

次世代原子炉ニュートリノ実験の質量階層性への Sensitivity

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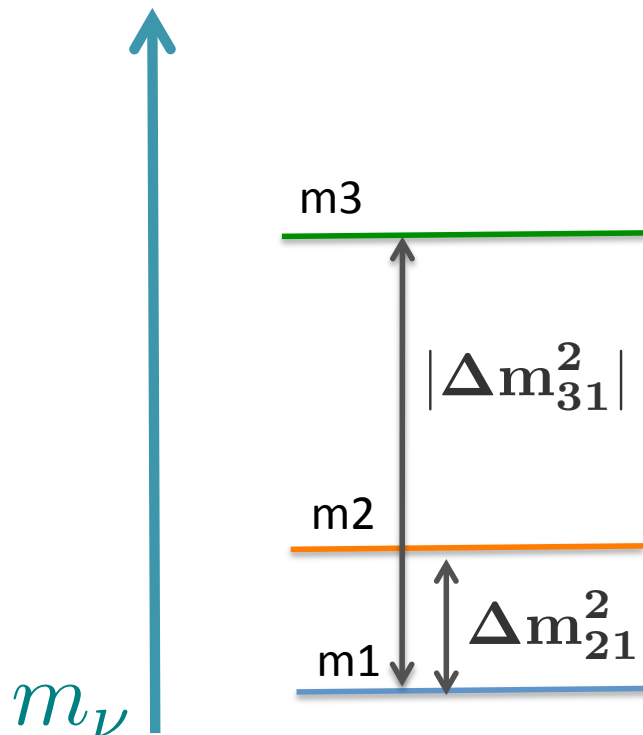
Introduction

Mass Hierarchy

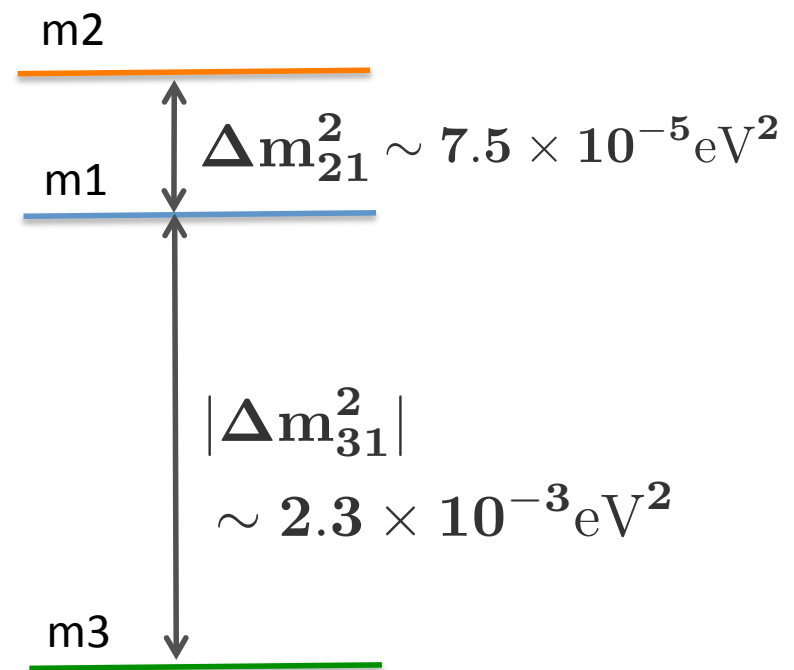
3 neutrinos flavors

$$\Delta m_{21}^2 = m_2^2 - m_1^2 \sim 7.5 \times 10^{-5}$$

$$\Delta m_{21}^2 < |\Delta m_{31}^2| \sim 2.3 \times 10^{-3}$$

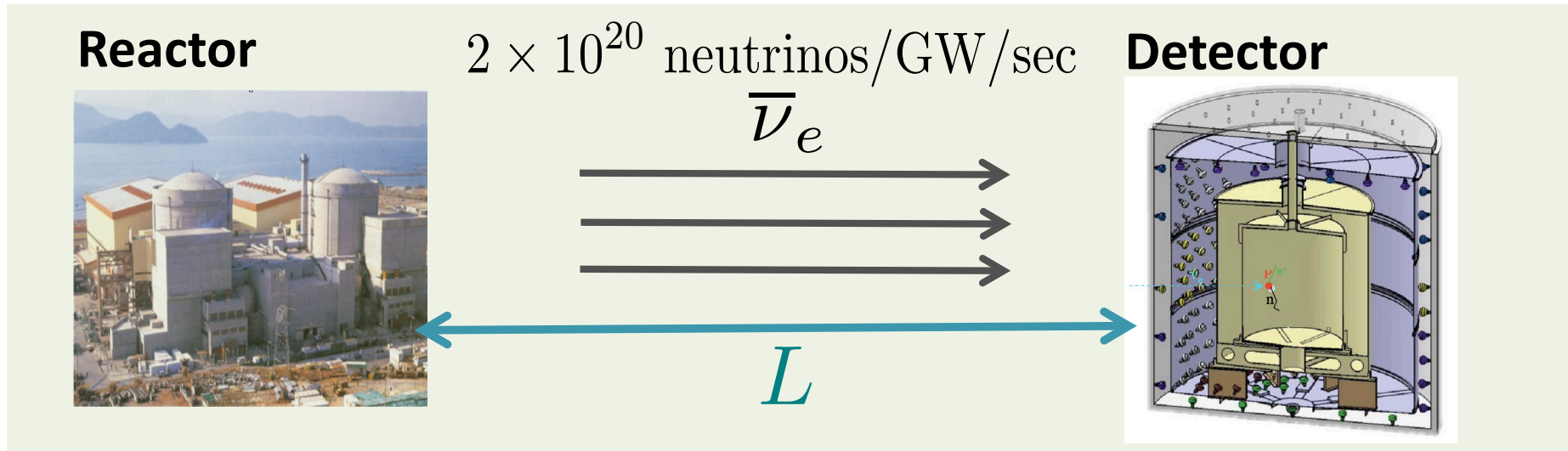


Normal Hierarchy
(NH)



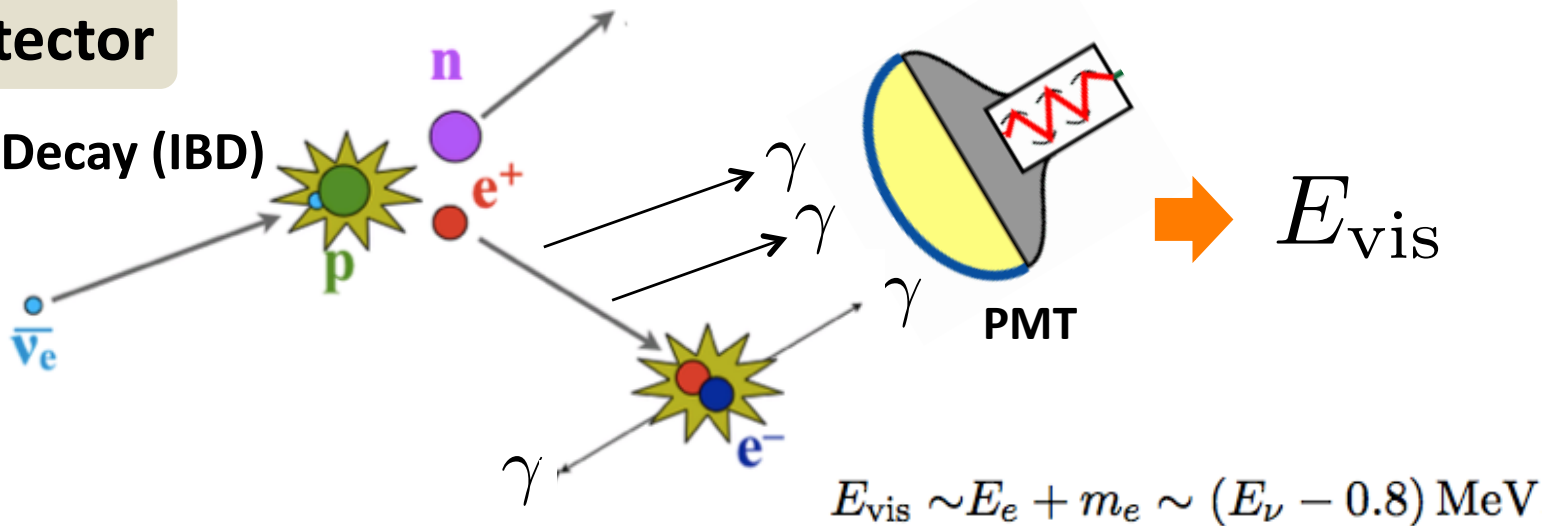
Inverted Hierarchy
(IH)

Reactor neutrino experiment

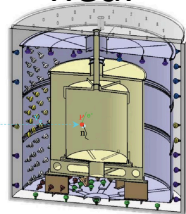
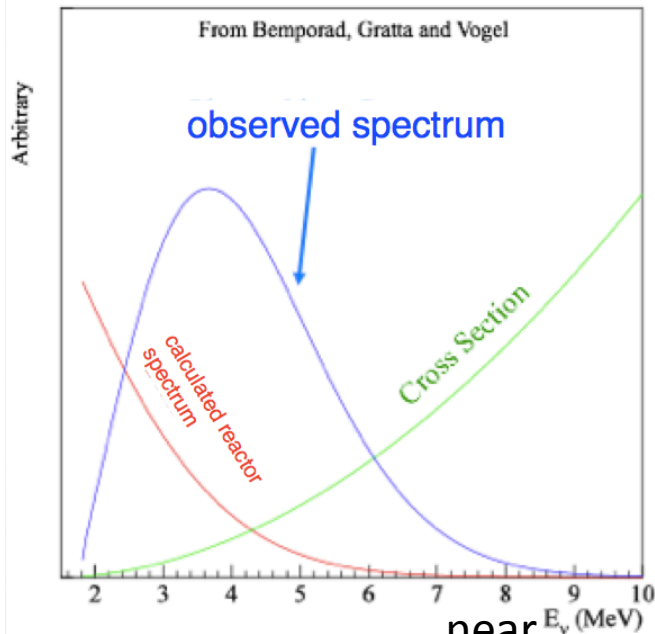


Inside Detector

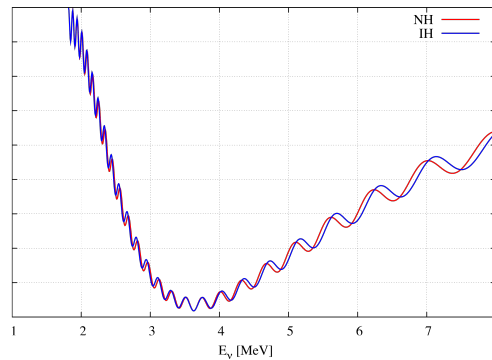
Inverse Beta Decay (IBD)



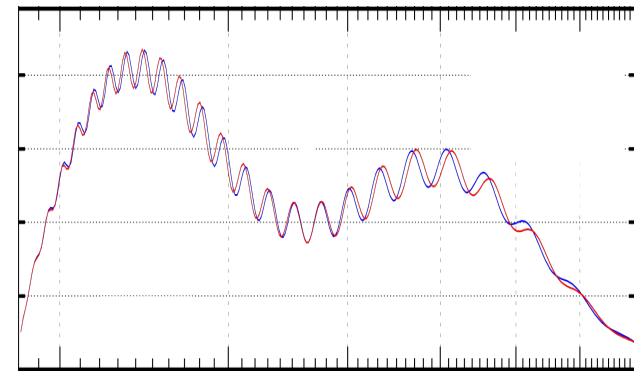
$\bar{\nu}_e$ Energy distribution



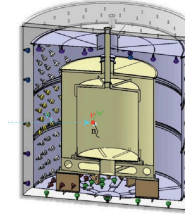
Neutrino oscillation
 P_{ee}



$\bar{\nu}_e$ @ detector



far

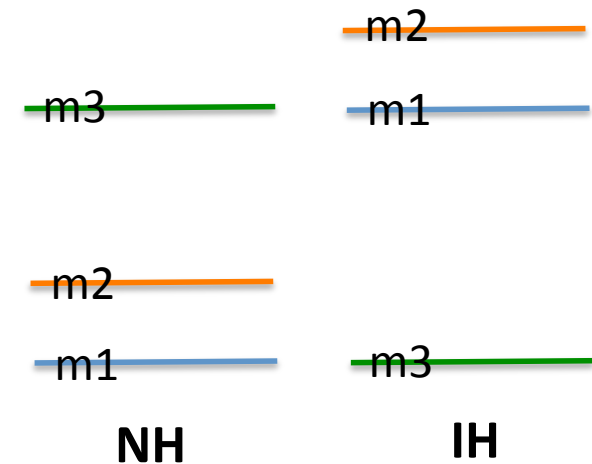


$$\frac{dN^{far}}{dE_{vis}} = \frac{N_p T}{4\pi L^2} \int_{E_{thr}}^{\infty} dE_\nu \phi(E_\nu) P_{ee} \sigma_{IBD} G(E_\nu, E_{vis})$$

How to distinguish Mass Hierarchy?

Detect the sign of Δm_{31}^2 (Δm_{32}^2)

$$\Delta m_{31}^2 \equiv \begin{cases} m_3^2 - m_1^2 > 0 & \text{(NH)} \\ m_3^2 - m_1^2 < 0 & \text{(IH)}. \end{cases}$$

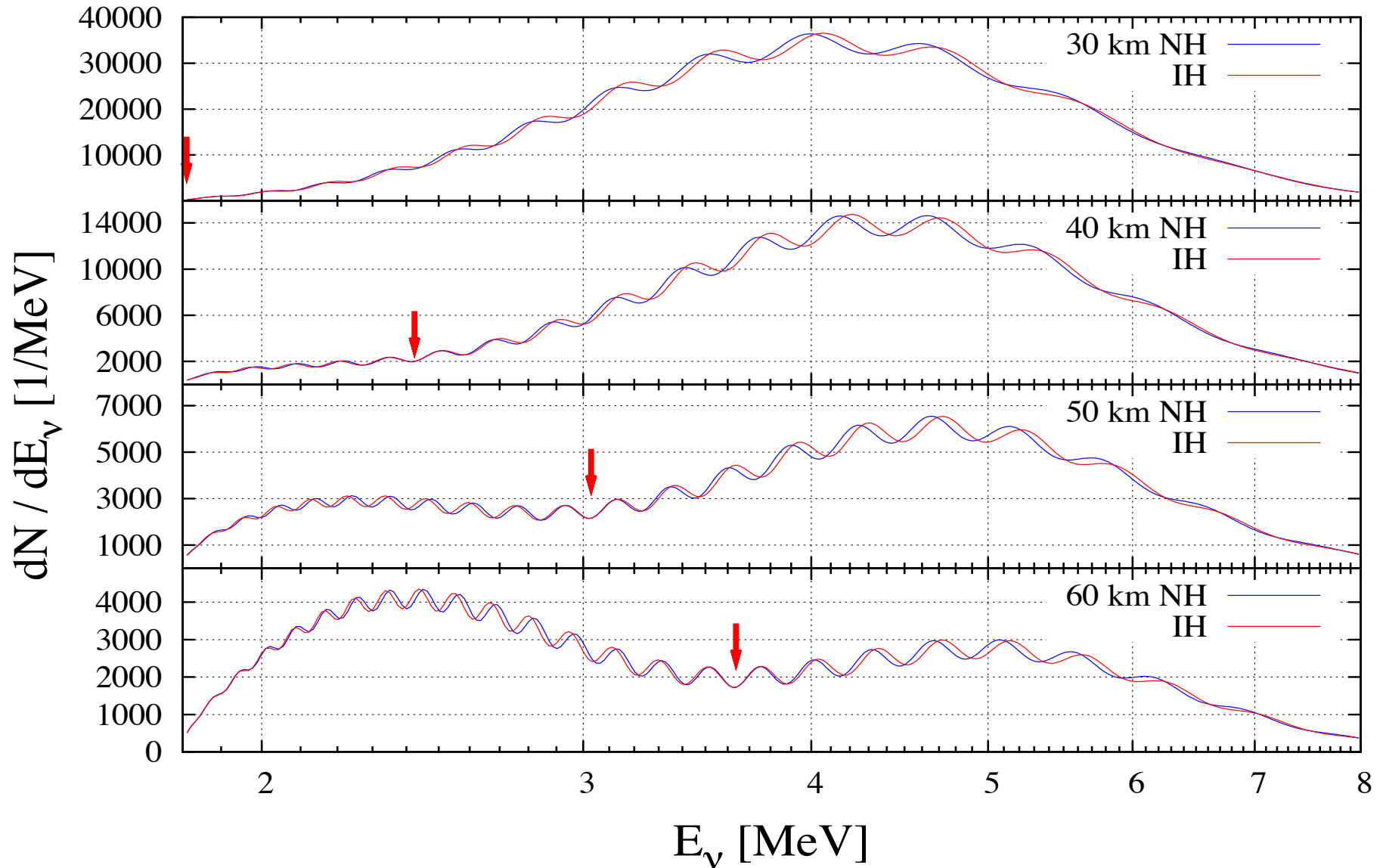


The information of mass² difference are in Oscillation Probabilities.

$$\begin{aligned}
 P_{ee} &= \left| \sum_{i=1}^3 U_{ei} \exp\left(-i \frac{m_i^2}{2E_i}\right) U_{ei}^* \right|^2 \\
 &= 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta_{21}) \\
 &\quad - \sin^2 2\theta_{13} \sin^2(|\Delta_{31}|) \\
 &\quad - \sin^2 \theta_{12} \sin^2 2\theta_{13} \sin^2(\Delta_{21}) \cos(2|\Delta_{31}|) \\
 &\quad \pm \frac{\sin^2 \theta_{12}}{2} \sin^2 2\theta_{13} \sin(2\Delta_{21}) \sin(2|\Delta_{31}|)
 \end{aligned}$$

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

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



Sensitivity

χ^2 analysis

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

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

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

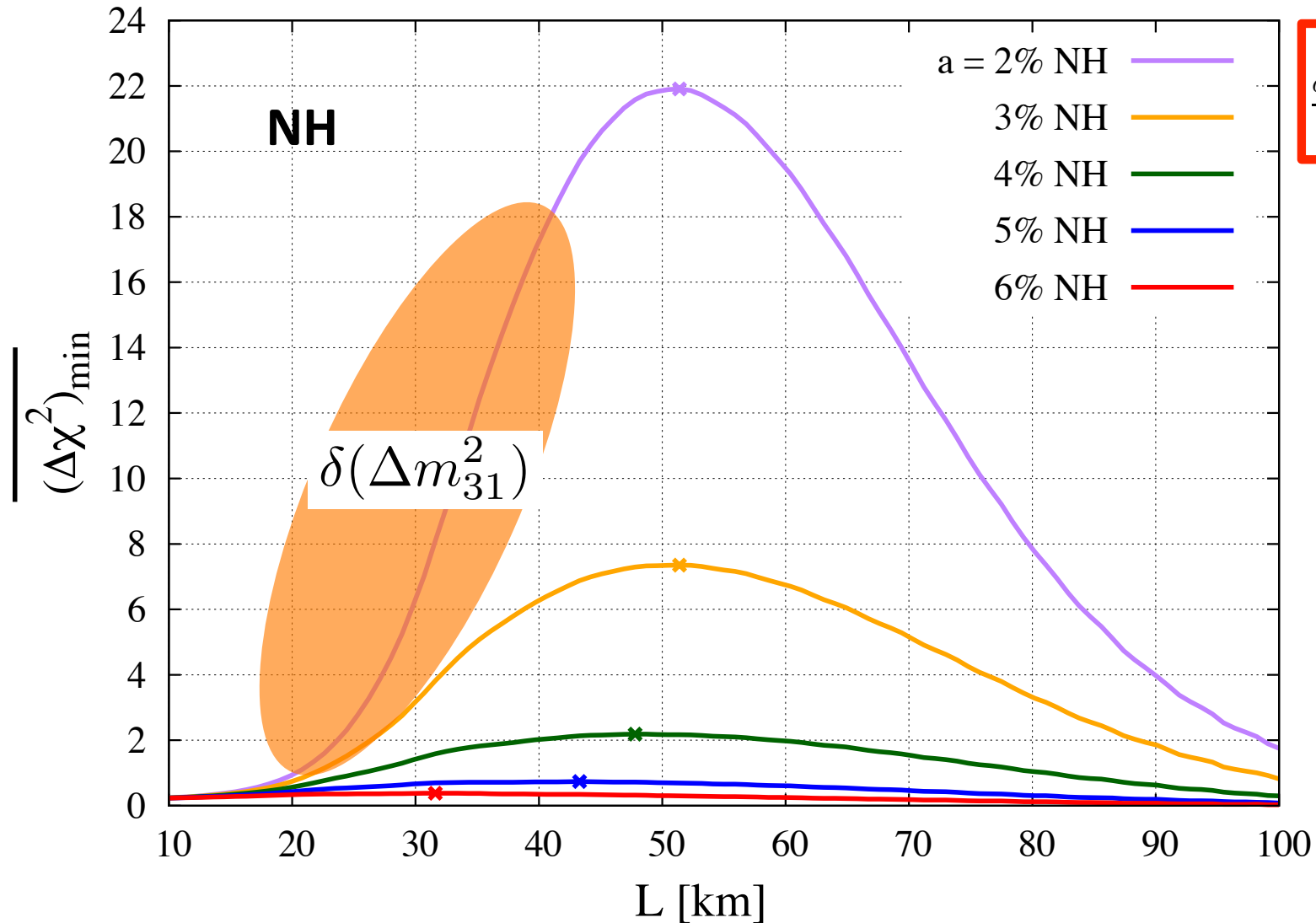
 $\chi_{\min}^2(NH) \quad \chi_{\min}^2(IH)$

Fitting parameters are $\theta_{12}, \theta_{13}, \Delta m_{21}^2, |\Delta m_{31}^2|, f_{\text{sys}}$

Y	$\sin^2 2\theta_{12}$	$\sin^2 2\theta_{13}$	$\Delta m_{21}^2 \text{ eV}^2$	$ \Delta m_{31}^2 \text{ eV}^2$	f_{sys}
Y^{input}	0.857	0.10	7.50×10^{-5}	2.32×10^{-3}	1
δY	0.024	0.005	0.20×10^{-5}	0.1×10^{-3}	0.03

Sensitivity to the Mass hierarchy

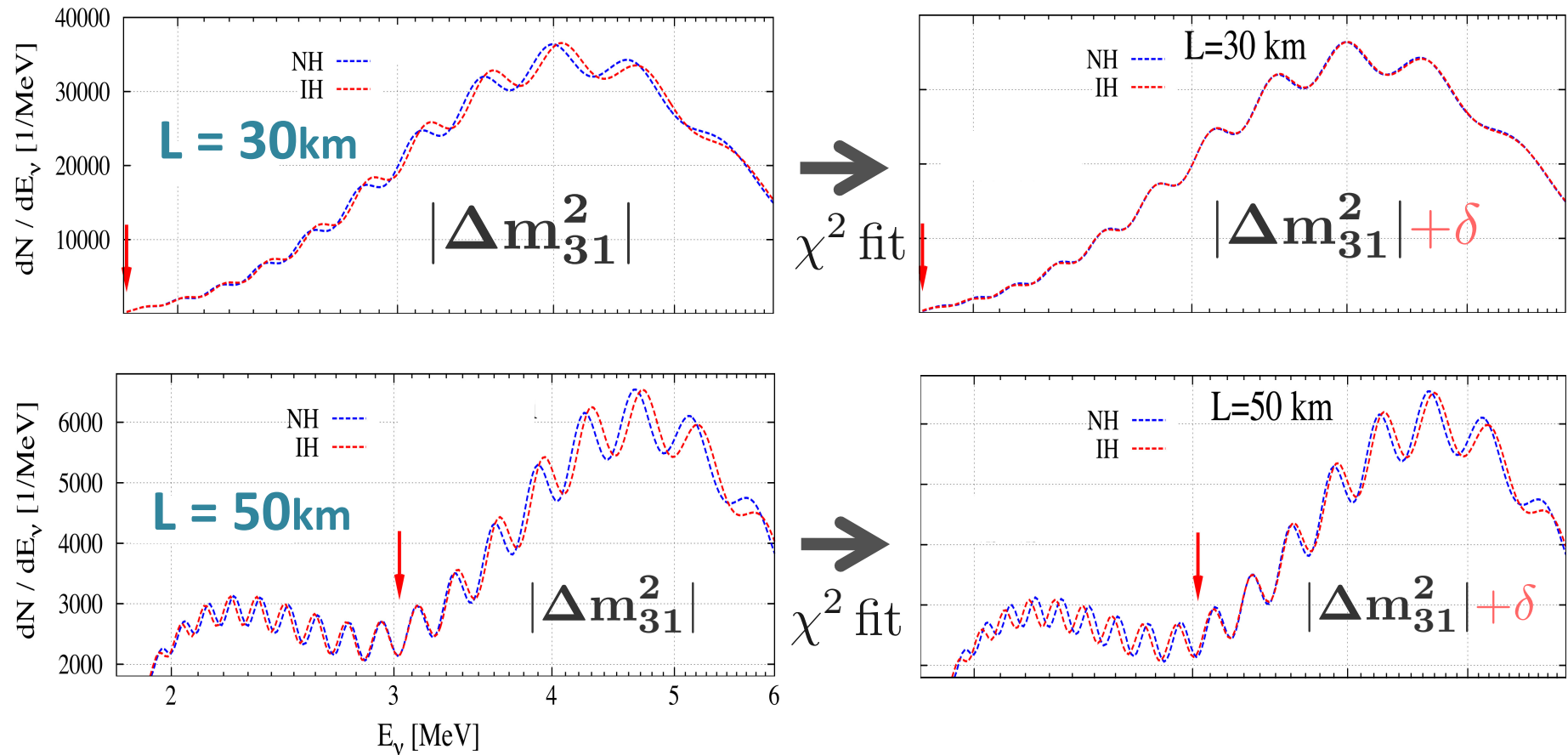
16.5GW 10kton 5yrs



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

Current value
 $a \simeq 7\%$

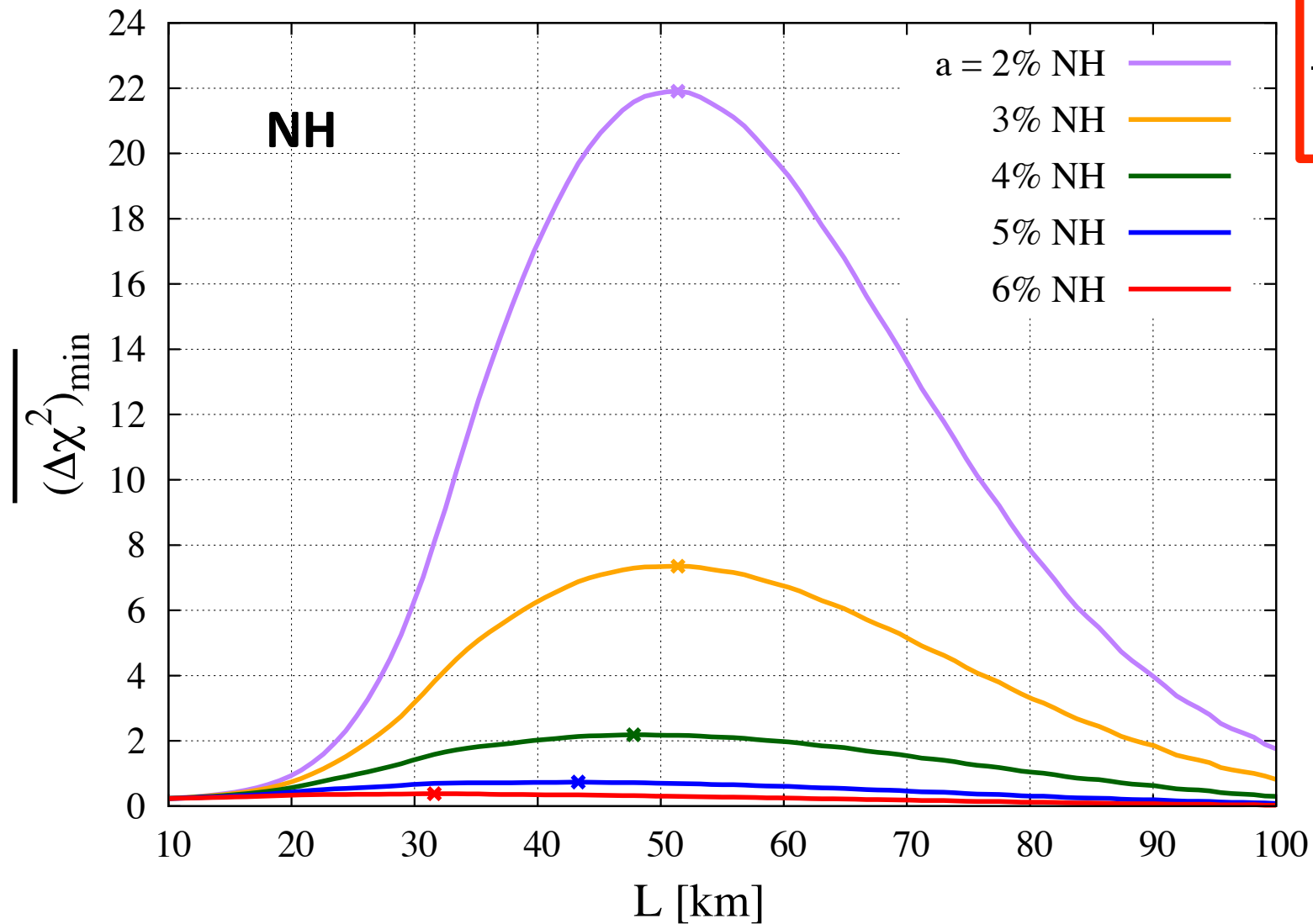
Effects of $\delta|\Delta m_{31}^2|$ to the sensitivity



Baseline should be long enough

Sensitivity to the Mass hierarchy

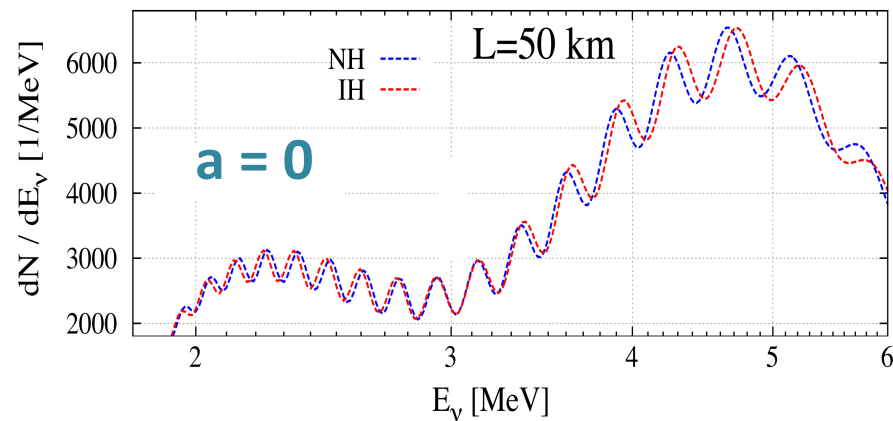
16.5GW 10kton 5yrs



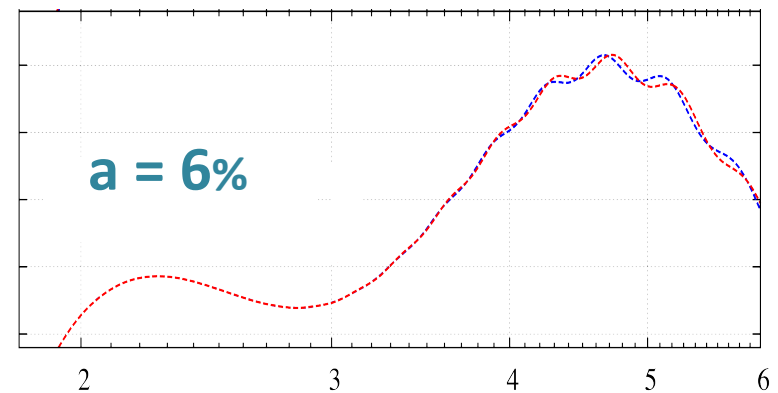
Effect of Energy Resolution

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

Energy Resolution affects the sensitivity significantly.

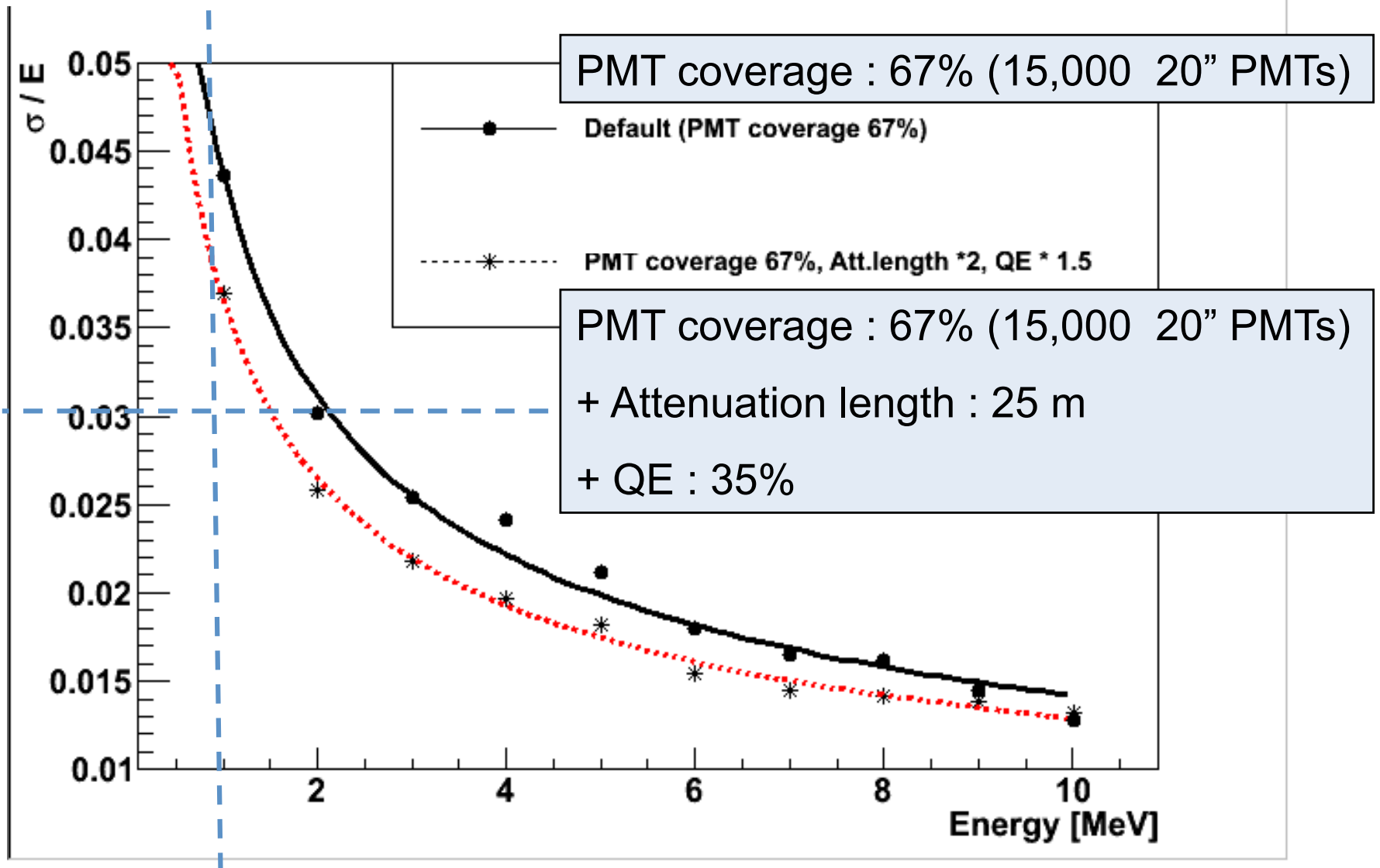


$\delta E \neq 0$



Expected Energy Resolution

J.S. Park, S.B. Kim



Effect of Energy Resolution 2

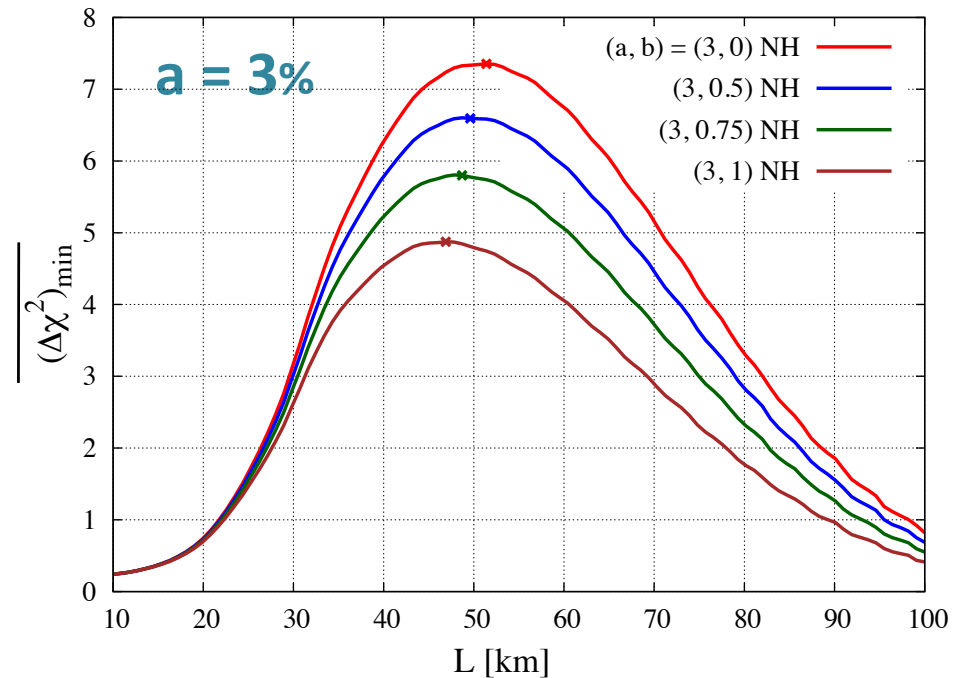
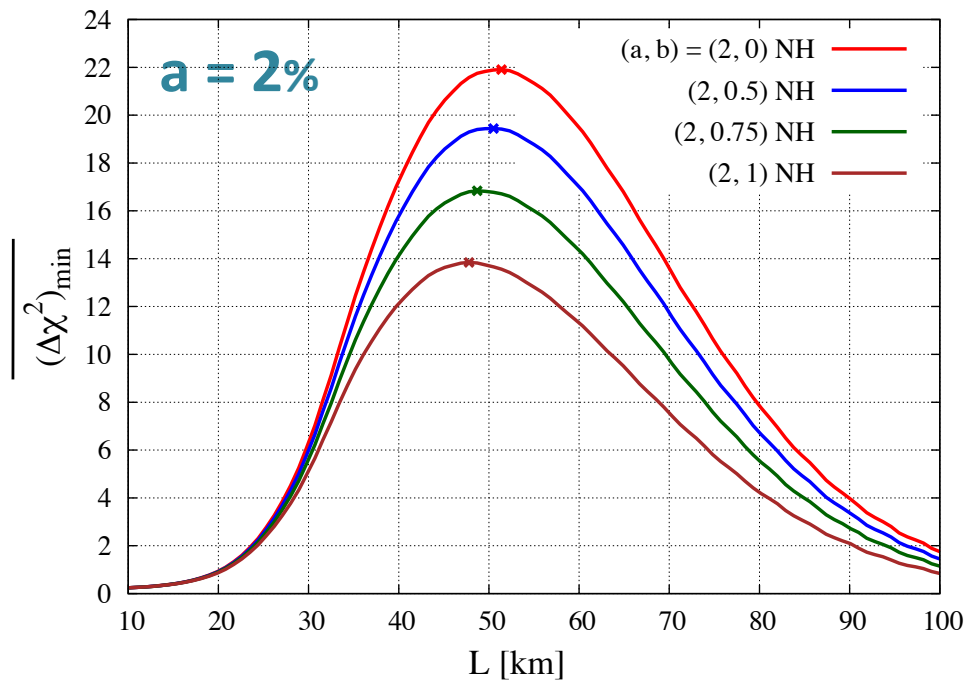
$$\frac{\delta E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2}$$

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



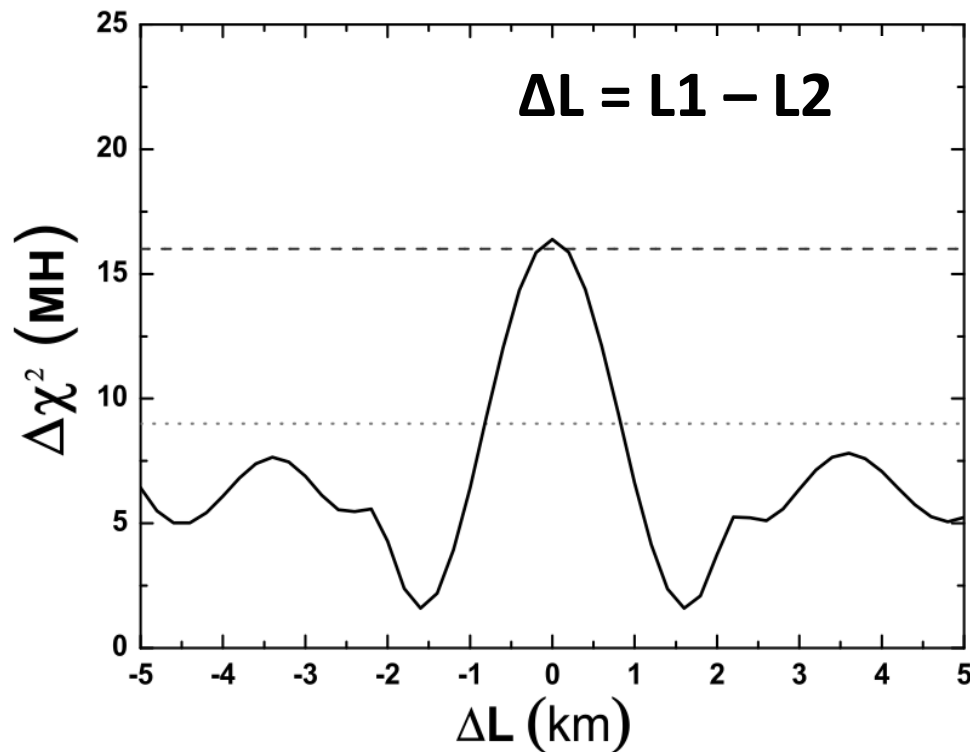
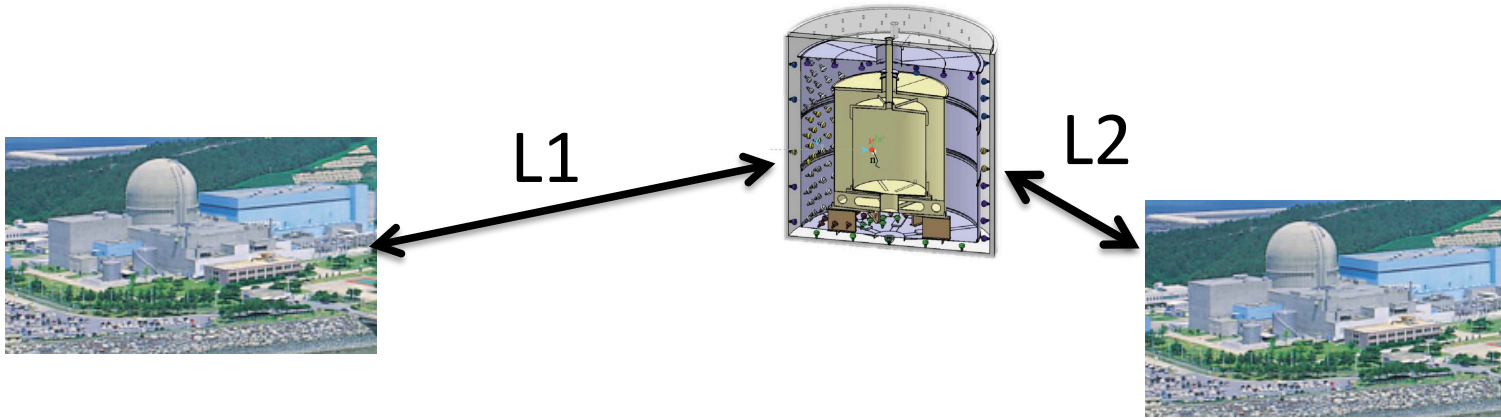
- Sensitivity is reduced by ~ 40%
- Optimized L is shortened by ~ 5 km

16.5GW 10kton 5yrs



Other Limitting Factors

Multi-reactor interference

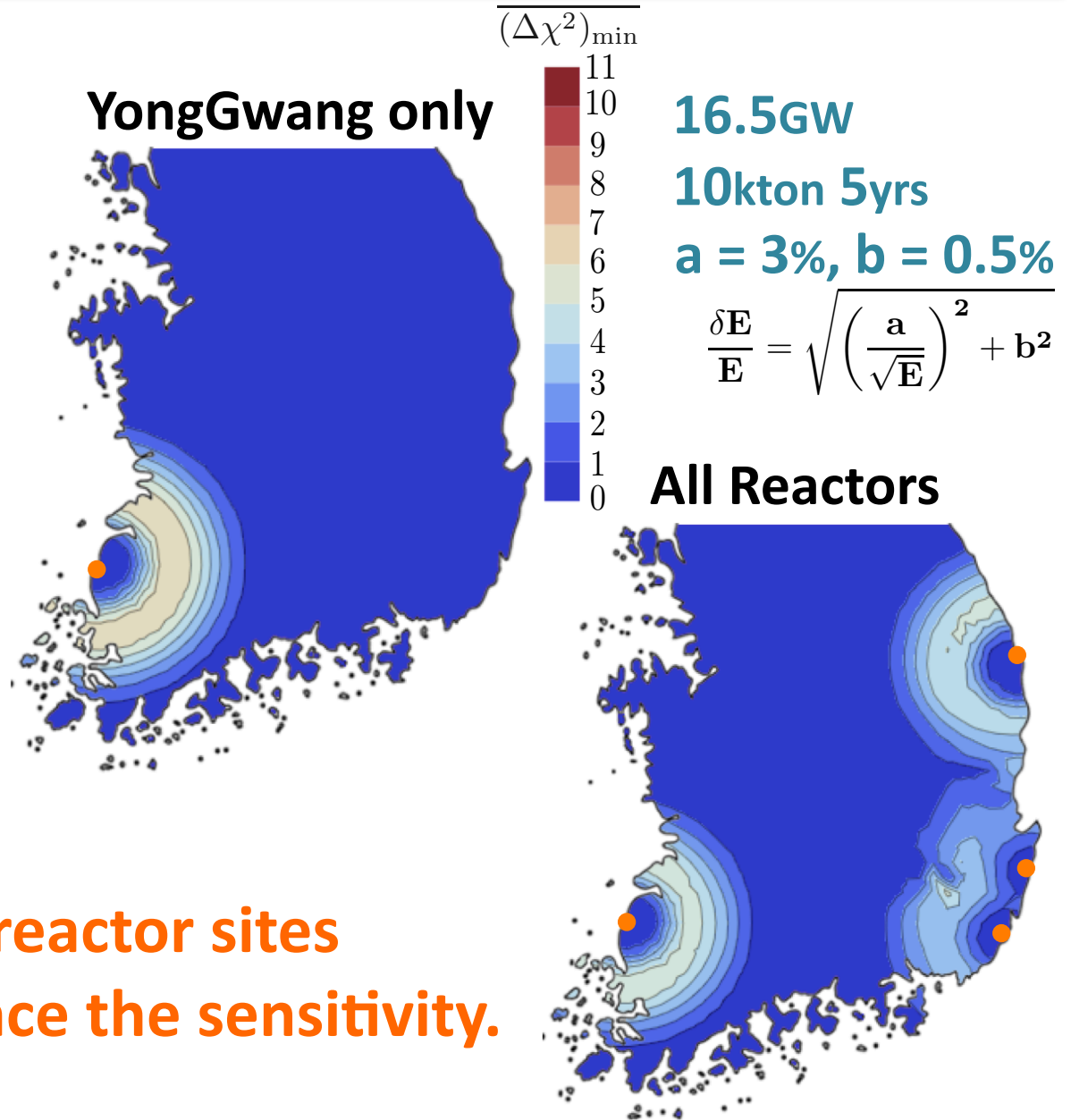
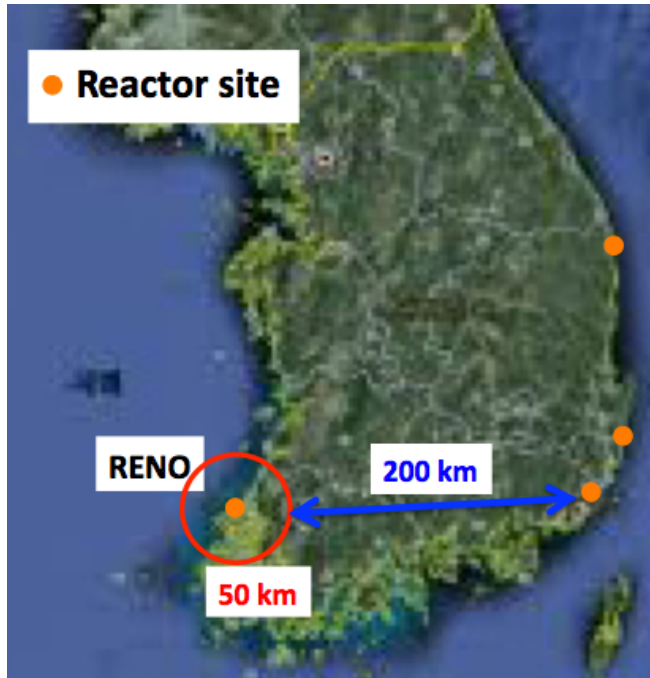


**Baseline difference
should be small.**

E. Ciuffoli, J. Evsline, X. Zhang: 1302.0624

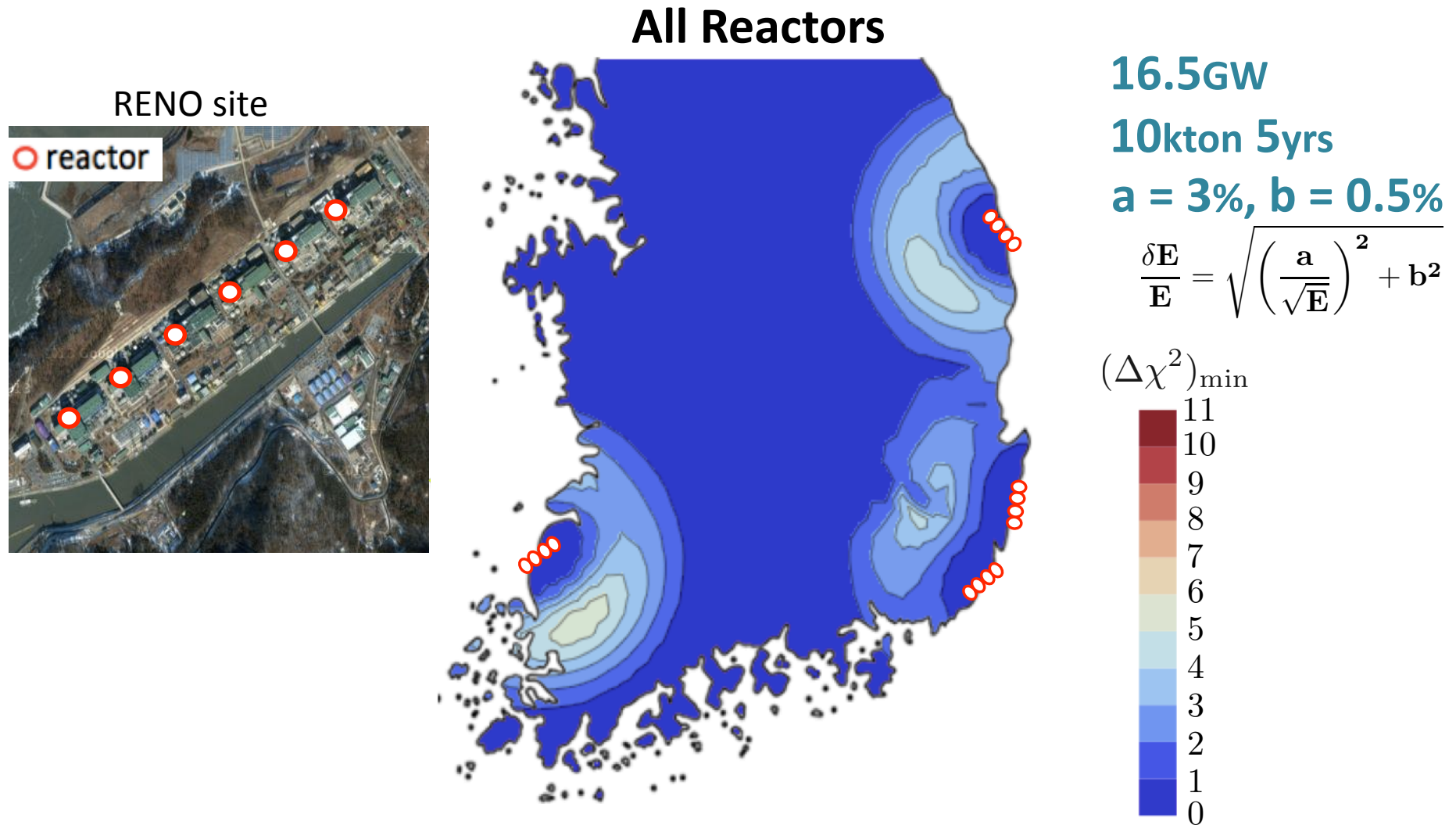
Y-F. Li, J. Cao, Y. Wang, L. Zhan: 1303.6733

Multi-reactor interference



Other reactor sites
influence the sensitivity.

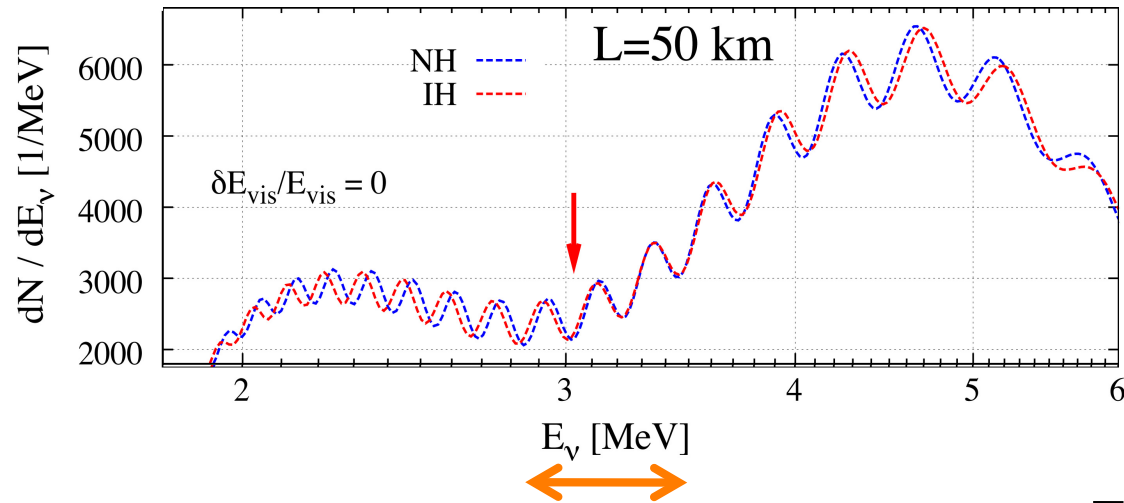
Multi-reactor interference



In latest RENO-50 proposal: **Site changed**
18 kton detector

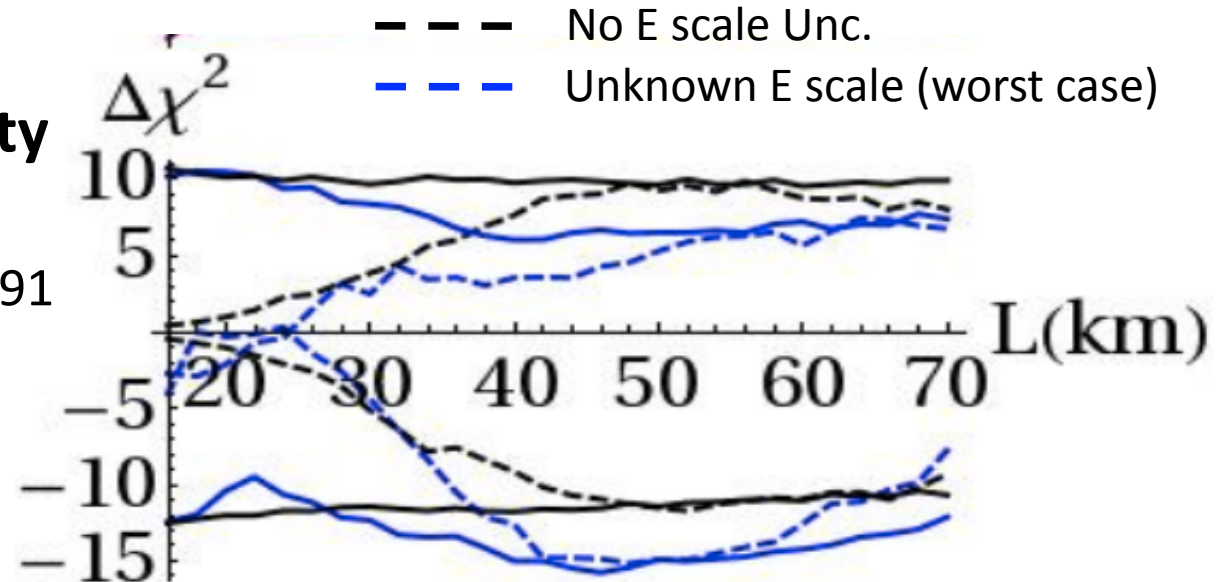
Energy scale uncertainty

Energy scale uncertainty is controlled $\sim 1\%$ for RENO detector.

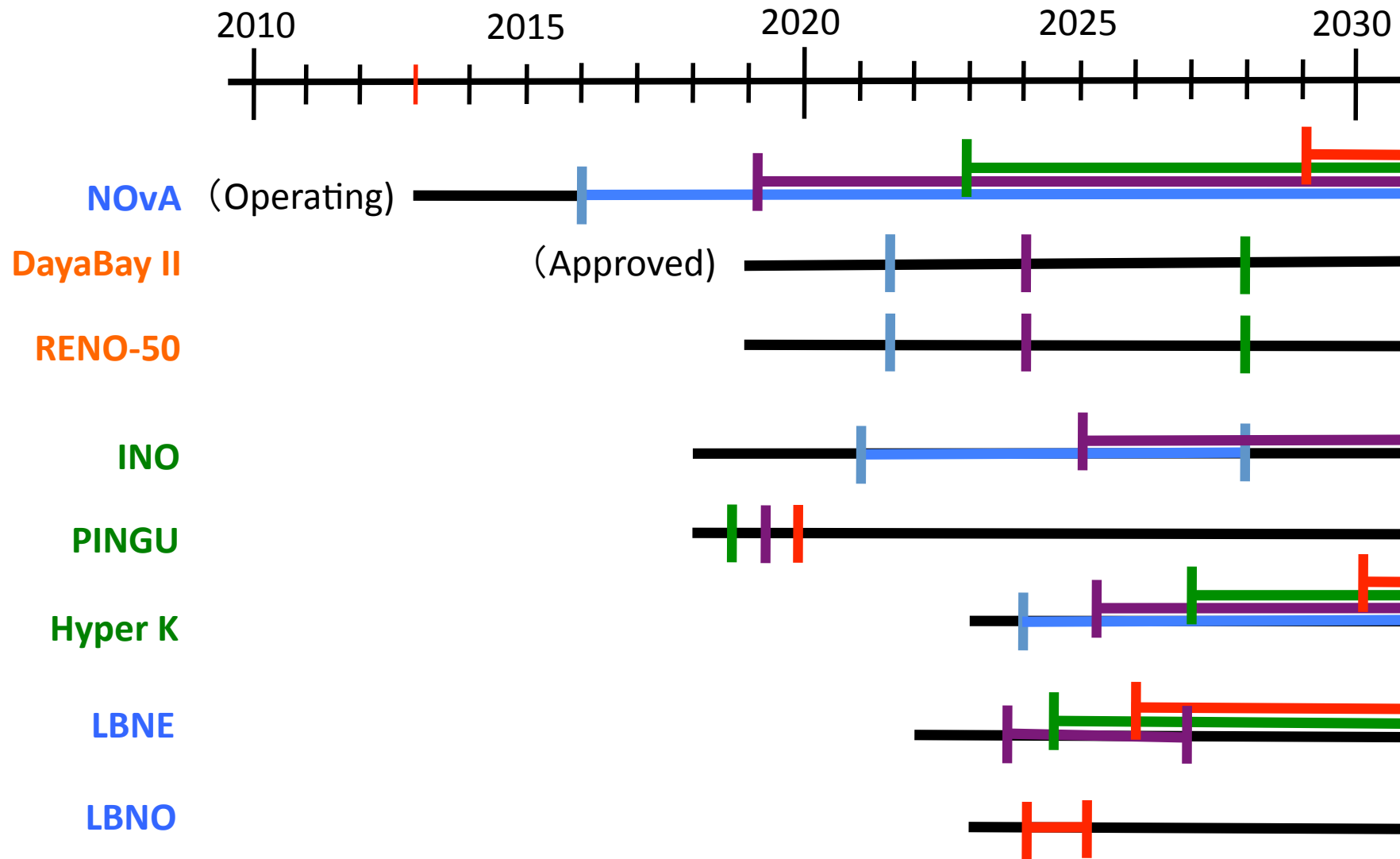


Effect of E scale Uncertainty

J. Evslin et.al.
arXiv: 1308.0591



Schedule for MH determination



* rough estimate

2 sigma 3 sigma 4 sigma 5 sigma

Summary

RENO50-like Experiment for MH determination.

With **16.5GW 18kton**,

$$a < 3\%$$

$$b < 0.5\%$$

} of *Energy Resolution* is required
> **2 ~ 3-sigma**
determination within **5 years**.

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

Interference among *reactor cores* significantly affects the sensitivity.

Energy Scale uncertainty should be controlled very Carefully.

Many Efforts for MH determination have started !