Prospects of Reactor ν Oscillation Experiments

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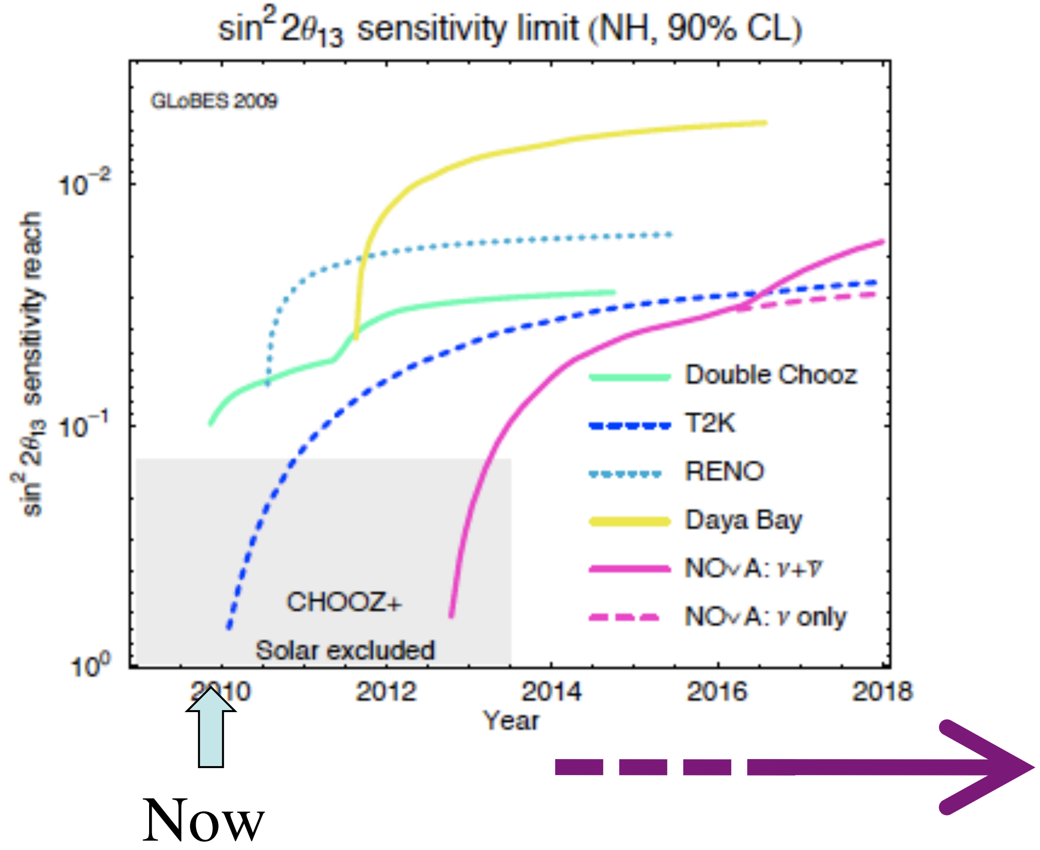
* Summary

An exciting time is just around the corner ....

Huber et al., heo-ph/0907.1896



What reactor experiments could do next?

Issues for ν oscillation & solving methods

4 still unknowns

(1) $\sin^2 2\theta_{13}$
(2)Mass Hierarchy
(3)θ_{23} degeneracy
(4) CP violating δ

Available information

(1) $\nu_\mu \Rightarrow \nu_e$ (accelerator)
(2) $\bar{\nu}_\mu \Rightarrow \bar{\nu}_e$ (accelerator)
(3) Matter effect (accelerator)
(4) $\nu_\mu \Rightarrow \nu_\mu$ (accelerator)
(5) $\bar{\nu}_e \Rightarrow \bar{\nu}_e$ (reactor)
(6) Solar, Atmospheric

(1)–(4): Construction($$$) +ν=$$

(5): Construction($~$$) ν= free

Reactor ν experiments are cost-effective way to get important information.

Physics of ν Oscillation (a different view)

Oscillation Formula:

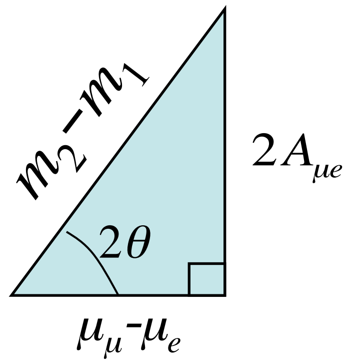
$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2 \Delta_{21}; \quad \Delta_{21} \equiv \frac{(m_2^2 - m_1^2)L}{4E}$$

Time evolution of mass eigenstate

Neutrino Mixing:

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

Mass eignstate

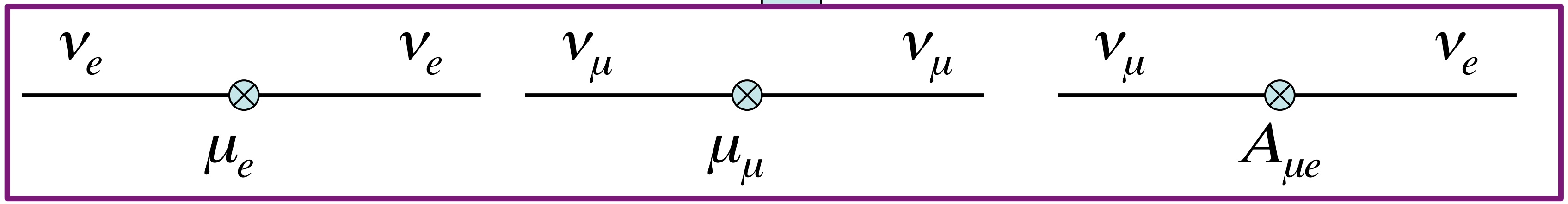


ν Equation of Motion:

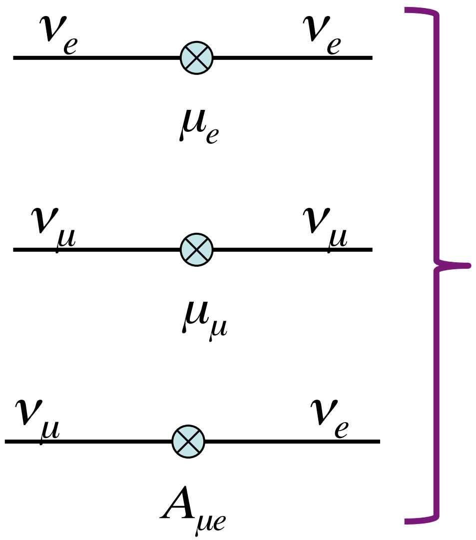
$$i\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \mu_e & A_{\mu e} \\ A_{\mu e} & \mu_\mu \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

Transition Amplitudes

Flavor Transitions:

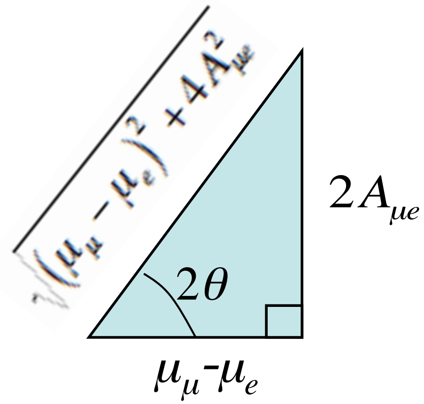


What we measure by ν Oscillation



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

$$\begin{cases} \tan 2\theta = \dfrac{2A_{\mu e}}{\mu_\mu - \mu_e} \\ \Delta m^2 = (\mu_\mu + \mu_e)\sqrt{(\mu_\mu - \mu_e)^2 + 4A_{\mu e}^2} \end{cases}$$

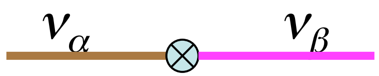


Existence of ν Oscillation is an evidence of finite $A_{\mu e}$

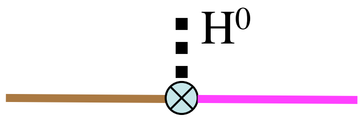
Transition amplitudes can be determined together with absolute mass.

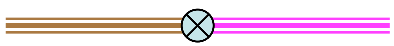
Purpose of ν Oscillation experiment

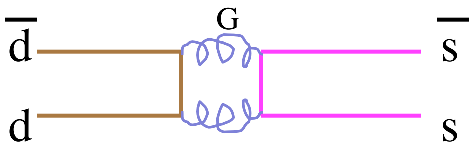
Physics of ν oscillation is to measure the flavor transition amplitudes (<= experimentalist) and think of its origin (<= theorist).

Now we know 

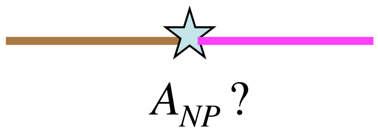
exists.

Non Standard Higgs? 

Sub Structure?? 

For Example, 

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

Or something else?? 

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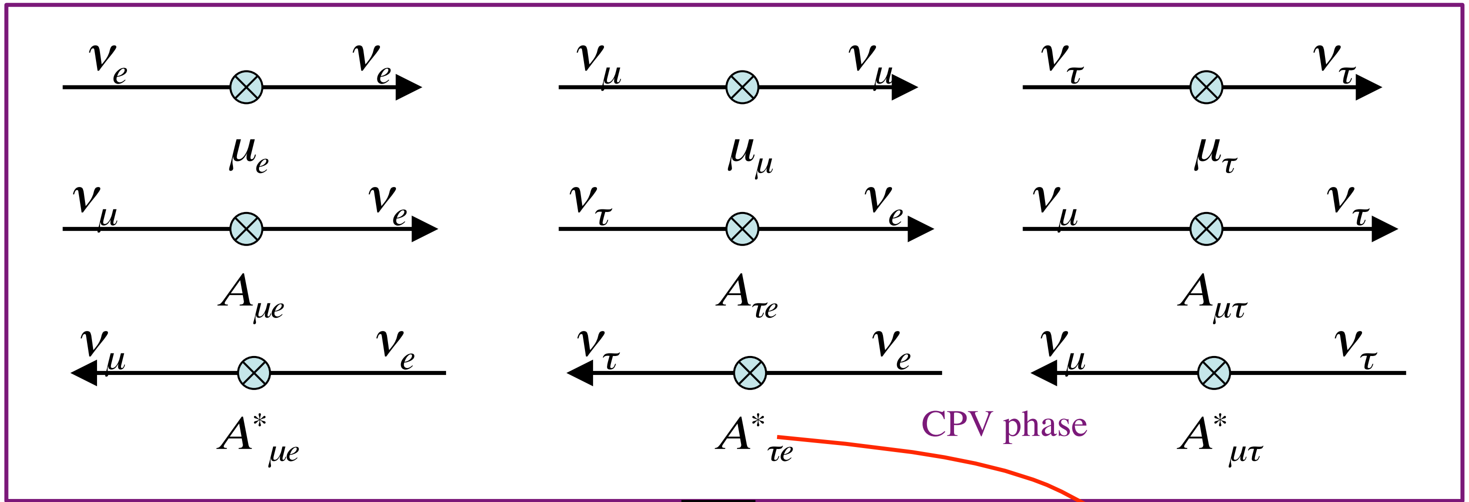
3 Flavors case

Transitions



Mixing

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

Oscillation

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

Our Current Knowledge

$$\left|m_3^2 - m_2^2\right| \sim 2.6\times10^{-3}\,\mathrm{eV}^2,\quad \left(m_2^2 - m_1^2\right) \sim 8\times10^{-5}\,\mathrm{eV}^2$$

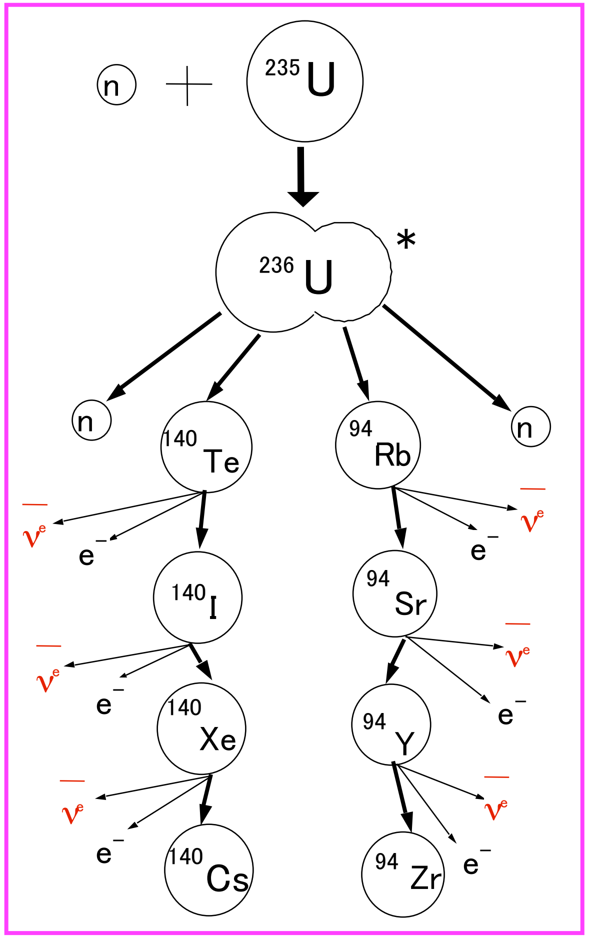
$$U_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & s_{13}e^{i\delta} \\ -0.4 & 0.6 & 0.7 \\ 0.4 & -0.6 & 0.7 \end{pmatrix} \quad |s_{13}| < 0.2$$

If $m_3 > m_2 >> m_1 \sim 0$,

ν_e — ν_e	ν_μ — ν_μ	ν_τ — ν_τ
$\mu_e \sim 3$meV	$\mu_\mu \sim 30$meV	$\mu_\tau \sim 30$meV
ν_e — ν_μ	ν_e — ν_τ	ν_μ — ν_τ
$A_{e\mu} \sim (30 s_{13} e^{i\delta} + 3)$meV	$A_{e\tau} \sim (30 s_{13} e^{i\delta} - 3)$meV	$A_{\mu\tau} \sim 20$meV

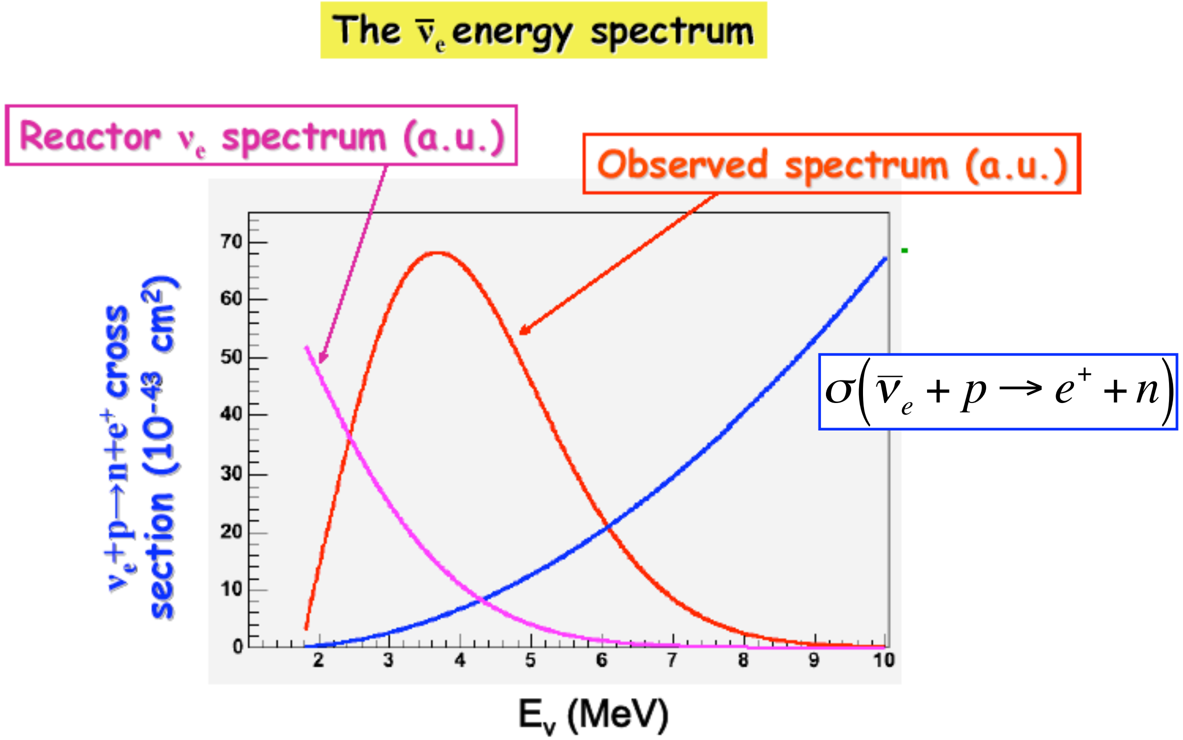
(charged lepton=mass eigenstate)

Reactor neutrino



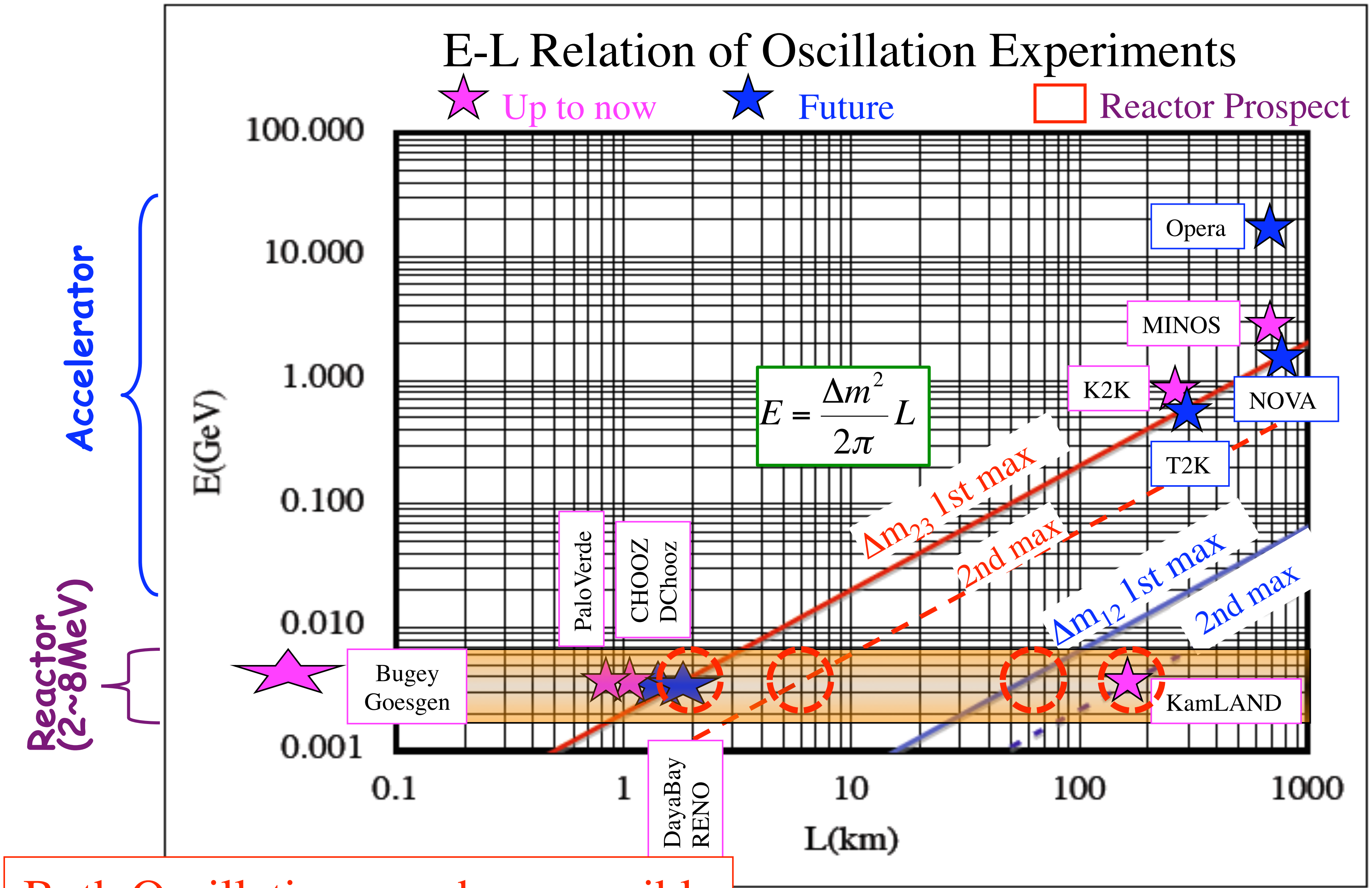
ν are produced in
β-decays of fission products.

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



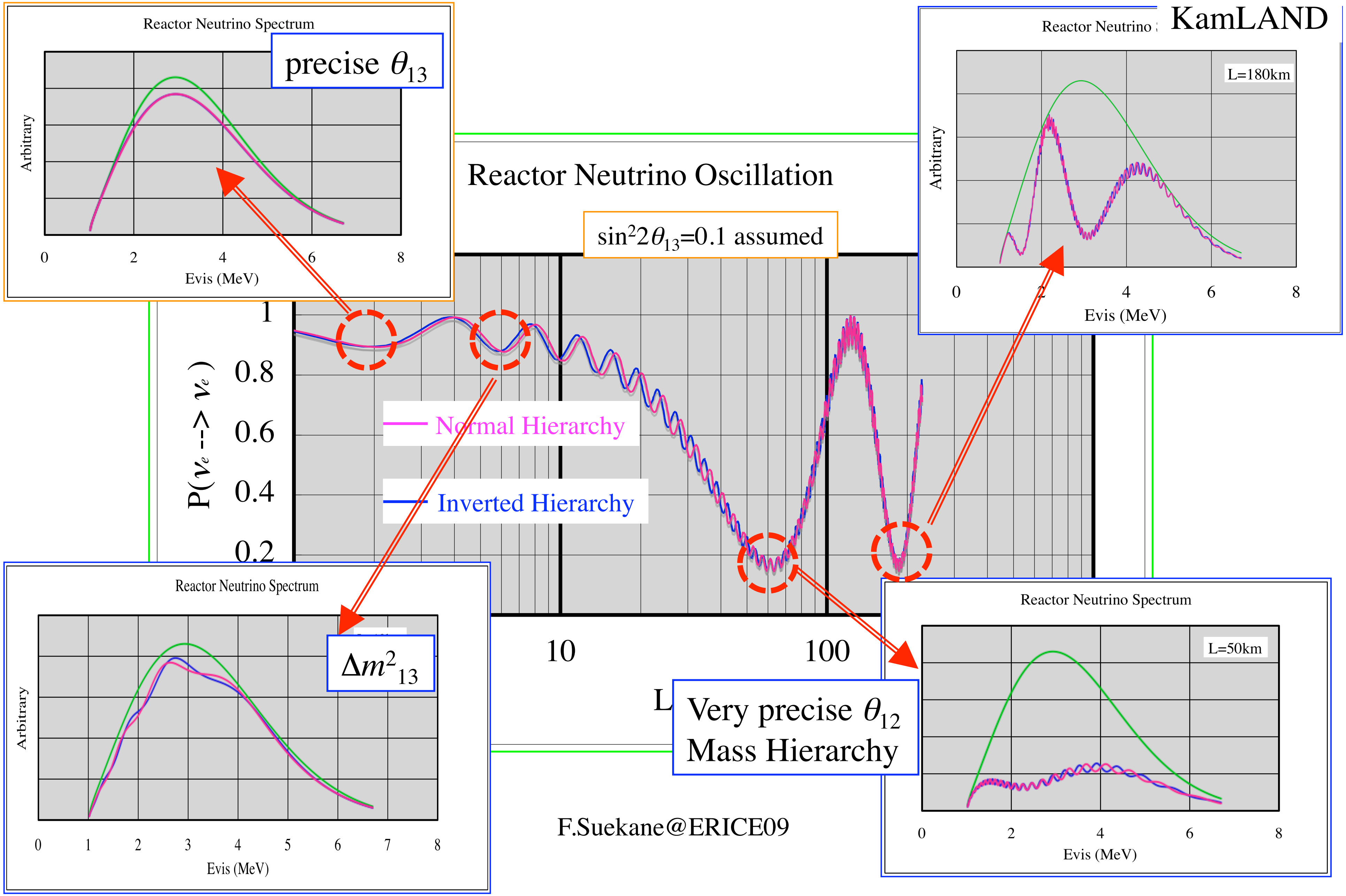
$$E_\nu \sim 4\,^{+4}_{-2} MeV$$

Accessible Oscillations by Reactor ν



Both Oscillations can be accessible

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right)$$



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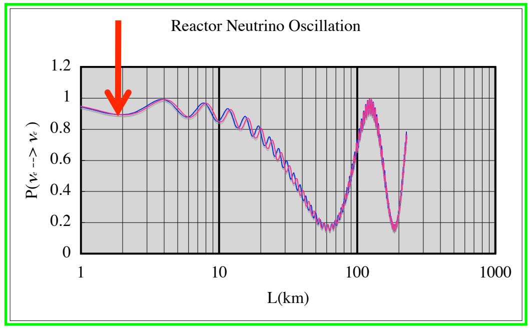
Physics @ 1st Δm^2_{13} Maximum (L~1.5km) ; θ_{13}



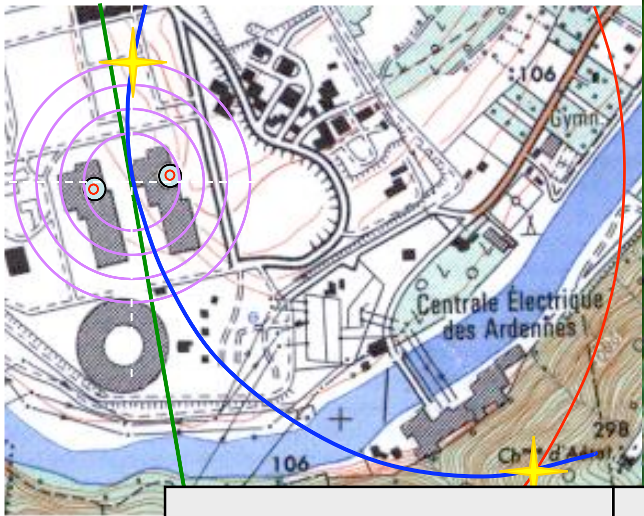
$$P_R(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \underline{\sin^2 2\theta_{13}} \sin^2 \Delta_{31}$$

Future ν experiments strongly depends on θ_{13}
Precise measurement of θ_{13} is very important.

Parameter	Measurement Method
δ_{CP}	$\left[P_A(\nu_\mu \to \nu_e) - P_A(\bar{\nu}_\mu \to \bar{\nu}_e)\right]_{@\Delta_{23}} \sim 0.1 \underline{\sin 2\theta_{13}} \sin\delta$ $P_A(\nu_\mu \to \nu_e)_{@\Delta 23} \sim 0.5 \underline{\sin^2 2\theta_{13}} \pm 0.05 \underline{\sin 2\theta_{13}} \sin\delta$
θ_{23} degeneracy	$\left[P_A(\nu_\mu \to \nu_e) + P_A(\bar{\nu}_\mu \to \bar{\nu}_e)\right]_{@\Delta_{23}} \sim 2\sin^2\theta_{23} \underline{\sin^2 2\theta_{13}}$
Mass Hierarchy	$\left[P_A(\nu_\mu \to \nu_e; L) + P_A(\nu_\mu \to \nu_e; L')\right]_{@\Delta_{23}} \sim sign(\Delta m^2_{23})(L' - L)\underline{\sin^2 2\theta_{13}}$ $P_R(\bar{\nu}_e \to \bar{\nu}_e)_{@\Delta_{12}} \sim 1 - 0.5\underline{\sin^2 2\theta_{13}}(\sin^2\Delta_{31} + \tan^2\theta_{12}\sin^2\Delta_{32})$

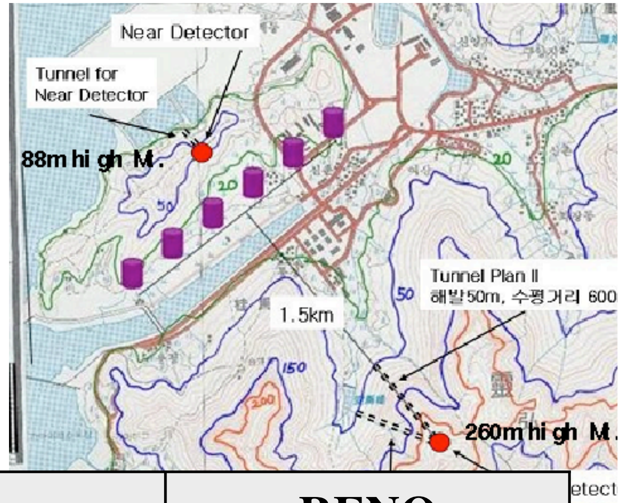
DoubleChooz, Dayabay, RENO

Double Chooz



Daya Bay

RENO



	Double Chooz	Dayabay	RENO
Power(GWth)	8.6GW	11.6GWth (17.4GW>2011)	16.4GW
Detector(ton)	8+8	20x4+2(20x2)	16+2
Baseline(km)	1.05	1.8	1.4
$\sin^2 2\theta_{13}$ Sensitivity	~0.03	~0.01	~0.02
Operation start	2010/2011	2011	2010

Results: within 2~5years

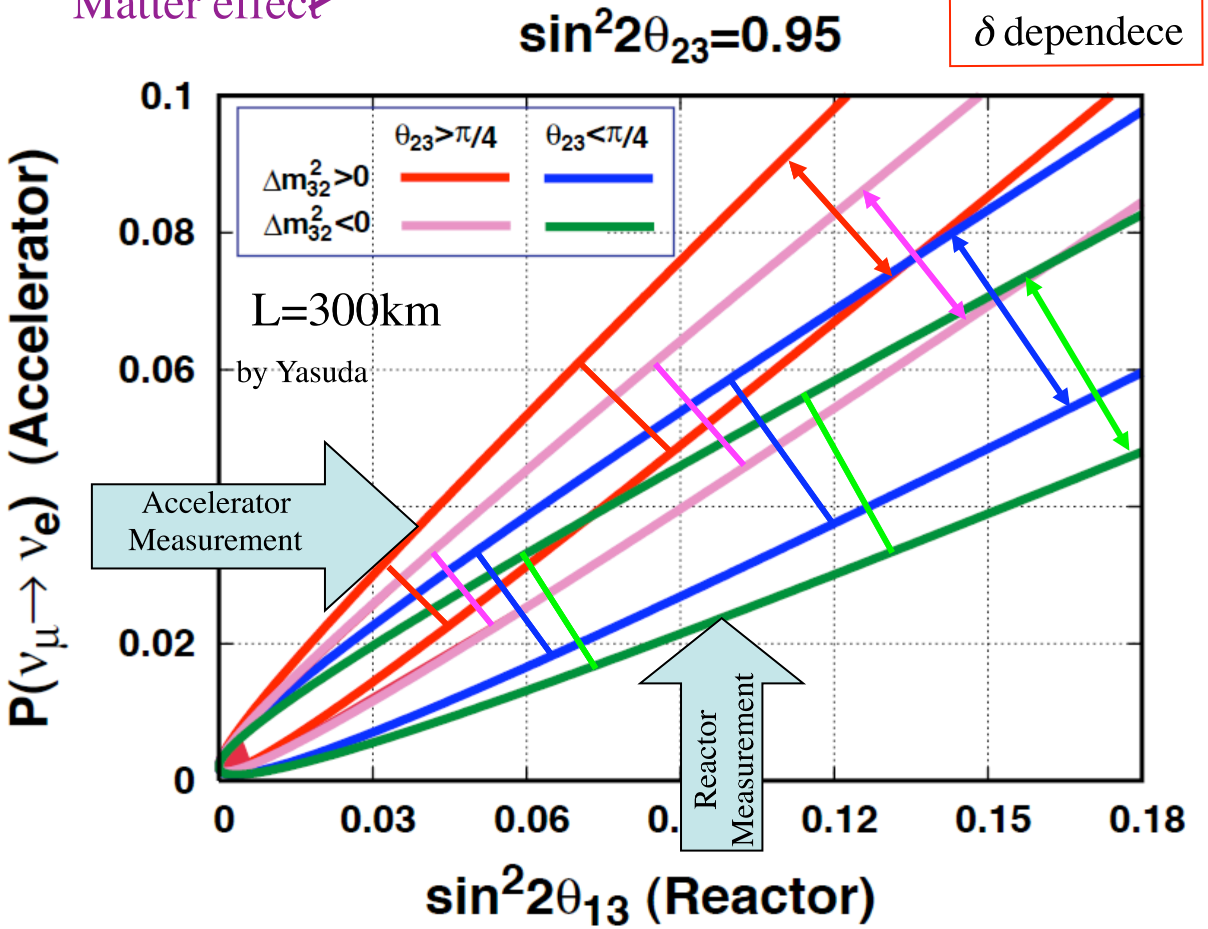
Complementarity of Reactor-Accelerator θ_{13} measurement

θ_{23} degeneracy

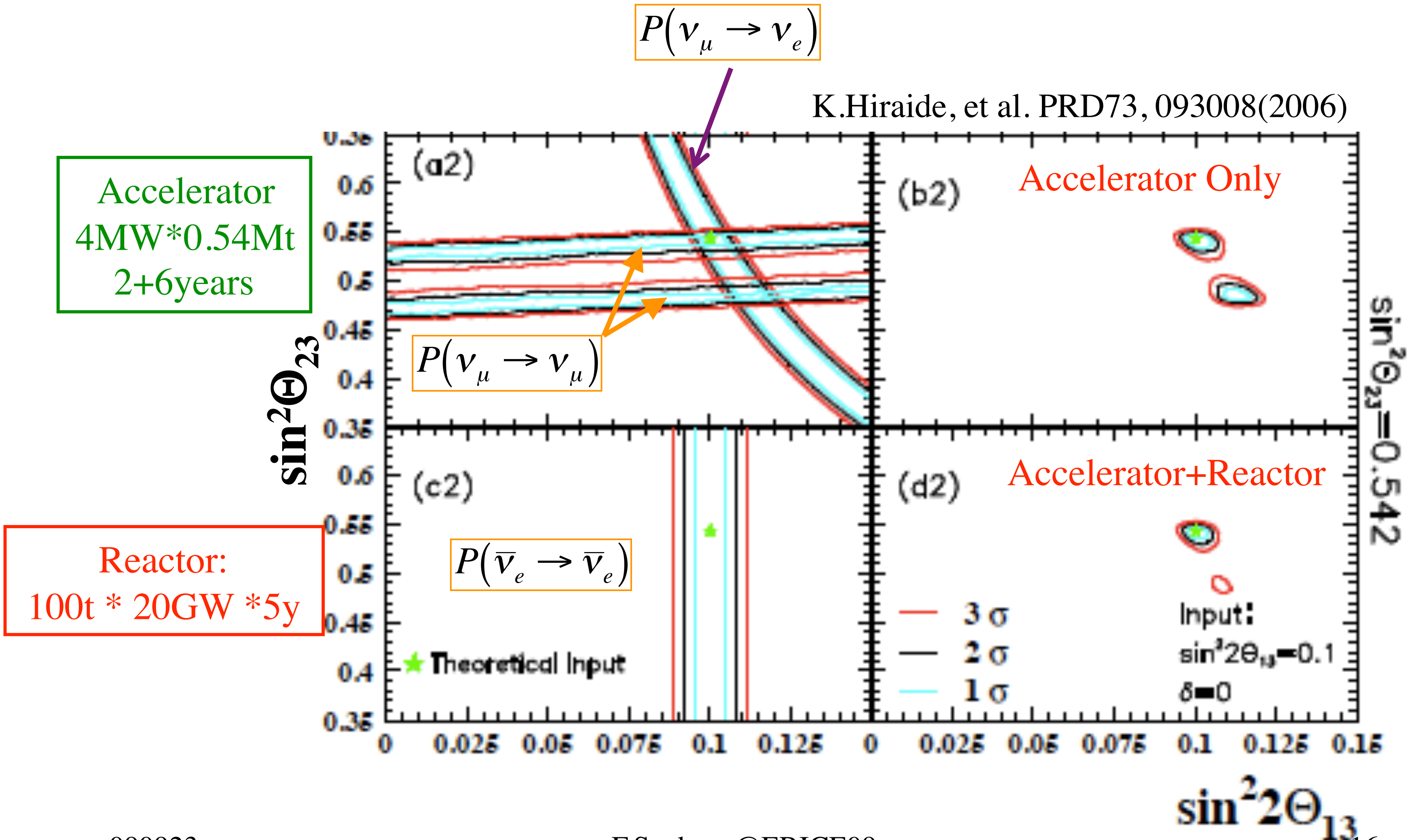
$$P_{AC}(\nu_\mu \to \nu_e) = \frac{0.50 \pm 0.11}{(1 \mp 0.00017L[km])^2}\sin^2 2\theta_{13} \pm 0.045\sin 2\theta_{13}\sin\delta$$

Matter effect

δ dependece

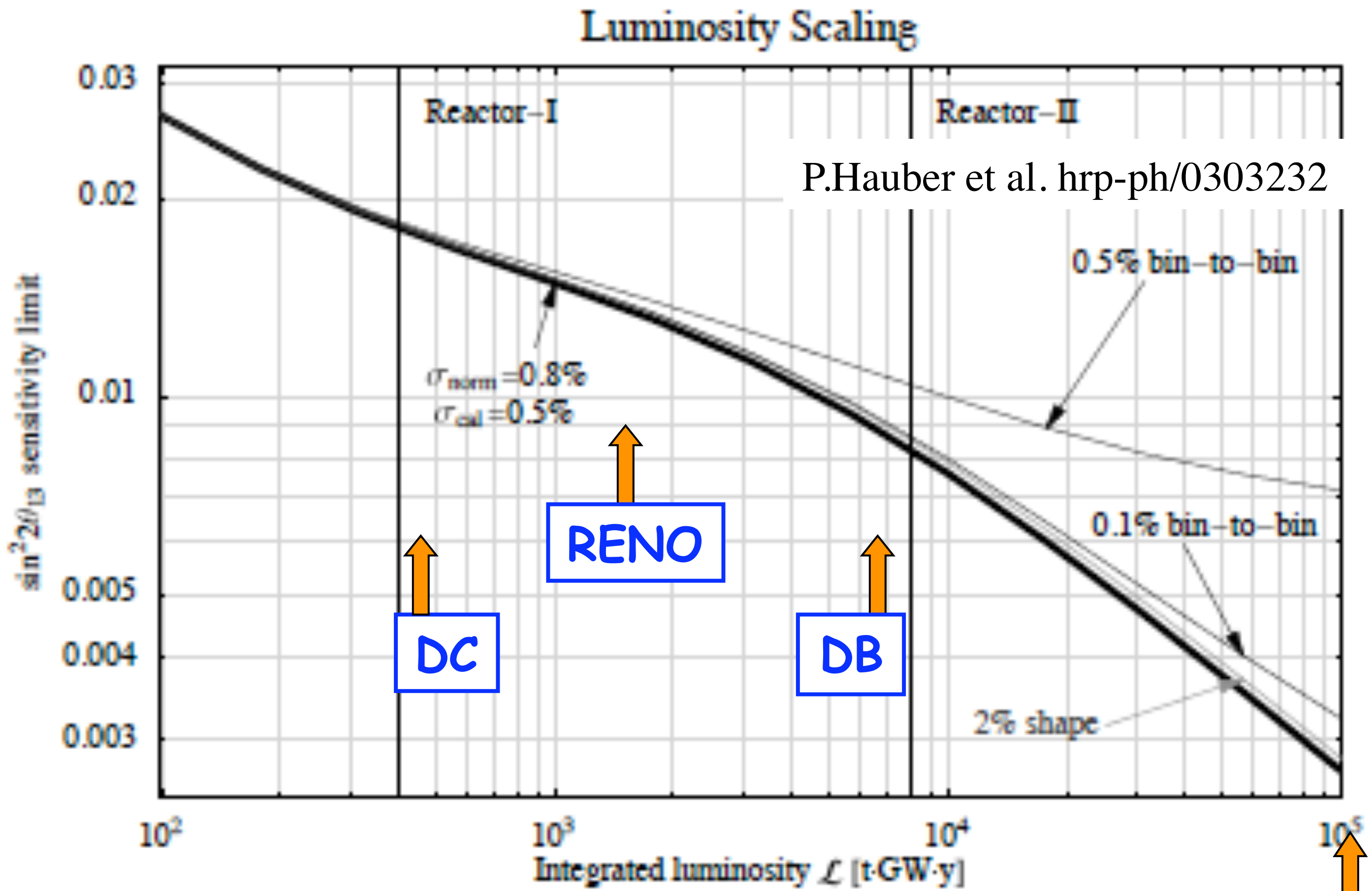


Settlement of θ_{23} Degeneracy



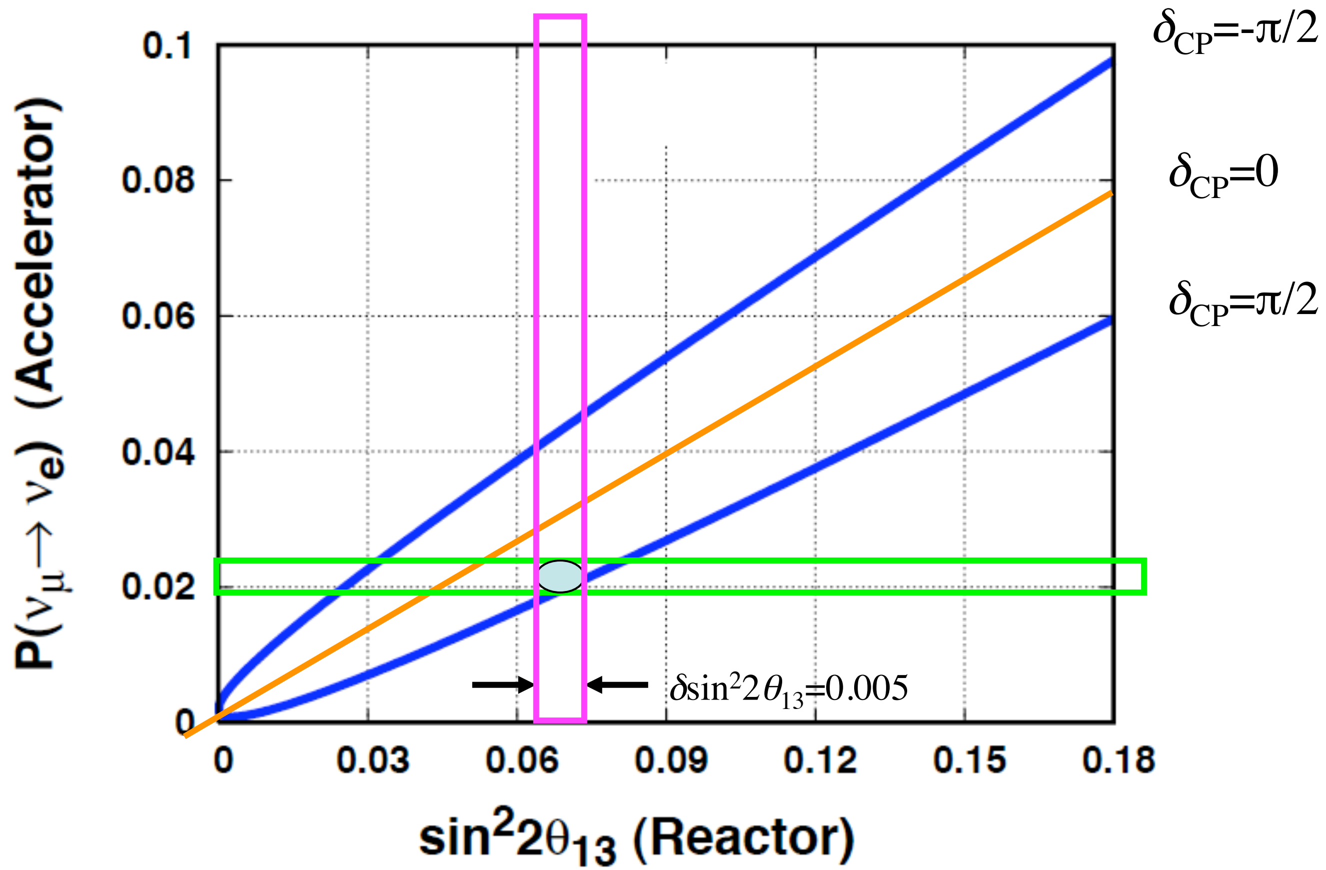
3rd Generation; More Precise θ_{13}

For higher statistics, θ_{13} cam be measured by energy spectrum distortion and $\delta\sin^2 2\theta_{13}<0.01$ is possible



1000ton x 20GW x 5year

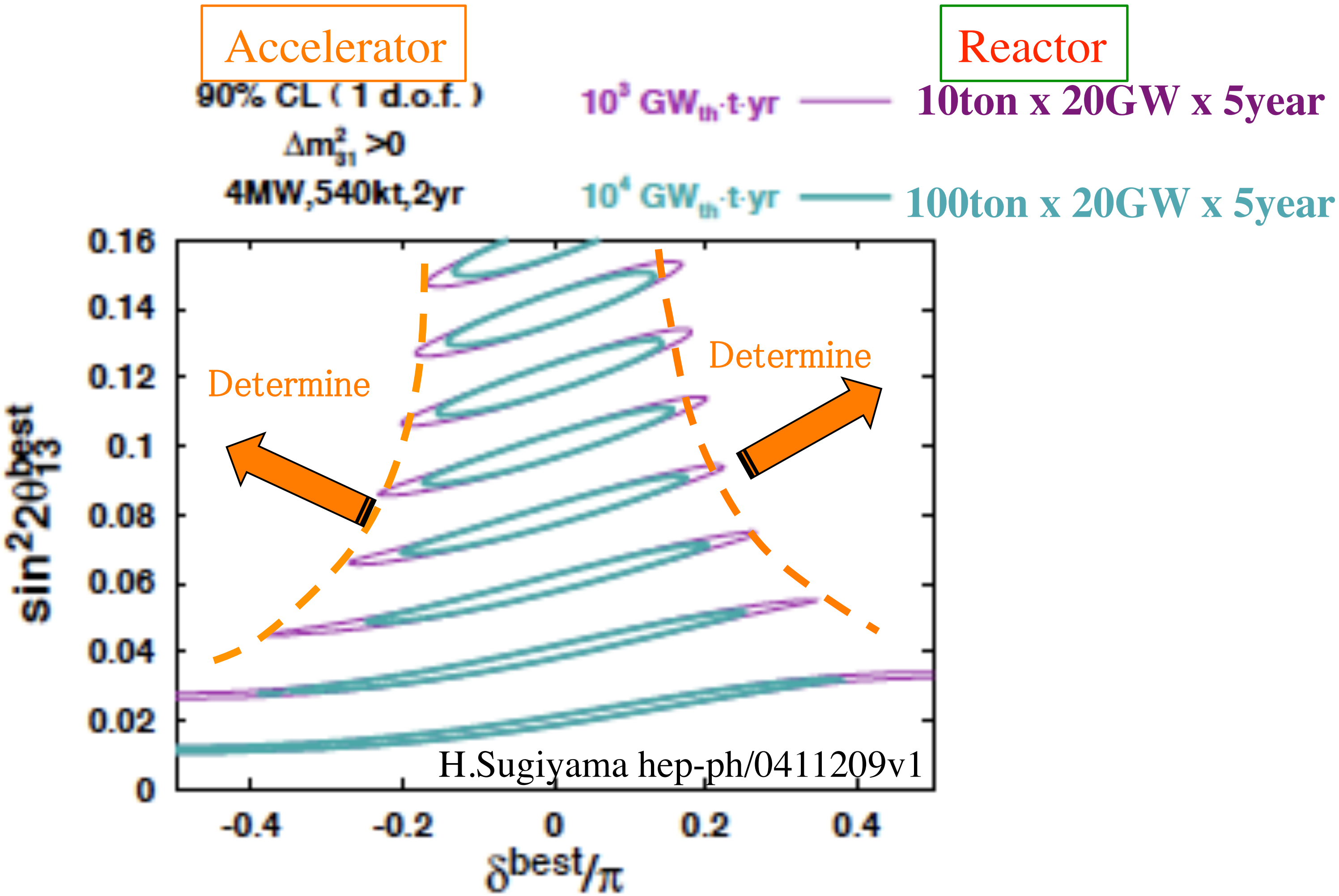
Quick Access to δ_{CP}



If θ_{23} degeneracy and Mass Hierarchy are solved, only δ remains to be solved.

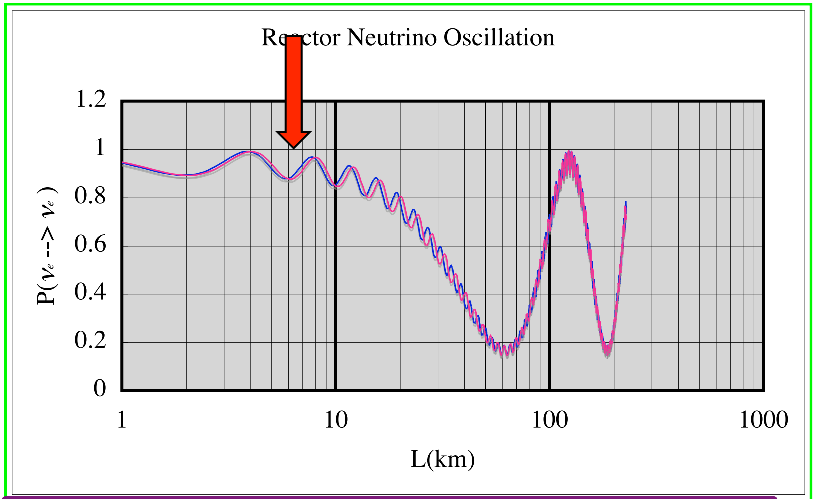
Combination of high precision Reactor-θ_{13} and Accelerator ν_e appearance may determine non-0 δ before anti-neutrino mode operation.

Parameter region to determine non-0 δ

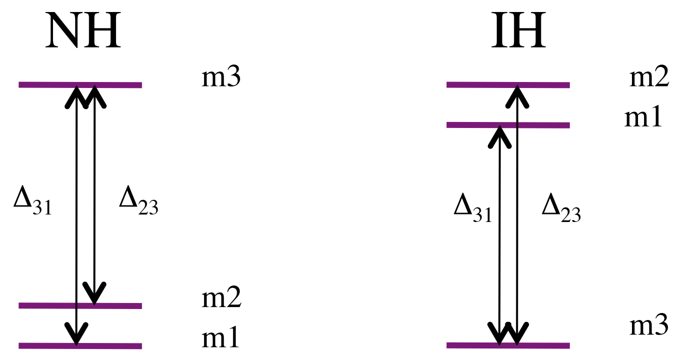


If $\sin^2 2\theta_{13} > 0.05$ there is a possibility to determine non-0 δ

Physics @ Δm^2_{13} 2nd Maximum (L~5km)
($|\Delta m^2_{13}|$ measurement)



$$P_R(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{31}$$



$|\Delta m^2_{31}| > |\Delta m^2_{23}|$ $\qquad$ $|\Delta m^2_{31}| < |\Delta m^2_{23}|$

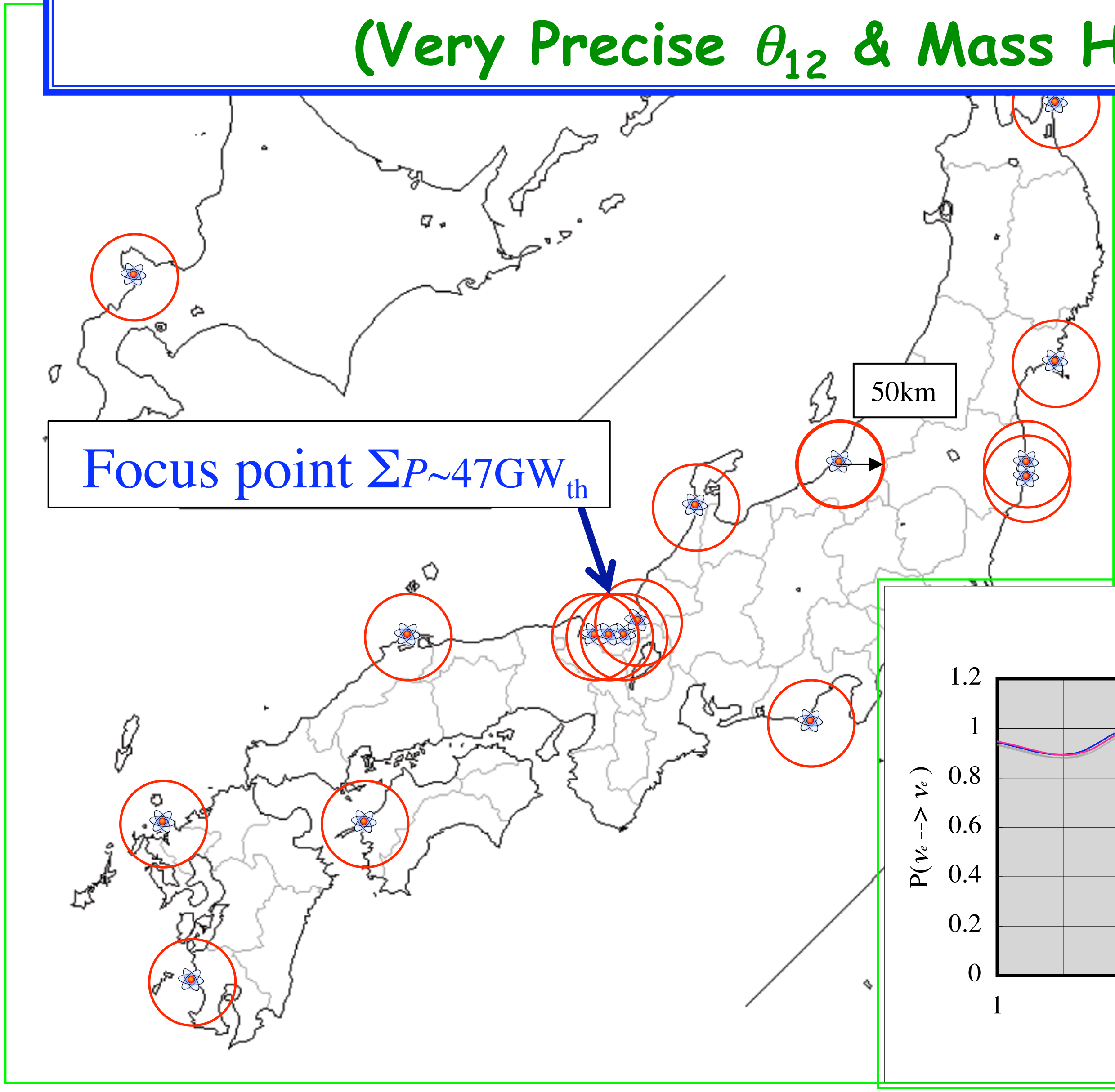
In principle, Mass Hierarchy is accessible

However, accurcy of $\dfrac{\delta|\Delta m^2_{31}|}{|\Delta m^2_{31}|}, \dfrac{\delta|\Delta m^2_{23}|}{|\Delta m^2_{23}|} << \dfrac{|\Delta m^2_{12}|}{|\Delta m^2_{23}|} \sim 3\%$ are necessary.

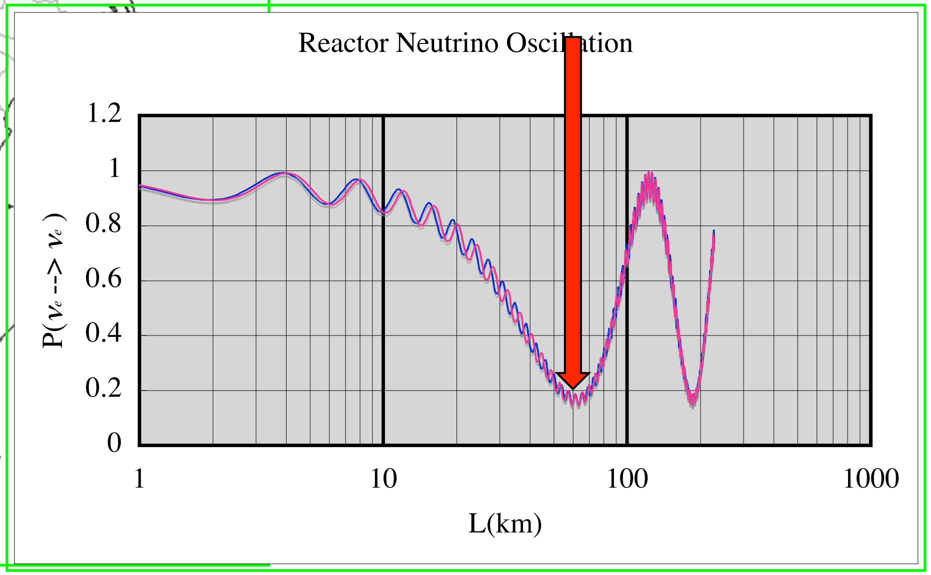
- T2K & Nova expected $\delta|\Delta m^2_{23}| / |\Delta m^2_{23}| \sim 4\%$ ⇨ Need to improve
- θ_{13} is necessary to evaluate $\delta|\Delta m^2_{13}|$ (KamLAND case; $\delta|\Delta m^2_{12}| / |\Delta m^2_{12}| \sim 2.6\%$)

Physics @ 1^{st} Δm^2_{12} Maximum(L~50km)

(Very Precise θ_{12} & Mass Hierarchy)

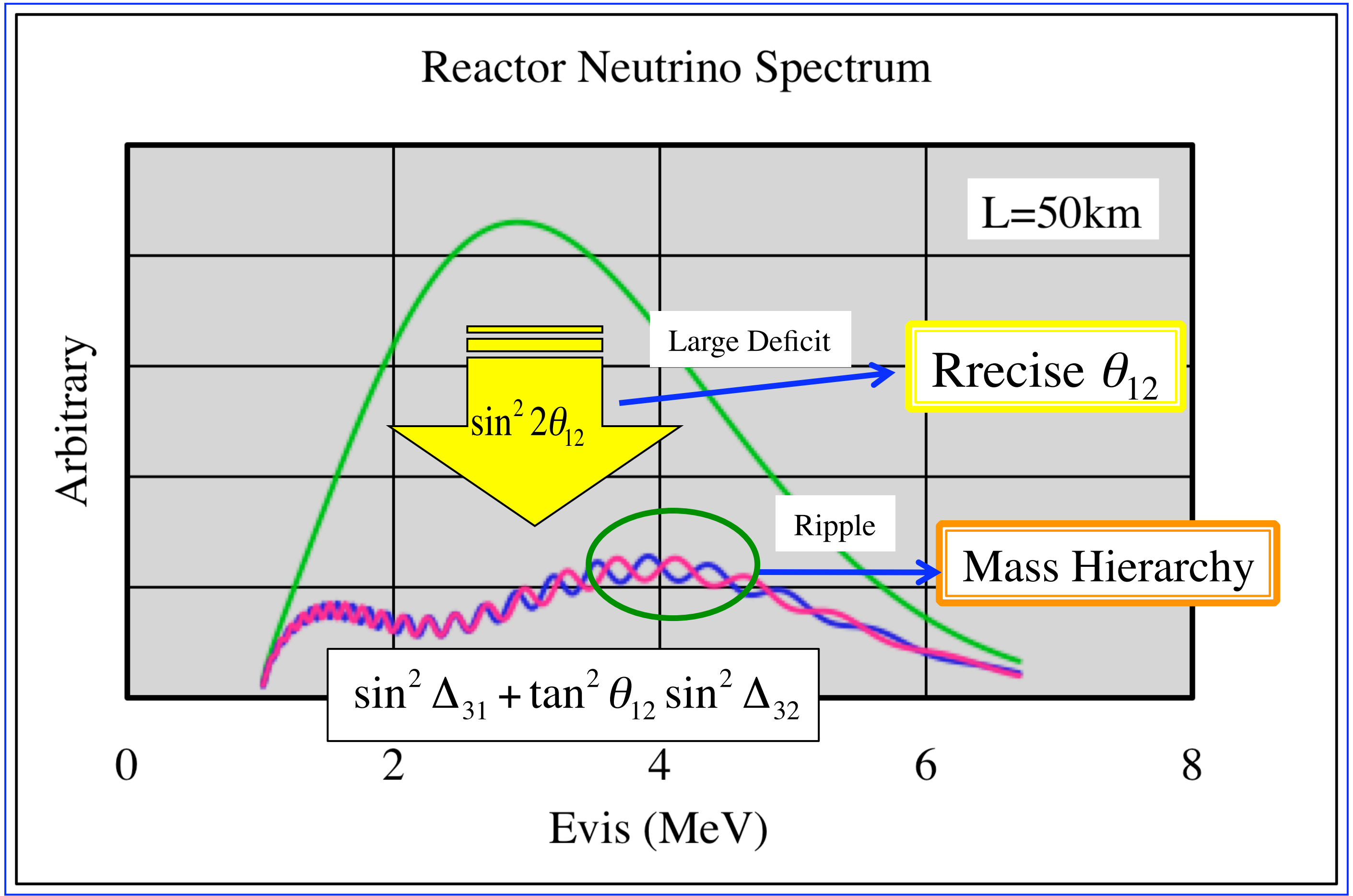


Example of Japan case



Physics @ 1^{st} Δm^2_{12} Maximum

$$P_R(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \left\{ \begin{matrix} \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ +\sin^2 2\theta_{13}\cos^2\theta_{12}\left(\sin^2\Delta_{31} + \tan^2\theta_{12}\sin^2\Delta_{32}\right) \end{matrix} \right\}$$



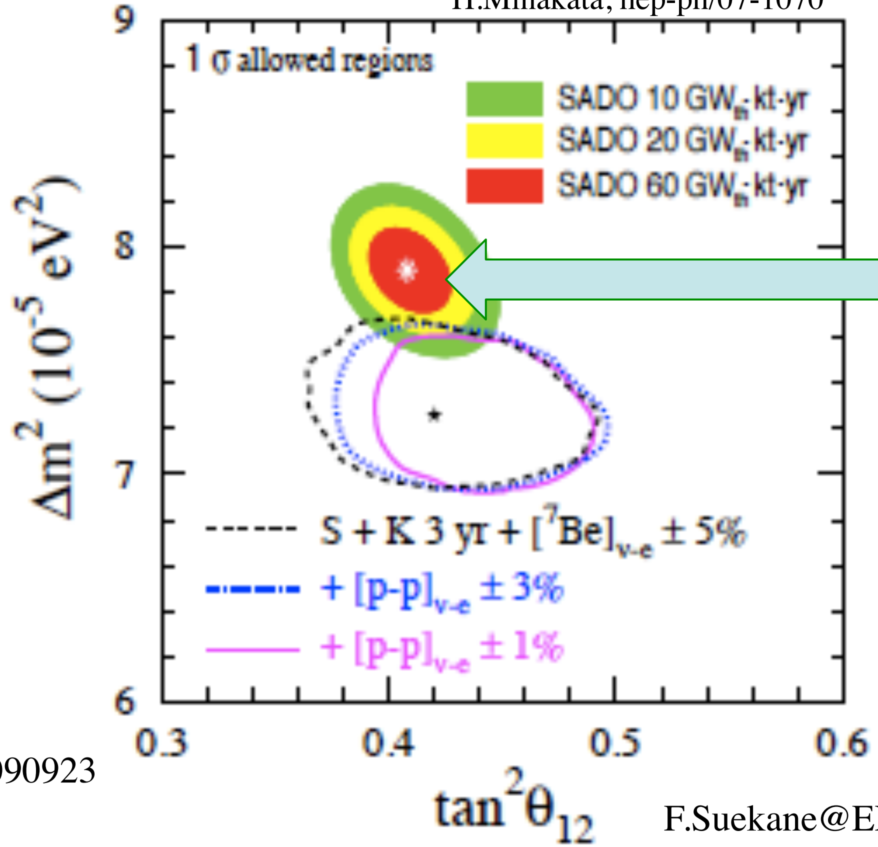
Precise θ_{12}

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \sim \cos^4\theta_{13}\left(1-\sin^2 2\theta_{12}\sin^2\Delta_{21}\right)$$

$$\delta\sin^2 2\theta_{12} \propto \frac{1}{\Lambda(L)},$$ Λ= Deficit probability; $$\Lambda(L) = \frac{\int f_\nu(E)\sin^2\Delta_{21}dE}{\int f_\nu(E)dE}$$

$$\left.\begin{array}{l}\Lambda(50km)\sim 0.8\\ \Lambda(180km)\sim 0.4\ \text{(KamLAND)}\end{array}\right\} \Rightarrow \delta\sin^2 2\theta_{12} \sim \frac{1}{2}\left(\delta\sin^2 2\theta_{12}\right)_{KamLAND}$$

H.Minakata, hep-ph/07-1070



& Low geo neutrino BKG
(high ν flux)

1kton x25GW x2.5y

$$\frac{\delta\sin^2\theta_{12}}{\sin^2\theta_{12}} \sim 2.4\%(1\sigma)$$

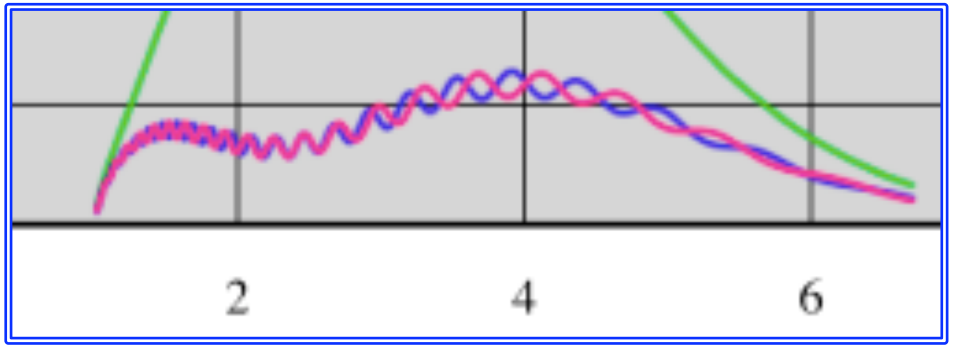
Current Global fit

$$\frac{\delta\sin^2\theta_{12}}{\sin^2\theta_{12}} \sim 6.3\%(1\sigma)$$

Determination of Mass Hierarchy@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

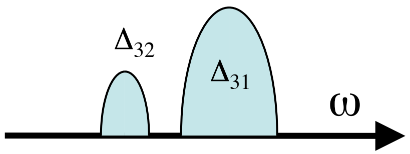


$$\text{Ripple} \propto \sin^2 2\theta_{13}\left(\sin^2 \Delta_{31} + \tan^2 \theta_{12} \sin^2 \Delta_{32}\right)$$

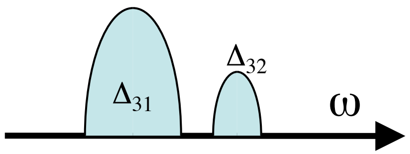
It is essential that θ_{12} is not maximum ($\tan^2\theta_{12}$~0.4)

Fourier Analysis => Power Spectrum Peaks at $\omega = \left|\Delta m^2_{31}\right|, \quad \left|\Delta m^2_{32}\right|$

The smaller peak is $\left|\Delta m^2_{32}\right|$ and larger peak is $\left|\Delta m^2_{31}\right|$,



$\Rightarrow \left|\Delta m^2_{31}\right| > \left|\Delta m^2_{32}\right|$: Normal Hierarchy



$\Rightarrow \left|\Delta m^2_{31}\right| < \left|\Delta m^2_{32}\right|$: Inverted Hierarchy

J.Learned et al. arXive-0612022

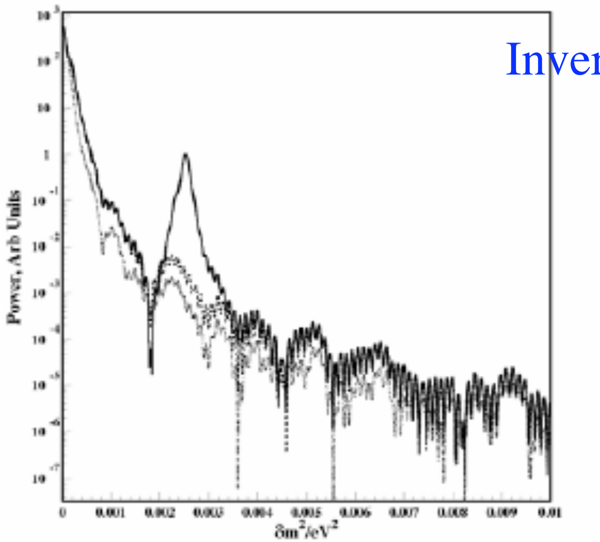


FIG. 2: Fourier power spectrum with modulation in units of eV^2 and power in arbitrary units on the logarithmic scale. The peak due to Δ_{31} with $\sin^2(2\theta_{13})=0.1$ is prominent.

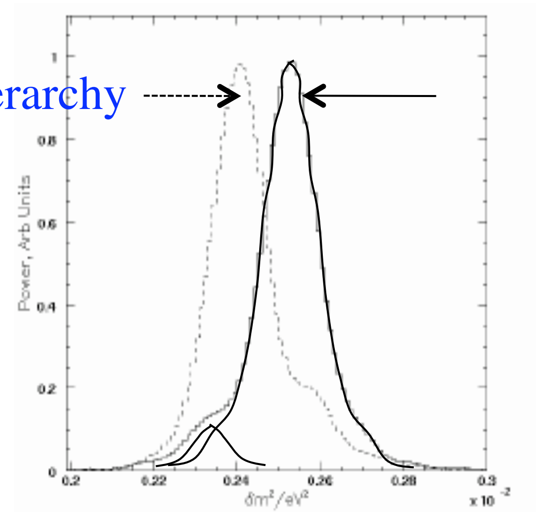


FIG. 3: Neutrino mass hierarchy (normal=solid; inverted=dashed) is determined by the position of the small shoulder on the main peak.

Simulation of power spectrum

If $\sin^2 2\theta_{13}=0.05$, 3kton x24GW x5yr ,

Mass Hierarchy can be determined with 1σ significance.

L.Zhan et al.=> Mass Hierarchy could be determined if $\sin^2 2\theta_{13}>0.005$.

Merit & Issues of this method.

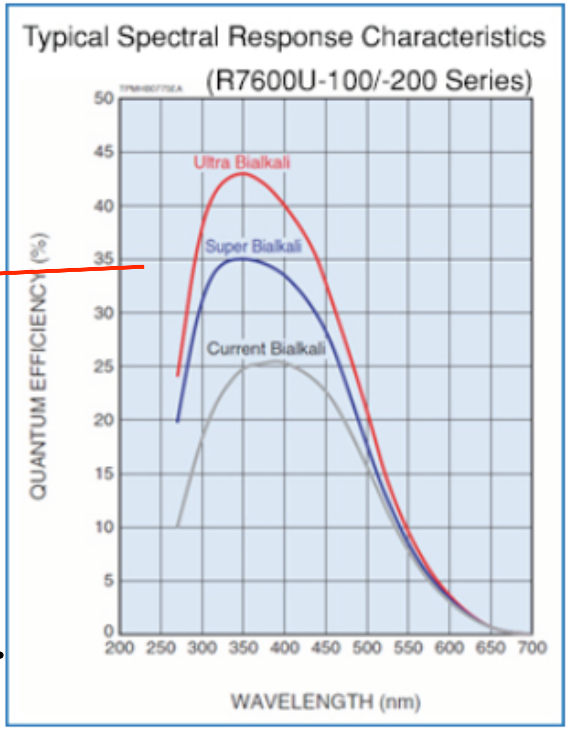
* Need not to know absolute $|m_{23}^2|$ so precisely.
It is enough only to separate two peak positions.

* However, a good energy resolution; $\frac{\delta E}{E} < \frac{3\%}{\sqrt{E(MeV)}}$ is necessary.

Borexino case $\frac{\delta E}{E} \sim \frac{5\%}{\sqrt{E(MeV)}}$

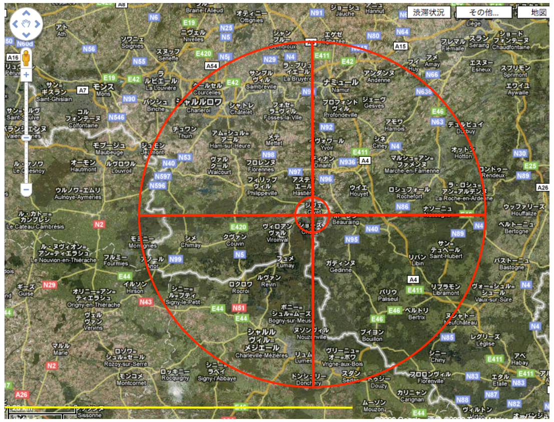
improvement of light yield:
x1.5 more PMT
x1.8 with UltraBialkali photocathode

$\Rightarrow \frac{\delta E}{E} = \frac{3\%}{\sqrt{E(MeV)}}$ can be achieved

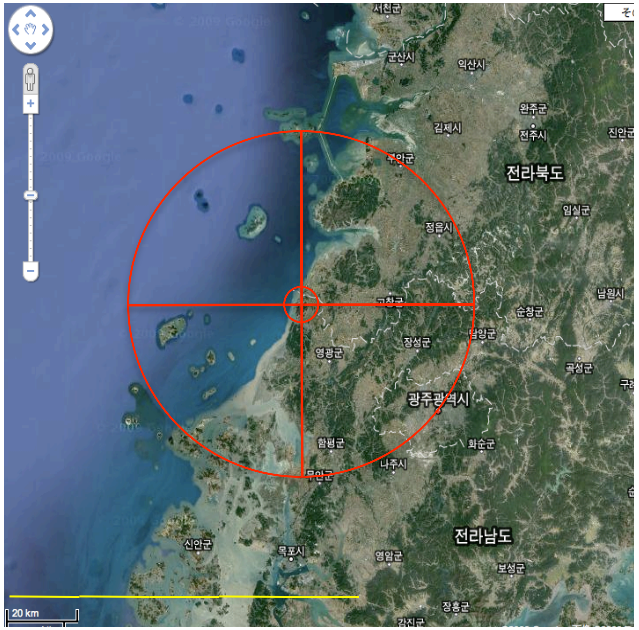


* Energy smearing due to recoil neutron energy
& baseline difference may degrade performance.

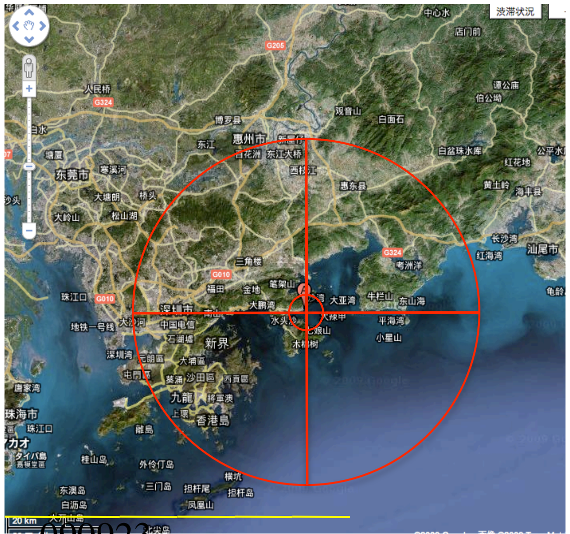
=> Need more studies for specific sites



DoubleChooz-50



RENO-50

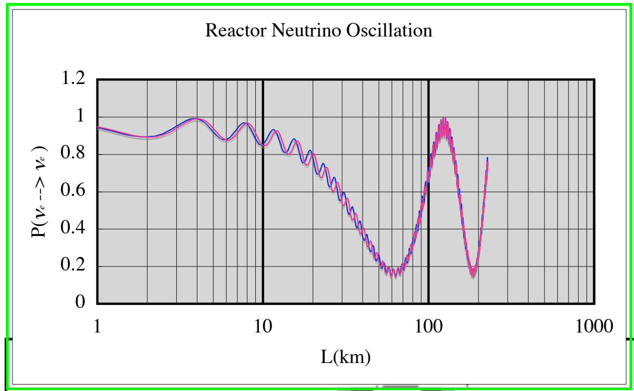


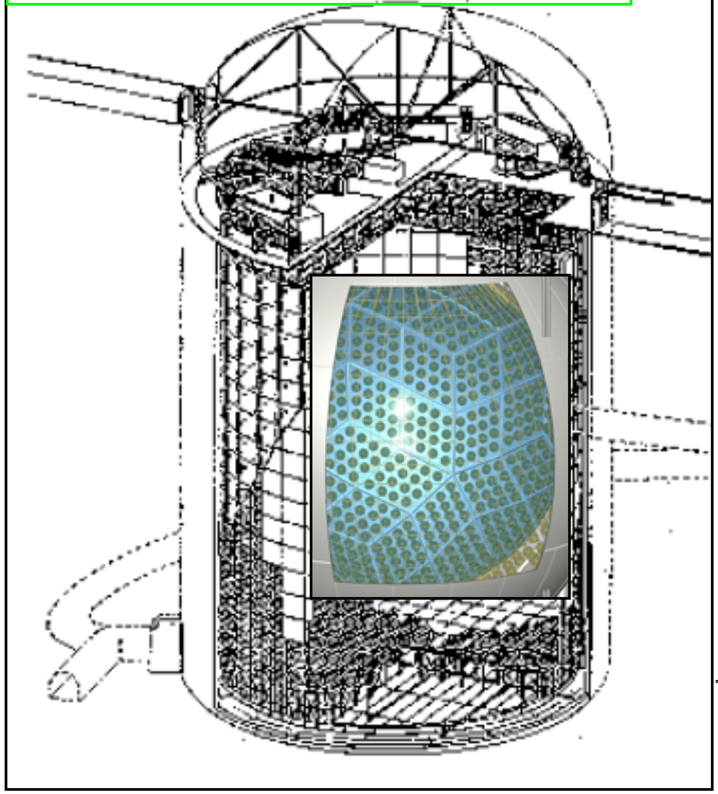
DayaBay-50

L~50km experiment may be a natural extension of current Reactor-θ_{13} Experiments

* θ_{13} detectors can be used as near detector
* Small background from other reactors.

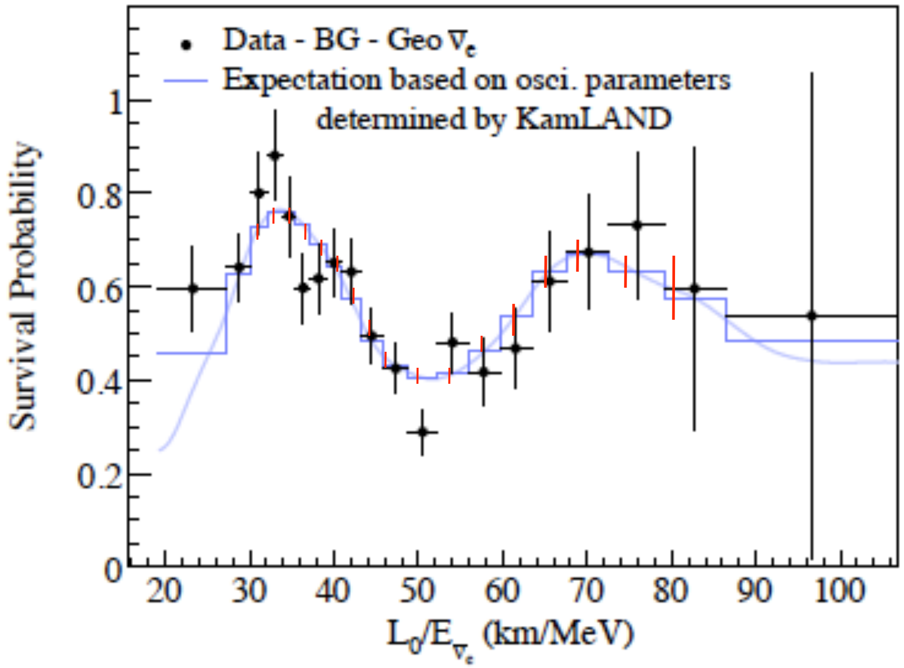
Physics @ Δm^2_{12} 2nd Maximum(L~150km)





If SK detector is filled with LS,

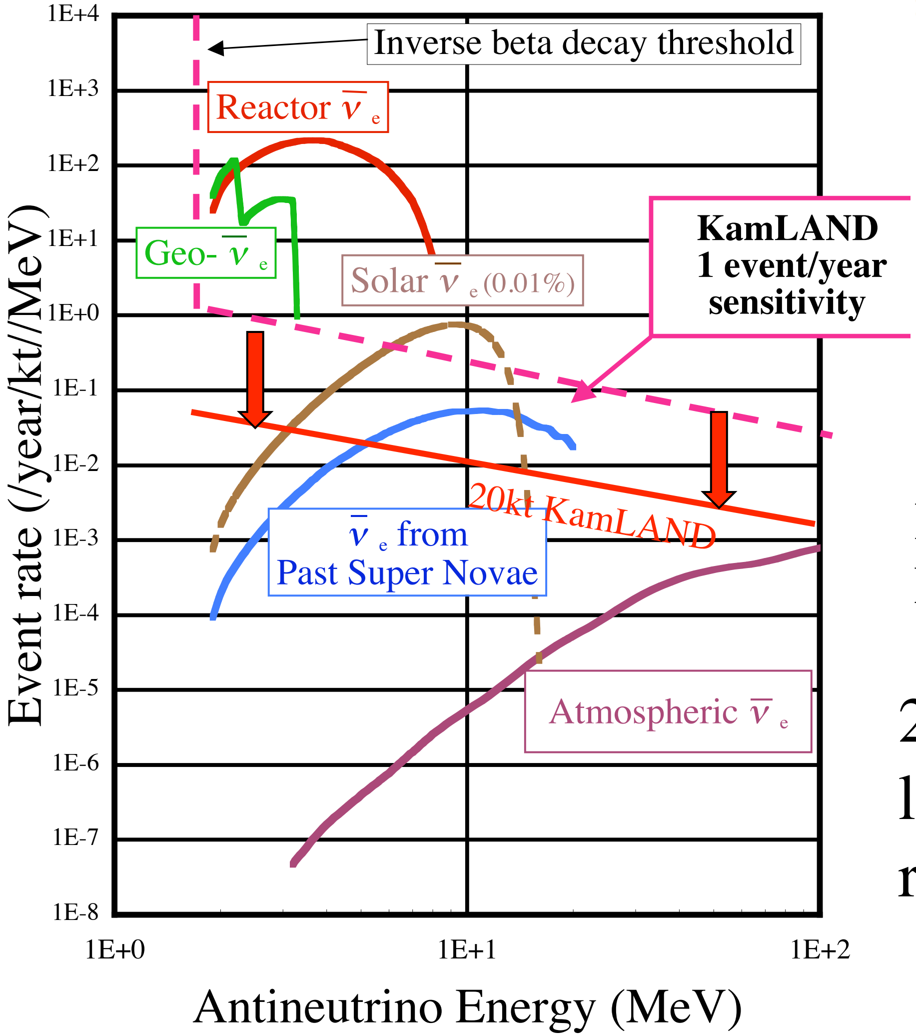
>20 times more statistics than KamLAND

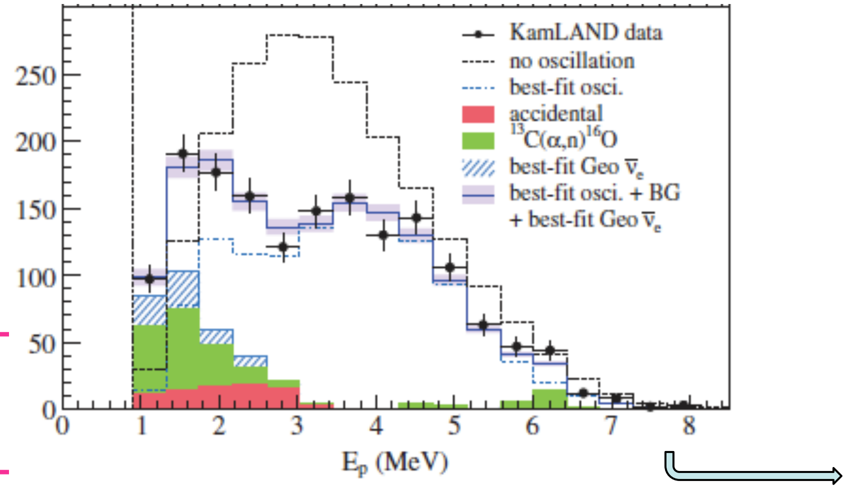


$$\begin{cases} \Delta m^2_{21} = 7.58^{+0.14}_{-0.13}(stat)^{+0.15}_{-0.15}(syst) \Rightarrow 7.58^{+0.03}_{-0.03}(stat)^{+0.15}_{-0.15}(syst) \\ \tan^2\theta_{12} = 0.56^{+0.10}_{-0.07}(stat)^{+0.10}_{-0.06}(syst) \Rightarrow 0.56^{+0.2}_{-0.014}(stat)^{+0.10}_{-0.06}(syst) \end{cases}$$

$$f_\nu(E_\nu)\times\sigma_{\bar{\nu}p\to e^+n}(E_\nu)$$

Electron Antineutrino Event Rate at Kamioka





No Backgrounds >8MeV

KamLAND detects any $\bar{\nu}_e$ with E>1.8MeV

20Kton KamLAND pushes the limit 20 times better and may reach Relic SN $\bar{\nu}_e$.

Summary

= Current =

θ_{13}: DoubleChooz, RENO, Dayabay are going to start in 2010.

$\delta\sin^2 2\theta_{13}$=0.01~0.03 in a few years.

= Future =

* L~1.8km, High Precision θ_{13};

  M~100ton x 24GW$_{th}$ => $\delta\sin^2 2\theta_{13}<0.01$

  ➔ θ_{23} Degeneracy with accelerator

  ➔ early $\sin\delta$ detection with accelerator

* L=50km, M~3Kton x 24GW$_{th}$,

  ➔ High Precision θ_{12};

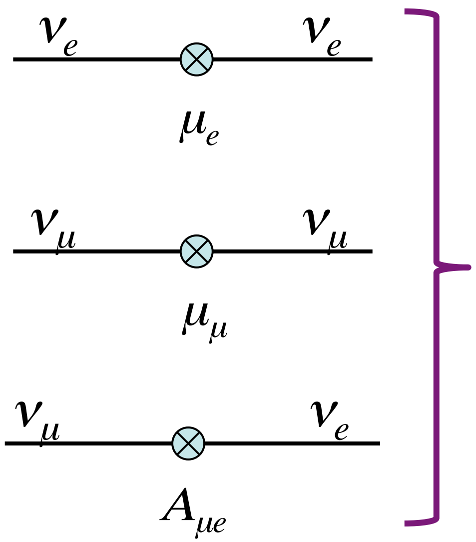
  ➔ Mass hierarchy determination

* L=180km 20Kton KamLAND???

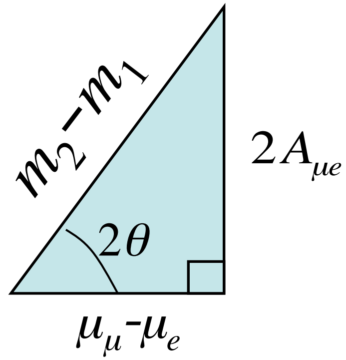
It is important to discuss about the future strategy taking into account the reactor-accelerator complementarity after the 1st phase θ_{13} measurements.

Back up slides

Relation of mass, mixing & transition amplitudes



$$\begin{cases} m_1 = \frac{1}{2}\left(\mu_\mu + \mu_e - \sqrt{(\mu_\mu - \mu_e)^2 + 4A_{\mu e}^2}\right) \\ m_2 = \frac{1}{2}\left(\mu_\mu + \mu_e + \sqrt{(\mu_\mu - \mu_e)^2 + 4A_{\mu e}^2}\right) \end{cases}$$



$$\tan 2\theta = \frac{2A_{\mu e}}{\mu_\mu - \mu_e}$$

$$\Delta m^2 = (\mu_\mu + \mu_e)\sqrt{(\mu_\mu - \mu_e)^2 + 4A_{\mu e}^2}$$

$$P_{Accel}(\nu_\mu \to \nu_e) \oplus P_{Accel}(\overline{\nu}_\mu \to \overline{\nu}_e) \oplus P_{Reactor}(\overline{\nu}_e \to \overline{\nu}_e)$$

Reactor θ_{13} helps to pin down parameters