Determination of mass hierarchy with reactor neutrino experiment

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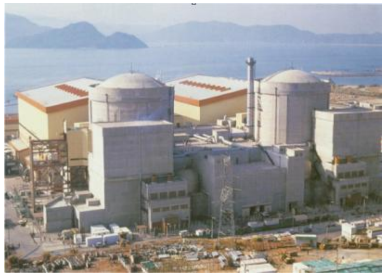
arXiv: 1210.8141

Introduction



$\sin^2 2\theta_{13} \sim 0.1$ ***is observed.***

Reactor Experiments

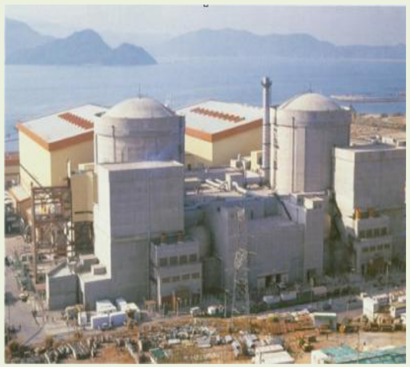
can determine the ***Neutrino Mass Hierarchy*** .

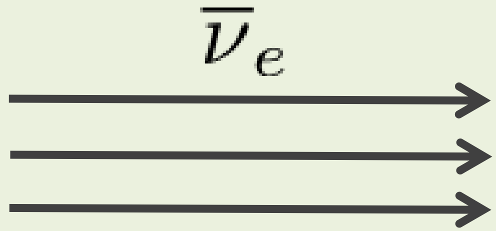
The sensitivity is studied

of future Medium Baseline Reactor Experiments for determining the Neutrino Mass Hierarchy

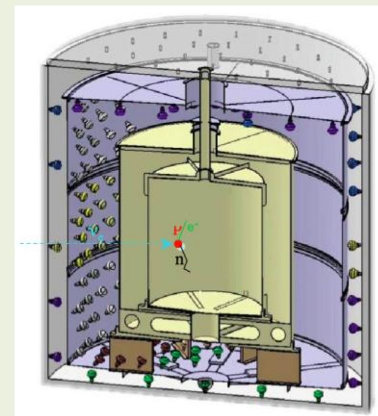
Reactor neutrino experiment

Reactor



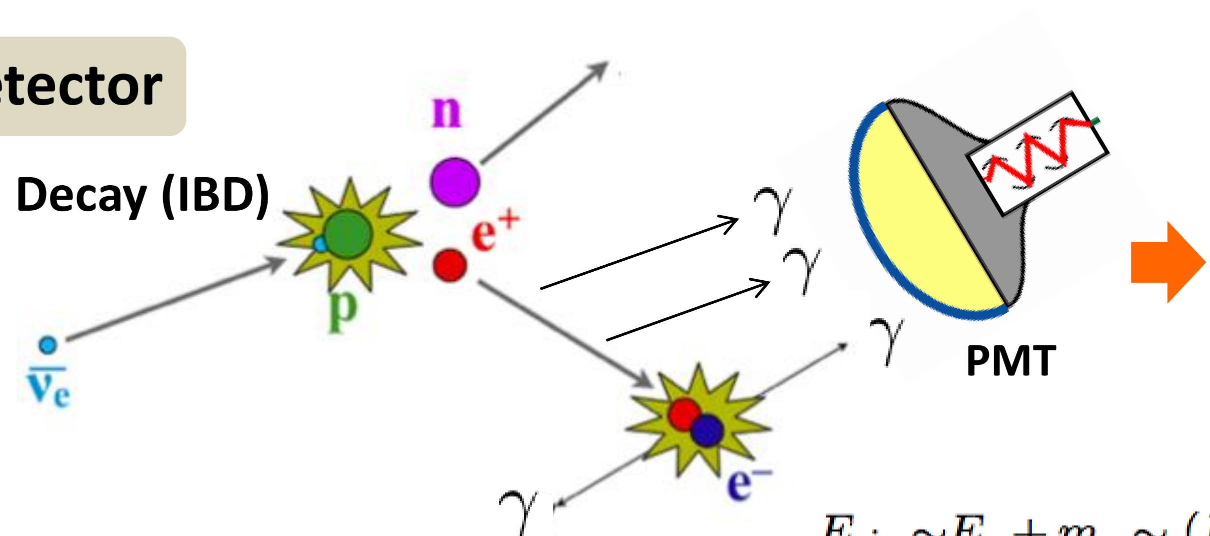


Detector



Inside Detector

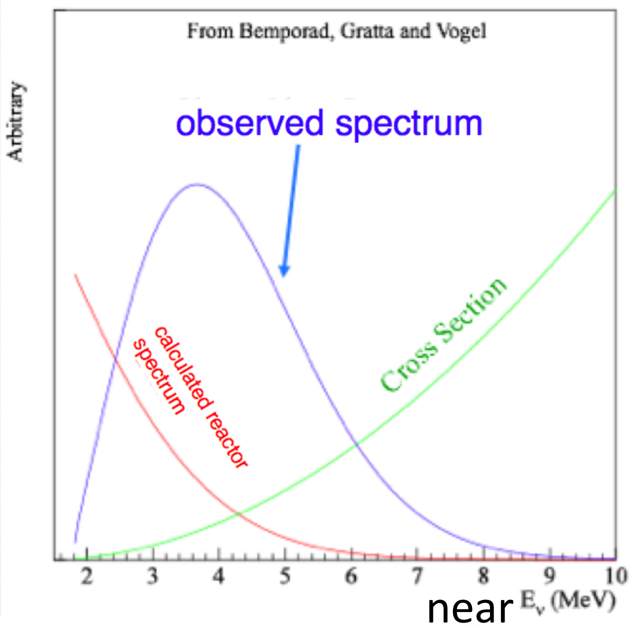
Inverse Beta Decay (IBD)

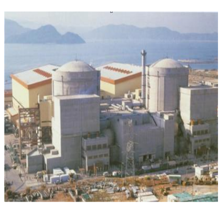


E_{vis}

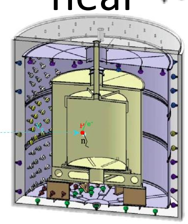
$$E_{\text{vis}} \sim E_e + m_e \sim (E_\nu - 0.8)\,\text{MeV}$$

$\overline{\nu}_e$ Energy Distribution

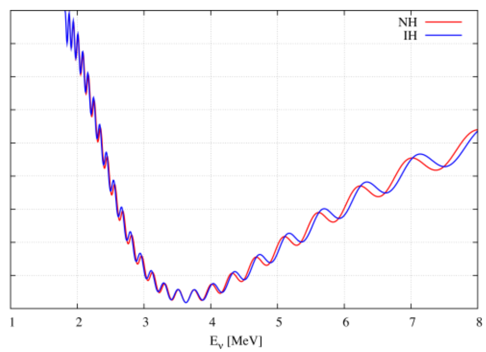




near

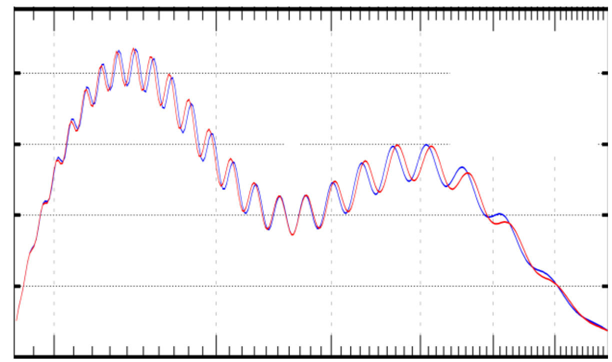


P_{ee}

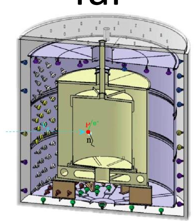


L

$\overline{\nu}_e$ @ Detector



far



$$\frac{dN^{far}}{dE_{\text{vis}}} = \frac{N_p T}{4\pi L^2} \int_{E_{\text{thr}}}^{\infty} dE_\nu \; \phi(E_\nu) \, P_{ee} \, \sigma_{IBD} \, G(E_\nu, E_{\text{vis}})$$

How to distinguish Mass Hierarchy ?

$$P_{ee} = \left| \sum_{i=1}^{3} U_{ei} \exp\left(-i \frac{m_i^2}{2E_i}\right) U_{ei}^* \right|^2$$

$$= 1 - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta_{21})$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}, \quad (\Delta m_{ij}^2 \equiv m_i^2 - m_j^2).$$

$$- \sin^2 2\theta_{13} \sin^2(|\Delta_{31}|)$$

$$- \sin^2\theta_{12} \sin^2 2\theta_{13} \sin^2(\Delta_{21}) \cos(2|\Delta_{31}|)$$

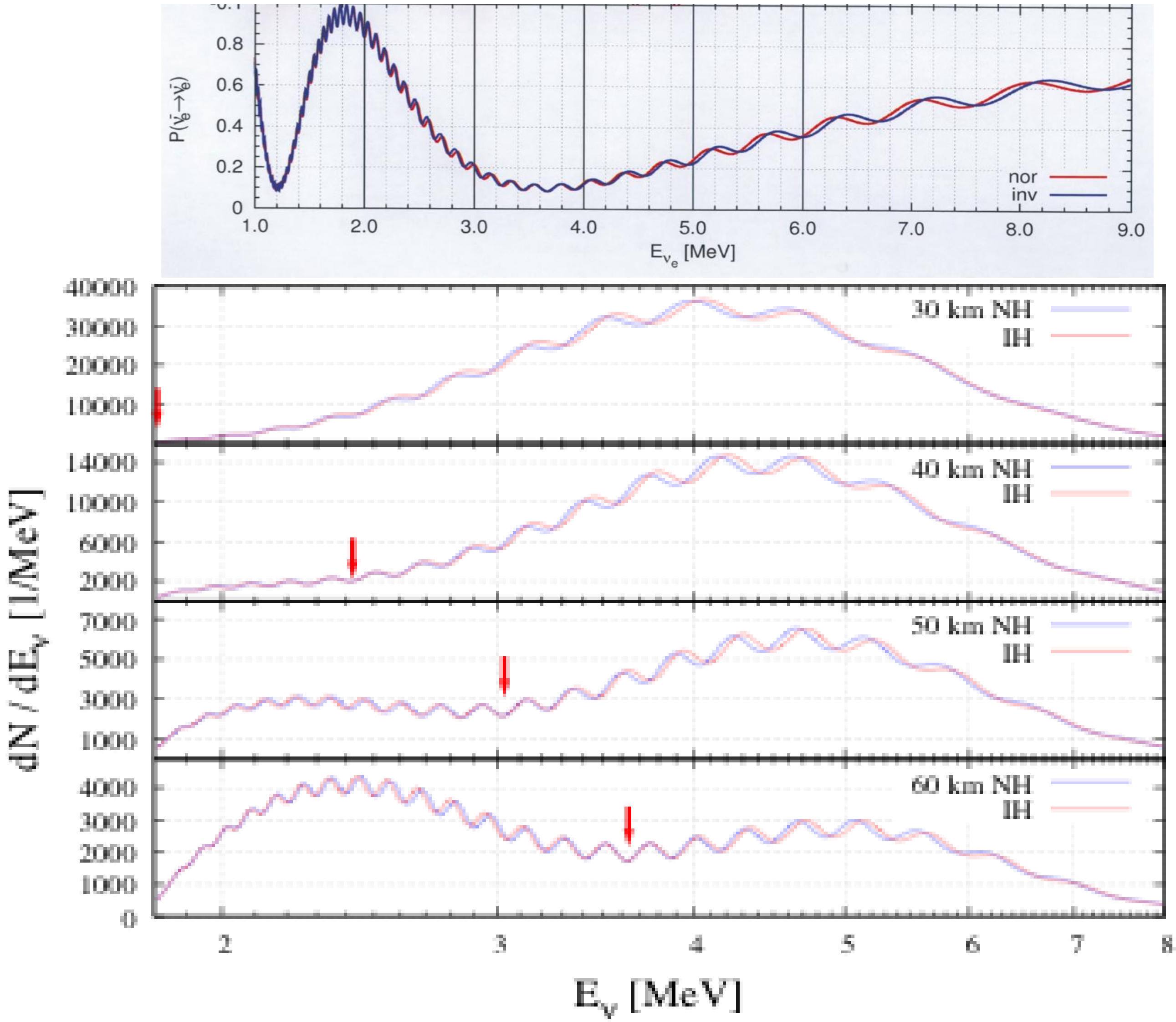
$$\pm \frac{\sin^2\theta_{12}}{2} \sin^2 2\theta_{13} \sin(2\Delta_{21}) \sin(2|\Delta_{31}|)$$

Mass Hierarchy difference

Max: $2\Delta_{21} = \frac{\pi}{2}(2n-1) \sim 36\,\mathrm{km}, \cdots \quad (E_\nu \sim 4\mathrm{MeV})$

vanish: $2\Delta_{21} = n\pi \sim 72\,\mathrm{km}, \cdots \, (E_\nu \sim 4\mathrm{MeV})$

MH difference in $\overline{\nu}_e$ spectrum



Advantages of Reactor Experiment

• Can determine MH independently from CP phase and matter effects.

•Need only smaller detector than other experiments (e.g., LBL, atmospheric).

•Free neutrino source with adjustable baseline length

Analysis methods for MH determination

- **Fourier analysis**

hep-ph/0612022 J.G. Learned et al.
arXiv: 0807.3203 L. Zhan et al.
arXiv: 0901.2976 L. Zhan et al.
arXiv: 1208.1551 X. Qian et al.
arXiv: 1208.1991 E. Ciuffoli et al.

- χ^2 **analysis**

hep-ph/030601 S. Choubey et.al.
arXiv: 0810.2580 M. Batygov et.al.
arXiv: 1011.1646 P. Ghoshal et.al.

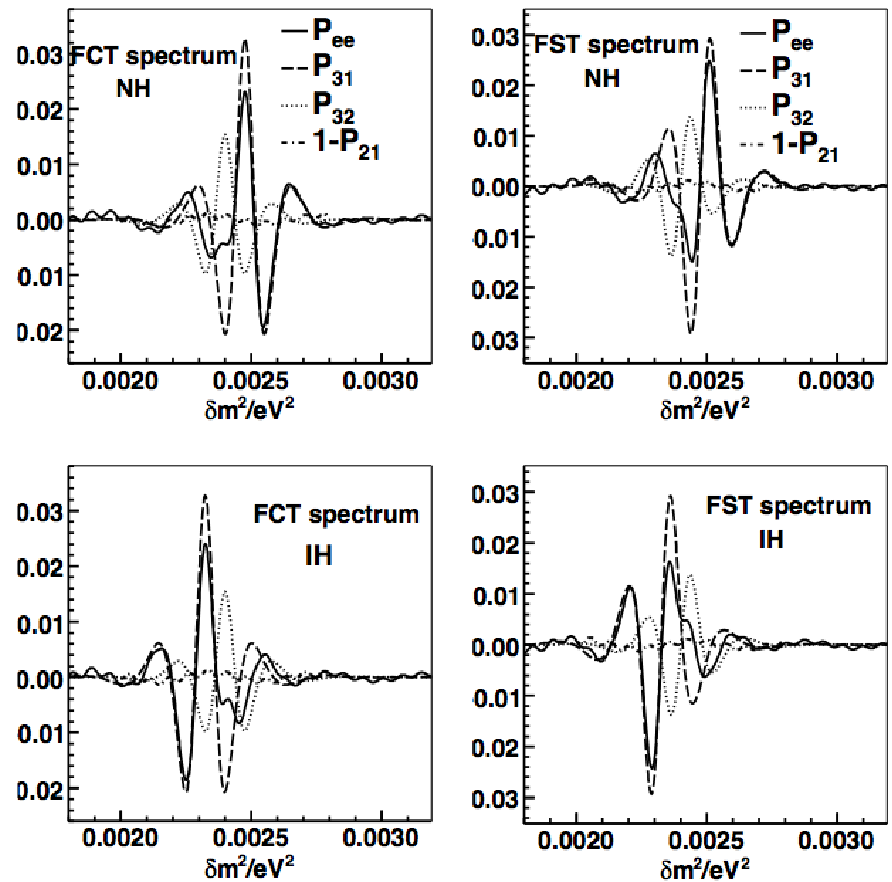
Fourier Analysis

$$
\begin{aligned}
P_{ee} &= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) \\
&\quad - \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{31}) \\
&\quad - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{32})
\end{aligned}
$$

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E_\nu}$$

$$\mathrm{FCT}(\delta m^2) = \int d\left(\frac{L}{E}\right)\frac{dN}{dE_{\mathrm{vis}}}\left(\frac{L}{E}\right)\cos\left(\delta m^2 \frac{L}{E}\right)$$

$$\mathrm{FST}(\delta m^2) = \int d\left(\frac{L}{E}\right)\frac{dN}{dE_{\mathrm{vis}}}\left(\frac{L}{E}\right)\sin\left(\delta m^2 \frac{L}{E}\right)$$



- has sensitivity for small $\sin^2 2\theta_{13} \leq 0.005$.
- Don't need accurate knowledge of $|\Delta m^2_{31(32)}|$ or $\overline{\nu}_e$ flux.

χ^2 analysis

$$\chi^2 = \sum_{i=1}^{\mathrm{nbin}} \left(\frac{N_i^{\mathrm{fit}} - N_i^{\mathrm{data}}}{\sqrt{N_i^{\mathrm{data}}}} \right)^2 + \underbrace{\sum_{i=1}^{\mathrm{nparam}} \left(\frac{X_i - X_i^{\mathrm{input}}}{\delta X_i} \right)^2}_{\text{Penalty term}},$$

Data is fitted with the theoretical prediction N_i^{fit}, assuming NH or IH.

$$N_i^{\mathrm{fit}} = \int dE_{\mathrm{vis}} \frac{N_p T}{4\pi L^2} \int_{E_{\mathrm{thr}}}^{\infty} dE_\nu \; \phi(E_\nu)\, P_{ee}\, \sigma_{IBD}\, G(E_\nu, E_{\mathrm{vis}})$$

$$\chi^2_{\mathrm{min}}(NH) \quad \chi^2_{\mathrm{min}}(IH)$$

Fitting parameters are $\theta_{12},\, \theta_{13},\, \Delta m^2_{21},\, |\Delta m^2_{31}|,\, f_{\mathrm{sys}}$

Y	$\sin^2 2\theta_{12}$	$\sin^2 2\theta_{13}$	Δm^2_{21} eV^2	$\lvert\Delta m^2_{31}\rvert$ eV^2	f_{sys}
Y^{input}	0.857	0.089	7.50×10^{-5}	2.32×10^{-3}	1
δY	0.024	0.005	0.20×10^{-5}	0.1×10^{-3}	0.03

χ^2 analysis – MH determination

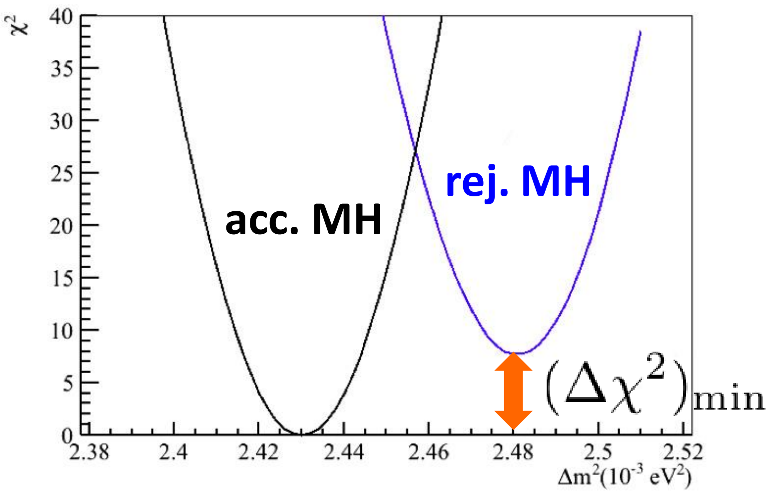
MH is determined as the hierarchy which gives smaller χ^2_{min}.

Ex) $\chi^2_{\mathrm{min}}(IH) > \chi^2_{\mathrm{min}}(NH)$ ➡ MH is NH.

Sensitivity is estimated by

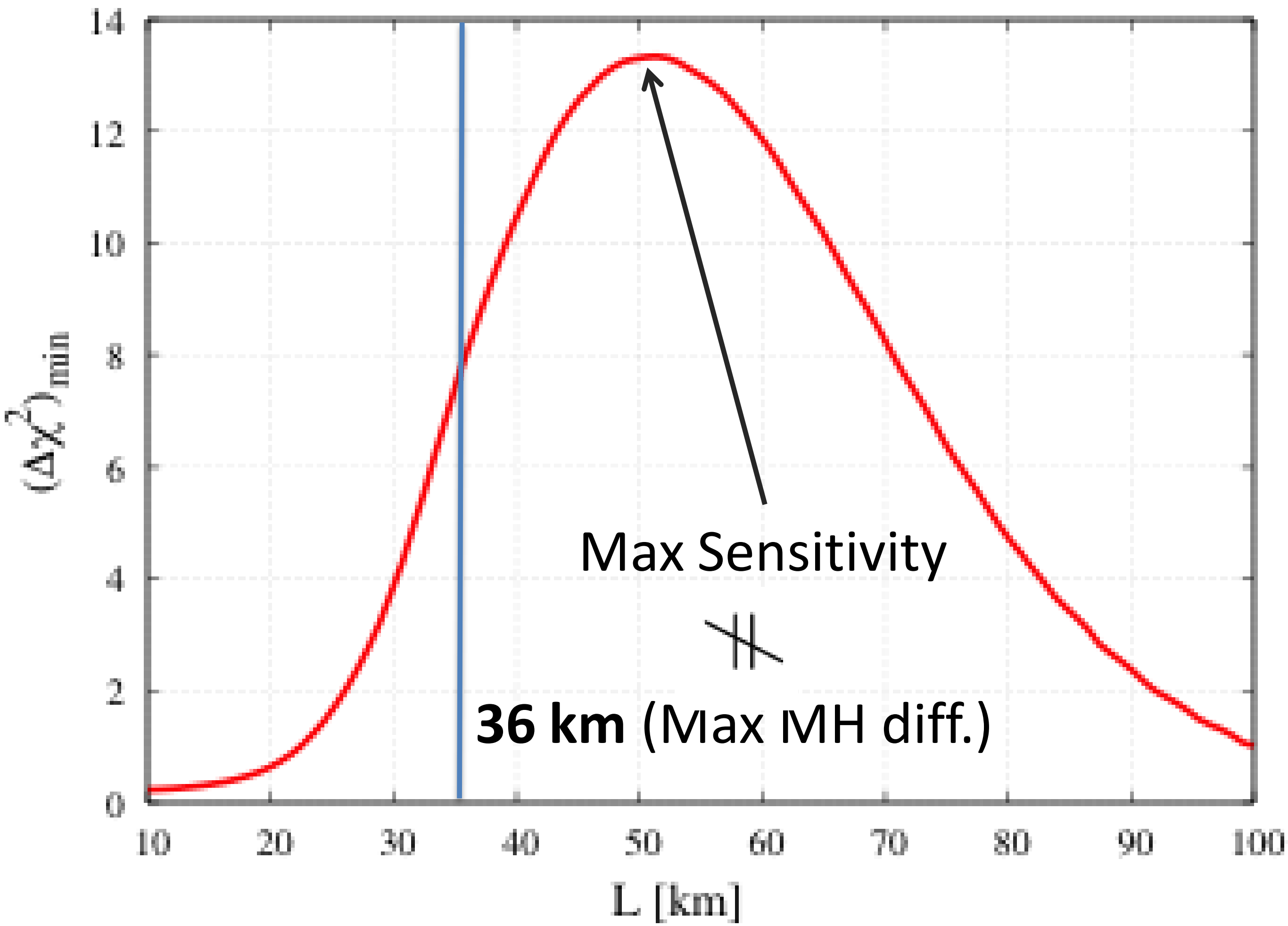
$$(\Delta\chi^2)_{\mathrm{min}} = \chi^2_{\mathrm{min}}(\mathrm{rejected\,MH}) - \chi^2_{\mathrm{min}}(\mathrm{accepted\,MH})$$

We claim that MH is determined with $\sqrt{(\Delta\chi^2)_{\mathrm{min}}}\ \sigma$ significane.

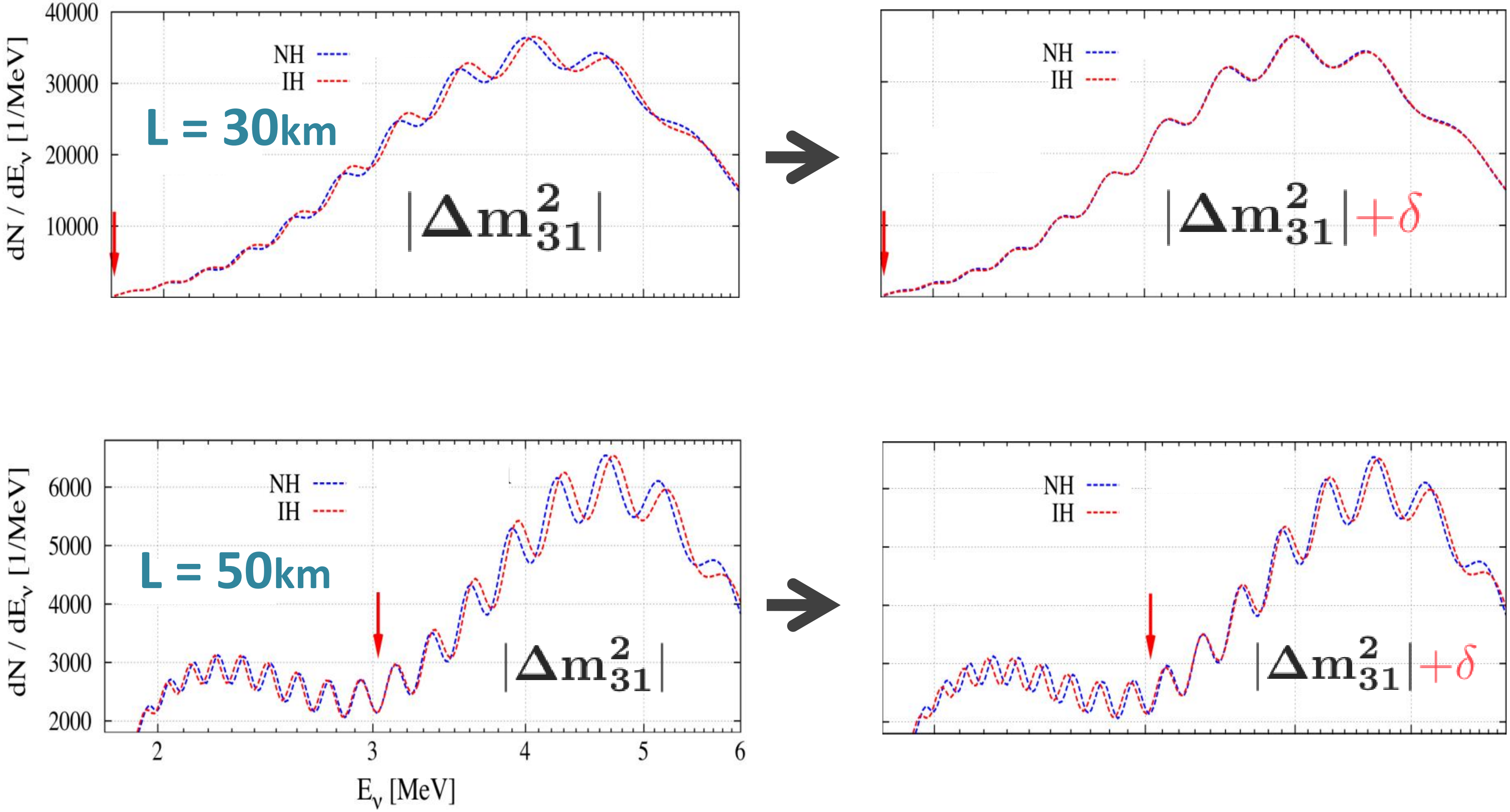


Sensitivity for MH determination

Typical sensitivity curve as a function of Baseline length L



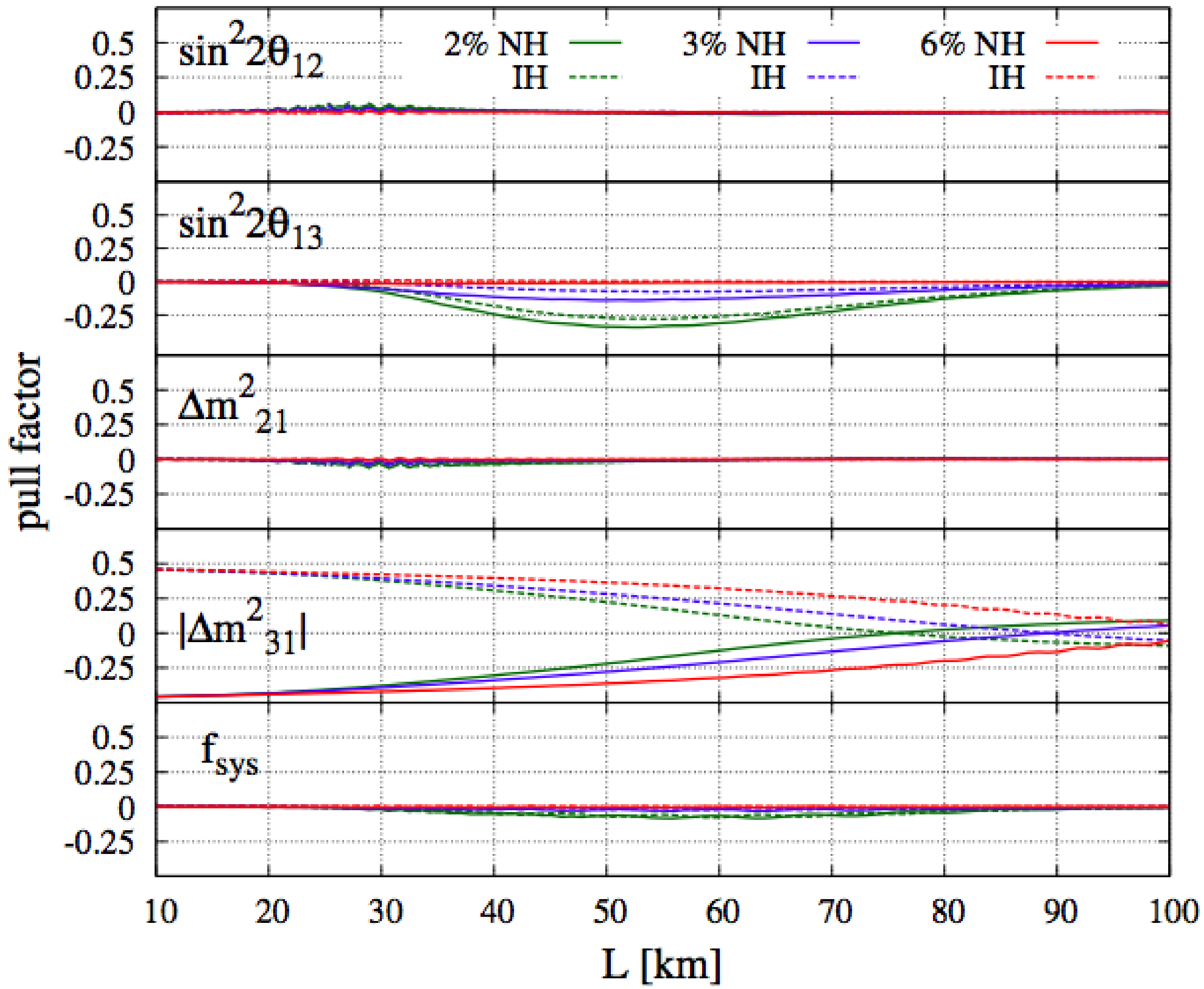
Effect of $\delta|\Delta m^2_{31}|$



Baseline Length L should be long enough.

Pull Factor

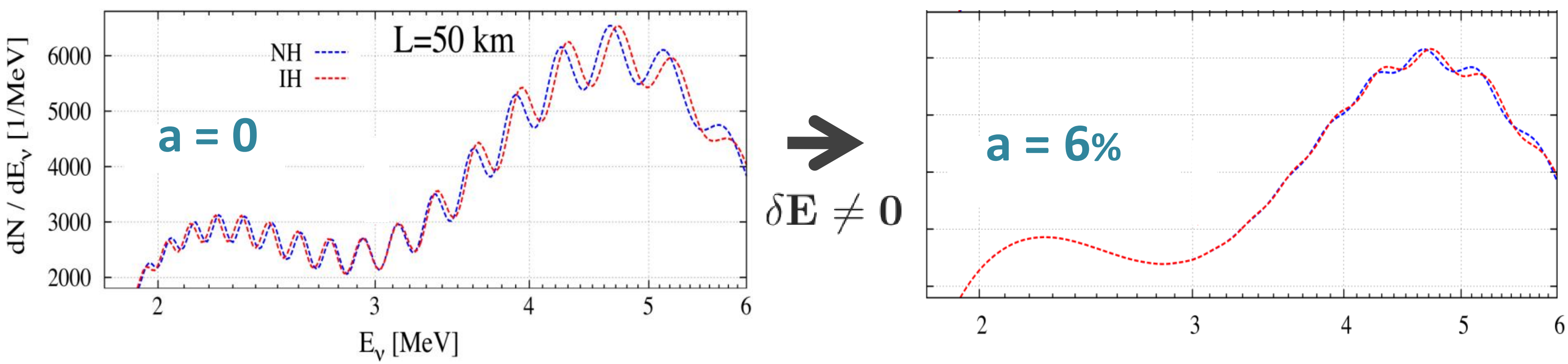
$$\frac{X_i - X_i^{\text{input}}}{\delta X_i}$$



Effect of Energy Resolution

$$\boxed{\frac{\delta E}{E} = \frac{a}{\sqrt{E}}}$$

Evergy Resolution affects the sensitivity significantly.

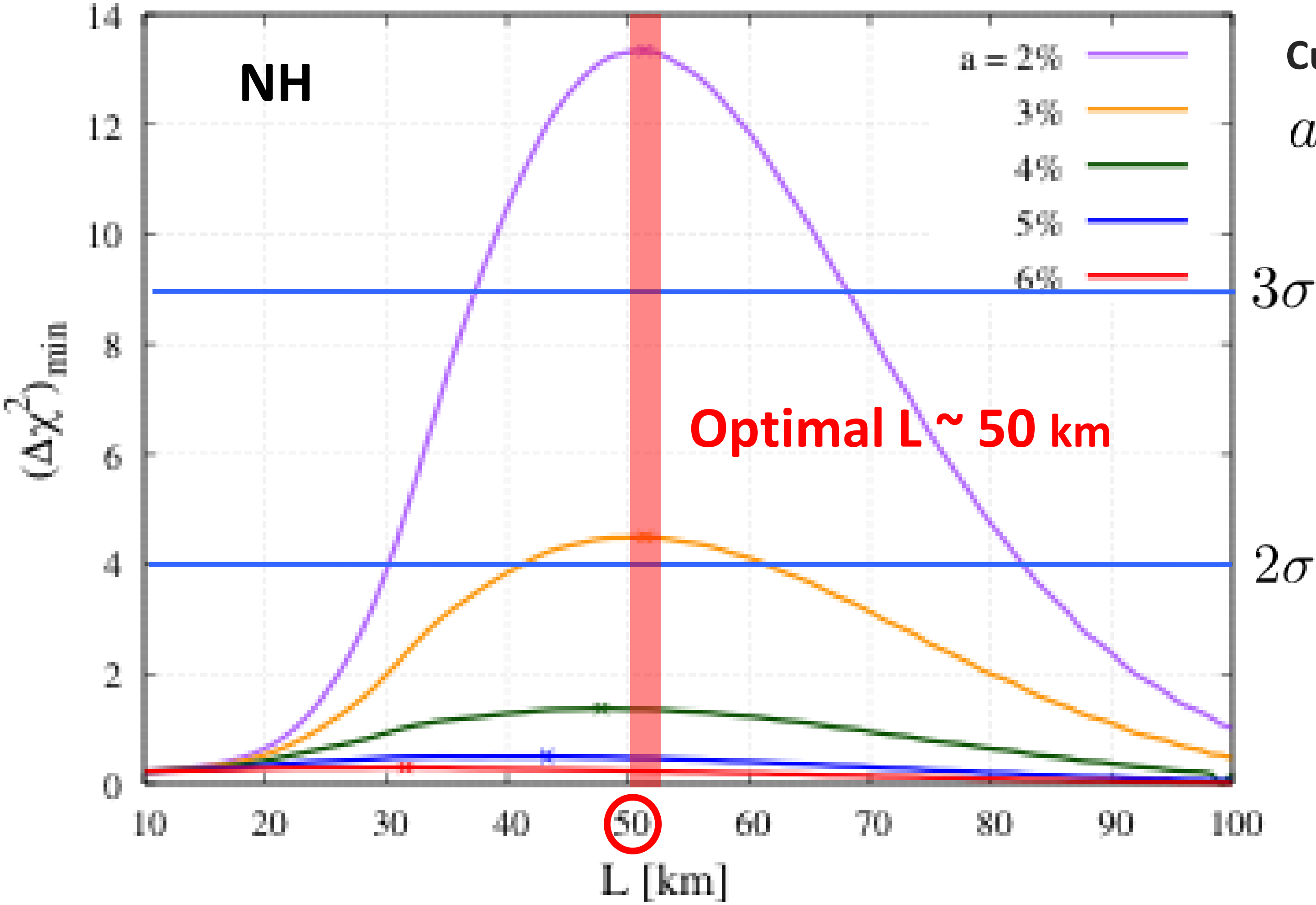


How good should the energy resolution be ?

3% ? ➡ Not enough for RENO50 class of detector (5kton).

Sensitivity for MH determination

20GW 5kton 5yrs



Current Resolution

$$a = 6\% - 7\%$$

Systematic part of Resolution

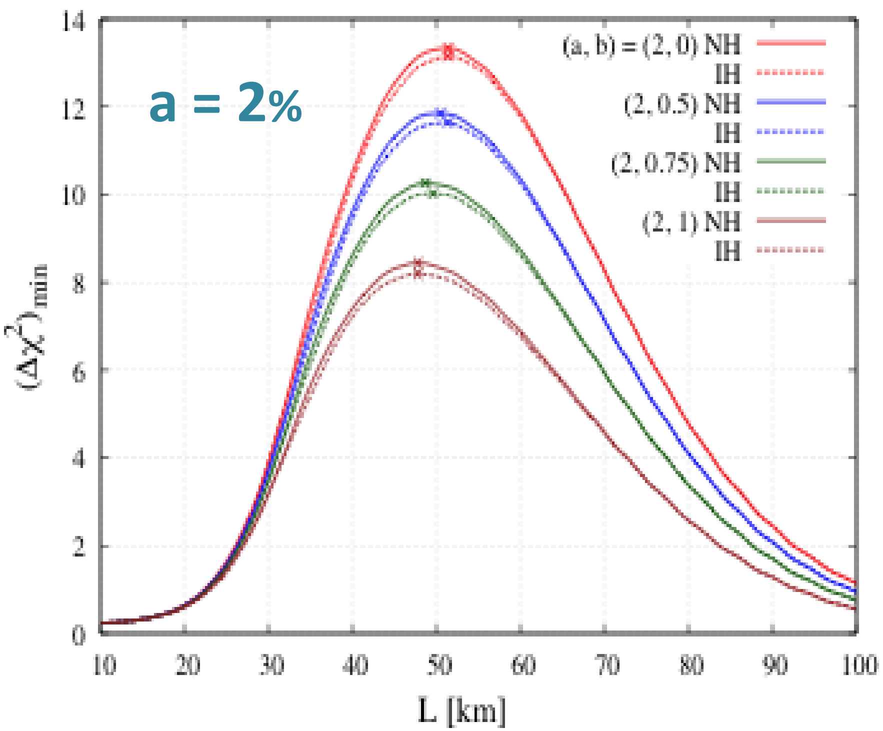
$$\frac{\delta E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2}$$

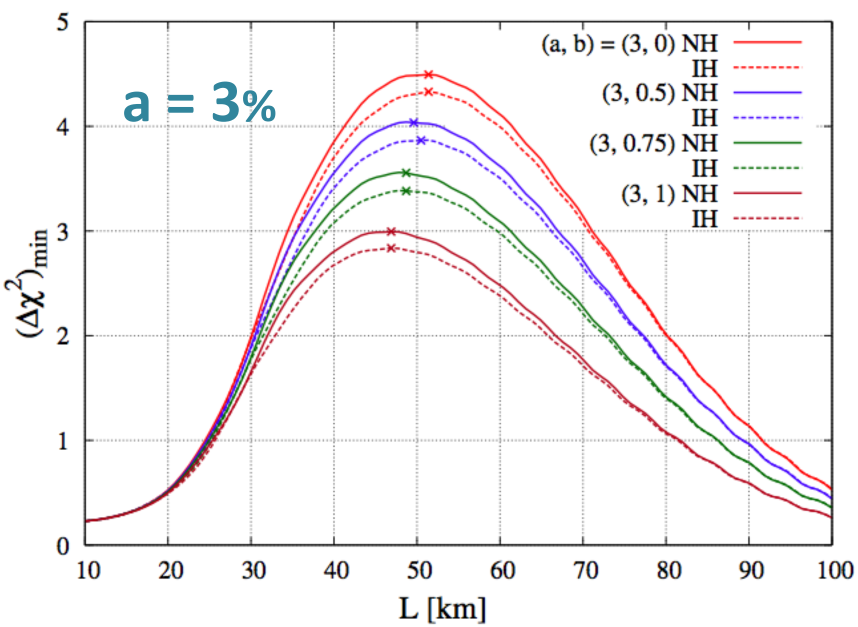
Current Resolution
$b \sim 1\%$

$b = 0 \rightarrow b = 1\%$

- Sensitivity is reduced by 40%.
- Optimal L is shortened by a few km.

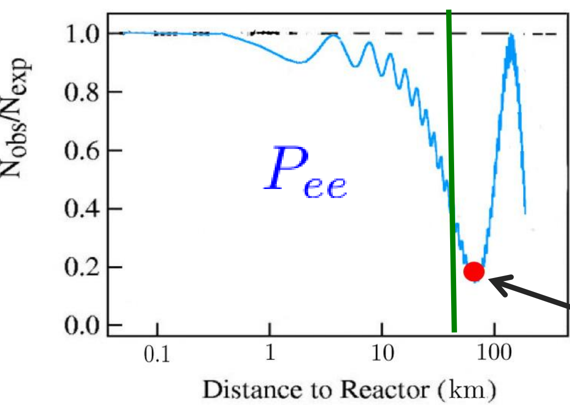
20GW 5kton 5yrs

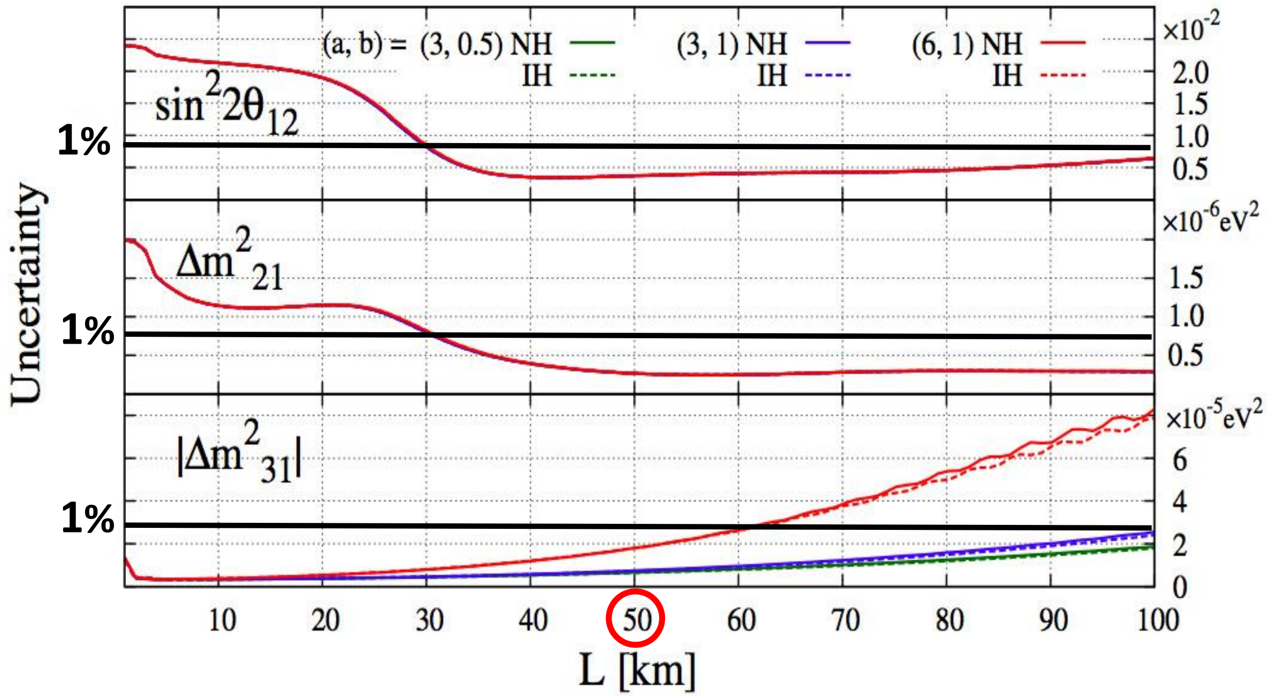




Parameter measurement @ L ~ 50 km

L = 50km





θ_{12} Oscillation Max.

$\sin^2 2\theta_{12}, \Delta m^2_{21}, \Delta m^2_{31}$ **can be measured accurately @ L ~ 50 km**

~ 0.5% ***accuracy***

Parameter measurement is ***not sensitive*** to the ***Energy Resolution.***

Fluctuation of Sensitivity

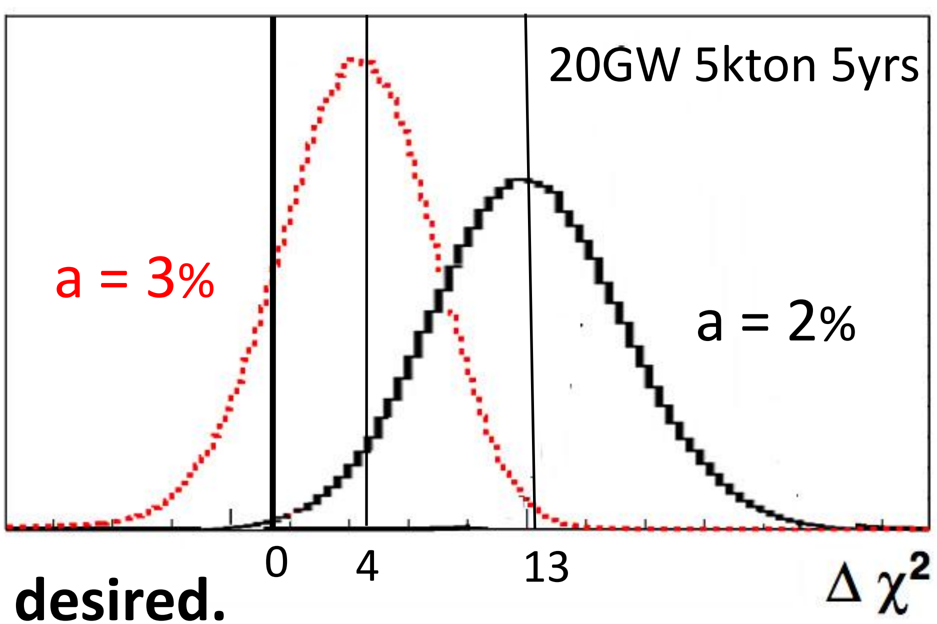
So far, we have discussed on the sensitivity using the "typical data set".

In the real experiments, event number in each bin, N_i^{data}, fluctuates from the "typical event number", $\overline{N}_i$.

$$N_i^{\mathrm{data}} = \overline{N}_i \pm \sqrt{\overline{N}_i}$$

Then, $(\Delta\chi^2)_{\min}$ follows Gaussian distribution.

$$\delta(\Delta\chi^2)_{\min} \sim 2\sqrt{(\Delta\chi^2)_{\min}}$$

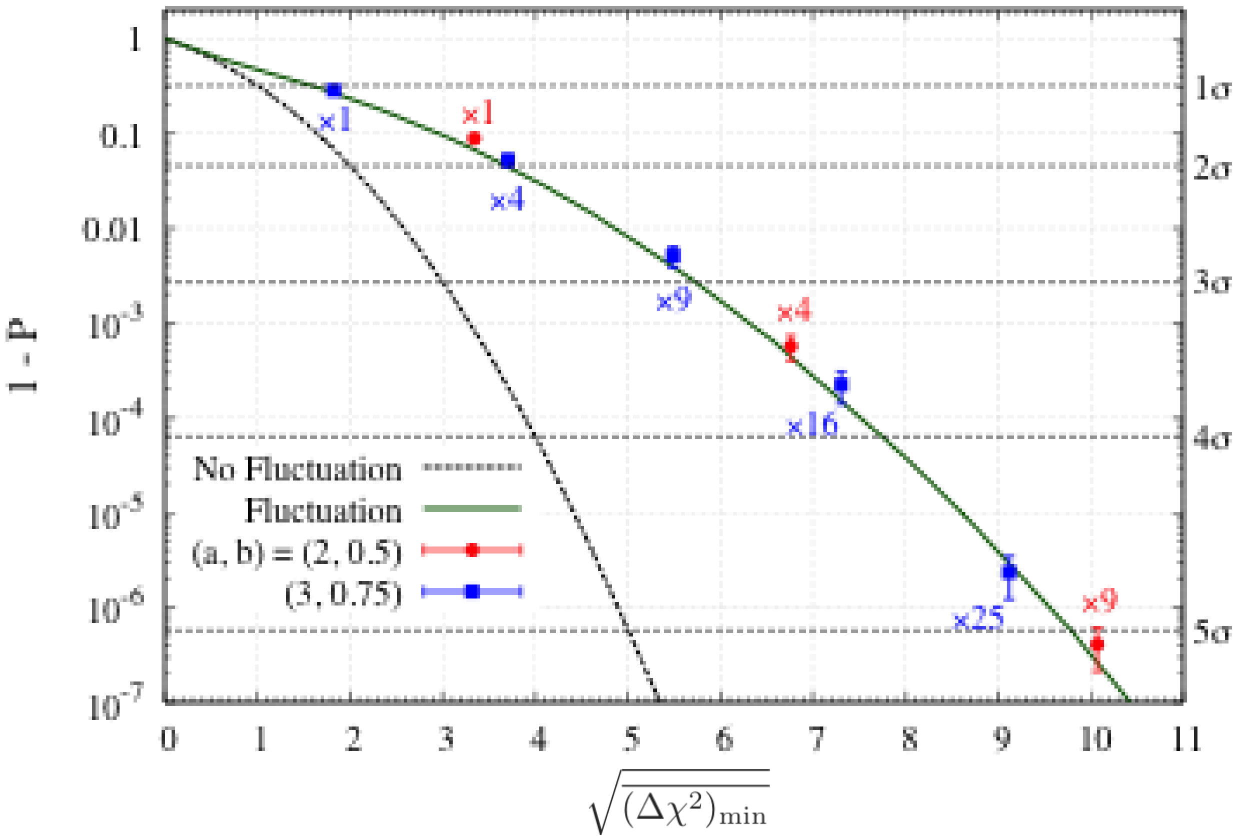


2% level of energy resolution is desired.

Expected Probability

$$P = \int_0^\infty dx\, N\left(x; \overline{(\Delta\chi^2)_{\rm min}}, \delta\left\{(\Delta\chi^2)_{\rm min}\right\}\right) \mathrm{erf}\left(\frac{\sqrt{x}}{\sqrt{2}}\right)$$

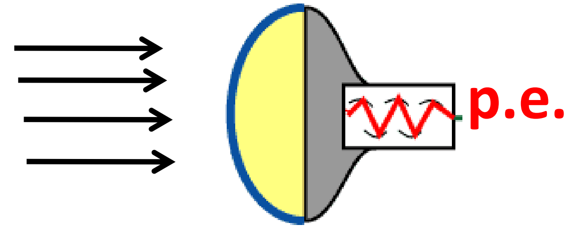
L = 50 km



How to achieve 2% energy resolution ?

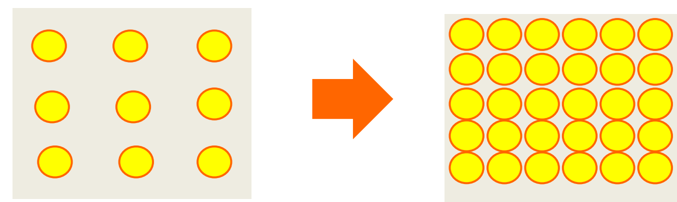
Increase the photo-electron (p.e.)detected by PMT.

~ 200 pe/MeV → **~ 2000 pe/MeV**

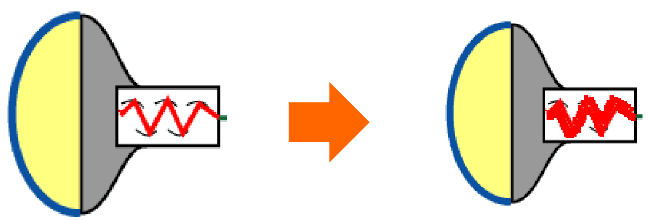


Ex)

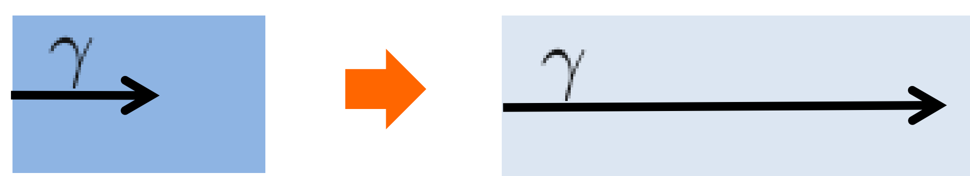
- Increase PMT coverage



- Increase QE of PMT



- More transparent LS



More photons, how?

- **Highly transparent LS:**
  - ⇨ Attenuation length/D: 15m/16m → 30m/34m ×0.9
- **High light yield LS:**
  - ⇨ KamLAND: 1.5g/l PPO → 5g/l PPO
    Light Yield: 30% → 45%; × 1.5
- **Photocathode coverage :**
  - ⇨ KamLAND: 34% → ~80% × 2.3
- **High QE "PMT":**
  - ⇨ 20" SBA PMT QE: 25% → 35% × 1.4
    or New PMT QE: 25% → 40% × 1.6
    Both: 25% → 50% × 2.0

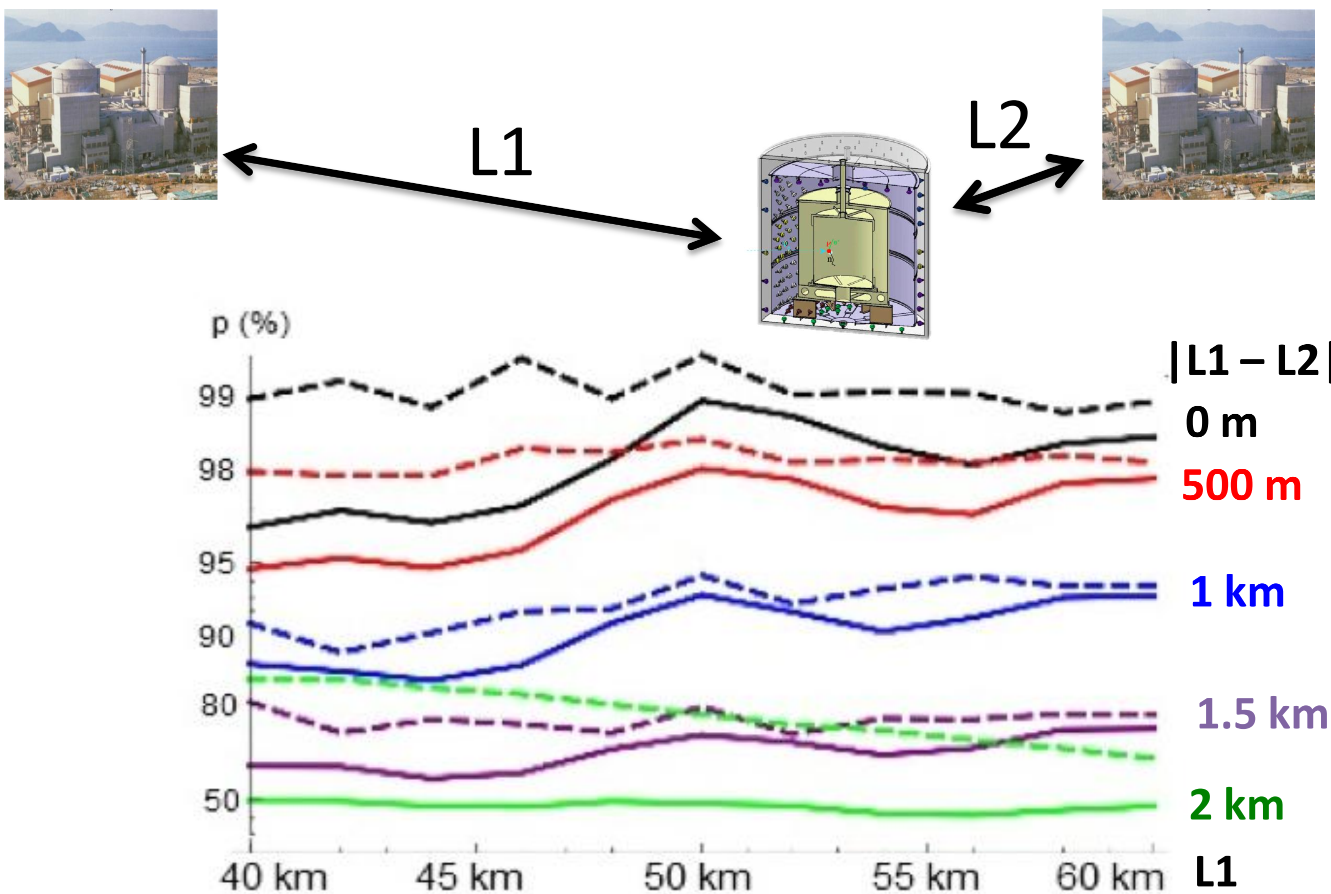
$\boxed{4.3 - 5.0 \rightarrow (3.0 - 2.5)\% /\sqrt{E}}$

Other contributions: 0.5% constant term & 0.5% neutron recoil uncertainty

By Channgen Yang @ NuMass 2013

Multi-reactor interference

Baseline difference should be < 500m.

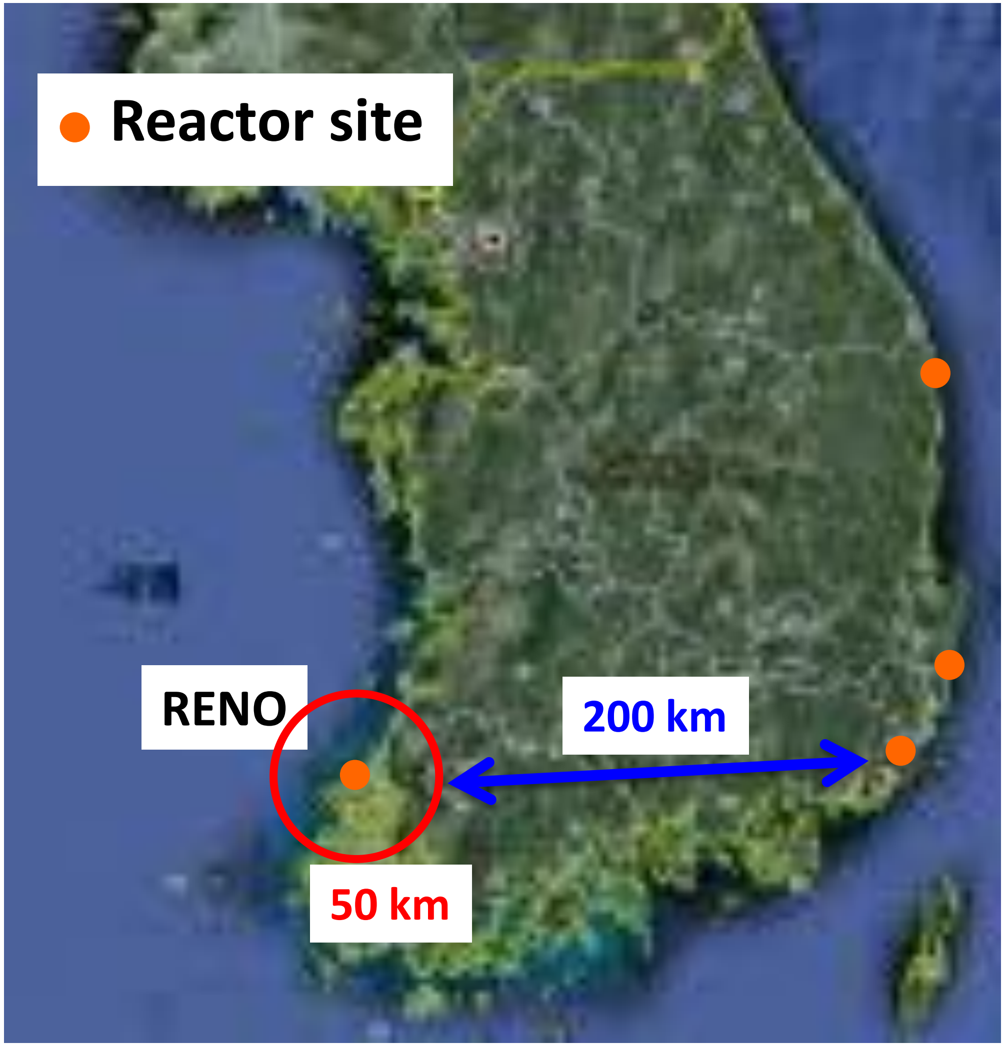


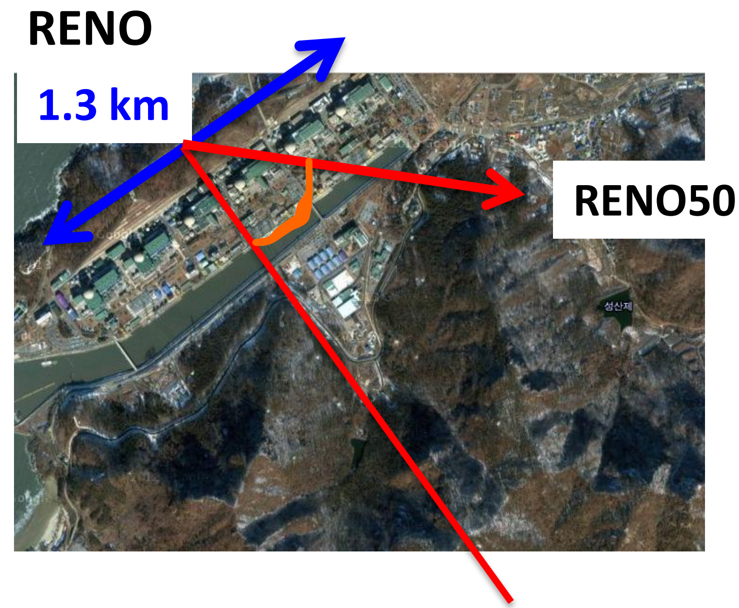
arXiv: 1302.0624

Multi-reactor interference

Because of this effect, DayaBayII has changed its location.

Multi-reactor interference





The angle to RENO50 may affect the sensitivity.

Summary

We have discussed ***the sensitivity*** of ***Medium Baseline Reactor Experiments*** for ***MH determination***.

For **20GW 5kton 5yrs** exposure,

50km optimal ***Baseline Length***

$$\frac{\delta \mathbf{E}}{\mathbf{E}} = \sqrt{\left(\frac{\mathbf{a}}{\sqrt{\mathbf{E}}}\right)^2 + \mathbf{b}^2}$$

$\left.\begin{array}{l} a < 3\% \\ b < 1\% \end{array}\right\}$ of ***Energy Resolution*** is required.

0.5% ***accuracy*** is achieved for $\sin^2 2\theta_{12}, \Delta m^2_{21}, \Delta m^2_{31}$