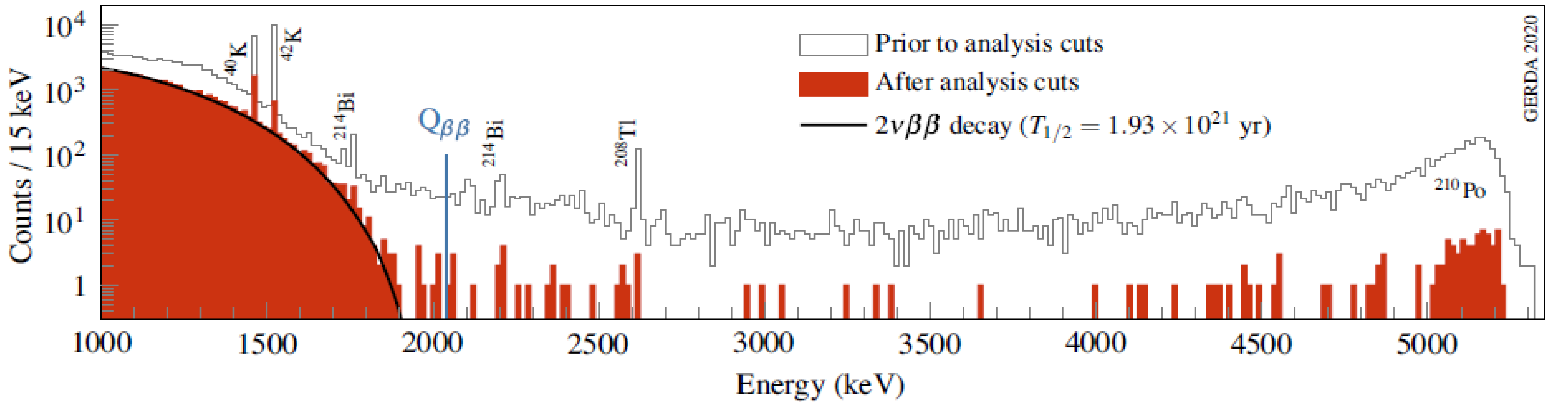
GERDA

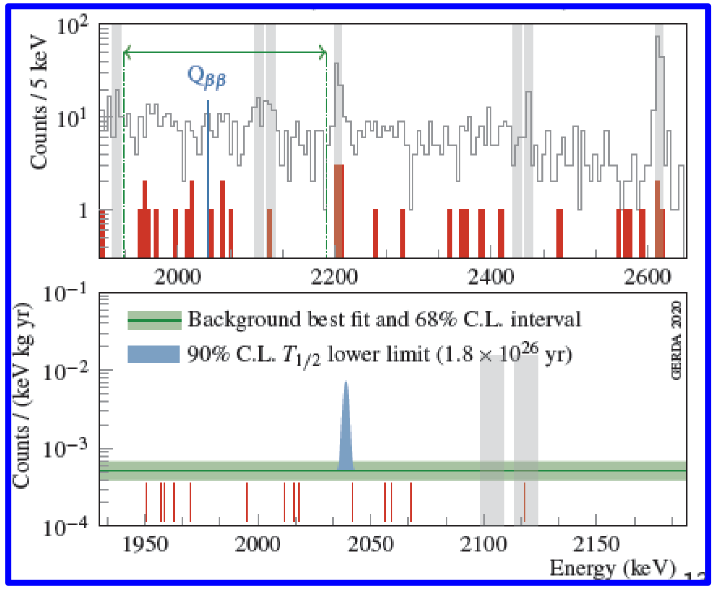
PRL 125 (2020) 252502

Ge detectors
Ge-76

Exposure: 127.2 kg x yr







- lowest background level achieved: $BI = 5.2 \times 10^{-4}$cts/(keV · kg · yr)
- Background-Free regime: < 1 count in $Q_{\beta\beta} \pm 0.5$ FWHM.

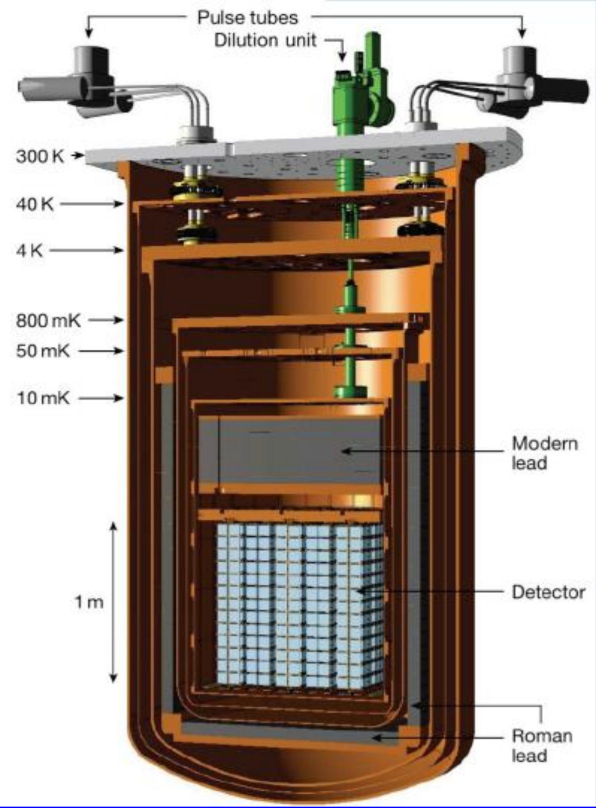
$T^{0\nu}_{1/2} > 1.8 \times 10^{26} yr$ 90% CL
$|m_{\beta\beta}| \leq 79 - 180\ meV$

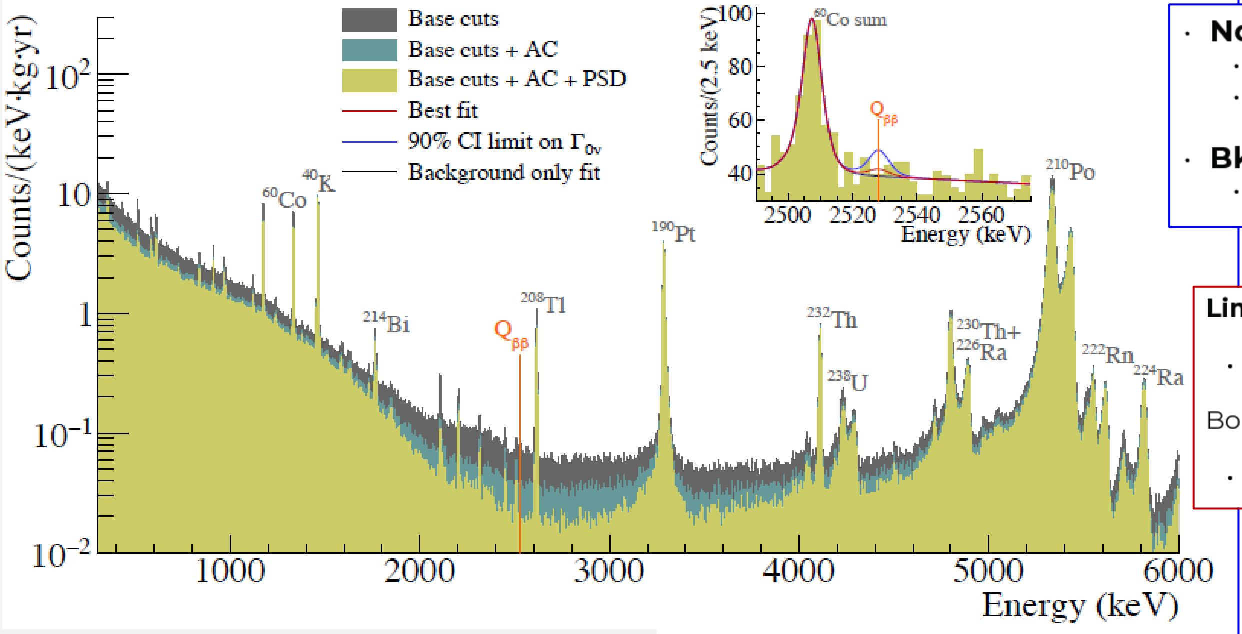
CUORE

Cryogenic detector
988 TeO_2 detectors
operating at T = 10 mK

1 ton·yr TeO_2

NATURE 604 (2022) 7904 53-58





- **No peak** found at $Q_{\beta\beta}$ of ^{130}Te
  - 1038.4 kg·yr of TeO_2
  - 289 kg·yr of ^{130}Te
- **Bkg** index:
  - 1.49 (4) · 10^{-2} counts·keV^{-1}·kg^{-1}·yr^{-1}

Limit on decay half-life

- $T^{0\nu}_{1/2} > 2.2 \cdot 10^{25} yr$ (90% C.I.)

Bound on effective Majorana mass:

- $m_{\beta\beta} < (90 - 305)\ meV$

Latest CUORE result

I.Nutini, talk at Moriond2024

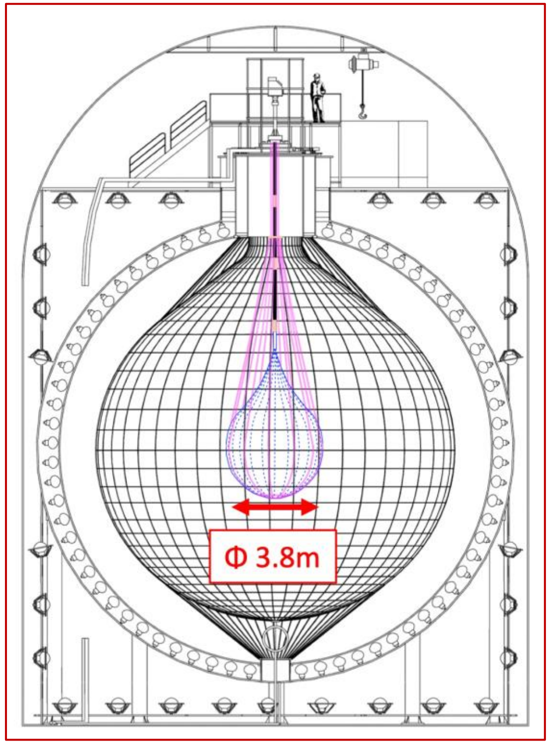
Total exposure for 0νββ decay search
2039.0 kg yr TeO_2,
567.0 kg yr ^{130}Te

$T^{0\nu}_{1/2} > 3.8\times 10^{25}$ yr (90% CL)
$m_{\beta\beta}$ < 70-240 meV

KamLAND – Zen

I.Shimizu, Neutrino2024

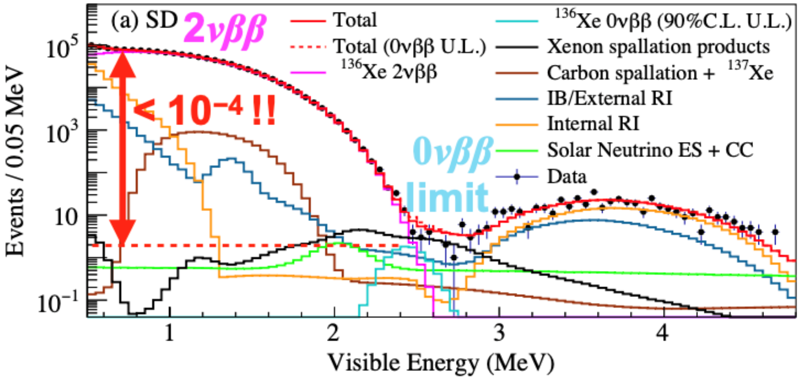
Detector KamLAND-ZEN
Liquid scintillator



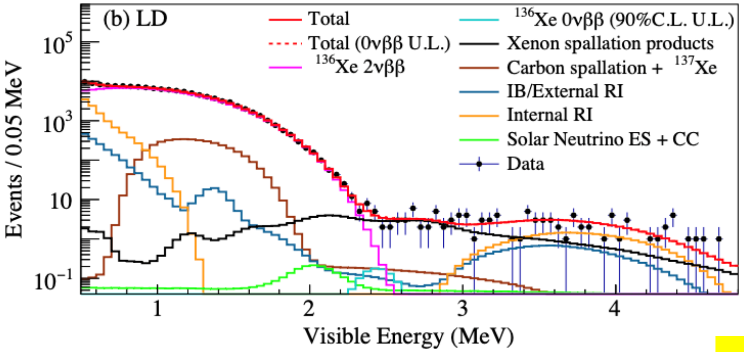
745 kg of enriched Xe-136

$0\nu2\beta$ candidate, exposure 1131 days

ββ isotope ^{136}Xe 90.85% enriched	$Q_{\beta\beta}$ = 2458 keV
745 kg Xe in all volume	Feb. 5, 2019 - Jan. 12, 2024



Long-live candidate, exposure 111 days

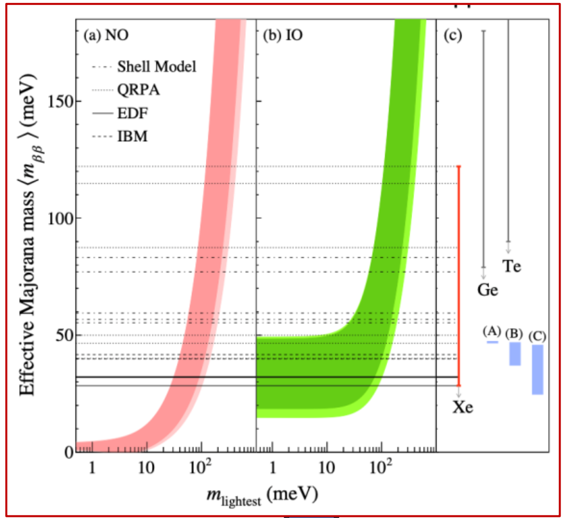


0νββ best-fit : **0 event**
upper limit : **< 10.0 event** at 90% C.L.

Half-life limit at 90% C.L.

Zen 400	$T^{0\nu}_{1/2} > 0.9 \times 10^{26}$ yr
Zen 800	$T^{0\nu}_{1/2} > 3.4 \times 10^{26}$ yr
Combined	$T^{0\nu}_{1/2} > 3.8 \times 10^{26}$ yr

KamLAND-Zen (^{136}Xe)
$\langle m_{\beta\beta} \rangle$ < 28–122 meV
$m_{lightest}$ < 84–353 meV



$m_{\beta\beta} < (28 - 122)$ meV

KamLAND-ZEN begins to test IO band

$0\nu\beta\beta$: future prospects

Expected sensitivities in about 10 years

KamLAND2-ZEN:
upgrade of KamLAND-ZEN, 1000 kg of Xe,
5 yr data taking $T_{1/2} > 2\times10^{27}$ yr (90% CL) $m_{\beta\beta} < (12 - 53)\ meV$

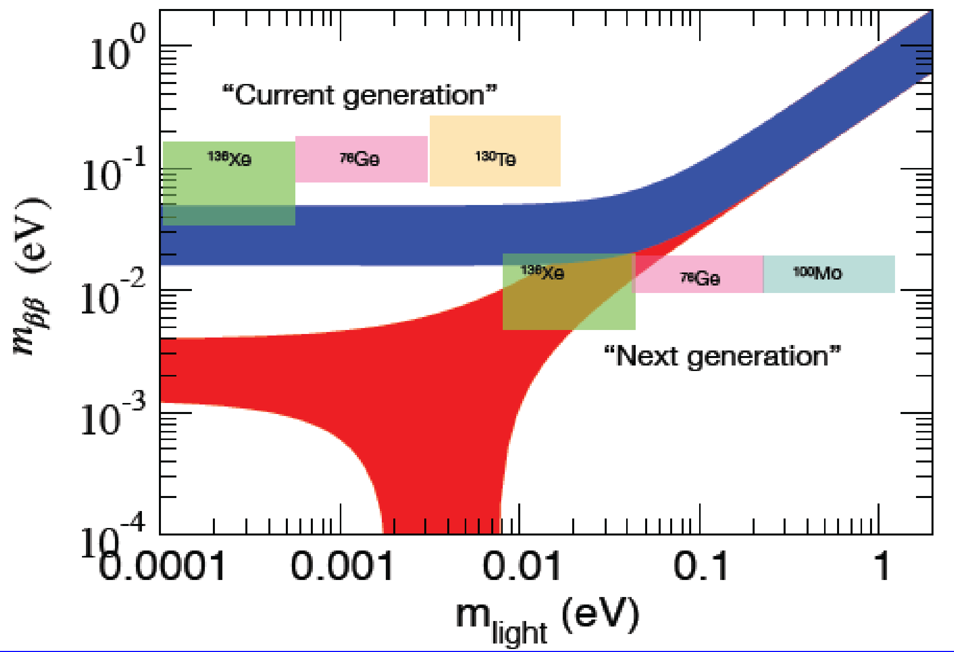
LEGEND-200: $T_{1/2} > 10^{27}$ yr (90% CL)
LEGEND-1000: $T_{1/2} \sim 1.6\times10^{28}$ yr (90% CL) $m_{\beta\beta} < (8.5 - 19)\ meV$

nEXO: 5t LXe (90% ^{136}Xe)
$T_{1/2} \sim 1.35\times10^{28}$ yr (90% CL) $m_{\beta\beta} < (5 - 20)\ meV$

AMORE-II: $Li_2{}^{100}MoO_4$ (360 crystals, 150 kg)
$T_{1/2} \sim 6\times10^{26}$ yr (90% CL) $m_{\beta\beta} < (15 - 27)\ meV$

CUPID (CUORE upgrade with particle ID):
$Li_2{}^{100}MoO_4$ (1596 crystals, 250 kg)
$T_{1/2} \sim 1.4\times10^{27}$ yr (90% CL) $m_{\beta\beta} < (10 - 17)\ meV$

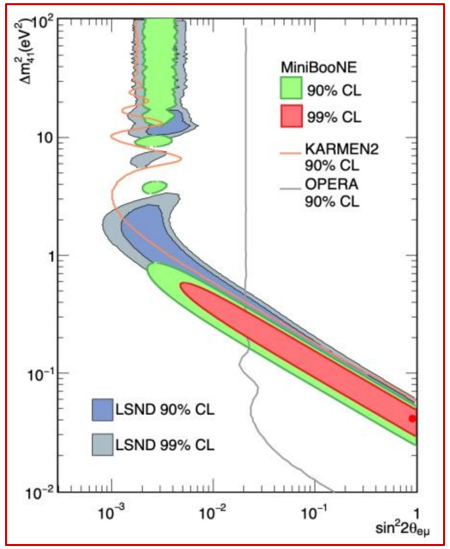
T.O'Donnel, talk at
Lepton Interactions with Nucleons and Nuclei 2023



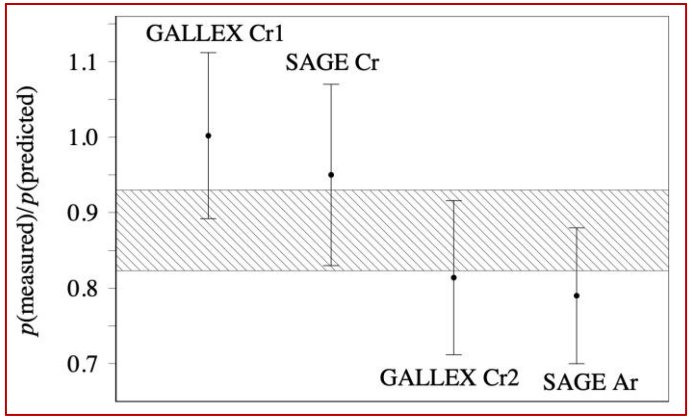
Sterile neutrinos ?

Light sterile neutrino

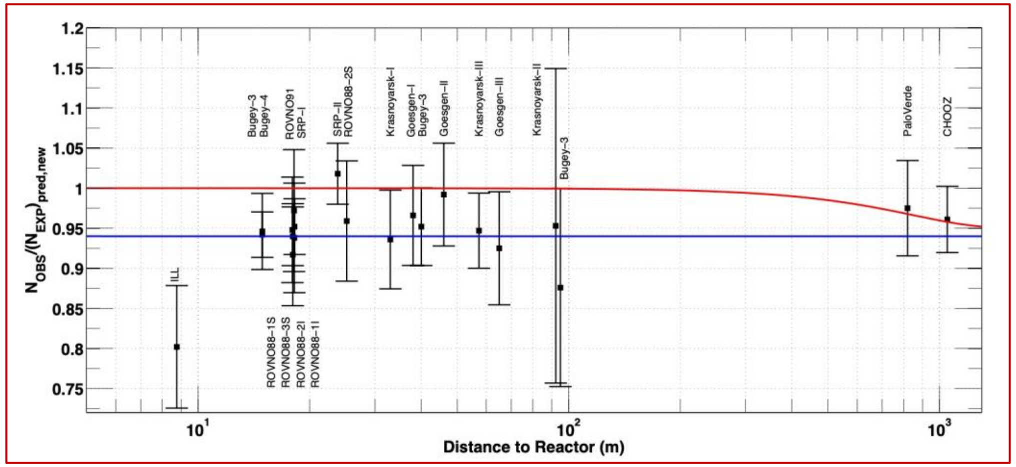
LSND/MiniBooNe anomaly



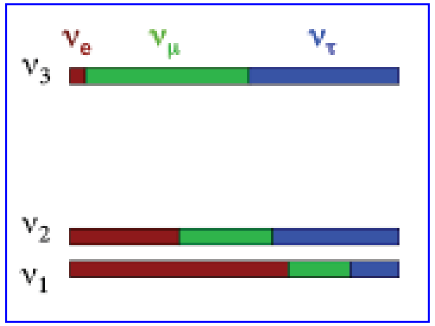
Ga anomaly



Reactor anomaly

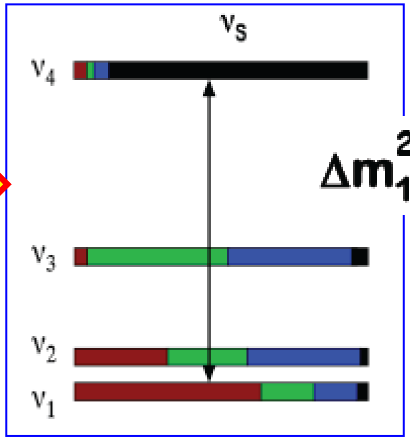


3ν, NO



?

$3\nu + 1\nu_s$



$\Delta m^2_{14} \sim 1$ eV^2

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

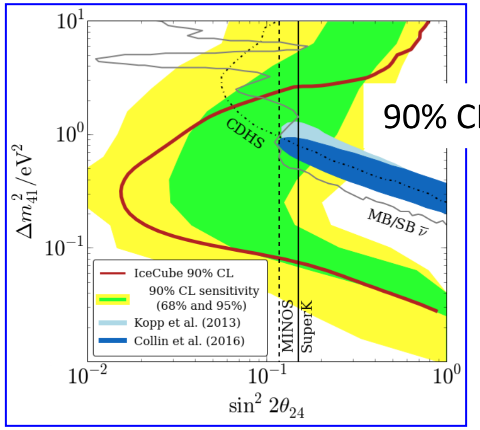
$$P_{\nu_e\to\nu_e} \simeq 1 - 2|U_{e4}|^2(1-|U_{e4}|^2)$$
$$P_{\nu_\mu\to\nu_\mu} \simeq 1 - 2|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)$$
$$P_{\nu_\mu\to\nu_e} \simeq 2|U_{e4}|^2|U_{\mu 4}|^2$$

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

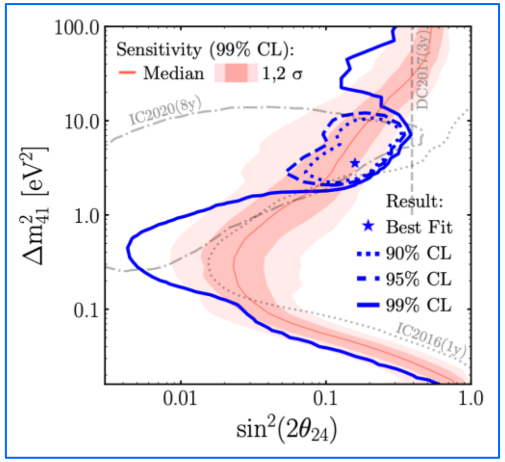
LSND/MiniBooNE anomaly

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

PRL 117 (2016) 071801



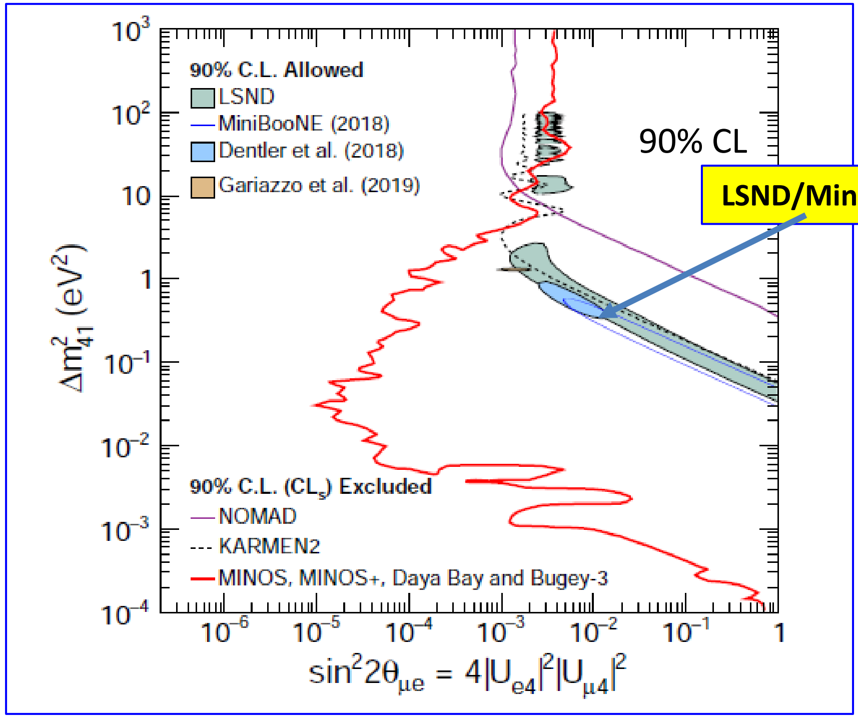
11 years of data taking, arXiv:2405.08070



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

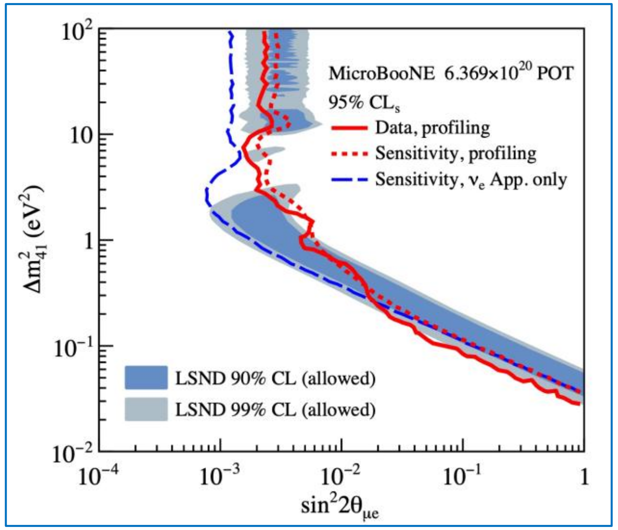
PRL 125 (2020) 131802

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



PRL 130 (2023) 011801

MicroBooNE, , LAr TPC



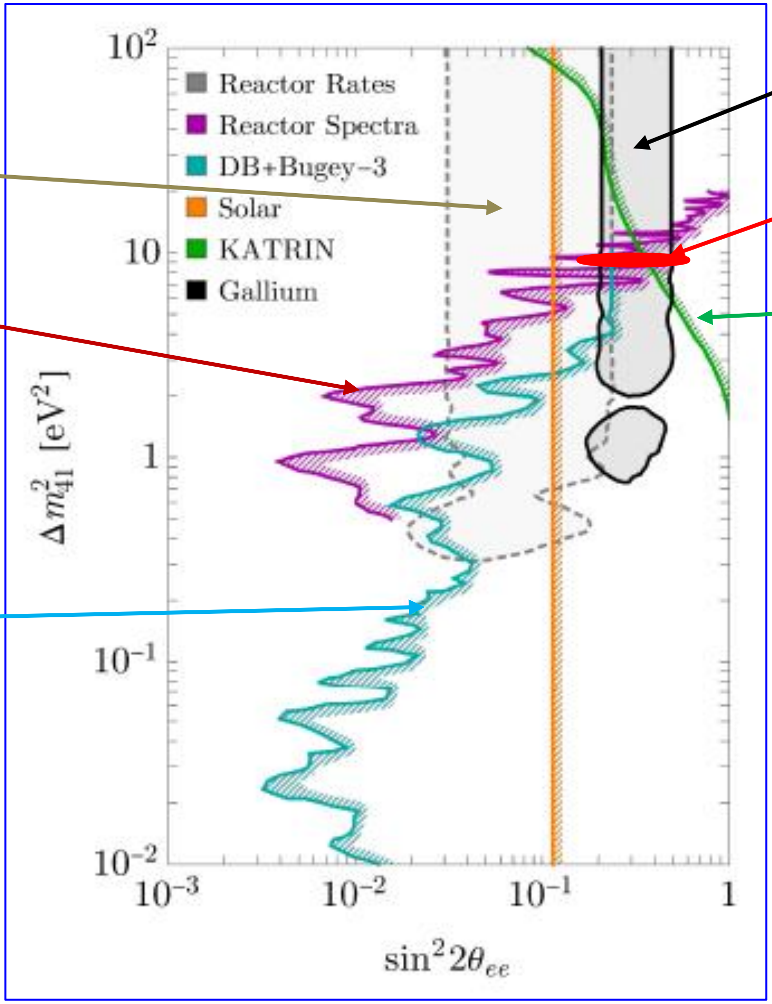
$$\sin^2 2\theta_{e\mu} \simeq \frac{1}{4} \sin^2 2\theta_{ee} \; \sin^2 2\theta_{\mu\mu}$$

Positive signal:
LSND/MiniBooNE
Not confirmed by:
MINOS, Daya Bay/Bugey-3
IceCube

Neutrino anomalies: Reactor, Ga

Elector neutrino disappearance

arXiv:2203.07214



Positive signals:
Neutrino-4
BEST

Negative results:
DANSS, NEOS, PROSPECT, STEREO, Daya Bay/Bugey-3

Future
DANSS and Neutrino-4 → upgrade
- PROSPECT-II
- TAO

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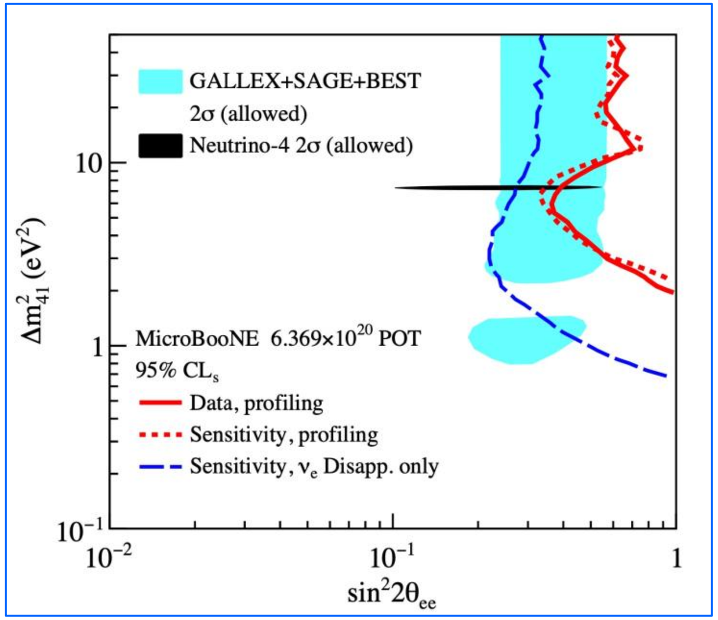
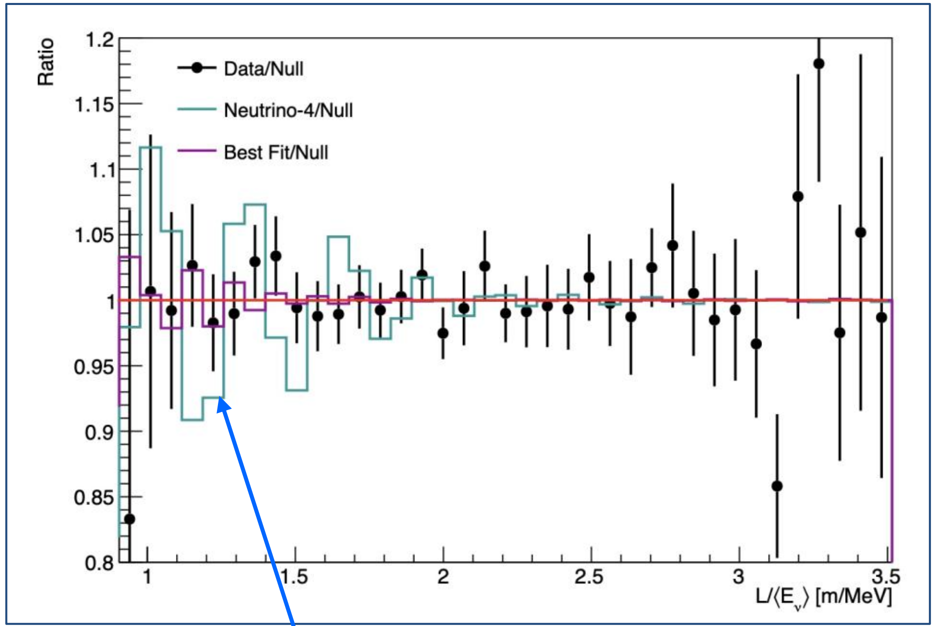
MicroBooNE, LAr TPC



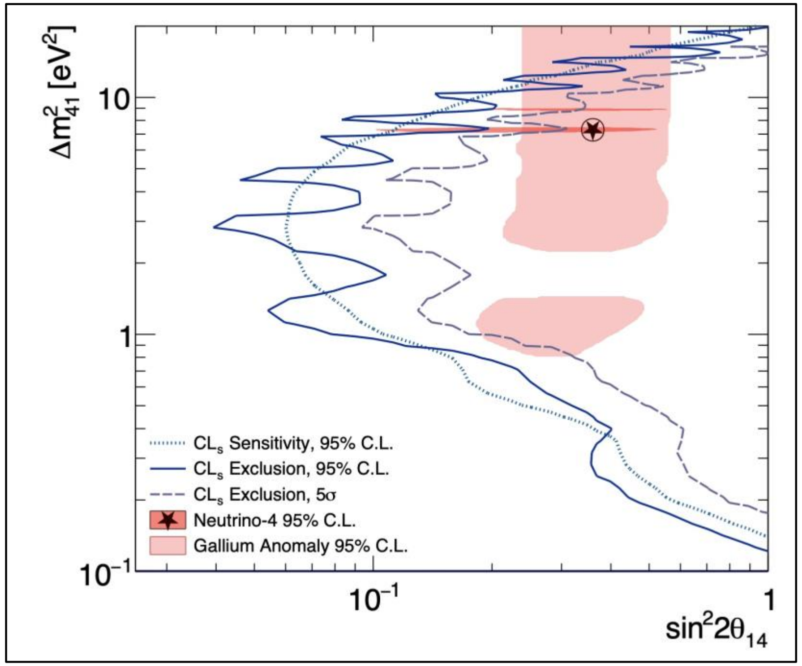
! P.Denton, arXiv: 2111.06793
2.4σ hint in favour of ν_s
using MicroBooNE data:
$\sin^2 (2\theta_{14}) = 0.35 + 0.19 - 0.16$
$\Delta m^2_{41} = 1.25 + 0.74 - 0.39$ eV^2 !

PROSPECT: new ν_s seacrh

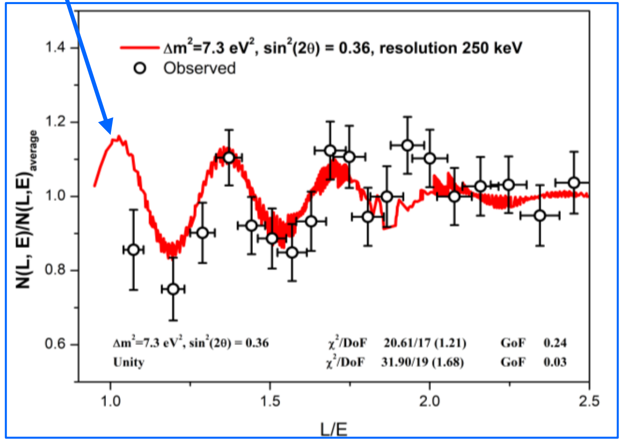
arXiv:2406.10408



PROSPECT – reactor experiment at 85 MW HFIR, ORNL
Detector Li-6 doped organic scintillator
L = 6.7-9.2 m from reactor core
Data taking: 95.6 reactor-on, 73.1 reactor-off days



Neutrino-4
2302.09958

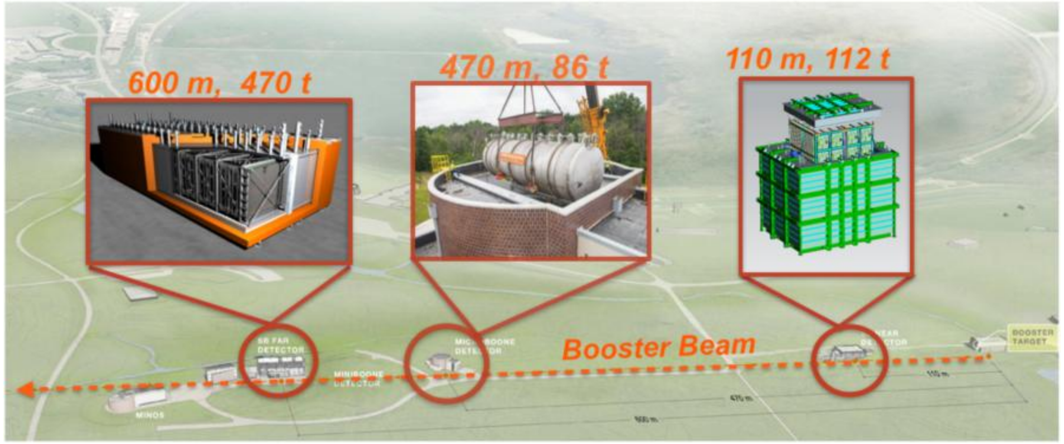


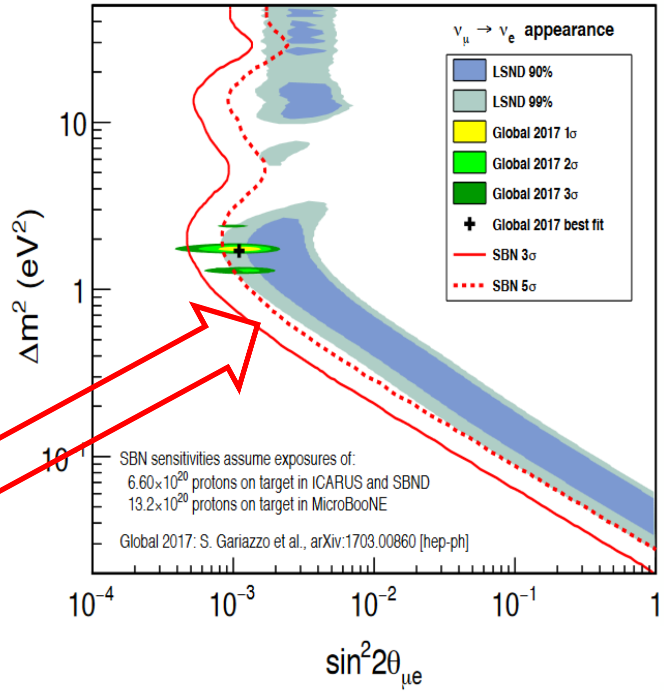
Neutrino-4 best fit point excluded at more than 5σ

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

LAr1-ND: will take data in 2024

Conclusion/Perspectives

Neutrino is a unique laboratory to study Physics Beyond SM

CP violation and Mass Ordering – primarily targets of current, coming and near future long baseline accelerator and reactor experiments

Direct m_ν measurement by KATRIN, KATRIN++, and Project8

Mass ordering, Dirac/Majorana - 0ν2β experiments

Sum of masses, Mass Ordering - cosmology

Sterile neutrinos will be probed in numerous experiments and cosmology

Very exiting physics now and ahead of us !

Thank you for your attention