Neutrino oscillations: experimental review

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OUTLINE

- **Neutrino oscillations**
  - discovery of neutrino oscillations
  - 3-neutrino scheme
  - running accelerator and reactor experiments
  - future projects

- **Light sterile neutrinos**
  - neutrino anomalies
  - new experimental tests

Solar neutrino problem

Davis R(Jr), Harmer DS, Hoffman KC
"Search for neutrinos from the Sun"
Phys. Rev. Lett. 20 1205 (1968)

….the flux of neutrinos from B^8 decay in the sun was equal to or less than 2×10^6 cm^{-2} sec^{-1} at the earth, and that less than 9% of the sun's energy is produced by the carbon-nitrogen cycle.

Exp flux < 3 SNU
SSM → 7.5 ± 3 SNU

Idea of neutrino oscillations – 1957

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

1965

Mesonium and anti-mesonium
B. Pontecorvo
Sov.Phys.JETP 6 (1957) 429
Zh.Eksp.Teor.Fiz. 33 (1957) 549-551

Inverse beta processes and nonconservation of lepton charge
B. Pontecorvo (Dubna, JINR)
Sov.Phys.JETP 7 (1958) 172-173, Zh.Eksp.Teor.Fiz. 34 (1957) 247

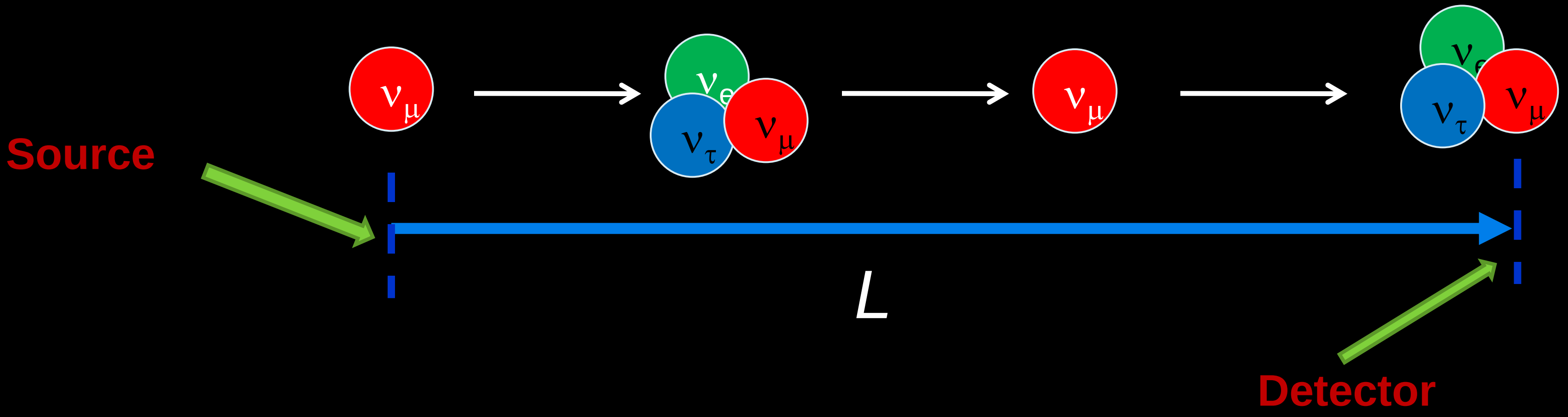
Neutrino Experiments and the Problem of Conservation of Leptonic Charge
B. Pontecorvo (Dubna, JINR)
Sov.Phys.JETP 26 (1968) 984-988, Zh.Eksp.Teor.Fiz. 53 (1967) 1717-1725

Z.Maki, M.Nakagawa, S.Sakata, Remarks on the unified model of elementary particles, Prog.Theor.Phys. 28 (1962) 870

Neutrino oscillations

- one flavor can transform into another
- neutrino should have a non-zero mass and mix
- oscillation probability depends on

  m_ν, E_ν and distance L



Weak eigenstates

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

m_1

m_2

m_3

Mass eigenstates

U – PMNS mixing matrix

Weak eigenstates differ from mass eigenstates

Mixing in two families

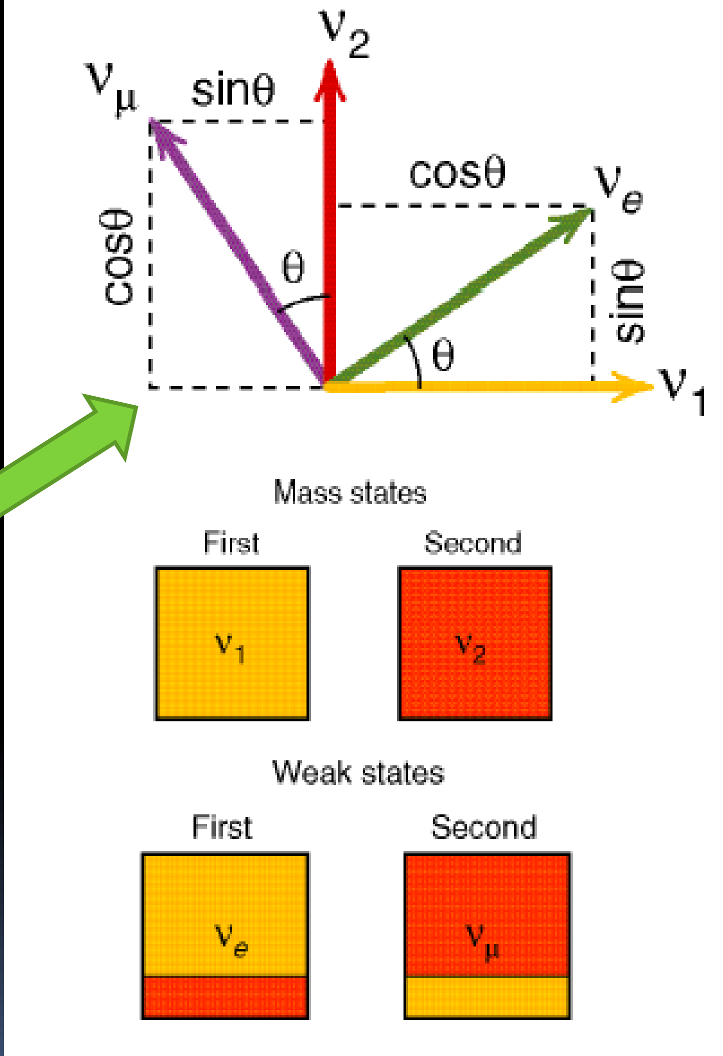
Consider for simplicity two families

Weak eigenstates : ν_μ ν_e

Mass eigenstates: ν_1 (m_1) ν_2 (m_2)

Then the mixing matrix depends of a single parameter, the mixing angle θ

The weak and mass eigenstates are connected by a simple two-dimensional rotation



$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

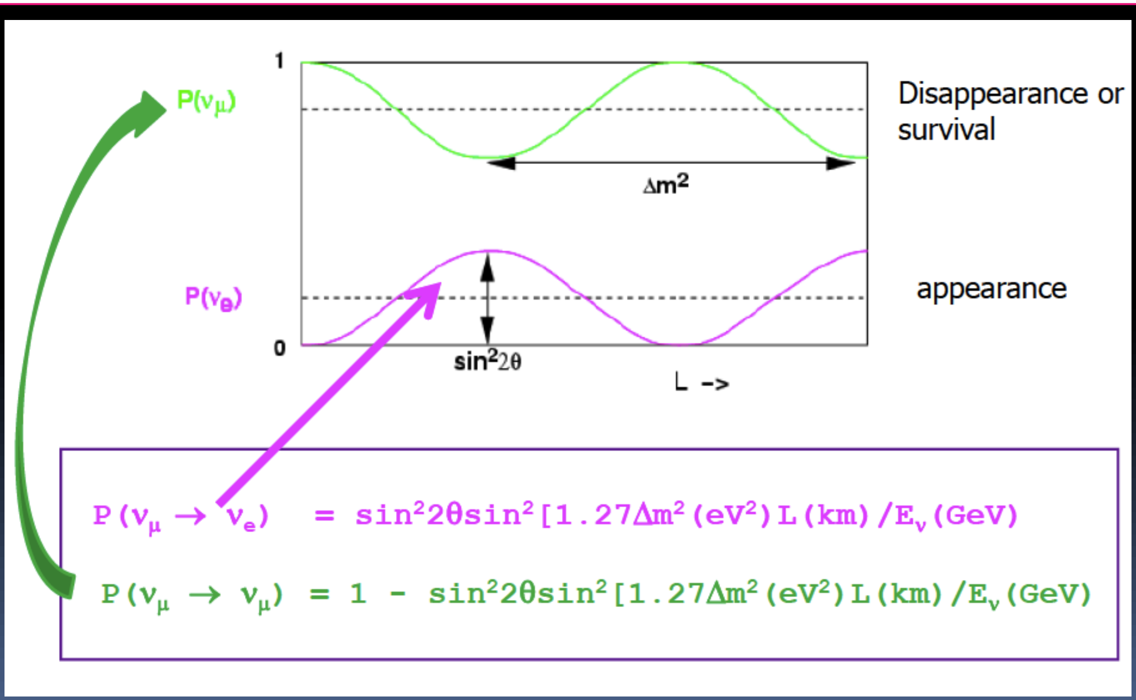
$$\nu_e = \cos\theta|\nu_1> + \sin\theta|\nu_2>$$
$$\nu_\mu = -\sin\theta|\nu_1> + \cos\theta|\nu_2>$$

ν oscillations in vacuum

2 neutrinos: ν_μ and ν_e with masses m_1 and m_2
2 oscillation parameters: $\Delta m^2 = m^2_2 - m^2_1$ and mixing angle θ

$\nu_e (t=0) = \cos\theta|\nu1> + \sin\theta|\nu2>$
$\nu_\mu (t=0) = -\sin\theta|\nu1> + \cos\theta|\nu2>$
$\nu(x,t) = \exp(ip\cdot x - E_1t)\cos\theta|\nu1> + \exp(ip\cdot x - E_1t)\sin|\nu2>$ E_i = \sqrt($p^2 + m_i^2$) $\approx p + m_i^2/2p$
$\nu(t) = \cos\theta|\nu1> + e^{i\phi}\sin\theta|\nu2>$
$\phi = [(m_1^2 - m_2^2)/2p]\cdot t$

$$P(\nu_e \to \nu_\mu) = |< \nu_\mu | \nu(t)>|^2 = \sin^2 2\theta \sin^2(\pi x/L)$$



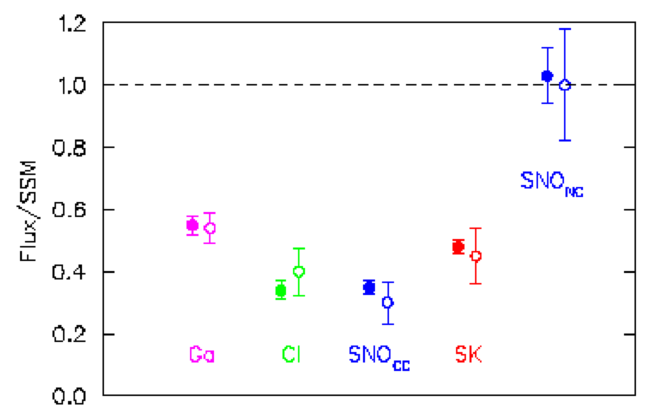
$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2[1.27\Delta m^2(eV^2)L(km)/E_\nu(GeV)$

$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2[1.27\Delta m^2(eV^2)L(km)/E_\nu(GeV)$

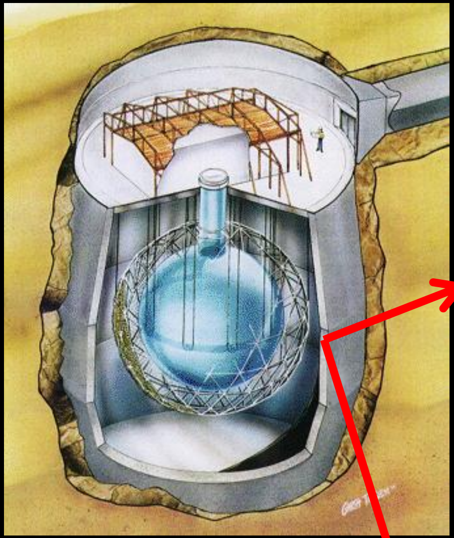
Solar neutrinos

Solar experiments

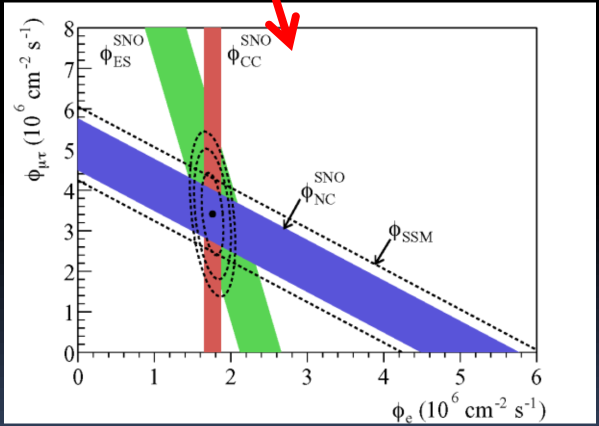
Homestake, Sage, Gallex/GNO, SK



SNO, Canada

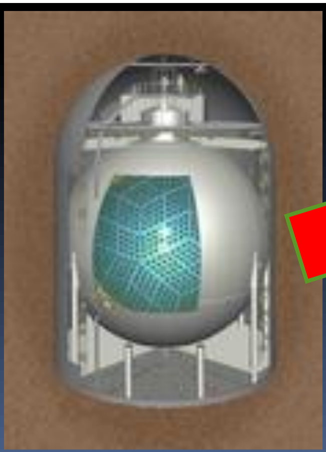


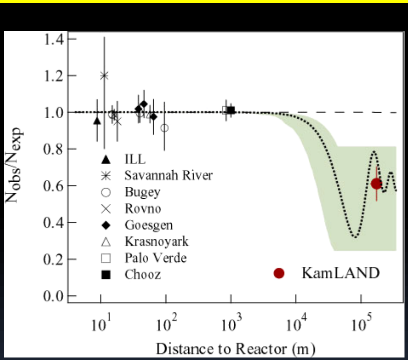
ν flux $(10^6\ cm^{-2}\ s^{-1})$	
ν_e	1.76(11)
$\nu_{\mu\tau}$	3.41(66)
ν_{total}	**5.09(64)**
ν_{SSM}	**5.05**

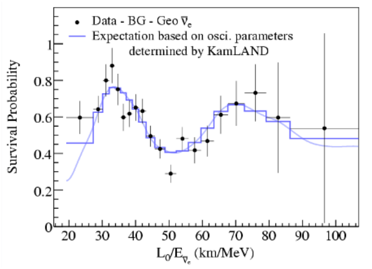


Reactor experiment

KamLand, Japan





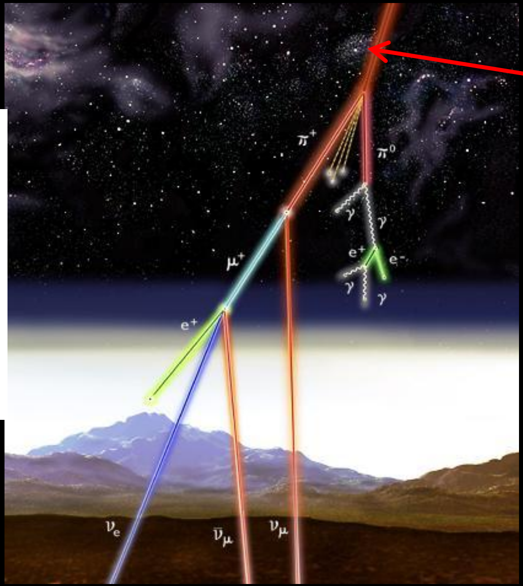


$\Delta m^2 \sim (7\text{-}8)\times 10^{-5}\ ev^2$

$\theta \sim 35$ deg

Atmospheric ν

Baselines L
20 km
15000 km
Neutrino energy E
0.5 - 1000 GeV



Neutrino sources

$\pi^+ \to \mu^+ + \nu_\mu, \qquad \pi^- \to \mu^- + \bar{\nu}_\mu$

$K^+ \to \mu^+ + \nu_\mu, \qquad K^- \to \mu^- + \bar{\nu}_\mu,$

$K^+ \to \pi^0 + \mu^+ + \nu_\mu, \qquad K^- \to \pi^0 + \mu^- + \bar{\nu}_\mu,$

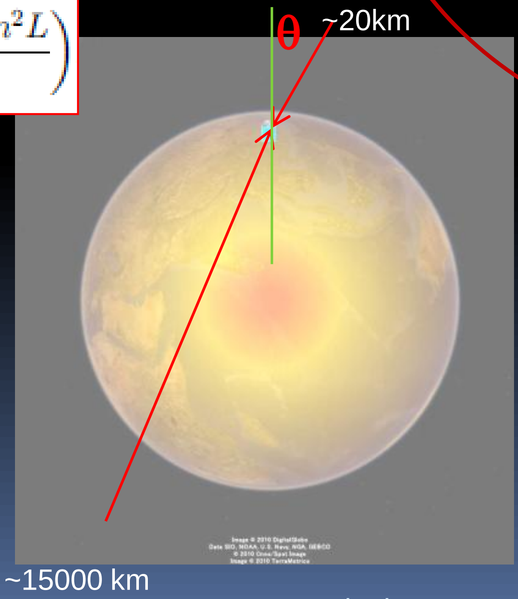
$K^+ \to \pi^0 + e^+ + \nu_\mu, \qquad K^- \to \pi^0 + e^- + \bar{\nu}_\mu.$

$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu, \qquad \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$

Roughly

$\nu_e : \nu_\mu \sim 1:2$

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \cdot \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$



Sensitive to oscillations with $\Delta m^2 \sim 10^{-4} - 10\ eV^2$

Atm neutrino flux
~ 1 см$^{-2}$с$^{-1}$

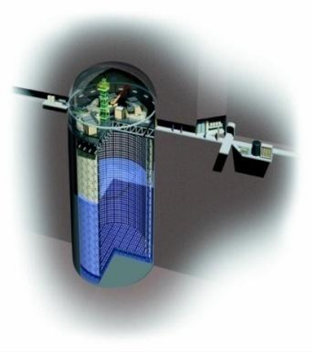
Atmospheric neutrinos

Super-Kamiokande
Japan

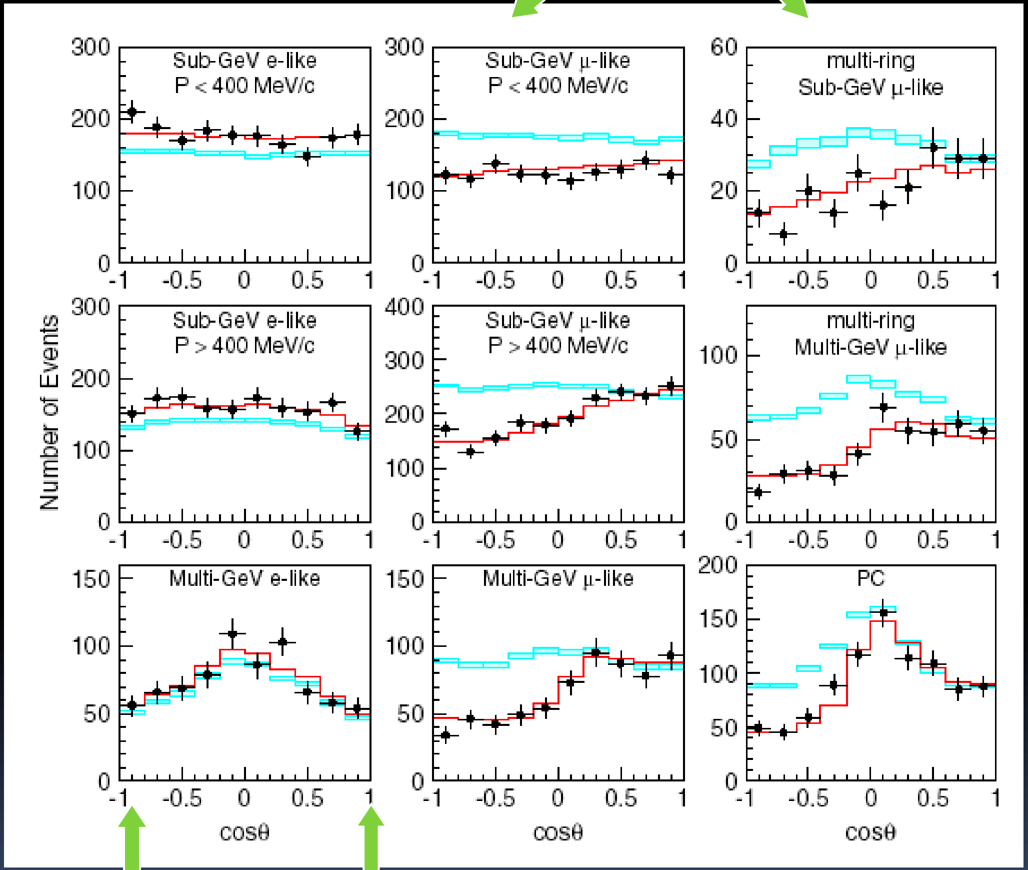
$0.2 < \cos\theta < 1$	L = 20-500 km
$-1 < \cos\theta < -0.2$	L = 500-13000 km

ν_e

ν_μ



SK



upgoing downgoing

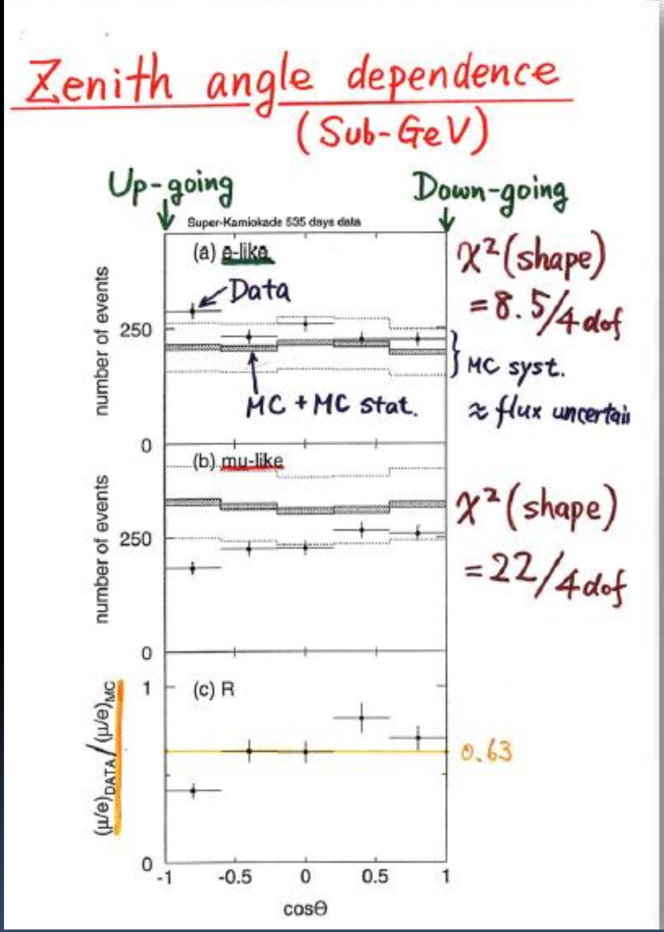
$(U/D)_\mu = 0.54 \pm 0.04 \pm 0.01$

SuperKamiokande: ν_μ oscillation with $\Delta m^2 \sim (2\text{-}3)\times10^{-3}\,\mathrm{eV}^2$

Atmospheric neutrinos

First result was reported at Neutrino98
in Toyama, Japan

T.Kajita, talk at Neutrino98

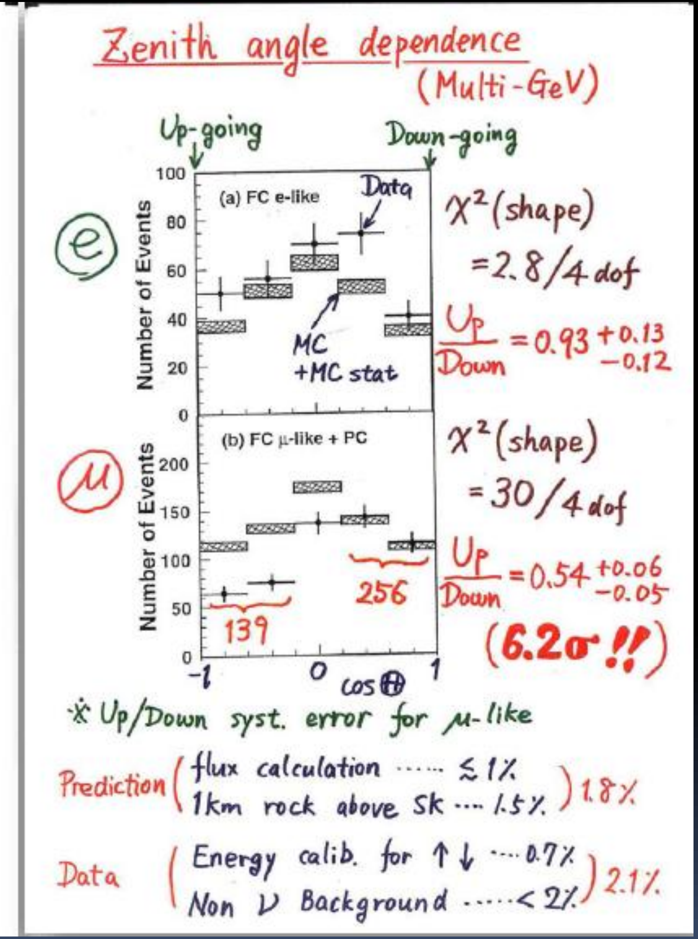


Zenith angle dependence
(Sub-GeV)

χ^2(shape) = 8.5/4 dof

} MC syst. ≈ flux uncertai

χ^2(shape) = 22/4 dof



Zenith angle dependence
(Multi-GeV)

ⓔ χ^2(shape) = 2.8/4 dof

$\frac{Up}{Down} = 0.93^{+0.13}_{-0.12}$

ⓜ χ^2(shape) = 30/4 dof

$\frac{Up}{Down} = 0.54^{+0.06}_{-0.05}$

(6.2σ !!)

※ Up/Down syst. error for μ-like

Prediction (flux calculation …… ≲ 1% ; 1km rock above SK …. 1.5%) 1.8%

Data (Energy calib. for ↑↓ …. 0.7% ; Non ν Background …..< 2%) 2.1%

$\Delta m^2 \sim$ (2-3)x10^{-3} eV^2
θ ~ 45 deg

NOBEL PRIZE IN PHYSICS 2015

Nobelpriset i fysik 2015 — The Nobel Prize in Physics 2015

Nobelpriset i fysik 2015

KUNGL.
VETENSKAPS-
AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

"för upptäckten av neutrinooscillationer, som visar att neutriner har massa"
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

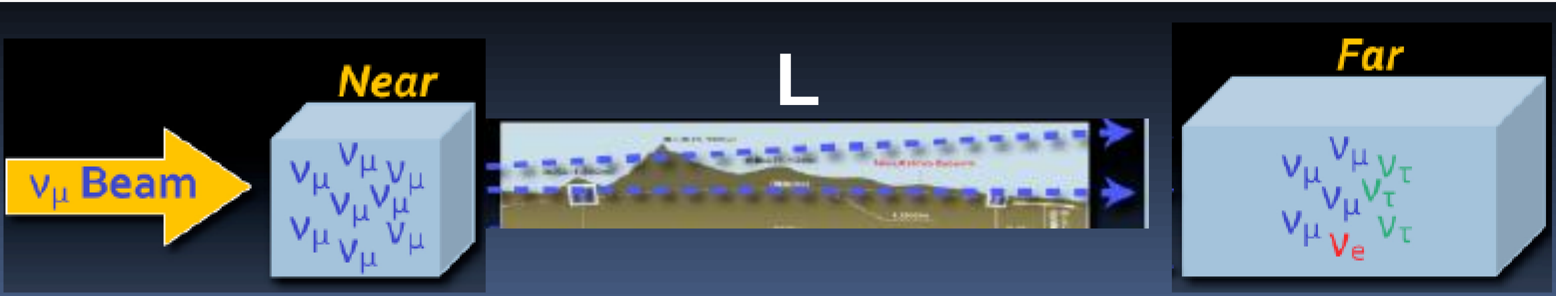
Confirmation of oscillations of atm ν's

$\Delta m^2 \sim 2\text{-}3\times 10\text{-}3\ \mathrm{eV}^2$, large mixing $\theta \sim 45$ deg

Long baseline accelerator experiments
Three main elements: neutrino beam, near detector, far detector

Experimental method

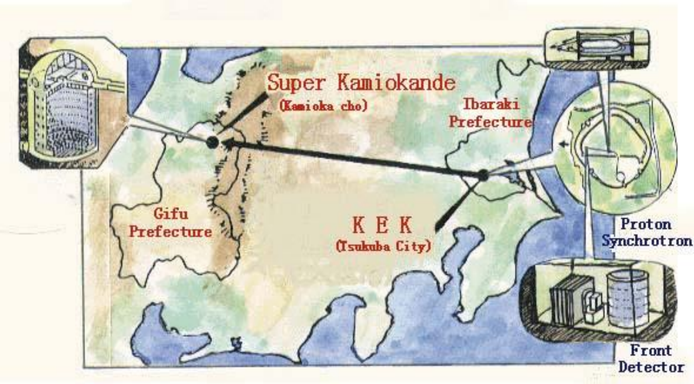
- produce pions in $p + A \rightarrow \pi + X$ at accelerator
- $\pi \rightarrow \mu + \nu_\mu$ focus pions
- select right E and baseline L to tune to oscillation maximum
- measure neutrino flux, energy, beam contamination before oscillations (near target)
-measure neutrino flux, energy at far detector
-compare predicted spectrum assuming no oscillations with measured spectrum
- extract oscillation parameters

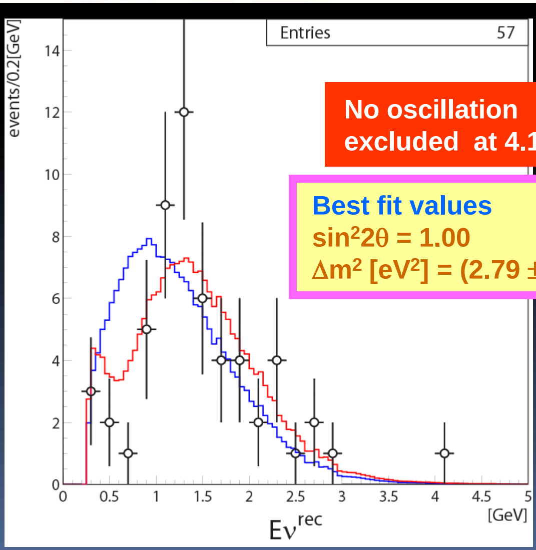


LBL accelerator experiments

- Test and measurements of atmospheric oscillation parameters
- On-axis neutrino beams

First LBL experiment
K2K, Japan L= 250 km

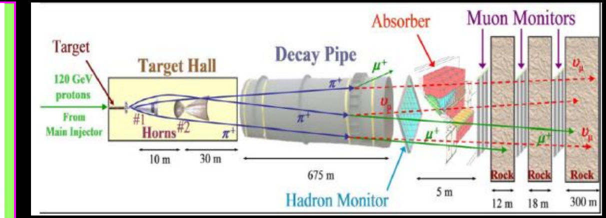




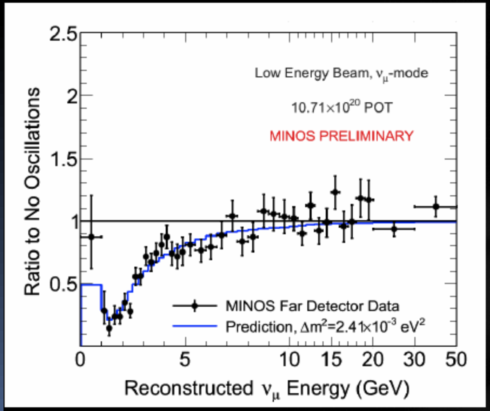
No oscillation excluded at 4.1σ

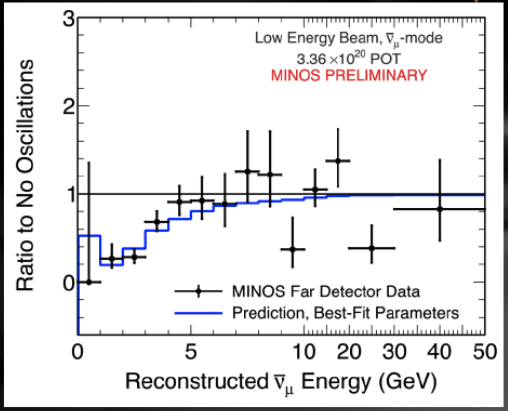
Best fit values
$\sin^2 2\theta = 1.00$
Δm^2 [eV^2] = $(2.79 \pm 0.36) \times 10^{-3}$

LBL experiment
MINOS, USA   L = 735 km



ν
$|\Delta m|^2=(2.35+0.11-0.08) \times 10^{-3}$
$\sin^2(2\theta)>0.91$ (90% CL)
anti-ν
$\Delta m^2=(2.64+0.28-0.27) \times 10^{-3}$
$\sin^2(2\theta)>0.78$ (90% CL)





Mixing matrix U

by 2011

atmospheric

solar

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$\theta_{23} \sim 45^0$
$\Delta m^2_{atm} \sim 2.5\times10^{-3}$ eV^2

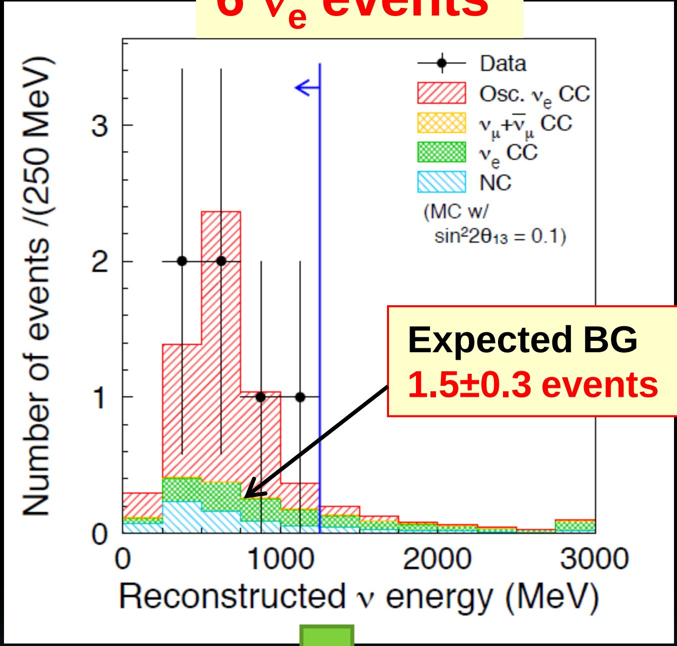
$\theta_{12} \sim 34^0$
$\Delta m^2_{atm} \sim 7.5\times10^{-5}$ eV^2

θ_{13}, δ = ?

θ_{13}

T2K first result, 2011

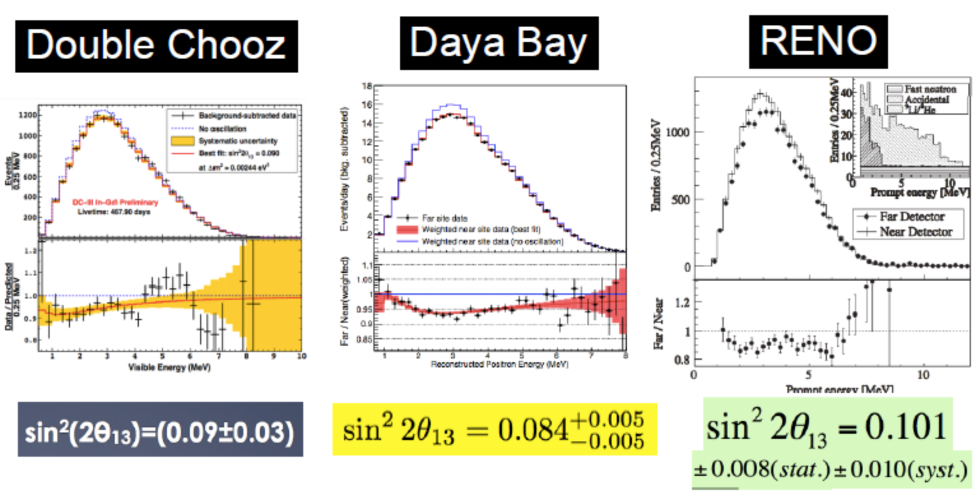
6 ν_e events



Expected BG
1.5±0.3 events

First clear indication of electron neutrino appearance ($\theta_{13} \neq 0$)

Reactor experiments 2012
Double Chooz, Daya Bay, RENO



$\sin^2(2\theta_{13})=(0.09\pm0.03)$

$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$

$\sin^2 2\theta_{13} = 0.101$
$\pm 0.008(stat.) \pm 0.010(syst.)$

Measurement of θ_{13}

$\theta_{13} \approx 9^o$

ν oscillations and mixing

Standard Model: neutrinos are *massless* particles

3 families

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

***U* parameterization:**

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

CP violating phase δ_{CP}

atmospheric

link between atmospheric and solar

solar

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix} \begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix} \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

SuperK, K2K,
MINOS, T2K, NovA

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

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

T2K

Daya Bay, RENO
Double Chooz

$\theta_{13} \approx 9^0$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$
$$\Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{31} = 0$$

Solar experiments, SuperK
KamLAND

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

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

two independent Δm^2

Main goals of oscillation experiments

- CP violation in lepton sector

Strength of CP violation in neutrino oscillations

$$J_{CP} = \mathrm{Im}(U_{e1}U_{\mu 2}U^*_{e2}U^*_{\mu 1}) = \mathrm{Im}(U_{e2}U_{\mu 3}U^*_{e3}U^*_{\mu 2})$$
$$= \cos\theta_{12}\sin\theta_{12}\cos^2\theta_{13}\sin\theta_{13}\cos\theta_{23}\sin\theta_{23}\sin\delta_{CP}$$

all mixing angles $\neq 0$ →
→ $J_{CP} \neq 0$ if $\delta_{CP} \neq 0$

neutrinos

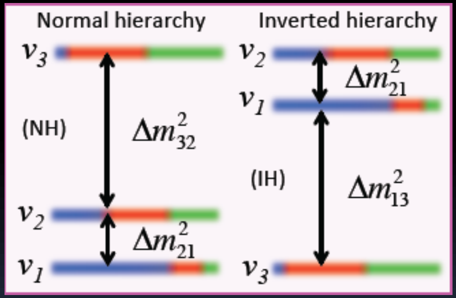
quarks

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

Quark sector $J_{CP} \approx 3\times 10^{-5}$

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

- Neutrino mass hierarchy



- θ_{23} – maximal? If not, what octant ($\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$)?

Neutrino cross sections

- Sterile neutrinos

$\nu_\mu \to \nu_e$ in matter

$$\begin{aligned}
P(\nu_\mu \to \nu_e) \;=\;& 4c_{13}^2 \boxed{s_{13}^2} s_{23}^2 \sin^2\frac{\Delta m_{13}^2 L}{4E_\nu} \times \left[1 + \frac{2a}{\Delta m_{13}^2}(1 - 2s_{13}^2)\right] && \longrightarrow \theta_{13} \\
&+ 8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\frac{\Delta m_{23}^2 L}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}\sin\frac{\Delta m_{12}^2 L}{4E_\nu} && \longrightarrow \text{CP-even} \\
&- 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\underline{\sin\delta}\sin\frac{\Delta m_{23}^2 L}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}\sin\frac{\Delta m_{12}^2 L}{4E_\nu} && \longrightarrow \text{CP-odd} \\
&+ 4s_{12}^2 c_{13}^2 (c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\frac{\Delta m_{12}^2 L}{4E_\nu} && \longrightarrow \text{Solar} \\
&- 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E_\nu}\frac{aL}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}(1 - 2s_{13}^2), && \longrightarrow \text{Matter}
\end{aligned}$$

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

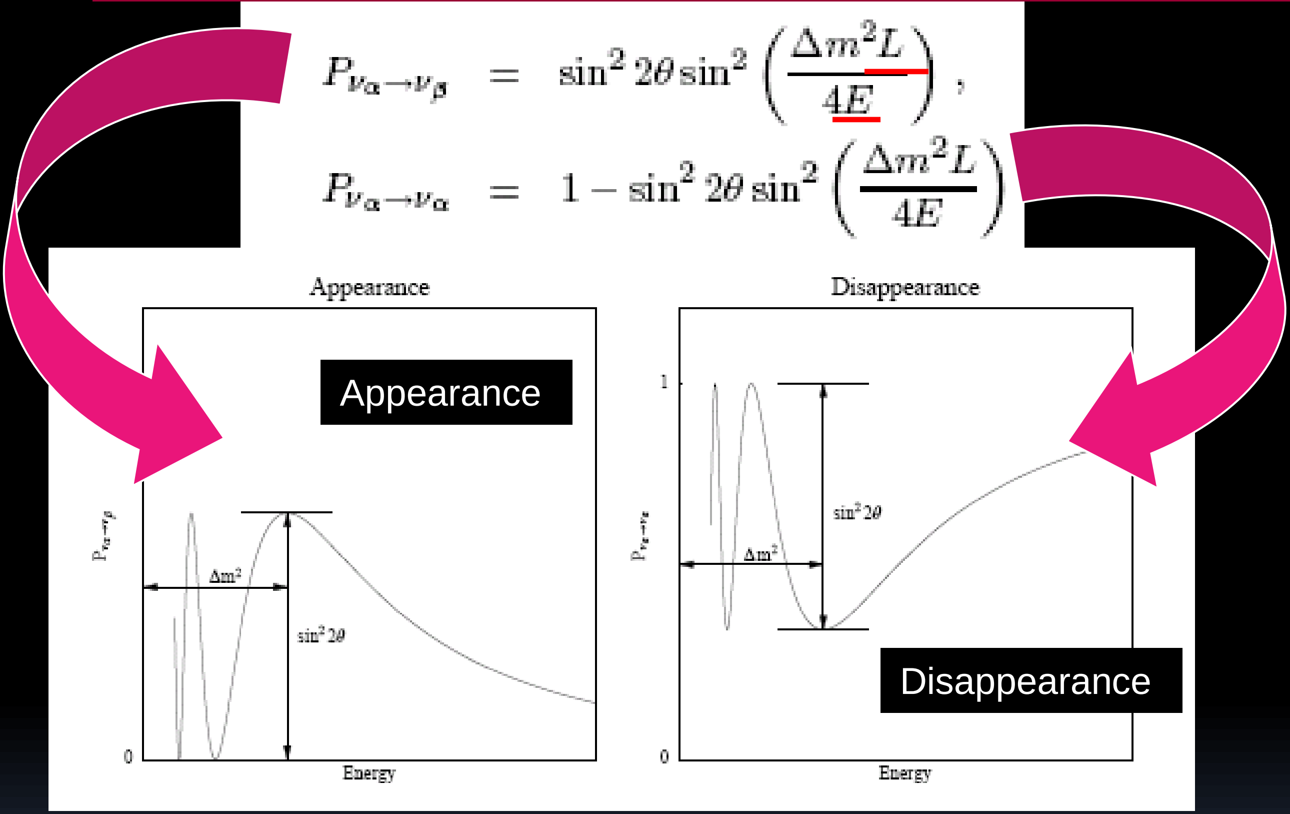
$$a\left[eV^2\right] = 2\sqrt{2}G_F n_e E_\nu = 7.6\times10^{-5}\rho\left[{}^{g}\!/\!{}_{cm^3}\right]E_\nu\left[GeV\right]$$

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

change sign for NH → IH

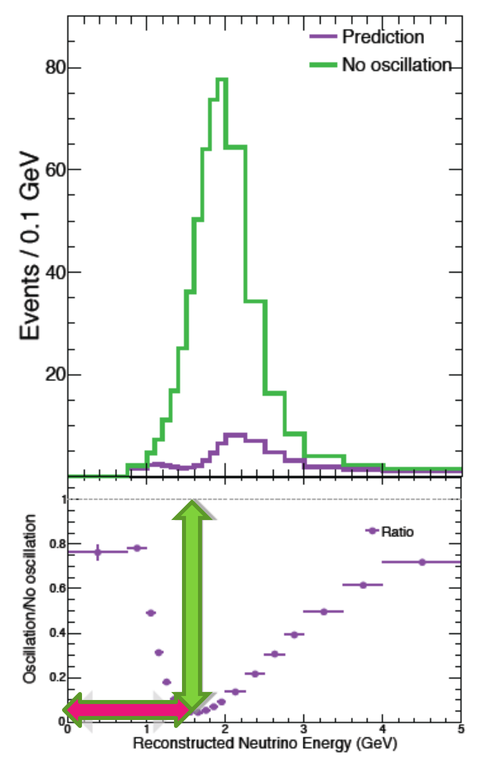
Experimental methods

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\Phi_{ij} \mp 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin 2\Phi_{ij}$$



$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 \underline{L}}{\underline{4E}}\right),$$

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



Search for CP violation in neutrino oscillations

Matter effect

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \cong \frac{\Delta m^2_{12} L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

Mass Hierarchy

Current experiments

T2K

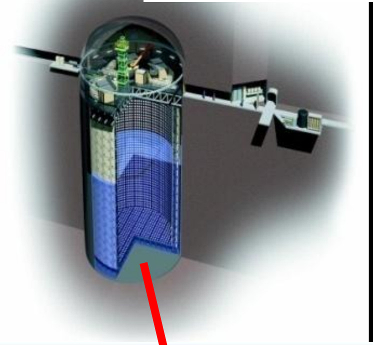
about 500 members
59 institutions
from 11 countries

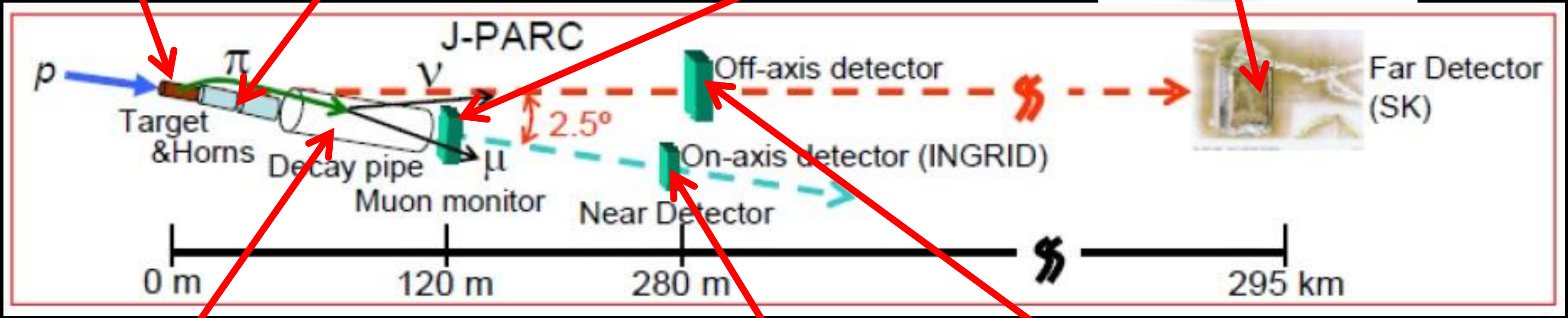
LONG-BASELINE NEUTRINO OSCILLATION EXPERIMENT

T2K experiment

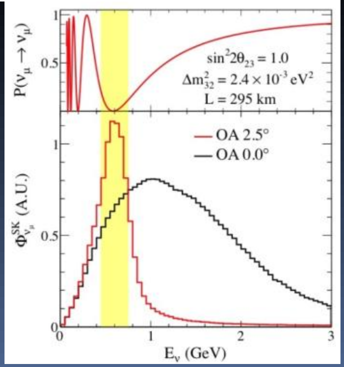
Collect data since 2010

Far neutrino detector
SuperKamiokande

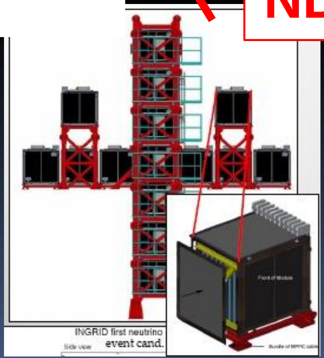




Off-axis neutrino beam

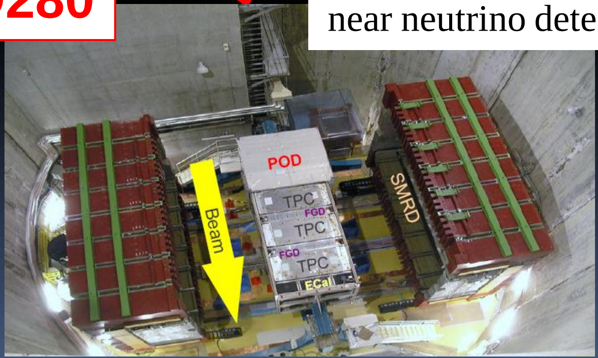


Neutrino monitor
INGRID



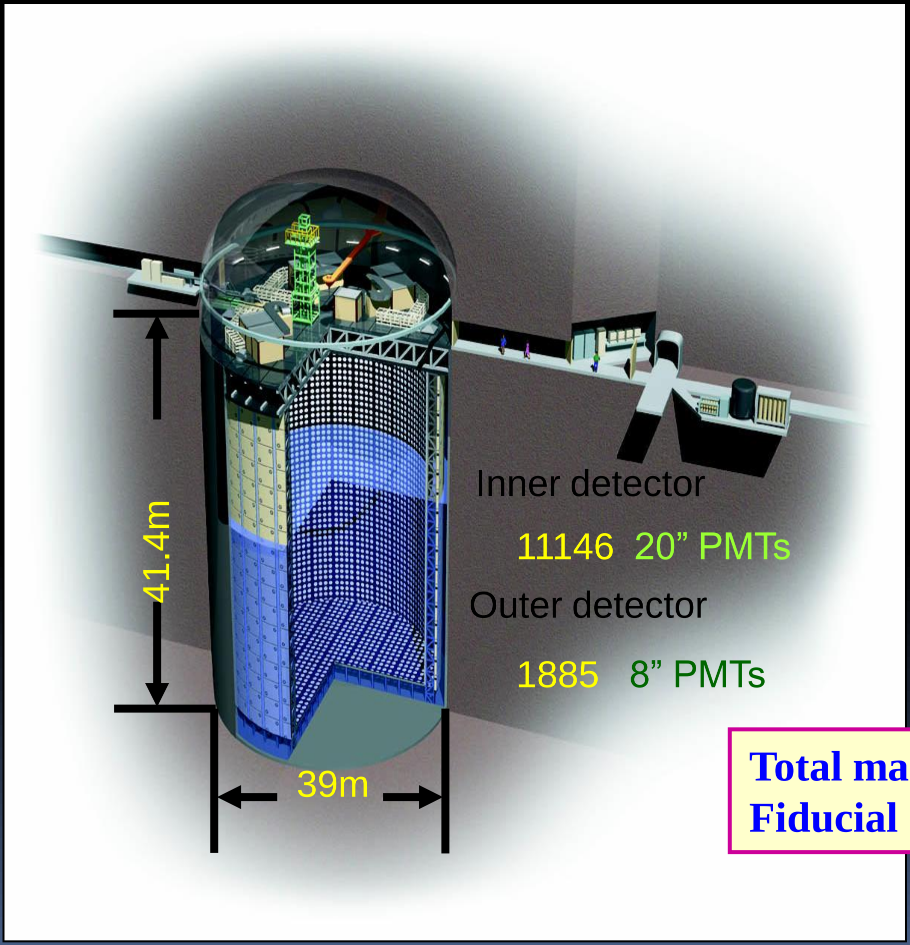
ND280

Off-axis
near neutrino detector



Far detector

Super-Kamiokande



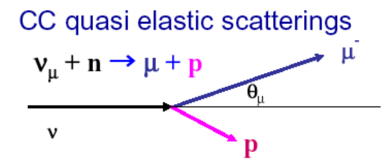
Inner detector

11146 20” PMTs

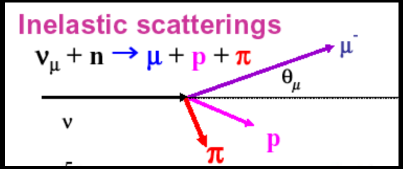
Outer detector

1885 8” PMTs

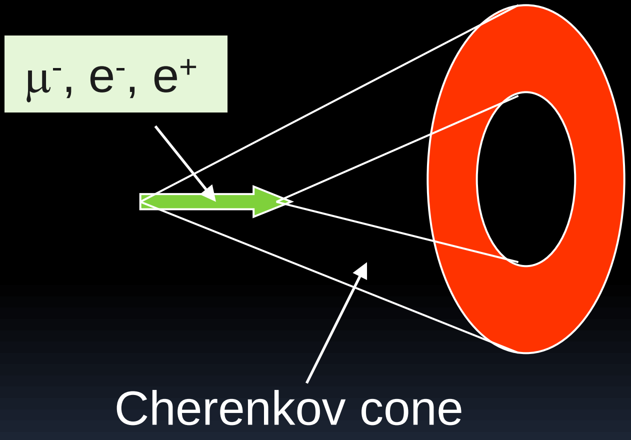
CC quasi elastic scatterings


$\nu_\mu + n \rightarrow \mu + p$

Inelastic scatterings


$\nu_\mu + n \rightarrow \mu + p + \pi$

$\nu_e + n \rightarrow e^- + p$

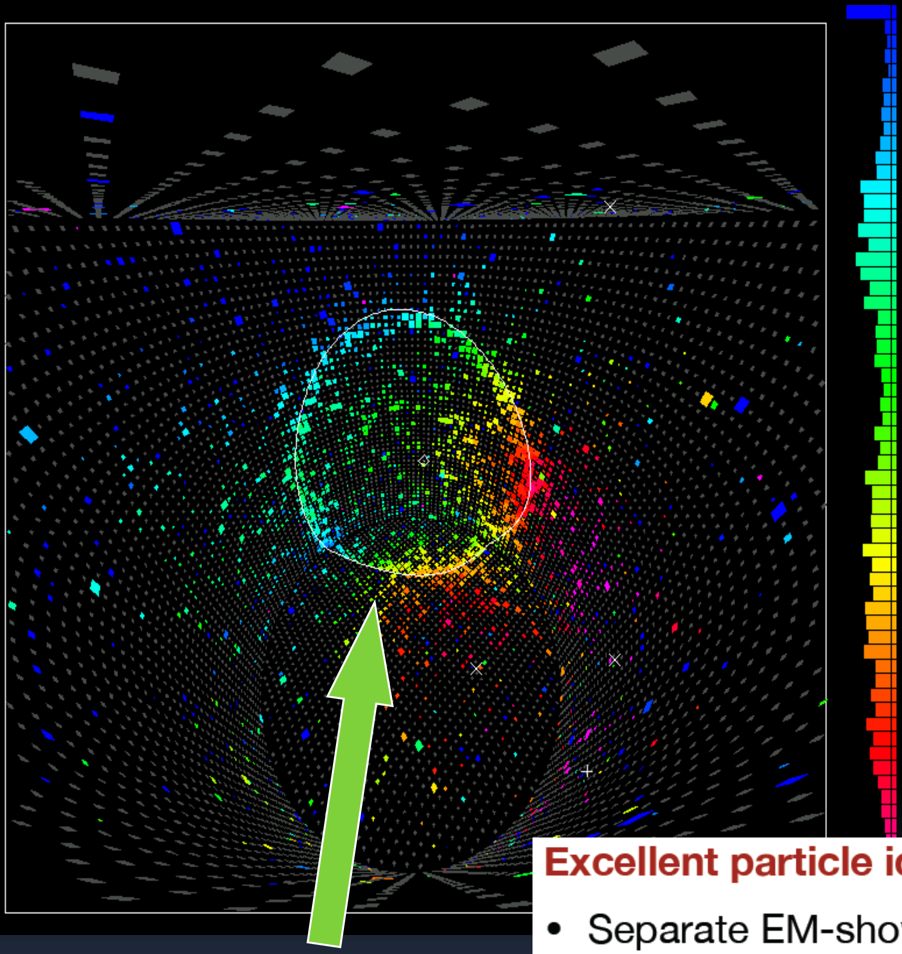


Cherenkov cone

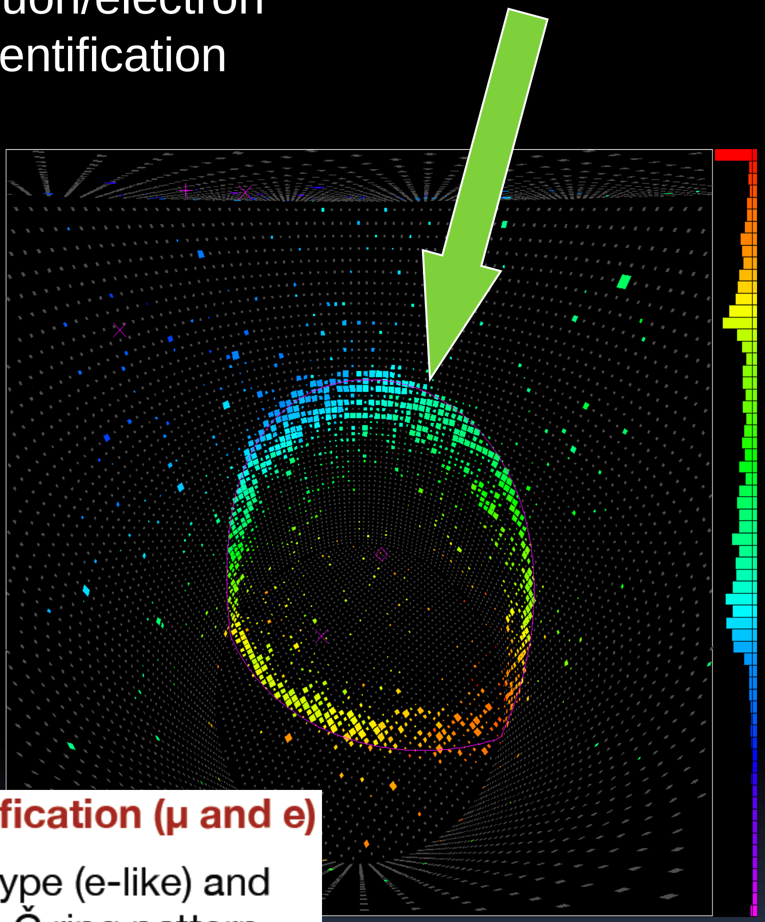
Total mass	**50 kt**
Fiducial mass	**22.5 kt**

SK events

Muon/electron identification



e - like



μ - like

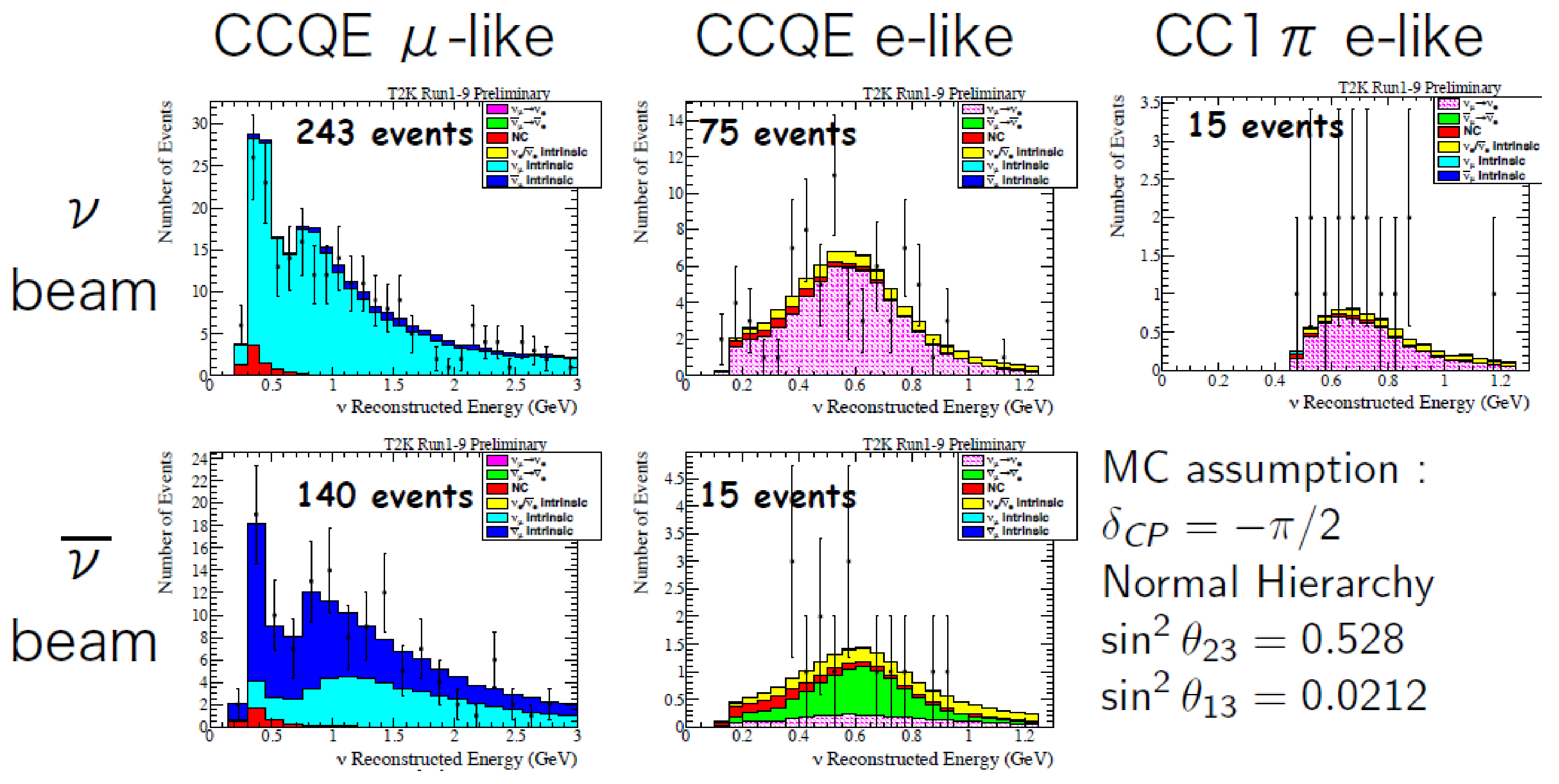
Excellent particle identification (μ and e)

- Separate EM-shower type (e-like) and muon type (μ-like) with Č ring pattern
- **Mis-PID rate below 1% at ~1GeV**

Good energy resolution: ~3% at ~1GeV

T2K data

ν-mode : $14.9\text{x}10^{20}$ POT , $\bar{\nu}$-mode : $16.3\text{x}10^{20}$ POT



CCQE μ-like

CCQE e-like

CC1 π e-like

ν beam

$\bar{\nu}$ beam

MC assumption :

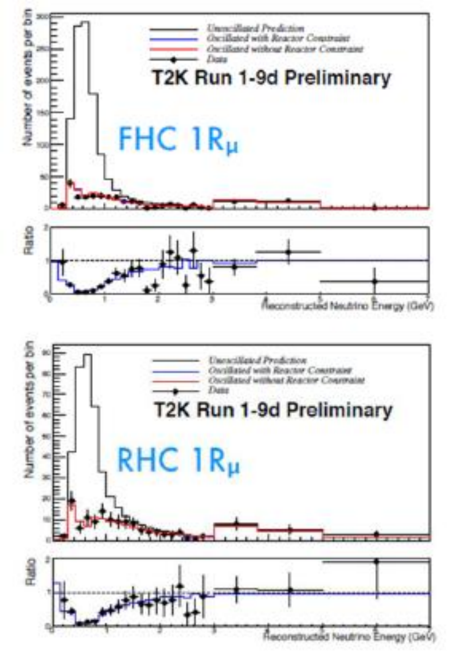
$\delta_{CP} = -\pi/2$

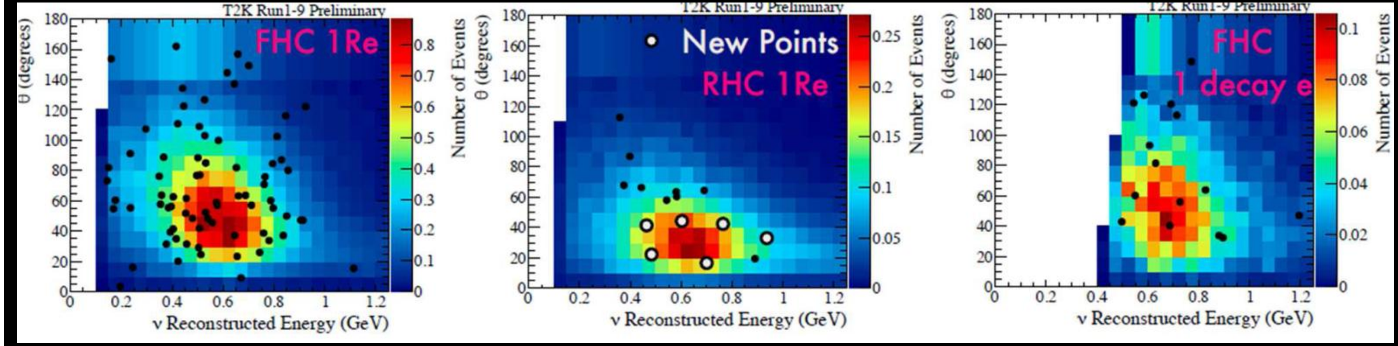
Normal Hierarchy

$\sin^2\theta_{23} = 0.528$

$\sin^2\theta_{13} = 0.0212$

T2K data and expectation





Monte Carlo

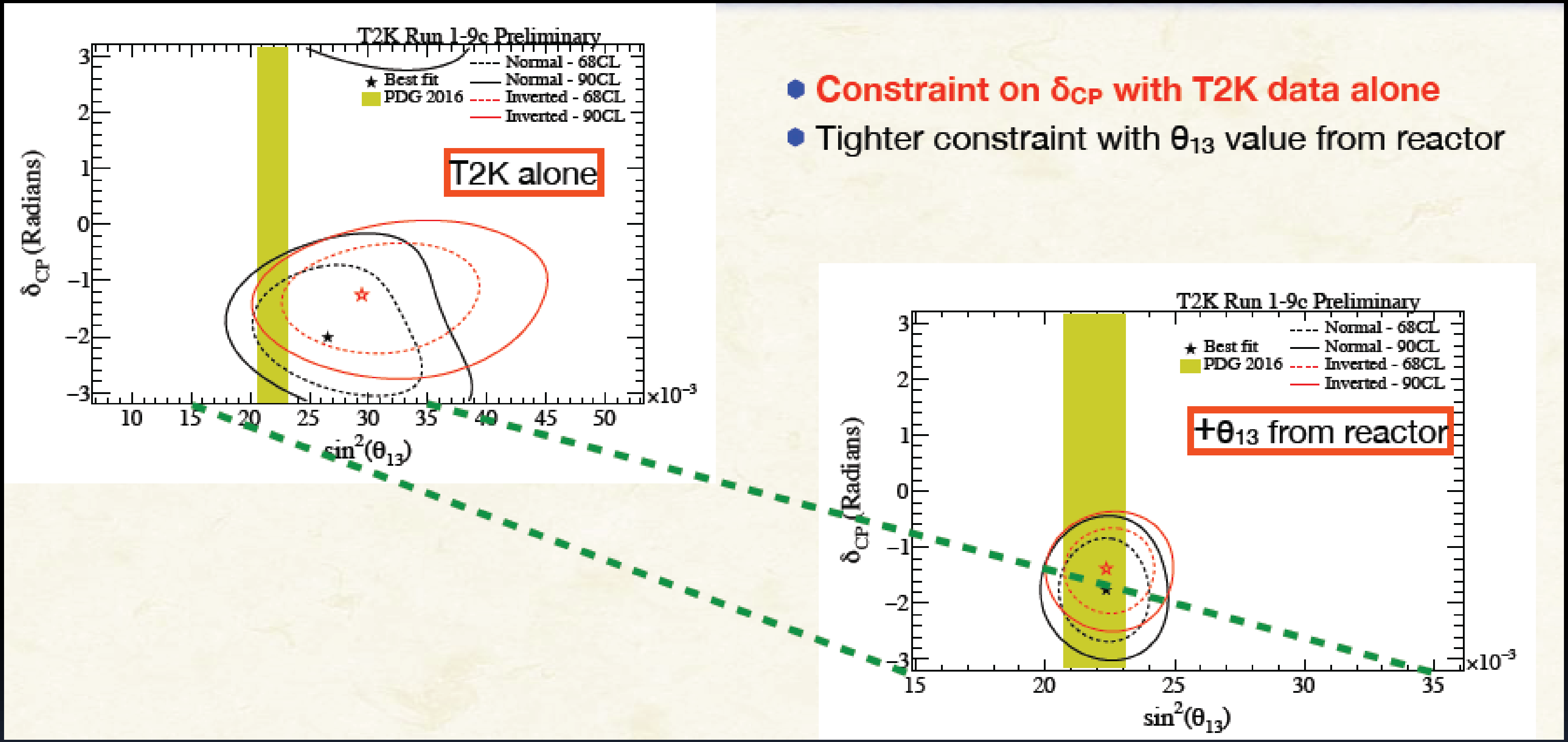
Sample	Predicted				Observed	Systematic uncertainty for prediction
	δ_{CP} = -π/2	δ_{CP} = 0	δ_{CP} = +π/2	δ_{CP} = π		
ν mode μ-like	272.4	272.0	272.4	272.8	243	5.1%
$\bar{\nu}$ mode μ-like	139.5	139.2	139.5	139.9	140	4.5%
ν mode e-like	74.4	62.2	50.6	62.7	75	8.8%
$\bar{\nu}$ mode e-like	17.1	19.4	21.7	19.3	15	7.1%
ν mode e-like + $1\pi^+$	7.0	6.1	4.9	5.9	15	18.4%

disappearance

appearance

T2K results

T2K ν_e / anti- ν_e



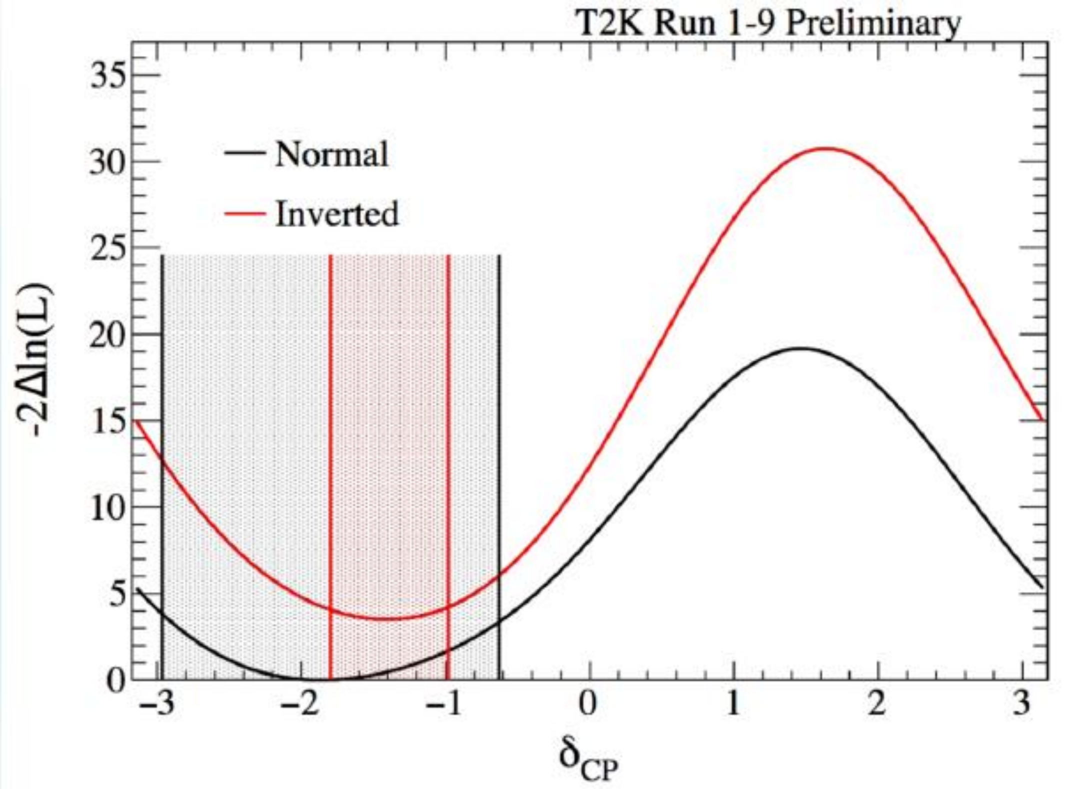
- Constraint on δ_{CP} with T2K data alone
- Tighter constraint with θ_{13} value from reactor

T2K alone

+θ_{13} from reactor

T2K ν_e / anti- ν_e + reactor θ_{13}

T2K: search for CP violation



Best fit

δ_{cp} = -1.885 rad for NH

δ_{cp} = -1.382 rad for IH

±1σ interval

[-2.460, -1.187] for NH

[-1.930, -0.906] for IH

CP-conservation hypothesis ($\sin\delta_{CP} = 0, \pi$) excluded at 2σ level

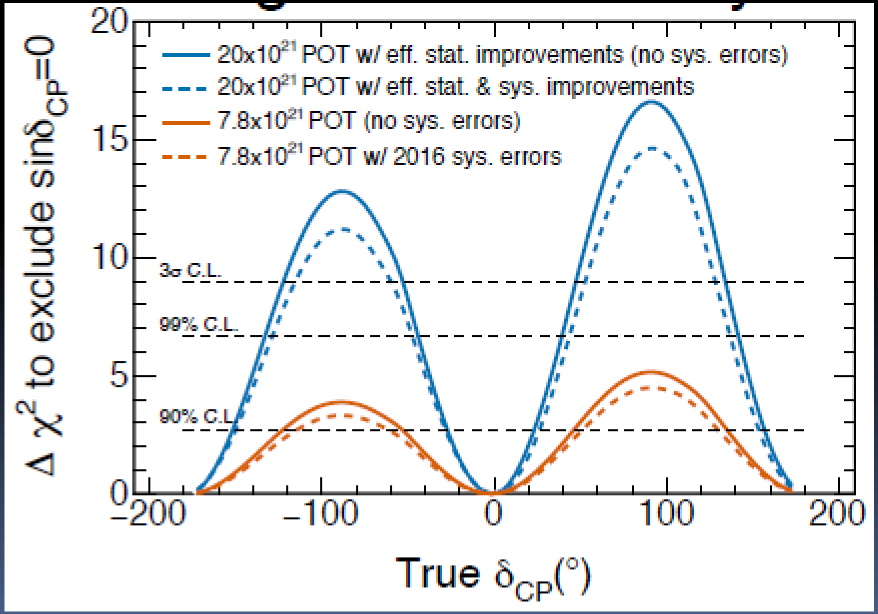
- **First hint for CP violation in the lepton sector**
- **T2K data favour $\delta_{CP} \sim -\pi/2$ and normal hierarchy**

Future plans

T2K expected to accumulate 7.8x10^{21} POT around 2021

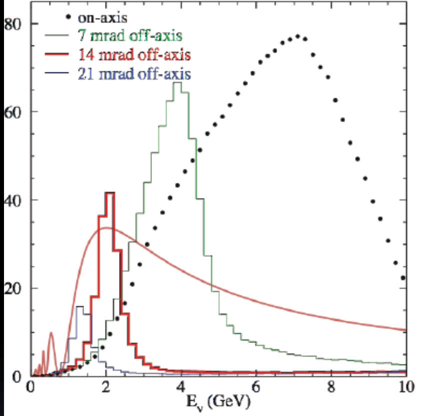
(now 3x10^{21} POT)

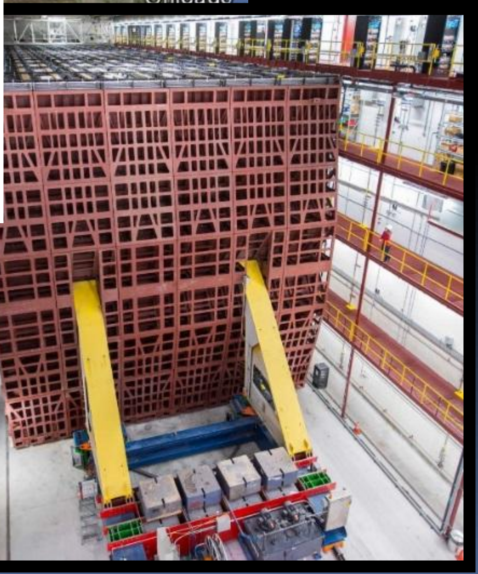
- **Upgrade of near detectors to improve systematic uncertainties**
  18% (2011) → 9% (2014) → 5% (2018) → goal ≤4% (2021)
- **Plan to increase the beam intensity up to 1 MW in 2021**
- **Beam power up to 1.3 MW in ~2028**
- **T2K-II: proposed extension up to 2027 for 20x10^{21} POT**
  3σ sensitivity to CP violation for $\delta_{CP} \sim -\pi/2$

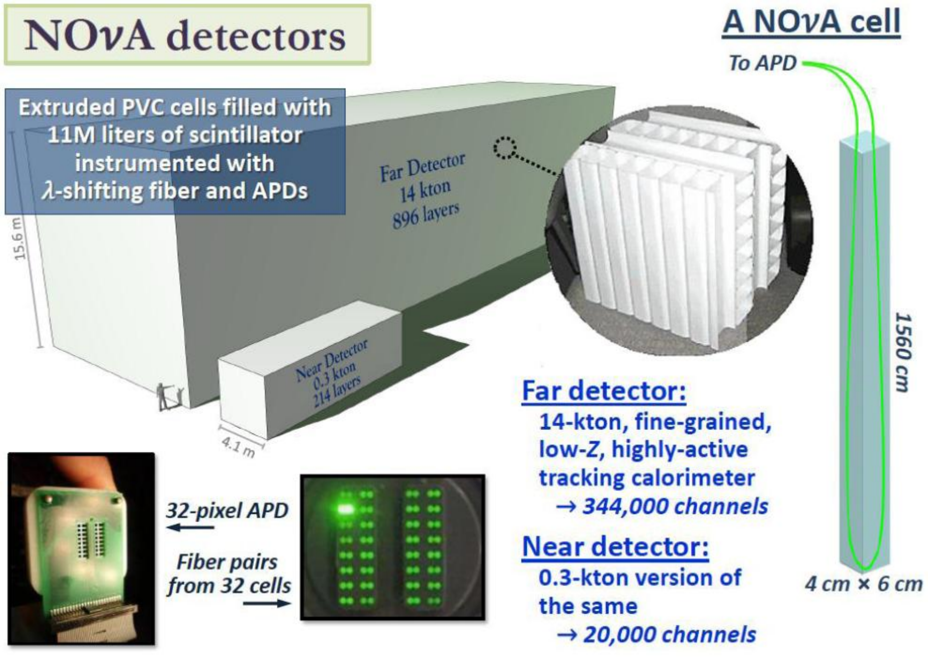


NOvA

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

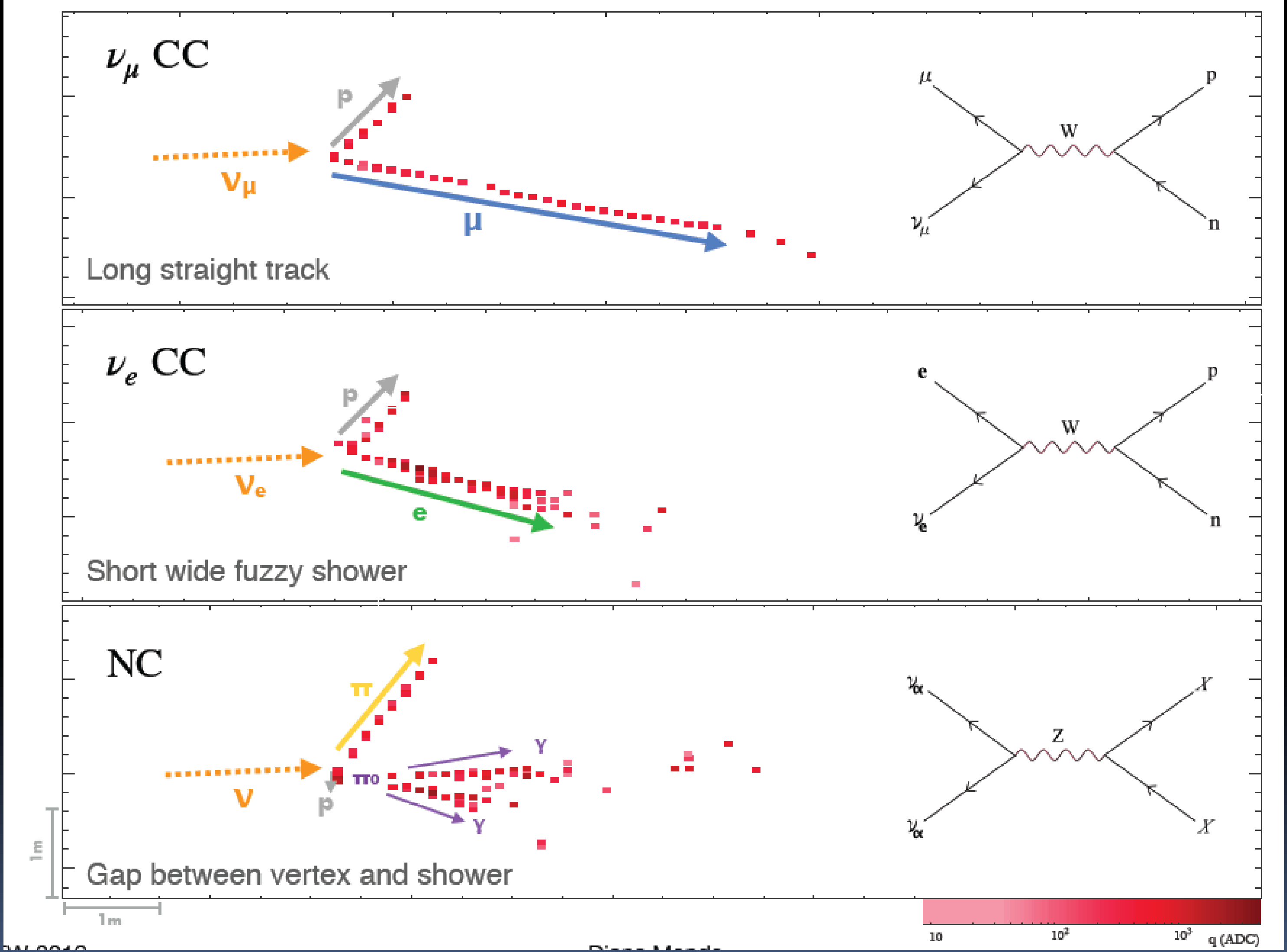






Taking data since Summer 2014
Study of $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_e$ oscillations

NOvA: event topology



Long straight track

Short wide fuzzy shower

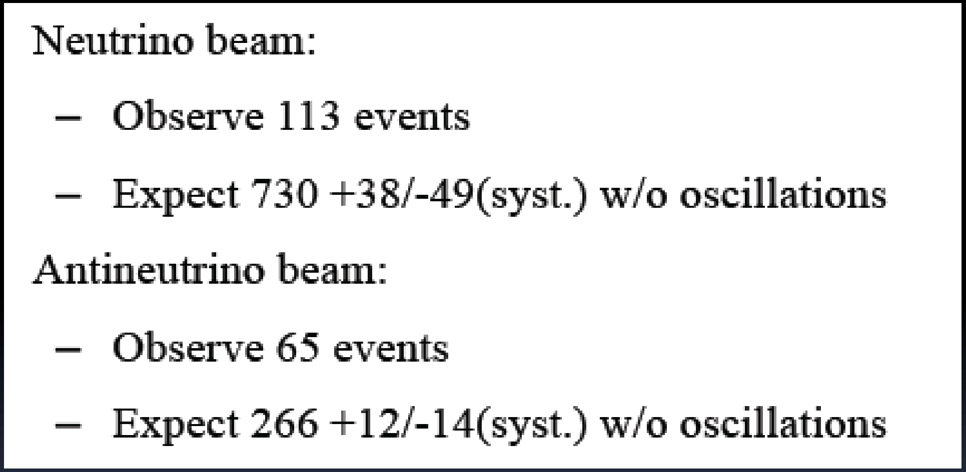
Gap between vertex and shower

NOvA: $\nu_\mu \to \nu_\mu$

D.Mendez Moriond 2019

Neutrino beam: 8.9×10^{20} POT
Antineutrino beam: 6.9×10^{20} POT

Events in Far Detector

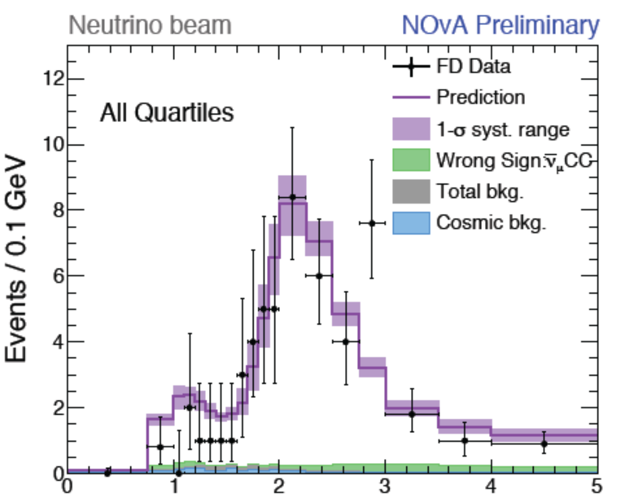


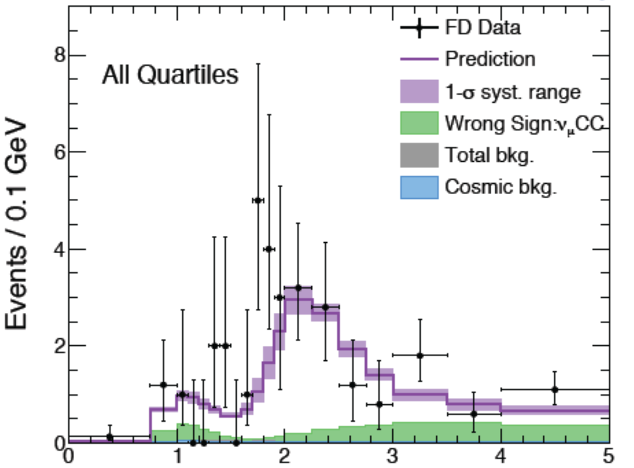
Neutrino beam:

- Observe 113 events
- Expect 730 +38/-49(syst.) w/o oscillations

Antineutrino beam:

- Observe 65 events
- Expect 266 +12/-14(syst.) w/o oscillations

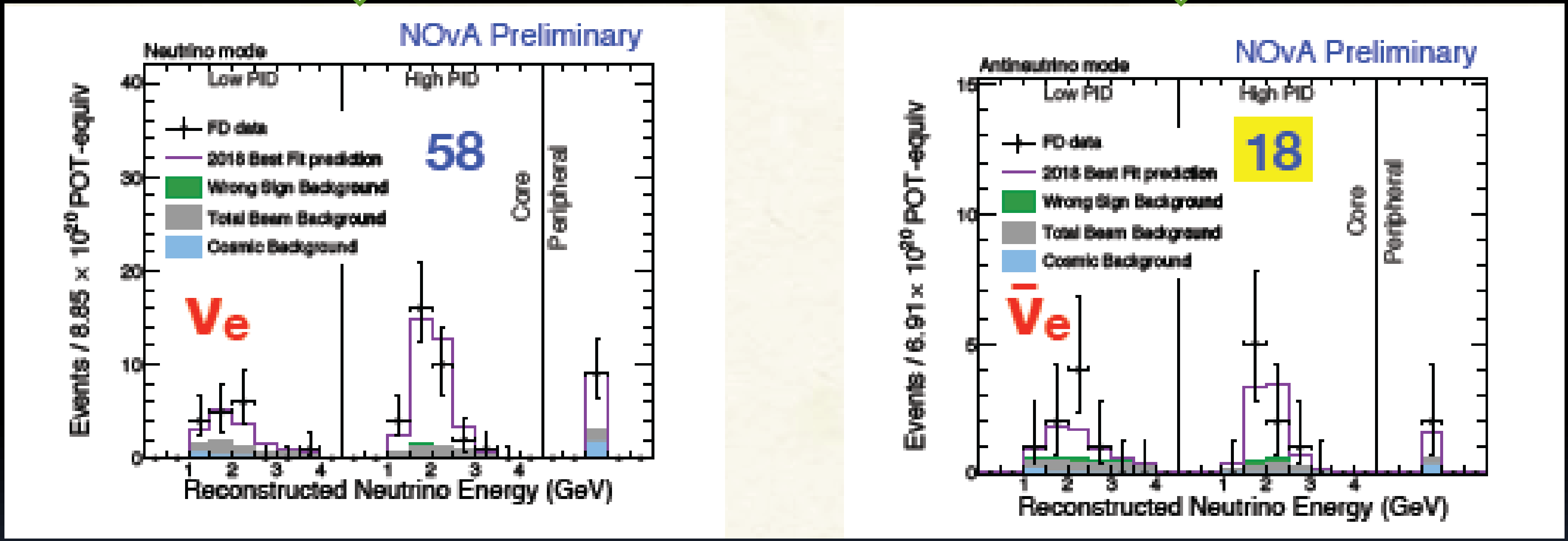




NOvA: ν_e/anti-ν_e

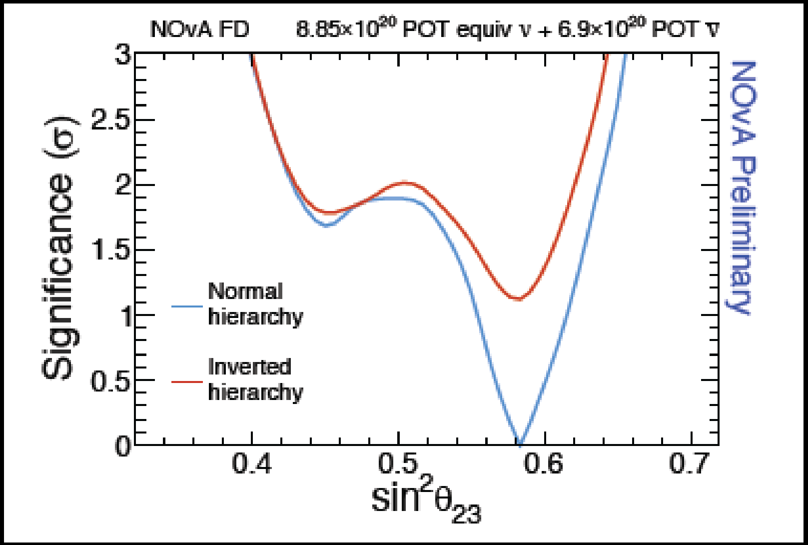
ν_e
58 events observed
15.1 background events expected

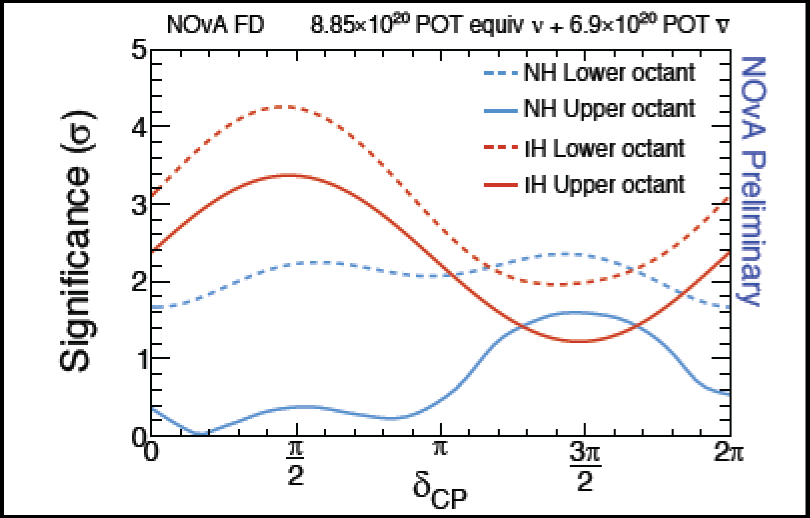
anti-ν_e
18 events observed
5.5 background events expected



$$\bar{\nu}_e \ \text{appearance} > 4\sigma$$

NOνA results

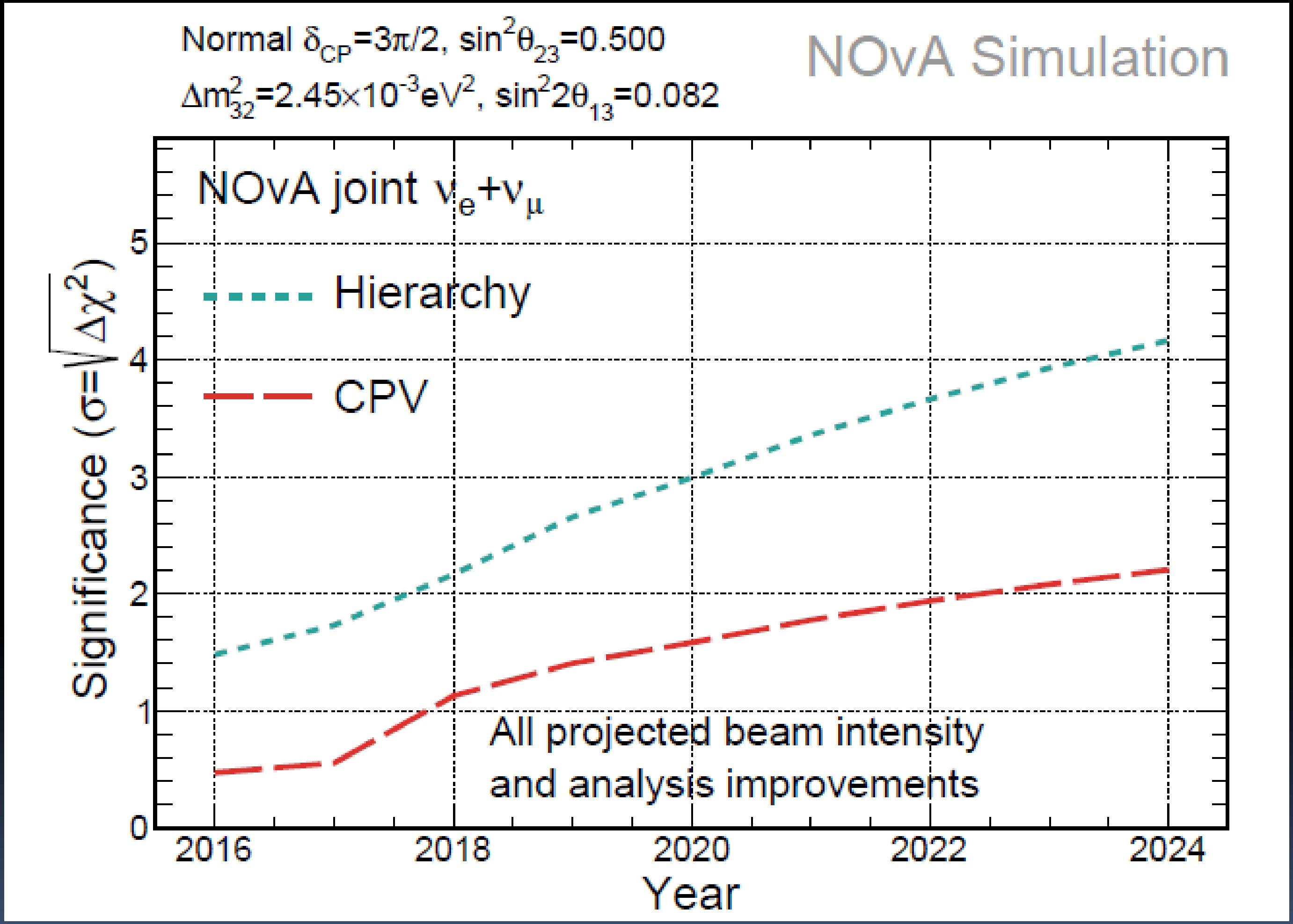




NOνA prefers Normal Hierarchy at 1.8σ

Best fit:
- Normal Hierarchy
- $\delta_{CP} = 0.17\pi$ but consistent with all δ_{CP} values at <1.6σ

Prospects for NOvA

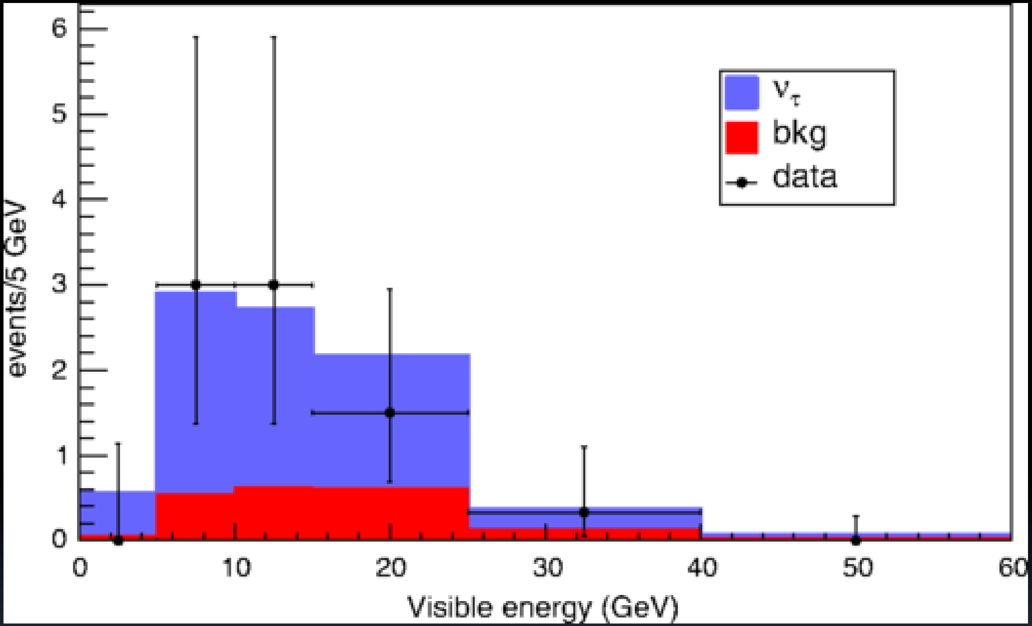


OPERA: final result

PRL 120 (2018) 211801

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

10 ν_τ events observed for 18×10^{19} POT
Expected 6.4 events for $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1.0$
Expected background 2.0±0.4 events



Significance of ν_τ appearance 6.1σ

OPERA: $\Delta m^2_{23} = (2.7 + 0.7 - 0.6) \times 10^{-3}$ eV^2, assuming $\sin^2 2\theta_{23} = 1.0$

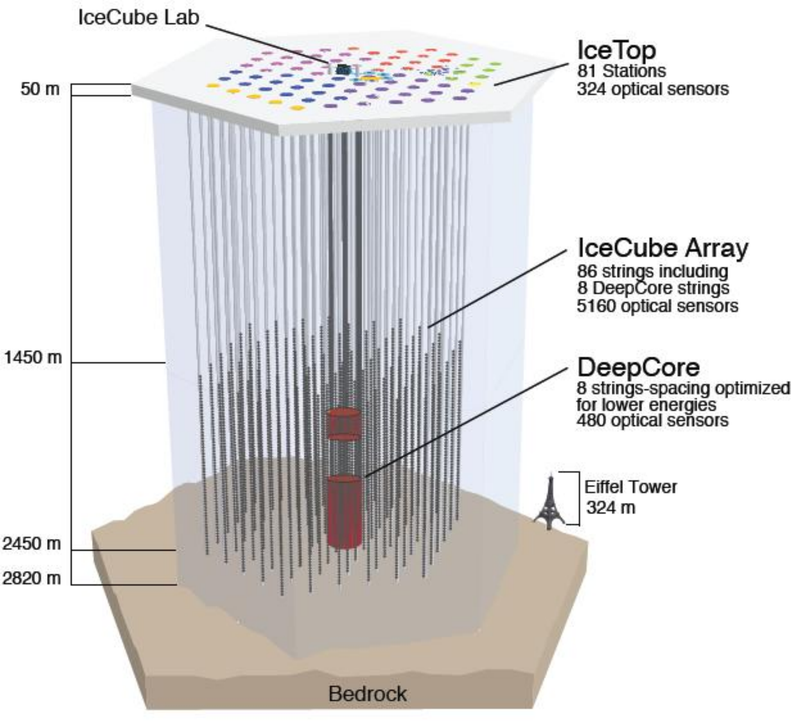
IceCube

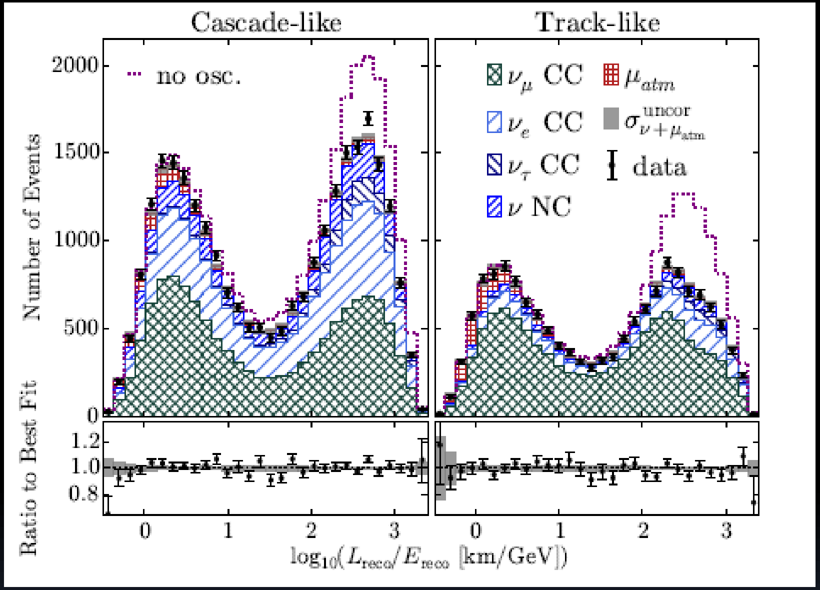
Neutrinos have the first maximum of disappearance at about 25 GeV

Energy threshold of Deep Core = 5 GeV

PRL 120 (2018) 071801

Data taking for 3 years

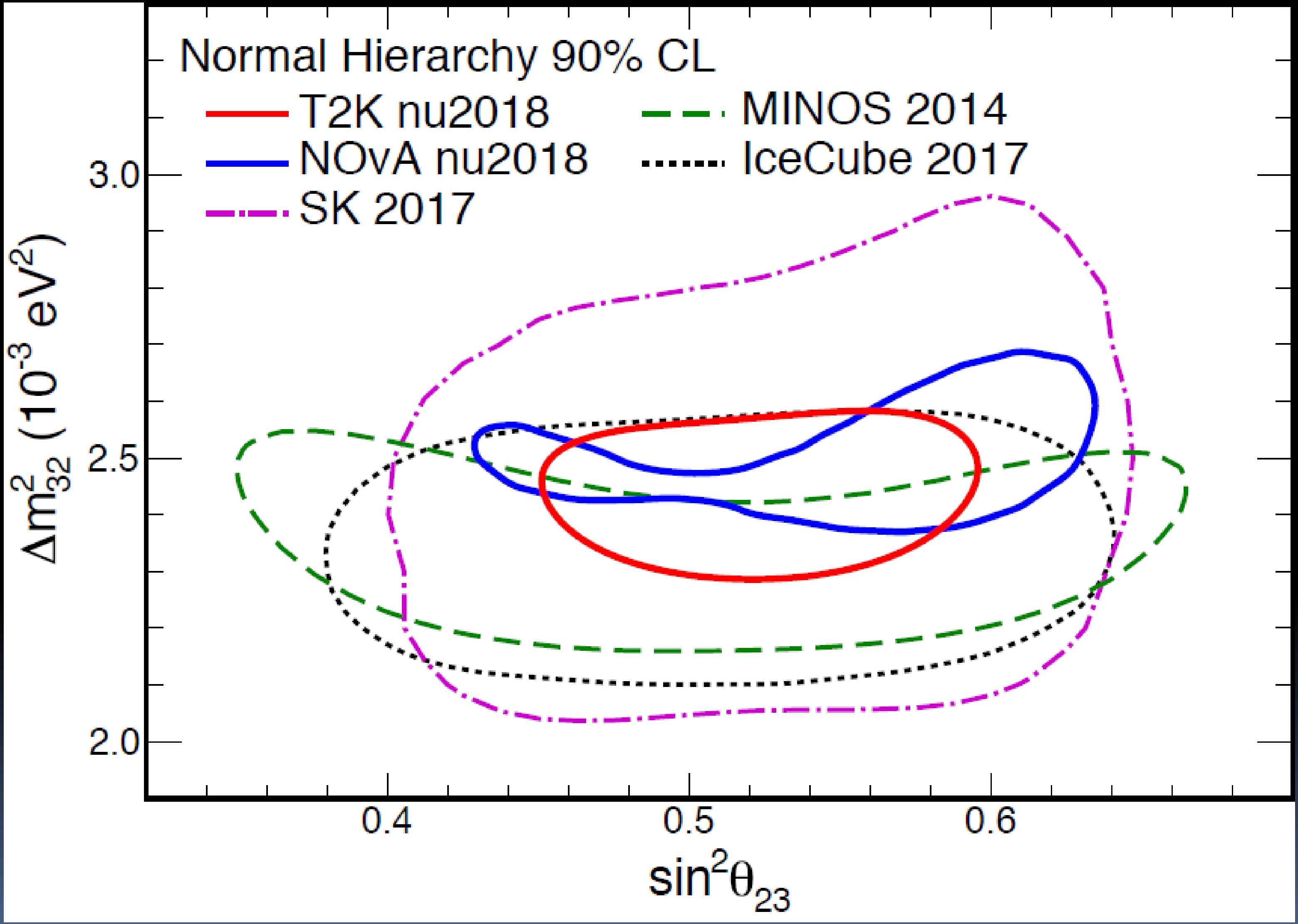




Δm^2_{32} = (2.31 +011-0.13)x10^{-3} eV^2 $\sin^2\theta_{23}$ = 0.51 +0.07 -0.09 for NH

Oscillation parameters: $\Delta m^2_{32} - \sin^2\theta_{23}$

M.Yokoyama ICHEP2018



Reactor experiments

Measurement of θ_{13}

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

Daya Bay, China

Among the top 5 most powerful reactor complexes in the world, 6 cores produce 17.4 GW$_{th}$ power, 35 × 10^{20} neutrinos per second

Spectral Oscillation Measurement at Daya Bay: D. Dwyer 7

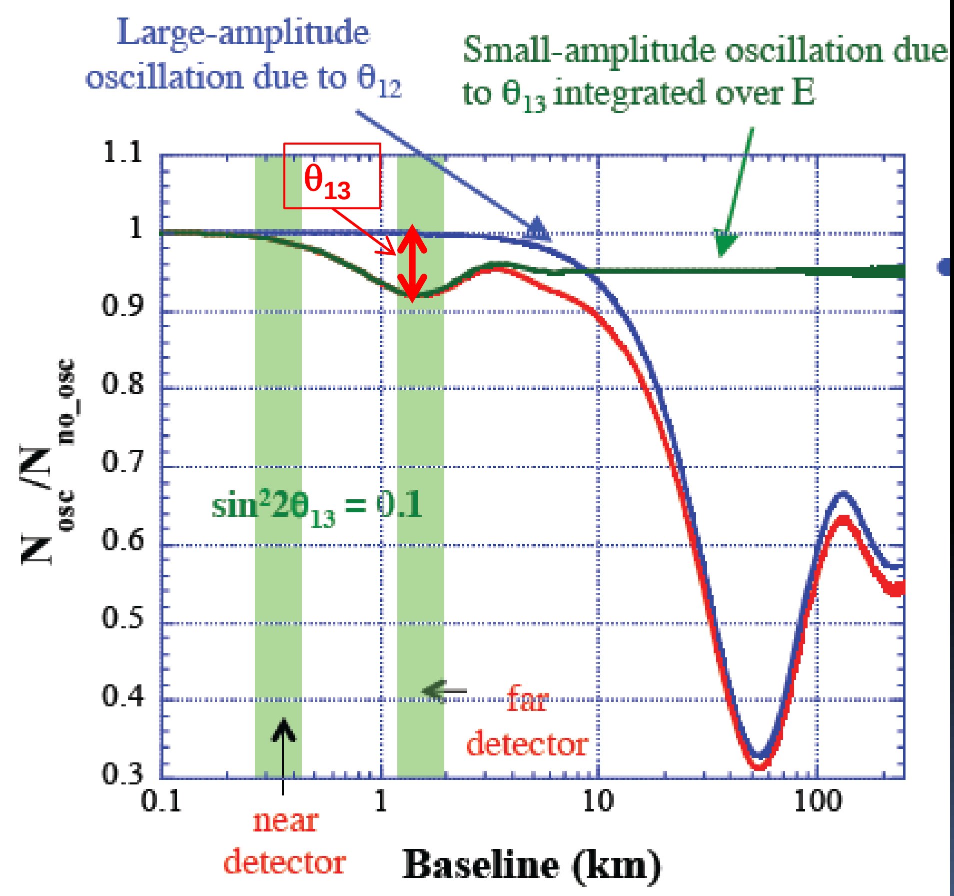
17.4 GW

RENO, Korea

16 GW

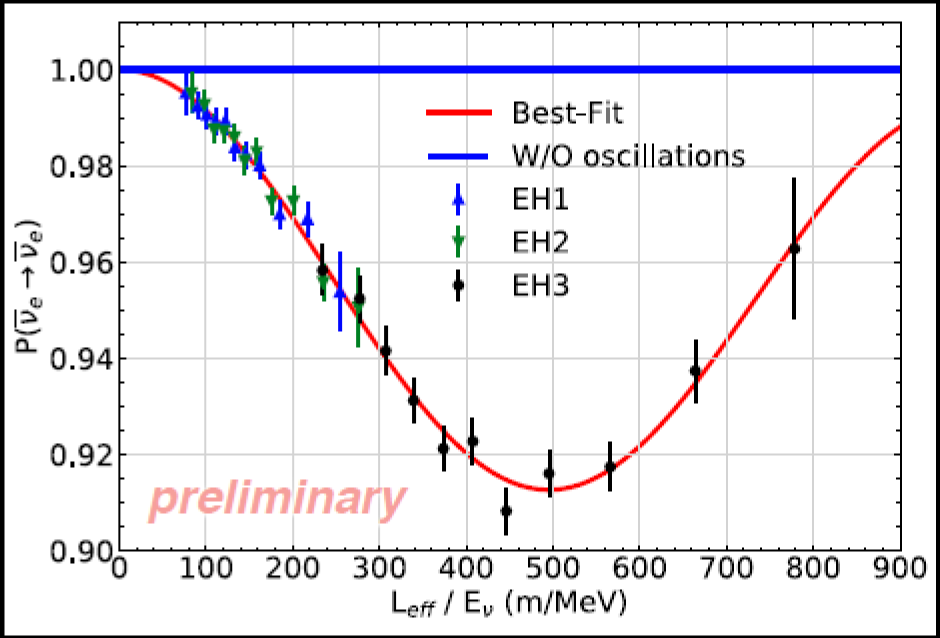
Double Chooz, France

8.5 GW

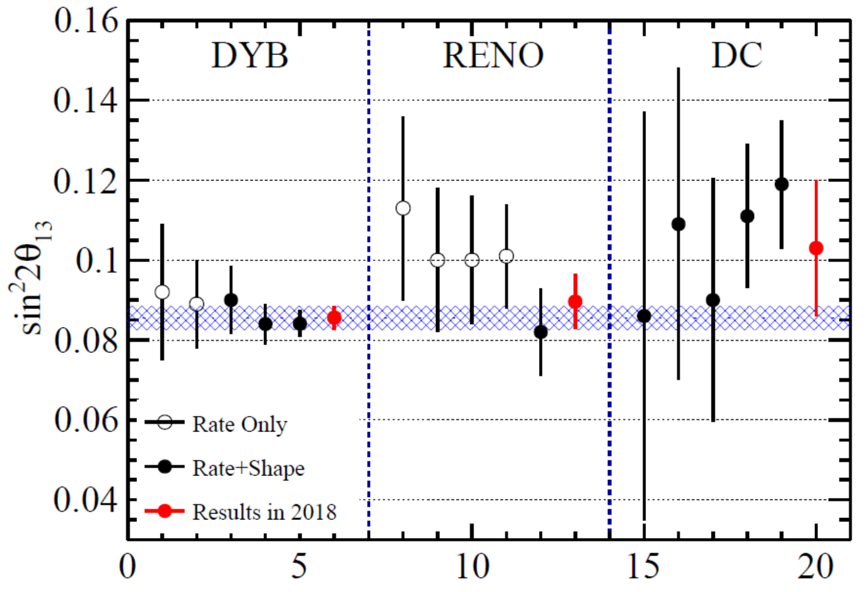


Oscillation results

Daya Bay



Liang Zhan, ICHEP2018



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

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

Future LBL Projects

- Reactor experiment JUNO
- Accelerator LBL experiment DUNE
- HyperKamiokande and T2HK

Reactor experiment JUNO

China

Construction started in 2015
Operation in 2021

66 institutions
> 400 collaborators

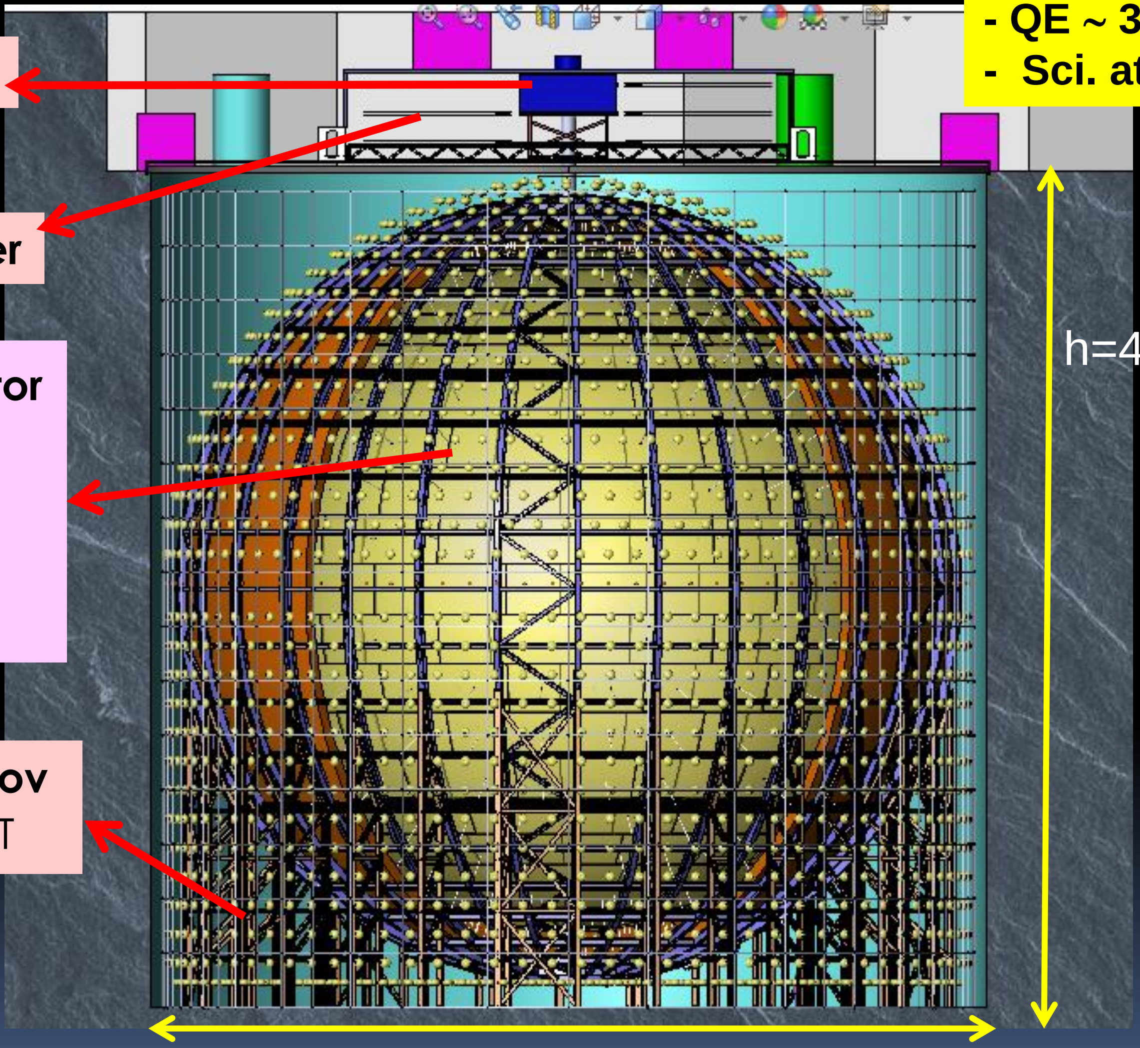
Main target:
Measurement of
neutrino mass hierarchy

- **700 m deep underground**
- **36 GW reactor power**
- **53 km baseline -> oscillation maximum θ_{12}**
- **20 kton LS detector**
- **3% energy resolution at 1MeV**
- **<1% energy scale uncertainty**

!?

Detector JUNO

Requirements:
- **PMT coverage 75% of total surface**
- **QE ~ 35%**
- **Sci. att. length >20 m**



Calibration

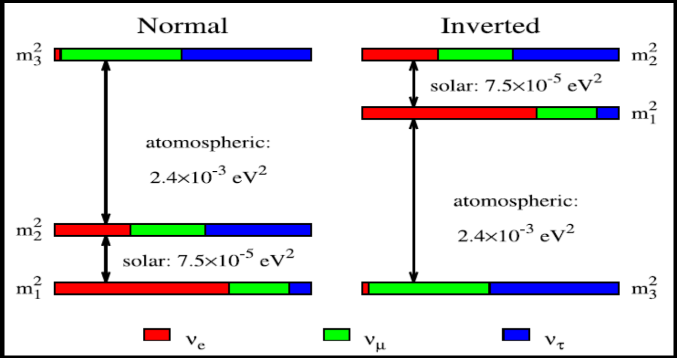
Top Tracker

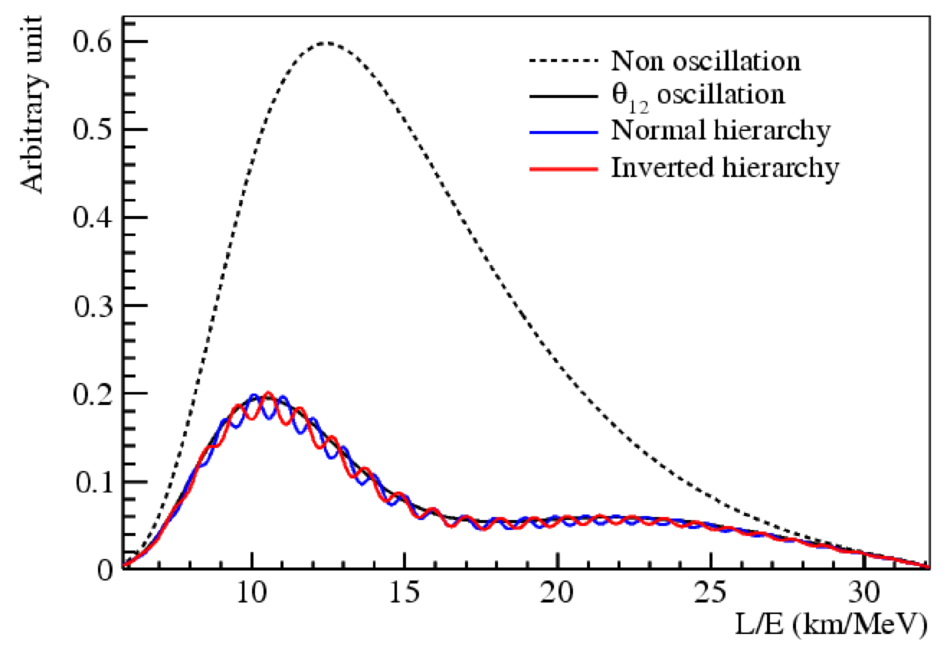
Central detector
Acrylic sphere
20kt Liquid Scin
~17000 20'' PMT
~36000 3'' PMT

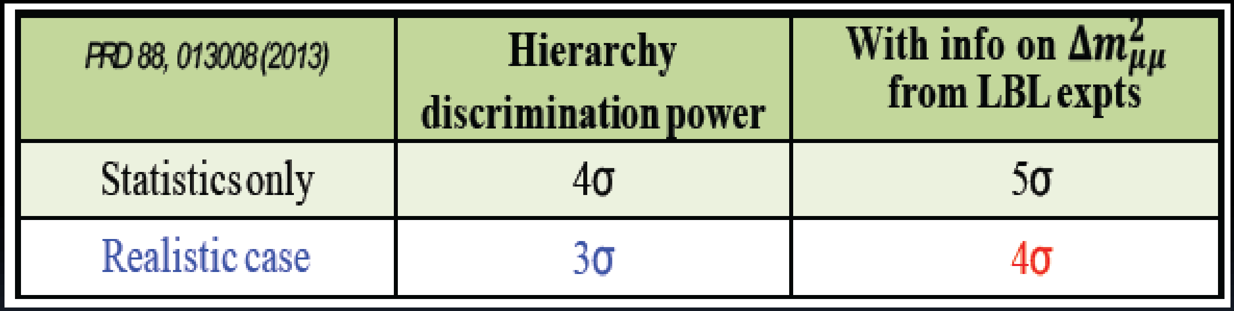
Water Cherenkov
~2000 20'' PMT

JUNO goals

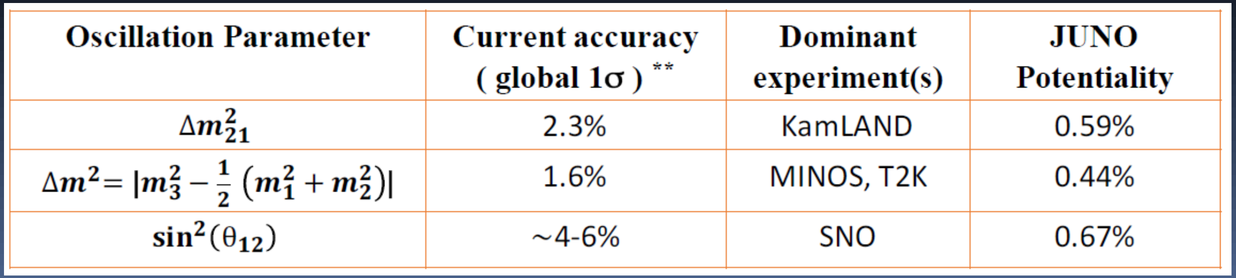
Main goal: determination of neutrino mass hierarchy







PRD 88, 013008 (2013)	Hierarchy discrimination power	With info on $\Delta m^2_{\mu\mu}$ from LBL expts
Statistics only	4σ	5σ
Realistic case	3σ	4σ



Oscillation Parameter	Current accuracy (global 1σ) **	Dominant experiment(s)	JUNO Potentiality
Δm^2_{21}	2.3%	KamLAND	0.59%
$\Delta m^2 = \lvert m_3^2 - \frac{1}{2}(m_1^2 + m_2^2)\rvert$	1.6%	MINOS, T2K	0.44%
$\sin^2(\theta_{12})$	~4-6%	SNO	0.67%

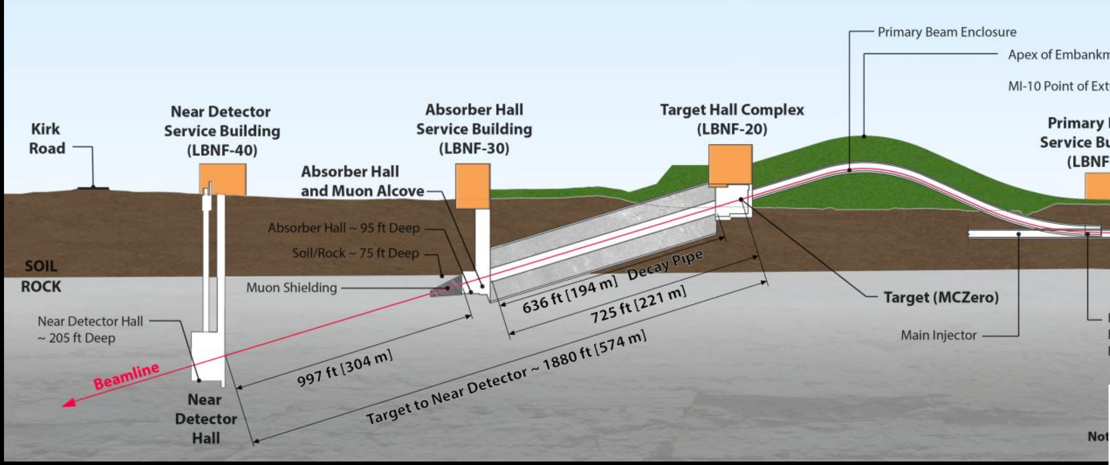
\+ Supernova neutrino
Geoneutrinos
Solar neutrinos

LBNF/DUNE Project

Flagship FNAL project

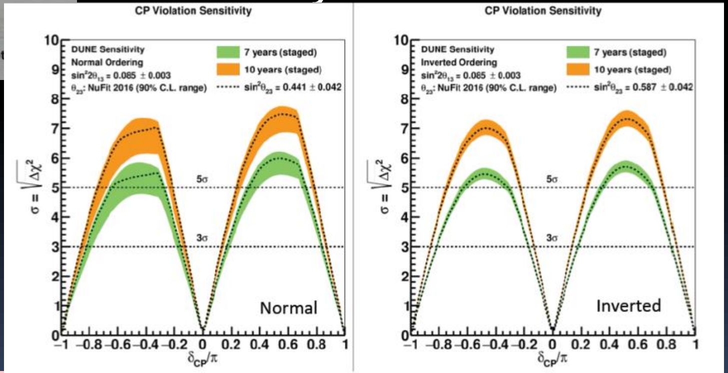
Main goals: - discovery of CP violation in leptonic sector
- neutrino mass hierarchy at >5σ level
- neutrino astronomy
- proton decay search

31 countries
177 institutions
>1000 collaborators



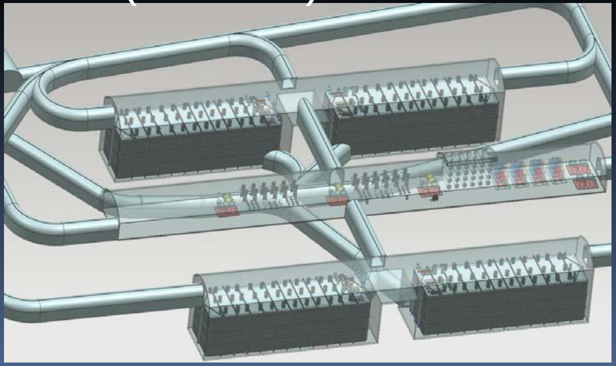
E_p = 60-120 GeV
Beam power 1.2 -> 2.4 MW
On axis neutrino beam
Eν ~ 1- 6 GeV
L=1300 km from FNAL to SURF, S.Dakota

Sensitivity to CP violation



Far detector 40 kt (4 x 10kt) LAr TPC

Single
and
Dual
phase
detectors



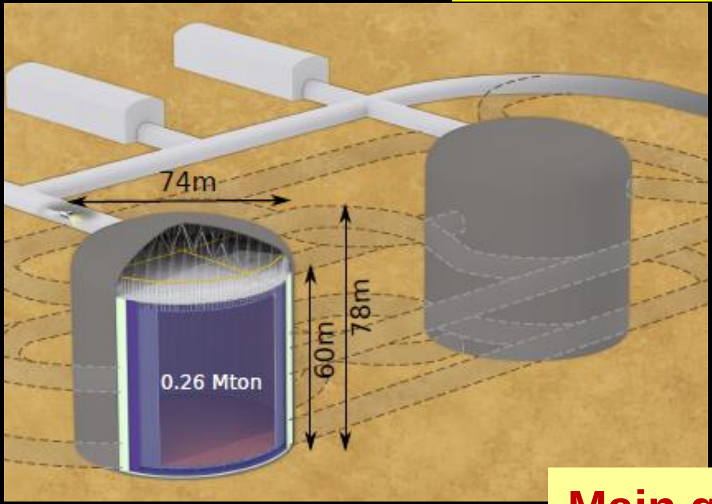
2022 – installation of 1st far detector
2024 – 2 modules operational
2026 – deliver neutrino beam

HyperKamiokande

Japan

HyperK: 1 water tank

12 countries
70 institutes
~300 members
Expected data taking start 2026

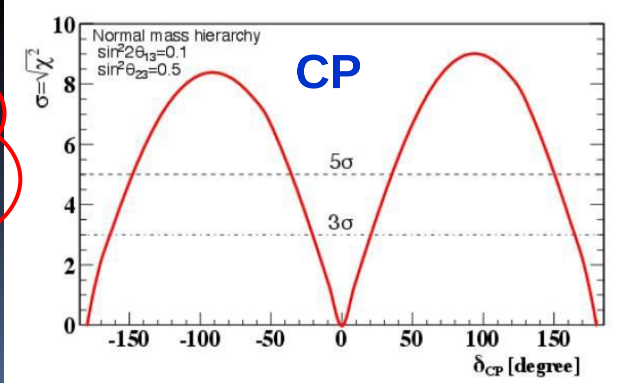


- Upgrade of JPARC to 1.3 MW beam power
- New/upgrade of near neutrino detectors

Main goals:
- **Search for CP violation**
- **Proton decay**
- **Neutrino astrophysics**

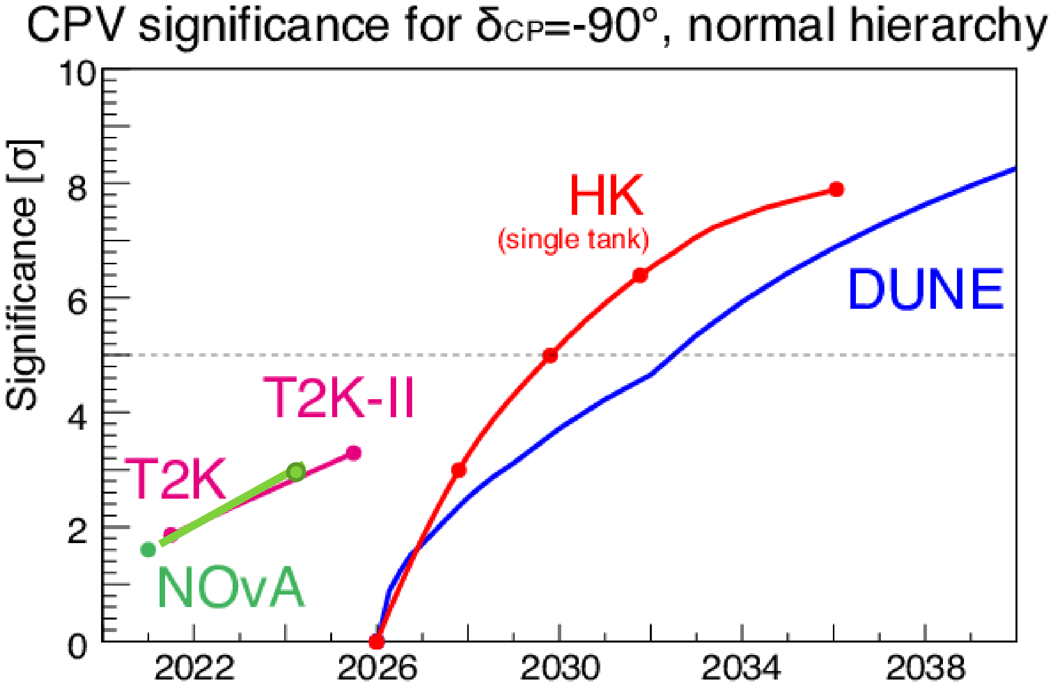
Water tank
60 m(H)x74m(D)
Total volume 260 kt
Fiducial volume 190 kt
~10xSuperK
PMT coverage 40%
40000 PMTs

10 years of running:
- 8σ for $\delta_{CP} = -\pi/2$
- 80% coverage of δ_{CP} parameter space with >3σ
- $p \to \pi^0 e^+$ $>10^{35}$ y

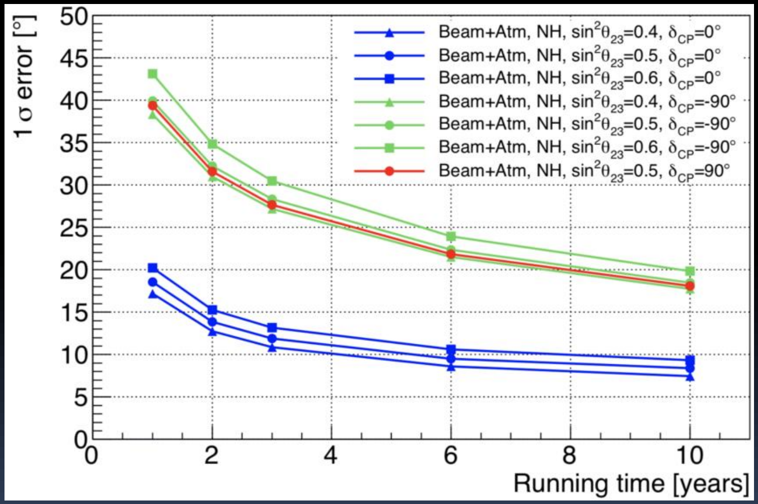


Expected sensitivity to CP

Significance for δ_{CP} = - $\pi/2$
Known MH



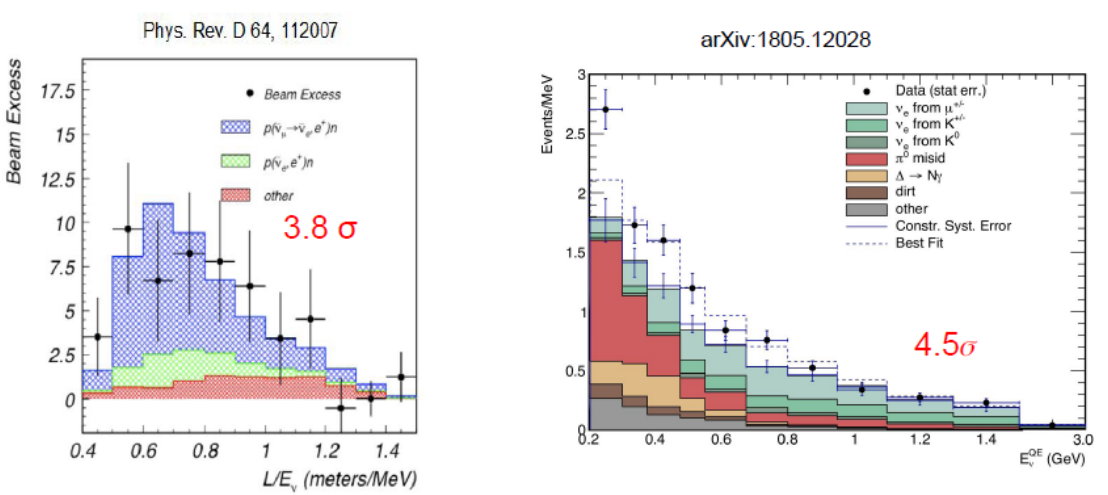
Hyper-Kamiokande:
1σ of δ_{CP} vs running time
18^o for +-90 deg, 8^o for $0,\pi$



Light sterile neutrinos

Neutrino anomalies

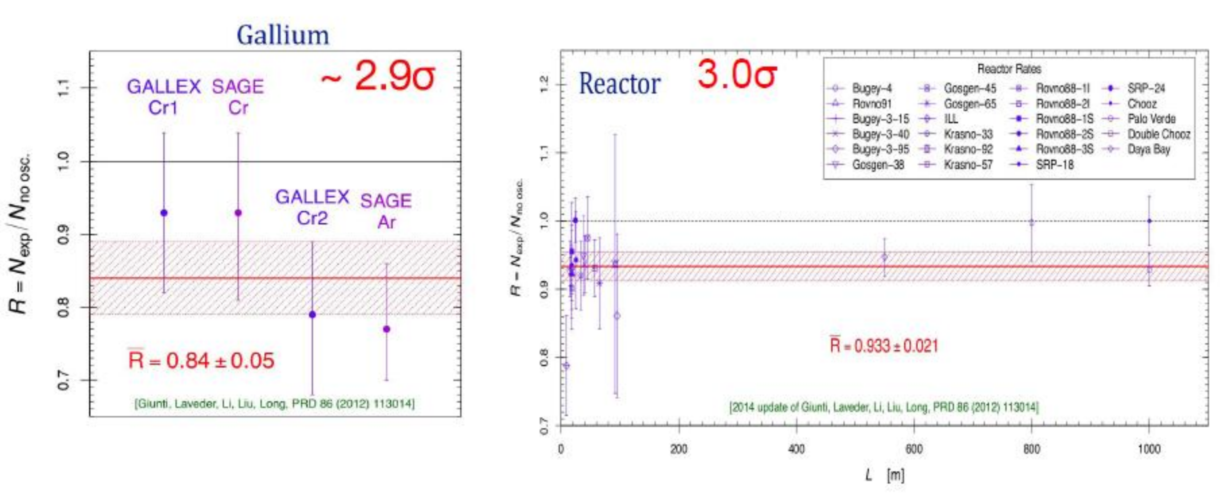
LSND/MiniBooNe anomaly



Phys. Rev. D 64, 112007

arXiv:1805.12028

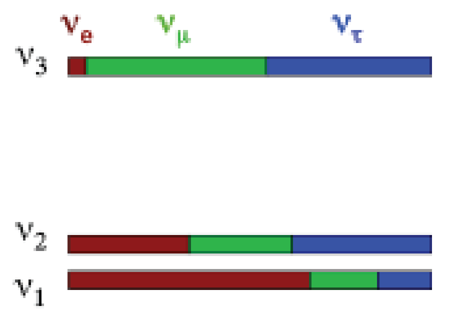
Gallium and Reactor anomalies



These anomalies can be interpreted as oscillations involving sterile neutrino with $\Delta m^2 \sim 1$ eV^2

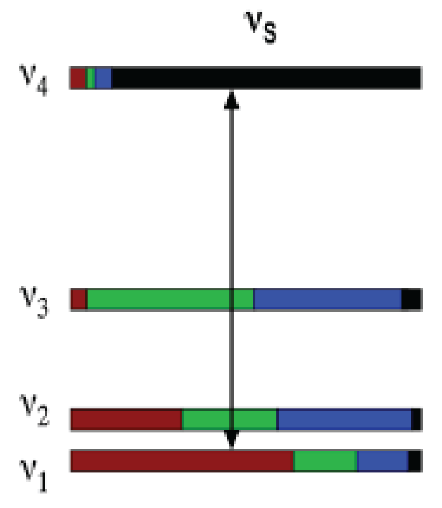
Sterile neutrino?

3ν



?

3ν + 1s



$\Delta m^2_{14} \sim 1$ eV²

PNMS matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} = \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

$$|U_{e4}|^2 = \sin^2\theta_{14}$$

$$|U_{\mu 4}|^2 = \sin^2\theta_{24} \cdot \cos^2\theta_{14}$$

$$|U_{\tau 4}|^2 = \sin^2\theta_{34} \cdot \cos^2\theta_{24} \cdot \cos^2\theta_{14}$$

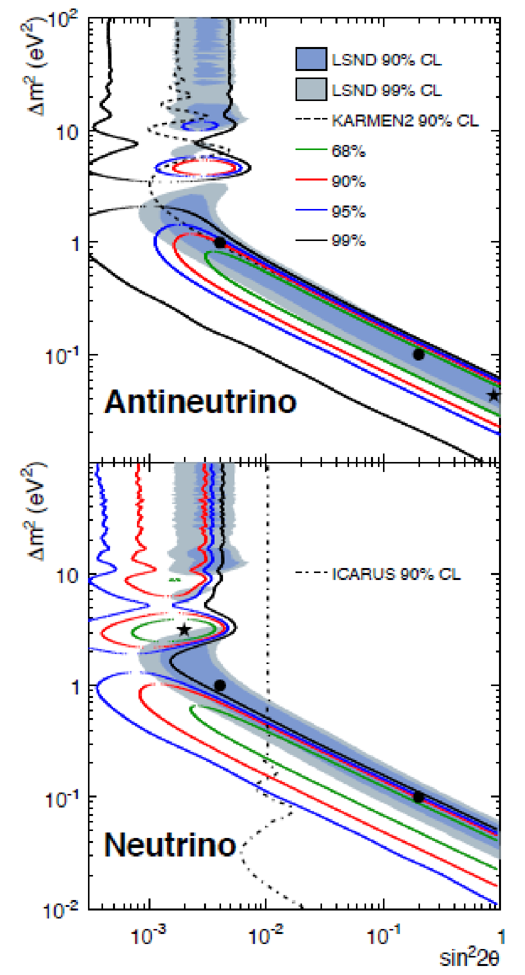
$$P_{\nu_e \to \nu_e} \simeq 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$

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

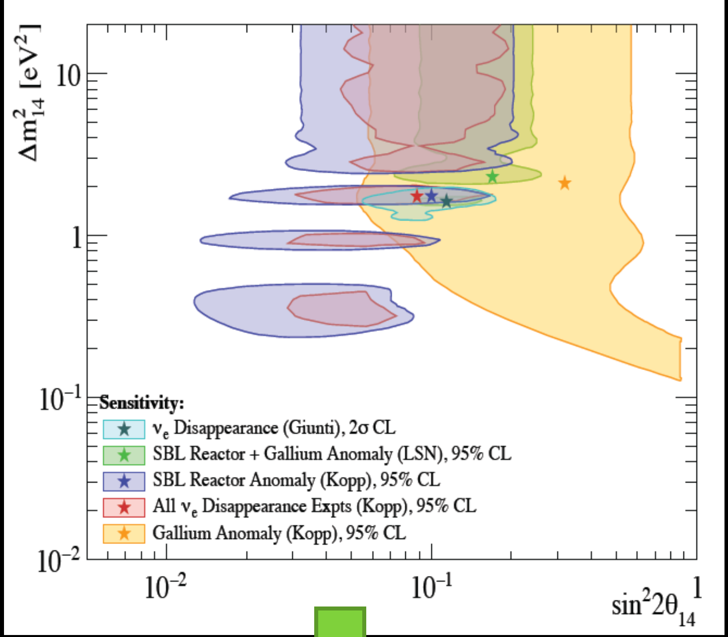
$$P_{\nu_\mu \to \nu_e} \simeq 2|U_{e4}|^2|U_{\mu 4}|^2$$

Parameter space for ν_s

LSND/MiniBooNe



Reactor/Gallium



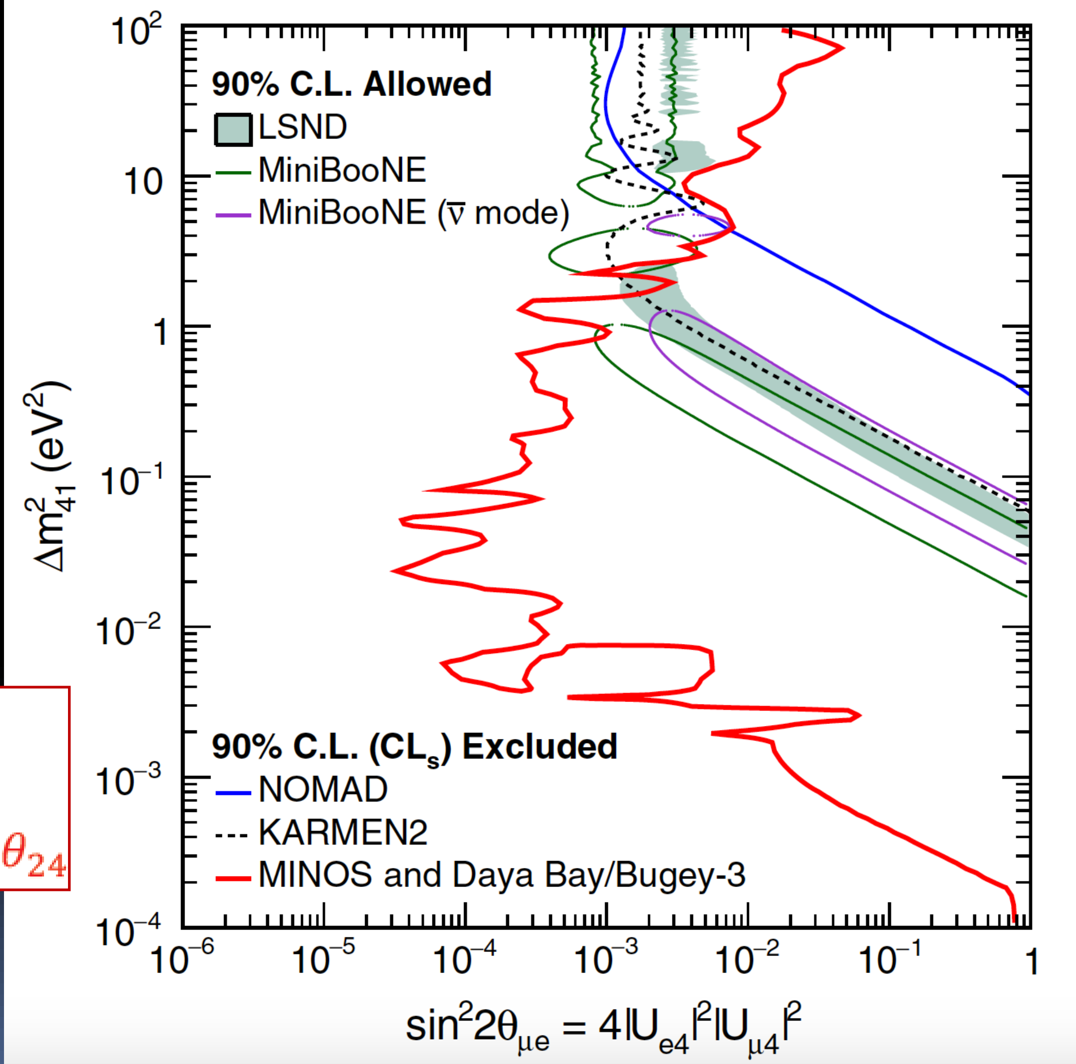
$\Delta m^2 \sim$ 1-2 eV^2

Sterile ν's: Daya Bay + MINOS+ Bugey-3

PRL117 (2016) 151801

- Daya Bay data
  - Constrains Δm^2_{41}(mainly 10^{-4} to 10^{-1} eV^2) and $\sin^2 2\theta_{14}$
- Bugey-3 data
  - constrains Δm^2_{41} (mainly 10^{-1} to 10 eV^2) and $\sin^2 2\theta_{14}$
- MINOS data
  - Constrains Δm^2_{41} (mainly 10^{-3} to 10^{2} eV^2) and $\sin^2 \theta_{24}$

- Combined all three
  - Constrains Δm^2_{41} and $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \cdot \sin^2 \theta_{24}$



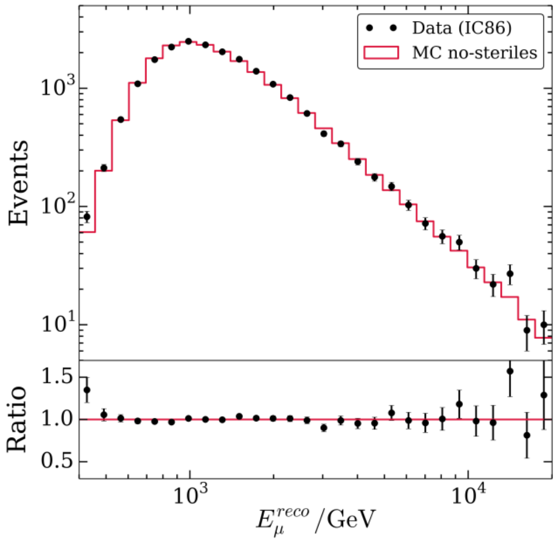
Sterile ν's: IceCube

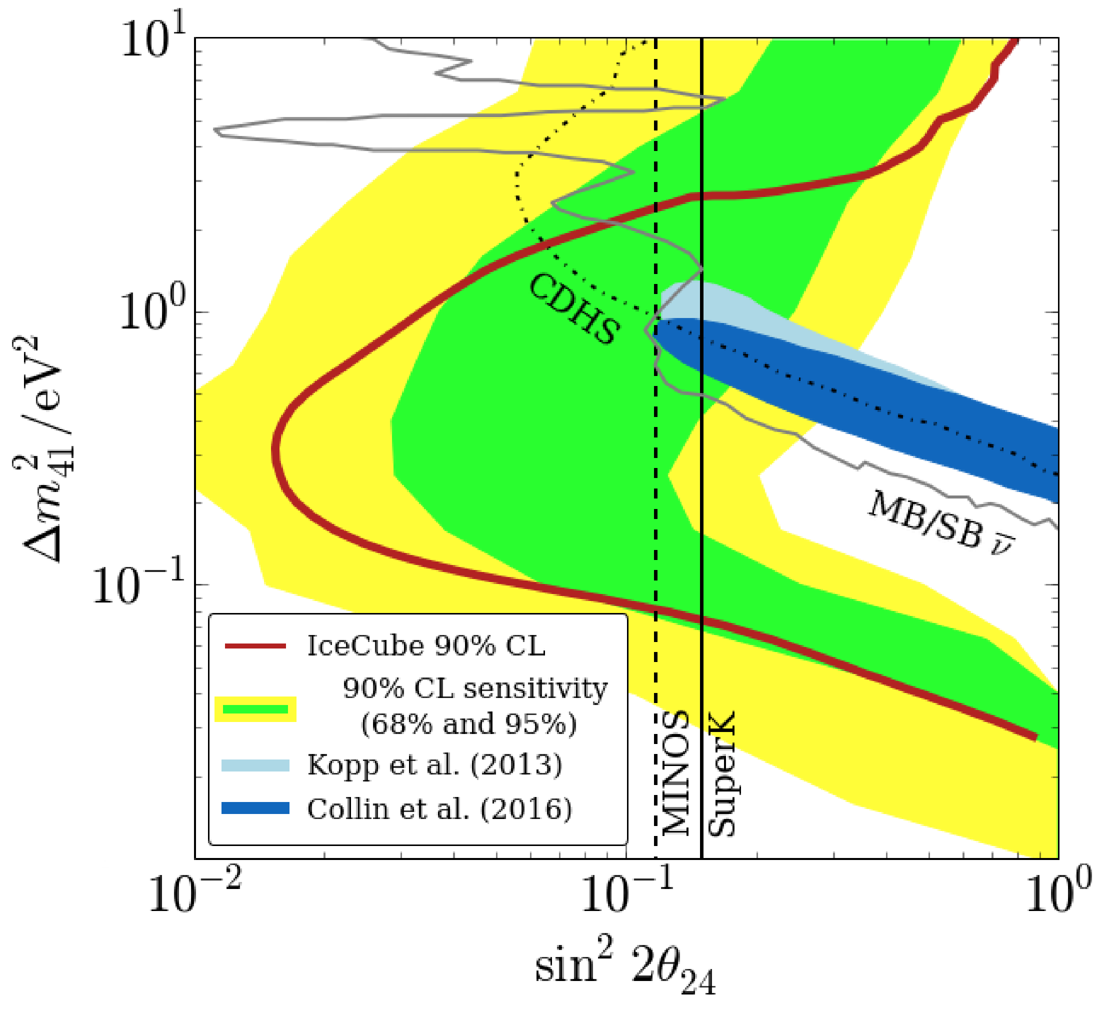
PRL 117 (2016) 071801

Eν = 320 GeV – 20 TeV

sterile neutrinos produce distortions of νμ + anti-νμ flux (energy and angle) in the range
$0.01 \leq \Delta m^2 \leq 10$ eV^2

- 1 year of data
- statistics limited

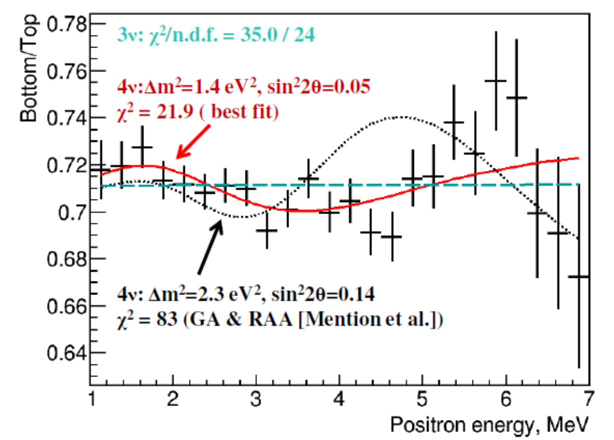




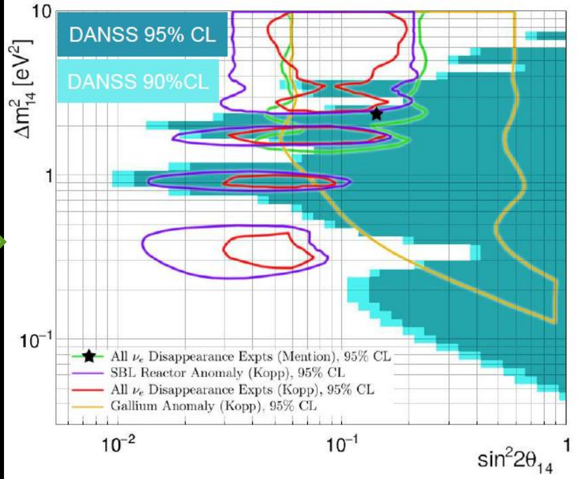
Result compatible with no-sterile hypothesis

SBL reactor experiments (I)

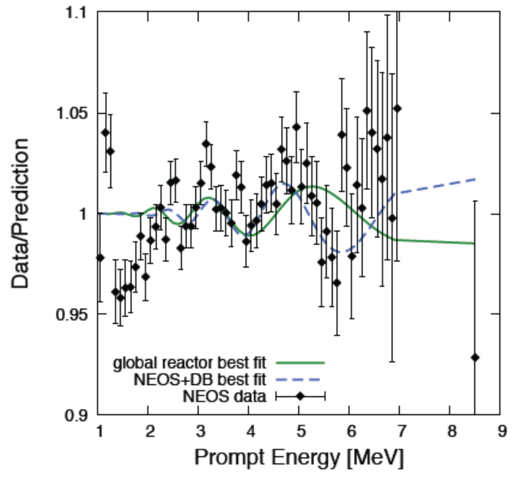
DANSS, (I.Alexeev et al. PL B787 (2018) 56)
Kalinin power station 3.1 GW
Segnebted detector 1 m3



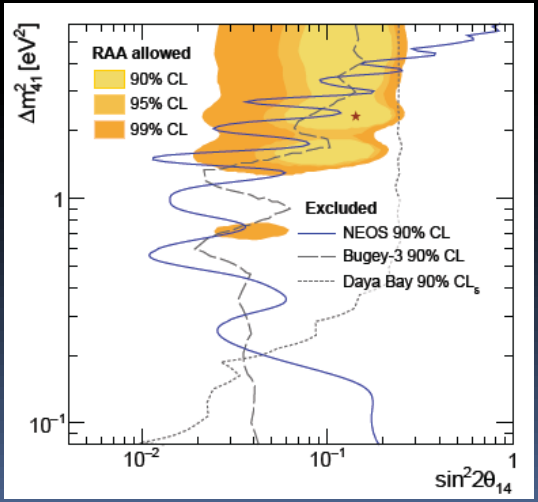
Reactor anomaly excluded at 5σ



NEOS (PRL 118 (2017) 121802)
Korea, Reactor 2.8 GW   Active zone ∅3.1 м h=3.8 м
Detector 1t LS + Gd

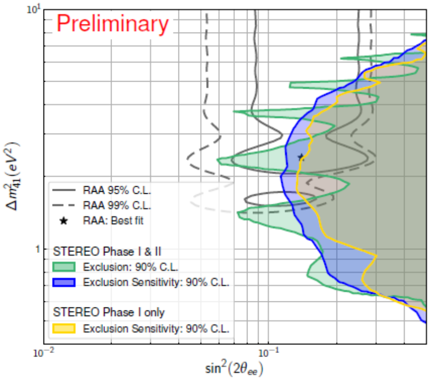


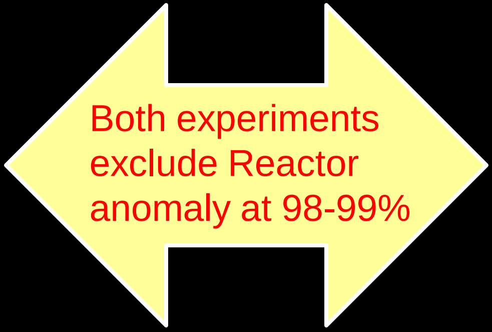
No evidence for ν_s with mass ~ 1 eV



SBL reactor experiments (II)

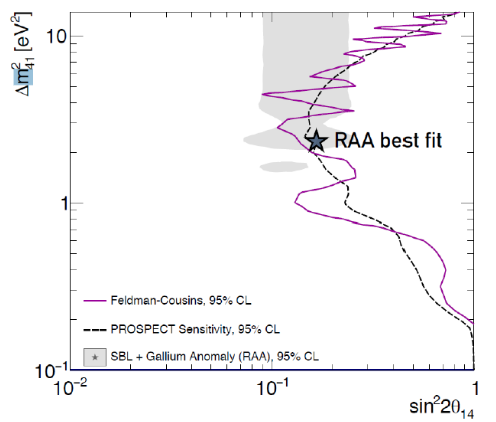
STEREO (L.Bernard, ICHEP2018)
ILL, Grenoble, France, Reactor 58.3 MW
Active zone ∅40x80 cm
Detector ~4t LS + Gd



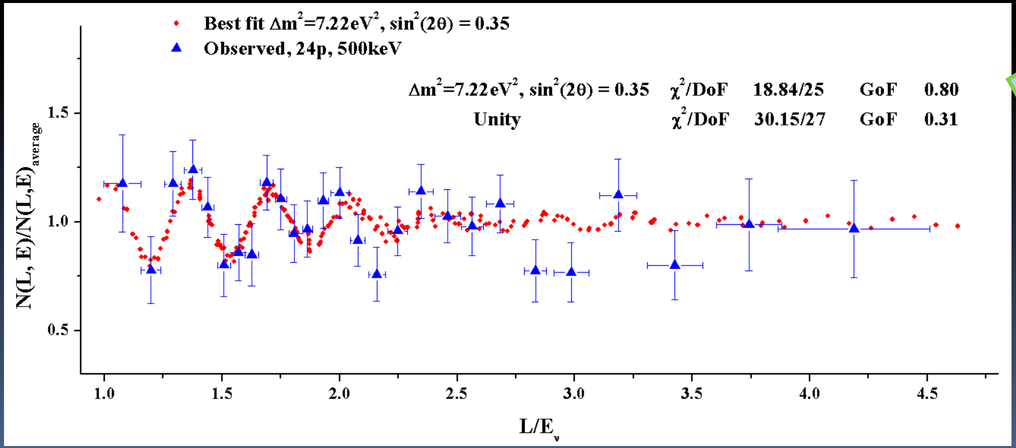


Both experiments exclude Reactor anomaly at 98-99%

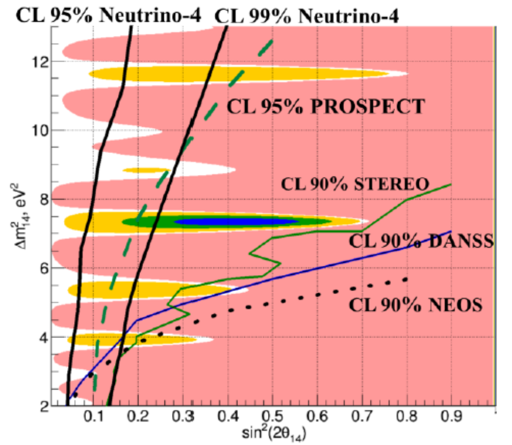
PROSPECT (arXiv:1806.02784)
HIFR, USA, Reactor 84 MW
Active Zone ∅43x h50 cm
Segmented detector ~4t LS + ^{6}Li



Neutrino-4 (A.Serebrov et al. arXiv:1809.10561)
Dimitrovgrad, Reactor Active Zone 35×42×42 cm
Segmented detector 1.8t LS + Gd

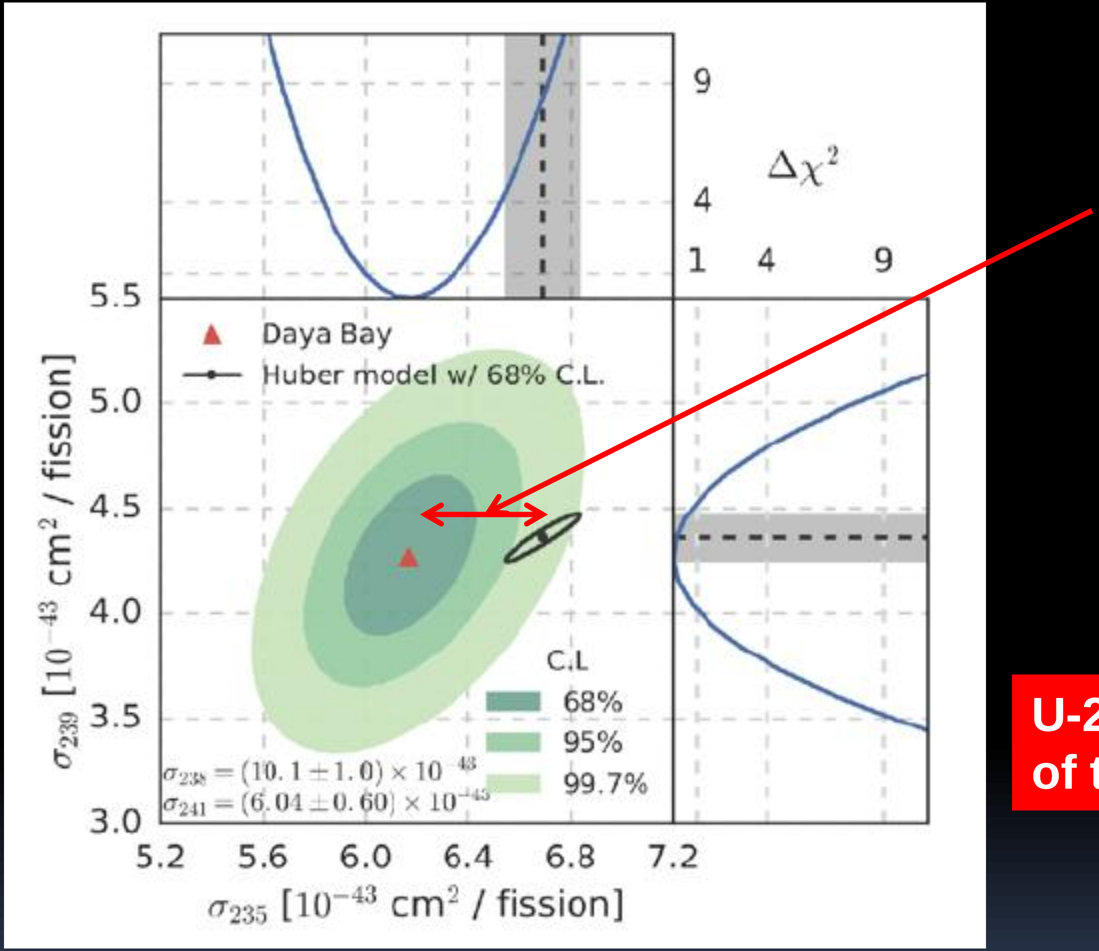


$$\Delta m^2_{14} \approx 7.34\text{eV}^2 \quad , \quad \sin^2 2\theta_{14} \approx 0.39$$



Daya Bay: anti-neutrino flux

PRL 118 (2017) 251801



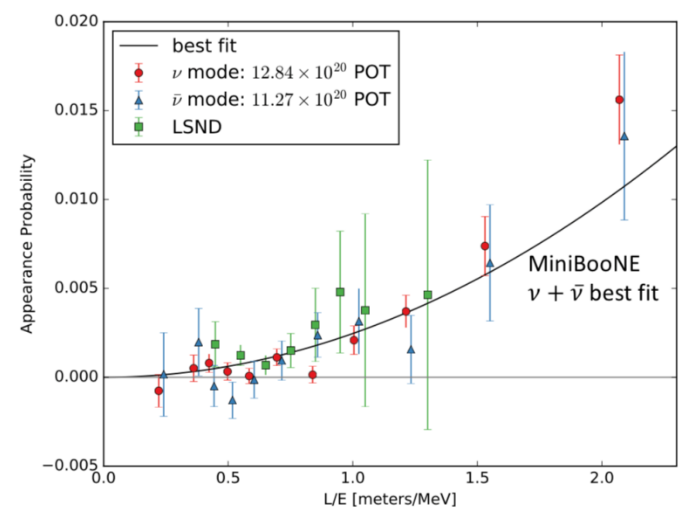
This discrepancy gives an overestimation of predicted antineutrino flux by 7.8%.

U-235 is a possible source of the Reactor Anomaly?

Short baseline experiments at U-enriched reactors are needed

New MiniBooNe result

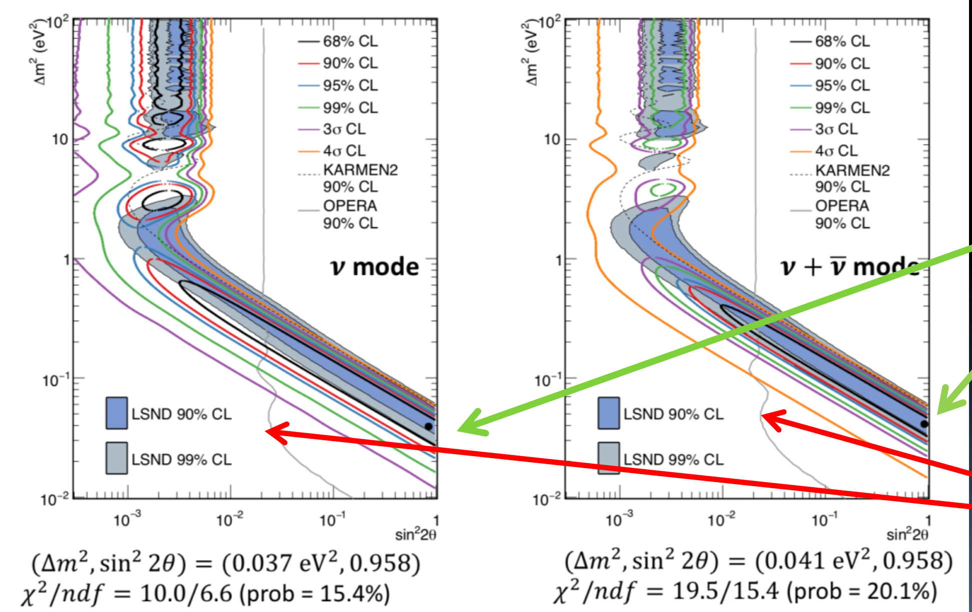
arXiv:1805.12028



MiniBooNe doubled
ν data since 2012
ν 12.84×10^{20} POT
anti-ν 11.27×10^{20} POT

neutrino +antineutrino total excess
460.5 ± 95.8 events (4.8σ)

Best fit point:
$\Delta m^2_{41} = 0.041$ eV^2
$\sin^2 2\theta = 0.958$



$(\Delta m^2, \sin^2 2\theta) = (0.037\ \text{eV}^2, 0.958)$
$\chi^2/ndf = 10.0/6.6$ (prob = 15.4%)

$(\Delta m^2, \sin^2 2\theta) = (0.041\ \text{eV}^2, 0.958)$
$\chi^2/ndf = 19.5/15.4$ (prob = 20.1%)

Excluded by OPERA and ICARUS

Sterile ν's: « pro» and « con»

+

LSND/MinBooNe
Reactor anomaly
Ga anomaly

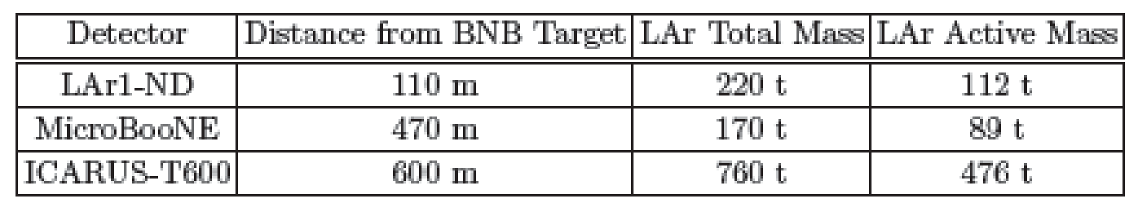
-

MINOS Disappearance
MINOS/Daya Bay/Bugey combined result
IceCube
NEOS
DANSS
Neutrino-4
STEREO

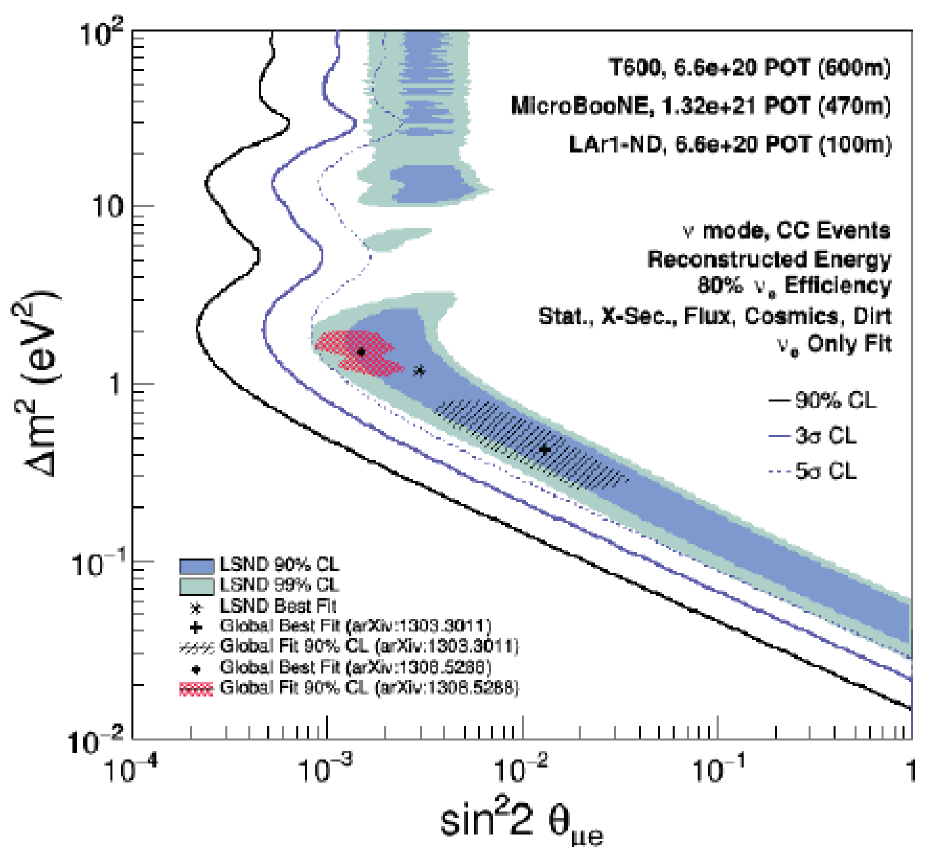
Problem to be solved soon

FNAL: Short Baseline Neutrino program

arXiv:1503.01520



Detector	Distance from BNB Target	LAr Total Mass	LAr Active Mass
LAr1-ND	110 m	220 t	112 t
MicroBooNE	470 m	170 t	89 t
ICARUS-T600	600 m	760 t	476 t



Conclusion

Neutrino oscillations – new physics beyond SM

Current LBL experiments T2K + NOvA

main goals: CP violation (3σ), Mass Hierarchy, θ_{23}

T2K: first hint of CP violation in lepton sector

Next generation experiments: discovery/measurement of CP violation, determination of Mass Hierarchy

JUNO	**(MH)**	***under construction***
DUNE	**(CP, MH)**	***approved***
HyperK and T2HK	**(CP)**	***approval in progress***

Light sterile neutrinos:

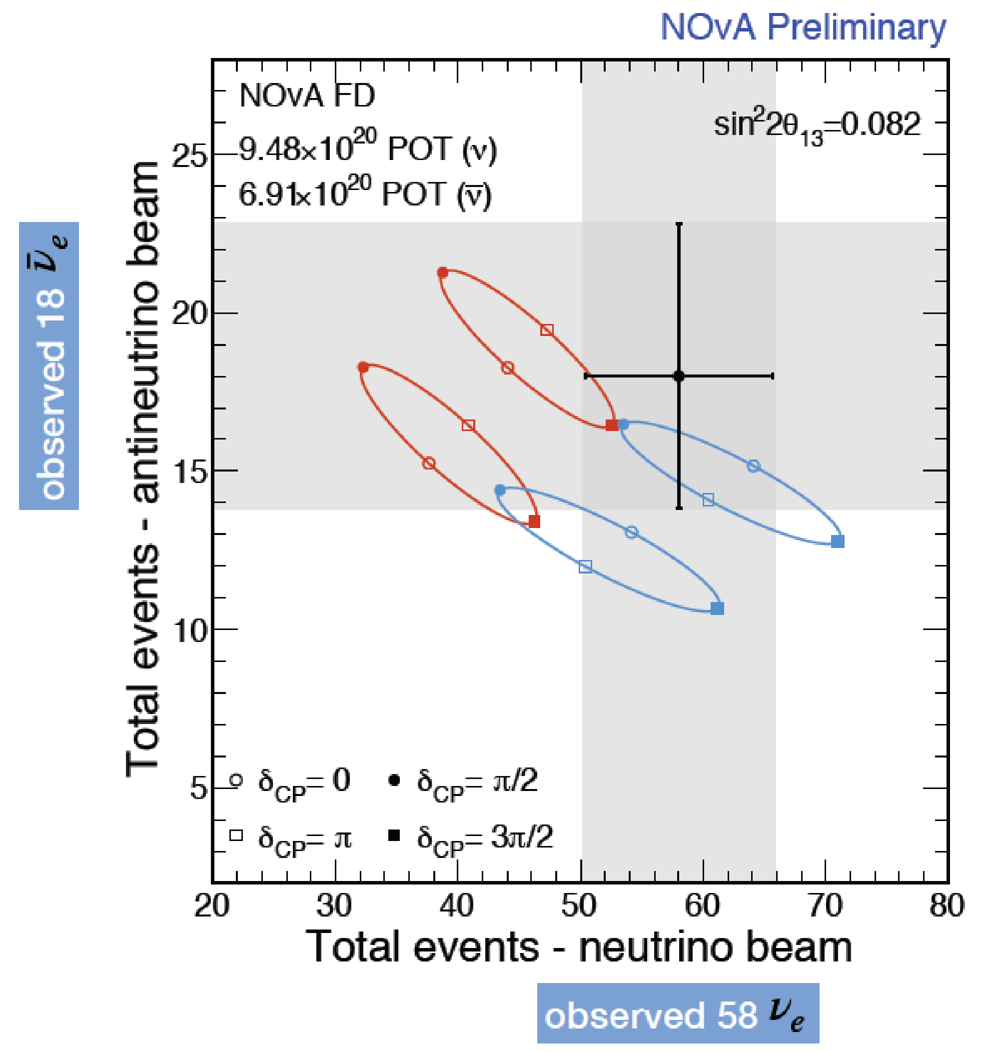
- no positive signal from running experiments

- crucial tests are coming

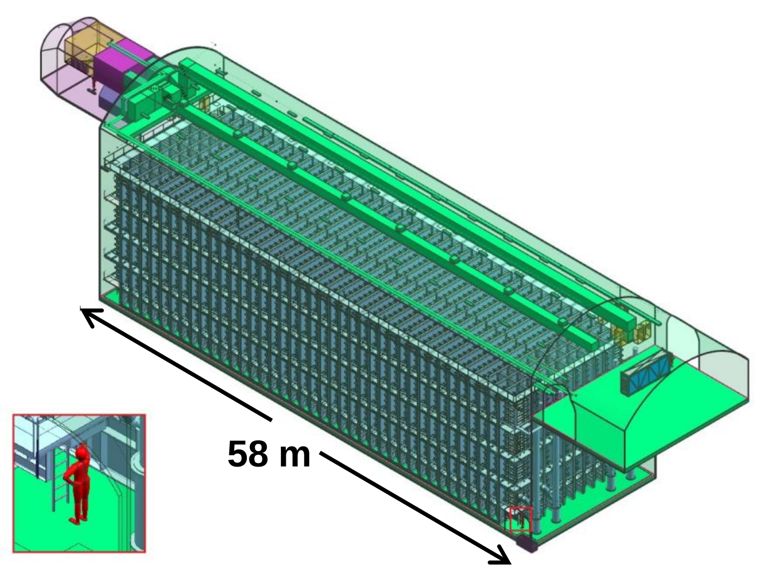
Thank you for attention!

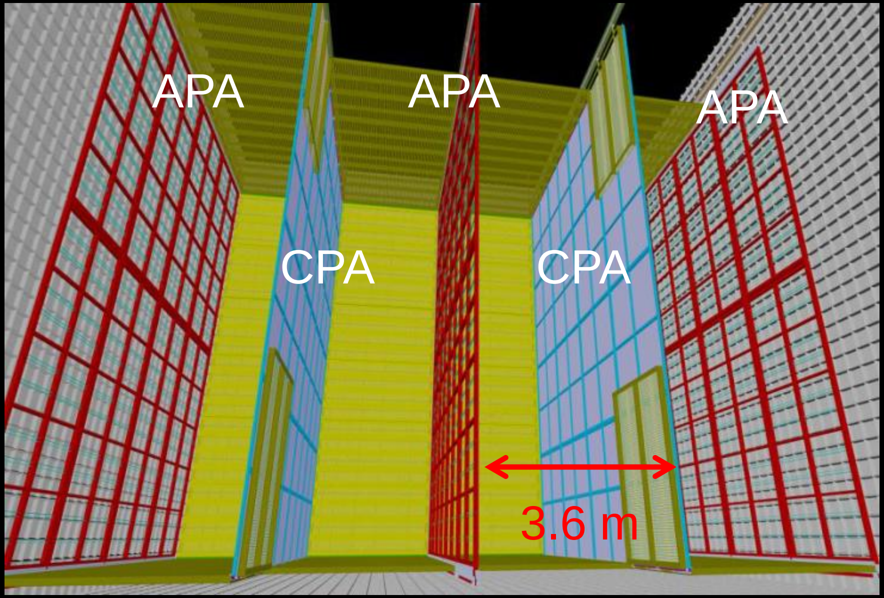
Backup slides

NOvA: ν_e and anti-ν_e appearance



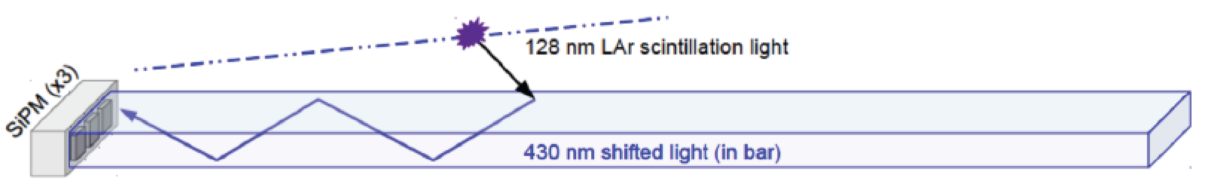
Single-phase LAr TPC





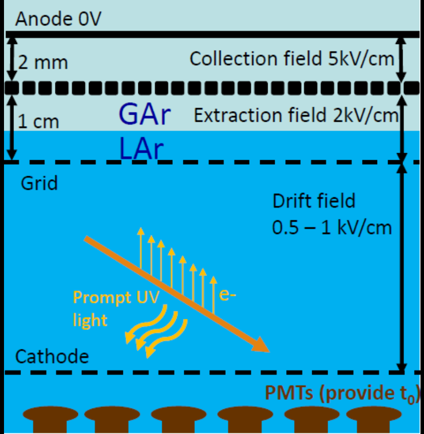
1st 10 kt module of DUNE - single-phase TPC
6m x 2.3 m anode and cathode planes 3.6 m spacing
Photon detectors – light guides + SiPMs embedded in APAs

J.Insler, talk at LLWI2017



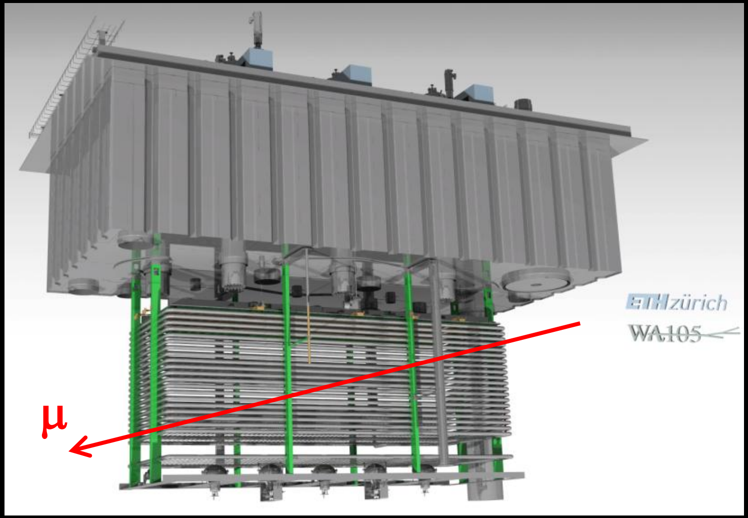
LAr detectors at CERN Neutrino Platform

NP02: WA105
(DP demonstrator + ProtoDUNE DP)

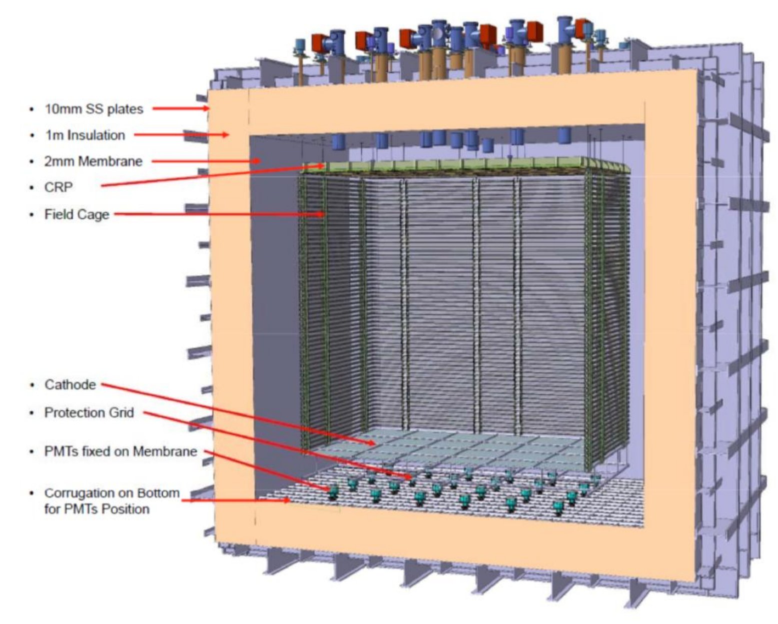


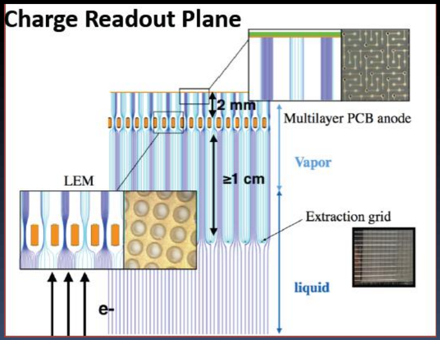
S.Murthy, talk at TPC-2016

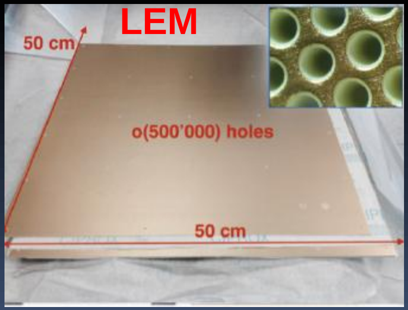
Demonstrator: 3x1x1 m^3 – 5 tons



ProtoDUNE DP:
6x6x6 m^3
300 tons active mass







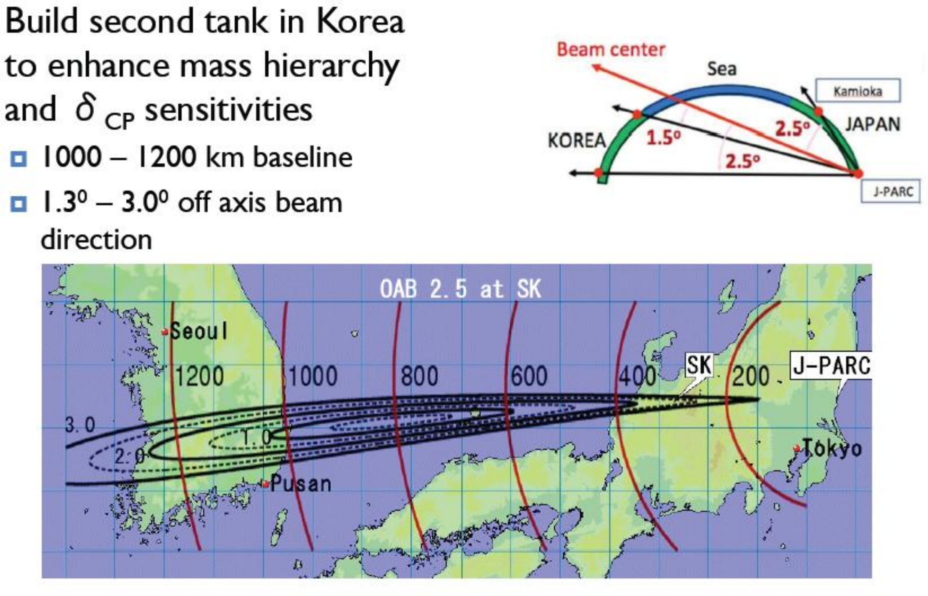
Cosmic data taking gas begun

Measurements with test beam in 2018

T2HKK

Second tank in Korea

arXiv:1611.06118

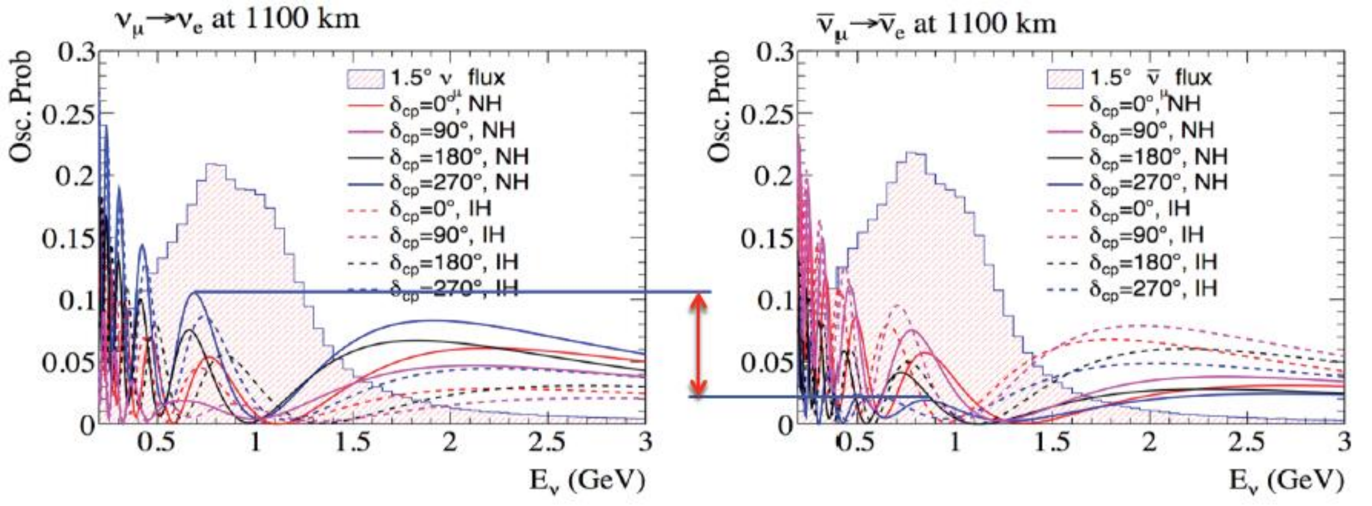


Build second tank in Korea to enhance mass hierarchy and δ_{CP} sensitivities

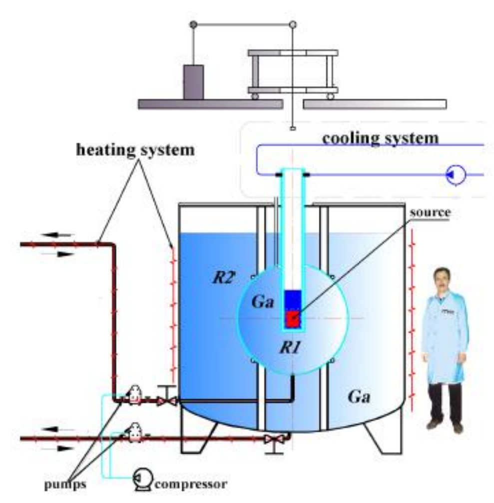
- 1000 – 1200 km baseline
- $1.3^0 - 3.0^0$ off axis beam direction

Neutrino and antineutrino spectra in T2HKK cover 1st and 2nd oscillation maximum

- A_{CP} ~3 times larger in 2nd maximum
- Sensitivity to MH



Source experiments

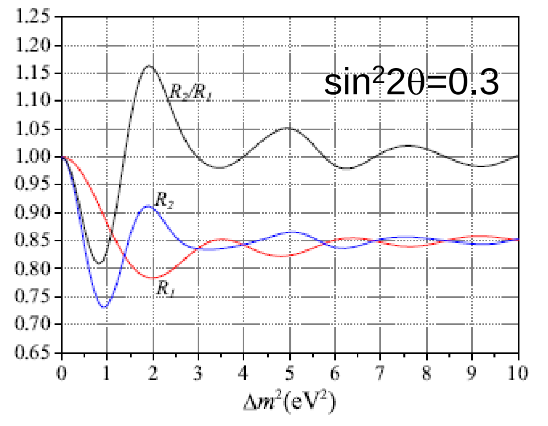


BEST

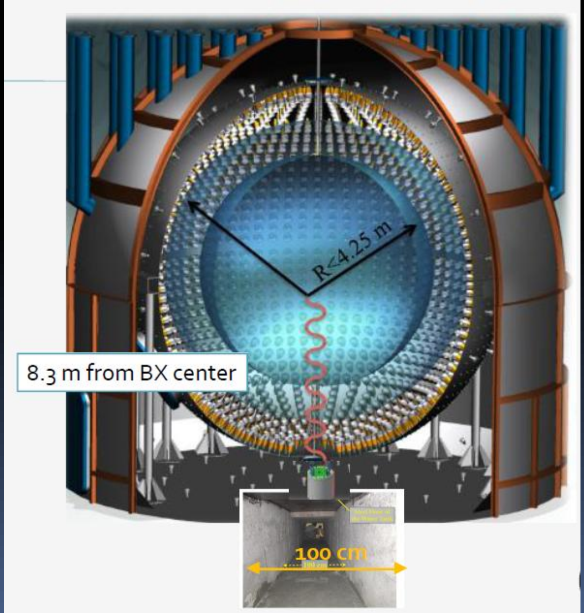
J.Phys.Conf.Ser. 798 (2017) 012113

3 MCi ^{51}Cr source

Two-zone 50 t
liquid Ga metal target



PRD 91 (2015) 072005



SOX **(terminated)**

Ultra-low radioactive background

- Spatial resolution: 12 cm @ 2 MeV
- Energy resolution: ~3,5% @ 2 MeV

^{144}Ce-^{144}Pr $\bar{\nu}_e$ source (100-150 kCi)

Source will be produced at Mayak, Russia

Start data taking in 2018