中微子物理实验研究进展

何苗
中国科学院高能物理研究所

中国物理学会高能物理分会第十三届全国粒子物理学术会议
2021.8.16-20 青岛→线上

中微子研究历史

◆ 中微子的发现及其性质

1930年 中微子假定 → 1956年 发现中微子（诺贝尔奖） → 1962年 发现μ中微子（诺贝尔奖） → 2000年 发现τ中微子 → 惰性中微子？马约拉纳中微子？中微子质量？

◆ 中微子振荡

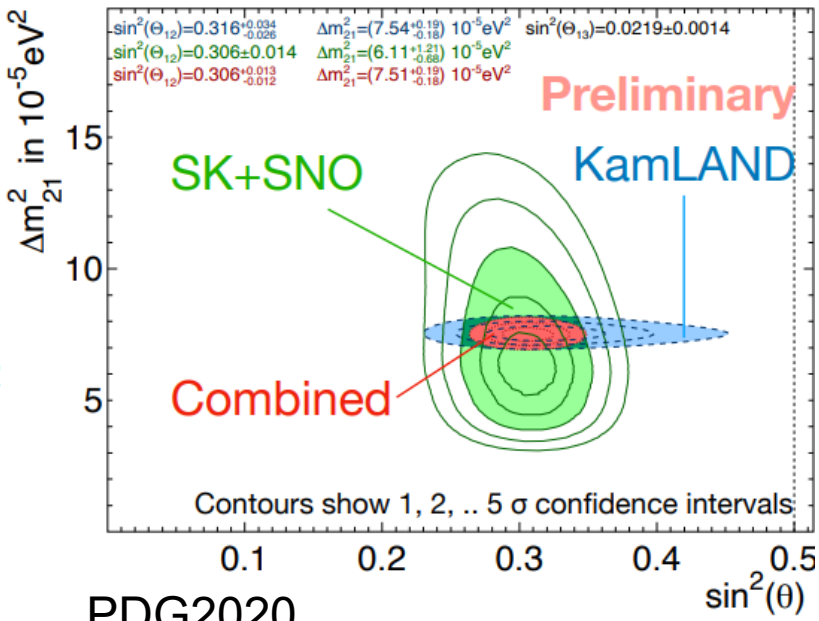
1998年 大气中微子振荡，测到θ_{23}和 $|\Delta m^2_{32}|$（诺贝尔奖） → 2002年 太阳中微子和反应堆中微子振荡，测到θ_{12}和Δm^2_{21}(诺贝尔奖) → 2012年 反应堆中微子和加速器中微子振荡，测到θ_{13} → 质量顺序？CP相角？……

◆ 中微子：探索自然界的工具

1960年代-90年代 测到太阳中微子（诺贝尔奖） → 1987年 测到超新星中微子（诺贝尔奖） → 2007年 测到地球中微子 → 大爆炸中微子？超新星遗迹？……

Recent solar neutrino results

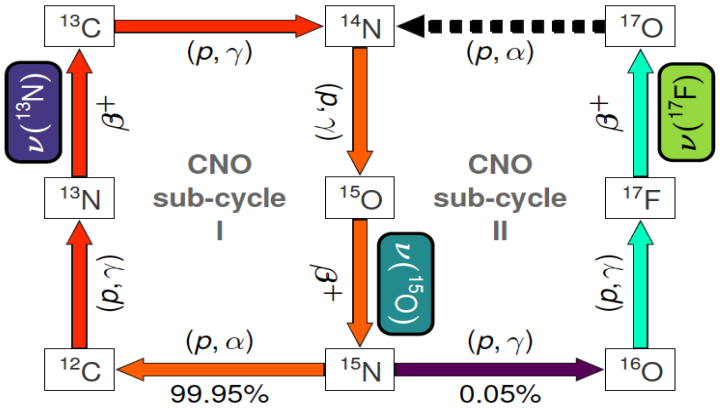
θ_{12} and Δm^2_{21} constrains by solar experiments and KamLAND



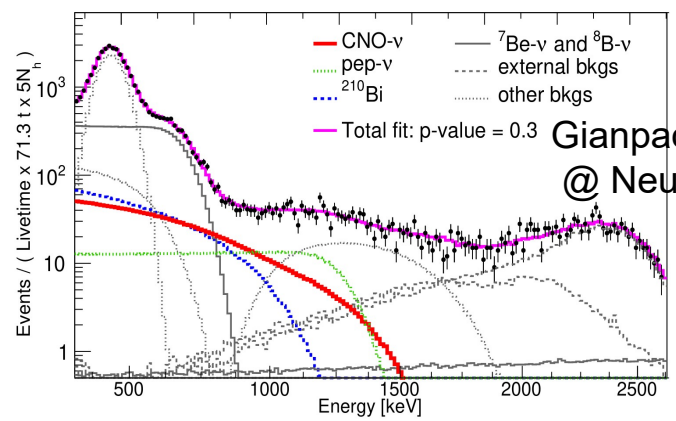
PDG2020

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

Observation of CNO neutrinos by Borexino



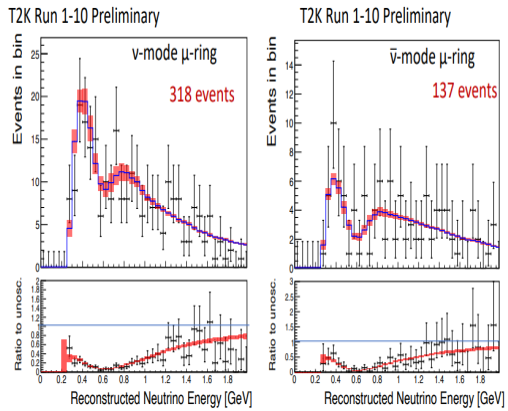
No CNO hypothesis disfavored at 5 σ



Gianpaolo Bellini @ NeuTel 2021

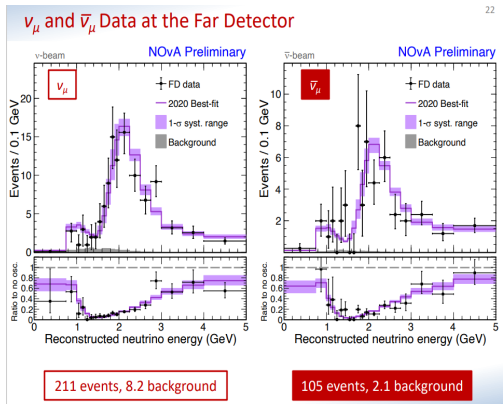
Recent ν_μ disappearance results

T2K: 295 km



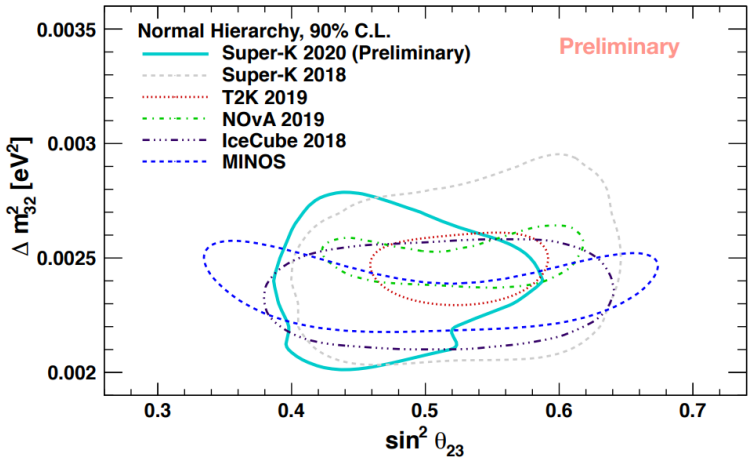
Patrick Dunne @ Neutrino 2020

NOvA: 810 km



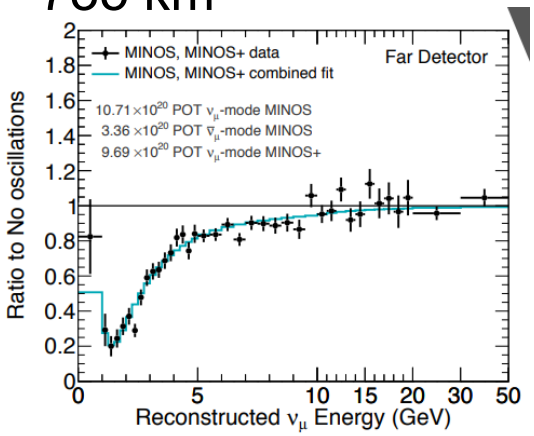
Alex Himmel @ Neutrino 2020

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



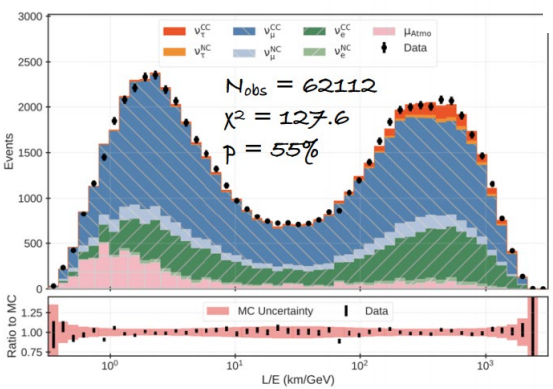
Yasuhiro Nakajima @ Neutrino 2020

MINOS/MINOS+: 735 km



Tom Carroll @ Neutrino 2020

IceCube-DeepCore: Atm. neutrinos



Summer Blot @ Neutrino 2020

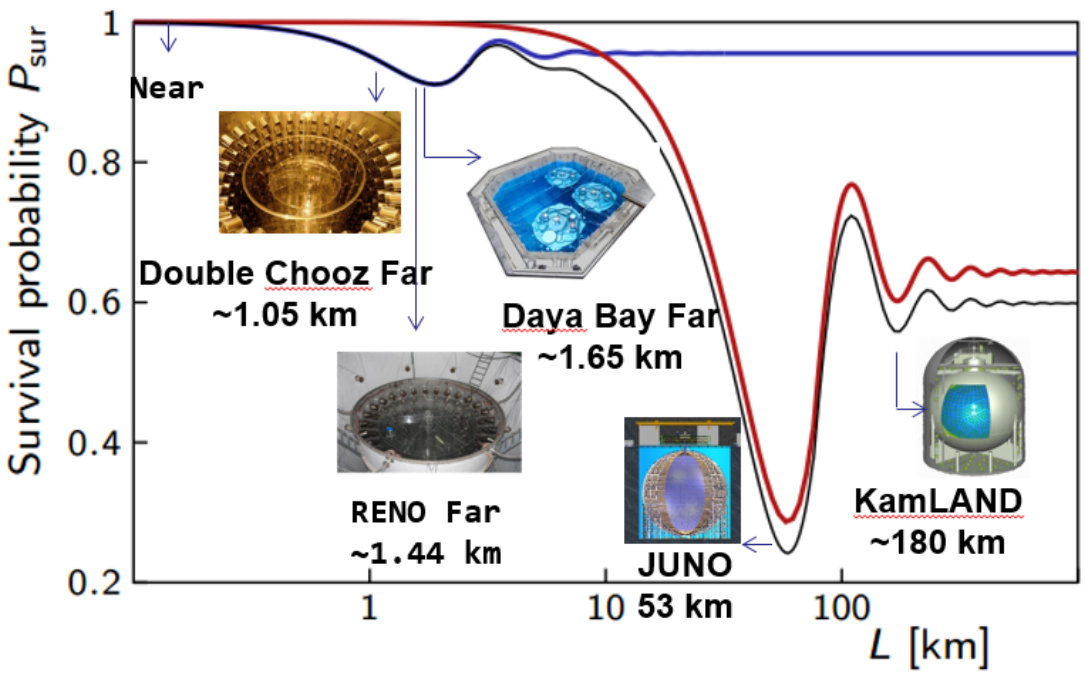
Parameter	Δm^2_{32}	$\sin^2\theta_{23}$
Precision	1.4%	4.9%

PDG2020

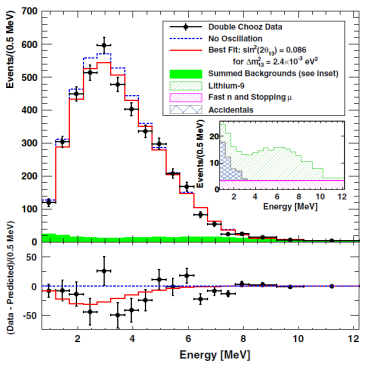
θ_{13} in reactor experiments

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

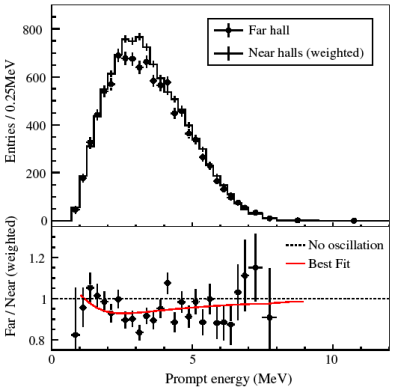
$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$



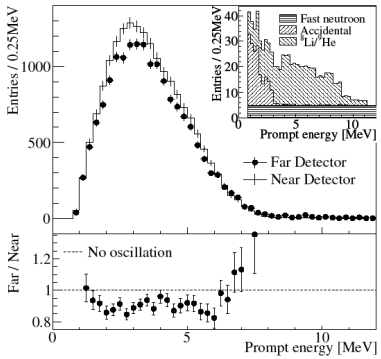
Double Chooz
(Nov. 2011)
1.7σ



Daya Bay
(March 2012)
5.2σ

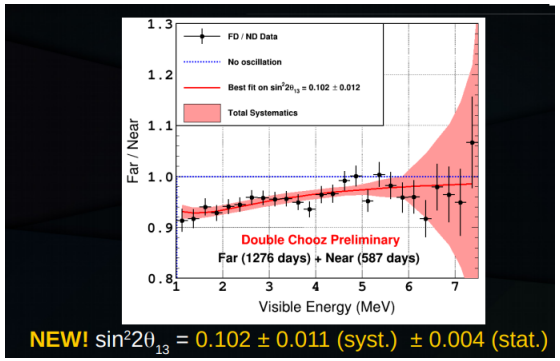


RENO
(April 2012)
4.9σ

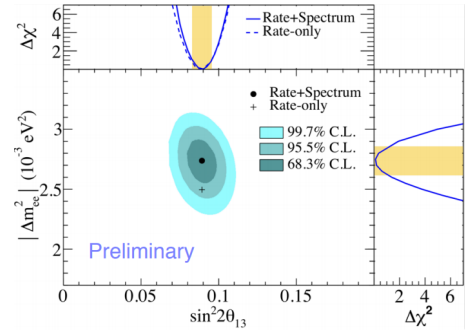


Latest results of reactor experiments

News from Neutrino 2020



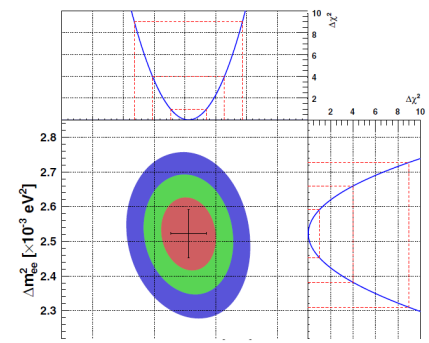
Double Chooz, *Thiago Bezerra*



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

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

Reno, *Jonghee Yoo*



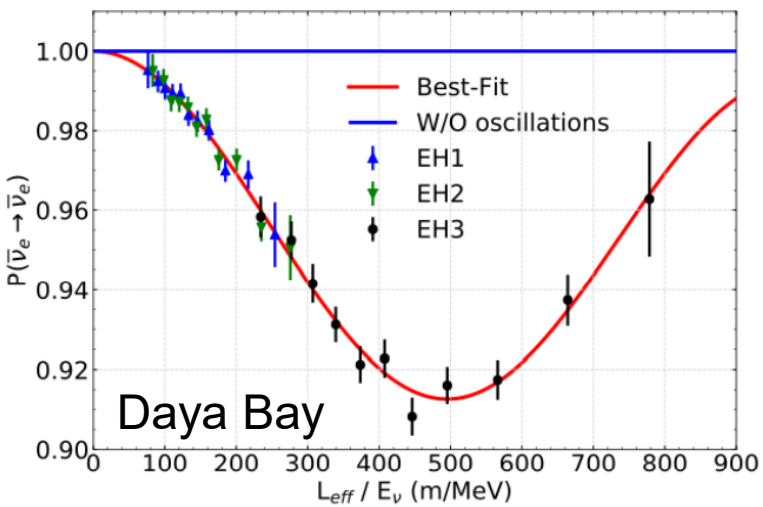
$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$

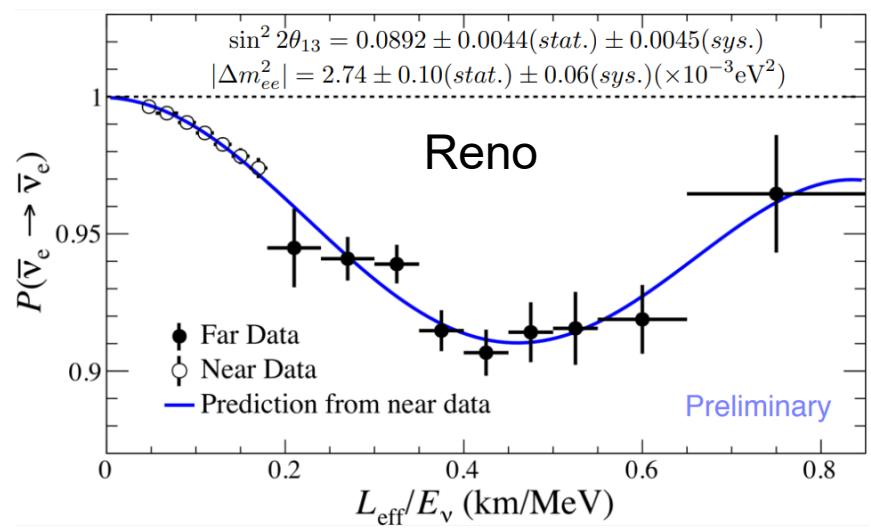
$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}$ eV²

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

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

Daya Bay, *Jiajie Ling*

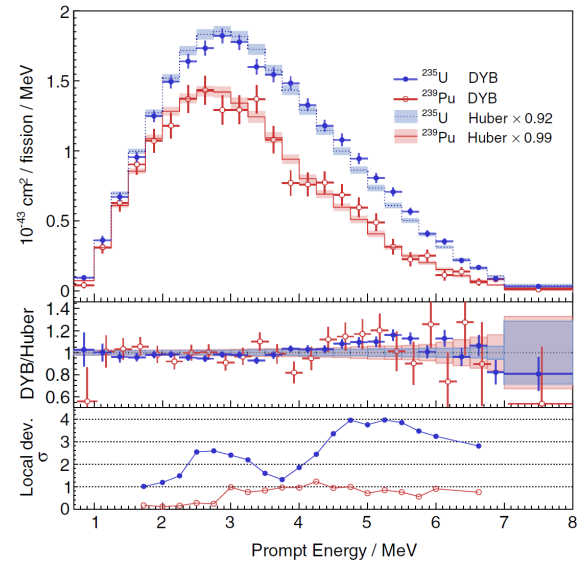


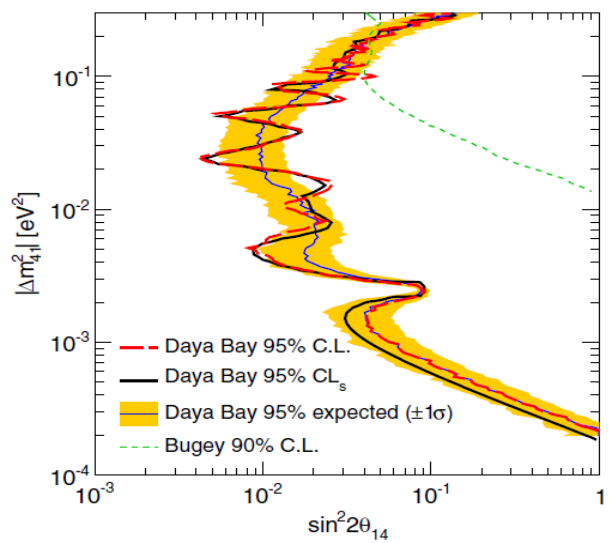


Daya Bay Mission Completed

- Precision measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$
- Precision measurement of reactor antineutrino flux and spectrum → two anomalies
- Most stringent limit on light sterile neutrinos

Ceremony on Dec. 12, 2020. Final results in 2022. Precision of $\sin^2 2\theta_{13}$ 2.7%.

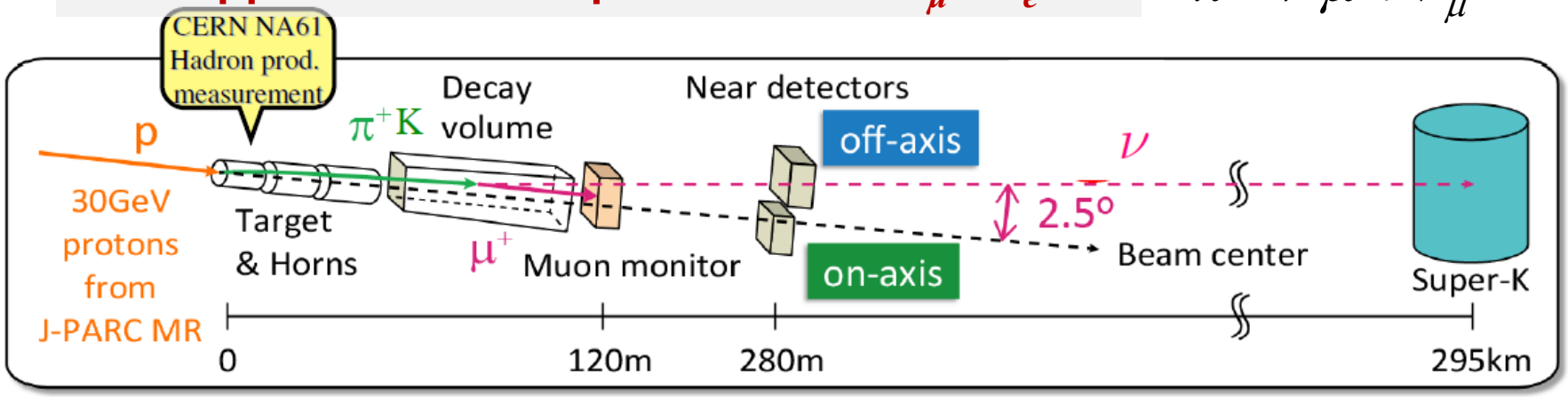




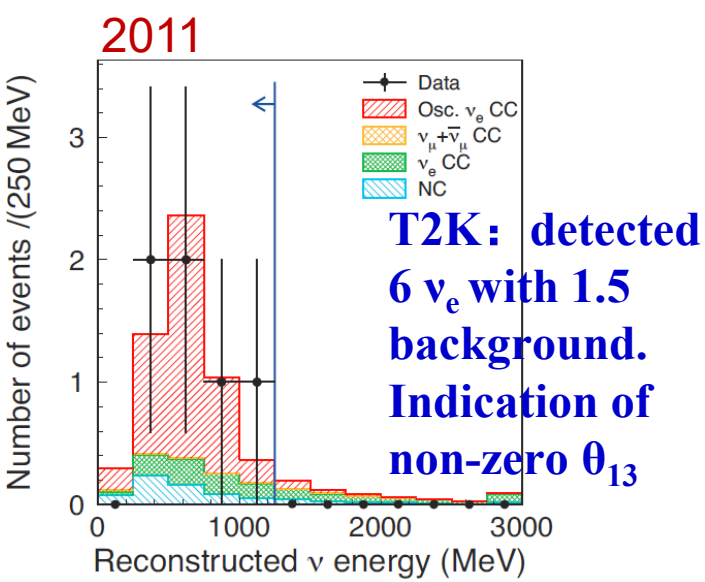
θ_{13} in accelerator experiments

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

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



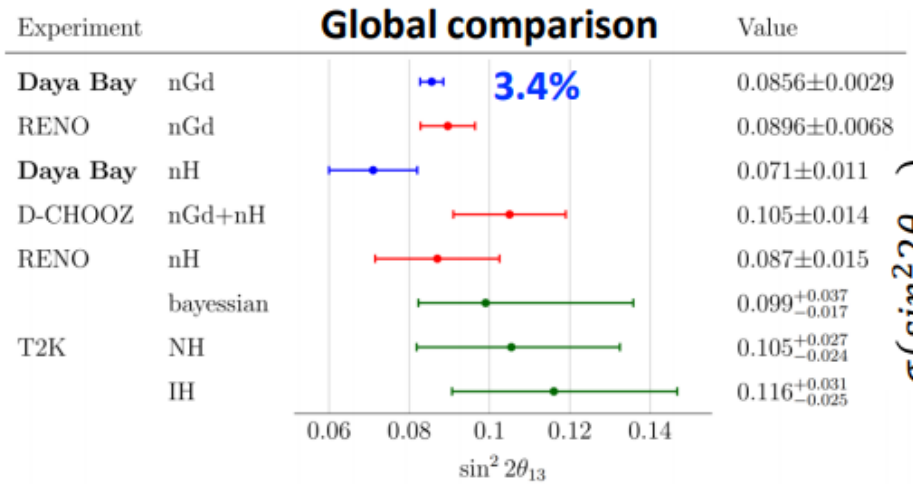
T2K EPS-HEP2015

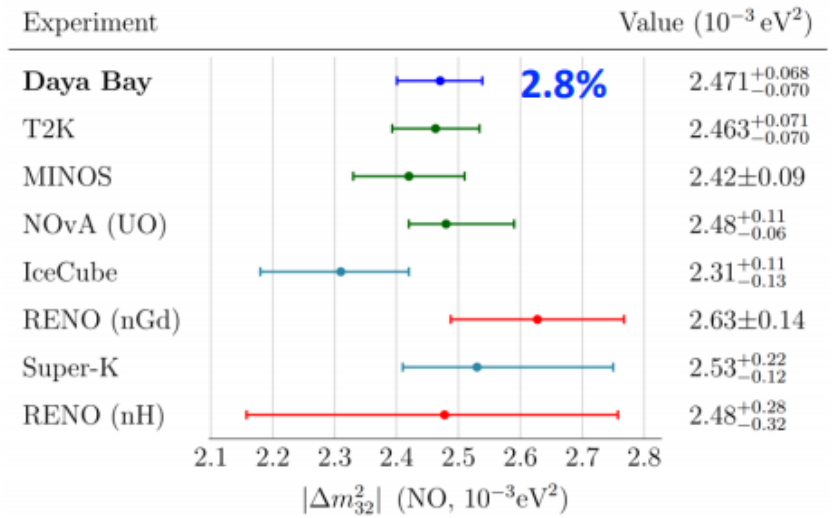


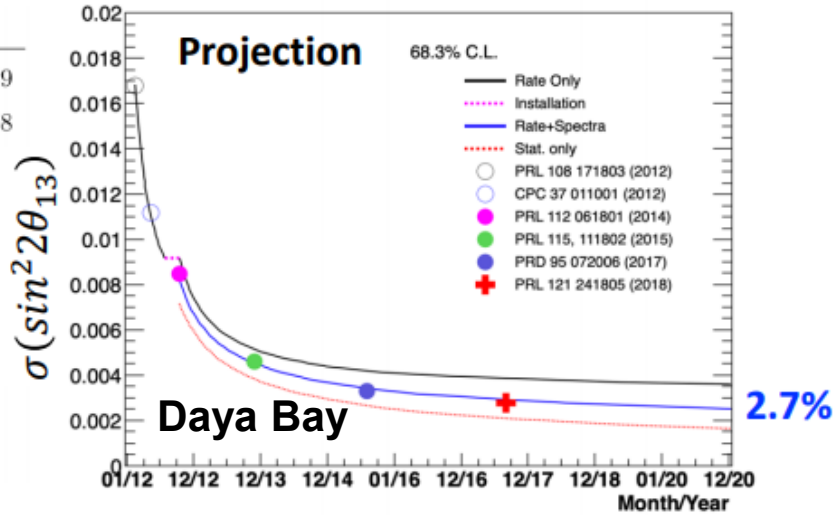
T2K: detected 6 ν_e with 1.5 background. Indication of non-zero θ_{13}

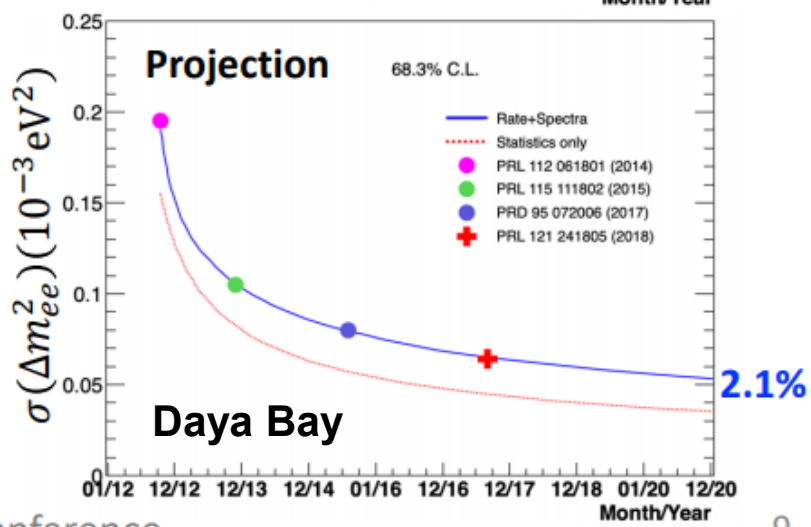
- **Indication** of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam, 2011. **2.5σ**
- **Evidence** of Electron Neutrino Appearance in a Muon Neutrino Beam, 2013. **>3σ**
- **Observation** of Electron Neutrino Appearance in a Muon Neutrino Beam, 2014. **>5σ**

Global comparison



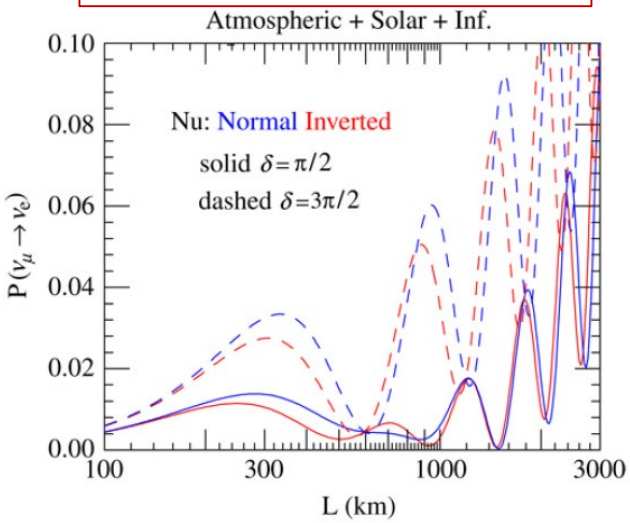


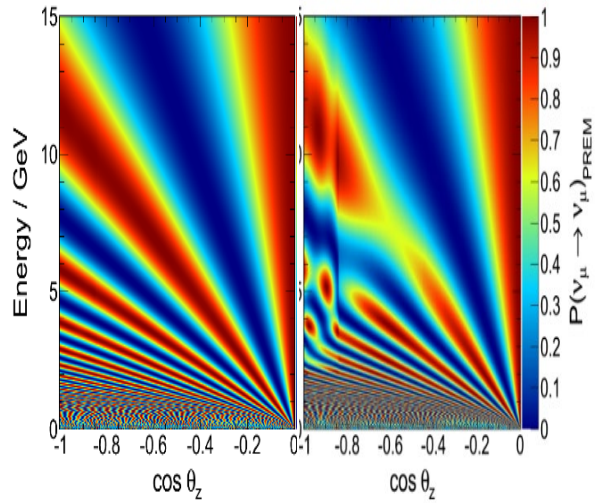




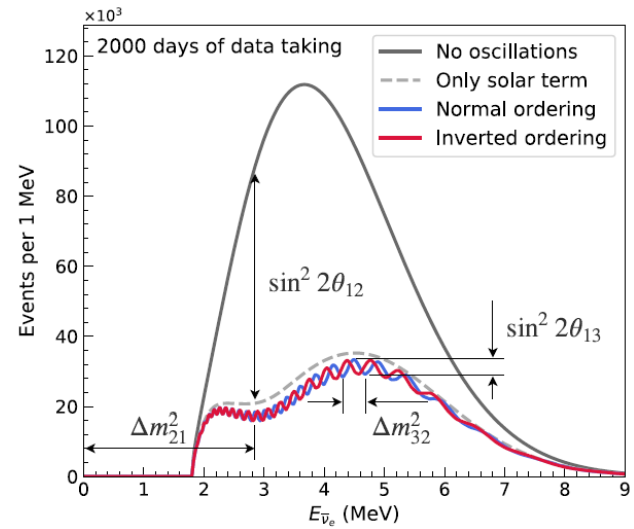
Mass ordering and CP violation

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





arXiv:2104.02565

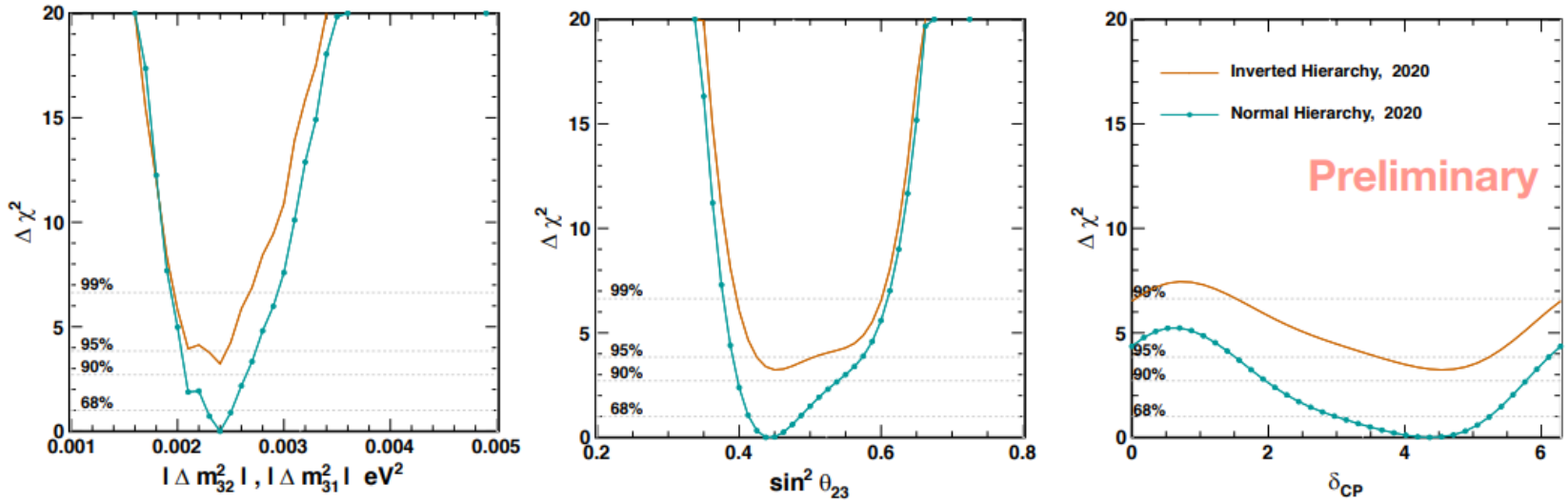


Accelerator neutrinos: asymmetry between ν_e and $\bar{\nu}_e$ appearance for both MO (matter effect) and CP

Atmospheric neutrinos: ν_μ and $\bar{\nu}_\mu$ disappearance, ν_e and $\bar{\nu}_e$ appearance for MO (matter effect)

Reactor neutrinos: $\bar{\nu}_e$ disappearance for MO (independent on θ_{23} and CP phase)

SuperK



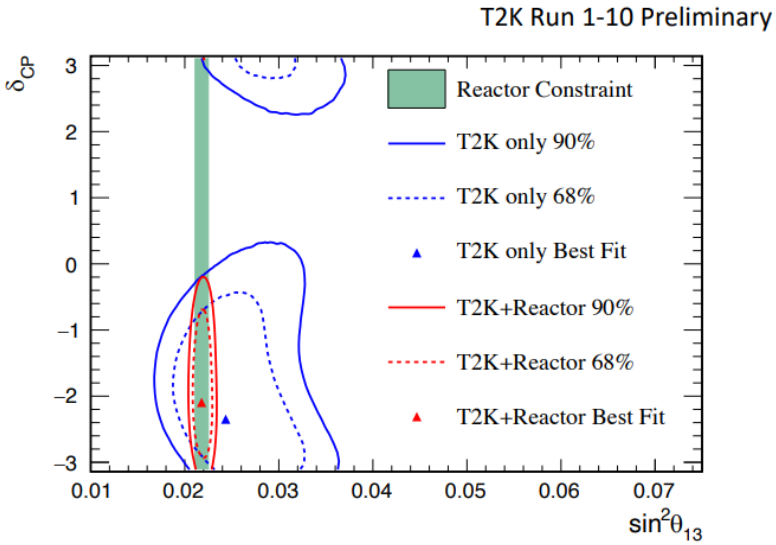
930 Bins	$\chi 2$	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} (x10^{-3})
SK (NH)	**1037.5**	0.0218	$4.36^{+0.88}_{-1.39}$	$0.44^{+0.05}_{-0.02}$	$2.40^{+0.11}_{-0.12}$
SK (IH)	**1040.7**	0.0218	$4.54^{+0.88}_{-1.32}$	$0.45^{+0.09}_{-0.03}$	$2.40^{+0.09}_{-0.32}$

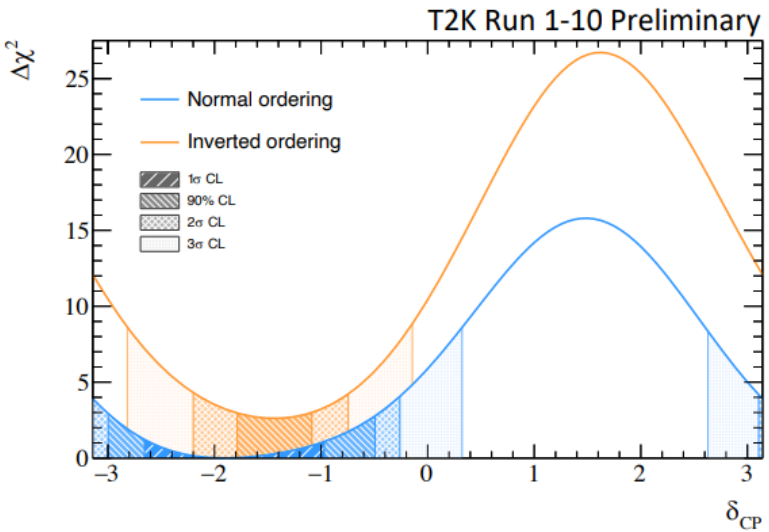
SK data disfavors Inverted Hierarchy at 71.4-90.3% CL_s (was 81.9-96.1% in 2018)

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

Yasuhiro Nakajima (Super-K) @ Neutrino 2020

T2K





1D δ_{CP}

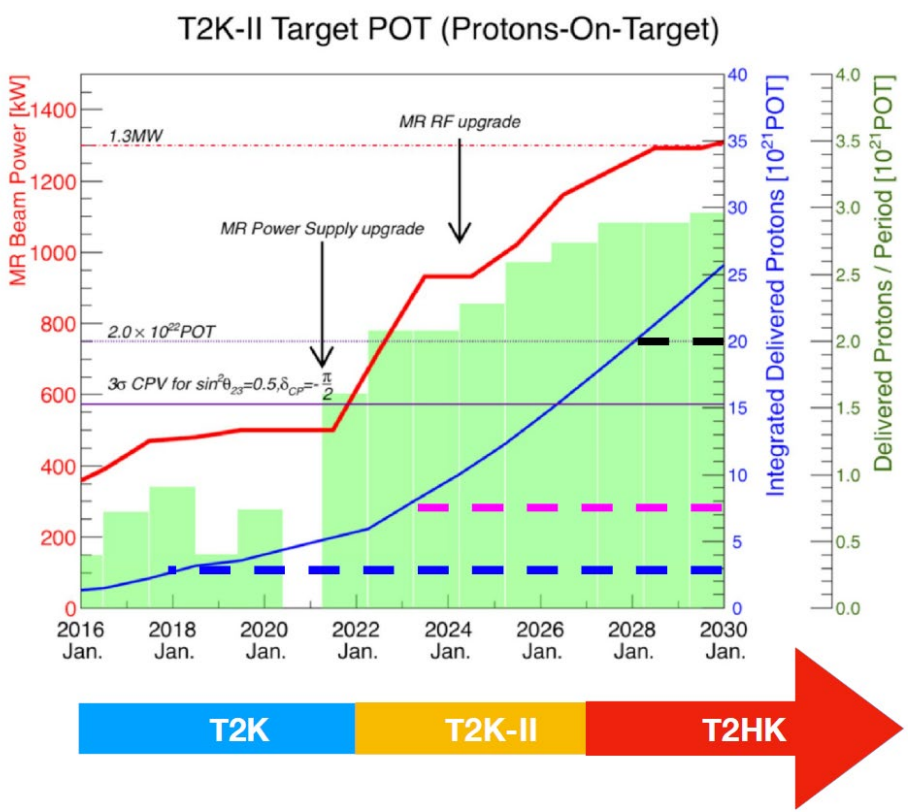
- 35% of values excluded at 3σ marginalized across hierarchies
- CP conserving values (0,π) excluded at 90% but π not quite at 2σ

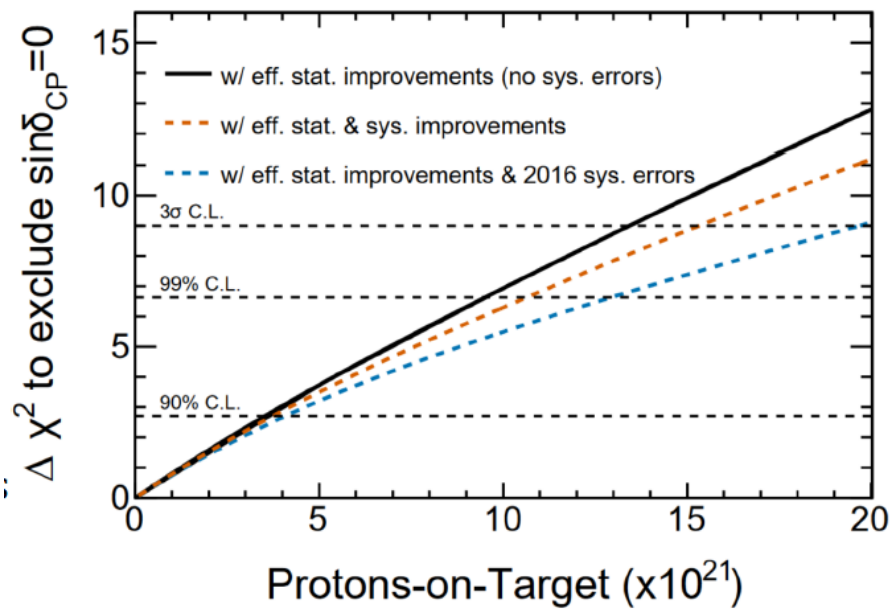
Patrick Dunne @ Neutrino 2020

T2K-II

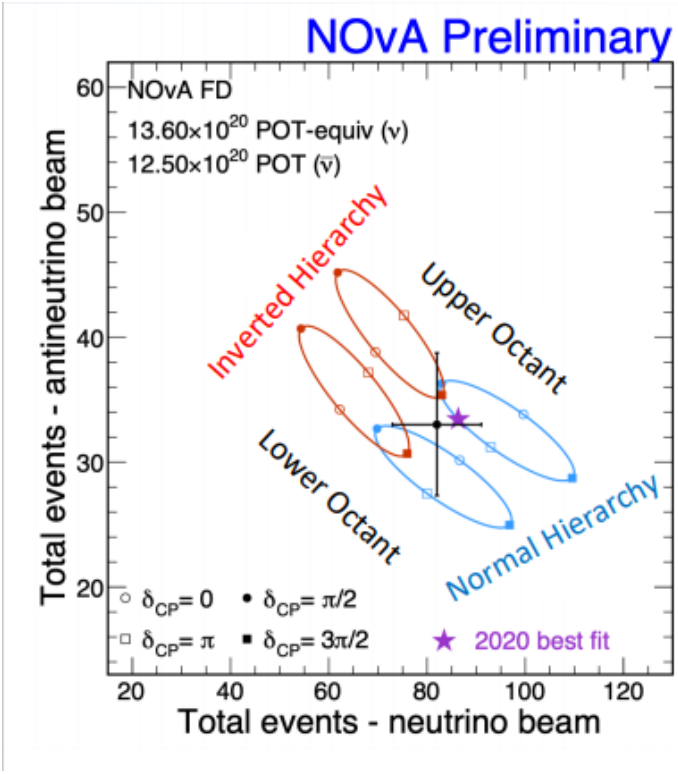
Mathieu Guigue @ WIN 2021

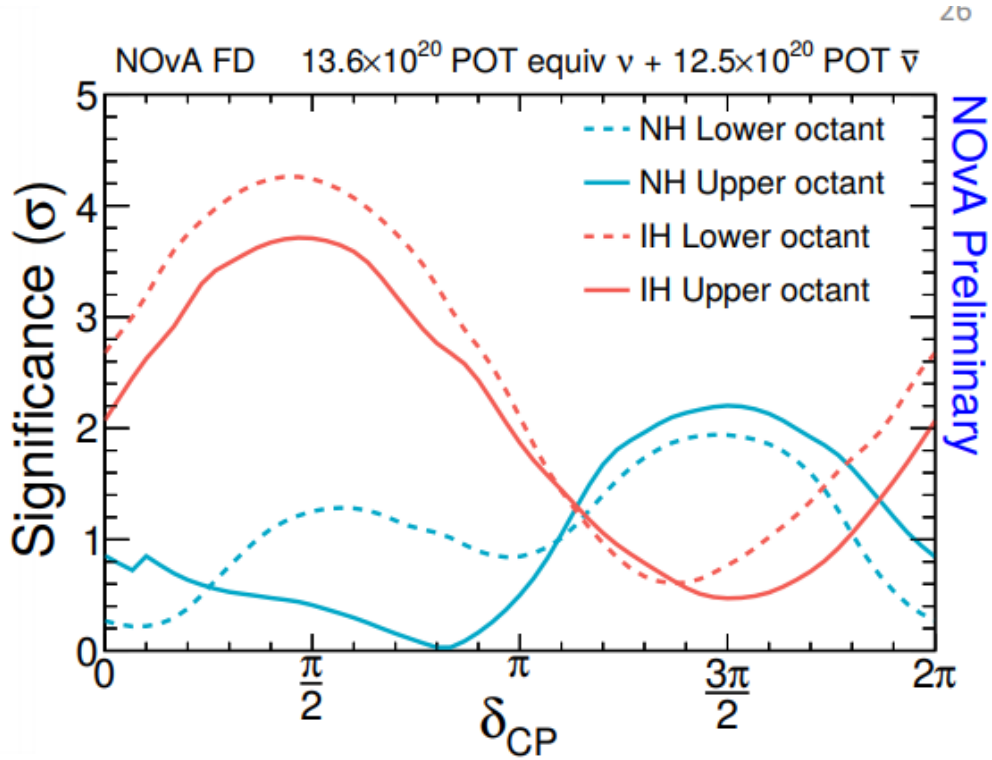
- Current exposure: ~3.6×10^{21} POT
- T2K target: 7.8×10^{21} POT
- T2K-II: 20×10^{21} POT (3σ to exclude $\sin(\delta_{CP}=0)$)





NOvA





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

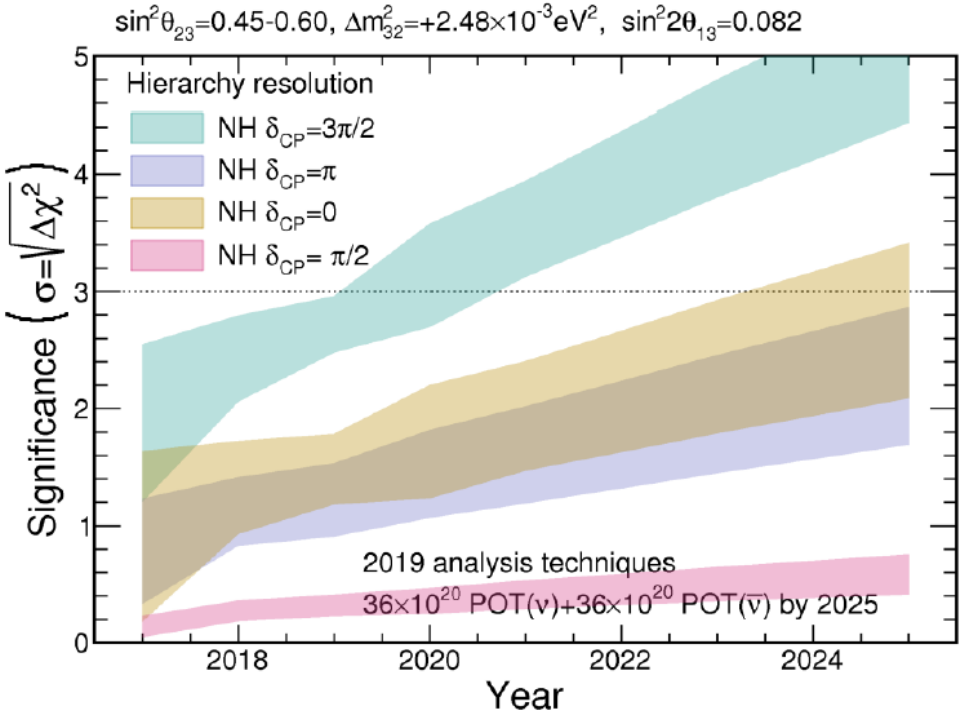
Disfavor NH $\delta = 3\pi/2$ at $\sim 2\sigma$

Alex Himmel @ Neutrino 2020

NOvA future

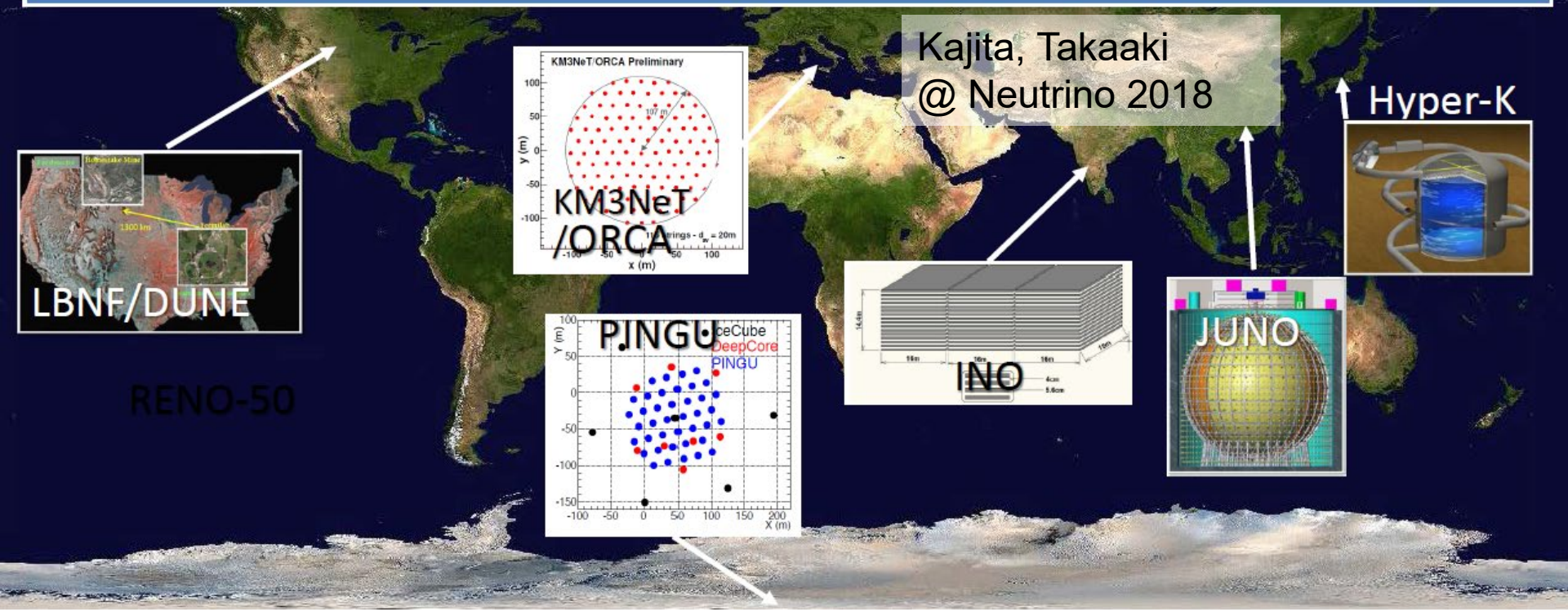
Future

- Expected to run through 2025
- Run plan: 50-50 neutrinos/antineutrinos
- Potential 3-5σ sensitivity to hierarchy
- Possible > 2σ sensitivity to CP violation
- Proposed accelerator improvements and test beam program enhance NOvA's reach
- Improvements in simulation will improve analysis robustness
- Joint T2K-NOvA analysis coming soon



Future projects for Mass Ordering

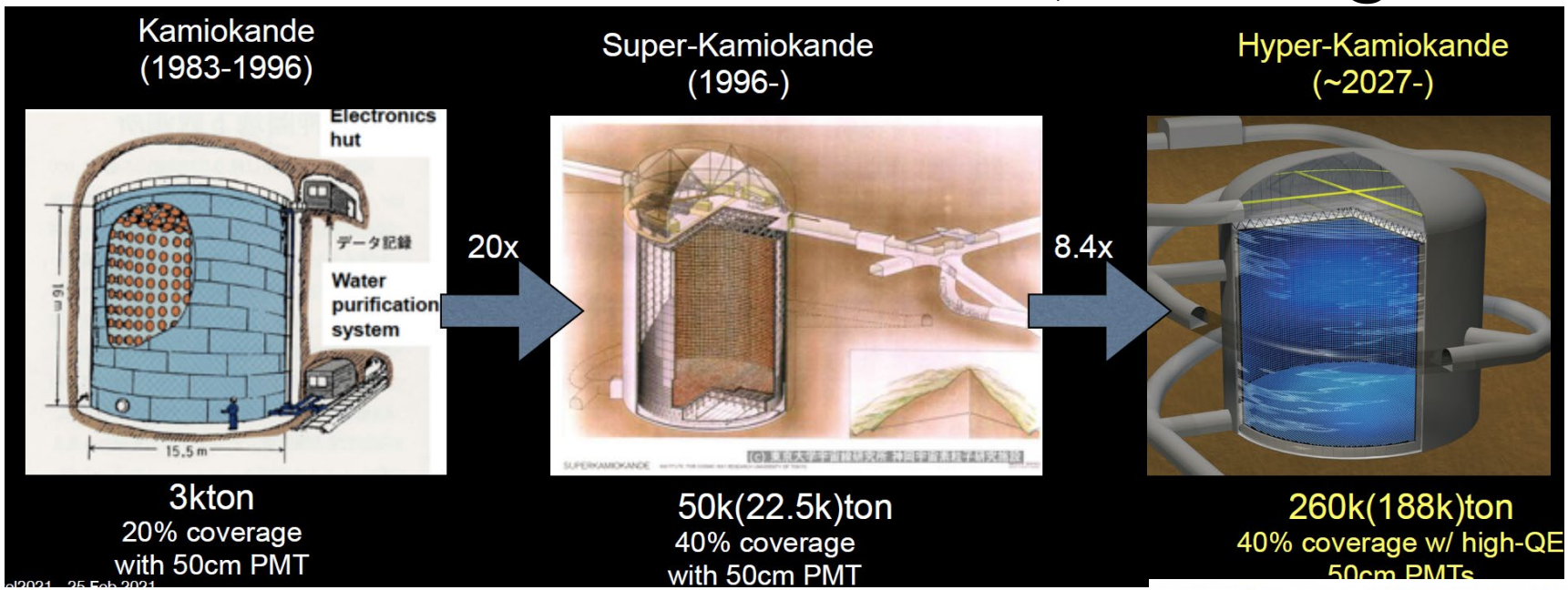
We would like to be convinced the neutrino mass ordering by consistent results from several different technologies/methods with > 3 σ CL from each exp.



- 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

Hyper-Kamiokande

F. Di Lodovico, G. Catanesi @NeuTel2021

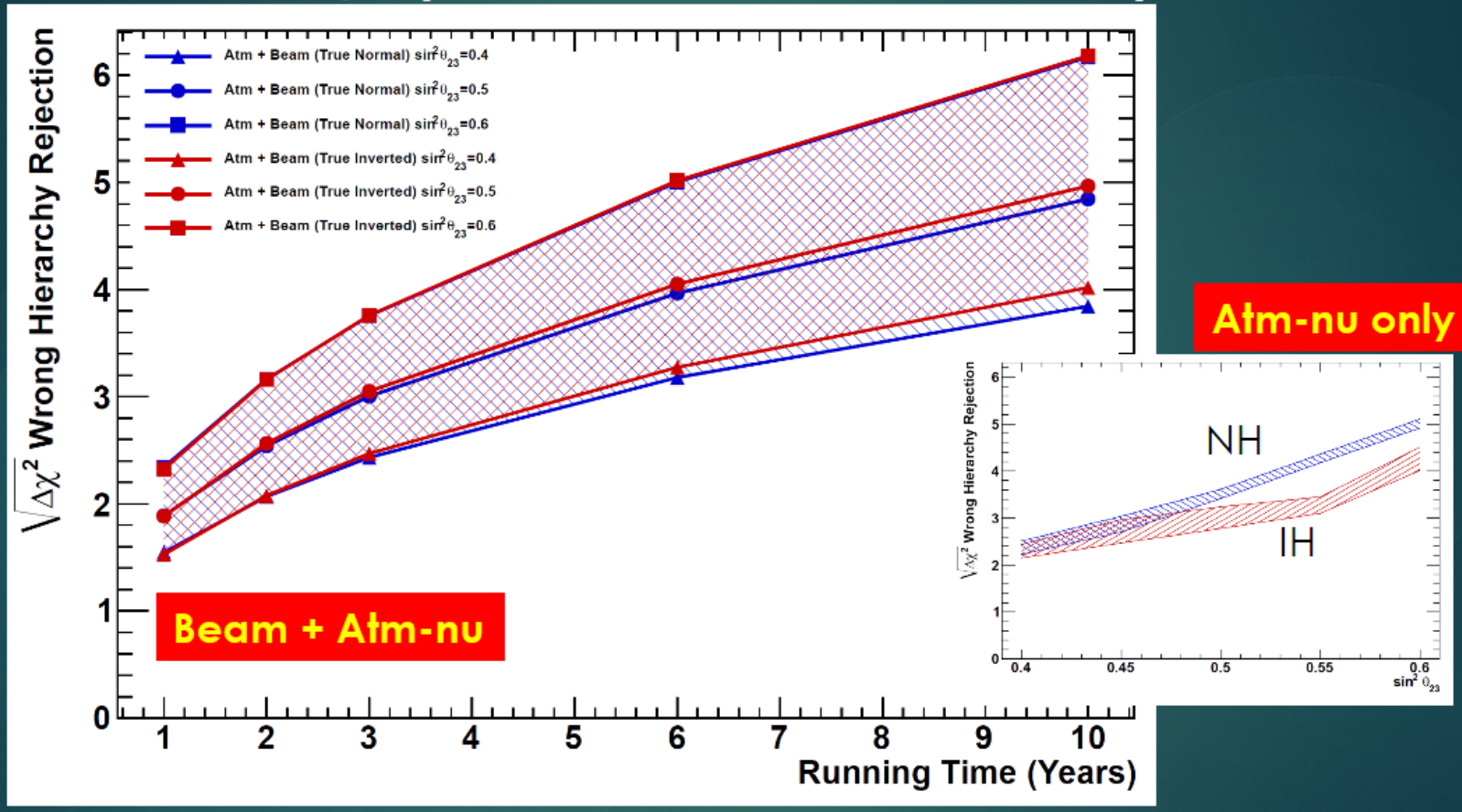


- Construction started 2020.
- Data taking from 2027.
- J-PARC neutrino beam will be upgraded from 0.5 to 1.3 MW

2020/12 First six PMTs delivered to Kamioka

Sensitivities on mass hierarchy (beam + atm nu)

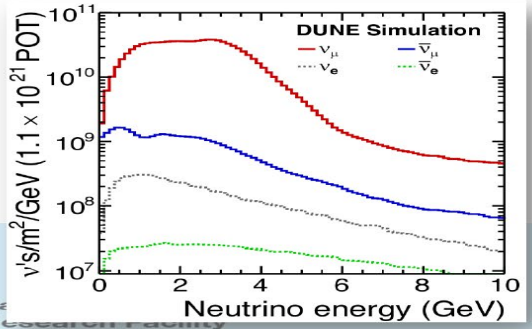
7

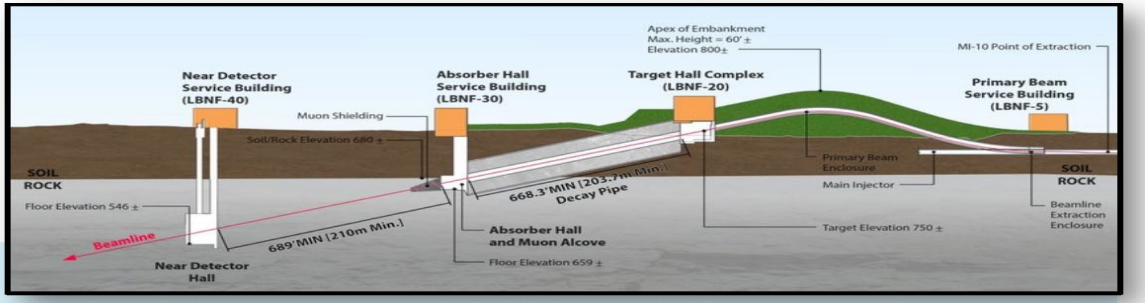


- ~ 4sigma in 10yrs by combination of beam and atm-nu
  - While Atm-nu only 2~4 sigma

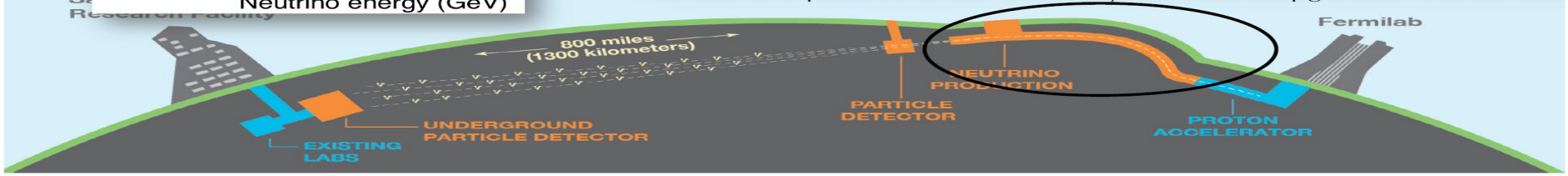
DUNE

- **DUNE's neutrino source: LBNF beam, from US Fermi National Lab (FNAL)**

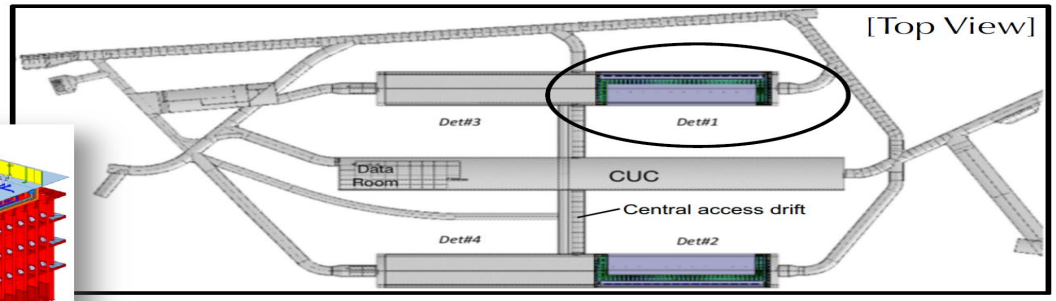


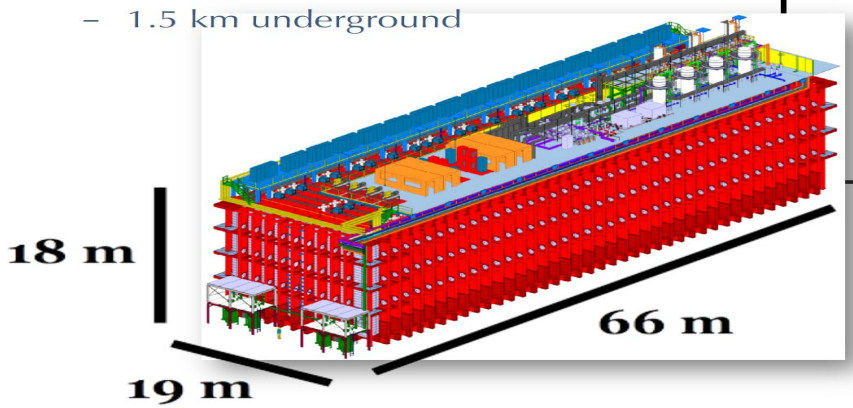


60-120 GeV proton beam, 1.2 MW by late 2020s, upgradable to 2.4 MW



- **Four (4) LArTPC FD Modules, deployed in stages**
  - 17 kton each
  - 1.5 km underground

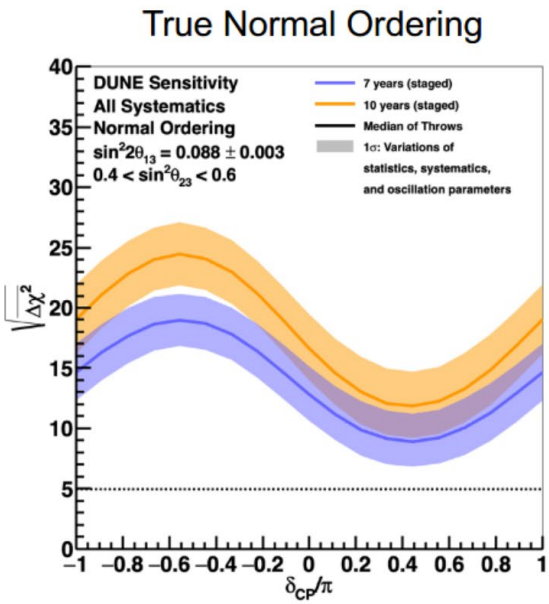


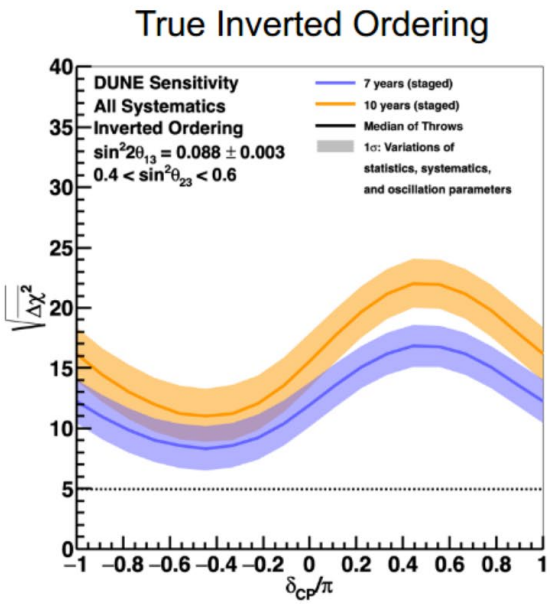


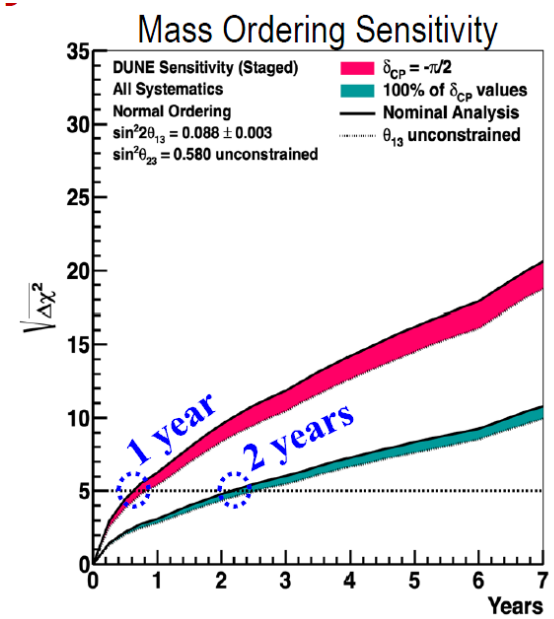
- Two far detector designs:
  Horizontal Drift and **Vertical Drift**
  (both employ liquid argon phase only)
- First detector module will be Horizontal Drift (HD)

G. Karagiorgi @NeuTel2021

MO sensitivity





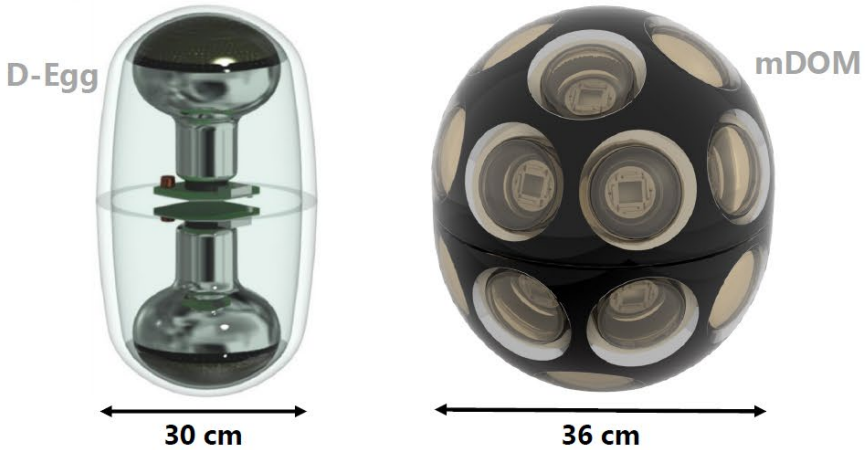


IceCube Upgrade

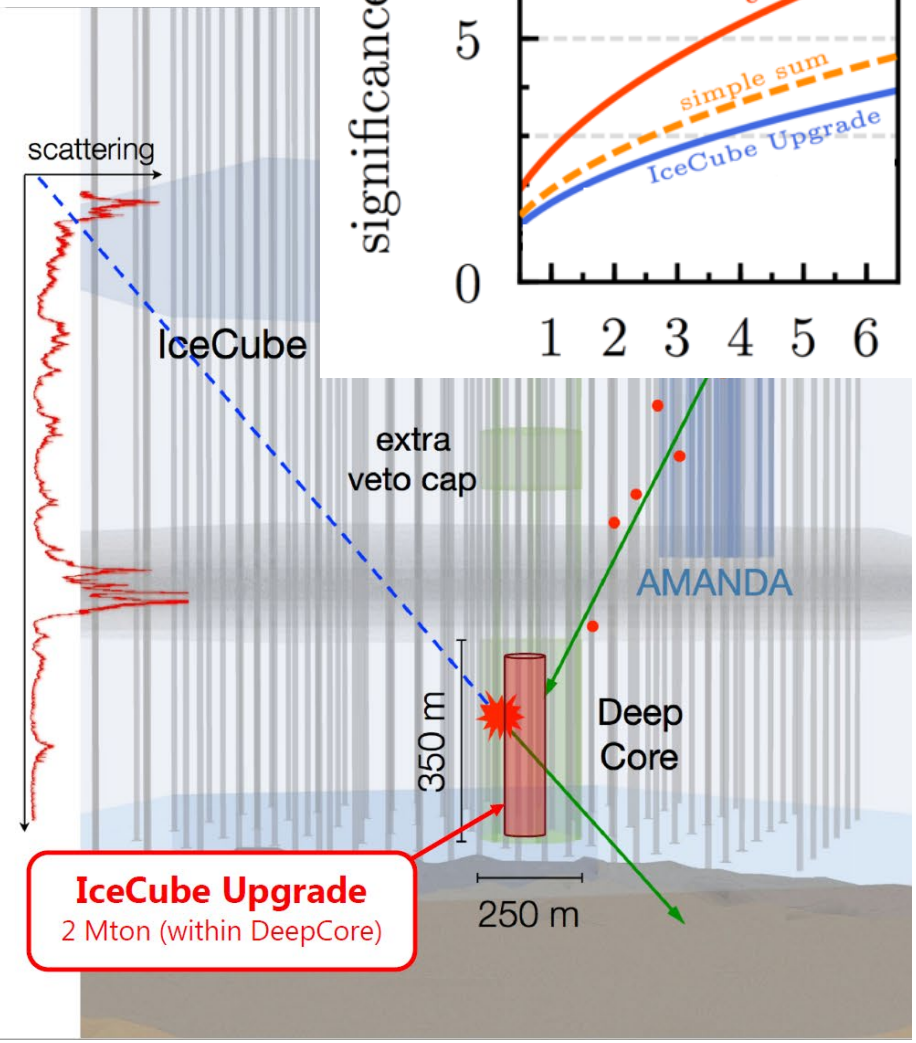
Tom Stuttard @ NeuTel 2021

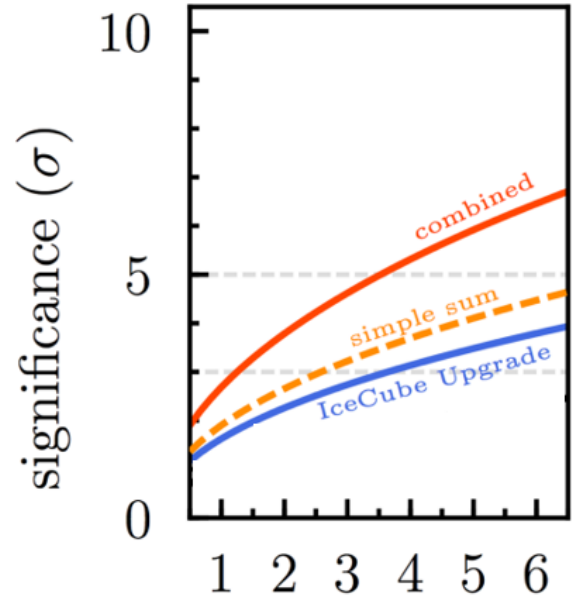
The IceCube Upgrade

- $30M extension to IceCube
  - Funded, planned deployment in 2022/3
  - Schedule under review due to COVID-19
- 700 multi-PMT sensors
  - Densely packed in 2 Mton core
- Improved detector/ice calibration



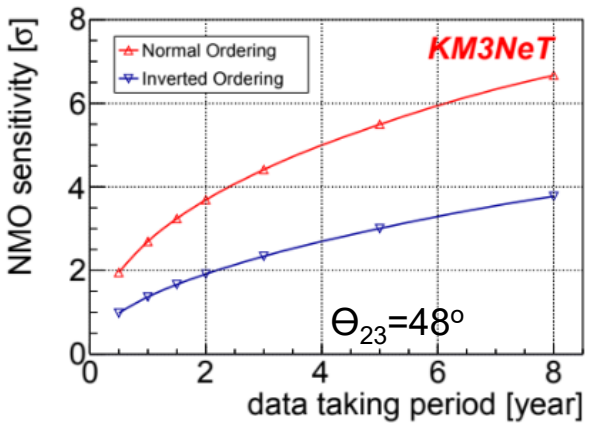
arXiv:1908.09441





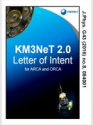
KM3NeT-ORCA

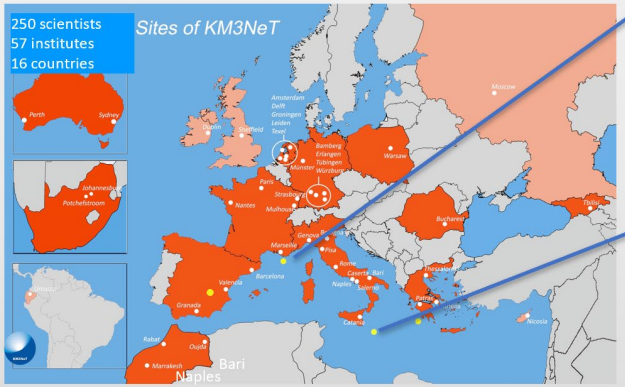
- 115 detection units
  - 6+1 in operation
  - Increase to 31 by end 2021



Aart Heijboer @ NeuTel 2021

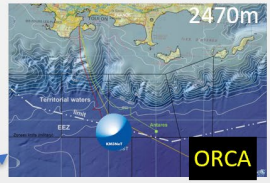
- Multi-site, deep-sea neutrino telescope
- Selected by ESFRI roadmap
- Single collaboration, Single technology





+Algeria

KM3NeT 2.0: Letter of Intent
http://dx.doi.org/10.1088/0954-3899/43/8/084001
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

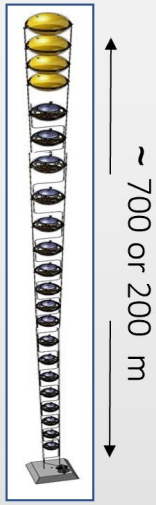


Oscillation Research
with Cosmics In the Abyss

Astroparticle Research
with Cosmics In the Abyss

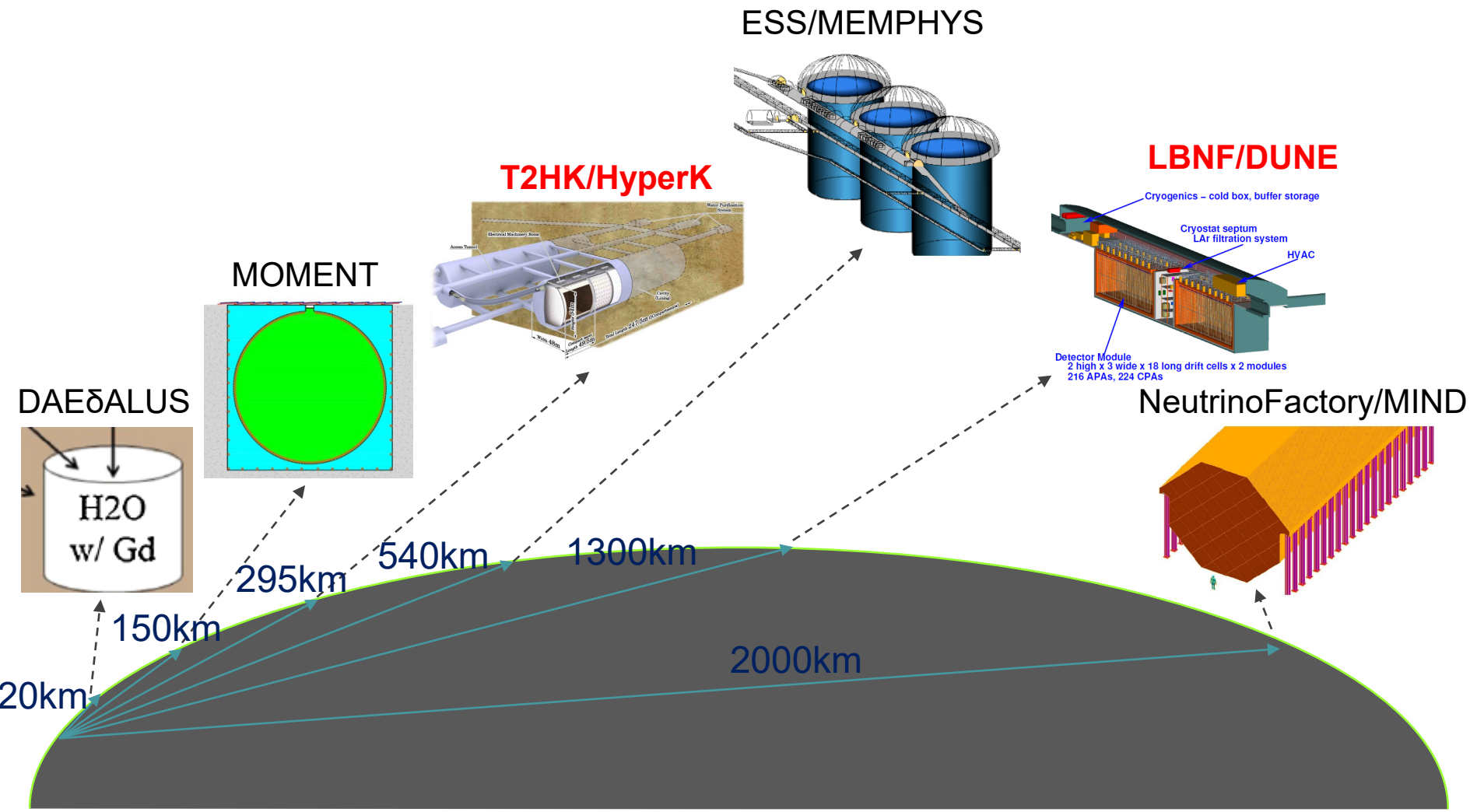
Connection nodes of
european multidisciplinary seafloor & water column observatory
emso

Digital Optical Module (DOM)
- Multi-PMT : 31 x 3" PMTs
- Gbit/s on optical fiber
- Positioning & timing



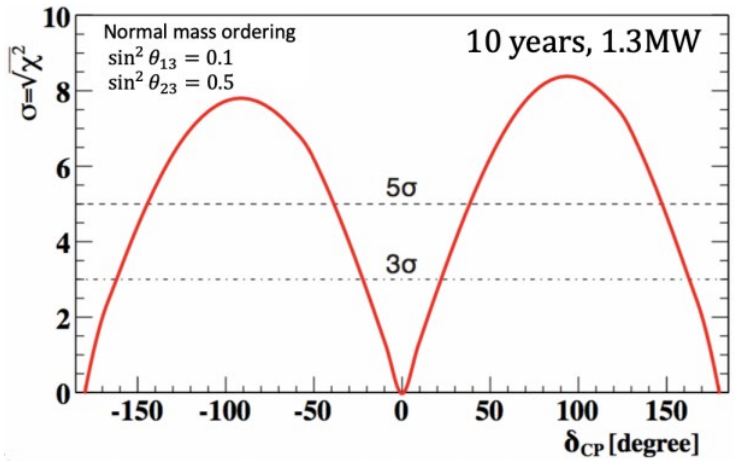
Detection Unit (DU)
- 18 DOMs
- Low-drag design

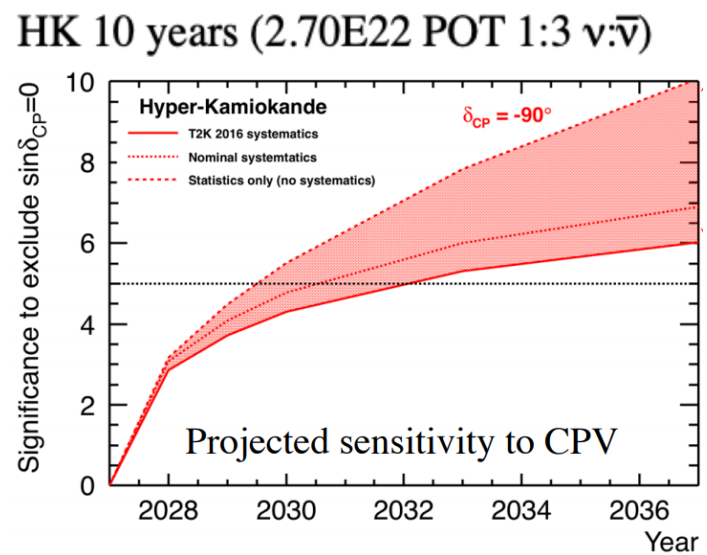
Future acc. exp. or concept for CP



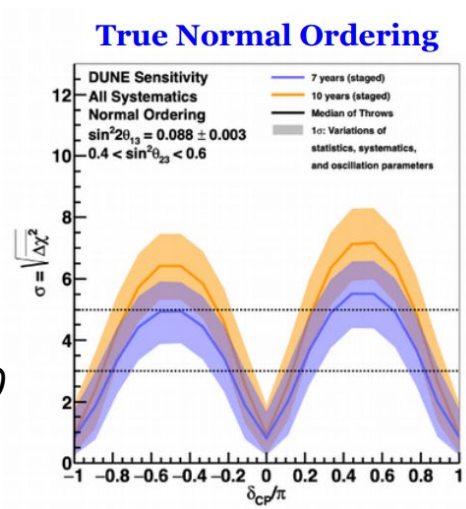
Prospective of CP

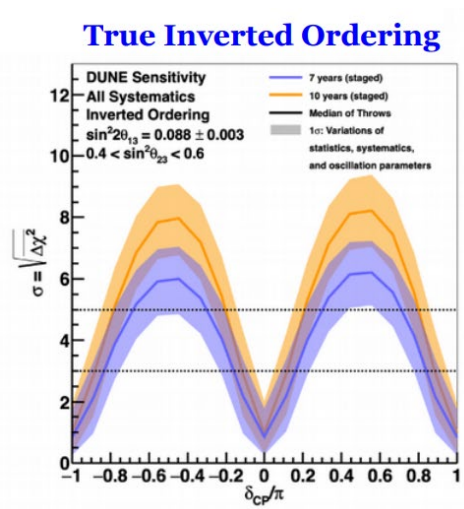
Hyper-K
Masaki Ishitsuka
@ Neutrino 2020

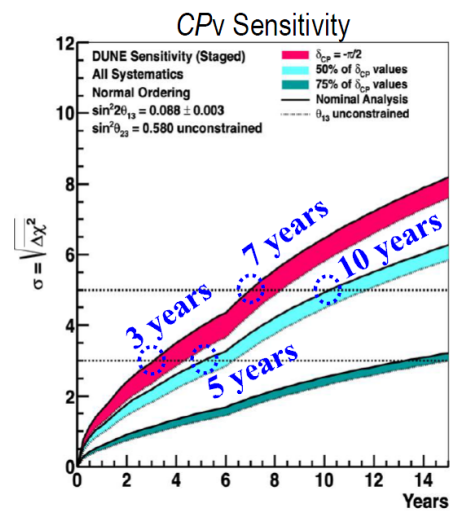




DUNE
Michael Mooney
@ Neutrino 2020



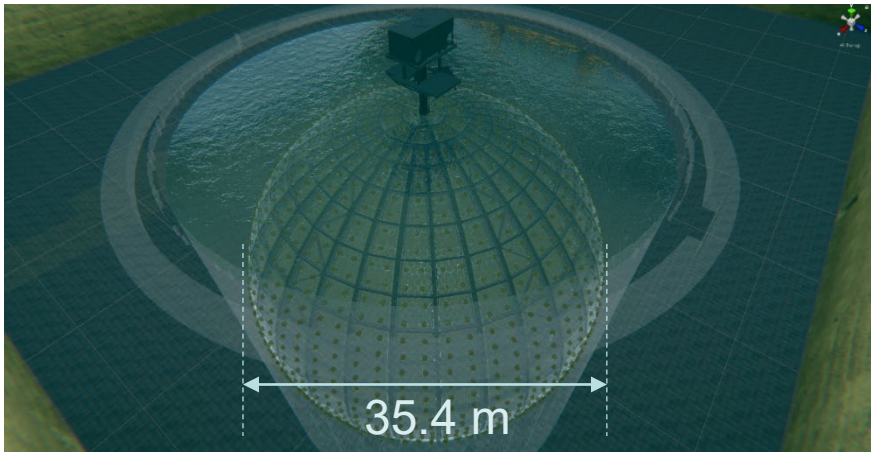




JUNO: a multipurpose neutrino experiment

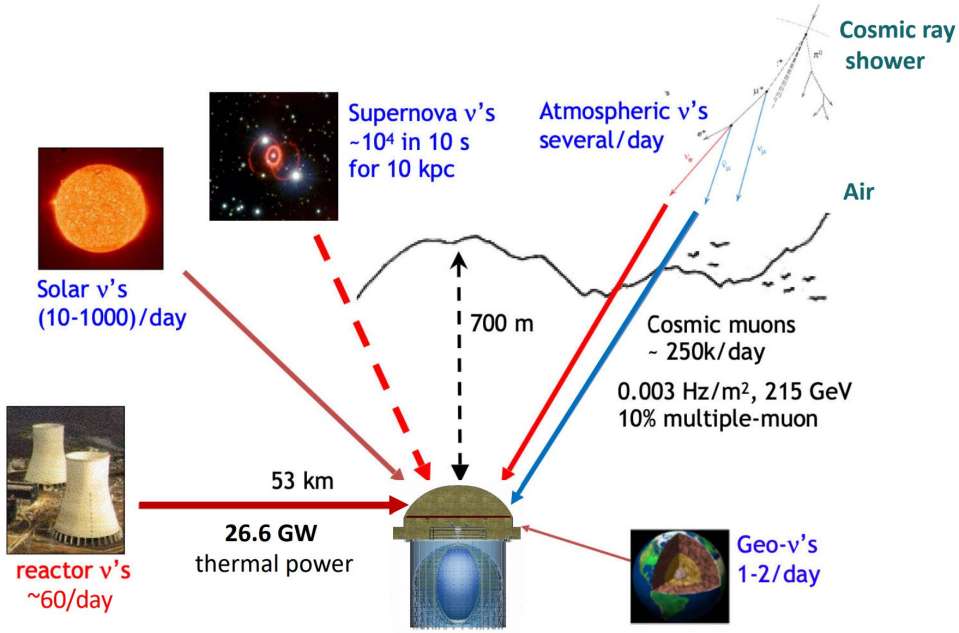
Project

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



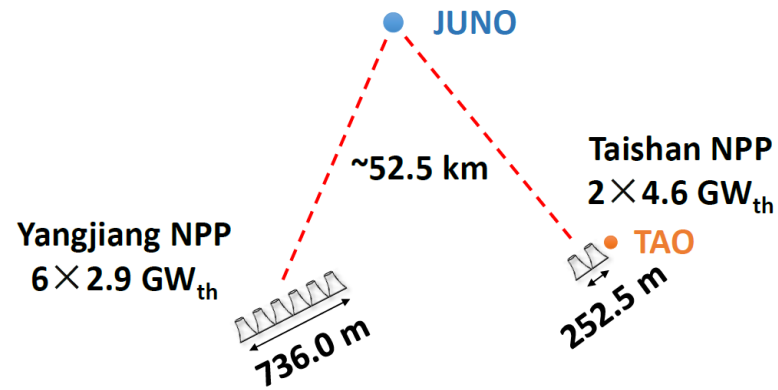
Physics

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



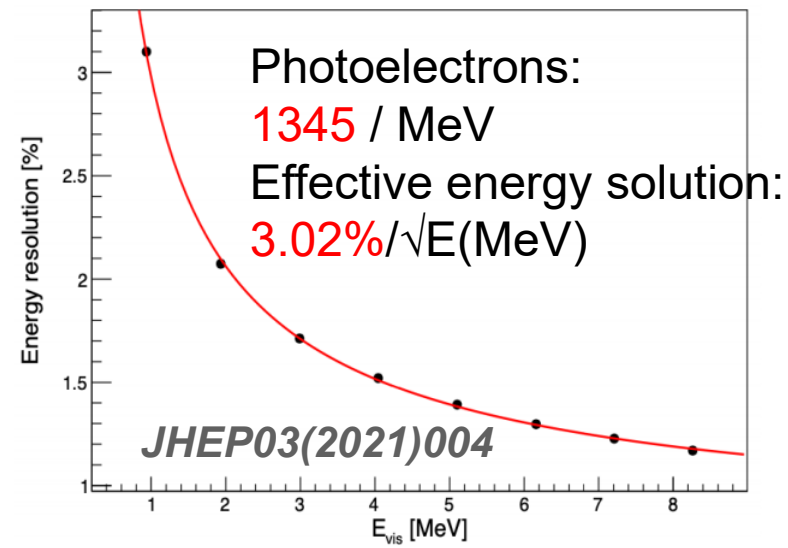
Reactor neutrino oscillation

- **Mass ordering**: 3σ for 6 years data → 4σ with accelerator constrain of Δm^2_{32}
  J. Phys. G 43, 030401 (2016)
- **Oscillation parameters**: precision of $\sin^2\theta_{12}$, Δm^2_{21}, Δm^2_{31} <0.6%
  arXiv:2104.02565



Updated analysis ongoing

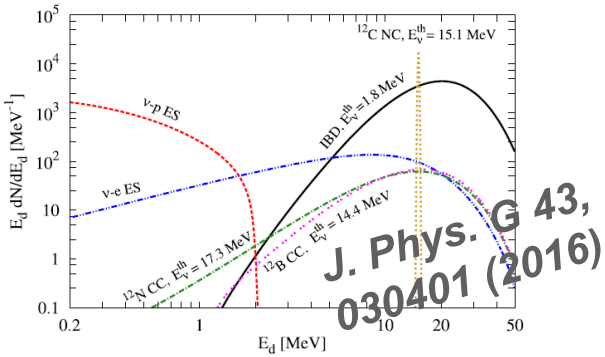
- Less reactor cores ↓
- New optical model, higher light yield ↑
- Higher PMT detection efficiency ↑
- $\bar{\nu}_e$ spectrum by TAO ↑
- Lower overburden ↓
- Better muon veto strategy ↑



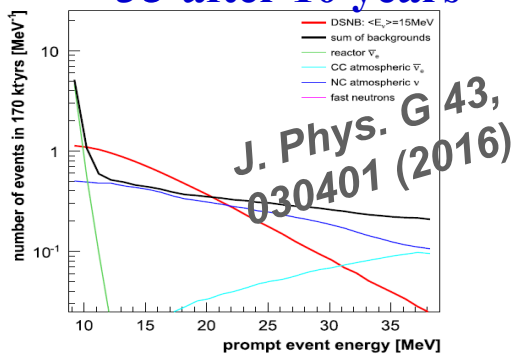
Obtained with the latest simulation, reconstruction and calibration

Rich physics potentials

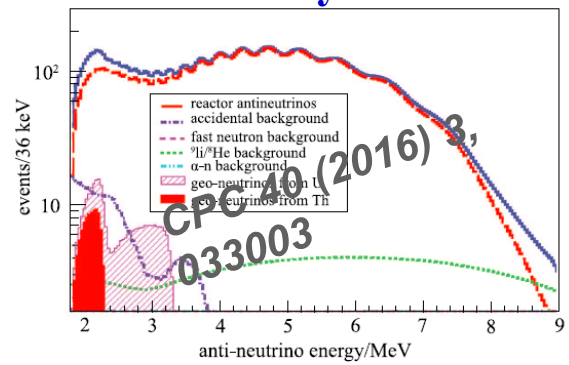
- **Supernova burst**
  - ⇨ ~5000 IBDs @10 kpc



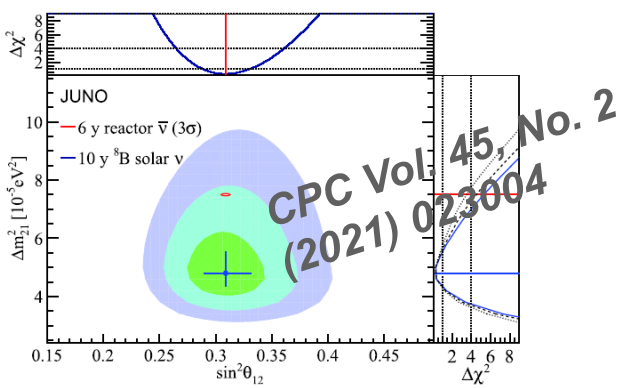
- **Diffuse Supernova neutrino background**
  - ⇨ ~3σ after 10 years



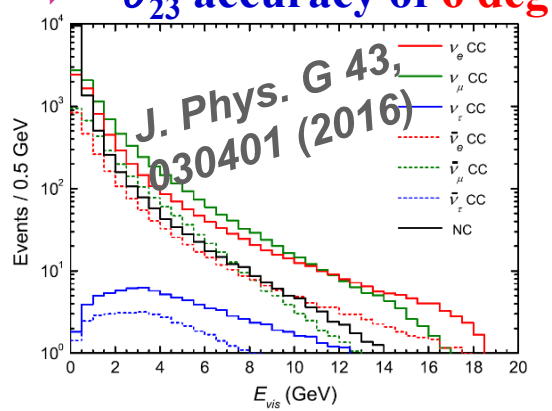
- **Geoneutrino**
  - ⇨ 5% uncertainty for 10 years



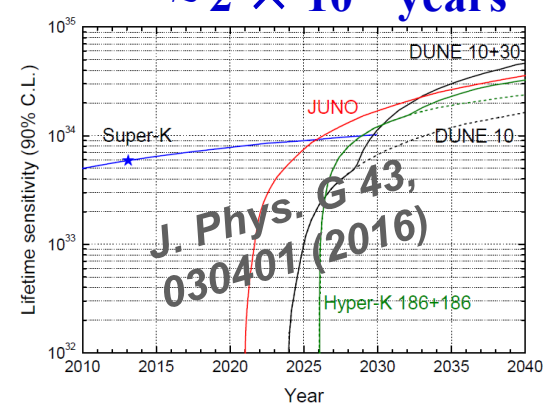
- **Solar neutrinos**
  - ⇨ 2 MeV threshold for ^{8}B neutrino



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



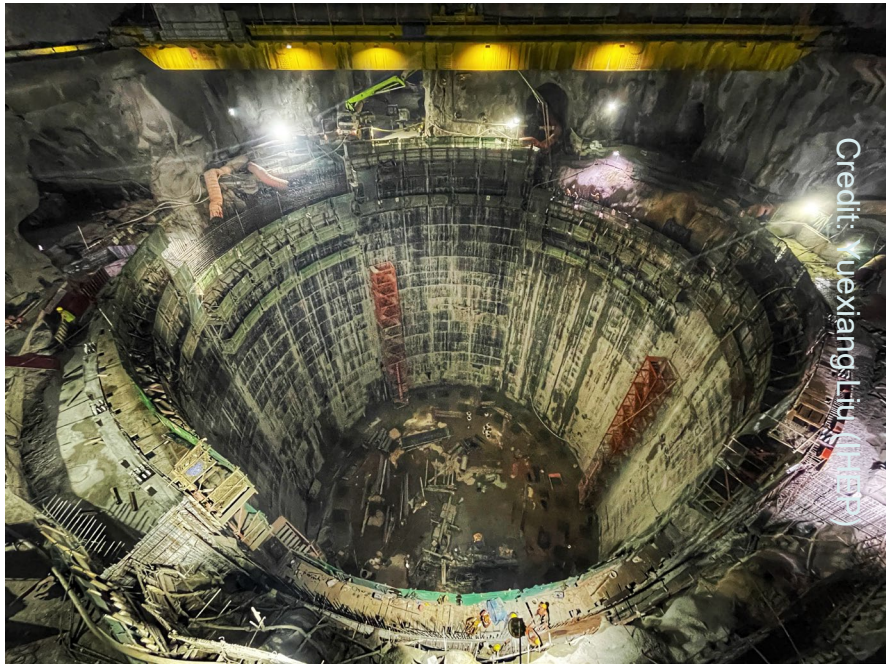
- **Nucleon Decay**
  - ⇨ τ (p→K$^+$ + ν) ~ 2 × 10^{34} years



Civil construction

- Underground experimental hall almost ready
- Detector installation starts in October

Surface buildings



Water pool

Detector main structure

- **Φ40.1 m** stainless steel truss
  - 30×23 H-beams
  - 140k screws
  - 590 connecting bars
  - Production 95% finished, shipping to JUNO site

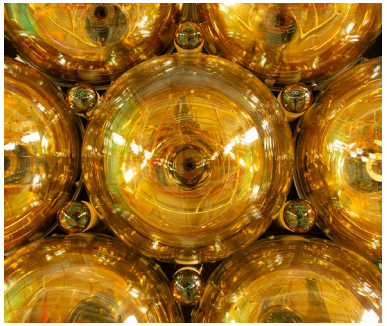
- **Φ35.4 m** acrylic sphere
  - 263 acrylic panels up to 3 m×8 m×120 mm
  - Flat panels 100%, thermal forming 80% finished
  - Transparency >96% in water
  - Radiopurity < 1 ppt
  - Bonding onsite

Pre-assembly and welding

Pre-assembly of two layers

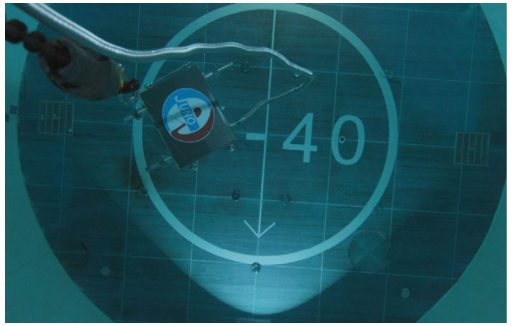
PMTs and electronics

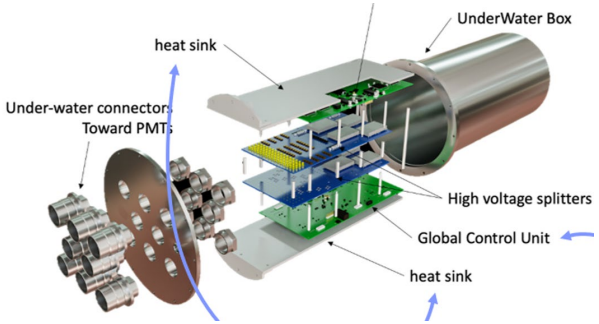
- Multiple types of PMTs
  - 5000 Hamamatsu 20-inch dynode-PMTs
  - 12612+2400 NNVT 20-inch MCP-PMTs
  - 25600 HZC 3-inch PMTs
- PMT instrumentations ongoing
  - 20-inch PMTs 100% finished
  - 3-inch PMTs 35% finished
- Readout electronics: **underwater**
- Reliability: <1% failure for 6 years (20-inch PMT + electronics)

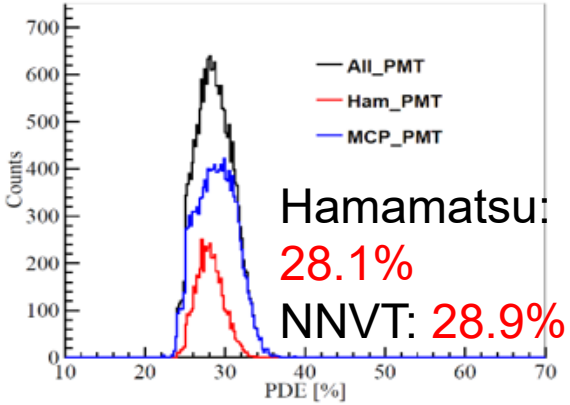


Optical coverage
20-inch PMT: 75.2%
3-inch PMT: 2.7%

PMT underwater **implosion test**



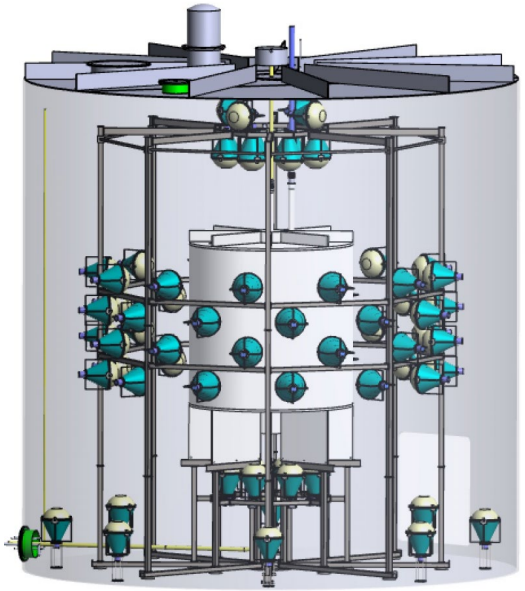




Large and small PMT underwater electronics boxes

Liquid scintillator

- JUNO LS recipe, similar to Daya Bay, optimized with a Daya Bay detector: **LAB + 2.5 g/L PPO + 3 mg/L Bis-MSB**
- No Gd-doping
- Attenuation length: >20 m @ 430 nm
- Low radioactive backgrounds
  - 10^{-15} g/g for reactor neutrinos
  - 10^{-17} g/g for solar neutrinos (**0.008 g dust in 20 kton LS**)



Online Scintillator Internal Radioactivity Investigation System

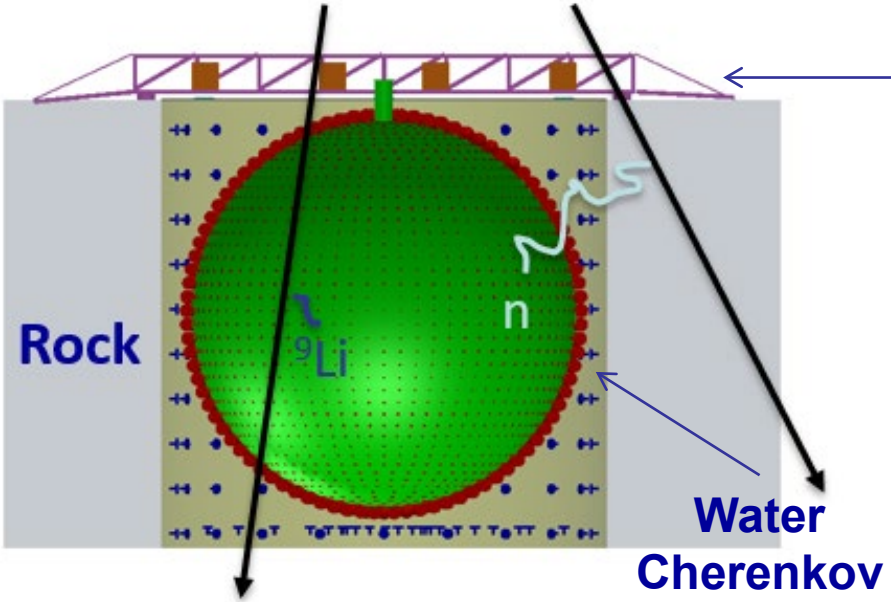
Cosmic muon veto

Water Cherenkov detector

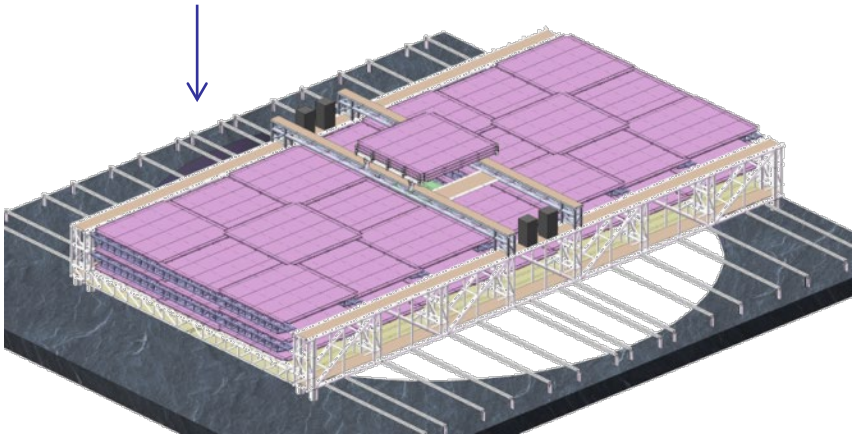
- 2400 20” MCP-PMTs
- 35 kton ultra pure water with circulation
- Temperature 21±1℃.
- Radon in water requirement: < 0.2 Bq/m^3, prototype reached 0.01 Bq/m^3

Top Tracker

- Recycling the plastic scintillators from OPERA Target Tracker



Top Tracker

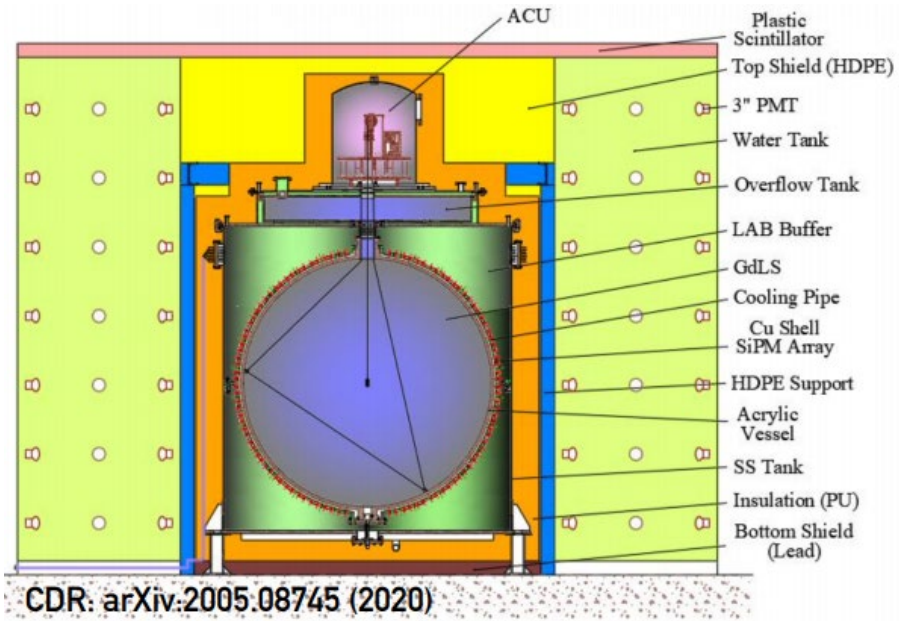


Taishan Antineutrino Observatory

- Provide model-independent reference spectrum for JUNO

- Tons fiducial mass - Gd doped LS
- Water tanks and Plastic Scintillators for shielding and muon veto
- ~30 m to one of the 4.6 GW_{th} reactor cores
- NPE ~ 4500/MeV, full coverage
- low-T (-50 ℃) → low dark noise
- σ_E/E ~2% @1MeV

- **Prototype 1-1 before end 2021**



CDR: arXiv:2005.08745 (2020)

Summary and prospective

- Neutrinos discovery and oscillation
  - 3-flavor neutrinos discovery in 1956-2000
  - Neutrino oscillation confirmed in 1998
  - Amplitudes (mixing angles) and frequencies (mass splitting) well understood and determined at a few percent precision
- Promising solutions to 3×3 mixing matrix in 10-20 years
  - Sub-percent precision of oscillation parameters
  - 3σ determination of mass ordering and CP violation in late 2020s → possibly 5σ in early 2030s
- Remain questions
  - Neutrino mass and neutrinoless ββ decay (JUNO upgrade …)
  - Astronomy and astrophysics (THU, SJTU, IHEP …)
  - Sterile neutrino

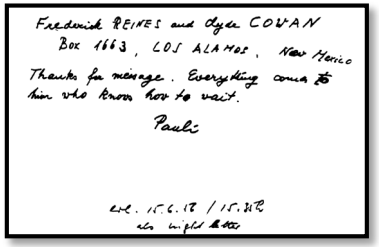
backup

Discovery of neutrinos

1956: electron neutrinos

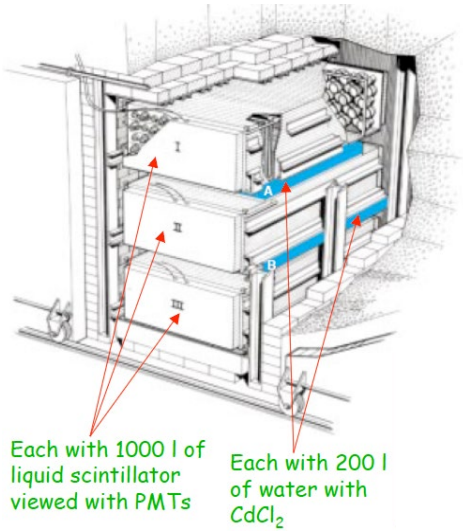
Frederick Reines (Nobel Prize in 1995)

Clyde L. Cowan



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

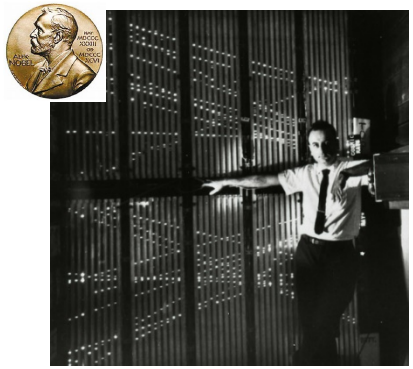
A telegram from Pauli: “Thanks for message. Everything comes to him who knows how to wait.”



Savannah River Exp.

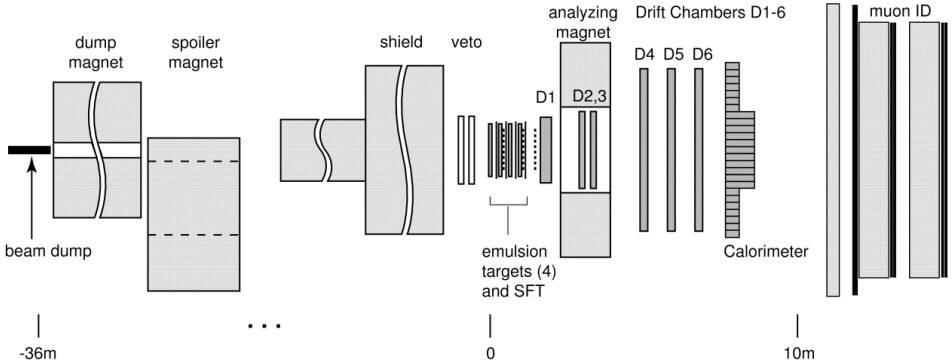
1962: muon neutrinos

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



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

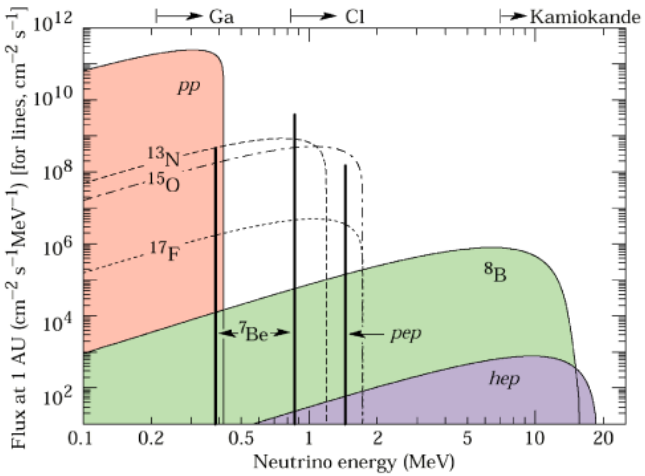
2000: tau neutrinos

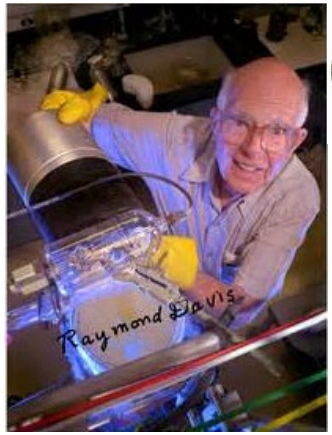


DONUT experiment in Fermilab

Explore the universe with neutrinos

Measurement of solar neutrinos since 1960s

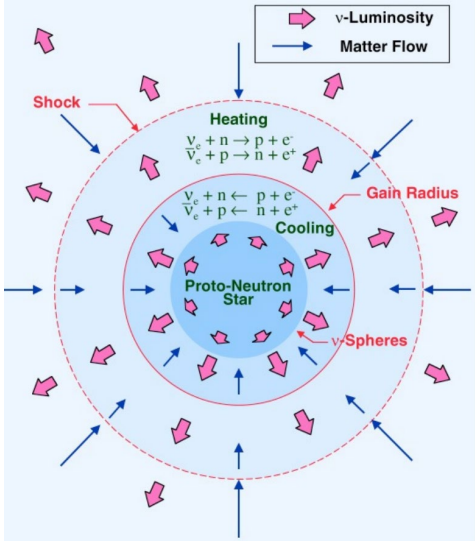


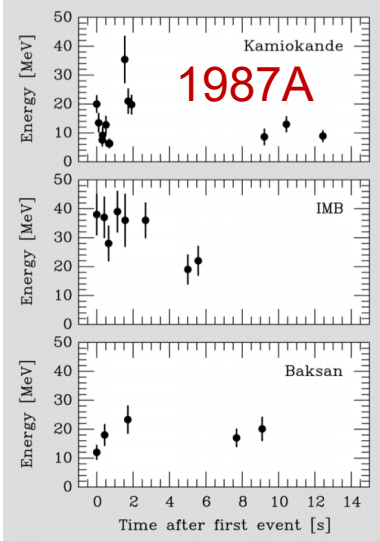


Ray Davis
(Nobel Prize in 2002)

Observation of supernova burst neutrinos in 1987

Masatoshi Koshiba
(Nobel Prize in 2002)

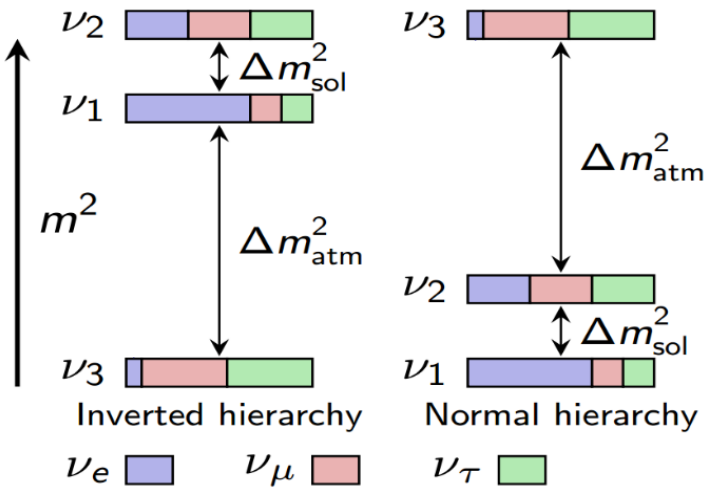




Neutrino oscillation

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

- Weak eigenstates
- PMNS matrix
- Mass eigenstates



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

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

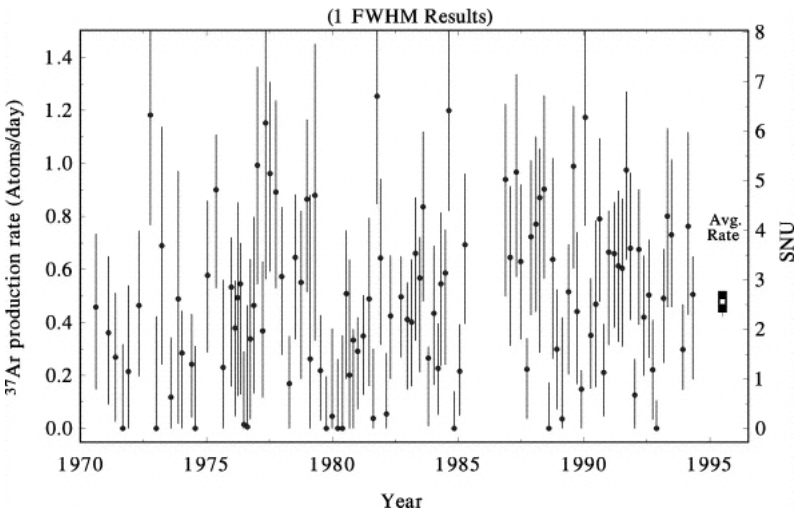
$\theta_{13} \approx 8.9^\circ$
$\delta_{CP} = ?$

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

neutrino-less double beta decay

Solar neutrino problem

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

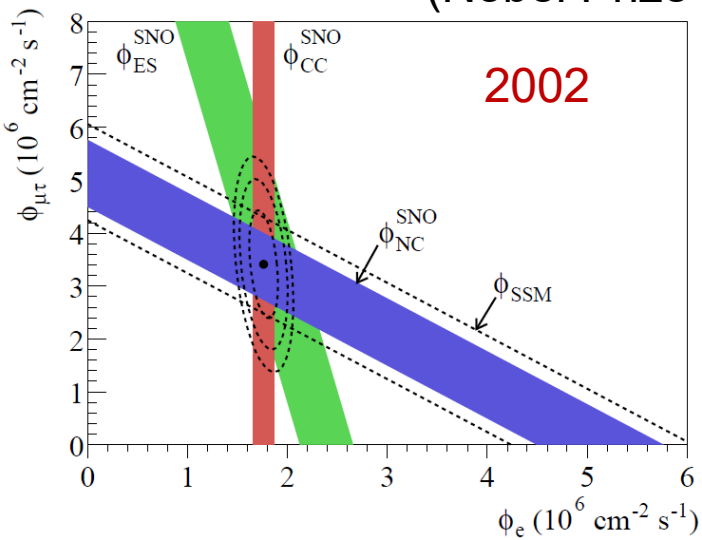


Observed solar neutrino flux

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

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

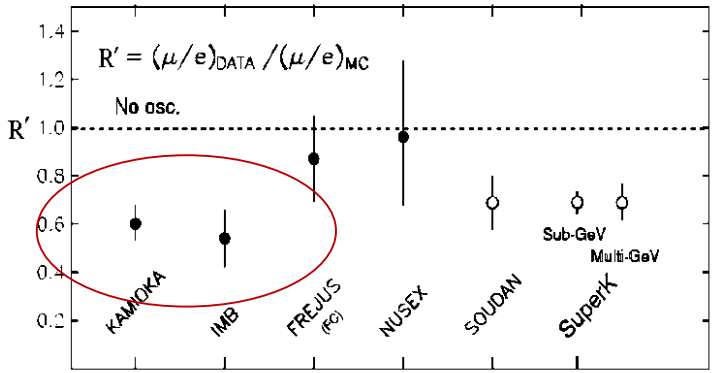
$\Rightarrow$ $\nu_\mu/\nu_e \approx 2$

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

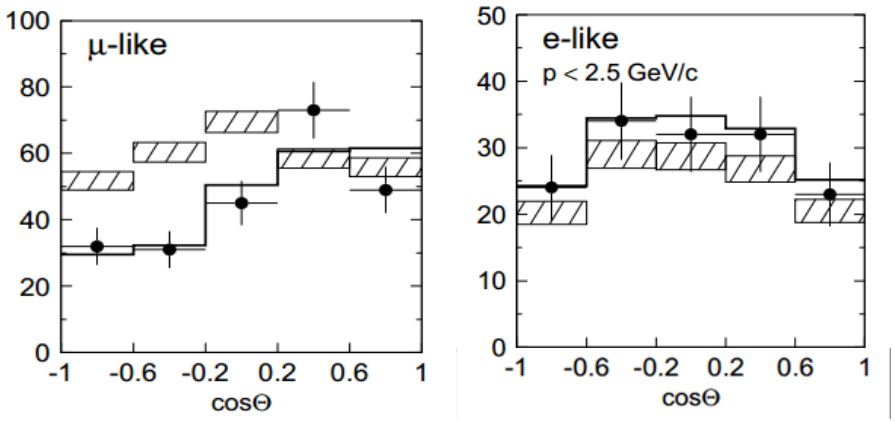
"atmospheric neutrino problem"

- 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)



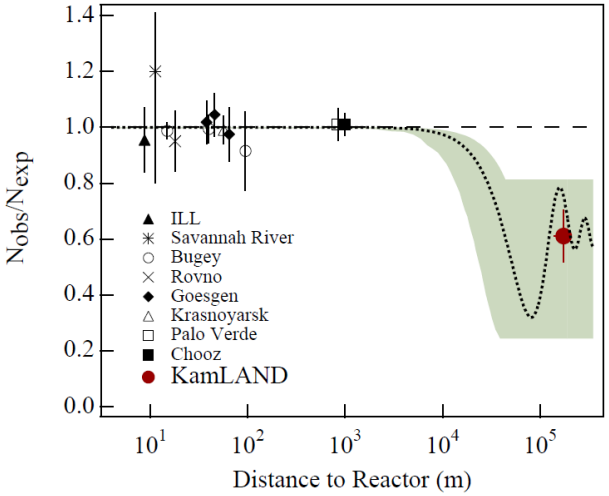
1998

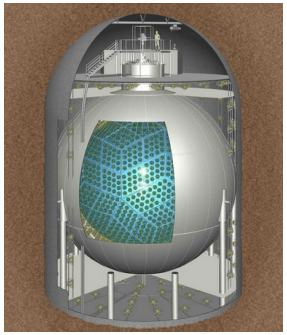


$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2 (1.27 \Delta m^2 L/E)$$

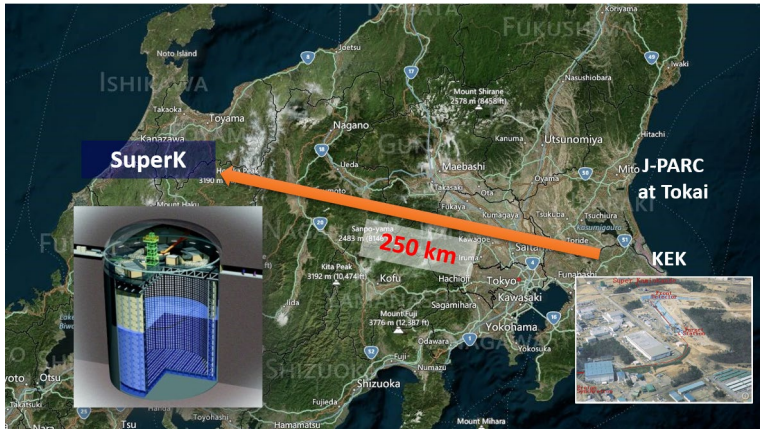
Artificial neutrinos oscillation

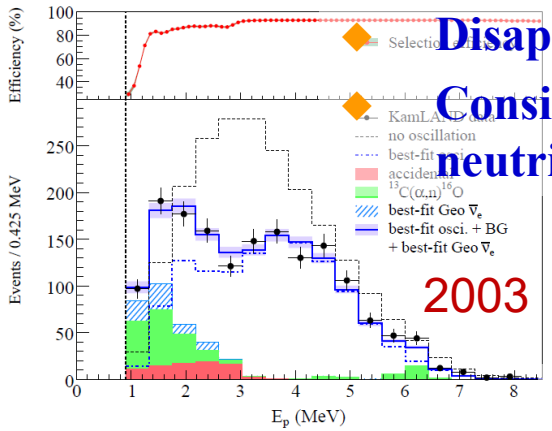
- KamLAND: 1,000 ton liquid scintillator, ~180 km to >50 reactors





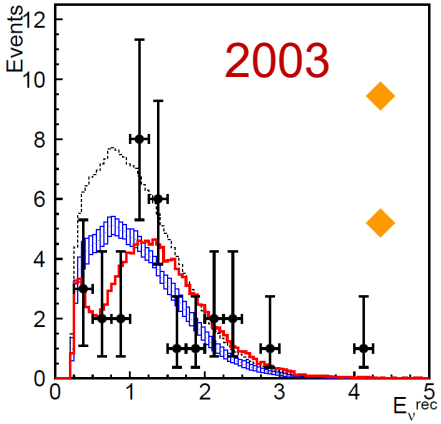
- K2K: first long-baseline accelerator experiment





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

θ_{12} and Δm^2_{21}

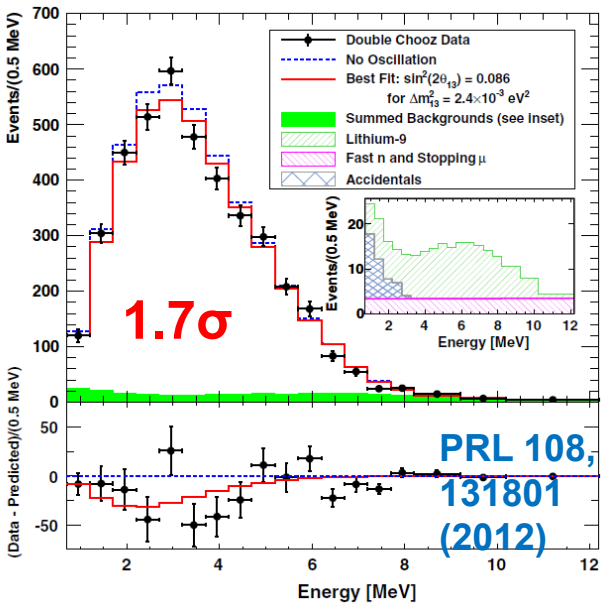


- K2K: detected 56 ν_μ while expected 80.1.
- Consistent to atmospheric neutrinos oscillation.

θ_{23} and $|\Delta m^2_{32}|$

Discovery of non-zero θ_{13}

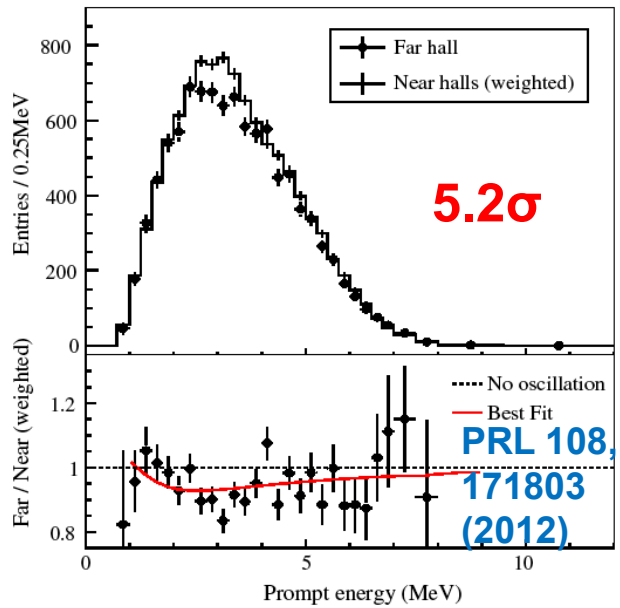
Double Chooz
with only a far detector
(Nov. 2011)



Rate+shape

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

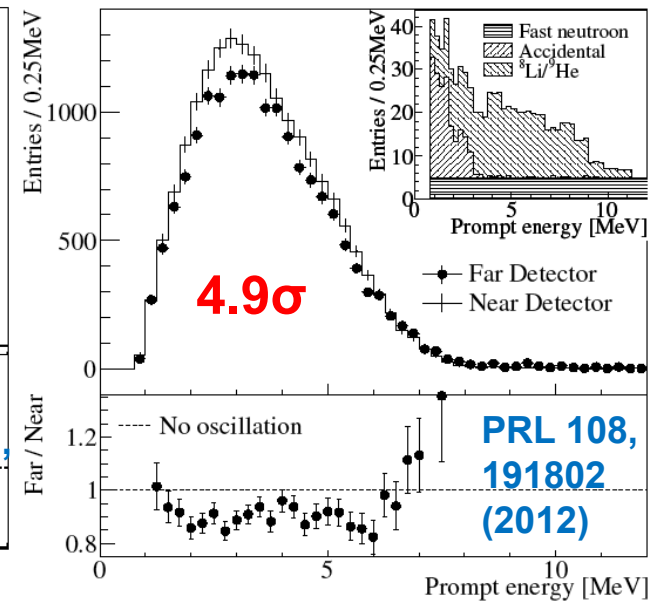
Daya Bay
(March 2012)



Rate only

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

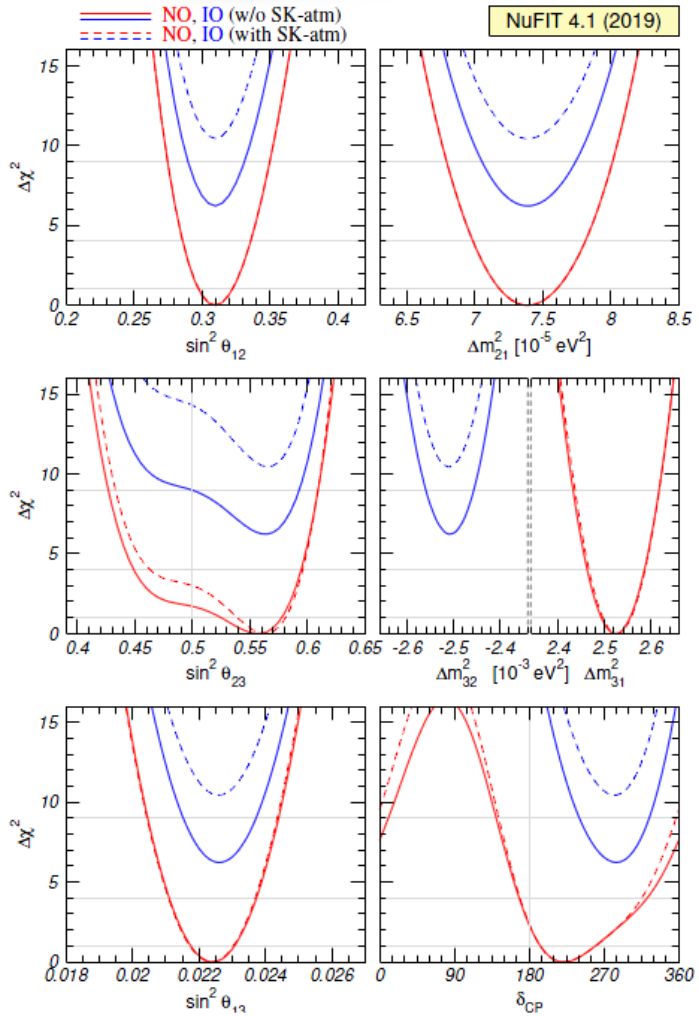
RENO
(April 2012)



Rate only

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

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)

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

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

Atmospheric term

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

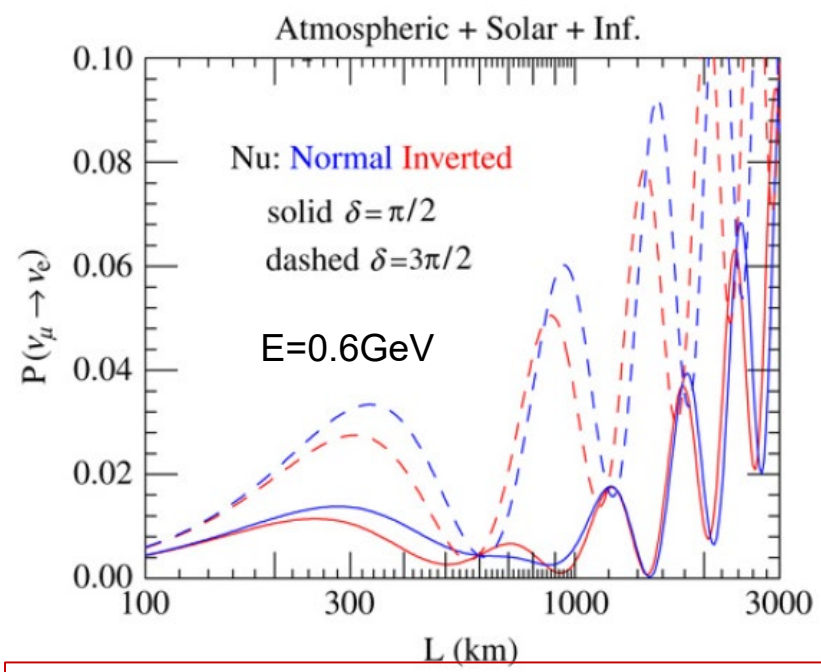
Interference term

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

Solar term

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

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



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

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

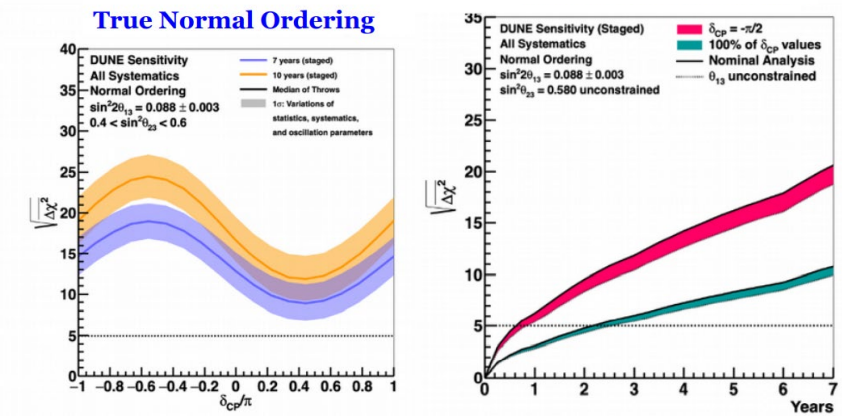
$$\sim \Delta_{31} \rightarrow -\Delta_{31}$$

Mass Ordering

Prospective of mass ordering

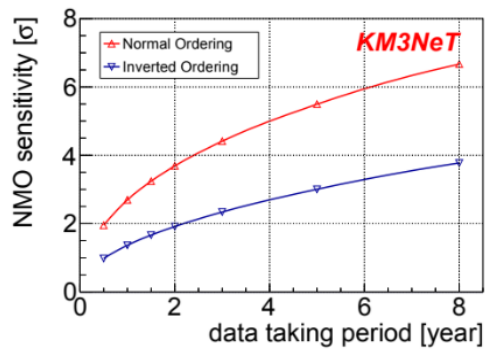
DUNE

Michael Mooney @ Neutrino 2020



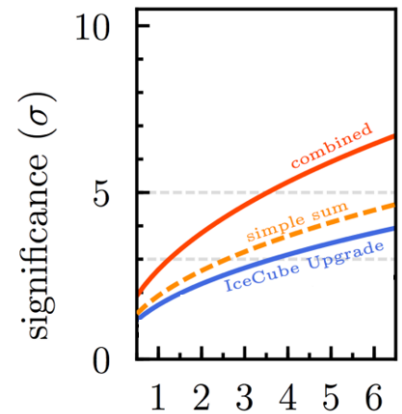
KM3NeT-ORCA

Aart Heijboer @ NeuTel 2021



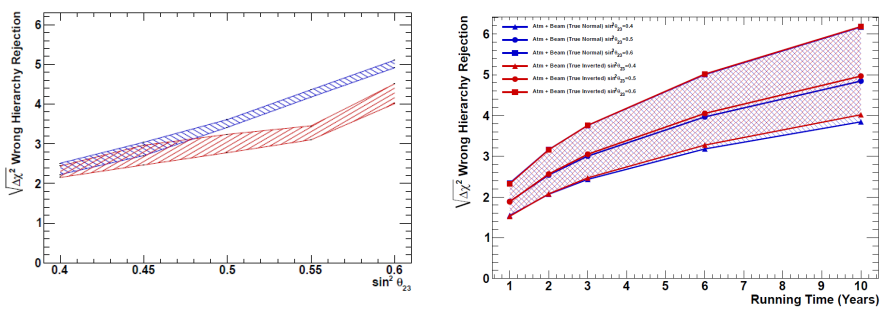
IceCube upgrade

Tom Stuttard @ NeuTel 2021

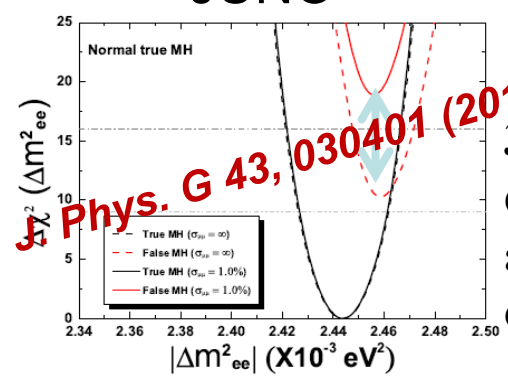


Hyper-K

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