Current and Future Reactor Based Neutrino Experiments

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Physics of Massive Neutrinos
@Milos Island
May 20, 2008

Χυρρεντ ανδ Φυτυρε Ρεαχτορ Βασεδ Νευτρινο Εξπεριμεντσ

Φ.Συεκανε

ΡΧνΣ

Τοηοκυ Υνιωερσιτψ

Πηψσιχσ οφ Μασσιωε Νευτρινοσ
@Μιλοσ Ισλανδ
Μαψ 20, 2008

Contents of this talk

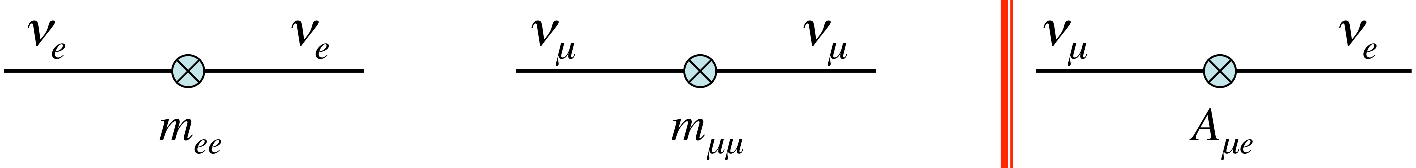
- Quick Review of ν Oscillation
- Scope of Reactor ν experiments
- θ_{12}, Δm^2_{12}: KamLAND
- θ_{13}: DoubleChooz, Dayabay, RENO
- Future prospects;

  Precise θ_{12}, Very Precise θ_{13}, Δm^2_{13}
- Summary

A Quick review of ν Oscillation

Charged lepton=mass eigenstate
Simplified view.

Flavor Transition Amplitudes



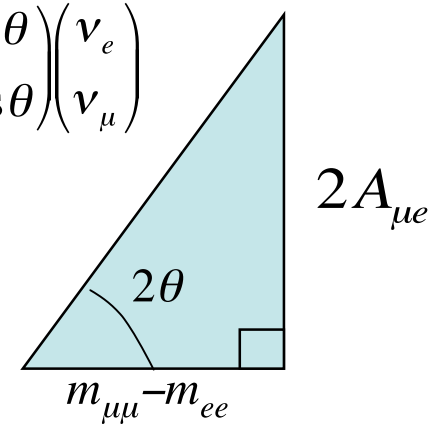
ν equation of motion:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\begin{pmatrix}m_{ee} & A_{\mu e}\\ A_{\mu e} & m_{\mu\mu}\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

Definition of mass eigenstate:

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

$$i\frac{d}{dt}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}=\begin{pmatrix}m_1 & 0\\ 0 & m_2\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$



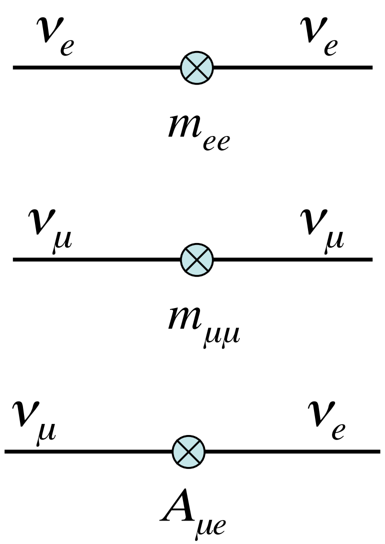
Then ν Oscillation takes place:

$(m_1, m_2 << E)$

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

$$2m_i=(m_{\mu\mu}+m_{ee})\pm\sqrt{(m_{\mu\mu}-m_{ee})^2+4A_{\mu e}^2}$$

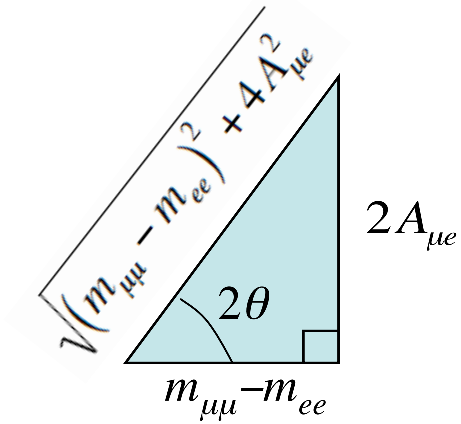
What We Measure by ν Oscillation



$$\begin{cases} \sin 2\theta = \dfrac{2A_{\mu e}}{\sqrt{(m_{\mu\mu} - m_{ee})^2 + 4A_{\mu e}^2}}, \\ \Delta m_{12}^2 = (m_{\mu\mu} + m_{ee})\sqrt{(m_{\mu\mu} - m_{ee})^2 + 4A_{\mu e}^2} \end{cases}$$

OR

$$\begin{cases} A_{\mu e} = \Delta m_{12}^2 \sin 2\theta / \langle m \rangle \\ m_\mu = \langle m \rangle + \Delta m_{12}^2 \cos 2\theta / \langle m \rangle \\ m_e = \langle m \rangle - \Delta m_{12}^2 \cos 2\theta / \langle m \rangle \end{cases}$$



$$\langle m \rangle = \frac{m_1 + m_2}{2}$$

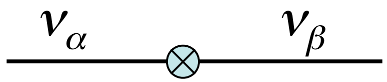
⇧

Direct mass measurement

Both Mass and Mixing are a combination of flavor transition amplitude.

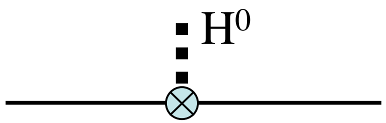
⇒Measurment of mixing angle is as importnat as measurement of mass.

Purpose of ν Oscillation Measurements

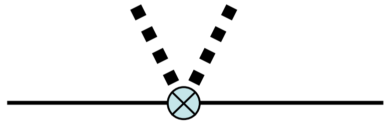
Now we know  exists.

What makes the transition amplitudes?

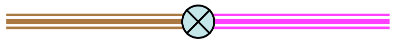
Higgs



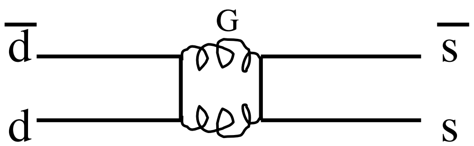
Dirac?


Majorana?

Sub Structure??



For Example,



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

Similar to MNS matrix!

Or something else?? 

A_{NP} ?

$\Rightarrow$ Physics of ν oscillation is to measure the flavor transition amplitudes and think of its origin.

ν Oscillations: 3 flavor case

Mixings **MNS Matrix** $s_{ij} = \sin\theta_{ij}, \quad c_{ij} = \cos\theta_{ij}$

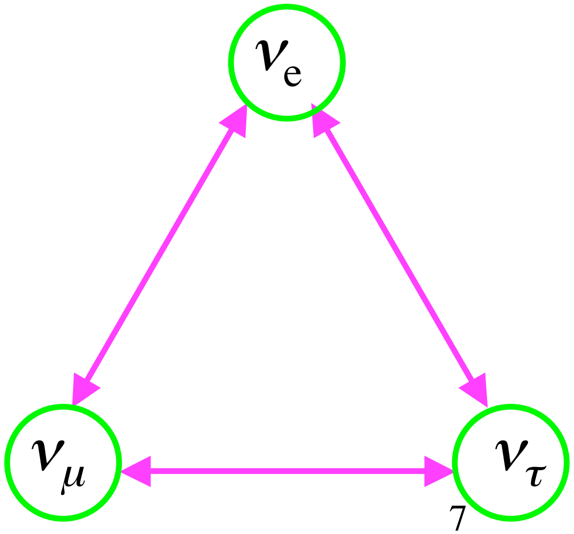
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}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

Oscillations

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

$$\left(\Phi_{ij} = \frac{\Delta m^2_{ij} L}{4E}, \quad \Delta m^2_{ij} = m^2_j - m^2_i \right)$$

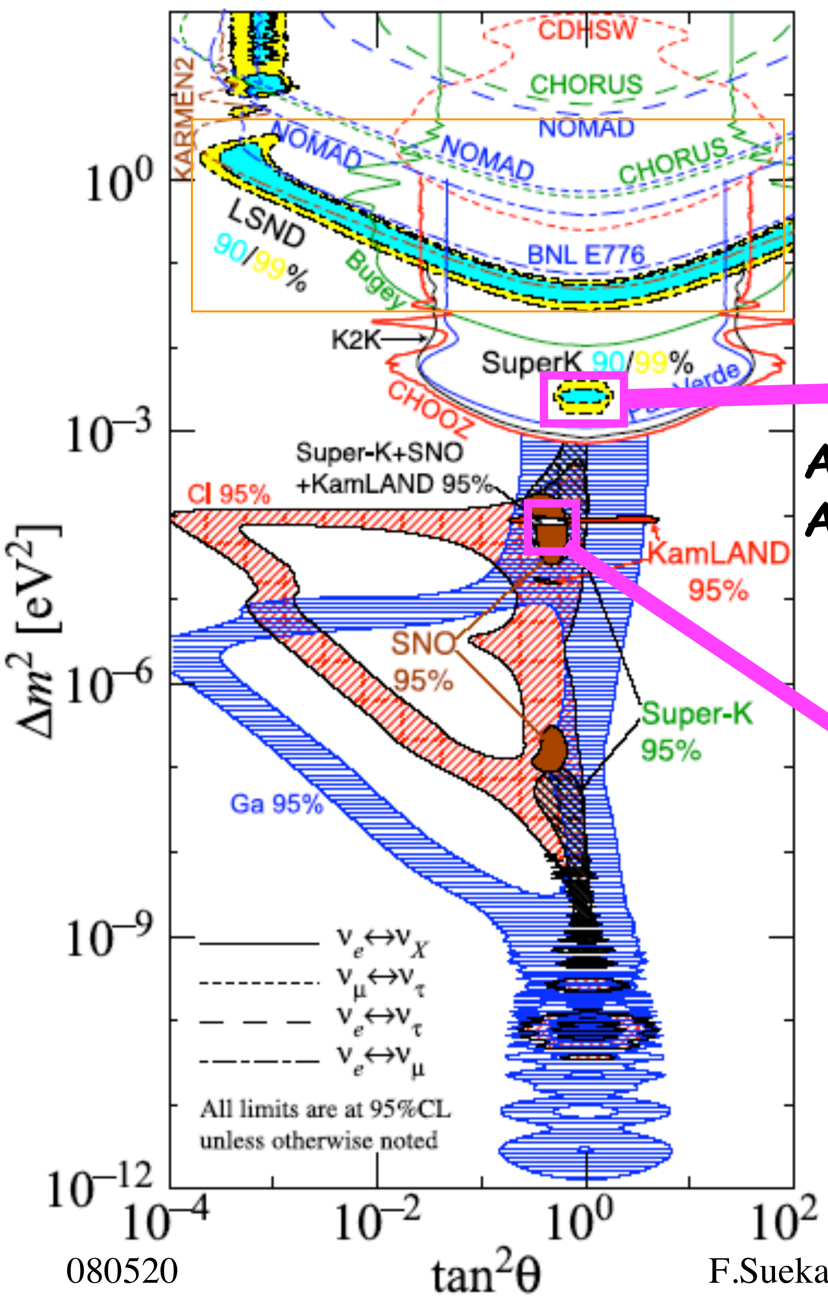
$$\left|\Delta m^2_{12}\right|, \quad \left|\Delta m^2_{23}\right|, \quad \theta_{12}, \quad \theta_{23}, \quad \theta_{31}, \quad \delta$$



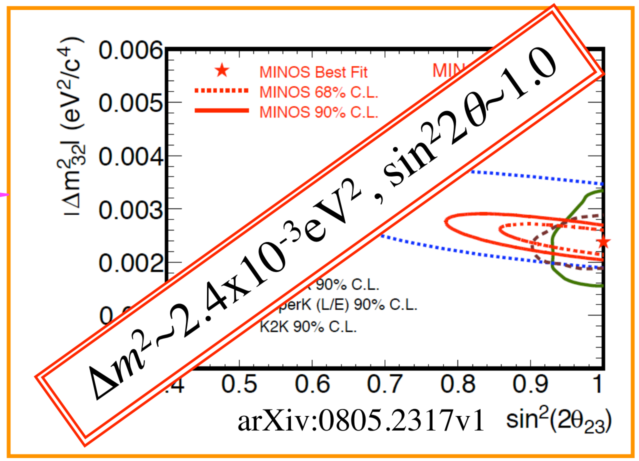
6 parameters can be accessible from neutrino oscillation.

Murayama

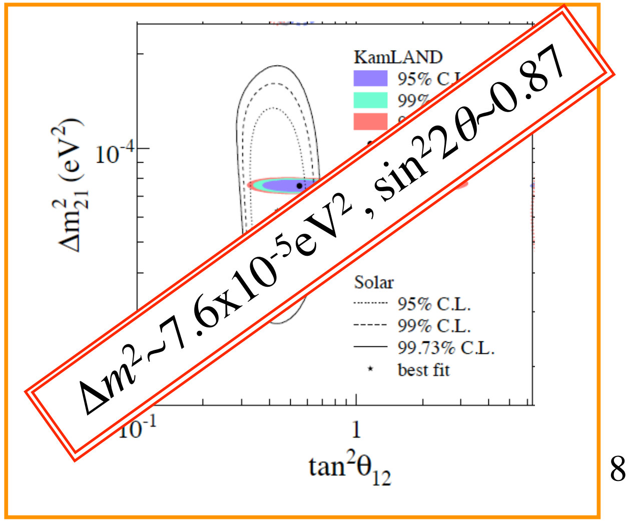
Two oscillations measured



Atmospheric
Accelerator

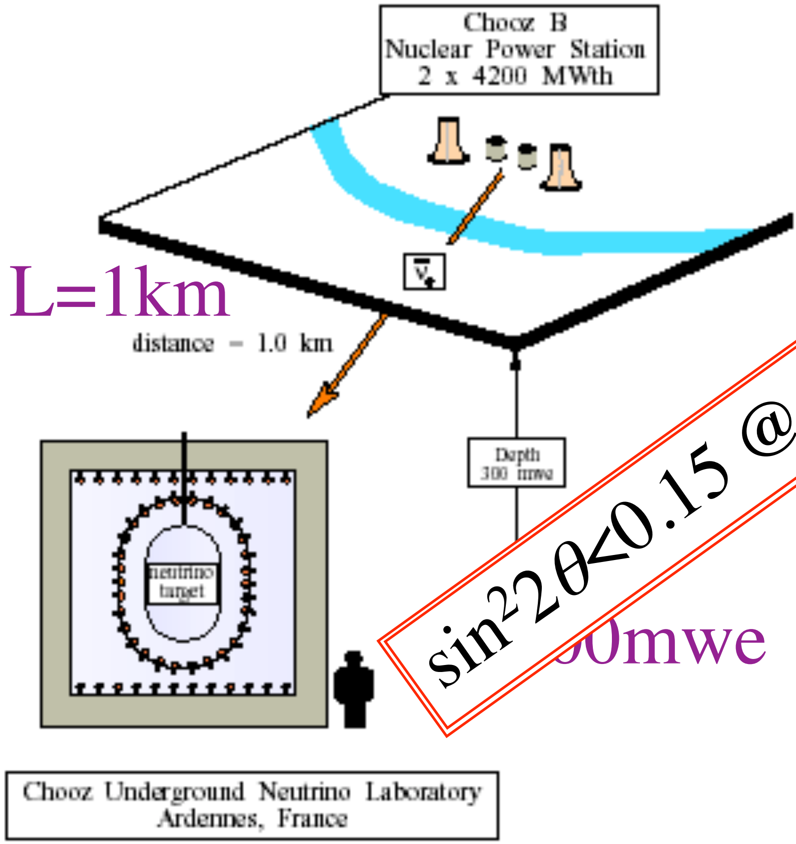


Solar
Reactor

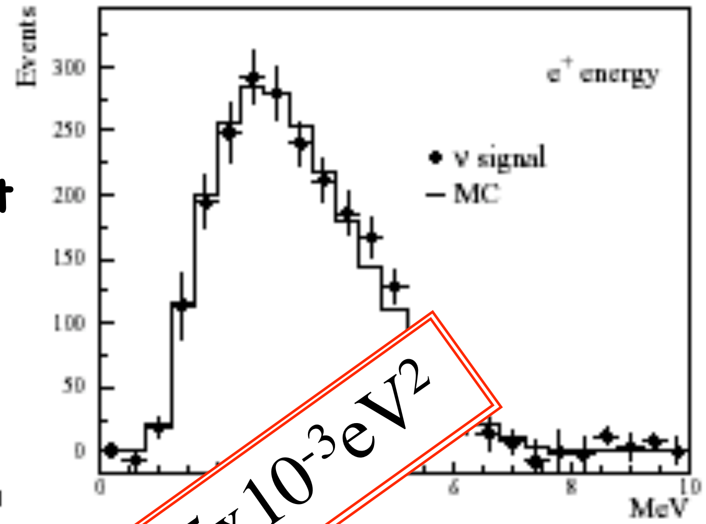


Upper limit

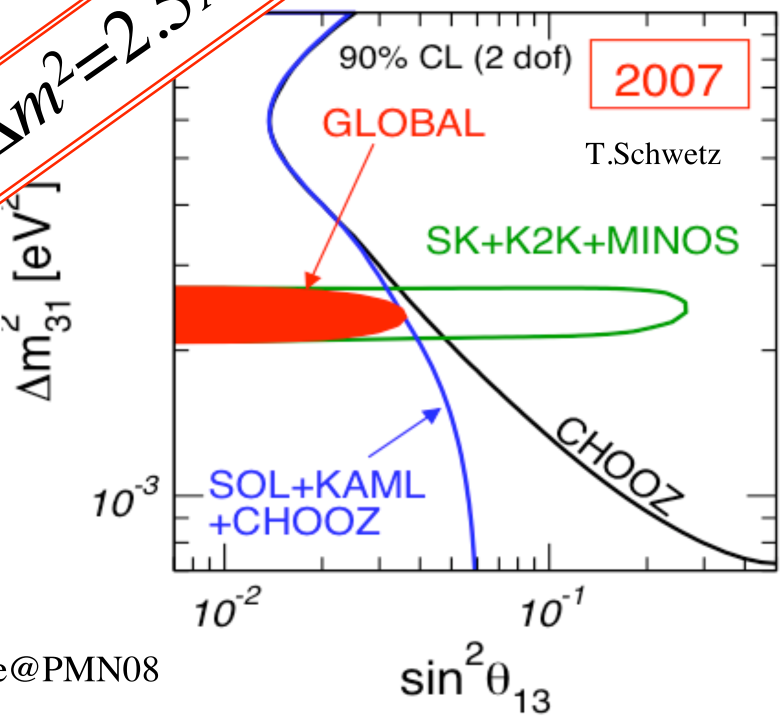
CHOOZ reactor ($\overline{\nu}_e$ ---> $\overline{\nu}_e$) experiment



L=1km



$\sin^2 2\theta < 0.15$ @ $\Delta m^2 = 2.5\times10^{-3}$eV^2



Our Current Knowledge

$$\left|m_3^2 - m_2^2\right| \sim 2.5\times10^{-3}\,\mathrm{eV}^2,\quad \left(m_2^2 - m_1^2\right) \sim 8\times10^{-5}\,\mathrm{eV}^2$$

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

If $m_3 > m_2 >> m_1 \sim 0$, Flavor Transition Amplitudes become,

ν_e — ○ — ν_e: m_{ee}~5meV

ν_μ — ○ — ν_μ: $m_{\mu\mu}$~30meV

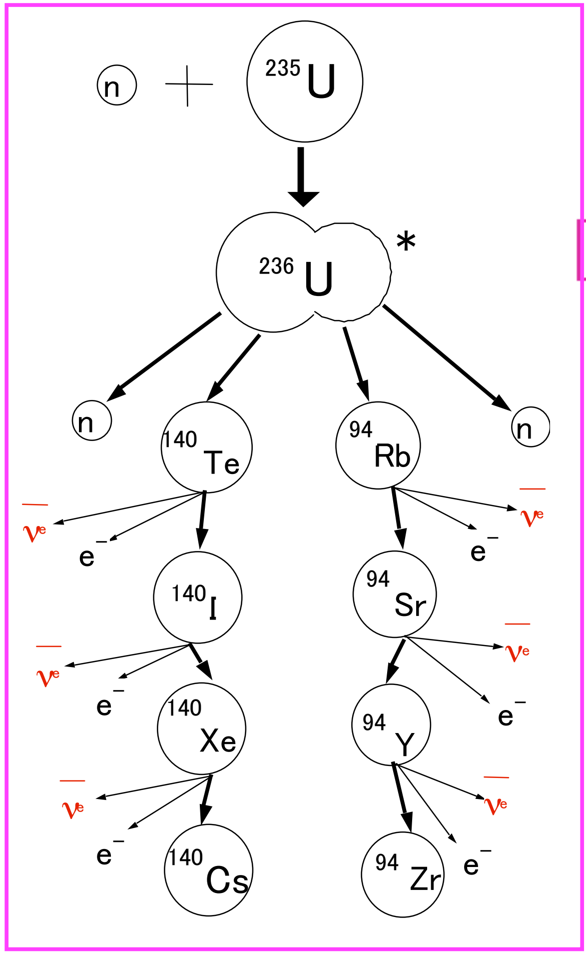
ν_τ — ○ — ν_τ: $m_{\tau\tau}$~30meV

ν_e — ○ — ν_μ: $A_{e\mu}$~$(30s_{13}e^{i\delta}+3)$meV

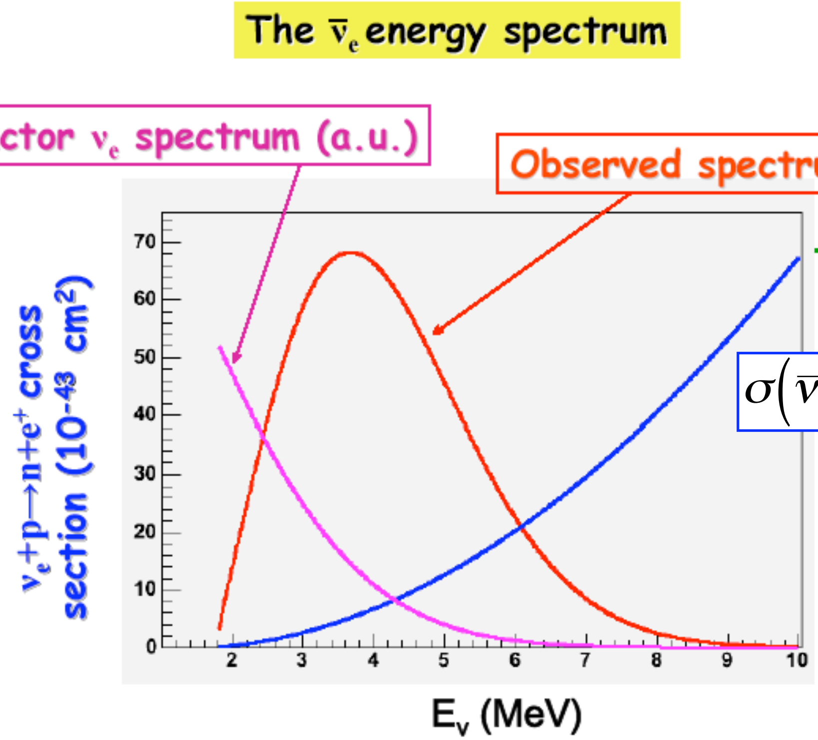
ν_e — ○ — ν_τ: $A_{e\tau}$~$(30s_{13}e^{i\delta}-3)$meV

ν_μ — ○ — ν_τ: $A_{\mu\tau}$~20meV

Reactor Neutrinos



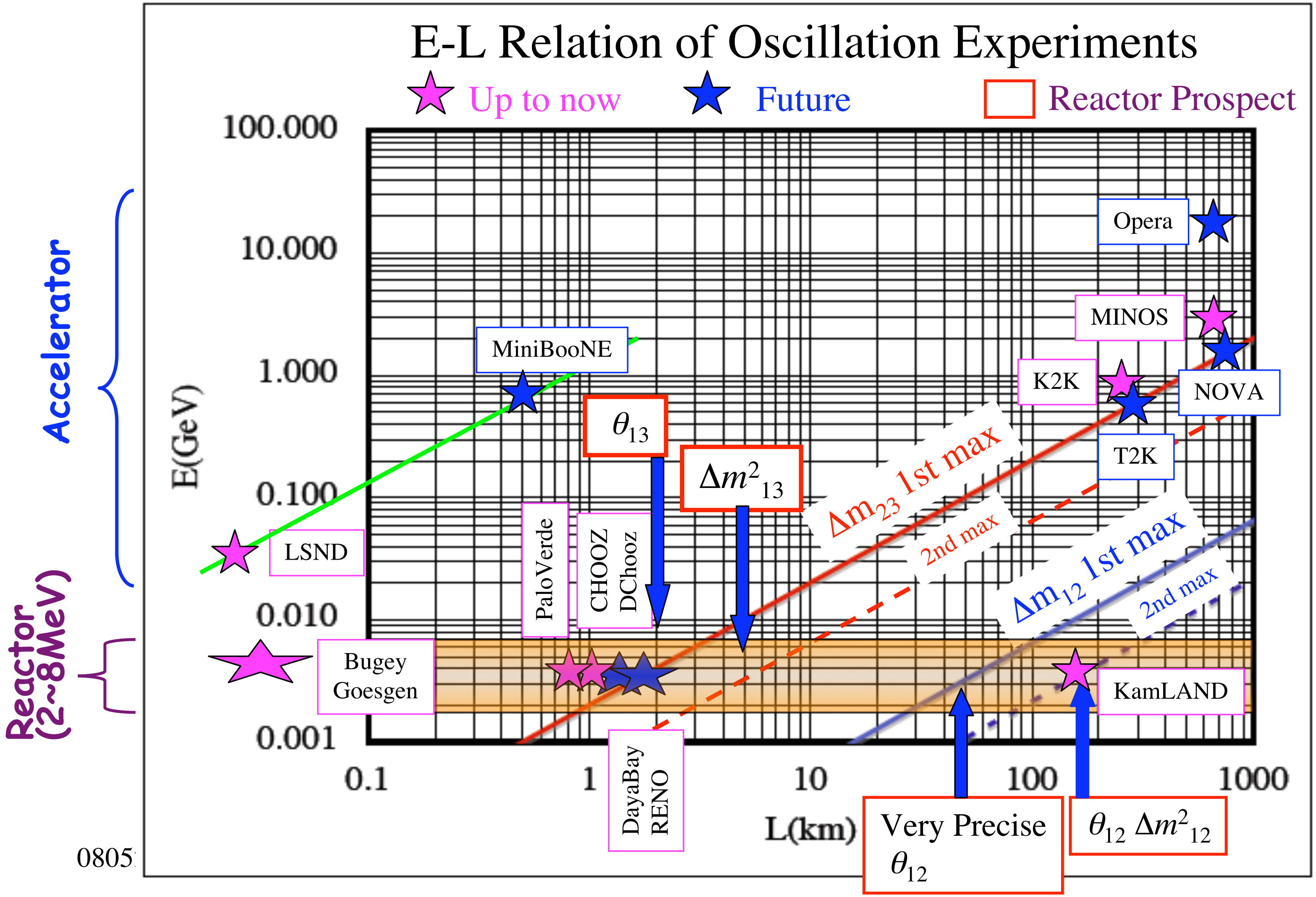
$$\sim 6 \times 10^{20} \bar{\nu}_e / s / reactor$$

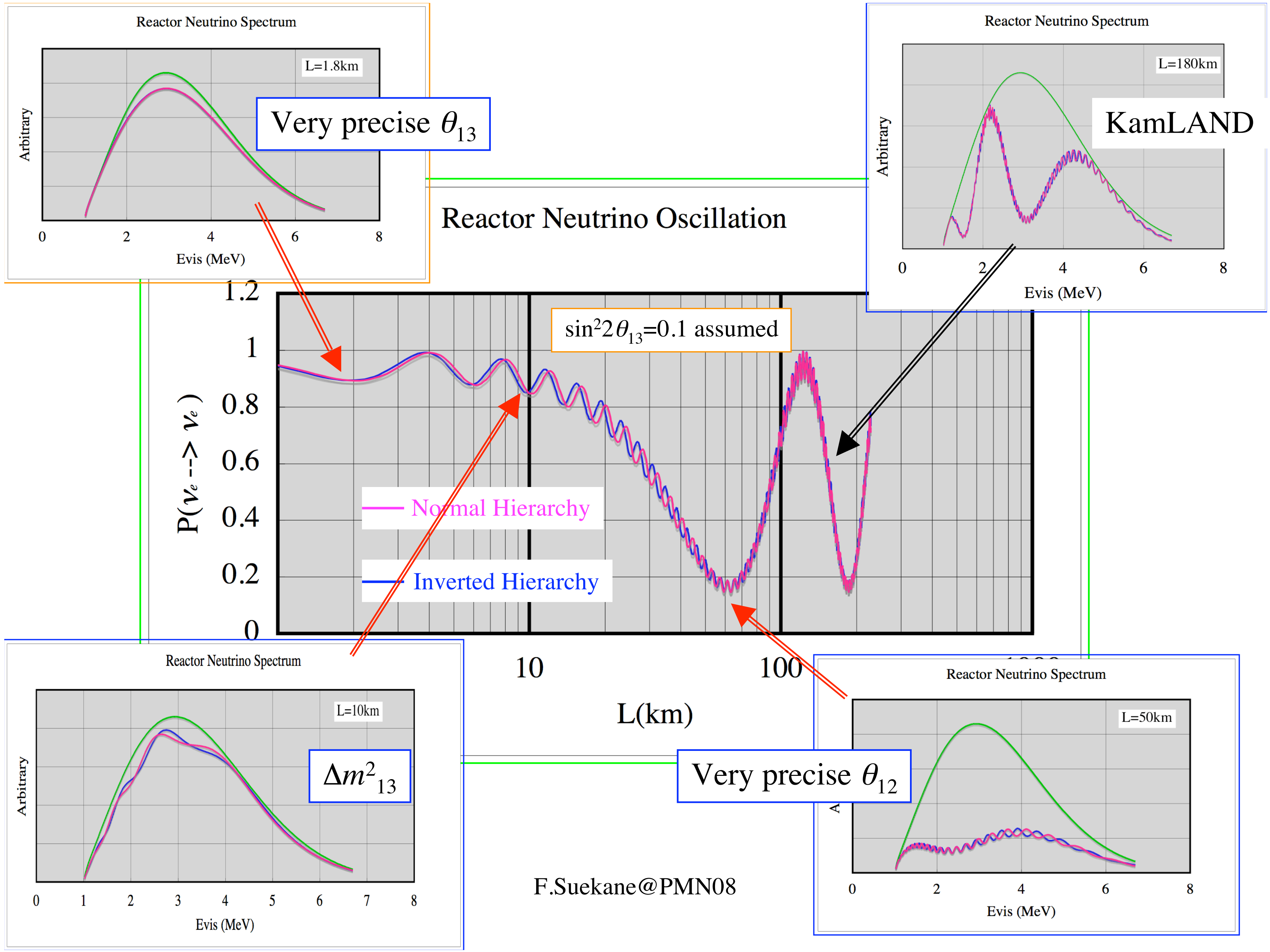


$$\sigma\left(\bar{\nu}_e + p \rightarrow e^+ + n\right)$$

$$E_\nu \sim 4 {}^{+4}_{-2} MeV$$

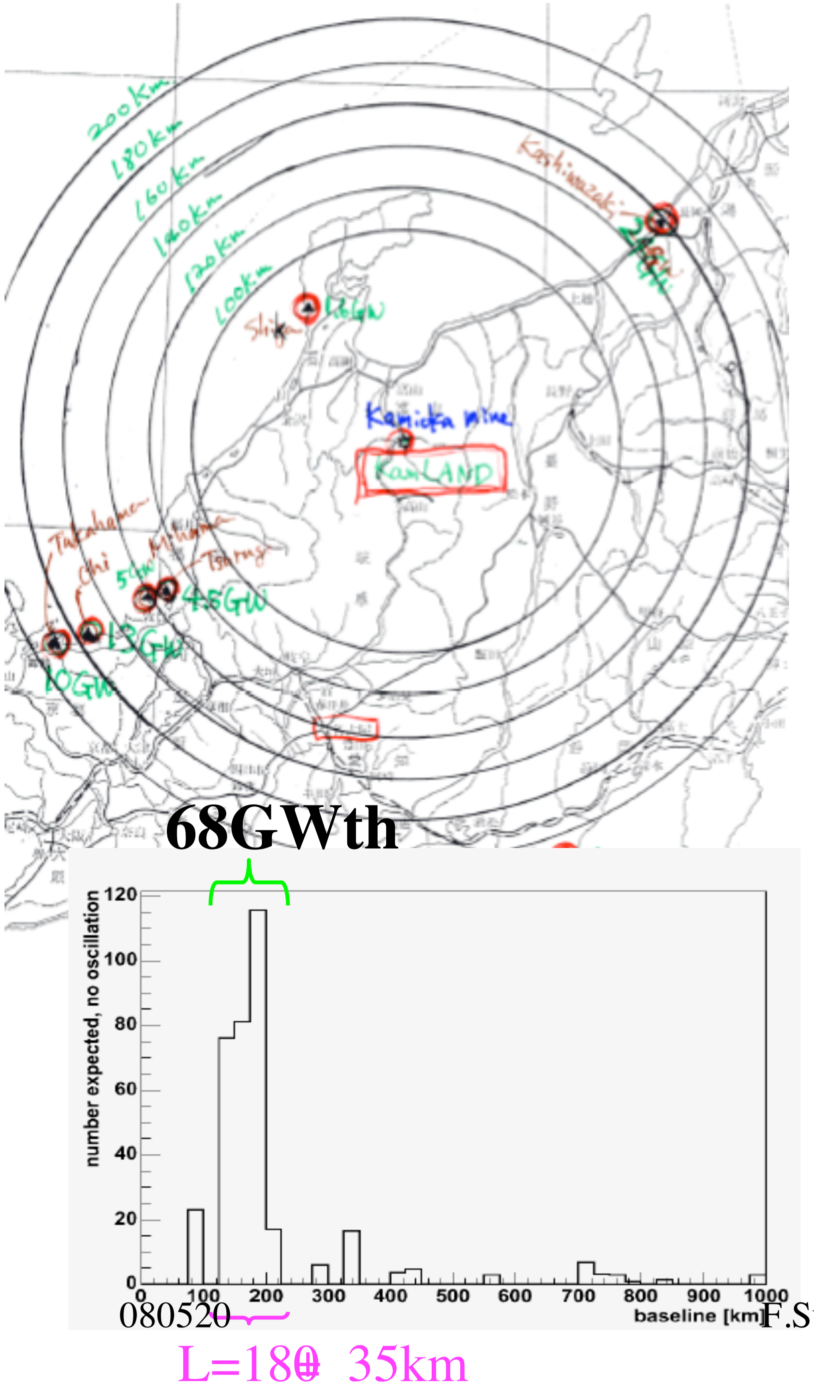
Accessible Oscillations by Reactor ν

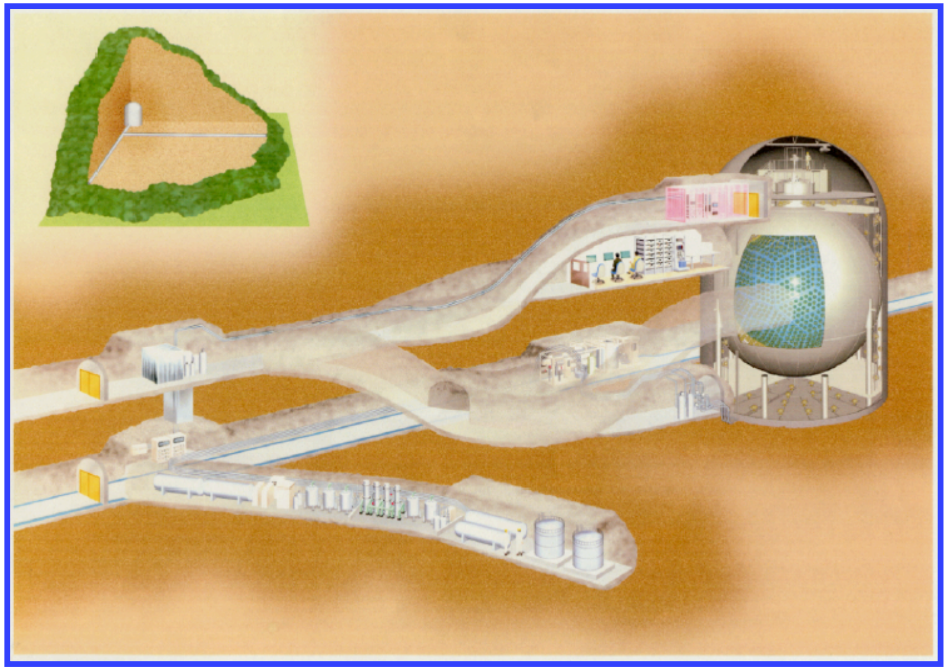




Reactor Neutrino Oscillation
Very precise θ_{13}
KamLAND
$\sin^2 2\theta_{13}$=0.1 assumed
Normal Hierarchy
Inverted Hierarchy
Δm^2_{13}
Very precise θ_{12}
$P(\nu_e \to \nu_e)$
L(km)
Reactor Neutrino Spectrum
L=1.8km
L=10km
L=50km
L=180km
Arbitrary
Evis (MeV)
F.Suekane@PMN08

Δm^2_{12}, θ_{12}; KamLAND

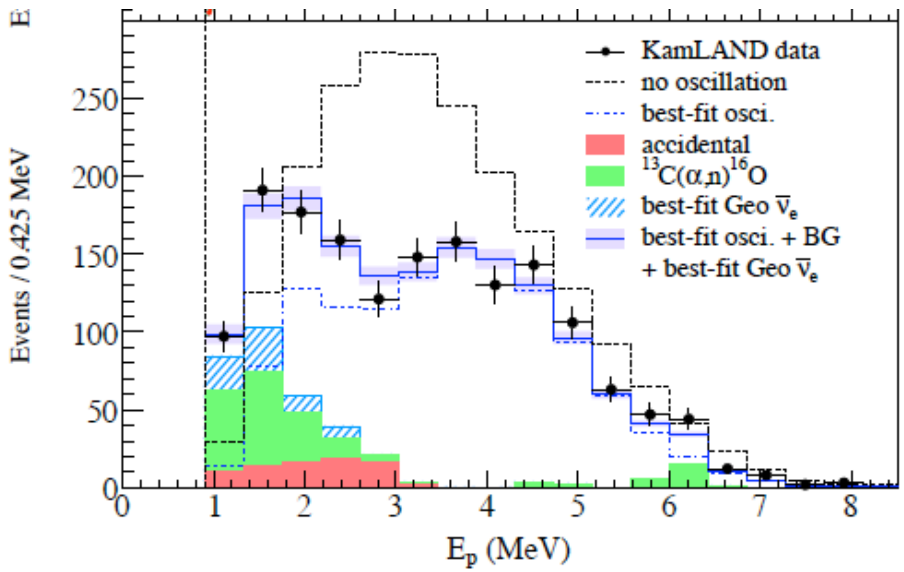


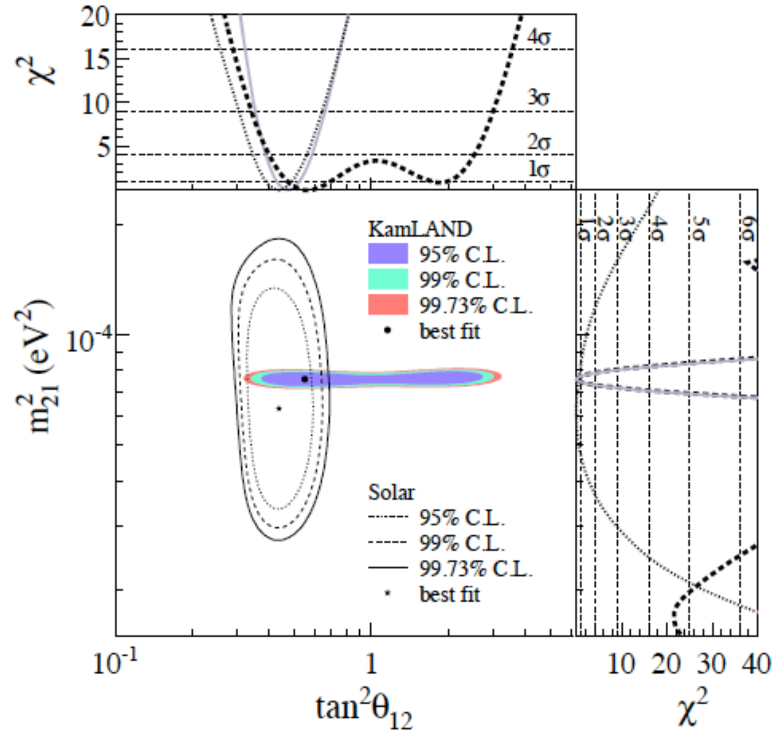


2002/12: Evidence of ν_e Deficit
(PRL 90:021802, 2003)

2004/06: Evidence of spectrum distortion
(PRL 94,081801,2005)

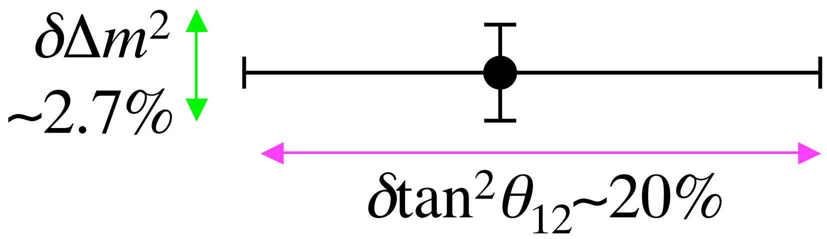
2008/01: Precise measurement of Δm^2_{12}&$\sin^2 2\theta_{12}$
(arXiv:0801.4589, submitted to PRL)





2008.1.30arXiv:0801.4589v1

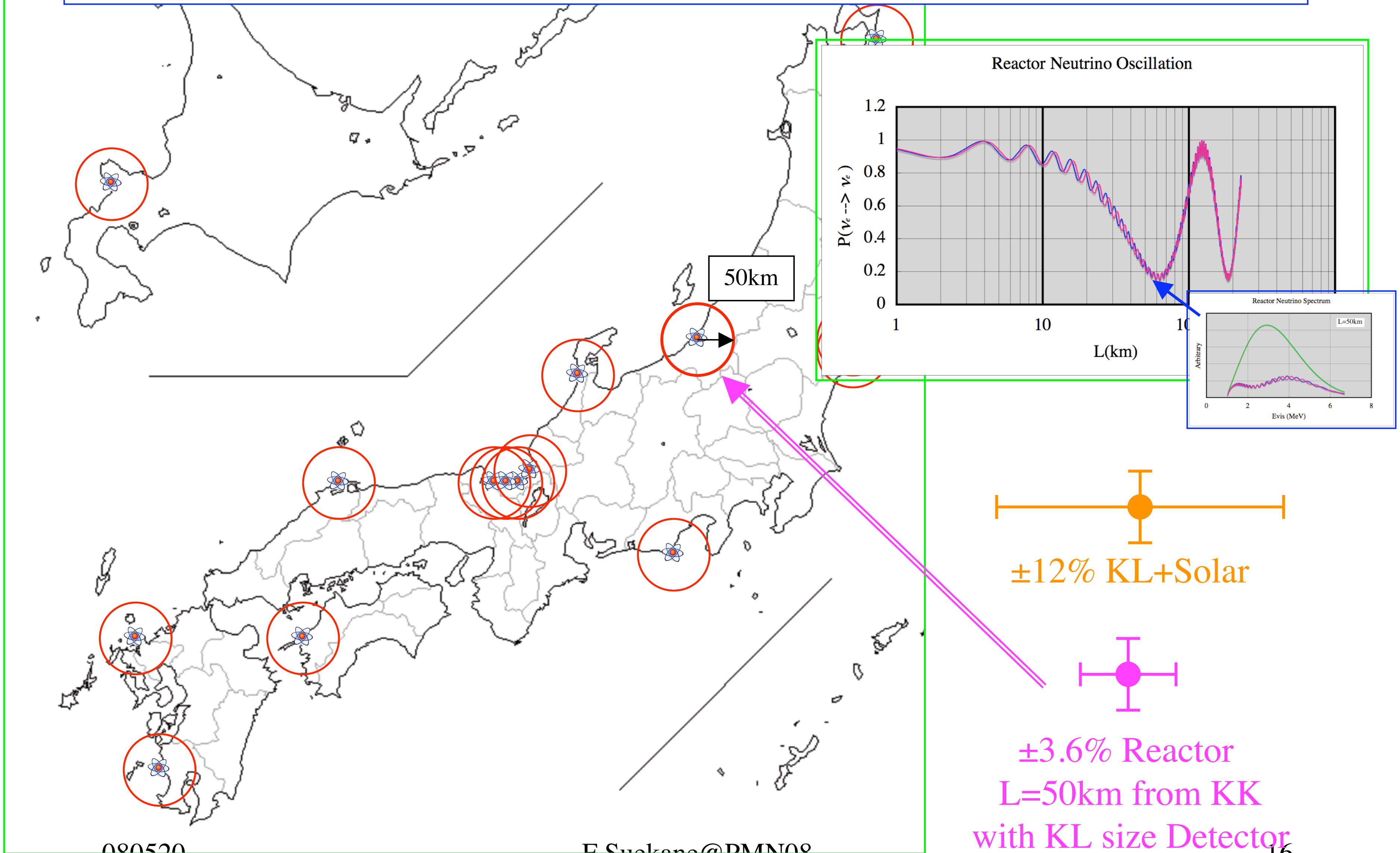
$$\begin{cases} \Delta m^2_{21} = 7.58^{+0.14}_{-0.13}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.}) \times 10^{-5}\,\text{eV}^2 \\ \tan^2\theta_{12} = 0.56^{+0.10}_{-0.07}(\text{stat.})^{+0.10}_{-0.06}(\text{syst.}) \end{cases}$$



KamLAND keeps taking reactor data while purification. However, KL has already run 5 years and significant improvement of the accuracy from here will be difficult.

On the other hand, precise θ_{12} is needed to understand the sun.

Precise $\tan^2\theta_{12}$ measurement can be performed
@ 1st oscillation maximum (L=50km)



±12% KL+Solar

±3.6% Reactor
L=50km from KK
with KL size Detector
(Minakata, et.al.)

θ_{13}

ν_e — $\nu_{\mu,\tau}$

$A_{e\mu} \sim (30\sin\theta_{13}e^{i\delta} + -3)$meV

Remaining Issue	How to measure
θ_{13}	$[\bar{\nu}_e \to \bar{\nu}_e]_R = 1 - \sin^2 2\theta_{13}$ $[\nu_\mu \to \nu_e]_A \sim \sin^2\theta_{23}\sin^2 2\theta_{13} \mp 0.05 \cdot \sin\theta_{13}\sin\delta$
δ	$[\nu_\mu \to \nu_e]_A - [\bar{\nu}_\mu \to \bar{\nu}_e]_A \sim \sin 2\theta_{13}\sin\delta$
θ_{23} degeneracy	$[\nu_\mu \to \nu_e]_A \sim \sin^2\theta_{23}\sin^2 2\theta_{13} \mp 0.05 \cdot \sin\theta_{13}\sin\delta$
Mass hierarchy	$Matter\ Effect \sim 0.00017L[km] \cdot sign(\Delta m^2_{23})\sin^2 2\theta_{13}$
Precise θ_{12}	$[\bar{\nu}_e \to \bar{\nu}_e]_{KamLAND} = \cos^4\theta_{13}(1 - \sin^2 2\theta_{12})$

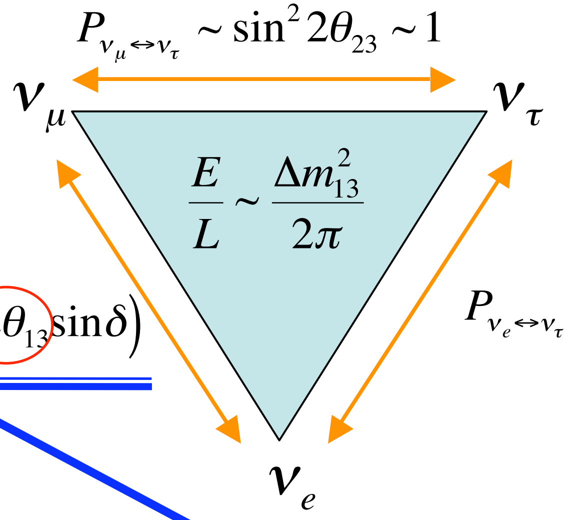
All the measurements are related to θ_{13}
=> Determination of θ_{13} is urgent

How to Measure θ_{13}

2.4×10^{-3}eV2

$$@\frac{\Delta m_{13}^2 L}{4E} \sim \frac{\pi}{2}$$

- E~MeV, L~1km — **Reactor Experiments**
- E~GeV, L=100~1000km; **Accelerator experiments**



$$P_{\nu_e \leftrightarrow \nu_\mu} \sim \frac{1}{2}\left(\sin^2 2\theta_{13} \mp 0.1 \cdot \sin 2\theta_{13} \sin\delta\right)$$

$$P_{\nu_e \leftrightarrow \nu_\tau} \sim \frac{1}{2}\left(\sin^2 2\theta_{13} \pm 0.1 \cdot \sin 2\theta_{13} \sin\delta\right)$$

Accelerator Measurement

$$1 - P_R(\bar{\nu}_e \to \bar{\nu}_e) = P_R(\bar{\nu}_e \to \bar{\nu}_\mu) + P_R(\bar{\nu}_e \to \bar{\nu}_\tau) = \sin^2 2\theta_{13}$$

Reactor Measurement

$$P_A(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13}\left(\sin^2\theta_{23} - \frac{0.05}{\sin 2\theta_{23}} \sin\delta\right)$$

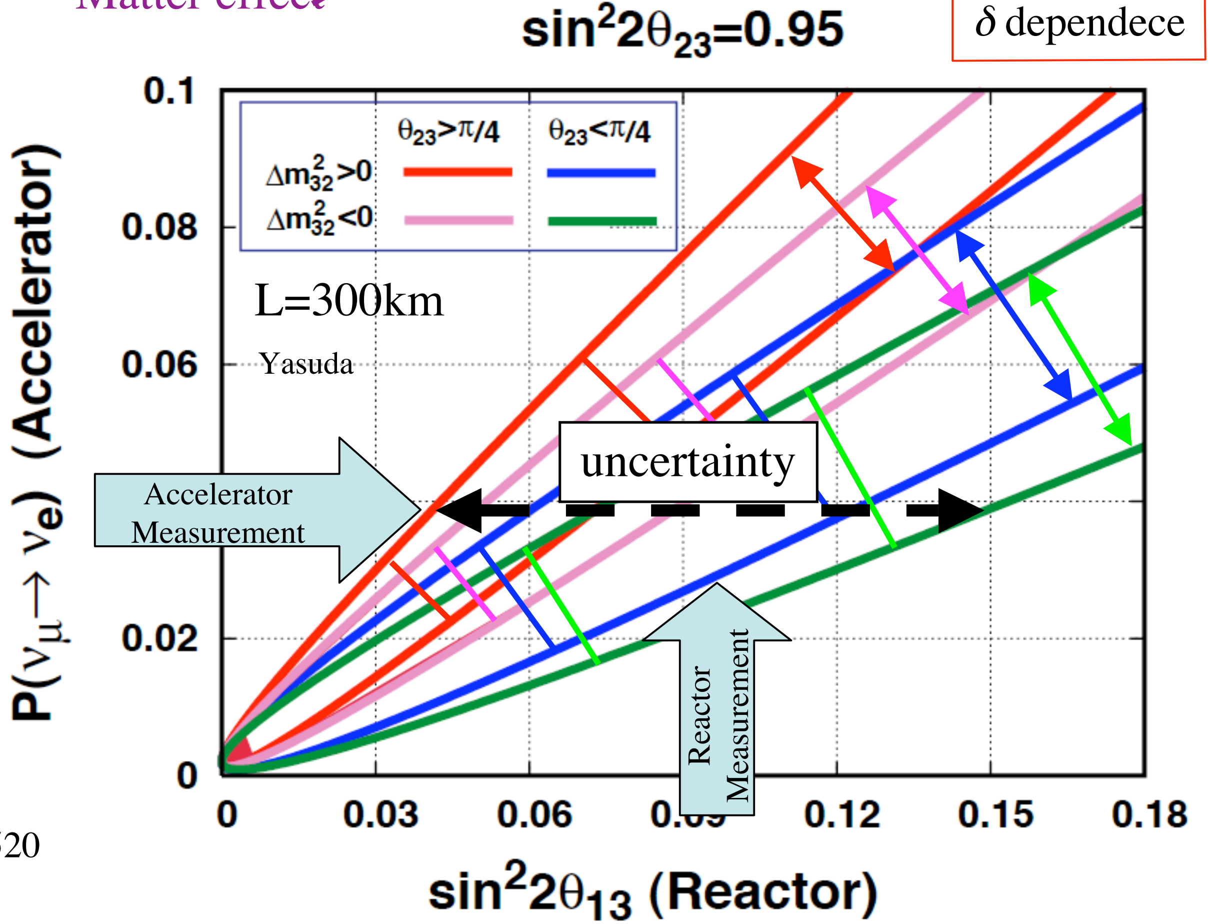
Complementarity of Reactor-accelerator θ_{13} measurement

θ_{23} degeneracy

$$P_{AC}(\nu_\mu \to \nu_e) = \frac{0.50 \pm 0.11}{(1 \mp 0.00017 L[km])^2} \sin^2 2\theta_{13} \pm 0.045 \sin 2\theta_{13} \sin\delta$$

Matter effect

δ dependece



How to improve the Chooz limit

Systematic Error:

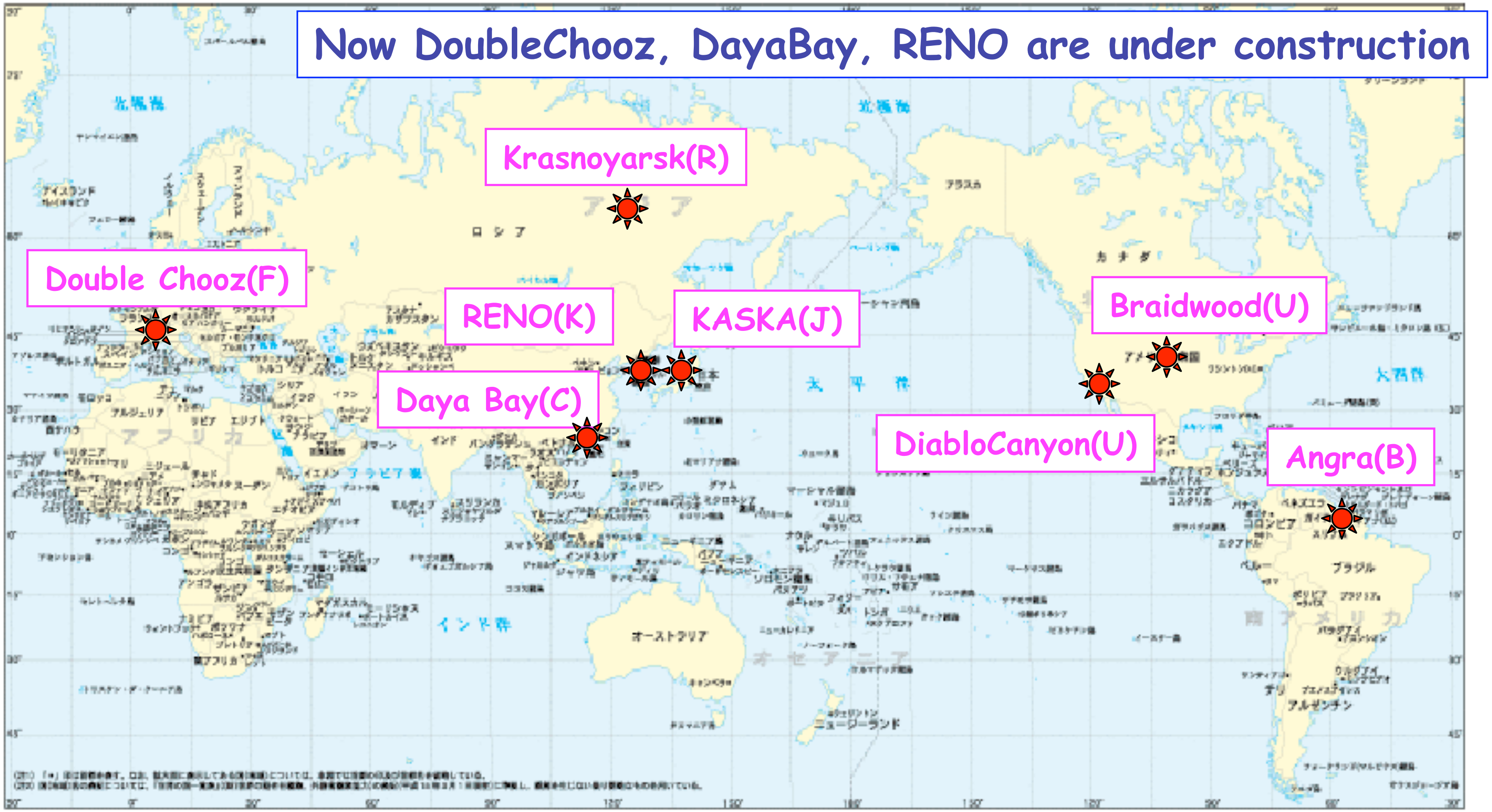
	Chooz
Reactor cross section	1.9 %
Number of protons	0.8 %
Detector efficiency	1.5 %
Reactor power	0.7 %
Energy per fission	0.6 %

Cancel → Near/Far detector comparison & Cut-insensitive measurement

Chooz case: $\left(\frac{\delta N_\nu}{N_\nu}\right)_{CHOOZ} = \pm 2.8\%(stat.) \pm 2.7\%(sys.) \Rightarrow sin^2 2\theta_{13} < 0.15$

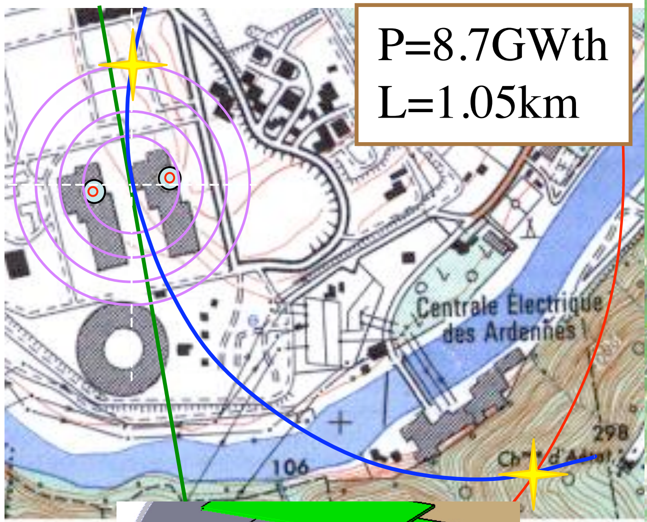
Statistic error:
Chooz ran only a few months
=> Longer run, Larger Detector & Higner Reactor Power

Reactor-θ_{13} Site Historical Map

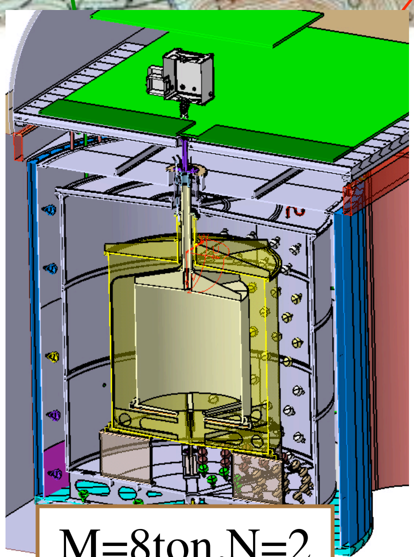


Reactors and Detectors

Double Chooz

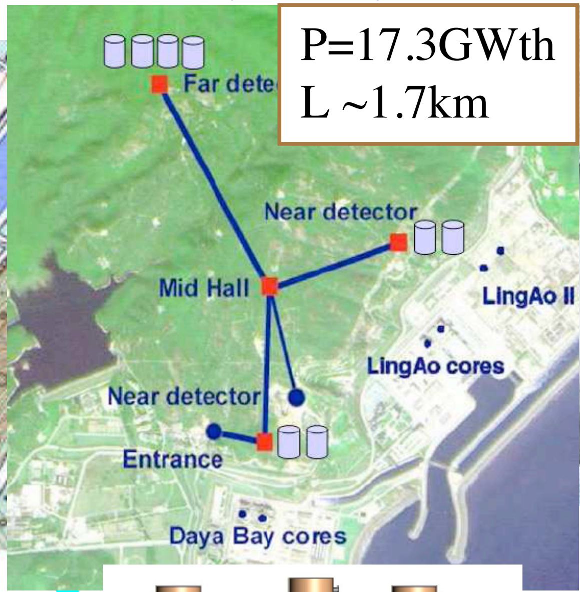


P=8.7GWth
L=1.05km

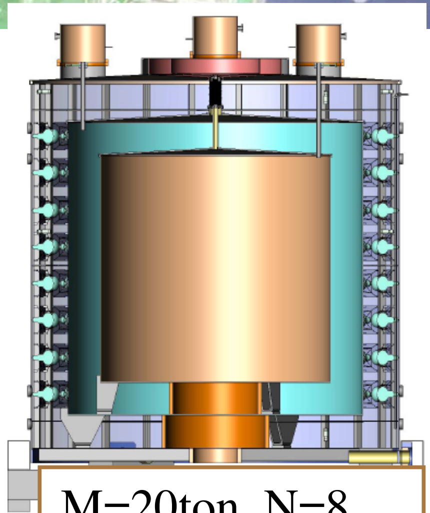


M=8ton,N=2

Daya Bay

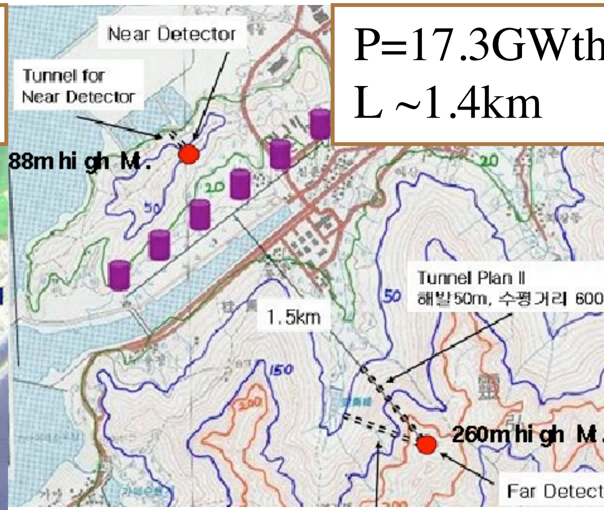


P=17.3GWth
L ~1.7km

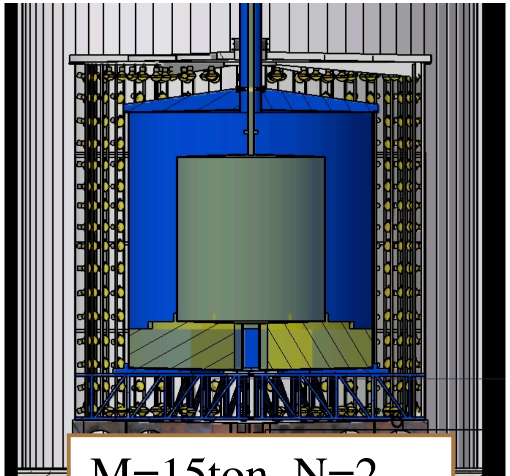


M=20ton, N=8

RENO



P=17.3GWth
L ~1.4km



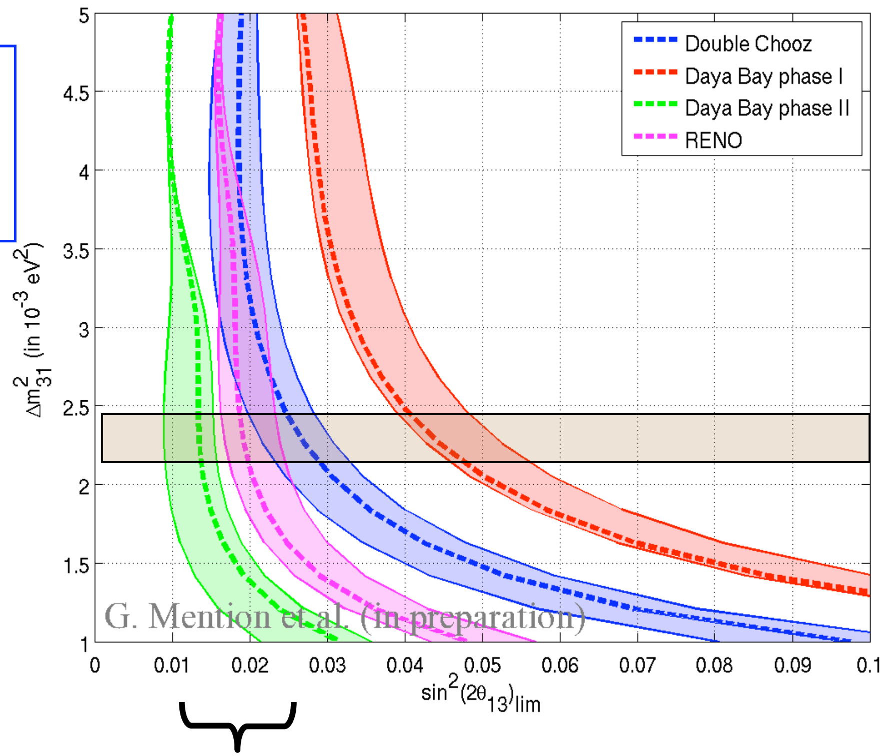
M=15ton, N=2

Sensitivity & Start years

DCHOOZ:
2009 Starts with Far Detector
2010 run with Far+Near Detector

DayaBay:
2010 Starts with P=11.6GW
2011 P=> 17.4GW

RENO:
2010 Starts



Sensitivities=0.01~0.03

→ We will know the results within a few years!

Status of the experiments

DoubleChooz
RENO
→ Please hear
the T. Lachenmaier & S.-B. Kim's talks
this afternoon

DayaBay → K.B.-Luk kindly provided me the following sliedes

Civil Construction

- Total tunnel length is about 3100 m
- SAB ready by July 2008
- Daya Bay Hall: Nov 2008
- Ling Ao Hall: Jun 2009
- Far Hall: Sept 2009

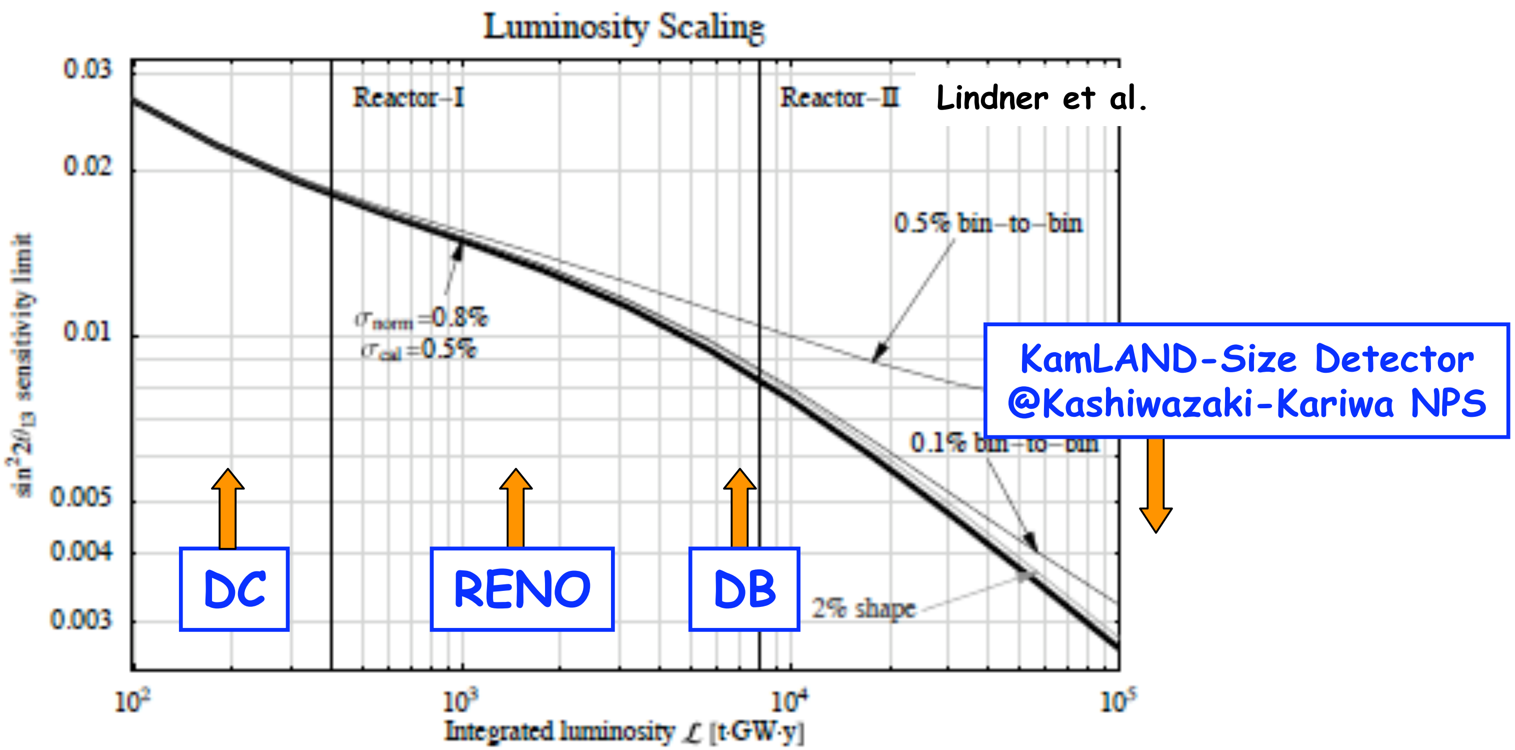
Getting Ready To Build The Detectors

4-m prototype in the U.S.

3-m prototype in Taiwan

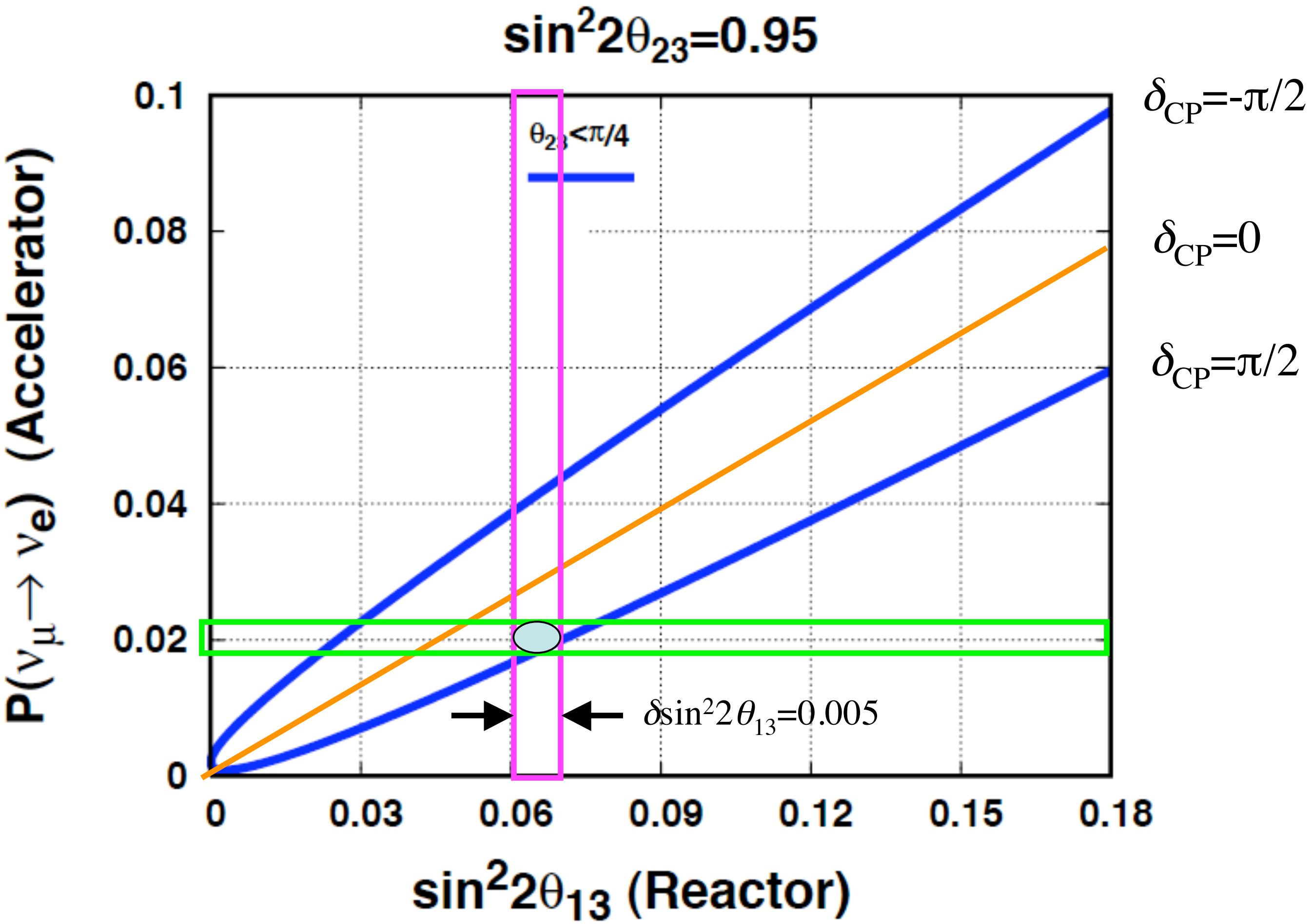
Very Precise θ_{13}

$\delta\sin^2 2q_{13}$<0.01 will be possible by large statisitics & shape analyisis.



The current Reactor θ_{13} experiments will be in stable condition within a few years
=> It is time to think of the next generation experiments seriously

δ_{CP} detection in future



If $\delta\sin^2 2\theta_{13}$<0.01 is achieved, there is chance to detect finite δ_{CP} combined with Accelerator data.

Reactor-Accelerator cooperation

J-Parc group has already started to discuss about post T2K CP experiments.

http://j-parc.jp/NP08/

The 4th International Workshop on Nuclear and Particle Physics at J-PARC
NP08
March 5-7, 2008
Mito, Ibaraki, Japan

Thursday 06 March 2008 top

09:30->*13:00* **Parallel sessions 1**

09:30 Future Beam Option for Long Baseline Neutrino Experiment (30') (Slides) — Yves Declais (*Lyon Univ. IPNL/IN2P3/CNRS*)

10:00 Introduction to the Work on the 2nd Phase Experiment with J-PARC Neutrino Facility (15') (Slides) — Takuya Hasegawa (*KEK*)

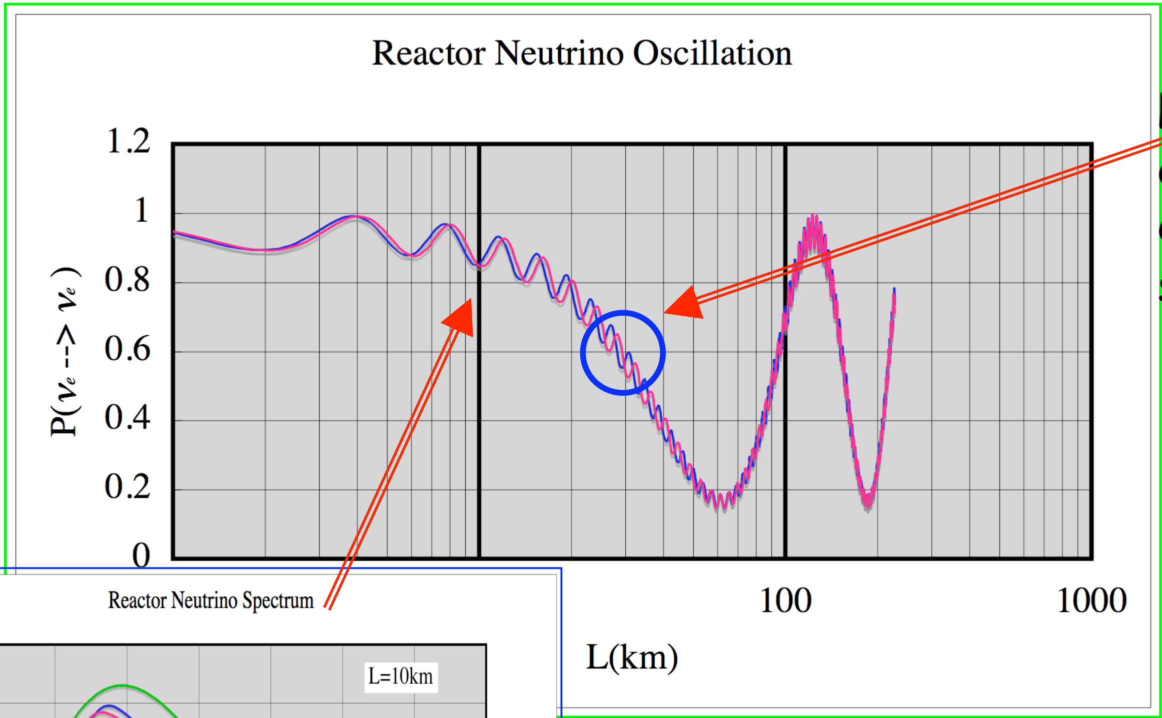
10:15 CP Violation Physics at a J-PARC Beam -Liquid Ar TPC Case- (45') (Slides) — Takasumi Maruyama (*Tsukuba Univ.*)

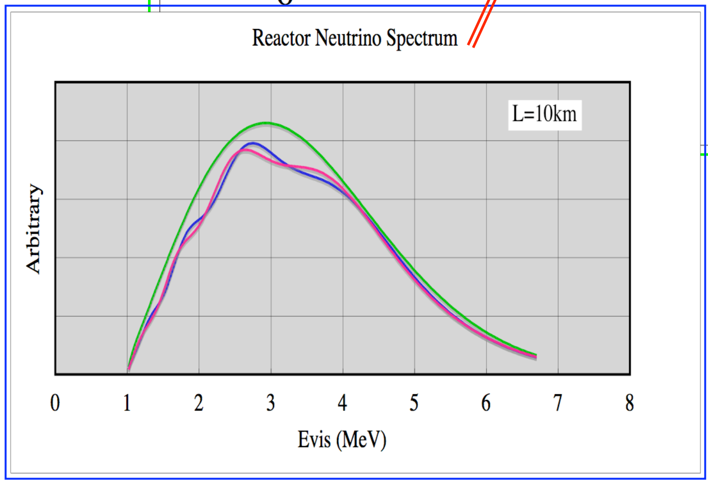
11:00 CP Violation Physics at a J-PARC Beam -Water Cherenkov Detector Case1- (25') (Slides) — Kenji Kaneyuki (*ICRR Univ. of Tokyo*)

11:25 CP Violation Physics at a J-PARC Beam -Water Cherenkov Detector Case2- (20') (Slides) — Fanny Dufour (*Boston Univ.*)

Future reactor and accelerator programs should be interweaved from the first, in order to make efficient storategy to attack δ_{CP}.

Δm^2_{13} & Mass Hierarchy





Large phase shift
due to mass hierarchy.
Can't this be used to
solve it??

Several Oscillations take place in the Energy Spectrum
⇒Precice Δm^2_{12} measurement will be possible @L~10km

Summary

- Typical energy of reactor ν is ~4MeV.
  Both Δm^2_{12} & Δm^2_{13} oscillations are accessible.

- $\tan^2\theta_{12}$, Δm^2_{12} are being measured by KamLAND with L~180km.

- For precise $\tan^2\theta_{12}$ measuremnt, L=50km with KamLAND size detector=> 3.6%

- 1st phase $\sin^2 2\theta_{13}$ experiments (DoublcChooz, Dayabay, RENO) will start within 1~2 years. Their targetting sinsitivities are $\delta\sin^2 2\theta_{13}$=0.01~0.03

- 2nd phase $\sin^2 2\theta_{13}$ experiment ($\delta\sin^2 2\theta_{13}<0.01$) should be useful to detect δ_{CP} together with accelerator measuremernt of precise $P(\nu_\mu \to \nu_e)$.

- There is a possiblity to measure Δm^2_{13} @L~10km.

- Reactor ν experiments /have had/are going to have/will have/ rich programs to do.