Review of Neutrino Physics (Experiment)

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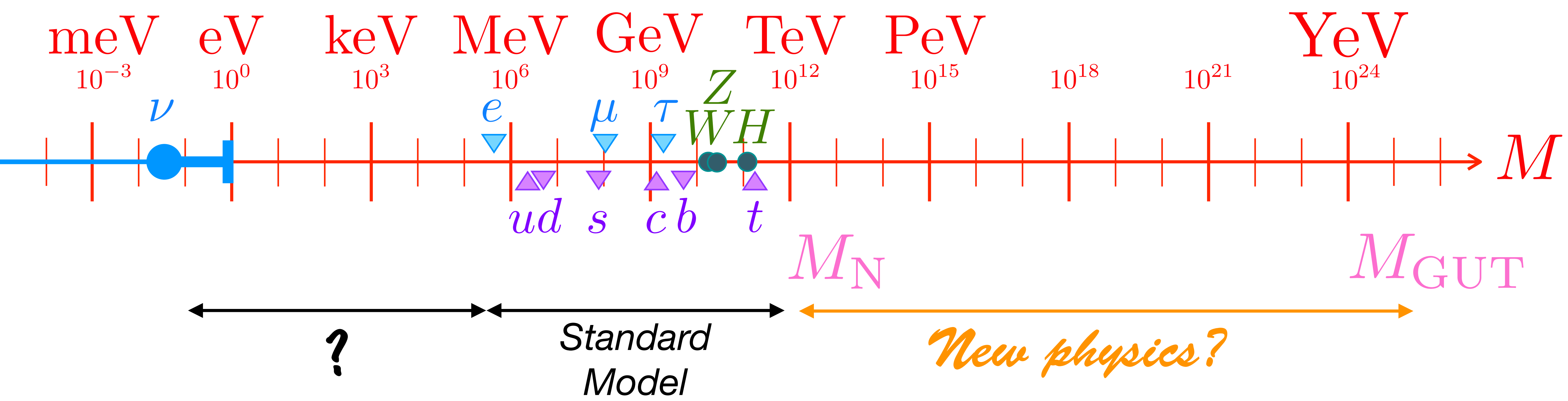
BEACH 2024

XV International Conference on Beauty, Charm, Hyperons in Hadronic Interactions

3-7 June 2024

Courtyard Charleston Historic District
Charleston, SC



$$\mathcal{L}_{\mathrm{mass}} = \begin{bmatrix} \bar{\nu}_{\mathrm{L}} & \bar{\nu}_{\mathrm{R}} \end{bmatrix} \begin{bmatrix} 0 & m_{\mathrm{D}} \\ m_{\mathrm{D}} & M_{\mathrm{M}} \end{bmatrix} \begin{bmatrix} \nu_{\mathrm{L}} \\ \nu_{\mathrm{R}} \end{bmatrix}$$

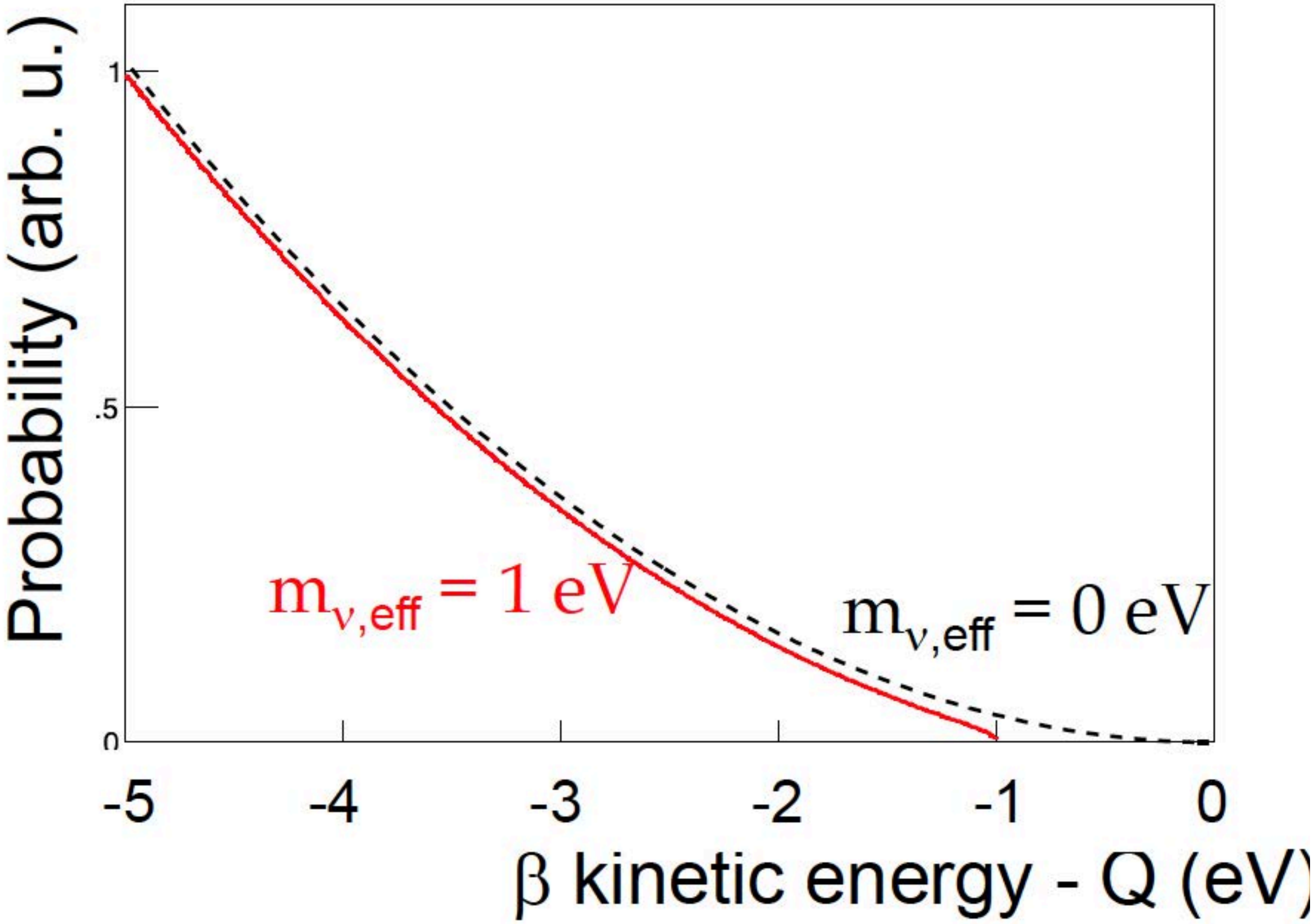
$$\lambda \simeq \frac{m_{\mathrm{D}}^2}{M_{\mathrm{M}}}$$

$$10^{-1}\ \mathrm{eV} \simeq \frac{(10^6 \ldots 10^{11})^2 \mathrm{eV}^2}{(10^{13} \ldots 10^{23})\ \mathrm{eV}}$$

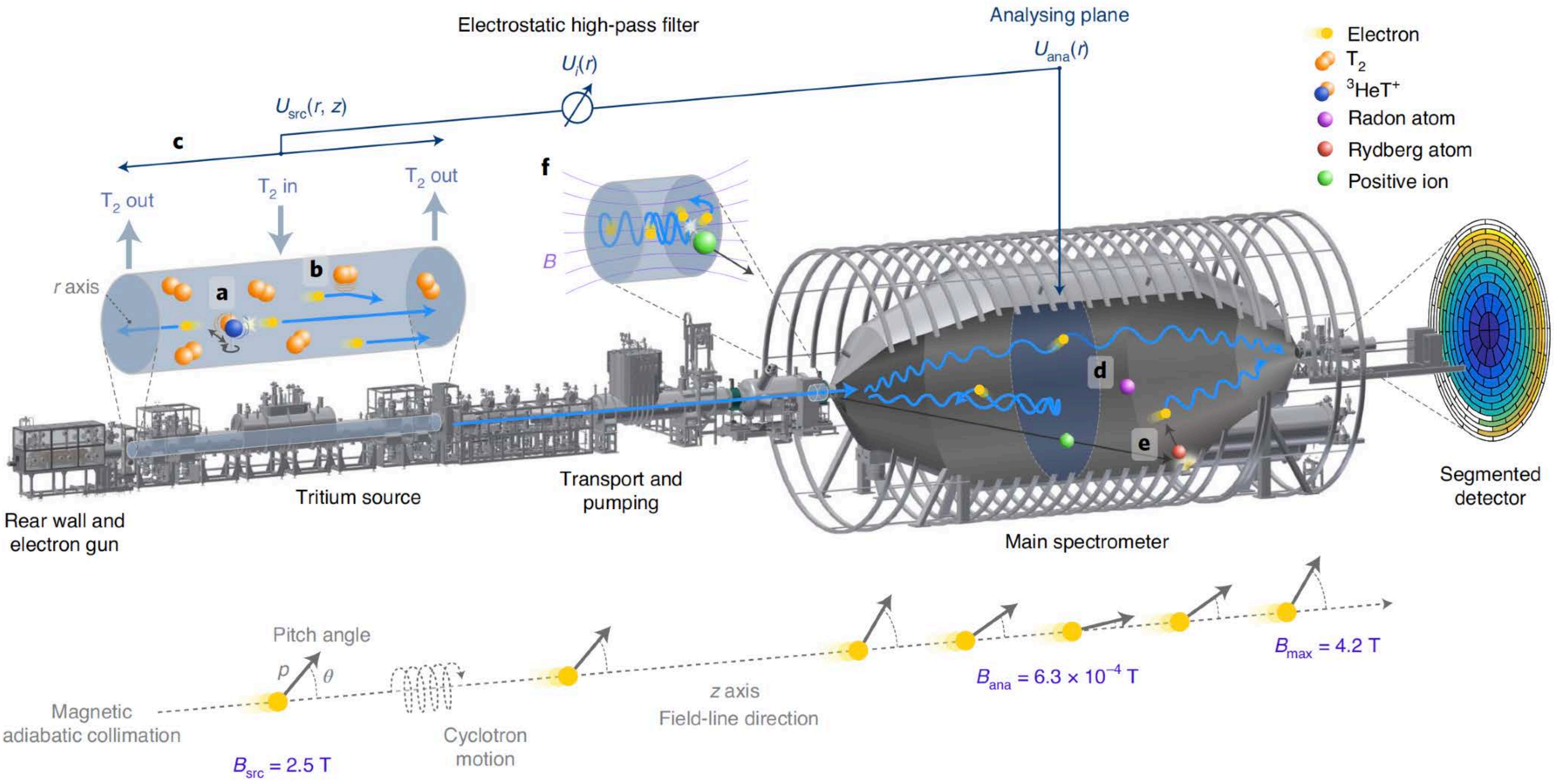
Neutrino mass requires new physics possibly approaching the GUT scale

Direct Neutrino Mass Detection

To date best limits on neutrino mass come from the measurement of the end point of the beta spectrum produced by molecular tritium decay

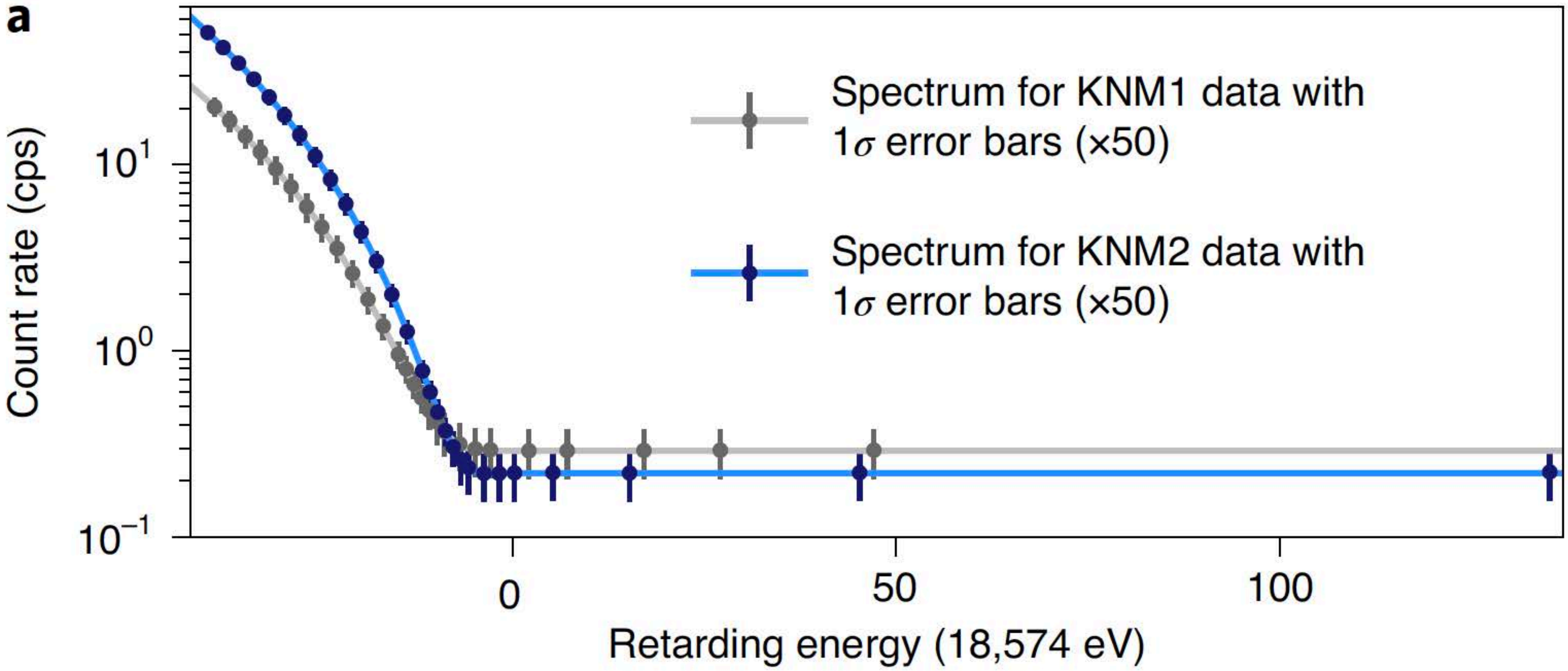


$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$



Magnetic Adiabatic Cooling and Electrostatic (MAC-E) Filter

Nature Physics 18, 160-166 (2022)



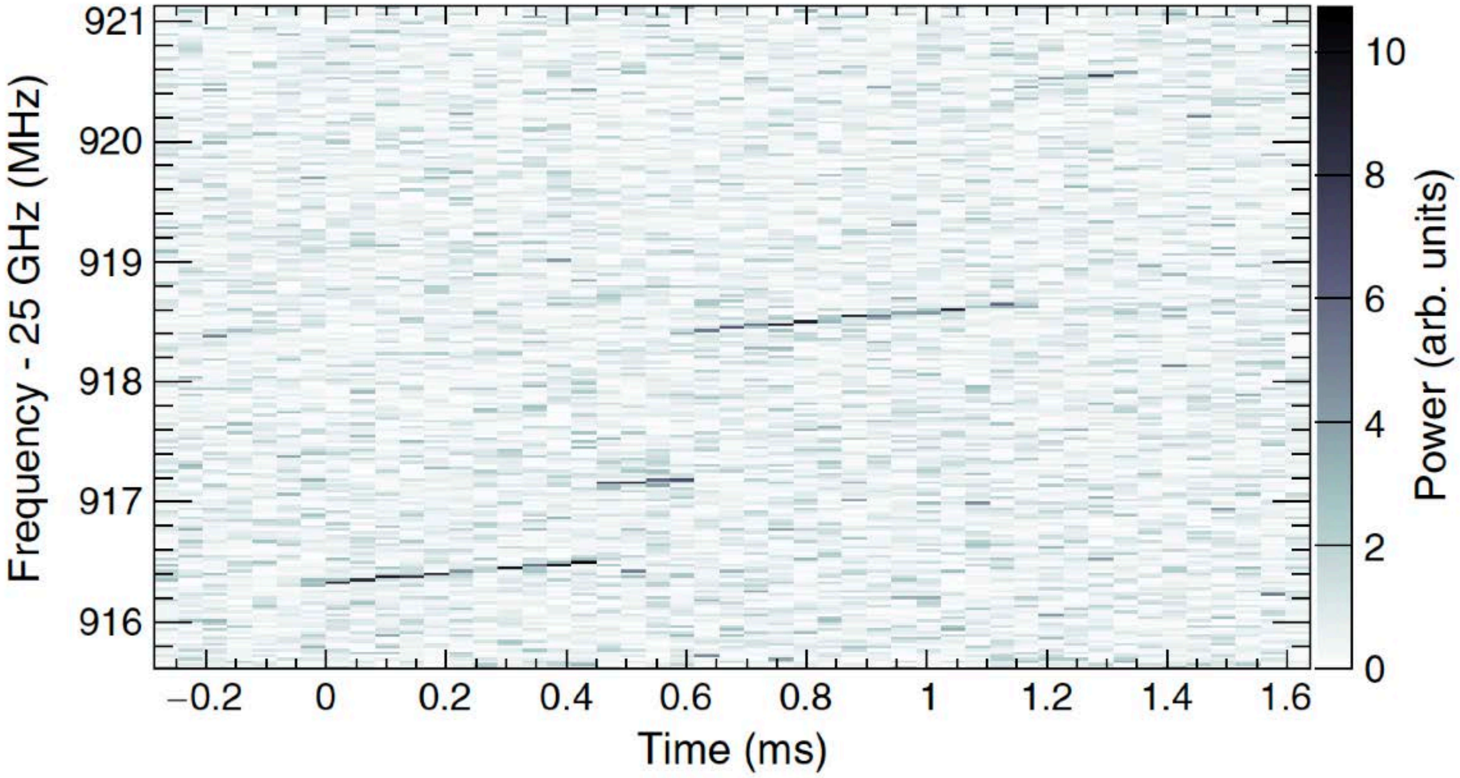
$$m_\nu < 0.8 \ \frac{\mathrm{eV}}{c^2} \ (90\%\mathrm{C.L.})$$

KATRIN Experiment

Nature Physics 18, 160-166 (2022)

Going beyond KATRIN? Project-8

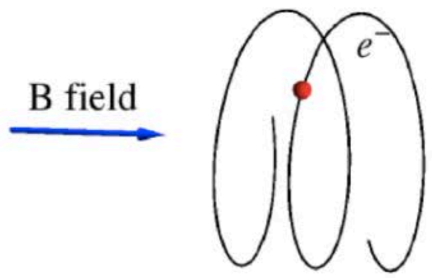
Future experiments will need to use atomic tritium and find a better way to measure the beta spectrum



Cyclotron motion:

$$f_\gamma = \frac{f_c}{\gamma}B = \frac{1}{2\pi}\frac{eB}{m_e + E_{\text{kin}}/c^2}$$

$f_c = 27\,992.491\,10(6)\ \text{MHz}\,\text{T}^{-1}$



$$m_\nu < 155\ \frac{\text{eV}}{c^2}\ (90\%\text{C.L.})$$

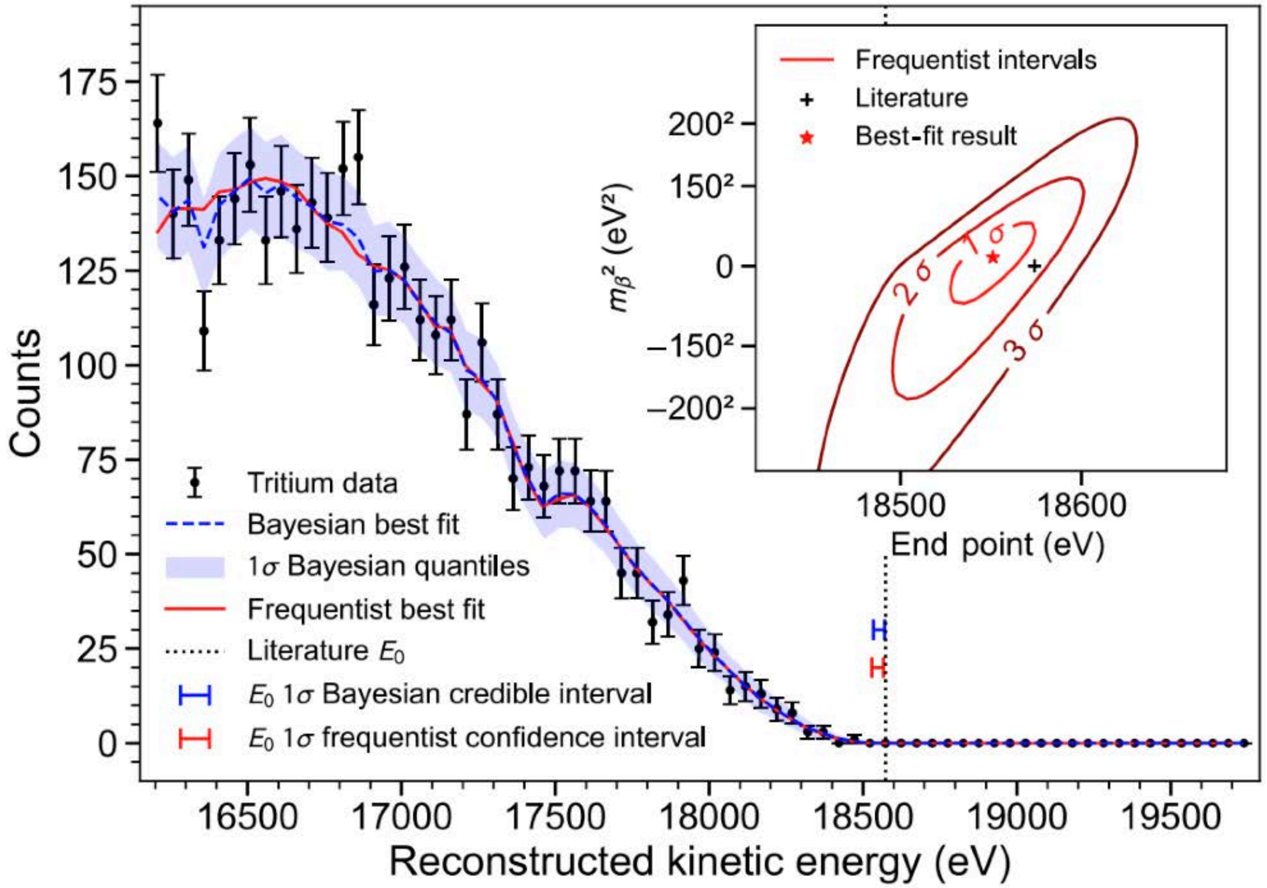
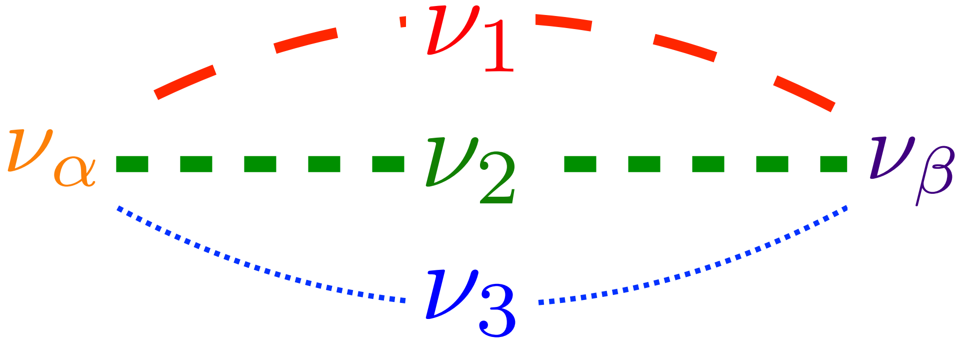


FIG. 5. Measured tritium end-point spectrum with Bayesian and frequentist fits. Inset: frequentist neutrino mass and end-point contours.

PHYSICAL REVIEW LETTERS **131,** 102502 (2023)

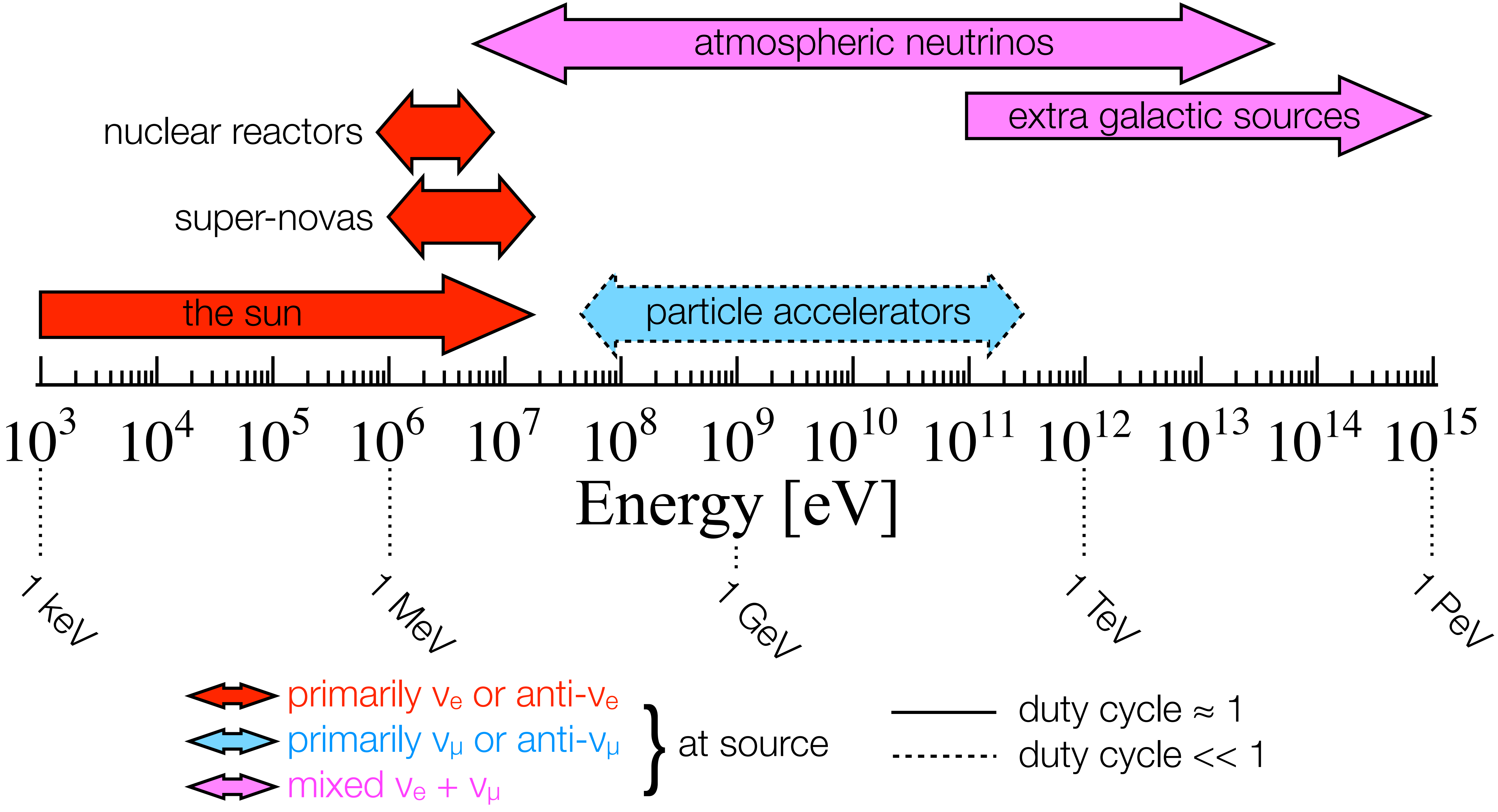
Neutrino oscillations



$$\left|\begin{array}{c}\nu_e\\ \nu_\mu\\ \nu_\tau\end{array}\right\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \left|\begin{array}{c}\nu_1\\ \nu_2\\ \nu_3\end{array}\right\rangle$$

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2\ [\mathrm{eV}^2]\frac{L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]}\right)$$

Neutrino Sources



atmospheric neutrinos

nuclear reactors

extra galactic sources

super-novas

the sun

particle accelerators

10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15}

Energy [eV]

1 keV

1 MeV

1 GeV

1 TeV

1 PeV

primarily ν_e or anti-ν_e

primarily ν_μ or anti-ν_μ

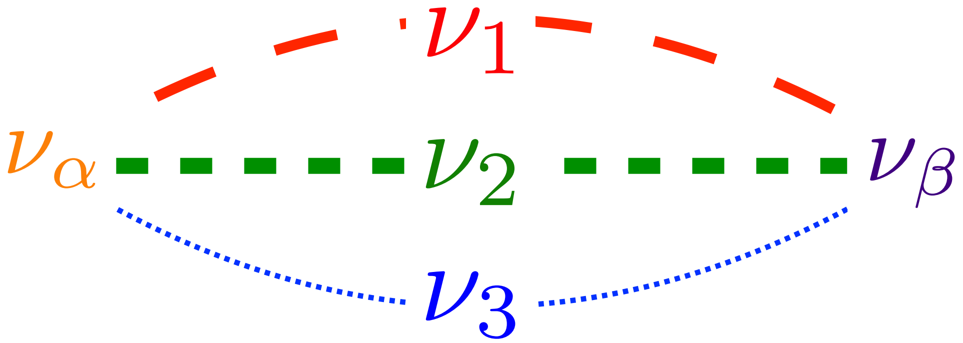
mixed $\nu_e + \nu_\mu$

} at source

duty cycle ≈ 1

duty cycle << 1

Neutrino oscillations



$$\left| \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \right\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \left| \begin{array}{c} \nu_1 \\ \nu_2 \\ \nu_3 \end{array} \right\rangle$$

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2\ [\mathrm{eV}^2]\frac{L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]}\right)$$

$$|\Delta m^2_{32}| \equiv |m^2_3 - m^2_2| \simeq 2\times 10^{-3}\ \mathrm{eV}^2$$

$$\nu_\mu \longrightarrow \nu_\mu$$
$$\nu_\mu \longrightarrow \nu_\tau$$

atmospheric and long baseline

$$\Delta m^2_{31} \simeq \Delta m^2_{32}$$

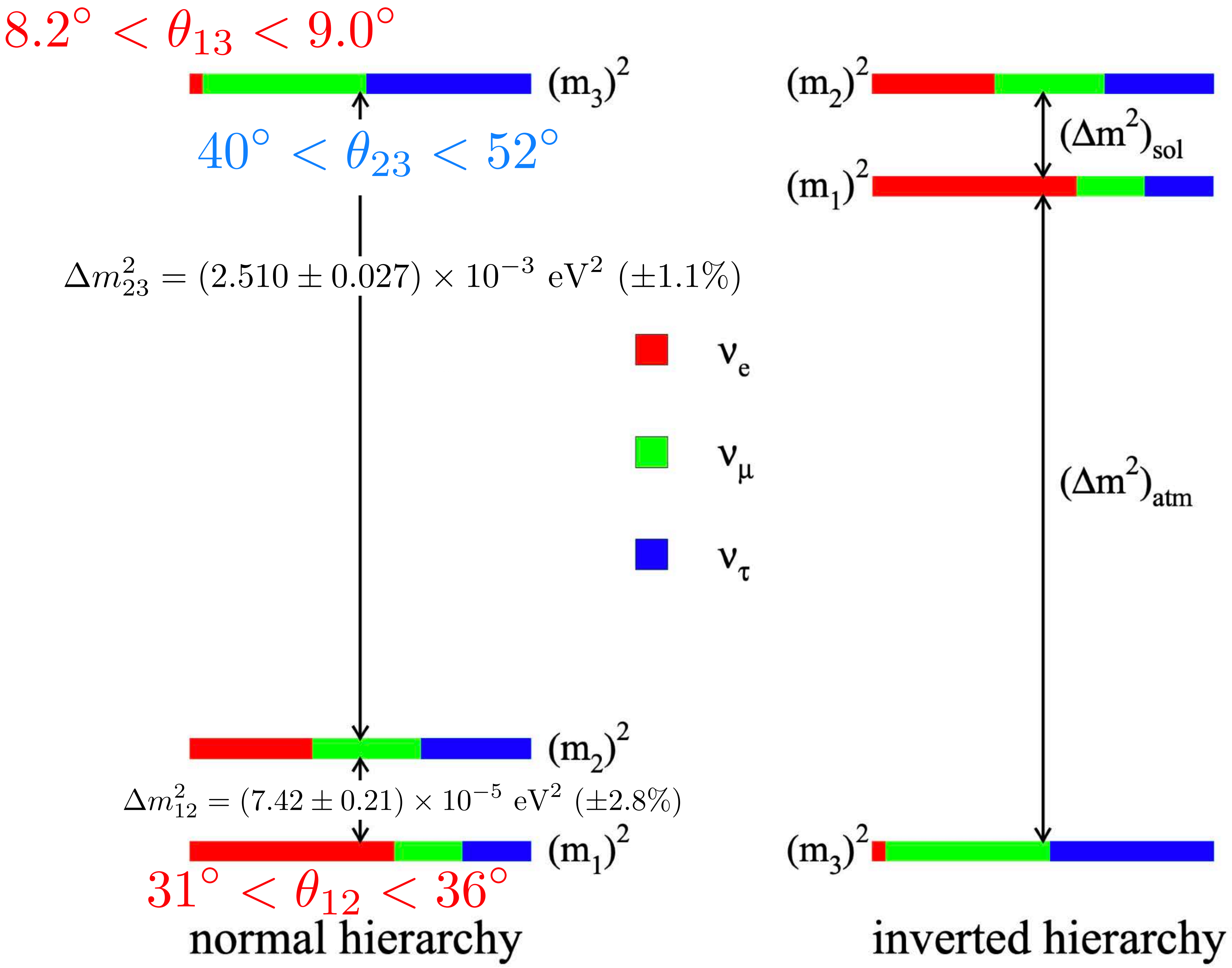
$$\nu_e \longrightarrow \nu_e$$
$$\nu_\mu \longrightarrow \nu_e$$

reactor and long baseline

$$\Delta m^2_{21} \simeq 8\times 10^{-5}\ \mathrm{eV}^2$$

$$\nu_e \longrightarrow \nu_e$$
$$\nu_e \longrightarrow \nu_\mu + \nu_\tau$$

solar and reactor



$8.2^\circ < \theta_{13} < 9.0^\circ$

$40^\circ < \theta_{23} < 52^\circ$

$\Delta m^2_{23} = (2.510 \pm 0.027) \times 10^{-3}\ \mathrm{eV}^2\ (\pm 1.1\%)$

$\Delta m^2_{12} = (7.42 \pm 0.21) \times 10^{-5}\ \mathrm{eV}^2\ (\pm 2.8\%)$

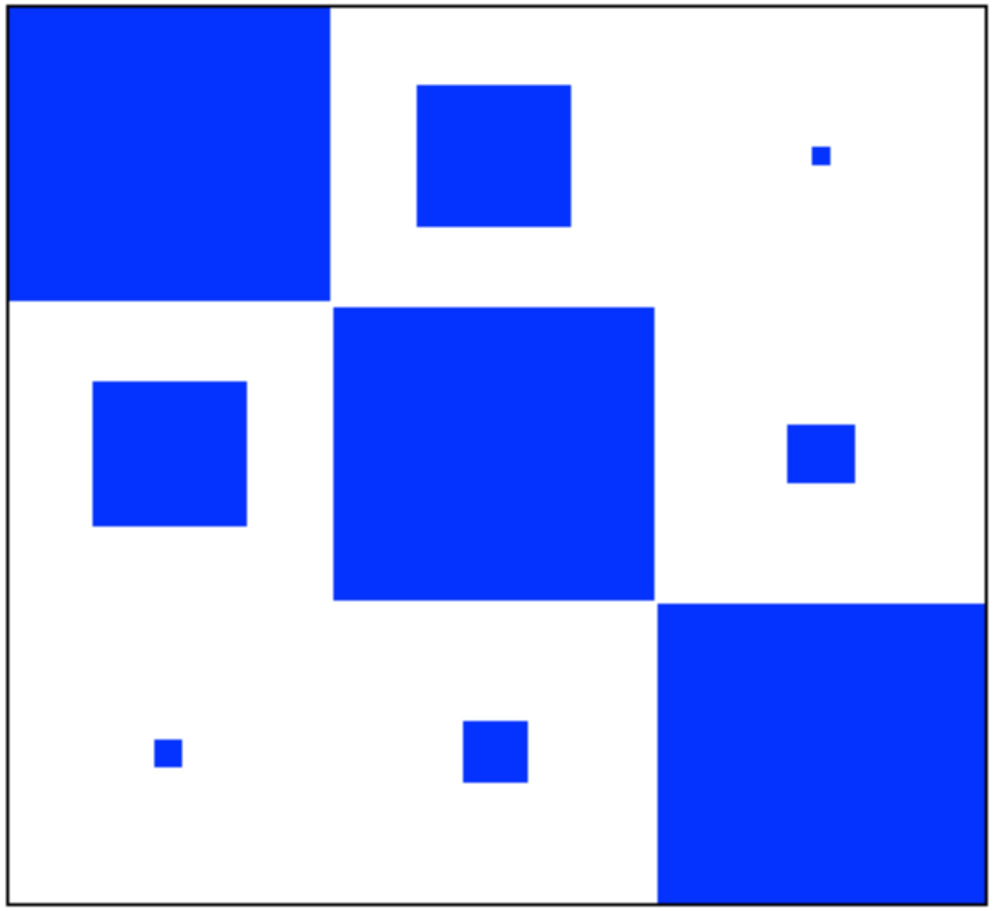
$31^\circ < \theta_{12} < 36^\circ$

normal hierarchy

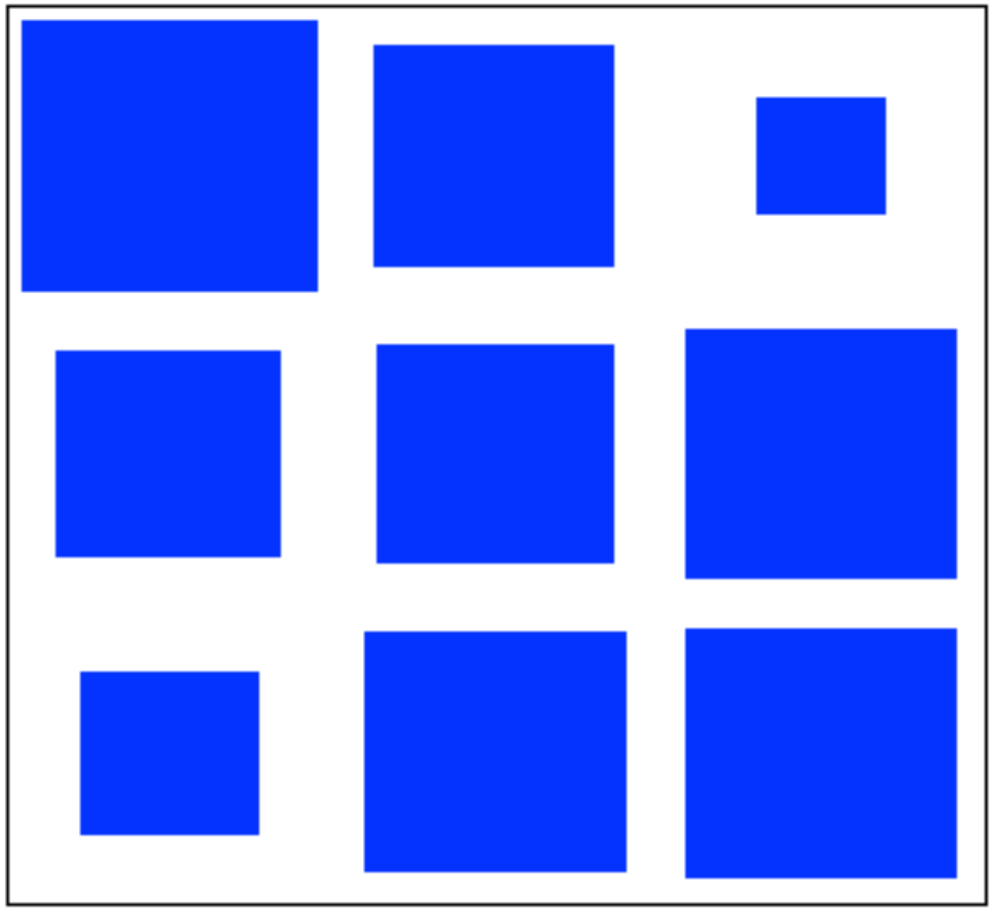
inverted hierarchy

arXiv:2102.00594 NuFit, arXiv:2111.03086

Quark mixing

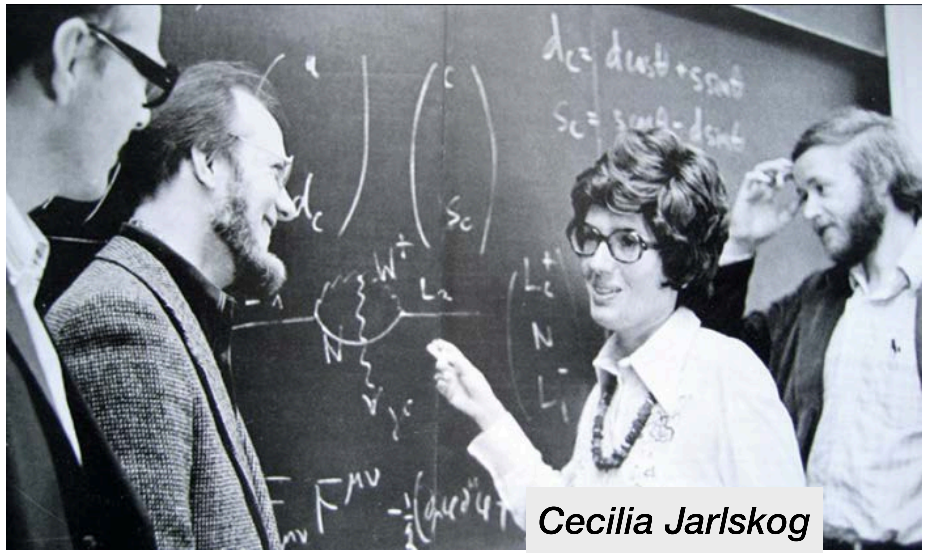


Neutrino mixing



$$\frac{J_{\mathrm{PMNS}}}{J_{\mathrm{CKM}}} = \frac{3 \times 10^{-2}}{3 \times 10^{-5}} \sin(\delta_{\mathrm{PMNS}})$$

CP violation in neutrinos could be 1000x larger than in quarks



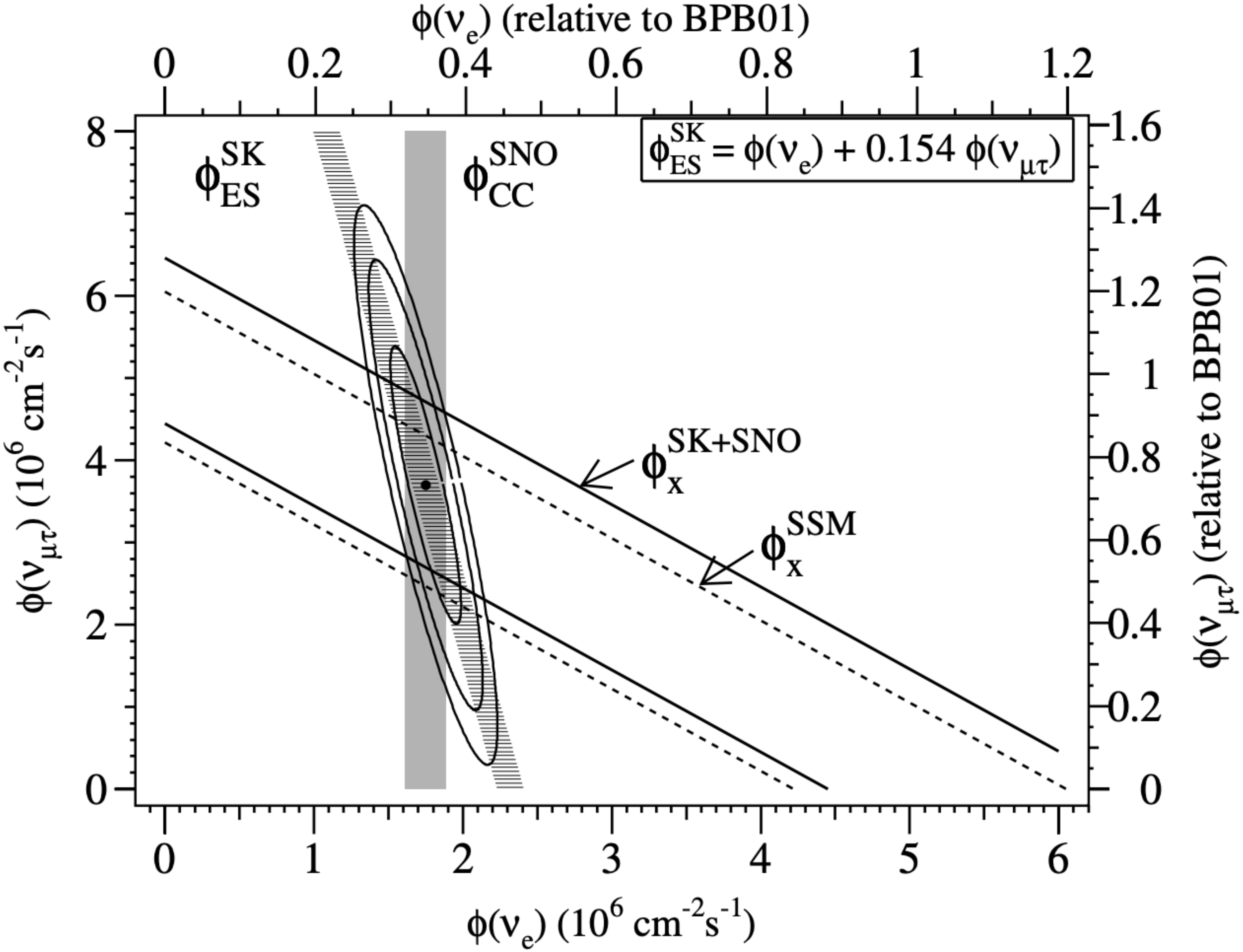
Cecilia Jarlskog

1-2 SECTOR

$$\theta_{12},\ \Delta m^2_{21}$$

1-2 Sector

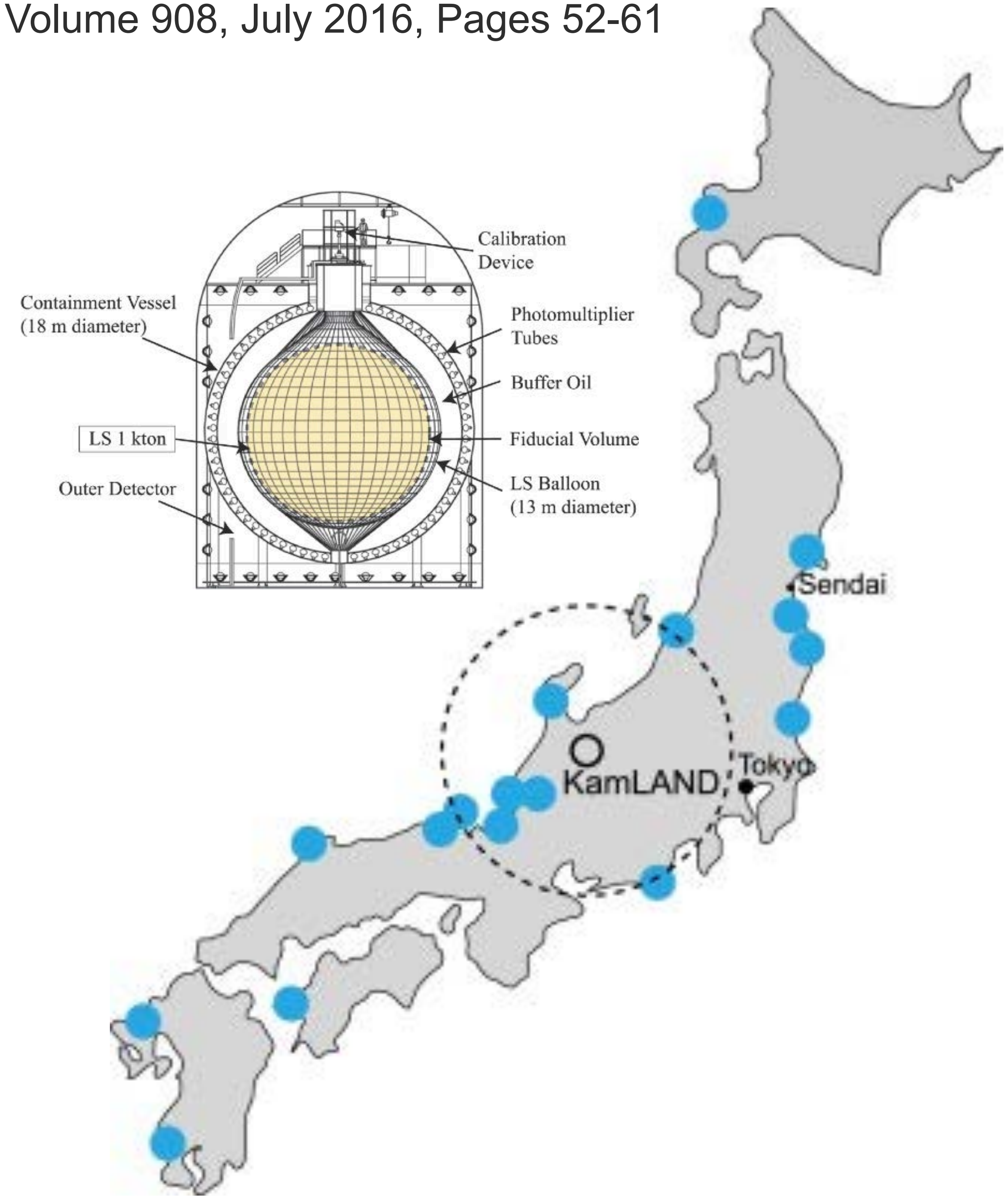
Solar Neutrinos at Super-Kamiokande and SNO



PRL 87 (2001)

1-2 Sector
KamLAND Experiment

Nuclear Physics B
Volume 908, July 2016, Pages 52-61



$$\langle L\rangle = 180\ \text{km}$$

REVIEWS OF MODERN PHYSICS, VOLUME 74, APRIL 2002

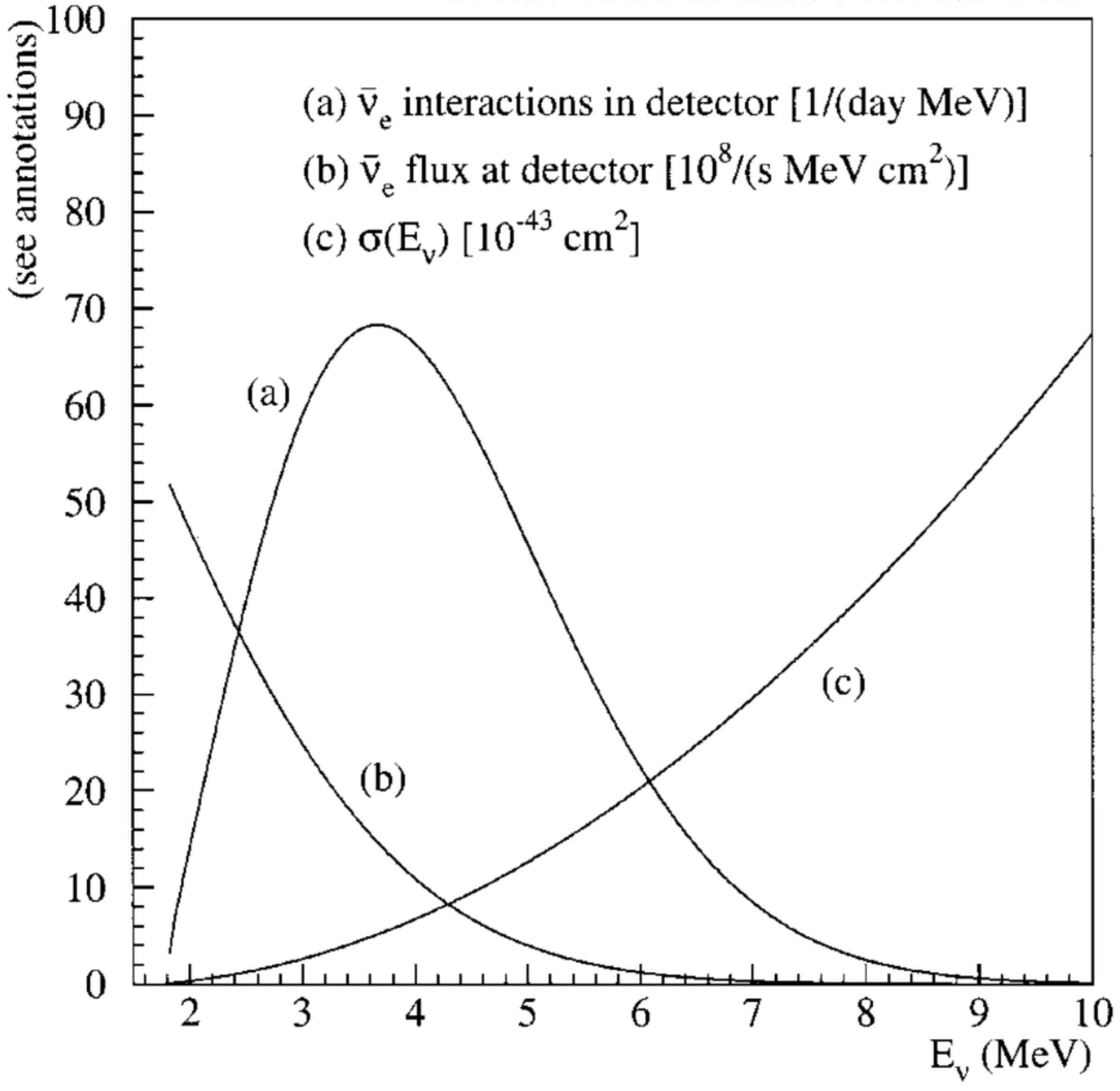
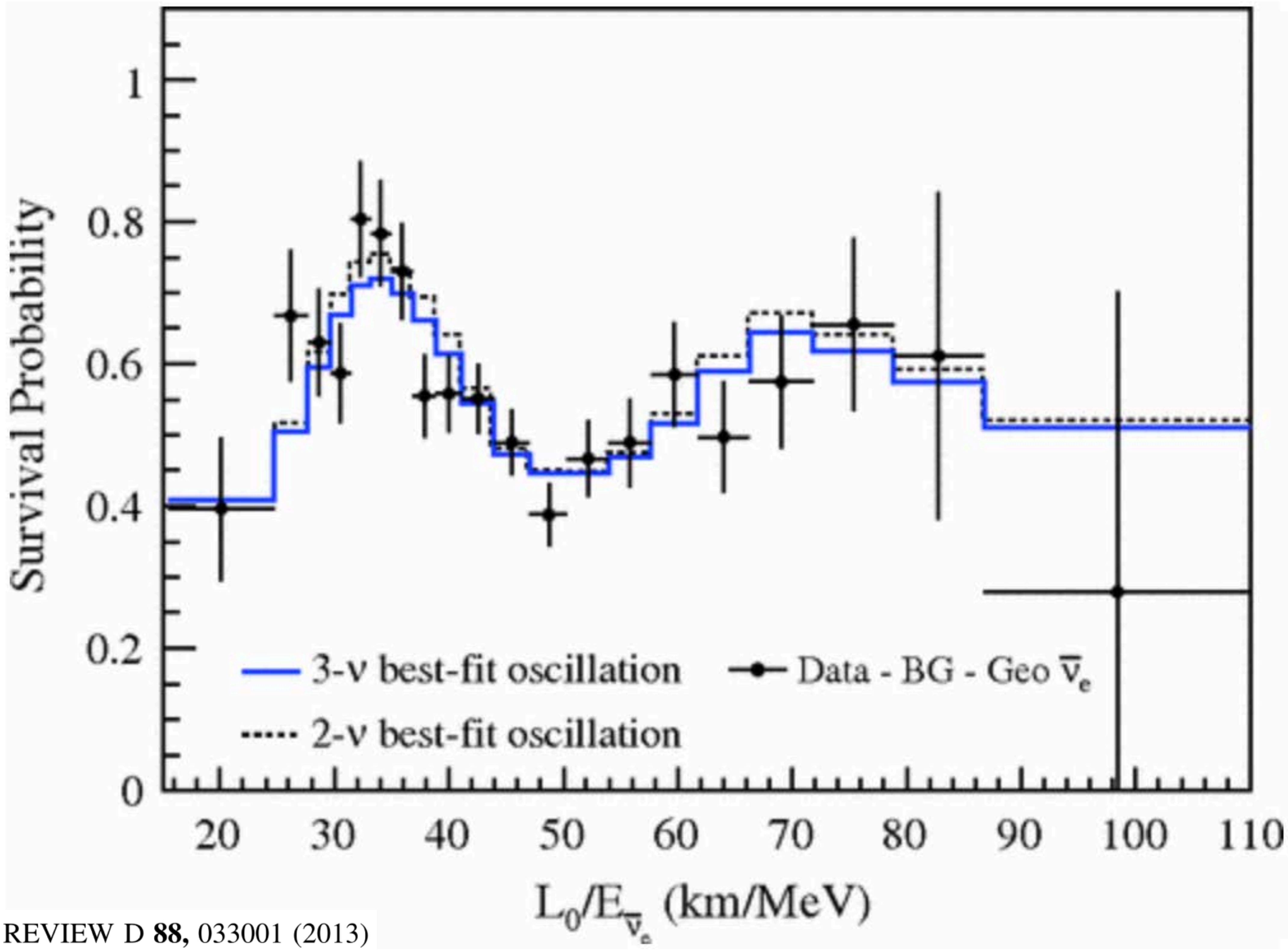


FIG. 2. Reactor $\bar{\nu}_e$ flux, inverse-beta-decay cross section, an
$\bar{\nu}_e$ interaction spectrum at a detector based on such a reactio
(a) and (b) refer to a 12-ton fiducial mass detector located 0.
km from 12-GW$_{th}$ power reactor.

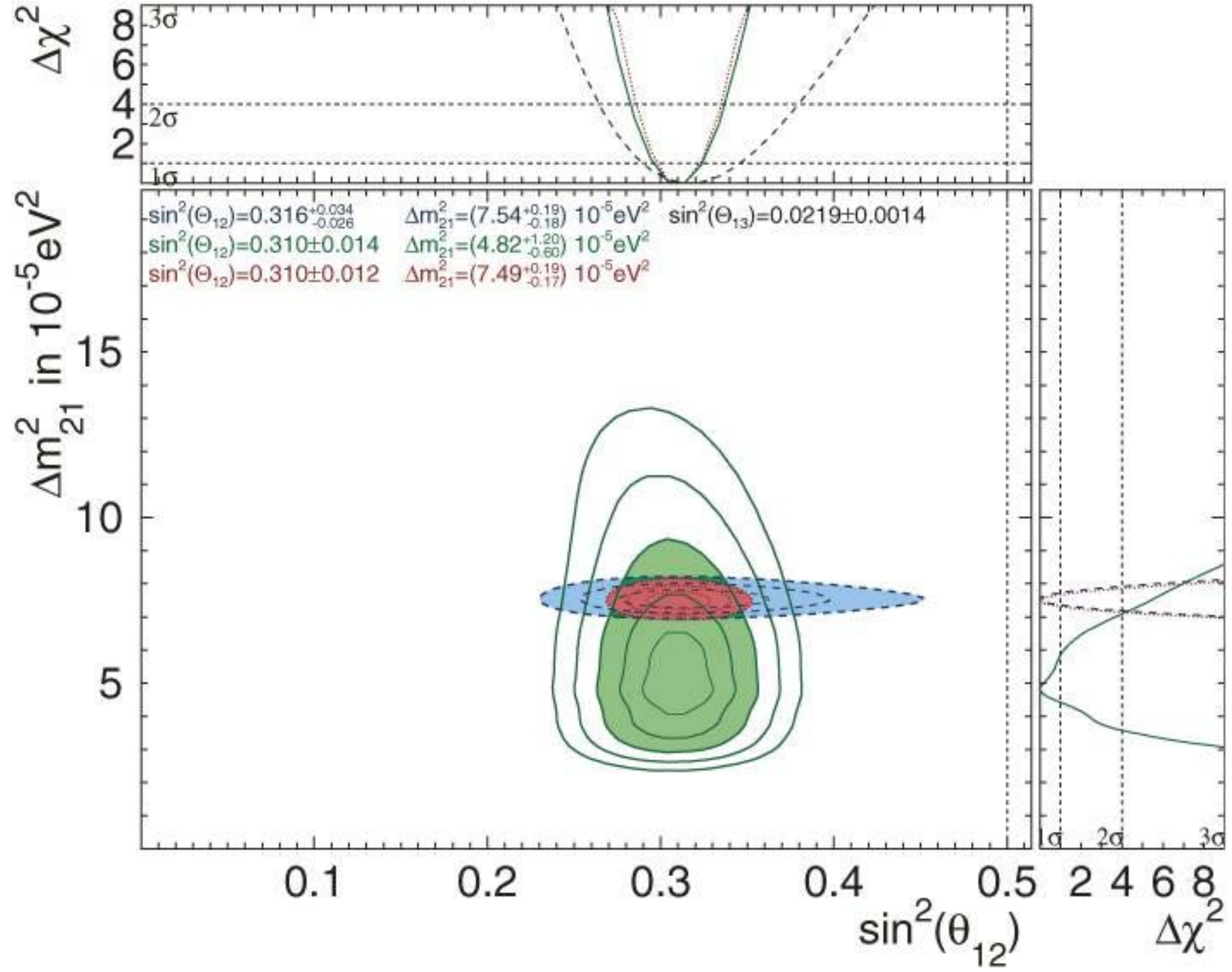
1-2 Sector
Reactor neutrinos with KamLAND



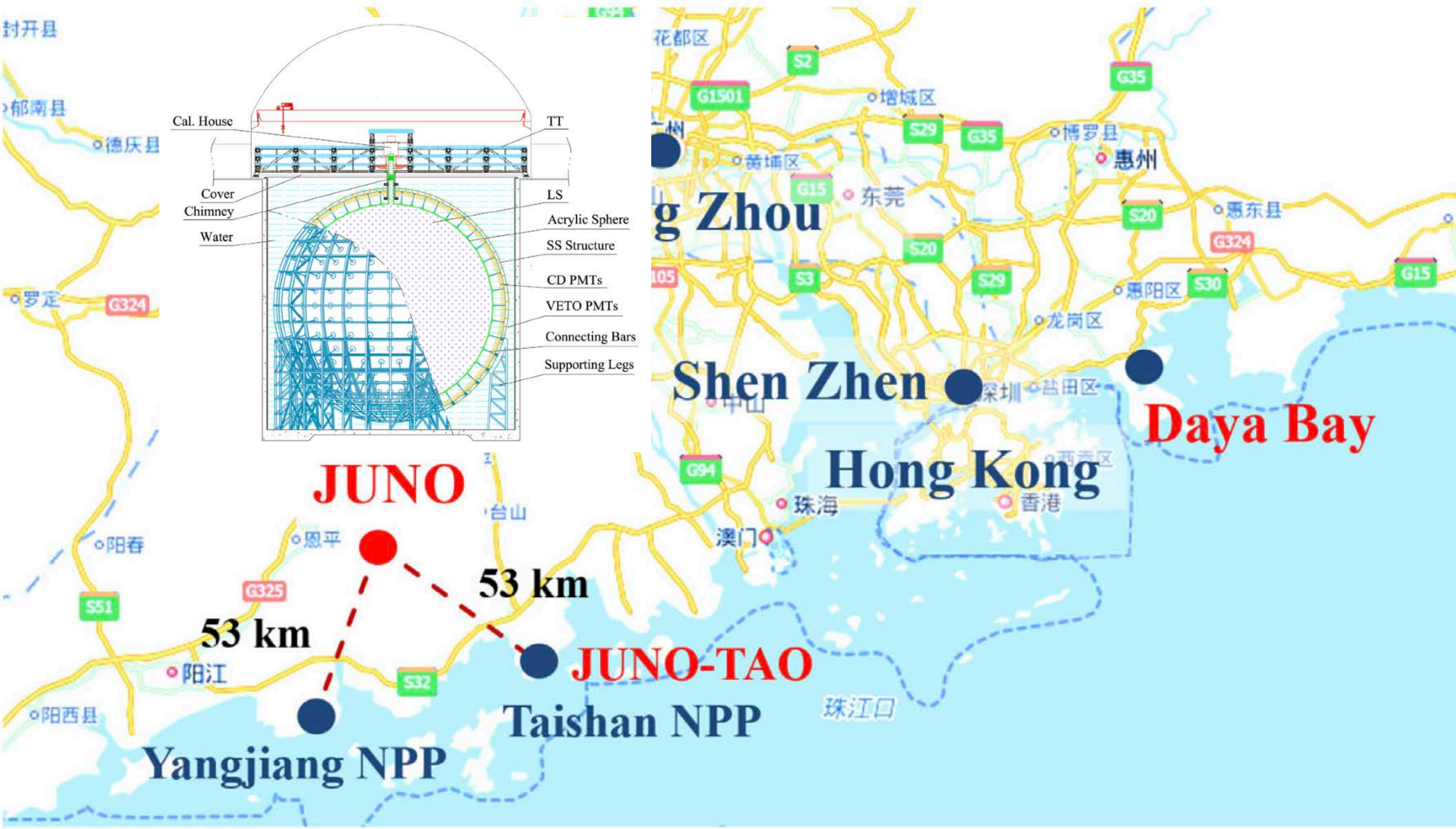
PHYSICAL REVIEW D **88,** 033001 (2013)

1-2 Sector

Solar Neutrinos at Super-Kamiokande and SNO
Reactor neutrinos with KamLAND



Suzuki Y. Proc Jpn Acad Ser B Phys Biol Sci. 2020;96(6):204-233. doi: 10.2183/pjab.96.017

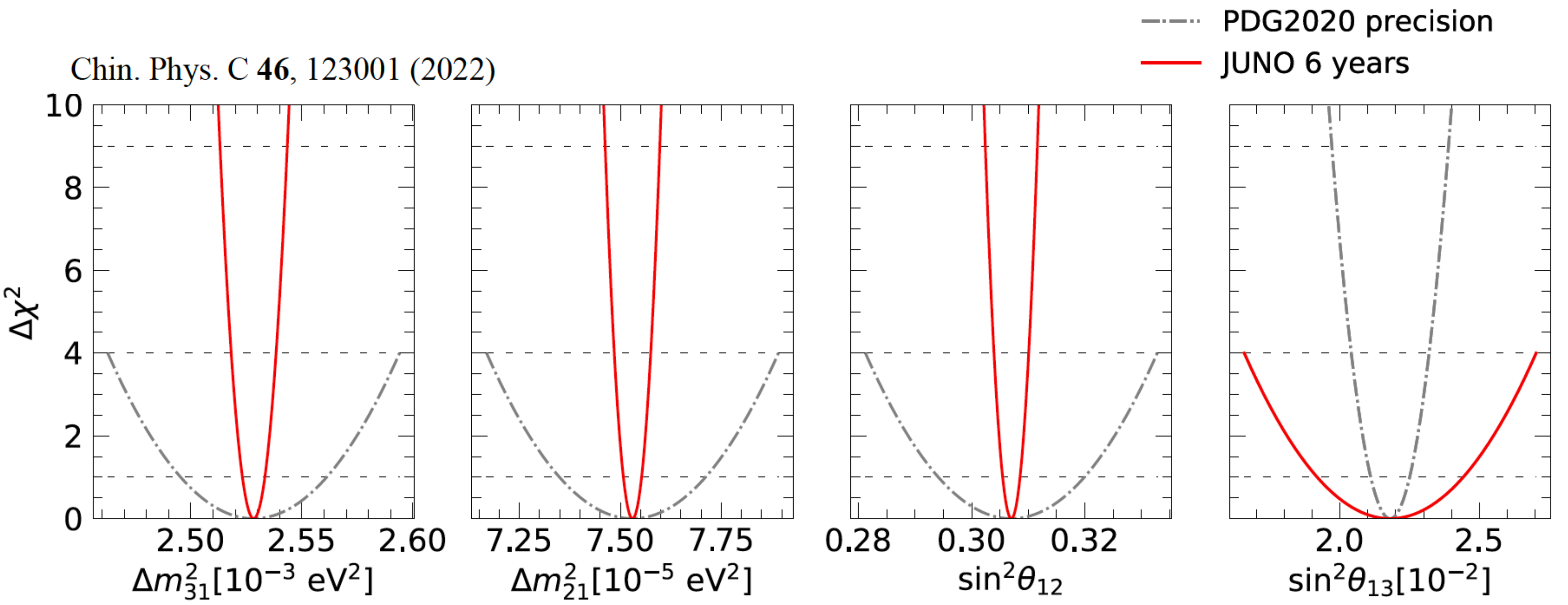


…the future: JUNO

20 ton detector at 53 km from sources

Progress in Particle and Nuclear Physics 123 (2022) 103927

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



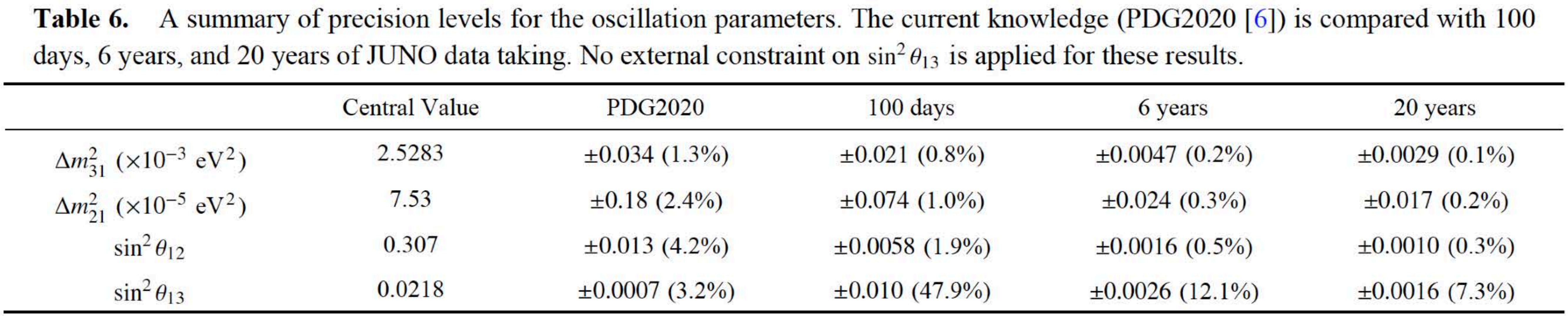


Table 6. A summary of precision levels for the oscillation parameters. The current knowledge (PDG2020 [6]) is compared with 100 days, 6 years, and 20 years of JUNO data taking. No external constraint on $\sin^2\theta_{13}$ is applied for these results.

	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)	±0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)	±0.0016 (7.3%)

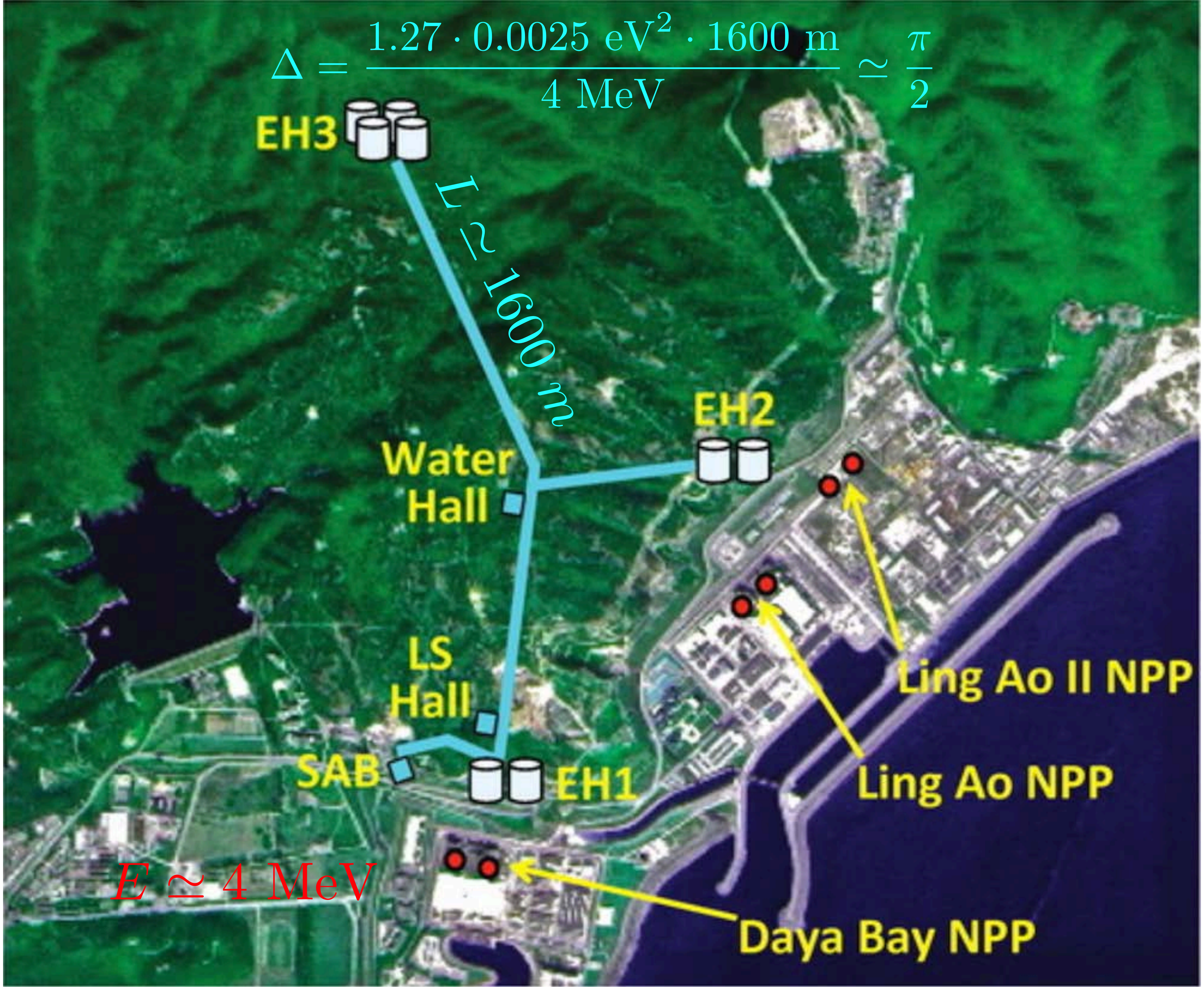
…the future: **JUNO**

Filling of demonstrator underway. Could see first data end of this year.

Nature | Vol 627 | 28 March 2024 |

1-3 SECTOR

$$\theta_{13},\ \Delta m^2_{31}$$



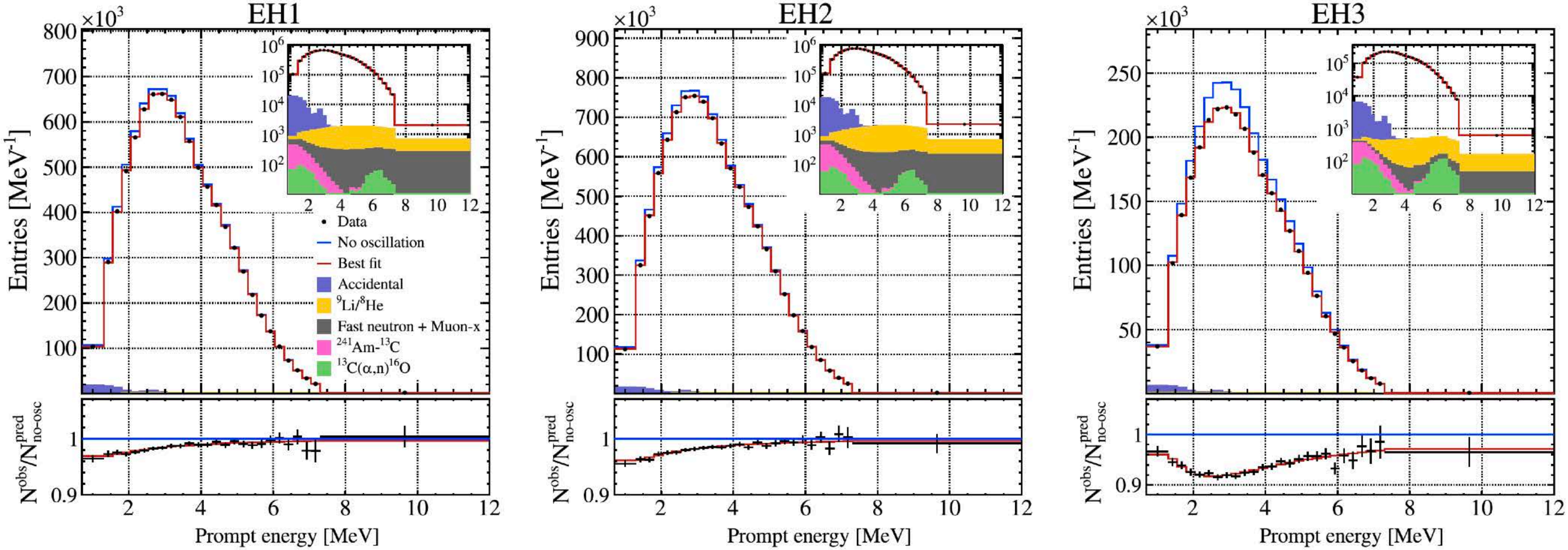
$$\Delta = \frac{1.27 \cdot 0.0025\ \mathrm{eV}^2 \cdot 1600\ \mathrm{m}}{4\ \mathrm{MeV}} \simeq \frac{\pi}{2}$$

$L \simeq 1600\ \mathrm{m}$

$E \simeq 4\ \mathrm{MeV}$

$\bar{\nu}_e \rightarrow \bar{\nu}_e$ at atmospheric mass scale

θ_{13}: Daya Bay, RENO, and Double CHOOZ



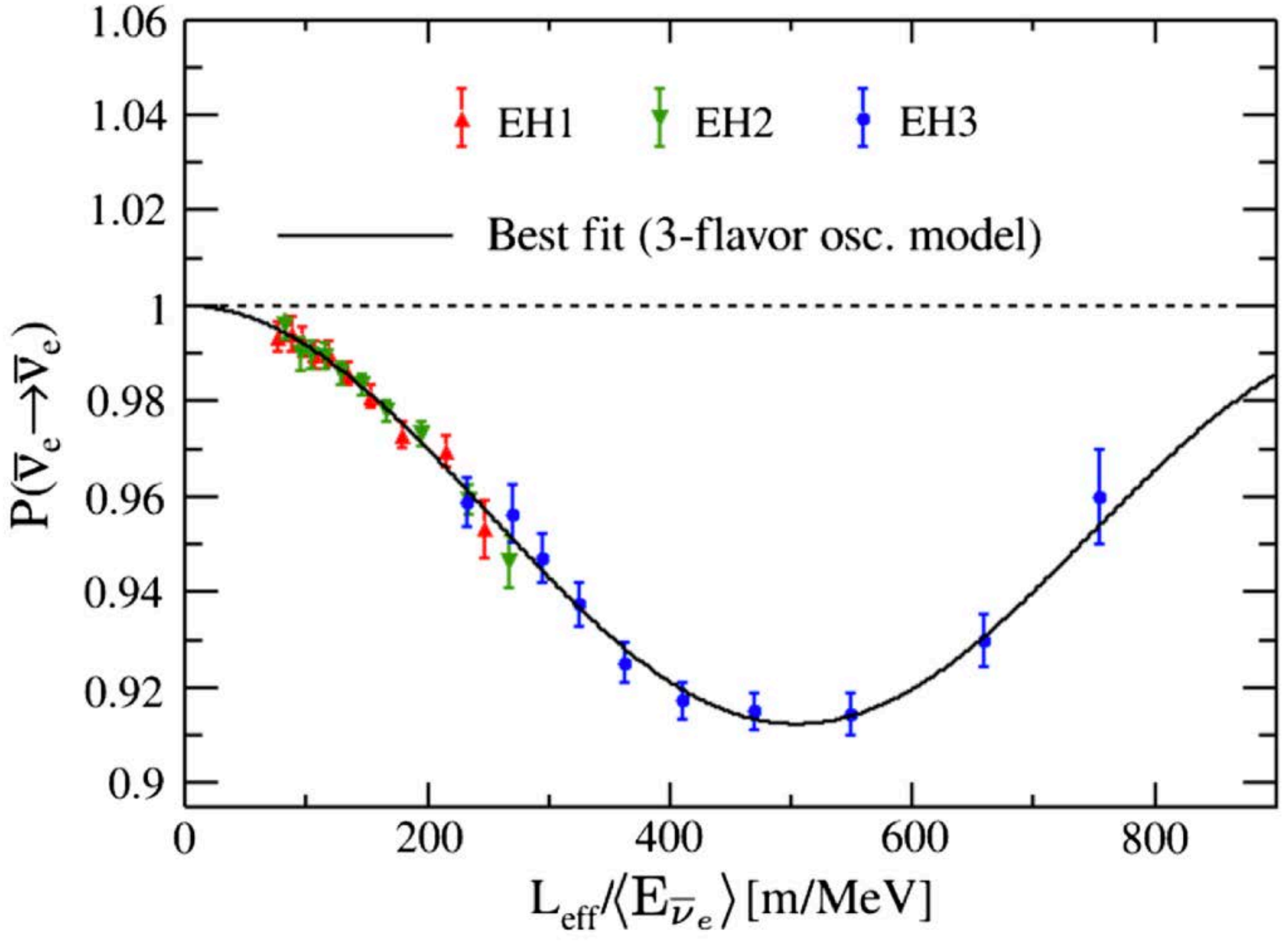
$$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$$

$$(\theta_{13} = 8.36^\circ)$$

$$\Delta m^2_{32} = (+2.466 \pm 0.0600) \times 10^{-3}\,\mathrm{eV}^2 \;\; NO$$

$$\Delta m^2_{32} = (-2.571 \pm 0.0600) \times 10^{-3}\,\mathrm{eV}^2 \;\; IO$$

1-3 Sector
Daya Bay
Reactor Experiment



PHYSICAL REVIEW LETTERS 130, 161802 (2023)

2-3 SECTOR

$$\Delta m^2_{23}, \ \ \sin^2\theta_{23},$$

mass ordering

$$\delta_{\mathrm{CP}}$$

T2K

Super-Kamiokande
(ICRR, Univ. Tokyo)

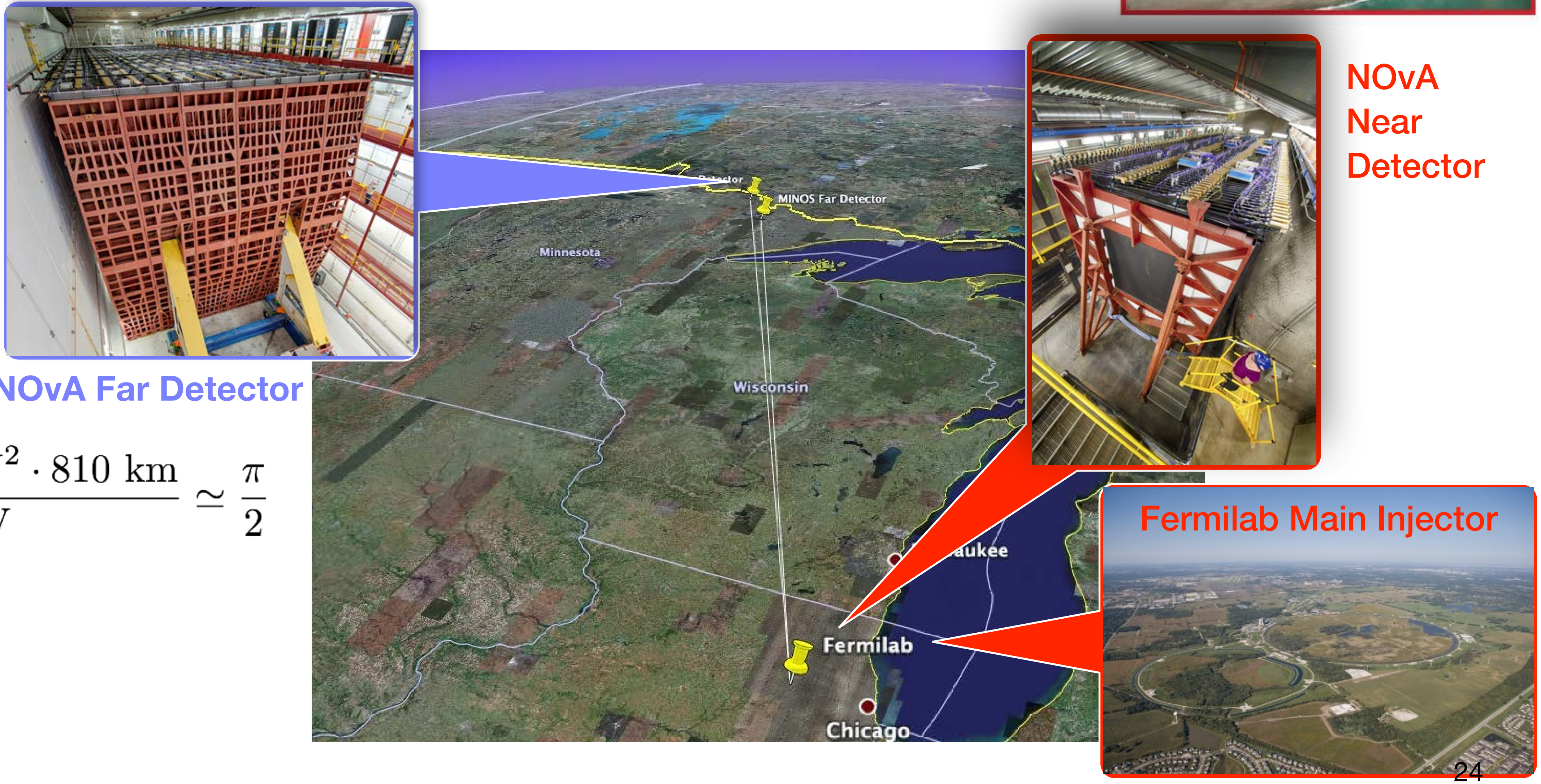
INGRID +
ND280

J-PARC Main Ring
(KEK-JAEA, Tokai)

$$E_\nu \simeq 0.7\ \mathrm{GeV},$$

$$\Delta \equiv \frac{1.27 \cdot 0.0025\ \mathrm{eV}^2 \cdot 295\ \mathrm{km}}{0.7\ \mathrm{GeV}} \simeq \frac{\pi}{2}$$

NOvA



NOvA Far Detector

NOvA
Near
Detector

Fermilab Main Injector

$$E_\nu \simeq 2\ \mathrm{GeV},$$

$$\Delta \equiv \frac{1.27 \cdot 0.0025\ \mathrm{eV}^2 \cdot 810\ \mathrm{km}}{2\ \mathrm{GeV}} \simeq \frac{\pi}{2}$$

Neutrino oscillations at long baseline

Following presentation by Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]

$$\begin{aligned} P(\nu_\mu \to \nu_\mu) &\simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}\left[1-\cos^2\theta_{13}\sin^2\theta_{23}\right]\sin^2\Delta_{3i} \\ &\simeq 1 - \sin^2 2\theta_{23}\sin^2\Delta_{3i} \end{aligned}$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) &\simeq |\sqrt{P_{\text{atm}}}e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{\text{sol}}}|^2 \\ &= P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}}P_{\text{sol}}}\left(\cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta\right) \end{aligned}$$

$$\sqrt{P_{\text{atm}}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{31}\mp aL)}{\Delta_{31}\mp aL}\Delta_{31}$$

$$\sqrt{P_{\text{sol}}} = \cos\theta_{23}\sin 2\theta_{12}\frac{\sin(aL)}{aL}\Delta_{21}$$

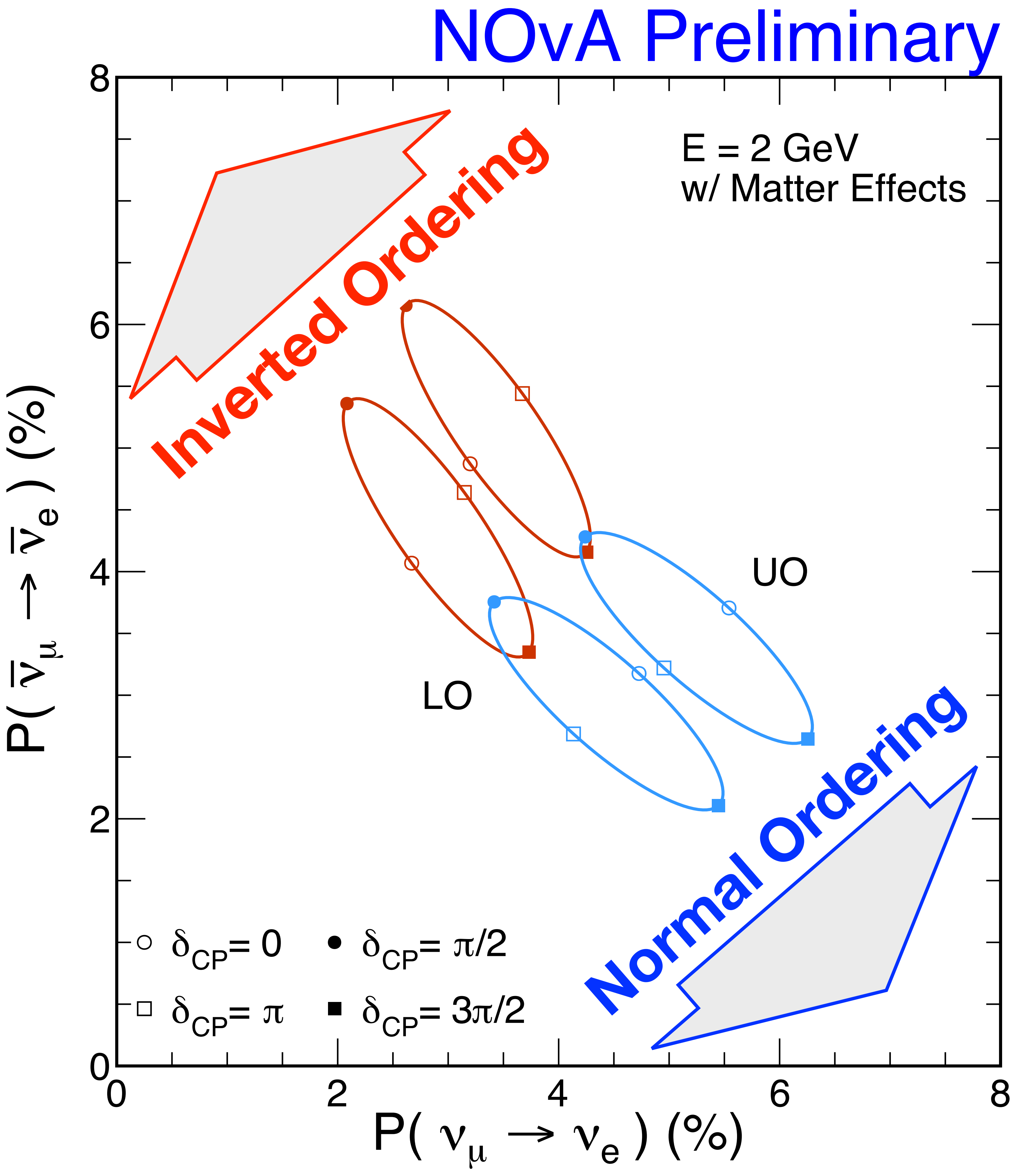
$$a = G_F N_e/\sqrt{2} \simeq \frac{1}{3500\text{ km}}$$

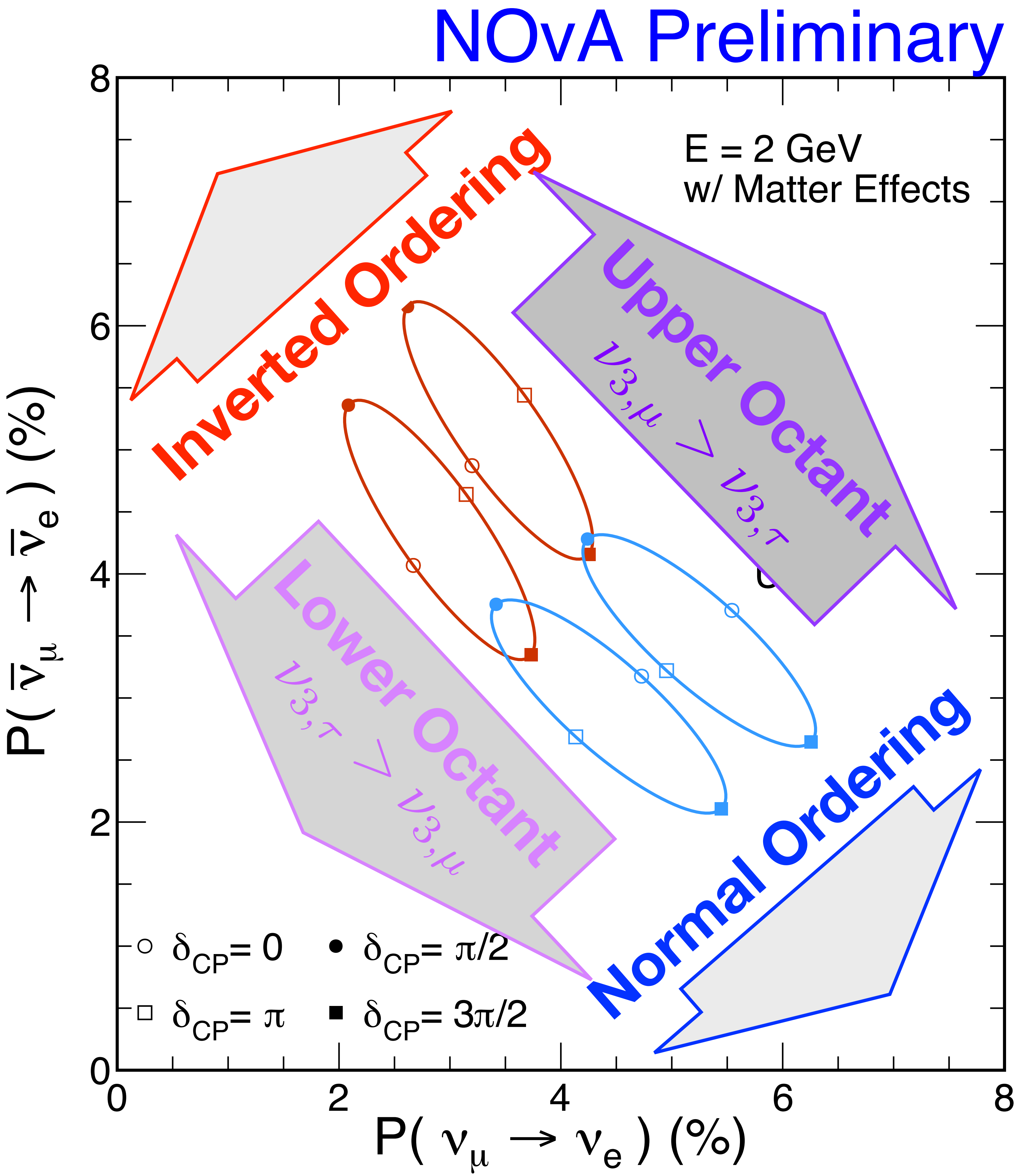
$aL = 0.08$ for $L = 295$ km

$aL = 0.23$ for $L = 810$ km

$aL = 0.37$ for $L = 1300$ km

Parameter	Channels	Question
$\sin^2 2\theta_{23}$:	$\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$:	Is θ_{23} maximal?
$\sin^2\theta_{23}\sin^2 2\theta_{13}$:	$\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$:	Octant of θ_{23}
$\text{sign}[\Delta_{31}]$:	$\nu_\mu \to \nu_e$ vs. $\bar{\nu}_\mu \to \bar{\nu}_e$:	Neutrino mass hierarchy
δ_{CP} :	$\nu_\mu \to \nu_e$ vs. $\bar{\nu}_\mu \to \bar{\nu}_e$:	Is CP violated?

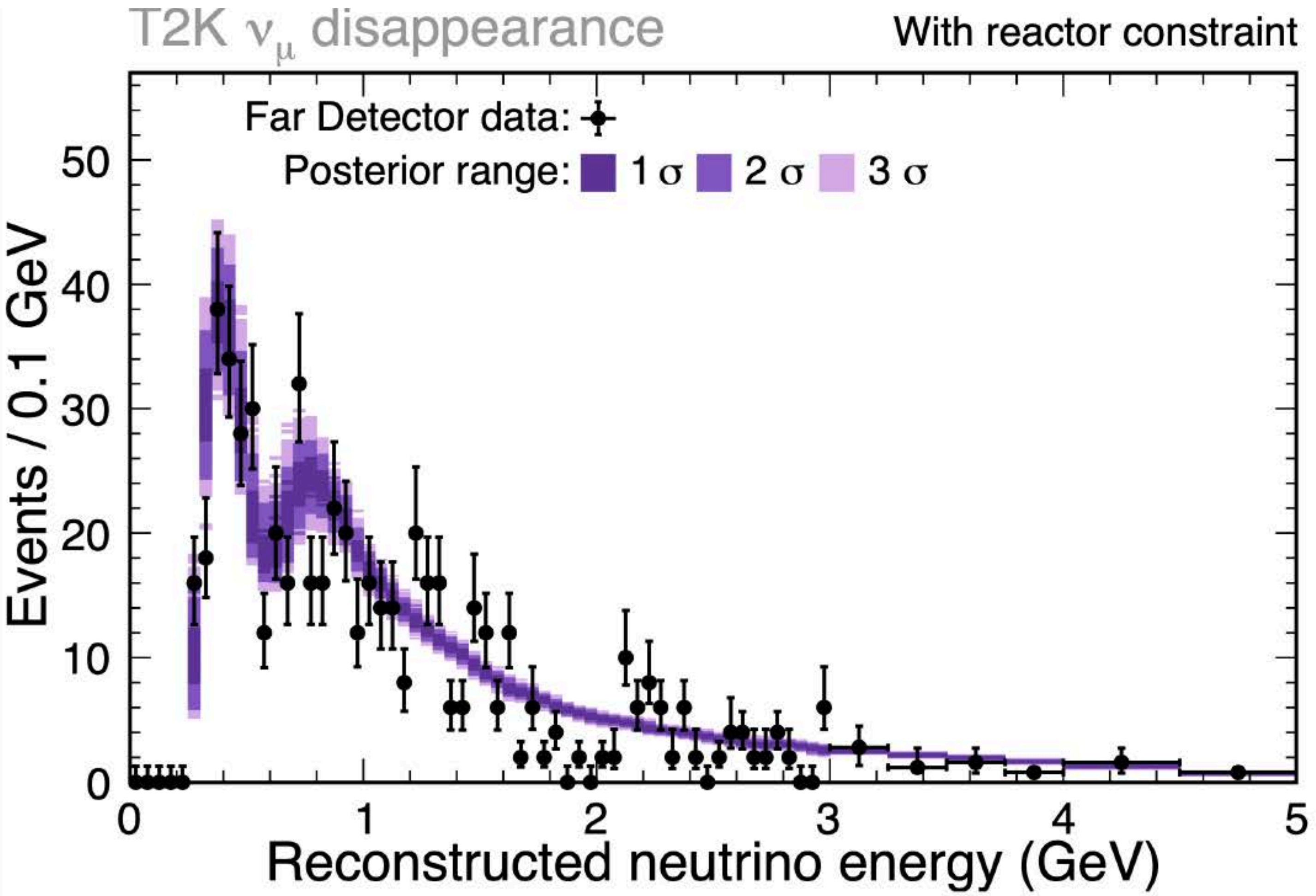

NOvA Preliminary
E = 2 GeV
w/ Matter Effects
Inverted Ordering
Normal Ordering
UO
LO
○ δ_{CP}= 0
● δ_{CP}= $\pi/2$
□ δ_{CP}= π
■ δ_{CP}= $3\pi/2$
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ (%)
$P(\nu_\mu \rightarrow \nu_e)$ (%)
0
2
4
6
8
0
2
4
6
8

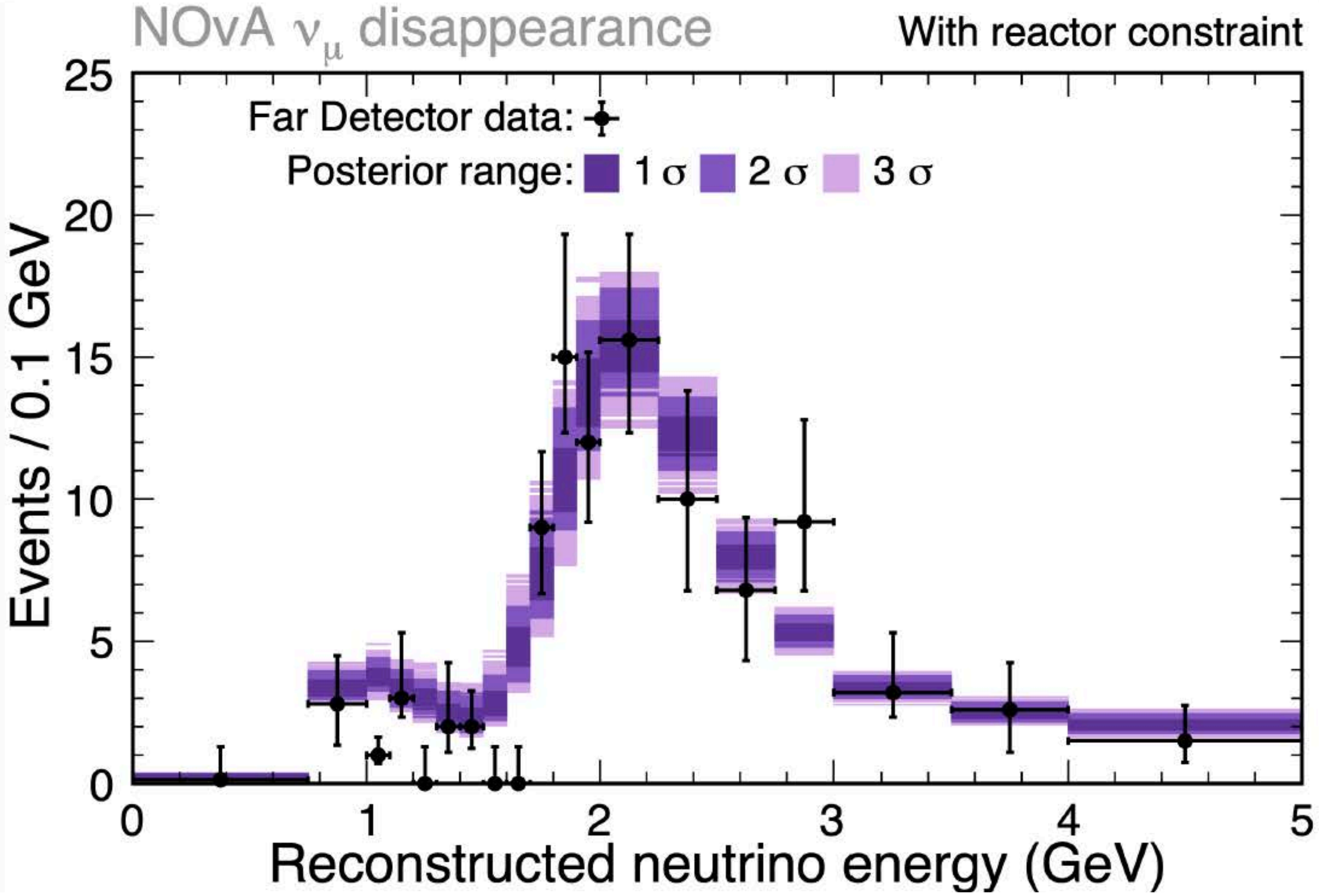

NOvA Preliminary
E = 2 GeV
w/ Matter Effects
Inverted Ordering
Upper Octant
$\nu_{3,\mu} > \nu_{3,\tau}$
Lower Octant
$\nu_{3,\tau} > \nu_{3,\mu}$
Normal Ordering
○ δ_{CP}= 0
● δ_{CP}= π/2
□ δ_{CP}= π
■ δ_{CP}= 3π/2
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ (%)
$P(\nu_\mu \rightarrow \nu_e)$ (%)
0
2
4
6
8
0
2
4
6
8

NOvA - T2K Joint Fit

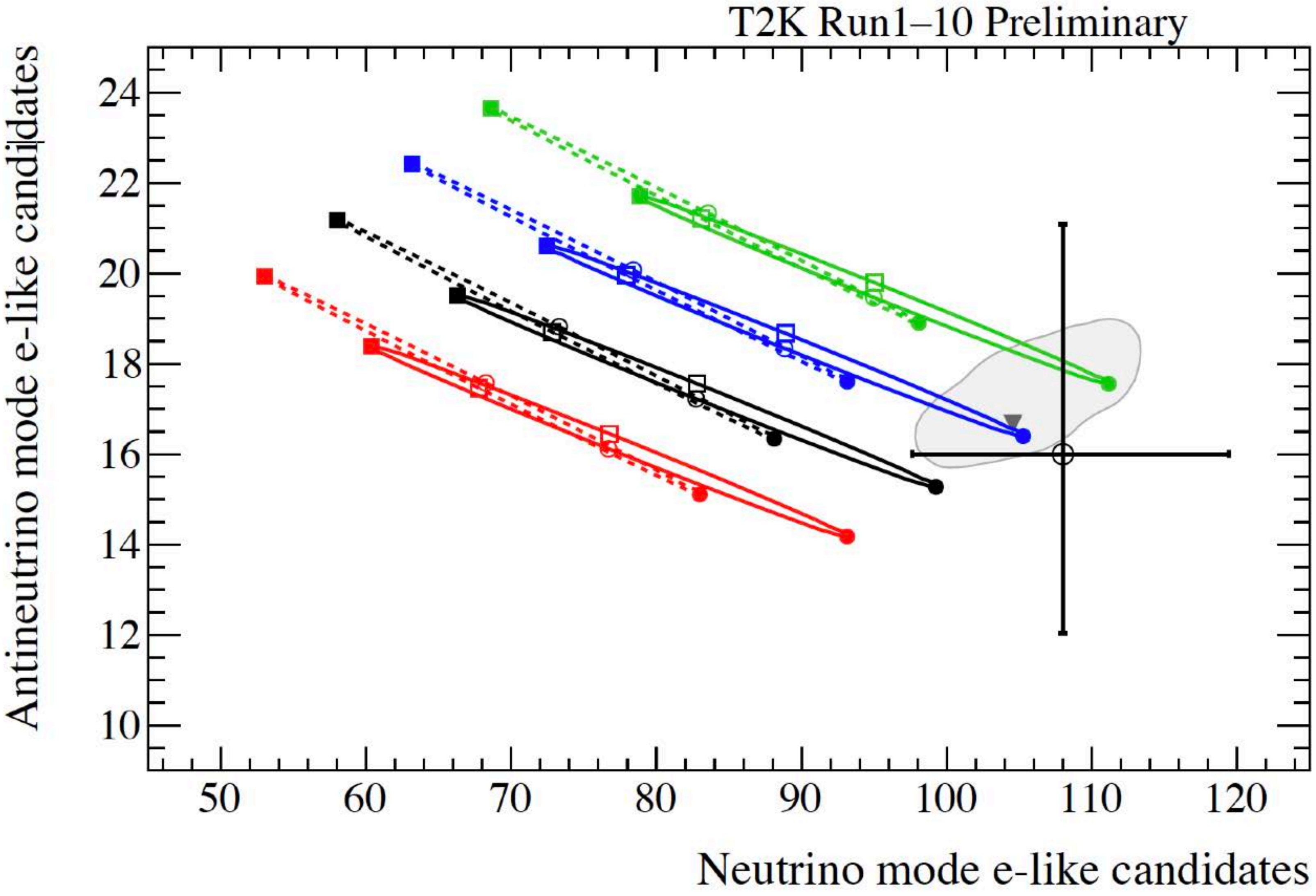
https://indico.fnal.gov/event/62062/

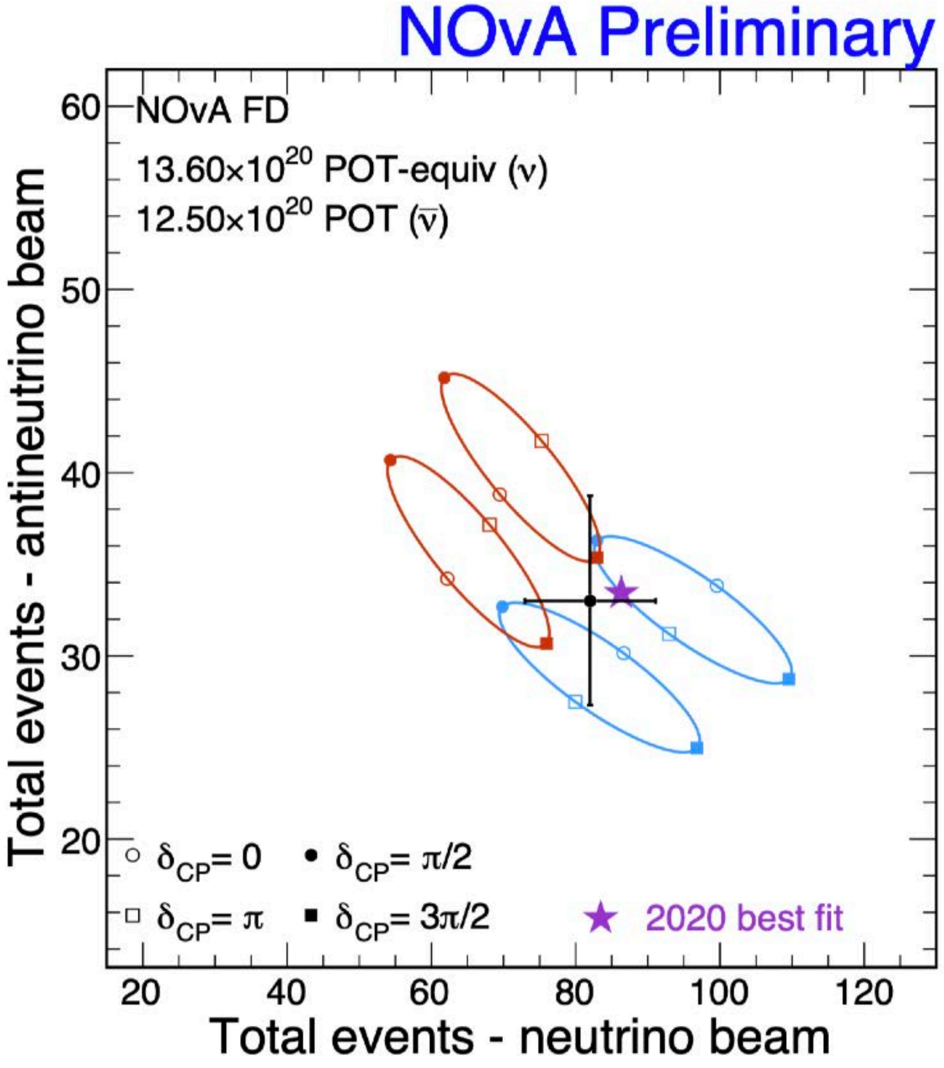
Channel	NOvA	T2K
ν_e	82	94 (ν_e) 14 ($\nu_e 1\pi$)
$\bar{\nu}_e$	33	16
ν_μ	211	318
$\bar{\nu}_\mu$	105	137





Mass ordering and CP violation

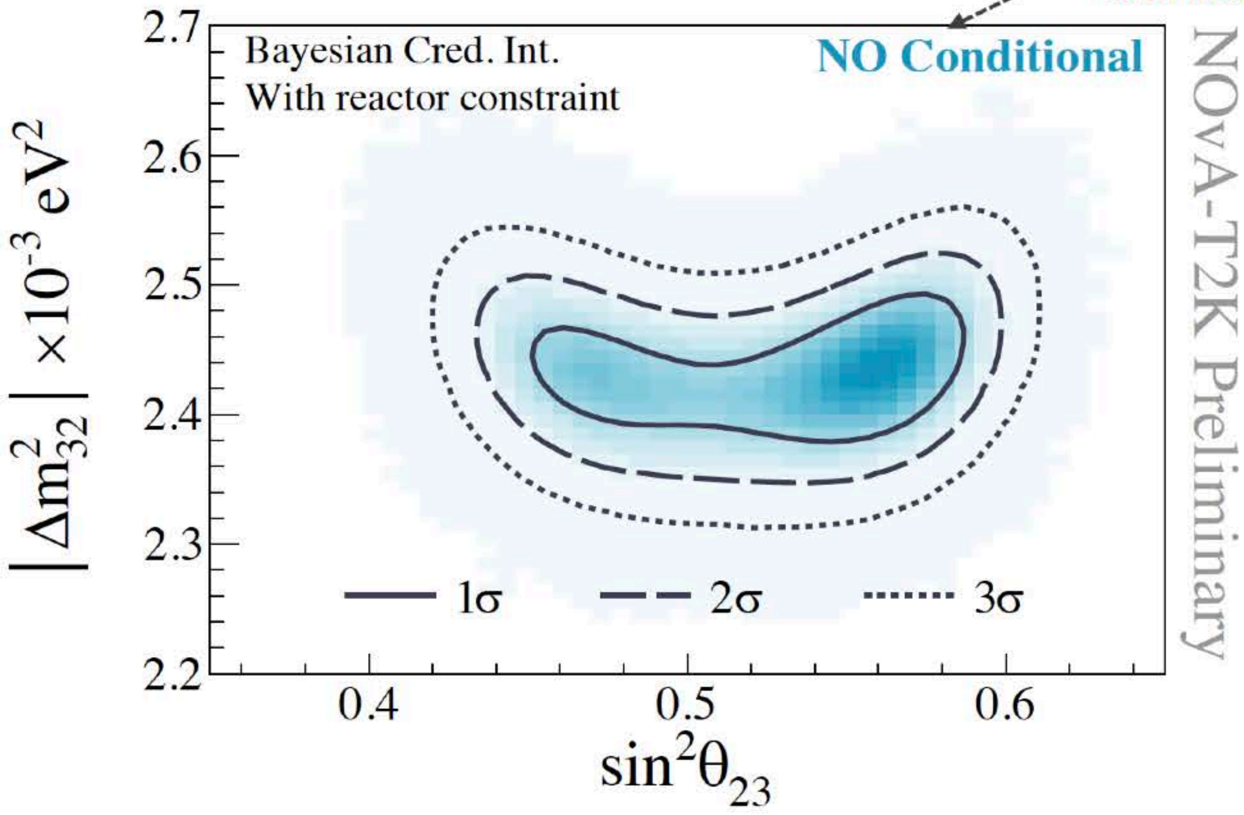


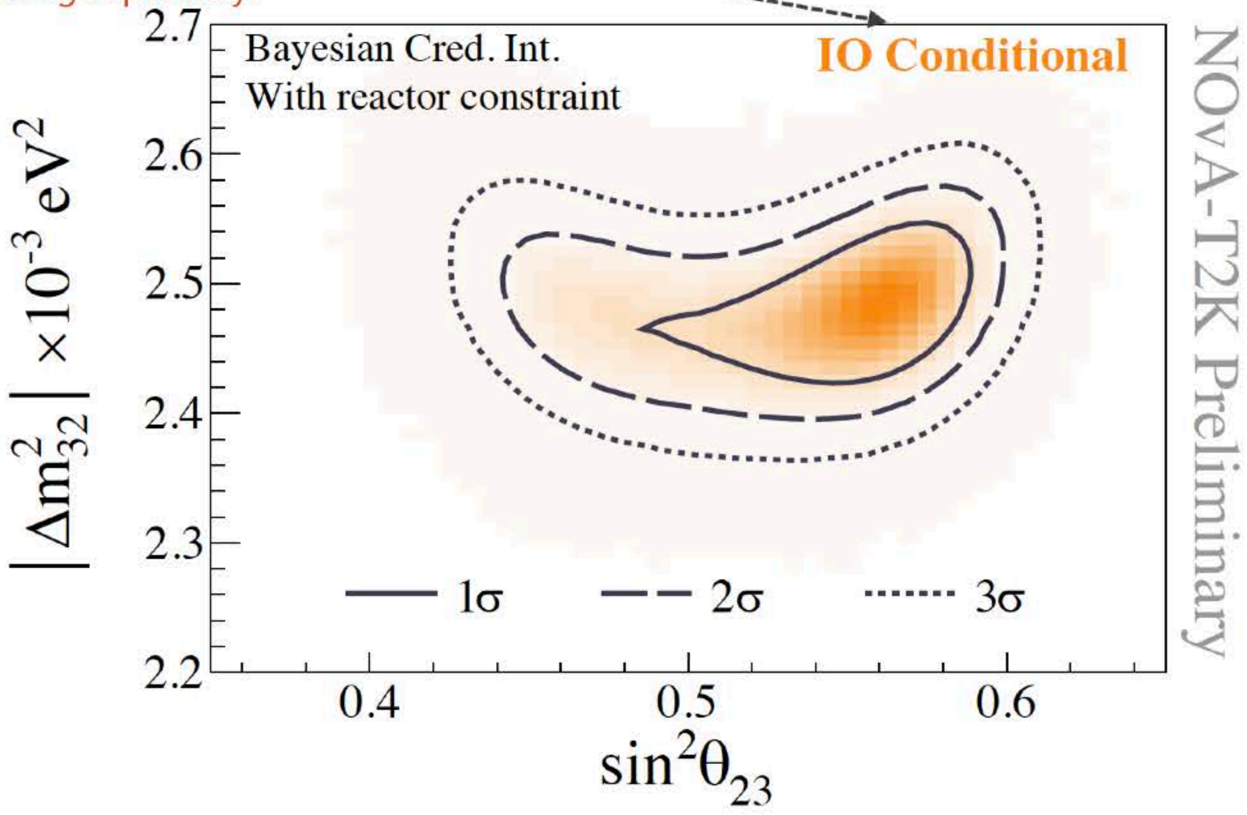


T2K sees a large difference between $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

NOvA does not. CPV and mass ordering remain to be resolved.

NOvA + T2K

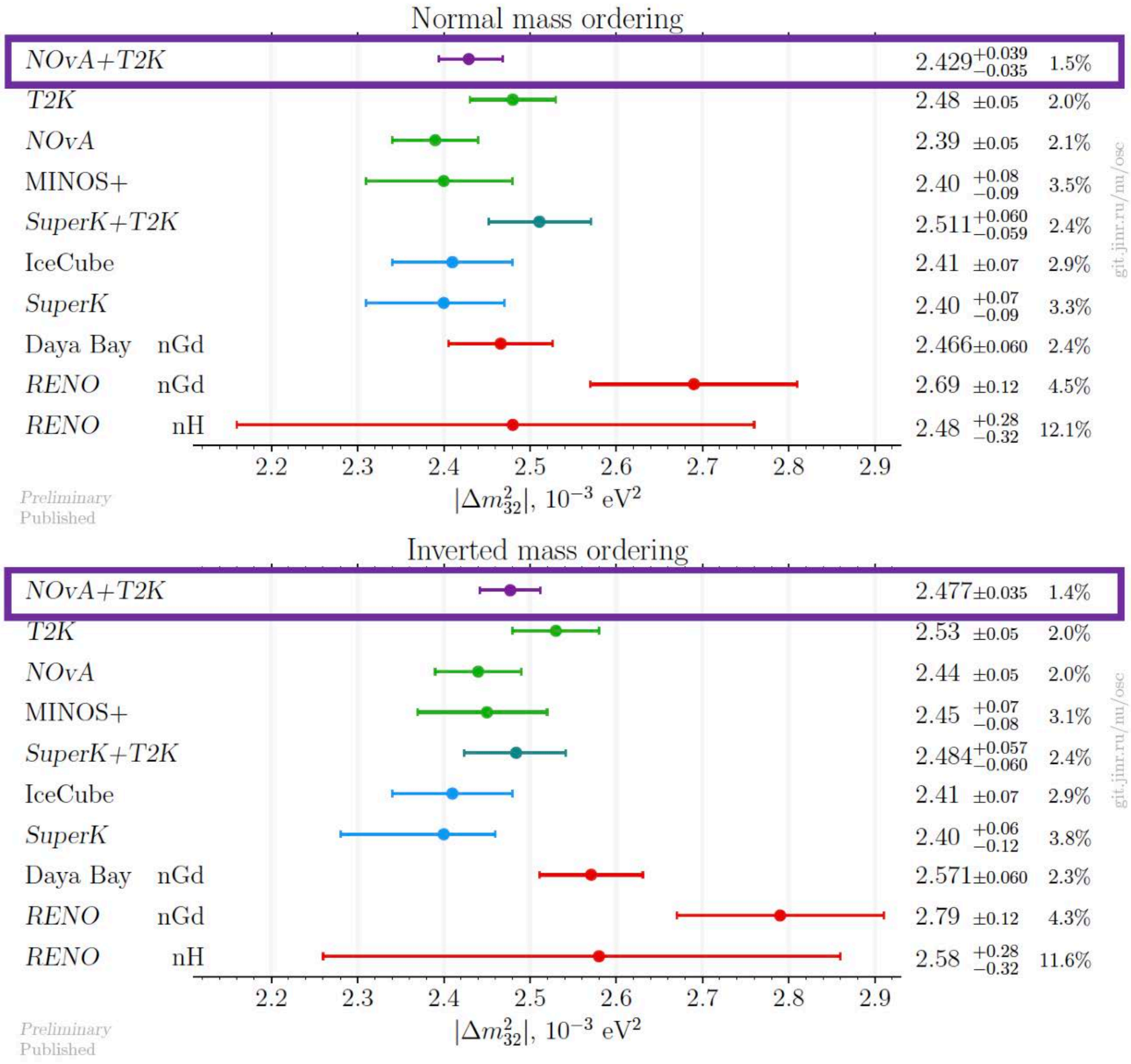




Note: Conditional posteriors are marginalized over each mass ordering separately.

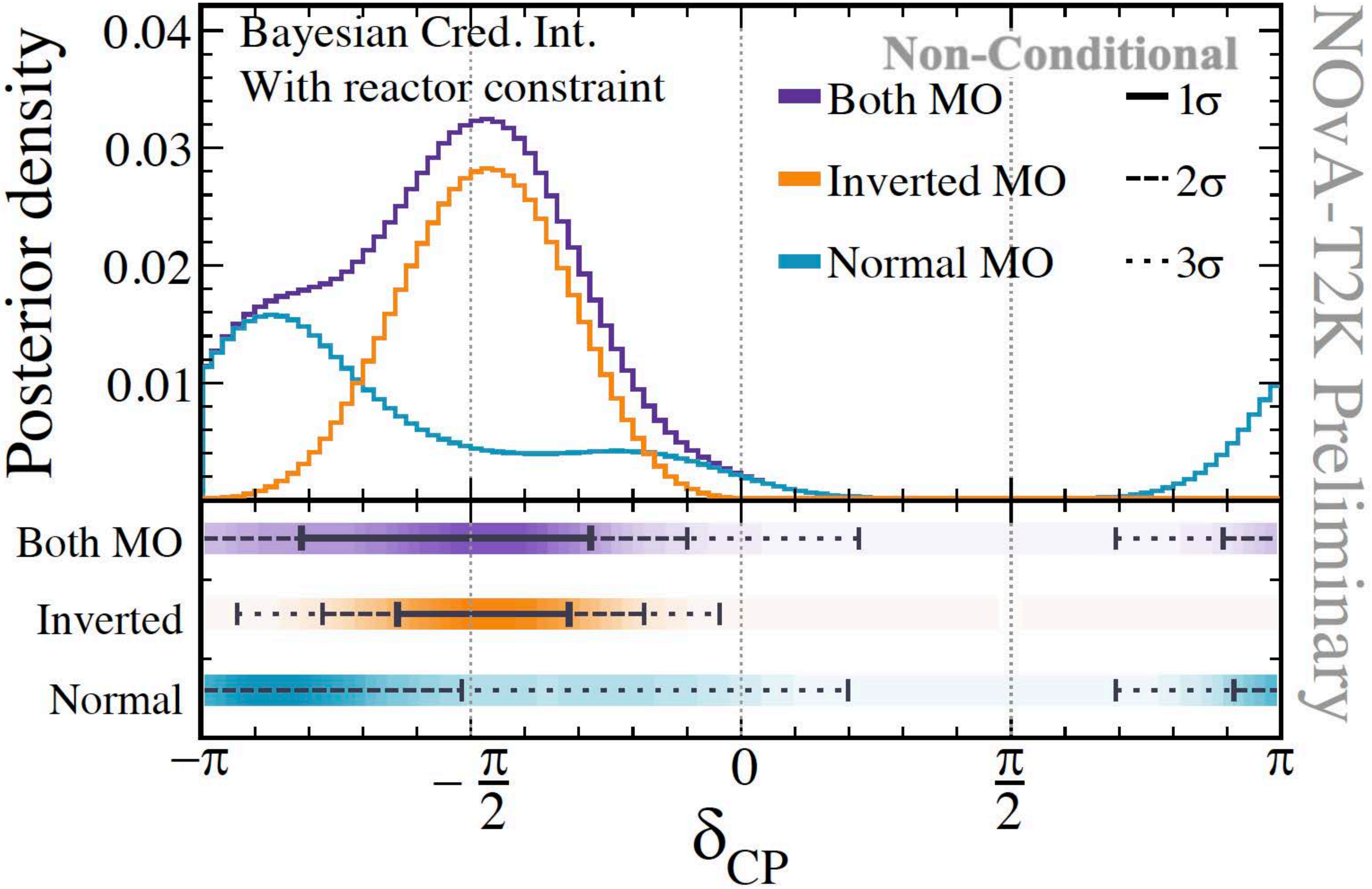
	NOvA - T2K w/o reactor	NOvA – T2K – w/ reactor
Bayes factor	**1.17** **Lower Octant/Upper Octant** **~54% : ~46% posterior**	**3.59** **Upper Octant/Lower Octant** **~78% : 22% posterior**

	NOvA – T2K – w/ reactor
Bayes factor	**1.36** **Inverted Ordering/Normal Ordering** **~58% : ~42% posterior**



NOvA + T2K

Combined fit it world’d best measurement of Δm^2_{32}

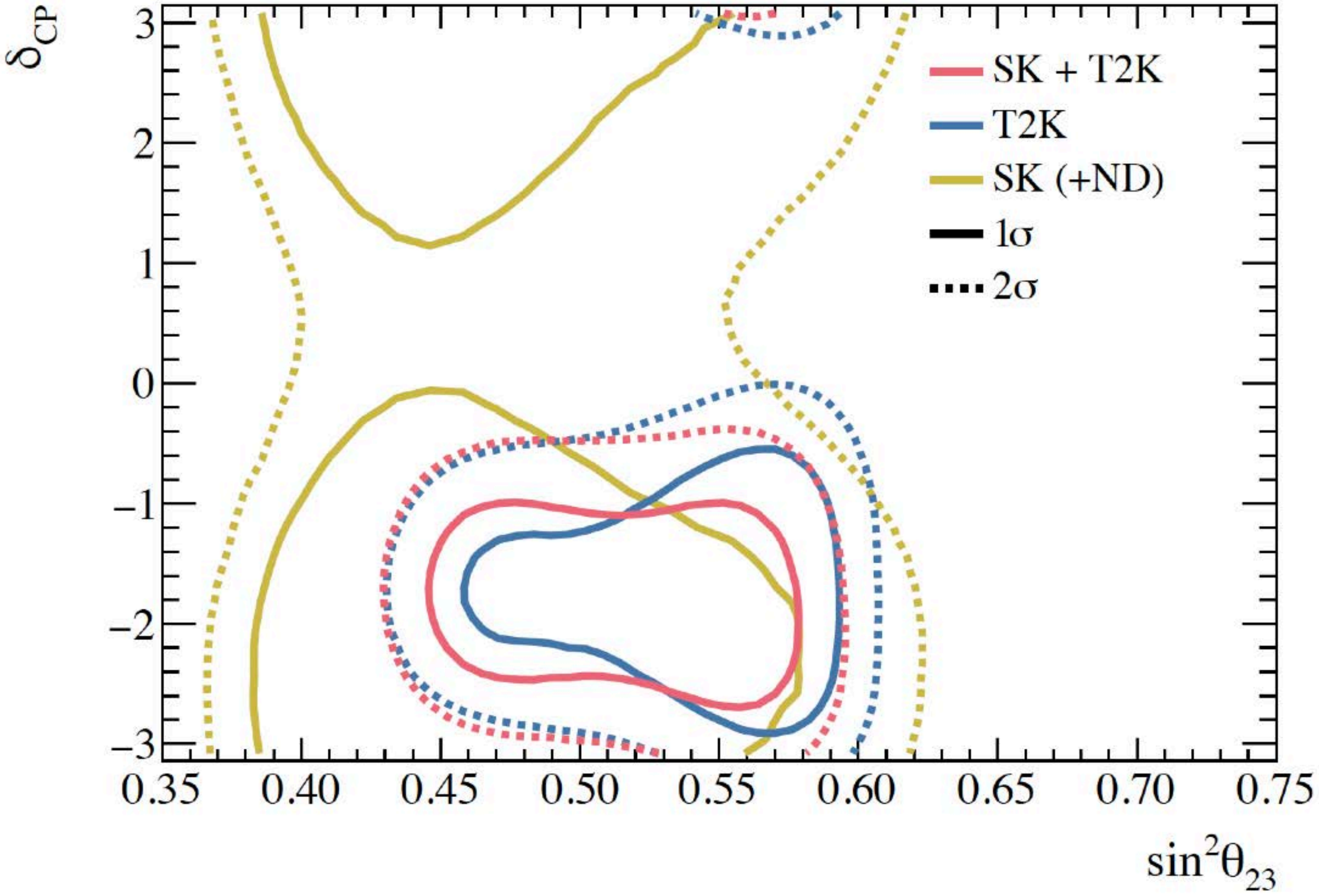


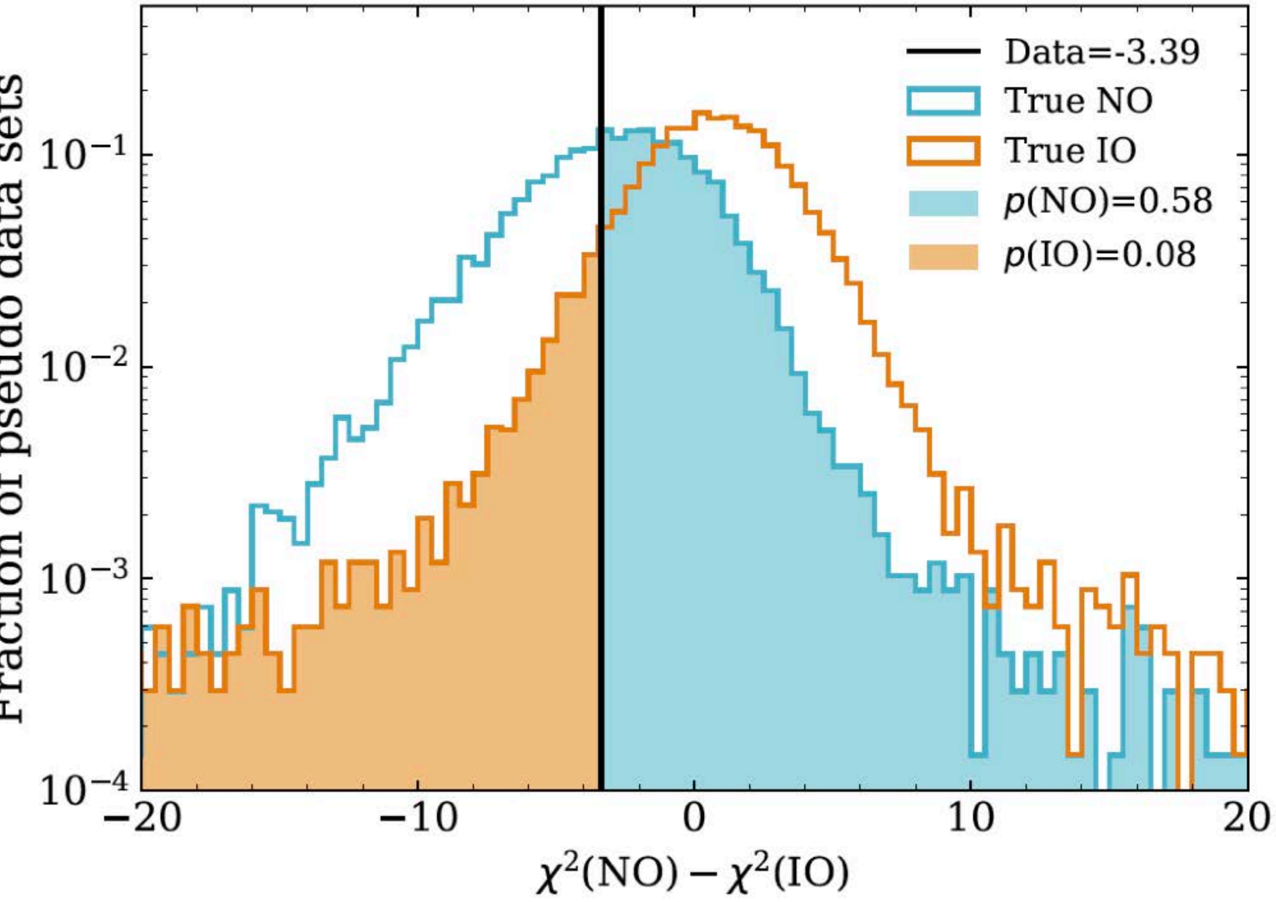
δCP = 0 allowed in normal ordering
δCP = 0 excluded at 2σ in inverted ordering

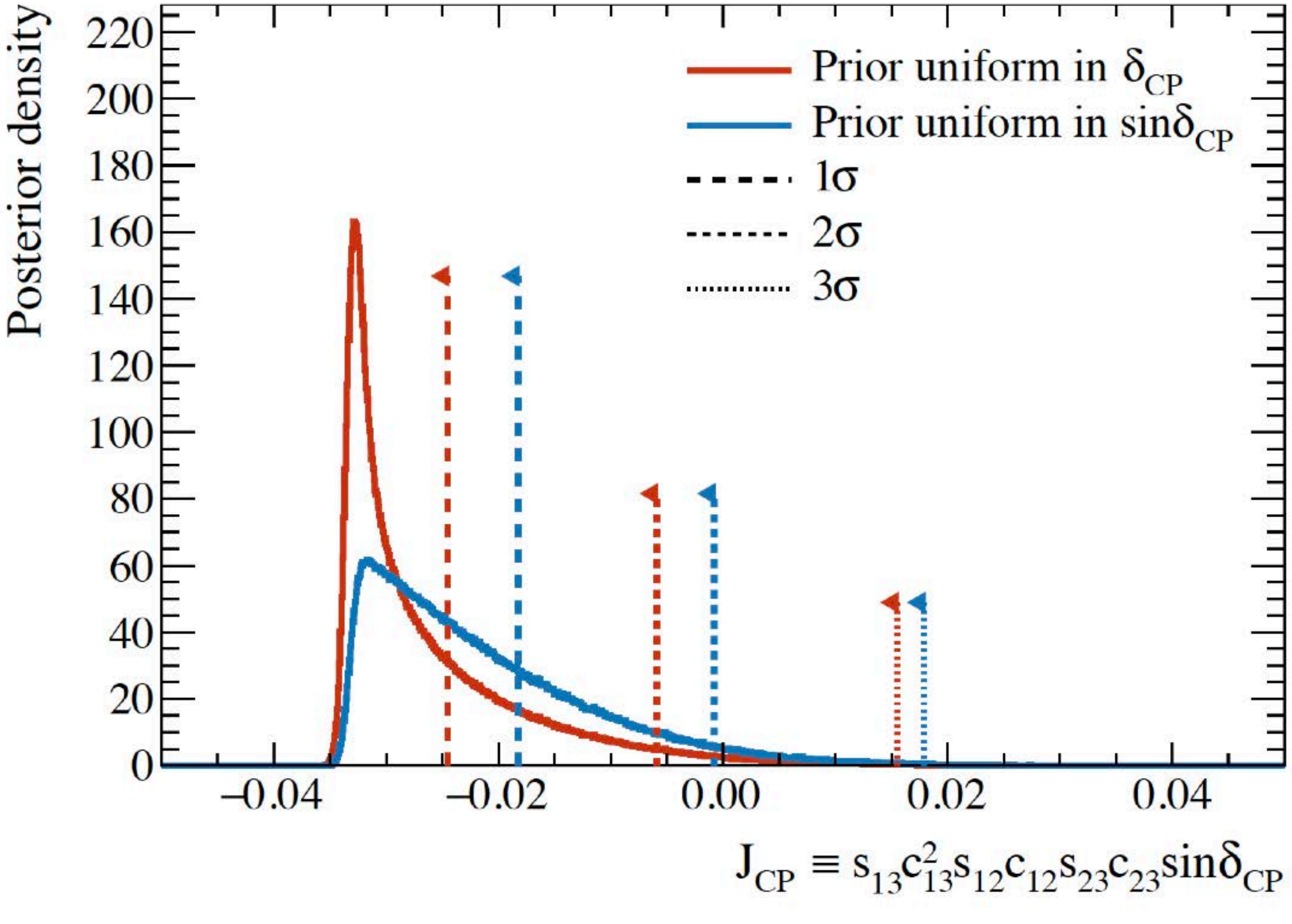
NOvA + T2K

Joint T2K + Super-K atmospheric neutrinos

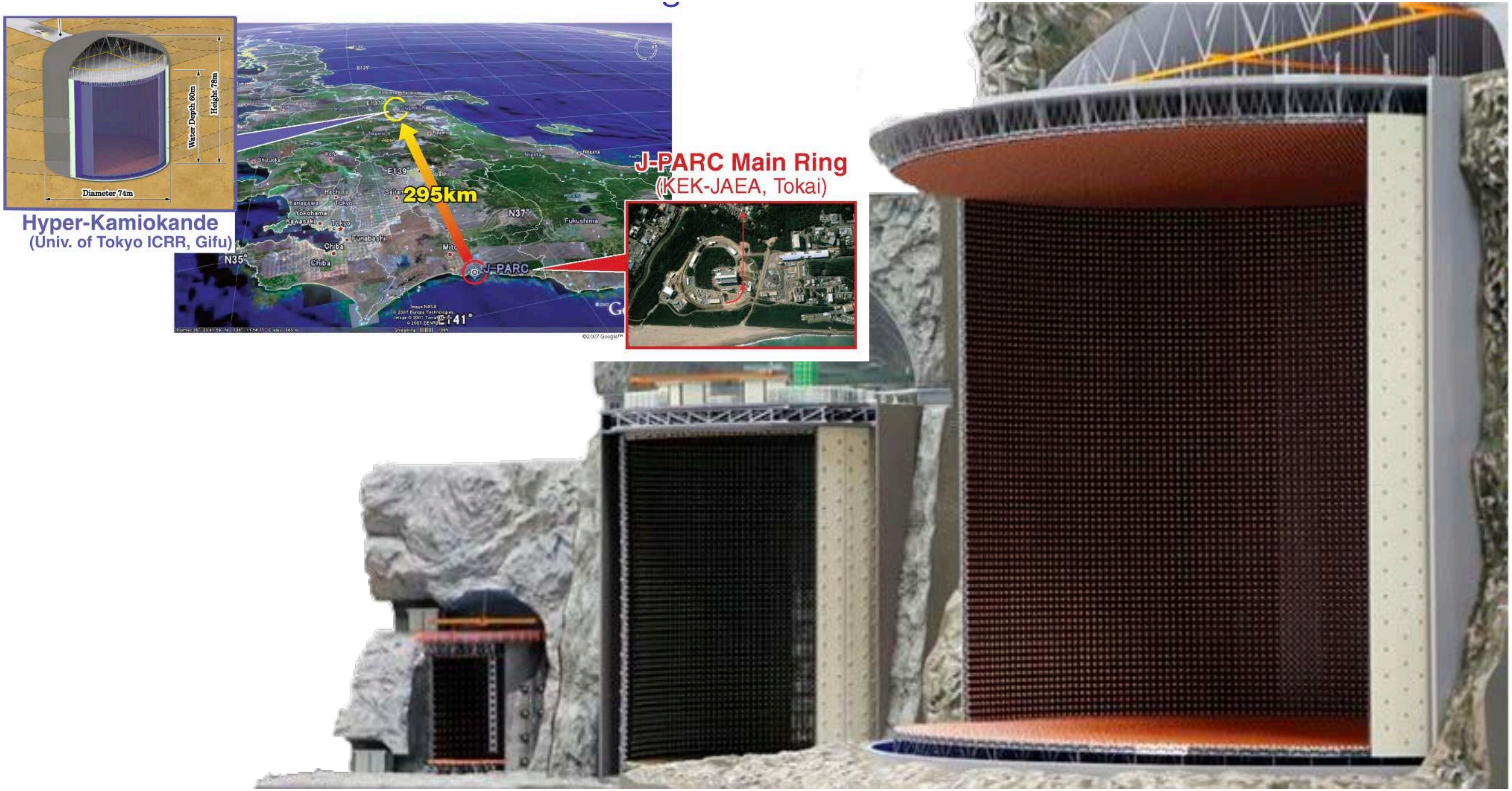
arXiv:2405.12488v1 [hep-ex] 21 May 2024







T2 Hyper-Kamiokande



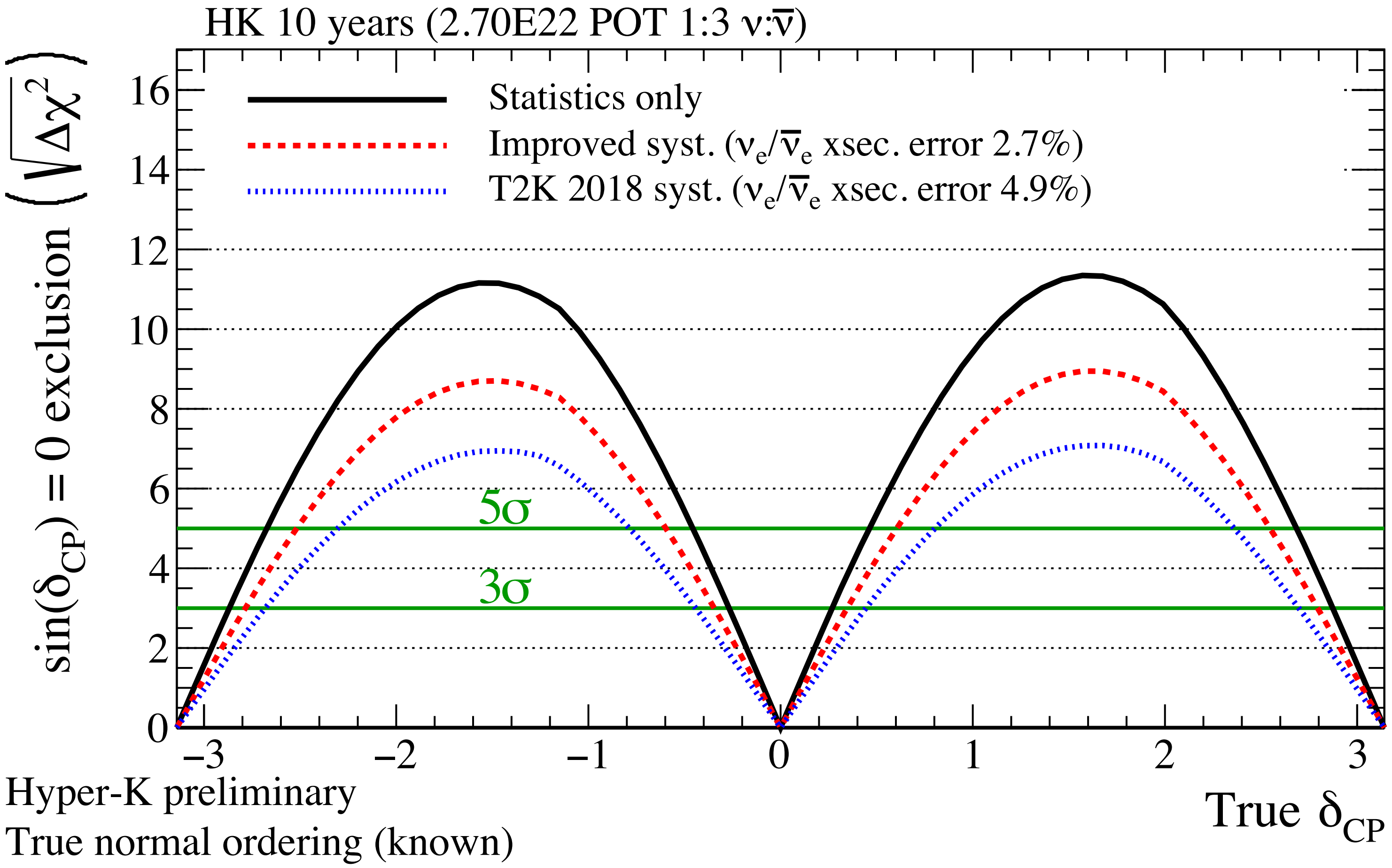
Kamiokande	**Super-Kamiokande**	**Hyper-Kamiokande**
3 kton	22.5 kton	188 kton

T2HK

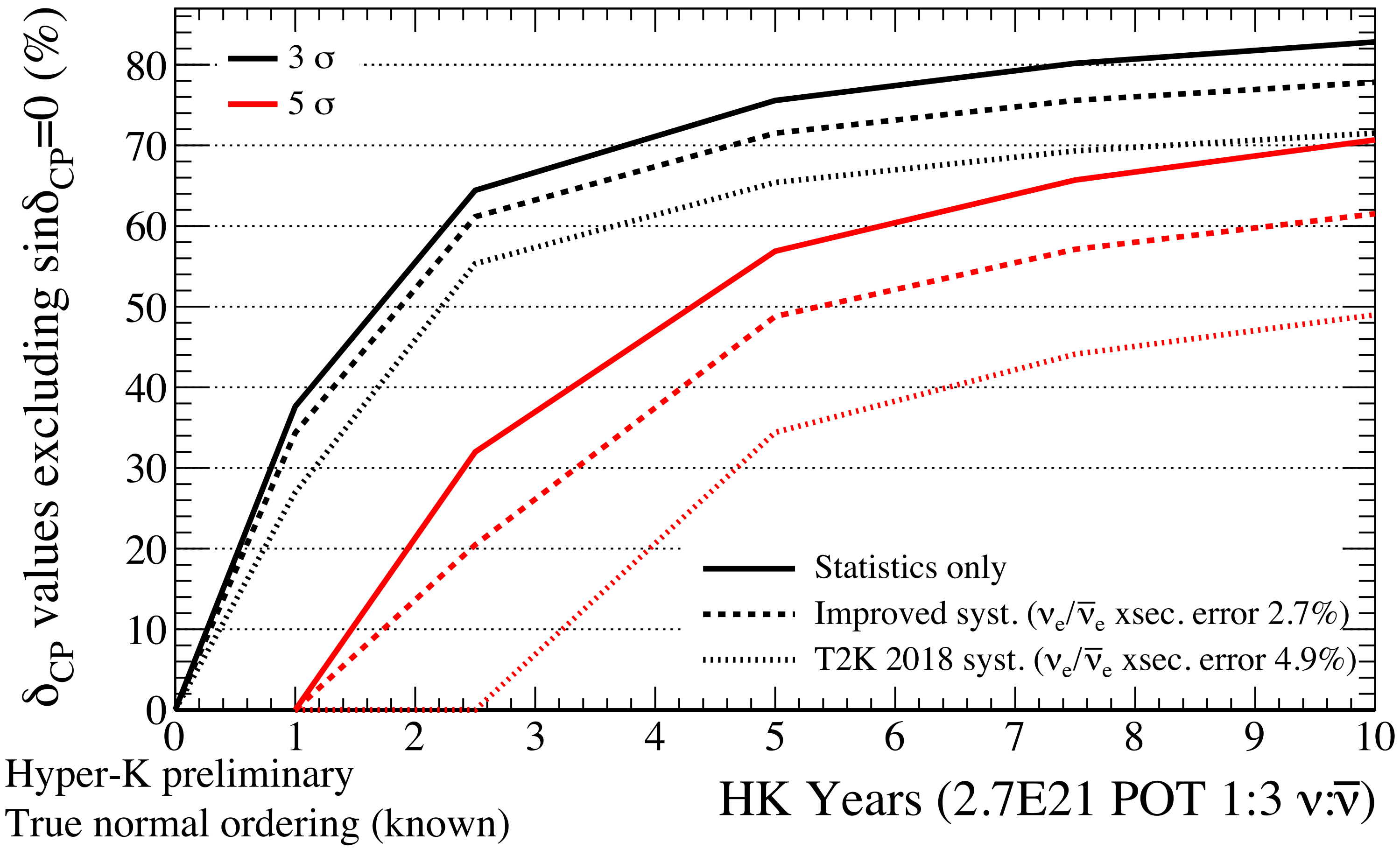
Data taking expected to begin in 2027

5σ discovery of CP violation in 10 years for 60% of δ_{CP} values

The search depends strongly on resolving the mass ordering and controlling systematic uncertainties



Hyper-K preliminary
True normal ordering (known)
$\sin^2(\theta_{13}) = 0.0218$ $\sin^2(\theta_{23}) = 0.528$ $|\Delta m^2_{32}| = 2.509\text{E-}3$



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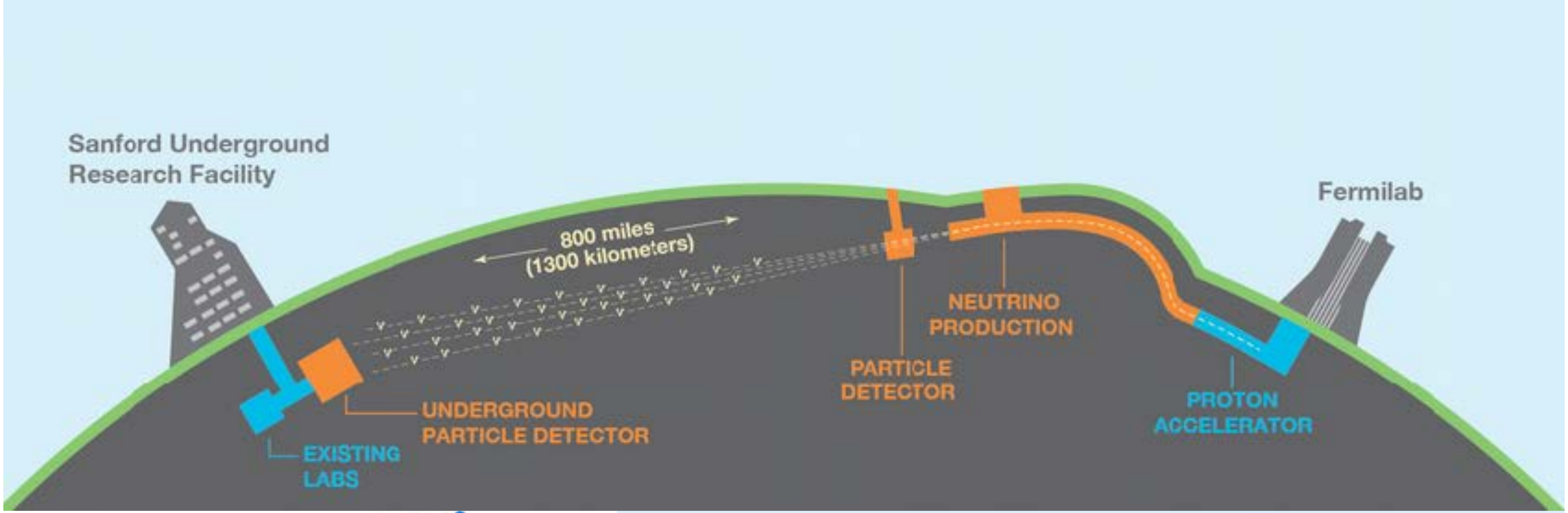
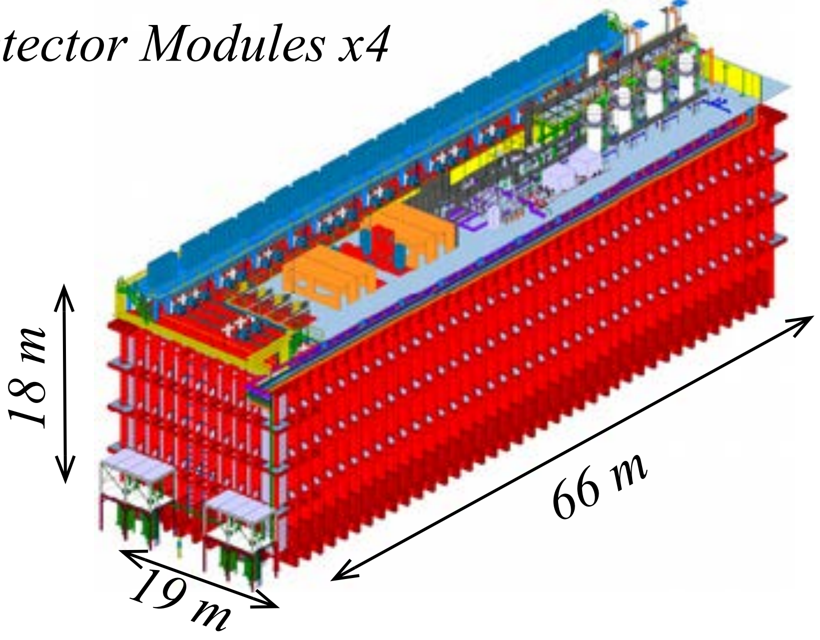
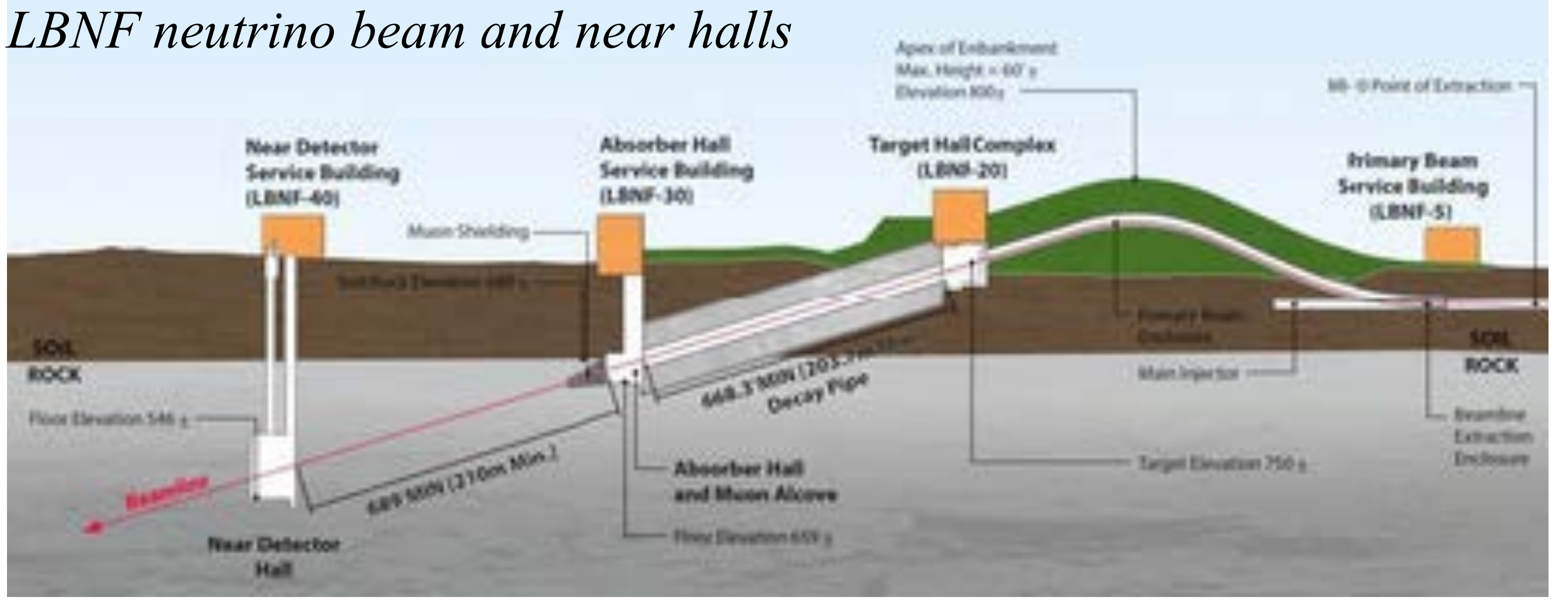
DUNE

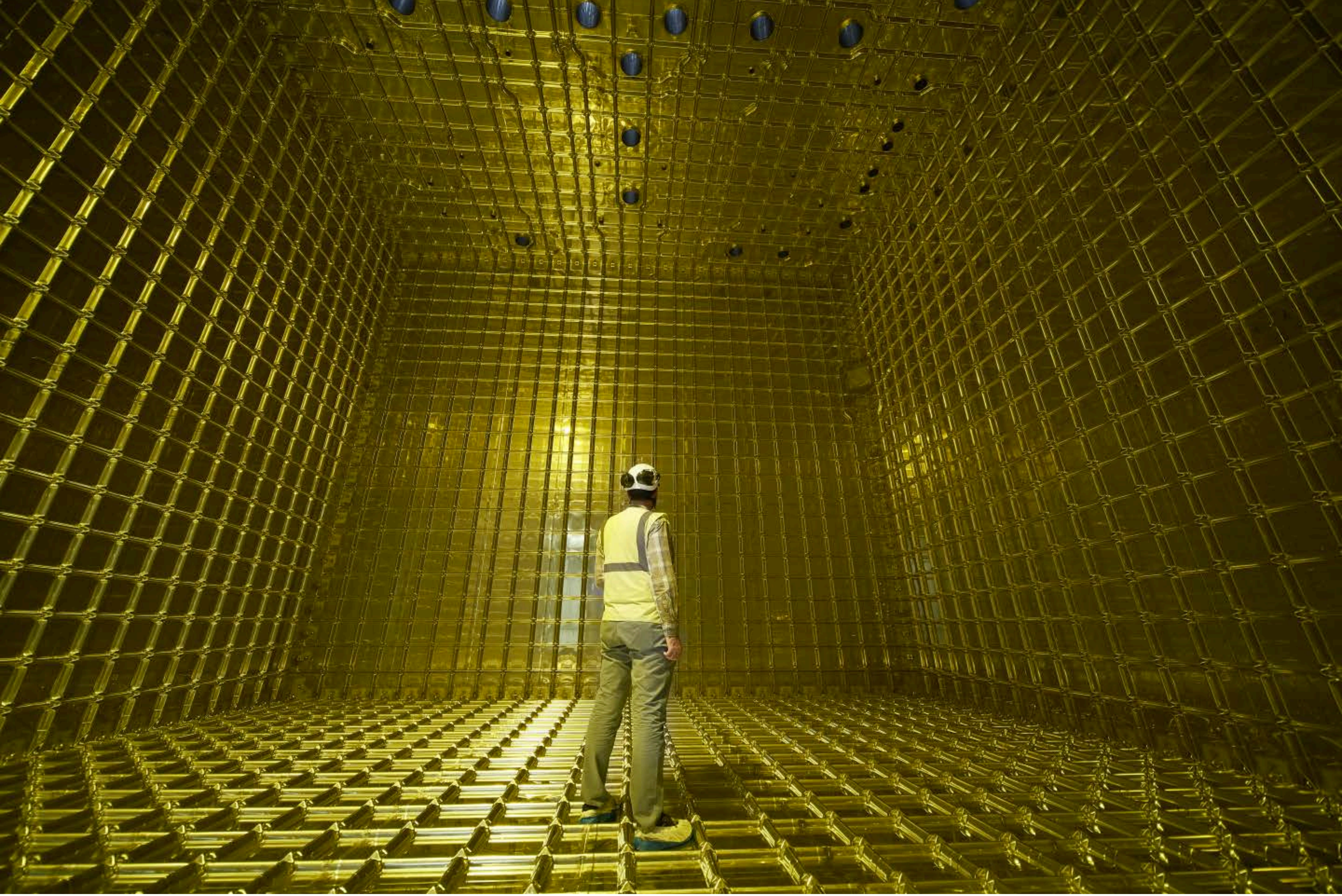


Detector Modules x4



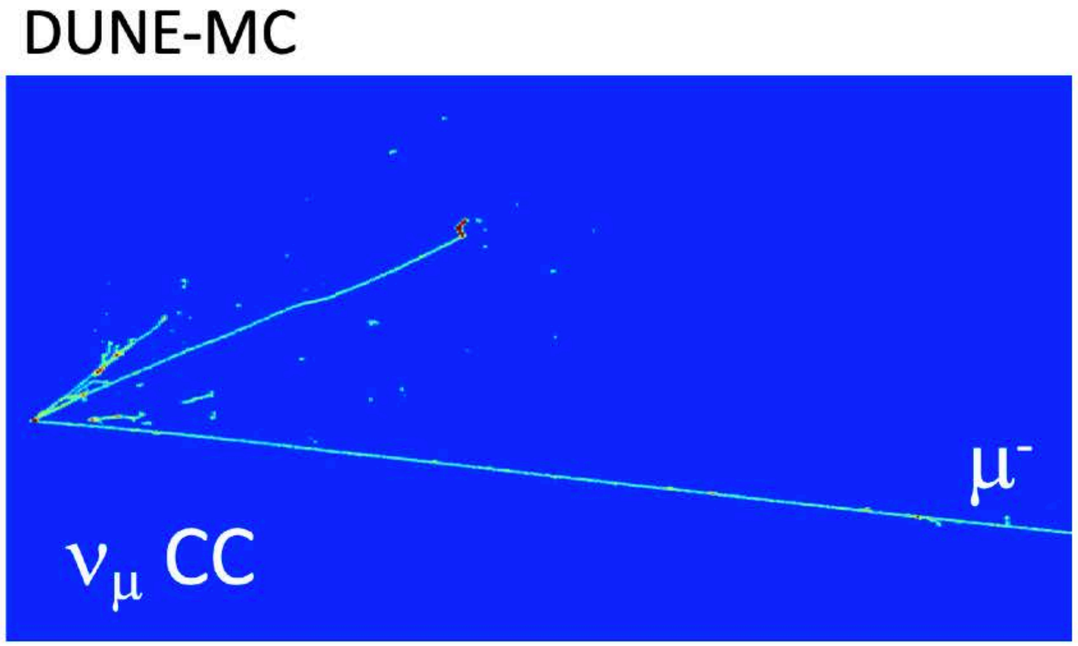
LBNF neutrino beam and near halls

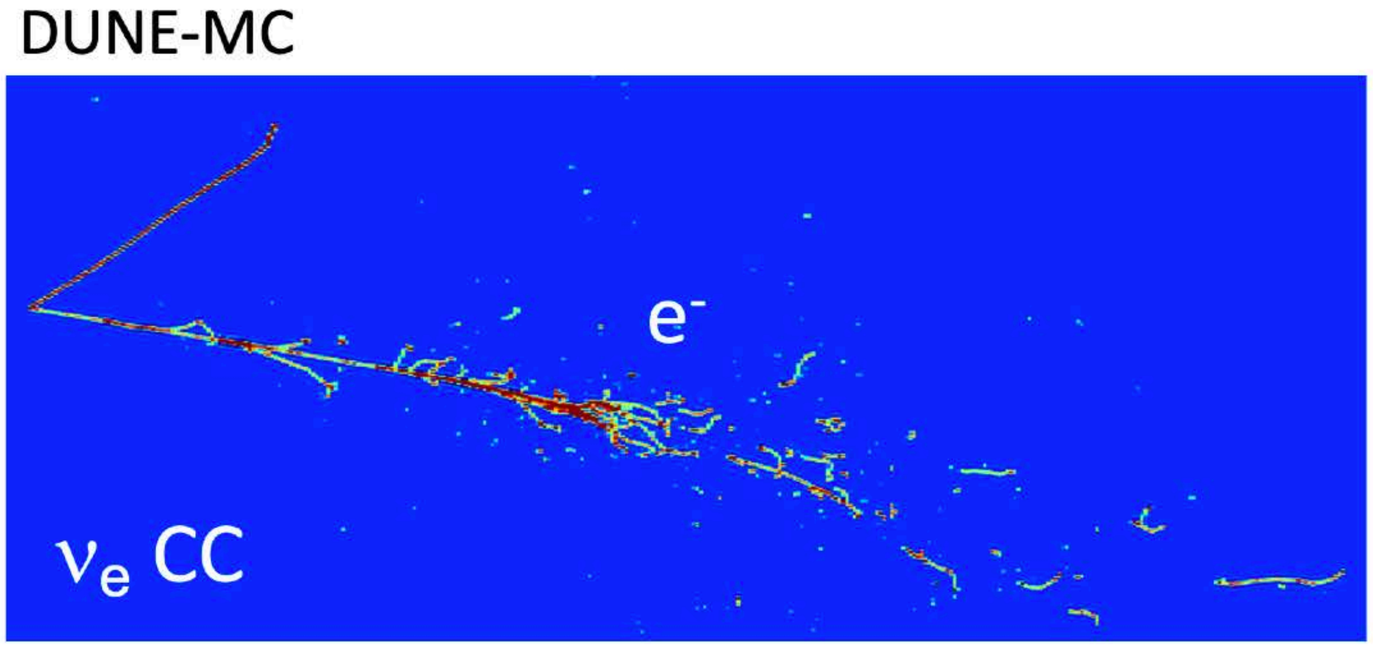




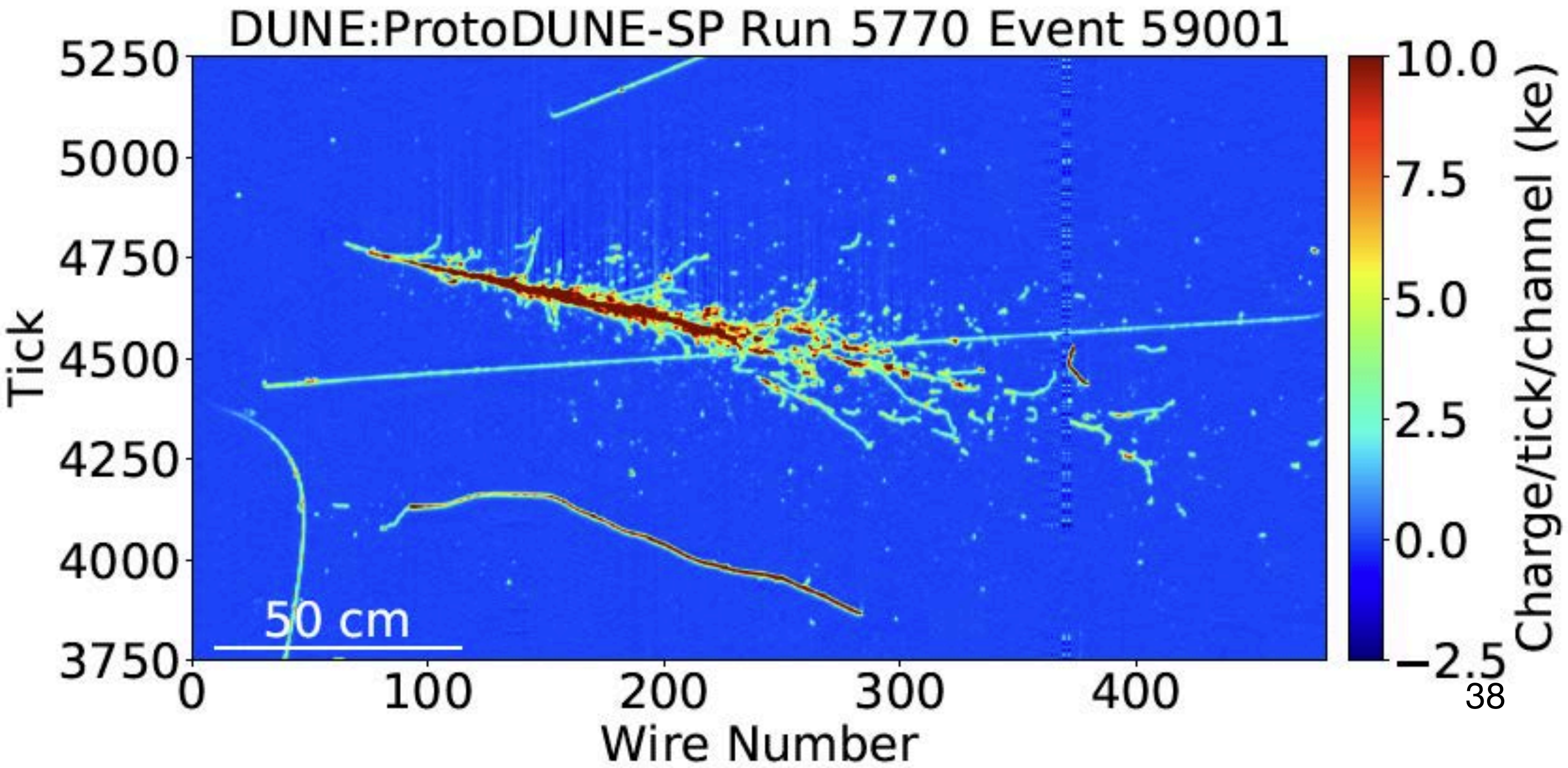
DUNE Prototype at CERN

Events in DUNE

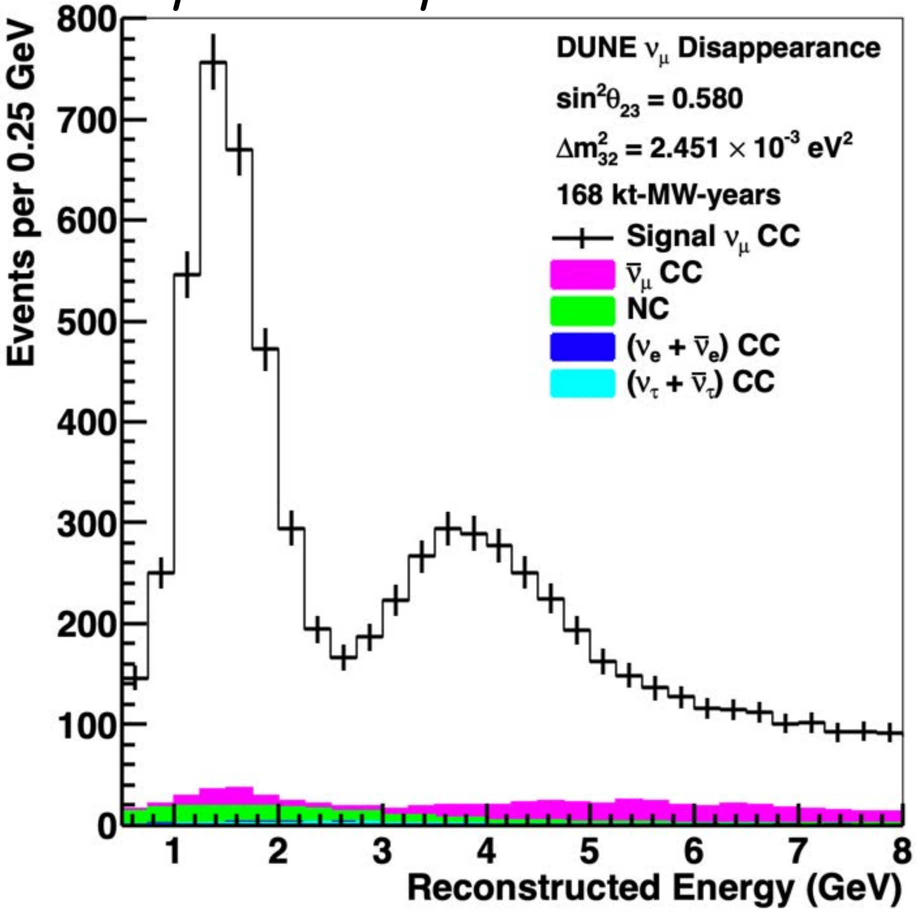




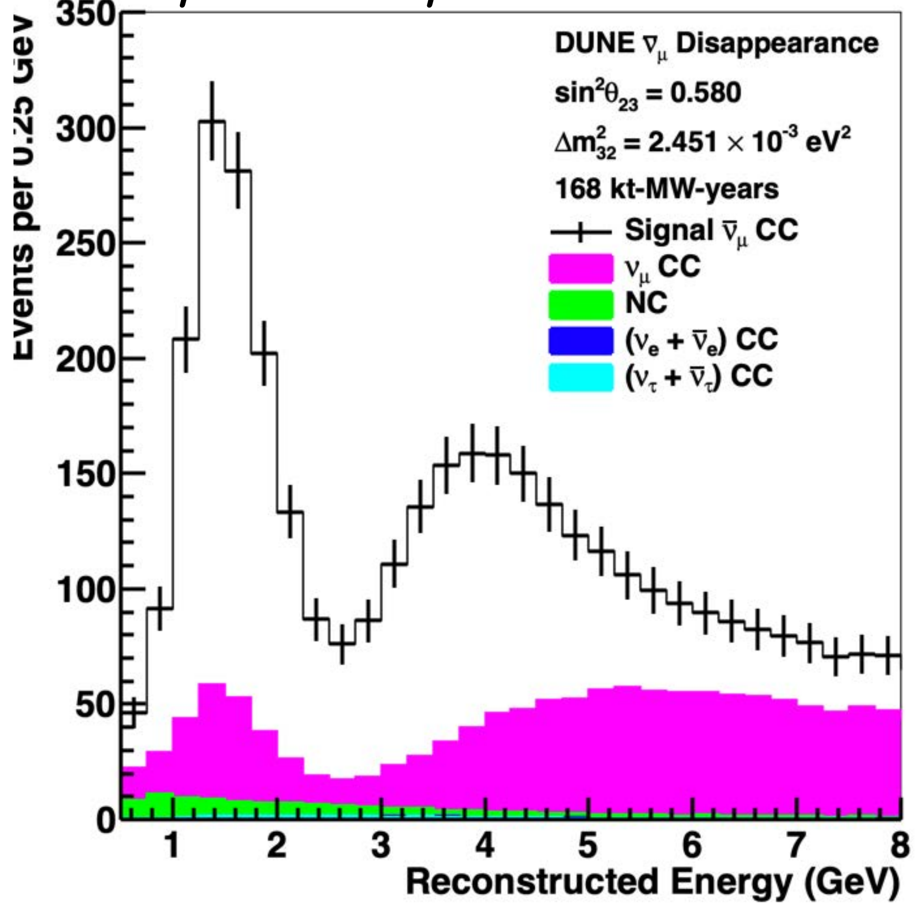
A 6 GeV electron recorded by DUNE prototype at CERN



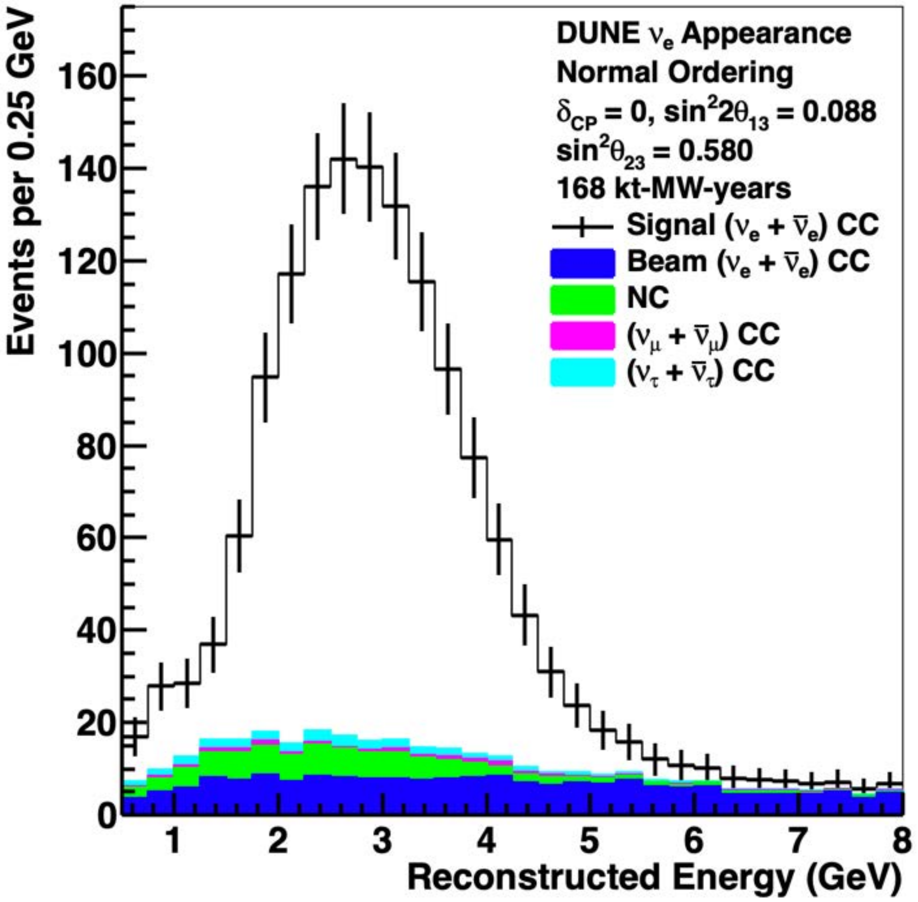
$\nu_\mu \rightarrow \nu_\mu$



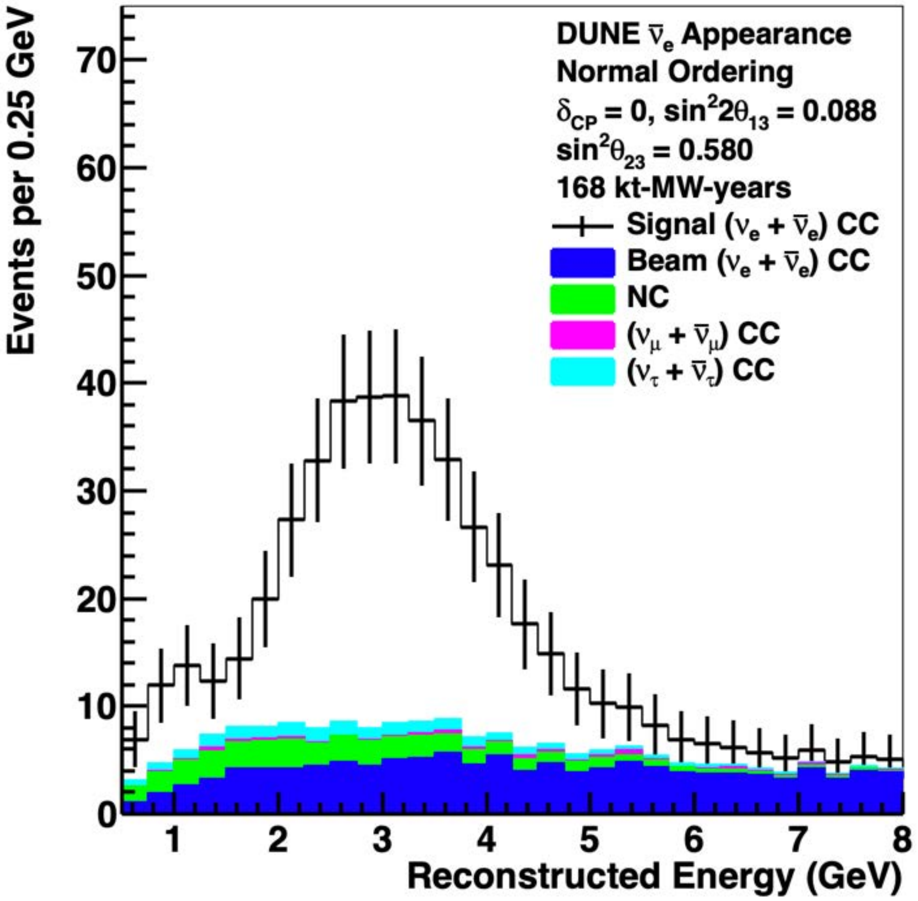
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$



$\nu_\mu \rightarrow \nu_e$



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



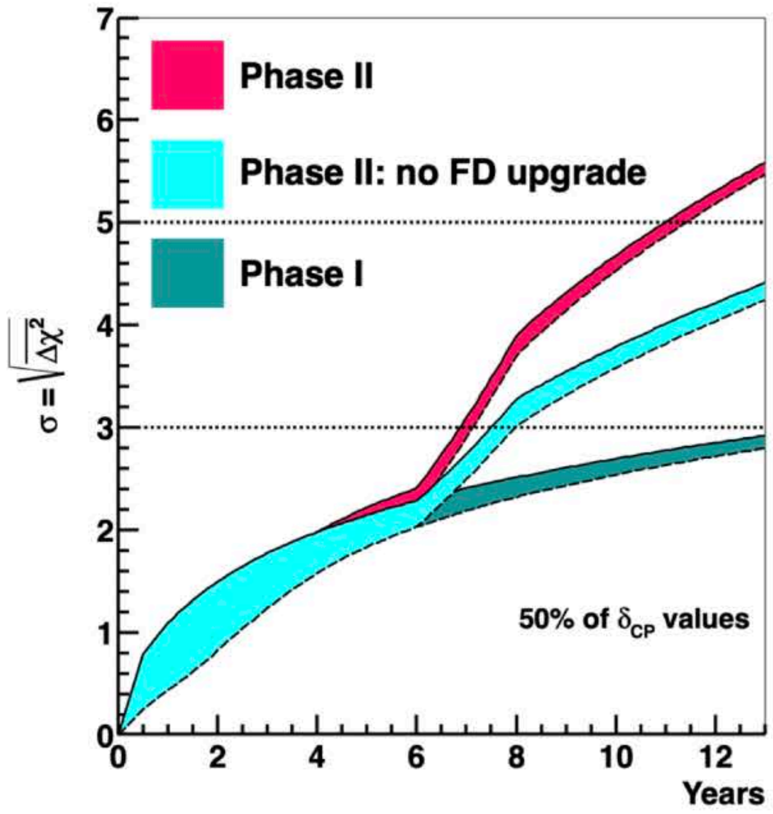
DUNE will measure $P(\nu_\mu \rightarrow \nu_\mu)$, $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$, $P(\nu_\mu \rightarrow \nu_e)$, and, $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$, at very long baseline and over a wide energy range.

Phase 1
Begins in 2029:
5σ resolution of mass ordering

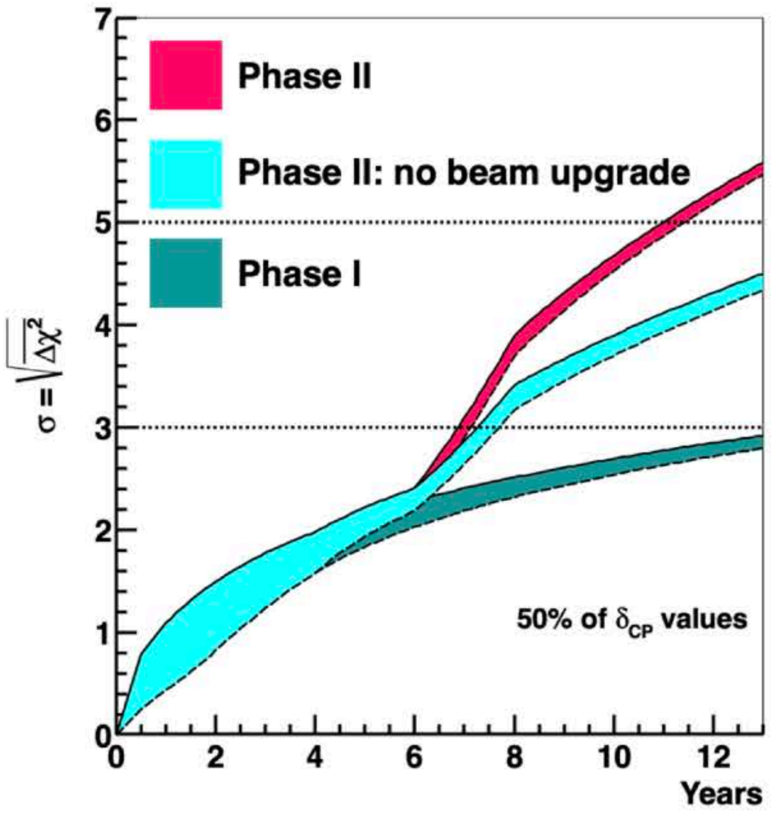
Phase 2
Begins mid 2030's:
5σ discovery of CP violation

Combination of high energy and long baseline gives unique sensitivity to physics beyond PMNS

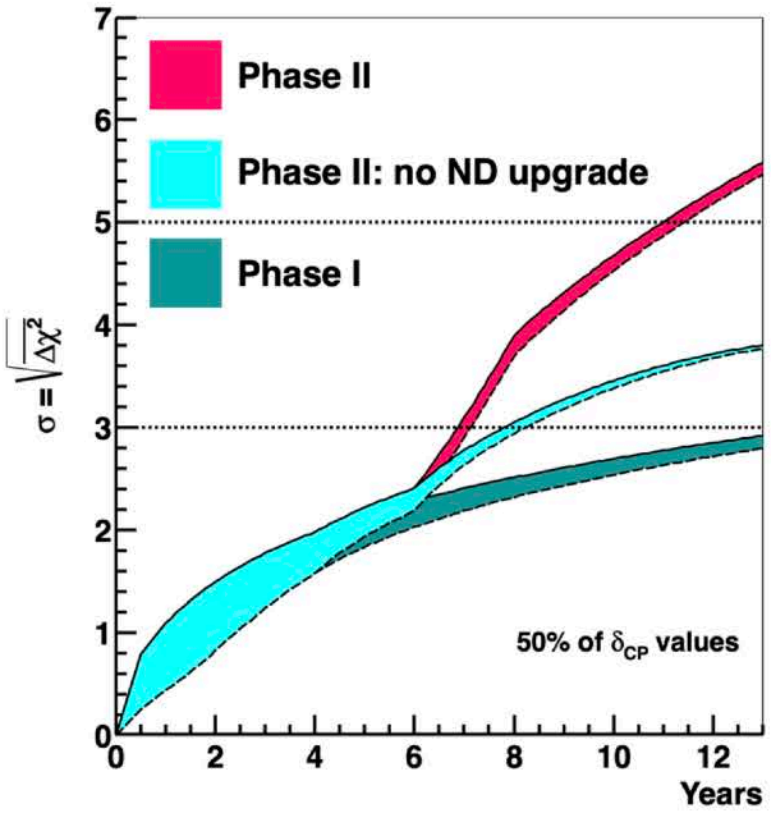
DUNE discovery potential for CP Violation and beyond



Start data taking with **2** detector modules then **4**



Fermilab proton power **1.2 MW** then **2.4 MW**



Phase one near detector and **Phase two near detector**

Summary

- Neutrino oscillations are an open window on new physics
- Big questions remain to be resolved: μ-τ symmetry, Mass ordering, CP violation
- Precision will be key to answering these questions and to make searches for new physics
- The future program is a world-wide endeavor and will require a diverse experimental program. In the U.S., the program will be anchored by DUNE.