General Review on Neutrino Oscillation

F.Suekane
RCνS/Tohoku Univ.,
APC/CNRS

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Flow of the talk

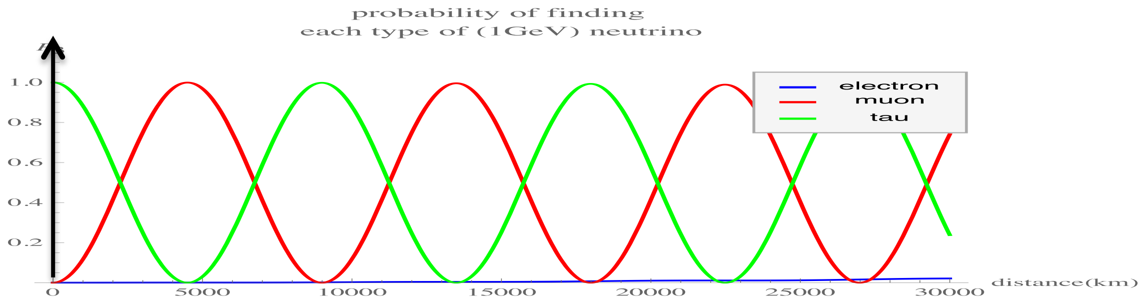
* What is neutrino oscillation (N.O.)?
* Why N.O. is important?
* History of N.O. measurements
* What we know now?
* Future N.O. measurements
* Summary

What is Neutrino Oscillation?

Electron stays as electron while it travels in space.

$$e^- \longrightarrow e^-$$

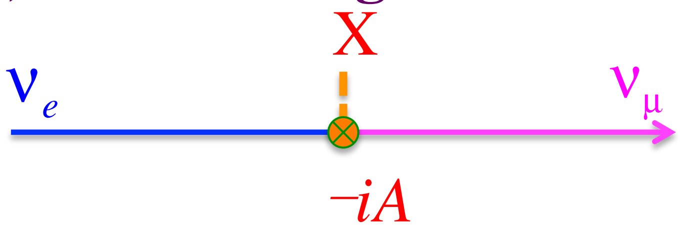
However, neutrinos change their flavors periodically.



This phenomenon is called neutrino oscillation

What causes the neutrino to oscillate?

We do not know yet. But in order for N.O. to happen, something(X) has to change ν flavor.



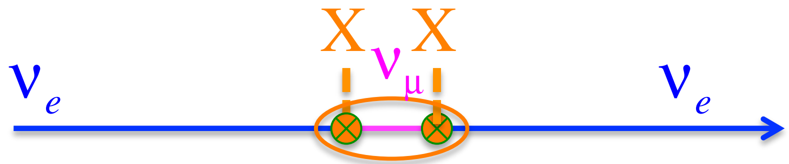
"A" indicates the strength of the transition (amplitude).

In this case the equations of motion of ν are

$$\frac{d}{dt}\nu_e = -iA\nu_\mu, \quad \frac{d}{dt}\nu_\mu = -iA\nu_e$$

$$\frac{d^2}{dt^2}\nu_e = -A^2\nu_e$$

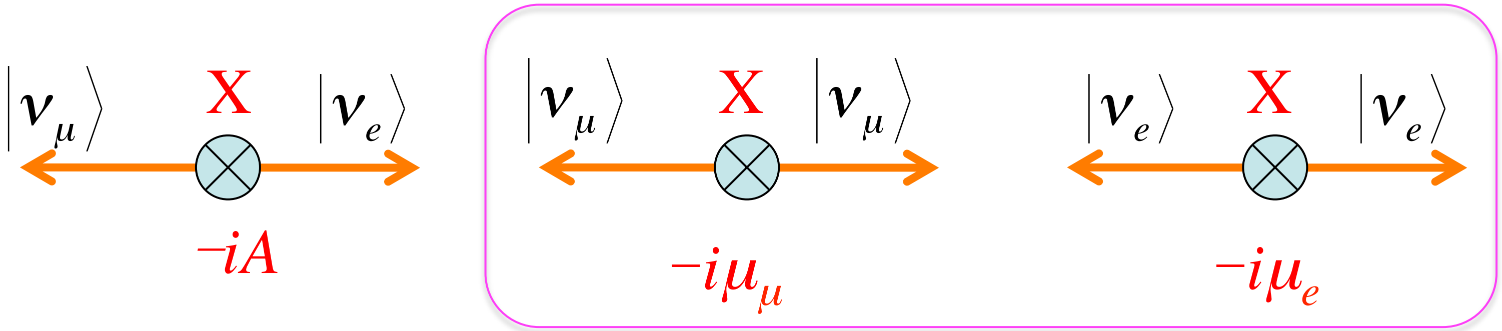
or

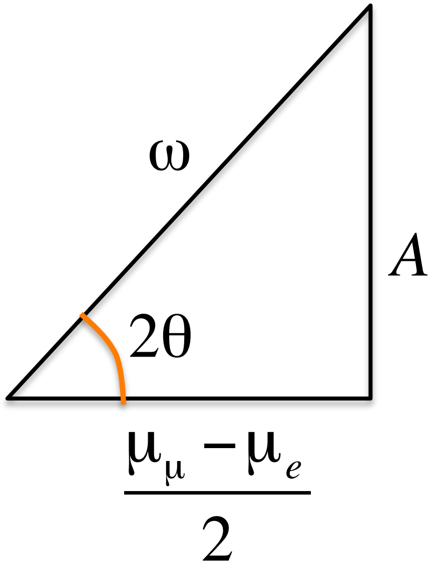


$$m = \pm A$$

➔ If this transition exists, neutrinos obtain mass.

General transition amplitudes & mass eigenstates





If there are self-transitions, the mass eigenstate become the superposition of flavor eigenstate;

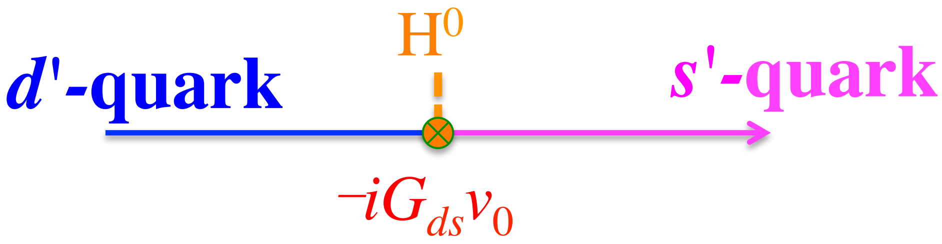
$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

The neutrino masses are

$$\begin{cases} m_1 = \bar{\mu} - \omega \\ m_2 = \bar{\mu} + \omega \end{cases}, \quad \bar{\mu} = \frac{\mu_\mu + \mu_e}{2}, \quad \omega = \frac{A}{\sin 2\theta}$$

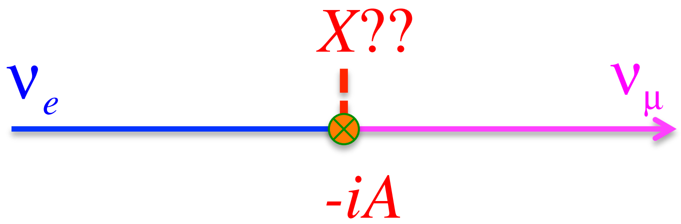
Comparison with quark case

For quark case, there are similar transitions which causes the quark masses, Cabbibo angle and CP violation. The transition is caused by the Yukawa Coupling to the Higgs field



$$\tan 2\theta_C = \frac{2G_{ds}}{G_{ss} - G_{dd}}, \quad m_d = \overline{G}_{ds} - \frac{G_{ds}}{\sin 2\theta_C}, \quad m_s = \overline{G}_{ds} + \frac{G_{ds}}{\sin 2\theta_C}$$

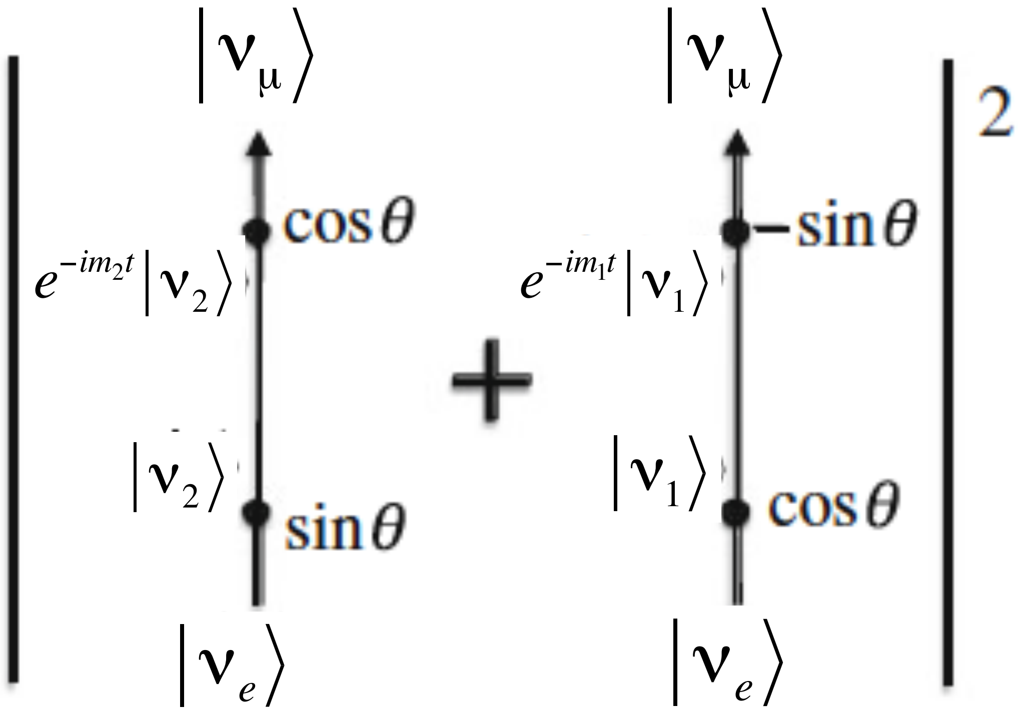
For neutrino case, we do not know what *X* is.



Study of N.O. = Study of *X*

ν oscillation to measure transition amplitude (non relativistic case)

$P[\nu_e \rightarrow \nu_\mu] =$

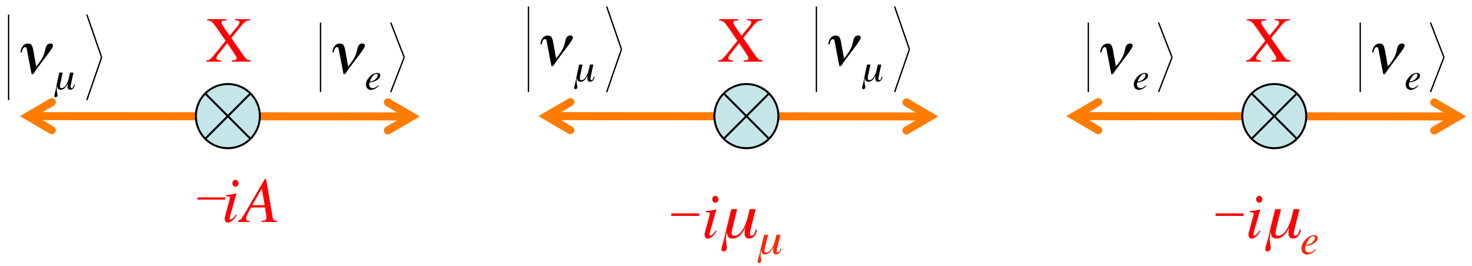


$$P[\nu_e \rightarrow \nu_\mu] = \left|\sin\theta\cos\theta e^{-im_1 t} - \sin\theta\cos\theta e^{-im_2 t}\right|^2$$

$$\rightarrow \sin^2 2\theta \sin^2 \frac{m_2 - m_1}{2} t$$

observable $\begin{cases} \Delta m = m_2 - m_1 \\ \theta \end{cases}$

Determination of transition amplitudes



There are 3 unknown parameters (A, μ_μ, μ_e) ,
while N.O. experiment can give only 2 $(\theta, \Delta m)$

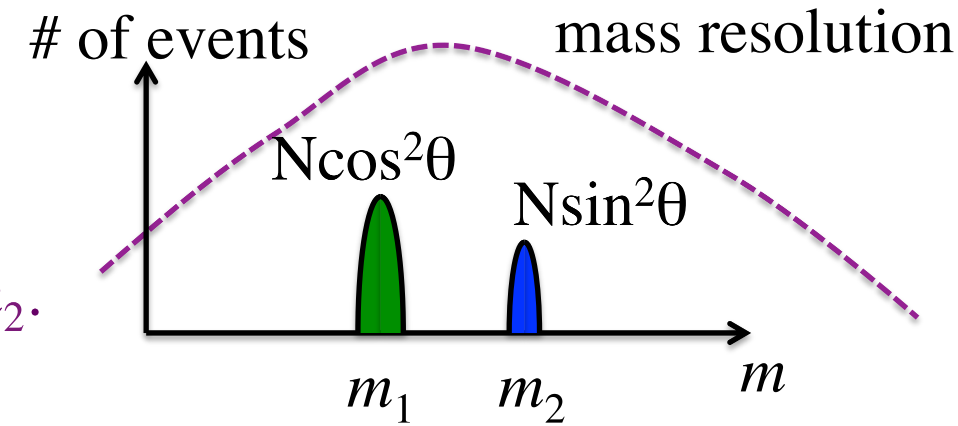
➔ One more parameter is necessary to determine all the transition amplitudes.

Neutrino mass!!

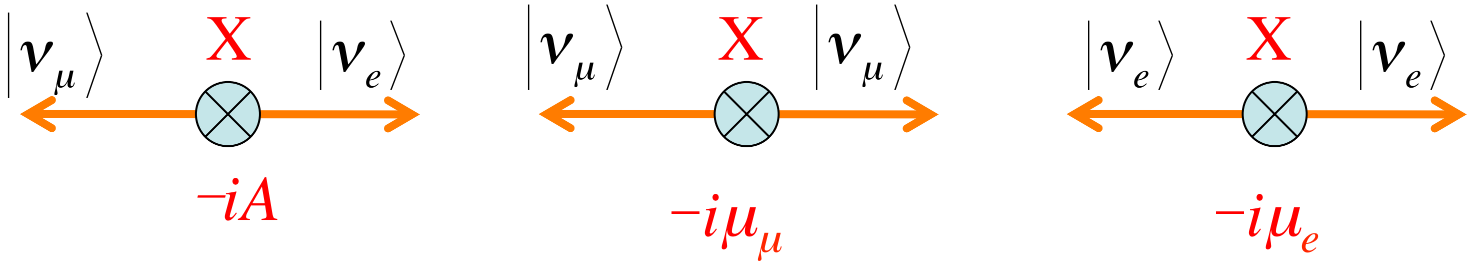
$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta$$

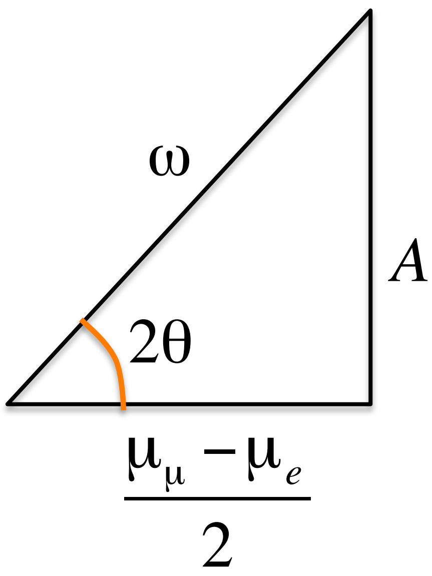
If we measure, ν_e mass, we will obtain weighted average of m_1 and m_2.

$$m_{\nu_e} = m_1 \cos^2\theta + m_2 \sin^2\theta = \mu_e$$



relation between ν oscillation parameters and transition amplitudes





$$\begin{cases} \mu_e = m_{\nu_e} \\ \mu_\mu = m_{\nu_e} + \Delta m \cos 2\theta \\ A = \frac{1}{2} \Delta m \sin 2\theta \end{cases}$$

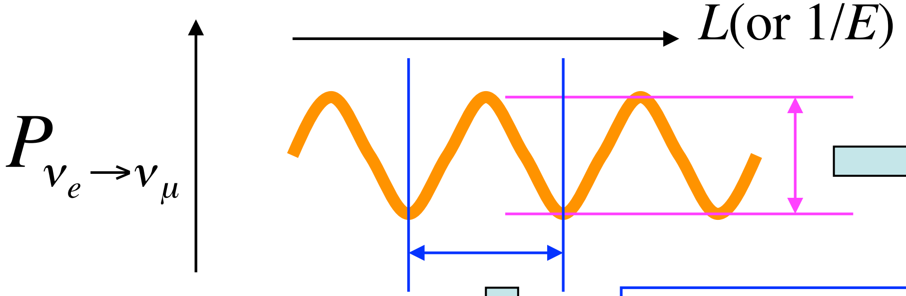
* ν_e **mass directly correspond to** μ_e**.**
* **All the transition amplitude can be determined from** $(\theta, \Delta m, m_{\nu_e})$

Relativistic Neutrino Oscillation

=Phenomenon for ν to Changes its Flavor Periodically

$$mt \rightarrow \frac{mt}{\gamma} = \frac{m^2}{E}t = \frac{m^2 L}{E}$$

$$P\left(\nu_\mu \rightarrow \nu_e\right) = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4E} L$$



Amplitude ==> $\sin^2 2\theta$

Frequency => $\Delta m^2 = \left| m_2^2 - m_1^2 \right|$

$\left.\begin{matrix} \Delta m^2 \\ \theta \end{matrix}\right\}$ ➔ **Information of transition amplitudes of neutrinos**

Why we mesure ν oscillations?

There are many oscillations (irrespective to it is observable or not).

- * $K^0 \Leftrightarrow \overline{K^0}$ oscillation. → CP violation, mass difference
- * $|u\bar{u}\rangle \Leftrightarrow |d\bar{d}\rangle$ oscillation in π^0, η → Hadron mass
- * $d \Leftrightarrow s$ oscillation →Cabbibo angle, quark mass.
- * $B \Leftrightarrow W_3$ oscillation → Weinberg angle, W, Z^0 mass

→ We have learned a lot from these "Oscillations"

We can expect to learn more from ν oscillations;

$$\nu_\alpha \Leftrightarrow \nu_\beta$$

"X" in the Neutrino Oscillation

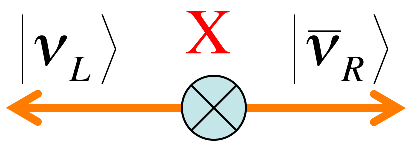
What causes X? (origin)

Why X is so small? (ν mass)

What is the ratio between off-diagonal to
the difference of diagonal amplitude? (mixing angle)

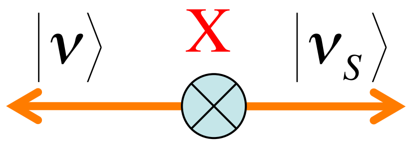
Is coupling to X complex number? (CP violation)

Can X change particle to antiparticle? (Majorana ν?)



?

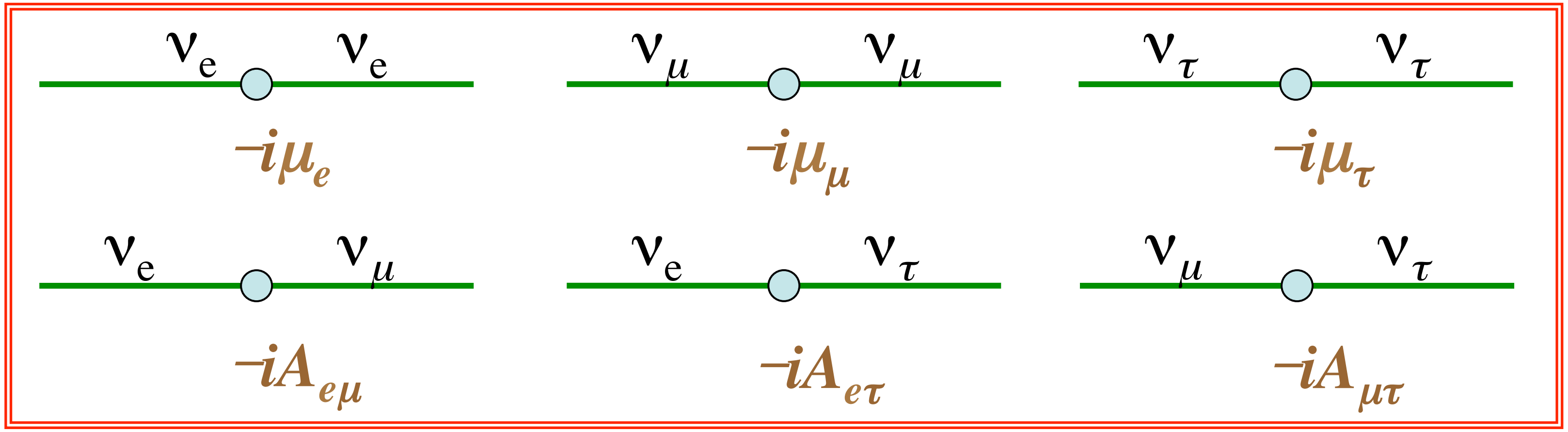
Can X connect our ν and sterile ν? (Sterile ν)



?

To answer these question, we need to measure X.

3 Flavor Neutrino Case



Mass eigenstates become superposition of flavor eigenstates

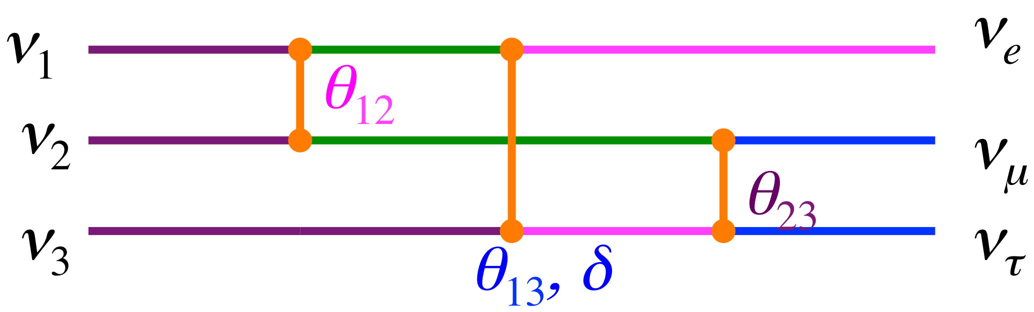
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad m_1, m_2, m_3 = \ldots$$

$A_{\alpha\beta}$ can be complex number and $U_{\alpha i}$ can also be complex number

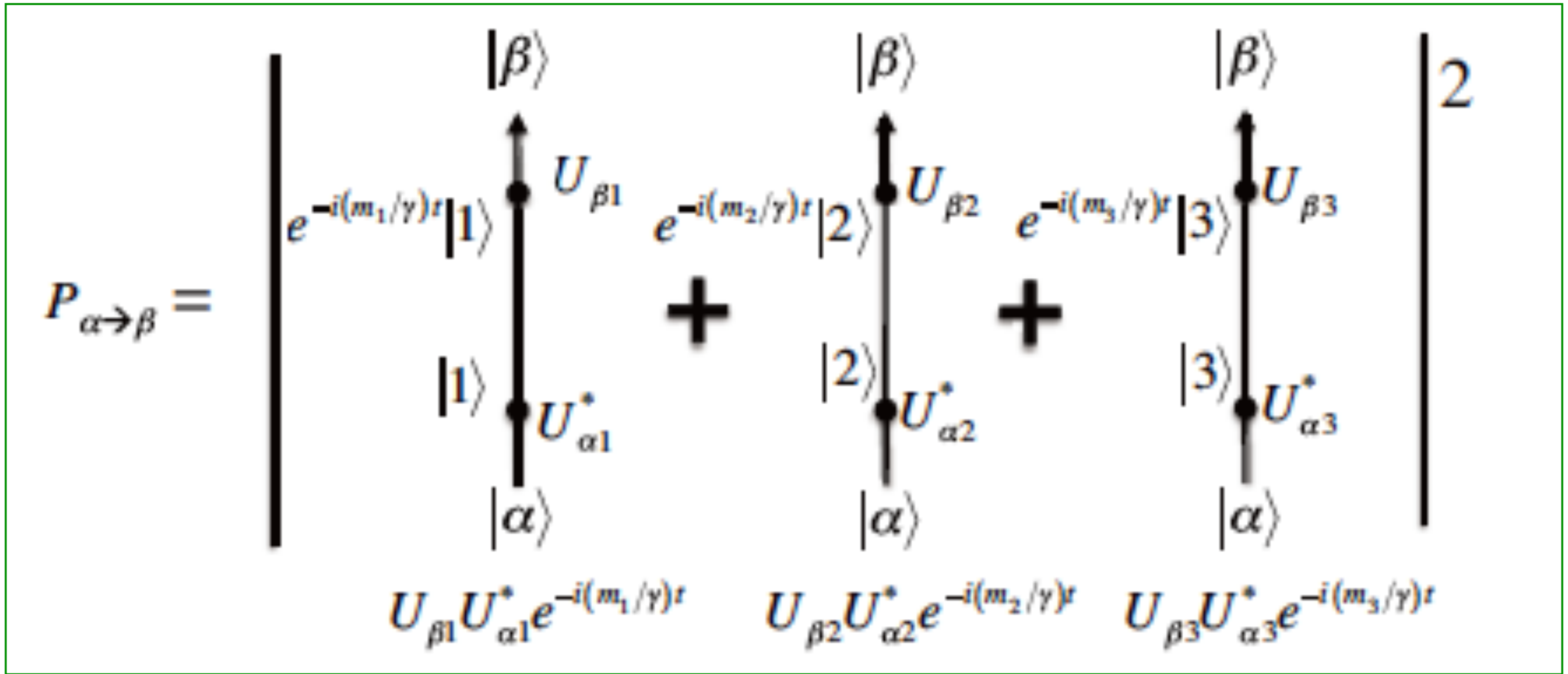
A useful parametrization of the mixing matrix

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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



3 flavor oscillation probabilities



$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left[\Omega_{ij}^{\alpha\beta}\right]\sin^2\Phi_{ij} \mp 2\sum_{i>j}\mathrm{Im}\left[\Omega_{ij}^{\alpha\beta}\right]\sin 2\Phi_{ij}$$

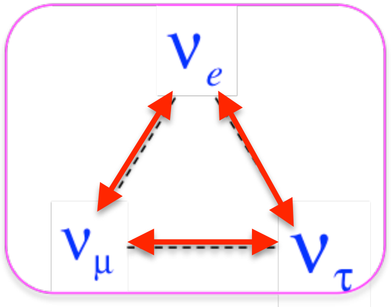
$$\Omega_{ij}^{\alpha\beta} \equiv U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j} \qquad \Phi_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}, \quad \Delta m_{ij}^2 \equiv m_j^2 - m_i^2$$

There are 6 independent oscillation parameters;

θ_{12}, θ_{23}, θ_{13}, δ_{CP}, Δm^2_{12}, Δm^2_{23}

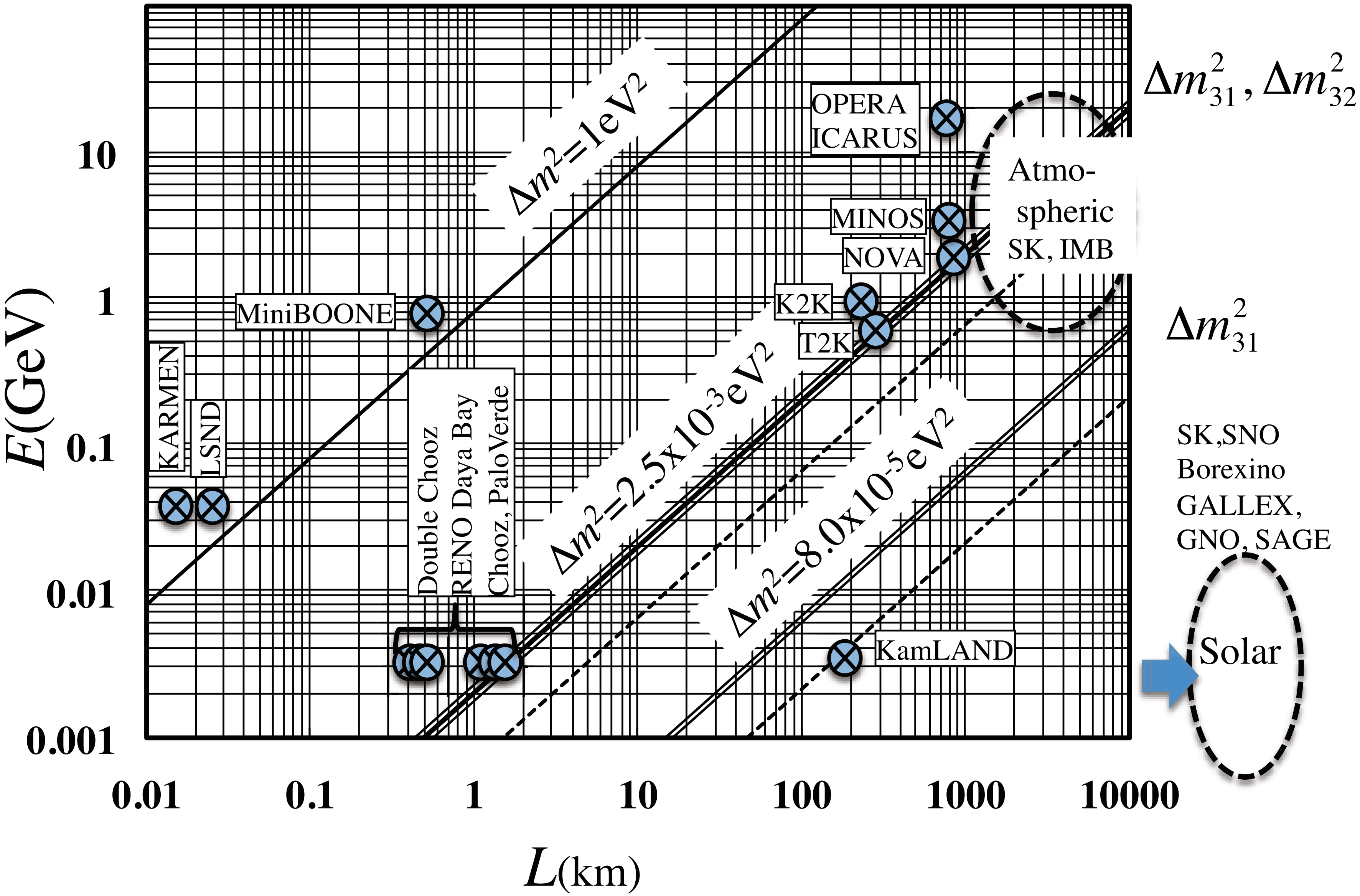
History of Neutrino Oscillation measurements

(Sorry this is not exhaustive list.)

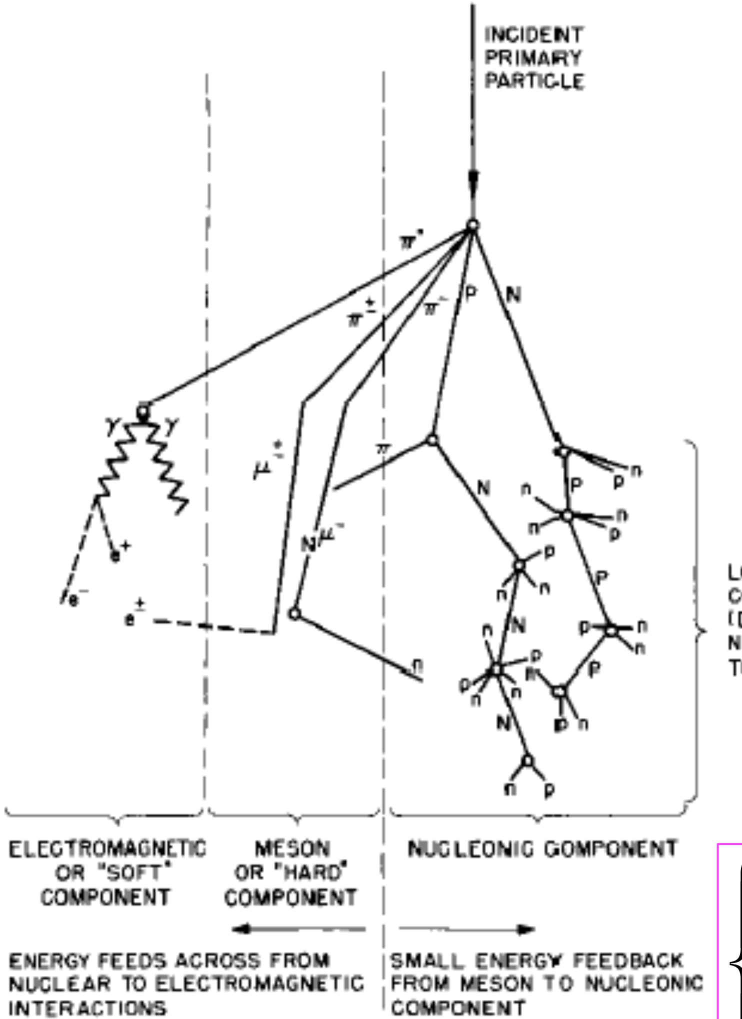


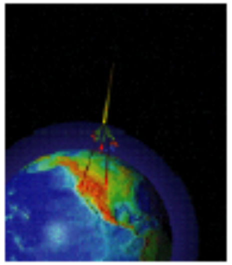
How neutrino oscillations have been measured?

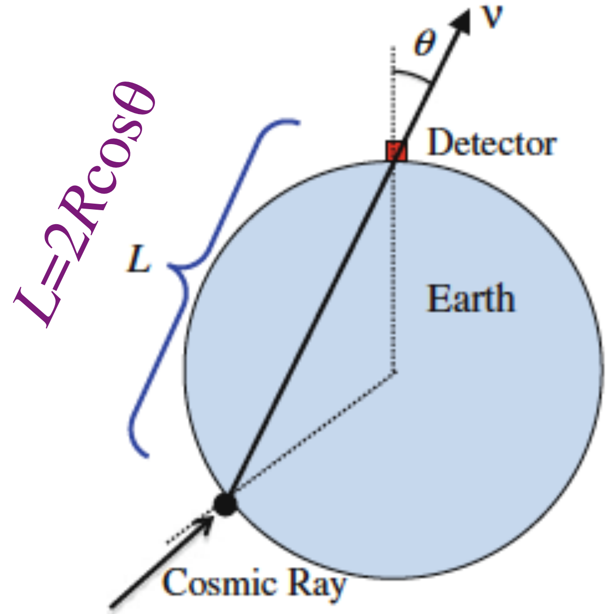
L-E relation of Neutrino Oscillation Experiments



Atmospheric ν anomaly (<1997)



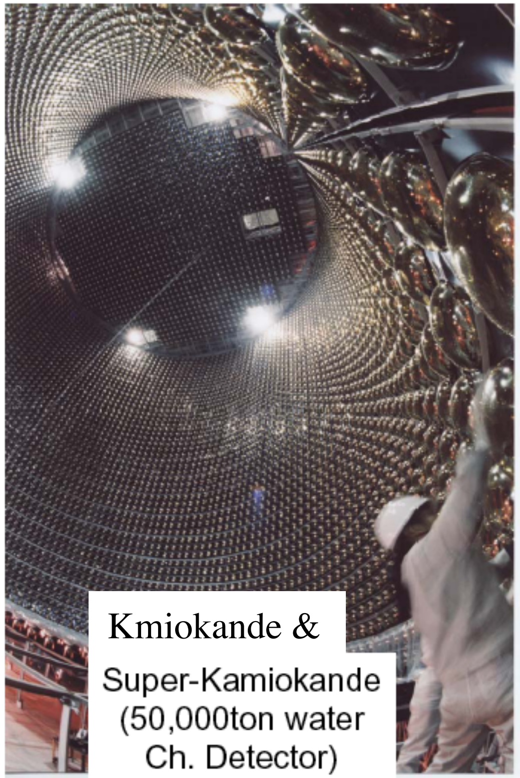




$$\begin{cases} \pi^{\pm} \rightarrow \mu^{\pm} + \left(\nu_{\mu}/\bar{\nu}_{\mu}\right) \\ \mu^{\pm} \rightarrow e^{\pm} + \left(\bar{\nu}_{\mu}/\nu_{\mu}\right) + \left(\nu_{e}/\bar{\nu}_{e}\right) \end{cases}$$

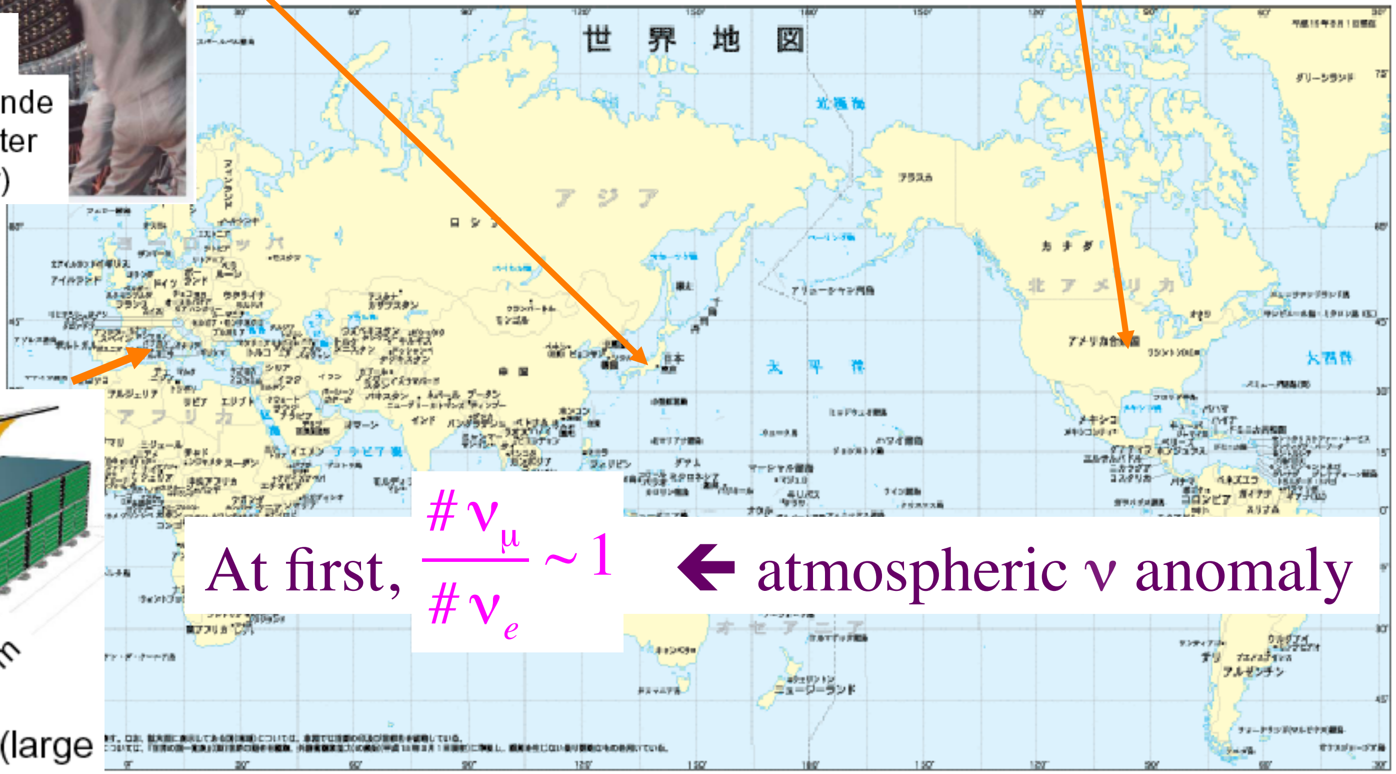
$$\frac{\# \nu_{\mu}}{\# \nu_{e}} = 2$$

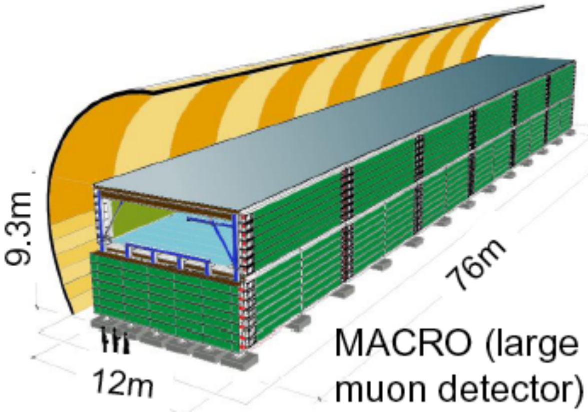
Atmospheric ν experiments



Kmiokande &
Super-Kamiokande
(50,000ton water
Ch. Detector)

Soudan-2 (1kton





MACRO (large
muon detector)

At first, $\frac{\#\nu_\mu}{\#\nu_e} \sim 1$ ← atmospheric ν anomaly

Evidence for oscillation of atmospheric neutrinos

1998

The Super-Kamiokande Collaboration

Y.Fukuda[a], T.Hayakawa[a], E.Ichihara[a], K.Inoue[a], K.Ishihara[a], H.Ishino[a], Y.Itow[a], T.Kajita[a],
J.Kameda[a], S.Kasuga[a], K.Kobayashi[a], Y.Kobayashi[a], Y.Koshio[a], M.Miura[a], M.Nakahata[a],
S.Nakayama[a], A.Okada[a], K.Okumura[a], N.Sakurai[a], M.Shiozawa[a], Y.Suzuki[a], Y.Takeuchi[a], Y.Totsuka[a],
S.Yamada[a], M.Earl[b], A.Habig[b], E.Kearns[b], M.D.Messier[b], K.Scholberg[b], J.L.Stone[b], L.R.Sulak[b],
C.W.Walter[b], M.Goldhaber[c], T.Barszczak[d], D.Casper[d], W.Gajewski[d], P.G.Halverson[d,*], J.Hsu[d],
W.R.Kropp[d], L.R. Price[d], F.Reines[d], M.Smy[d], H.W.Sobel[d], M.R.Vagins[d], K.S.Ganezer[e], W.E.Keig[e],
R.W.Ellsworth[f], S.Tasaka[g], J.W.Flanagan[h,†] A.Kibayashi[h], J.G.Learned[h], S.Matsuno[h], V.J.Stenger[h],
D.Takemori[h], T.Ishii[i], J.Kanzaki[i], T.Kobayashi[i], S.Mine[i], K.Nakamura[i], K.Nishikawa[i], Y.Oyama[i],
A.Sakai[i], M.Sakuda[i], O.Sasaki[i], S.Echigo[j], M.Kohama[j], A.T.Suzuki[j], T.J.Haines[k,d] E.Blaufuss[l],
B.K.Kim[l], R.Sanford[l], R.Svoboda[l], M.L.Chen[m], Z.Conner[m,‡] J.A.Goodman[m], G.W.Sullivan[m], J.Hill[n],
C.K.Jung[n], K.Martens[n], C.Mauger[n], C.McGrew[n], E.Sharkey[n], B.Viren[n], C.Yanagisawa[n], W.Doki[o],
K.Miyano[o], H.Okazawa[o], C.Saji[o], M.Takahata[o], Y.Nagashima[p], M.Takita[p], T.Yamaguchi[p],
M.Yoshida[p], S.B.Kim[q], M.Etoh[r], K.Fujita[r], A.Hasegawa[r], T.Hasegawa[r], S.Hatakeyama[r], T.Iwamoto[r],
Suzuki[r], F.Tsushima[r], M.Koshiba[s], M.Nemoto[t],
a[u], K.Kaneyuki[u], Y.Watanabe[u], D.Kielczewska[v,d],
L.L.Wai[w,**], R.J.Wilkes[w], K.K.Young[w]

5138 cites
(as of 28/05/2017)

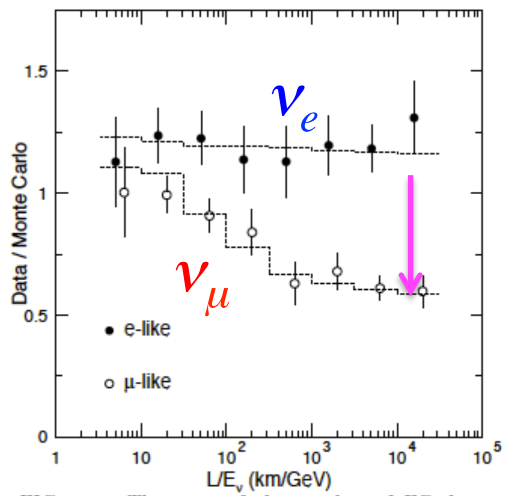


FIG. 4. The ratio of the number of FC data events to FC Monte Carlo events versus reconstructed L/E_ν. The points show the ratio of observed data to MC expectation in the absence of oscillations. The dashed lines show the expected shape for $\nu_\mu \leftrightarrow \nu_\tau$ at $\Delta m^2 = 2.2 \times 10^{-3}\text{eV}^2$ and $\sin^2 2\theta = 1$. The slight L/E_ν dependence for e-like events is due to contamination (2-7%) of ν_μ CC interactions.

ν_μ disappeared due to N.O.

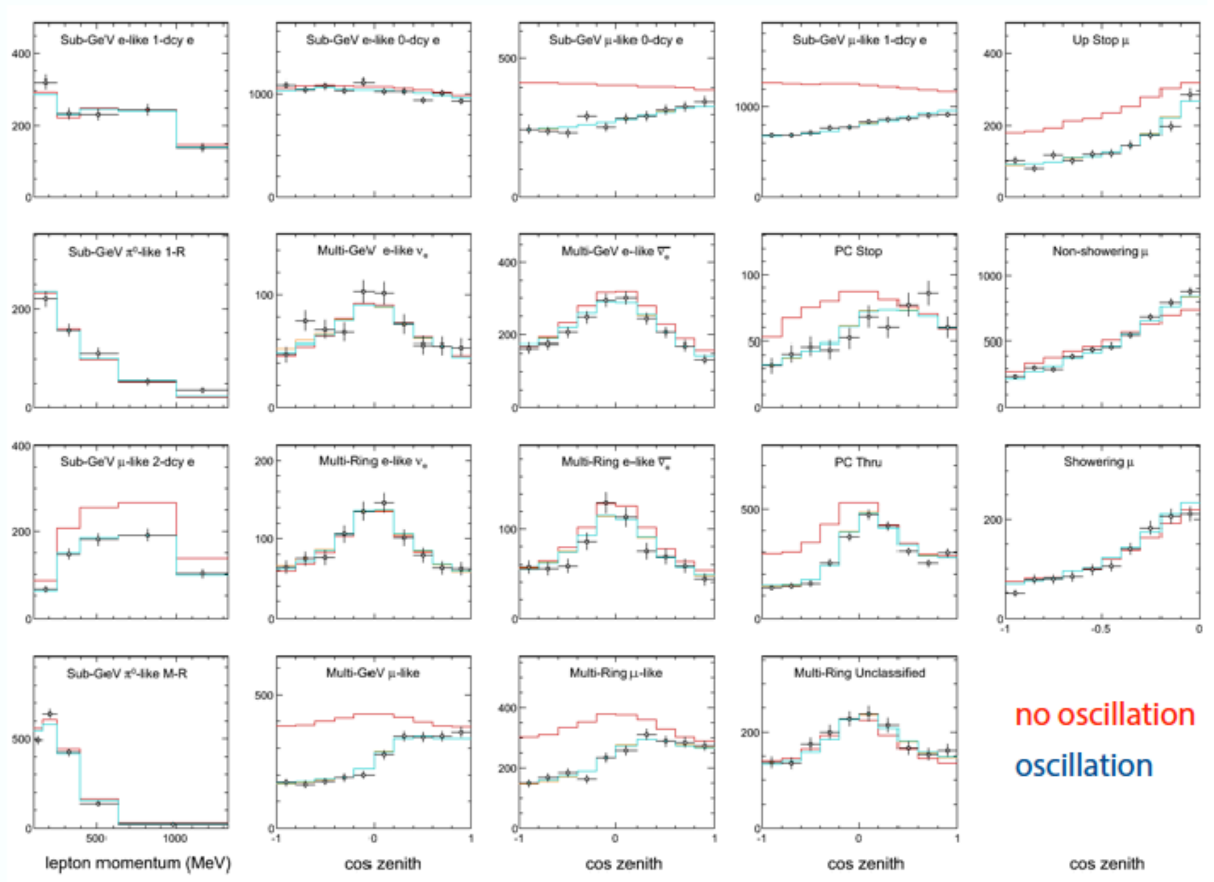
$\sin^2 2\theta \sim 1$
$\Delta m^2 \sim 2\text{x}10^{-3}\text{eV}^2$

2015 Nobel Prize
Takaaki Kajita

Photo: A. Mahmoud
Takaaki Kajita

Recent Progresses

Super-K Updated Data

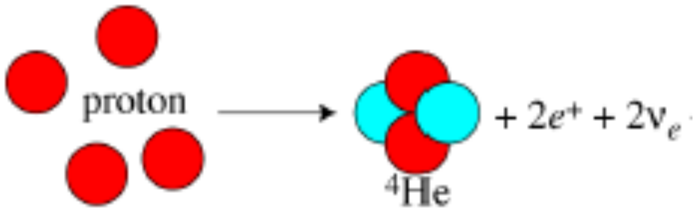


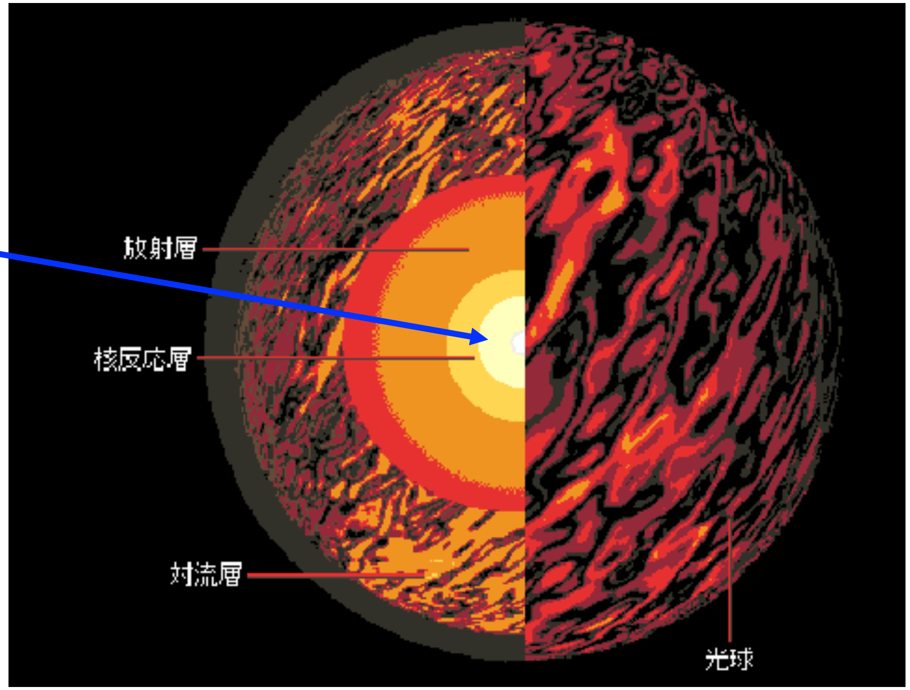
Errors have become much smaller

Solar ν anomaly (<2002?)

Production of solar ν

$\rho_c \approx 150 g/cc, \quad T_c \approx 1.6 KeV$





$$4p + 2e^- \rightarrow {}^4He + \underline{2\nu_e} + 26.73 MeV - E_\nu$$

$$\langle E_\nu \rangle \sim 0.6 MeV$$

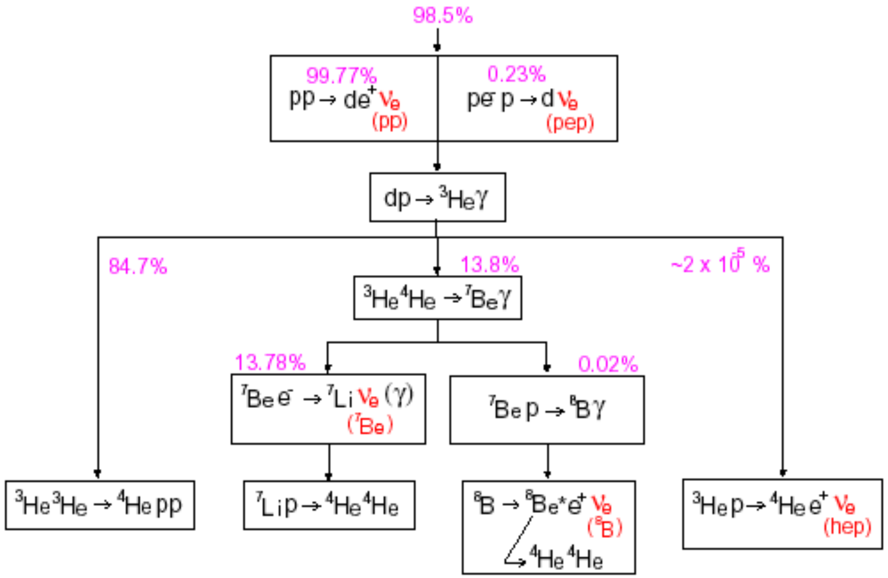
ν flux @ Earth

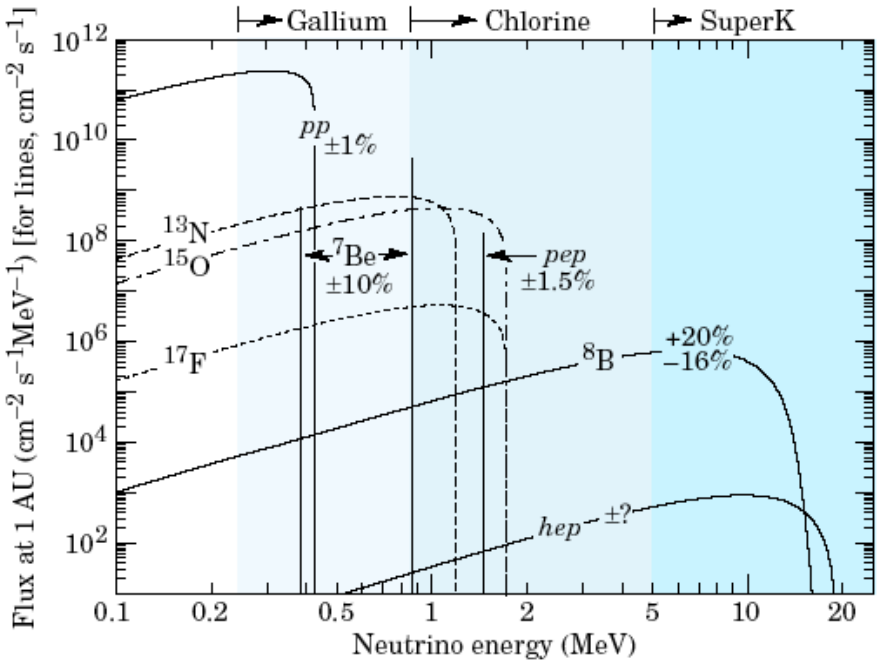
$$J_\nu = \frac{n_\nu}{Q} J_Q \approx \frac{2\nu}{26.1 MeV} \times 8.56 \times 10^{11} \left[MeV/cm^2/s \right] = 6.6 \times 10^{10} \left[\nu/cm^2/s \right]$$

➔ Total number of ν can be precisely known.

Solar neutrino spectrum

However, energy spectrum is somewhat model dependent.





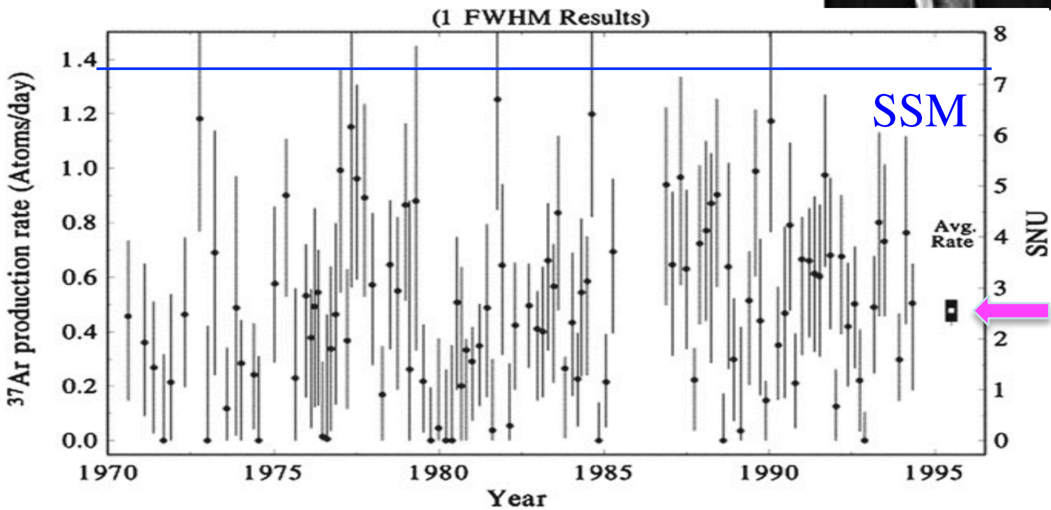
Solar Neutrino Experiments

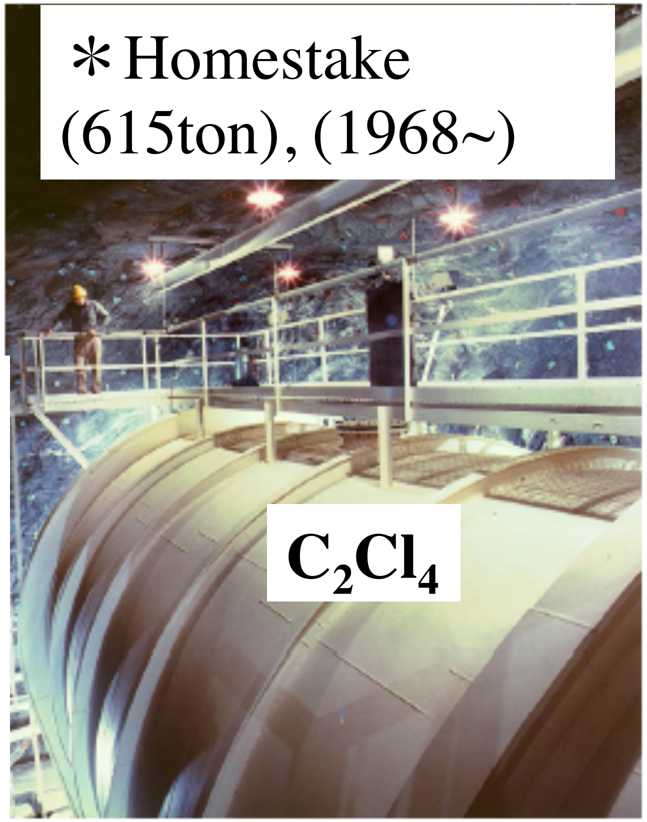
	ν target	ν	rate/SSM
Homestake	Cl	^{8}B	0.31
GALLEX/GNO	Ga	pp	0.51
SAGE	Ga	pp	0.53
SK/Kamiokande	H2O	^{8}B	0.465
SNO	D20	^{8}B	1 (neutral current)
Borexino	CH2	^{7}Be	~0.5

The 1st solar neutrino detection & indication of solar ν deficit

Pioneer of Solar Neutrino Science

2002 Nobel Prize
Raymond Davis Jr.





$$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$$

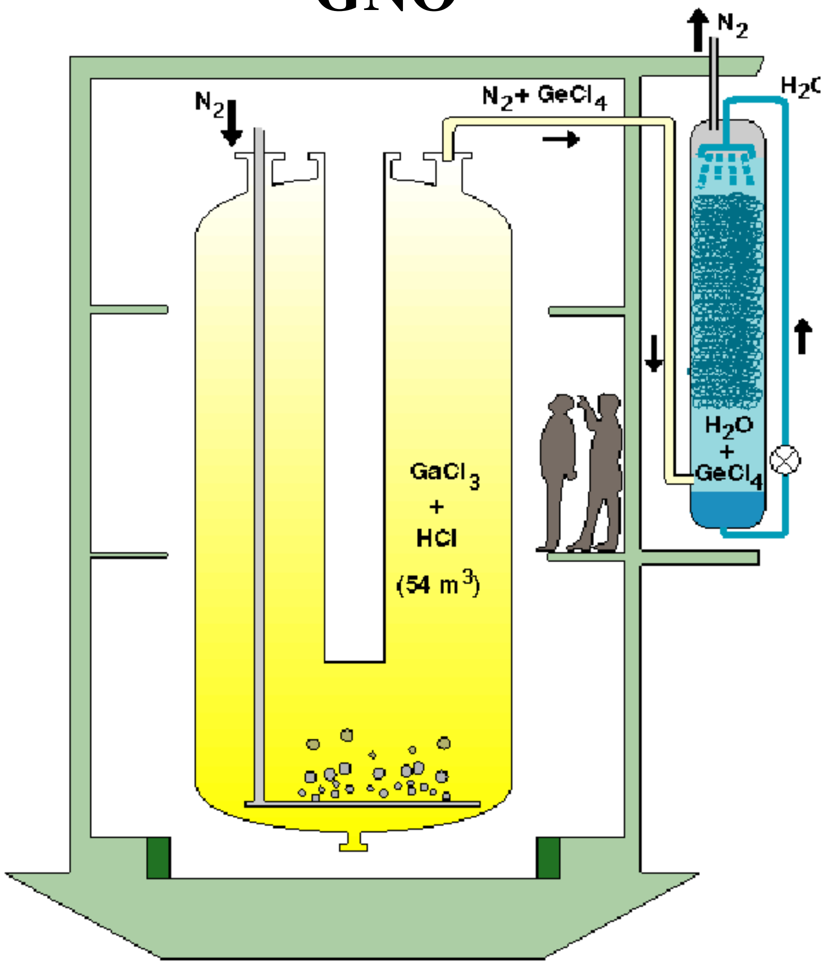
The data showed only 1/3 of prediction.
➔ "solar neutrino problem"

GNO/GALLEX/SAGE to detect *pp*-ν

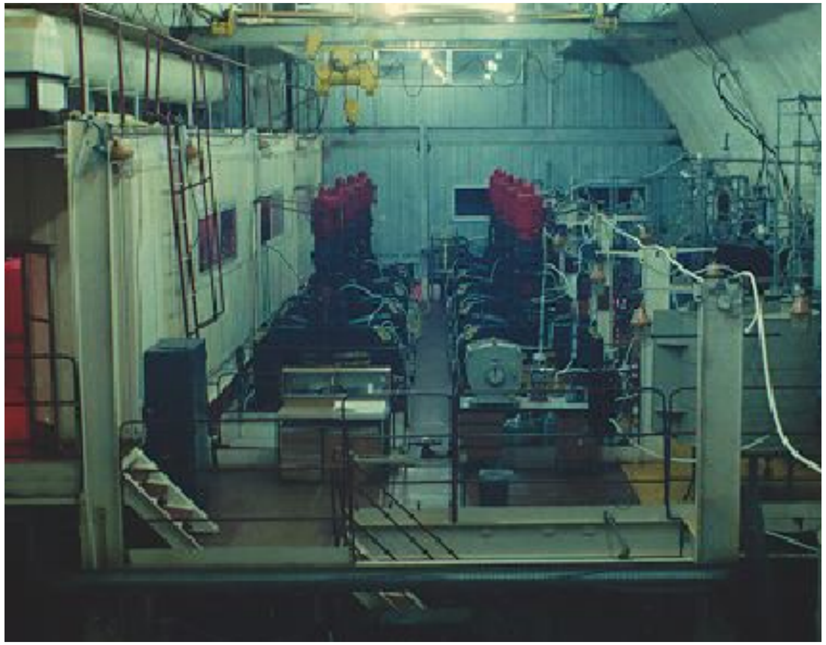
$$\nu_e + {}^{37}Ga \rightarrow e^- + {}^{37}Ge\left(E_{th} = 233KeV\right)$$

$$^{37}Ge \rightarrow {}^{37}Ga + e^- \left(Auger\right) + \nu_e\left(\tau_{1/2} \sim 11days\right)$$

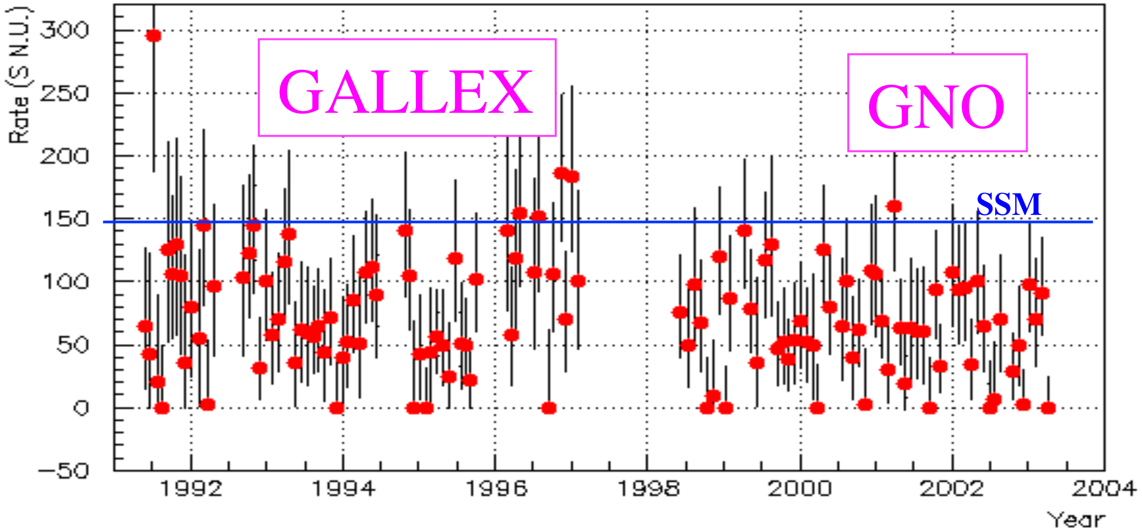
GNO



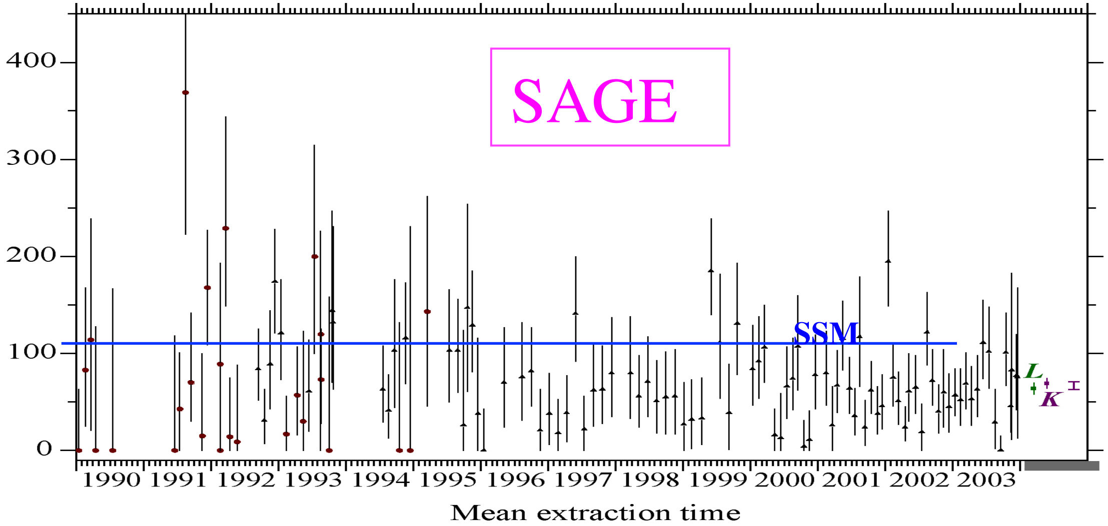
SAGE



Results of GNO/GALLEX/SAGE



DATA/Prediction ~0.51



DATA/Prediction ~0.53

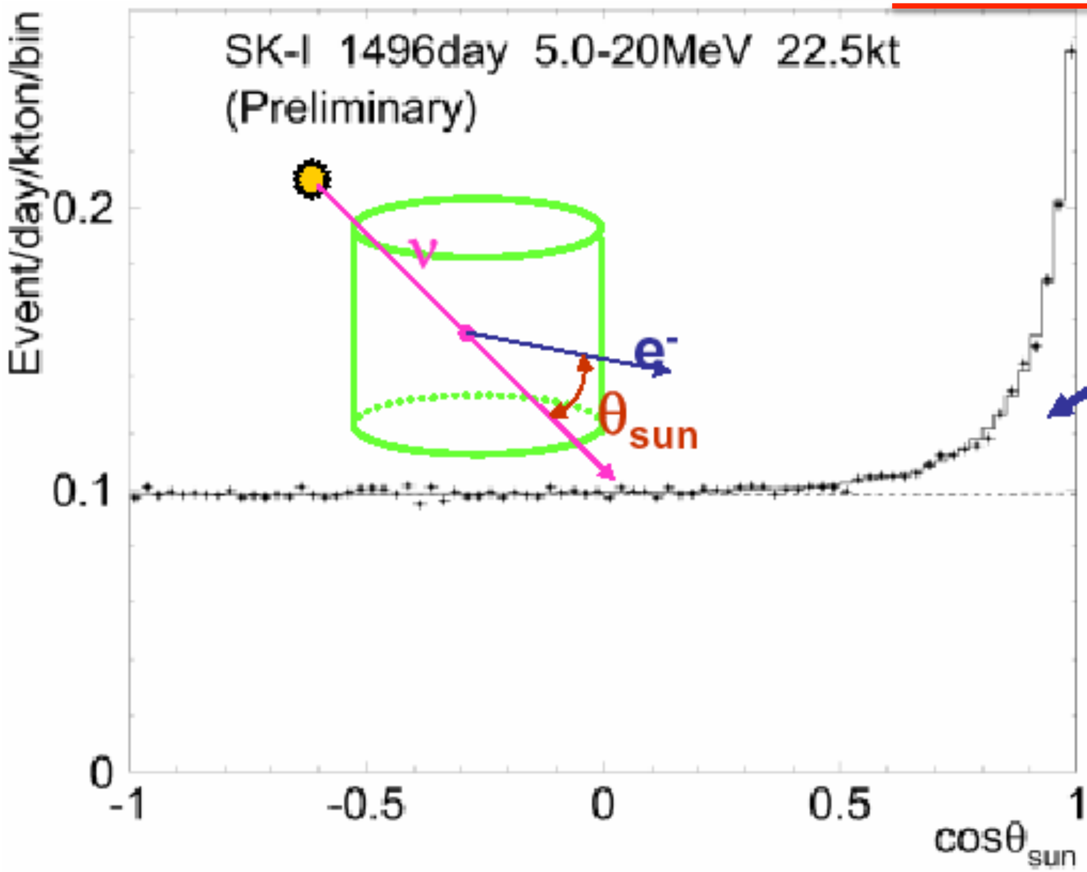
➔ pp-ν also gone to somewhere.

Solar neutrino data from Super-K

flux is

$2.35 \pm 0.02(\text{stat.}) \pm 0.08(\text{sys.}) \times 10^6/\text{cm}^2\cdot\text{s}$

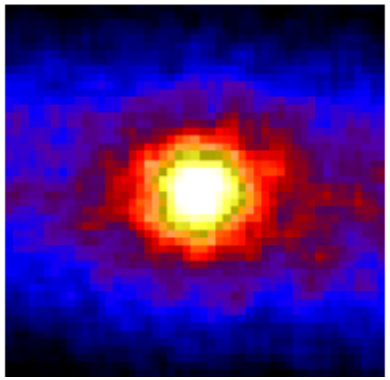
or $0.465 \pm 0.005(\text{stat.})^{+0.016}_{-0.015}(\text{sys.}) \times \text{SSM}$



$\nu e \rightarrow \nu e$

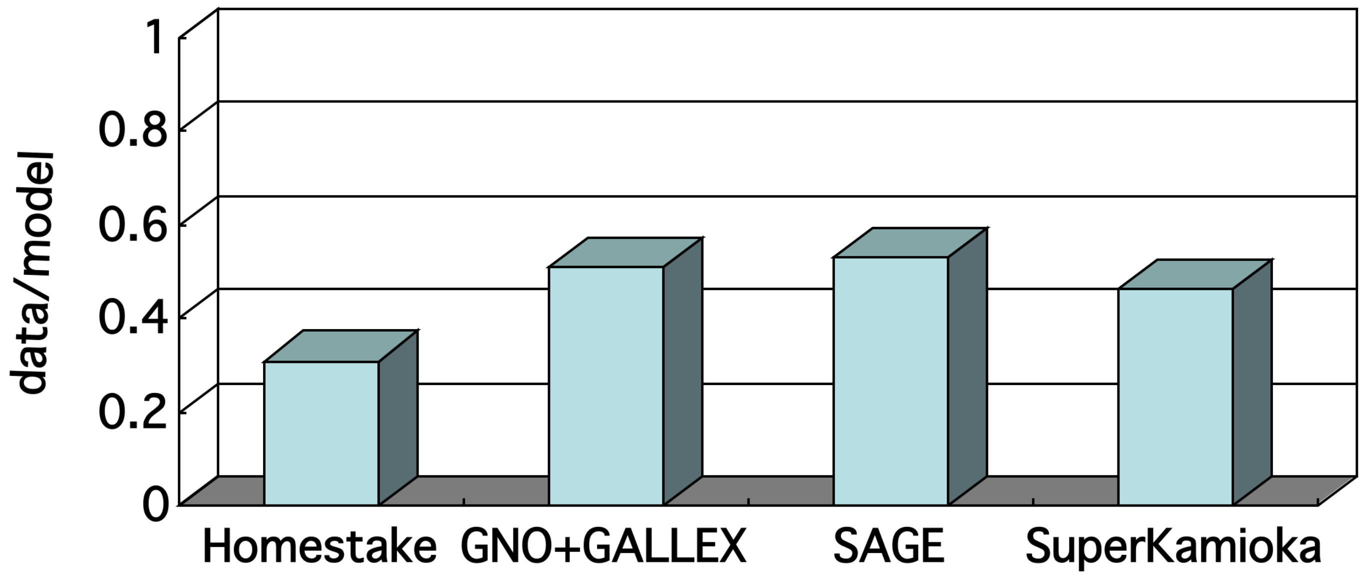
22,400 events

above 5MeV (^{8}B ν)



Solar image by neutrinos

The solar neutrino deficit

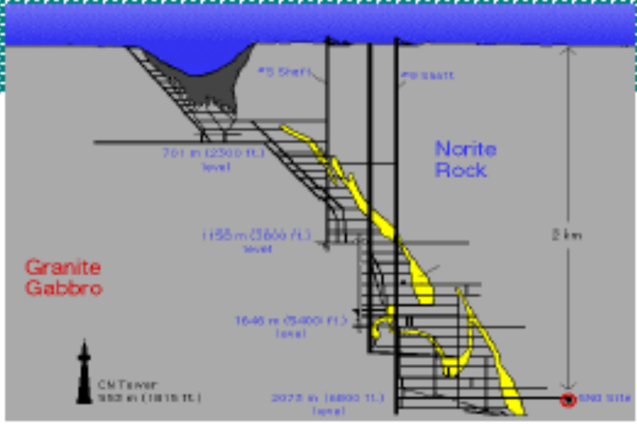


For all the experiments, the observed neutrino fluxes are smaller than predicted value.

Is it due to neutrino oscillation ?
Solar model may be wrong.

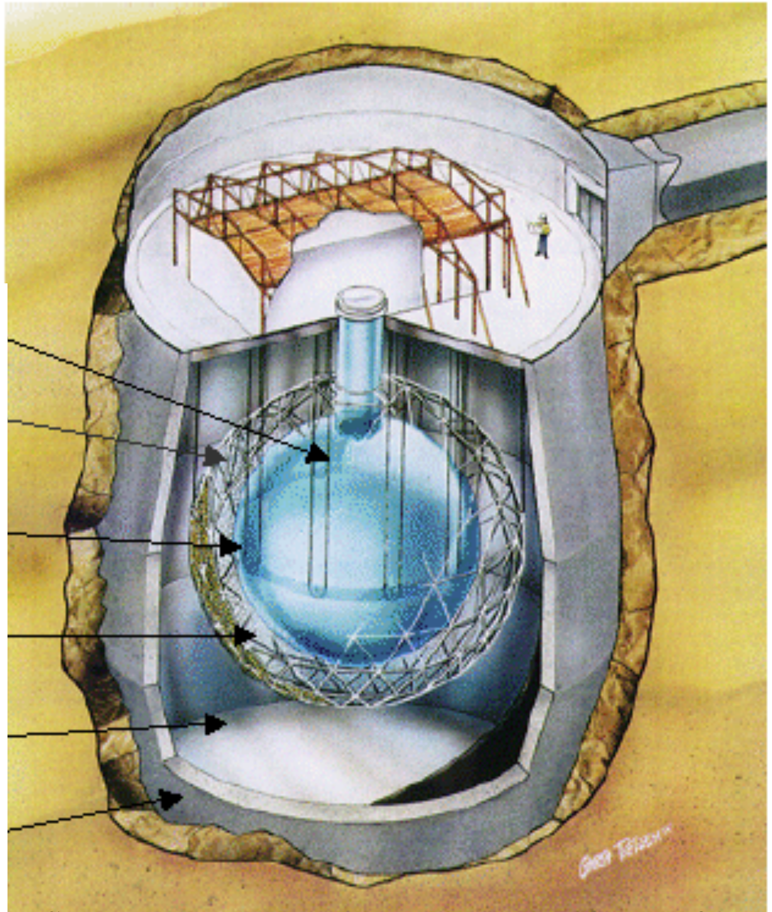
➔ If neutral current interaction is used, it is possible to measure the total (flavor independent) ν flux.

Sudbury Neutrino Observatory



Measure the Neutral Current

1000 tonnes D_2O



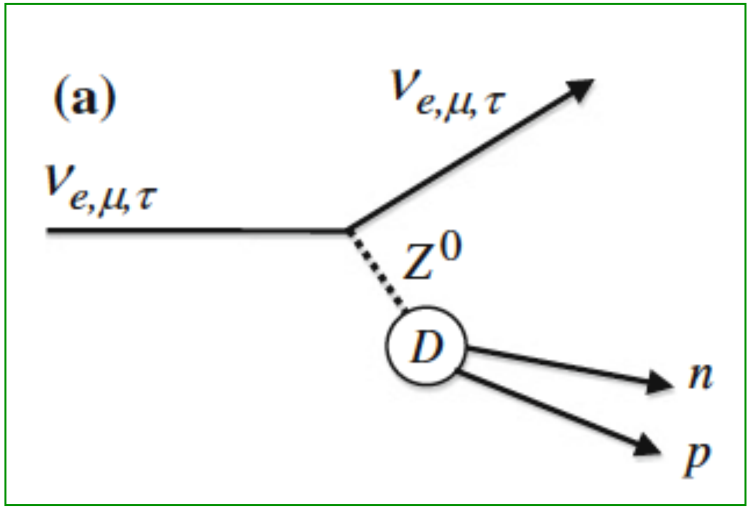
2015 Nobel Prize
Arthur B. McDonald

Photo: A. Mahmoud
Arthur B. McDonald

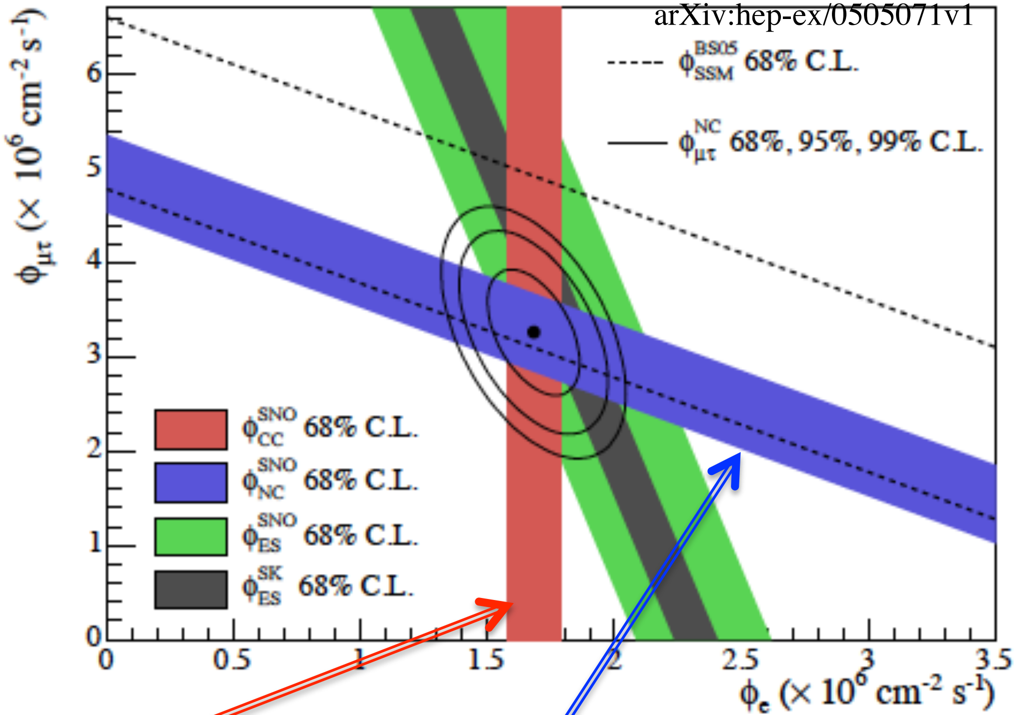
Evidence of Flavor Transmutation： SNO experiment

2002

$$\nu_x + D \rightarrow \nu_x + p + n$$



NC interaction



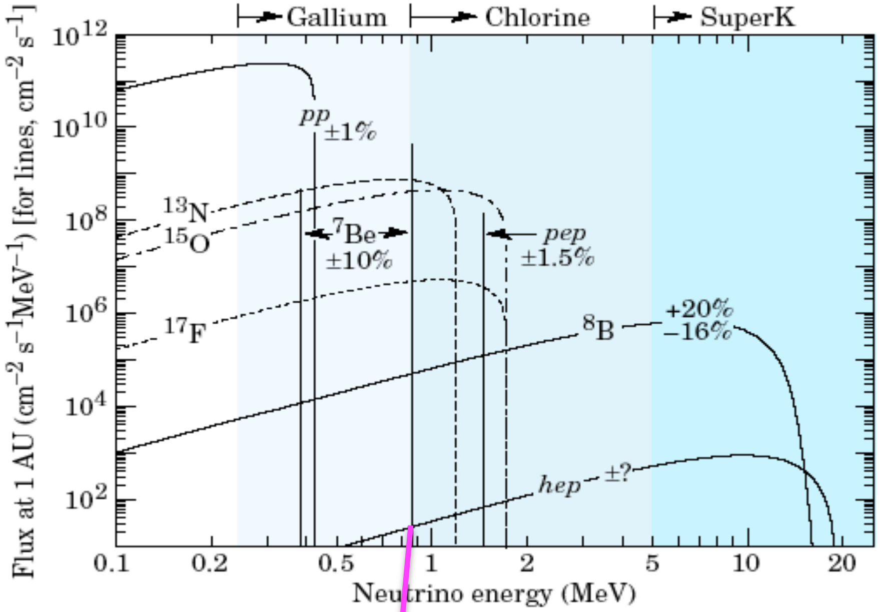
Although $\Phi(\nu_e) < \Phi(SSM)$, $\Phi(\nu_e) + \Phi(\nu_\mu) + \Phi(\nu_\tau) = \Phi(SSM)$

➔ **Solar neutrino problem was solved.**

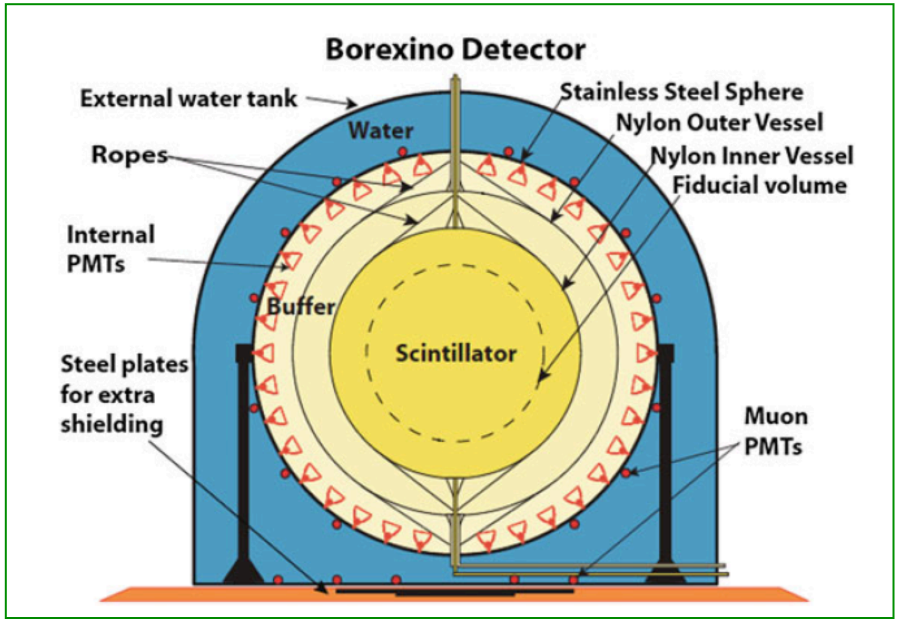
Borexino:

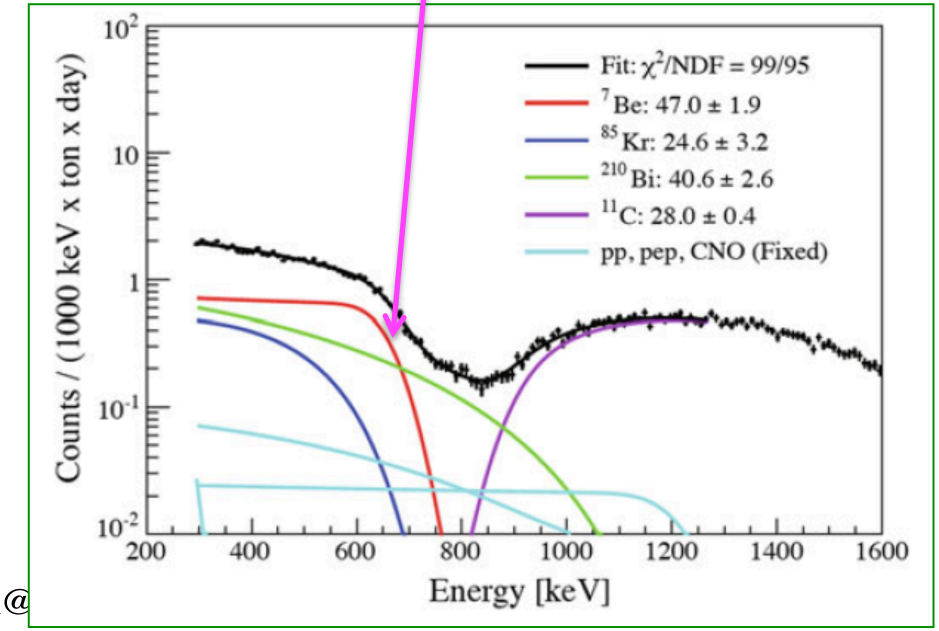
^{7}Be solar neutrino detection,

^{7}Be ν has monochromatic energy at a MSW transition energy



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





Δm_{21}^2 mass hierarchy was determined by using matter effect

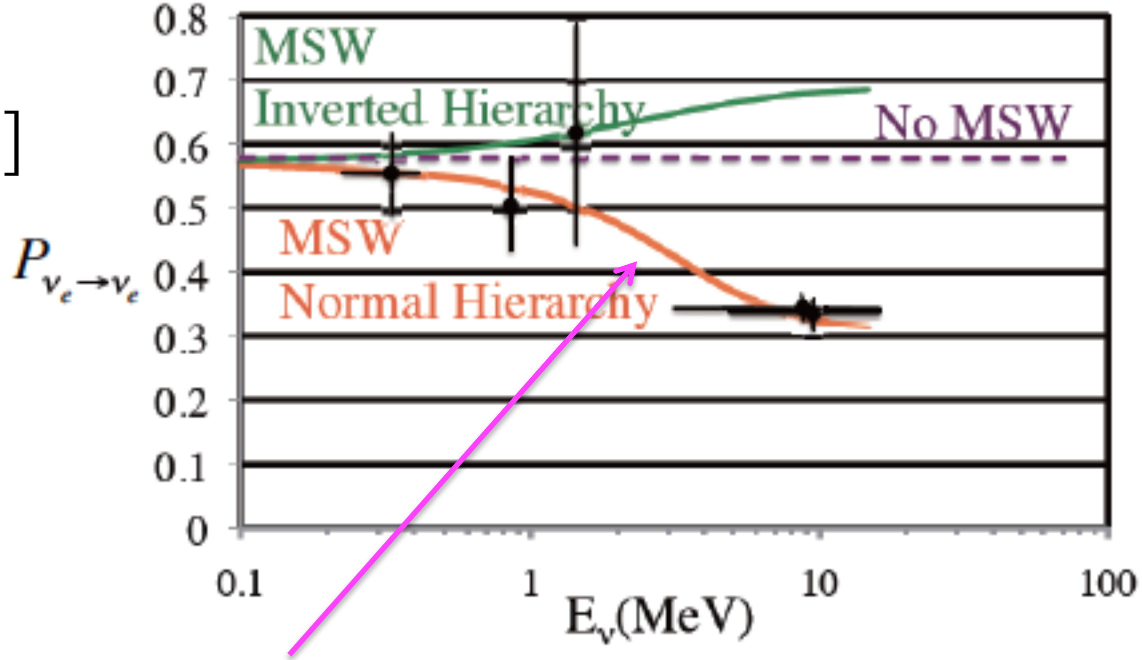
After some lengthy calculation, solar ν flux with matter effect is

$$P(\nu_e \to \nu_e; @solar) \sim \frac{1}{2}\left(1 + \frac{\cos 2\theta_{12}(\cos 2\theta_{12} - V_W)}{\sqrt{(\cos 2\theta_{12} - V_W)^2 + \sin^2 2\theta_{12}}}\right)$$

Weak potential

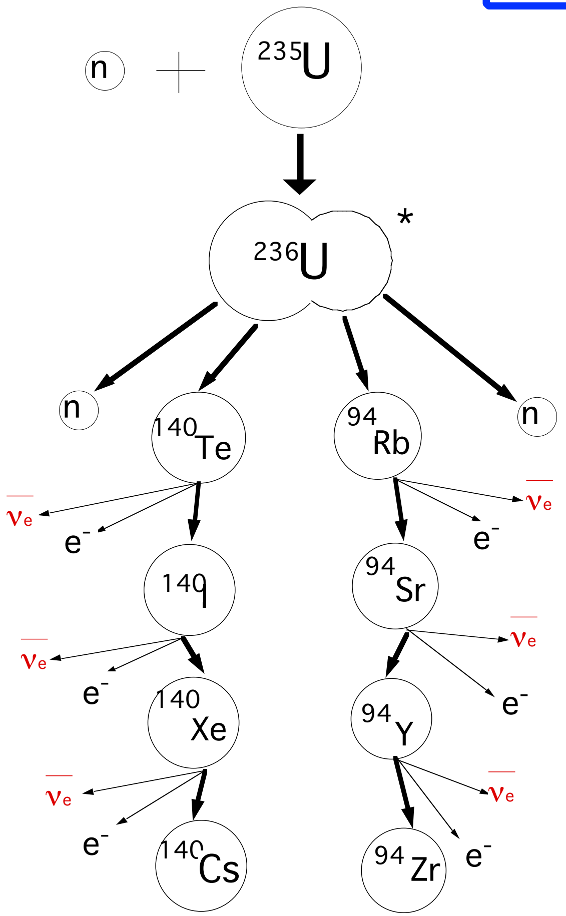
$$|V_W| = \frac{2\sqrt{2} E G_F n_e}{\Delta m_{21}^2} \sim 0.25 E[MeV]$$

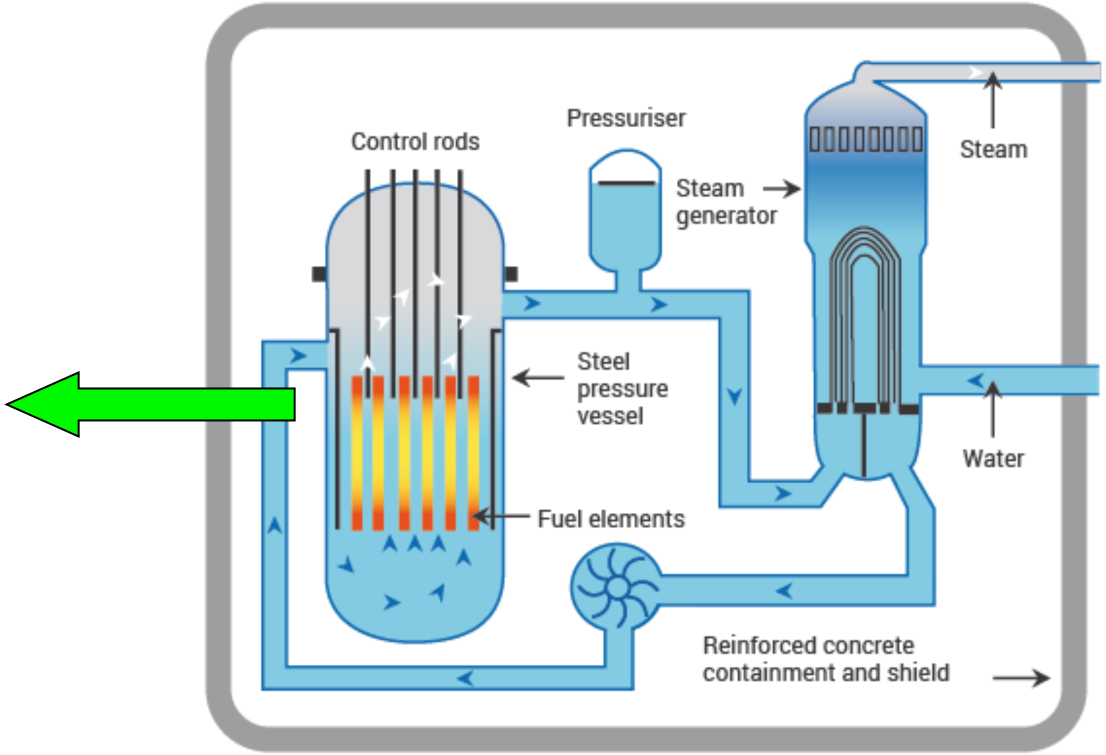
V_W changes sign depending on the mass hierarchy



$V_W > 0 \Rightarrow m_2 > m_1$ was determined here.

Reactor Neutrino





~6ν/fission & ~200MeV/fission

$$\sim 6 \times 10^{20} \, \bar{\nu}_e \, / \, s \, / \, 1\text{GWe reactor}$$

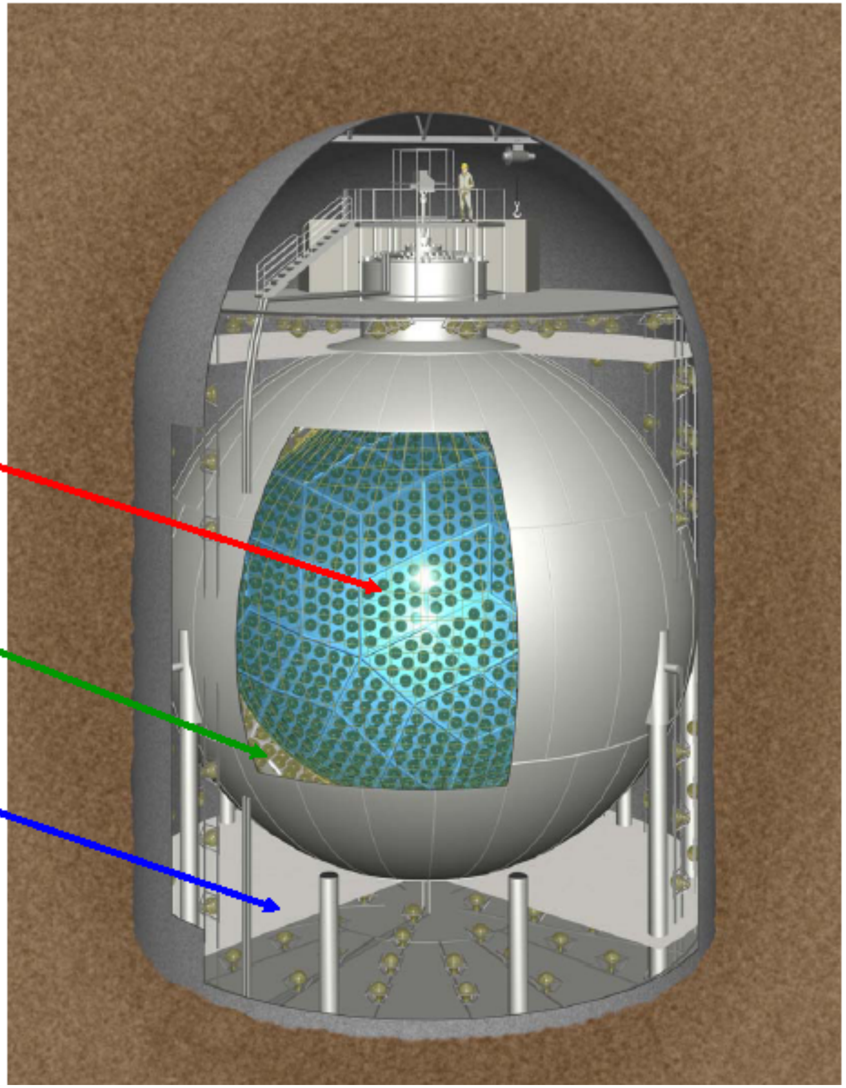
$\bar{\nu}_e$ are produced in β decays of fission products

E_ν~4MeV

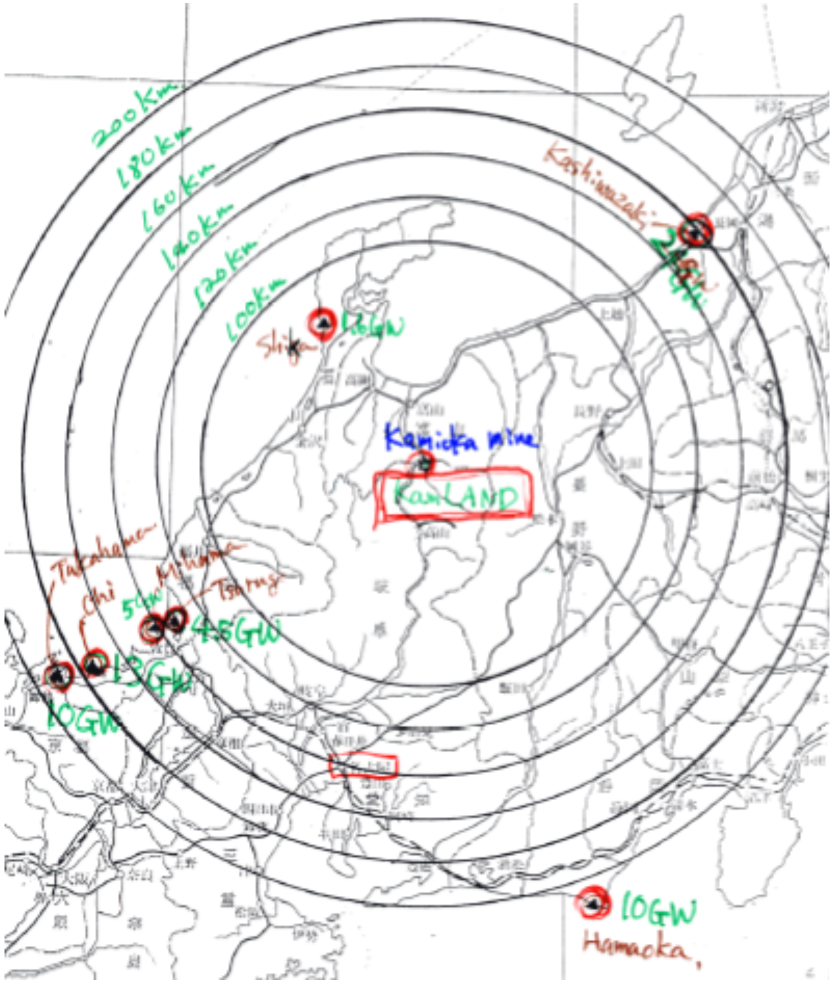
KamLAND and θ_{12}, Δm^2_{12}

KamLAND:
Kamioka Liquid scintillator AntiNeutrino Detector

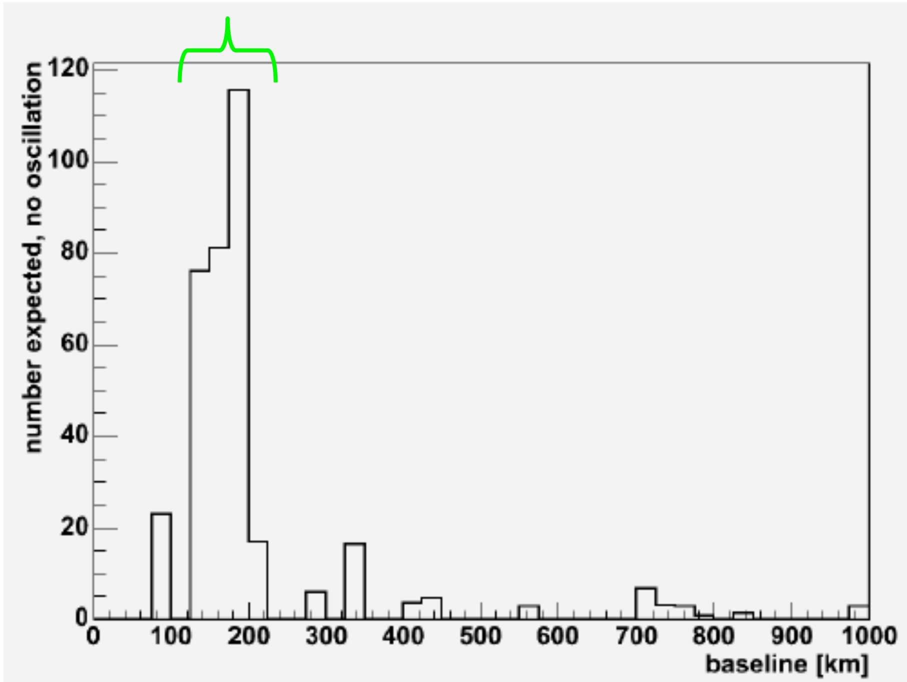
- 1 kton liq. Scint. Detector in the Kamiokande cavern
- 1325 17" fast PMTs
- 554 20" large area PMTs
- 34% photocathode coverage
- H_2O Cerenkov veto counter



KamLAND and Rectors



68GWth

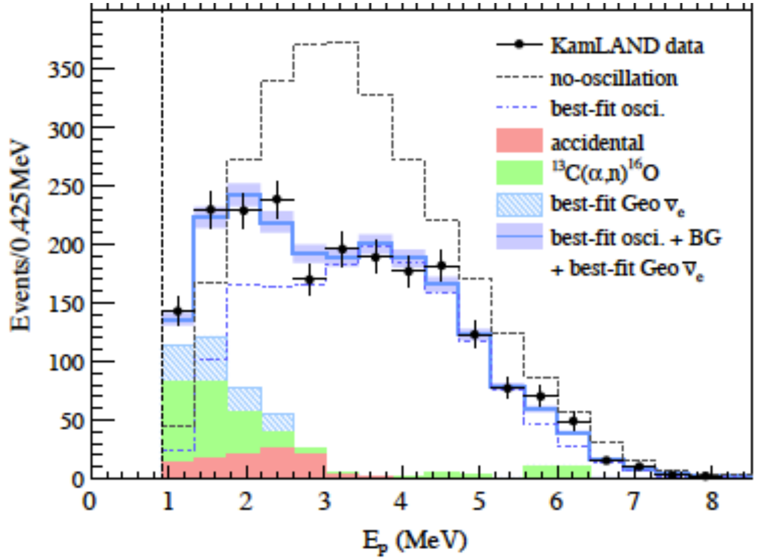


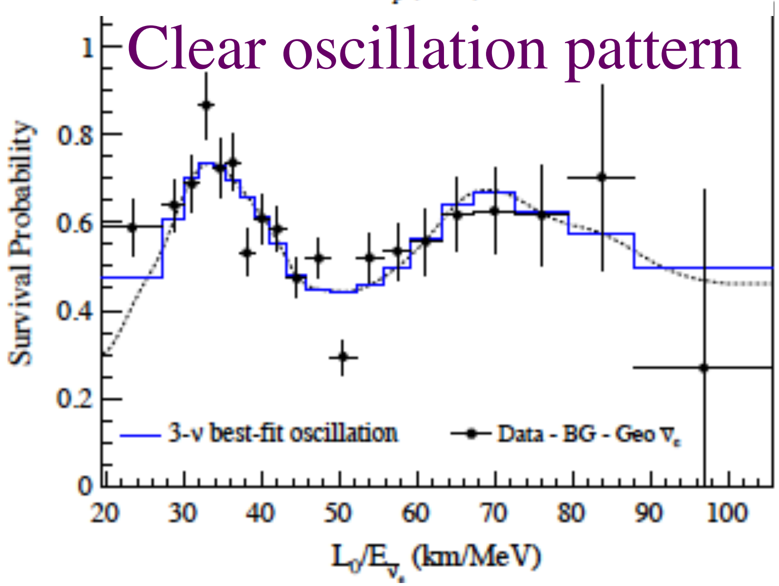
<Baseline>~180km

Although there are many reactors, the baselines are rather unique.

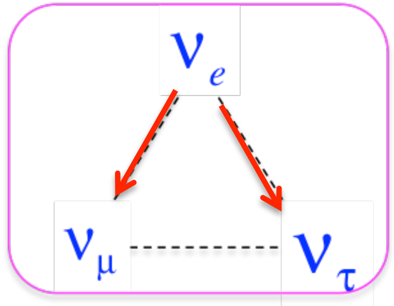
~One gigantic reactor ($68GW_{th}$) @ L~180km

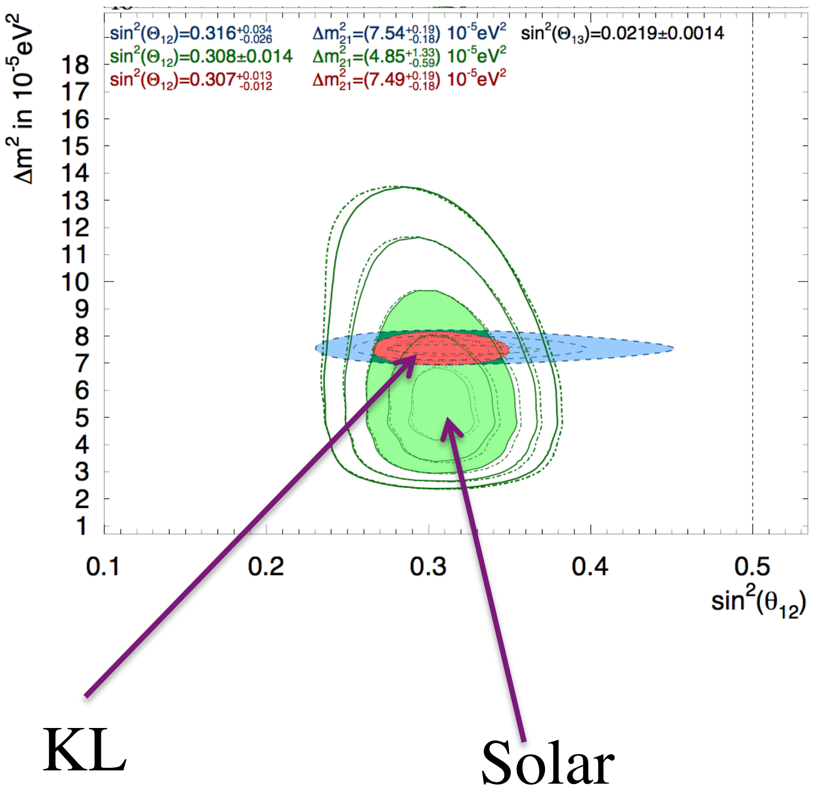
Results





Clear oscillation pattern





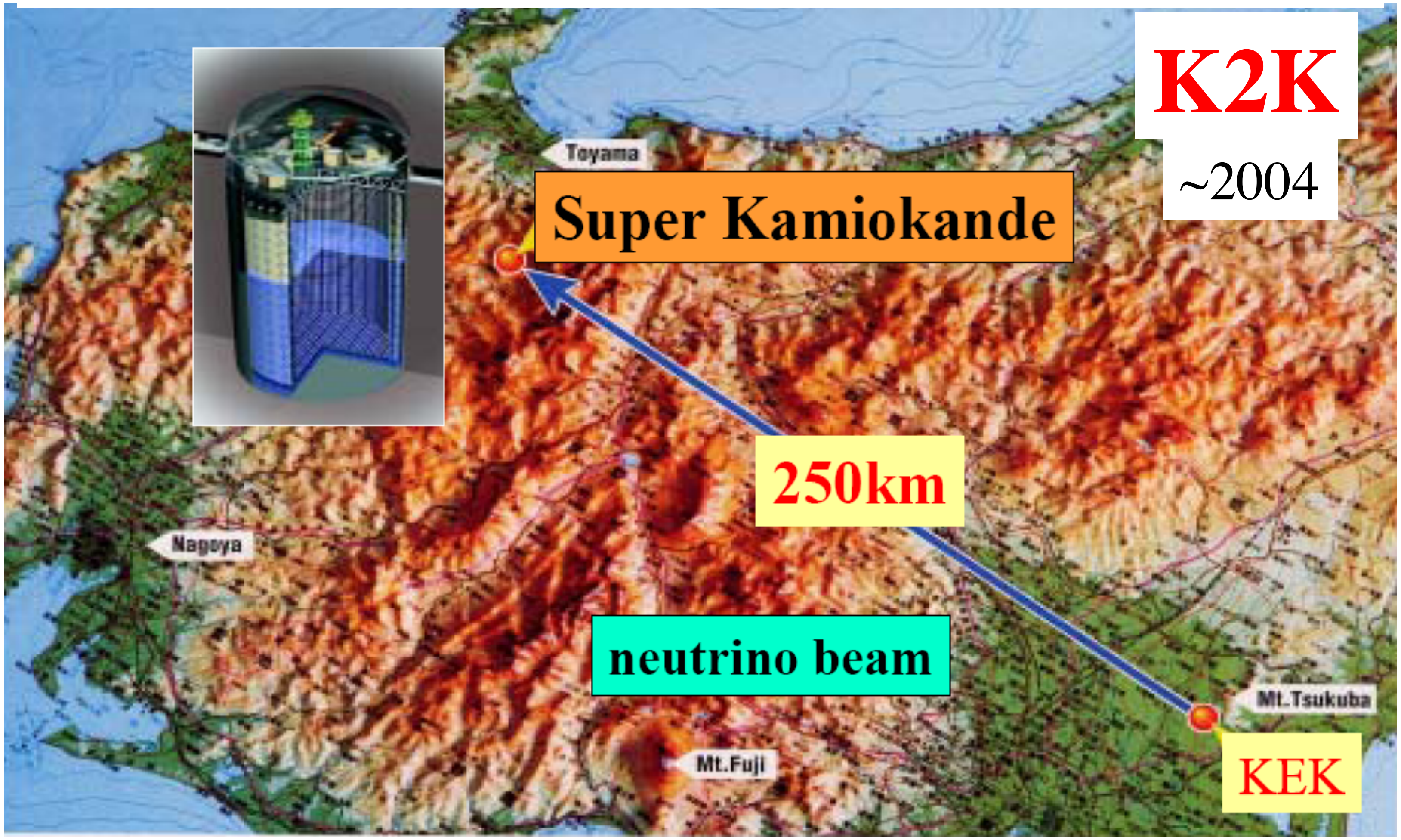
There is a slight tension in Δm^2 between KL and Solar ν exp.

$$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}, \quad |\Delta m^2_{21}| = 7.53^{+0.18}_{-0.18}\times 10^{-5}\,eV^2$$

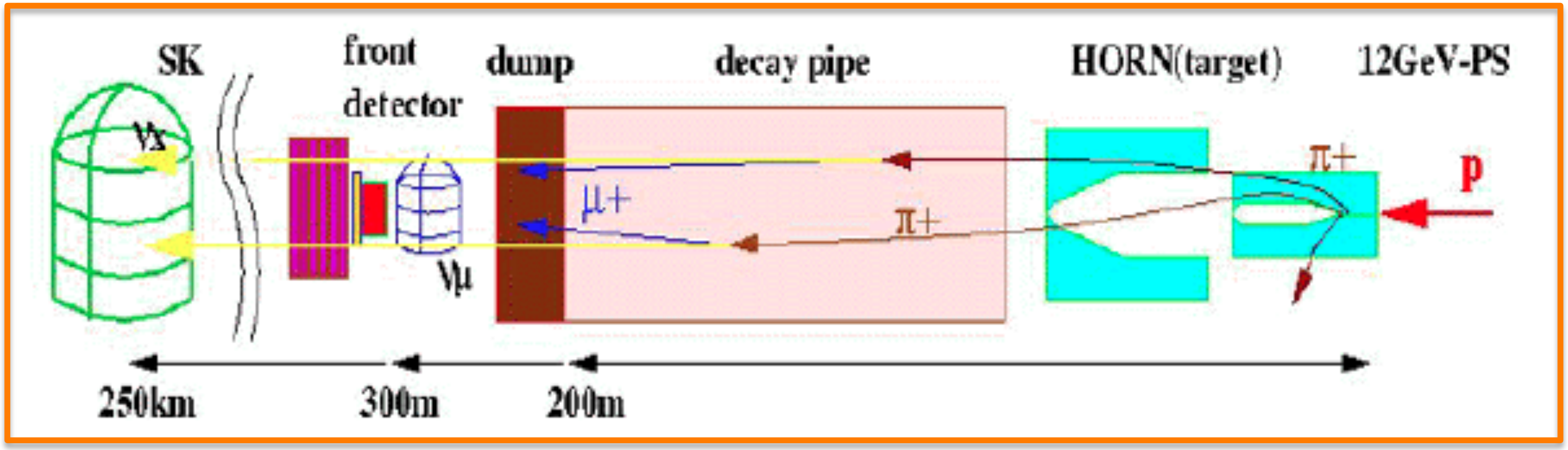
Accelerator based experiments

The 1st one= K2K=KEK to Kamioka

Check the atmospheric ν oscillation using man-made ν.



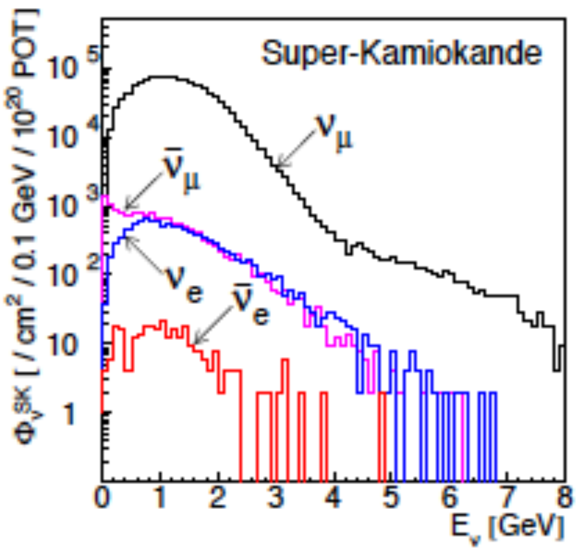
How ν beam was generated



$$p + A \rightarrow \pi^+ : \pi^+ \rightarrow \mu^+ + \underline{\underline{\nu_\mu}}$$

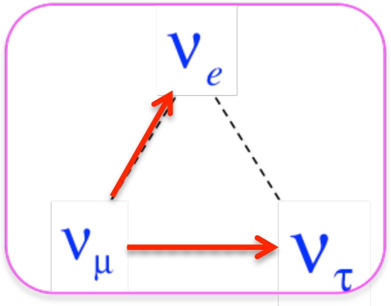
$$\frac{\pi^+ \rightarrow e^+ + \nu_e}{\pi^+ \rightarrow \mu^+ + \nu_\mu} \sim 10^{-4}$$

(Helicity Suppression => Almost pure ν_μ



$P(\nu_\mu \rightarrow \nu_\mu)$

K2K result



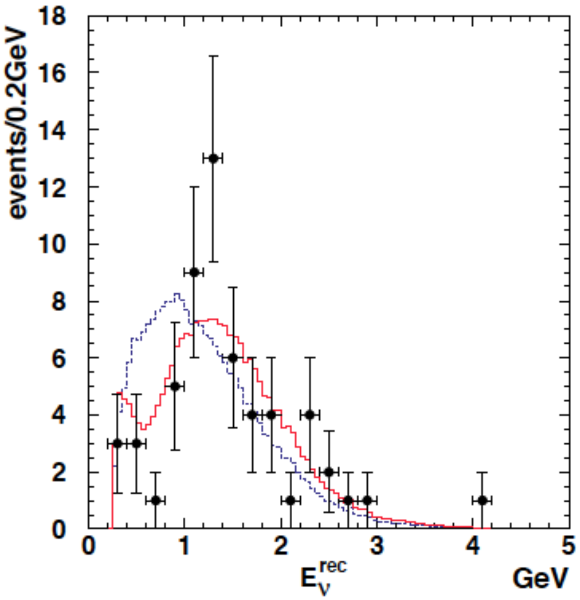


FIG. 43: The reconstructed E_ν distribution for the 1-ring μ-like sample. Points with error bars are data. The solid line is the best fit spectrum with neutrino oscillation and the dashed line is the expectation without oscillation. These histograms are normalized by the number of events observed (58).

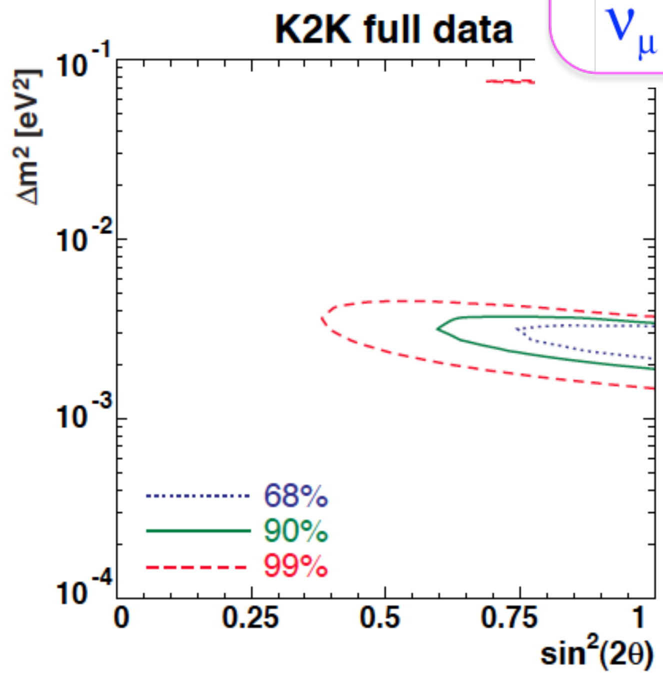


FIG. 44: Allowed regions of oscillation parameters. Three contours correspond to the 68% (dotted line), 90% (solid line) and 99% (dashed line) CL. allowed regions, respectively.

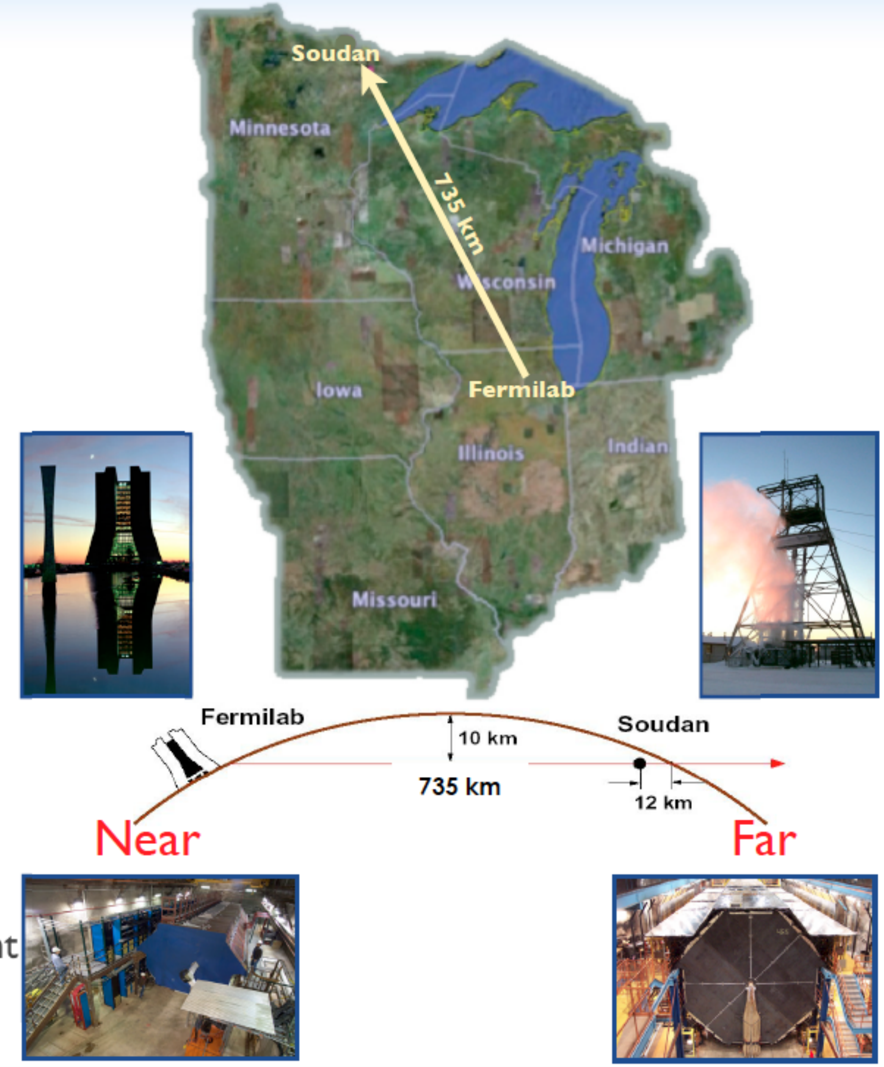
$\sin^2 2\theta \sim 1$

$\Delta m^2 = \left(2.8^{+0.7}_{-0.9}\right) \times 10^{-3} \left[eV^2\right] (90\% CL)$

➔ Consistent with atmospheric ν result

MINOS Overview

- **MINOS (Main Injector Neutrino Oscillation Search)**
  - High intensity **NuMI ν_μ beam** produced at Fermilab
  - **Near Detector** at Fermilab
  - **Far Detector**, 735 km away, in the Soudan mine, MN
- Magnetized detectors allow unique ability to distinguish between ν_μ and $\bar{\nu}_\mu$ charged-current interactions on an event-by-event basis
- Compare Far Detector observations with extrapolation of Near Detector measurement to study neutrino oscillations

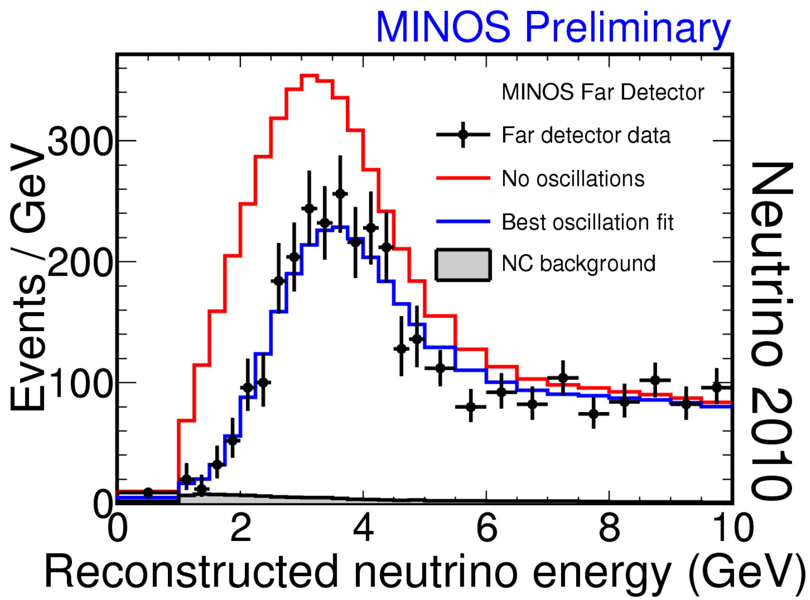


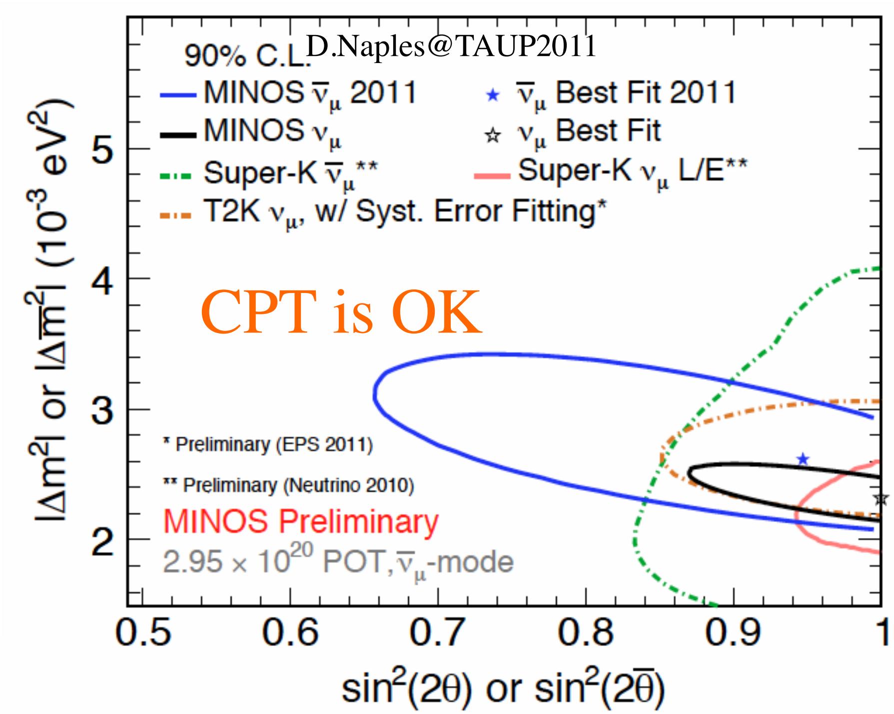
MINOS $\bar{\nu}_\mu \to \bar{\nu}_\mu$ oscillation measurement

$$p + Z \to n\pi^- + m\pi^+ + X$$

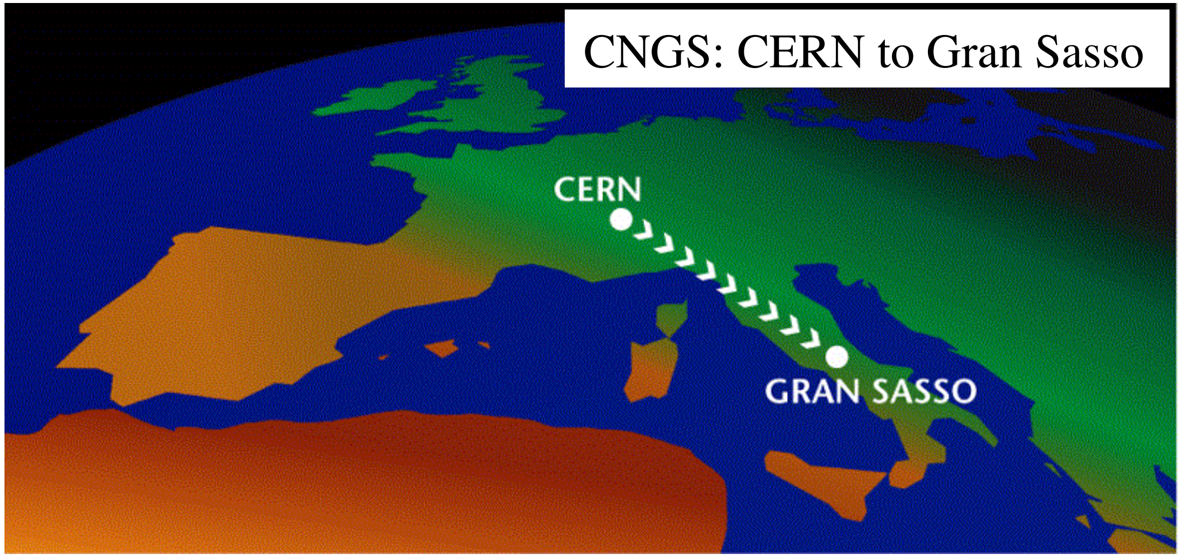
$$\pi^+ \to \nu_\mu + \mu^+ : \nu_\mu \to \nu_\mu : \nu_\mu + A \to \mu^- + X$$

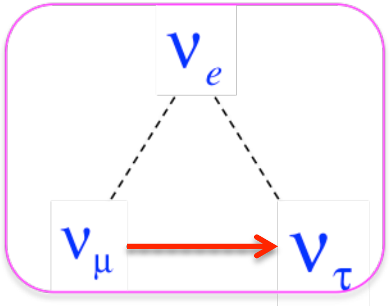
$$\pi^- \to \bar{\nu}_\mu + \mu^- : \bar{\nu}_\mu \to \bar{\nu}_\mu : \bar{\nu}_\mu + A \to \mu^+ + X$$

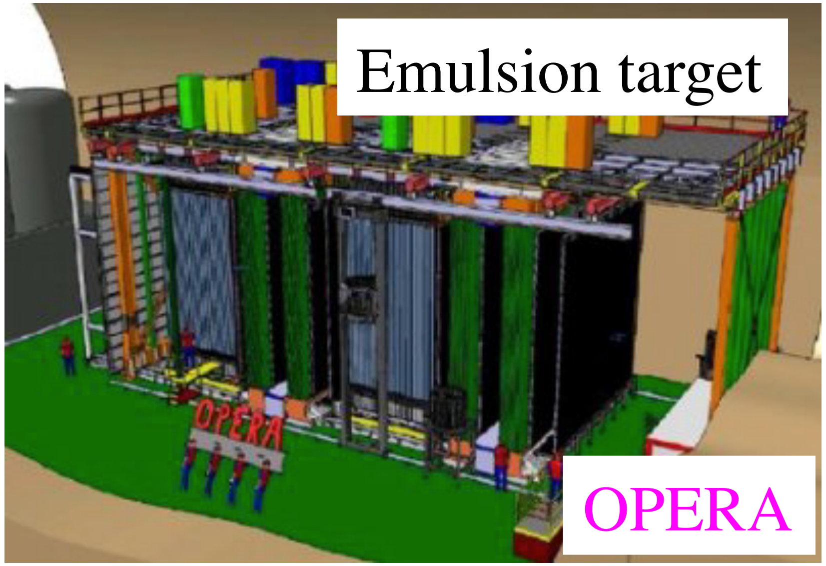


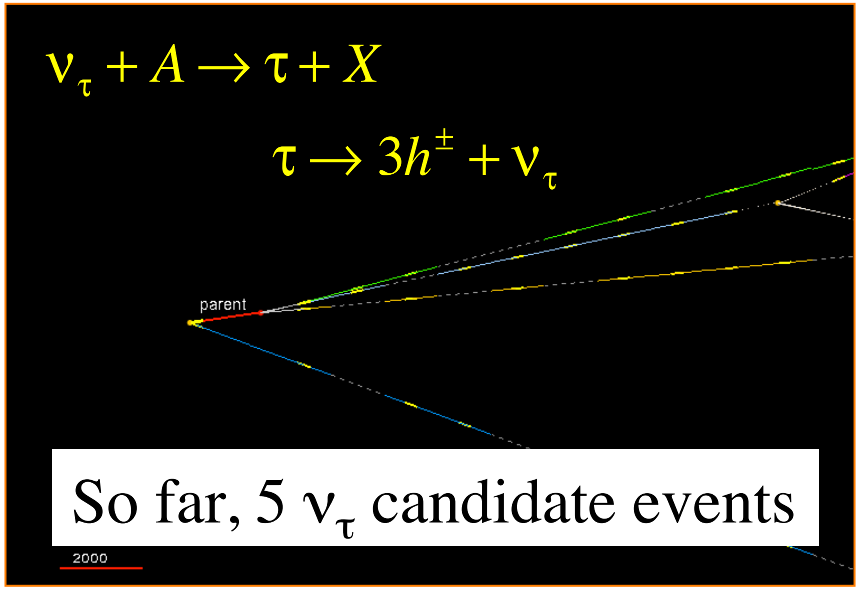


OPERA Exp. @ Gran Sasso: Direct ν_τ appearance



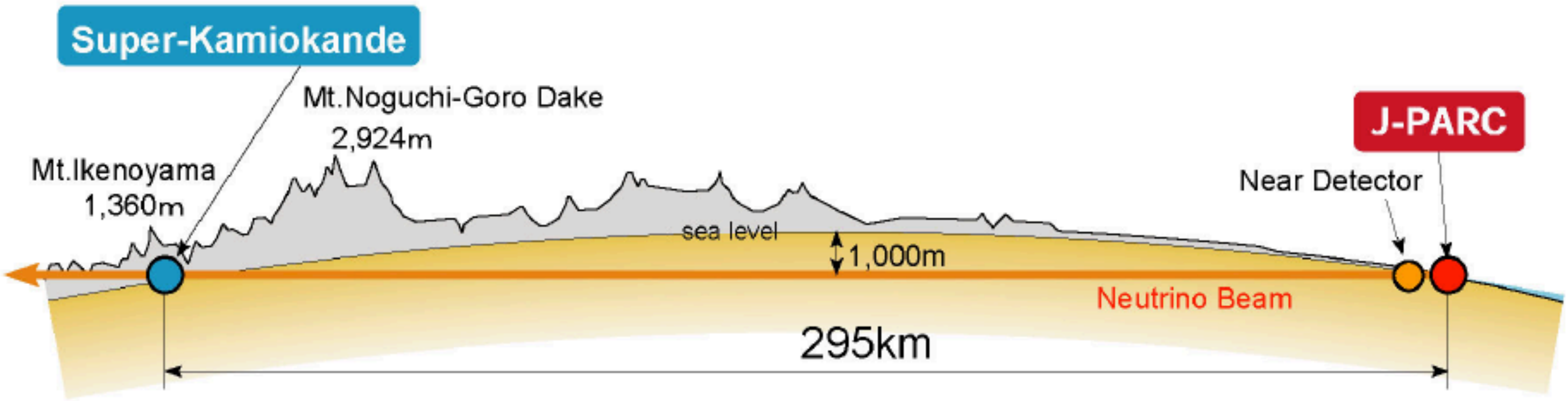






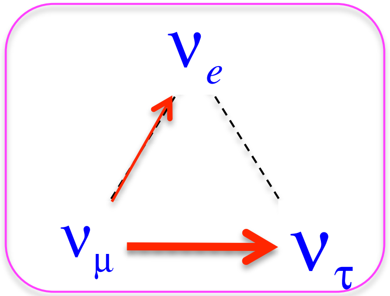
T2K Experiment

K.Iwamoto@ICHEP16



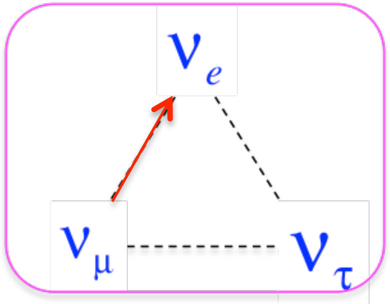
T2K has been measuring

$$\left(\nu_\mu \to \nu_\mu\right),\ \left(\bar{\nu}_\mu \to \bar{\nu}_\mu\right),\ \left(\nu_\mu \to \nu_e\right),\ \left(\bar{\nu}_\mu \to \bar{\nu}_e\right)$$



$$\left.\begin{matrix} \nu_\mu \to \nu_\mu \\ \bar{\nu}_\mu \to \bar{\nu}_\mu \end{matrix}\right\} \qquad P_D \sim 1 - \underline{\sin^2 2\theta_{23}} - P_A$$

small (P_A)



$$\nu_\mu \to \nu_e \qquad P_A \sim \sin^2 2\theta_{13} - 0.043 \sin 2\theta_{13} \sin 2\theta_{23} \underline{\sin\delta}$$

$$\bar{\nu}_\mu \to \bar{\nu}_e \qquad \bar{P}_A \sim \sin^2 2\theta_{13} + 0.043 \sin 2\theta_{13} \sin 2\theta_{23} \underline{\sin\delta}$$

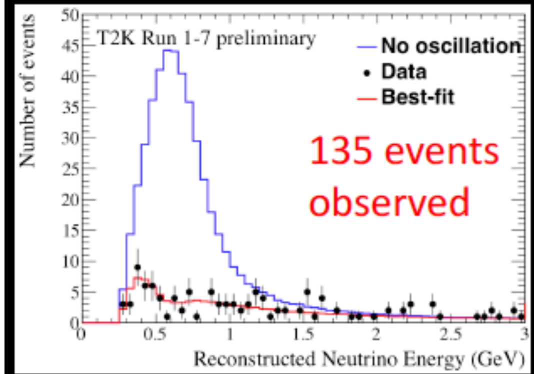
$$\boxed{A_{CP} = \frac{P_A - \bar{P}_A}{P_A + \bar{P}_A} = \frac{0.1 \cot\theta_{23} \sin\delta}{\sin 2\theta_{13}} \sim 0.3 \sin\delta}$$

Observed SK neutrino event candidates

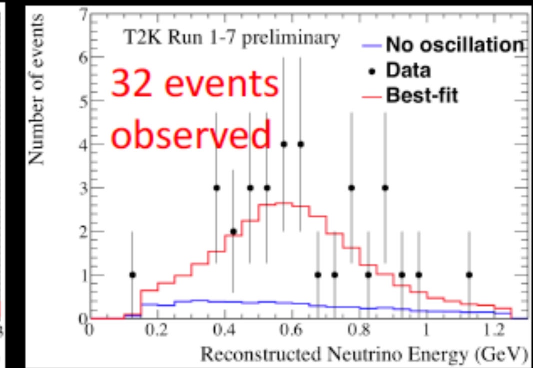
- Oscillation parameter is determined by fitting 5 event categories simultaneously.

New event sample

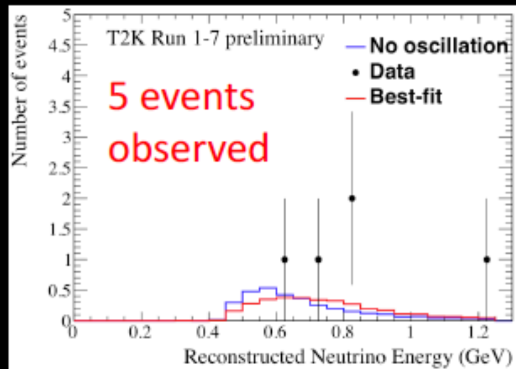
$\nu_\mu/\bar{\nu}_\mu$ CC-QE in ν-beam



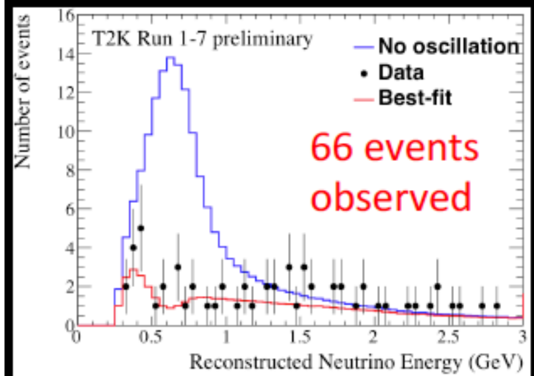
$\nu_e/\bar{\nu}_e$ CC-QE in ν-beam



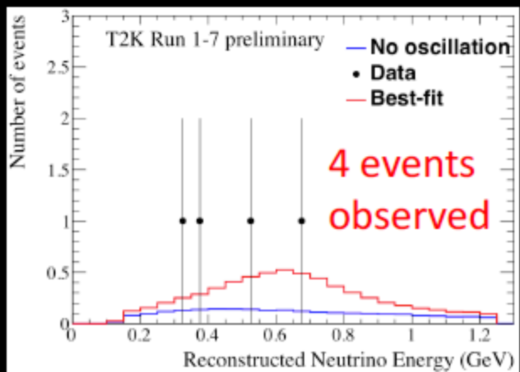
$\nu_e/\bar{\nu}_e$ CC-1π in ν-beam



$\nu_\mu/\bar{\nu}_\mu$ CC-QE in $\bar{\nu}$-beam



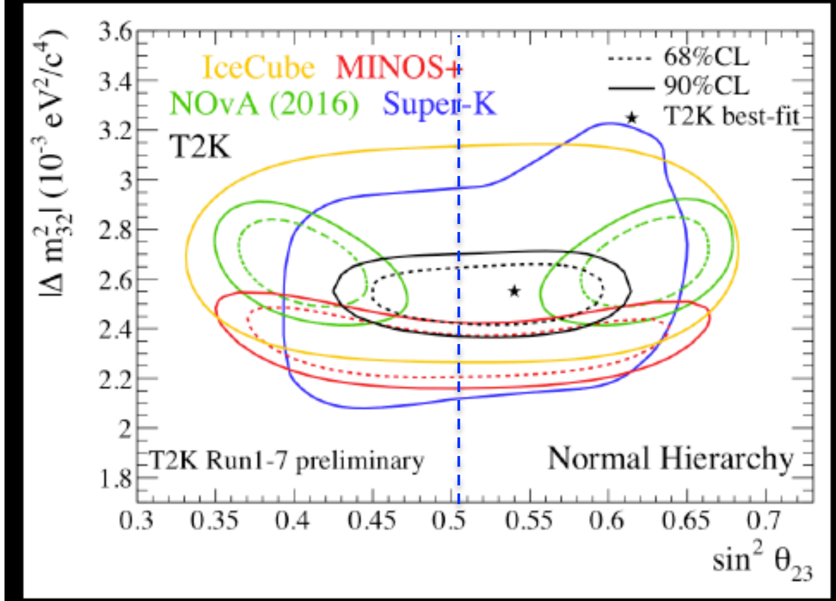
$\nu_e/\bar{\nu}_e$ CC-QE in $\bar{\nu}$-beam

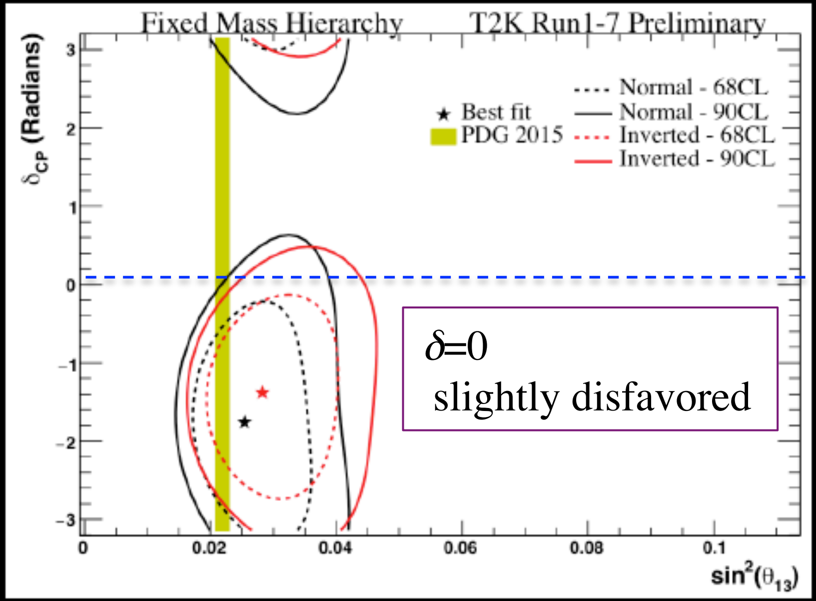


Expected # of events		δ_{CP} = -1.6	δ_{CP} = 0
ν-beam	$\nu_\mu/\bar{\nu}_\mu$ CC-QE	135.8	135.5
	$\nu_e/\bar{\nu}_e$ CC-QE	28.7	24.2
	$\nu_e/\bar{\nu}_e$ CC-1π	3.1	2.7
$\bar{\nu}$-beam	$\nu_\mu/\bar{\nu}_\mu$ CC-QE	64.2	64.1
	$\nu_e/\bar{\nu}_e$ CC-QE	6.0	6.9

Results on oscillation parameters

- T2K results consistent with the max. oscillation ($\sin^2\theta_{23}=0.5$).



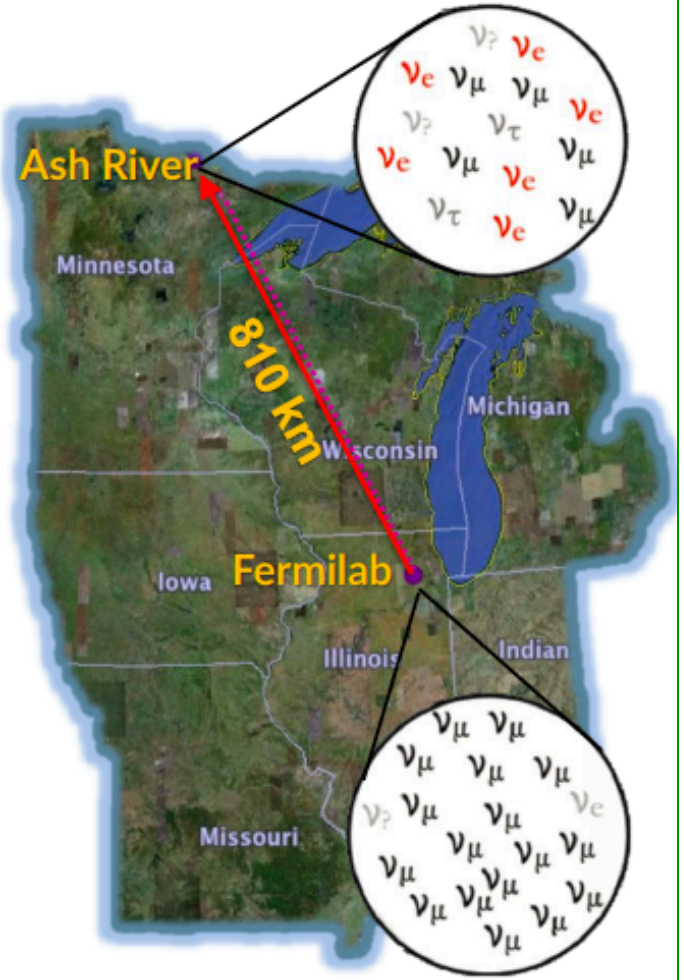


Super-K: PoS ICRC2015 (2015) 1062
Minos+: Neutrino 2014
NOvA : ICHEP2016
IceCube DeepCore: Phys.Rev. D91 (2015) 072004

Nova

NuMI Off-axis ν_e Appearance Experiment

- Long-baseline, two-detector ν oscillation experiment
- Looks for ν_e in ν_μ NuMI beam
- 14 mrad off-axis
- 2 liquid scintillator detectors
- FD (14 kton), ND (0.3 kton)
- Cooled APD readout (live)
- Appearance & disappearance
- Exotics, non-beam…



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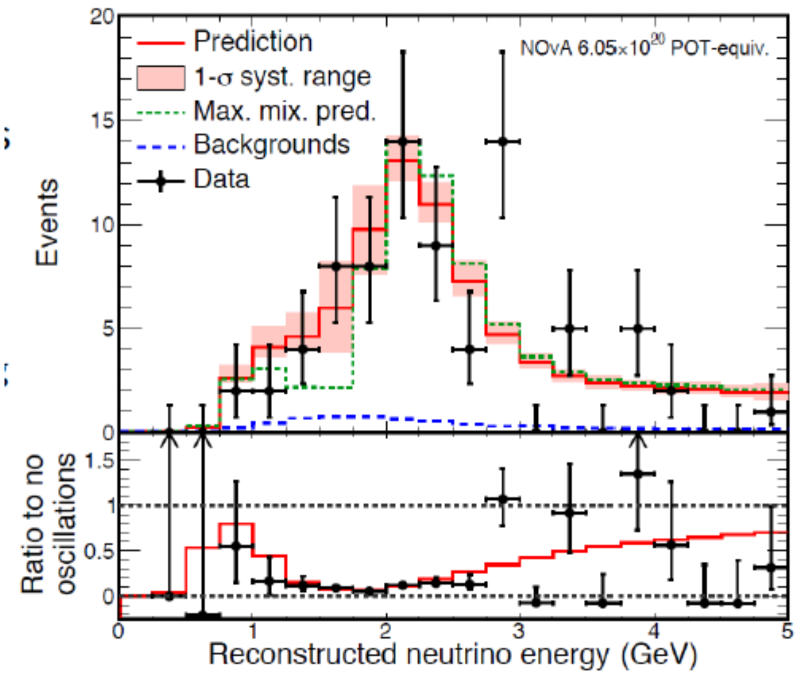
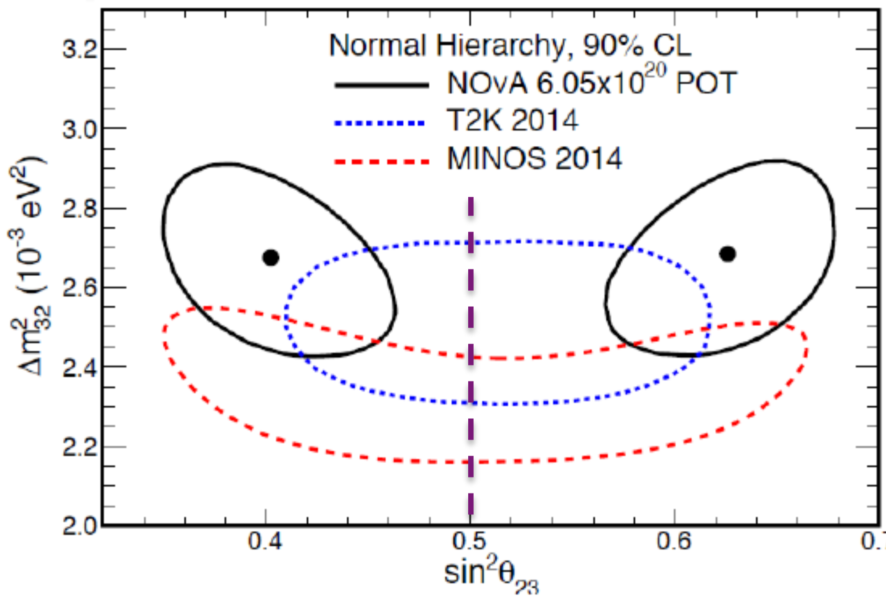
ν_μ disappearance results





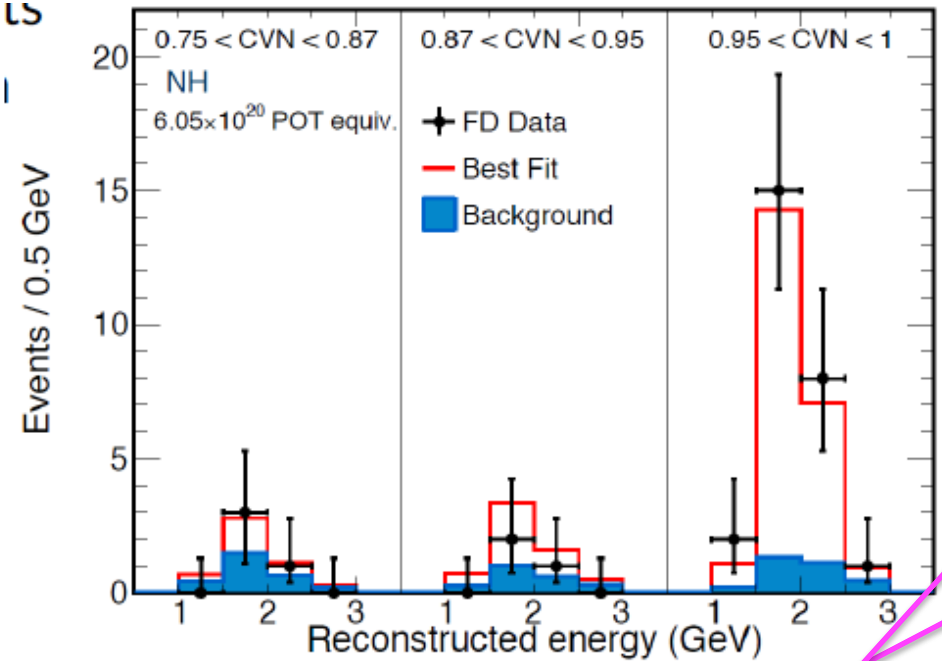
$$|\Delta m^2_{32}| = 2.67 \pm 0.11 \times 10^{-3} \mathrm{eV}^2$$

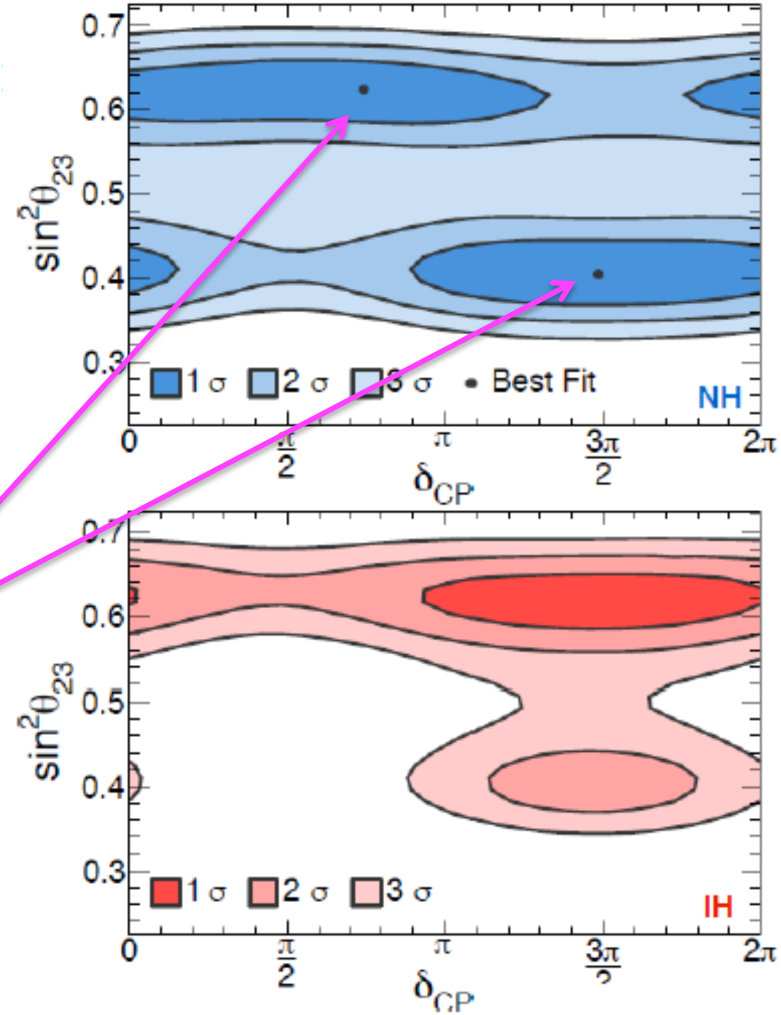
$$\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022} (0.624^{+0.022}_{-0.030})$$

Maximal mixing disfavored at 2.6 σ

ν_e appearance results

- Observe 33 events on a background of 8.2 ± 0.8





- 2 degenerate best fit points:
  - NH, $\delta_{CP} = 1.48\pi$, $\sin^2\theta_{23} = 0.404$
  - NH, $\delta_{CP} = 0.74\pi$, $\sin^2\theta_{23} = 0.623$

NOVA

Filip Jediny @ 2017.3 Moriond

Summary

- 6.05×10^{20} POT NOvA data analyzed, 3 flavor fit
- ν_μ disappearance favors non-maximal mixing
  - **Exclude $\sin^2\theta_{23} = 0.5$** at 2.6σ
  - arXiv:1701.05891
- Joint fit to ν_μ disappearance and ν_e appearance
  - Novel CVN PID used
  - **Excludes inverted hierarchy, lower octant** at 93% C.L.
  - Weak preference for the normal hierarchy overall
  - arXiv:1703.03328
- Anti-neutrino mode beam from last month
  - First antineutrino few hours after launch

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T2K

T.Nakadaira @ 2017.3 Moriond

Summary

- Latest T2K results on neutrino oscillation by adding new event sample (ν_e CC1π) is reported.
  - CP conservation hypothesis ($\sin\delta_{CP} = 0$) is disfavored with 90% CL.
  - Neutrino oscillation via mixing angle θ_{23} is consistent with Max. oscillation ($\sin^2\theta_{23}$=0.5).
- T2K propose to collect 2×10^{22} POT with aim to search for CPV with 3σ sensitivity.
  - Scientific merit is recognized by J-PARC PAC (stage-1 status)
  - Near detector upgrade has been started.
  - Effort to beam-power improvement is also on-going. New collaborators are very welcome!

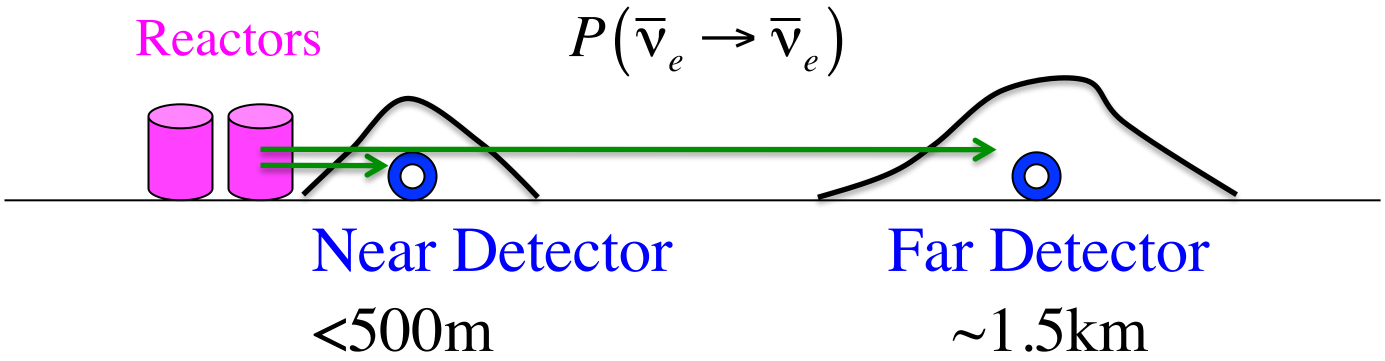
Slight tension in $\sin^2 2\theta_{23}$= 1 or not.

Reactor-θ_{13} Experiment

θ_{13} was a key parameter to proceed to CPV measurement.
But it was known small ($\sin^2 2\theta_{13}$<0.1)

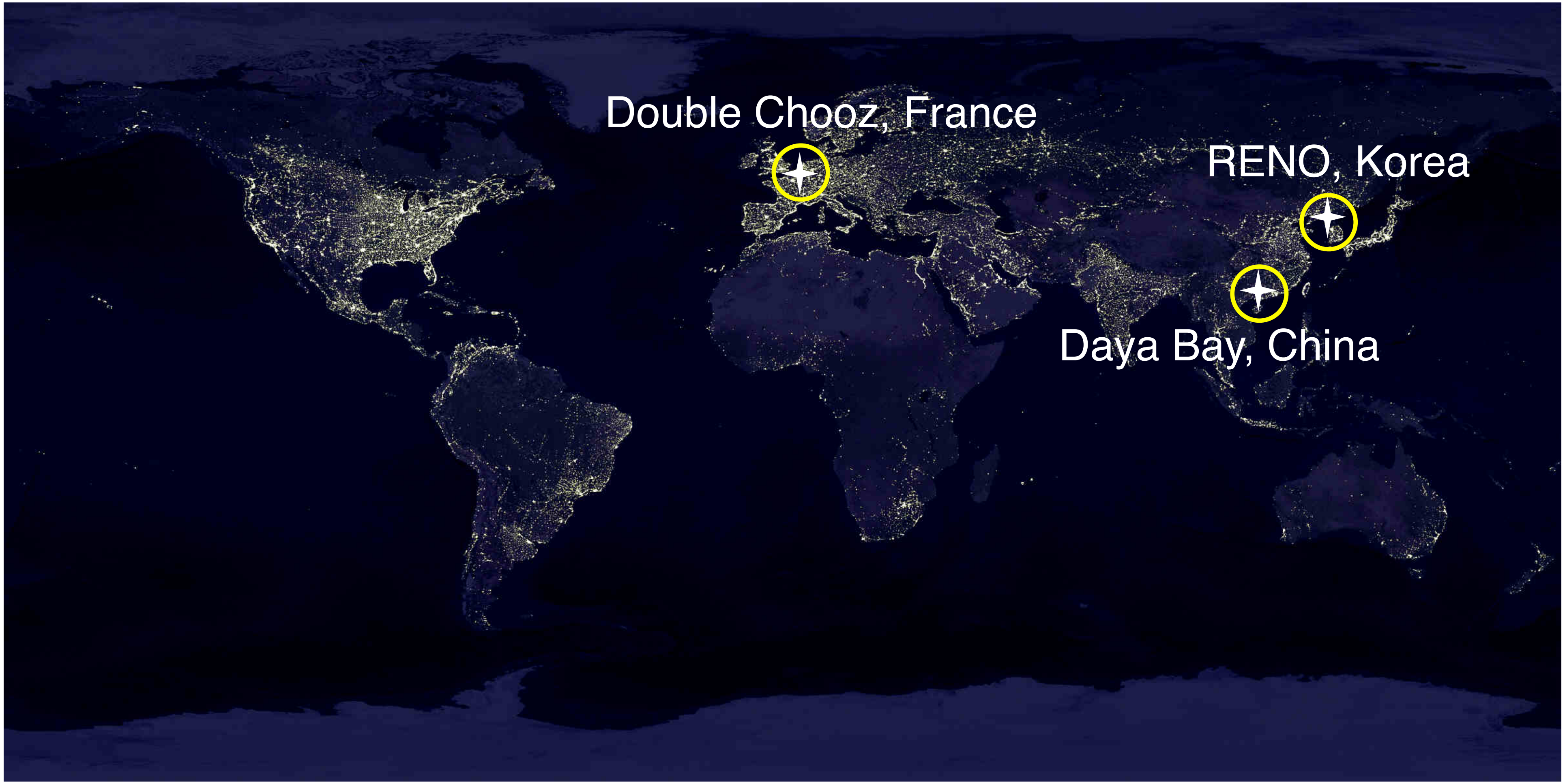
➔ Reactor measurement of θ_{13}

$$P\left(\bar{\nu}_e \rightarrow \bar{\nu}_e; L \sim 1.5km\right) \sim 1 - \sin^2 2\theta_{13}$$



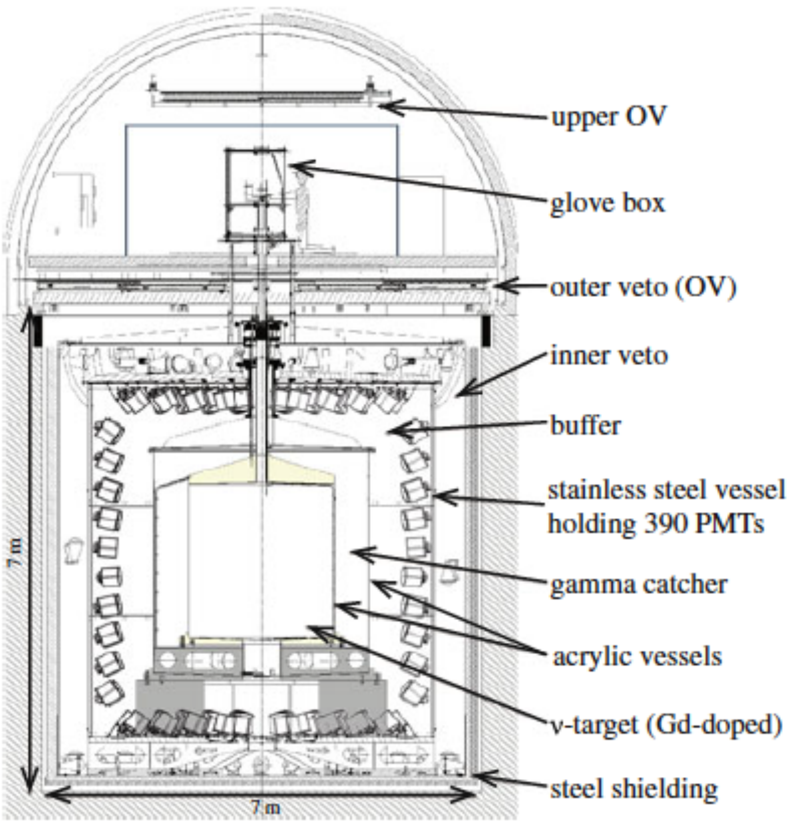
Two detector concept: Cancel uncertainty of neutrino flux and detection efficiency by comparing near & far detector

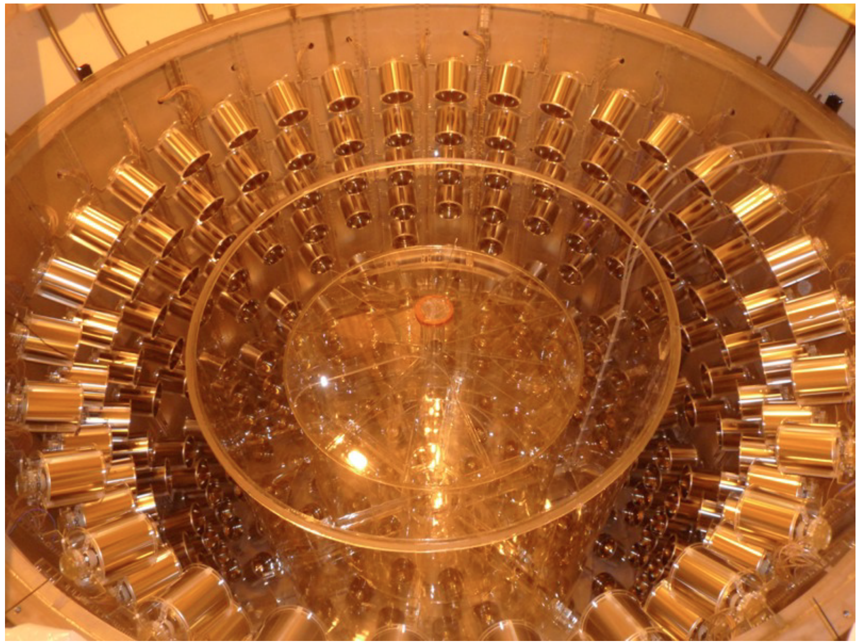
3 reactor-θ_{13} experiments in the world



Our experiment: Double Chooz

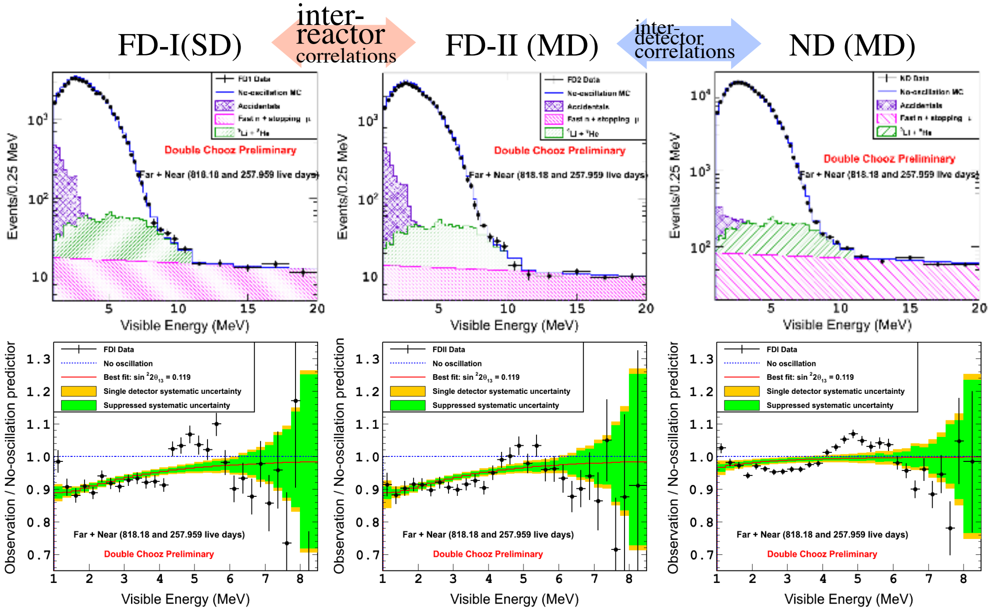
Most of the ideas of the reactor θ_{13} experiment/detector were proposed by the DC group members.



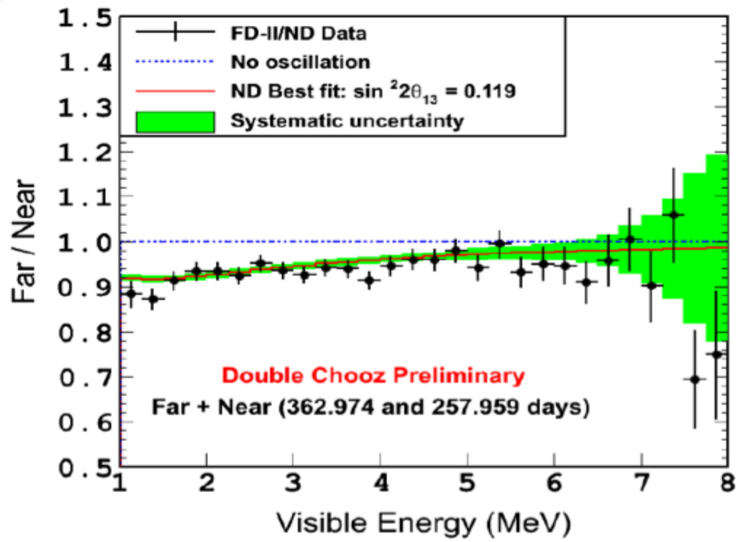


Double Chooz Oscillation fit result

Simultaneous χ^2 fit with Data-to-MC comparison for each data set



Far/Near ratio

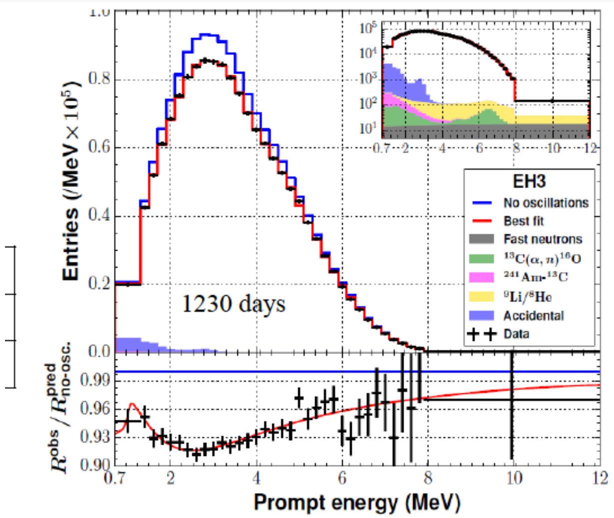


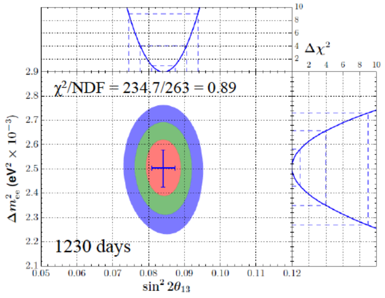
$\sin^2 2\theta_{13} = 0.119 \pm 0.016$ with $\chi^2/\mathrm{ndf} = 236.2/114$ (preliminary)

Daya Bay Result

Logan Lebanowski @ 2016.11 NNN16

Oscillation analysis result





$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(stat.) \pm 0.0019(syst.)$

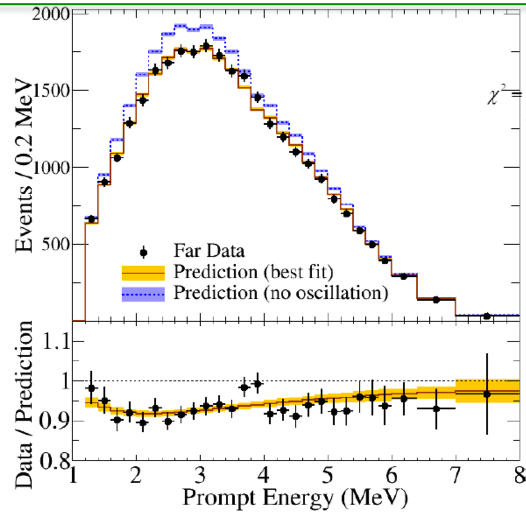
$|\Delta m^2_{ee}| = [2.50 \pm 0.06(stat.) \pm 0.06(syst.)] \times 10^{-3} eV^2$

Multiple analyses yield consistent results.

[arXiv:1610.04802]

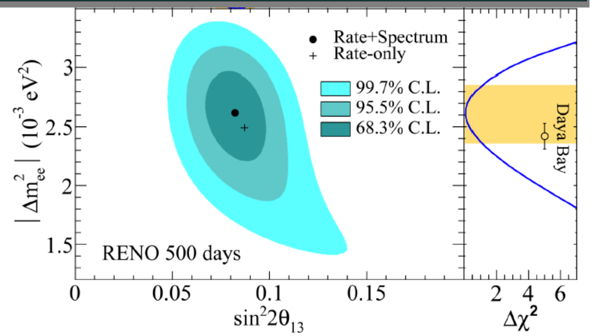
RENO result

Hyunkwan Seo @ 2016.11 NNN16



@APC

Results from Spectral Fit

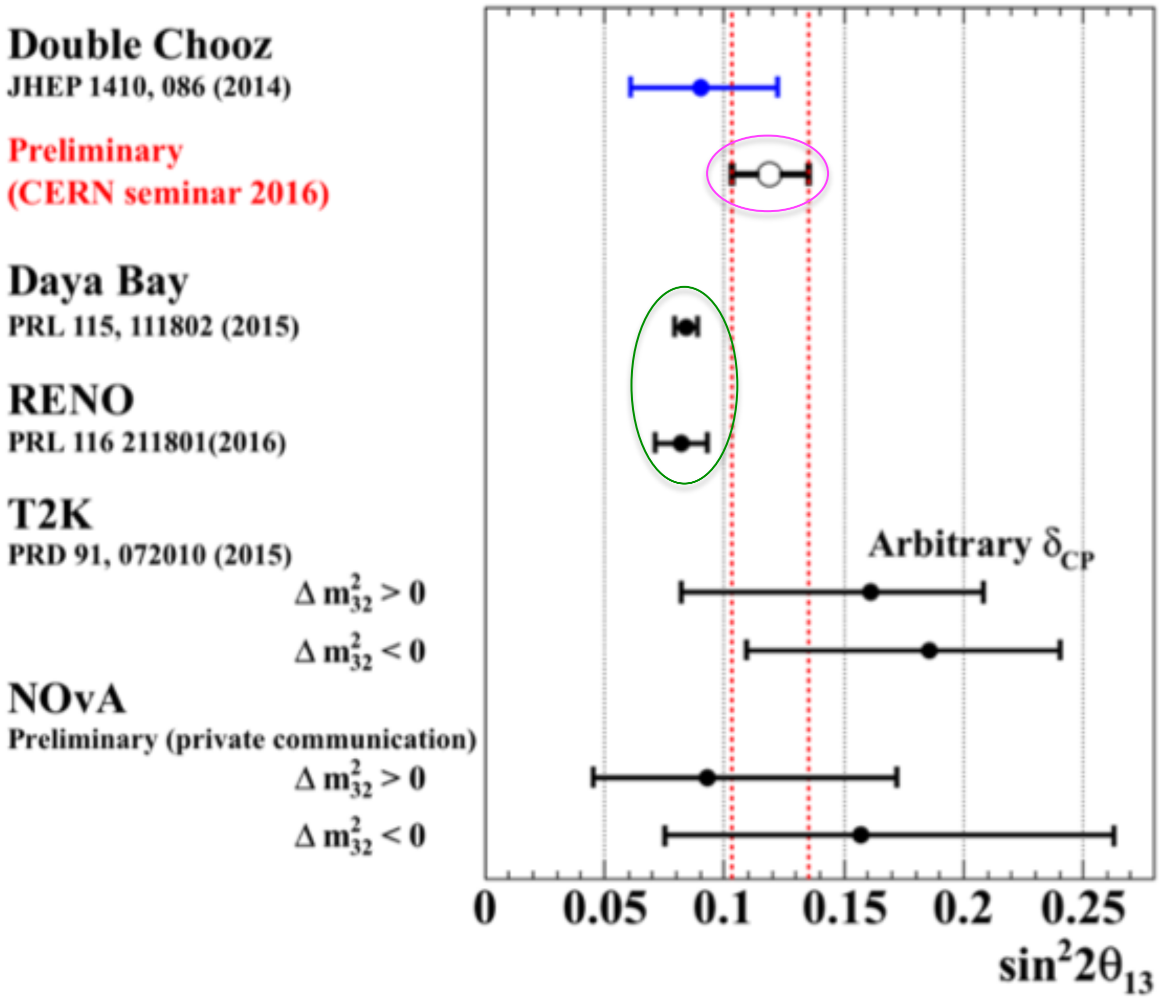


Rate+shape new results

$\sin^2 2\theta_{13} = 0.082 \pm 0.009(\text{stat.}) \pm 0.006(\text{syst.})$

$|\Delta m^2_{ee}| = 2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.})\ (10^{-3} eV^2)$

Current θ_{13} in the world



0.119 +/- 0.016

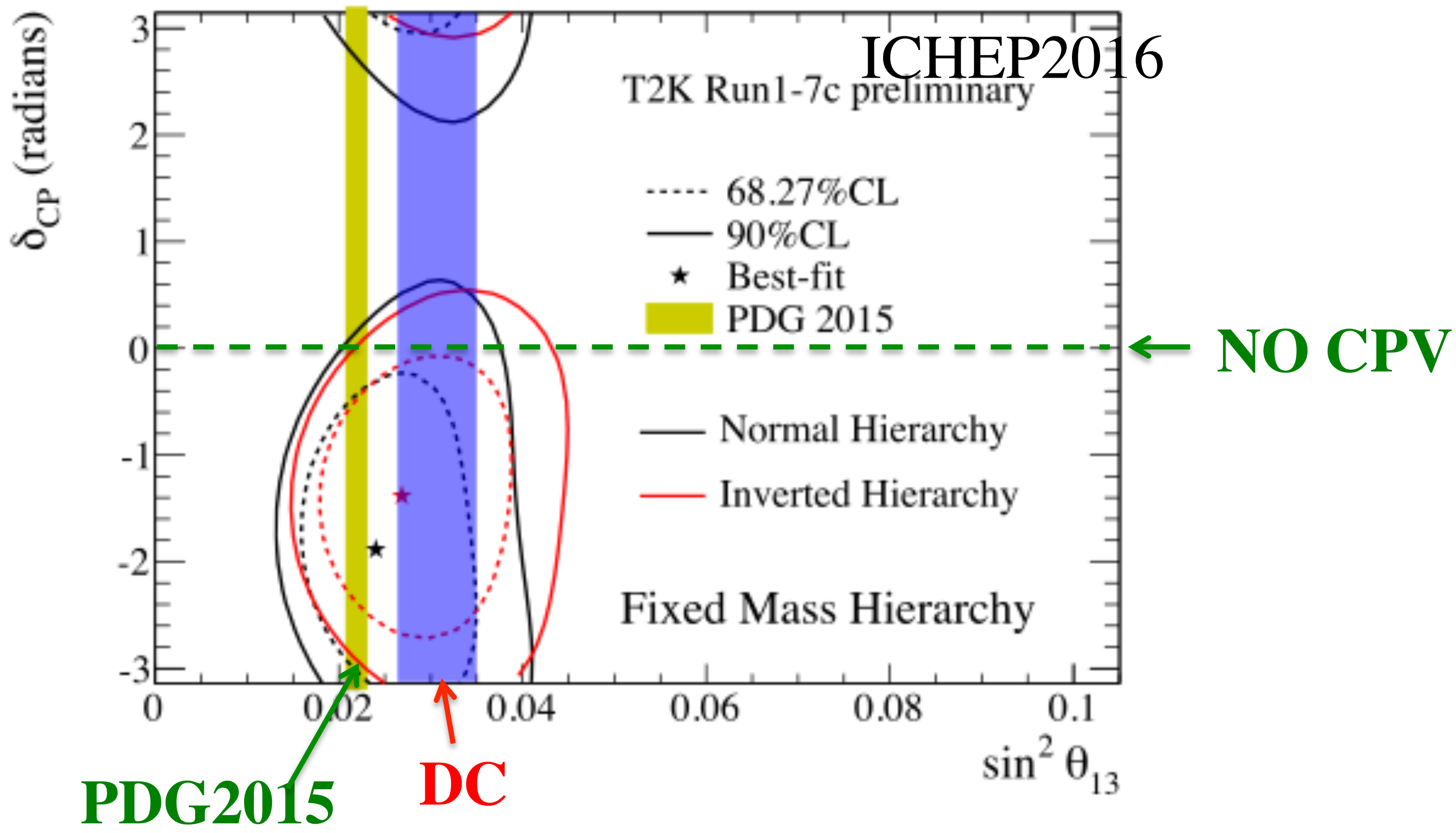
0.0841 +/- 0.0033

0.082 +/- 0.011

⇔

~2σ tension Between DayaBay/RENO ⇔ DC

T2K result and Reactor θ_{13}.

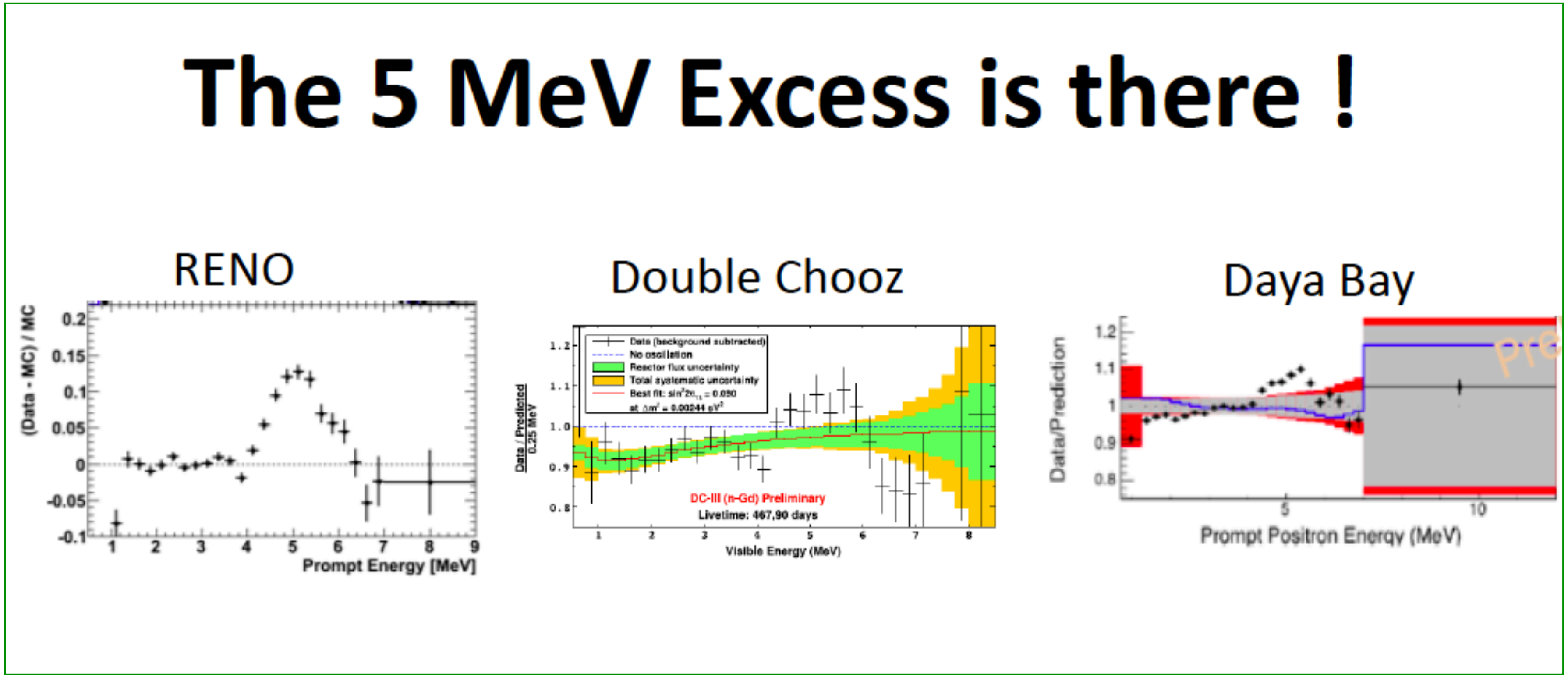


If DC, No CPV is still allowed.

➔ DC+DB+RENO analysis experts meeting will take place next week at APC (A.Cabrera)

And ...

Hyunkwan Seo @ 2016.11 NNN16



What is this??

What we know now

Global fit result (2016) — **Ivan Esteban et al. arXive: 1611.01514v2**

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{\rm CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix}+2.407 \to +2.643 \\ -2.629 \to -2.405\end{bmatrix}$

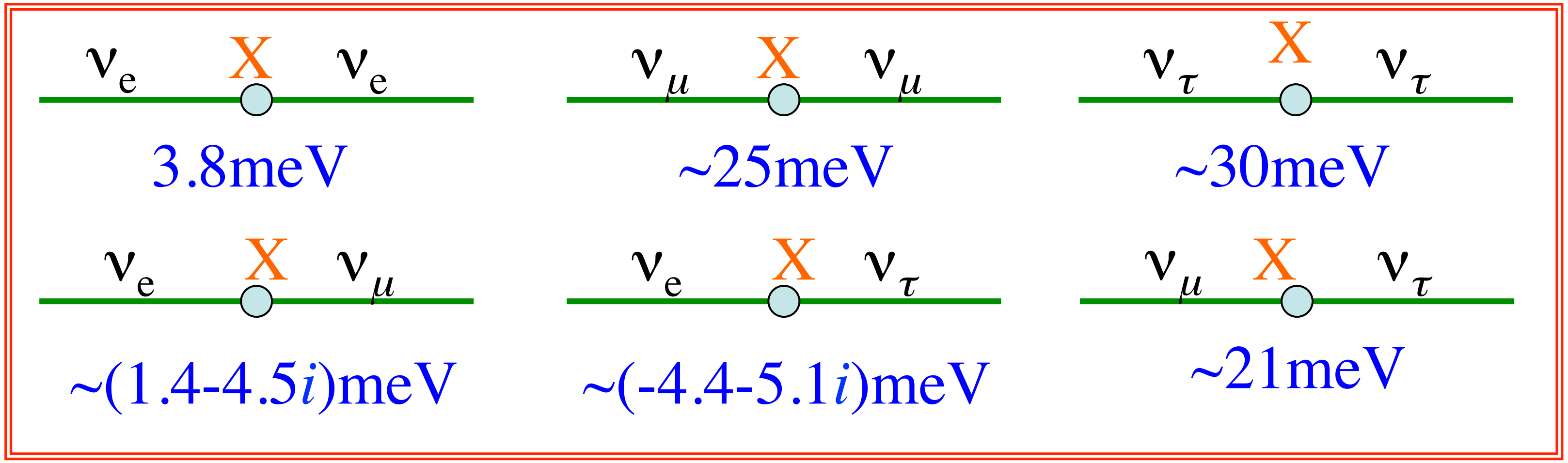
Table 1. Three-flavor oscillation parameters from our fit to global data after the NOW 2016 and ICHEP-2016 conference. The numbers in the 1st (2nd) column are obtained assuming NO (IO), *i.e.*, relative to the respective local minimum, whereas in the 3rd column we minimize also with respect to the ordering. Note that $\Delta m^2_{3\ell} \equiv \Delta m^2_{31} > 0$ for NO and $\Delta m^2_{3\ell} \equiv \Delta m^2_{32} < 0$ for IO.

Our Current Knowledge of Neutrino Transition Amplitude

For Example: If NH and δ=-π/2,

$$U_{NH} \sim \begin{pmatrix} 0.82 & 0.55 & -0.09+0.13i \\ -0.36+0.07i & 0.65+0.05i & 0.67 \\ 0.43+0.08i & -0.53+0.05i & 0.73 \end{pmatrix}$$

Assumption: m_1~0, ➔ m_2 =8.7meV, m_3=50meV



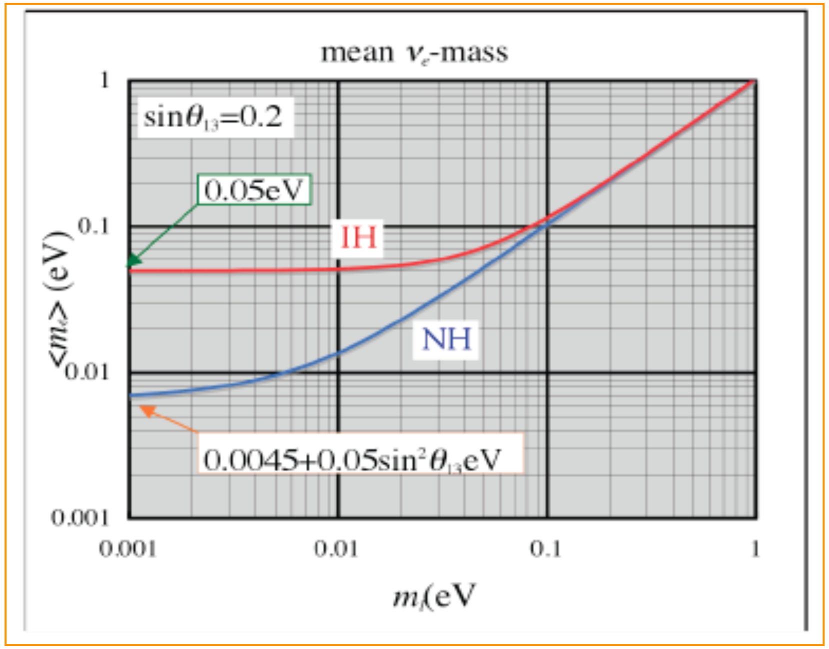
How this pattern and smallness can be explained??

Relation to the ν_e mass

Impact to absolute ν_e mass measurement

$$\langle m_{\nu_e}^2 \rangle = |U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2 \sim \begin{cases} m_1^2 + (10meV)^2 & for \quad NH \\ m_3^2 + (48meV)^2 & for \quad IH \end{cases}$$

$<m_{\nu e}>$ [eV]



minimum neutrino mass [eV]

There is minimum neutrino mass.
If IH, the mass will be definitely observed at > 0.048eV.
(KATRIN Sensitivity ~0.2eV)

(I hope it is IH.)

Relation to ν_μ, ν_τ masses

$$\langle m^2_{\nu_\mu} \rangle = |U_{\mu 1}|^2 m_1^2 + |U_{\mu 2}|^2 m_2^2 + |U_{\mu 3}|^2 m_3^2 = \langle m^2_{\nu_e} \rangle \pm (30 meV)^2$$

$$\langle m^2_{\nu_\tau} \rangle = |U_{\tau 1}|^2 m_1^2 + |U_{\tau 2}|^2 m_2^2 + |U_{\tau 3}|^2 m_3^2 = \langle m^2_{\nu_e} \rangle \pm (36 meV)^2$$

Since $\sqrt{\langle m^2_{\nu_e} \rangle} < 2.2 eV,\qquad \sqrt{\langle m^2_{\nu_\mu} \rangle},\ \sqrt{\langle m^2_{\nu_\tau} \rangle} < 2.3 eV$

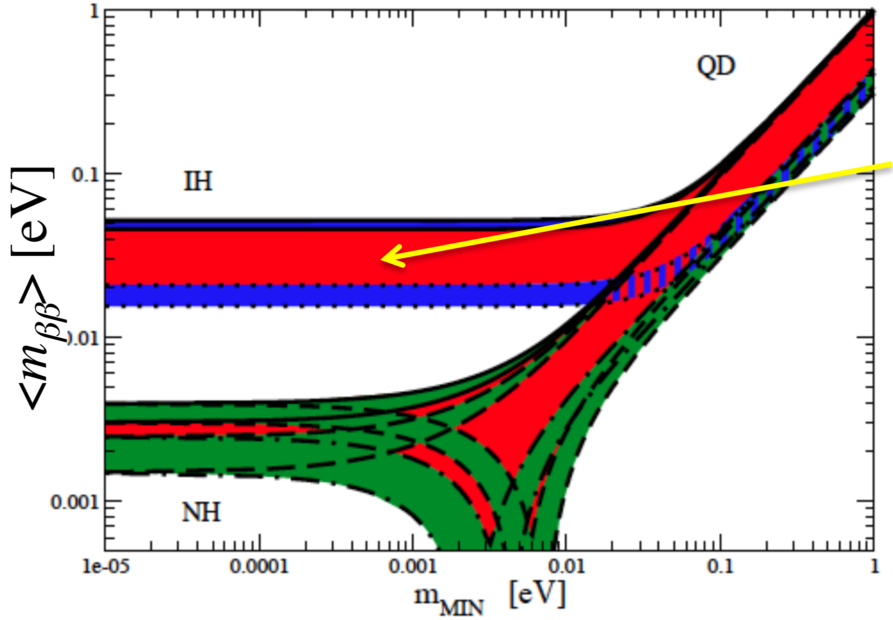
No practical way to measure m_{ν_μ} and m_{ν_τ} with this precision ....

only m_{ν_e} measurement has hope .....

Relation to the Majorana mass

Double Beta Decay mass: $m_{\beta\beta}$

$$\left|m_{\beta\beta}\right|^2 = \left|c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{-2i\alpha} + s_{13}^2 m_3 e^{-2i(\beta+\delta)}\right|^2$$

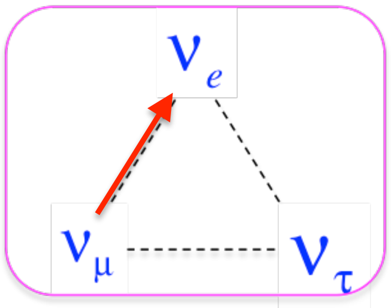


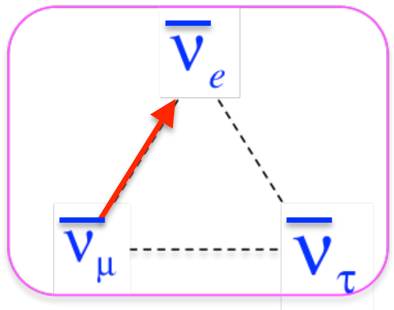
minimum neutrino mass [eV]

If IH, there is lower limit of $m_{\beta\beta}$~15meV.

=> Either ν is Dirac or Majorana can be definitely determined with experiment with sensitivity 15meV.

Future

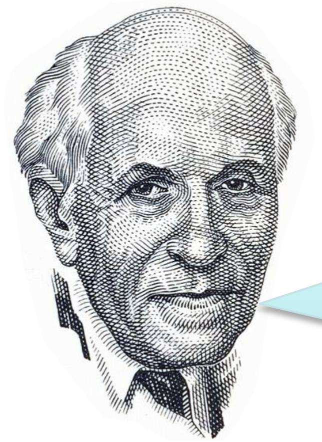




Measurement of CPV δ

In order to realize the matter dominance of the current universe,

The Sakharov conditions for Baryogenesis



(1) Baryon number non-conservation.
(2) C and CP violation
(3) Thermal non-equilibrium.

However, CPV effect of quark interactions is very small.

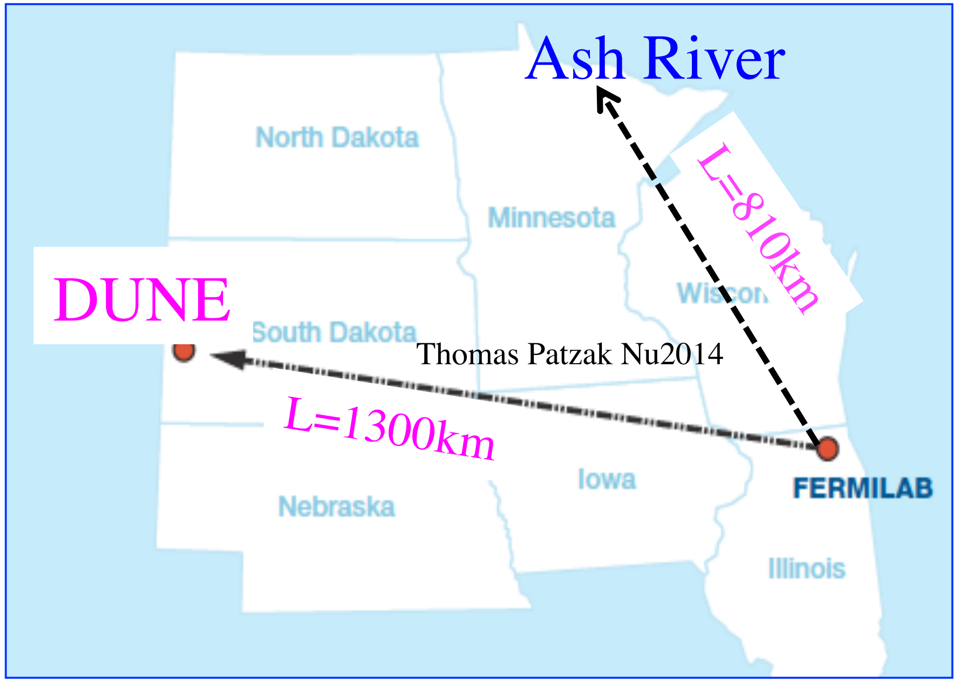
$$\text{CPV effect} \propto J_q = \frac{1}{8} c_{13}^q \sin 2\theta_{12}^q \sin 2\theta_{23}^q \sin 2\theta_{13}^q \sin \delta_q \quad \sim 3\text{x}10^{-5}$$

If quarks can not explain it, leptons should be responsible for it.

CPV effect of ν can be x1,000 times larger: $J_\nu \sim 0.04 \sin\delta_\nu$

Present and Future long baseline experiments

NOVA



CP Asymmetry

* Difference between $P(\nu_\alpha \to \nu_\beta)$ and $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

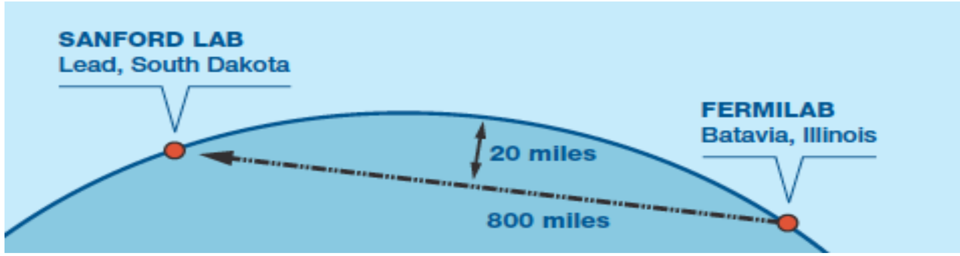
* Experimentally:

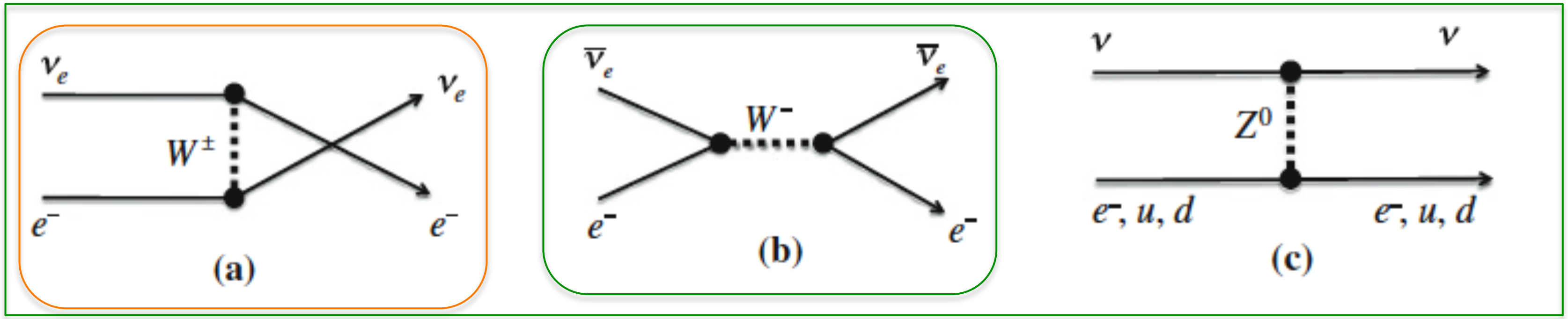
$$A_{CP}(@\Phi_{31} = \pi/2) = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

$$\sim -\left|\frac{\Delta m_{12}^2}{\Delta m_{31}^2}\right| \frac{\pi \sin 2\theta_{12}}{\tan\theta_{23} \sin 2\theta_{13}} \sin\delta \sim \underline{-0.29 \sin\delta}$$

* However, the matter effect introduces a fake A_{CP}

Earth Matter Effect





ν_e and $\bar{\nu}_e$ feel different weak potential

Effective Weak Potential

$$V_W = 2\sqrt{2}E_\nu \frac{n_e G_F}{m_3^2 - m_1^2}$$

changes the coupling sign depending on ν or $\bar{\nu}$

changes sign depending on the mass hierarchy

Energy dependent

Weak Potential & Oscillation Probability

After lengthy calculation, main effect of the weak potential on the oscillation:

$$\sin\Phi_{31} \to \frac{\sin\left(\left(1-V_W\right)\Phi_{31}\right)}{1-V_W}; \qquad \Phi_{31} = \frac{\Delta m_{31}^2}{4E}L$$

Then, the appearance probability with the matter effect is,

$$P\left(\nu_\mu \to \nu_e; @\Phi_{31}\right) \sim \frac{s_{23}^2 \sin^2 2\theta_{13}}{\left(1-V_W\right)^2} \pm \frac{\pi}{2}\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\frac{\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}}{\left(1-V_W\right)}\sin\delta$$

	L[km]	V_W (=L/L_0)
T2K/HK	295	**±0.055**
NOVA	810	**±0.15**
DUNE	1,300	**±0.24**

CP asymmetry with the matter effect

$$A_{CP}(@\Phi_{13}) = \frac{P-\bar{P}}{P+\bar{P}} \sim -\pi\left|\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\right|\frac{\sin 2\theta_{12}}{t_{23}\sin 2\theta_{13}}\sin\delta_{CP} \pm 2\left(\frac{L}{L_0}\right)$$

$$\sim -0.29\sin\delta_{CP} \pm A_{FK}$$

← fake CP asymmetry

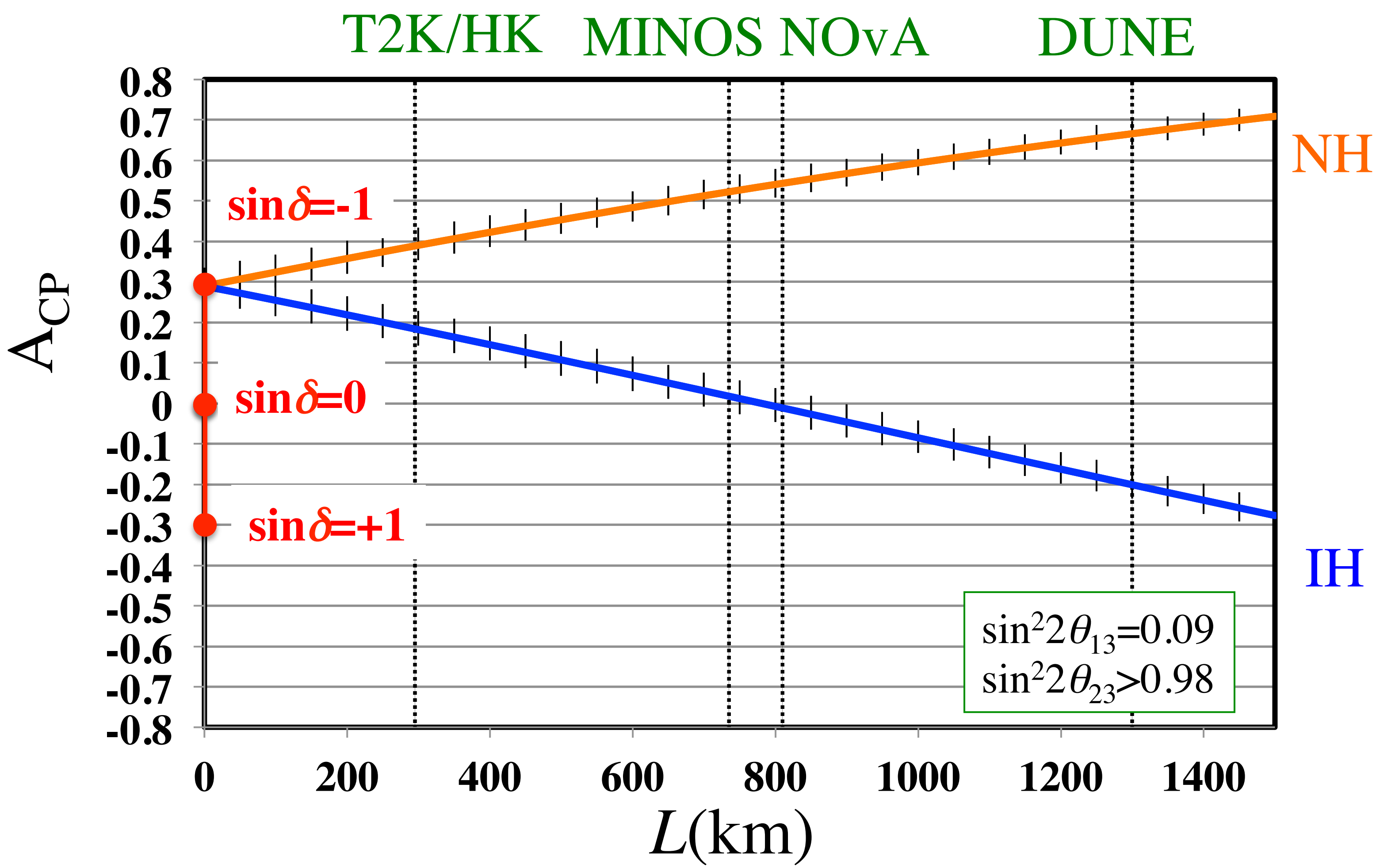
	L[km]	V_W	$A_{FK}=2(L/L_0)$
T2K/HK	295	±0.055	**±0.11**
Nova	810	±0.15	**±0.30**
DUNE	1,300	±0.24	**±0.48**

Error of the sinδ measurement

$$\delta(\sin\delta_{CP}) = 3.4\sqrt{(\delta A_{CP})^2 + \left(A_{FK}(\delta\bar{n}_e/\bar{n}_e)\right)^2}$$

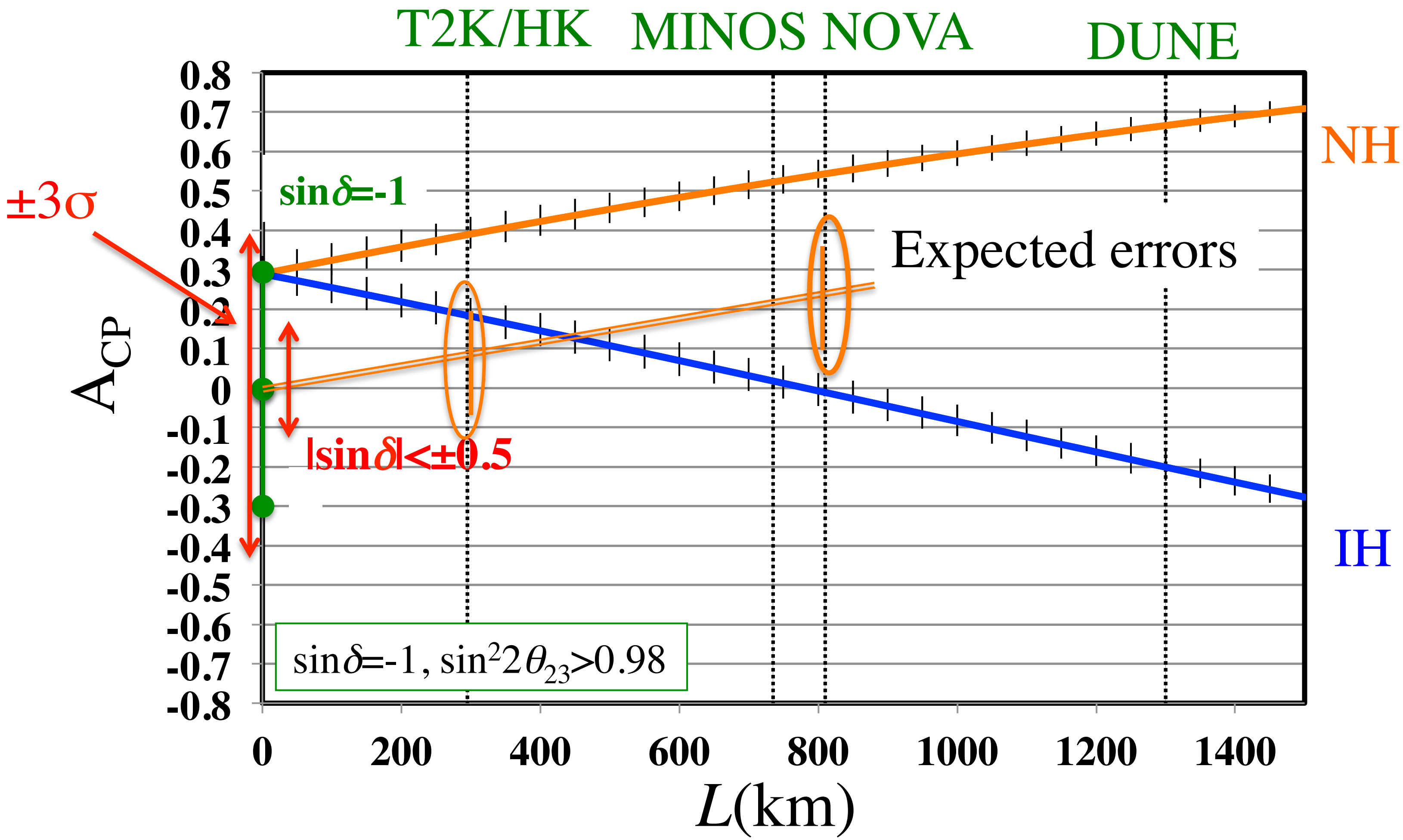
Baseline Dependence of CP asymmetry

$$A_{CP} \sim -0.29 \sin\delta \pm 2\left(\frac{L}{L_0}\right)$$



NOVA + T2K

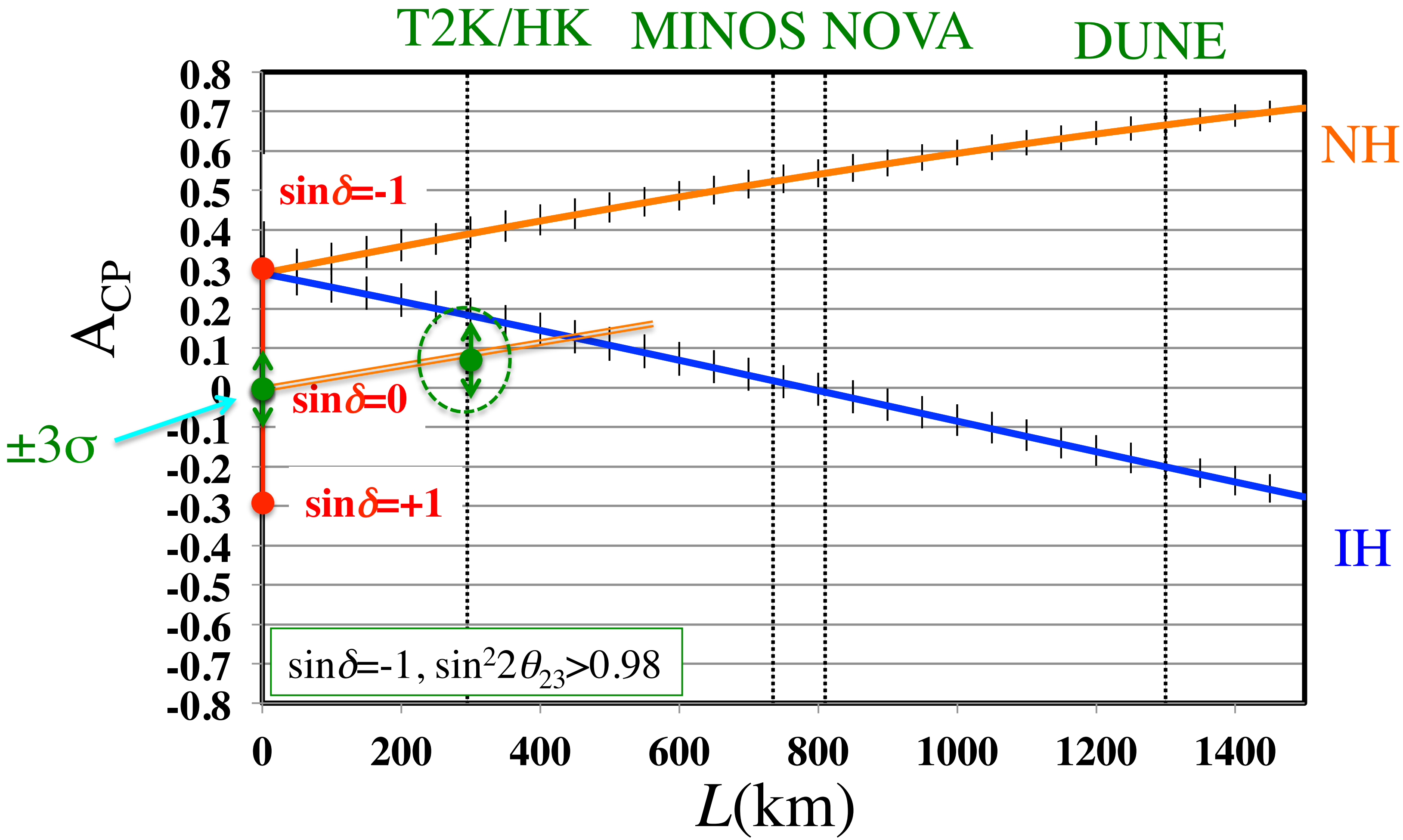
$$A_{CP} \sim -0.29\sin\delta \pm 2\left(L/L_0\right)$$



May be possible to limit δ_{CP} by 2σ but not 3σ.

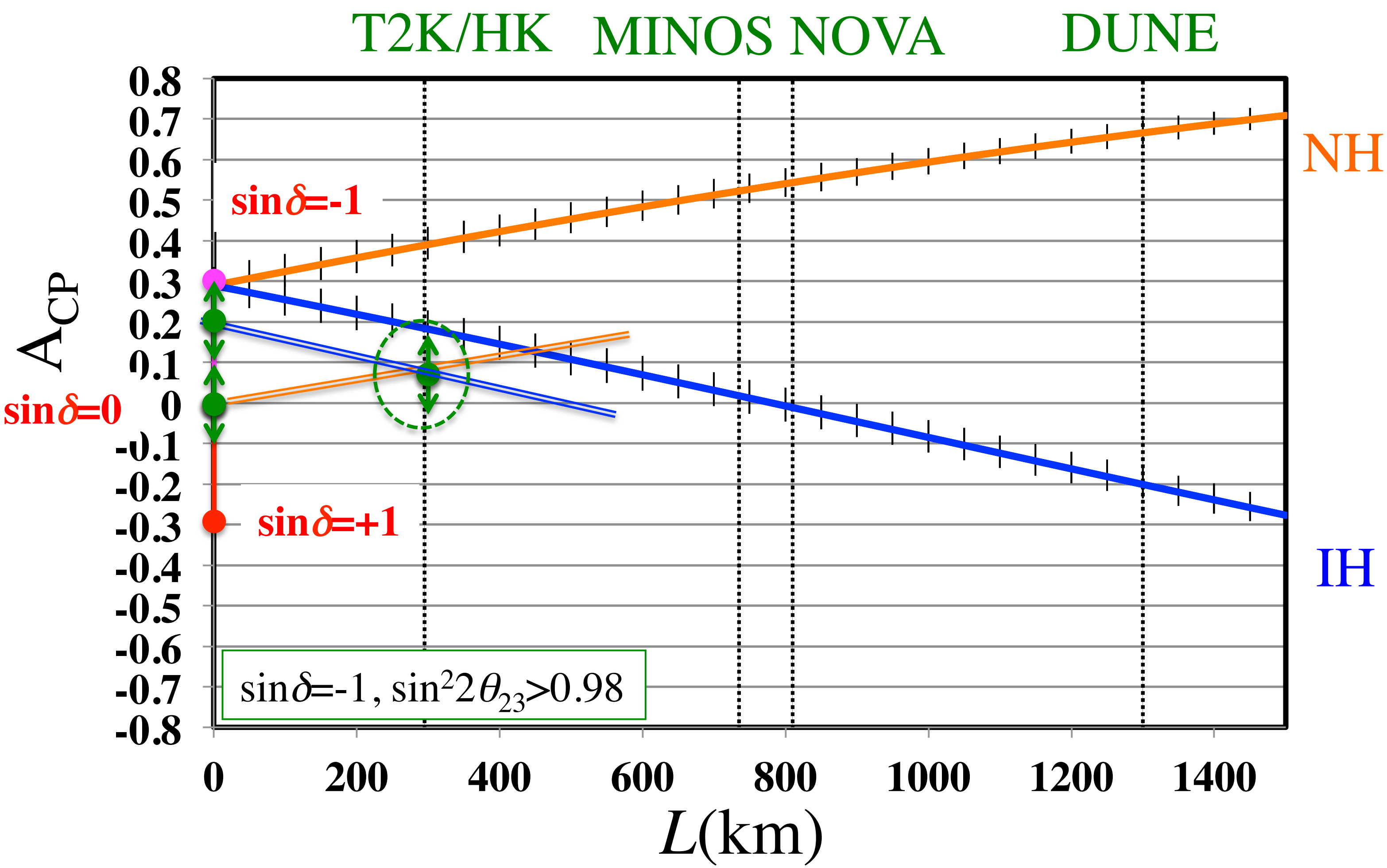
HK case

If sinδ=0 & N.H. and HK measured the expected value.



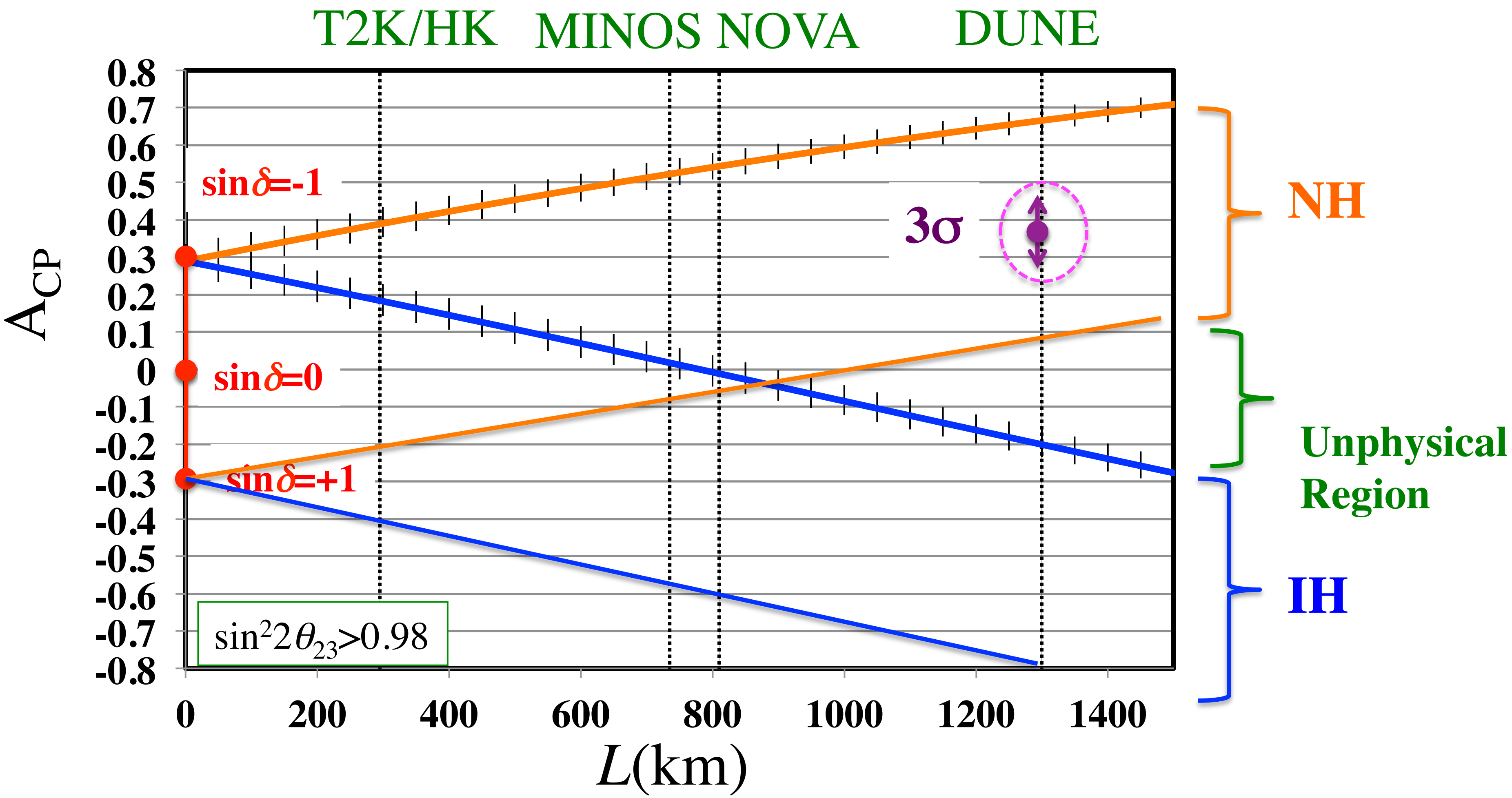
If M.H. is known, |sinδ|<0.33(3σ) can be obtained.

HK only case



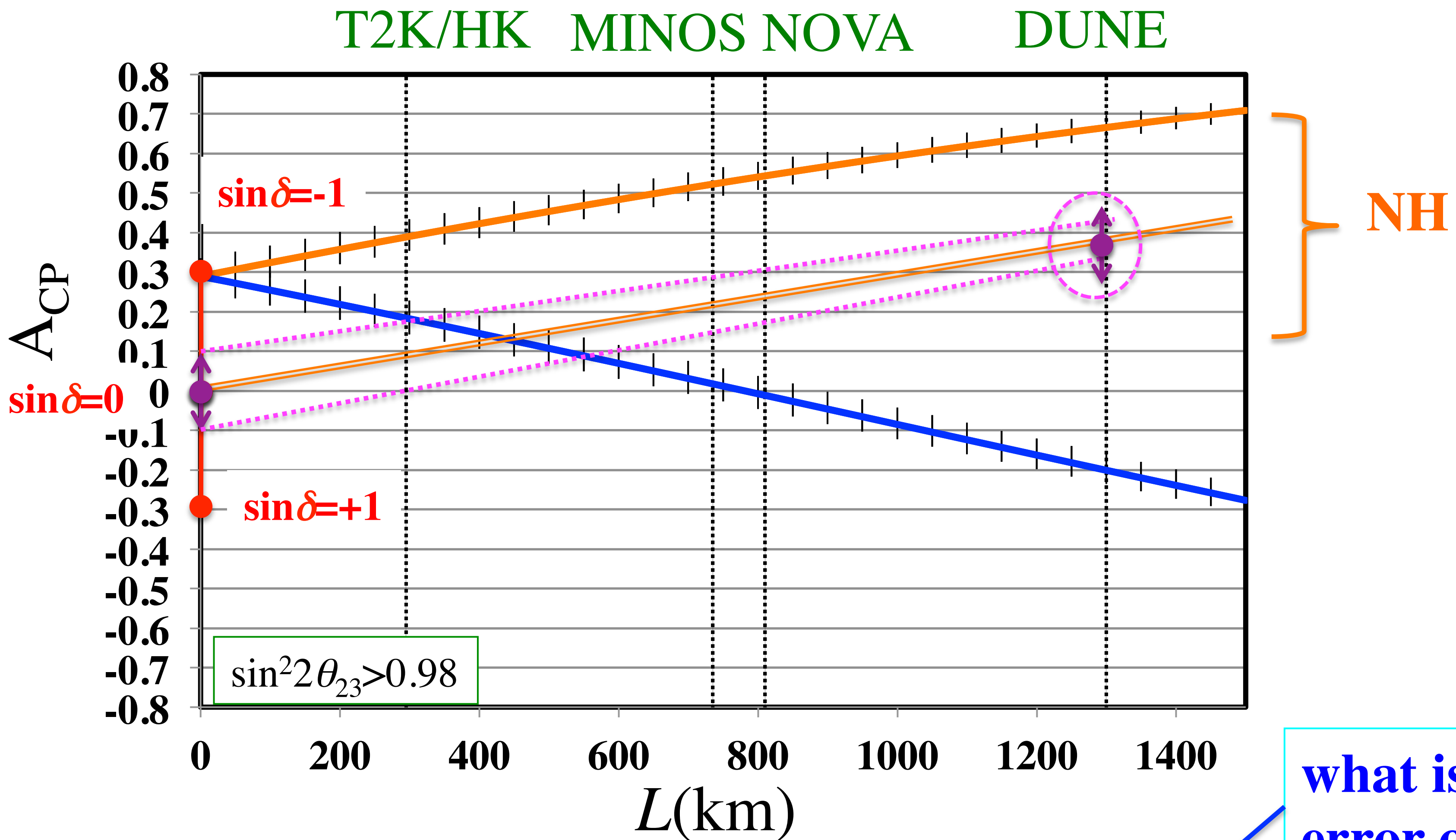
If M.H. is not known, there are two solutions.
sinδ=0 can not be confirmed. ➔ M.H. is necessary.

DUNE only case



This case, M.H. is determined to be N.H.

DUNE only case



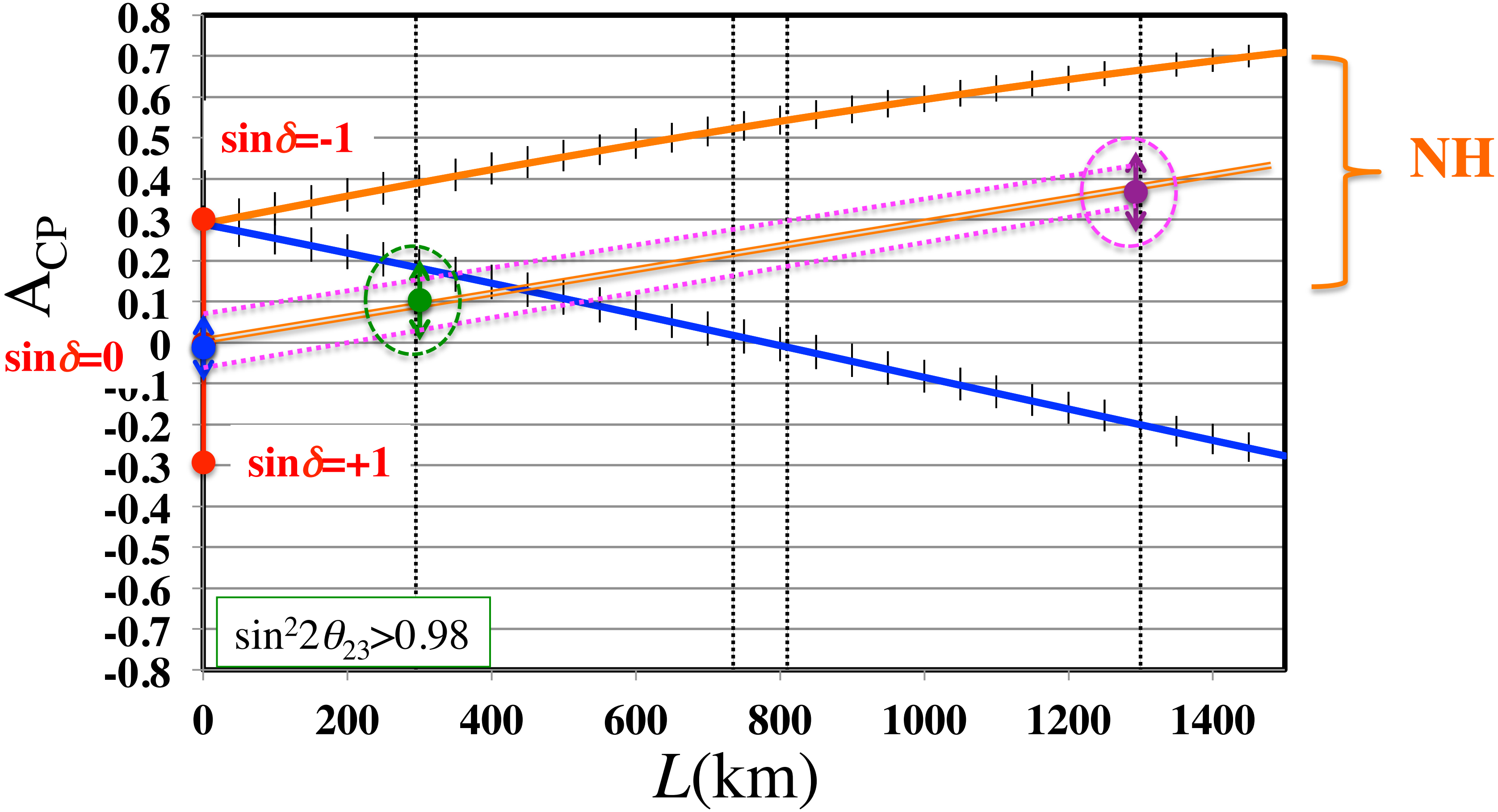
Then extrapolate to L=0 to obtain $\sin\delta_{CP}$.

$$\delta(\sin\delta_{CP}) = 3.4\sqrt{(\delta A_{CP})^2 + \left(A_{FK}\left(\delta\bar{n}_e/\bar{n}_e\right)\right)^2}$$

what is the error of the integrated density?

HK+DUNE case

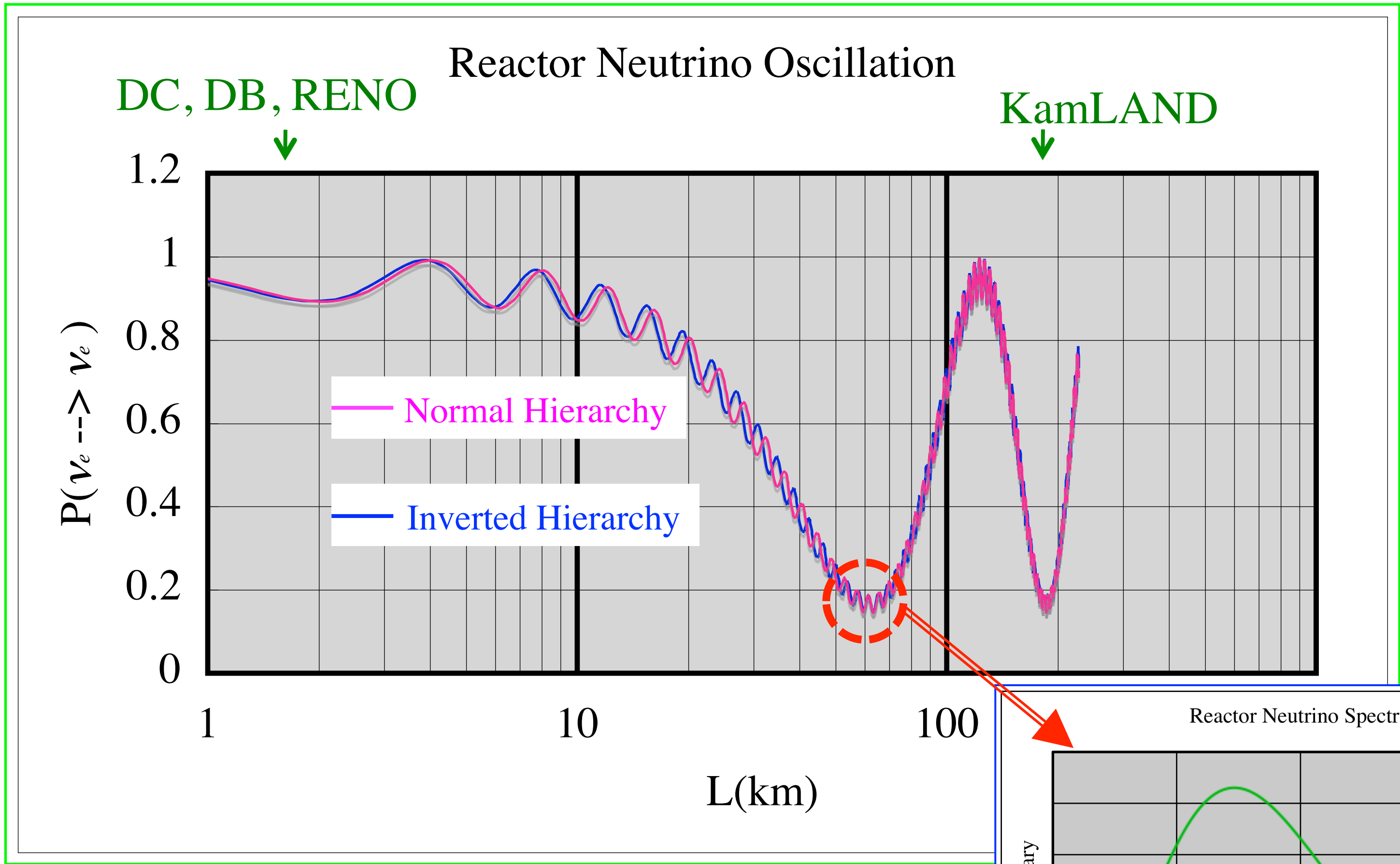
Improvement of $\sin\delta$ accuracy

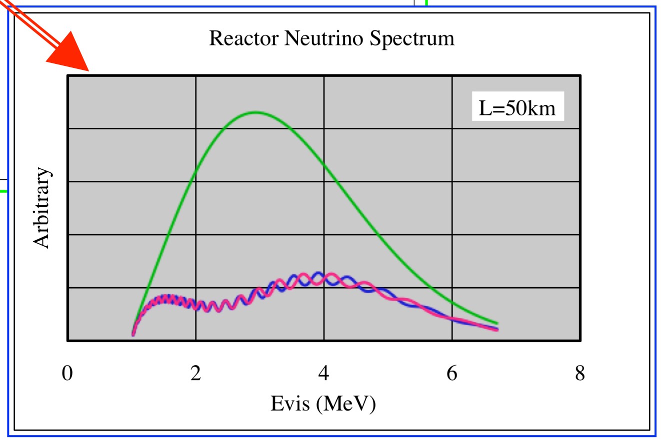


* **MSW independent analysis is possible.**

$$\sin\delta = 3.4\,\frac{L_{HK}A_{LB} - L_{LB}A_{HK}}{L_{LB} - L_{HK}}$$

M.H. by medium baseline reactor experiment

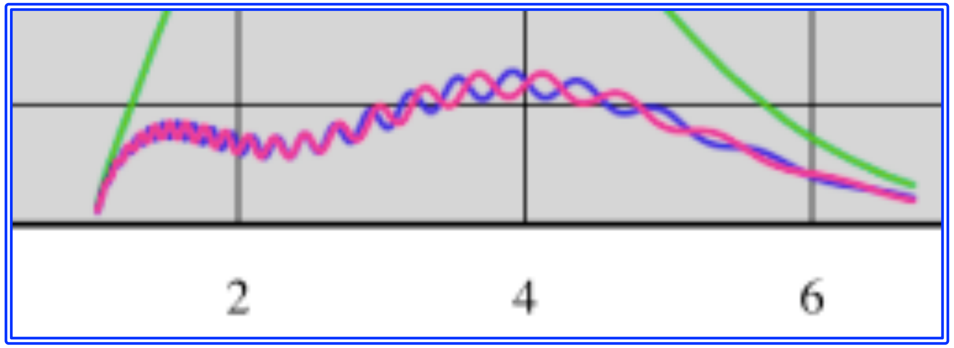




Reactor Neutrino Oscillation @L~50km

Principle

Petcov et al., Phys. Lett. B 533, 94 (2002)
S.Choubey et al., Phys. Rev. D 68,113006 (2003)
J. Learned et al., hep-ex/062022
L.Zhan et al., hep-ex/0807.3203
M.Batygov et al., hep-ex/0810.2508



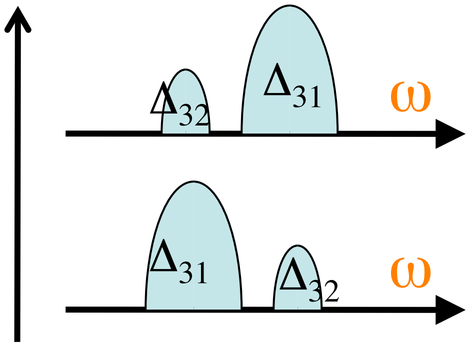
Ripple $\propto \sin^2 2\theta_{13}\left(\sin^2 \Delta_{31} + \tan^2 \theta_{12} \sin^2 \Delta_{32}\right)$

It is essential that θ_{12} is not maximum ($\tan^2\theta_{12}$~0.4)

Fourier Trans. => peaks at $\omega = \left|\Delta m^2_{31}\right|, \quad \left|\Delta m^2_{32}\right|$

Smaller peak corresponds to $\left|\Delta m^2_{32}\right|$ larger peak corresponds to $\left|\Delta m^2_{31}\right|$,

Power

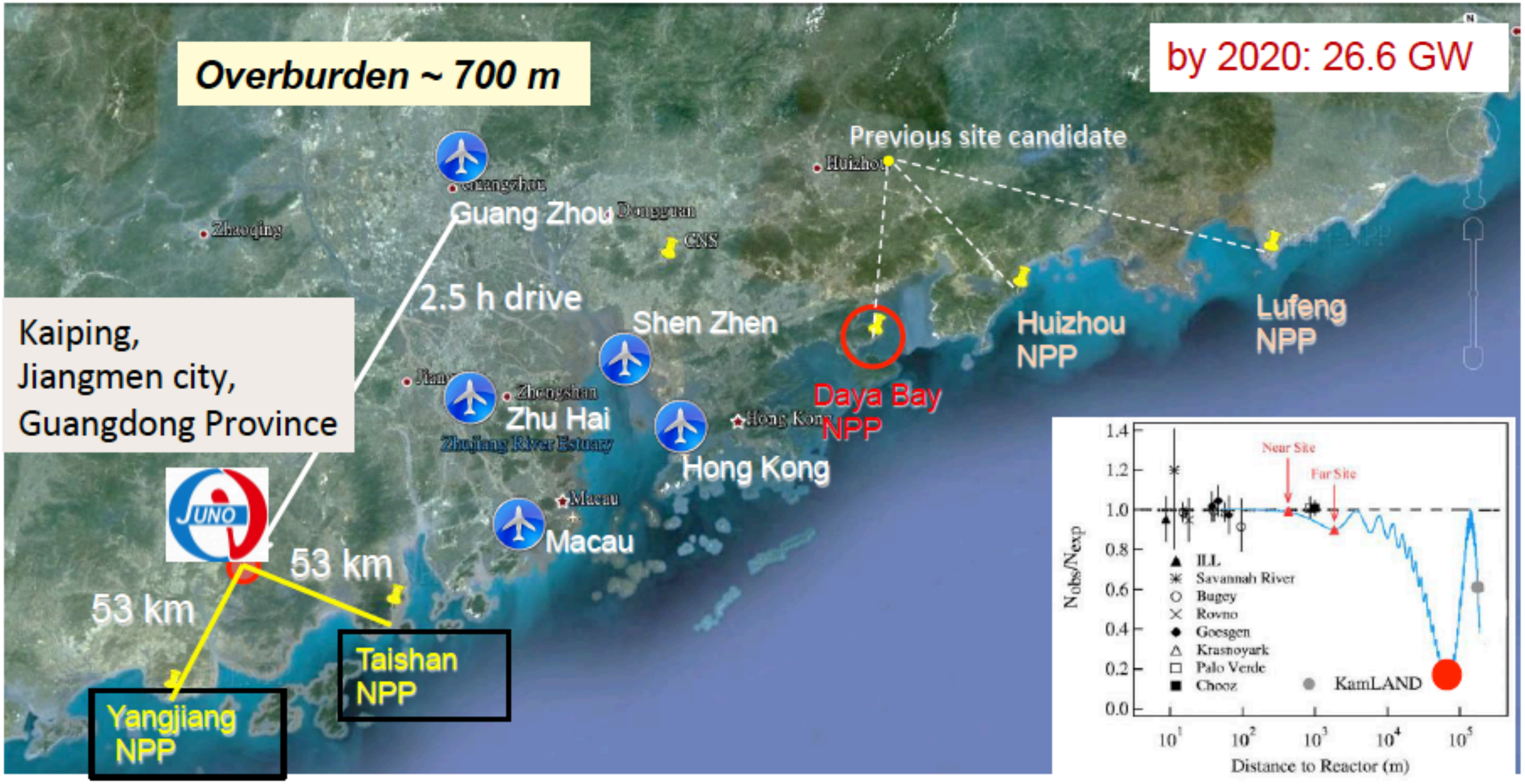


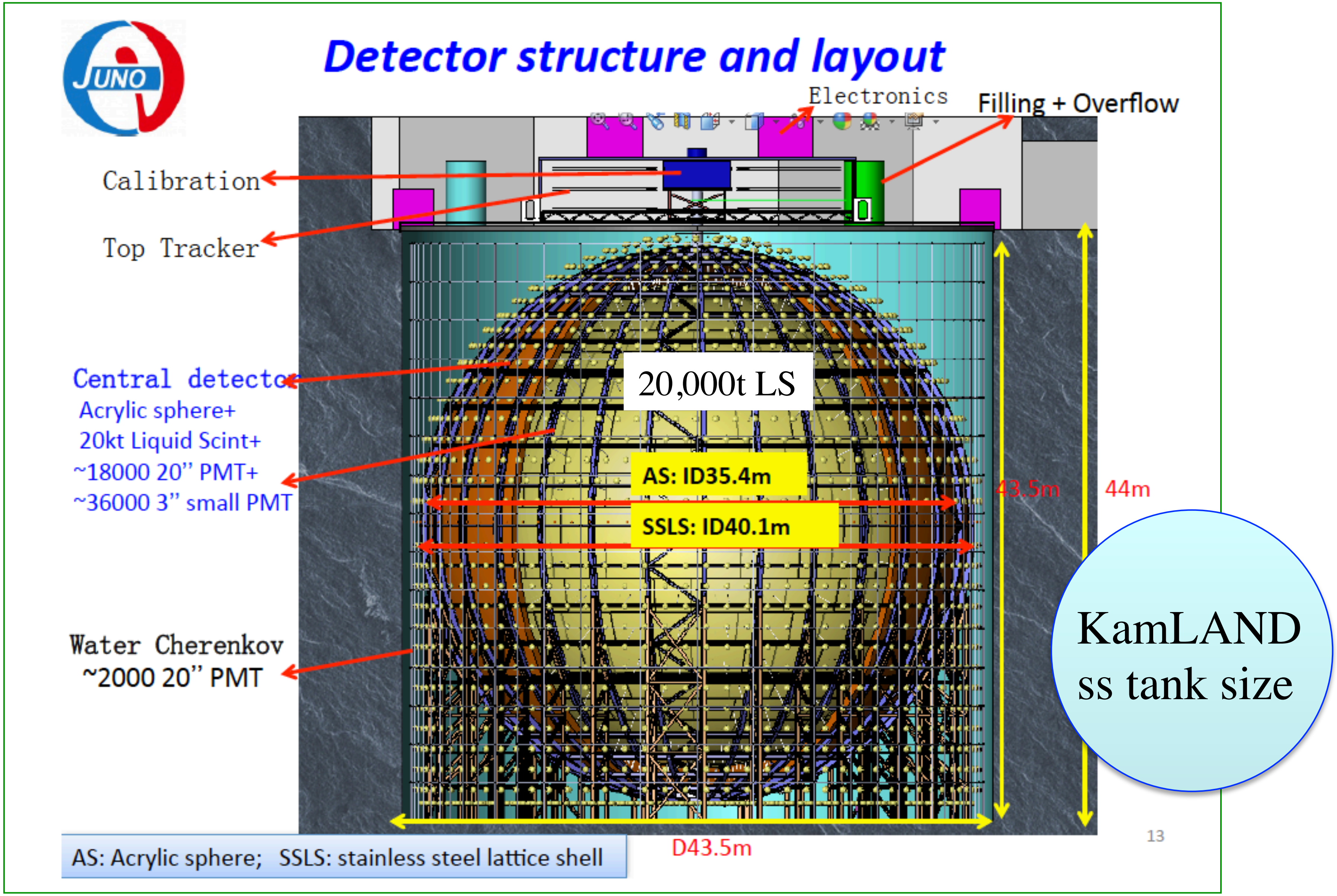
: Normal Hierarchy

: Inverted Hierarchy

Location of JUNO

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW




Detector structure and layout
JUNO
Electronics
Filling + Overflow
Calibration
Top Tracker
Central detector
Acrylic sphere+
20kt Liquid Scint+
~18000 20" PMT+
~36000 3" small PMT
20,000t LS
AS: ID35.4m
SSLS: ID40.1m
43.5m
44m
Water Cherenkov
~2000 20" PMT
KamLAND
ss tank size
AS: Acrylic sphere; SSLS: stainless steel lattice shell
D43.5m
13

Summary

JUNO will measure mass hierarchy (3-4 σ by 2026) and 3 oscillation parameters to <1% level.

JUNO also has a rich physics potential in supernova neutrinos, geo-neutrinos, solar neutrinos, and other oscillation physics such as searches for sterile neutrinos, among others.

•Curent Schedule as following:

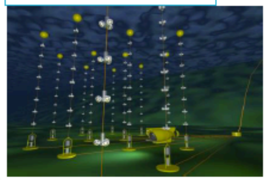
- Civil preparation： 2013-2014
- Civil construction： 2014-2018
- Detector component production： 2016-2017
- Detector assembly & installation： 2018-2019
- Filling & data taking： 2020

KM3Net-ORCA MH by atmospheric ν using matter effect

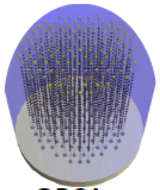
Detector sizes

	ANTARES	ORCA (denser)	ARCA (larger)
Eff. Mass	10 Mt	5.7 Mt	1 Gt
Line length	350 m	200 m	650 m
Interline distance	70 m	20 m	90 m

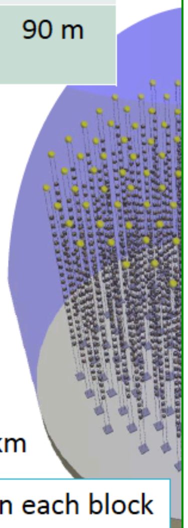
12 lines
25 sectors/line



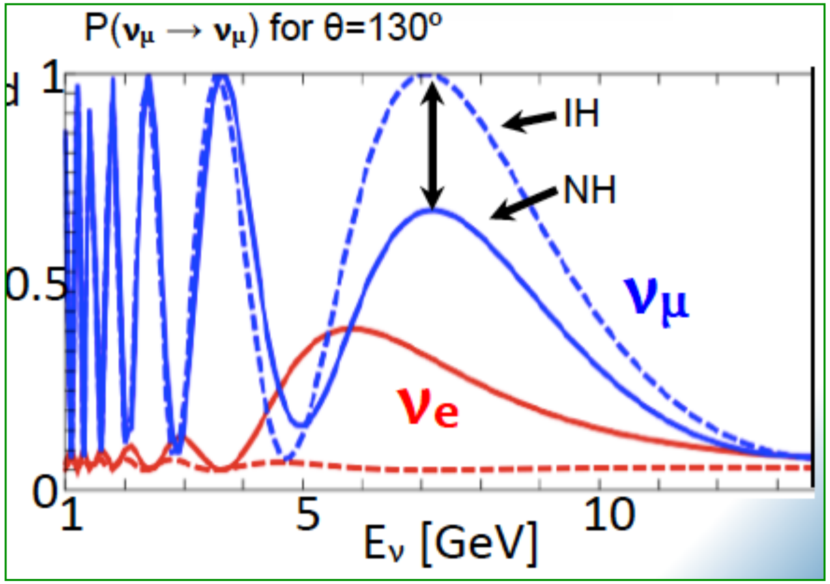
ANTARES
depth 2.5 km

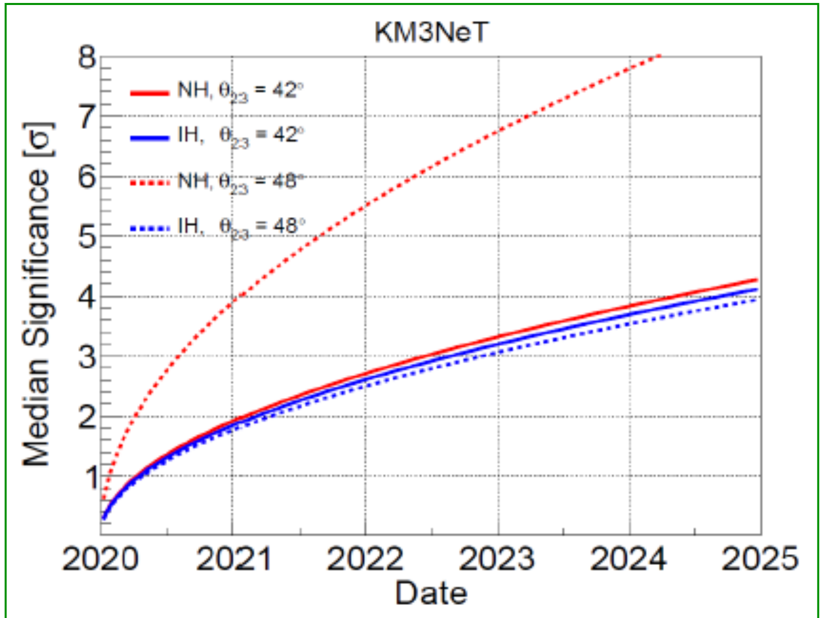


ORCA
depth 2.5 km

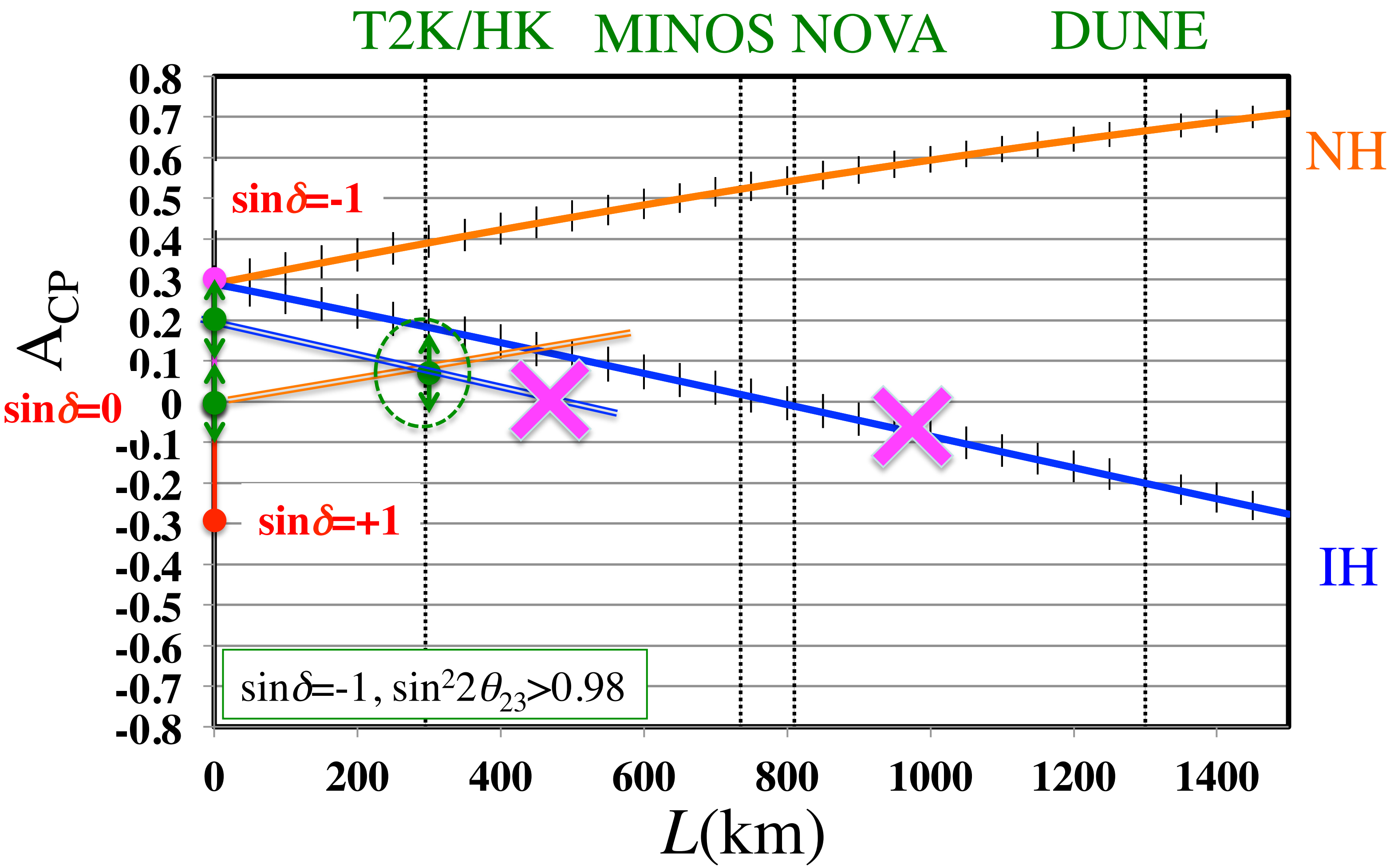


115 lines in each block
18 DOMs/line





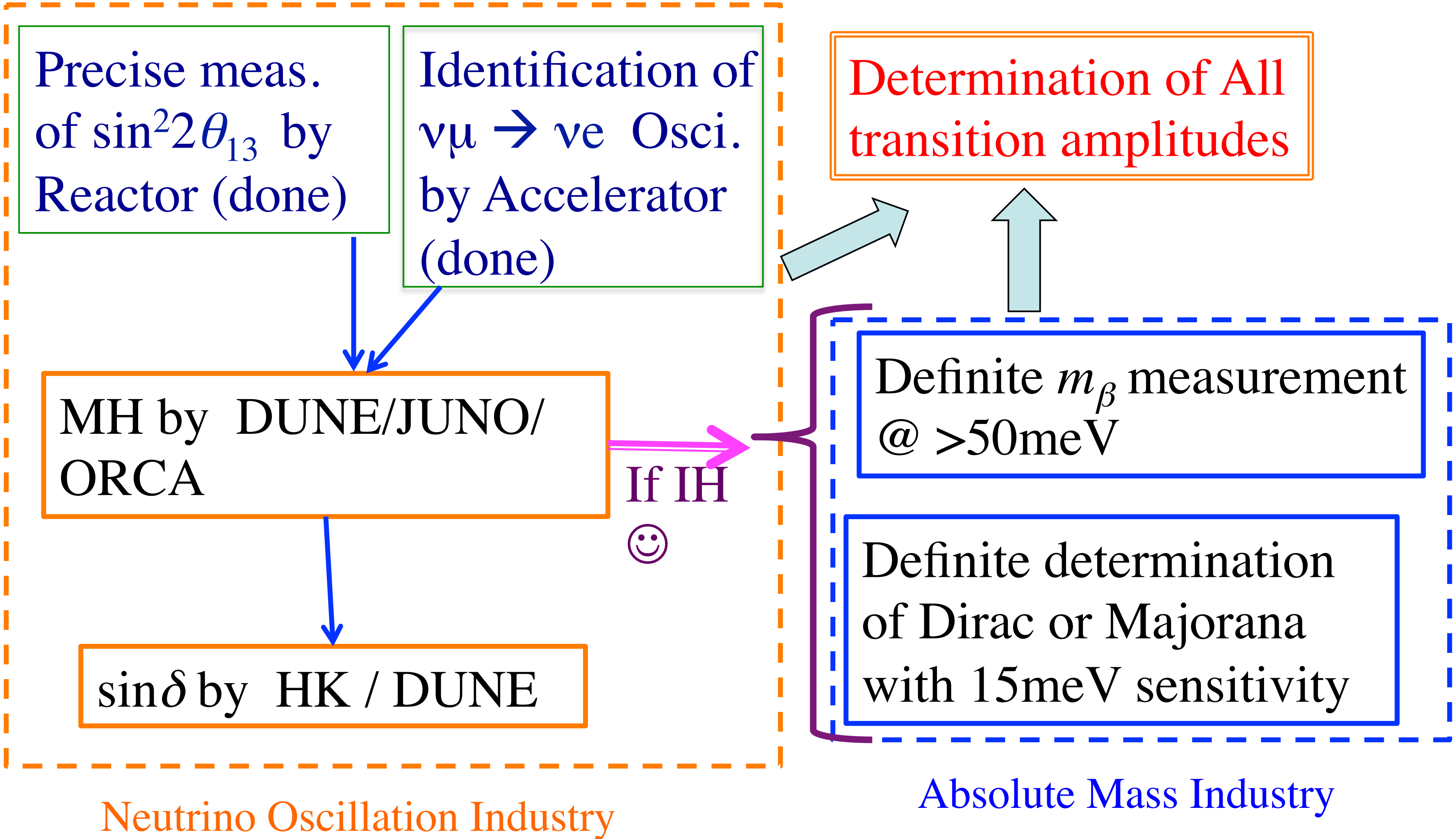
JUNO/ORCA will kill one line.



Hyper-K+DUNE+JUNO+OCA =
Redundant analysis of CPV & Mass Hierarchy.

A Golden Scenario

The nature has been amazingly kind to us. ☺
Let's assume she will be kind to us in the future also. ☺



Summary

* Thanks to the huge experimental efforts, θ_{12}, θ_{23}, θ_{13},

  Δm_{12}^2, $\left|\Delta \tilde{m}_{32}^2\right|$, $\left|\Delta \tilde{m}_{31}^2\right|$ have been measured.

* Measurements of δ, M.H. have become realistic.

* There are several tensions.

  ➔ Redundant experiments to check each other are important.

* A strategy on how to make the most of synergy effect between different experiments is important.