Prospects for
Future Reactor ν Experiments

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@Japan-US seminar on Double Beta Decay and Neutrinos
12/Oct./2009

Contents

＊ Neutrino Oscillation & Double Beta decays

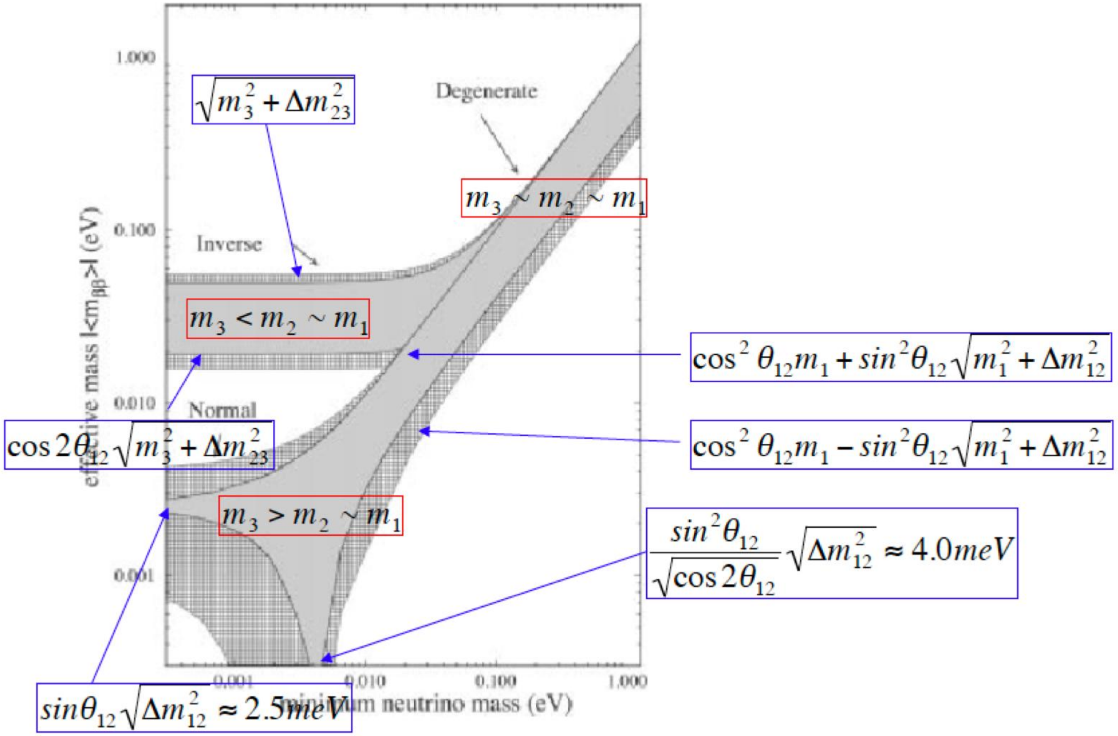
＊ Accessible Parameters of Reactor Neutrinos

＊ Possibilities of Reactor Neutrinos

＊ Summary

Relation of ν Oscillation and ββ decay

- Now: Oscillation parameters limit the ββ decay parameters and give



$\sqrt{m_3^2+\Delta m_{23}^2}$

$m_3 \sim m_2 \sim m_1$

$m_3 < m_2 \sim m_1$

$\cos^2\theta_{12} m_1 + \sin^2\theta_{12}\sqrt{m_1^2+\Delta m_{12}^2}$

$\cos 2\theta_{12}\sqrt{m_3^2+\Delta m_{23}^2}$

$\cos^2\theta_{12} m_1 - \sin^2\theta_{12}\sqrt{m_1^2+\Delta m_{12}^2}$

$m_3 > m_2 \sim m_1$

$\frac{\sin^2\theta_{12}}{\sqrt{\cos 2\theta_{12}}}\sqrt{\Delta m_{12}^2} \approx 4.0meV$

$\sin\theta_{12}\sqrt{\Delta m_{12}^2} \approx 2.5meV$

- Future: Oscillation parameters + $\beta\beta$ decay parameters
  =determine ν flavor transition amplitudes

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

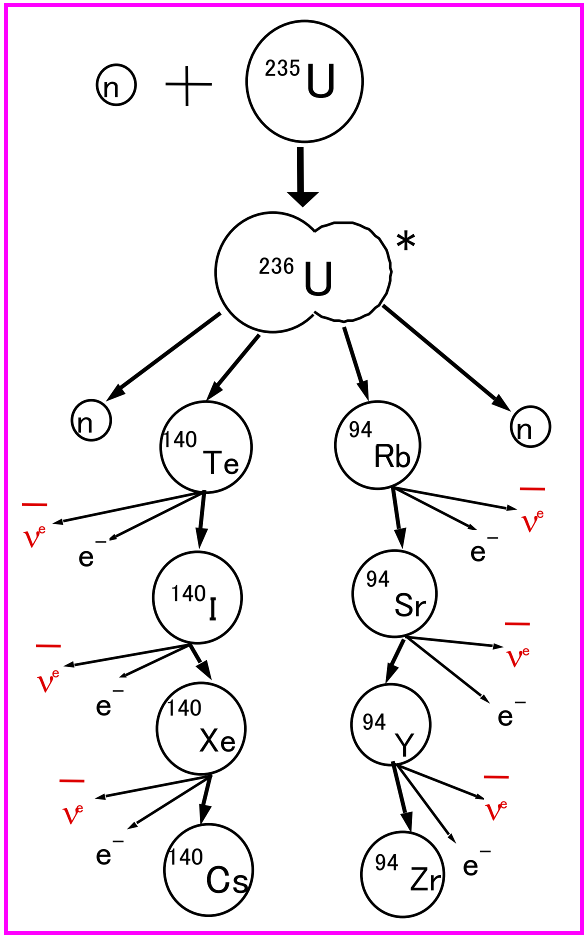
(1) $\nu_\mu \Rightarrow \nu_e$ (accelerator)
(2) $\nu_\mu \Rightarrow \nu_e$ (accelerator)
(3) Matter effect (accelerator)
(4) $\nu_\mu \Rightarrow \nu_\mu$ (accelerator)
(5) $\nu_e \Rightarrow \nu_e$ (reactor)
(6) Solar, Atmospheric

Construction ($$$)
+ν=$$

Construction ($~$$)
ν= free

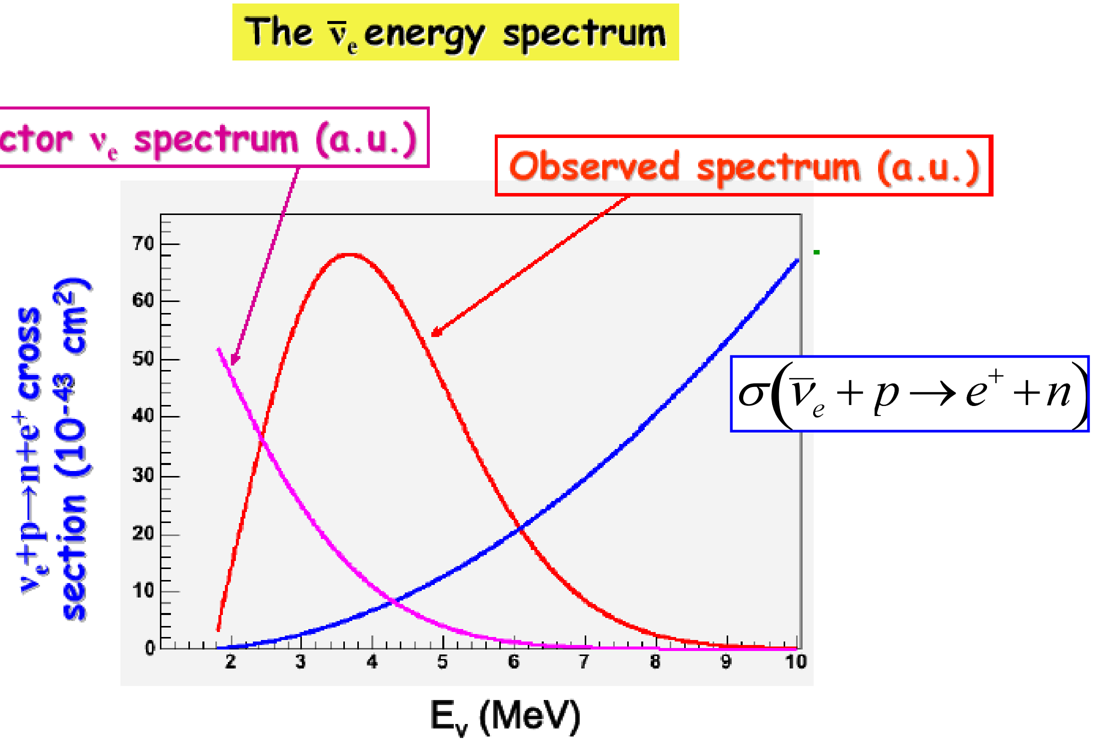
Reactor ν experiments are cost-effective way to get important information.

Reactor neutrino



ν are produced in
β-decays of fission products.

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



The $\bar{\nu}_e$ energy spectrum

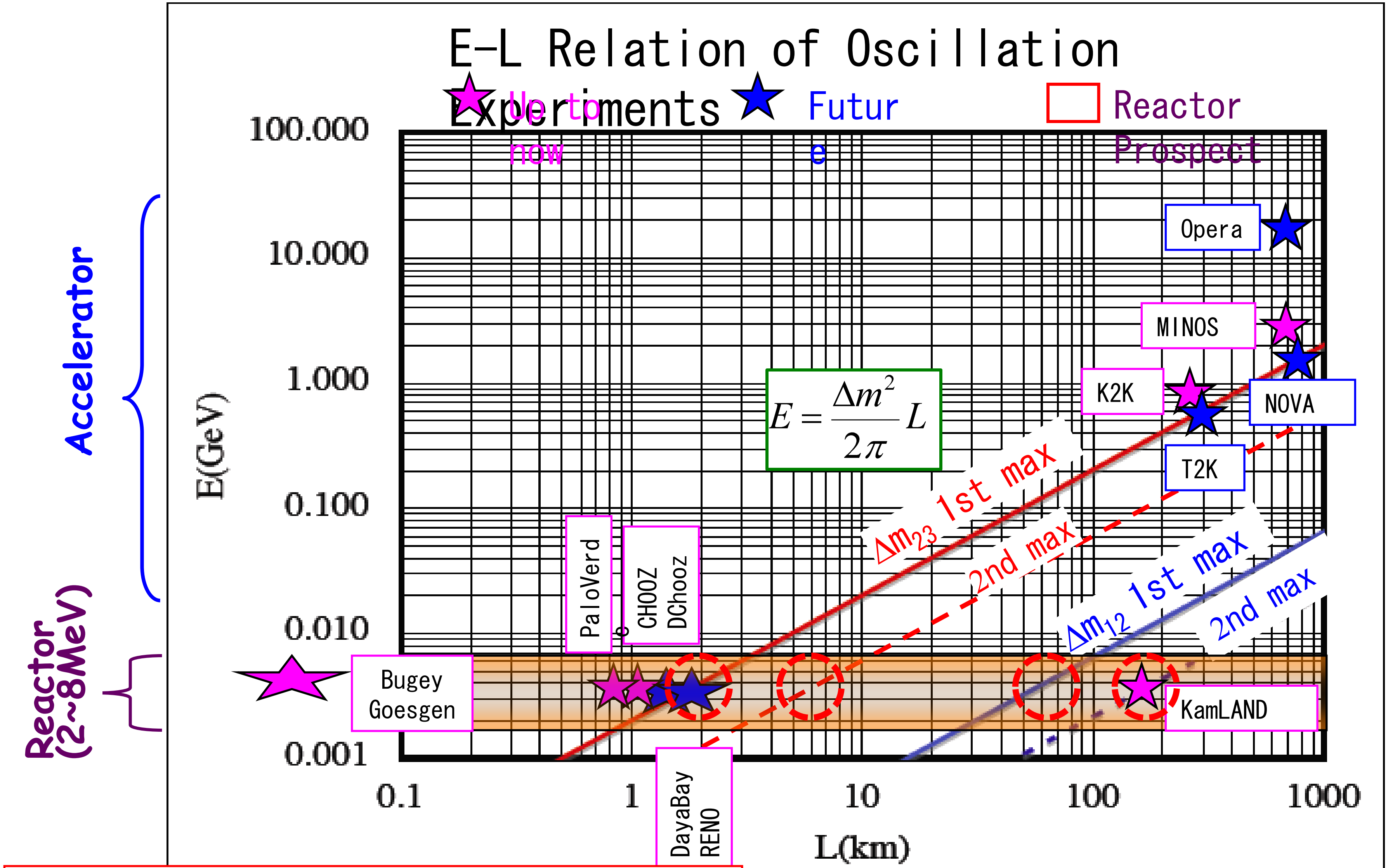
Reactor ν_e spectrum (a.u.)

Observed spectrum (a.u.)

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

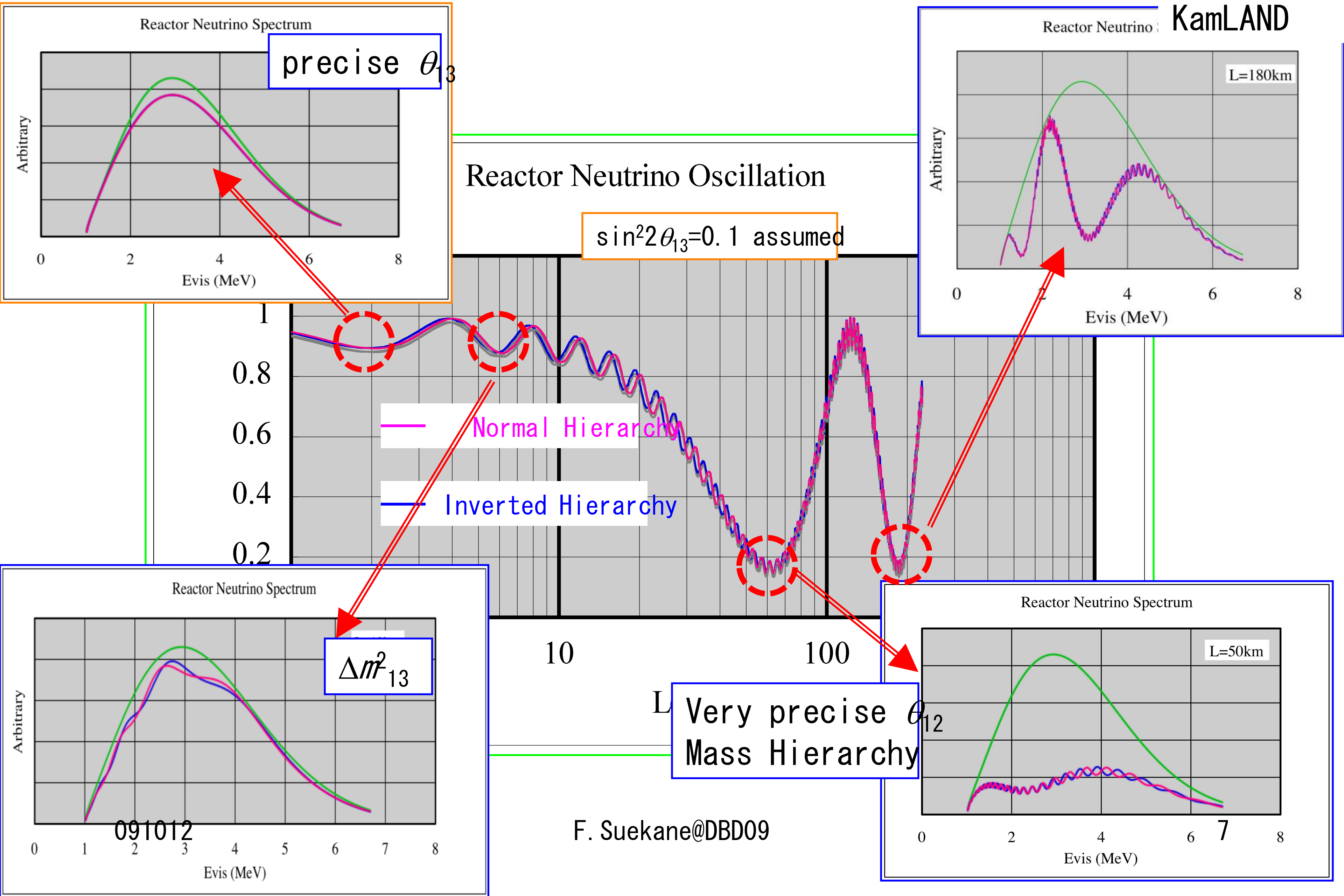
$$\boxed{E_\nu \sim 4\,^{+4}_{-2}\,MeV}$$

Accessible Oscillations by Reactor ν



oth Oscillations can be accessible

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



$\sin^2 2\theta_{13}$=0.1 assumed

precise θ_{13}

Δm^2_{13}

KamLAND

Very precise θ_{12}
Mass Hierarchy

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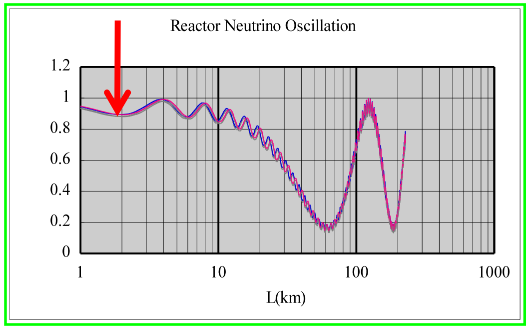
F. Suekane@DBD09

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



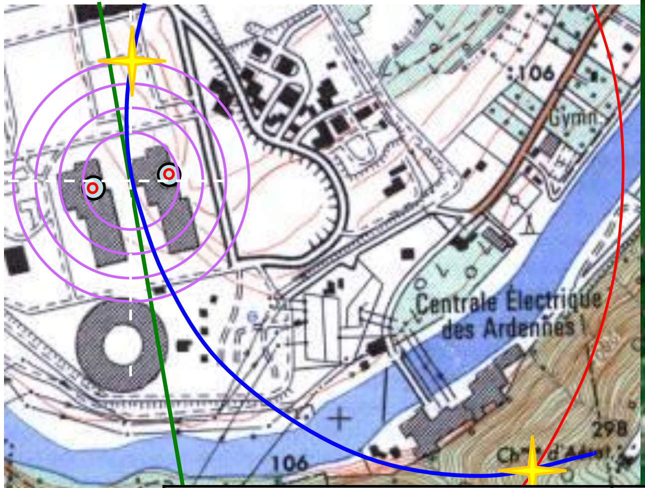
$$P_R(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \underline{\underline{\sin^2 2\theta_{13}}} \sin^2 \Delta_{31}$$

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	$\left[P_A(\nu_\mu \to \nu_e; L) + P_A(\nu_\mu \to \nu_e; L')\right]_{@\Delta_{23}} \sim sign(\Delta m^2_{23})(L' - L)\underline{\sin^2 2\theta_{13}}$ $P_R(\bar{\nu}_e \to \bar{\nu}_e)_{@\Delta_{12}} \sim 1 - 0.5\underline{\sin^2 2\theta_{13}}\left(\sin^2\Delta_{31} + \tan^2\theta_{12}\sin^2\Delta_{32}\right)$

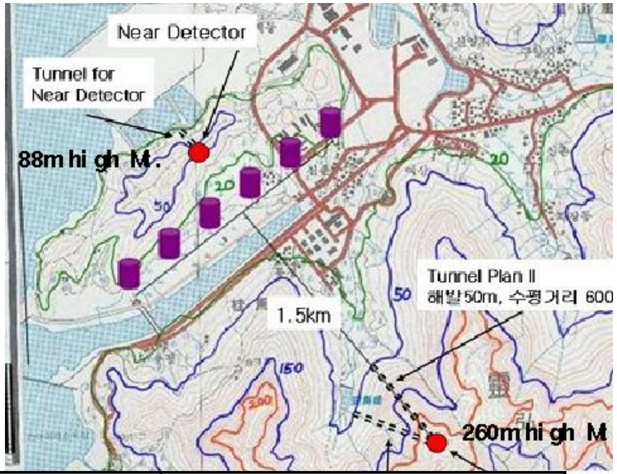
DoubleChooz, Dayabay, RENO

Double Chooz



Daya Bay

RENO

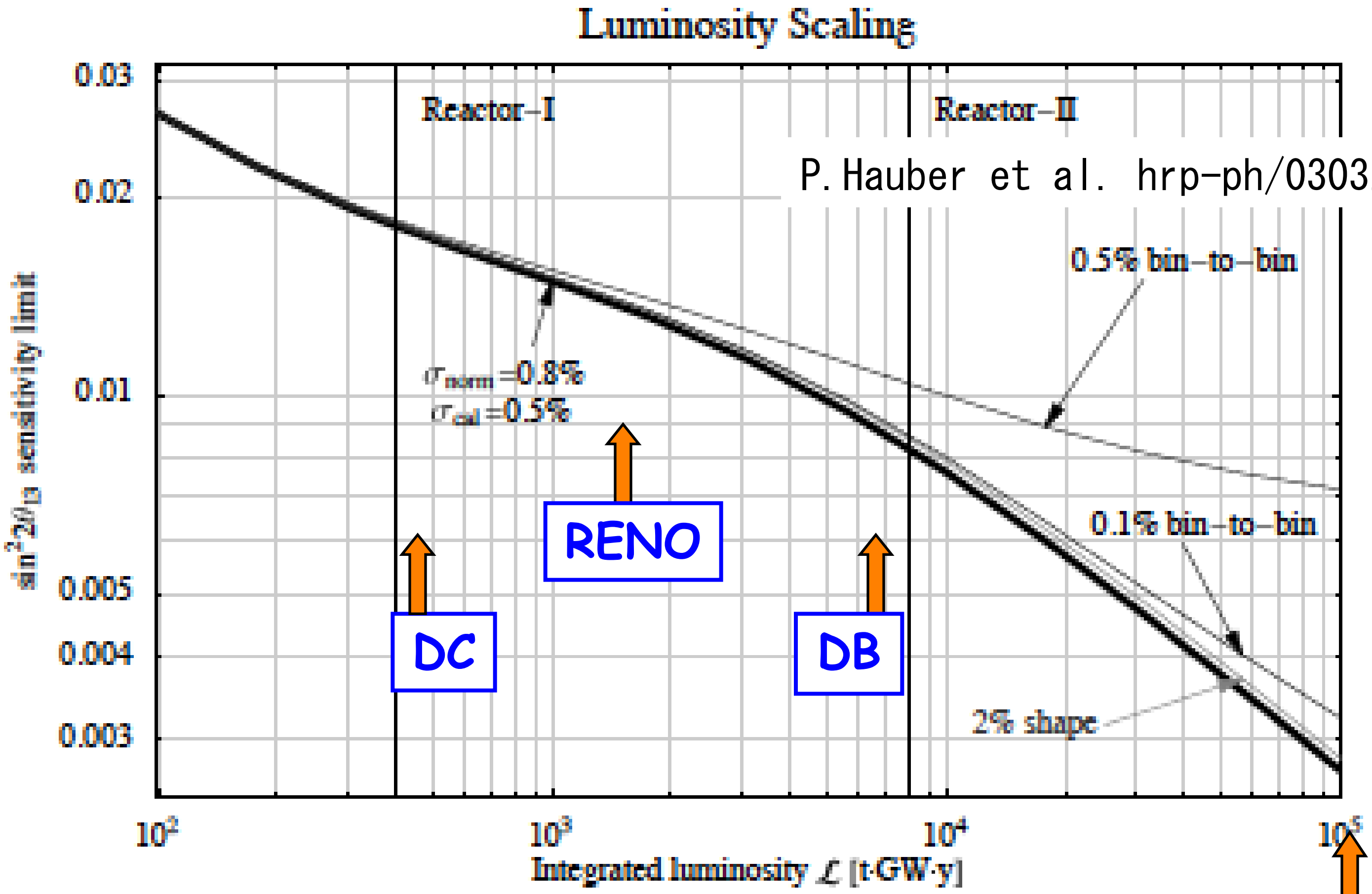


	Double Chooz	Dayabay	RENO
Power (GWth)	8.6GW	11.6GWth (17.4GW>2011)	16.4GW
Detector (ton)	8+8	20x4+2 (20x2)	16+2
Baseline (km)	1.05	1.8	1.4
$\sin^2 2\theta_{13}$ Sensitivity	~0.03	~0.01	~0.02
Operation start	2010F/2011N	2010N/2011F	2010

Results: within 2~5years

3rd Generation; More Precise θ_{13}

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



P.Hauber et al. hrp-ph/0303232

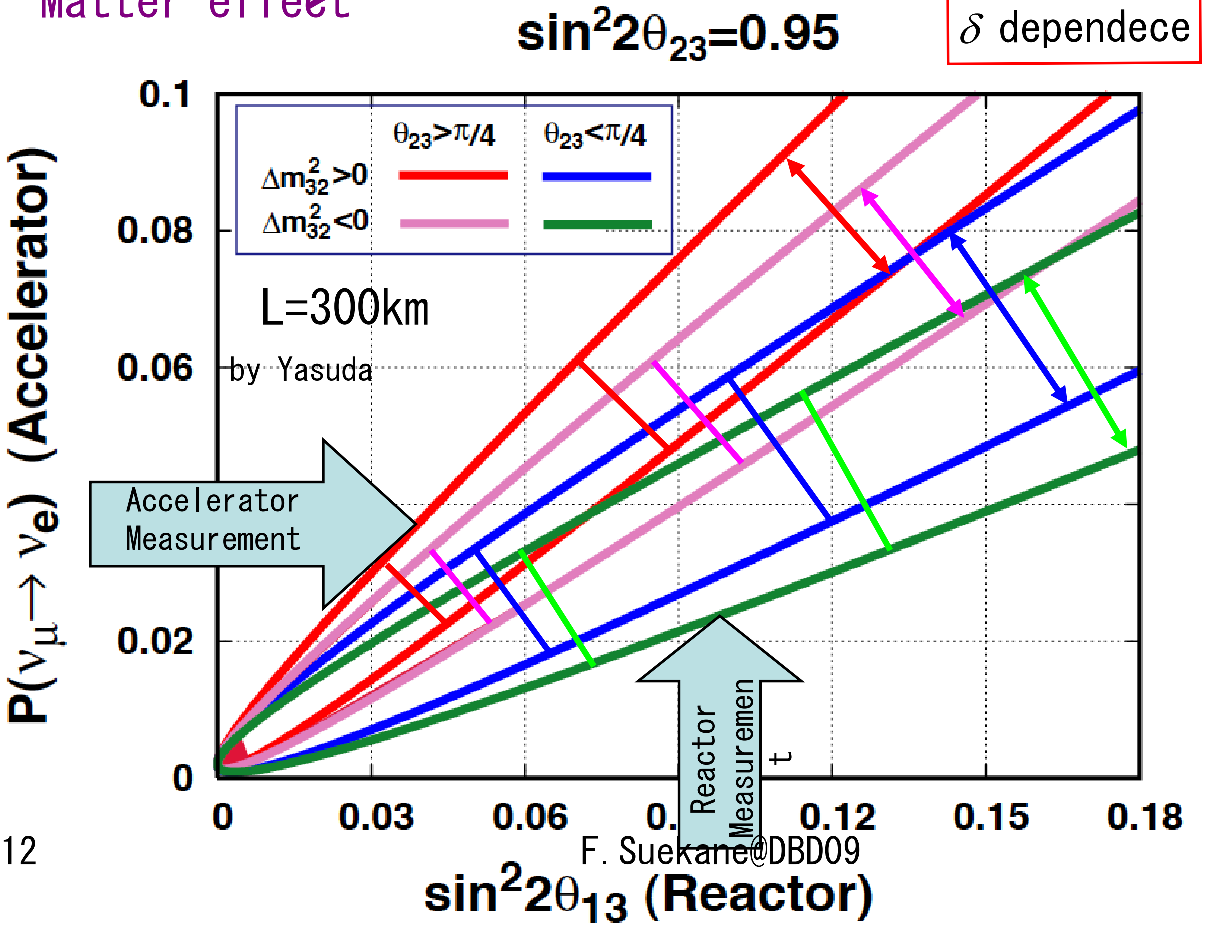
1000ton × 20GW × 5year

Complementarity of Reactor-Accelerator θ_{13} measurement

θ_{23} degeneracy

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

Matter effect



Settlement of θ_{23} Degeneracy

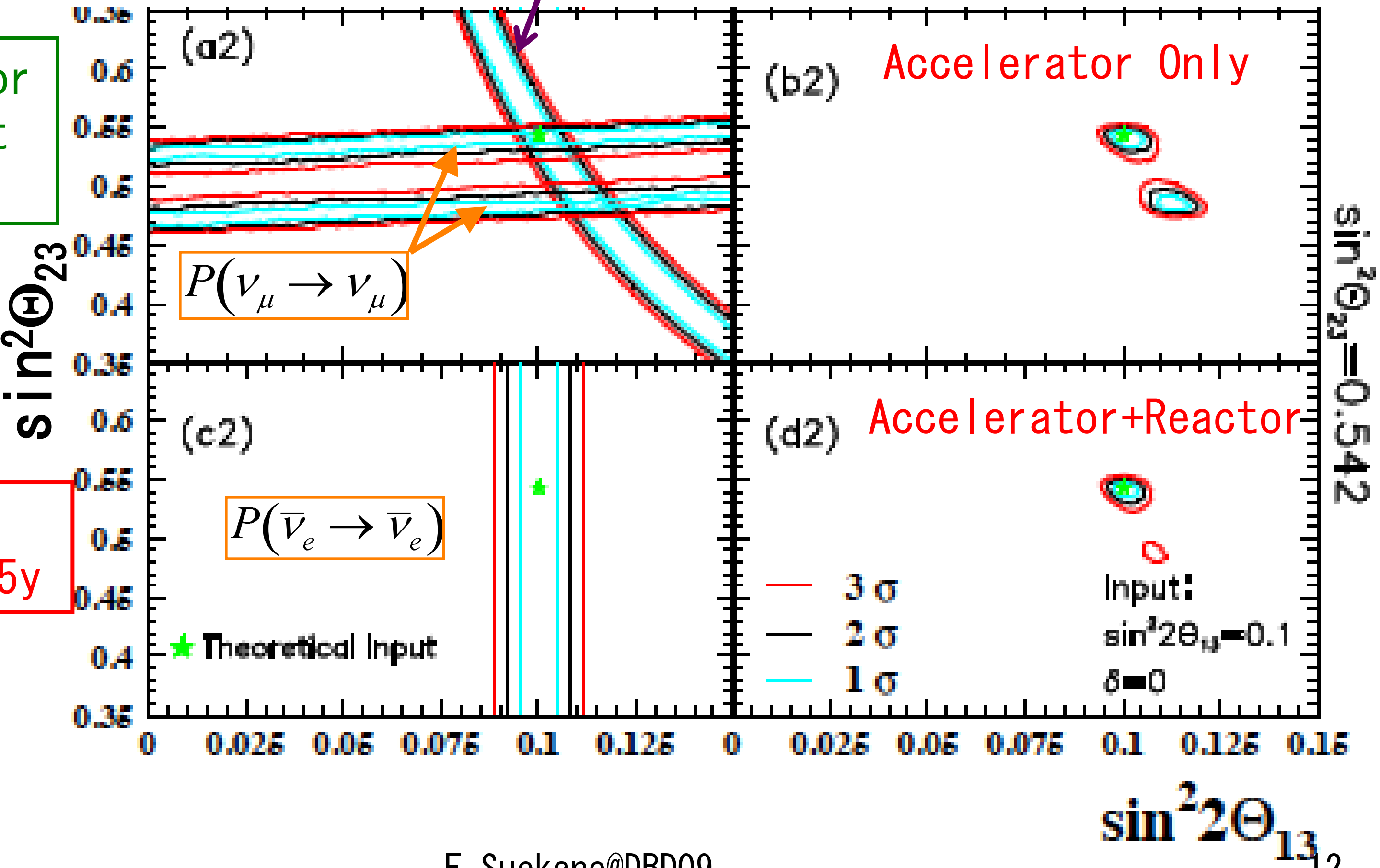
$$\sin^2\theta_{23} = \frac{1 \pm \sqrt{1-\sin^2 2\theta_{23}}}{2}$$

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

K.Hiraide, et al. PRD73, 093008(2006)

Accelerator
4MW*0.54Mt
2+6years

Reactor:
100t * 20GW *5y



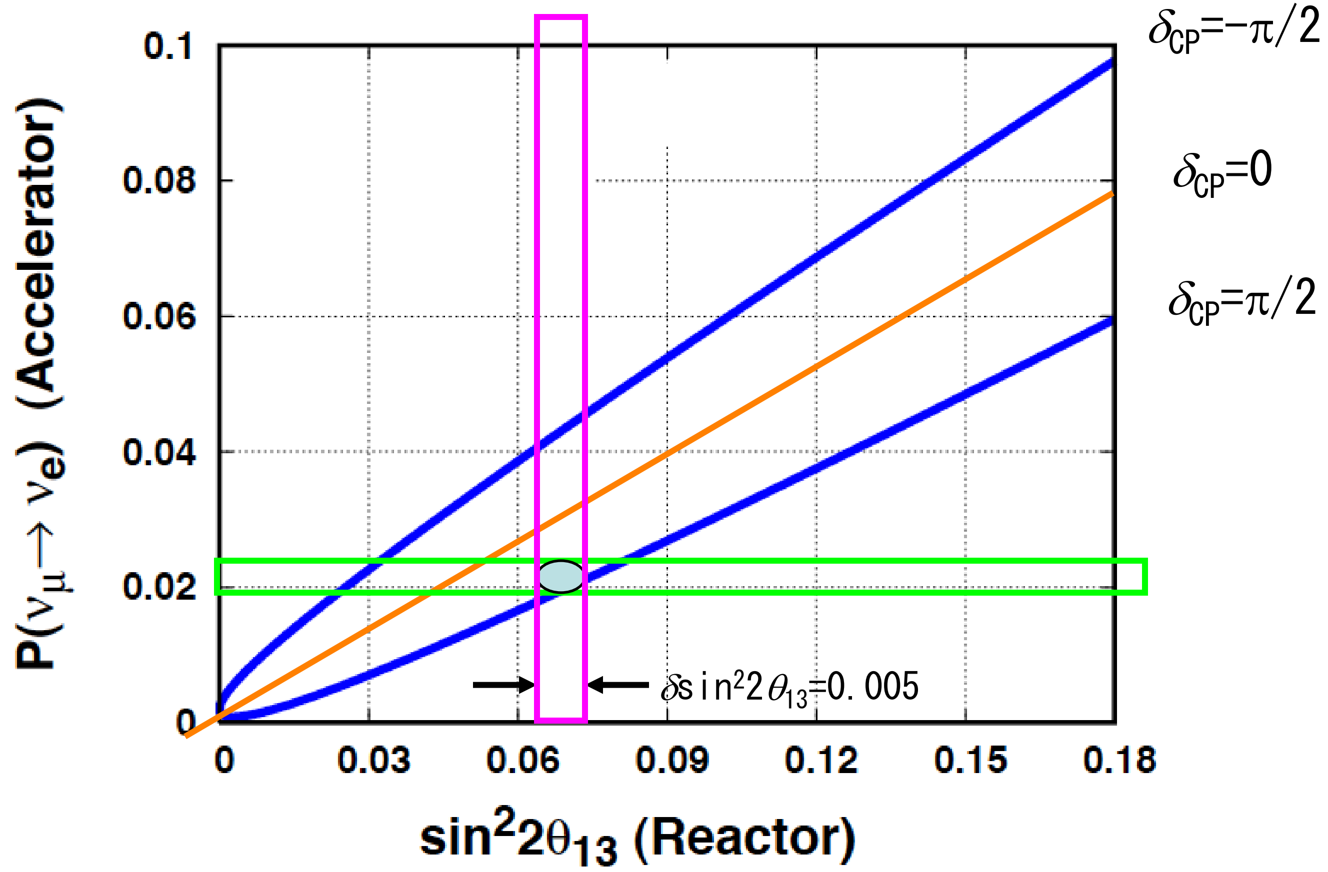
Accelerator Only

Accelerator+Reactor

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

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$

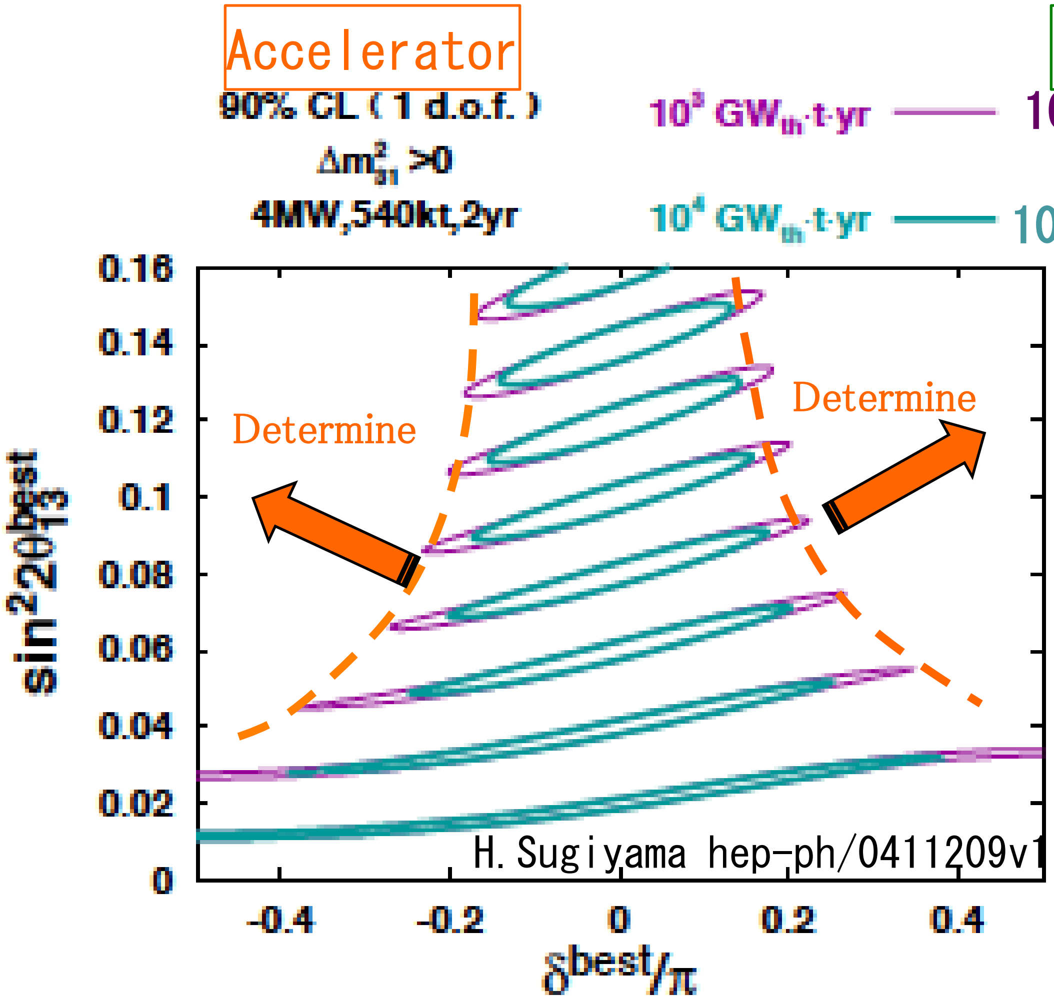
Quick Access to δ_{CP}



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

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

Parameter region to determine non-0 δ



H.Sugiyama hep-ph/0411209v1

Reactor

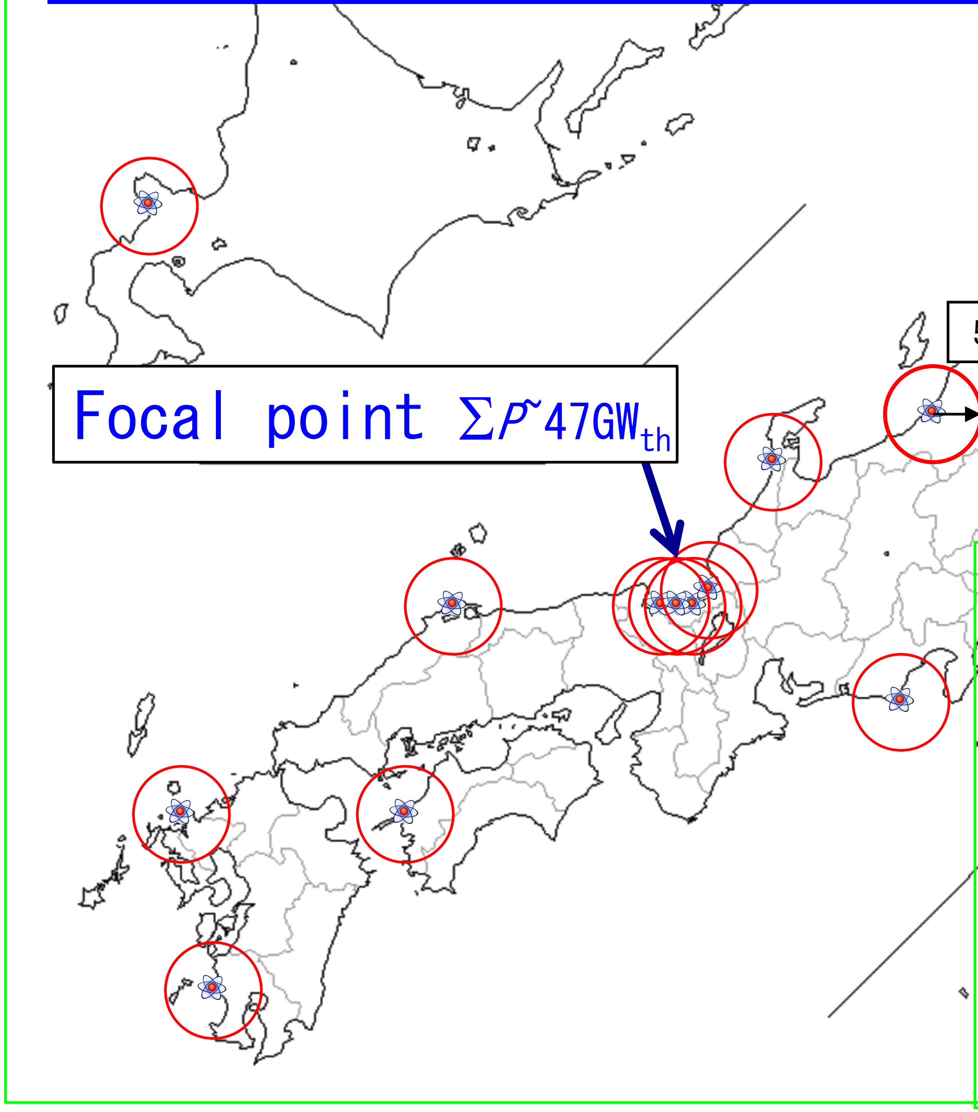
10ton x 20GW x 5year

100ton x 20GW x 5year

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

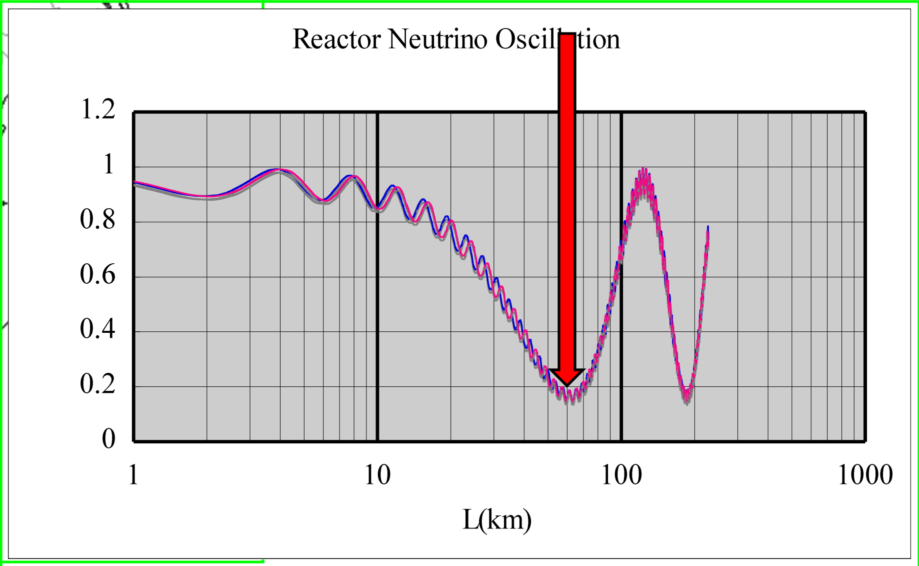
Physics @ 1st Δm^2_{12} Maximum(L~50km)

(Very Precise θ_{12} & Mass Hierarchy)



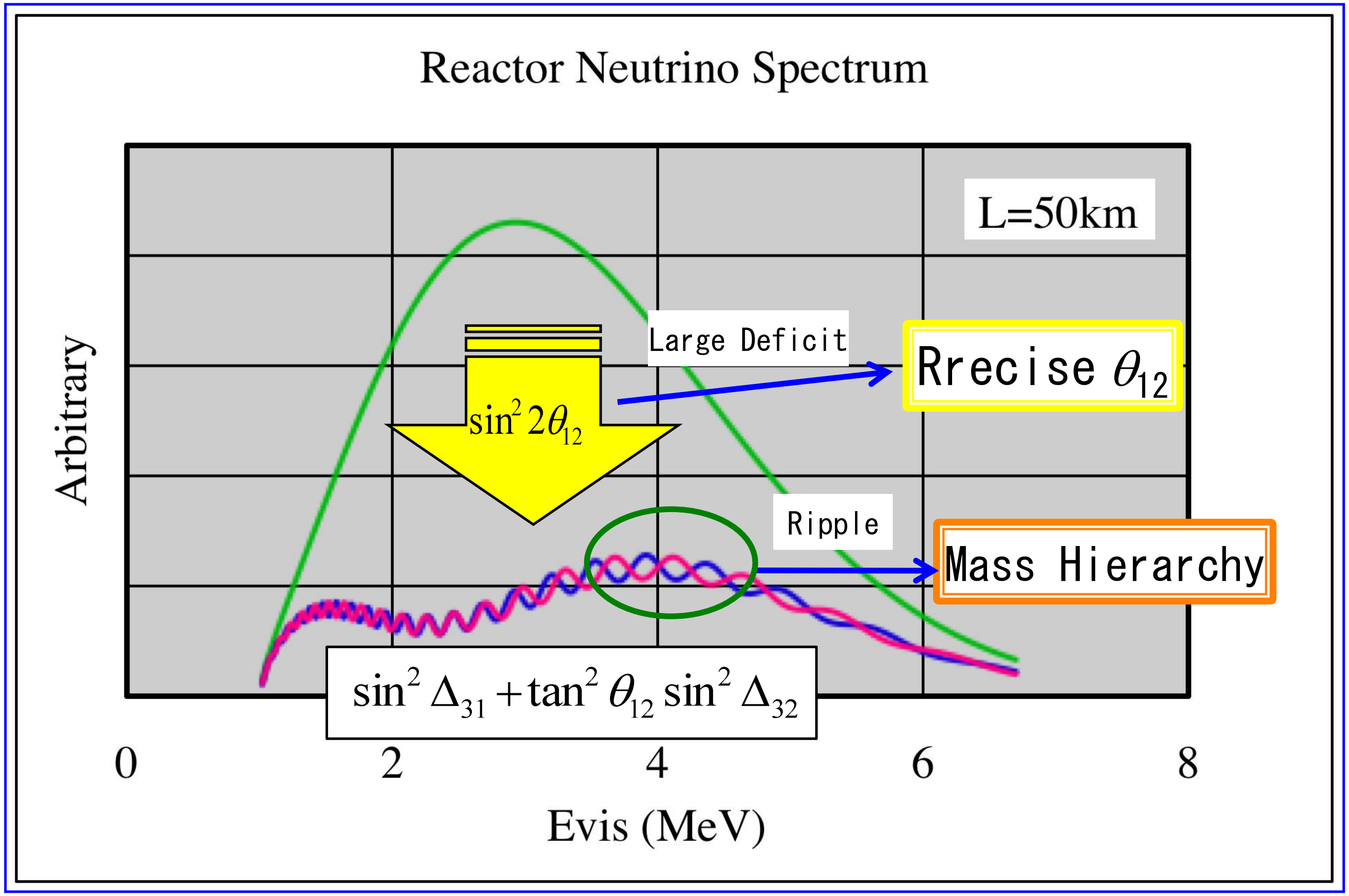
Focal point ΣP~47GW$_{th}$

Example of Japan case



Physics @ 1st Δm^2_{12} Maximum

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

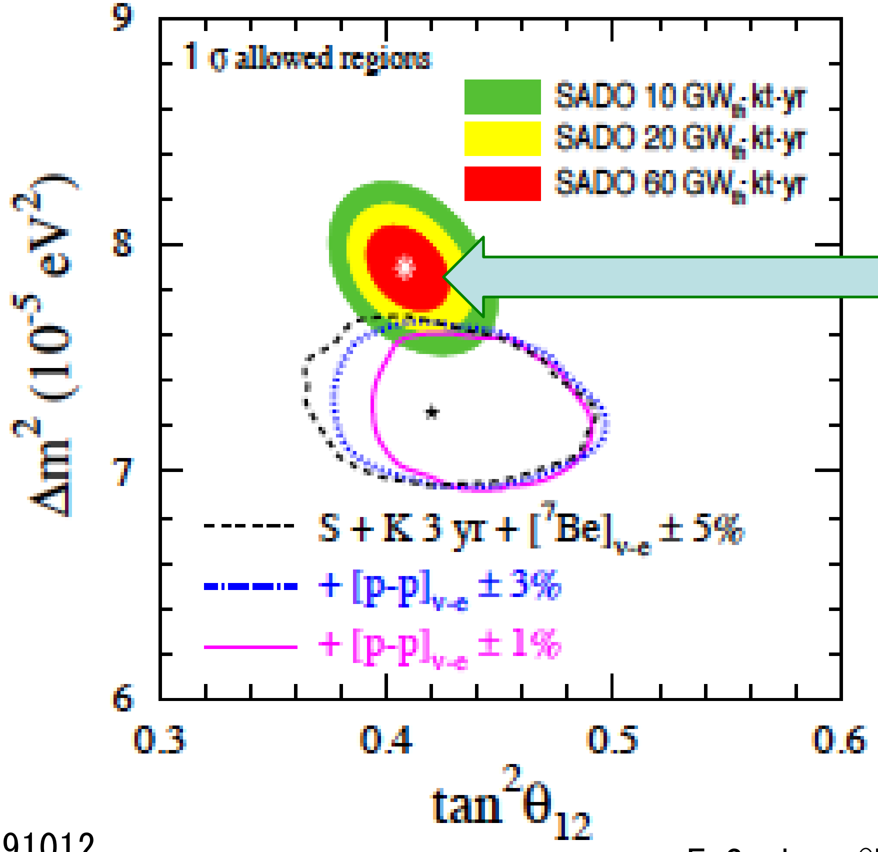


Precise θ_{12} measurement by large deficit

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \sim \cos^4\theta_{13}\left(1-\underbrace{\sin^2 2\theta_{12}\sin^2\Delta_{21}}_{\sim 0.7}\right)$$

(~0.4 in KamLAND)

H.Minakata, hep-ph/07-1070



1kton x25GW x2.5y

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

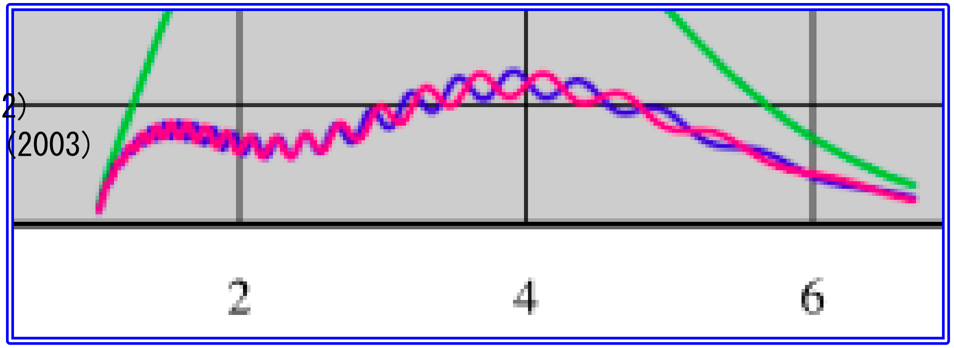
Current Global fit

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

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

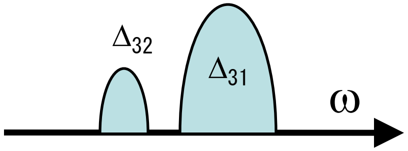


$$\text{Ripple} \propto \sin^2 2\theta_{13}\left(\sin^2\Delta_{31} + \underbrace{\tan^2\theta_{12}}\sin^2\Delta_{32}\right)$$

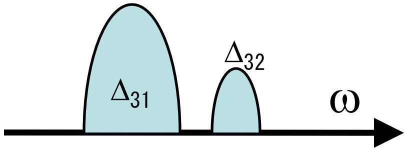
It is essential that θ_{12} is not maximum ($\tan^2\theta_{12}$~0.4)

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 $\left|\Delta m^2_{31}\right|$,



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



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

J.Learned et al. arXive-0612C

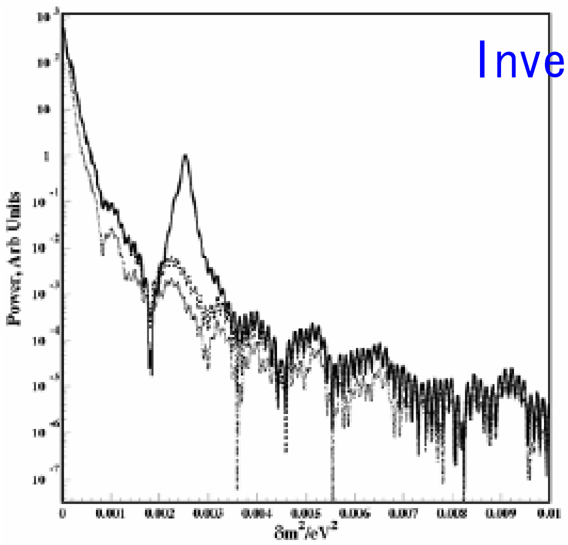


FIG. 2: Fourier power spectrum with modulation in units of eV^2 and power in arbitrary units on the logarithmic scale. The peak due to Δ_{31} with $\sin^2(2\theta_{13})$=0.1 is prominent.

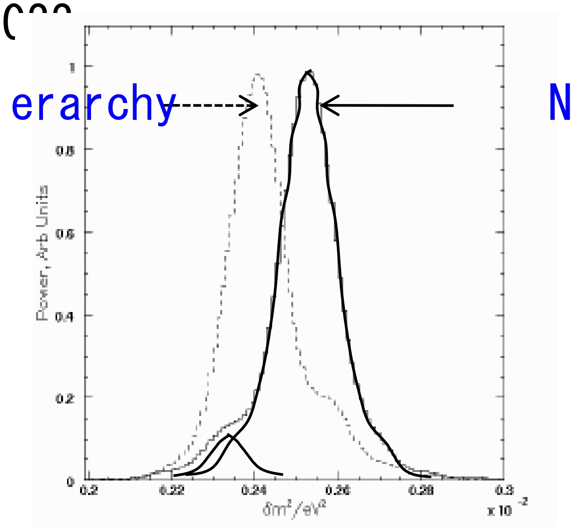


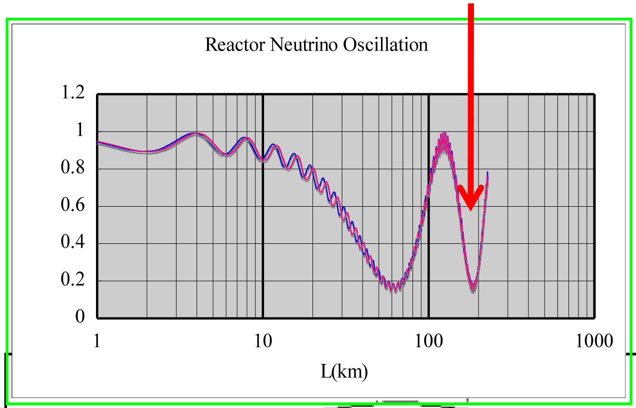
FIG. 3: Neutrino mass hierarchy (normal=solid; inverted=dashed) is determined by the position of the small shoulder on the main peak.

Simulation of power spectrum

If $\sin^2 2\theta_{13}$=0.05, 3kton x24GW x5yr ,
Mass Hierarchy can be determined with 1σ significance.

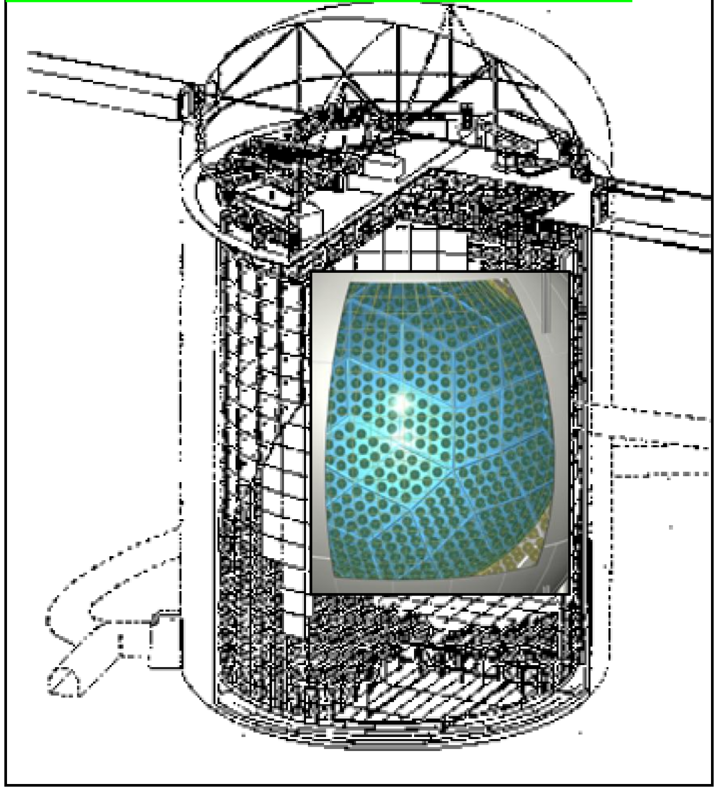
L.Zhan et al.=> Mass Hierarchy could be determined if $\sin^2 2\theta_{13}$>0.

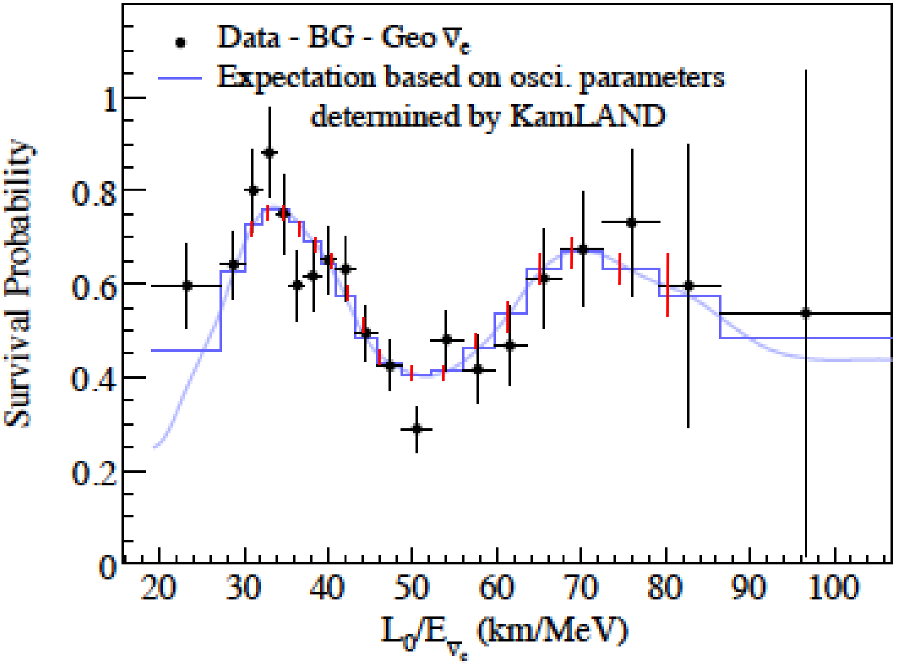
Physics @ Δm^2_{12} 2nd Maximum(L~150km)



If KamLAND is enlarged to SK size,

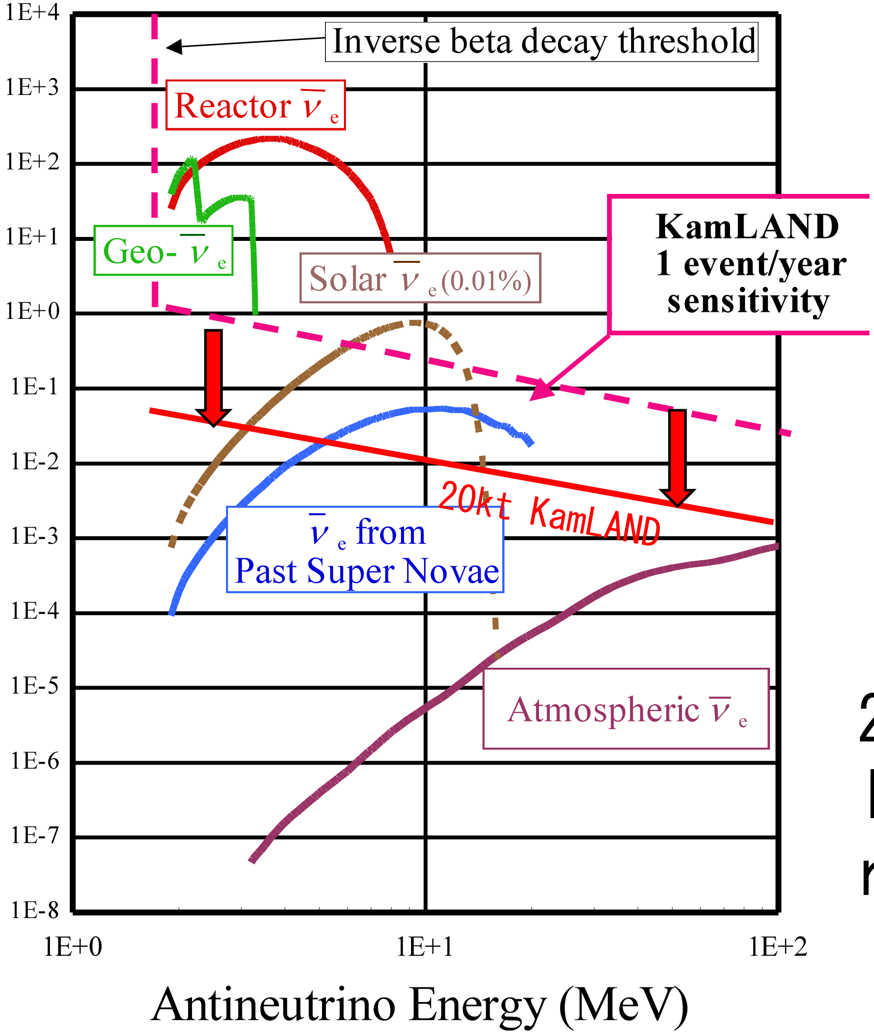
>20 times more statistics than KamLAND

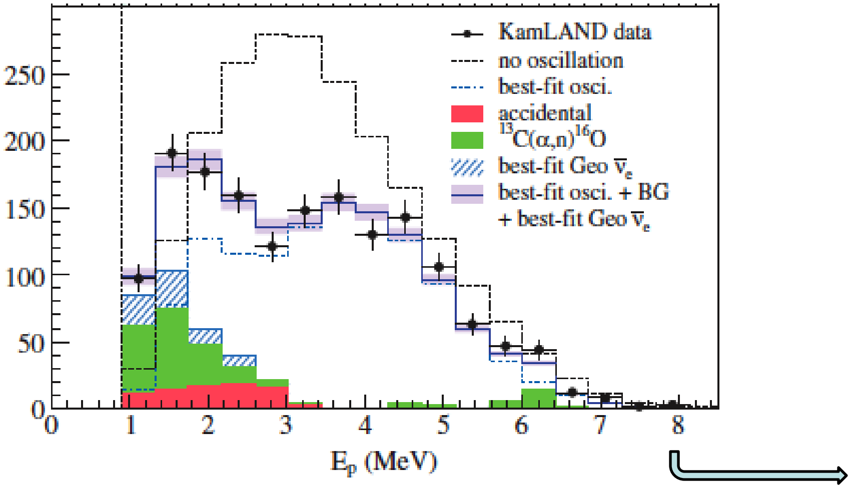




$$f_\nu(E_\nu)\times\sigma_{\bar{\nu}p\to e^+n}(E_\nu)$$

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 ma

reach Relic SN$\bar{\nu}_e$.

Summary

= Current =

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

$\delta\sin^2 2\theta_{13}=0.01\sim0.03$ within 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 solution with accelerator

➔ early sinδ 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 acc
reactor-accelerator complementarity after the 1st phase θ_{13} measuremen

Back up slides

Merit & Issues of this method.

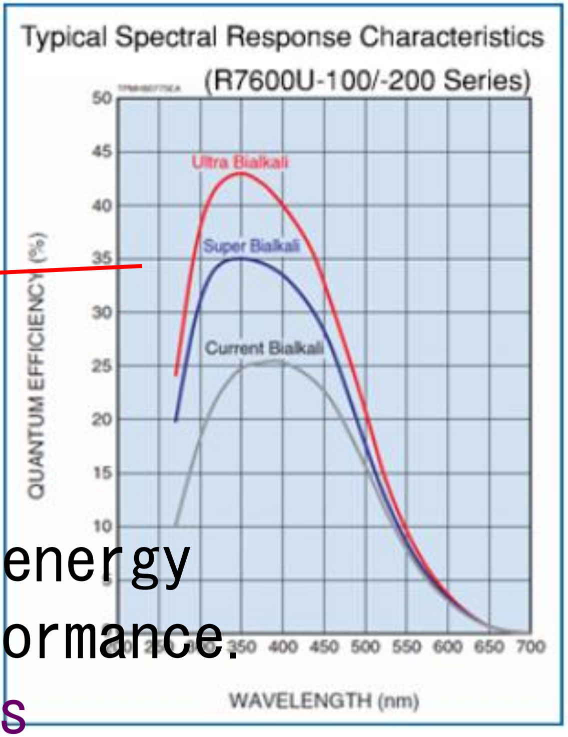
- Need not to know absolute $|m_{23}^2|$ so precisely.
  It is enough only to separate two peak positions.

- However, a good energy resolution; $\frac{\delta E}{E}\ \frac{3\%}{\sqrt{E(MeV)}}$

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

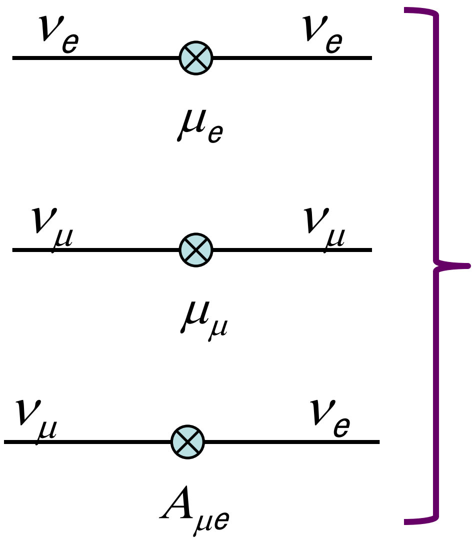
  improvement of light yield:
  x1.5 more PMT
  x1.8 with UltraBialkali photocathode

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

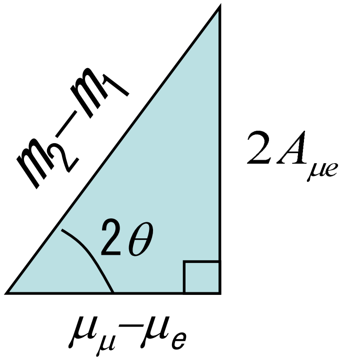


- Energy smearing due to recoil neutron energy
  & baseline difference may degrade performance.
  => Need more studies for specific sites

Relation of mass, mixing & transition amplitudes



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



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

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

$$\boxed{P_{Accel}\left(\nu_\mu \to \nu_e\right) \oplus P_{Accel}\left(\bar{\nu}_\mu \to \bar{\nu}_e\right) \oplus P_{\mathrm{Re}actor}\left(\bar{\nu}_e \to \bar{\nu}_e\right)}$$

Reactor θ_{13} helps to pin down parameters