Resolving Neutrino Mass Hierarchy and CP Degeneracy Using Two Identical Detectors with Different Baselines

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Based on the work with M. Ishitsuka, T. Kajita and H. Minakata, hep-ph/0504026

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Outline

- Introduction
- Basic Idea of 2 Detectors with Different Baselines
- Results of Our Analysis
- Summary

Introduction

Current Knowleadge about ν Mixing parameters

$$+7.3 \times 10^{-5}\mathrm{eV}^2 < \Delta m^2_{21} < +9.0 \times 10^{-5}\mathrm{eV}^2$$

$$0.25 < \sin^2\theta_{12} < 0.37$$

$$1.5 \times 10^{-3}\mathrm{eV}^2 < |\Delta m^2_{32}| < 3.4 \times 10^{-3}\mathrm{eV}^2$$

$$0.36 < \sin^2\theta_{23} \leq 0.64$$

$$0 \leq \sin^2\theta_{13} < 0.04$$

@ 90 % C.L.

Unknowns

- How small is θ_{13} ?
- Is Mass Hierarchy Normal or Inverted ?
- What is the value of CP phase δ ?

However, it is well known that so called parameter degeneracy makes these determinations difficult

(1) θ_{23} octant degeneracy (Fogli and Lisi, 1996)

(2) Intrinsic θ_{13}-δ degeneracy (Burguet-Castell et al, 2001)

(3) sign of Δm^2_{13} degeneracy (Minakata, HN, 2001)

$\Rightarrow$ 8 fold degeneracy (Barger et al, 2002)

Proposed Experiments

- T2K (Phase I + Phase II)
- NOvA
- BNL VLBL
- SPL-Frejus
- β Beam
- Reactor

It is GOOD to consider some alternative

We propose to determine both Mass Hierarchy and CP phase at the same time

- by using two Identical detectors with Different baselines
  $\rightarrow$cancellation of systematic errors
- in such a way that both detectors receive the neutrino beam with the same energy spectrum w/o oscillation
  $\rightarrow$reduction of BG uncertainties
- by running both $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ modes

$\Downarrow$

Clean Measurement of Specturm Modulation by Oscillation Effect

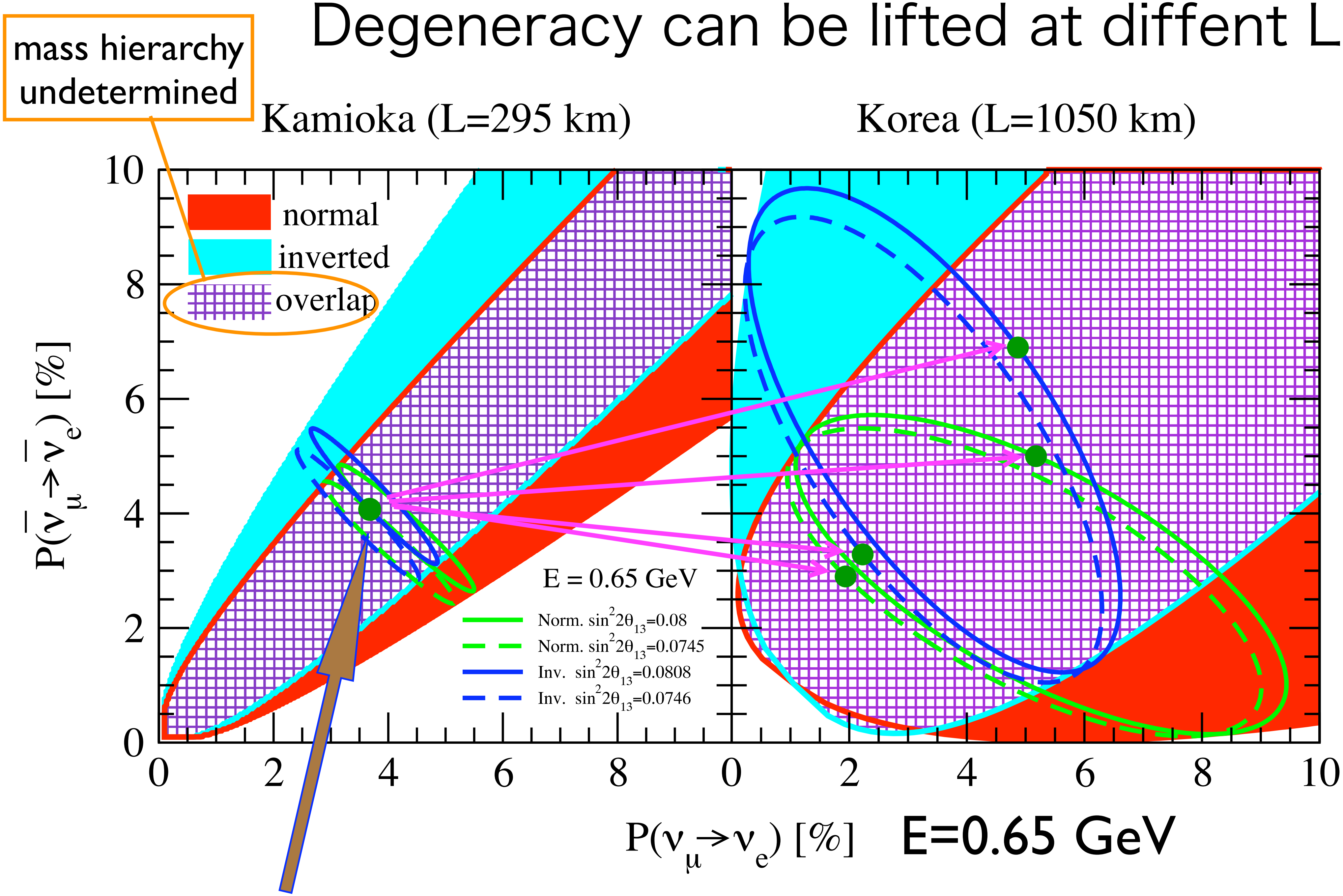
As a concrete example, we condisder JPARC as a source and 1 detector at Kamioka (L=295km) and other at Korea (L=1050km)

For alternative methods using only neutrino mode

See S. Palomarse-Ruiz's (hep-ph/0504015) talk

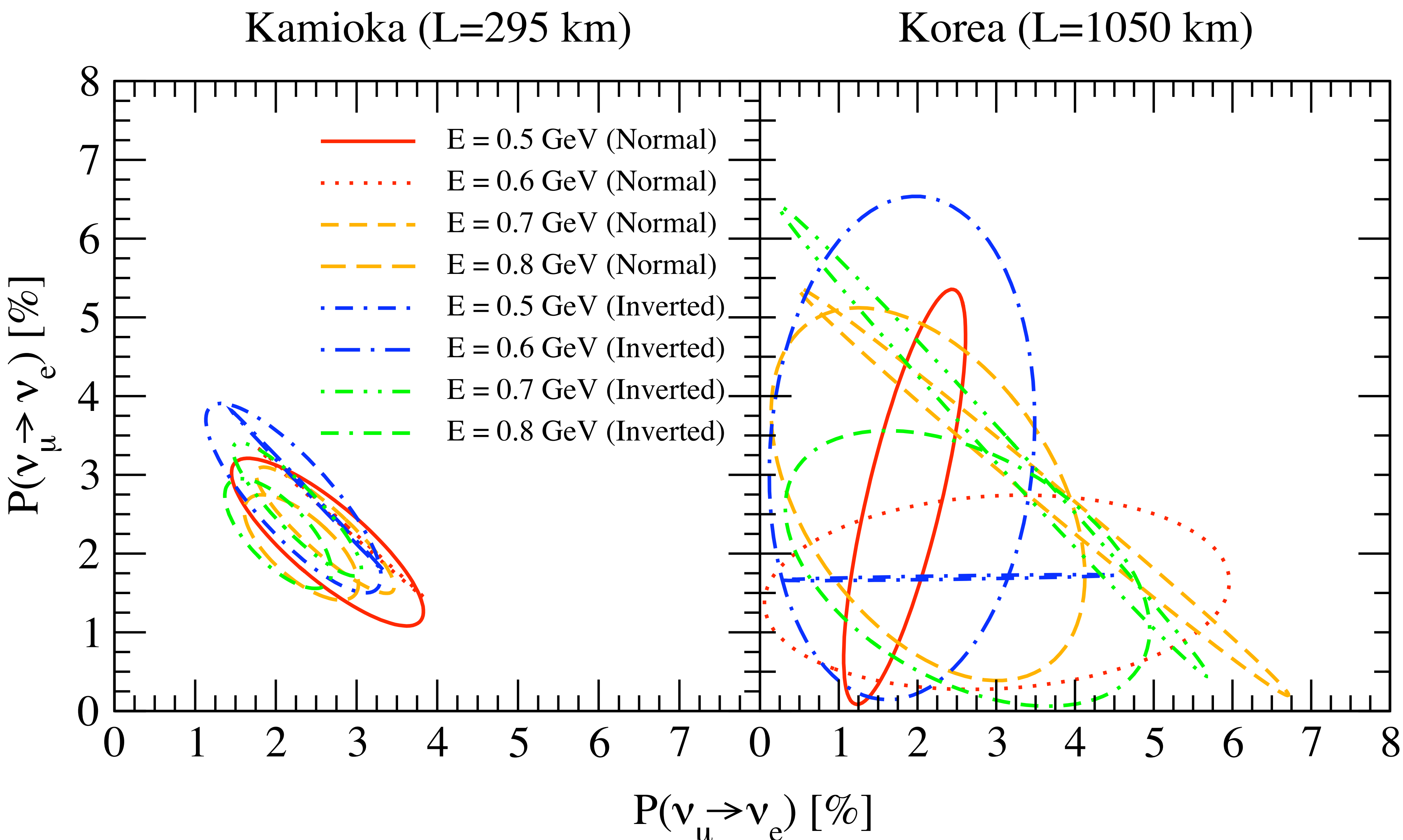
See N. Okamura's (hep-ph/0504061) talk

Degeneracy can be lifted at diffent L



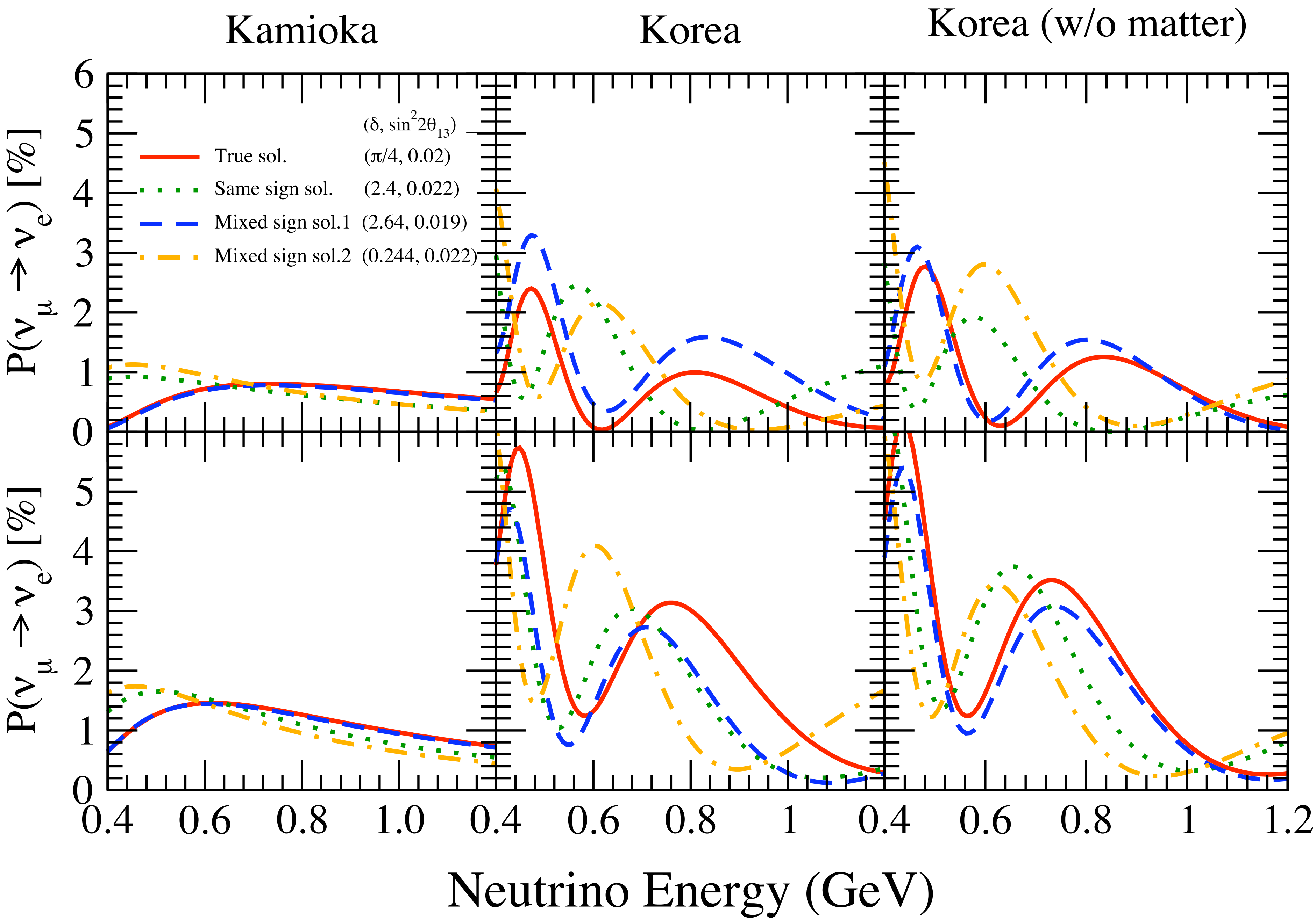
4 degenerate solutions → 4 non-degenerate points

Comparing Probabilities at Different Baselines

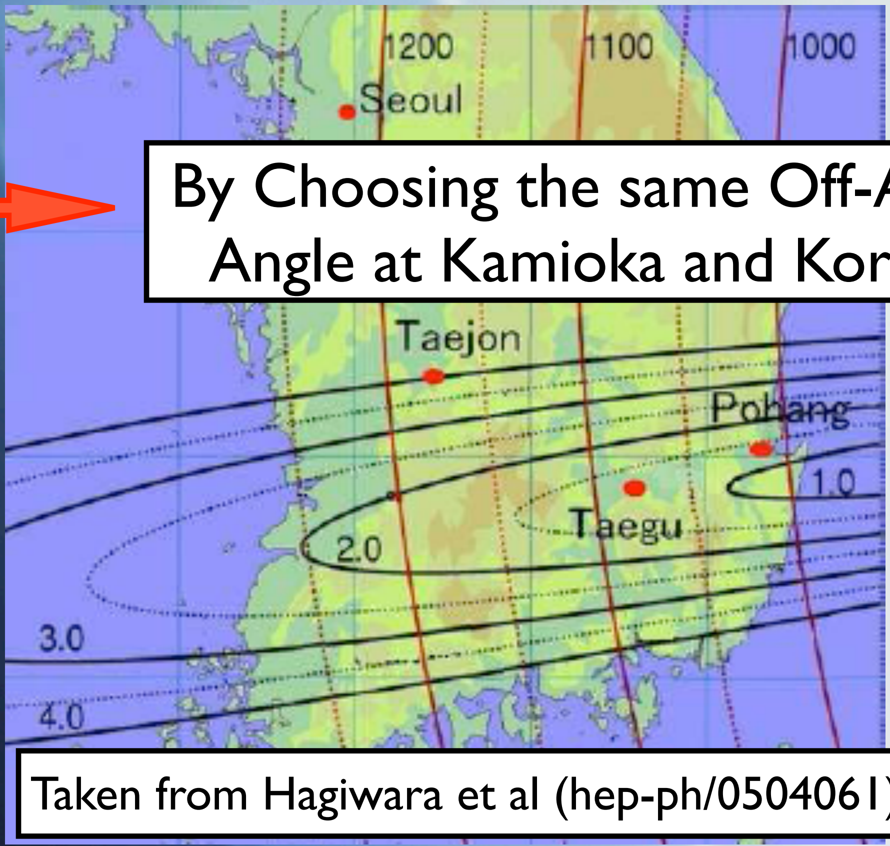


Despite that events # is smaller at Korea, energy depedendence is much stronger !

Energy Spectrum Information is Crucial



How can we get the same energy spectrum at 2 detectors with different baselines?

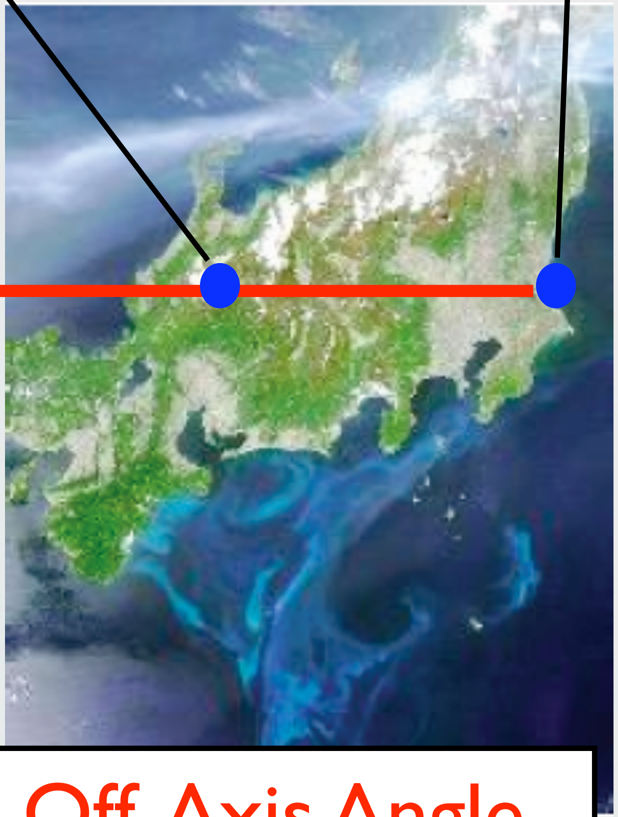


By Choosing the same Off-Axis Angle at Kamioka and Korea

Taken from Hagiwara et al (hep-ph/0504061)

Kamioka

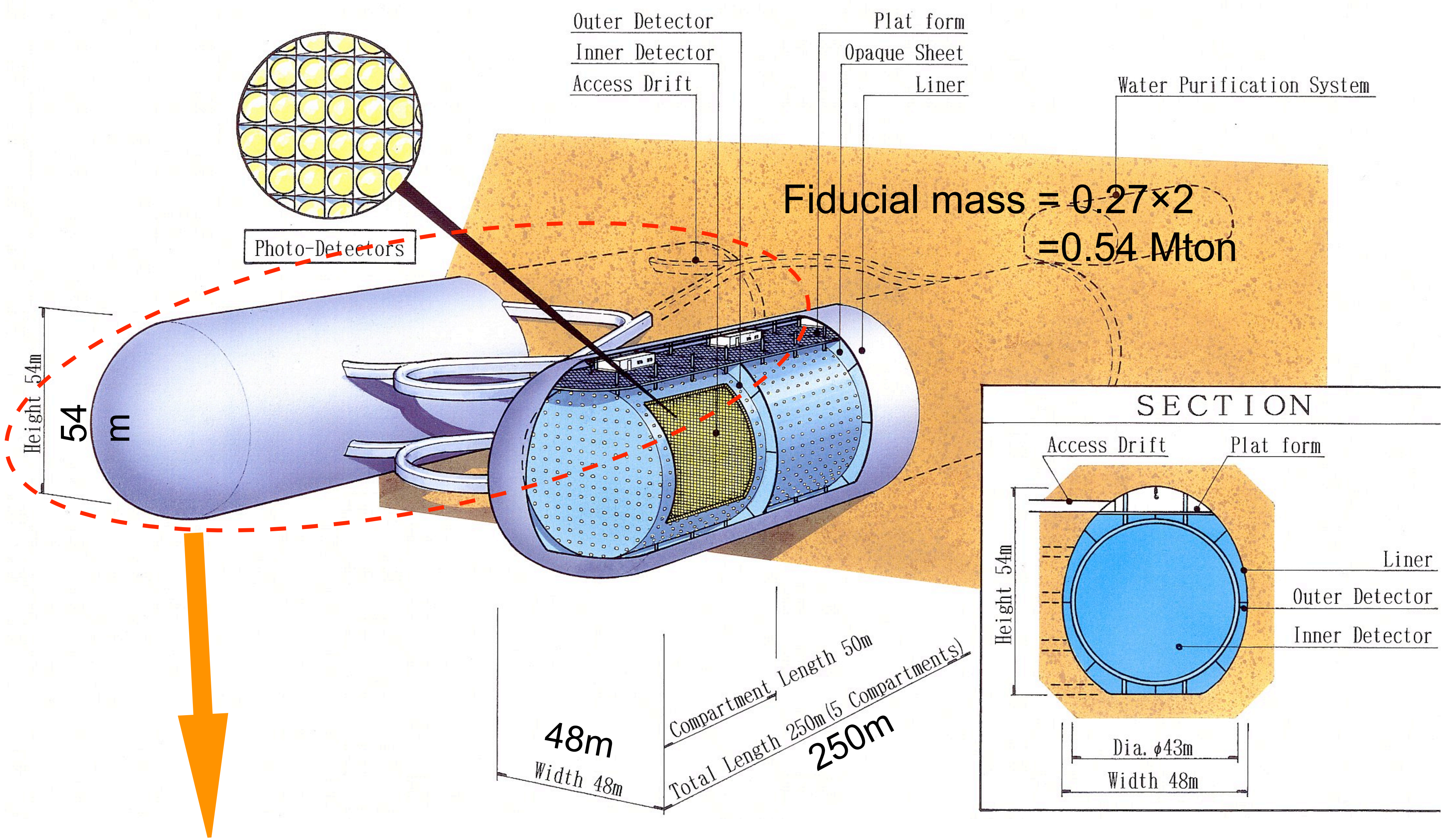
JPARC



It is possible to get the same Off-Axis Angle both at Kamioka and Korea

We assume OA 2.5° Beam with 4 MW Power and 2 HK (Mt) class detectors

Hyper-Kamiokande



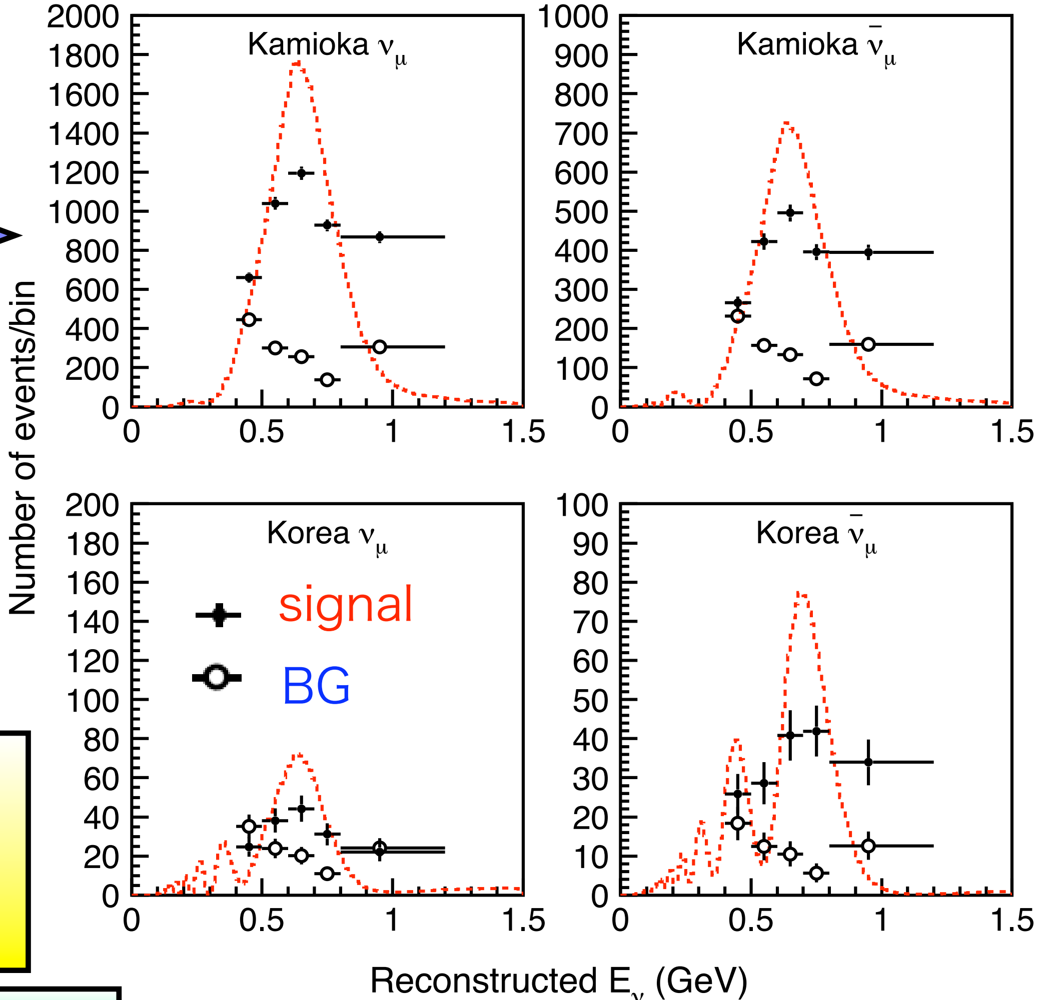
We propose to place one of them at somewhere in Korea

Expected Event # Dist.

4+4 yrs of $\nu+\bar{\nu}$

2×0.27 Mt FV

$\sin^2 2\theta_{13}=0.1, \delta = \pi/2$



Definiton of χ^2

$\begin{pmatrix}\nu \\ \bar{\nu}\end{pmatrix} \times \begin{pmatrix}\text{kamioka} \\ \text{korea}\end{pmatrix}$ = 4 combinations

5 energy bins

$$\chi^2 = \sum_{k=1}^{4} \left(\sum_{i=1}^{5} \frac{\left(N(e)_i^{\text{obs}} - N(e)_i^{\text{exp}}\right)^2}{\sigma_i^2} \right) + \sum_{j=1}^{3} \left(\frac{\epsilon_j}{\tilde{\sigma}_j} \right)^2$$

$$N(e)_i^{\text{exp}} = N_i^{\text{BG}} \cdot (1 + \sum_{j=1}^{2} f_j^i \cdot \epsilon_j) + N_i^{\text{signal}} \cdot (1 + f_3^i \cdot \epsilon_3)$$

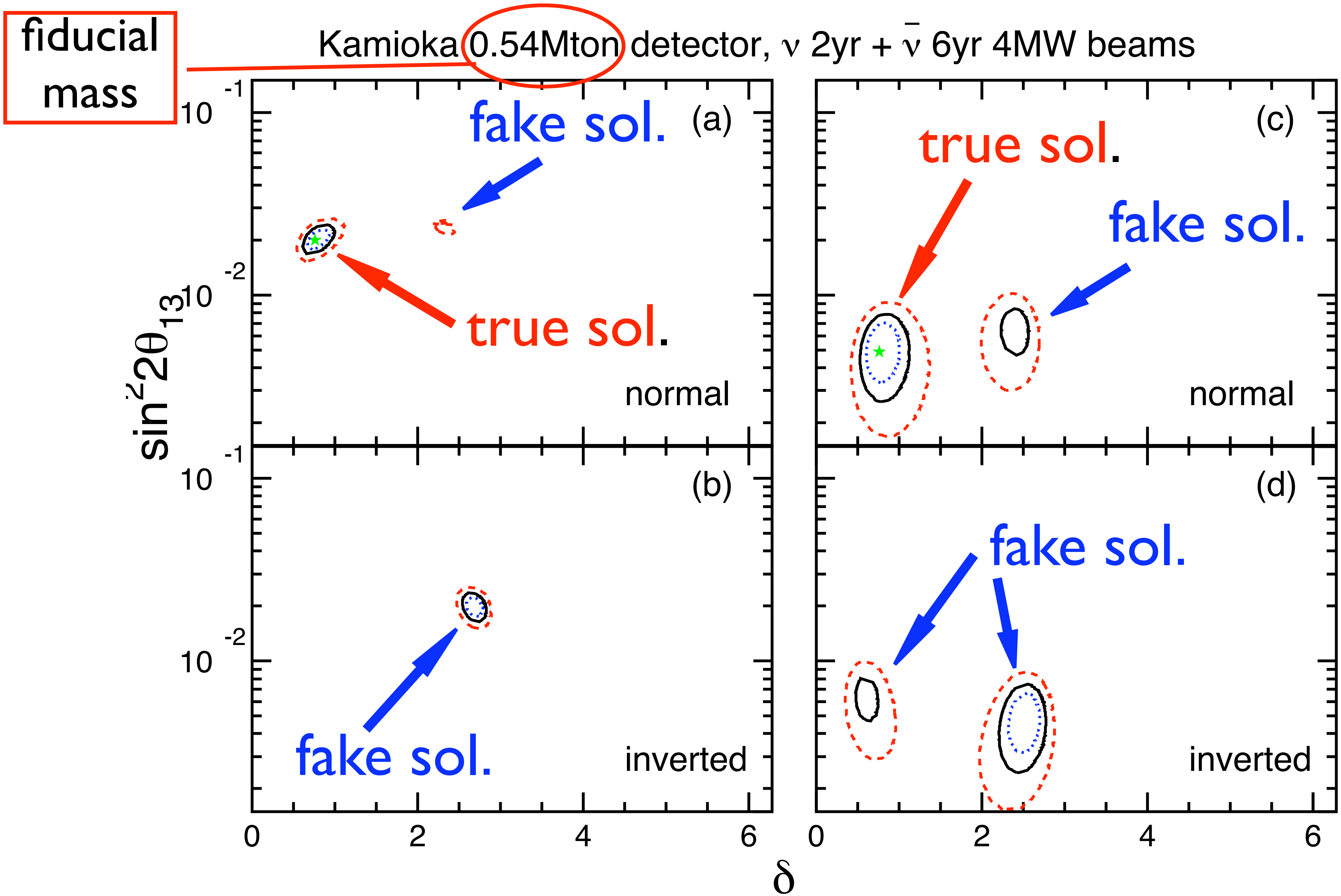
Systematic Errors

5 % BG (Overall)

5 % BG (Energy Dep.)

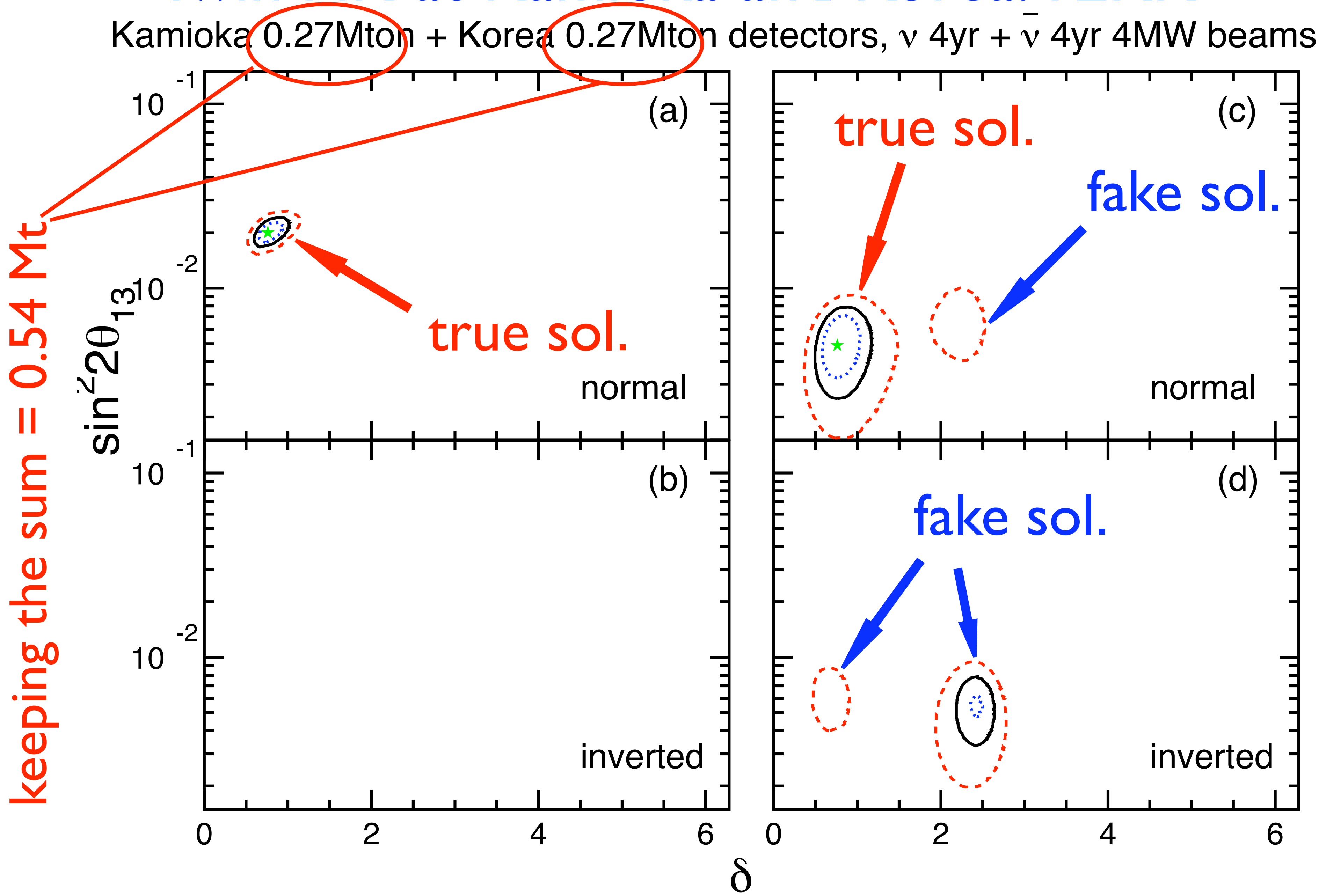
5 % Signal Efficiency

Examples of Degenerate Solutions (w. only HK@Kamioka)



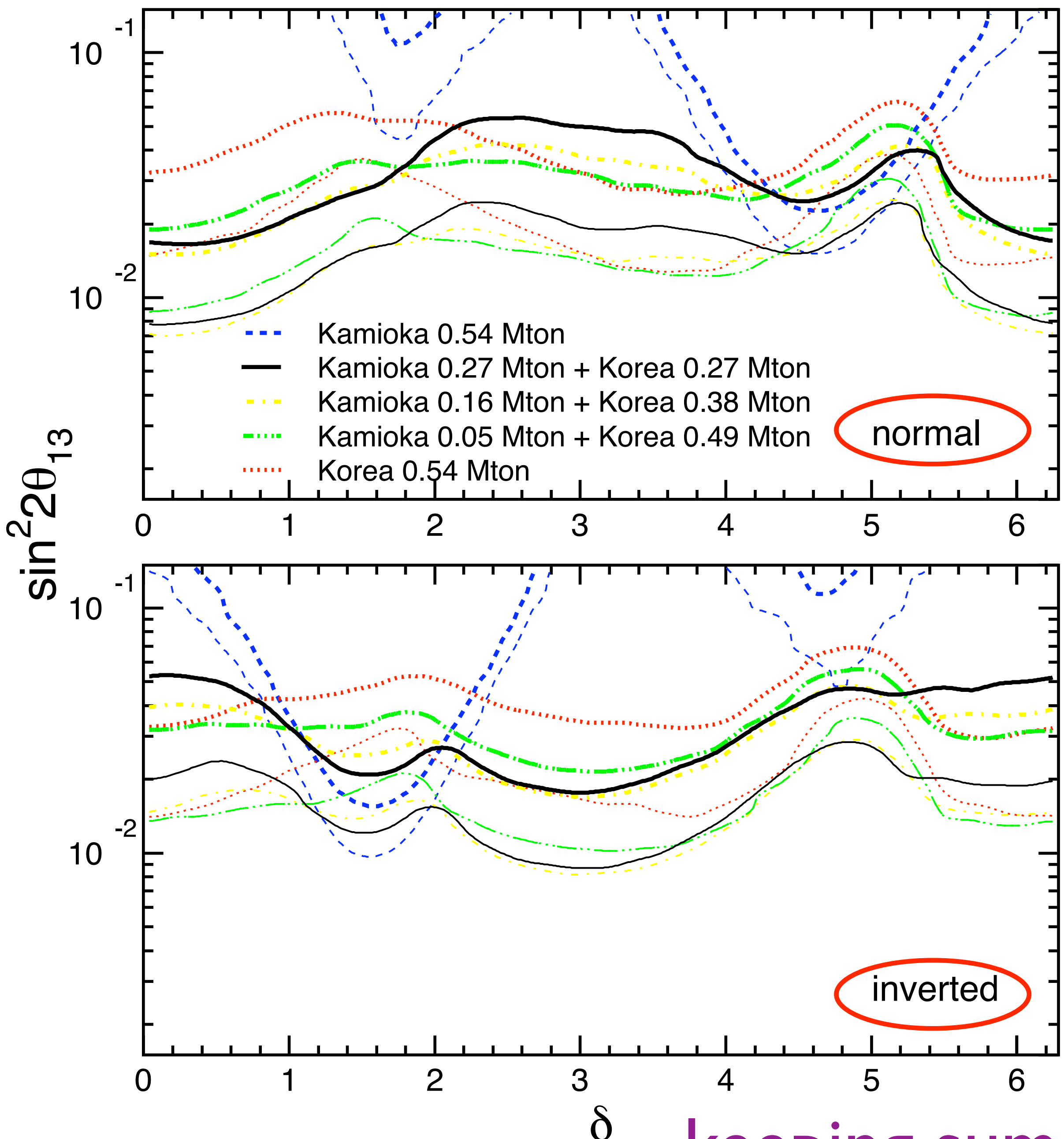
Only HK@Kamioka can not Resolv All the Degeneray

Twin HK at Kamioka and Korea: T2KK



Twin HKs can determine Mass Hierarchy if θ_{13} is not so small!

Regions of Sensitivities for Mass Hierarchy



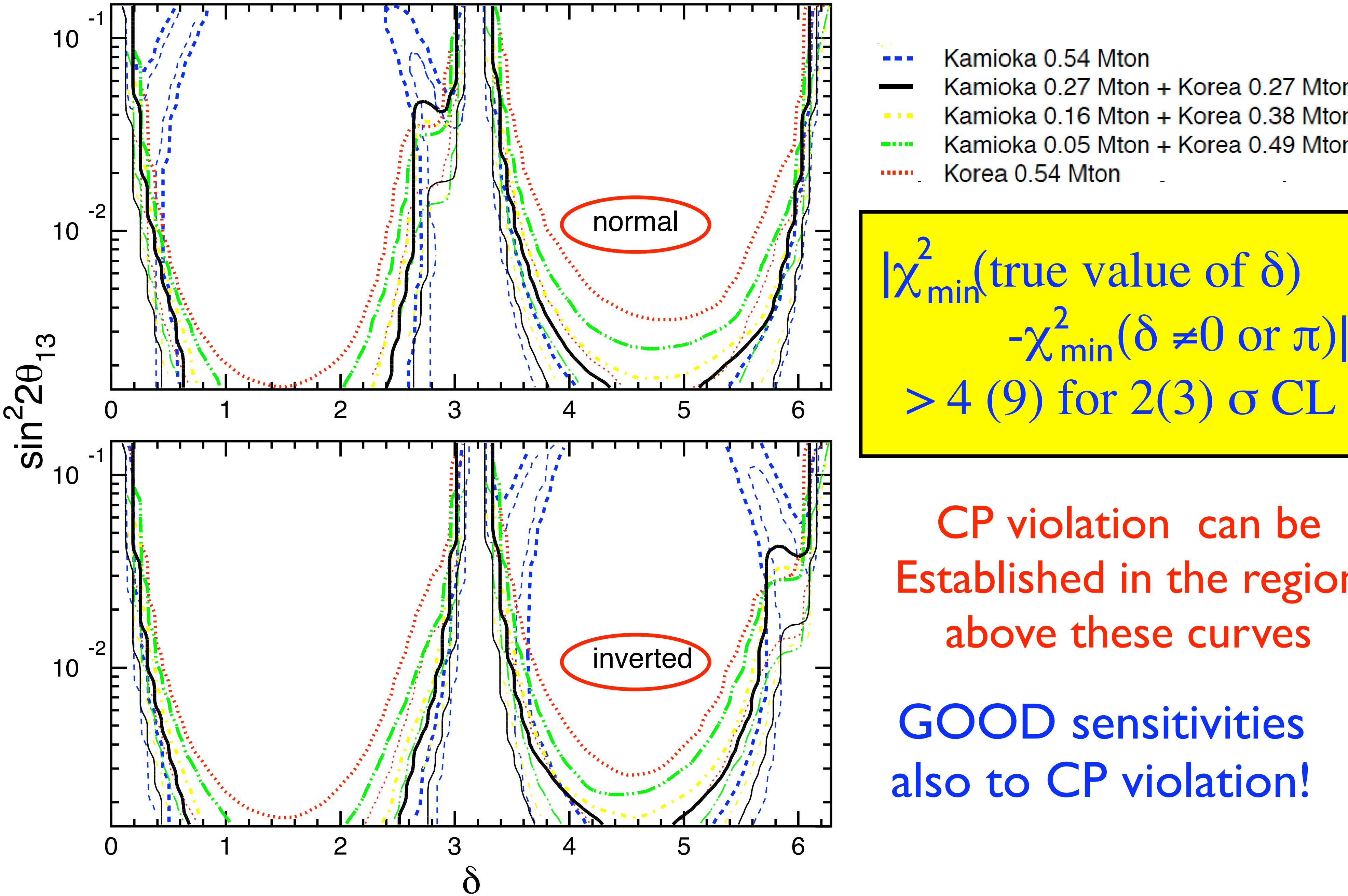
$|\chi^2_{min}$(true hierachy)
$-\chi^2_{min}$(wrong hierachy)$|$
> 4 (9) for 2(3) σ CL

Mass Hierarchy can be Determined in the region above these curves

Choice of the same detector size is BEST!

keeping sum of total FV = 0.54 Mt

Sensitivity to CP violation



$|\chi^2_{min}(\text{true value of } \delta)$
$-\chi^2_{min}(\delta \neq 0 \text{ or } \pi)|$
$> 4\ (9)$ for $2(3)\ \sigma$ CL

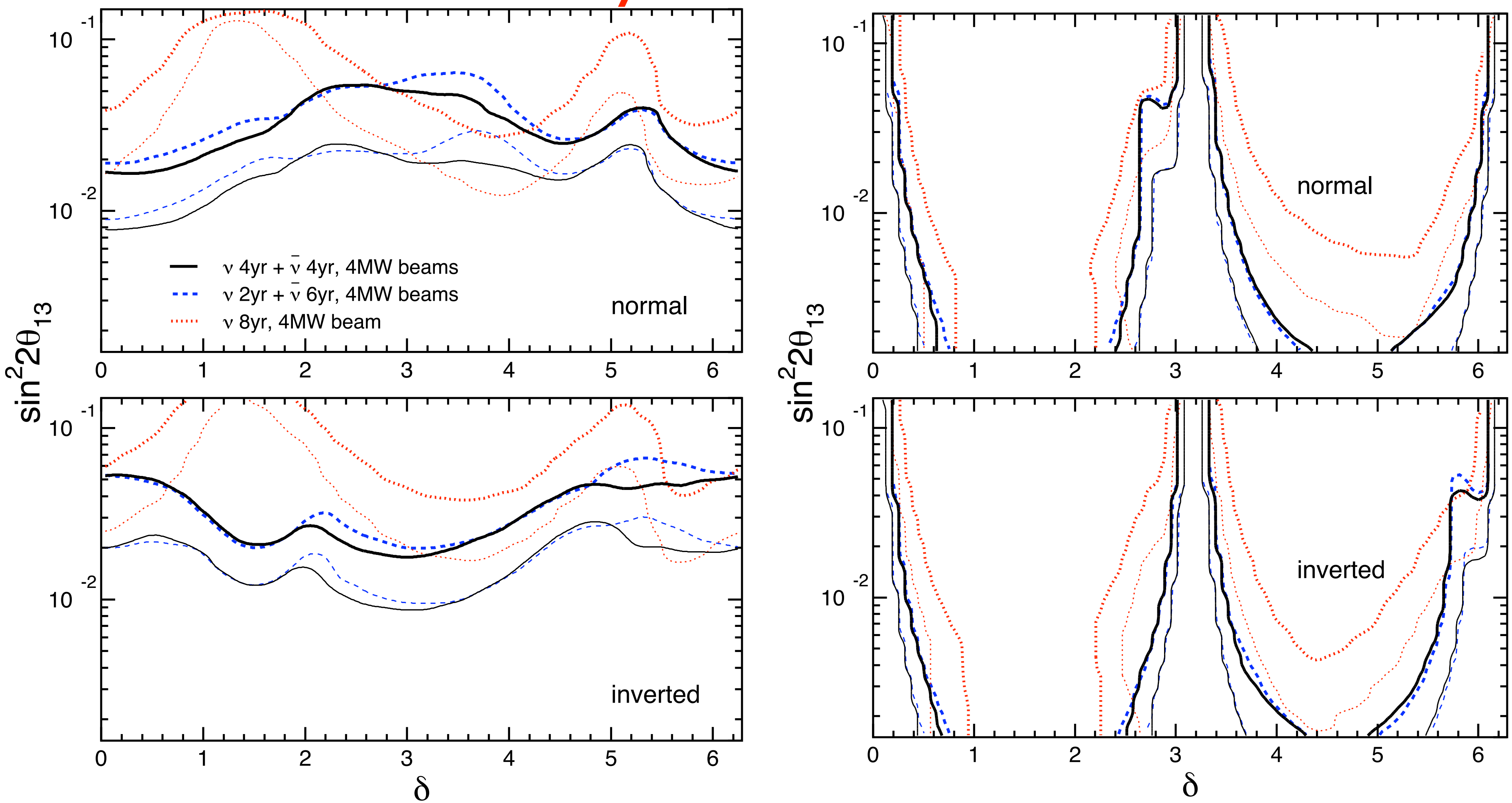
CP violation can be Established in the region above these curves

GOOD sensitivities also to CP violation!

Optimizing Running Time

Mass Hierarchy

CP Violation



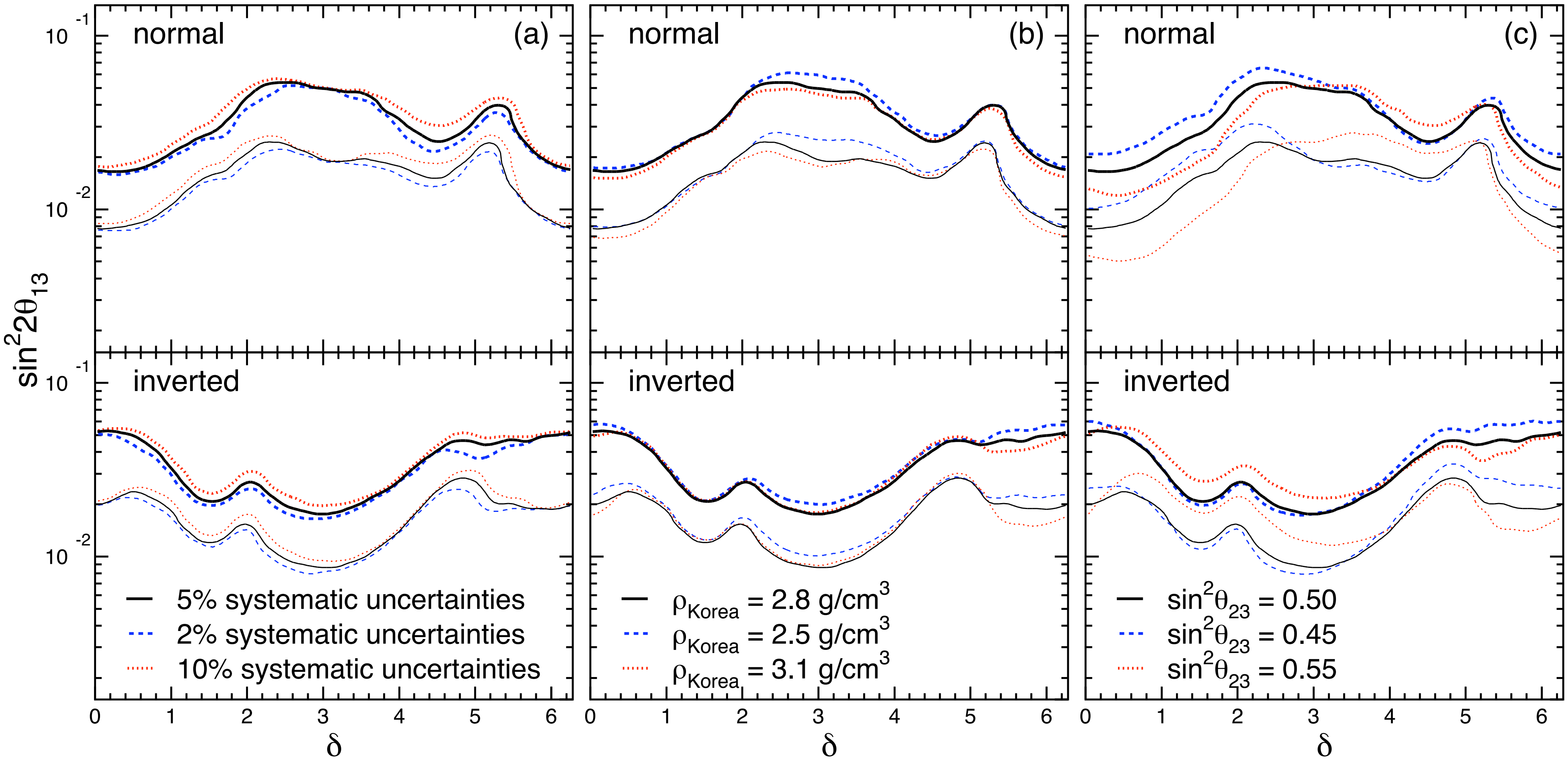
4+4 yrs runs of $\nu + \bar{\nu}$ seems to be Optimal

Stability Check of Our Results Against

Change of Systematic errors

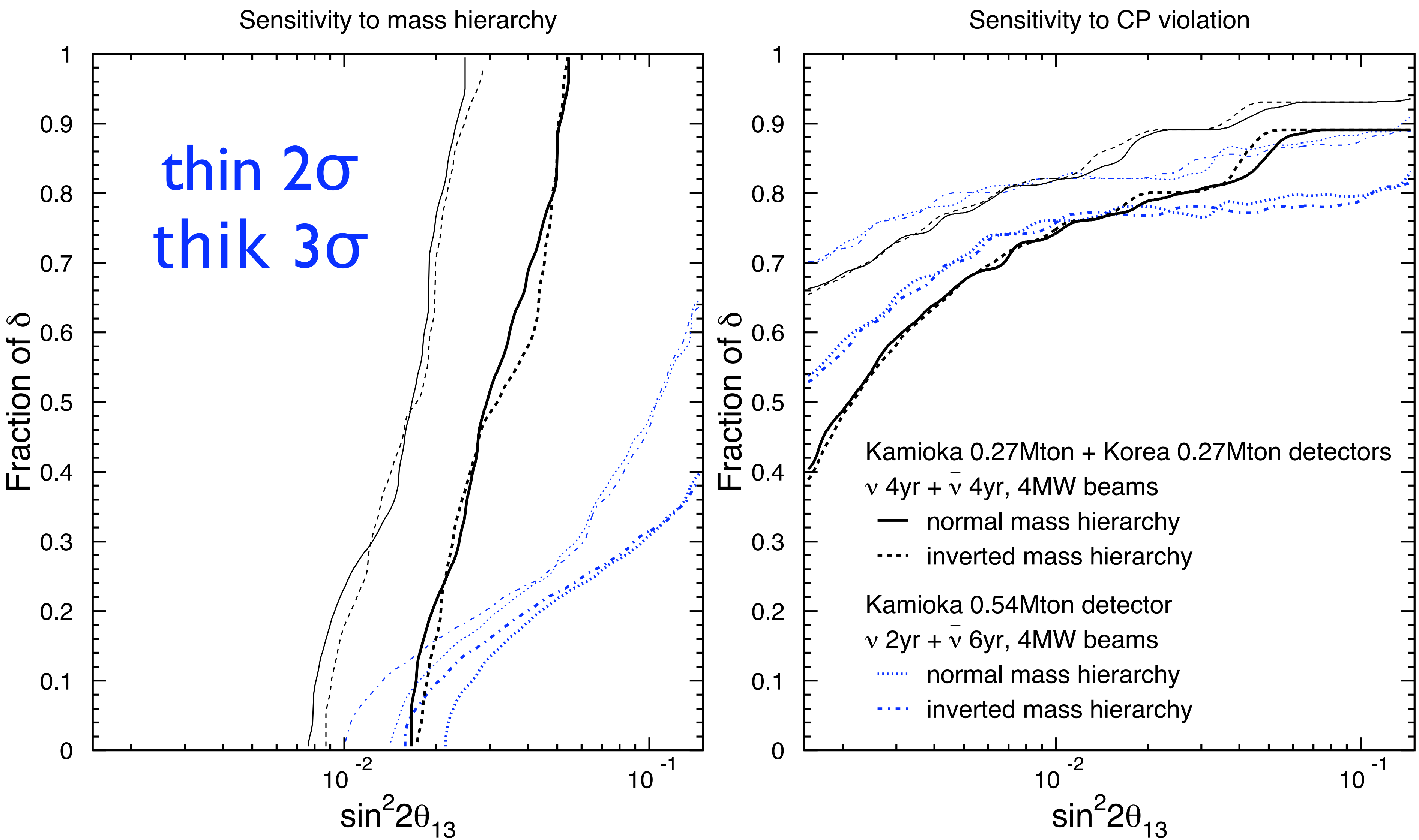
Change of mater density

Deviation of θ_{23} from maximal

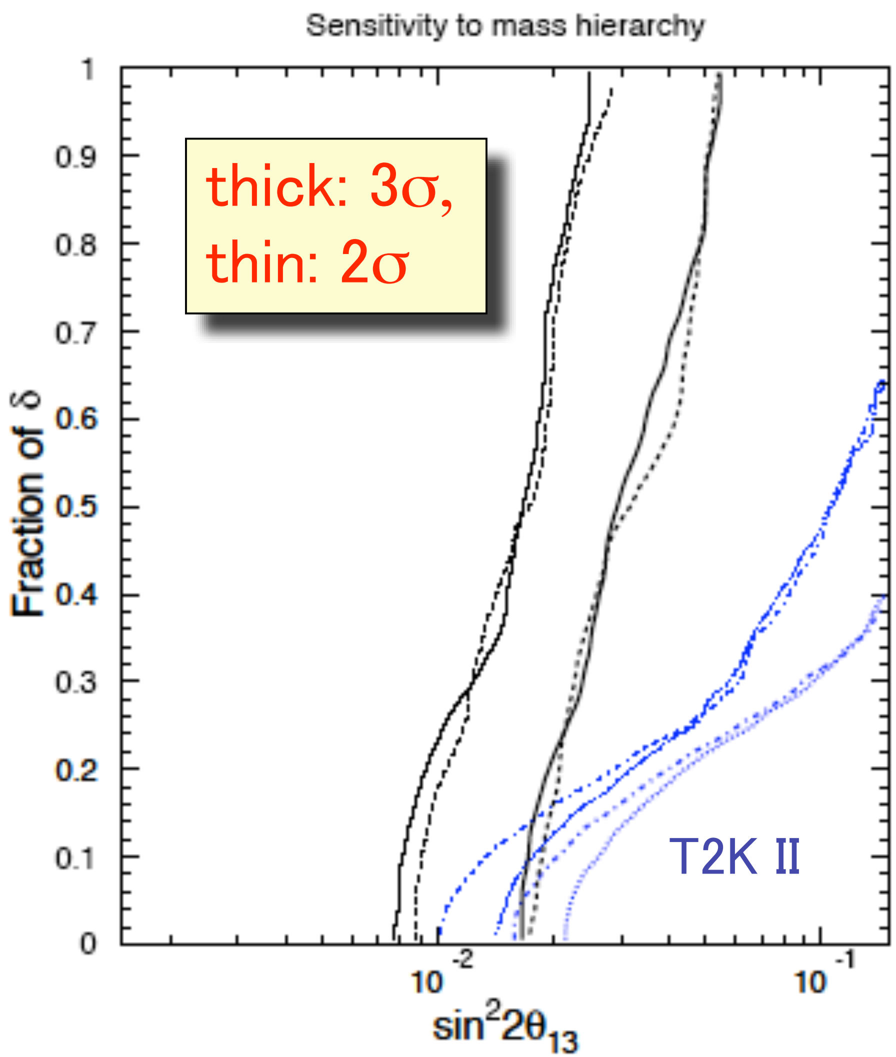


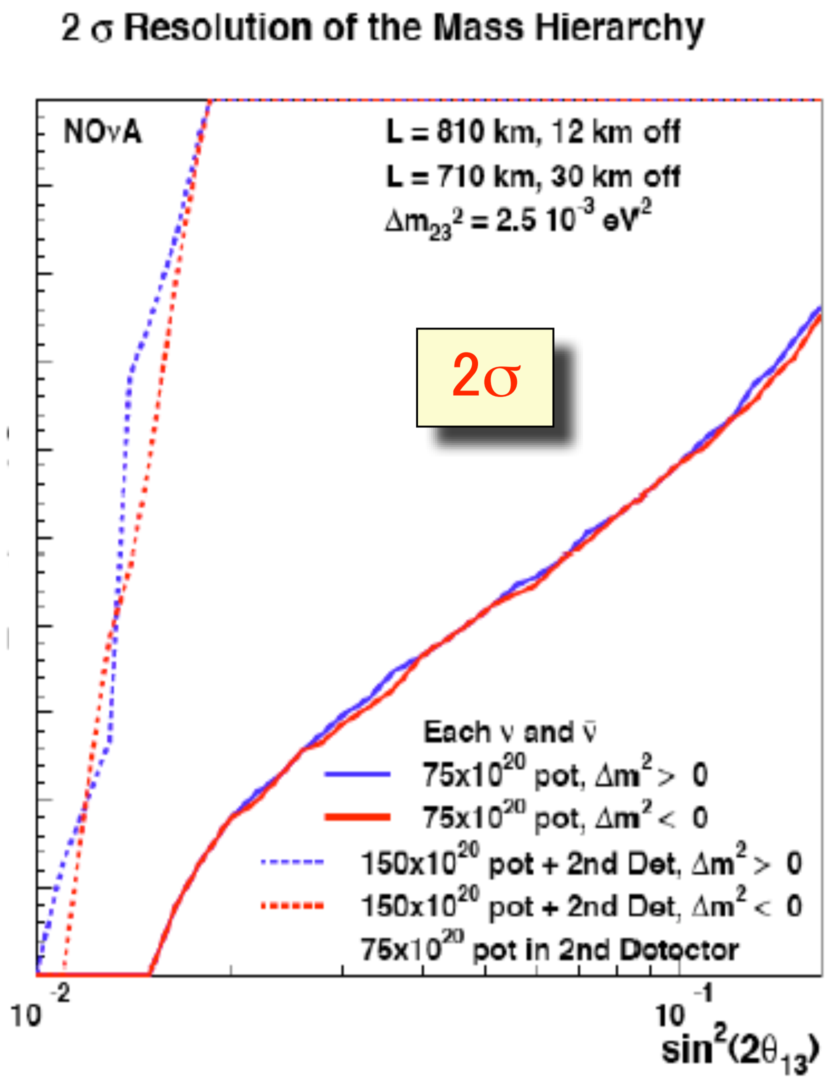
Our Results are Stable

Sensitivity: T2KK vs T2K-II (Orignal)

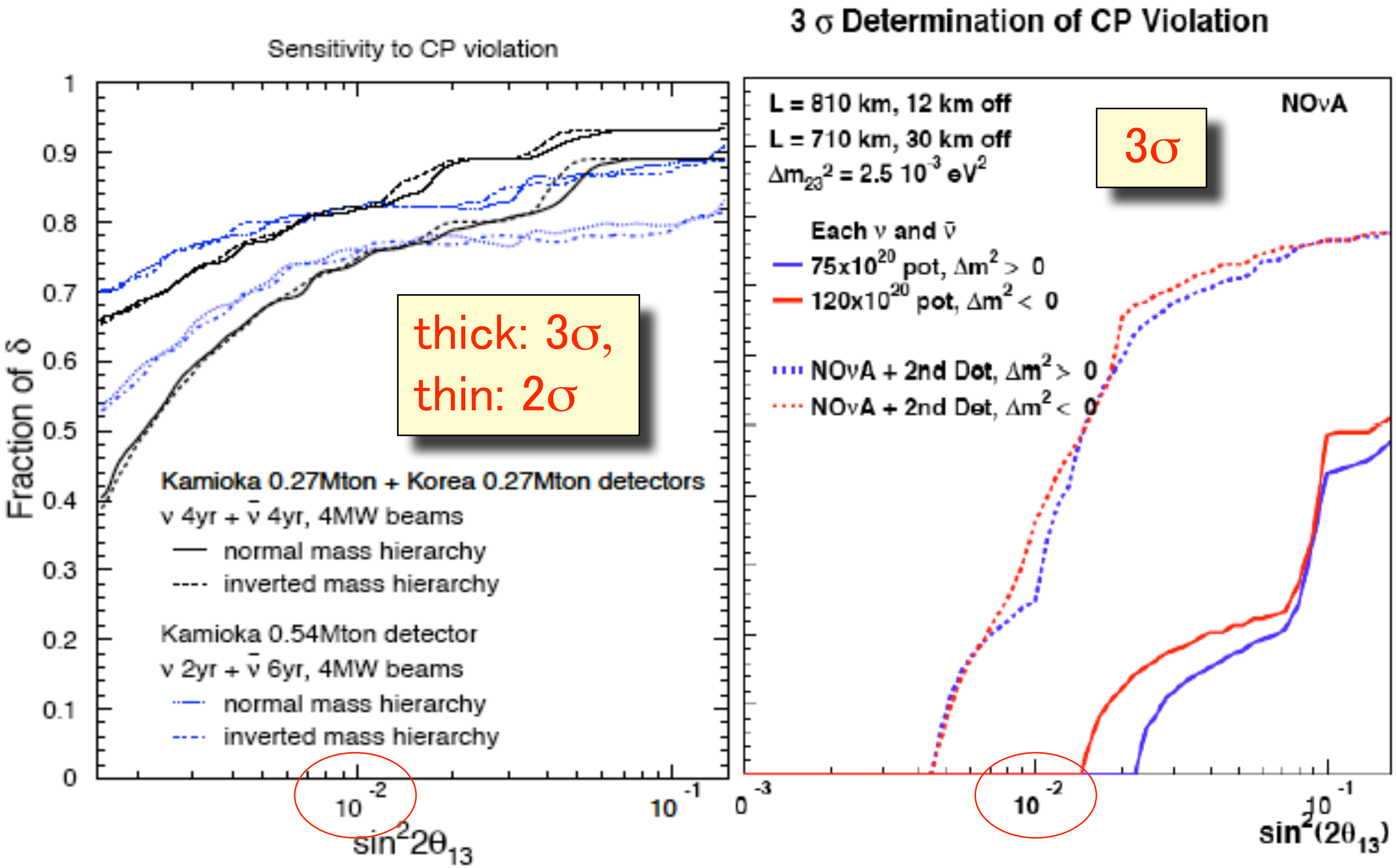


Sensitivity to mass hierarchy: T2K-II vs. (Kam+Korea) vs. Nova

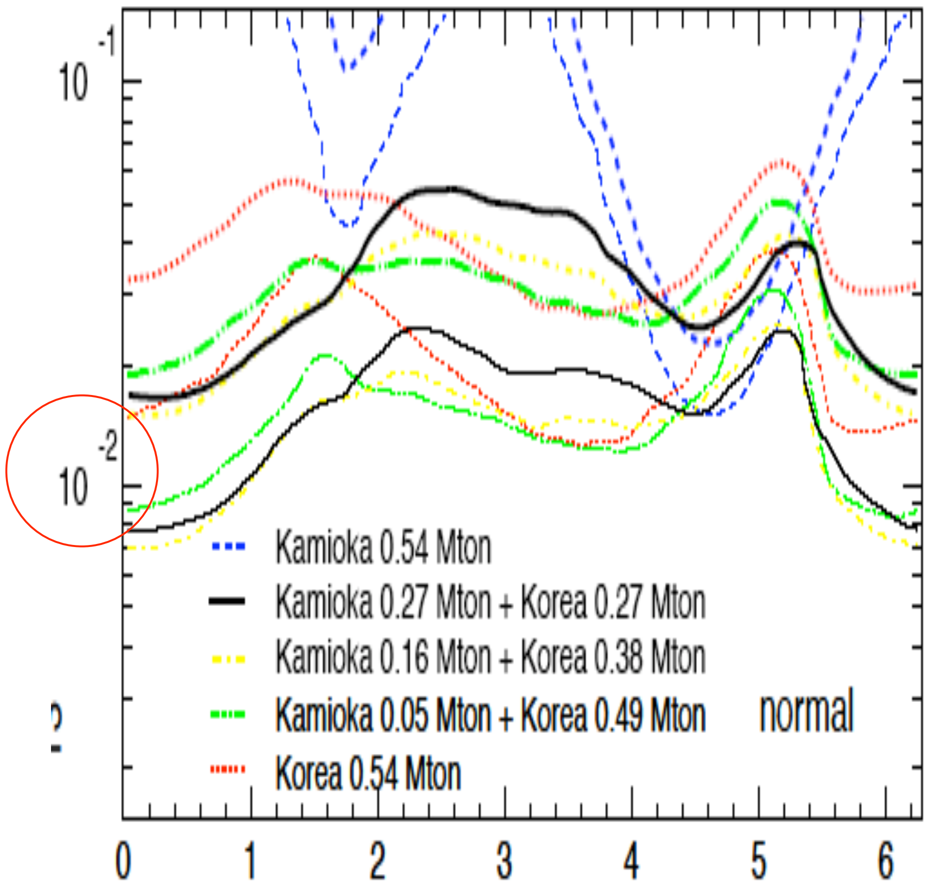




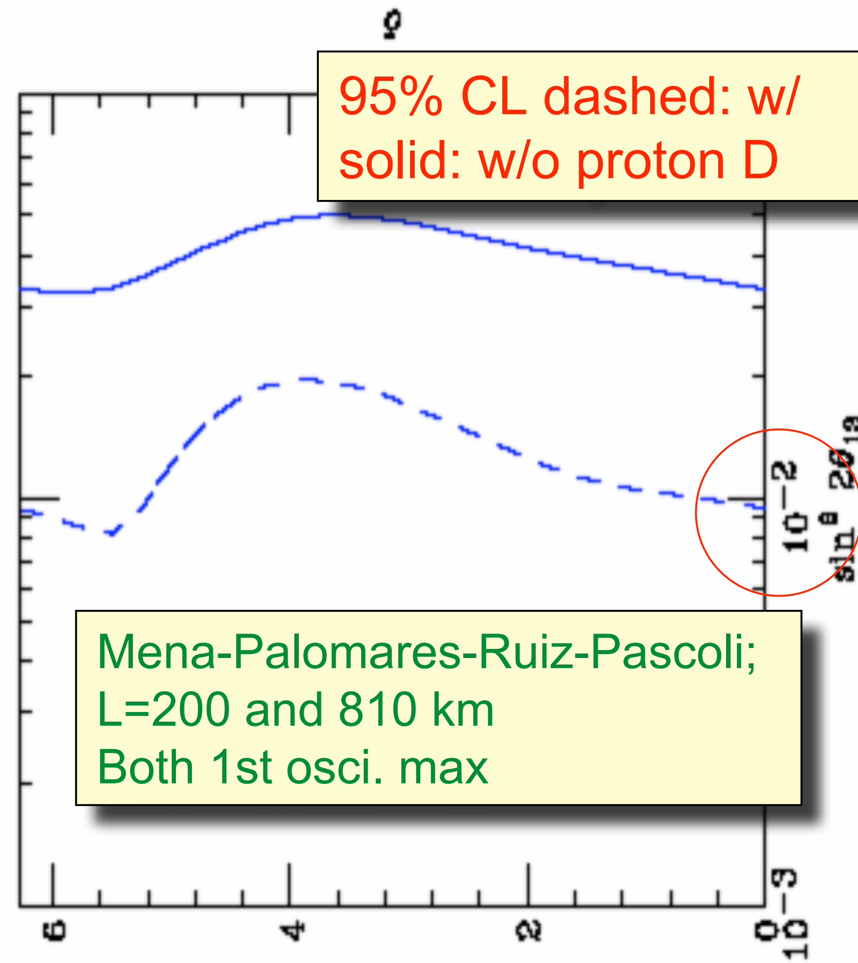
Sensitivity to CP:
T2K-II vs. (Kam+Korea) vs. Nova



Sensitivity to mass hierarchy: T2K-II vs. (Kam+Korea) vs. super-Nova



thick: 3σ,
thin: 2σ



95% CL dashed: w/
solid: w/o proton D

Mena-Palomares-Ruiz-Pascoli;
L=200 and 810 km
Both 1st osci. max

δ

Summary

- We propose to determine mass hierarchy and CP phase at the same time by using Two Identical Detectors with Different Baselines
- As a concrete example, we consider JPARC Phase II 4MW Beam Power and 0.27 Mt Detector at Kamioka and other 0.27 Mt one at Korea
- 4 + 4 yrs runs of $\nu+\bar{\nu}$ modes, it is possible to determine mass hierachy for $\sin^2 2\theta_{13} > 0.03$ (0.055) at 2 (3) σ CL for any value of δ
- At the same time, good sensitivity to CP violation