

Neutrino Oscillations: The Present and Perspectives

F.Suekane

Research Center for Neutrino Science

Tohoku University

(suekane@awa.tohoku.ac.jp)

2nd Symposium on
Neutrinos and Dark Matter in Nuclear Physics
(NDM06)
2006.9.6

An excuse

Program from NuFact06

3h20m {

Thursday, August 24		
Morning: Motivation and Overview		
Chair: D. Casper (UC Irvine)		
08:00	Welcome	J. Hemminger (Irvine)
08:10	Neutrino Physics Overview	J.W.F. Valle (Valencia)
08:50	The Last Five Years	S. Wojcicki (Stanford)
09:30	The Next Five Years	T. Nakaya (Kyoto)
10:10	Break	
	Chair: J.J. Gomez Cadenas (Valencia)	
10:35	Getting the Most from Oscillation Experiments	H. Minakata (Tokyo Metro)
11:15	Beyond T2K and NOvA	W. Winter (IAS)

It took 200min. for those prominent physicists to describe neutrino physics (mostly oscillation).

So please forgive me for skipping many subjects in this 25min. talk.

Contents

- Quick overview of ν oscillation
- Present
- Issues
- Perspective
- Summary

A Quick Review of ν Oscillation

2 flavor mixing case

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

ν_e state at t=0,

$$\phi(0) = \nu_e = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

after t at rest

$$\phi(t) = \cos\theta|\nu_1\rangle e^{-im_1 t} + \sin\theta|\nu_2\rangle e^{-im_2 t}$$

$$= (\cos^2\theta e^{-im_1 t} + \sin^2\theta e^{-im_2 t})|\nu_e\rangle + \underline{\sin\theta \cos\theta (e^{-im_2 t} - e^{-im_1 t})} |\nu_\mu\rangle$$

The transition probability at rest is,

$$P_{\nu_e \rightarrow \nu_\mu} = |\sin\theta \cos\theta (e^{-im_2 t} - e^{-im_1 t})|^2 = \sin^2 2\theta \sin^2 \frac{(m_2 - m_1)t}{2}$$

Since E>>m,

Lorentz boost ($\gamma = 2E/(m_1 + m_2)$)

$$P_{\nu_e \rightarrow \nu_\mu} = \sin^2 2\theta \sin^2 \frac{(m_2^2 - m_1^2)L}{4E}$$

Amplitude ==> $\sin^2 2\theta$, Frequency ==> $|m_2^2 - m_1^2|L$

3 flavor case

Mixings

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

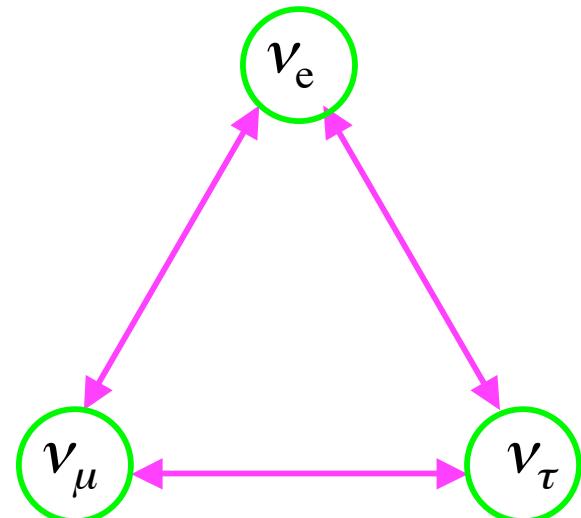
Oscillations

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \Phi_{ij}$$

$$\mp 2 \sum_{i>j} \text{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin 2 \Phi_{ij}$$

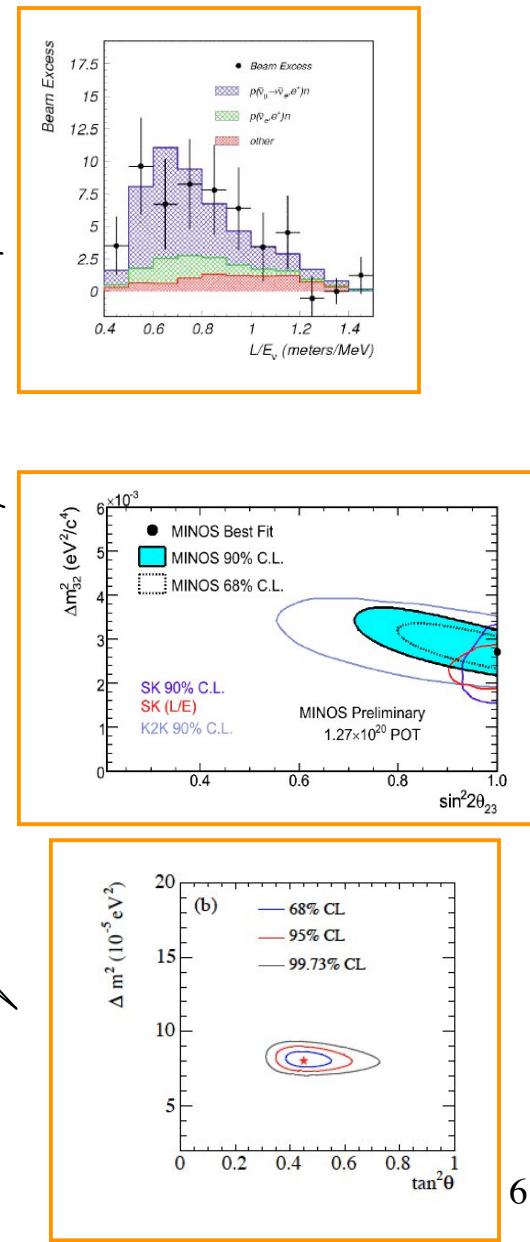
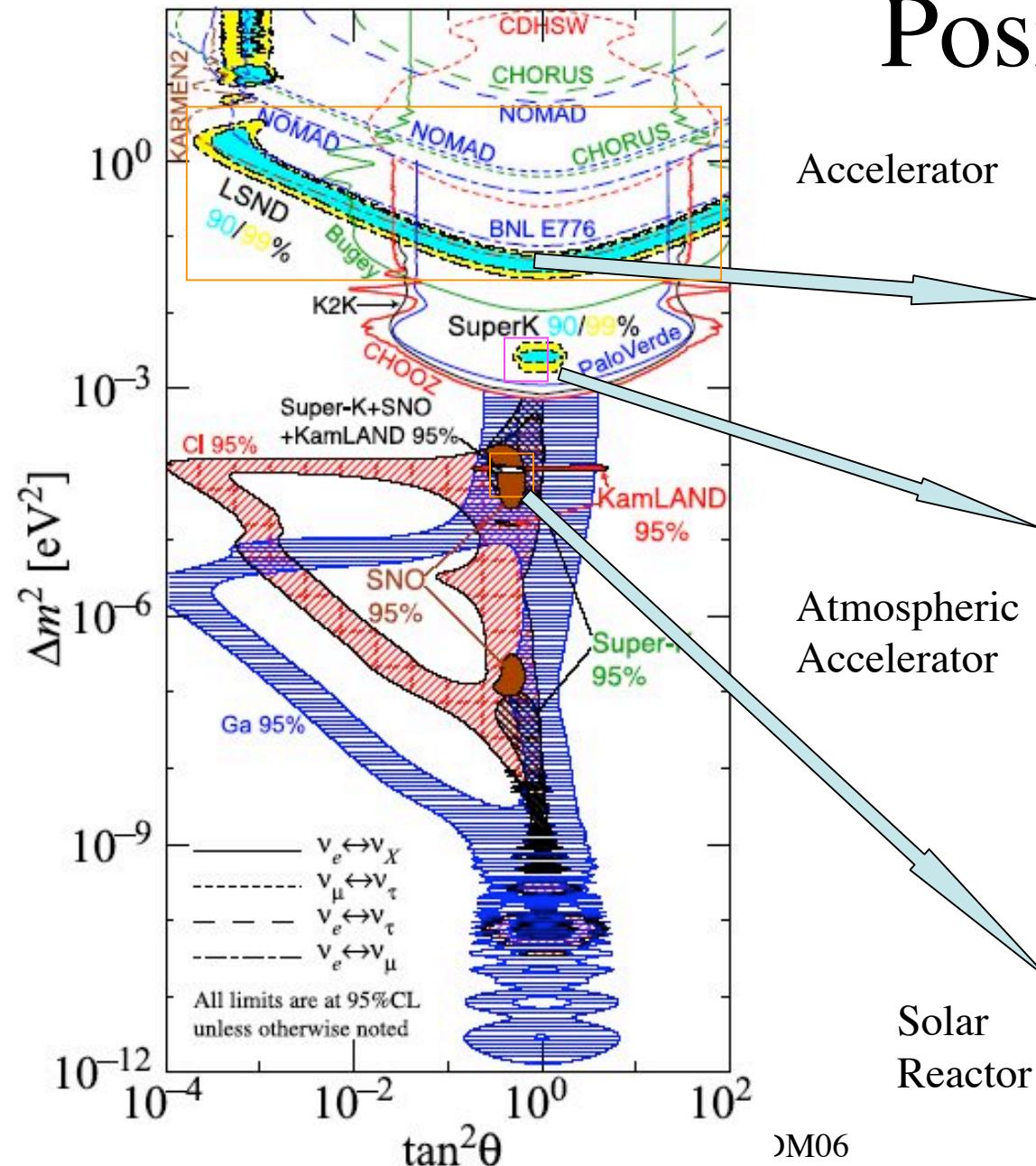
$$\left(\Phi_{ij} = \frac{\Delta m_{ij}^2 L}{4E}, \quad \Delta m_{ij}^2 = m_j^2 - m_i^2 \right)$$

$$|\Delta m_{12}^2|, \quad |\Delta m_{23}^2|, \quad (|\Delta m_{31}^2|), \quad \theta_{12}, \quad \theta_{23}, \quad \theta_{31}, \quad \delta$$

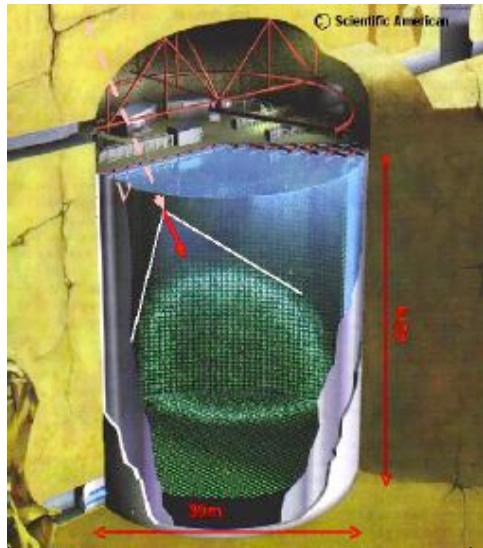


6 parameters can be accessible from neutrino oscillation.

Positive results



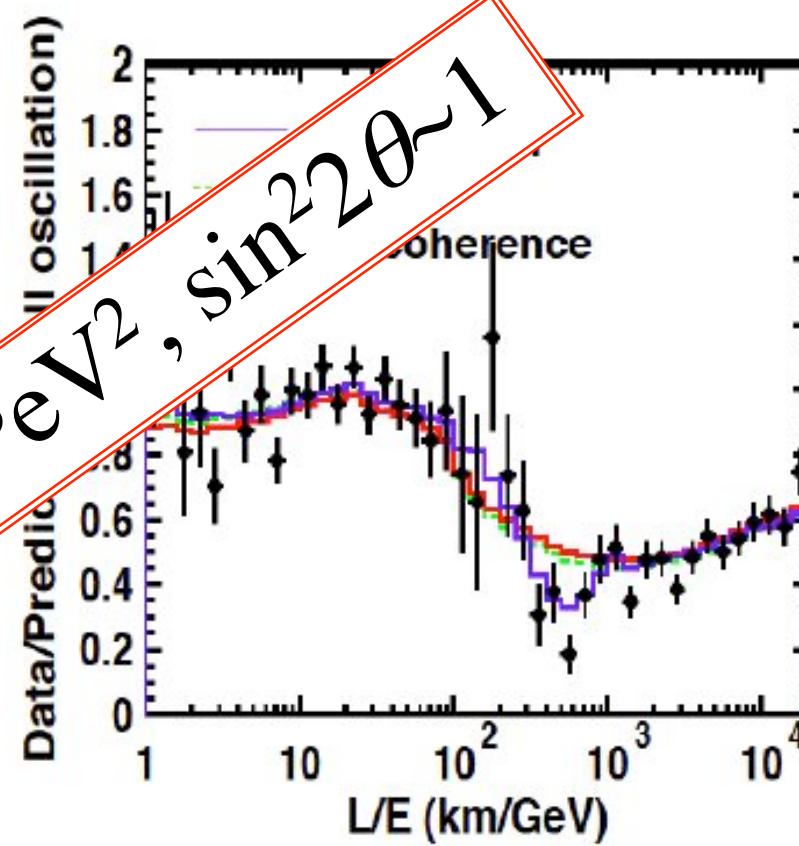
SK atmospheric ($\nu_\mu \rightarrow \nu_\mu$) ($\nu_\mu \rightarrow \nu_e$)



Cosmic ray

06.09.06

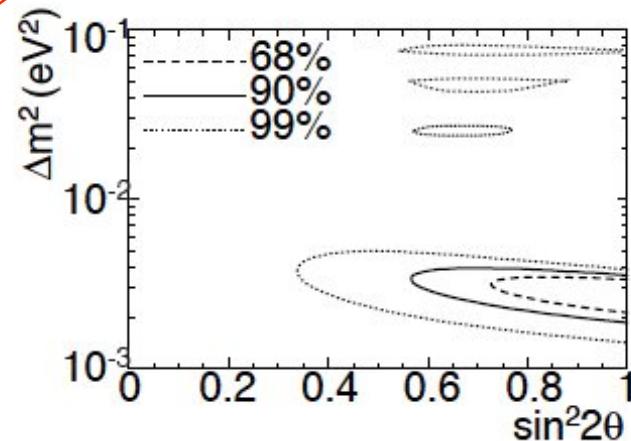
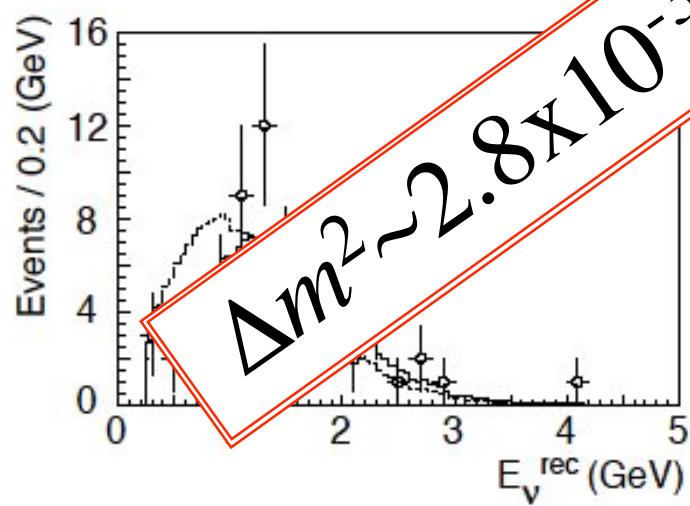
(The first firm evidence of ν oscillation)



NDM06

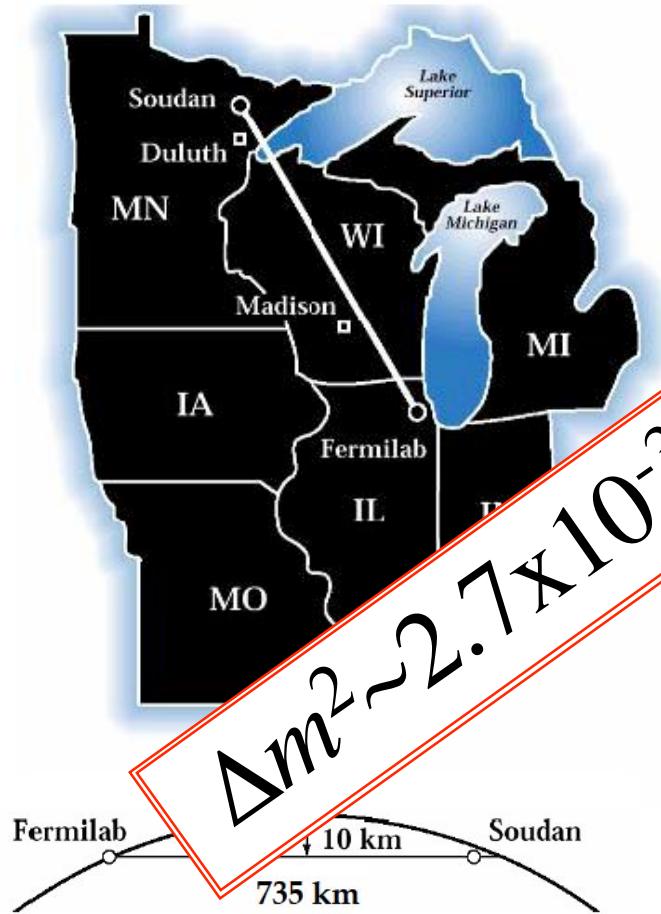
K2K $\nu_\mu \rightarrow \nu_\mu$

E~1GeV, L=250km



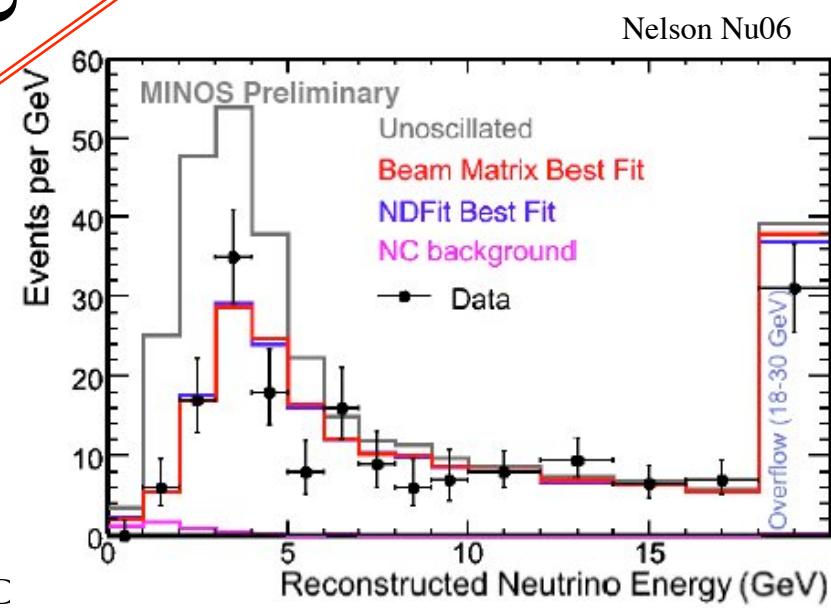
MINOS ($\nu_\mu \rightarrow \nu_\mu$)

E~4GeV, L=735km

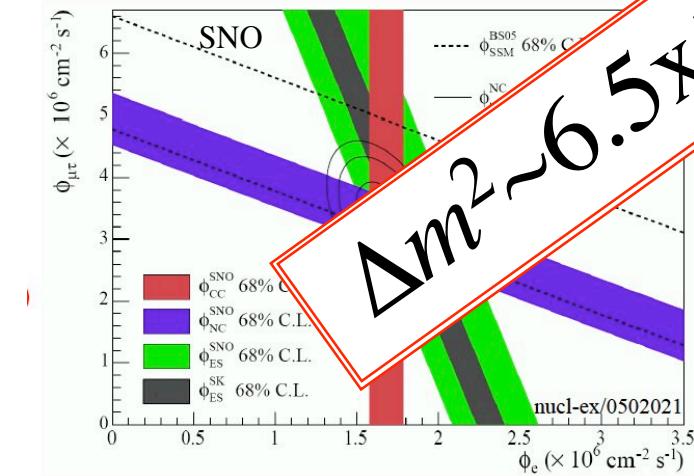
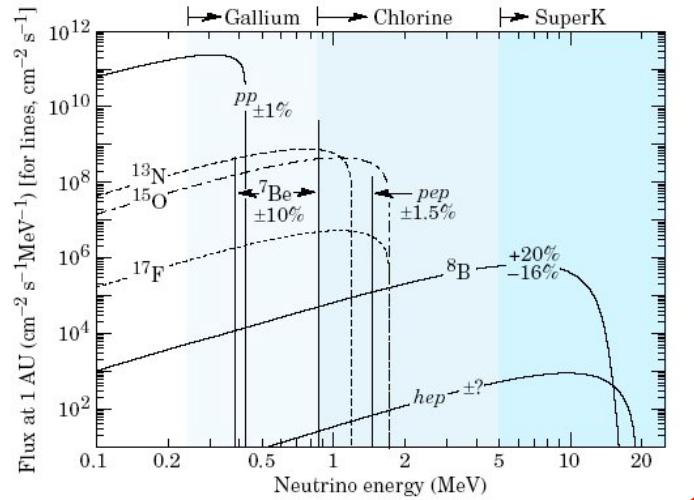


06.09.06

NC



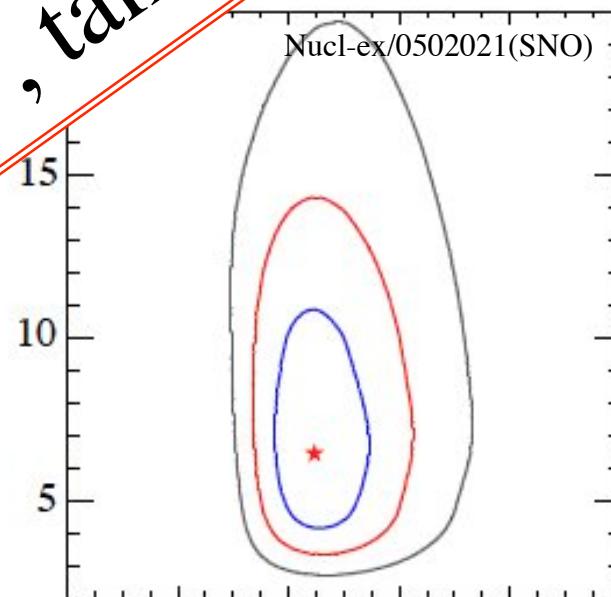
Solar ($\nu_e \rightarrow \nu_e, \nu_x$)



Deficits on $\nu_e \rightarrow \nu_e$

But no deficit on $\nu_e \rightarrow \nu$

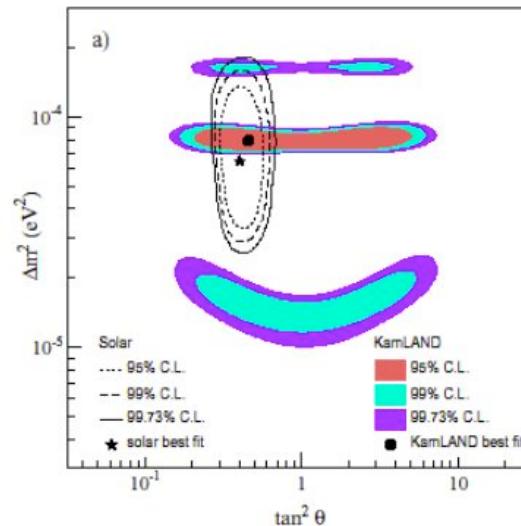
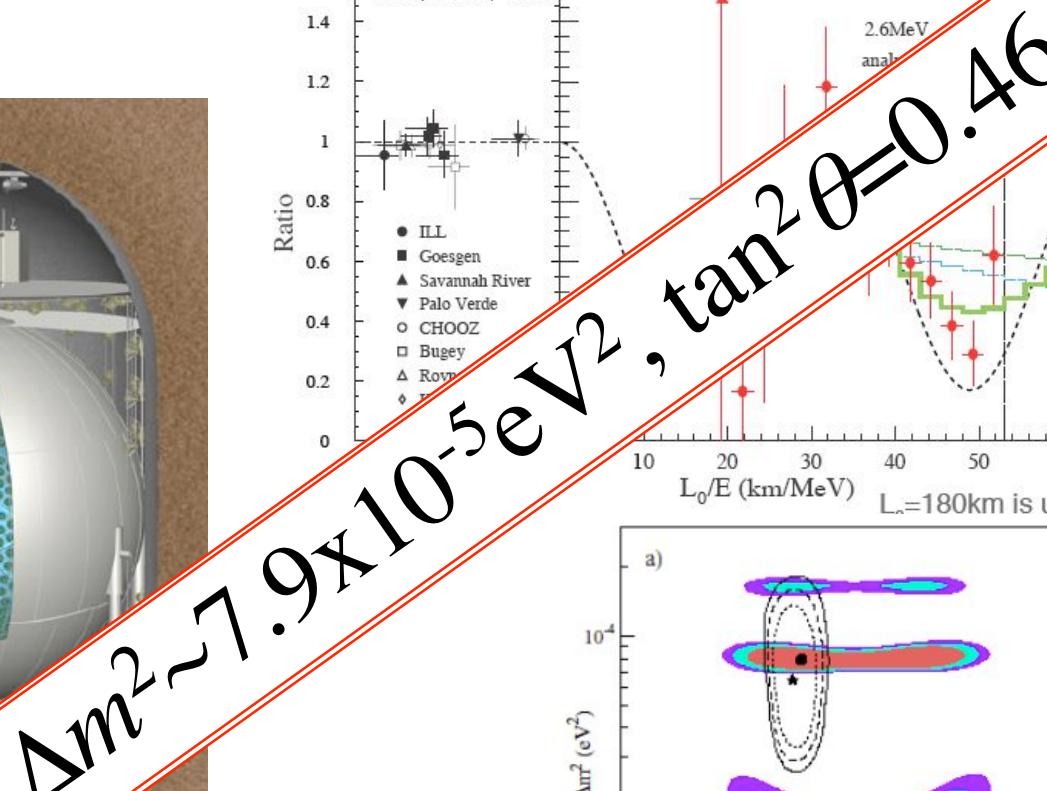
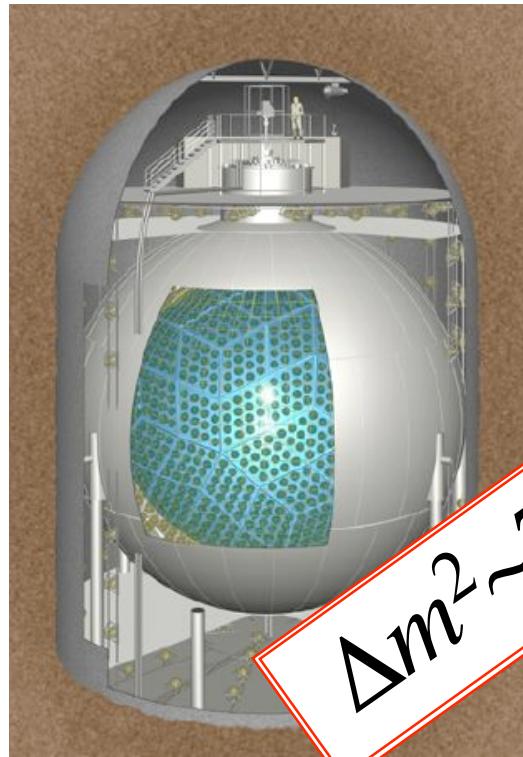
$\Delta m^2 \sim 6.5 \times 10^{-3} \text{ eV}^2$, $\tan^2 \theta = 0.45$



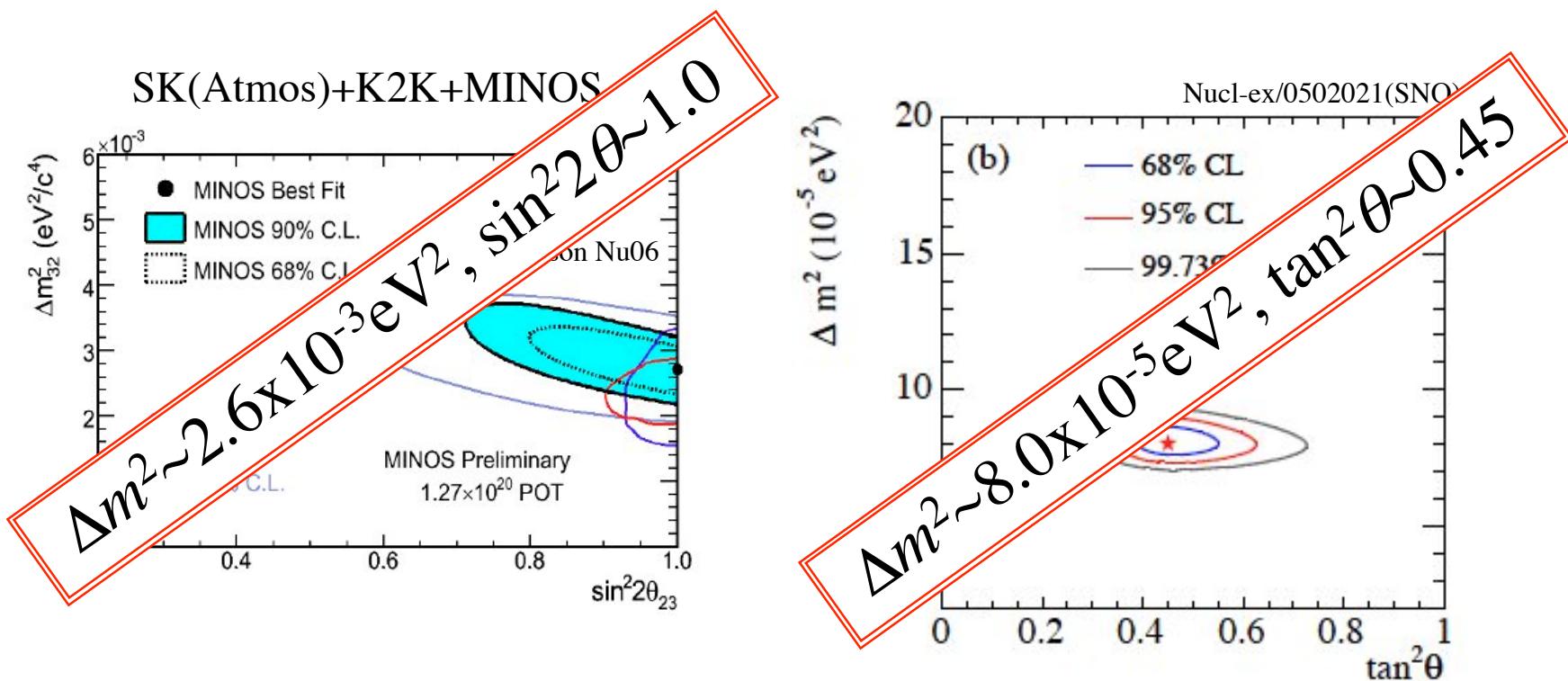
KamLAND

Reactor ($\overline{\nu}_e \rightarrow \overline{\nu}_e$)

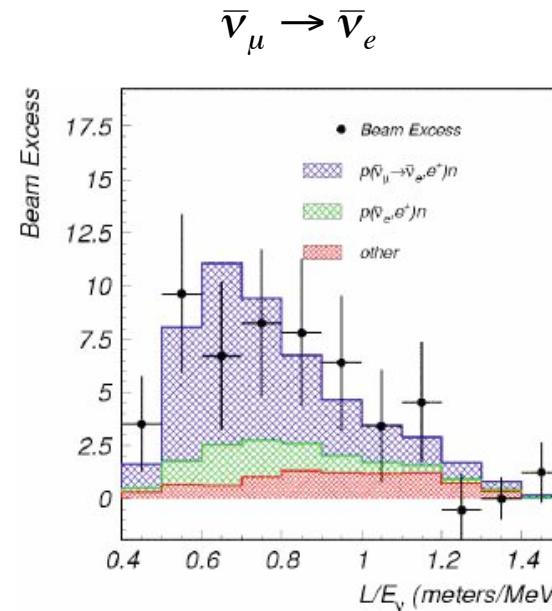
$E \sim 4\text{MeV}$, $L \sim 180\text{km}$



Combined



LSND



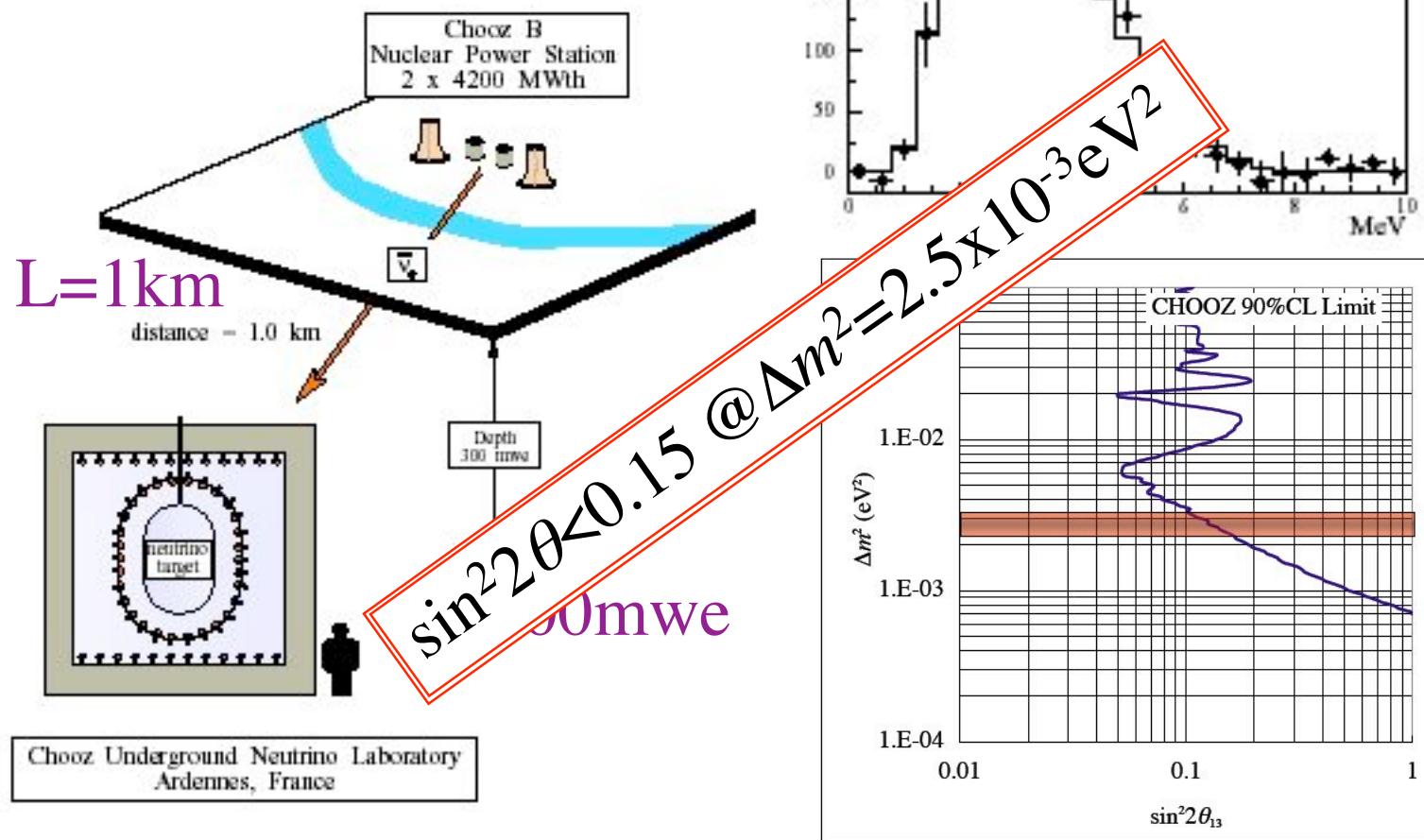
$$\sin^2 2\theta = 0.001 \sim 0.04, \quad \Delta m^2 = 0.1 \sim 10 \text{ eV}^2$$

3 independent Δm^2 parameters \rightarrow may be sterile ν ??

\implies Wait for MiniBooNE result which is coming soon.

Upper limit

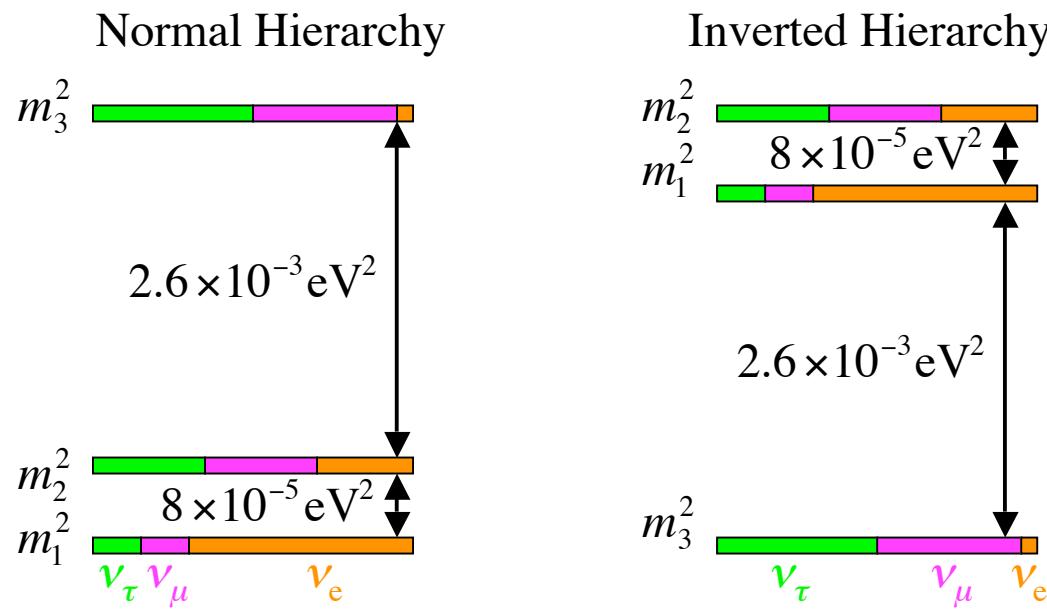
CHOOZ reactor ($\bar{\nu}_e \rightarrow \bar{\nu}_e$) experiment



What we now know

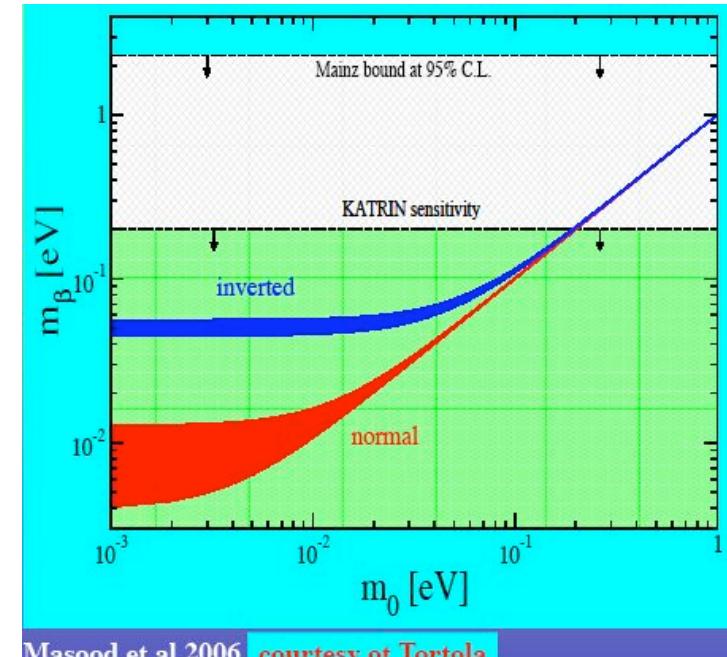
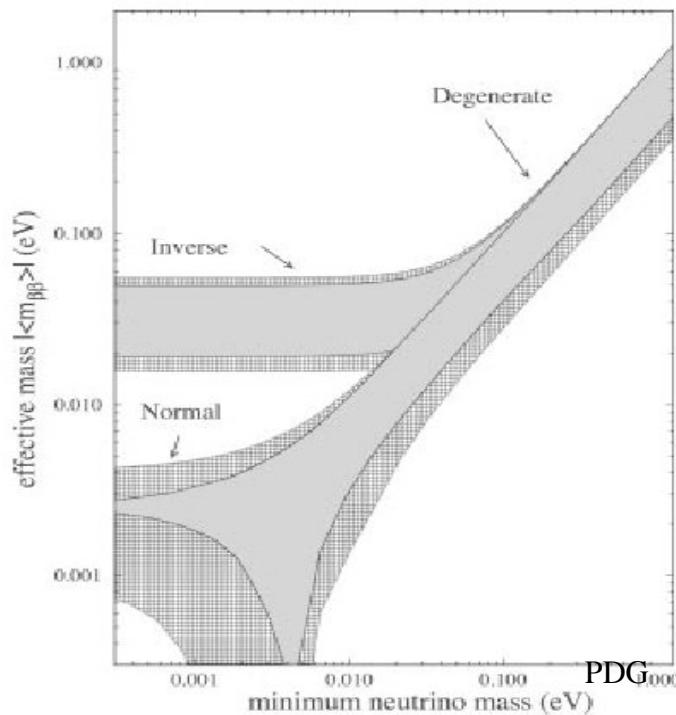
$$\Delta m_{23}^2 \sim 2.6 \times 10^{-3} \text{ eV}^2, \quad \Delta m_{12}^2 \sim 8.0 \times 10^{-5} \text{ eV}^2$$

$$U_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & s_{13}e^{i\delta} \\ -0.4 & 0.6 & 0.7 \\ 0.4 & -0.6 & 0.7 \end{pmatrix} \quad |s_{13}| < 0.2$$



Impact on $0\nu\beta\beta$ & direct m_ν experiments

$$m_{\beta\beta} = \sum m_i U_{ei}^2 \sim \frac{1}{2} \left| m_1 + m_2 e^{2i\beta} + 2 s_{13}^2 m_3 e^{2i(\gamma-\delta)} \right| \quad \langle m_\nu \rangle = \sqrt{\sum |U_{ei}|^2 m_i^2} \sim \sqrt{\frac{1}{2} (m_1^2 + m_2^2) + s_{13}^2 m_3^2}$$



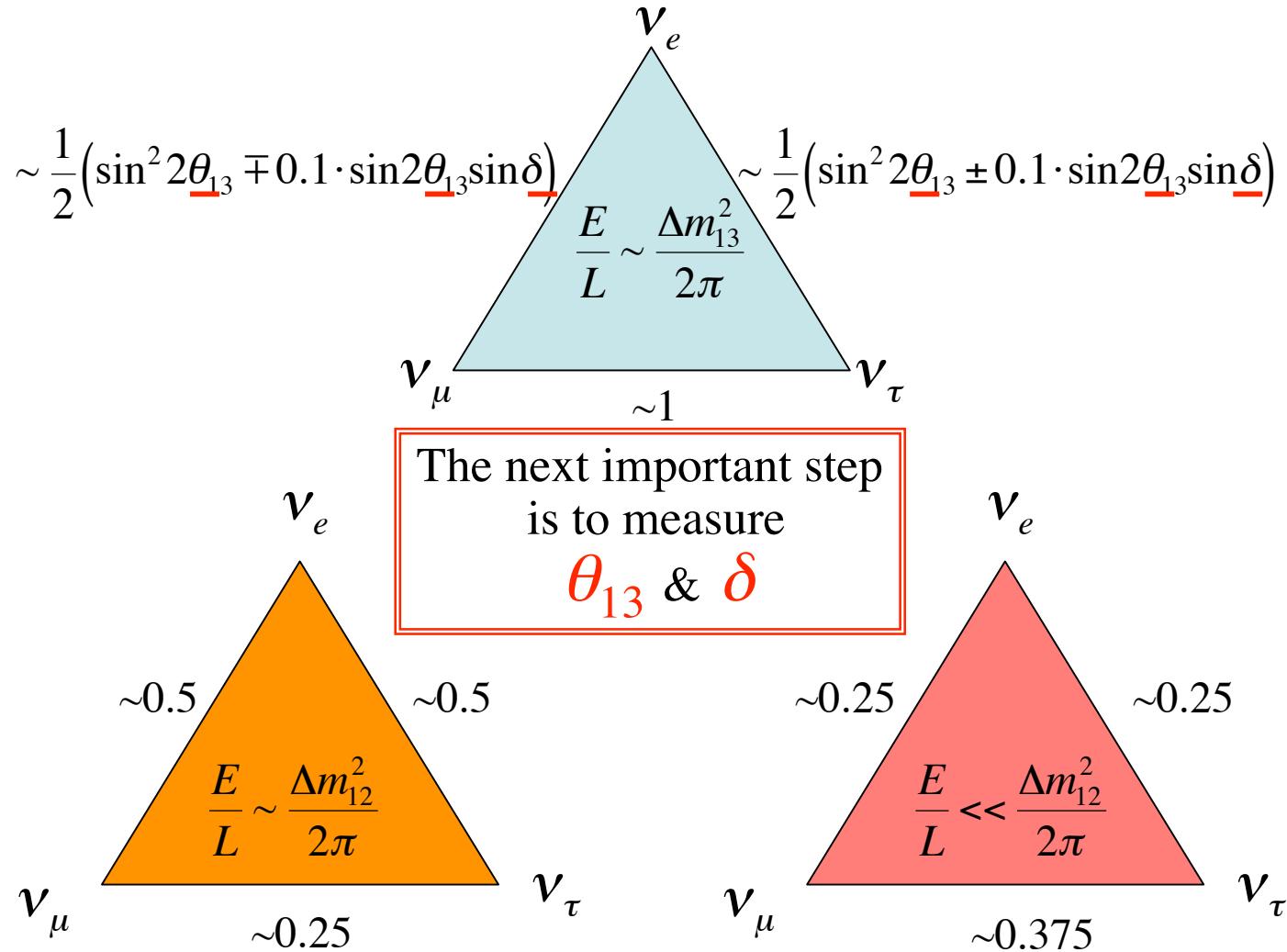
Masood et al 2006 courtesy of Tortola

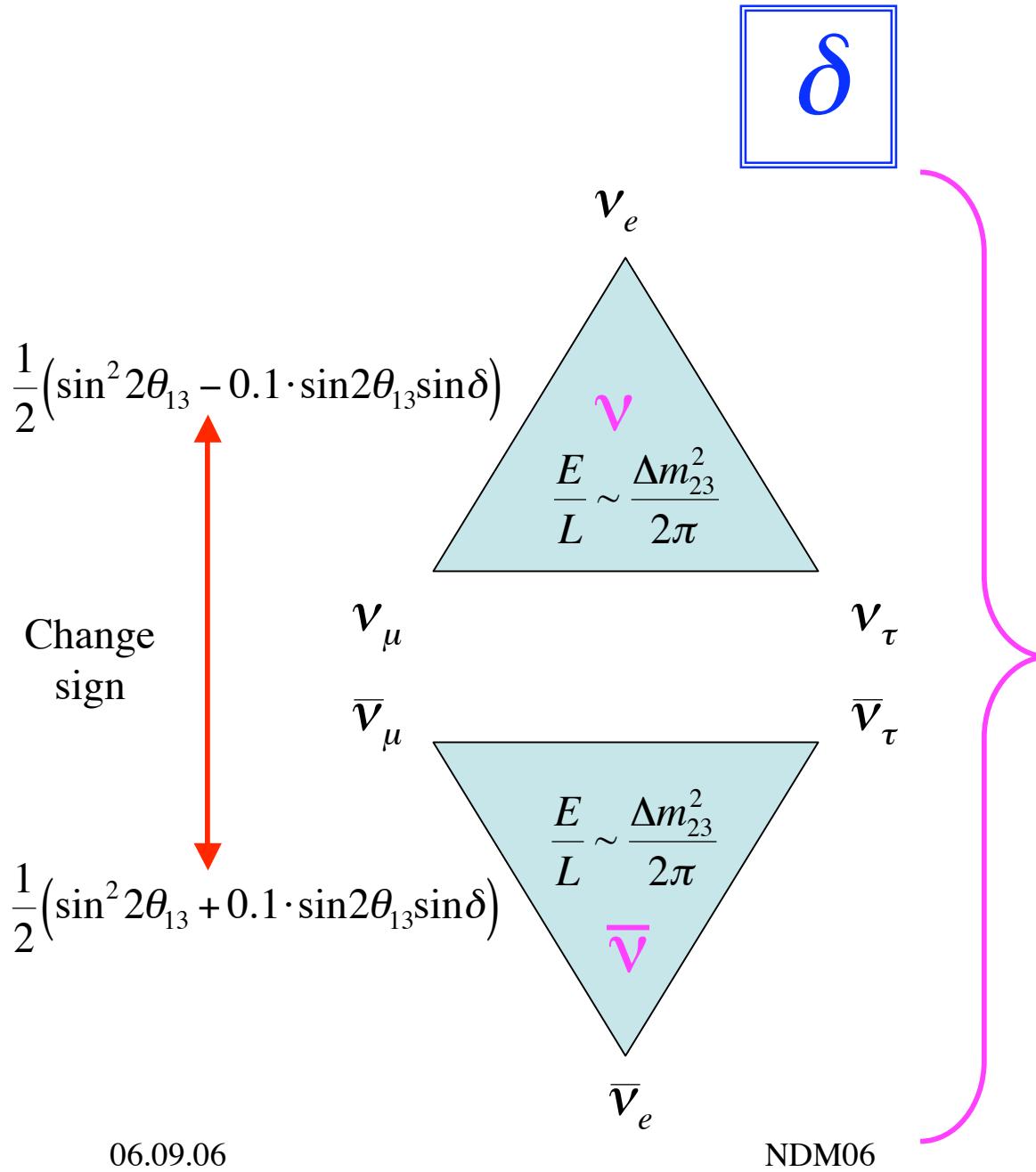
From J.W.F.Valle slide inNufact06

Oscillation results show clear targets to
direct m_ν and $0\nu\beta\beta$ experiments

Summary of Oscillation Amplitudes

($\sin^2 2\theta_{23} \sim 1, \sin^2 2\theta_{12} \sim 1, \sin^2 2\theta_{13} \ll 1$ assumed)





Accelerator only

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \\ \sim 0.1 \cdot \sin 2\theta_{13} \sin \delta$$

Accelerator(ν) + Reactor

$$P_{acc.}(\nu_\mu \rightarrow \nu_e) - \frac{1}{2} P_{reactor}(\bar{\nu}_e \rightarrow \bar{\nu}_e) \\ \sim 0.05 \cdot \sin 2\theta_{13} \sin \delta$$

In any case, asymmetry depends on θ_{13}
 \Rightarrow Need to attack θ_{13} before δ .

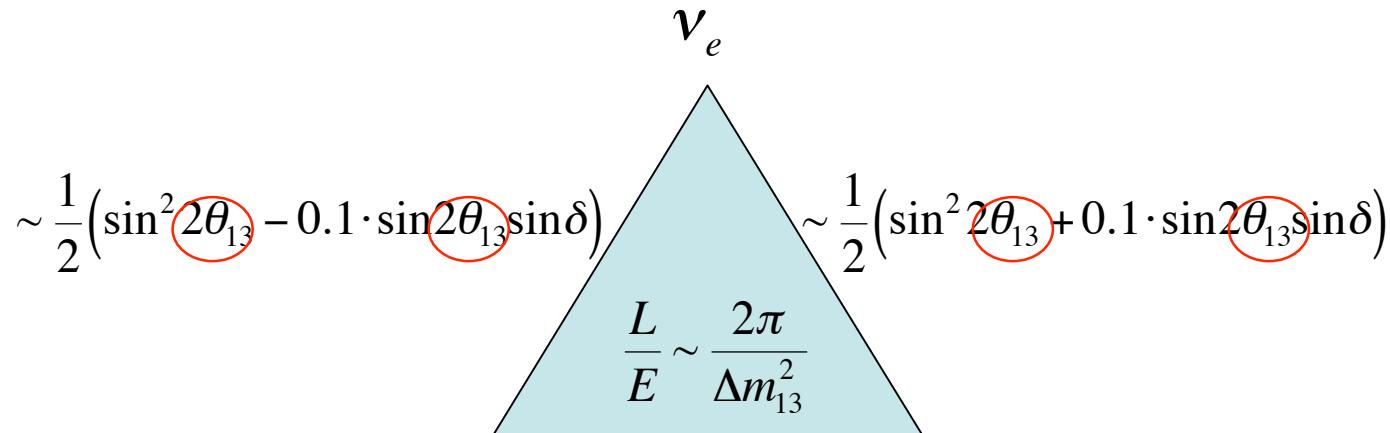
$$\theta_{13}$$

The measurement is important because

(1) => could be a key information for unified theory.

(2) => detectability of CP violating parameter δ .

Especially, if $\sin^2 2\theta_{13} < 0.01$, it will be very difficult to measure δ . We need to check it ASAP.



ν_μ
Accelerator based measurement

$$P(\nu_\mu \rightarrow \nu_e) \sim \frac{1}{2}(\sin^2 2\theta_{13} - 0.1 \cdot \sin 2\theta_{13} \sin \delta)$$

$$P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2 2\theta_{13}$$

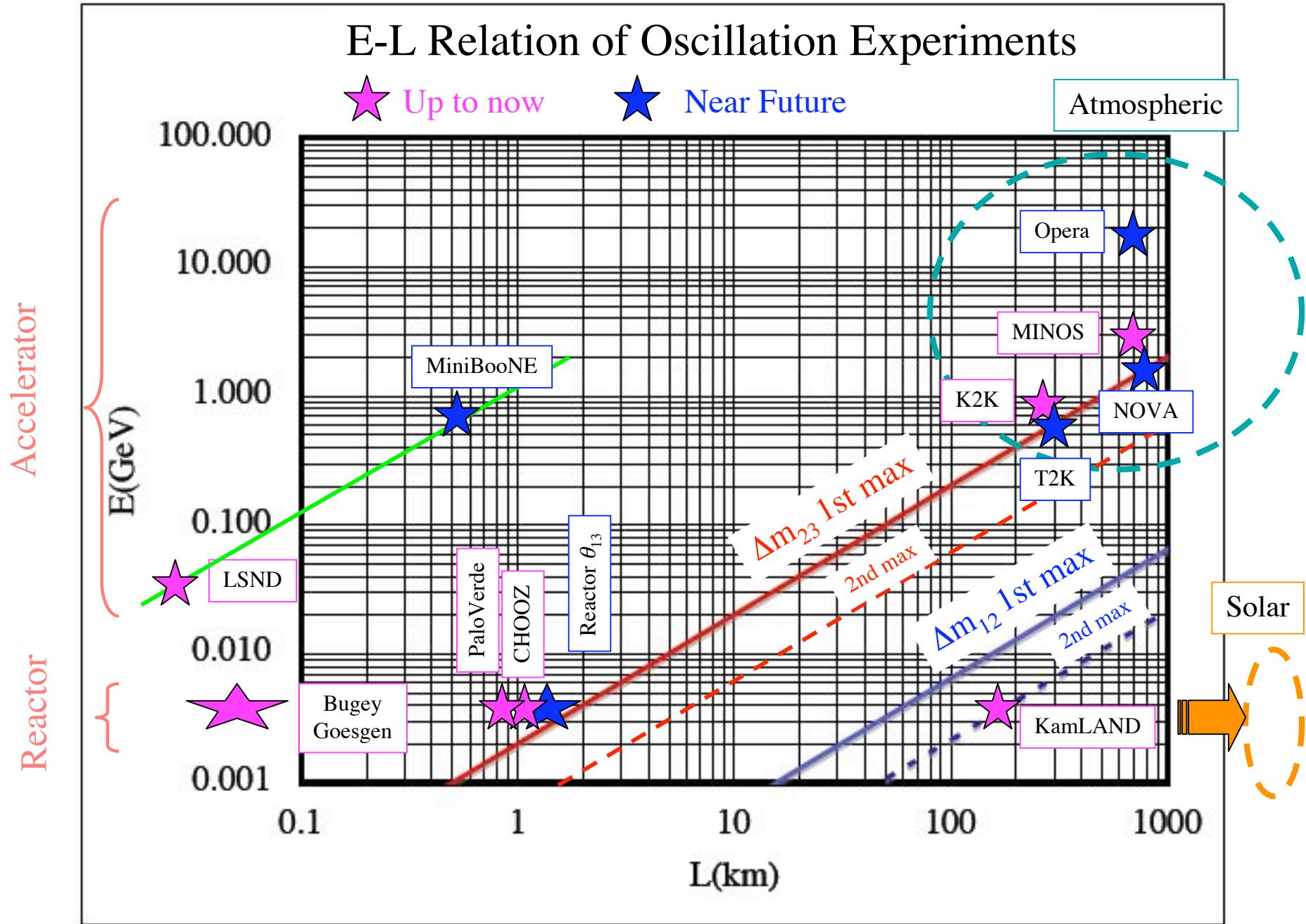
06.09.06

NDM06

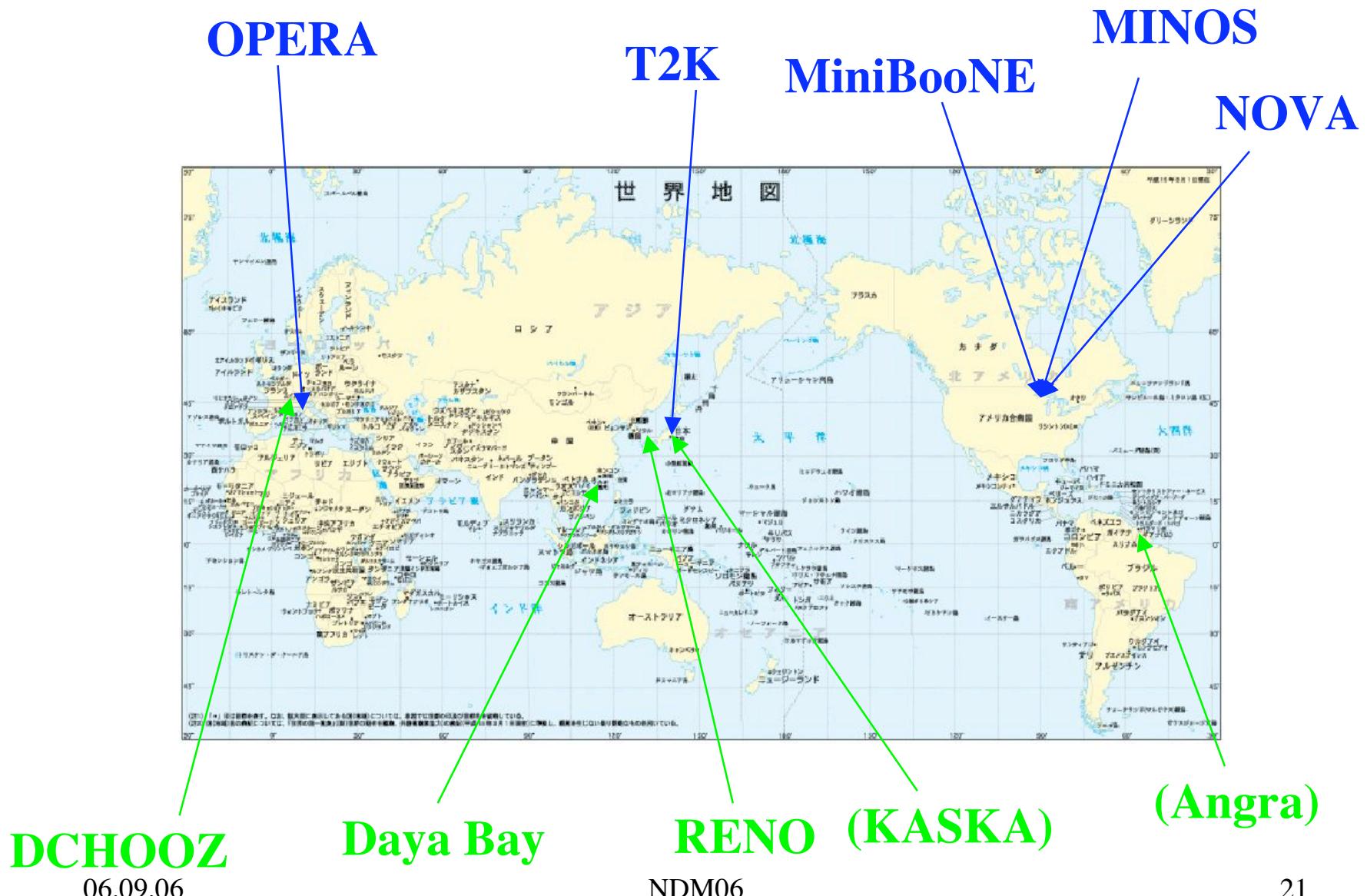
Reactor based measurement

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu + \bar{\nu}_\tau) \sim \sin^2 2\theta_{13}$$

19



Near Future Site Map

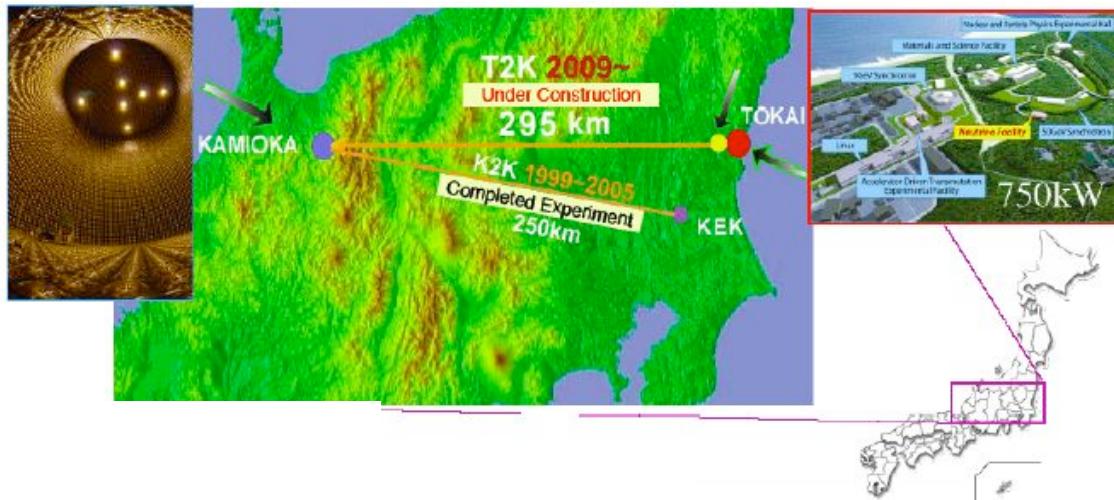


T2K

L=295km, E~0.6GeV

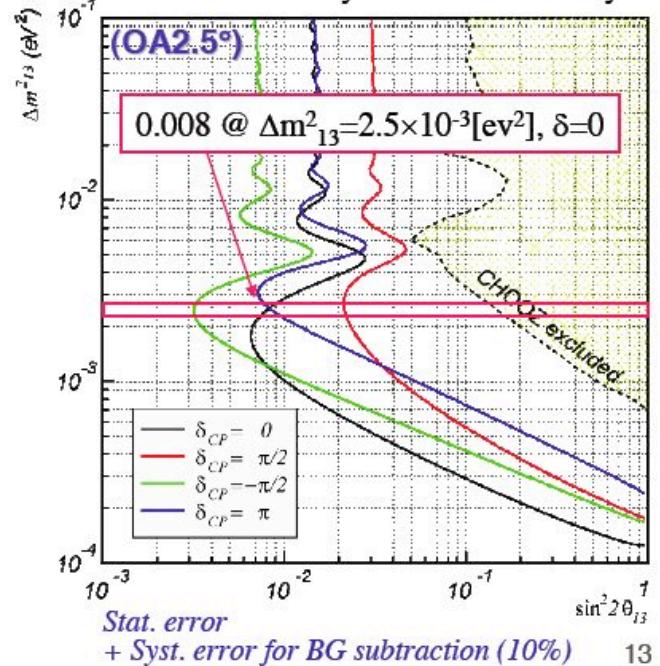
T2K: Jparc to SK 2009~

θ_{13} by $\nu_\mu \rightarrow \nu_e$ appearance



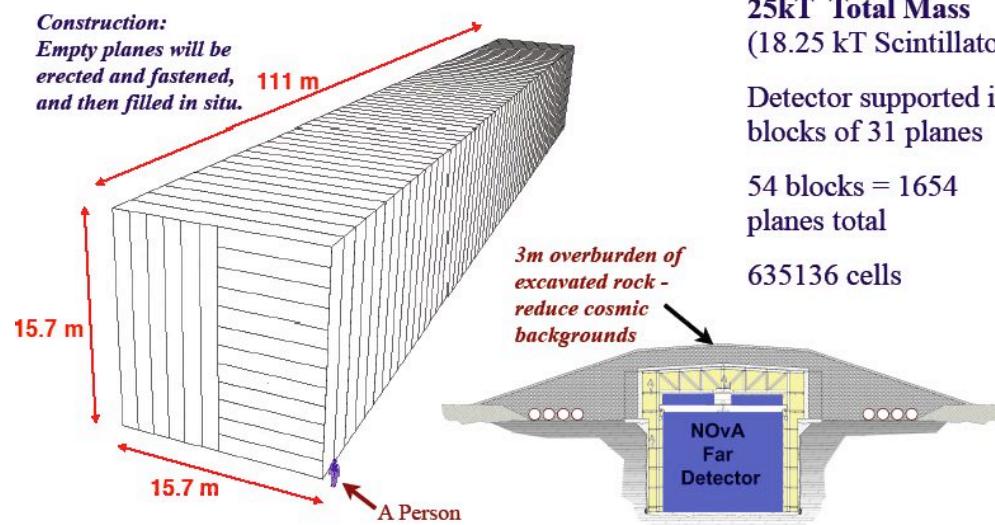
T2K 90% CL sensitivity

$\sin^2 2\theta_{23} = 1.0$ is assumed.
 5×10^{21} POT ~ 5 years@ full intensity

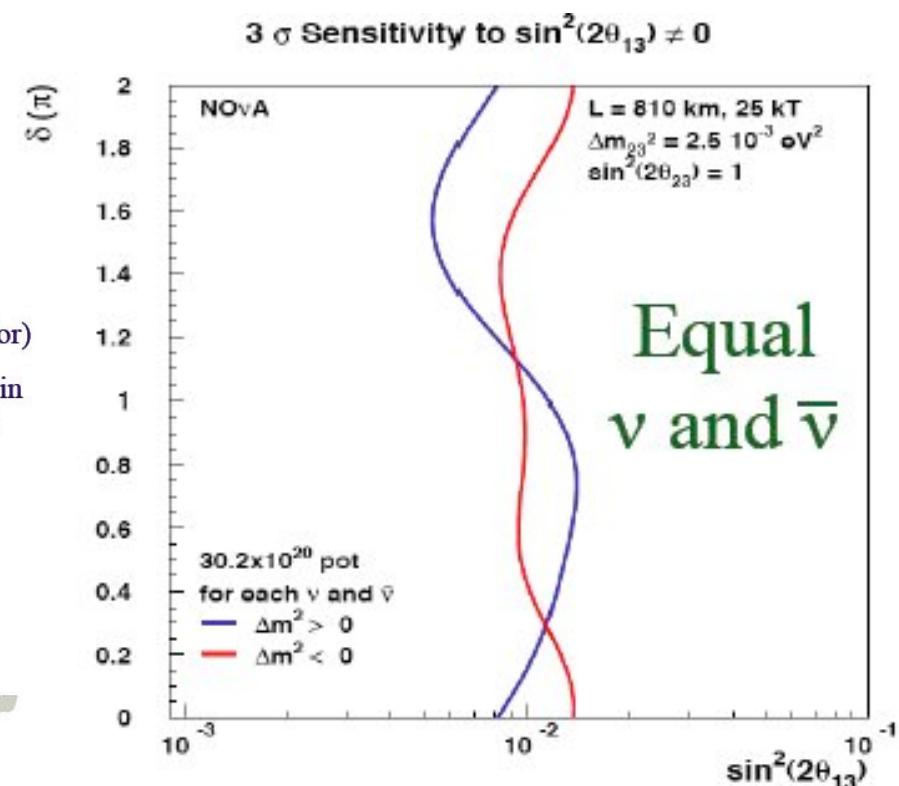


NOvA

L=810km, E~2GeV



$$(\nu_\mu \rightarrow \nu_e) \& (\nu_\mu \rightarrow \nu_e) + (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

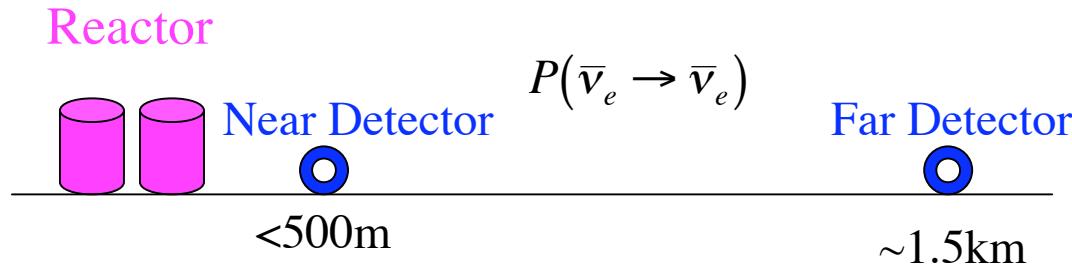


NDM06

2011~

23

Reactor- θ_{13}



Cancel systematics by near detector

Sensitivity(1st generation): $\sin^2 2\theta_{13} = 0.01 \sim 0.03$

Proposed Reactor θ_{13} Neutrino Experiments

	Location	Thermal Power (GW)	Distances Near/Far (m)	Depth Near/Far (mwe)	Target Mass (tons)
Angra	Brazil	4.1	300/1500	250/2000	500
Daya Bay	China	11.6 17.4 after 2010	360(500)/1750	260/910	40
Double-CHOOZ	France	8.7	150/1067	60/300	10.2
KASKA	Japan	24.3	350/1600	90/260	6
RENO	Korea	17.3	150/1500	230/675	20



The Site

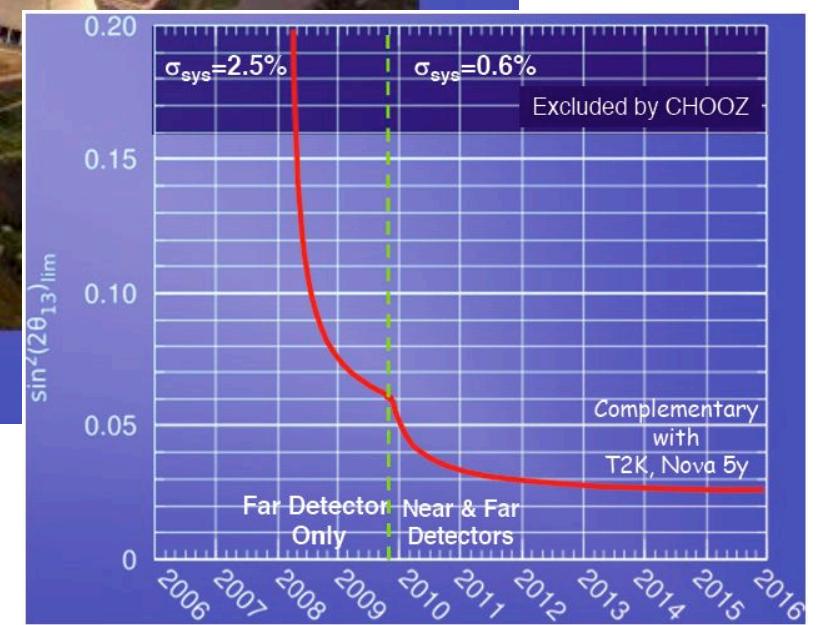


15 June 2006

D. Reyna (ANL)

06.09.06

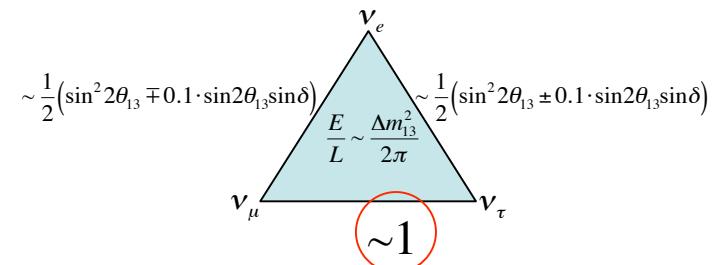
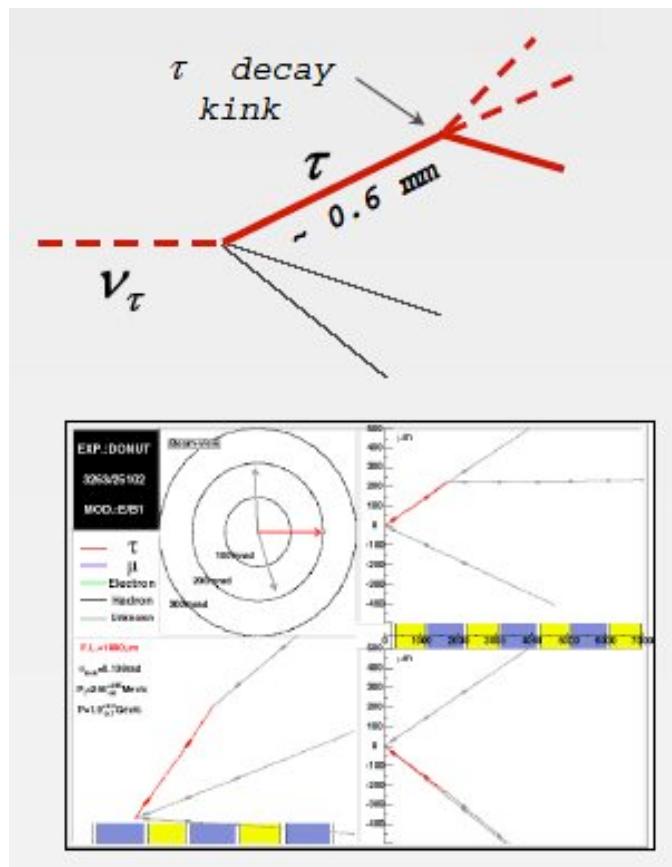
NDM06



OPERA

E~17GeV, L=732km

Sirignano Nu06



$\nu_\mu \rightarrow \nu_\tau$ appearance by emulsion target

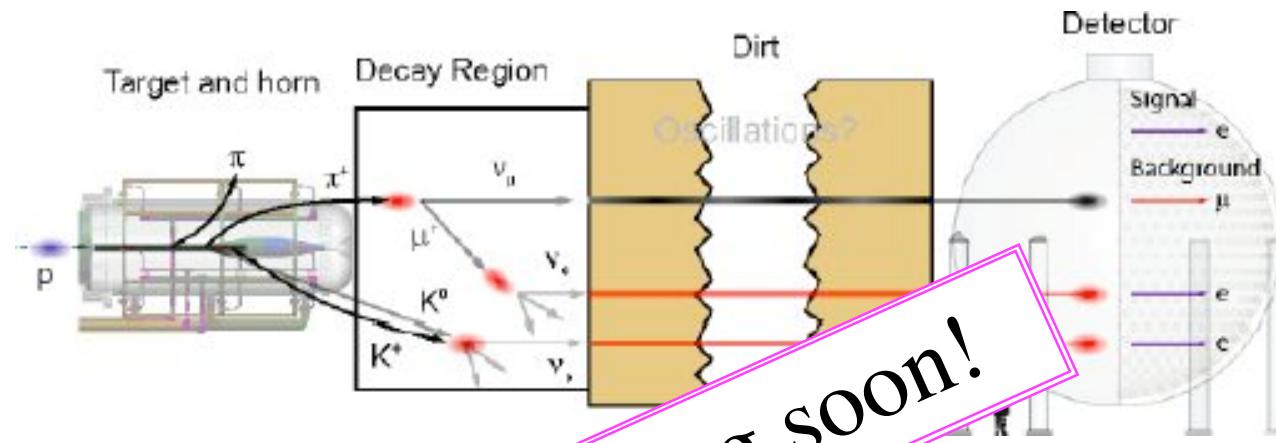
τ decay channel	Signal		Background
	$\Delta m^2 = 2.4 \times 10^{-3} \text{ eV}^2$	$\Delta m^2 = 3.0 \times 10^{-3} \text{ eV}^2$	
$\tau \rightarrow \mu$	3.6	5.6	0.23
$\tau \rightarrow e$	4.3	6.7	0.23
$\tau \rightarrow h$	3.8	5.9	0.32
$\tau \rightarrow 3h$	1.1	1.7	0.22
ALL	12.8	19.9	1.0

full mixing, 5 years run @ 4.5×10^{19} pot / year

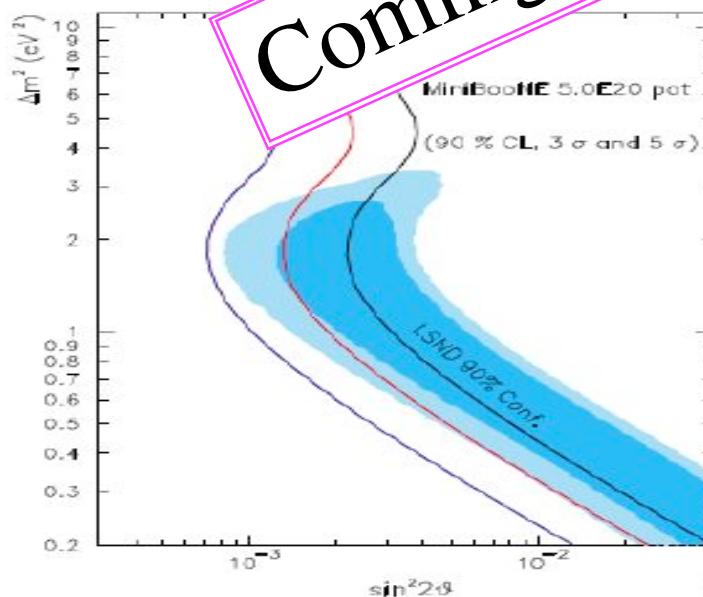
2006~

MiniBooNE

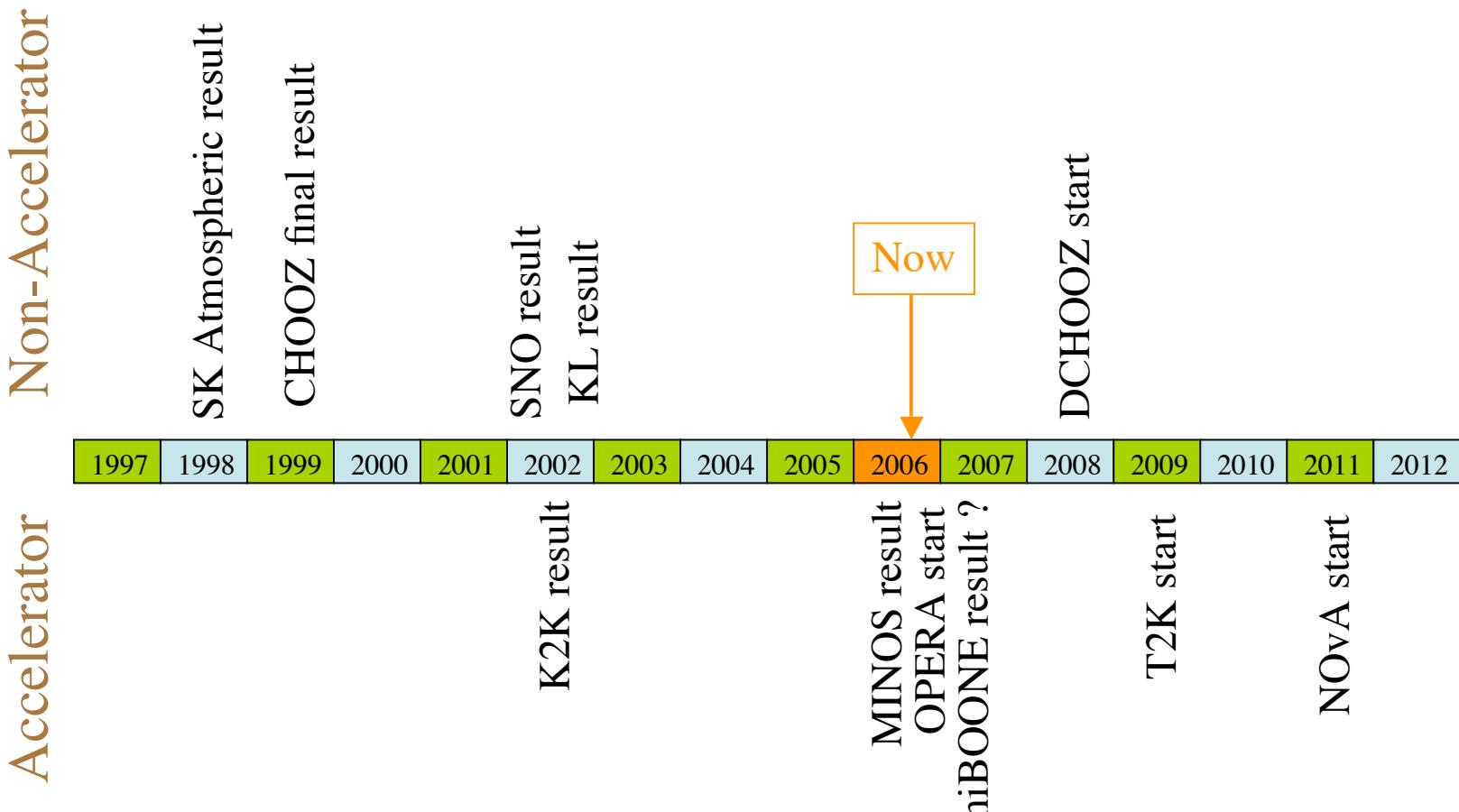
To test the LSND region with different L and E (but same L/E) and systematics.



Coming soon!



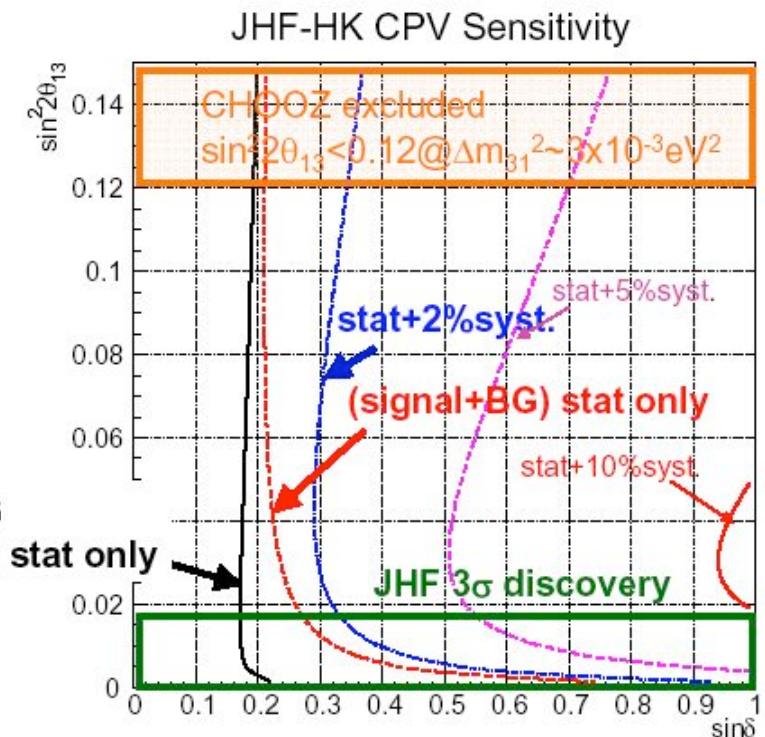
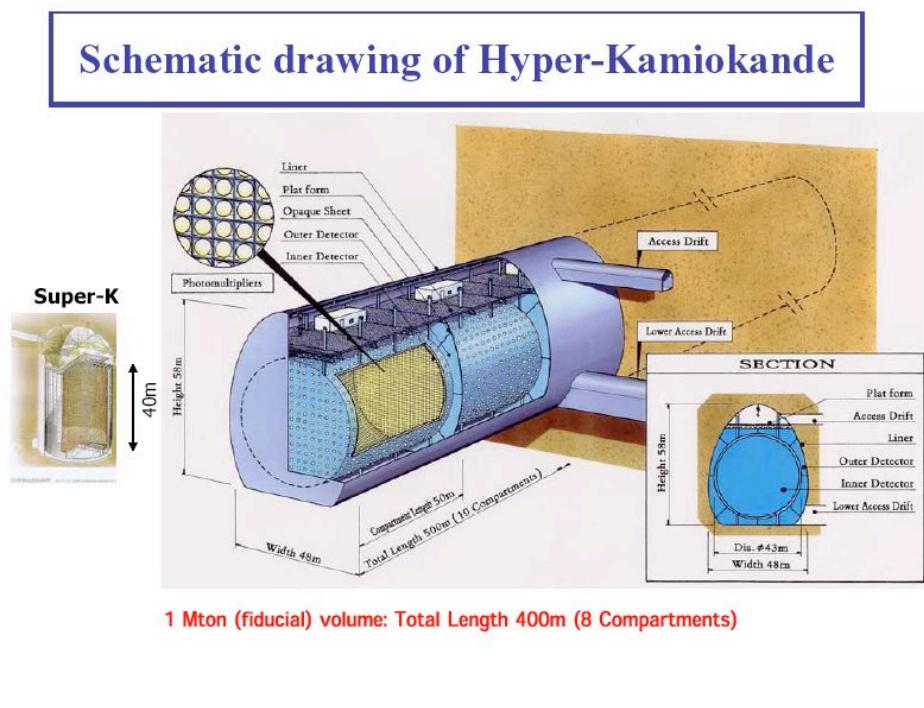
Time line of major mile stones



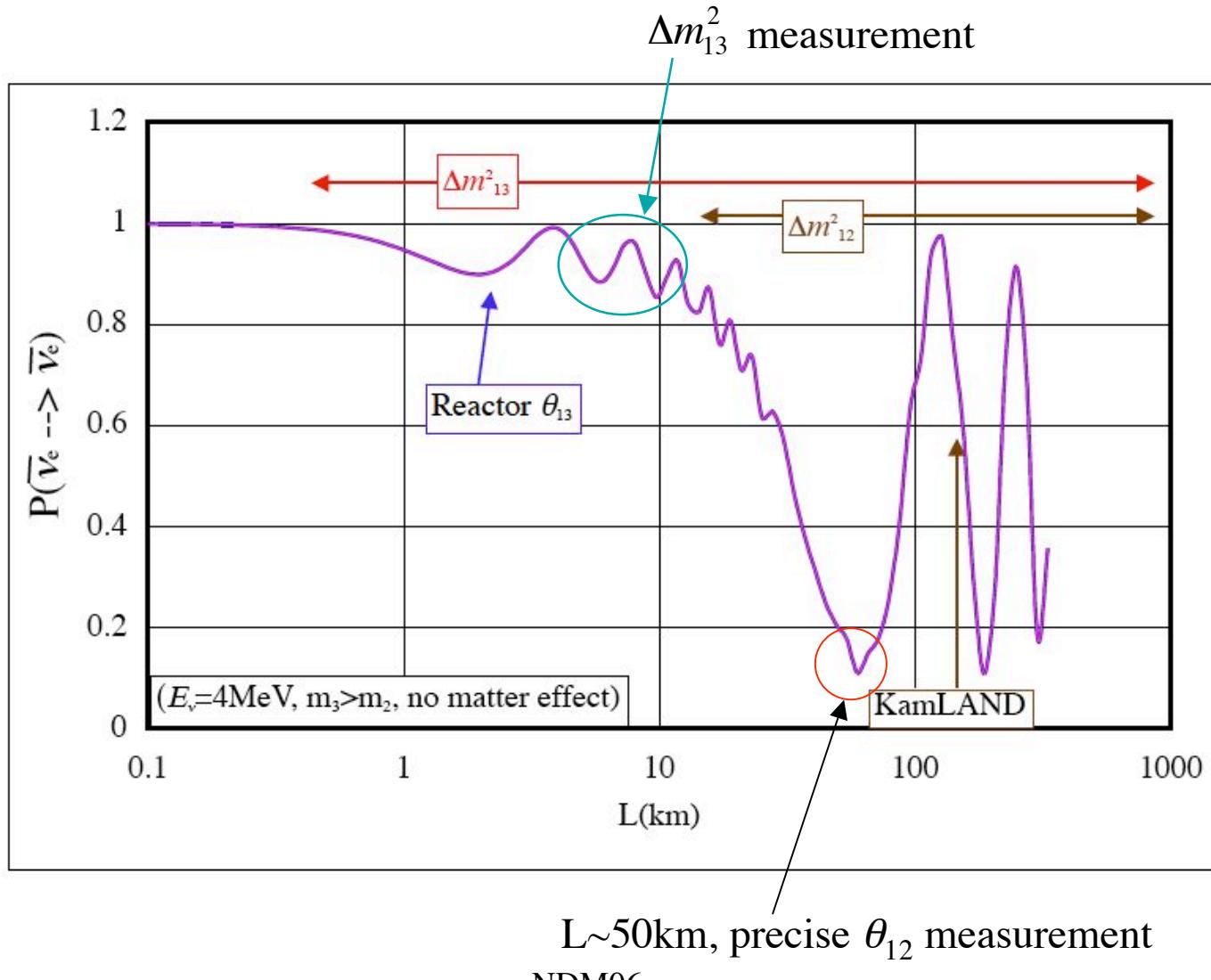
More Future

T2HK 20??

Tokai to Hyper Kamiokande
100x of T2K



Precise measurement of Oscillation Parameters by Reactor experiment



Summary

The nature has been kind enough so that we could measure,

$$\theta_{12}, \theta_{23}, \Delta m_{12}^2, \Delta m_{23}^2$$

The next important step is to measure

$$\theta_{13}$$

And already several experiments are starting to catch it.

If θ_{13} is reasonably large ($\sin^2 2\theta_{13} > 0.01$), detection of
 δ

is straight forward and will be measured by gigantic experiments.

If $\sin^2 2\theta_{13} < 0.01$, we have to sit and think.

Let's pray to nature for keeping her kindness.

& There are possibilities to solve other important issues, such as determination of mass hierarchy, θ_{23} degeneracy, precise measurements of oscillation parameters.

Quiz

We now know the neutrino mixing is like,

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & \varepsilon \\ -0.4 & 0.6 & 0.7 \\ 0.4 & -0.6 & 0.7 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

We already know similar mixing,

$$\begin{pmatrix} \pi^0 \\ \eta \\ \eta' \end{pmatrix} \sim \begin{pmatrix} 0.7 & 0.7 & 0 \\ -0.4 & 0.4 & 0.8 \\ 0.6 & -0.6 & 0.6 \end{pmatrix} \begin{pmatrix} |u\bar{u}\rangle \\ |d\bar{d}\rangle \\ |s\bar{s}\rangle \end{pmatrix}$$

What mixing is it?

Answer: Quark contents of pseudoscalar particles.

For PS case, the mixing pattern is understood by universality of strong interaction and difference of quark masses.

How we can understand the neutrino mixing?