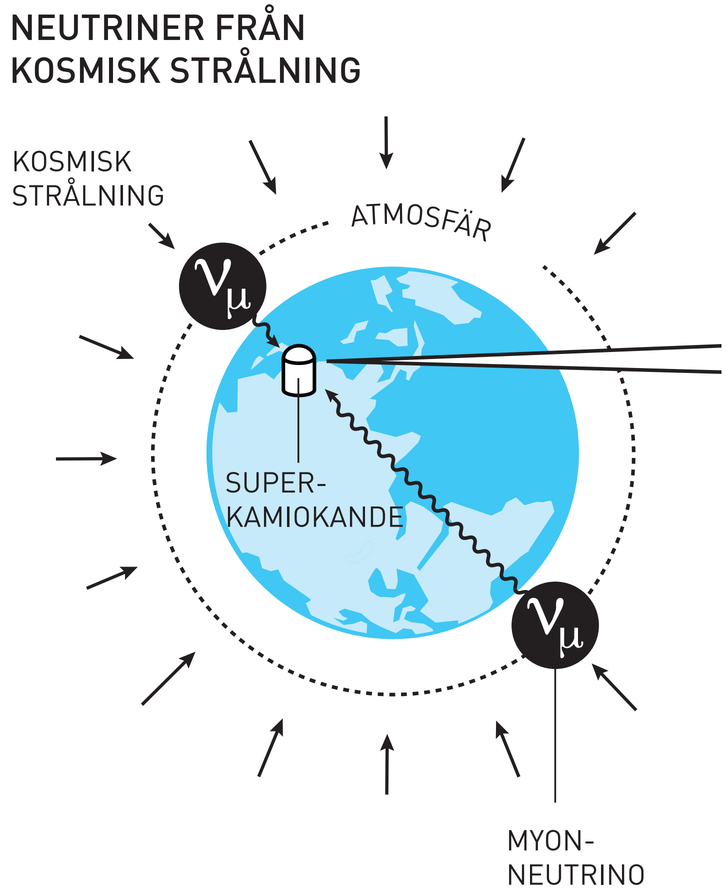
ICPPA2020@Moscow (online)
October 8, 2020

Neutrino oscillations in long baseline experiments

T. Nakaya (Kyoto U.)

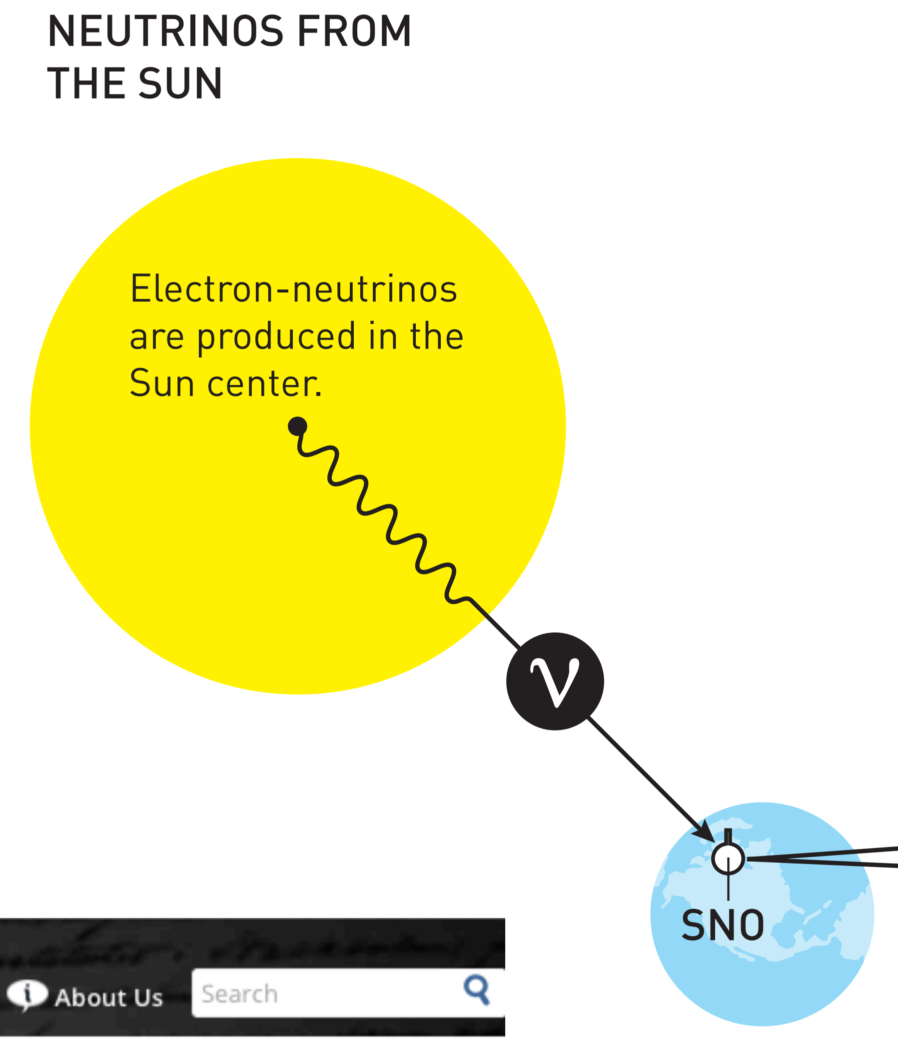
Recent results in neutrino physics are found in the NEUTRINO2020 page:
https://conferences.fnal.gov/nu2020/

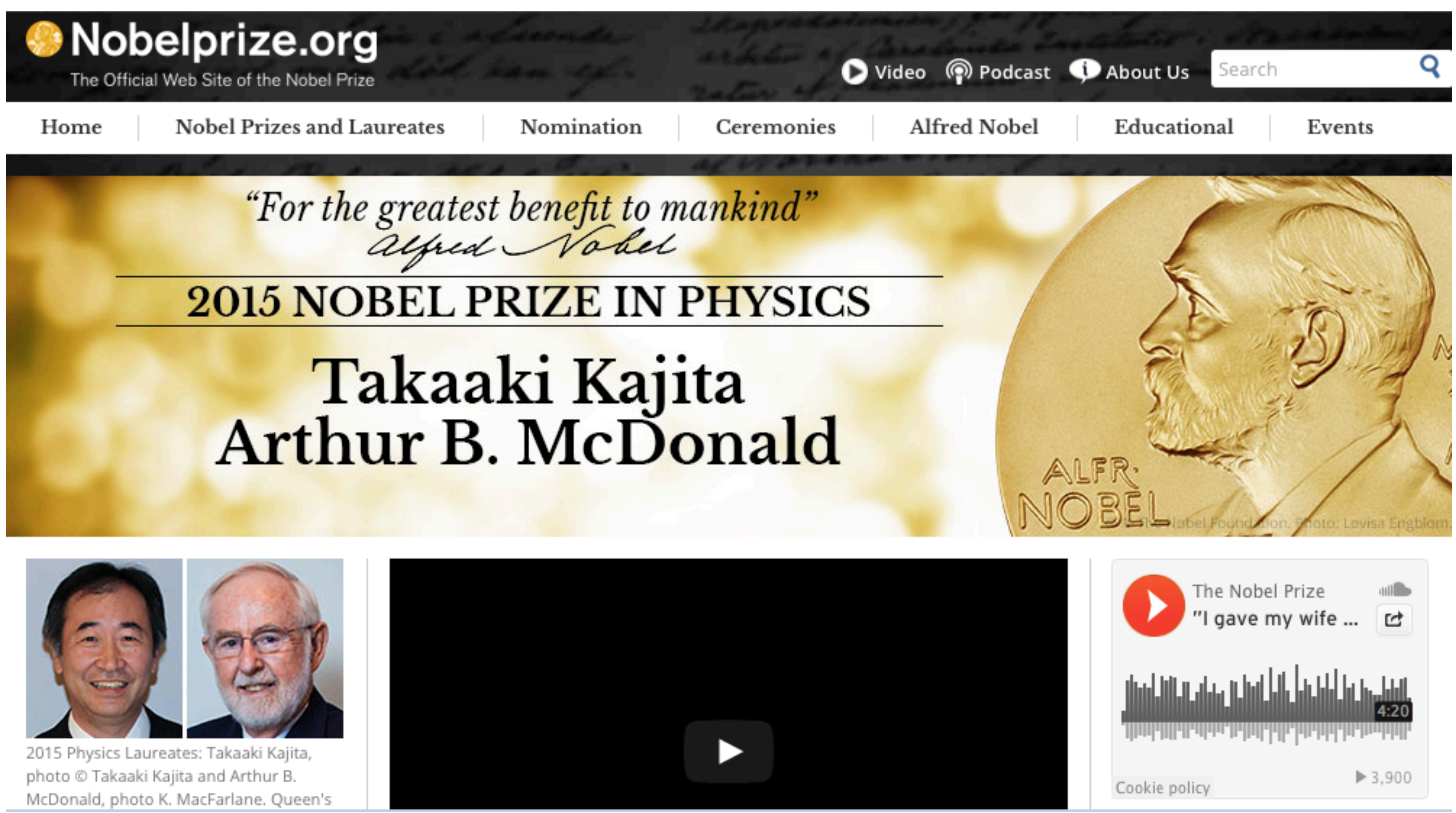


Nobel week

Black hole

in 2015

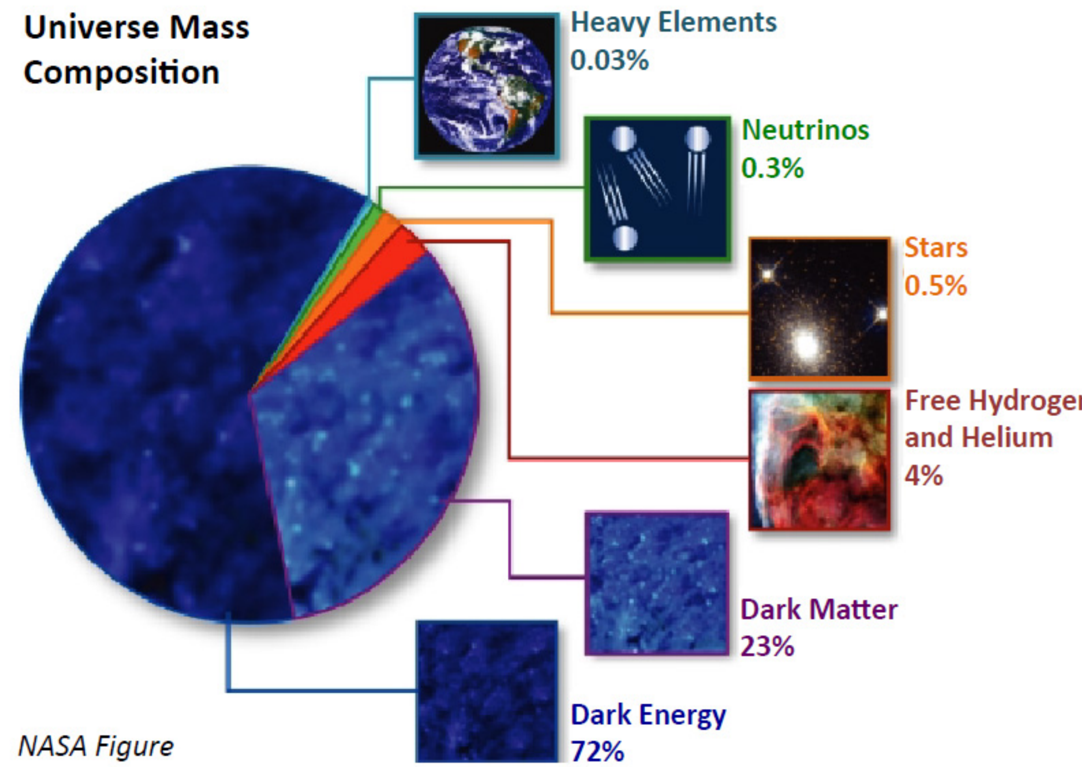


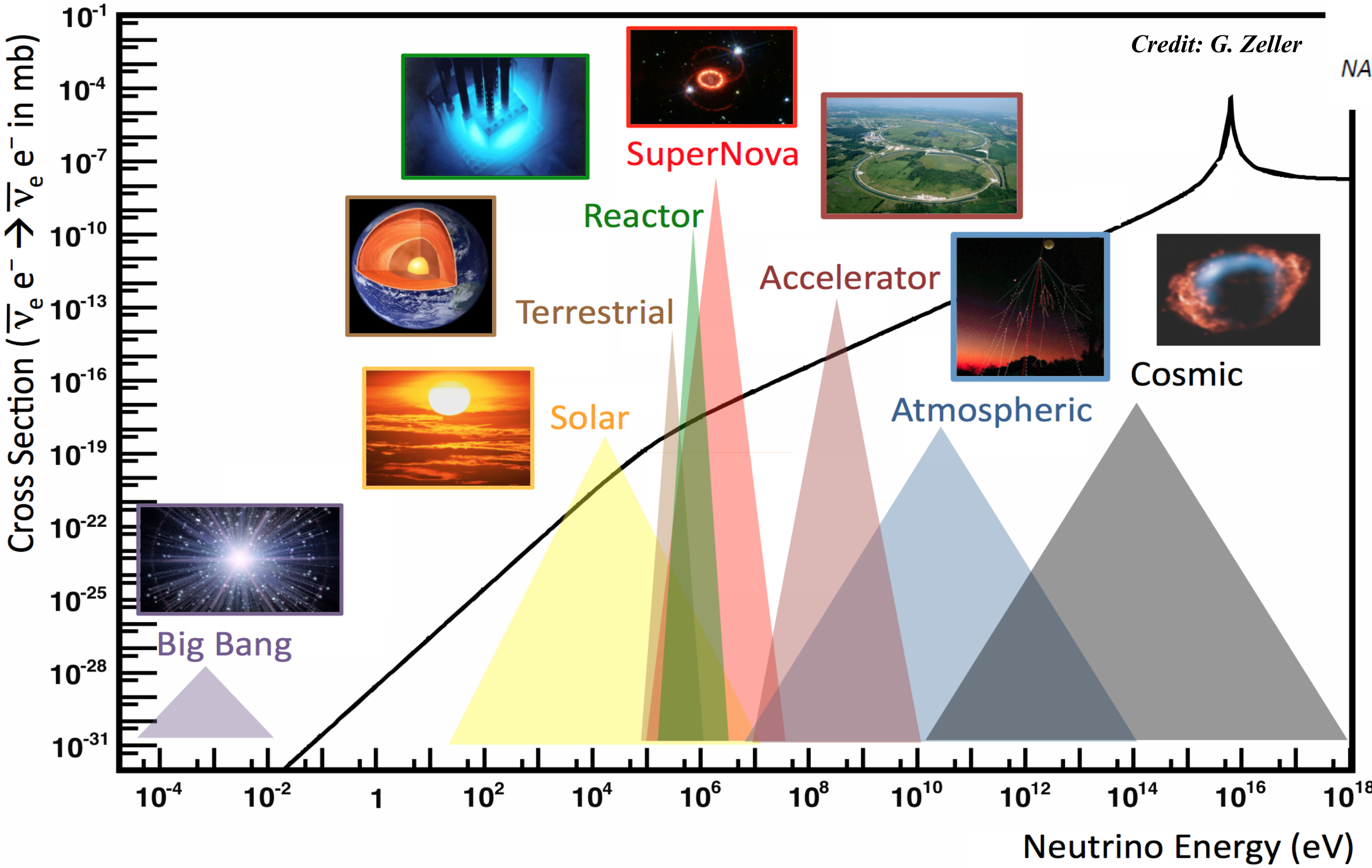


Why Neutrinos?

They are always around us and mysterious!

- T_ν=1.95K
- $\#N_\nu=112\times3cm^{-3}$





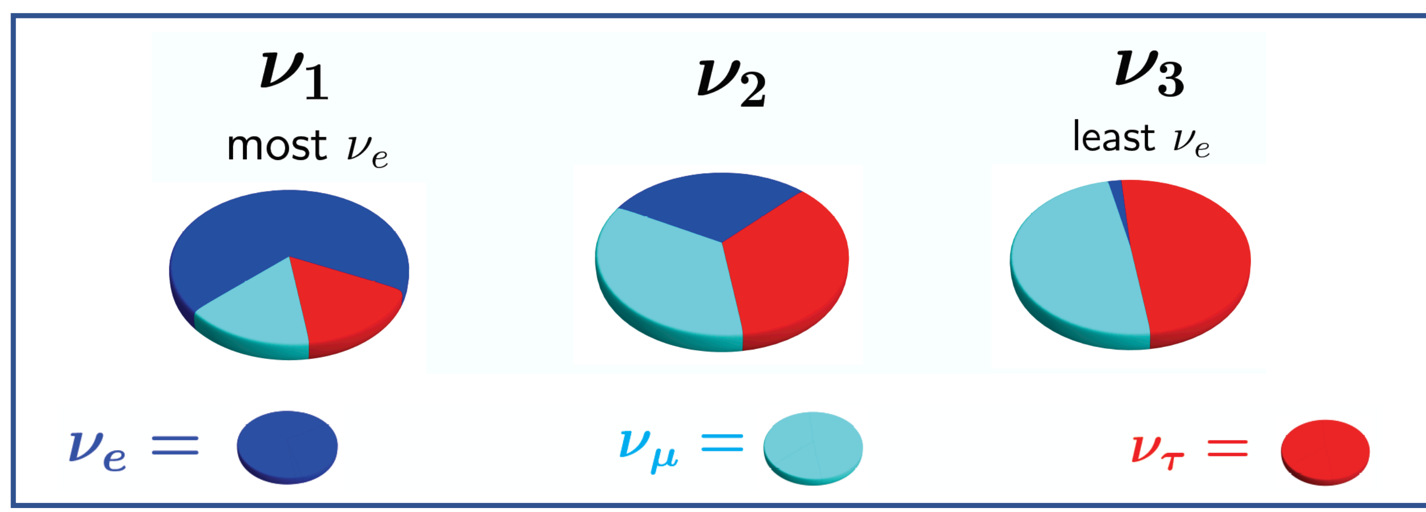
- Particle Physics
- AstroPhysics
- Cosmology
- High energy Astro-particle physics
- Nuclear physics

by S. Gollapinni @ICHEP2020

Neutrino oscillation

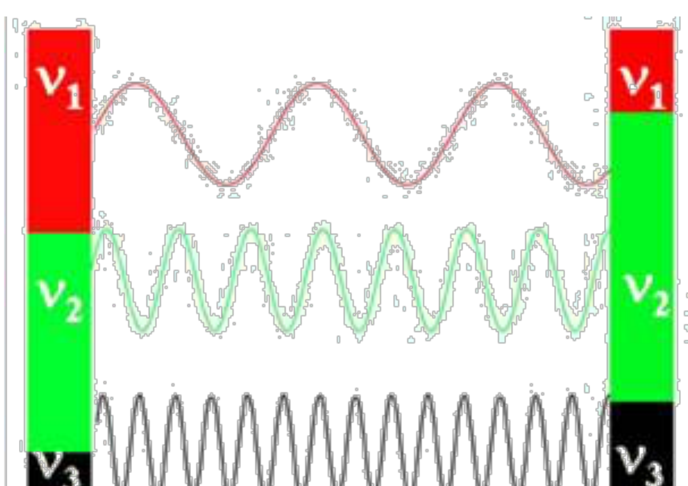
Probing very small neutrino masses

- Interferometer to be sensitive to the small masses (and a potential)
  - $\Delta m_{32}^2 \equiv m_3^2 - m_2^2 \sim 2.5\times10^{-3}$ eV^2
    - If $m_3 >> m_2$, m_3 ~ 0.05 eV (⇄ m_e~511,000 eV)
  - $\Delta m_{21}^2 \equiv m_2^2 - m_1^2 \sim 7.5\times10^{-5}$ eV^2
    - If $m_2 >> m_1$, m_2 ~ 0.009 eV (⇄ m_e~511,000 eV)



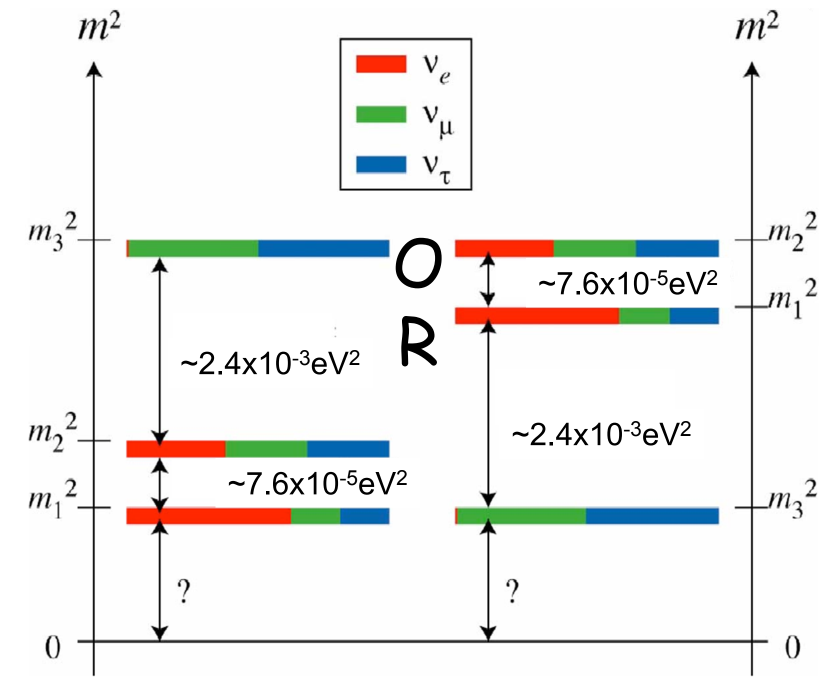
by S. Seo@WIN 2019

$|\nu_e\rangle =$



$= c_1|\nu_e\rangle + c_2|\nu_\mu\rangle + c_3|\nu_\tau\rangle$

Neutrino Oscillation



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

Solar, Reactor (ν_1, ν_2)

Atmospheric, Accelerator (ν_2, ν_3)

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

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric
Accelerator

Accelerator
Reactor
Atmospheric

Solar
Reactor

$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.55 & 0.15 \\ -0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$\delta \sim -\pi/2$?

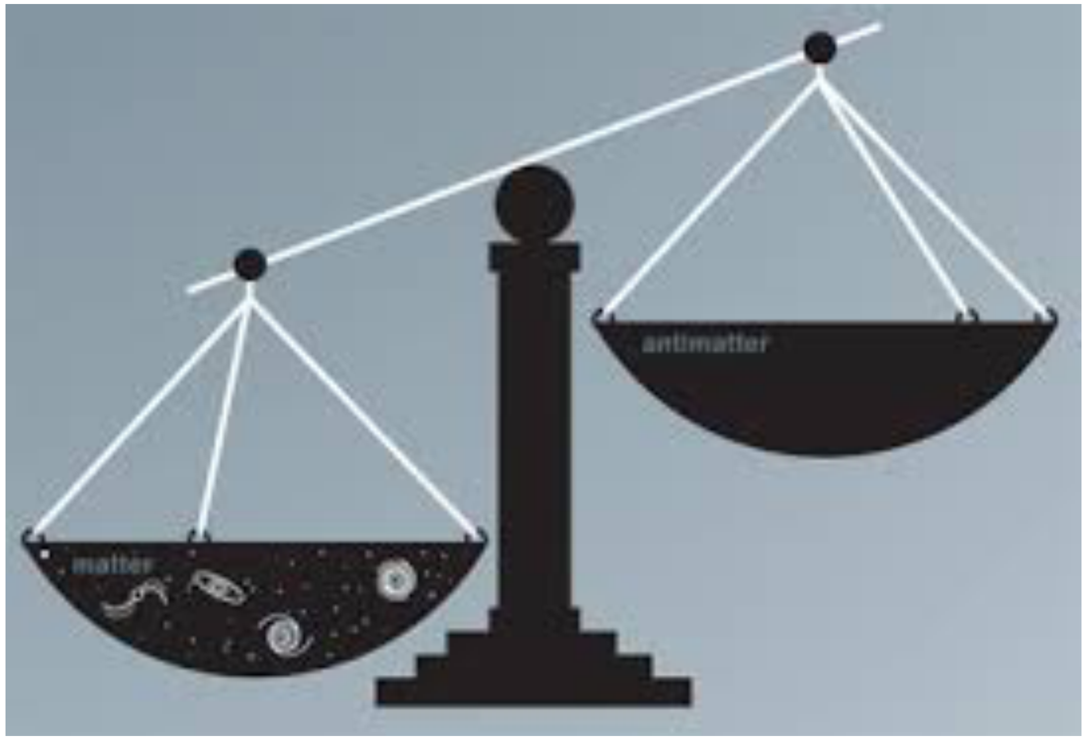
$$U_{CKM} \sim \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & \sim 1 \end{pmatrix}$$

$\delta = 60°$

- In the framework of 3 neutrinos, the unknowns are
  - mass ordering
  - CP violation parameter: δ_{CP}

CP Violation

- In the Big-Bang, particles and anti-particles were produced in same amounts.
- Later, they would annihilate.
  - $e^+ + e^- \rightarrow$ photons
  - $p + p_{bar} \rightarrow$ photons ($\pi^+ + \pi^-$)



- Violation of the symmetry between a particle and the anti-particle.
  - CP violation

CP violation is necessary for particles only to survive and to form our universe.

Leptogenesis and Neutrino CPV

- Saharov conditions for Baryon Asymmetry
  - [B] Baryon Number Violation
  - [CP] C and CP violation
  - [T] Interactions out of thermal equilibrium

- Leptogenesis and Low Energy CP violation in Neutrinos
  - [B] Sphaleron process for $\Delta(B+L)\neq 0$
  - [CP] Many models predicting Baryon asymmetry
    - Examples "Heavy Majorana Neutrino decay and/or Neutrino oscillations"
      - [Phys. Rev. D75, 083511 (2007)] $|\sin\theta_{13}\sin\delta|>0.09$ is a necessary condition for a successful "flavoured" leptogenesis with hierarchical heavy Majorana neutrinos when the CP violation required for the generation of the matter-antimatter asymmetry of the Universe is provided entirely by the Dirac CP violating phase in the neutrino mixing matrix.
      - $\sin\theta_{13}\sim 0.15$ ➡ $|\sin\delta|>0.6$

Long baseline experiments

Various neutrino sources for various experiments

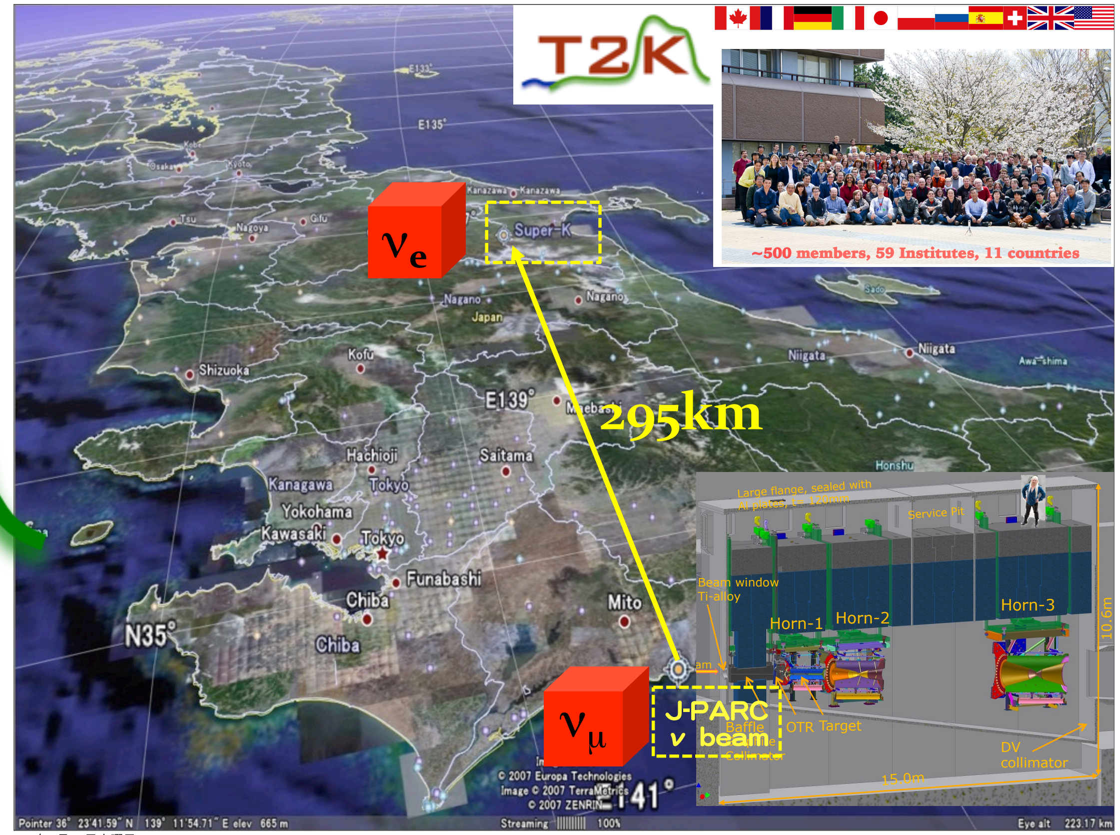
ν source	Baseline	Energy	Sensitive parameters
Solar	1.5×10^8 km	0.1-10 MeV	θ_{12} and Δm_{21}^2
Atmospheric	10~13,000 km	0.1 ~ 100 GeV	θ_{23}, (θ_{13}), Δm_{32}^2, and (δ_{CP})
Reactor	1~200 km	2~8 MeV	θ_{12}, θ_{13}, Δm_{21}^2, Δm_{32}^2
Accelerator	250 ~ 1300 km	0.1 ~ 10 GeV	θ_{23}, θ_{13}, Δm_{32}^2, and δ_{CP}

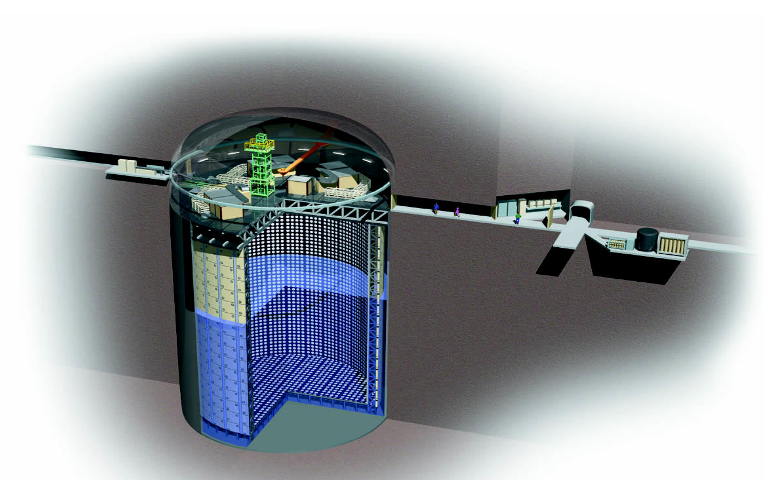
- Many types of experiments are essential to resolve regeneracies.

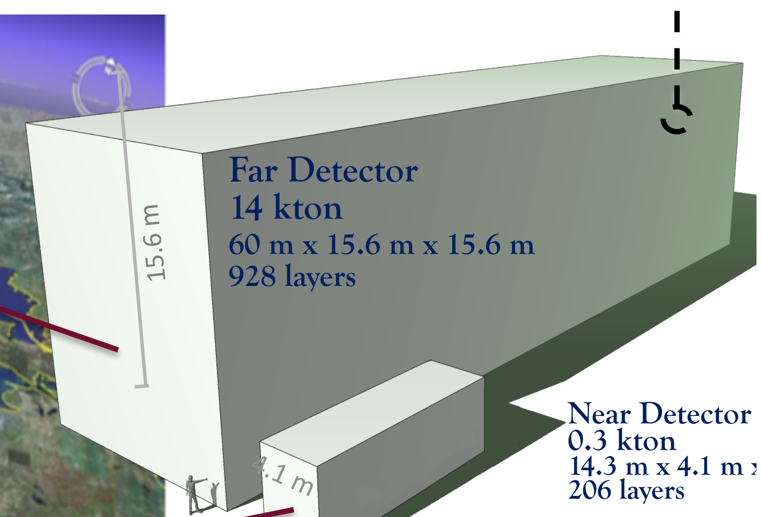
In this talk

- Accelerator: NOvA, T2K, Hyper-K and DUNE
- Reactor: Daya Bay, RENO, Double Chozo and JUNO
- Atmospheric: Super-K (NOvA, Hyper-K)
- Solar: Super-K

Long baselines accelerator experiments

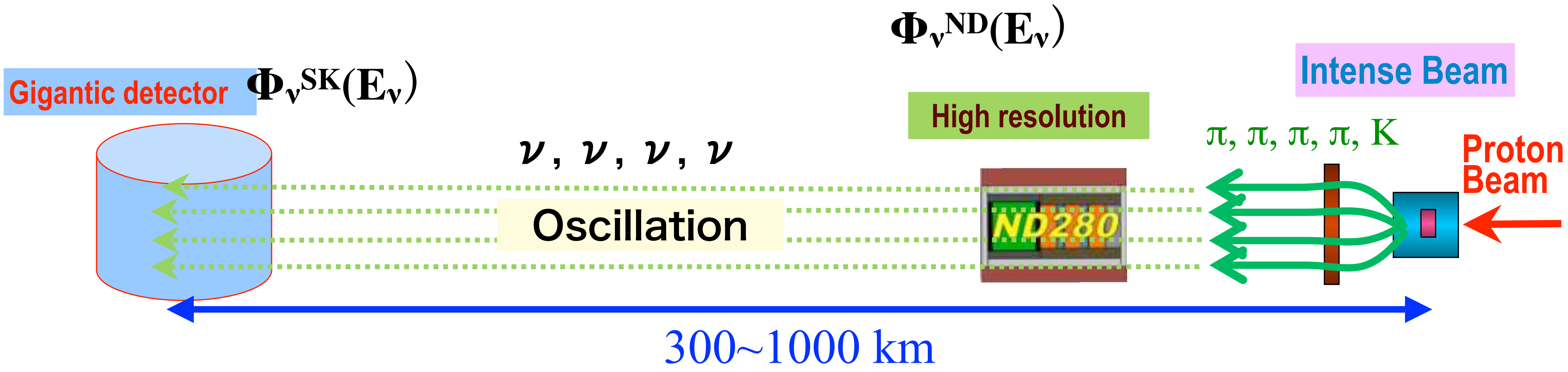






- Low-Z tracking calori
- High power NuMI bea
  - -upgraded for NOvA to t
  - the power 350 – 700 kW
  - (700 kW expected in 20
  - -this run: 85% uptime, 3

Basic of accelerator experiments



- High power proton accelerator to produce high flux neutrino beam
  - J-PARC for T2K (~520 kW power now)
  - FNAL Main Injector/NuMI for NOvA (~750 kW power now)
- Gigantic far detector to observe many neutrinos (high statistics)
  - Super-Kamiokande (22.5+α kton fiducial mass) at 295km away for T2K
  - NOvA detector (14 kton) at 810 km away for NOvA

FRAMEWORK

- Four modes of observation observed at T2K and NOvA
  - $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance
  - $\nu_\mu \nrightarrow \nu_\mu$, $\bar{\nu}_\mu \nrightarrow \bar{\nu}_\mu$ disappearance
  - use all information to constrain oscillation parameters

constrain by reactor

$$P(\nu_\mu \to \nu_e) \approx \boxed{\sin^2 2\theta_{13}} \times \boxed{\sin^2 \theta_{23}} \times \frac{\sin^2[(1-x)\Delta_{31}]}{(1-x)^2}$$

constrain by ν_μ disp.

switches sign for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$$\boxed{-\alpha \sin \delta_{CP}} \times \sin 2\theta_{12} \boxed{\sin 2\theta_{13}} \boxed{\sin 2\theta_{23}} \times \sin \Delta_{31} \frac{\sin[x\Delta_{31}]}{x} \frac{\sin[(1-x)\Delta_{31}]}{1-x}$$

$$+(\text{CP even}) \quad +\mathcal{O}(\alpha^2)$$

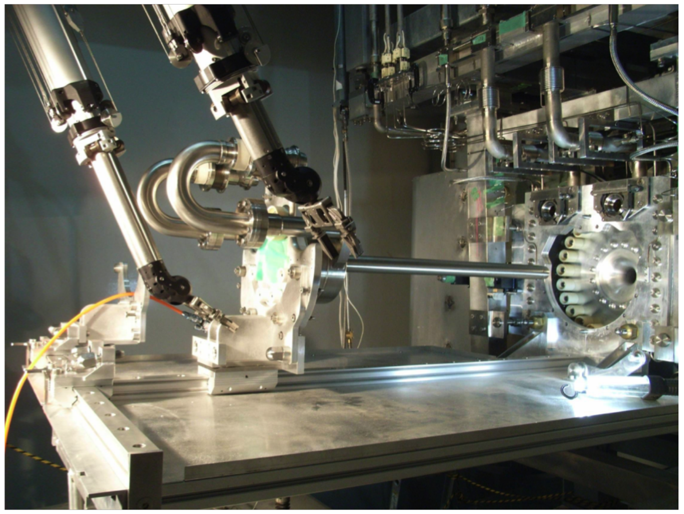
M. Freund, Phys.Rev. D64 (2001) 053003

$$\alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad \boxed{x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}}$$

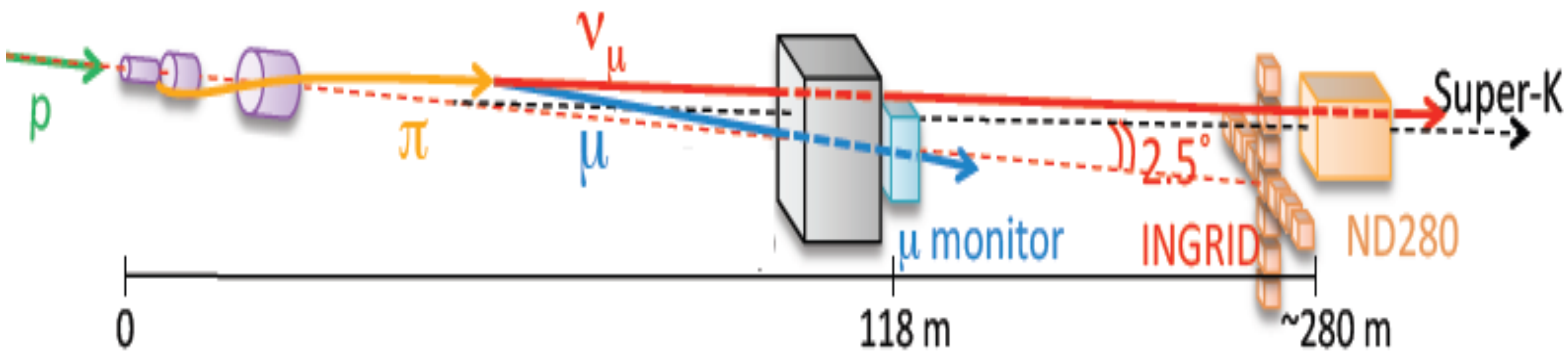
$$P(\nu_\mu \to \nu_\mu) \sim 1 - (\cos^4 2\theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2 \Delta m^2_{31} \frac{L}{4E}$$

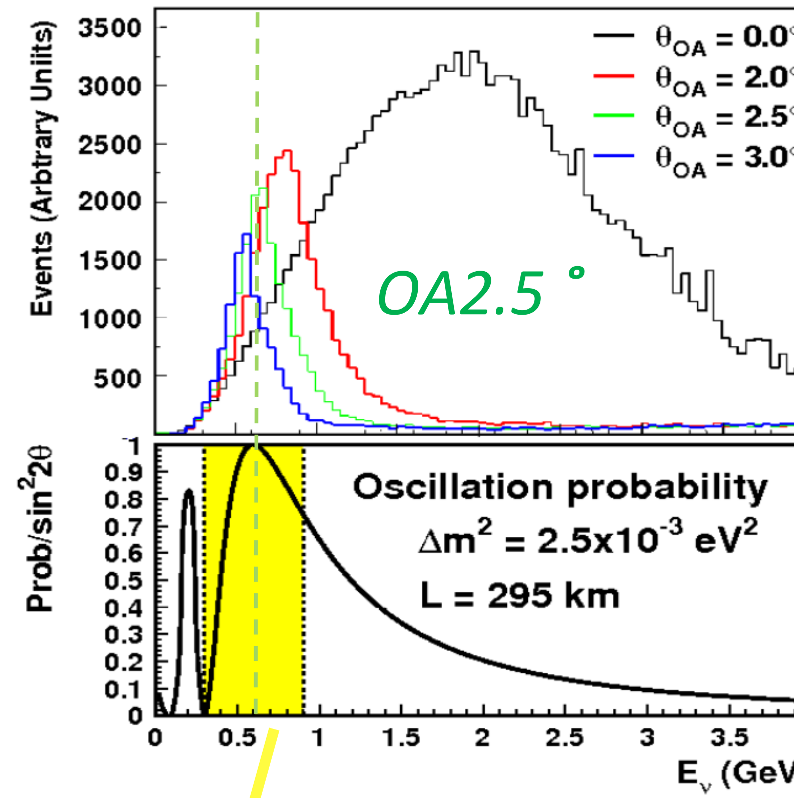
- Large θ_{23}: enhances both $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- δ_{CP} =-π/2: enhance $\nu_\mu \rightarrow \nu_e$, suppress $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Δm^2_{31}>0 (normal hierarchy): enhance $\nu_\mu \rightarrow \nu_e$, suppress $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

T2K ν beam and near detectors

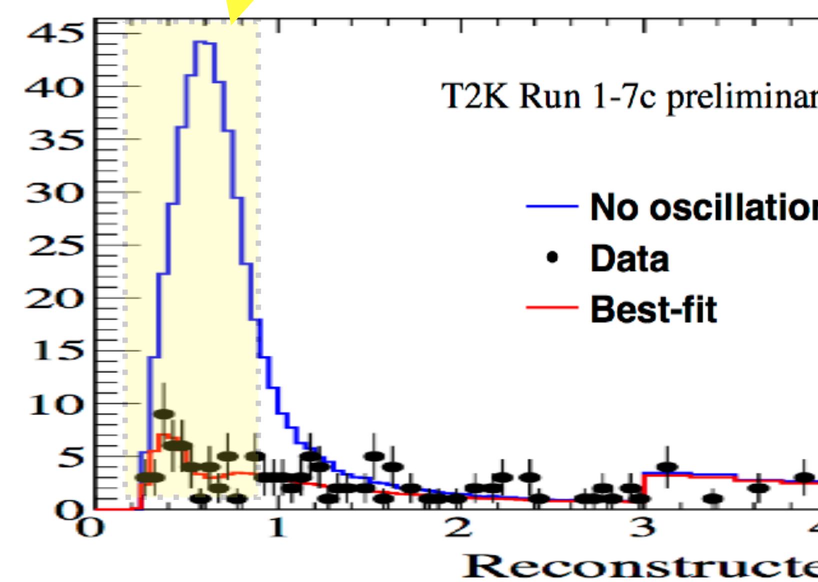


Target + remote handling system



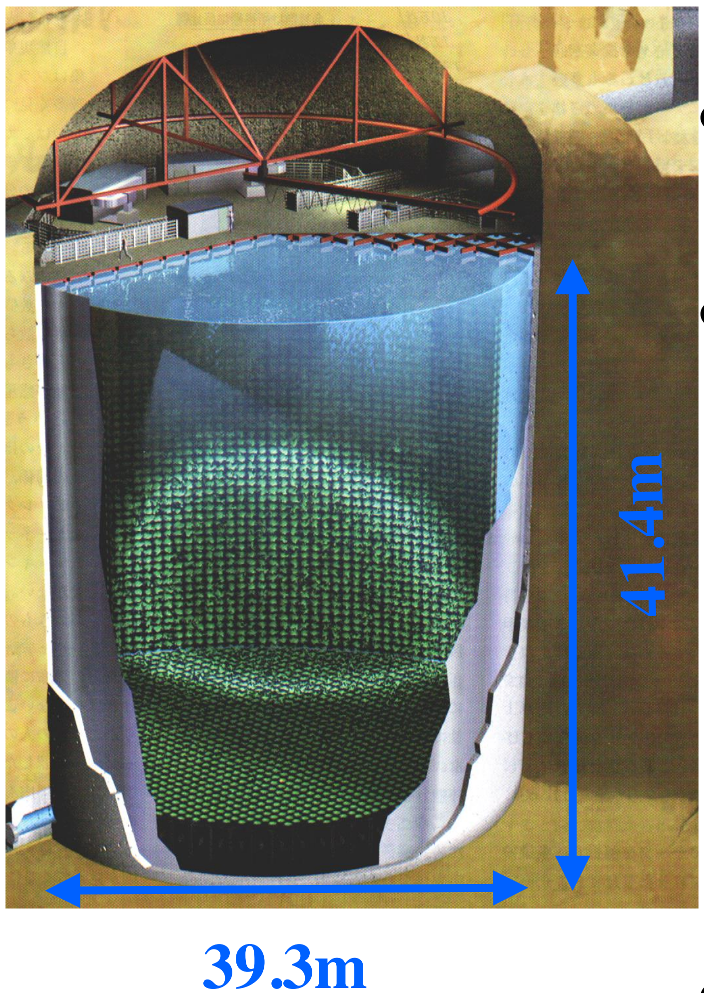


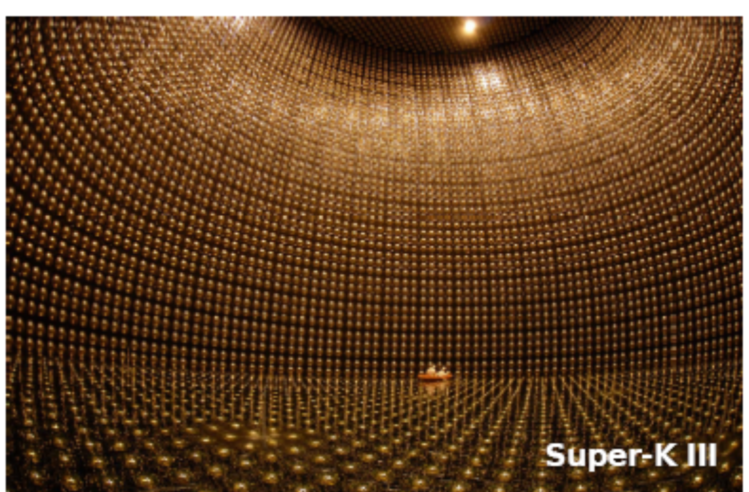
- 30 GeV **~2×10^{14}** protons extracted every 2.5 sec. Secondary π^+(and K^+) focused by three electromagnetic horns
- ν_μ from mainly $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - ν_e in the beam come from K and μ decays
- **Off-axis (2.5 ˚) ν_μ beam**
  - Intense, low energy narrow-band with a peak E_ν tuned for oscillation max. (~0.6 GeV)
- **Near detectors**
  - Both on-axis (INGRID) and off-axis (ND280)
  - ND280 is under upgrade now



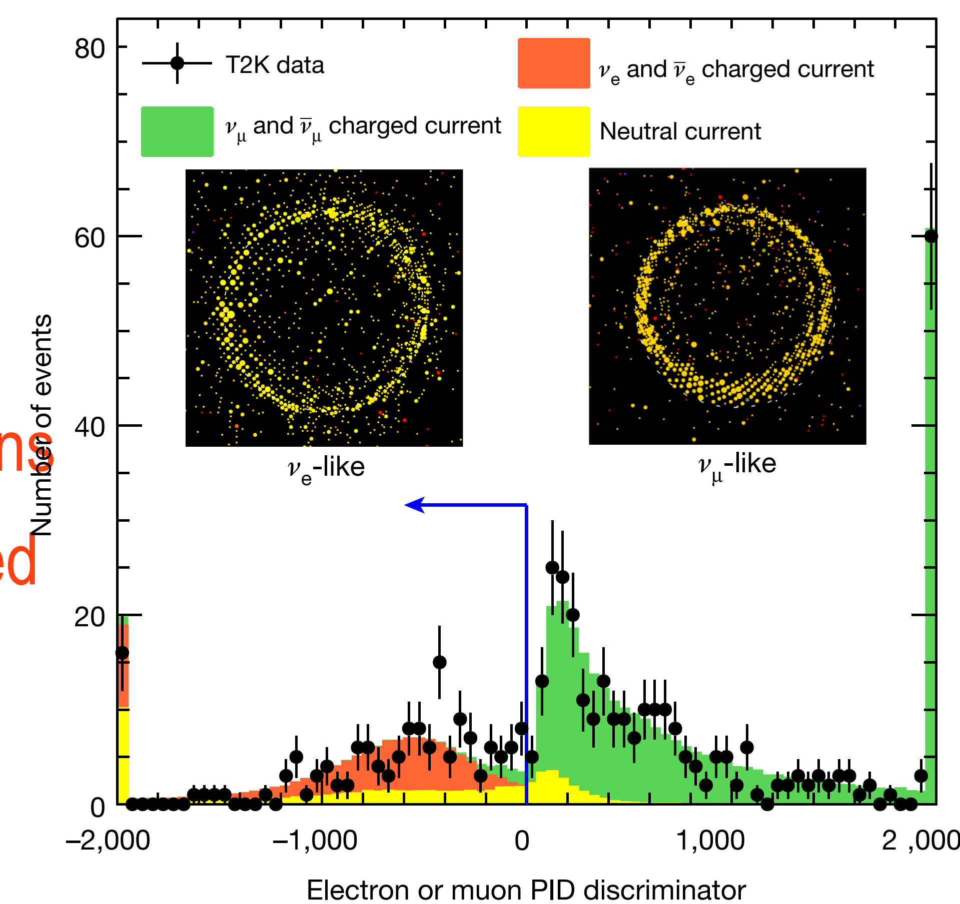
T2K 2016 ν_μ disappearance

T2K-Far Detector: Super-Kamiokande



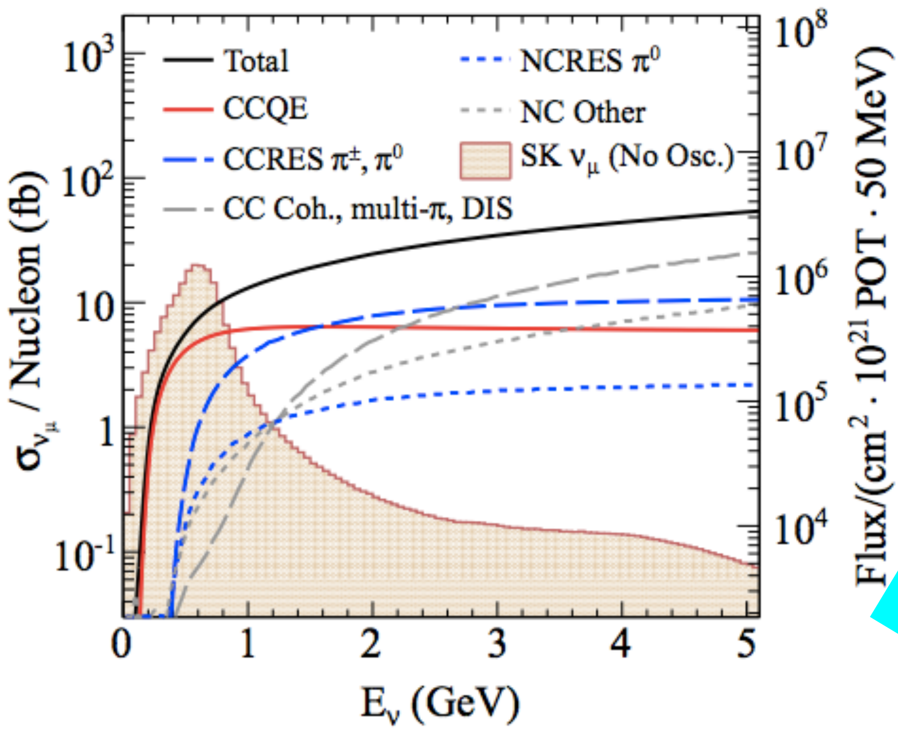


- Water Cherenkov detector with 50 kton mass (22.5 kton Fiducial volume) located at 1km underground
  - Good performance (momentum and position resolution, PID, charged particle counting) for sub-GeV neutrinos.
  - [Typical] 61% efficiency for T2K signal ν_e with >95% NC-1π^0 rejection
    - Inner tank (32 kton) :11,129 20inch PMT
    - Outer tank:1,885 8inch PMT
- Dead-time-less DAQ
- GPS timing information is recorded real-time at every accelerator spill
  - T2K recorded events: All interactions within a ±500μsec window centered on the the neutrino arrival time.

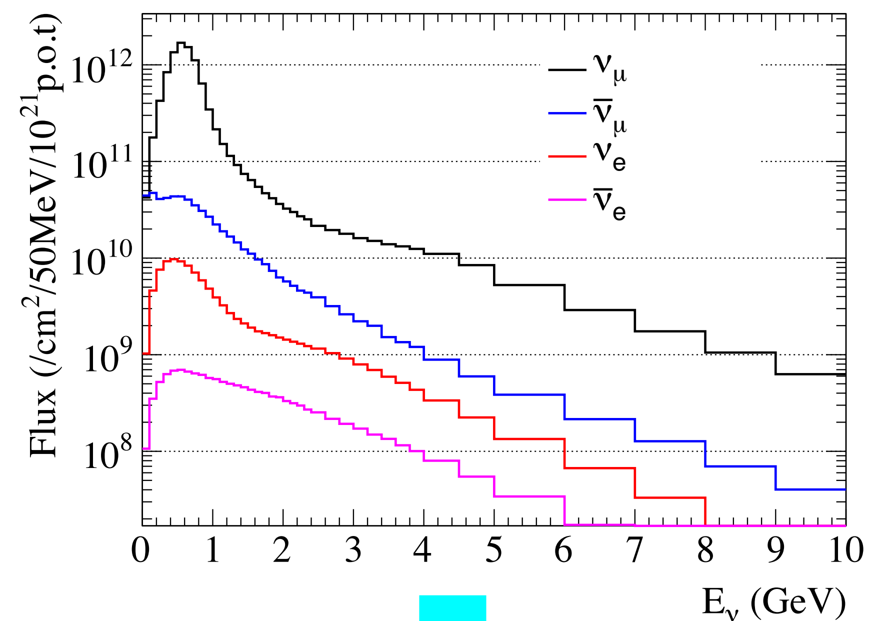


Oscillation Analysis

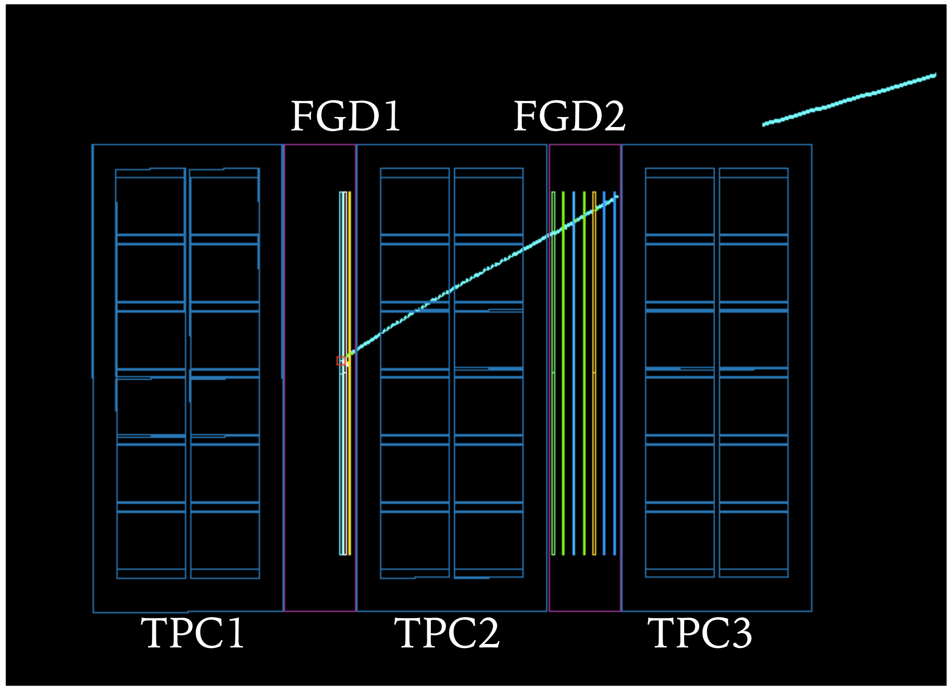
Neutrino Interactions



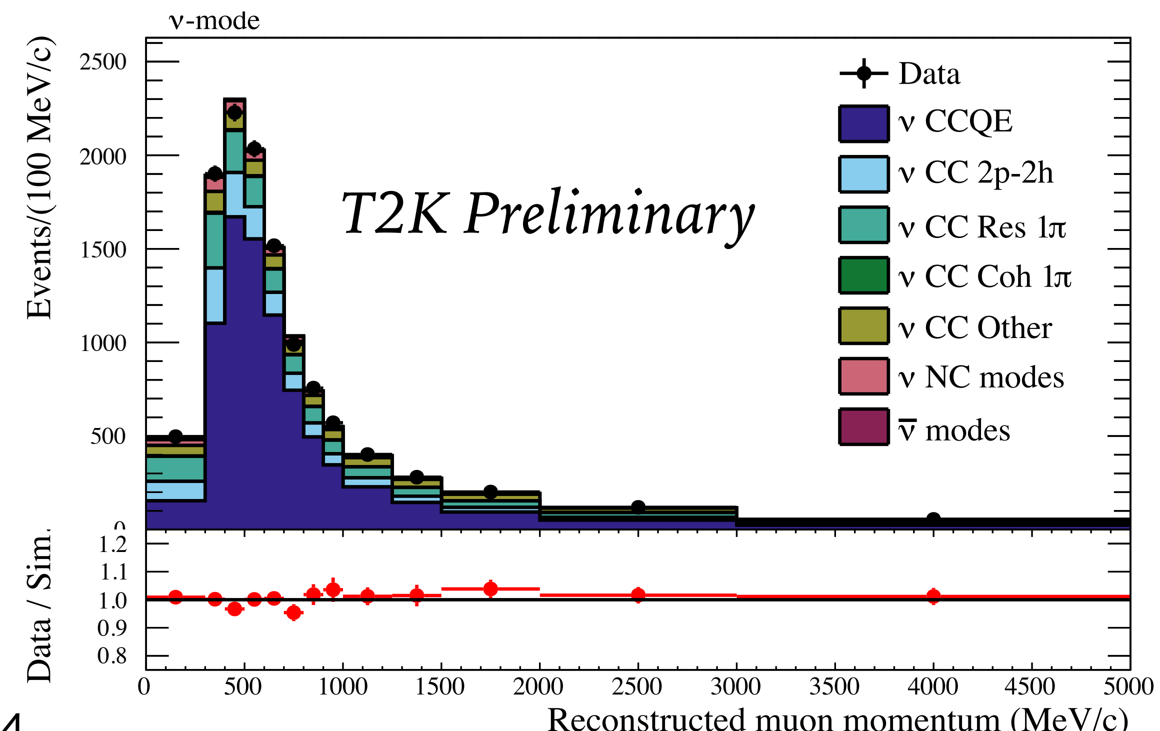
Neutrino Beam Flux



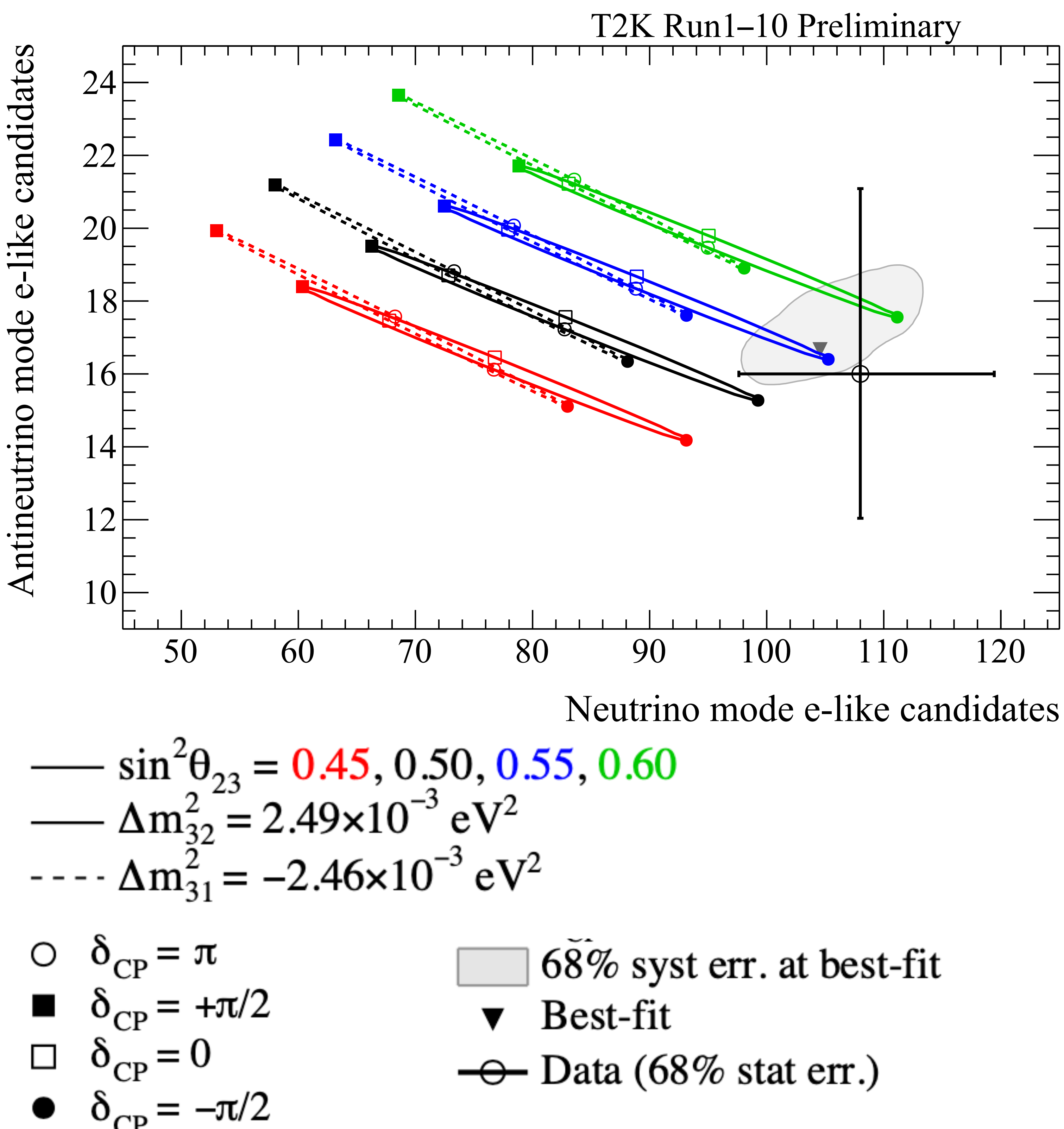
Measurements in ND280

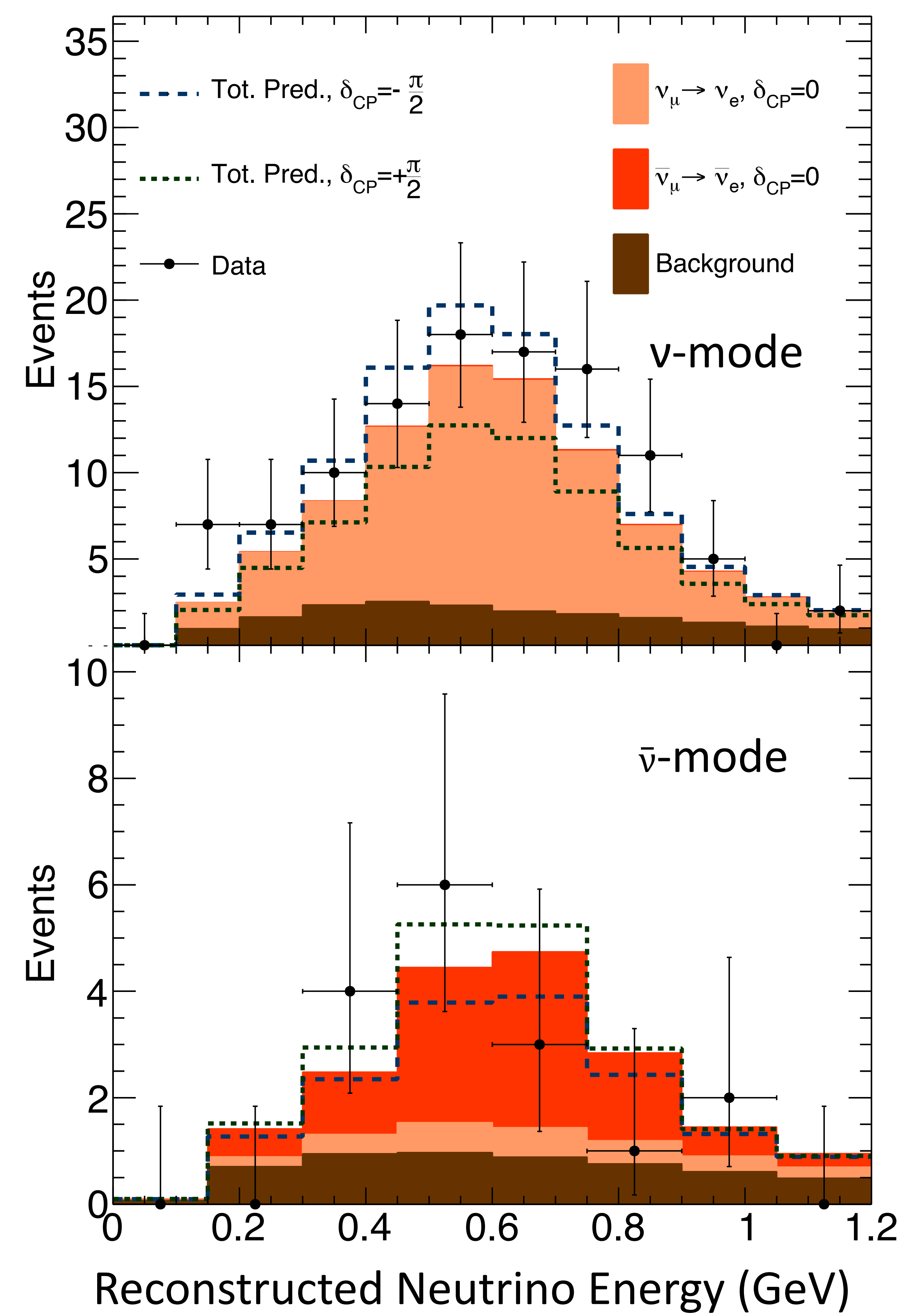


Constraints on flux and Interaction models



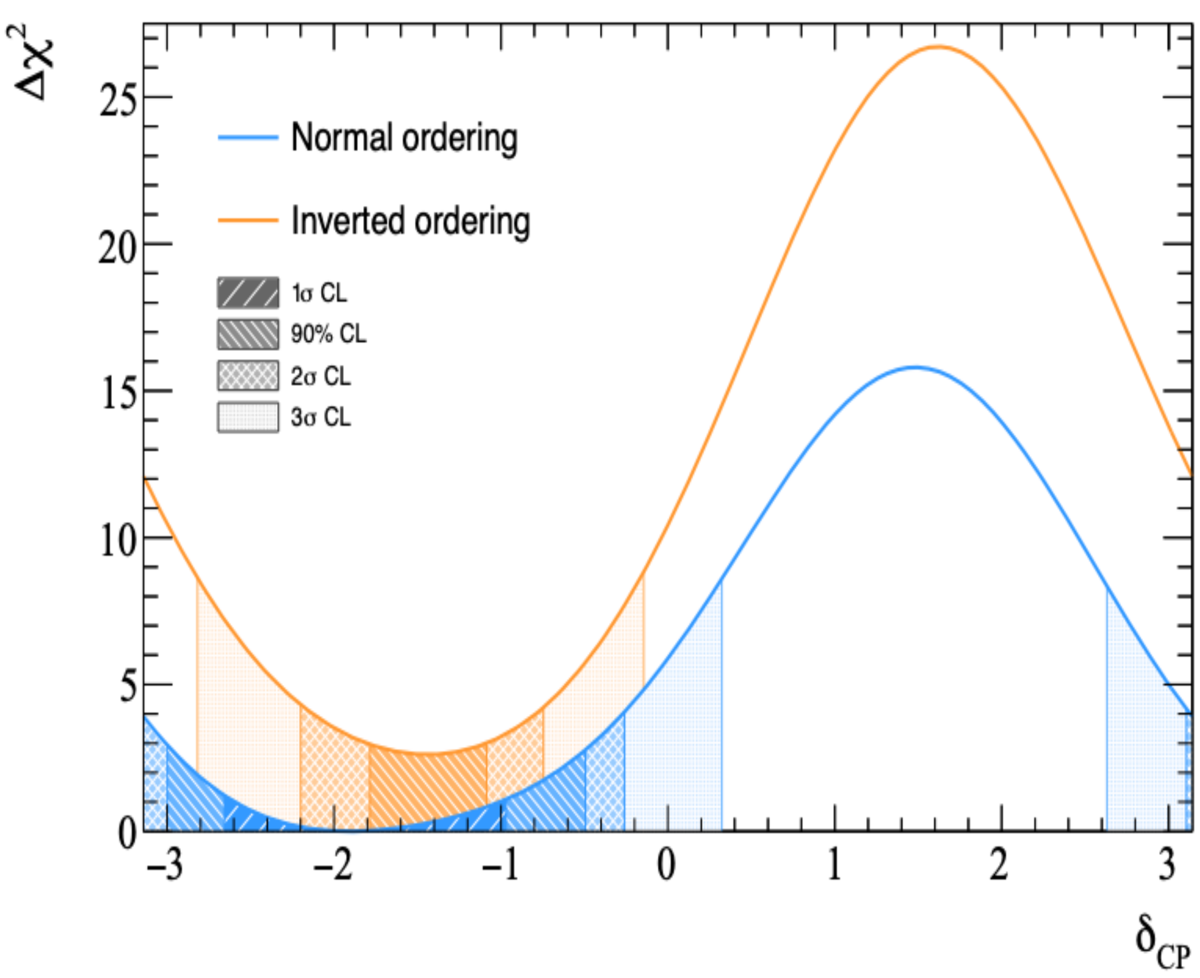
T2K ν_e and $\bar{\nu}_e$ events

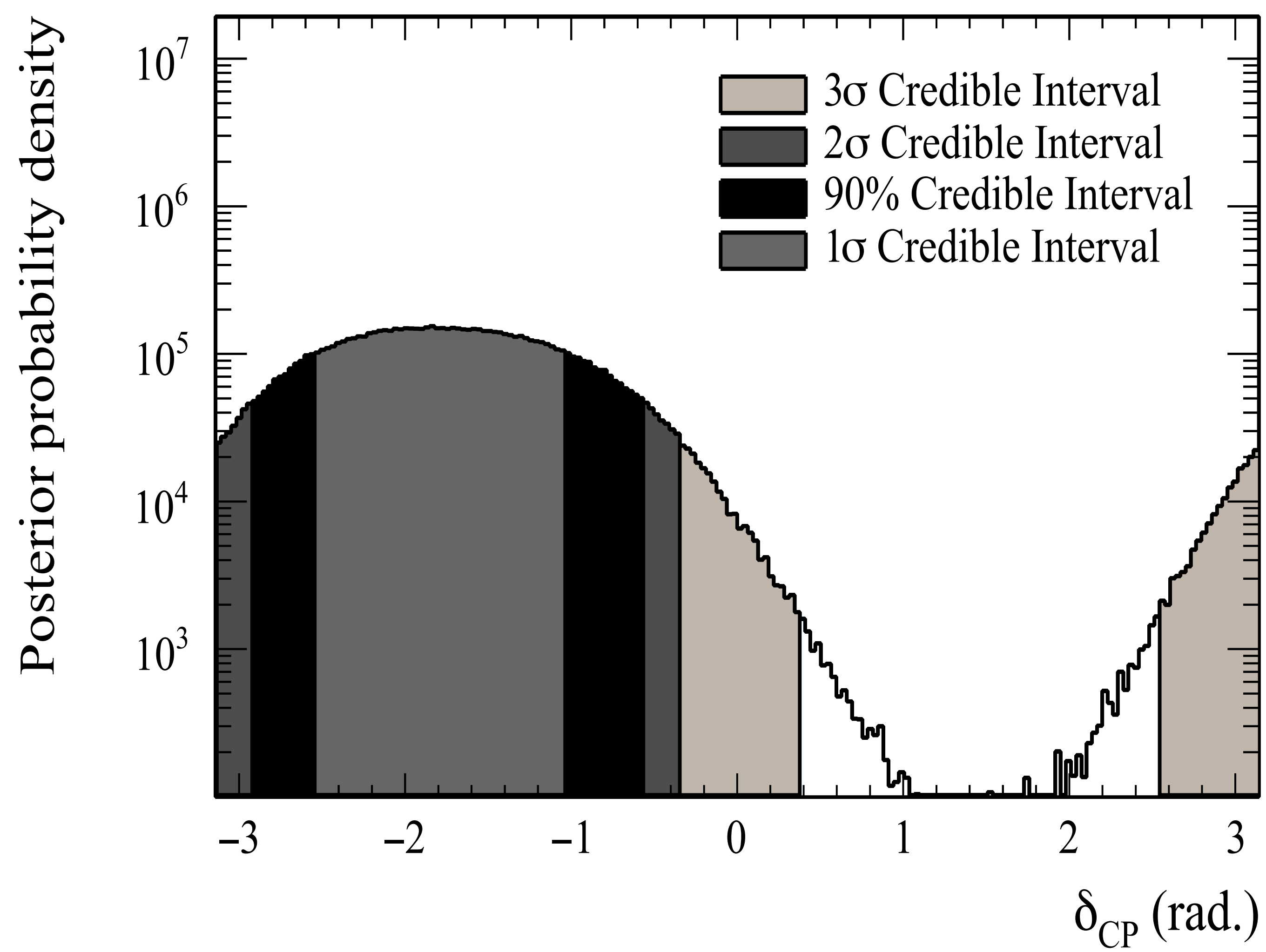




T2K 1D δ_{CP}

- 35% of values excluded at 3σ marginalized across hierarchies
- CP conserving values $(0,\pi)$ excluded at 90% but π not quite at 2σ





NOvA

This evening, "Recent three-flavor neutrino oscillation results from the NOvA experiment" by Liudmila Kolupaeva

Neutrino ID

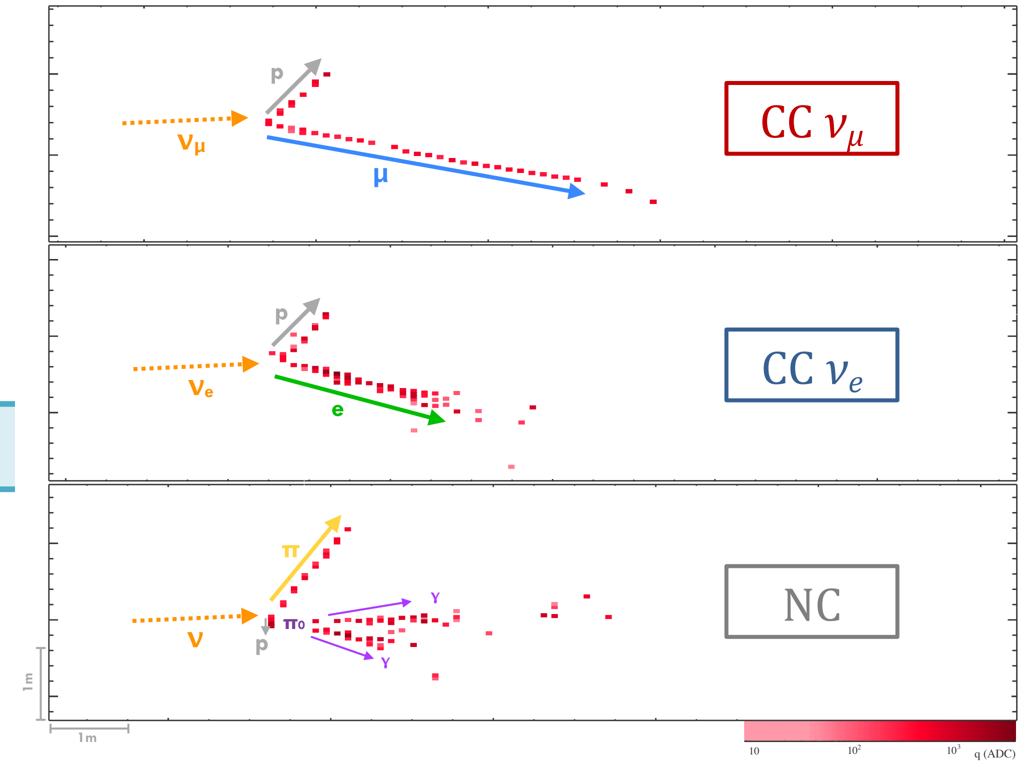
Reconstruction

Observe flavor change as a function of energy over a long distance while mitigating uncertainties on neutrino flux, cross sections, and detector response.

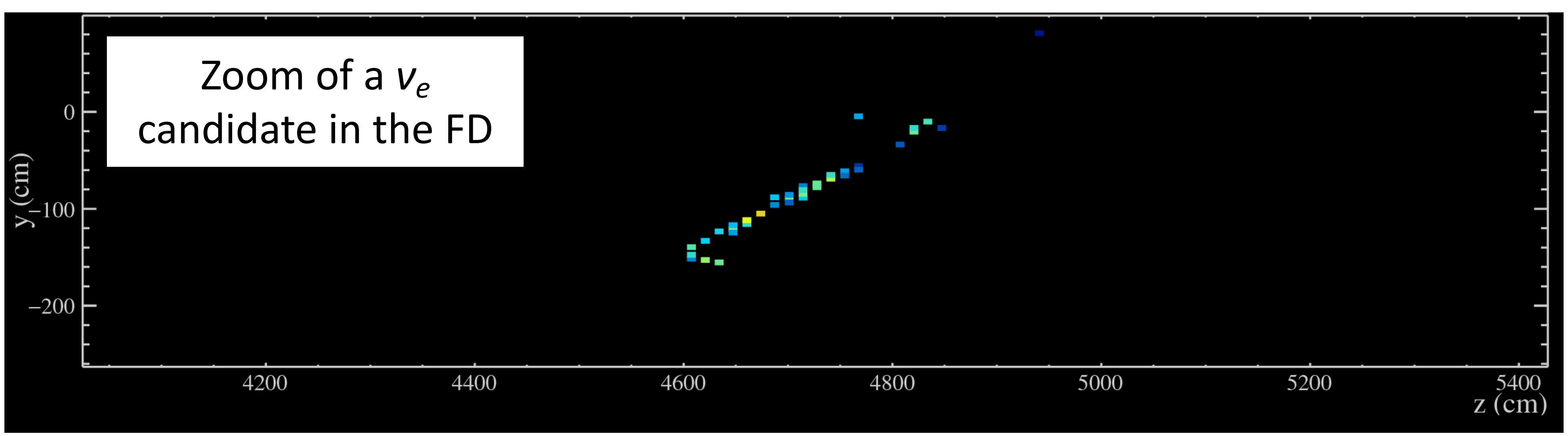
Extrapolation

Models

Updated for 2020

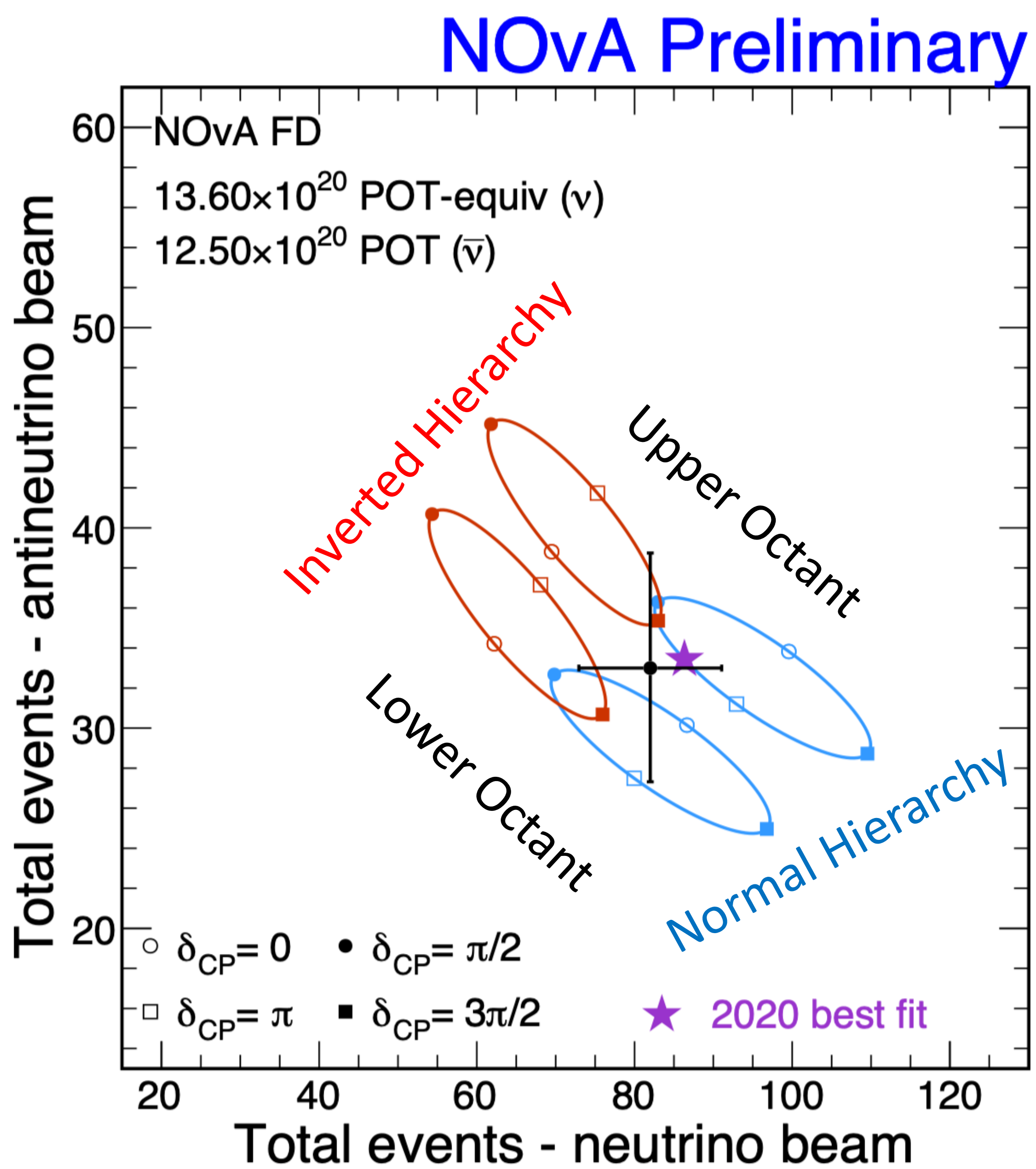


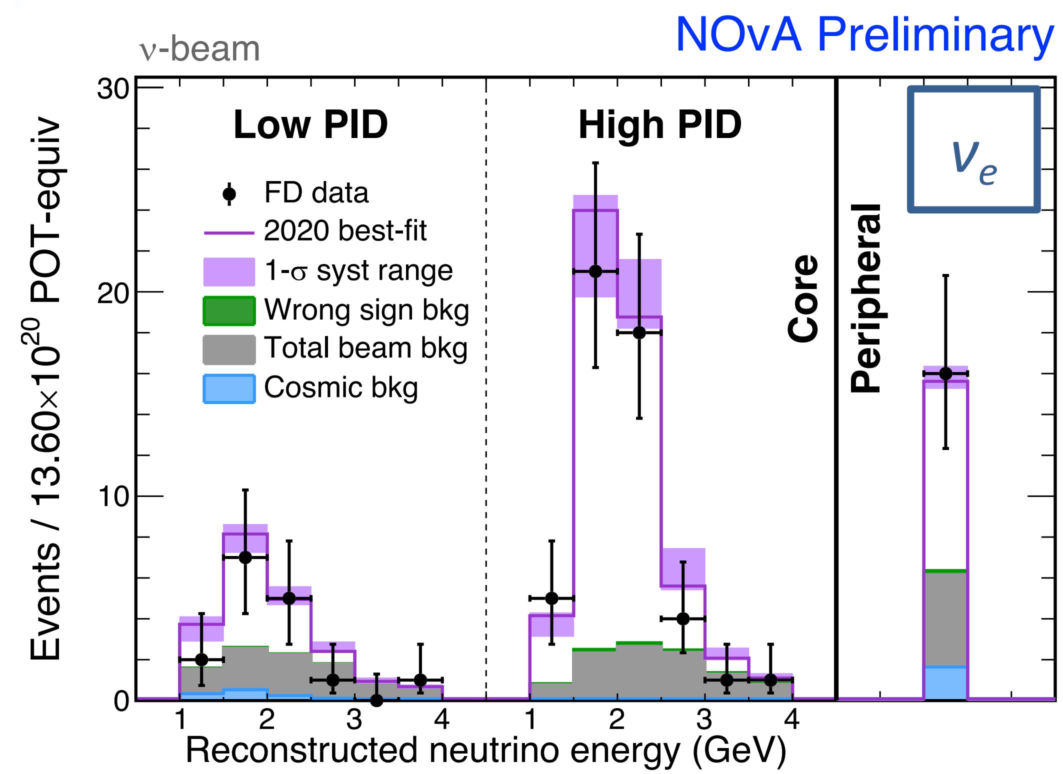
- Segmented liquid scintillator detectors provide 3D tracking and calorimetry
- Optimized for electron showers: ~6 samples per X_0 and ~60% active

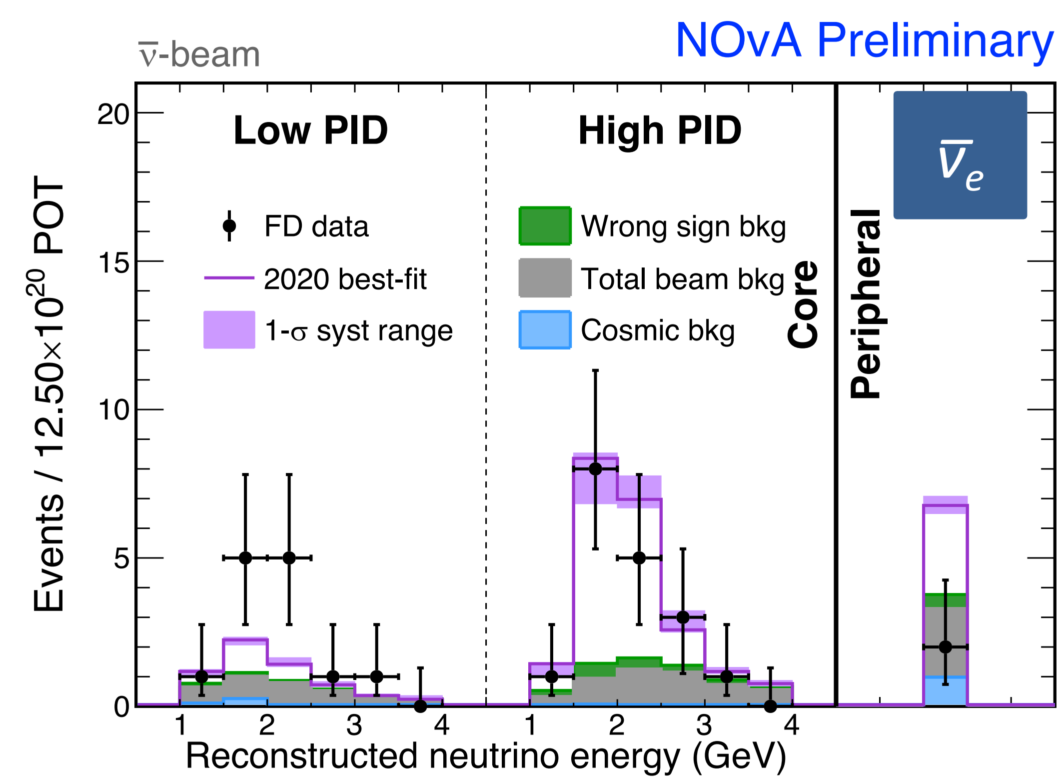


by A. Himmel @NEUTRINO2020

NOvA ν_e and $\overline{\nu}_e$ events







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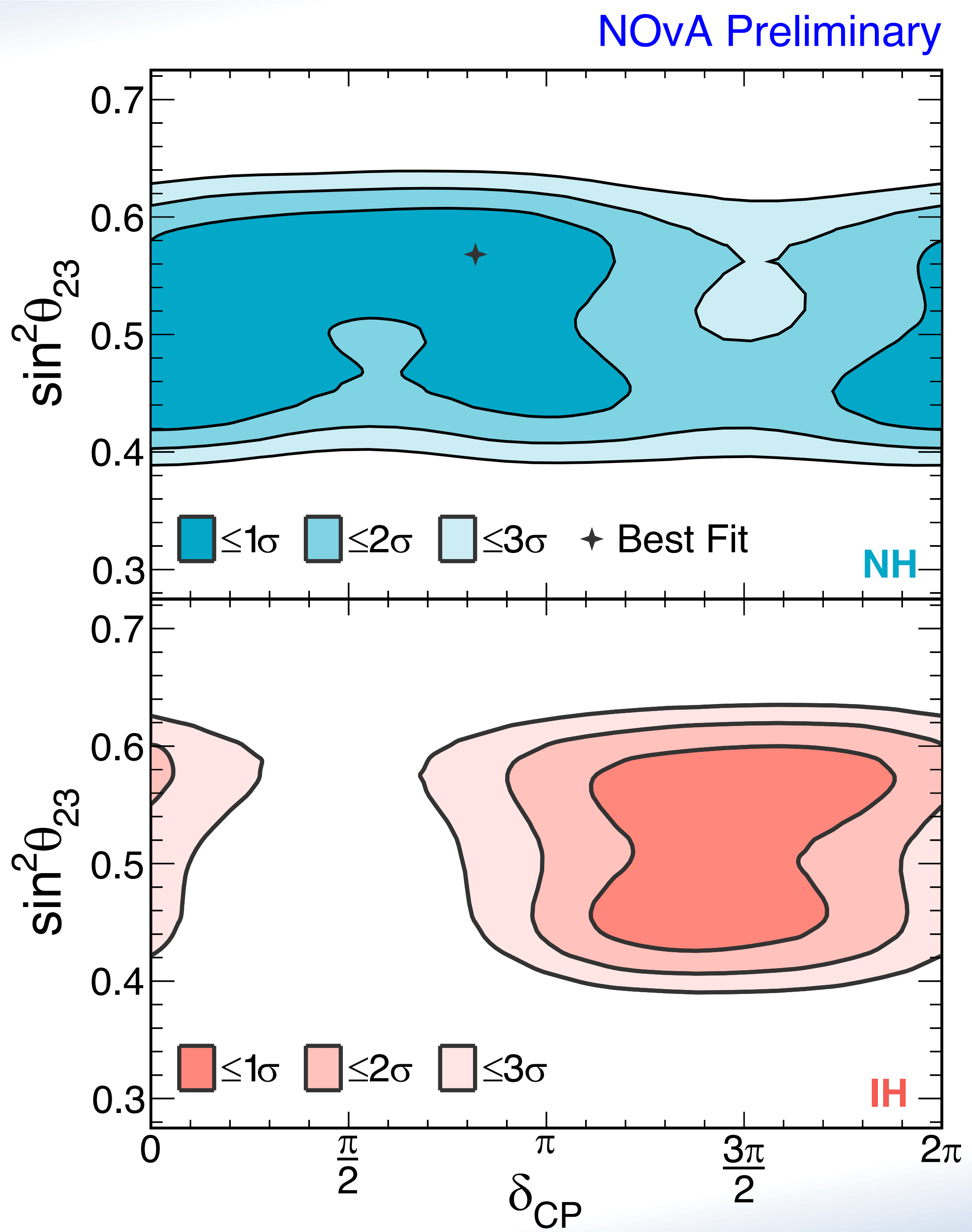
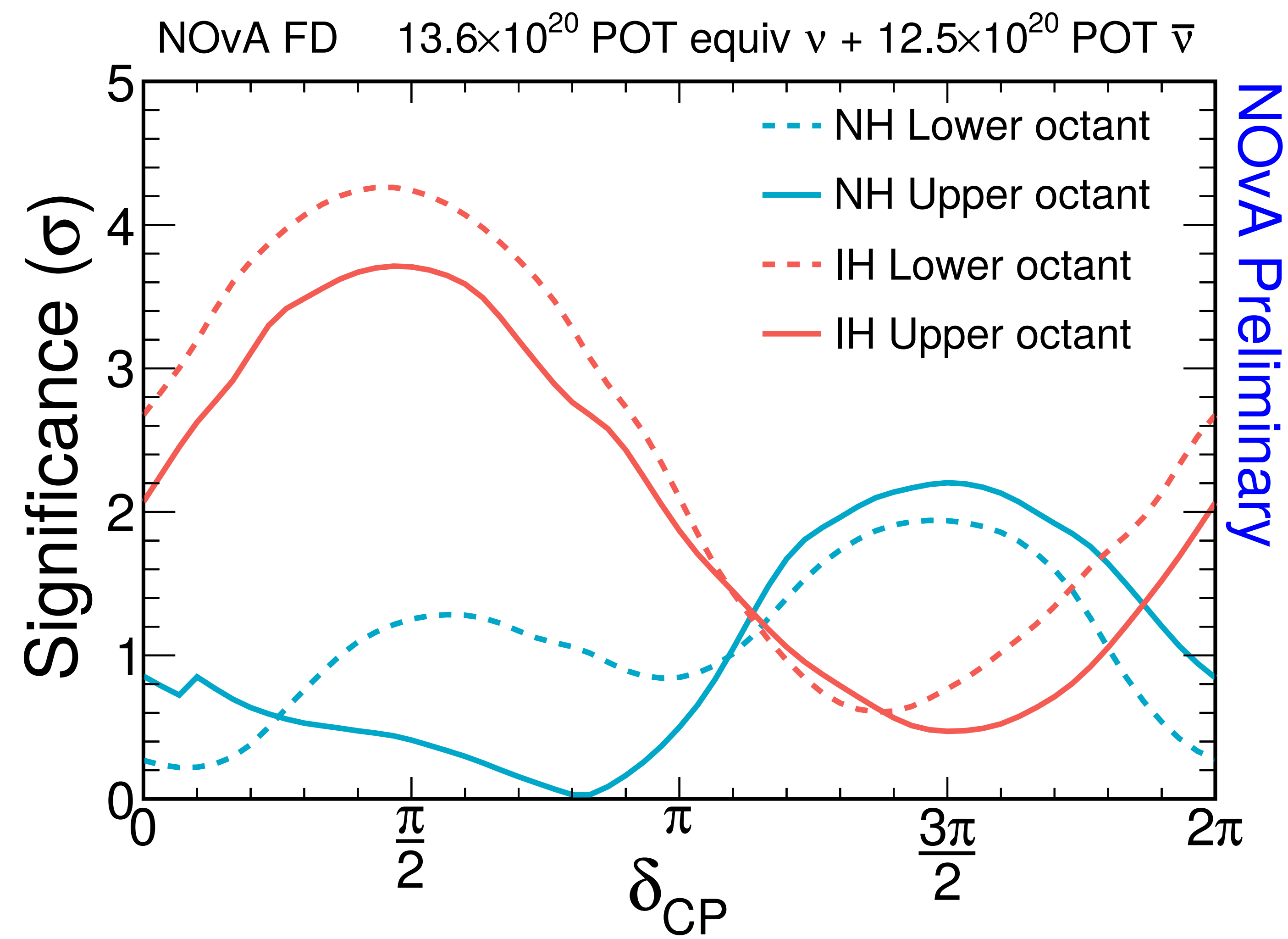
NOvA δ_{CP}





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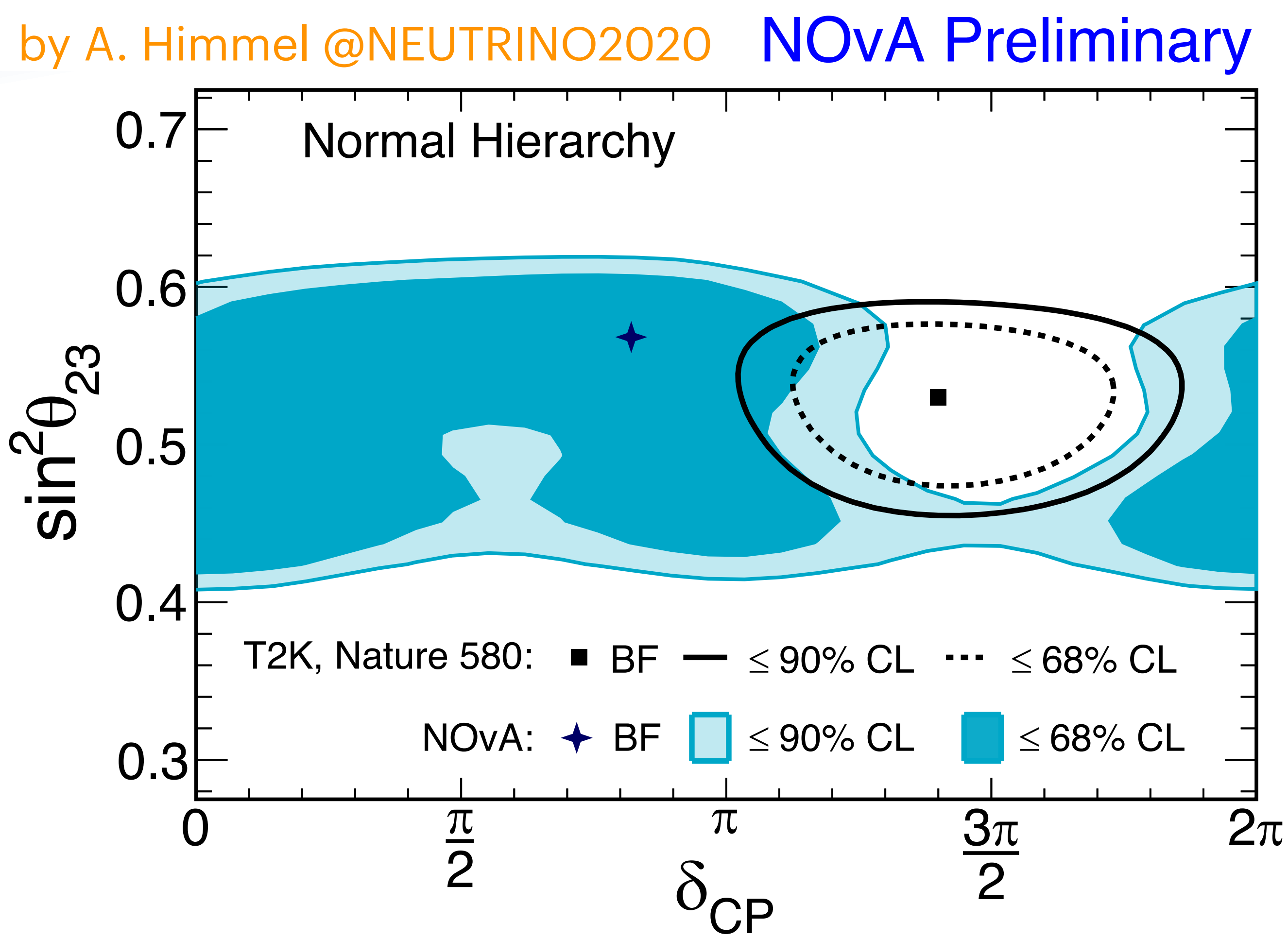
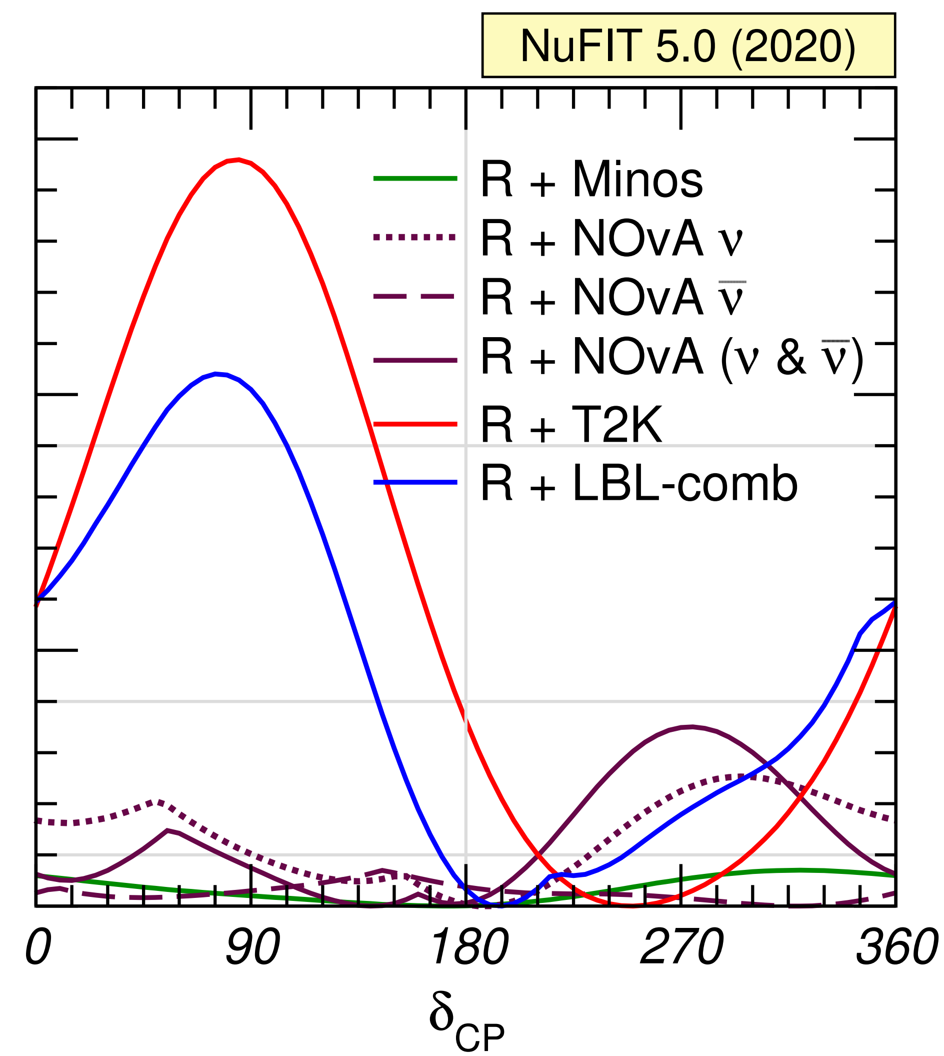
T2K and NOvA

CP violation

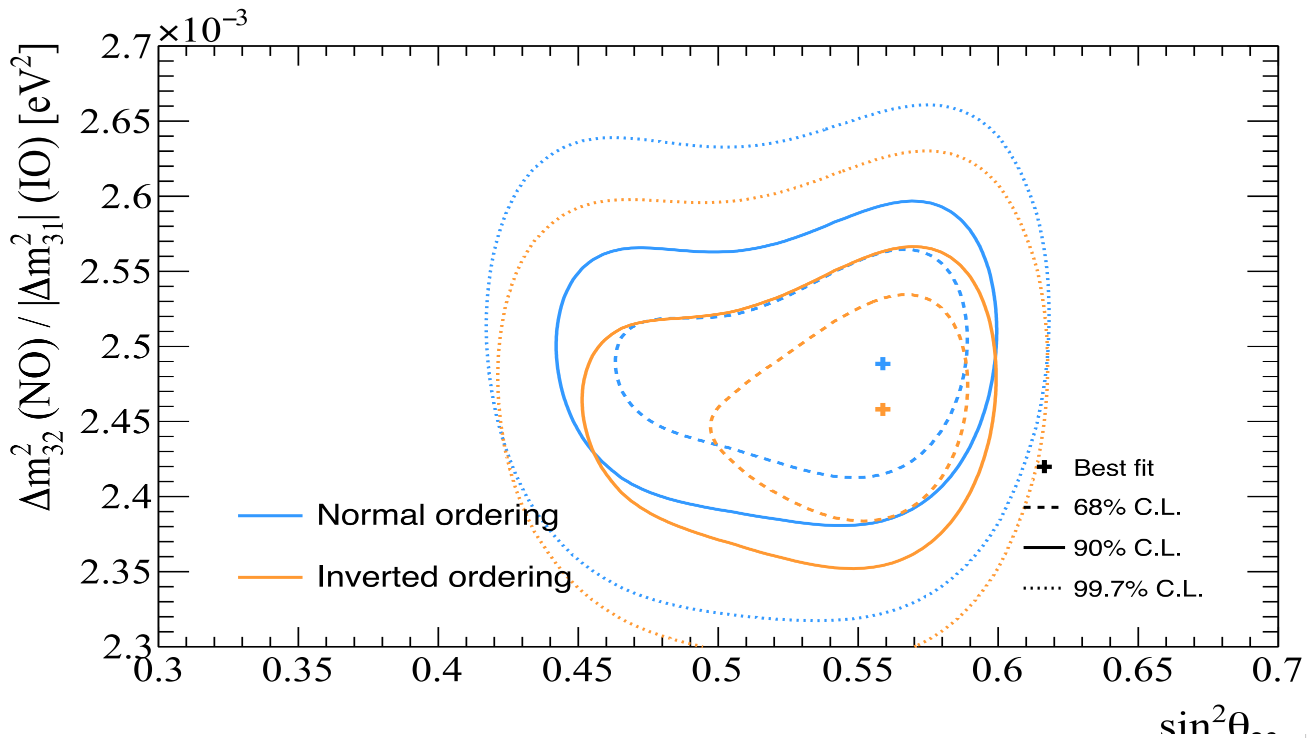




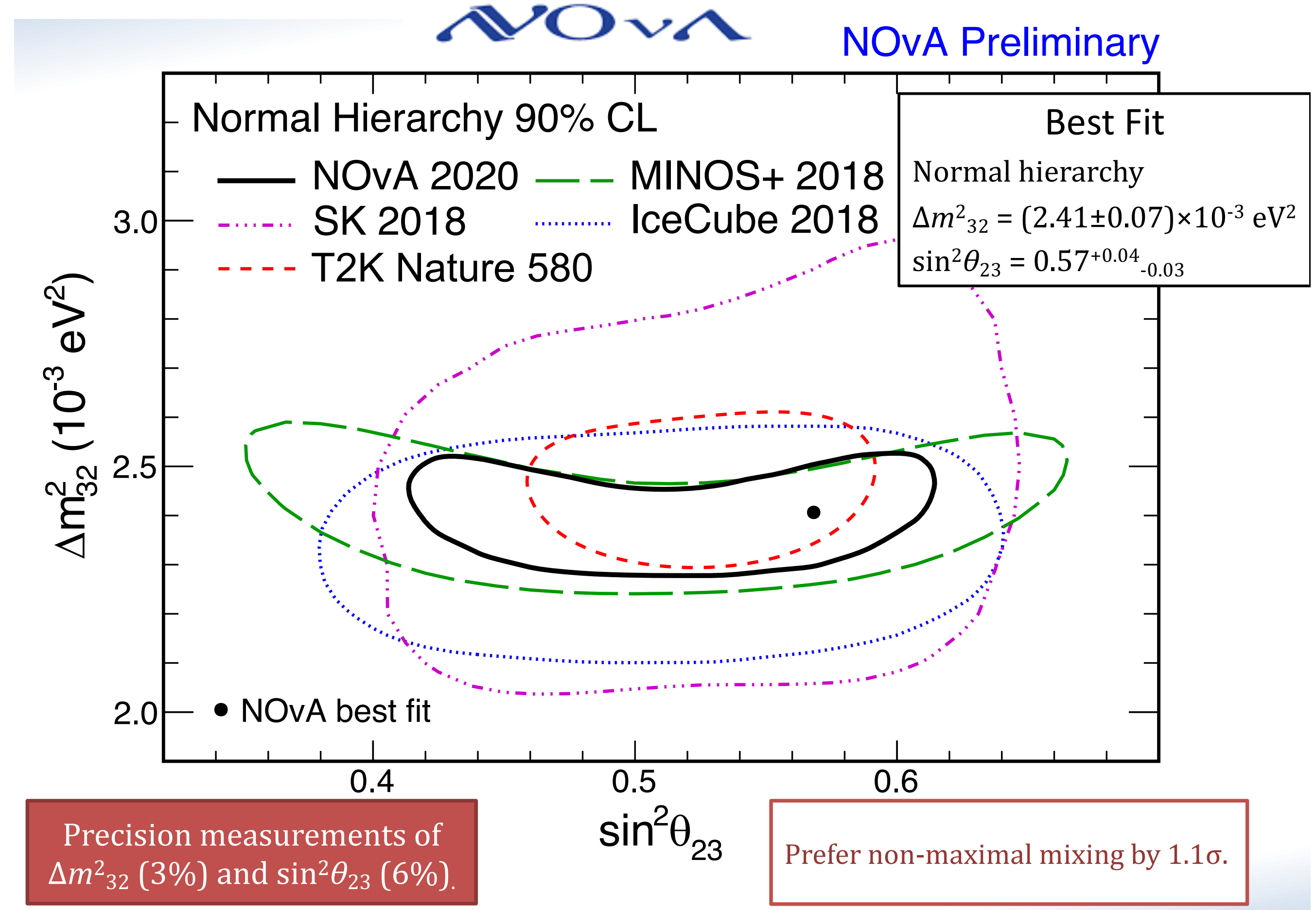
- Is CP violating (δ_{CP}~270°) or not (δ_{CP}~180°) in neutrinos?
  - T2K is pointing to δ_{CP}~270° and NOvA is to δ_{CP}~180°
- Need more statistics!
  - Both NOvA and T2K plan to collect more data with the upgrades.

T2K and NOvA

θ23 and Δm_{32}^2



	$\sin^2\theta_{23}$	$\Delta m^2_{32}(\times 10^{-3})\mathrm{eV}^2$
2D best fit	0.546	2.49
68% C.I. (1σ) range	0.50 – 0.57	2.408 – 2.548
90% C.I. range	0.460 – 0.587	−2.596 – −2.452 & 2.368 – 2.592

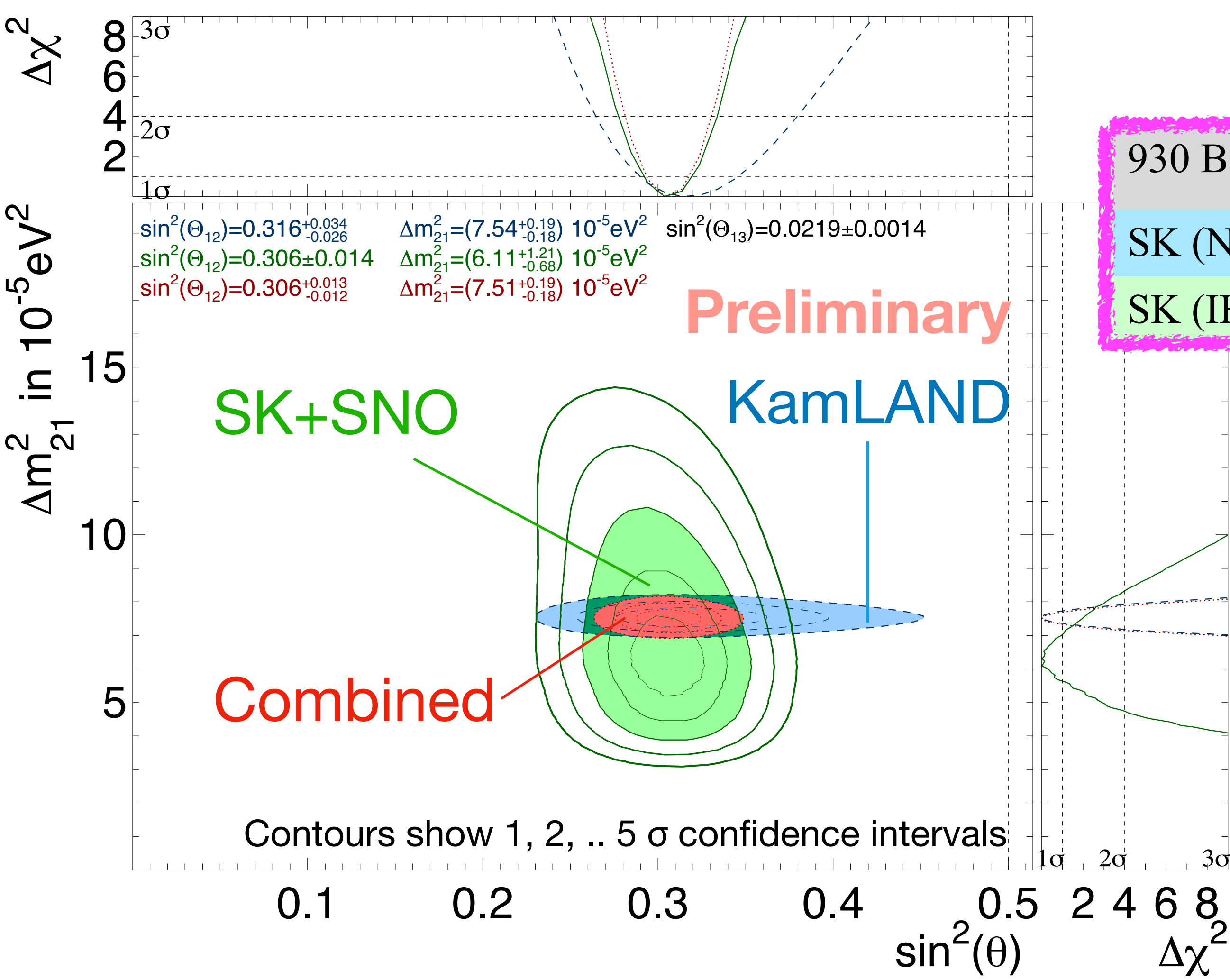


- $\sin^2\theta_{23}$
  - 0.546 (T2K) and 0.57 (NOvA)
- Δm_{32}^2
  - 2.49×10^{-3} eV^2 (T2K) and 2.41×10^{-3} eV^2 (NOvA)

consistent

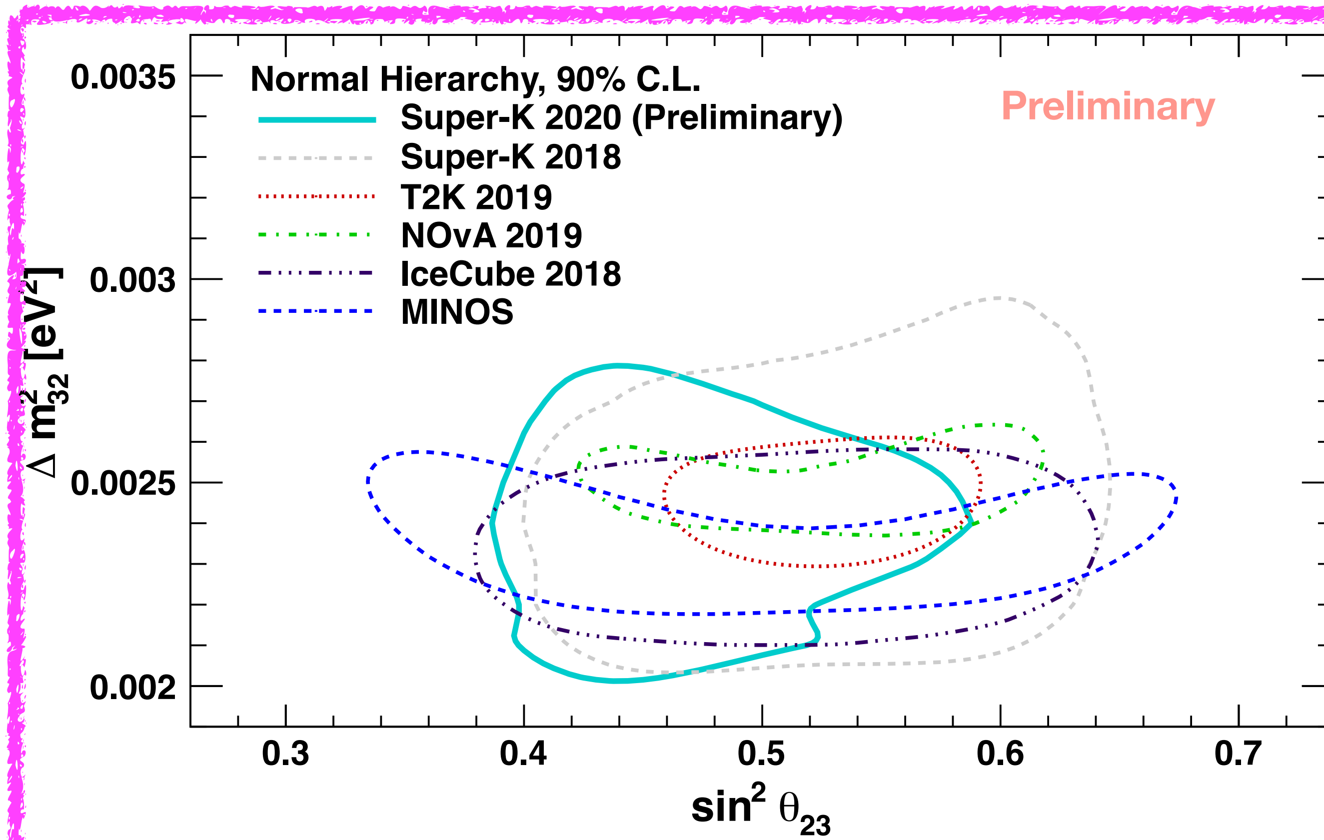
Super-Kamiokande

Solar and Atmospheric neutrinos



	$\sin^2(\theta_{12})$	Δm^2_{21} [10^{-5} eV^2]
KamLAND	$0.316^{+0.034}_{-0.026}$	$7.54^{+0.19}_{-0.18}$
SK+SNO	0.306 ± 0.014	$6.11^{+1.21}_{-0.68}$
Combined	$0.306^{+0.013}_{-0.012}$	$7.51^{+0.19}_{-0.18}$

930 Bins	$\chi2$	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} (x10^{-3})
SK (NH)	**1037.5**	0.0218	$4.36^{+0.88}_{-1.39}$	$0.44^{+0.05}_{-0.02}$	$2.40^{+0.11}_{-0.12}$
SK (IH)	**1040.7**	0.0218	$4.54^{+0.88}_{-1.32}$	$0.45^{+0.09}_{-0.03}$	$2.40^{+0.09}_{-0.32}$

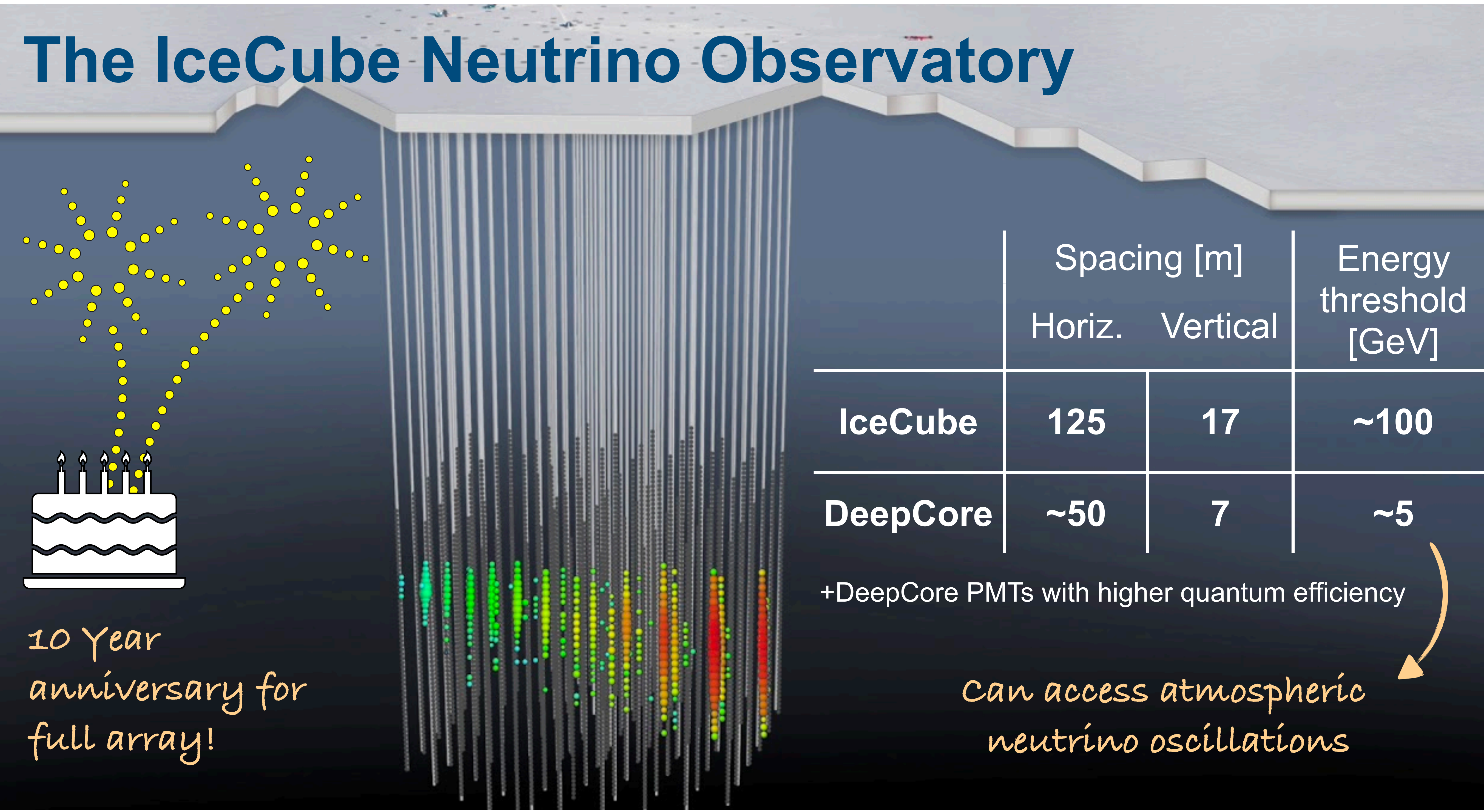


by Y. Nakajima @NEUTRINO2020

IceCube

Neutrino oscillation measurements with atmospheric neutrinos

The IceCube Neutrino Observatory



	Spacing [m] Horiz.	Spacing [m] Vertical	Energy threshold [GeV]
IceCube	**125**	**17**	**~100**
DeepCore	**~50**	**7**	**~5**

+DeepCore PMTs with higher quantum efficiency

by S. Blot @NEUTRINO2020

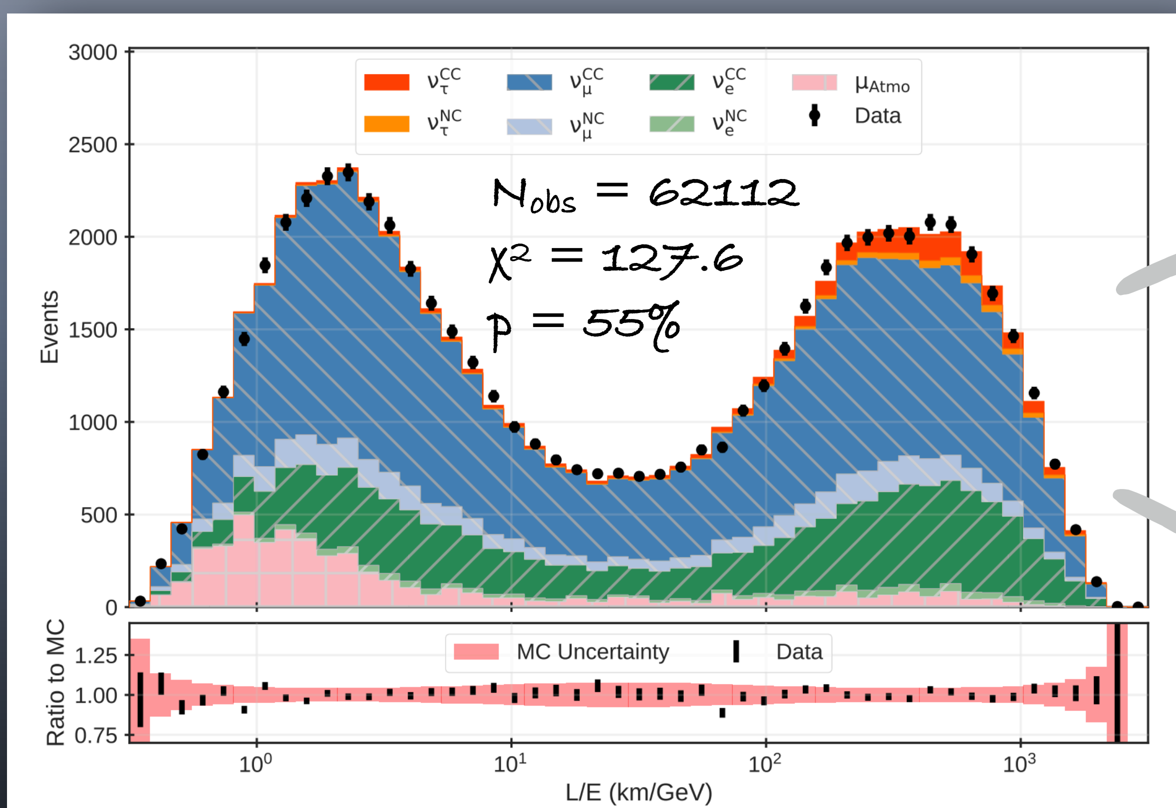
IceCube

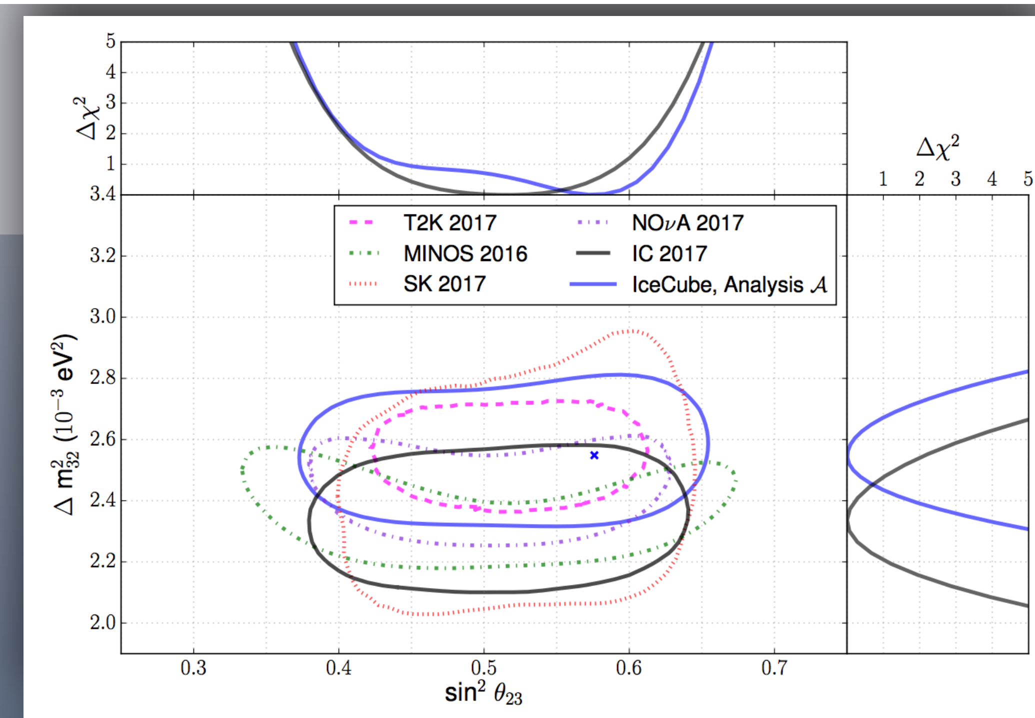
$\nu_\mu \rightarrow \nu_\tau$

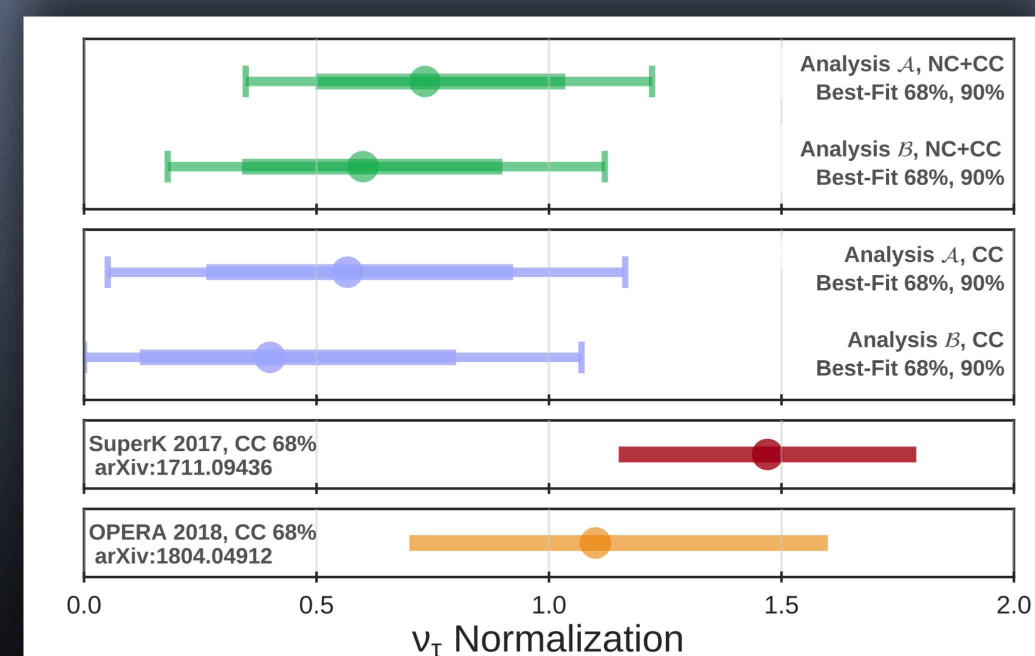
Standard oscillation results

Phys. Rev. D 99, 032007 (2019)

$\Delta m^2_{32} = 2.55^{+0.12}_{-0.11} \times 10^{-3}\ \mathrm{eV}^2$ $\sin^2\theta_{23} = 0.58^{+0.04}_{-0.13}$







Norm $\nu_\tau^{(CC+NC)} = 0.73^{+0.34}_{-0.24}$ Reject no-ν_τ with 3.2σ (CC+NC)

by S. Blot @NEUTRINO2020

Daya Bay

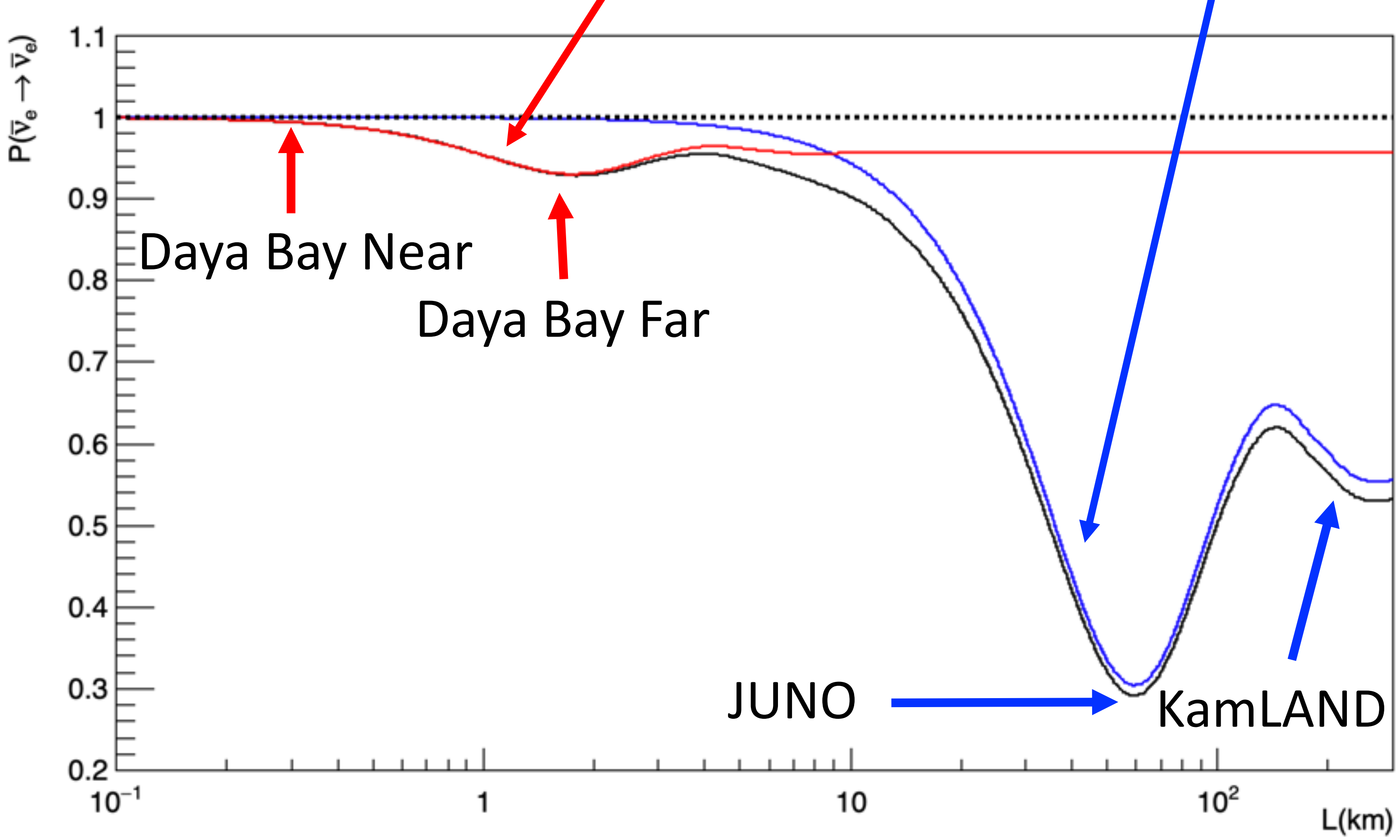
The most sensitive experiment to θ_{13}

Reactor Antineutrino Oscillation

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} (\cos^2\theta_{12} \sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$\approx 1 - \sin^2 2\theta_{13}\sin^2\Delta_{ee} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$\Delta_{ij} = \Delta m^2_{ij}\frac{L}{4E}$$



Immune to CP violation and matter effects

Key for a precise measurement:

✓ **Baseline Optimization**

$$L(\mathrm{m}) \sim \frac{\pi \cdot E\ (\mathrm{MeV})}{2.54 \cdot \Delta m^2(\mathrm{eV}^2)}$$

✓ **Large statistics**

Large $\bar{\nu}_e$ flux

Massive target mass

✓ **Background control**

Large overburden

Detector shielding

✓ **Systematics control**

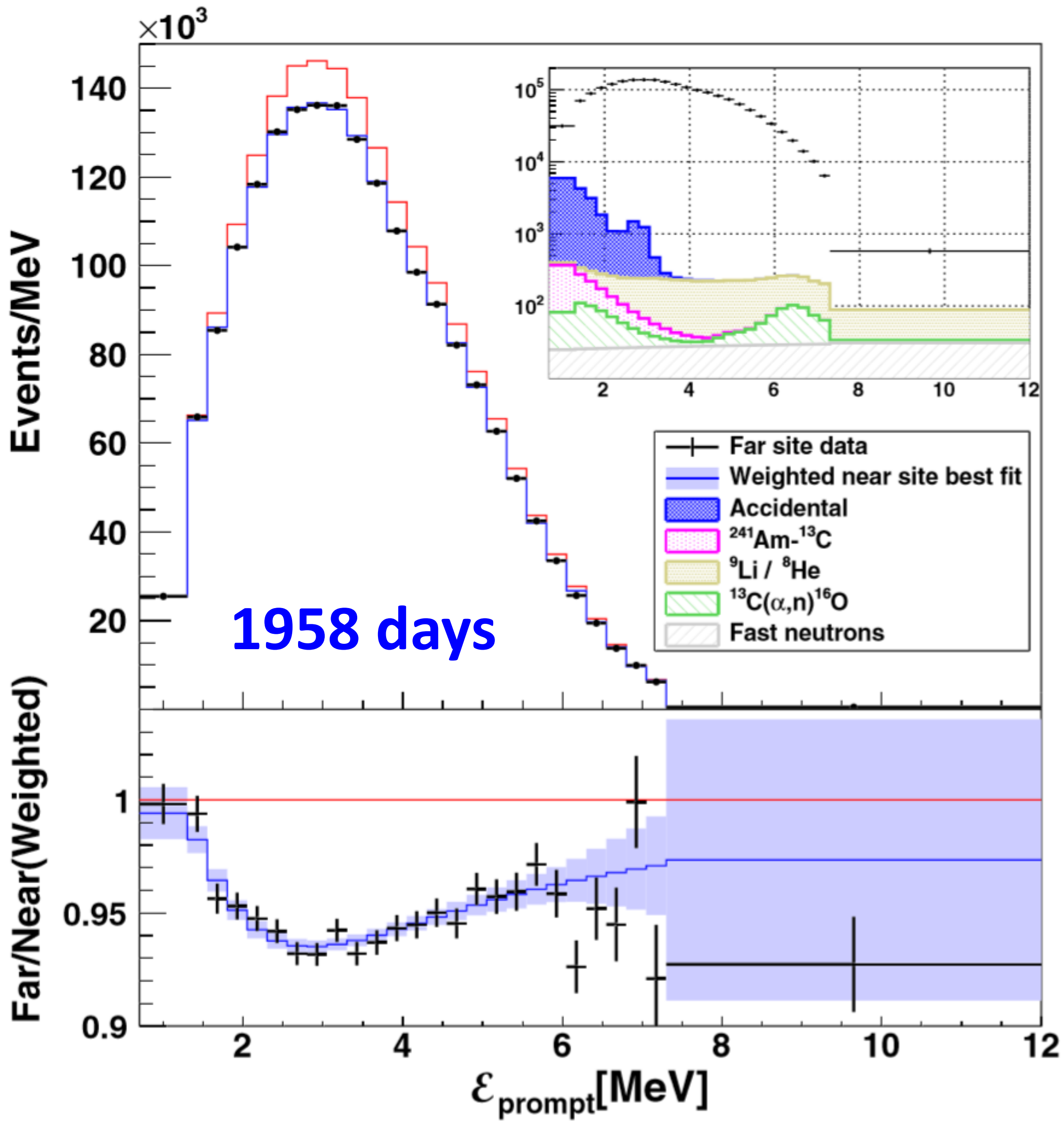
Relative Far/Near measurement

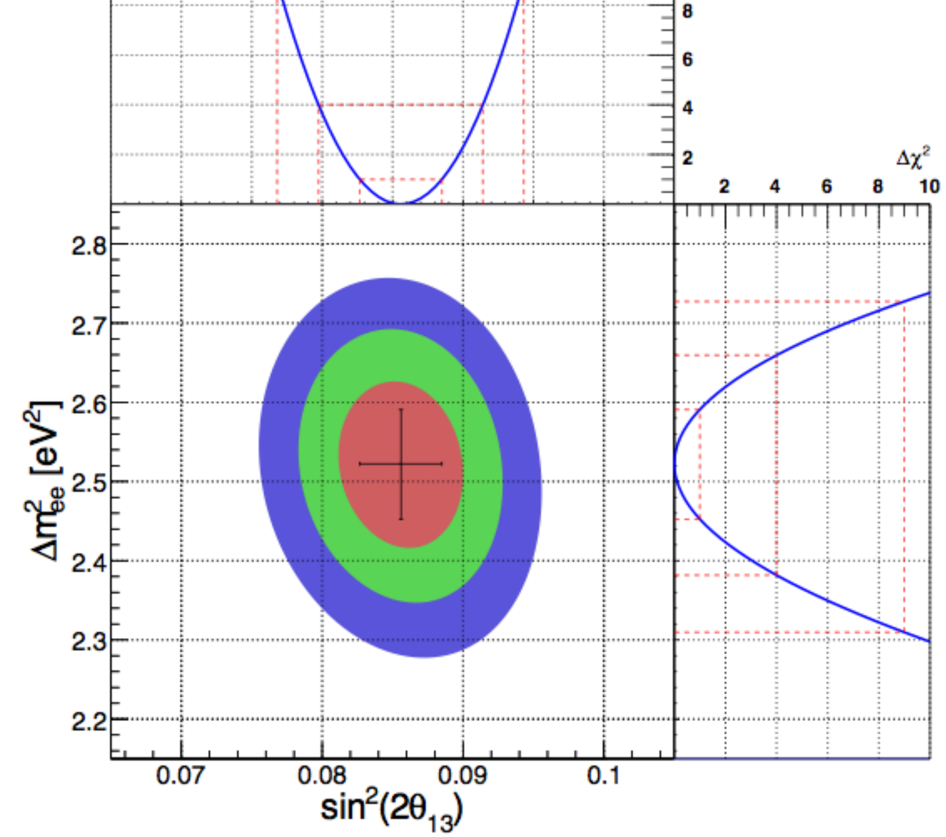
by J. Ling @NEUTRINO2020

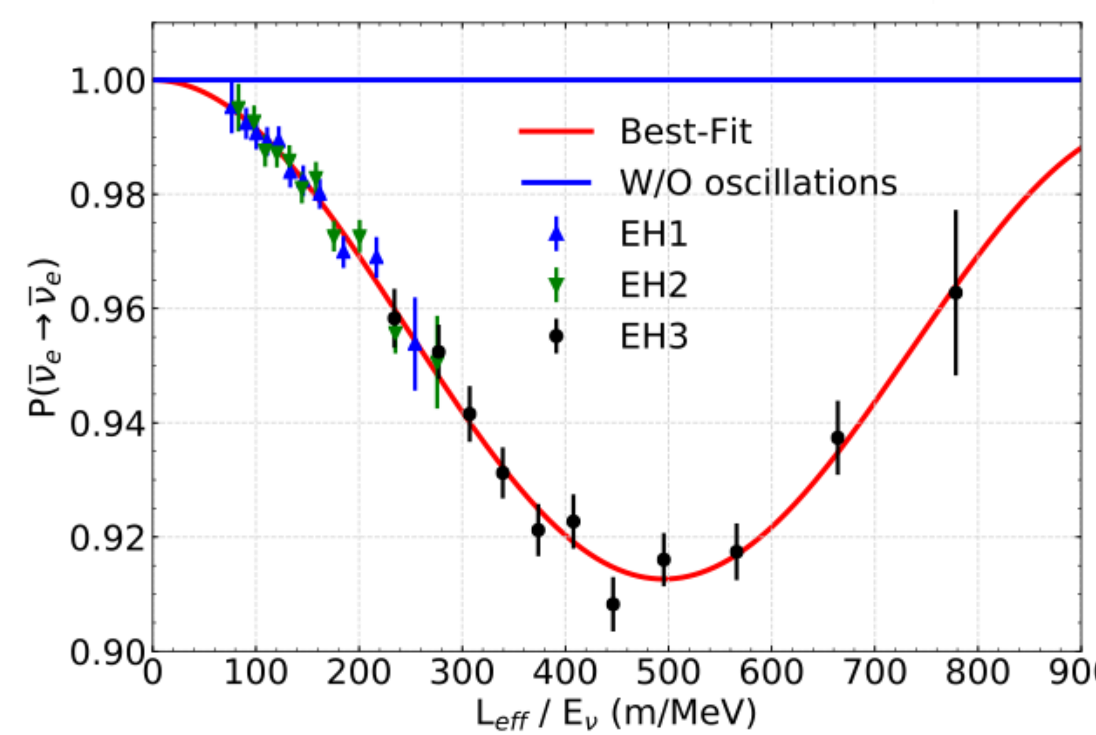
Daya Bay

The result

PRL 121, 241805 (2018)







$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \text{eV}^2$$

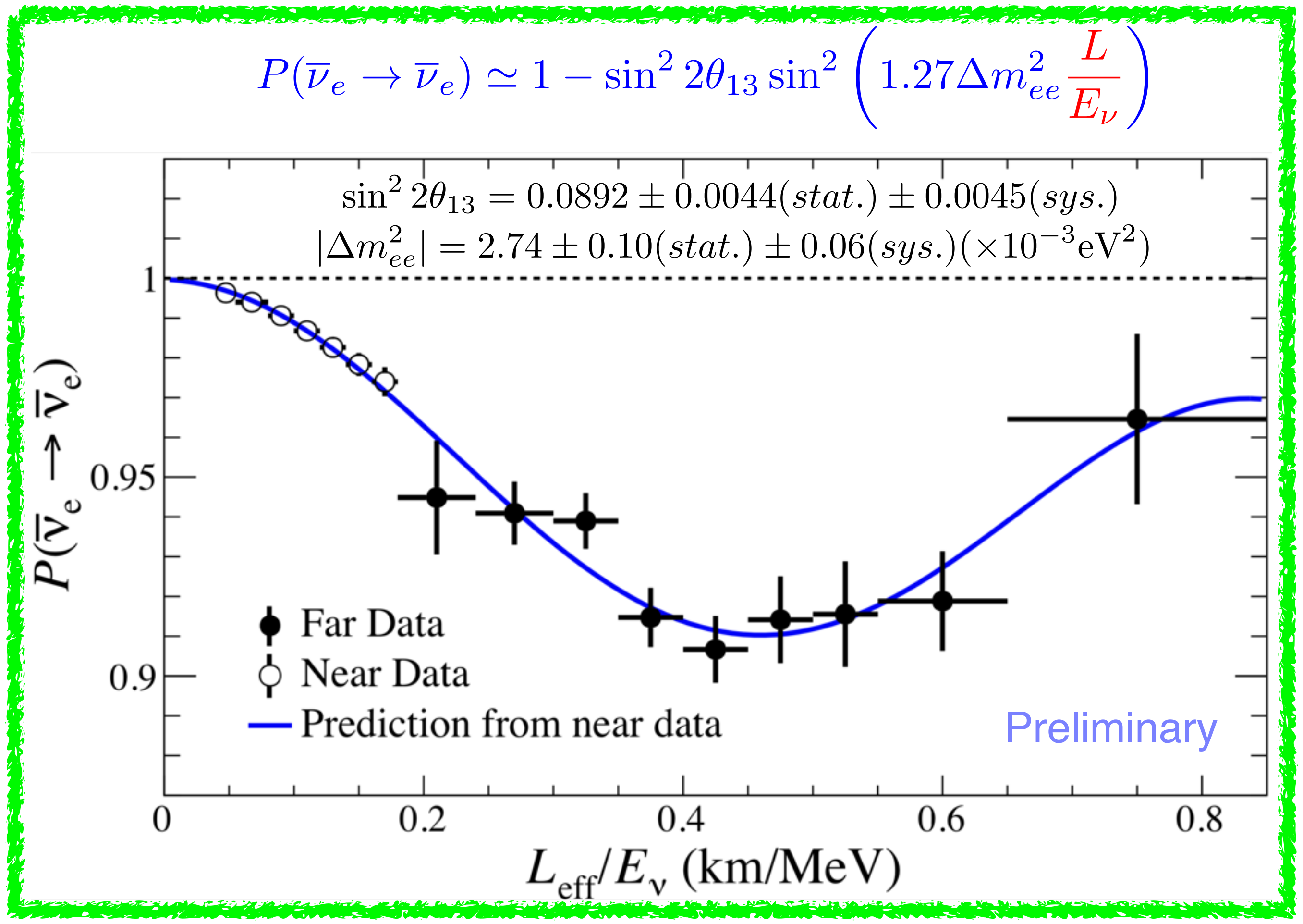
$$\Delta m^2_{32} = (2.47 \pm 0.07) \times 10^{-3}\ \text{eV}^2\ (\text{NO})$$

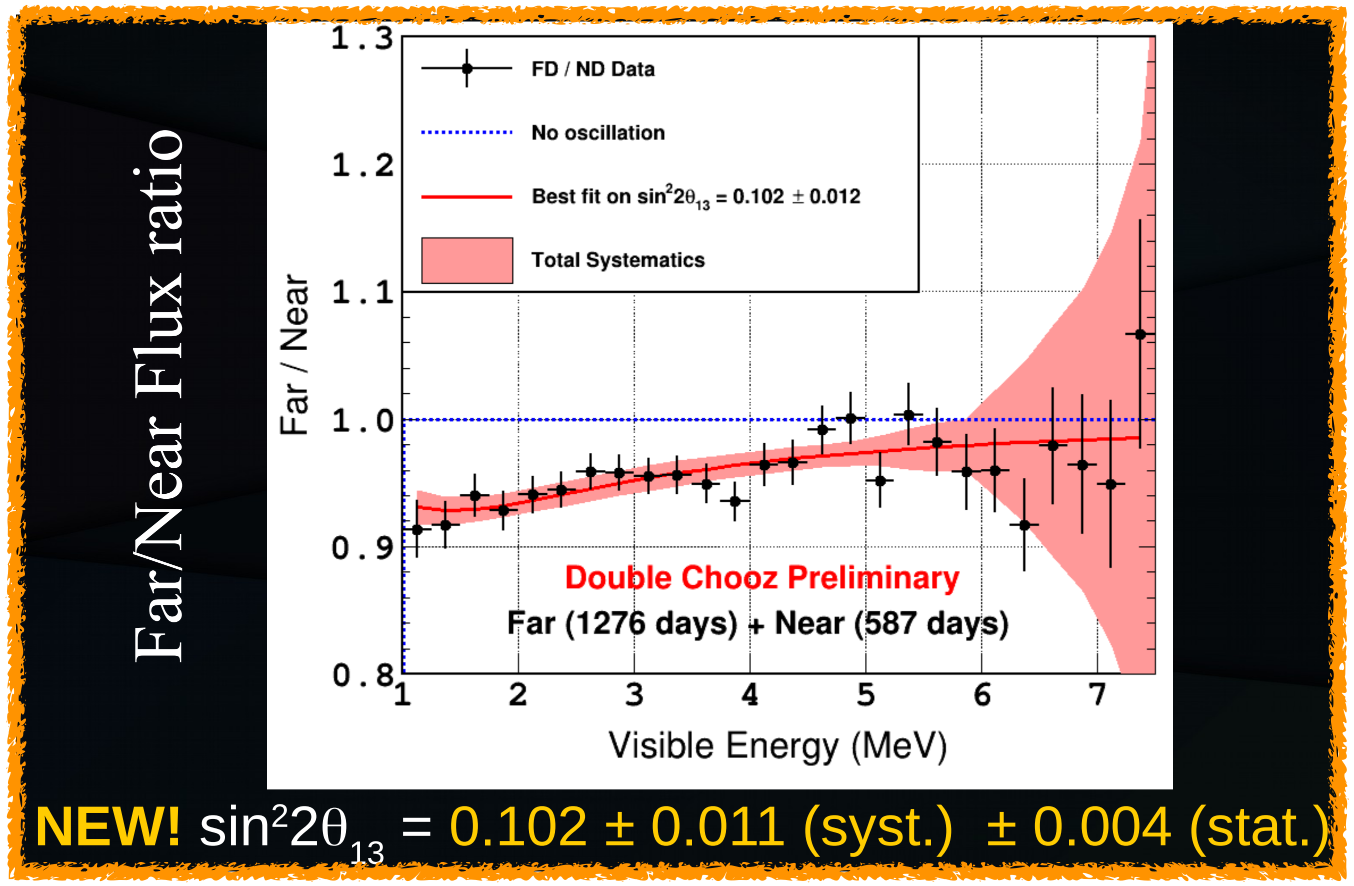
$$\Delta m^2_{32} = (-2.58 \pm 0.07) \times 10^{-3}\ \text{eV}^2\ (\text{IO})$$

by J. Ling @NEUTRINO2020

RENO and Double Chooz

Ref. Daya Bay sinθ$_{13}$=0.0856±0.0029





by J. Yoo @NEUTRINO2020

by T. Bezerra @NEUTRINO2020

- RENO: The experiment at the Korean reactor
- Double Chozo: The experiment at the French reactor

Current Status

Global FIT

NuFIT 5.0 (2020)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

- CP violation (δ_{CP} != 0 or 180°) is not established yet!
- A preference of normal mass ordering.

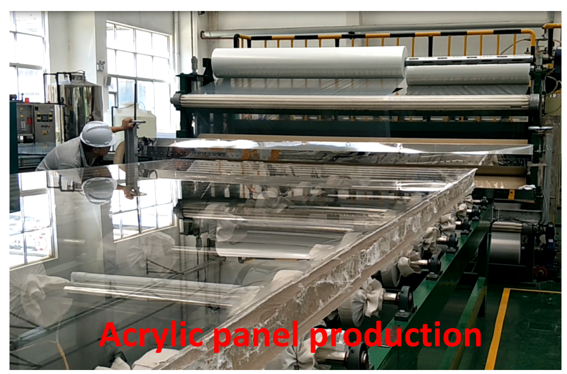
Future

Challenge

JUNO

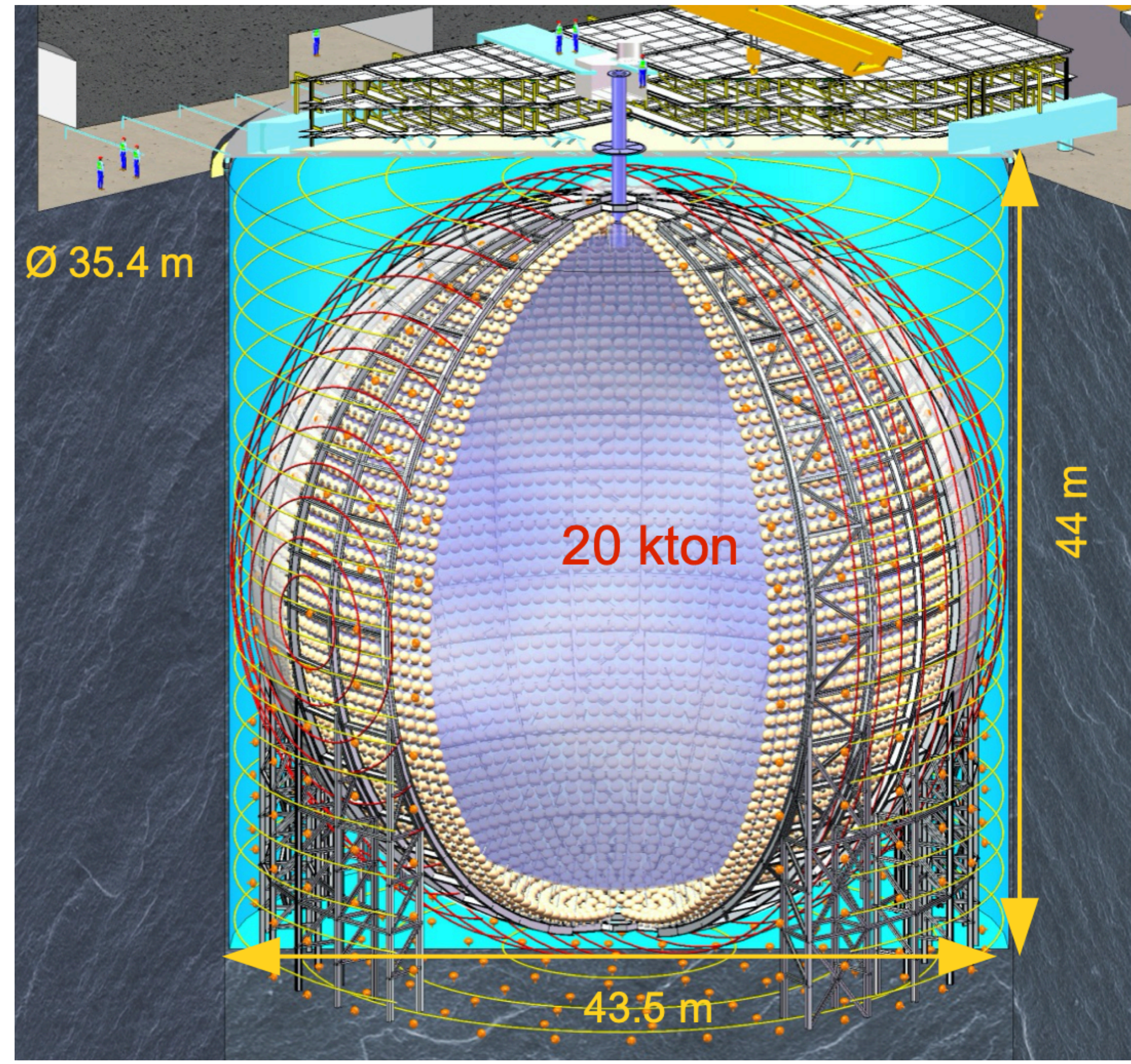
Big Lq. Scintillator Neutrino detector (in China)

- 35 m diameter acrylic sphere
- Stainless steel truss
- 20,000 tons purified liquid scintillator
- 18,000 20-inch PMTs
- 25,600 3-inch PMTs
- Filling/Overflow/Circulation (FOC) system



2019-2021
- **Electronics production starts**
- **Civil construction and lab preparation completed**
- **Detector construction**

2022
- **Detector ready for data taking**



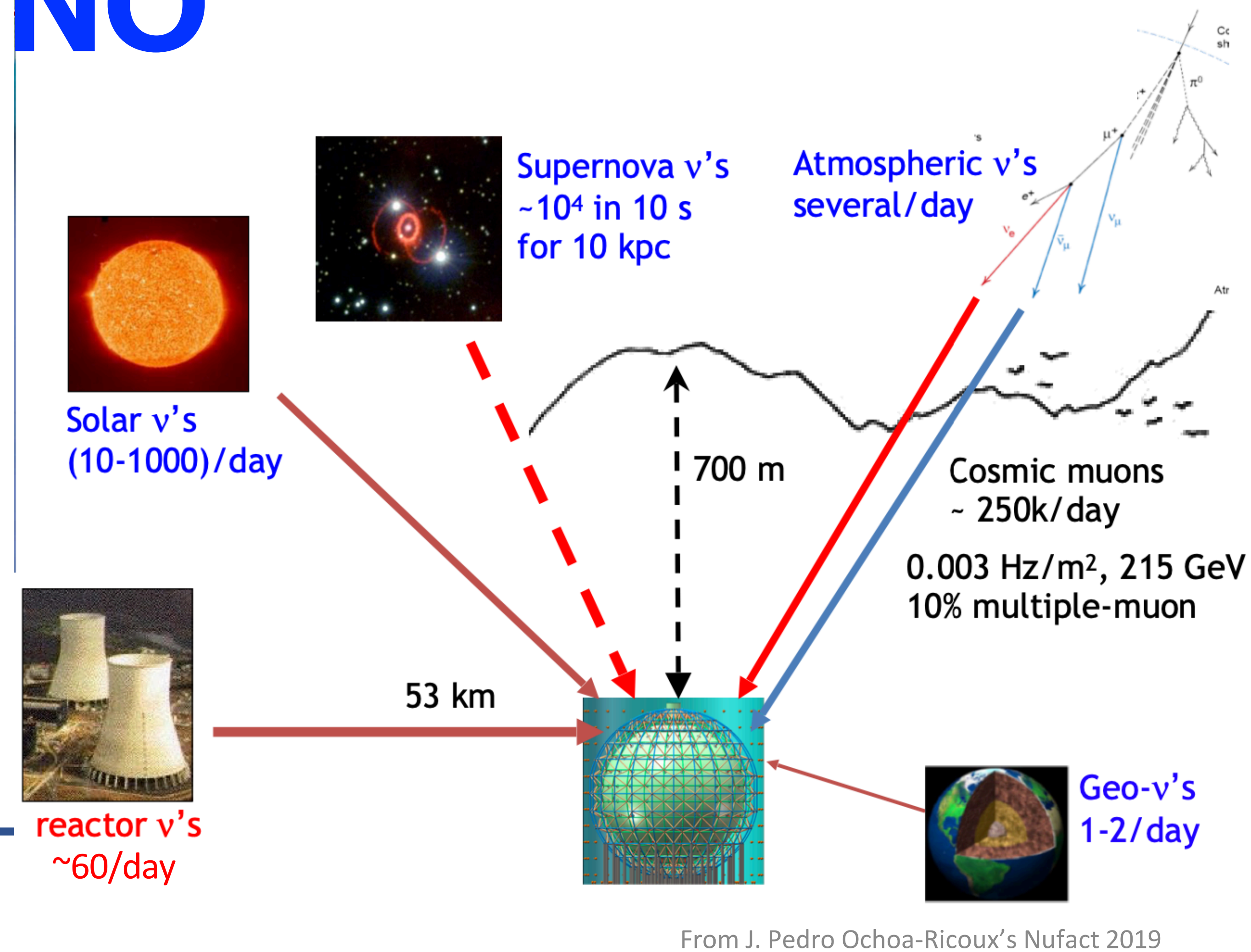
by Y. Meng @NEUTRINO2020

JUNO

Physics Prospect

$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

$$\Delta_{ij} = 1.27\Delta m^2_{ij} L/E$$



From J. Pedro Ochoa-Ricoux's Nufact 2019

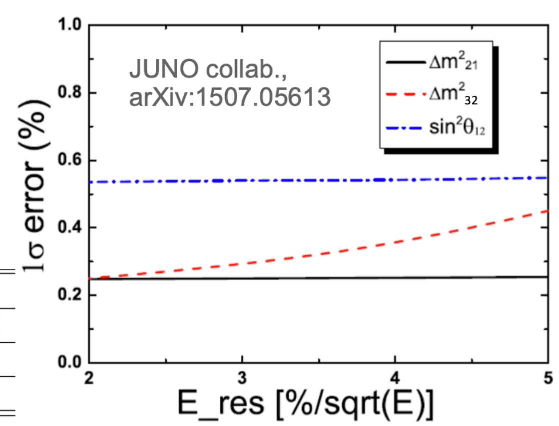
Neutrino mass ordering

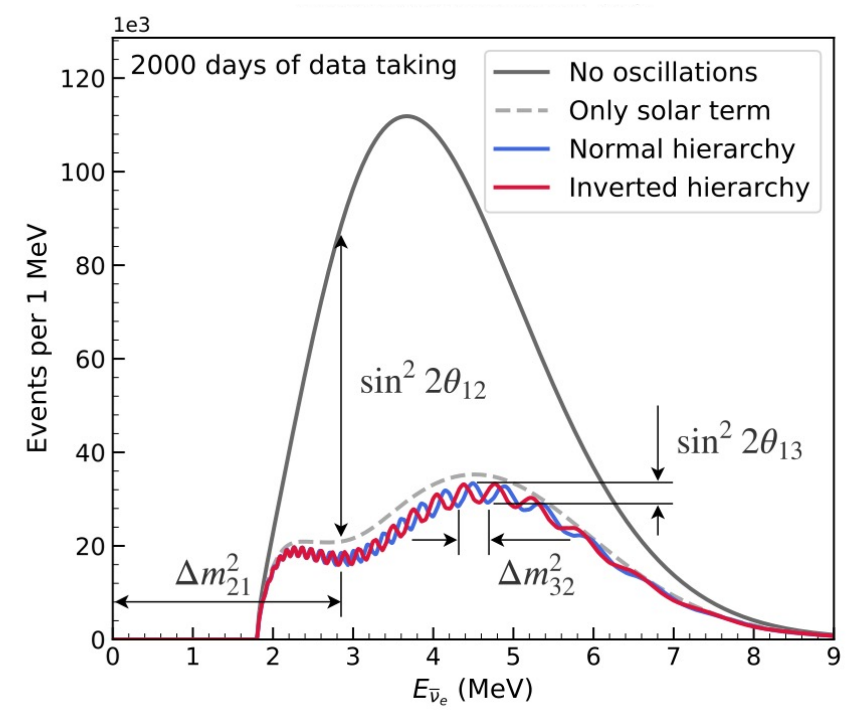
- 3σ neutrino mass ordering sensitivity within 6 years.
- 4σ with Δm^2_{32} input from accelerator experiments.
- > 5σ combined analysis with IceCube within 3–7 years or PINGU in 2 years (arXiv: 1911.06745)

Neutrino oscillation parameters

- Sub-percent accuracy for θ_{12}, Δm^2_{21} and Δm^2_{31}
- Current precision

	Δm^2_{21}	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	δ
Dominant Exps.	KamLAND	T2K	SNO+SK	Daya Bay	NOνA	T2K
Individual 1σ	2.4%	2.6%	4.5%	3.4%	5.2%	70%
Nu-FIT 4.0	2.4%	1.3%	4.0%	2.9%	3.8%	16%





by Y. Meng @NEUTRINO2020

Yue Meng, Neutrino2020

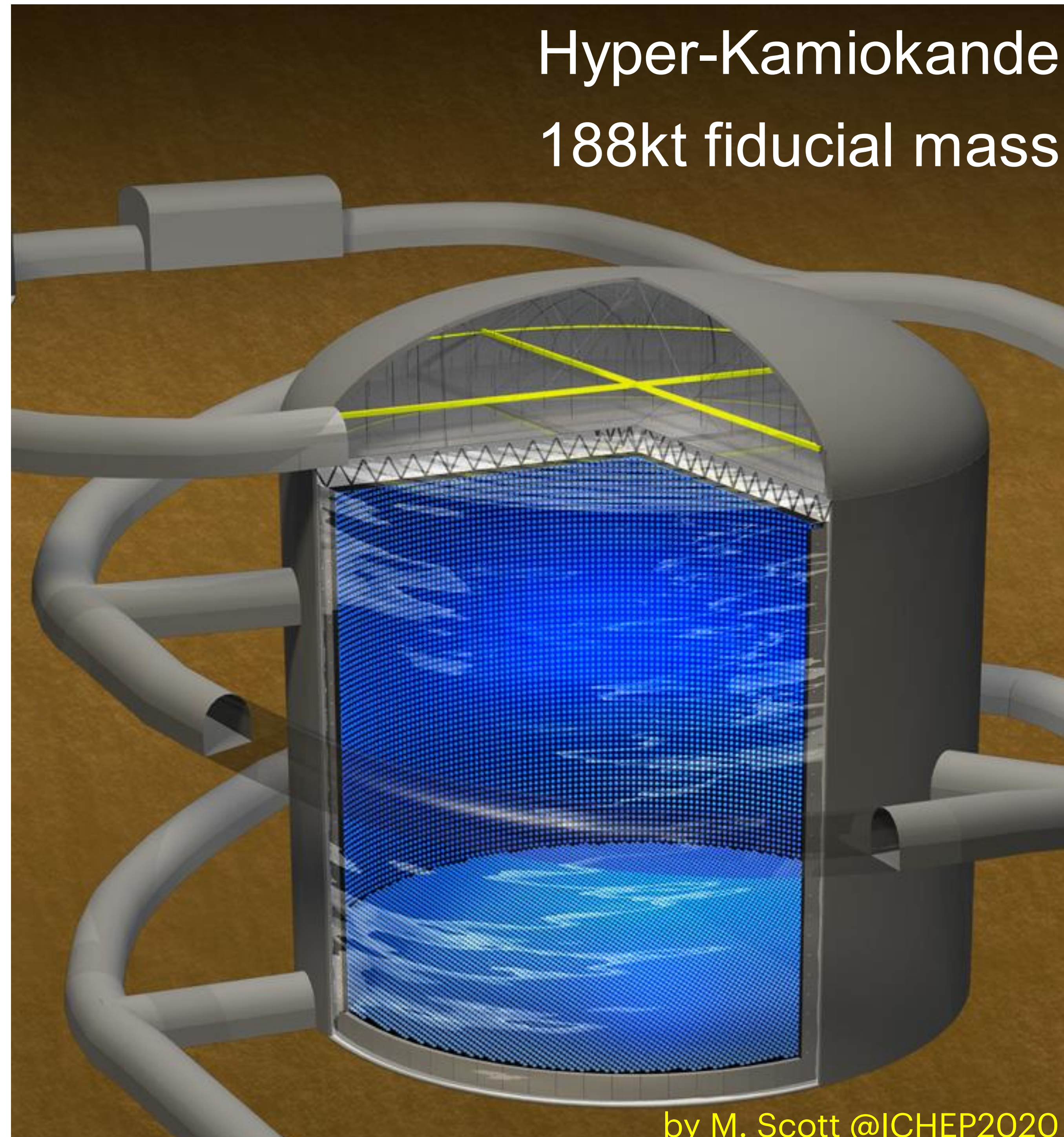
Hyper-Kamiokande

The talk by Prof. Masashi Yokoyama tomorrow.

Water Cherenkov detectors in Kamioka

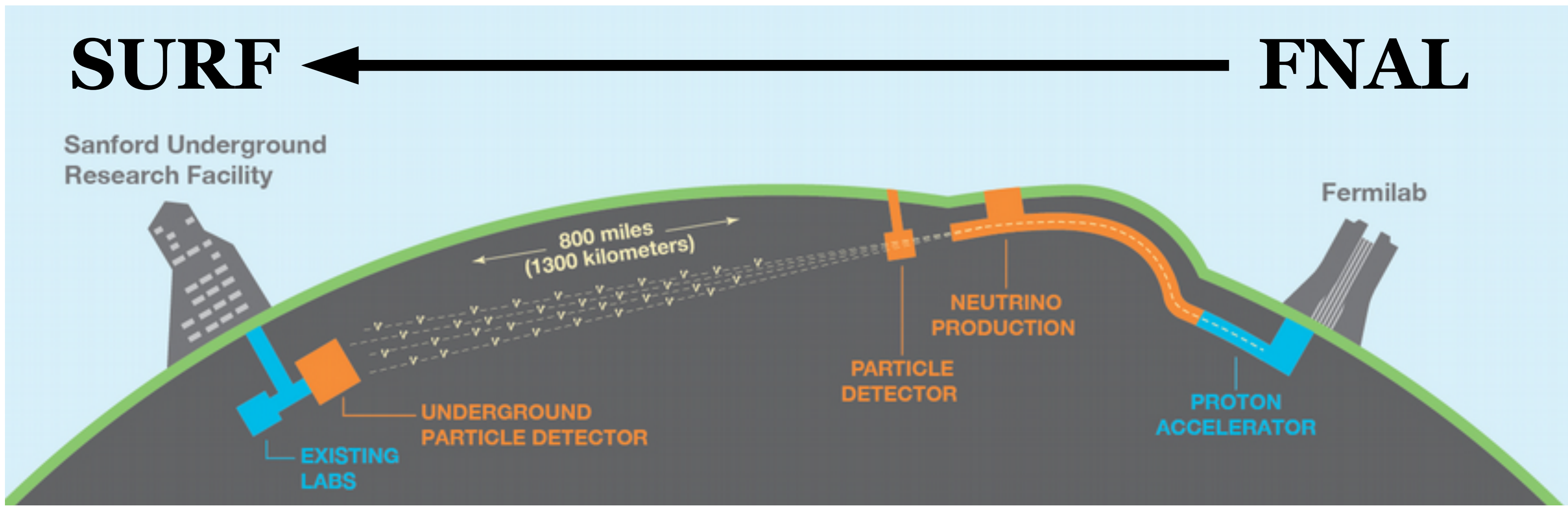
Super-Kamiokande
22.5kt fiducial mass

Kamiokande
3kt mass



DUNE

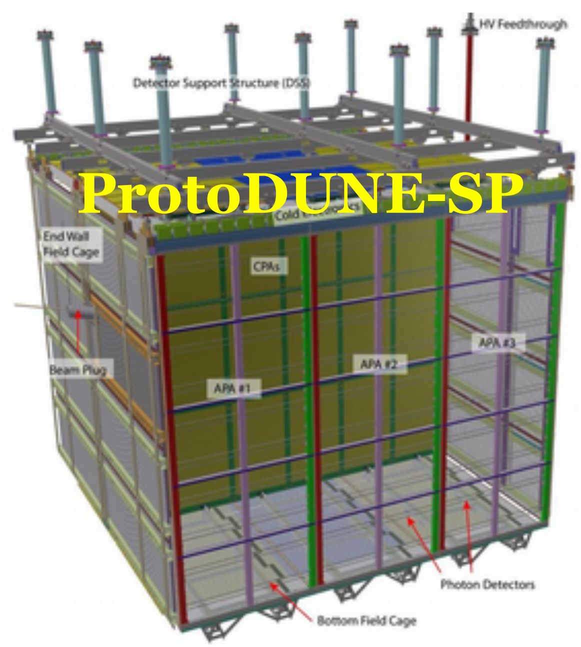
Long baseline experiment with Large (70 kt) LArTPC



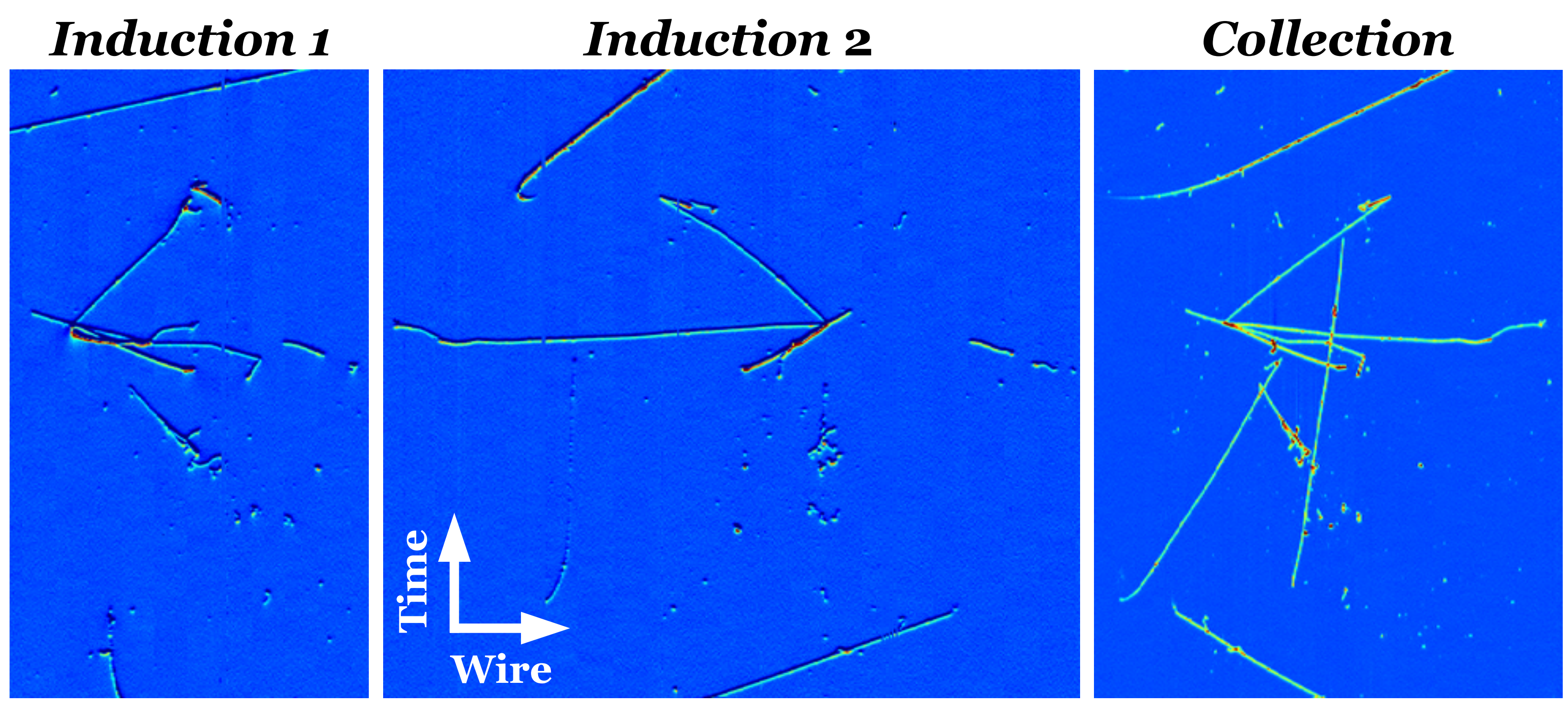
- "Deep Underground Neutrino Experiment"
  - 1300 km baseline
  - Large (70 kt) LArTPC **far detector** 1.5 km underground
  - **Near detector** w/ LAr component
- Primary physics goals:
  - ν oscillations ($\nu_\mu/\bar{\nu}_\mu$ disappearance, $\nu_e/\bar{\nu}_e$ appearance)
    - $\boldsymbol{\delta_{CP}}$, θ_{23}, θ_{13}
    - **Ordering of ν masses**
  - Supernova burst neutrinos
  - BSM processes (baryon number violation, NSI, etc.)

DUNE

Highlights (Status)



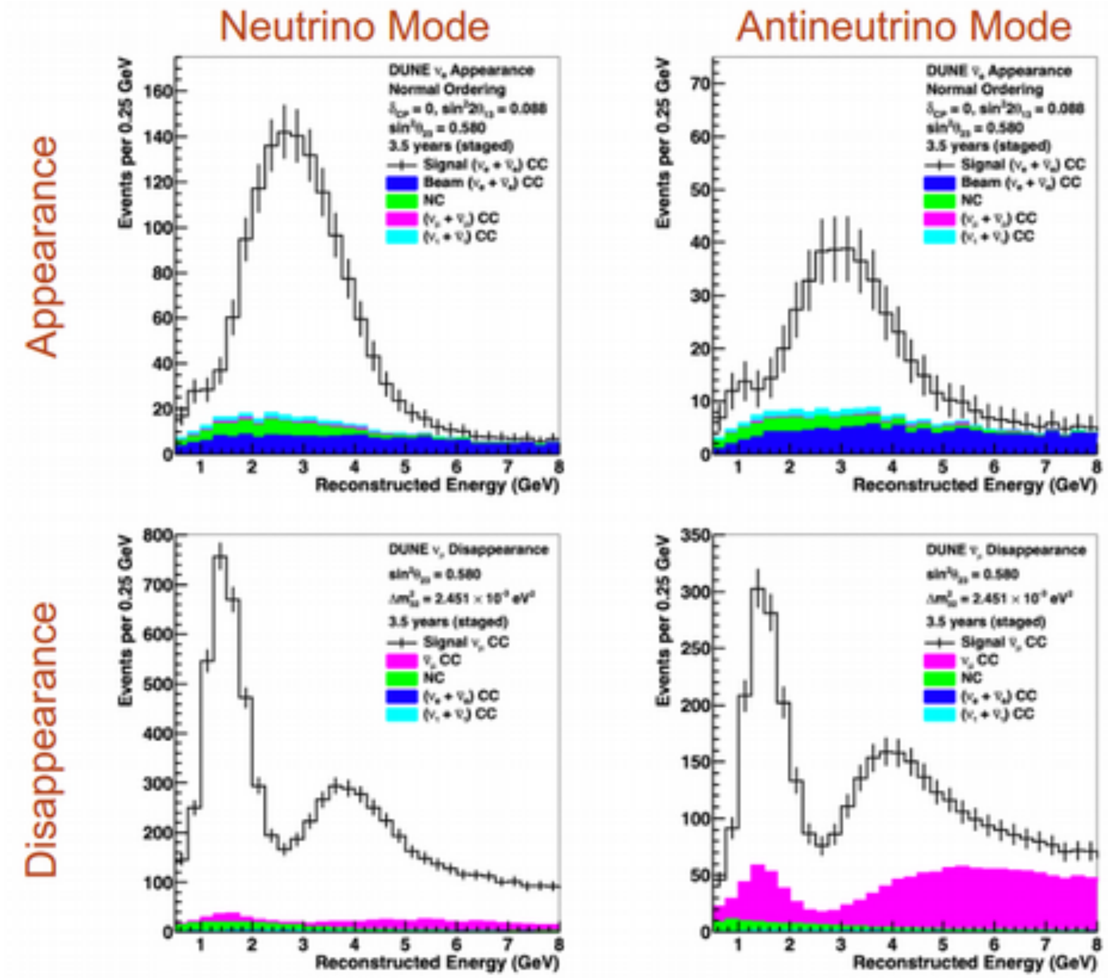
- Two 1-kt "ProtoDUNEs" in charged test beam at CERN (one per FD design)
- Test of component installation, commissioning, and performance
- ProtoDUNE-SP operating since 2018; ProtoDUNE-DP since 2019



- First beam data events: **noise levels low** on all three planes
- S/N ratio > 10 in all cases (> 40 for collection plane)
- **Stable running** since first operations began in 2018

DUNE

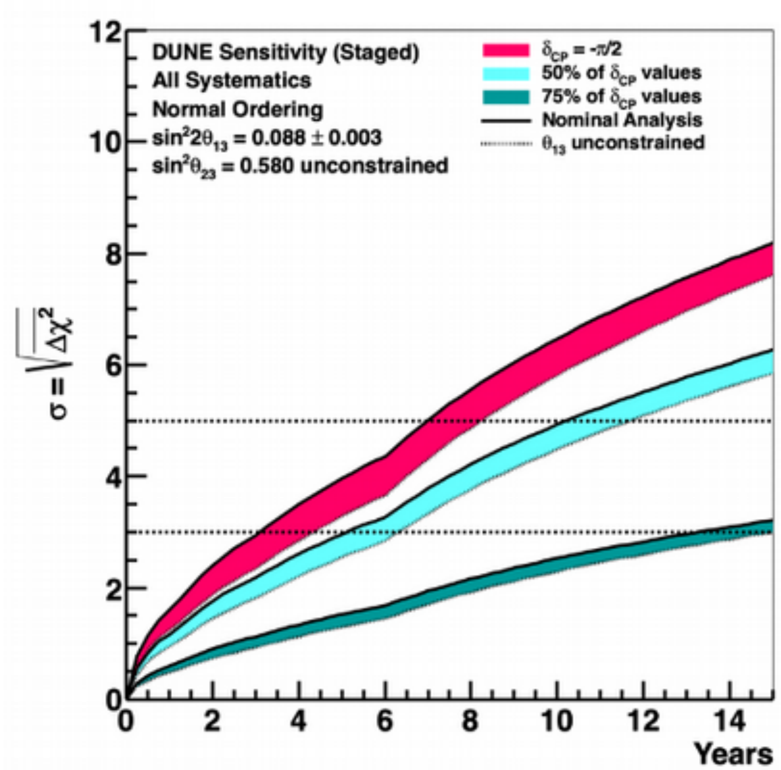
Physics prospect



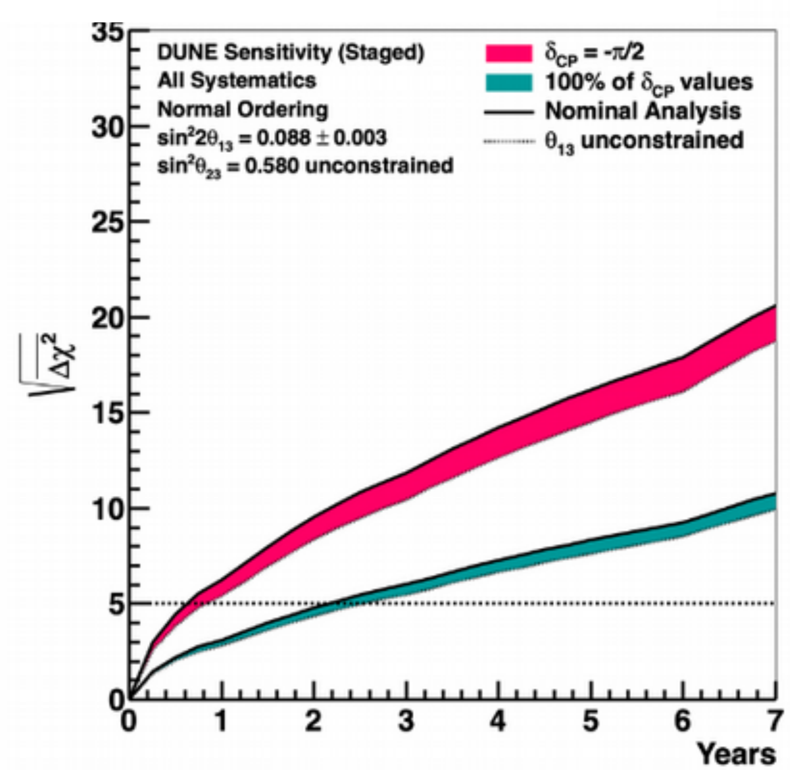
~1,000 ν_e events in 7 years (staged)

~10,000 ν_μ events in 7 years (staged)

CP Violation Sensitivity



Mass Ordering Sensitivity



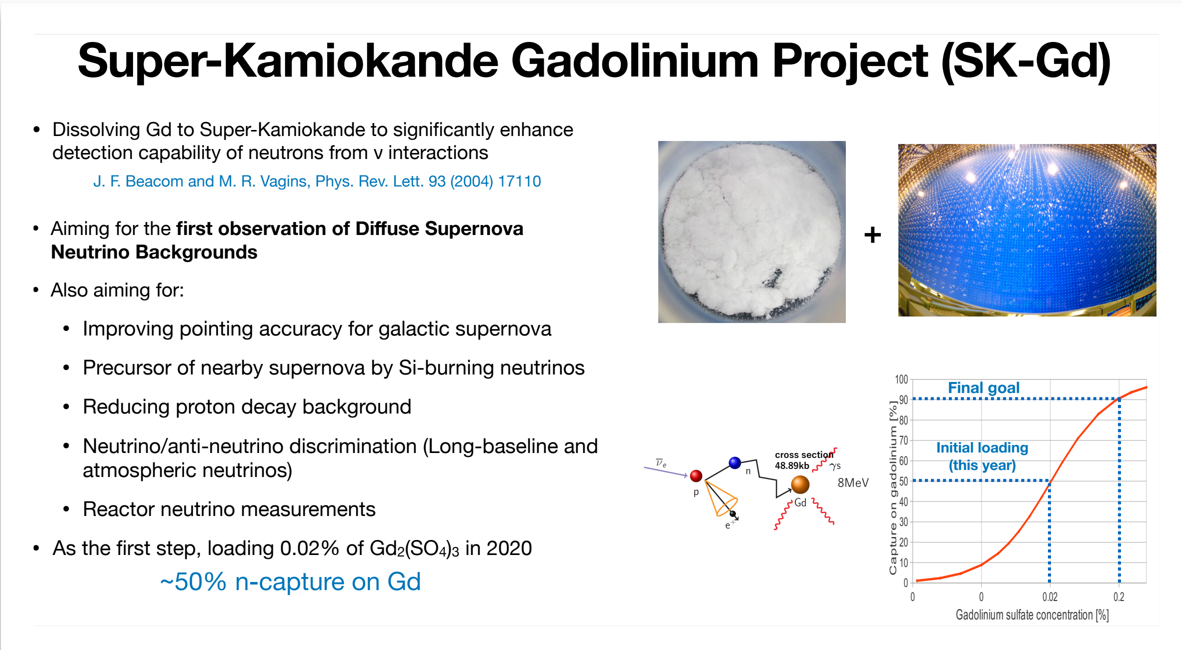
What are we doing?

Everyday efforts as step by step approaches

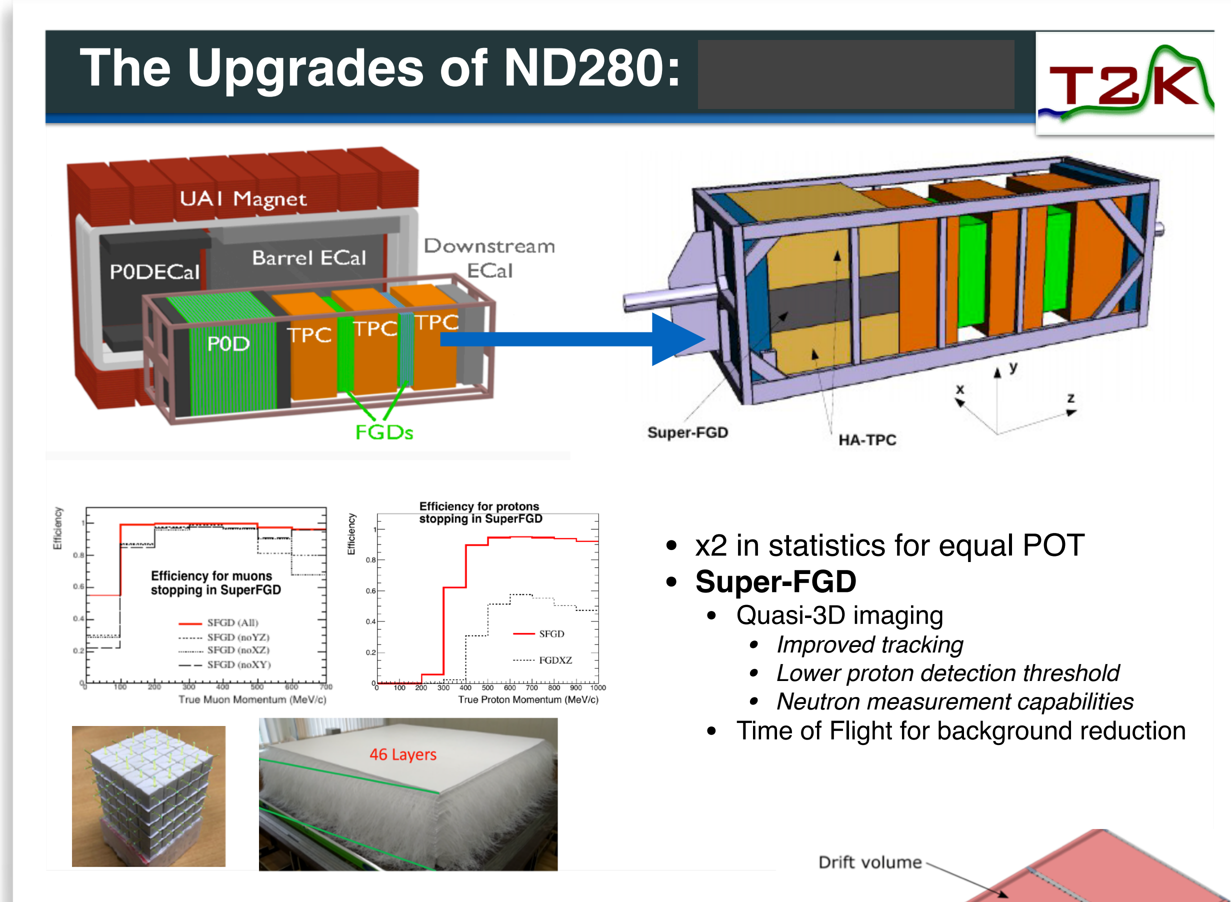
- Improving the accelerator performance
- Developing the better and bigger detectors.
- Study many physics subjects.
    - Astrophysics, Astro-particle physics, Test of GUT, Neutrino-nucleus scattering, search for new particle and new interactions (sterile neutrinos, test of CPT, etc..)

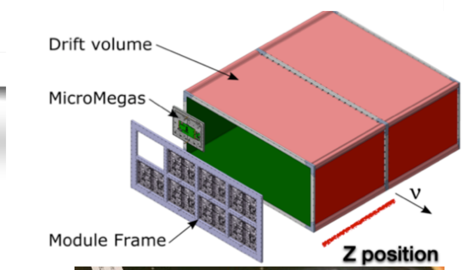
A few more topics

This evening, "Physics and Performance of the Upgraded T2K's Near Detector" by Adrien Blanchet



by Y. Nakajima @NEUTRINO2020





by A. Himmel @NEUTRINO2020

Summary

Prospects

- Precise Neutrino oscillation measurements are the essential step to the future progress.

- CP violation (and neutrino mass ordering) will be discovered (determined) anytime soon from today to the next 10 years!

- Neutrino Physics has tightly connected to astro-physics, astro-particle physics, physics of GUT, nuclear physics, etc.

Stay tuned