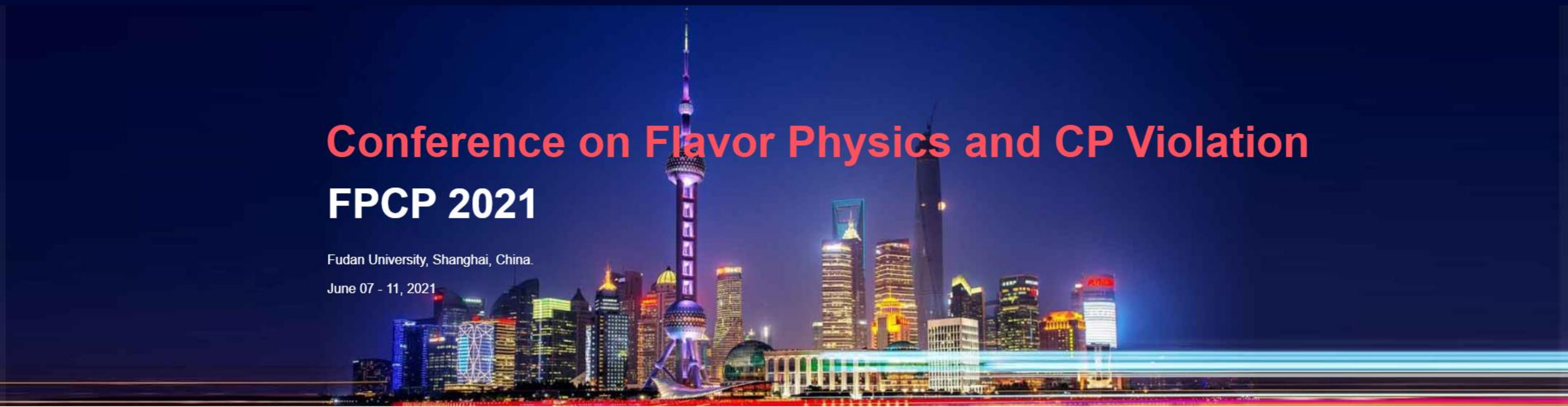
Overview on

Neutrino Oscillation Experiments

Miao HE

Institute of **H**igh **E**nergy **P**hysics,
Chinese **A**cademy of **S**ciences

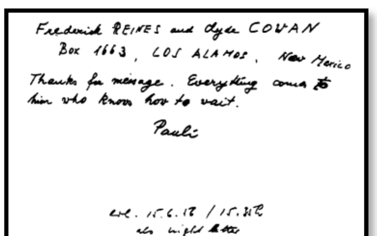


Discovery of neutrinos

1956: electron neutrinos

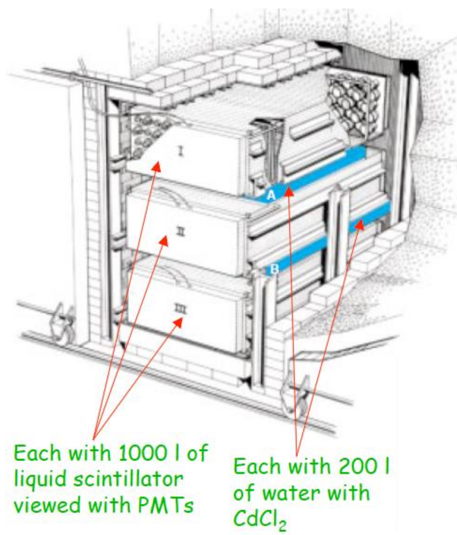
Frederick Reines
(Nobel Prize in 1995)

Clyde L. Cowan



Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico
Thanks for message. Everything comes to him who know how to wait.
Pauli

A telegram from Pauli: "Thanks for message. Everything comes to him who knows how to wait."



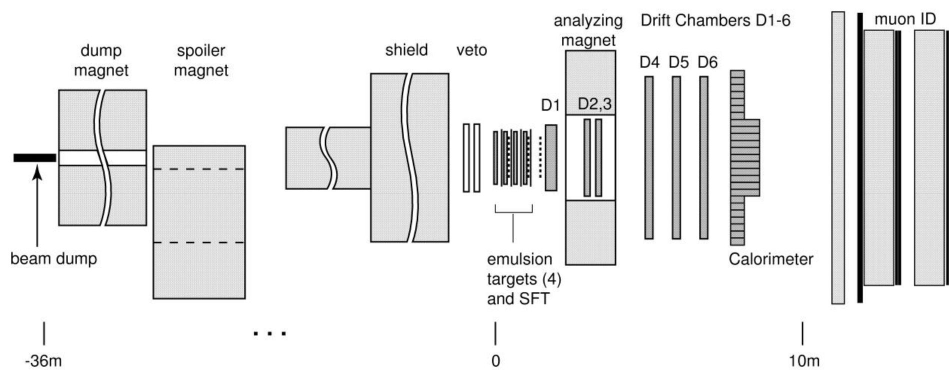
Savannah River Exp.

1962: muon neutrinos

Leon M. Lederman, Melvin Schwartz and Jack Steinberger (Nobel Prize in 1988)

Melvin Schwartz and a 10-ton spark chamber in Brookhaven National Laboratory.

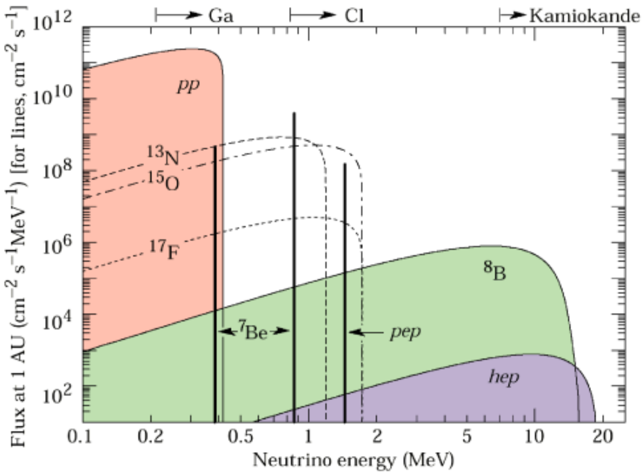
2000: tau neutrinos

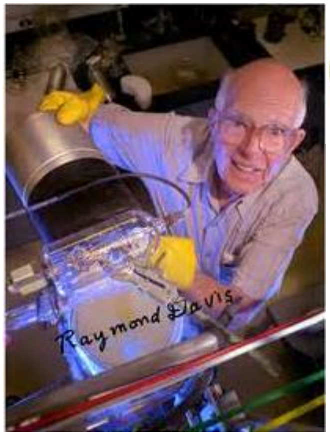


DONUT experiment in Fermilab

Explore the universe with neutrinos

Measurement of solar neutrinos since 1960s

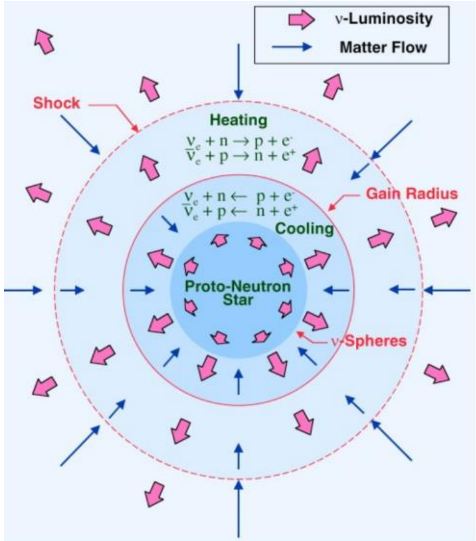


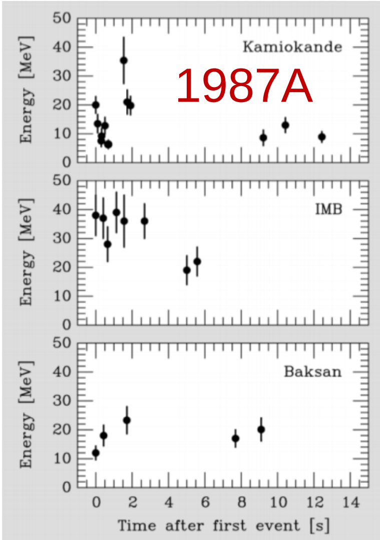


Ray Davis
(Nobel Prize in 2002)

Observation of supernova burst neutrinos in 1987

Masatoshi Koshiba
(Nobel Prize in 2002)

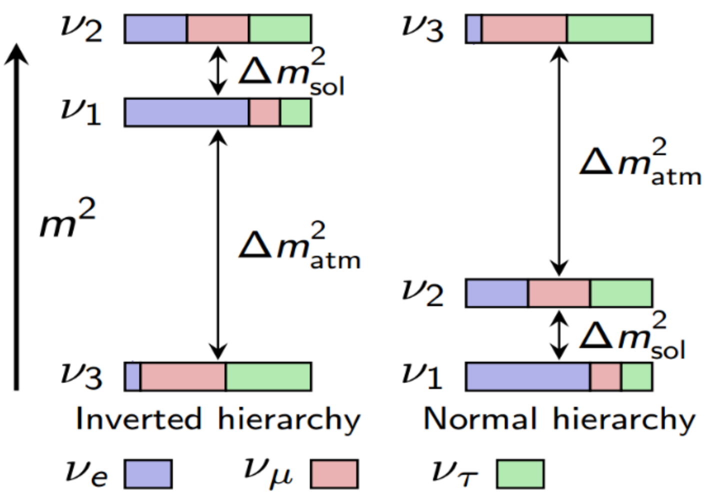




Neutrino oscillation

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha,i} |\nu_i\rangle$$

- Mass eigenstates
- PMNS matrix
- Weak eigenstates



$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{-i\delta_1} & 0 & 0 \\ 0 & e^{-i\delta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \approx 45^\circ$

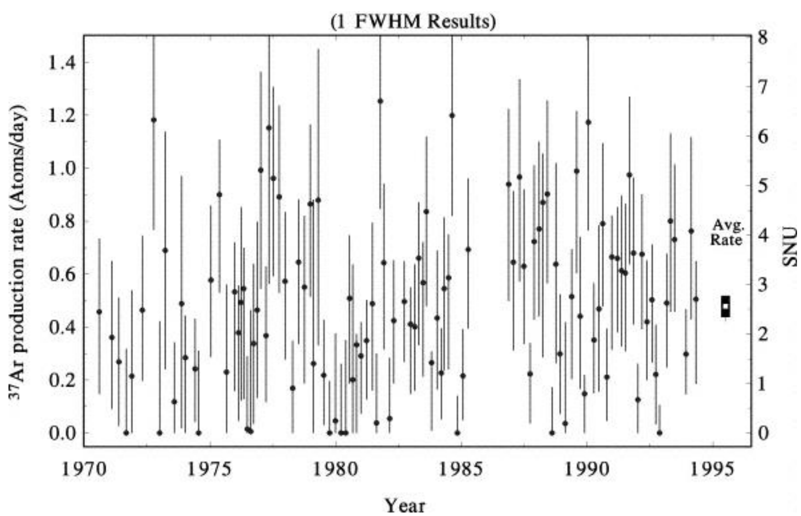
$\theta_{13} \approx 8.9^\circ$
$\delta_{CP} = ?$

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

neutrino-less double beta decay

Solar neutrino problem

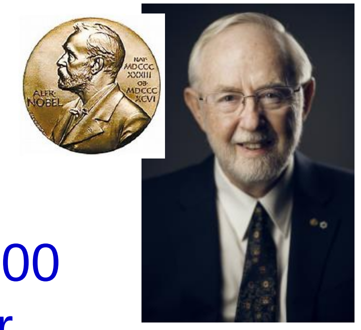
- Measurement / expectation ≈ 1/3 → "solar neutrino problem"



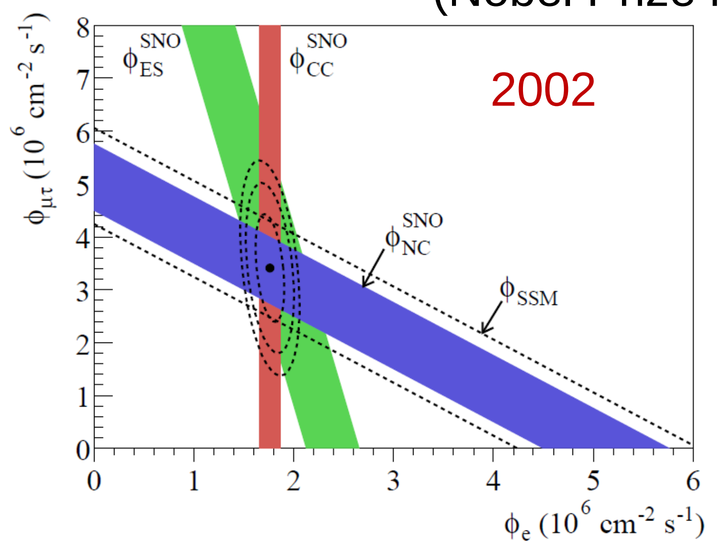
Observed solar neutrino flux

Pioneering experiment:
Homestake (Ray Davis)

- SNO: detect charge current and neutral current with 1,000 ton heavy water



Arthur B. McDonald
(Nobel Prize in 2015)



Solar neutrinos do not disappear, but oscillate to other flavors.

Atmospheric neutrinos problem

$$\pi \rightarrow \mu + \nu_\mu,$$
$$\mu \rightarrow e + \nu_e + \nu_\mu.$$

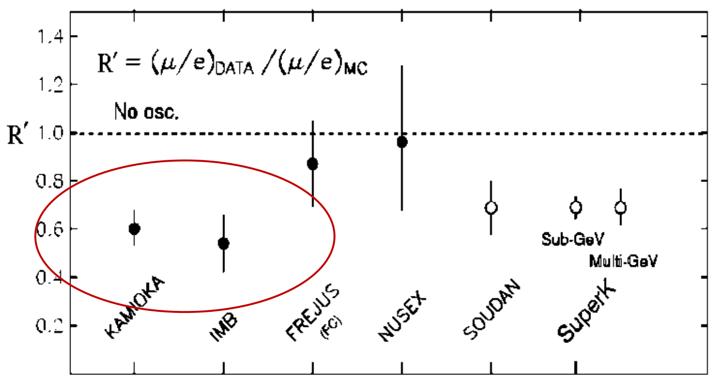
$\Rightarrow$ $\nu_\mu/\nu_e \approx 2$

- In 1980s, $\nu_\mu/\nu_e < 2 \rightarrow$

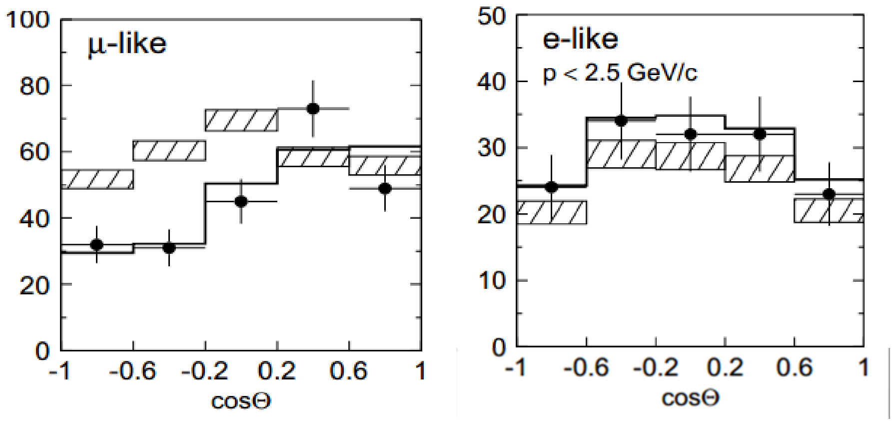
"atmospheric neutrino problem"

- SuperK: 50 kton water
  - ν_μ : disappear with propagation distance
  - Driven by $\nu_\mu \rightarrow \nu_\tau$ oscillation (θ_{23} and Δm^2_{32})

Takaaki Kajita
(Nobel Prize in 2015)



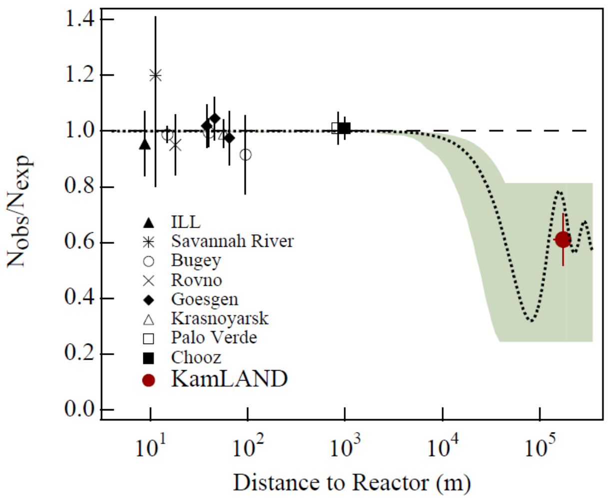
1998

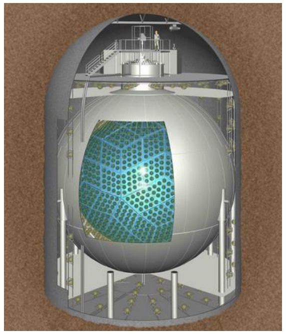


$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 (1.27 \Delta m^2 L/E)$$

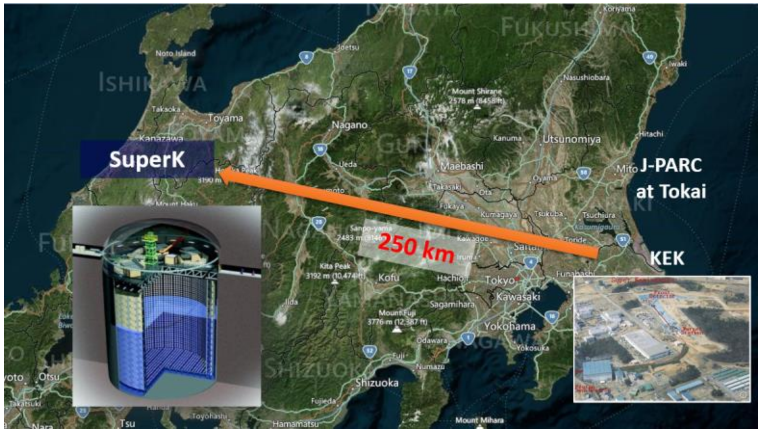
Artificial neutrinos oscillation

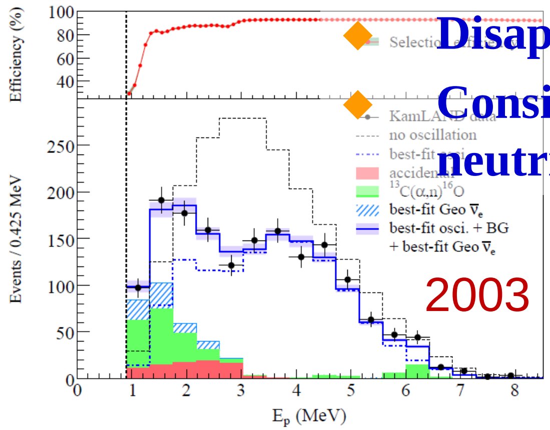
- KamLAND: 1,000 ton liquid scintillator, ~180 km to >50 reactors



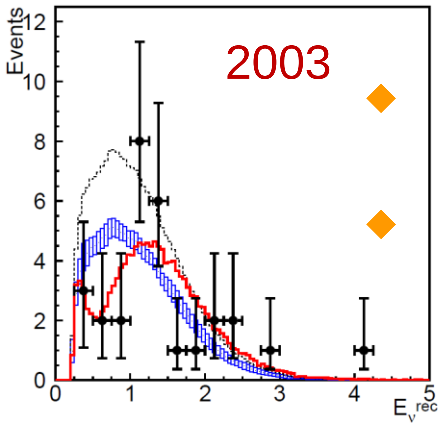


- K2K: first long-baseline accelerator experiment





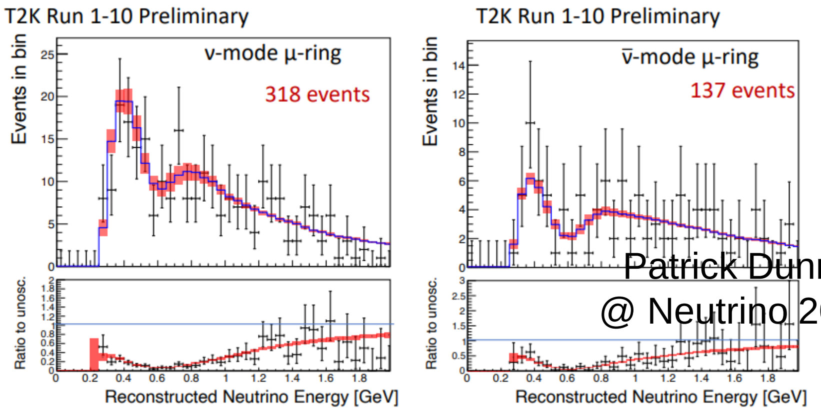
- **Disappearance of $\bar{\nu}_e$.**
- **Consistent to solar neutrinos oscillation.**



- **K2K: detected 56 ν_μ while expected 80.1.**
- **Consistent to atmospheric neutrinos oscillation.**

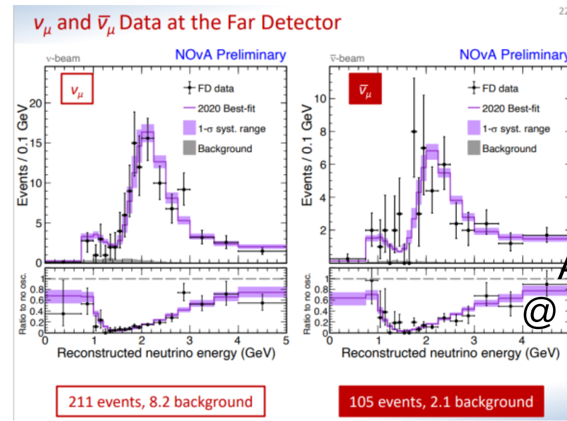
More ν_μ disappearance experiments

T2K: 295 km baseline



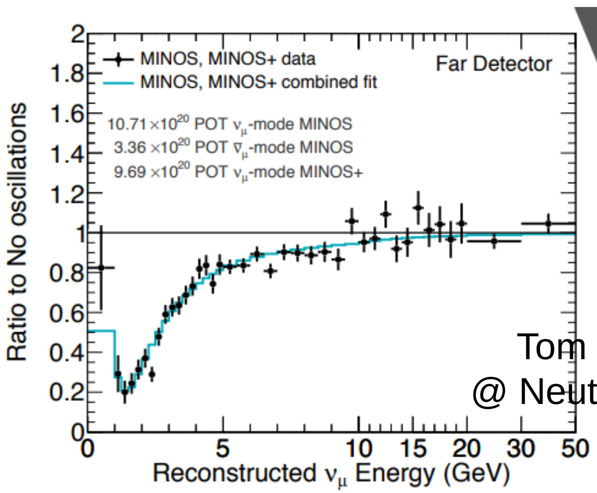
Patrick Dunne
@ Neutrino 2020

NOvA: 810 km baseline



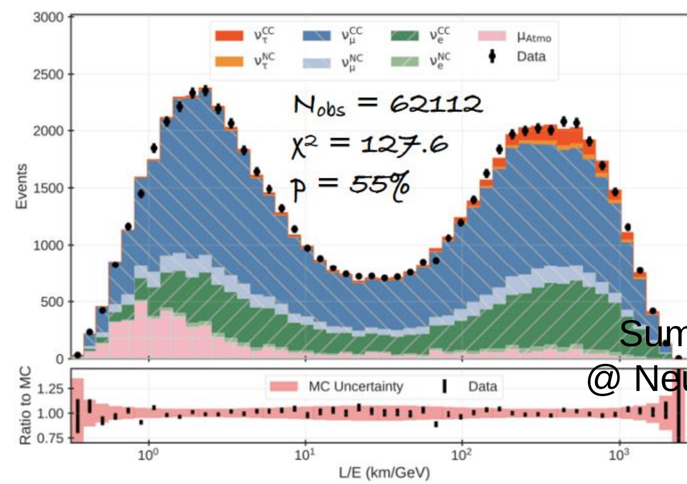
Alex Himmel
@ Neutrino 2020

MINOS/MINOS+: 735 km baseline



Tom Carroll
@ Neutrino 2020

IceCube-DeepCore: Atm. neutrinos

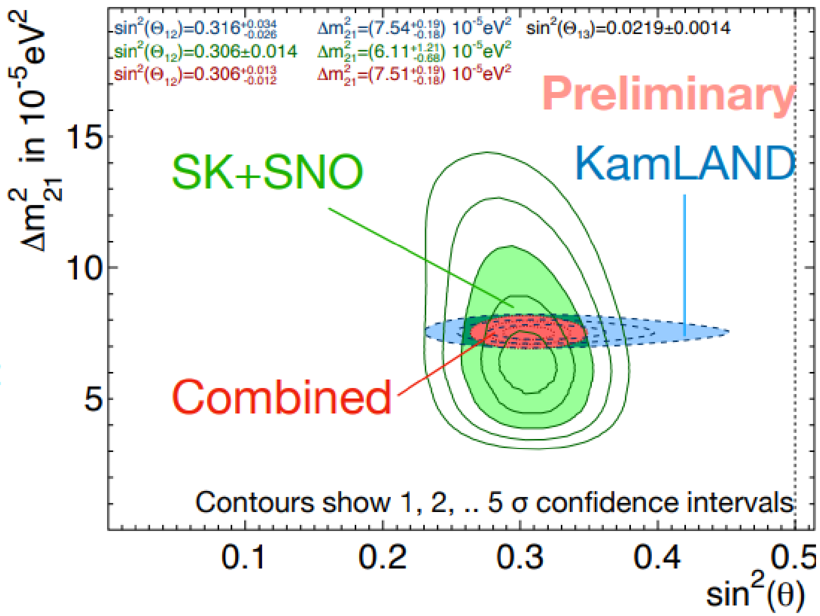


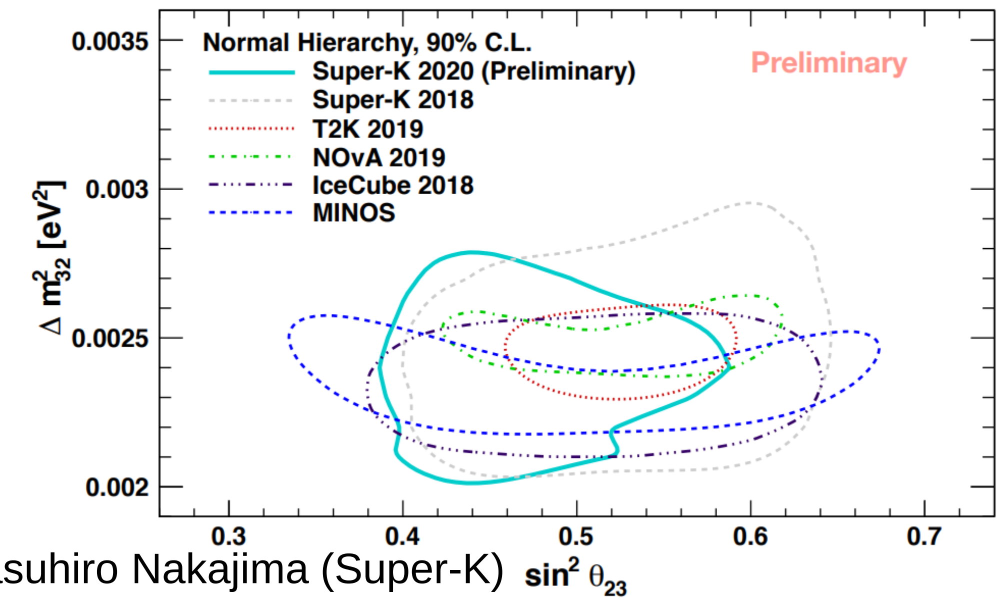
Summer Blot
@ Neutrino 2020

Global comparison

θ_{12} and Δm^2_{21} constrains by solar experiments and KamLAND

θ_{23} and $|\Delta m^2_{32}|$ constrains by atmospheric and accelerator experiments





Yasuhiro Nakajima (Super-K) @ Neutrino 2020

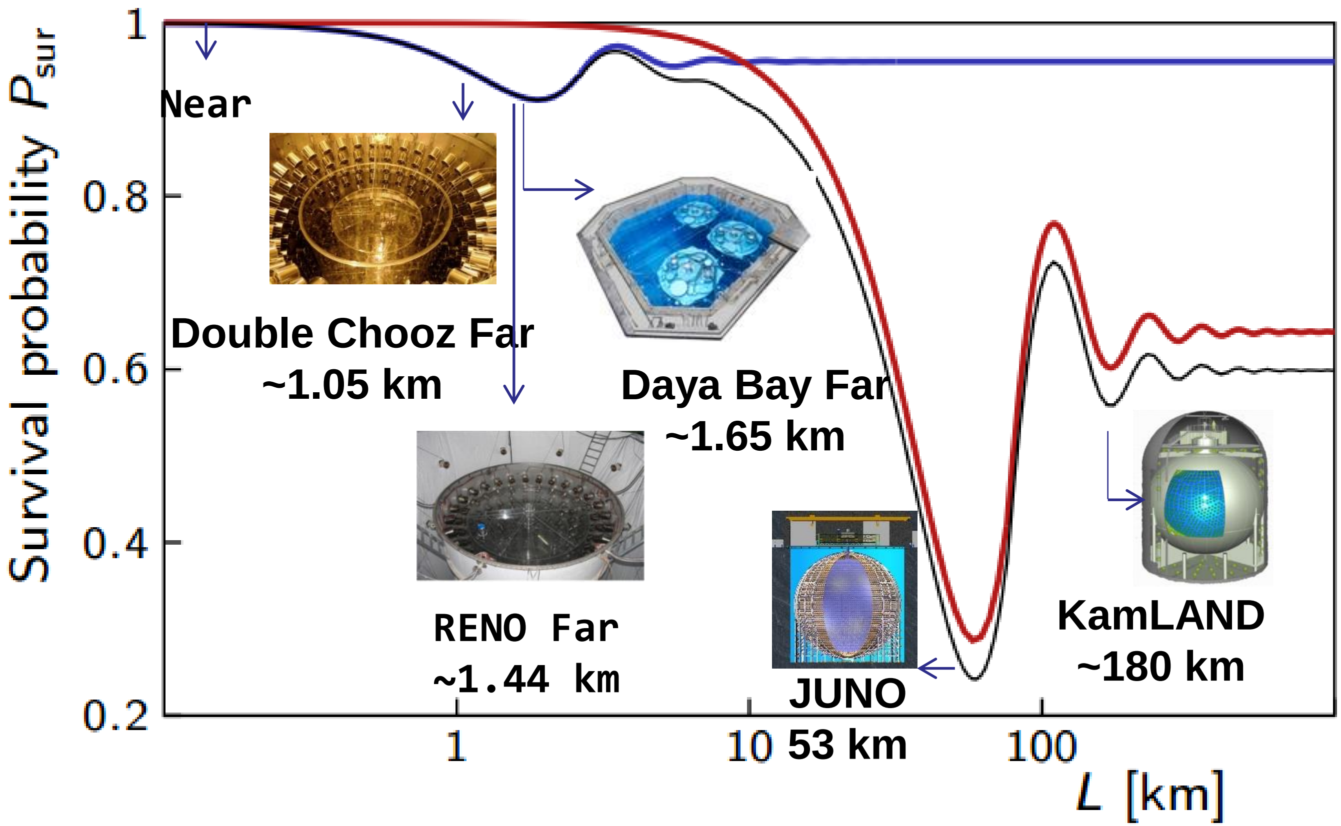
Parameter	Δm^2_{21}	$\sin^2\theta_{12}$	Δm^2_{32}	$\sin^2\theta_{23}$
Precision	2.4%	4.2%	1.4%	4.9%

PDG2020

θ_{13} in reactor experiments

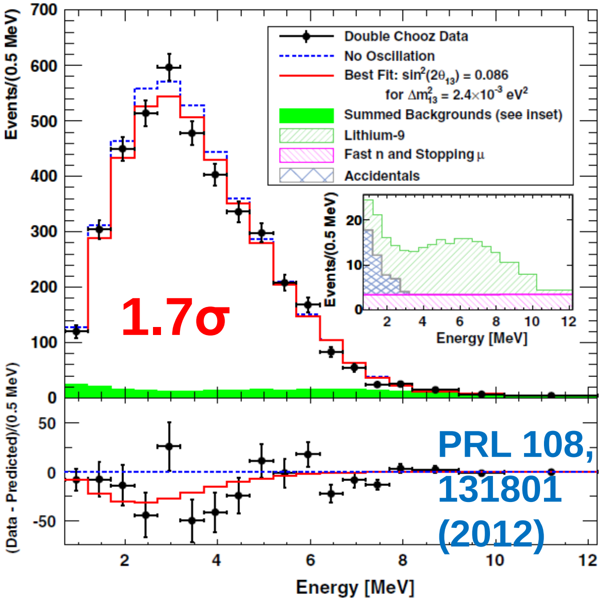
"Disappearance" experiments: $\bar{\nu}_e \rightarrow \bar{\nu}_e$

$$P_{\bar{\nu}_e\rightarrow\bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee}\frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\left(\Delta m^2_{21}\frac{L}{4E}\right)$$



Discovery of non-zero θ_{13}

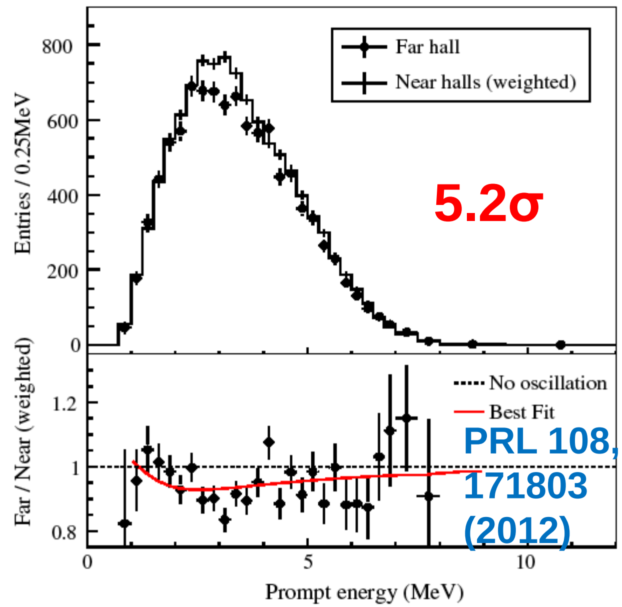
Double Chooz
with only a far detector
(Nov. 2011)



Rate+shape

$$\sin^2 2\theta_{13} = 0.086 \pm 0.041(\text{stat}) \pm 0.030(\text{syst})$$

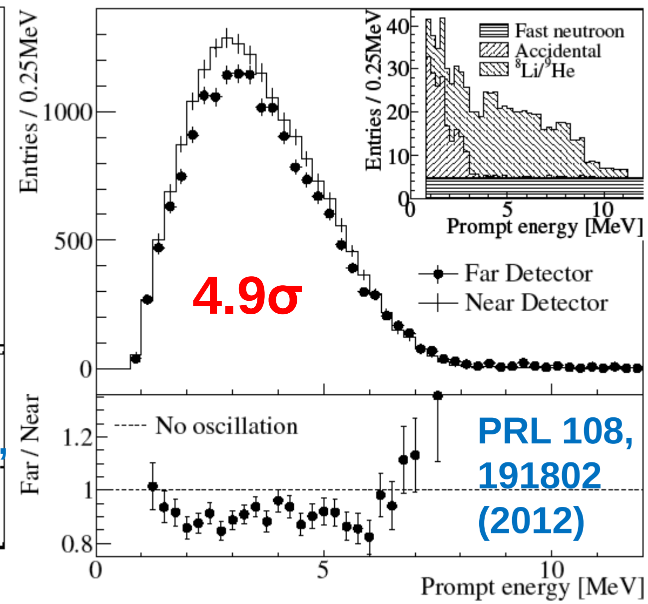
Daya Bay
(March 2012)



Rate only

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat.}) \pm 0.005(\text{syst.})$$

RENO
(April 2012)

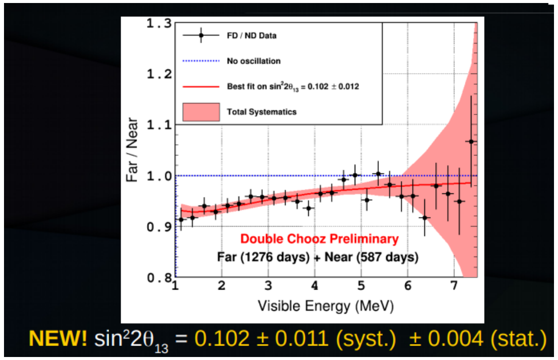


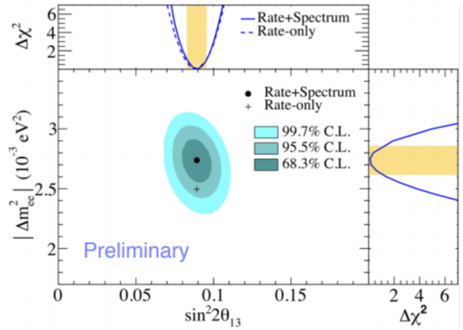
Rate only

$$\sin^2 2\theta_{13} = 0.103 \pm 0.013(\text{stat.}) \pm 0.011(\text{syst.})$$

Latest results of reactor experiments

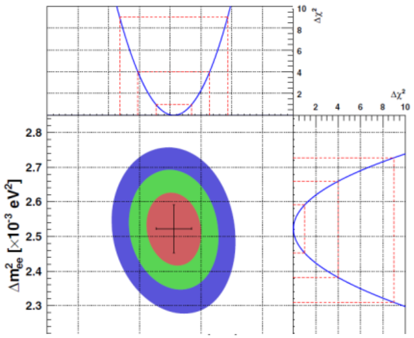
News from Neutrino 2020





$\sin^2 2\theta_{13} = 0.0892 \pm 0.0044(stat.) \pm 0.0045(sys.)$ ± 7.0%

$|\Delta m^2_{ee}| = 2.74 \pm 0.10(stat.) \pm 0.06(sys.)(\times 10^{-3}\text{eV}^2)$ ± 4.4%



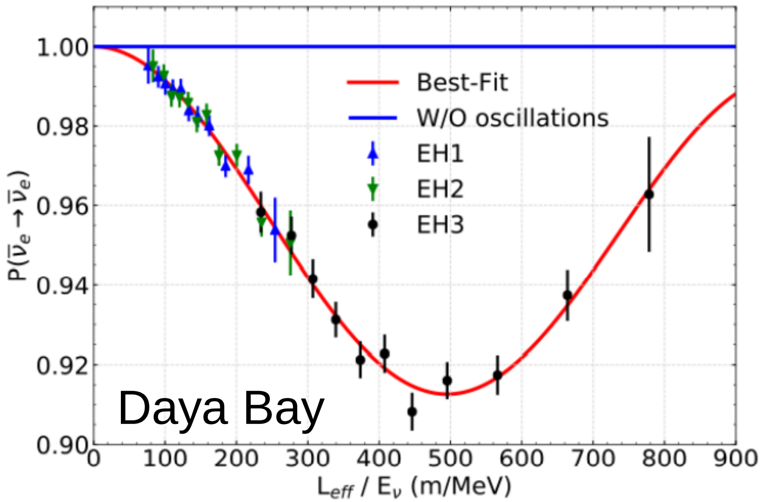
$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$

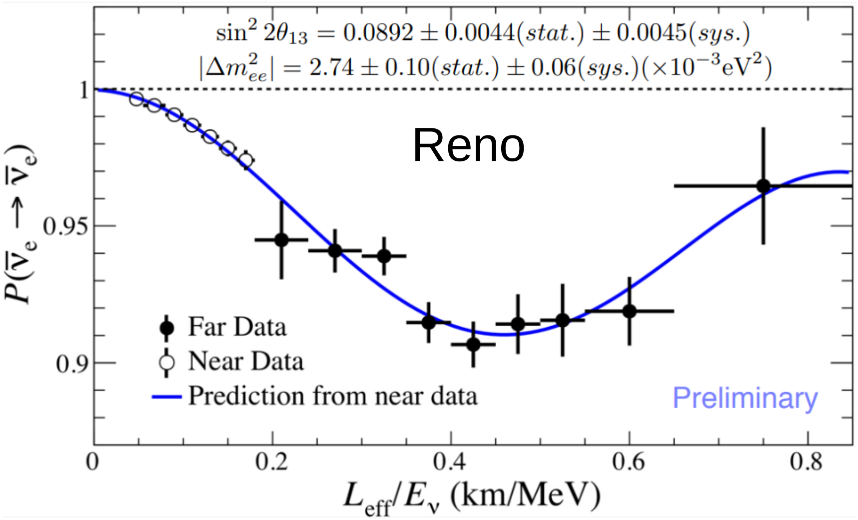
$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}$ eV²

$\Delta m^2_{32} = (2.47 \pm 0.07) \times 10^{-3}$ eV² (NO)

$\Delta m^2_{32} = (-2.58 \pm 0.07) \times 10^{-3}$ eV² (IO)

Double Chooz, *Thiago Bezerra* Reno, *Jonghee Yoo* Daya Bay, *Jiajie Ling*

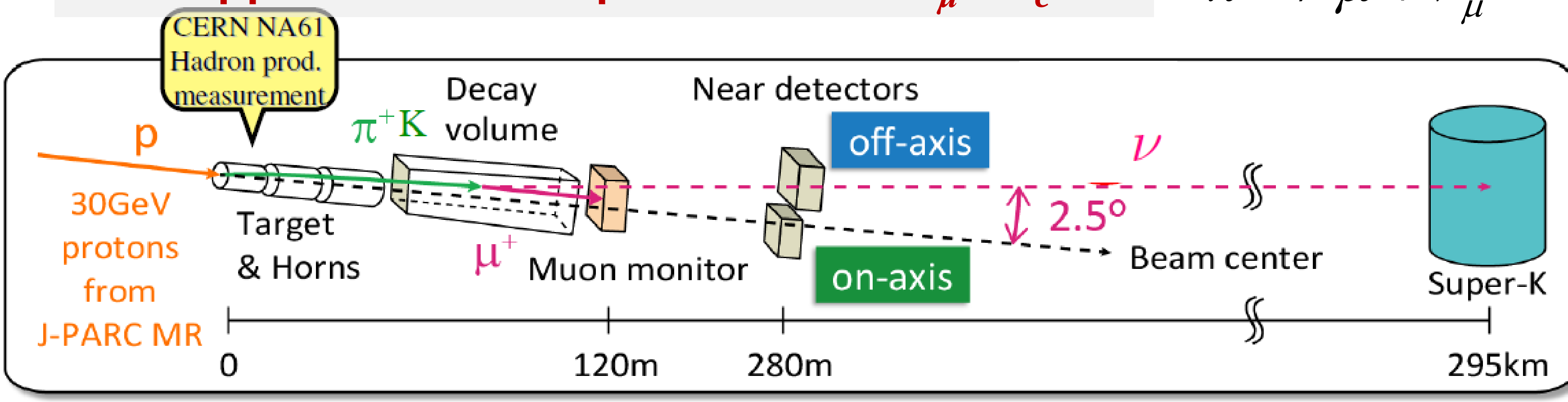




θ_{13} in accelerator experiments

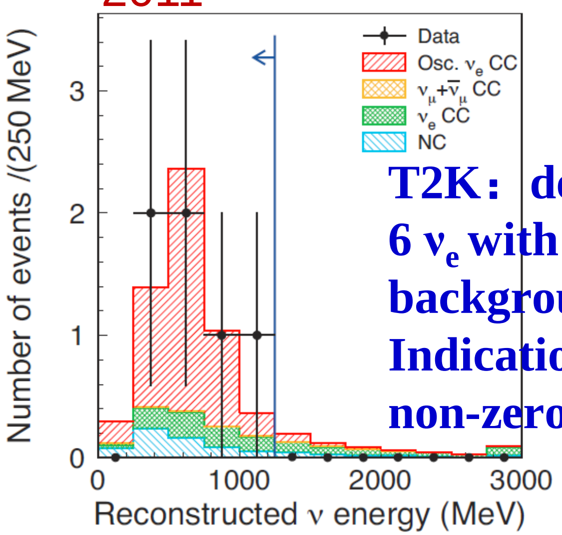
"Appearance" experiments: $\nu_\mu \rightarrow \nu_e$

$$\pi \rightarrow \mu + \nu_\mu$$



T2K EPS-HEP2015

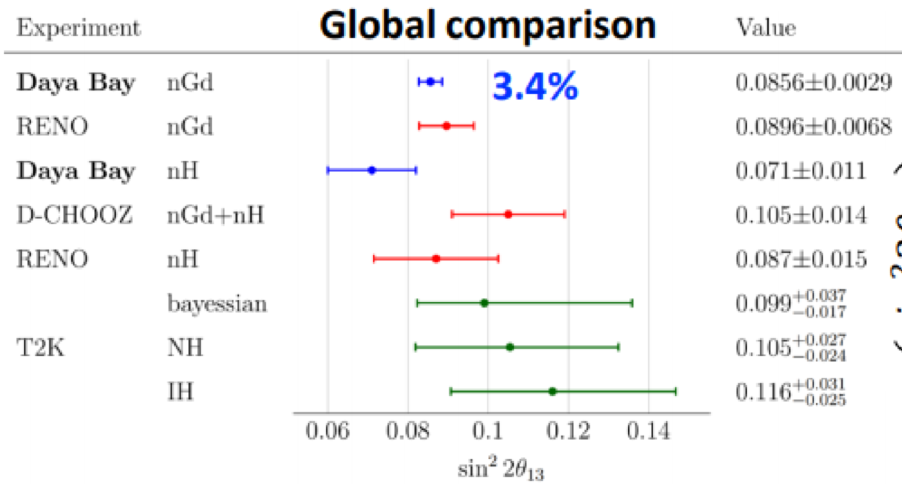
2011

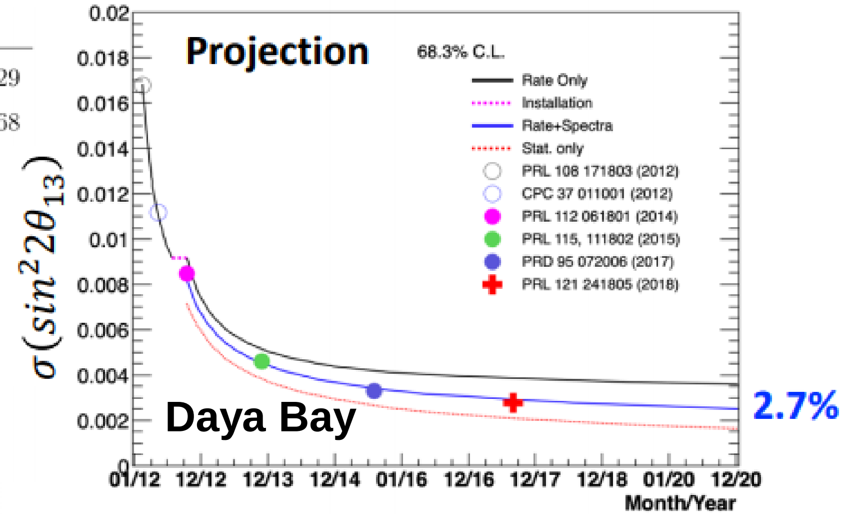


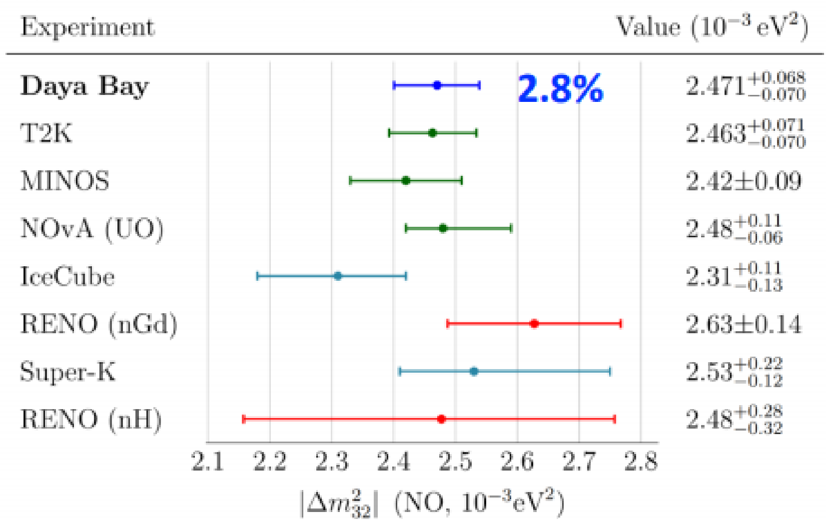
T2K: detected 6 ν_e with 1.5 background. Indication of non-zero θ_{13}

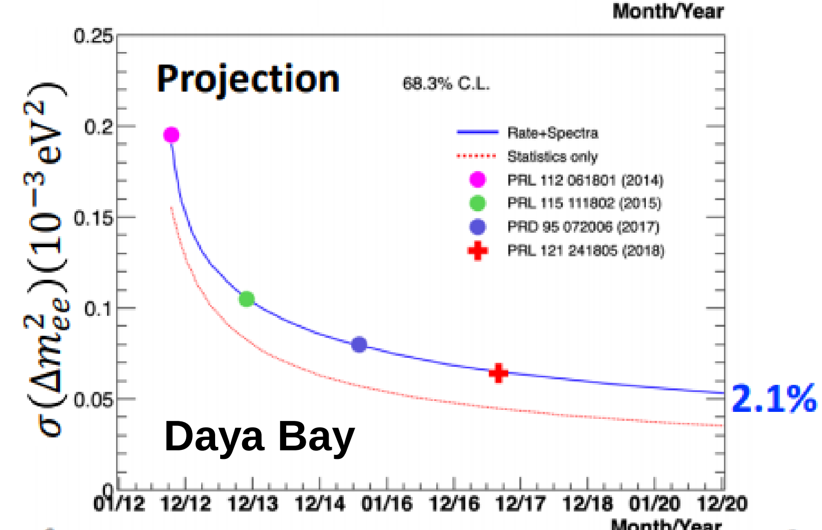
- **Indication** of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam, 2011. **2.5σ**
- **Evidence** of Electron Neutrino Appearance in a Muon Neutrino Beam, 2013. **>3σ**
- **Observation** of Electron Neutrino Appearance in a Muon Neutrino Beam, 2014. **>5σ**

Global comparison



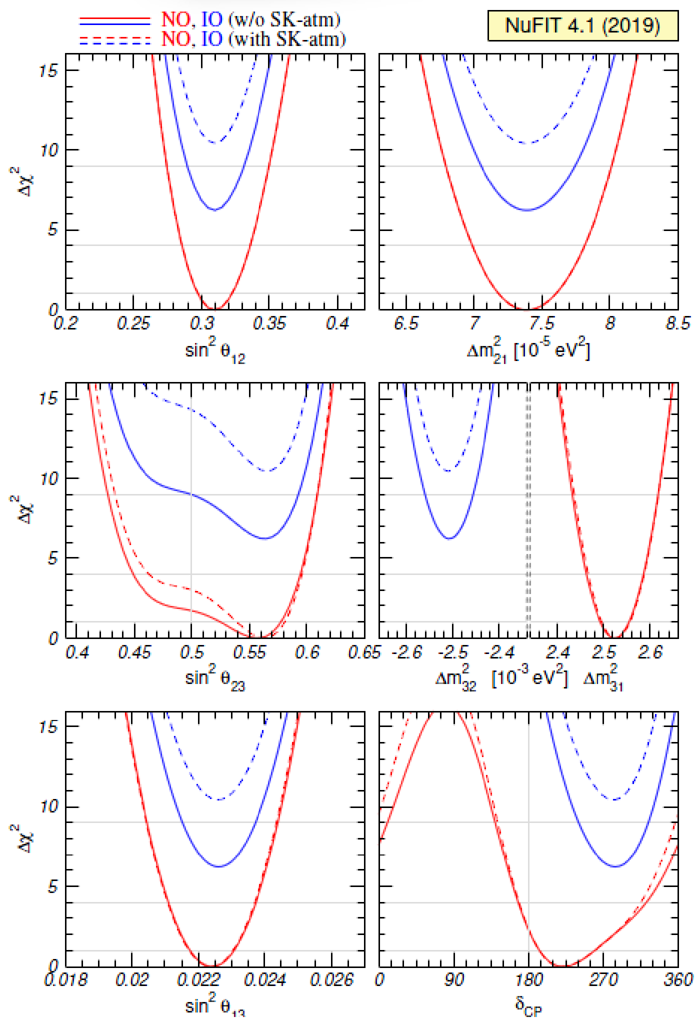






Jiajie Ling (SYSU) XXIX Neutrino Conference 9

3-ν oscillation status



NuFIT 4.1 (2019), www.nu-fit.org

✓ Known

- $\sin^2\theta_{12}$, $\sin^2\theta_{23}$, and $\sin^2\theta_{13}$ (~ 4%, 6%, 3%)
- $|\Delta m^2_{31}|$ and Δm^2_{21} (~ 1%, 3%)

– Unknown

- Mass ordering (MO, sign of Δm^2_{31})
- Octant of θ_{23} (>, < or = $\pi/4$?)
- Leptonic CP-violating phase δ

Global fit, Mariam ICHEP 2020,

parameter	best fit ± 1σ	3σ range	
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.50^{+0.22}_{-0.20}$	6.94–8.14	2.7%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	$2.56^{+0.03}_{-0.04}$	2.46–2.65	1.2%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	2.46 ± 0.03	2.37–2.55	?
$\sin^2\theta_{12}$ $/10^{-1}$	3.18 ± 0.16	2.71–3.70	5.2%
$\sin^2\theta_{23}$ $/10^{-1}$ (NO)	$5.66^{+0.16}_{-0.22}$	4.41–6.09	4.9%
$\sin^2\theta_{23}$ $/10^{-1}$ (IO)	$5.66^{+0.18}_{-0.23}$	4.46–6.09	4.8%
$\sin^2\theta_{13}$ $/10^{-2}$ (NO)	$2.225^{+0.055}_{-0.078}$	2.015–2.417	3.0%
$\sin^2\theta_{13}$ $/10^{-2}$ (IO)	$2.250^{+0.056}_{-0.076}$	2.039–2.441	

MO and CP in $\nu_\mu \rightarrow \nu_e$ oscillation

- **CP**: asymmetry between ν_e and $\bar{\nu}_e$ appearance
- **MO**: coherent forward scattering (matter effect)

$$\mathcal{A} \equiv \frac{P - \bar{P}}{P + \bar{P}}$$

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\ \sin^2 2\theta_{13}\ \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\ \Delta_{31}^2$$

$$+ \sin 2\theta_{23}\ \sin 2\theta_{13} \sin 2\theta_{12}\ \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)}$$

$$\times \Delta_{31}\ \frac{\sin(aL)}{(aL)}\ \Delta_{21}\ \cos(\Delta_{31} + \delta)$$

$$+ \cos^2\theta_{23} \sin^2 2\theta_{12}\ \frac{\sin^2(aL)}{(aL)^2}\ \Delta_{21}^2,$$

Atmospheric term (first line)

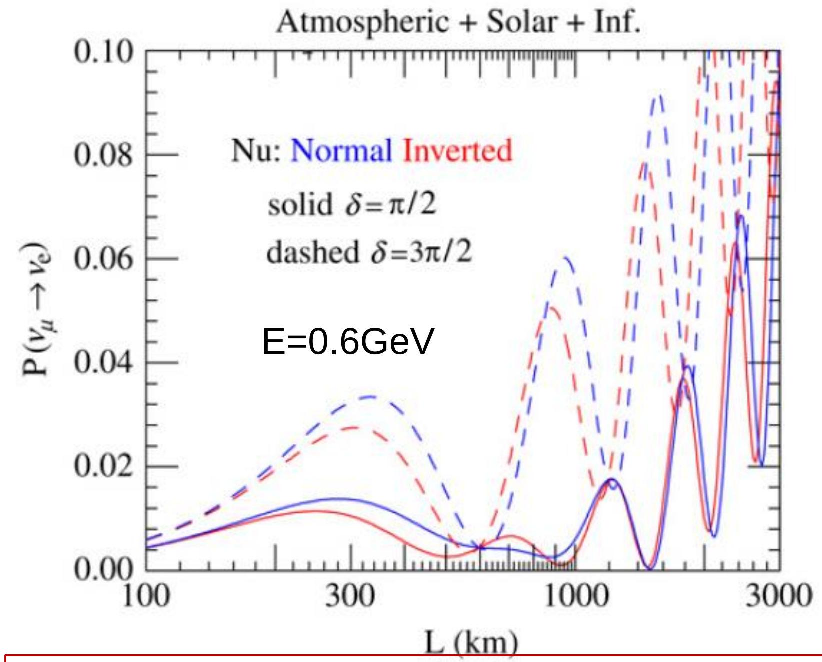
Interference term (second and third lines)

Solar term (fourth line)

In earth, $a \equiv G_F N_e / \sqrt{2} \approx (3500\text{km})^{-1}$

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

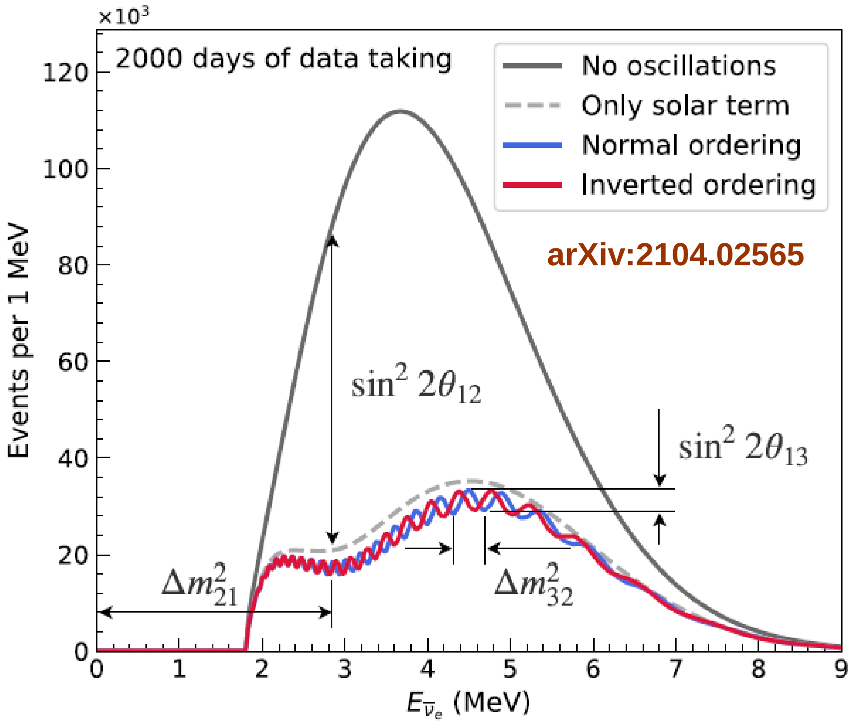
$\sim \Delta_{31} \to -\Delta_{31}$ ⇒ Mass Ordering



Progress in Particle and Nuclear Physics 60 (2008) 338–402

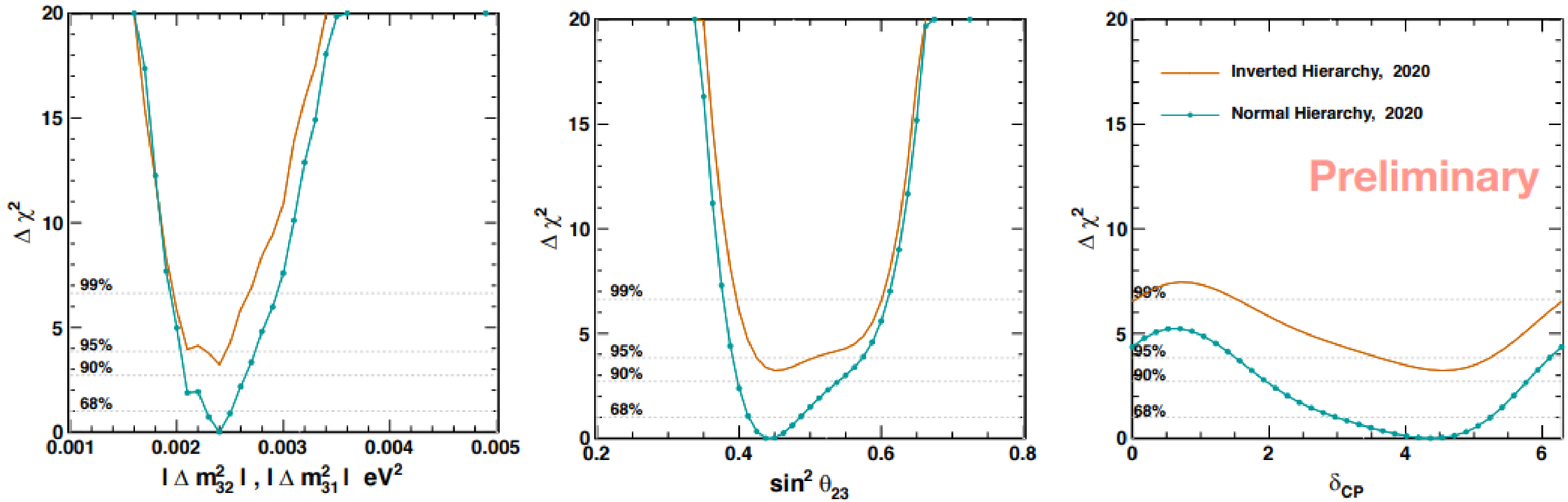
MO in the reactor experiment

- **Disappearance of reactor electron antineutrinos at ~60 km: interference between Δm^2_{31} and Δm^2_{32}**
- **Very unique approach, independent on θ_{23} and CP phase**
- **Key: energy resolution**



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

SuperK



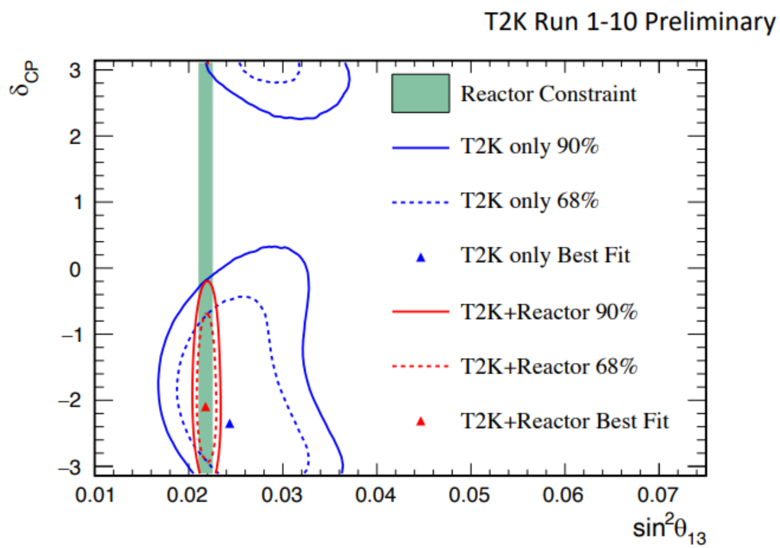
930 Bins	$\chi 2$	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} ($x10^{-3}$)
SK (NH)	**1037.5**	0.0218	$4.36^{+0.88}_{-1.39}$	$0.44^{+0.05}_{-0.02}$	$2.40^{+0.11}_{-0.12}$
SK (IH)	**1040.7**	0.0218	$4.54^{+0.88}_{-1.32}$	$0.45^{+0.09}_{-0.03}$	$2.40^{+0.09}_{-0.32}$

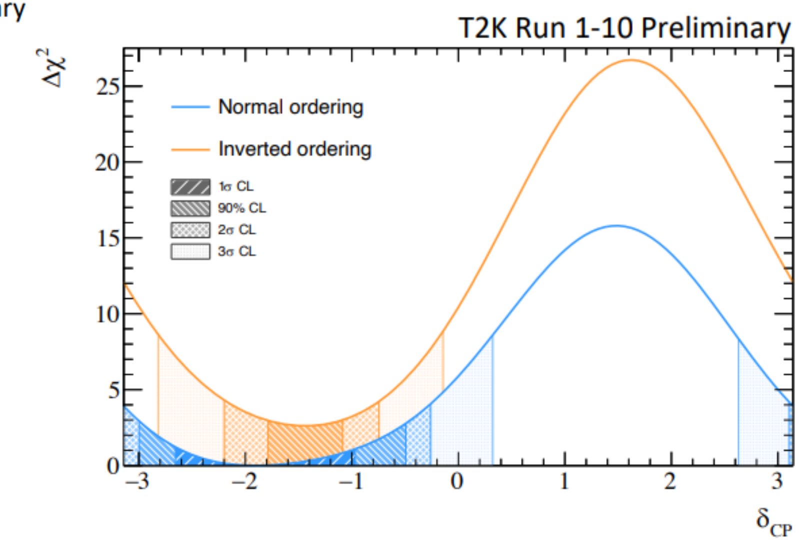
SK data disfavors Inverted Hierarchy at 71.4-90.3% CL_s (was 81.9-96.1% in 2018)

Also prefers: 1st θ_{23} octant and δ_{CP}~3/2π

Yasuhiro Nakajima (Super-K) @ Neutrino 2020

T2K



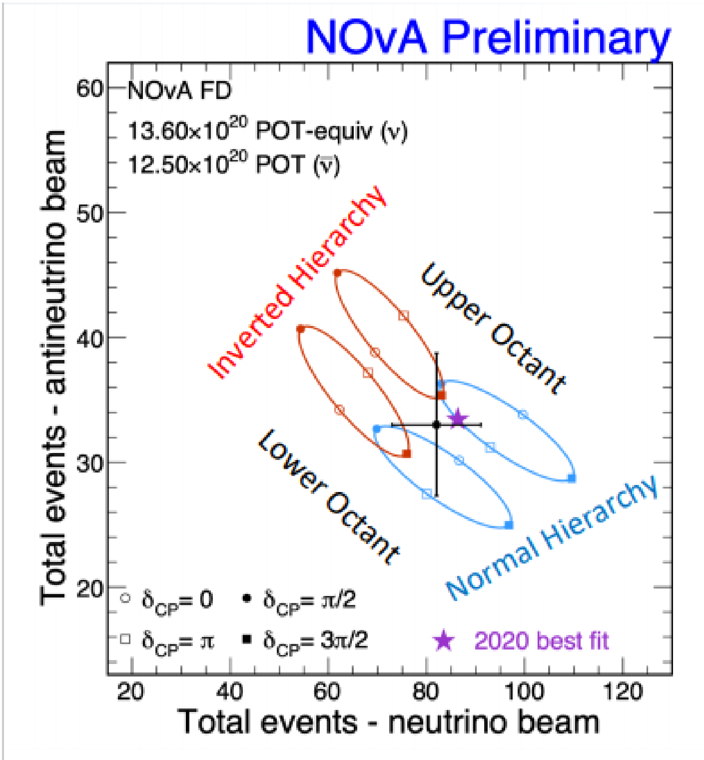


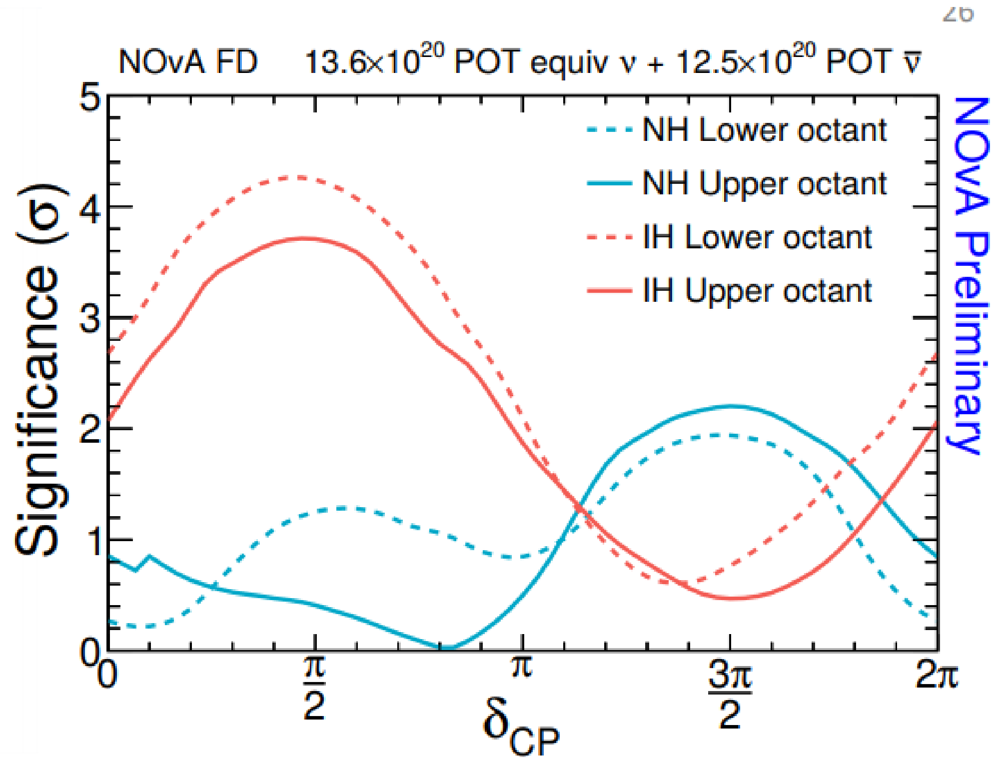
1D δ_{CP}

- 35% of values excluded at 3σ marginalized across hierarchies
- CP conserving values (0,π) excluded at 90% but π not quite at 2σ
- Largest $\Delta\chi^2$ change seen in any of our robustness studies would cause left (right) edge of 90% interval to move by 0.073 (0.080)

Patrick Dunne @ Neutrino 2020

NOvA



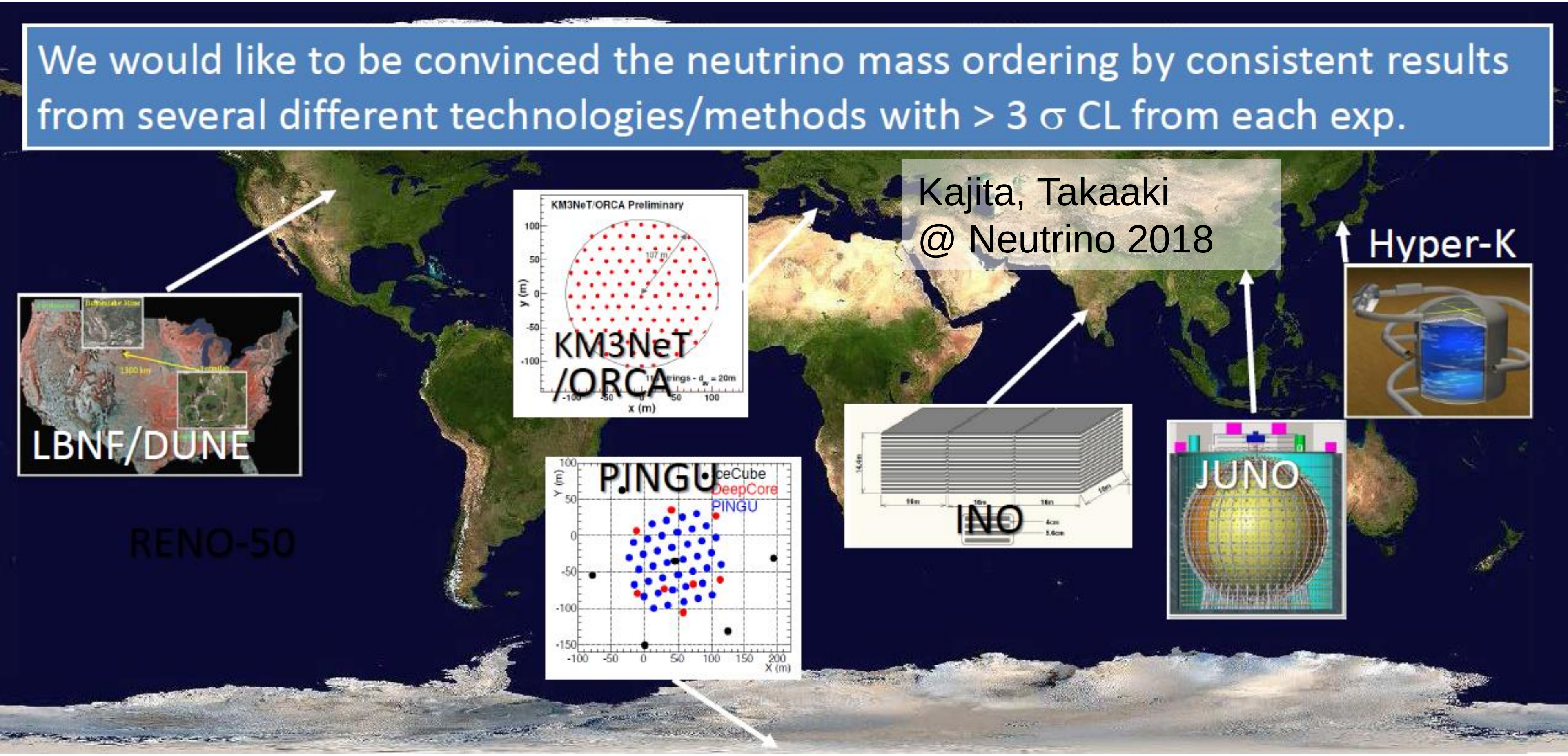


Exclude IH $\delta = \pi/2$ at $>3\sigma$

Disfavor NH $\delta = 3\pi/2$ at $\sim 2\sigma$

Alex Himmel @ Neutrino 2020

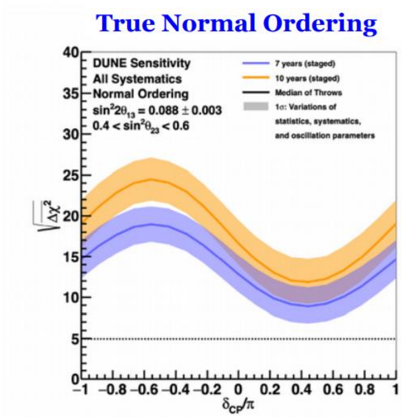
Future projects for Mass Ordering

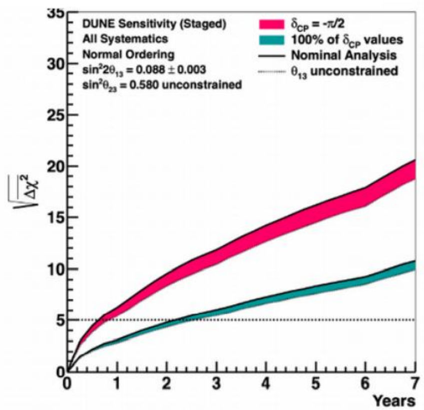


- Matter effect with Atm or Acc neutrino: HyperK, DUNE, INO, ORCA, PINGU
- Interference between Δm^2_{31} and Δm^2_{32} with reactor neutrino: JUNO

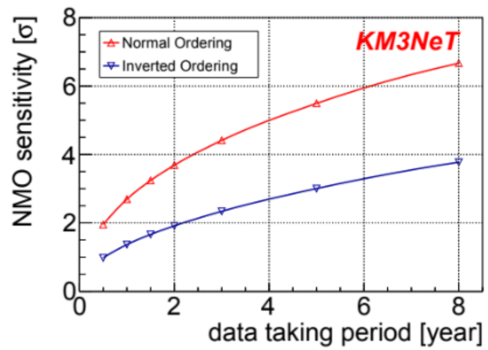
Prospective of mass ordering

DUNE
Michael Mooney @ Neutrino 2020

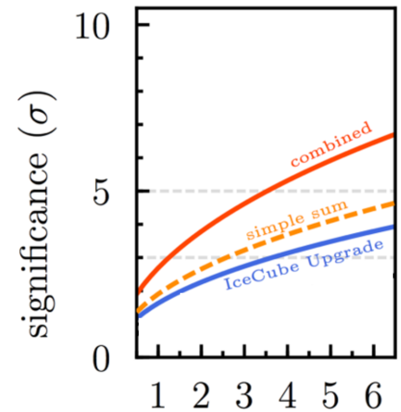




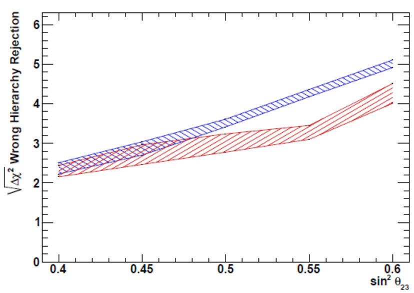
KM3NeT-ORCA
Aart Heijboer
@ NeuTel 2021

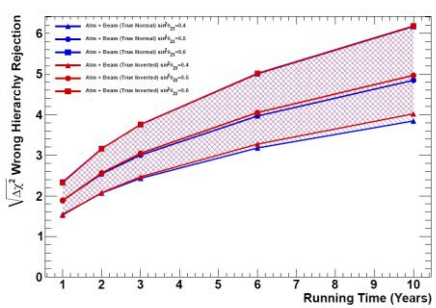


IceCube upgrade
Tom Stuttard
@ NeuTel 2021

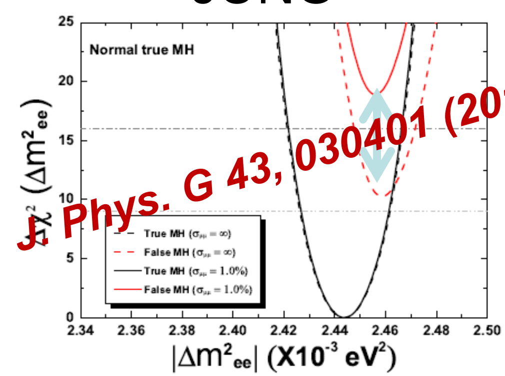


Hyper-K
arXiv:1805.04163





JUNO

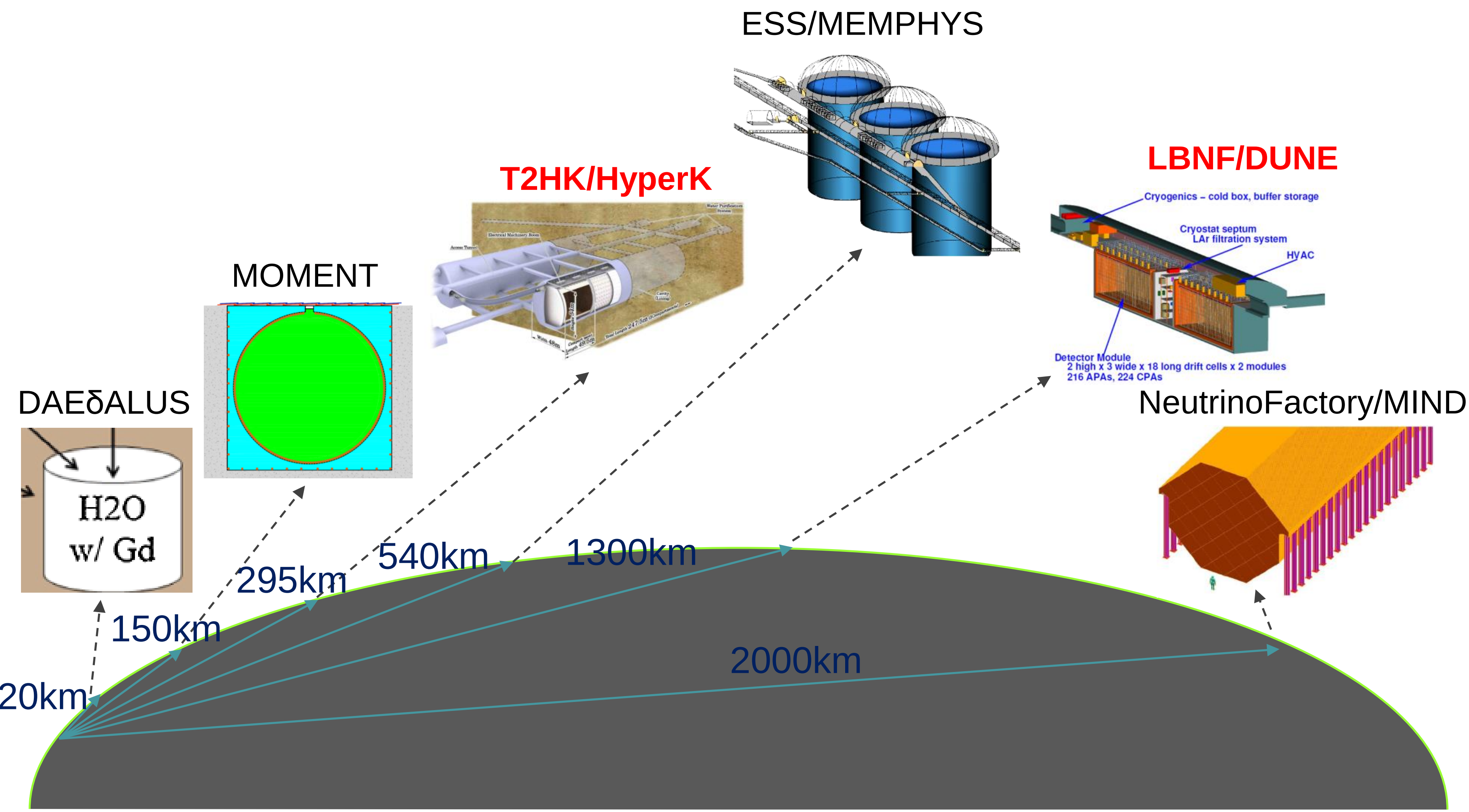


J. Phys. G 43, 030401 (2016)

3σ for 6 years data → 4σ with accelerator constrain of Δm^2_{32}

Large synergy between reactor (JUNO) and accelerator/atmospheric experiments due to disagreement on Δm^2_{31} in the wrong MO hypothesis

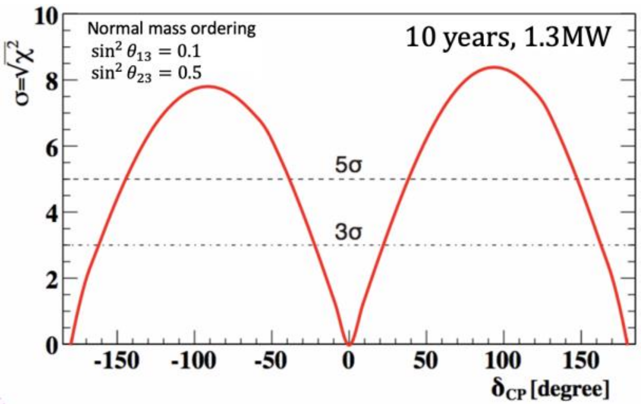
Future acc. exp. or concept for CP

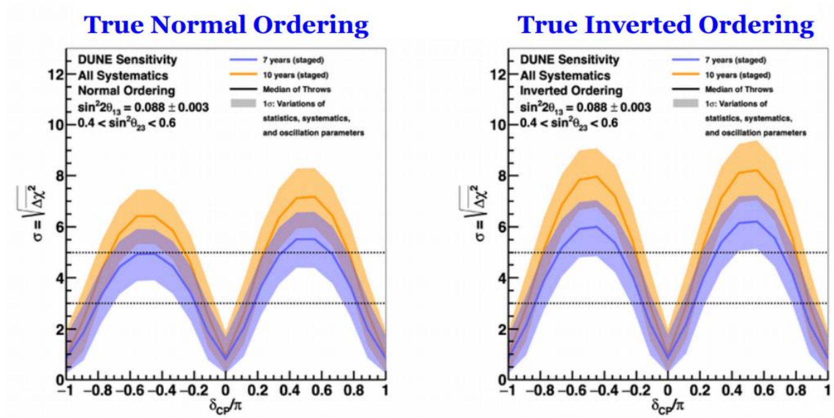


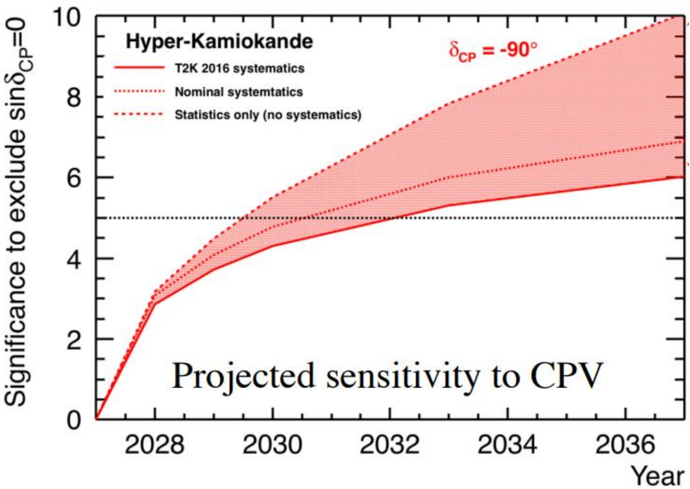
Prospective of CP

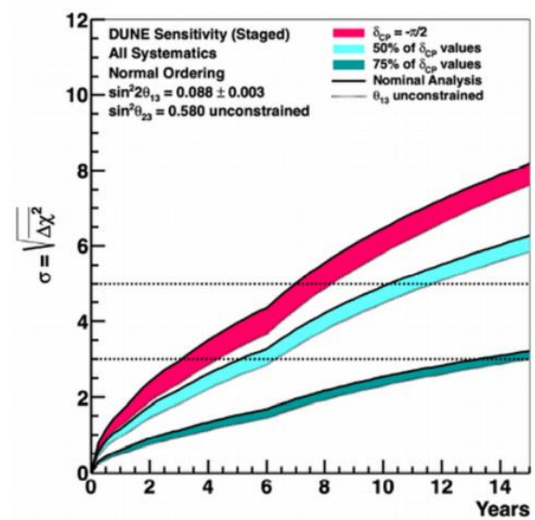
Hyper-K
Masaki Ishitsuka @ Neutrino 2020

DUNE
Michael Mooney @ Neutrino 2020









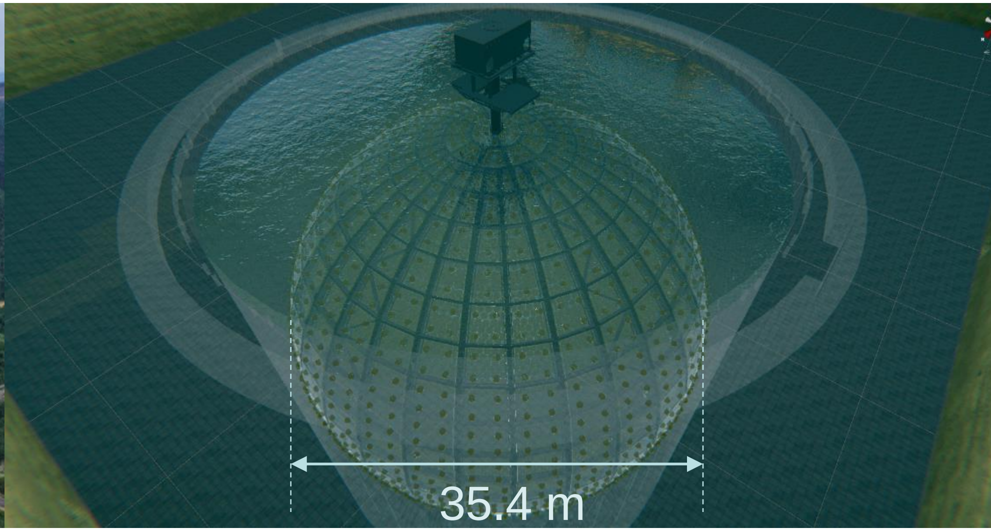
JUNO

Project

- 20 kton liquid scintillator, 3%@1MeV energy resolution, 700 m underground
- Approved in **2013**, construction started in **2015**, operation in **2023**

Physics

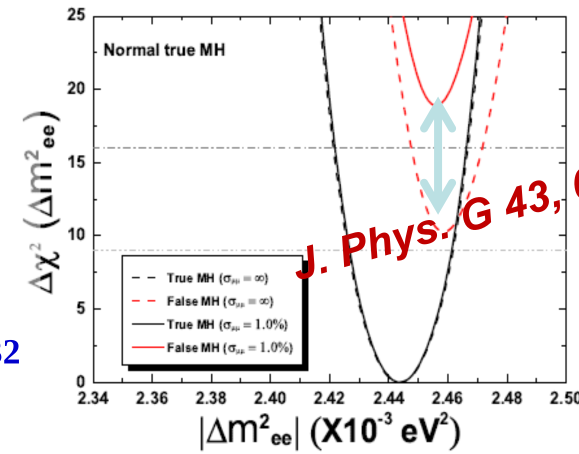
- Determine mass ordering
- Precision measurement of oscillation parameters
- Astronomical and geo- ν
- Proton decay and exotics



JUNO oscillation physics

Reactor neutrinos

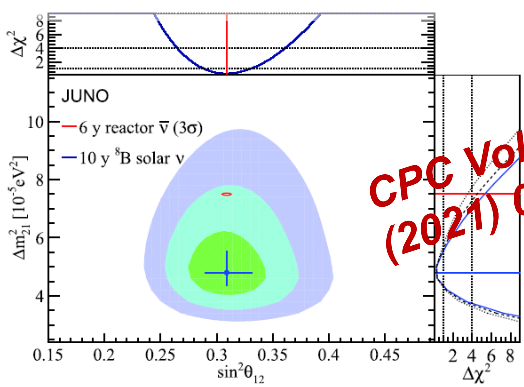
- **Mass ordering: 3σ for 6 years data → 4σ with accelerator constrain of Δm^2_{32}**



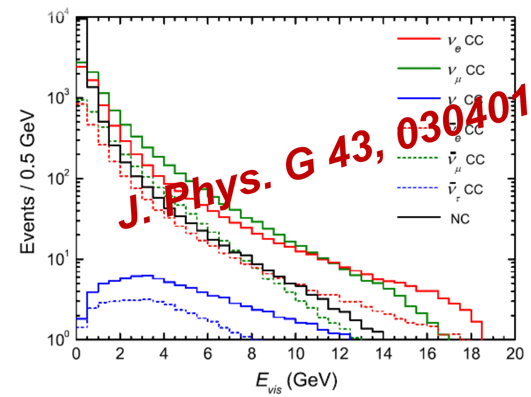
- **Sub-percent precision of 3 oscillation parameters**

	Precision
$\sin^2\theta_{12}$	0.67%
Δm^2_{21}	0.59%
Δm^2_{31}	0.44%

- **Solar neutrinos**
  - ⇨ 2 MeV threshold for ^{8}B neutrino
  - ⇨ CC and day-night asymmetry

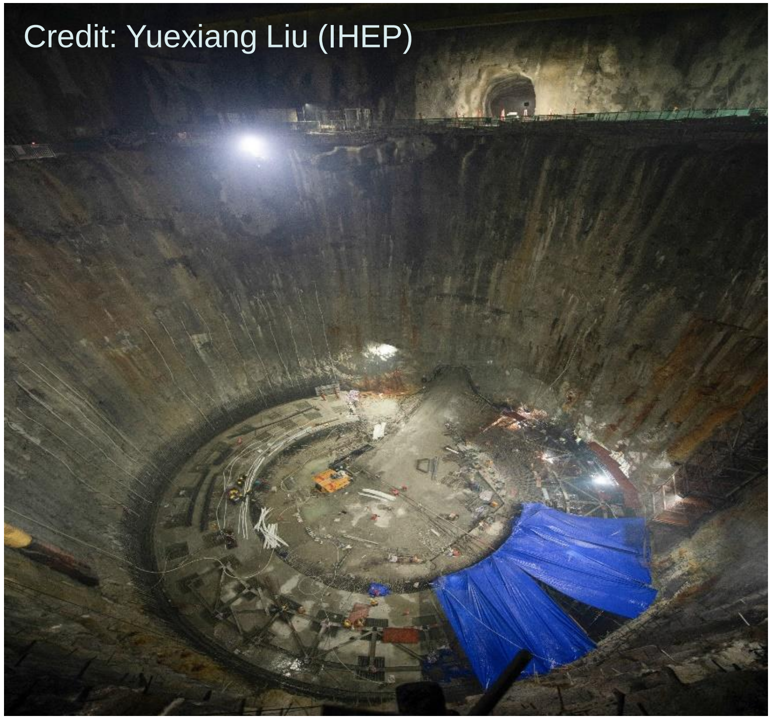


- **Atmospheric neutrinos**
  - ⇨ 1-2σ of MO for 10 years data
  - ⇨ θ_{23} accuracy of 6 deg



Project status of JUNO

- Blasting for the underground hall, the water pool and the all tunnels were completed on Dec. 30, 2020
- Detector installation starts soon!



Detector supporting structure

Acrylic sphere installation exercise

Summary and prospective

- Neutrino oscillation discovered in 1998
- Amplitudes (mixing angles) and frequencies (mass splitting) well understood and determined at a few percent precision with 3-flavor neutrino oscillation

Aaron MISLIVEC on Jun 7: Long-baseline Accelerator Neutrino Experiments
WING YAN MA on Jun 9: Atmospheric Neutrino Oscillation Experiments

- Promising solutions to 3×3 mixing matrix in 2030s
  - 5σ determination of mass ordering (combined analysis, DUNE)
  - Possible 5σ determination of CP violation (Hyper-K, DUNE)
  - Sub-percent precision of oscillation parameters (JUNO+T2K)

Gabriella CATANESI on Jun 11: Next generation neutrino experiment

- Sterile neutrinos?
  - Many of experimental indications excluded, still exploring