Нейтриная физика: современное состояние, аномалии, перспективы

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Сессия Секции ядерной физики ОФН РАН
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Standard Model: neutrinos are *massless* particles

However, the discovery of *neutrino oscillations*

Бруно Понтекорво

$$K^0 \leftrightarrow \overline{K}^0$$

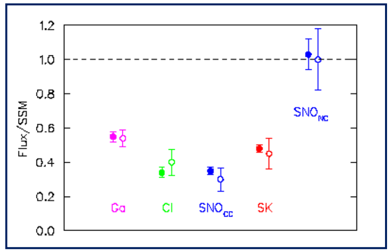
$$\nu \leftrightarrow \overline{\nu}$$

$m_\nu \neq 0$

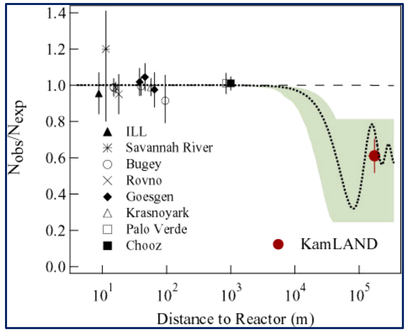
↓

NEW PHYSICS
beyond
STANDARD MODEL

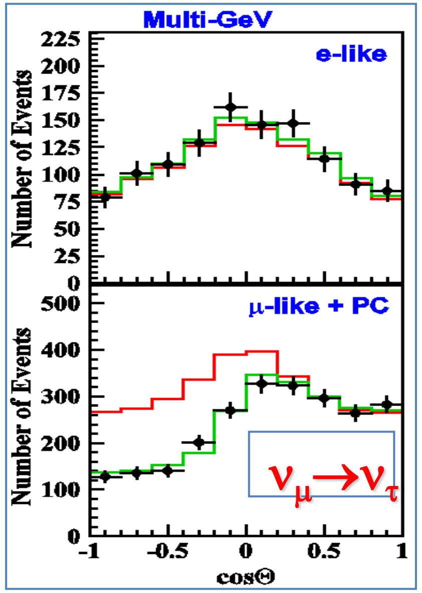
Solar ν



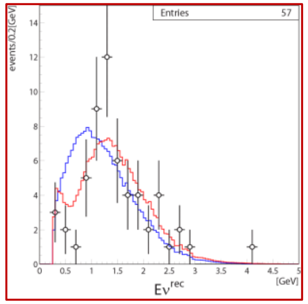
Reactor ν

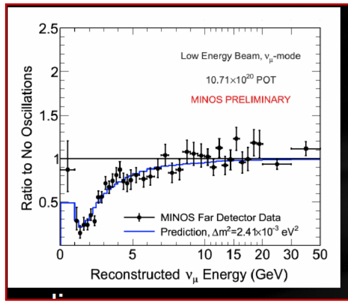


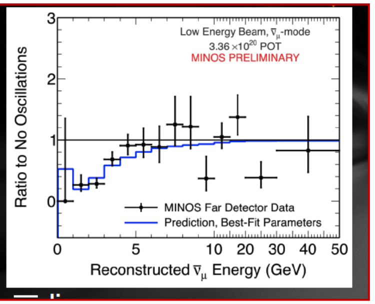
Atm ν

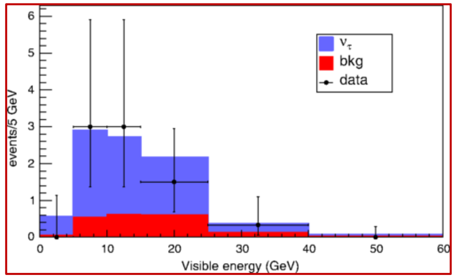


Accelerator ν









Neutrino oscillations and mixing

3 families

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

***U* parameterization:**

three mixing angles θ_{12} θ_{23} θ_{13}

CP violating phase δ_{CP}

Pontecorvo-Maki-Nakagawa-Sakata 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

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

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

T2K, NOvA

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

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

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

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

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

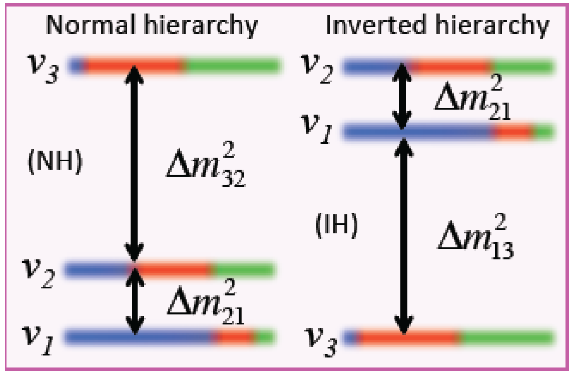
quarks

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

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

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

- Neutrino mass ordering (NMO)



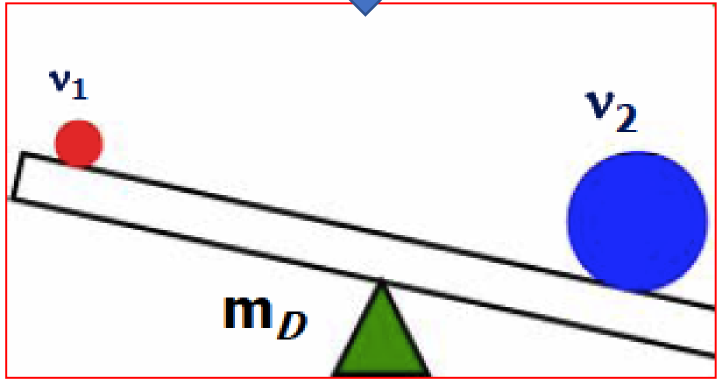
IO: $\Sigma m_i \approx 100\ meV$
NO: $\Sigma m_i \approx 60\ meV$

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
$\nu_2 \to M_R \le 10^{14}$ 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 ??

- 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

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

leading term

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

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

Matter effect

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

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

change sign for NH → IH

Search/measurement of CP violation

Long baseline accelerator experiments

Direct search: compare oscillation probabilities

muon neutrino → electron neutrino

and

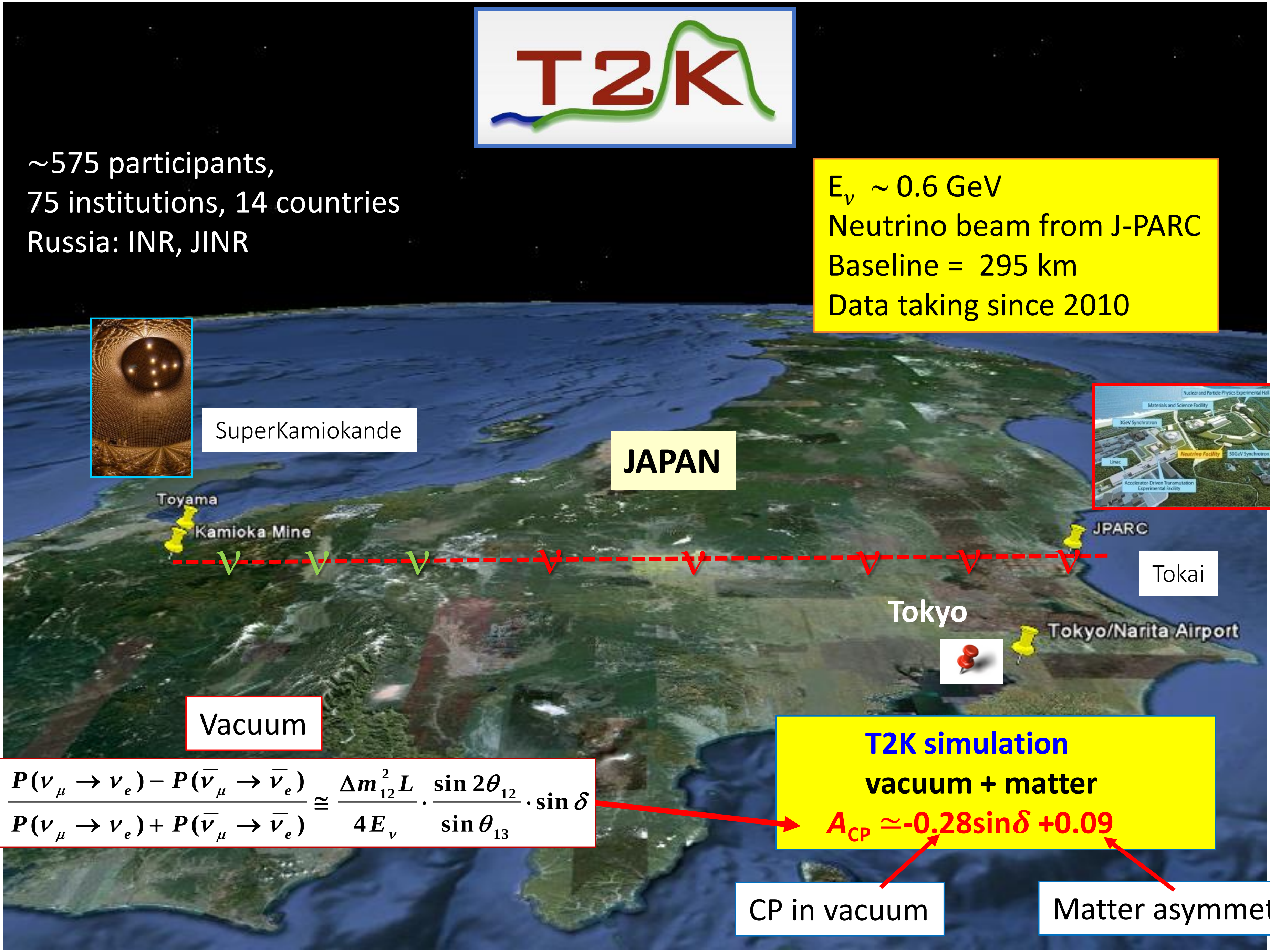
muon antineutrino → electron antineutrino

CP asymmetry A_{CP}

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

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

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



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

$E_\nu \sim 0.6$ 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
$A_{CP} \simeq -0.28 \sin\delta + 0.09$

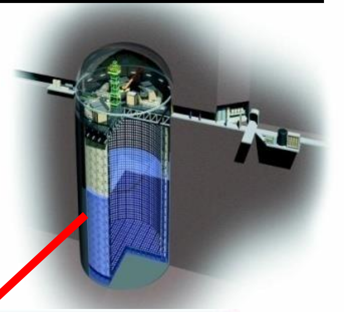
CP in vacuum

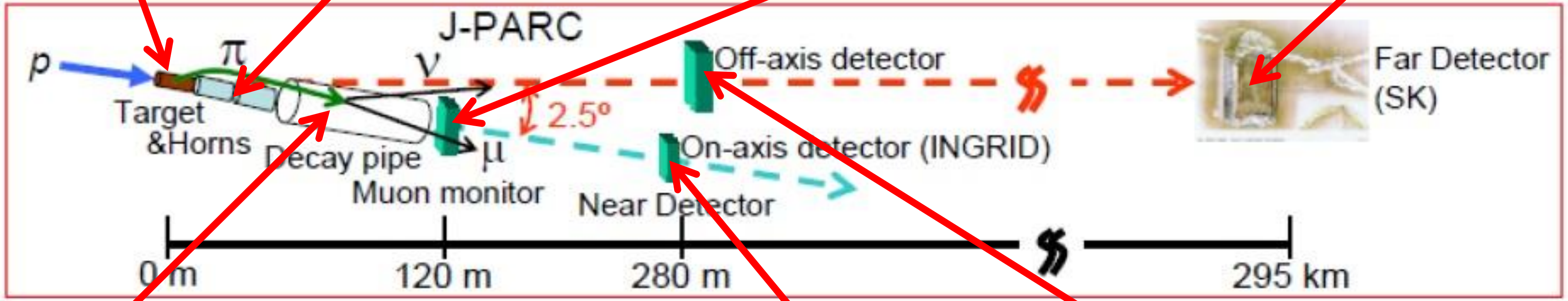
Matter asymmetry

Experiment T2K

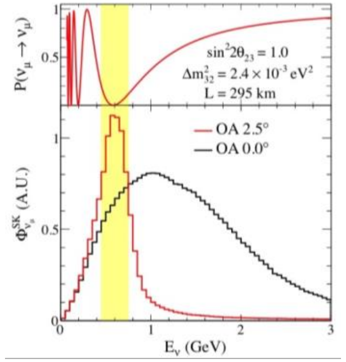
LBL accelerator experiment

Far neutrino detector
SuperKamiokande

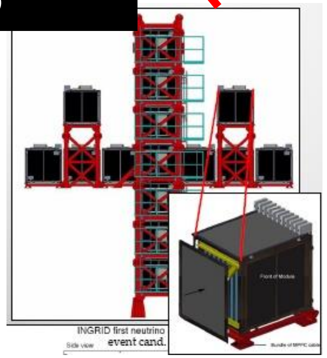




Off-axis neutrino beam

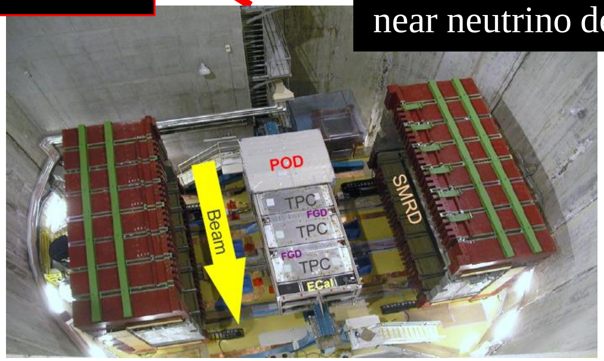


Neutrino monitor
INGRID



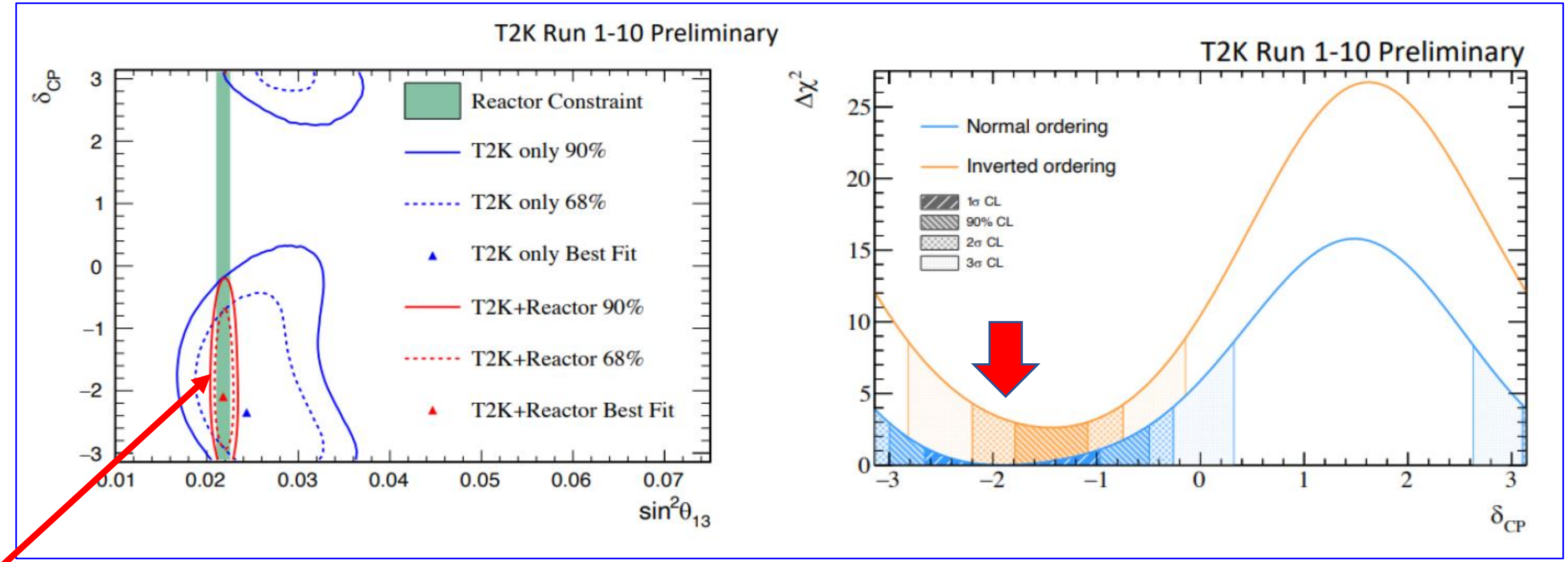
ND280

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

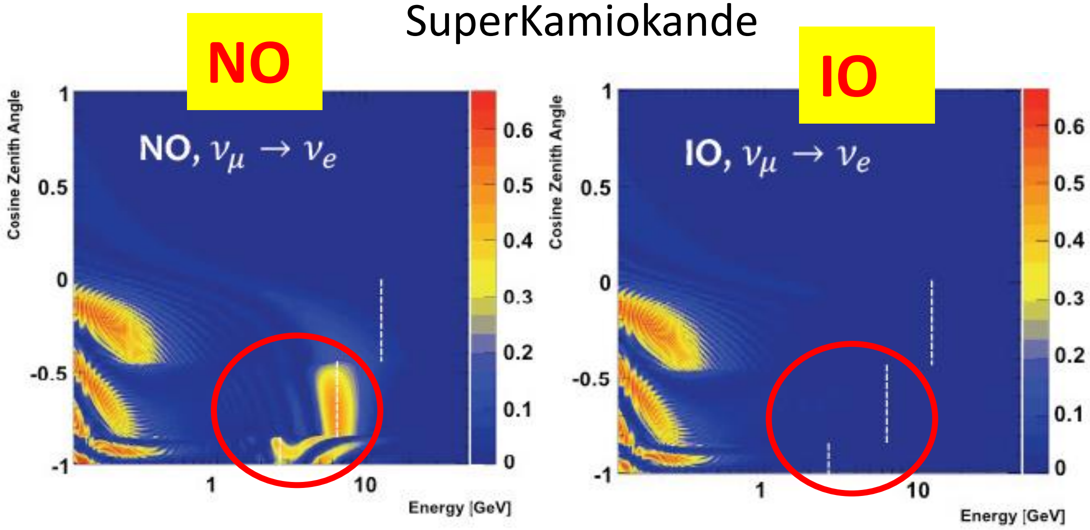
Best fit: $\delta_{CP} \sim -\pi/2$ → close to maximum CP violation

Normal mass ordering is preferred at 80% CL

Mass ordering: SuperKamiokande + T2K

SuperKamiokande

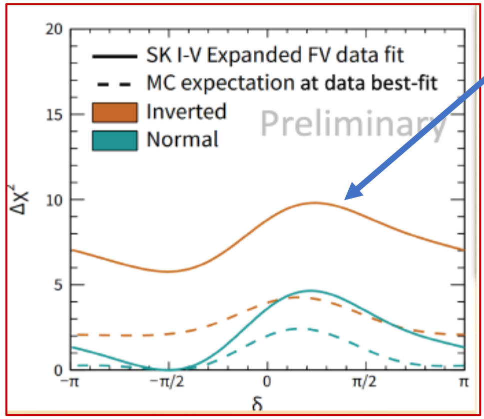
M.Pasiadala-Zezula, ICHEP2022

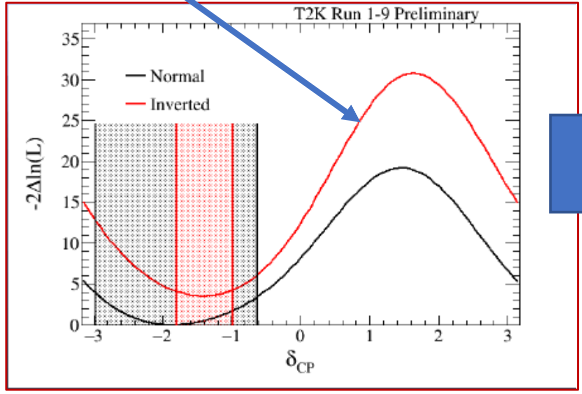


SuperKamiokande
- Atmospheric neutrino sensitive to mass ordering due to matter effect
- MSW resonance at ~ 10 GeV $2\sqrt{2}G_F E_\nu = \Delta m^2_{31}\cos 2\theta_{13}$

K.Sakashita, talk at NPB2024

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





Joint analysis SuperK+T2K increases sensitivity to MO

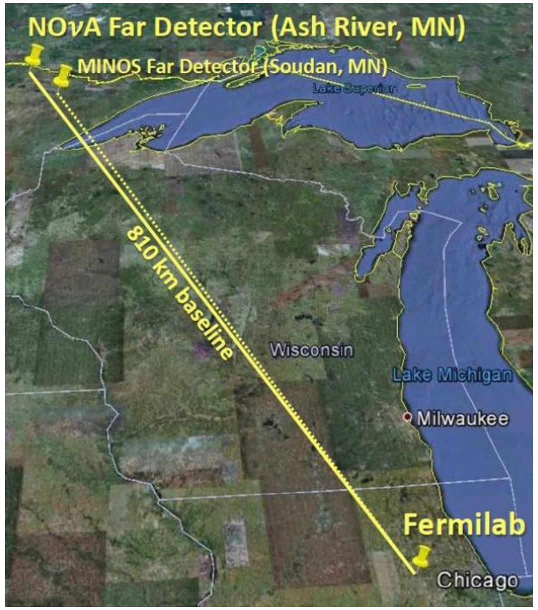
- SuperK provided an additional rejection of $\delta_{CP} = 0, \pi$
- Joint analysis prefers $\delta_{CP} \sim -\pi/2$ in both orderings with +π/2 lying outside the 3σ interval
- CP conservation $\delta_{CP} = 0, \pi$ is excluded at $\sim 2\sigma$ in IO; $\delta_{CP} = \pi$ still within 2σ in NO
- Preference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

Experiment NOvA

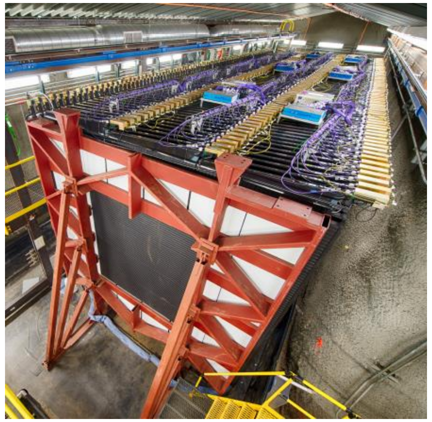
NOvA (USA)

Taking data since Summer 2014

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



Near Detector



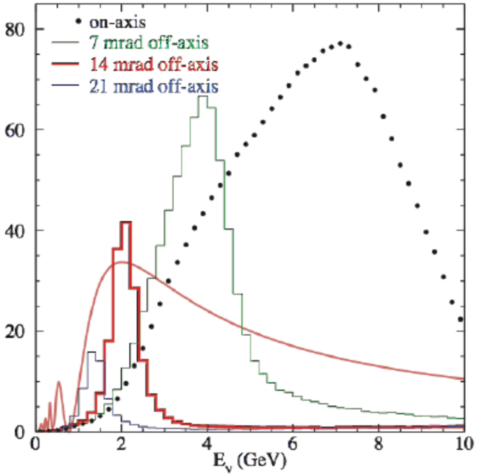
Neutrino beam from FNAL to Ash River
Baseline 810 km
Neutrino beam 14 mrad off-axis
Far detector : 14 kt fine-grained calorimeter
65% active mass
Near Detector: 0.3 kt fine-grained calorimeter

Protons on target

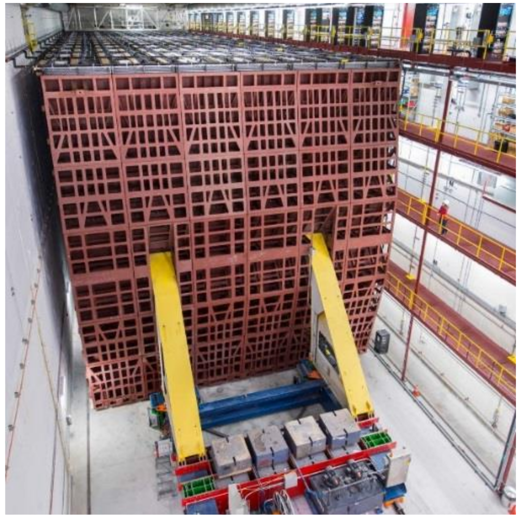
ν: 13.6×10^{20} POT

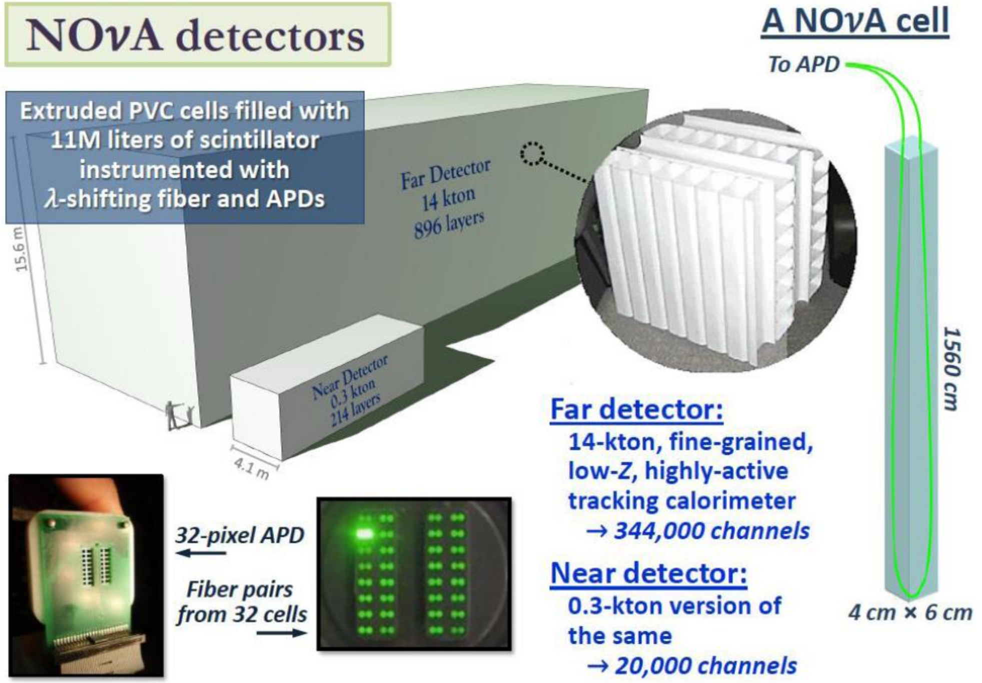
$\bar{\nu}$: 12.5×10^{20} POT

Neutrino beam

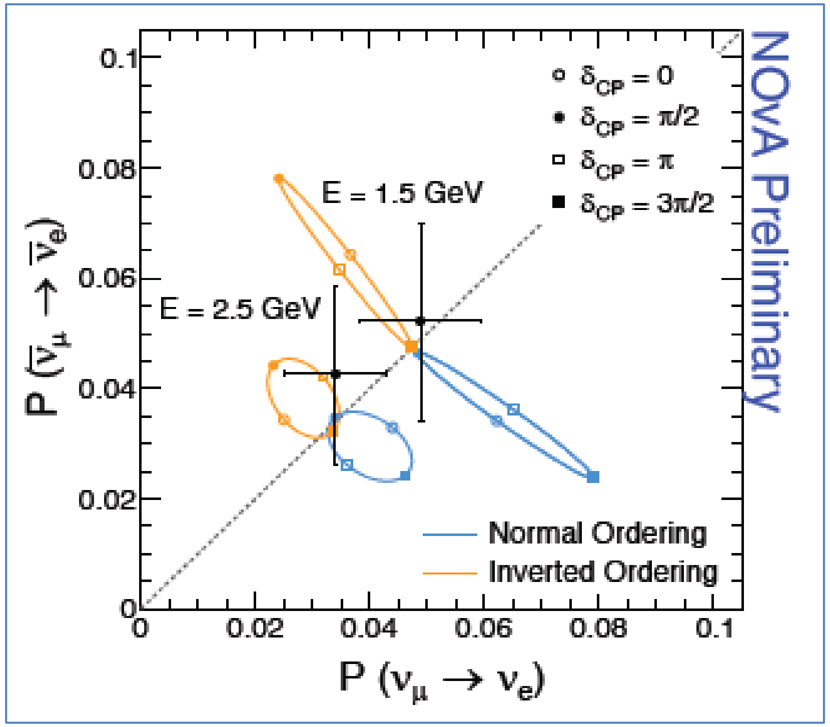


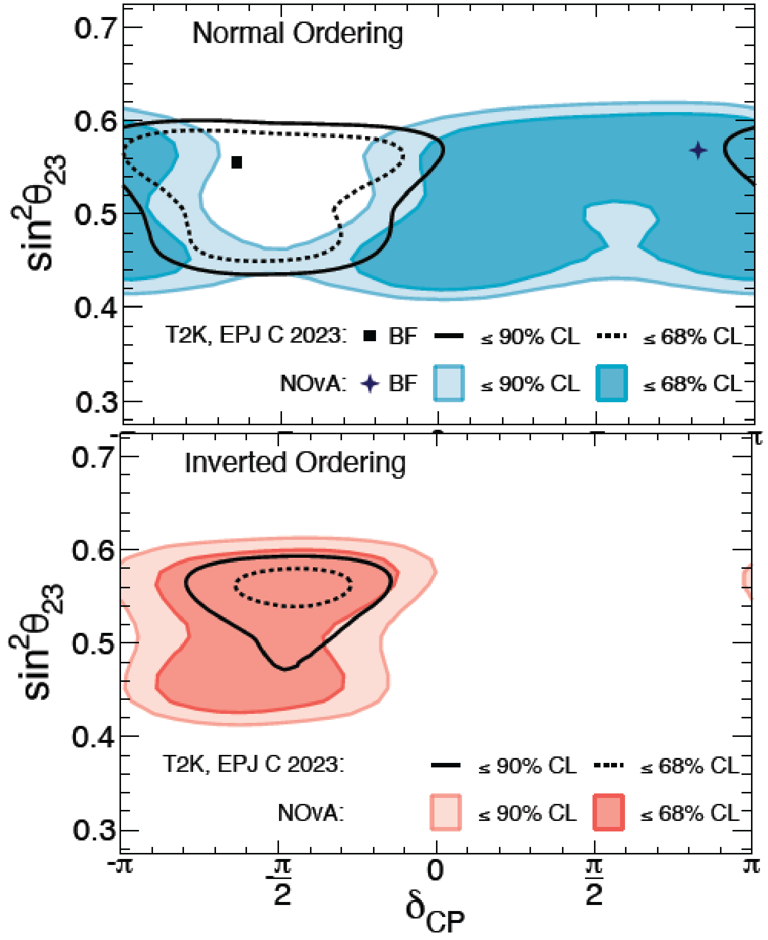
Far Detector





NOvA: search for CP violation





M.Frank, talk at EPS-HEP 2023

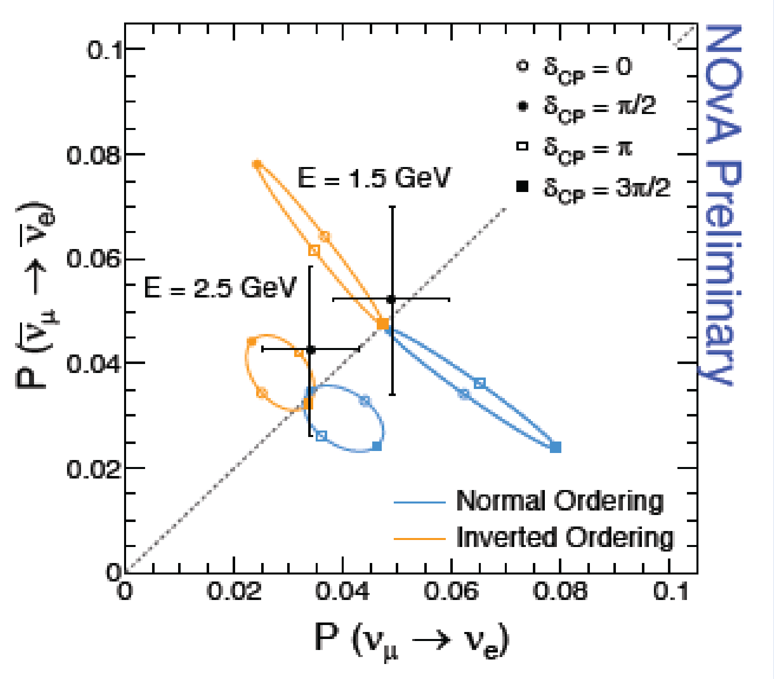
NOvA best fit:
$\delta_{CP} = 0.82\pi$

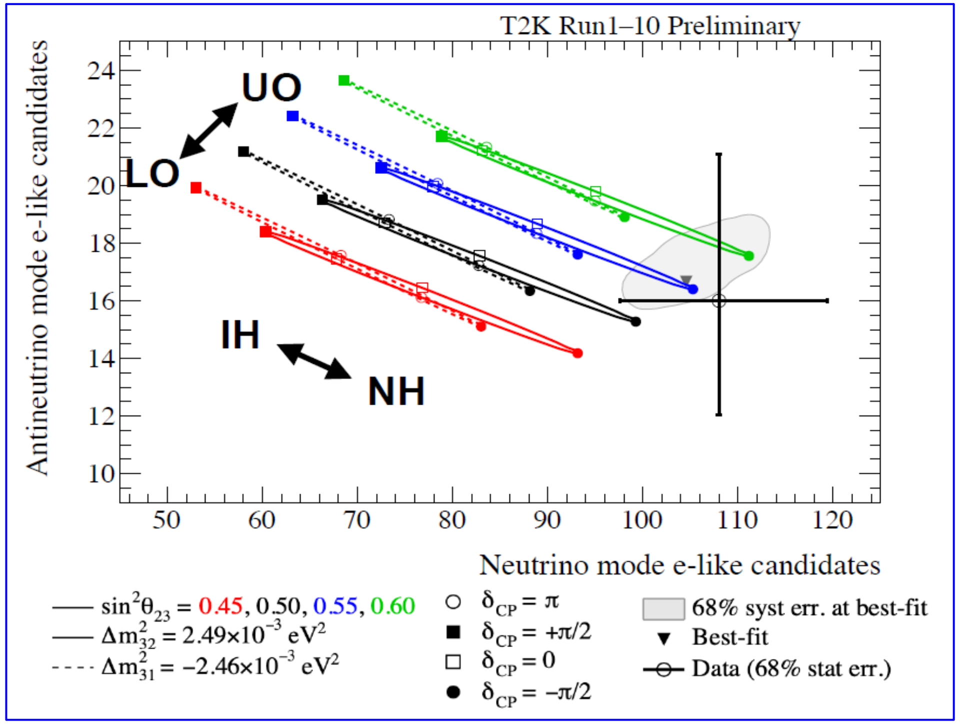
Exclude IH $\delta = \pi/2$ at > 3σ
Disfavor NH $\delta = 3\pi/2$ at ~2σ

- Weak preference for normal ordering
- No significant CP asymmetry was observed

CP: T2K and NOvA

T2K Preliminary





NOVA ($\nu+\bar{\nu}$) prefers:
NO
CP conservation
octants ~degenerate

T2K →

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

NOvA →

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

T2K ($\nu + \bar{\nu}$) prefers
NO
$\delta \sim -\pi/2 (\frac{3\pi}{2})$ **(~max CPV)**
2nd octant

T2K and NOvA joint analysis

R.Sanchez, Moriond 2024

T2K and NOvA data: *mild tension*

Normal Ordering

- **1σ overlap for some regions**

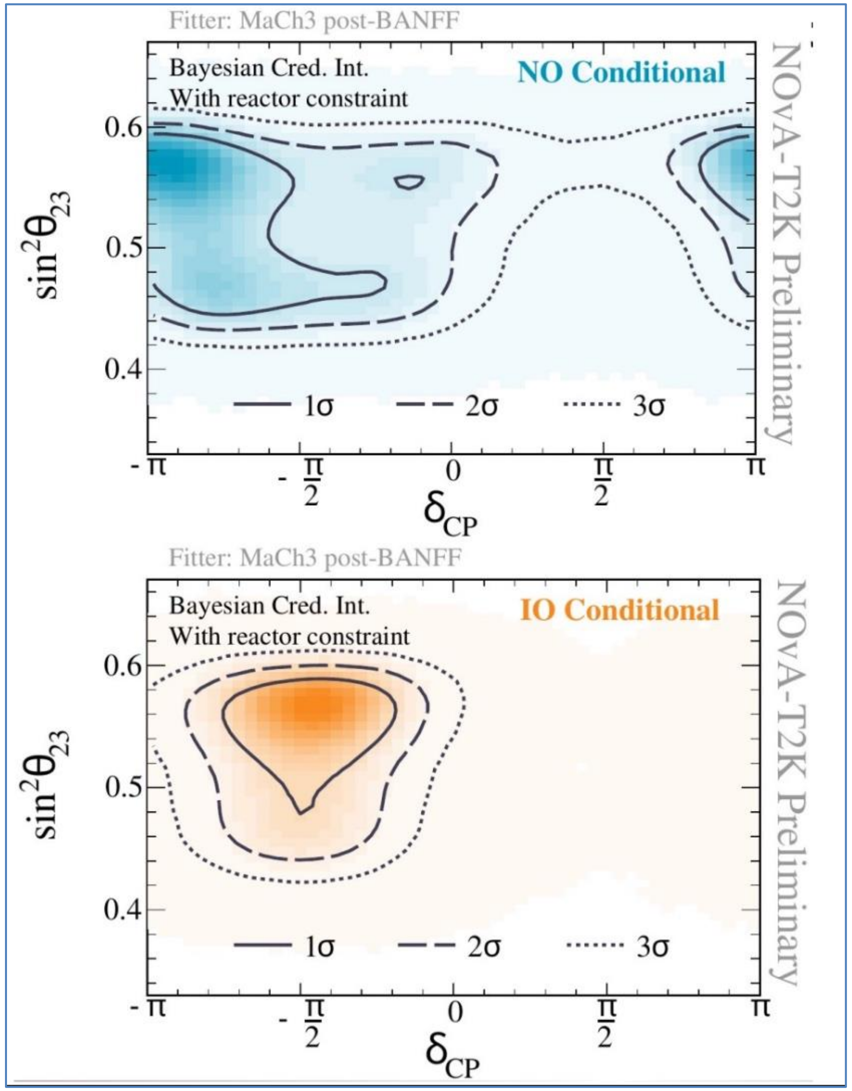
Inverted Ordering

- **very similar allowed regions**

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

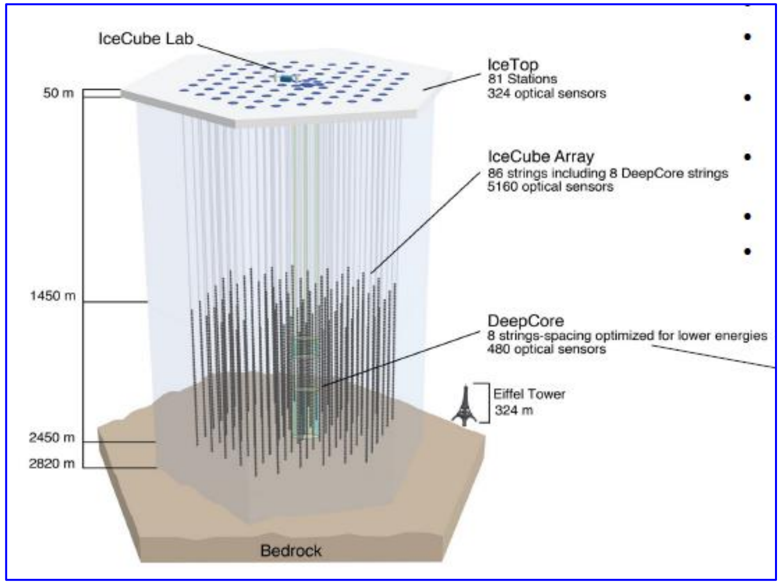
Main results of joint analysis

- 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



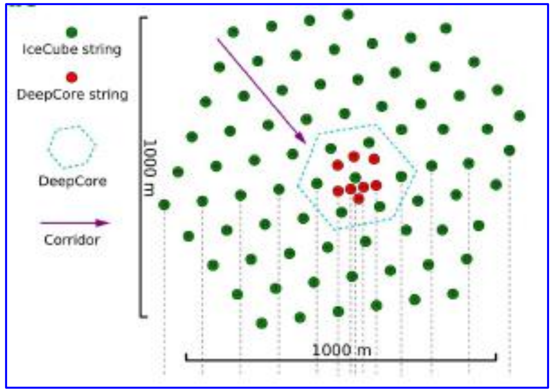
IceCube DeepCore: $\nu_\mu \to \nu_\mu$

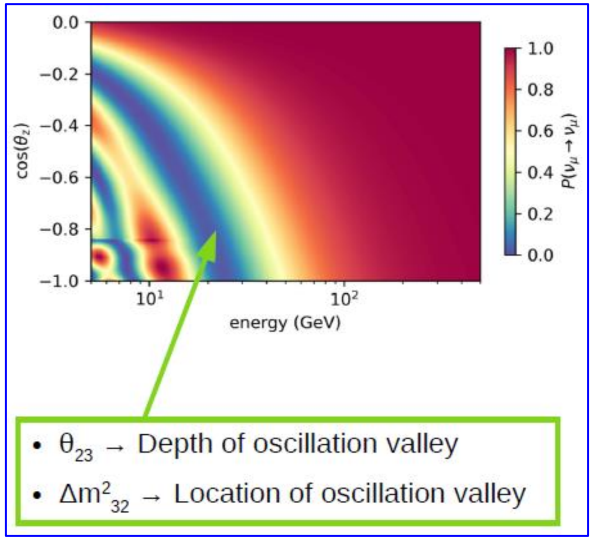
A.Kumar, EPS-HEP 2023



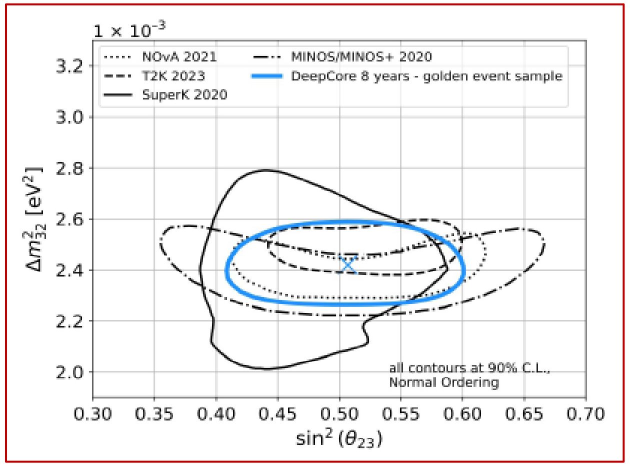
Livetime: 8 year

Total events: 21914

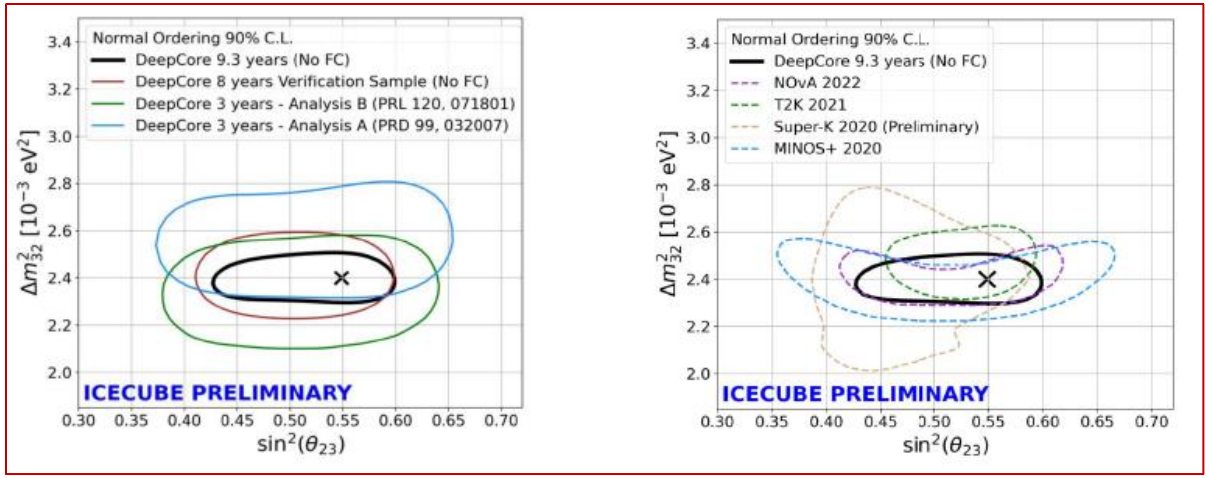




Golden sample, 8 years: about 20k events



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

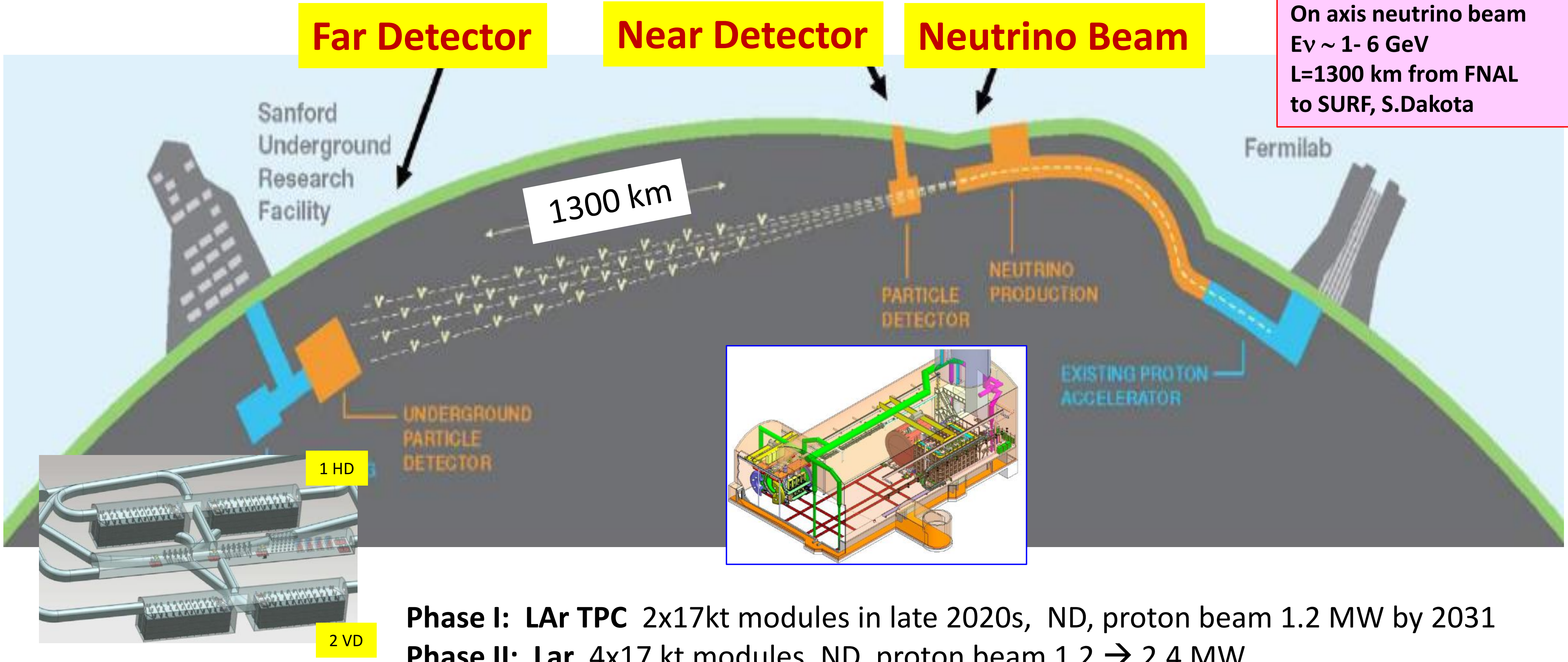
Future projects
DUNE,Hyper-Kamiokande, JUNO

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

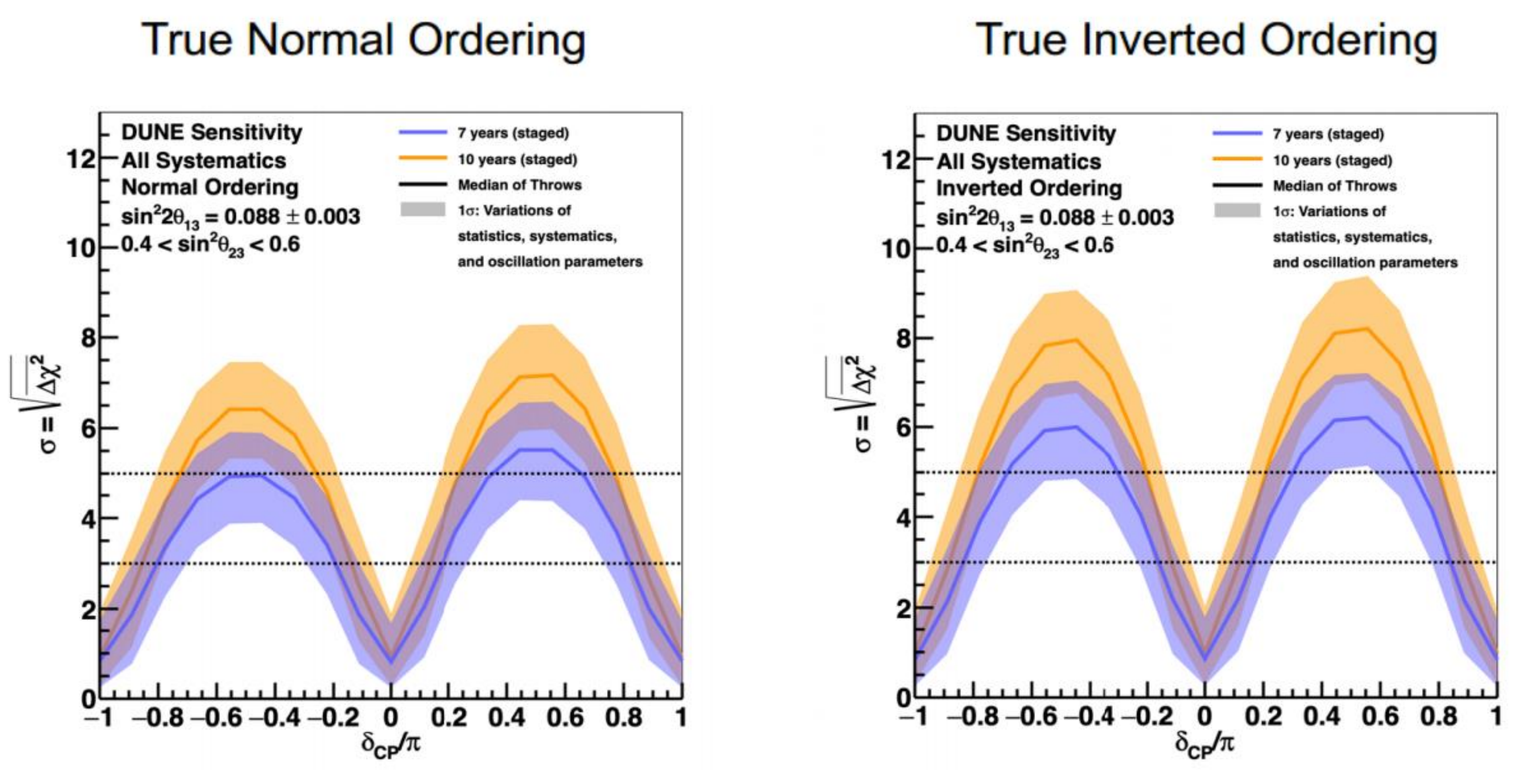
Sensitivity to δ_{CP}

- 7 years data taking
- 10 years data taking

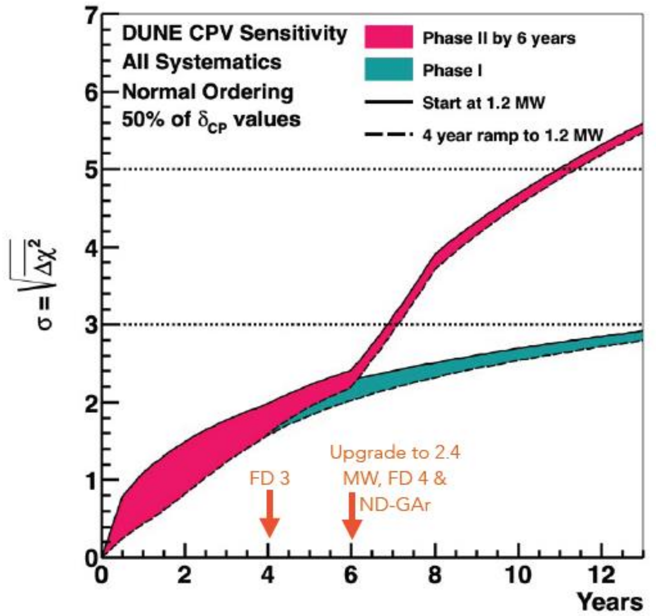
$\nu : \bar{\nu}$ = 50% : 50%

3.5 years, staged exposure

Sample	Expected Events $\delta_{CP} = 0$ NH	$\delta_{CP} = 0$ IH	$\delta_{CP} = -\frac{\pi}{2}$ NH	$\delta_{CP} = -\frac{\pi}{2}$ 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



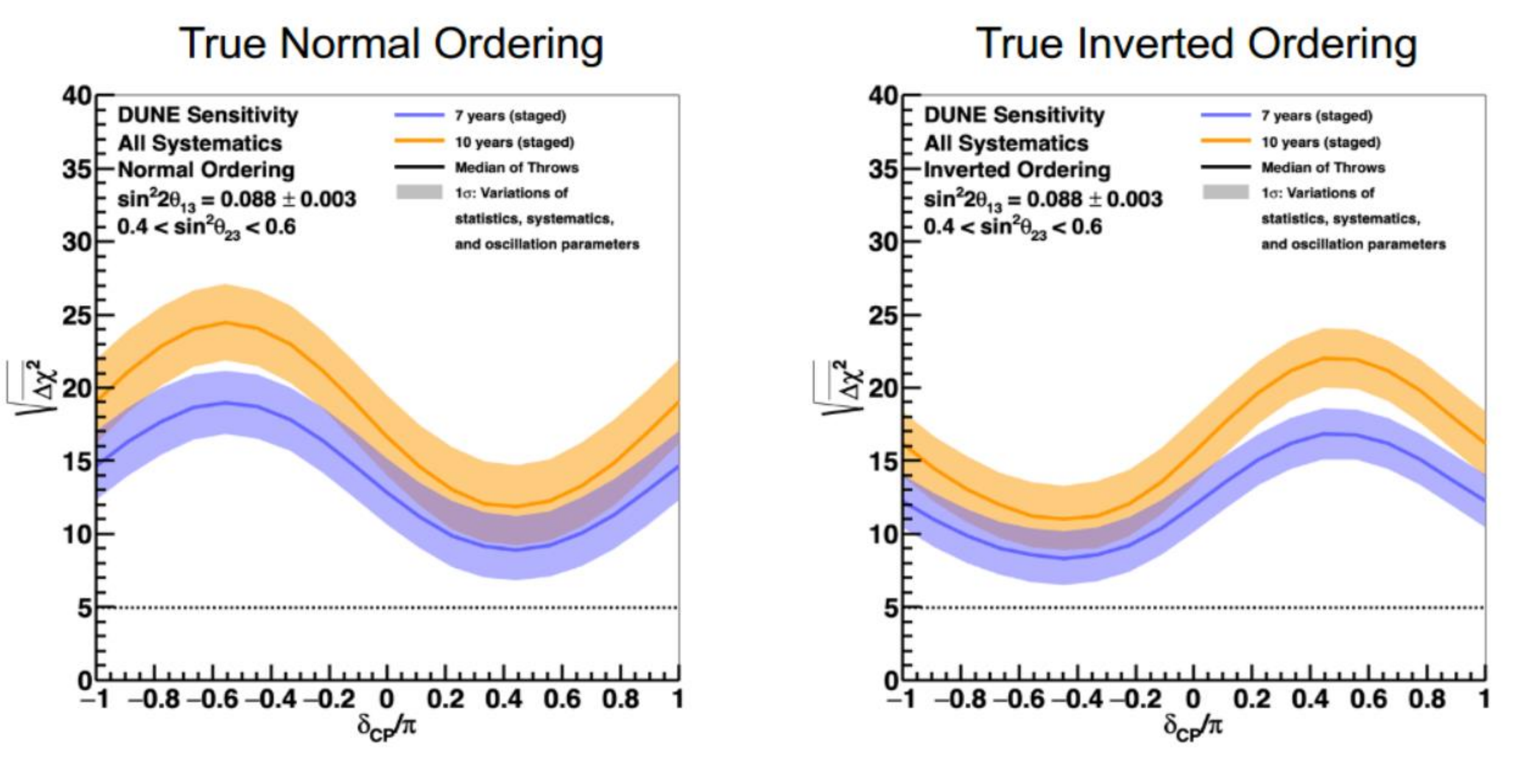
A.Booth, ICHEP2022



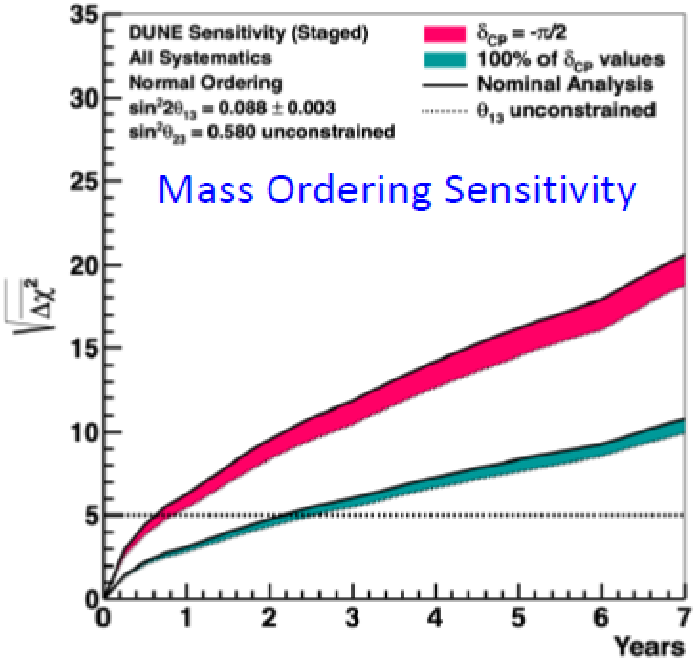
DUNE: Mass Ordering

DUNE Collaboration, 2006.16043

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

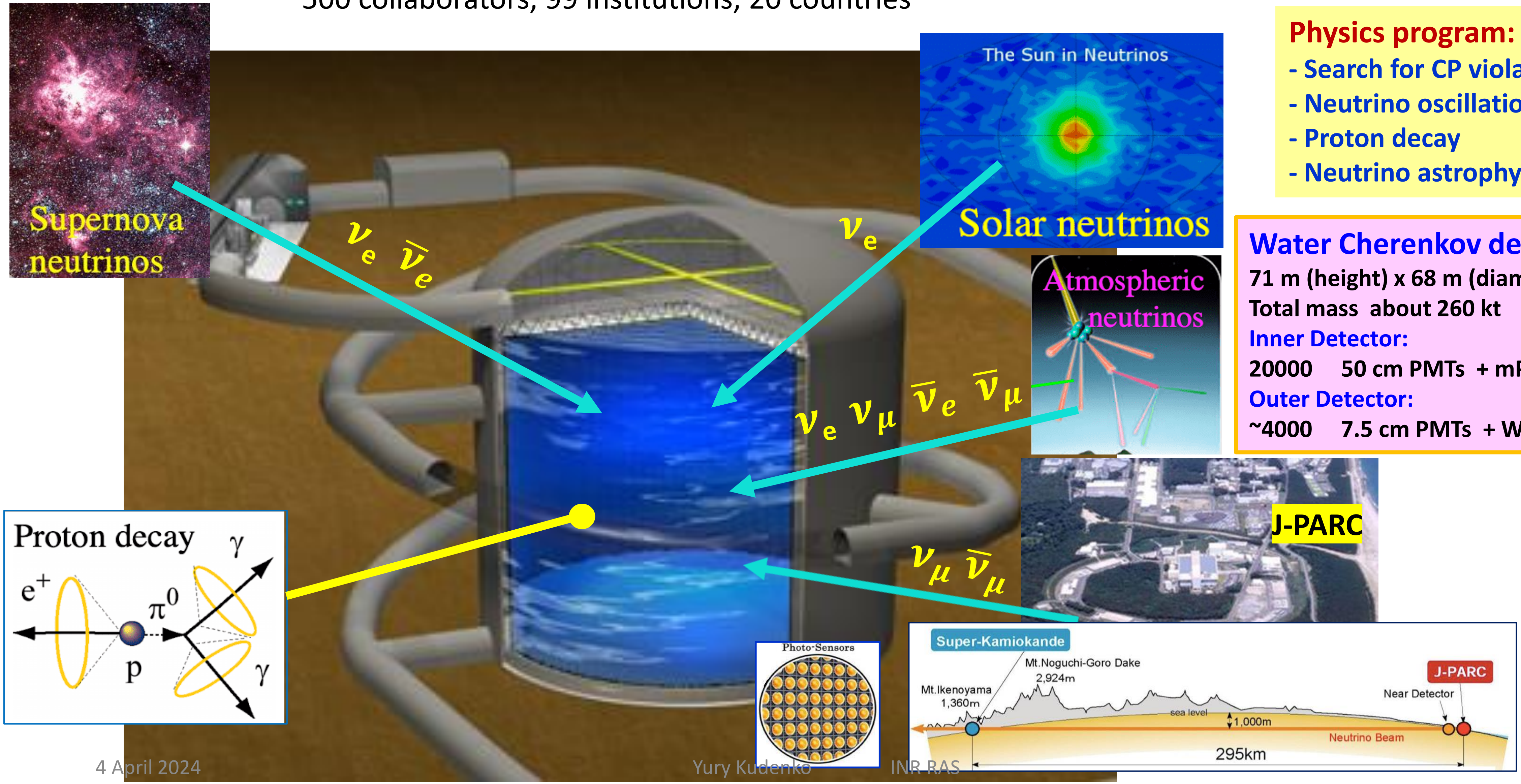


$> 5\sigma$ discovery
for all possible δ_{CP} values
after 7 years of data taking



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**

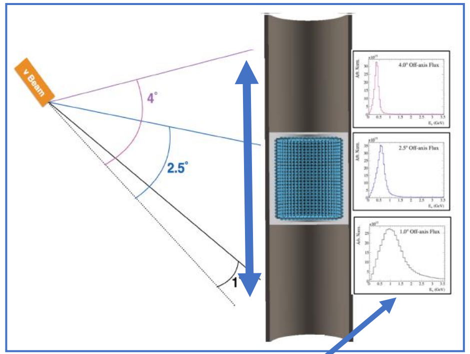
J-RARC beam
30 GeV
1.3 MW

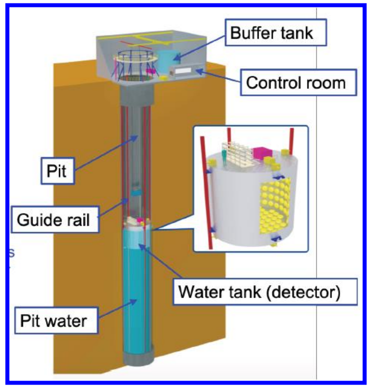
New ND **~1 km from target**

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

IWCD: Movable water Cherenkov detector

IWCD

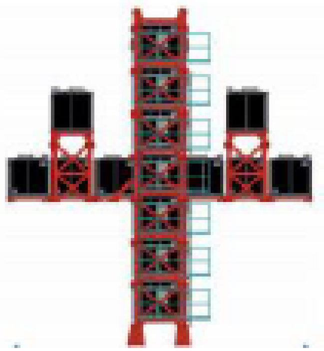




Neutrino spectra

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

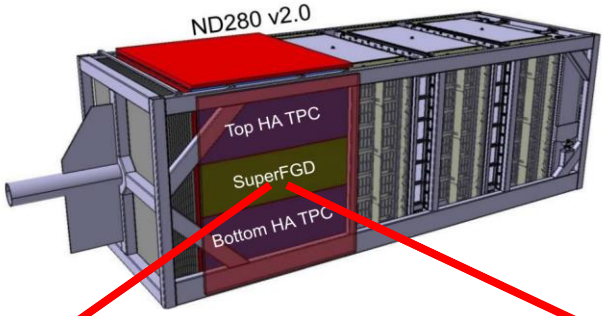
INGRID



Neutrino on/off axis beam monitor

ND280 upgraded

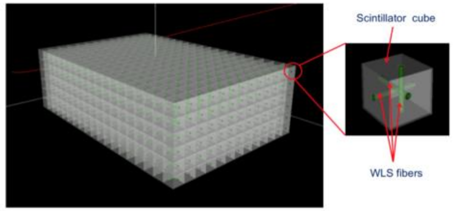
Magnetized off-axis detector

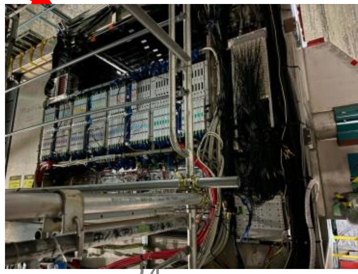


3D detector SuperFGD:
$2x10^6$ scintillator cubes each of $1cm^3$ with WLS readout

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

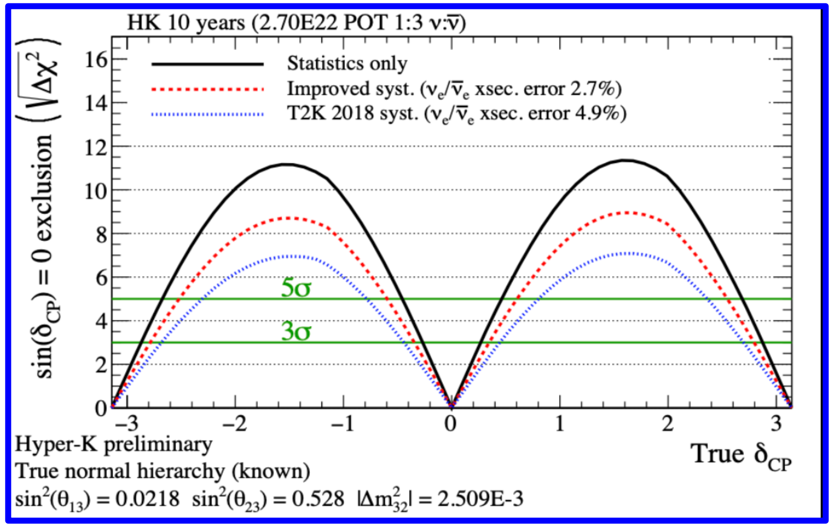
SuperFGD





Sensitivity to CP violation

Projected HyperK sensitivity to CP violation



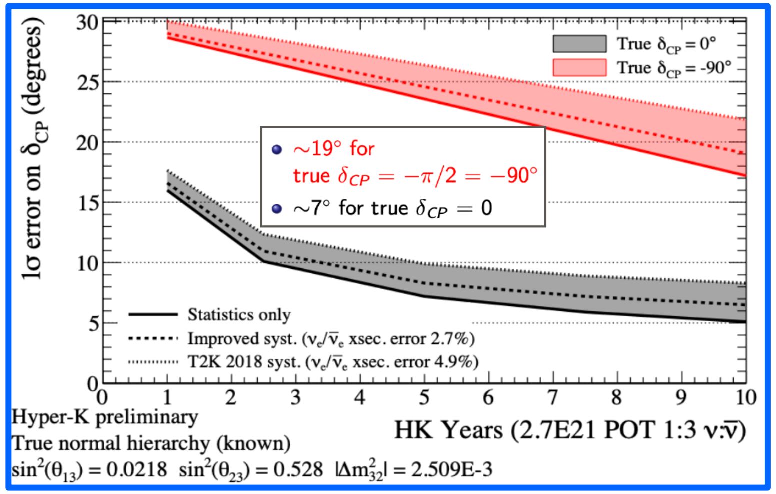
Hyper-Kamiokande, arXiv:1805.04163

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

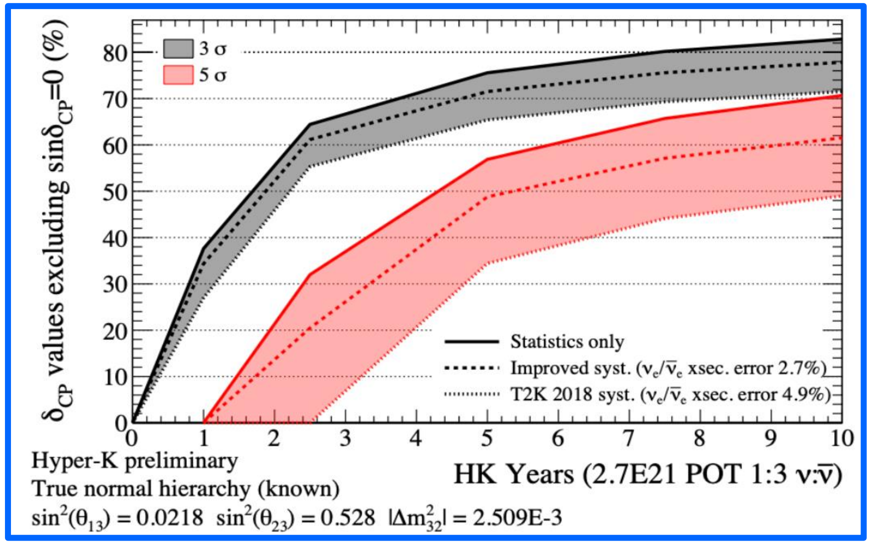
Expected number of events at HyperK for $\nu_e:\bar{\nu}_e = 1:3$ and $\sin\delta_{CP} = 0$

2300 ν_e 1300 $\bar{\nu}_e$

Measurement of δ_{CP}



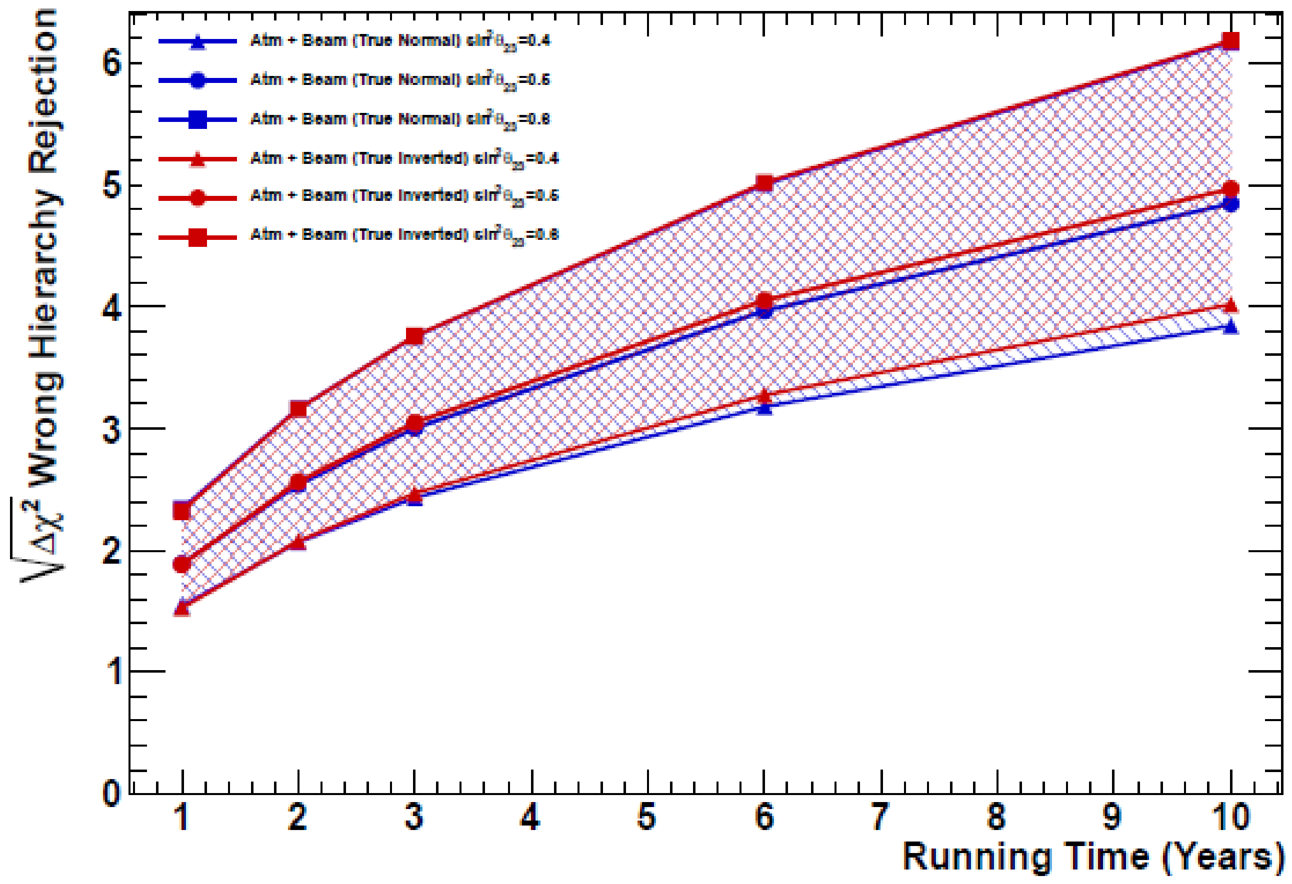
Exclusion of CP conservation



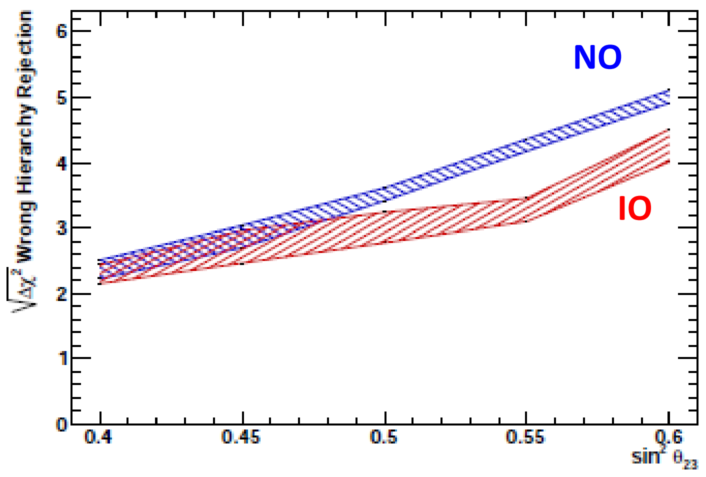
Hyper-Kamiokande: Mass Ordering

HyperKamiokande 10 years of data taking

Hyper-Kamiokande, arXiv:1805.04163



HyperKamiokande, atm neutrinos

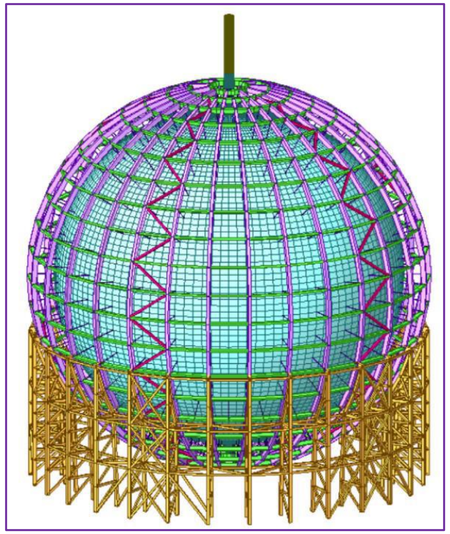


	$\sin^2\theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	$2.2\,\sigma$ →	$3.8\,\sigma$
	0.60	$4.9\,\sigma$ →	$6.2\,\sigma$
θ_{23} octant	0.45	$2.2\,\sigma$ →	$6.2\,\sigma$
	0.55	$1.6\,\sigma$ →	$3.6\,\sigma$

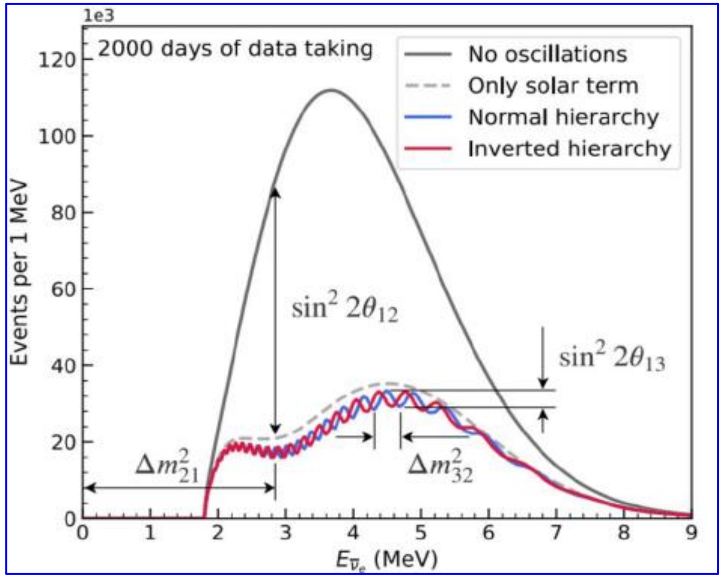
JUNO: Mass Ordering

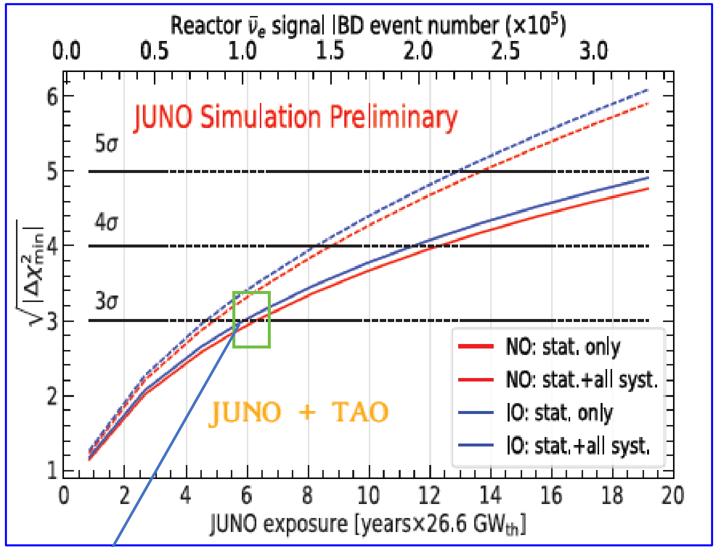
Reactor experiment JUNO, China

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 $< 1\%$





3σ within 6 years of data taking

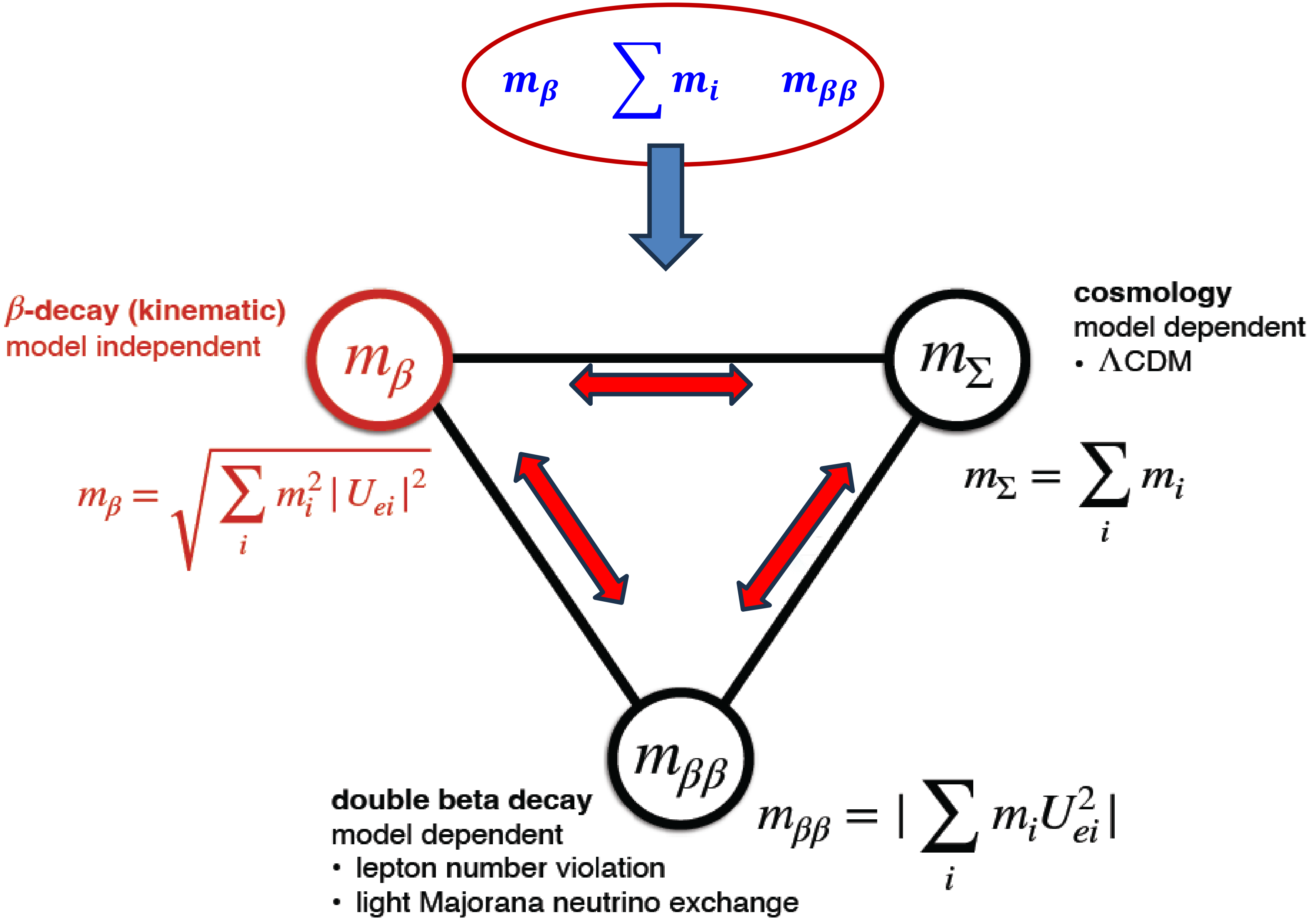
20 kt liquid scintillator detector
20k - 50 inch PMT; 25.6k - 3 inch PMT
Baseline 53 km, 650 m overburden

- Detector construction is ongoing
- Start data taking in 2024

Far future:
JUNO-0νββ

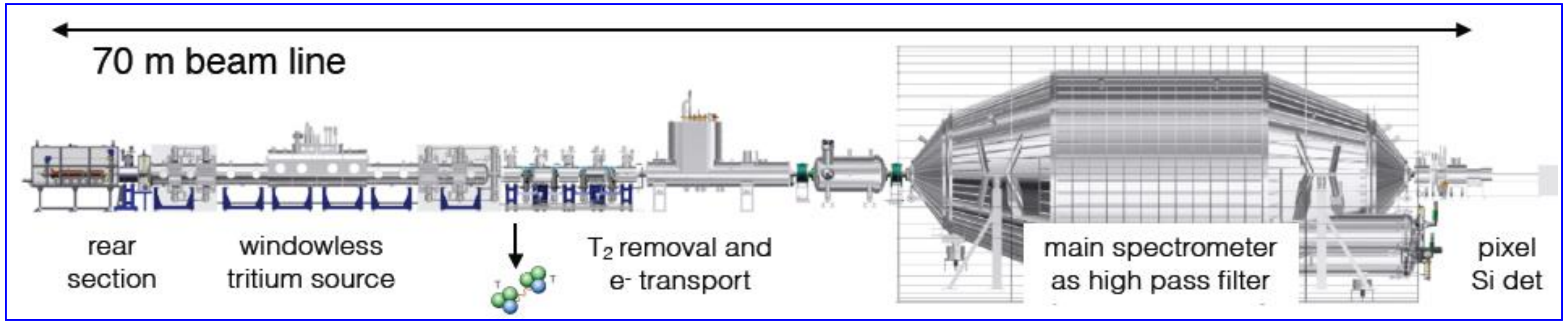
- Measurement of neutrino mass
- Neutrino nature: Dirac or Majorana

Neutrino mass observables

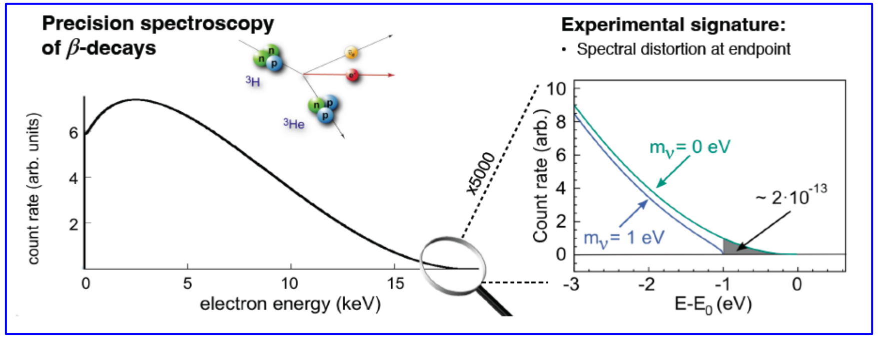


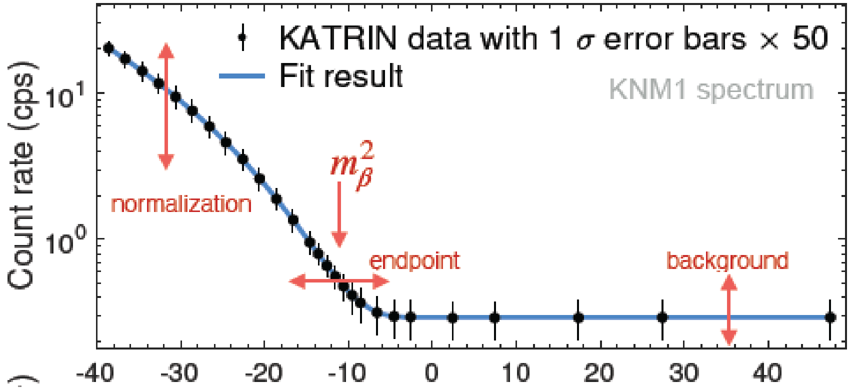
Direct measurement of neutrino mass

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



B.Lehnert, talk at LL Winter Institute 2023





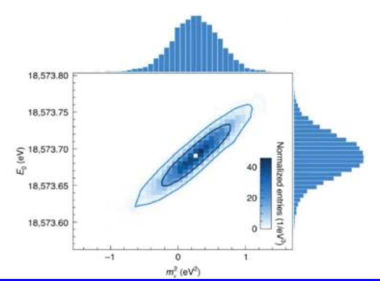
2 Datasets:	KNM1	KNM2
Date	04-05 2019	09-11 2019
Number scans	274	361
Measurement time	21.7 d	31.0 d
Source activity	25 GBq	95 GBq
Background rate	0.29 cts/s	0.22 cts/s
Signal-to-bg ratio	3.7	9.9

Upcoming result expected in Summer 2024

5 datasets, 6-fold increase in statistics

projected sensitivity m_β **< 0.5 eV** (90% CL)

Nature Physics 18 (2022) 160



Last result:

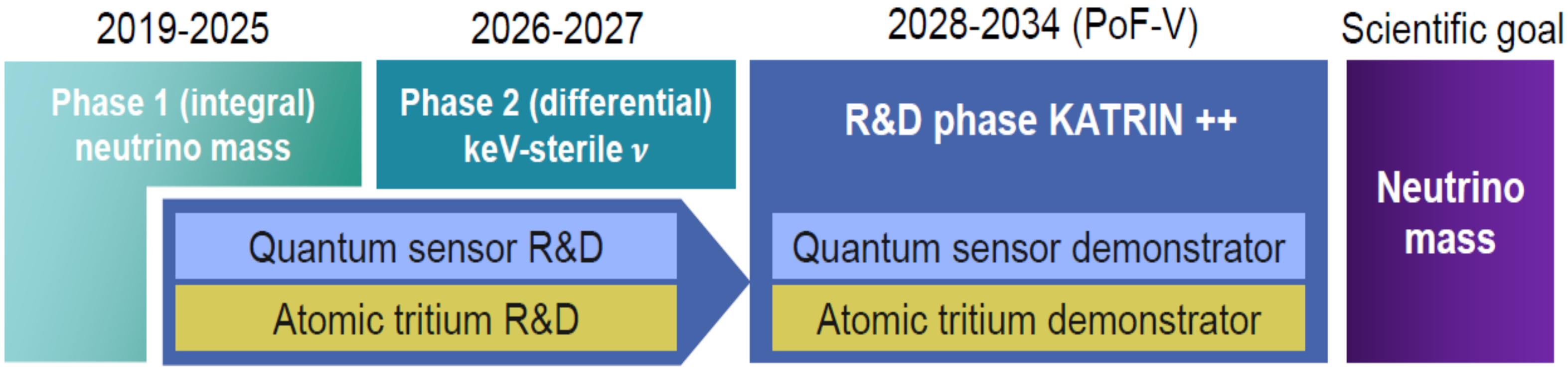
- $m_\beta^2 = 0.1 \pm 0.3\ \mathrm{eV}^2$
- $m_\beta < 0.8\ \mathrm{eV}\ (90\,\%\ \mathrm{CL})$

Current program will continue through 2025

Expect to reach sensitivity < 0.3 eV (90% CL)

Perspectives of m_ν measurements

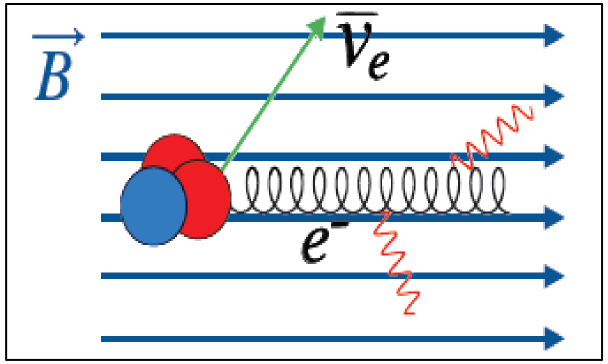
KATRIN prospects



M.Shlosser, talk at NuMass2024

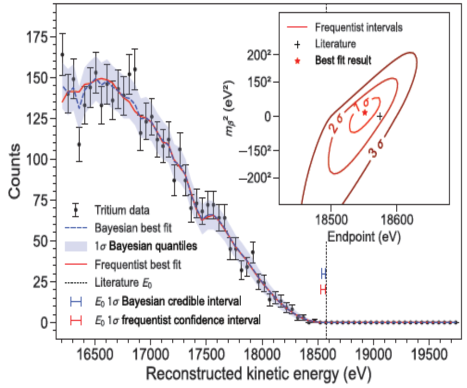
sensitivity on m_β < 40 meV

Project-8: Cyclotron Radiation Emission Spectroscopy



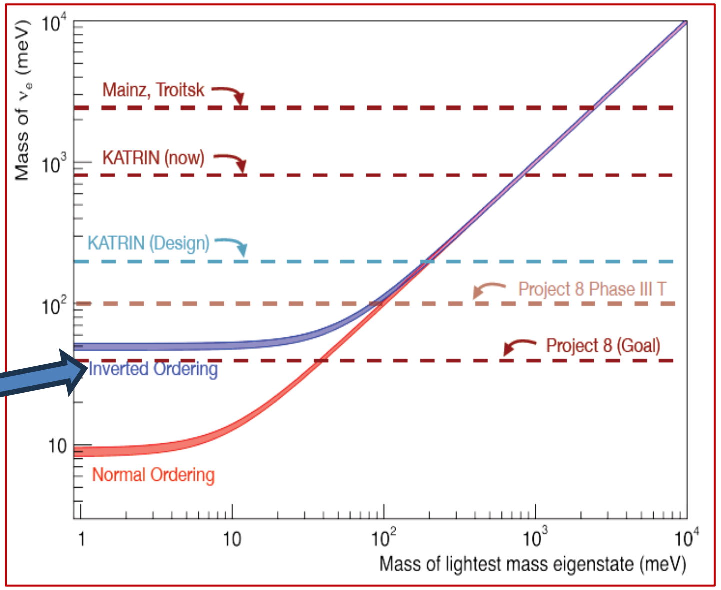
$$f_{Cyc} = \frac{1}{2\pi}\frac{qB}{m\gamma} = \frac{1}{2\pi}\frac{qB}{m_e + E_e}$$

Phys.Rev.Lett. 131 (2023) 102502

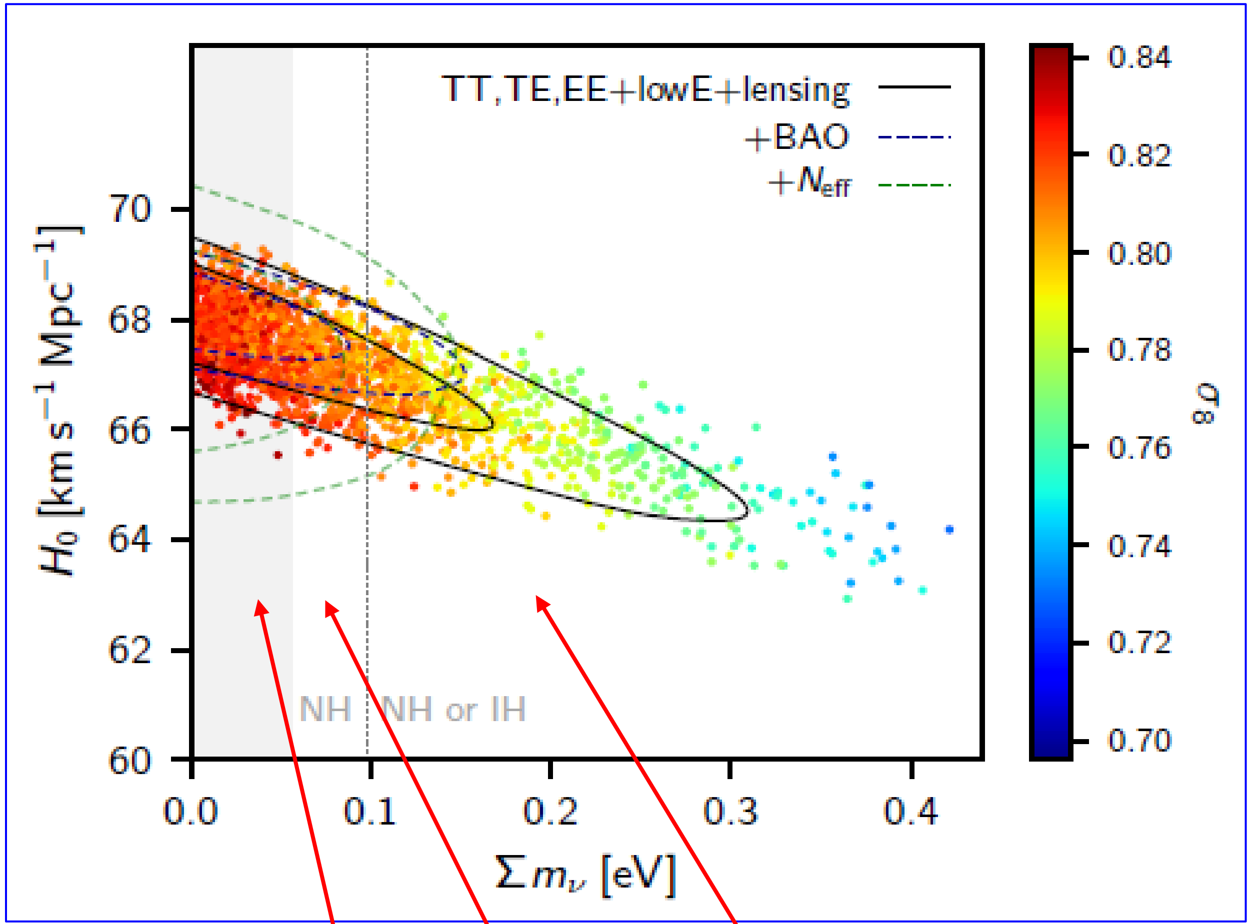


m_ν< 152 eV (90% CL)

Projected sensitivity 40 meV



Cosmology: $\sum m_i$



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

Planck, A&A 641 (2020) A6

Model dependent **ΛCDM**

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

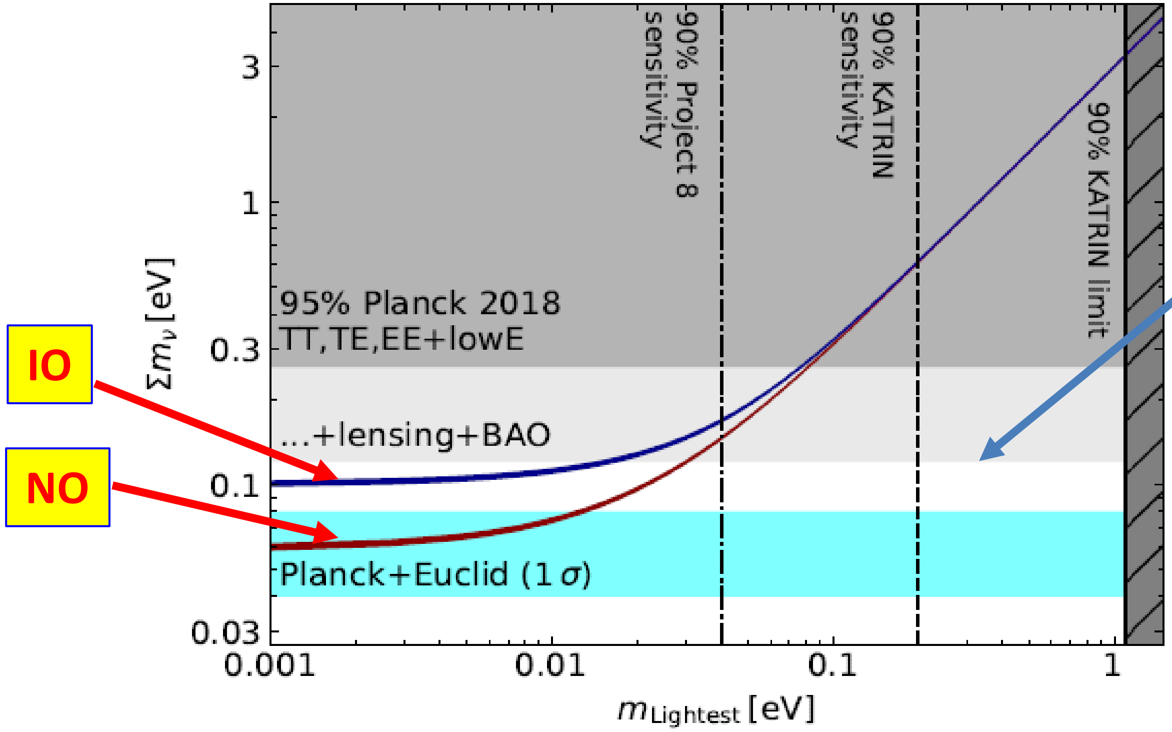
IO: $\Sigma m_i \approx 100\ meV$
NO: $\Sigma m_i \approx 60\ meV$

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

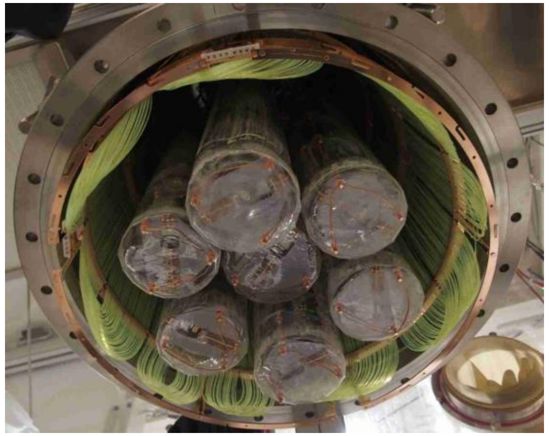
ESA Euclid: expected 1σ sensitivity $0.011 - 0.02$ **eV**
(3-4)σ detection of $\sum m_i$ **(NO) may be possible!?**

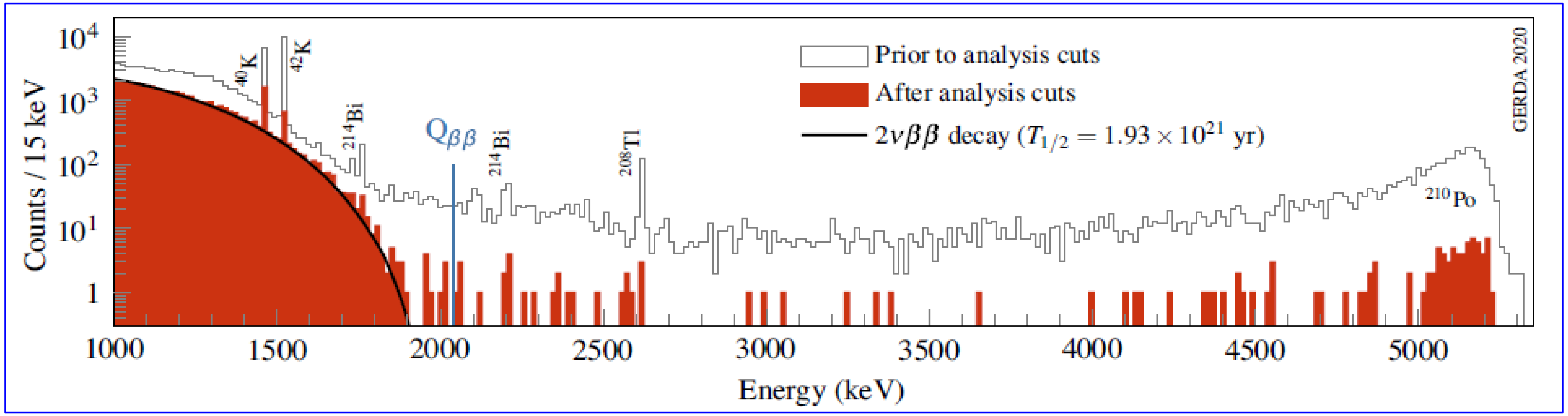
0νββ: GERDA

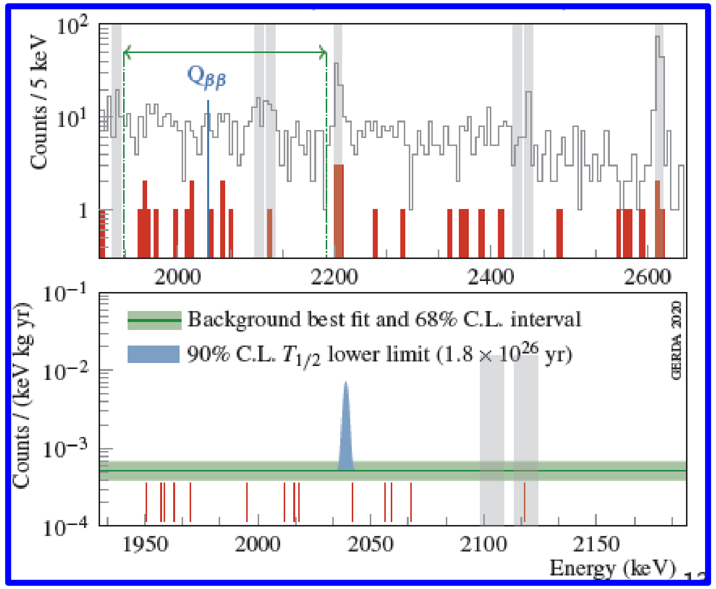
PRL 125 (2020) 252502

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**

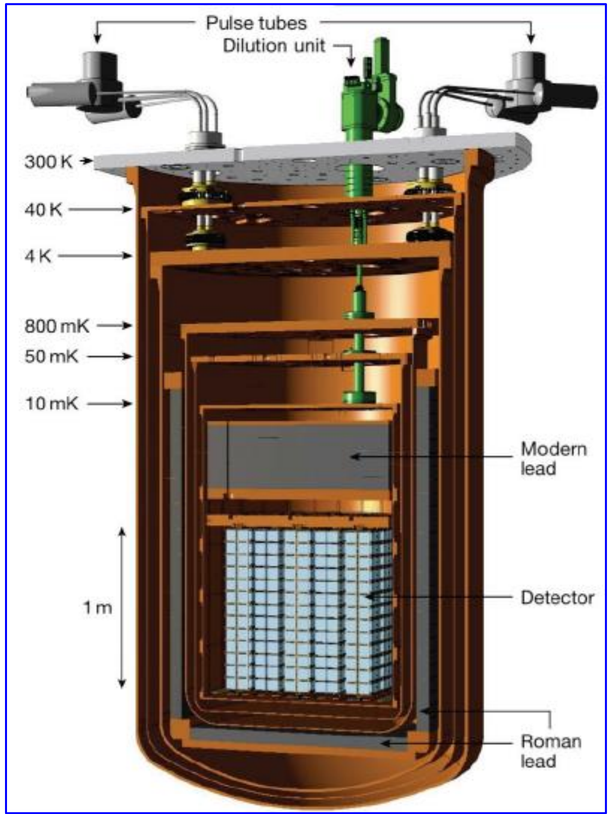
$|m_{\beta\beta}| \leq 79 - 180\ meV$

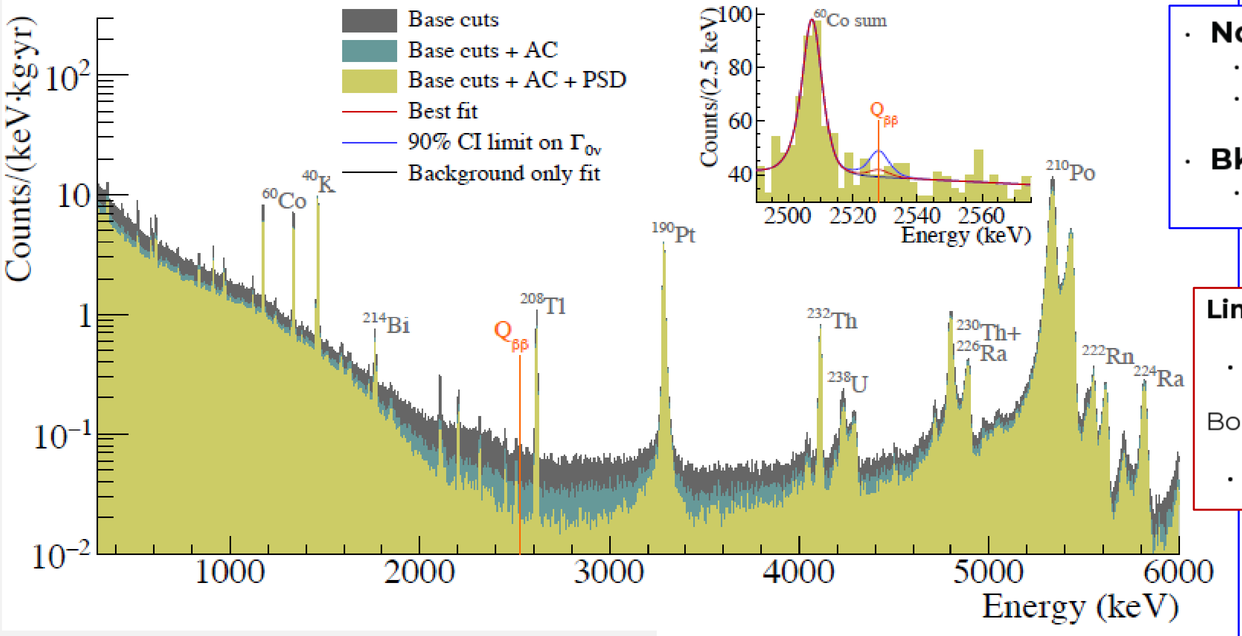
0νββ: CUORE

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

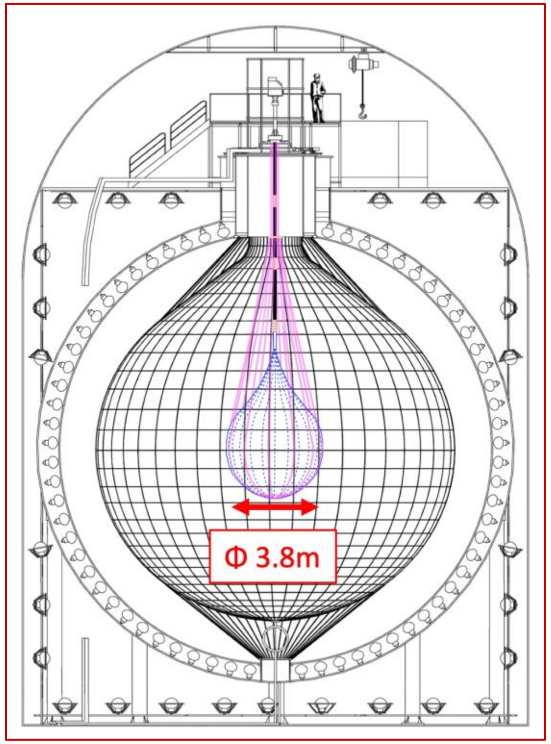
Total exposure for 0νββ decay search
2039.0 kg yr TeO_2,
567.0 kg yr ^{130}Te

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

0νββ: KamLAND – Zen

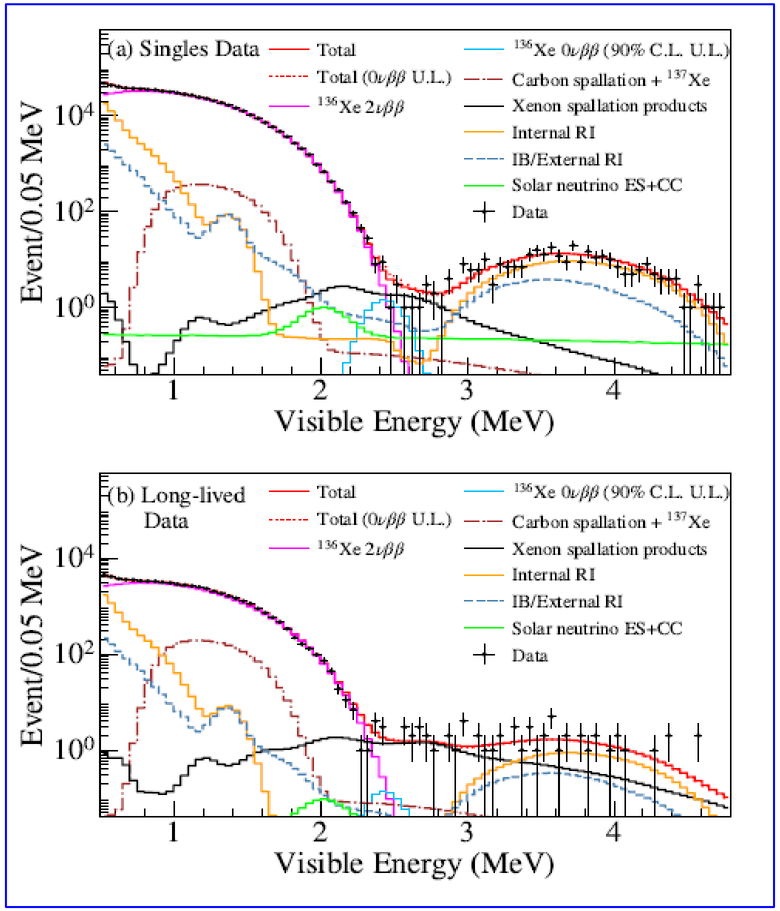
PRL 130 (2023) 5, 051801

Detector KamLAND-ZEN
Liquid scintillator



745 kg of enriched Xe-136

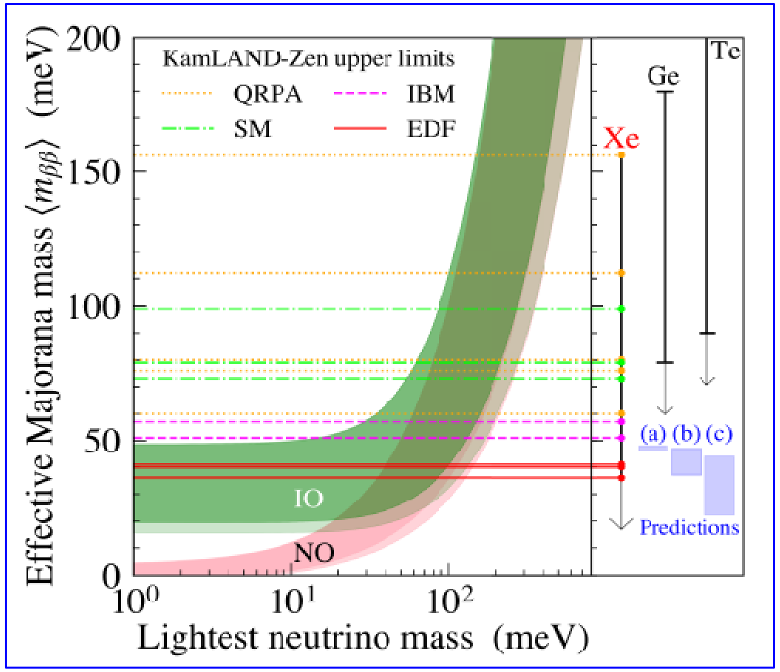
Exposure: 970 kg·y Xe-136



$T_{1/2}^{0\nu} > 2.3 \times 10^{26}\ y \quad (90\%\ CL)$

$\mathbf{m_{\beta\beta} < (36 - 156)\ meV}$

$g_a = 1.27$



KamLAND-ZEN begins to test IO band

0νββ: 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) $m_{\beta\beta} < (12 - 53)\ meV$

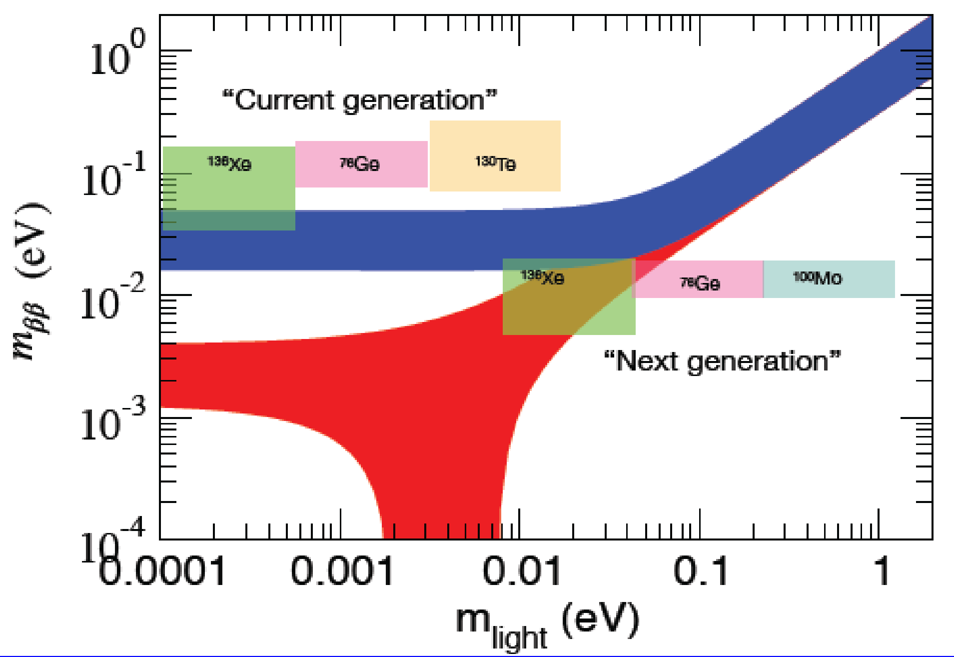
LEGEND-200: $T_{1/2} > 10^{27}$ yr (90% CL)
LEGEND-1000: $T_{1/2} \sim 1.6\times10^{28}$ yr (90% CL) $m_{\beta\beta} < (8.5 - 19)\ meV$

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) $m_{\beta\beta} < (10 - 17)\ meV$

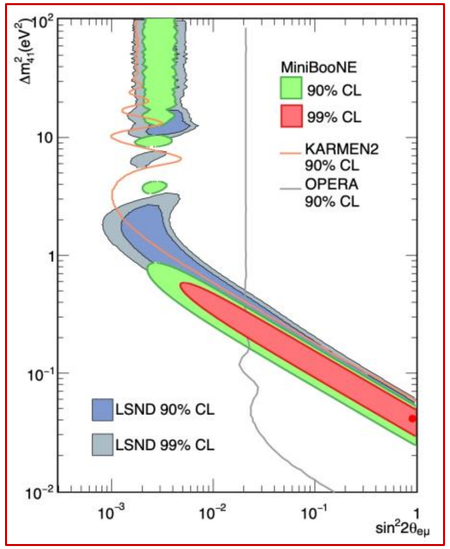
T.O'Donnel, talk at
Lepton Interactions with Nucleons and Nuclei 2023



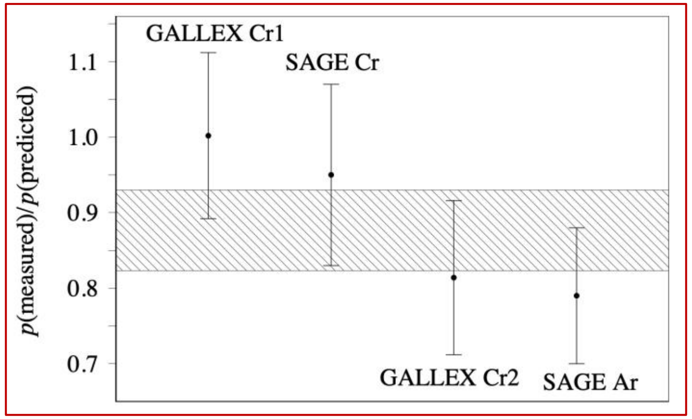
Sterile neutrinos ?

Light sterile neutrino

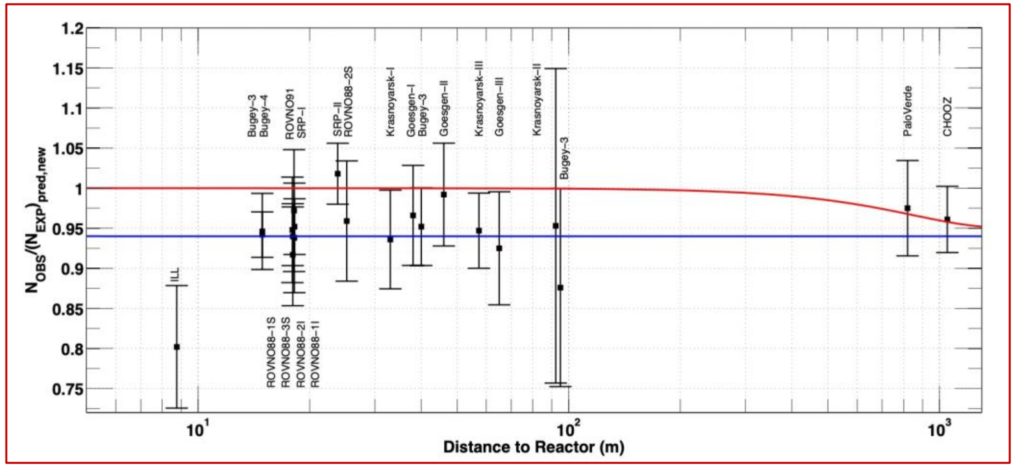
LSND/MiniBooNe anomaly



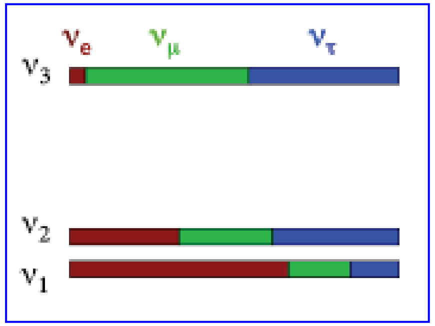
Ga anomaly



Reactor anomaly

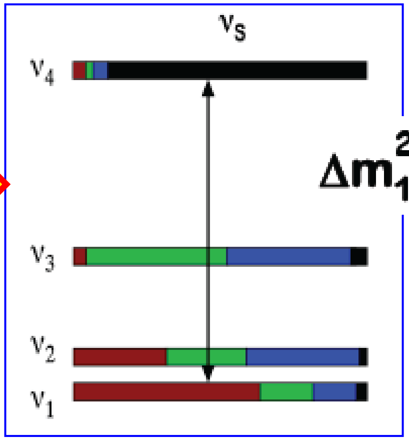


3ν, NO



?

$3\nu + 1\nu_s$



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

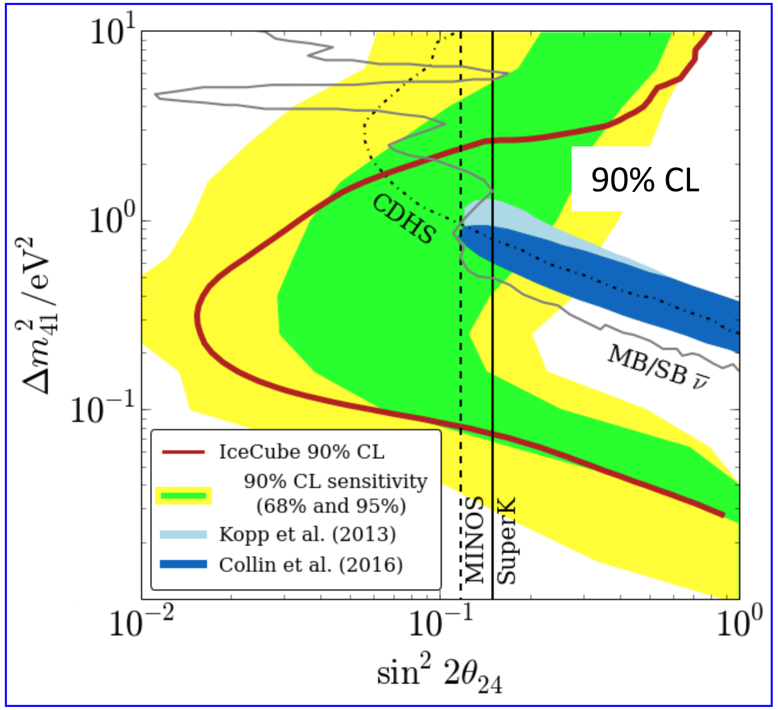
$$P_{\nu_e\to\nu_e} \simeq 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$
$$P_{\nu_\mu\to\nu_\mu} \simeq 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$
$$P_{\nu_\mu\to\nu_e} \simeq 2|U_{e4}|^2|U_{\mu 4}|^2$$

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

LSND/MiniBooNE anomaly

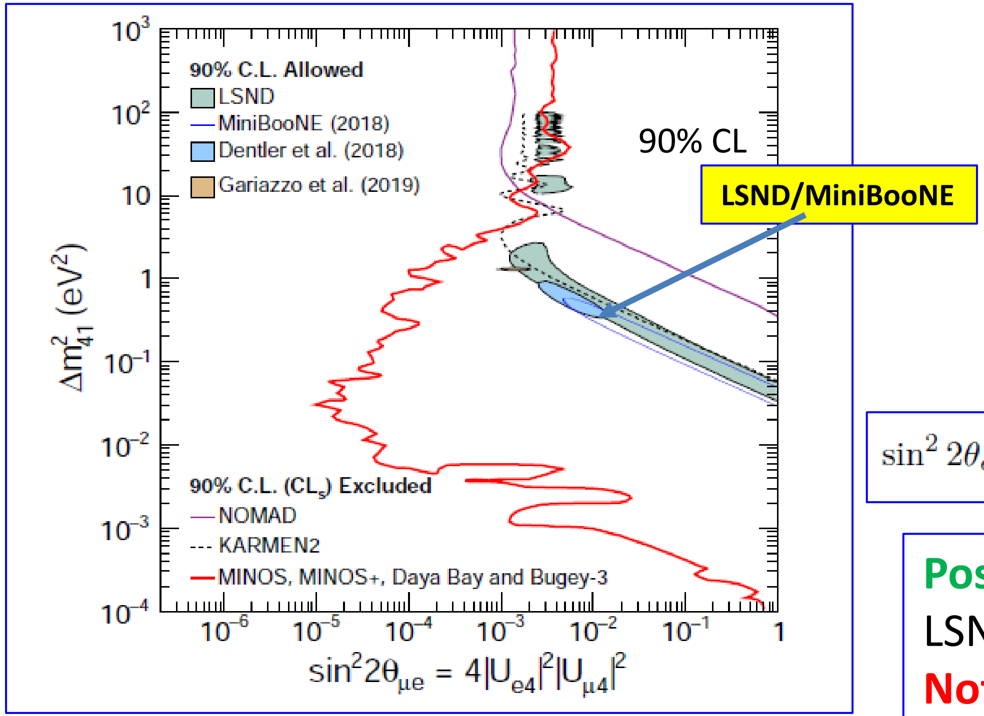
PRL 117 (2016) 071801

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



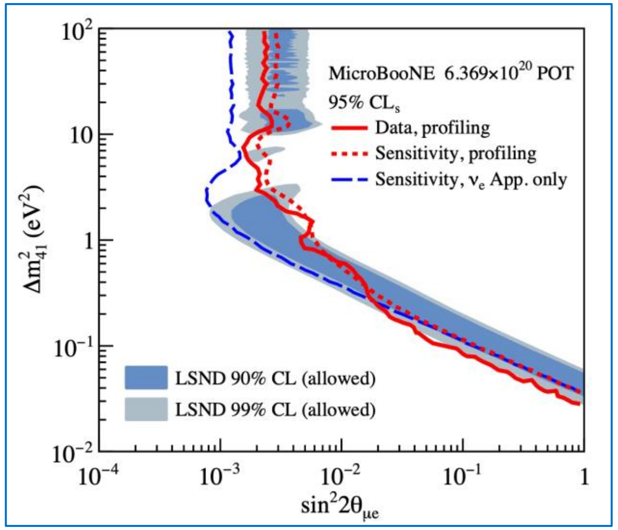
PRL 125 (2020) 131802

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
Not confirmed by:
MINOS, Daya Bay/Bugey-3
IceCube

Neutrino anomalies: Reactor, Ga

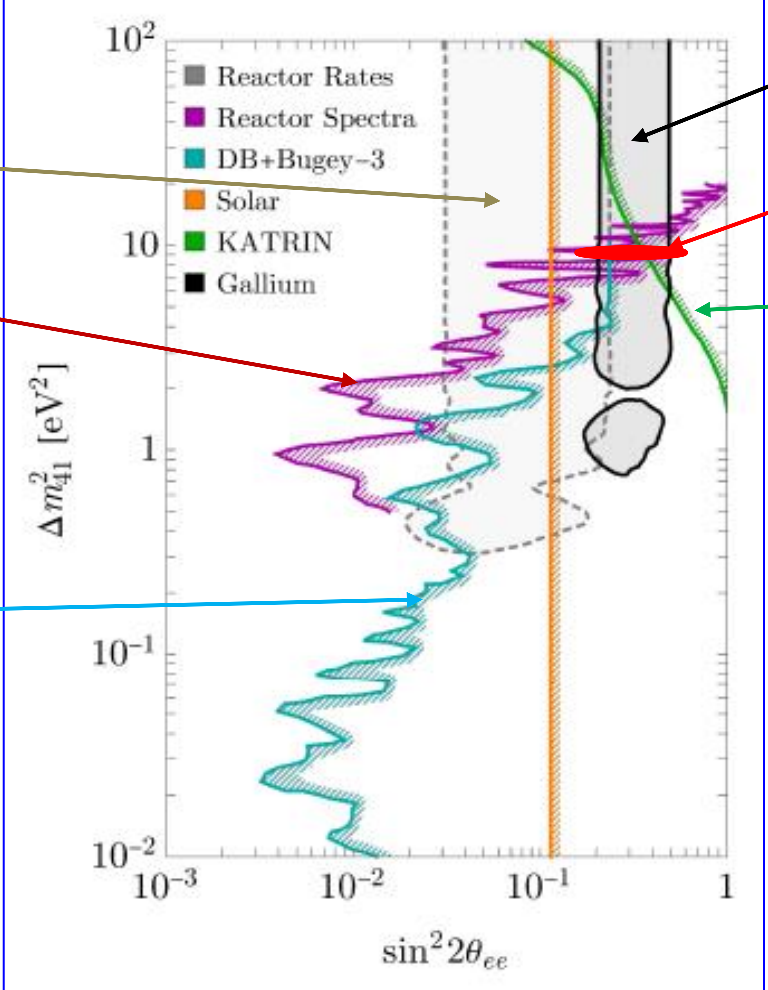
Elector neutrino disappearance

arXiv:2203.07214

Reactor anomaly

DANSS, NEOS, PROSPECT, STEREO

Daya Bay, Bugey-3



BEST

Neutrino-4

KATRIN

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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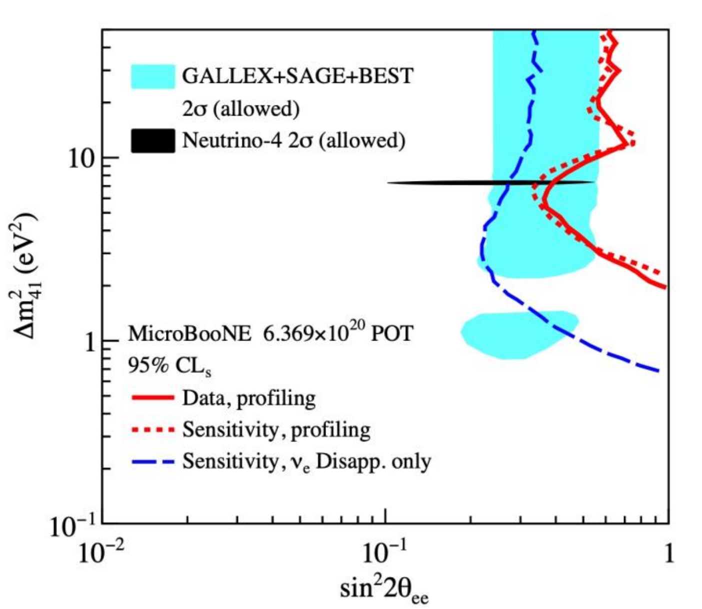


!

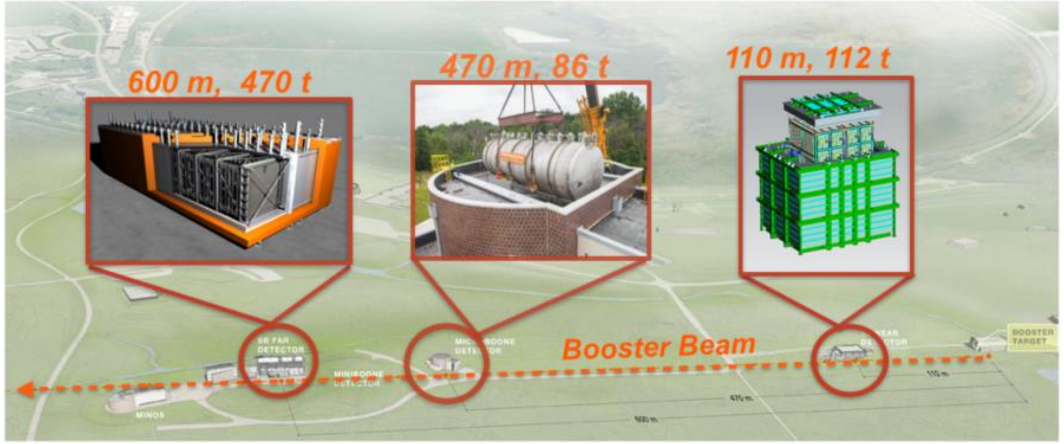
P.Denton, arXiv: 2111.06793
2.4σ hint in favour of ν_s
using MicroBooNE data:
$\sin^2(2\theta_{14}) = 0.35 + 0.19 - 0.16$
$\Delta m^2_{41} = 1.25 + 0.74 - 0.39$ eV^2

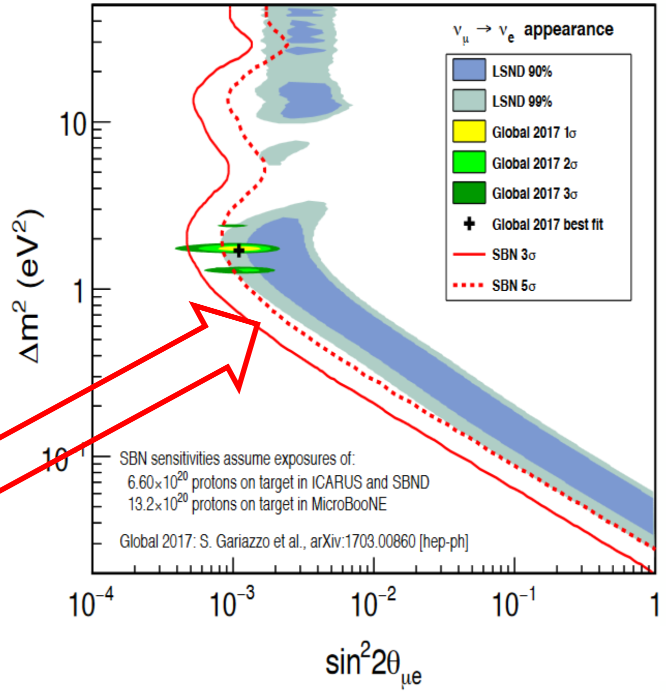
!

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 ahead of us !

Thank you for your attention