Kamioka-Korea 2 detector complex for determining neutrino parameters

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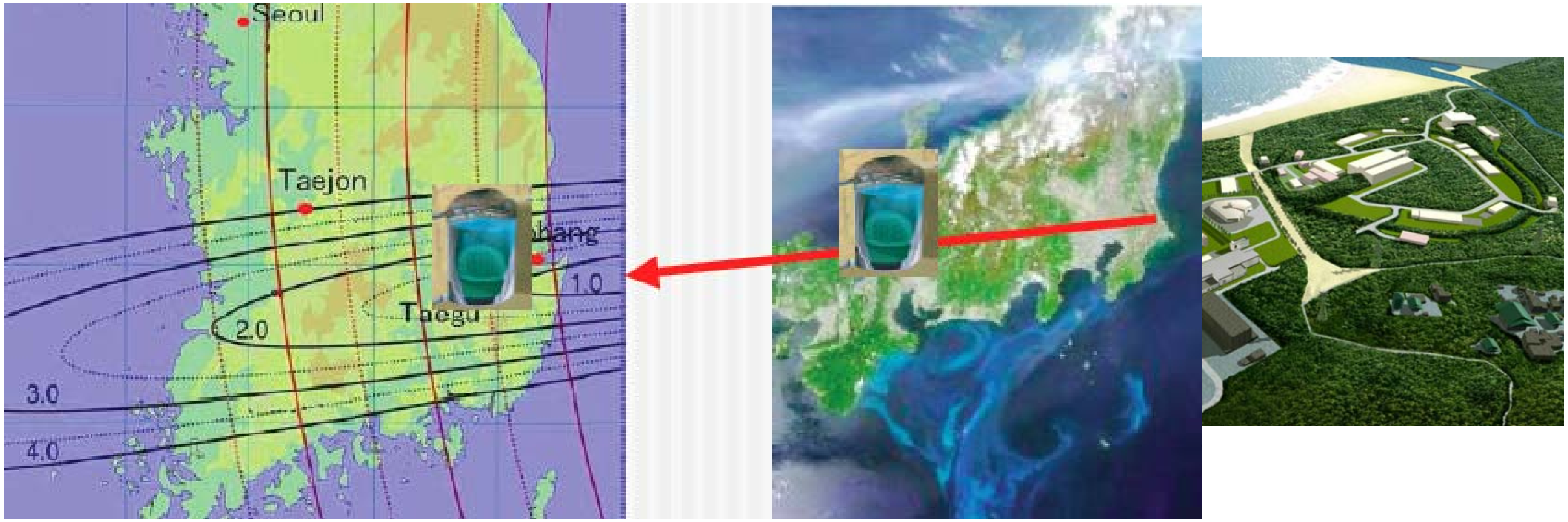
T2KK; Tokai-to-Kamioka-Korea identical two-detector complex

Ishitsuka et al., hep-ph/0504026
Kajita et al., hep-ph/0609286

- An improvement over T2K II design with Hyper-K @ Kamioka with 1 megaton water



Exploring the unknowns; 1-3 sector and ν mass hierarchy

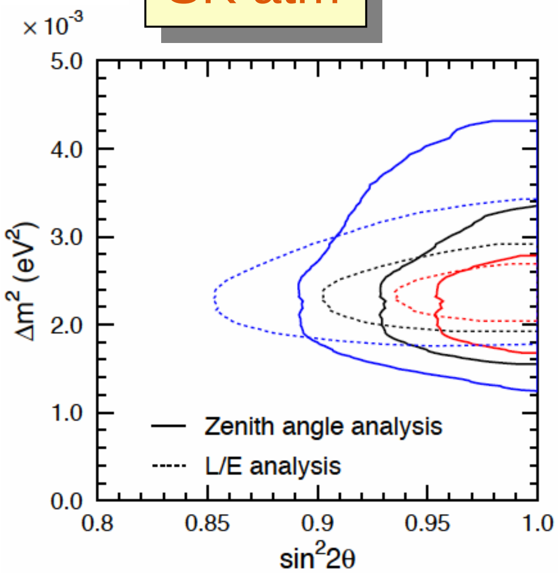
$\nu_\alpha = U_{\alpha i}\, \nu_i$

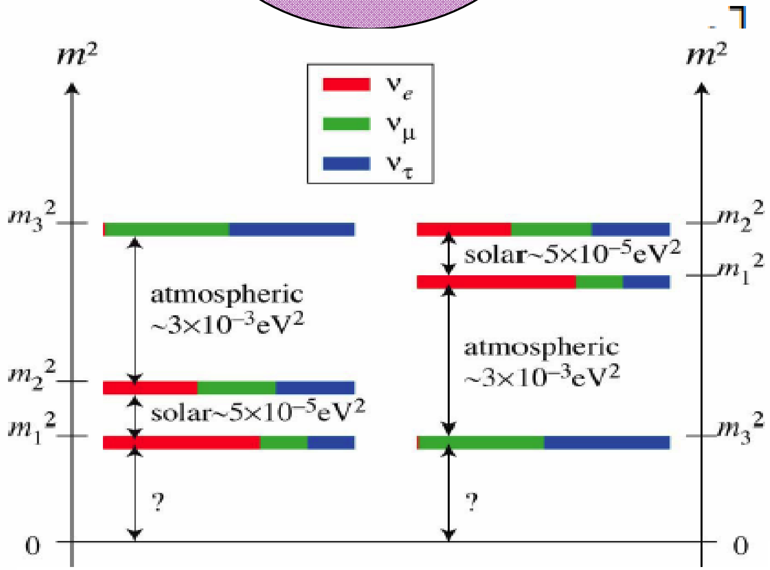
Atm + accel ν =>

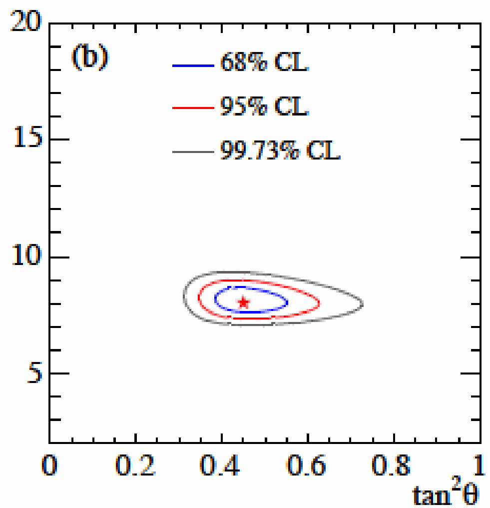
$$U \equiv U_{\rm MNS}\cdot\Gamma = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times$$

<= solar + reactor ν

SK atm

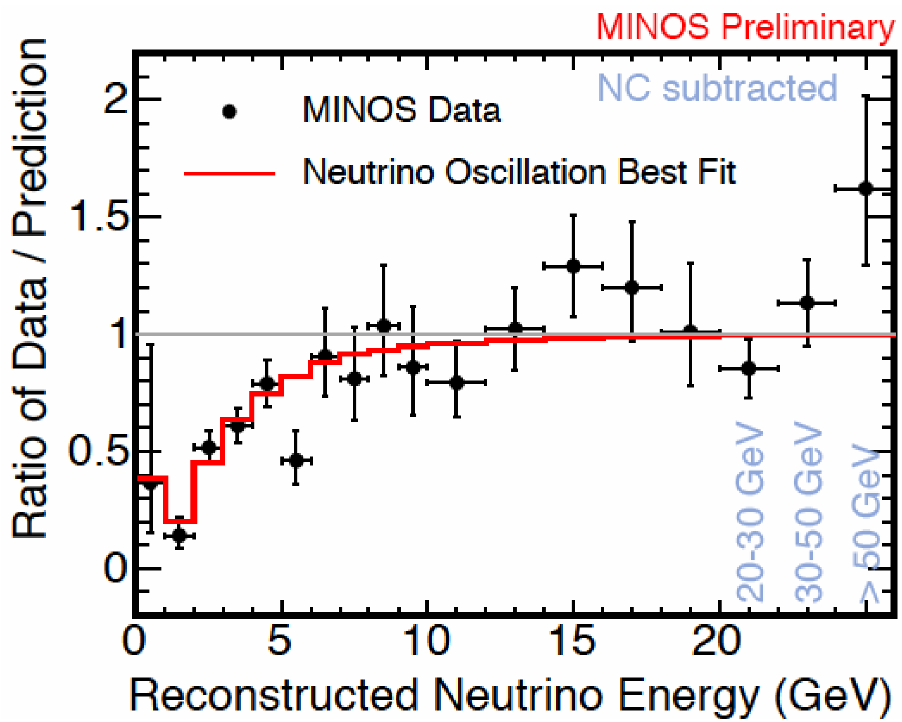


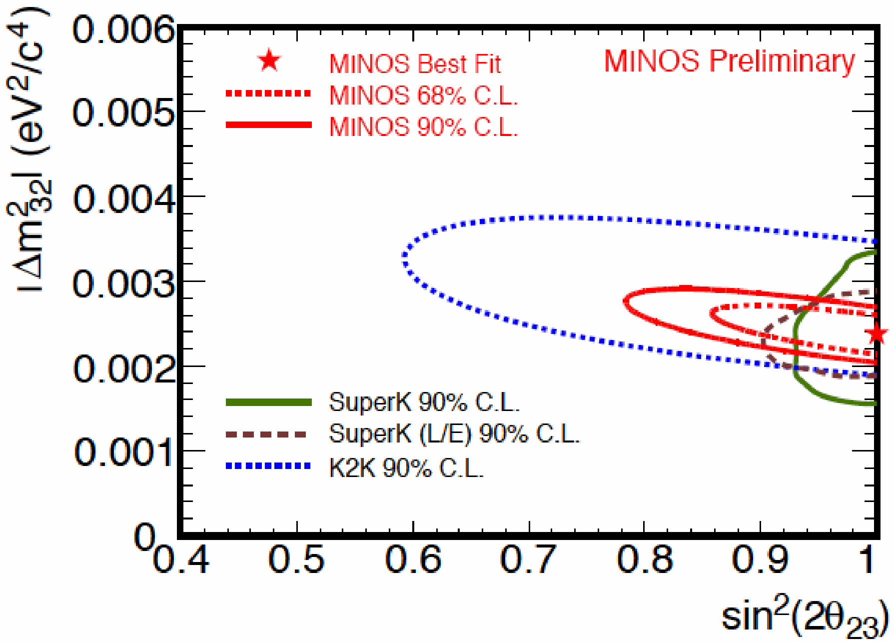




solar+KamLAND

The era of precision measurement is coming to reality



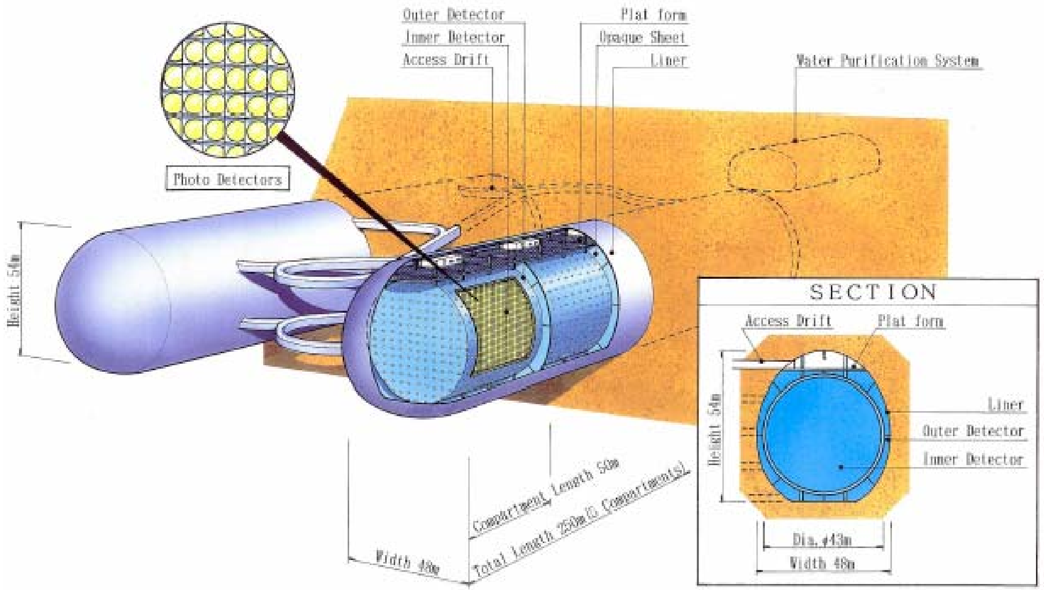


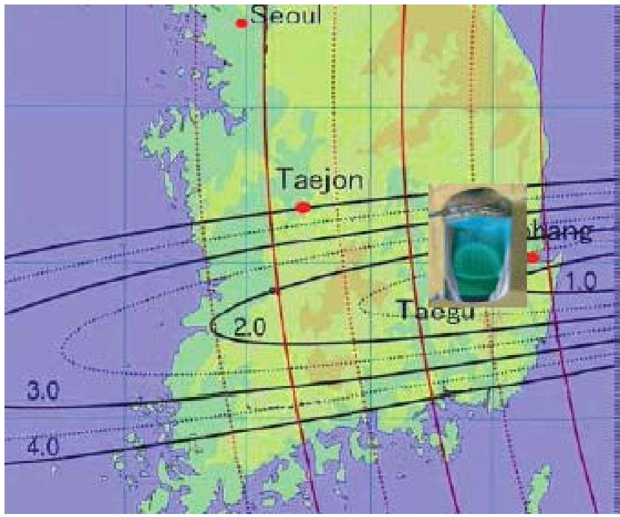
- By only 2 years of running, MINOS improved the current uncertainty of Δm^2_{atm} !

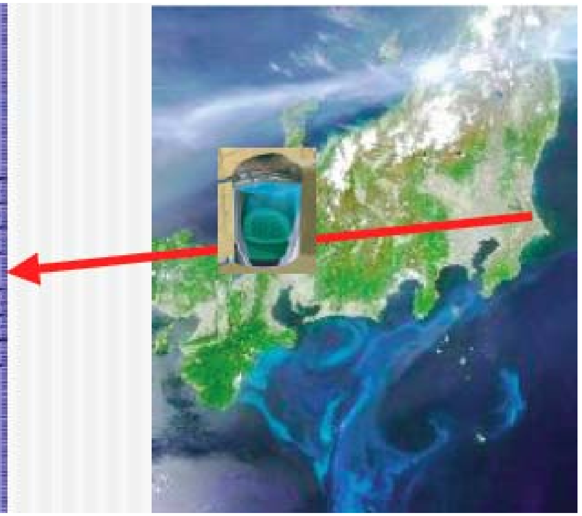
What's good in T2KK?

#1. Current design of Hyper-K contains 2 tanks, thus ``prepares'' for T2KK

Why don't you bring one of the 2 tanks to Korea? (@EPP2010)

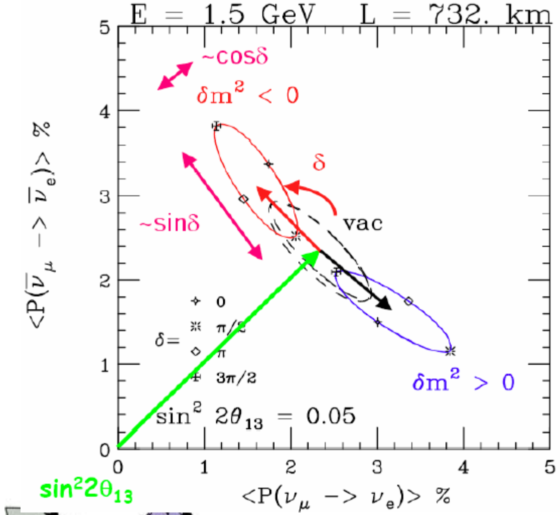


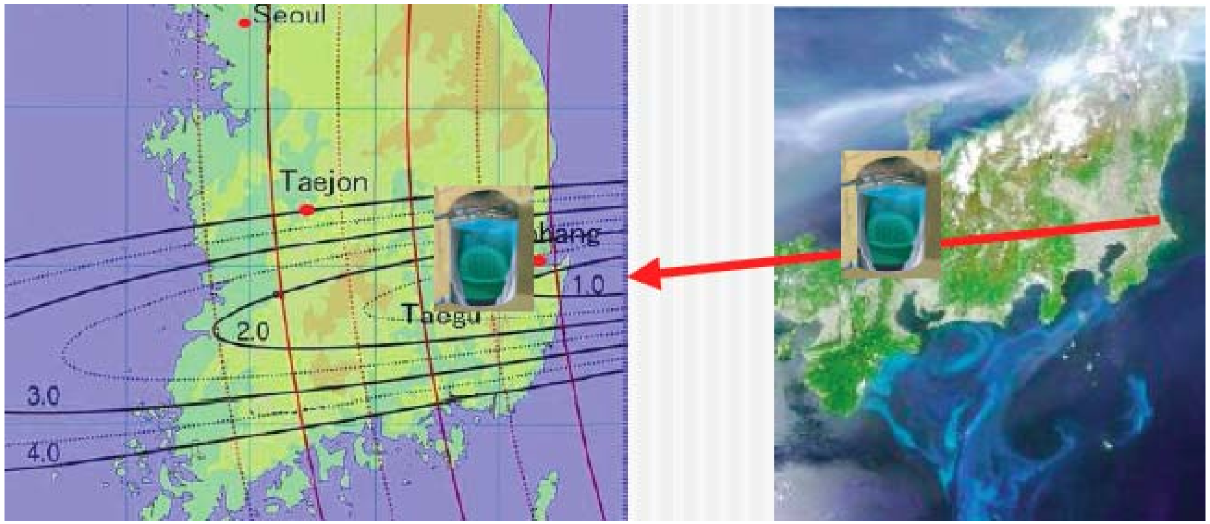


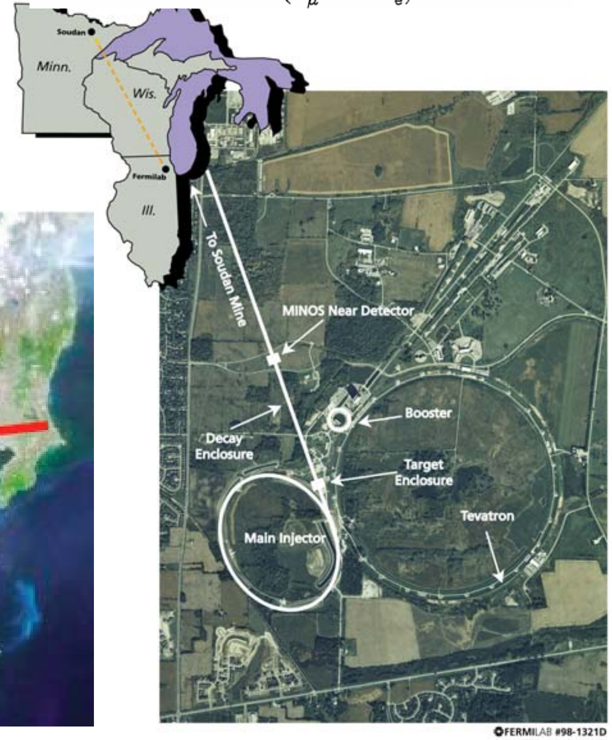


#2. Sign-Δm^2 degeneracy

- Resolution of sign-Δm^2 degeneracy requires the matter effect
- Requires baseline ~1000 km
- 2nd detector seems required to go down to $\sin^2 2\theta_{13}$=.02







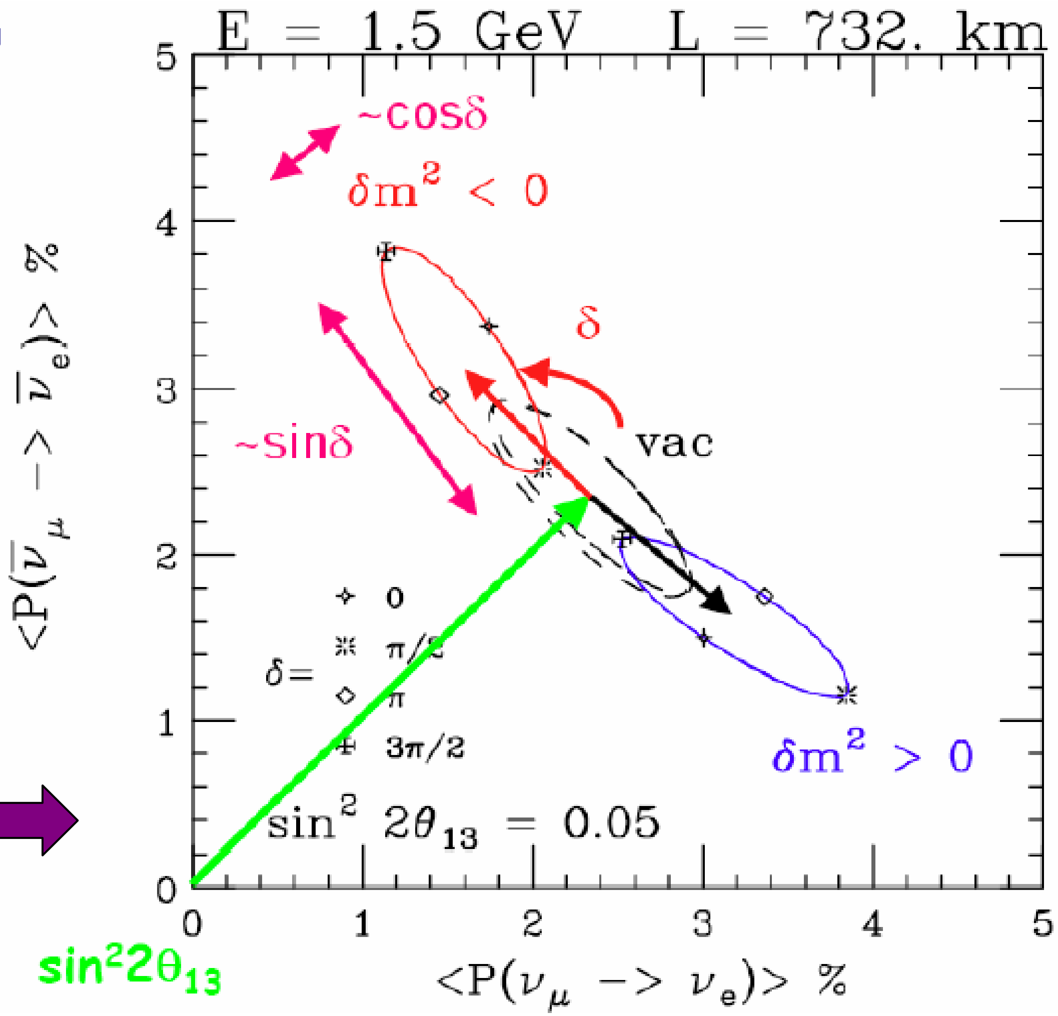
A machinery in my talk

Oscillation probability draw ellipse if plotted in bi-P plane

Role played by CP phase δ and the matter clearly distinguished

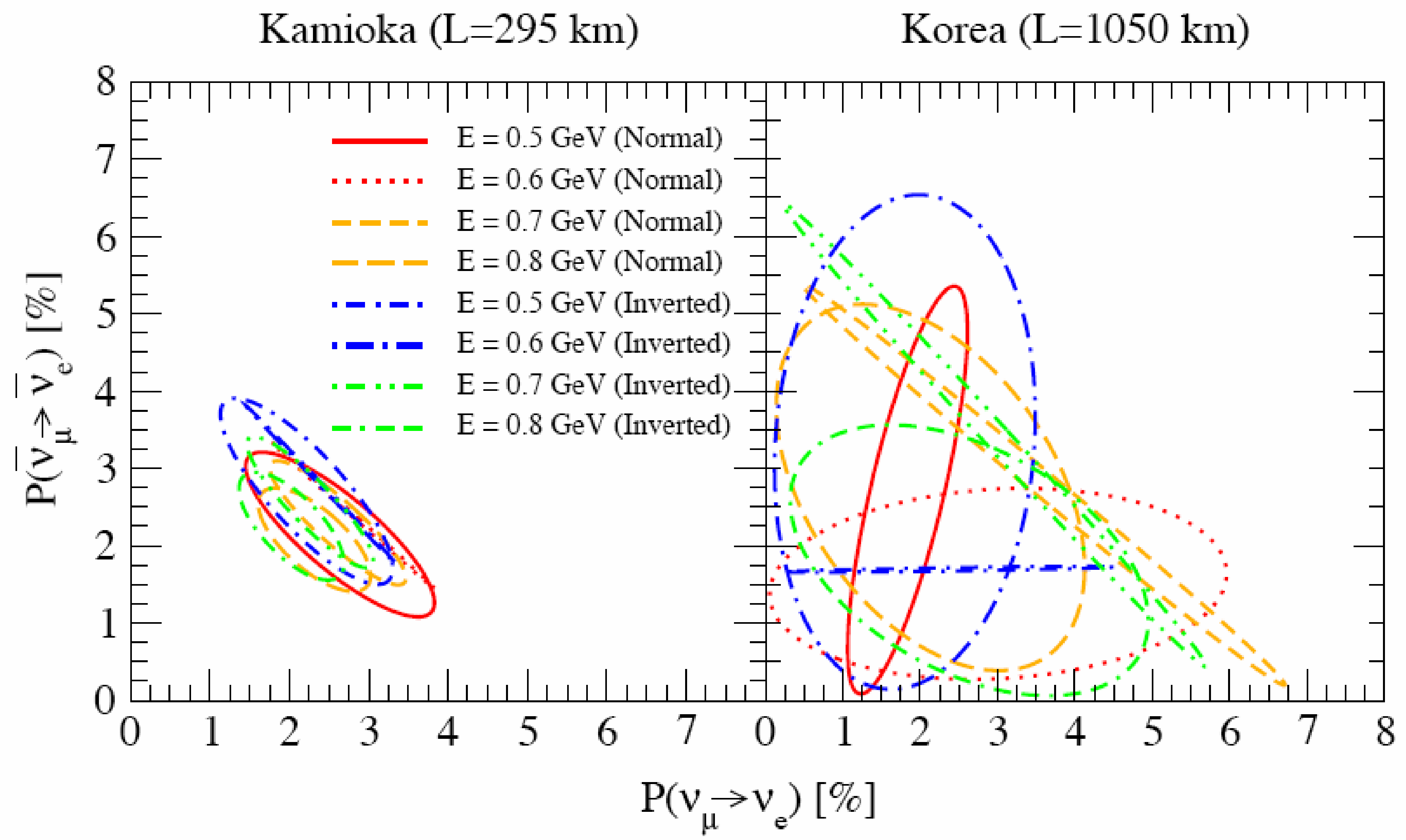
Art work by Adam Para

Two solutions of S_{23}^2 x



HM-H.Nunokawa JHEP01

#3. Sensitive to δ because energy dependence is far more dynamic in 2nd oscillation maximum



Degeneracy; a notorious obstacle

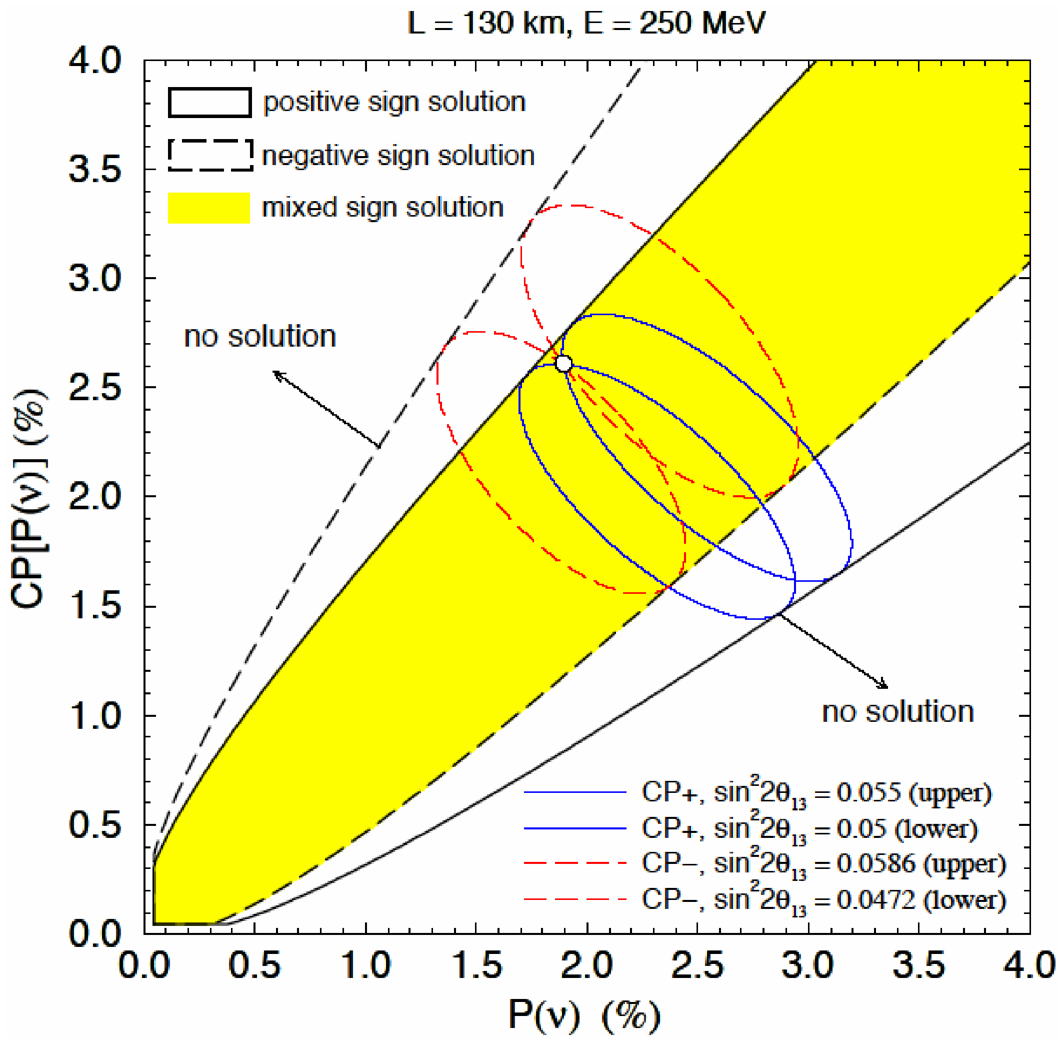
Cause of the degeneracy; easy to understand

- You can draw two ellipses from a point in P-Pbar space

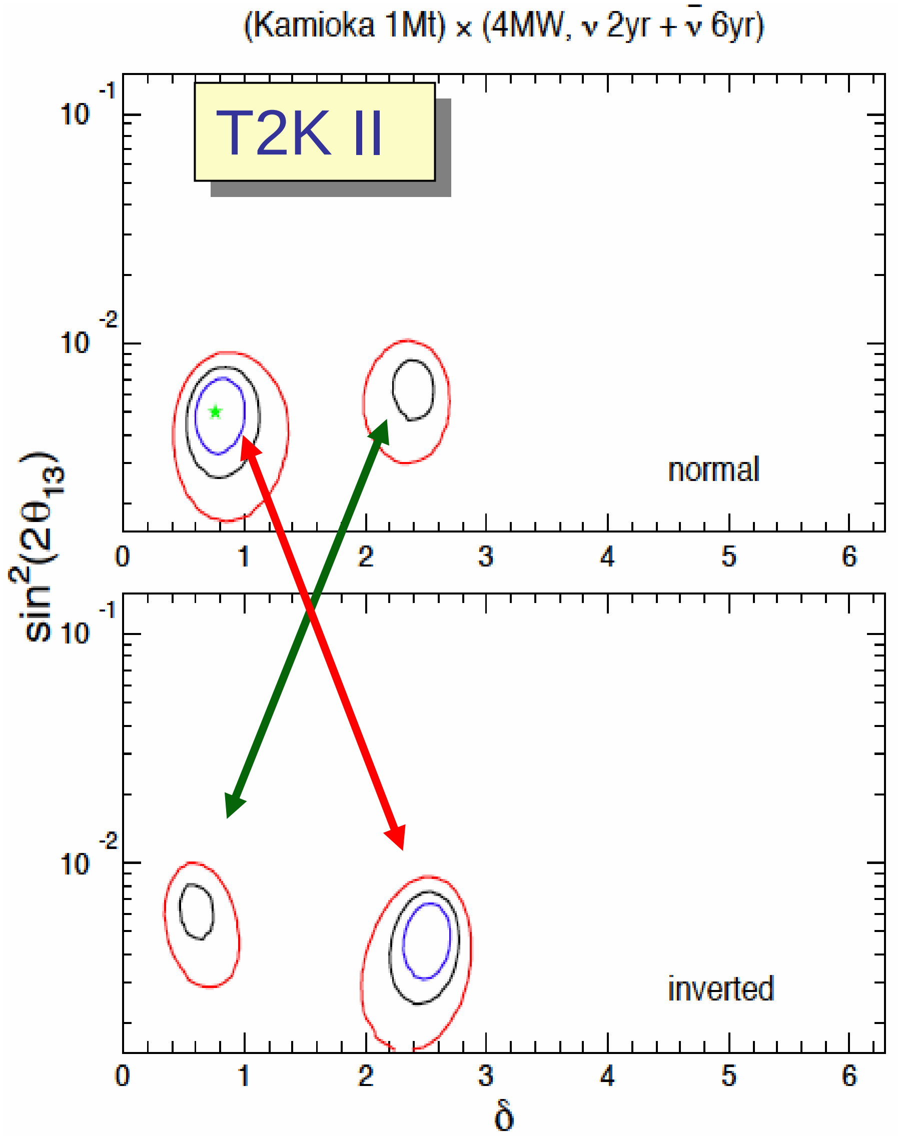
→ Intrinsic degeneracy

- Doubled by the unknown sign of Δm^2

→ 4-fold degeneracy



Structure of intrinsic & sign-Δm2 degeneracy in matter-perturbative regime

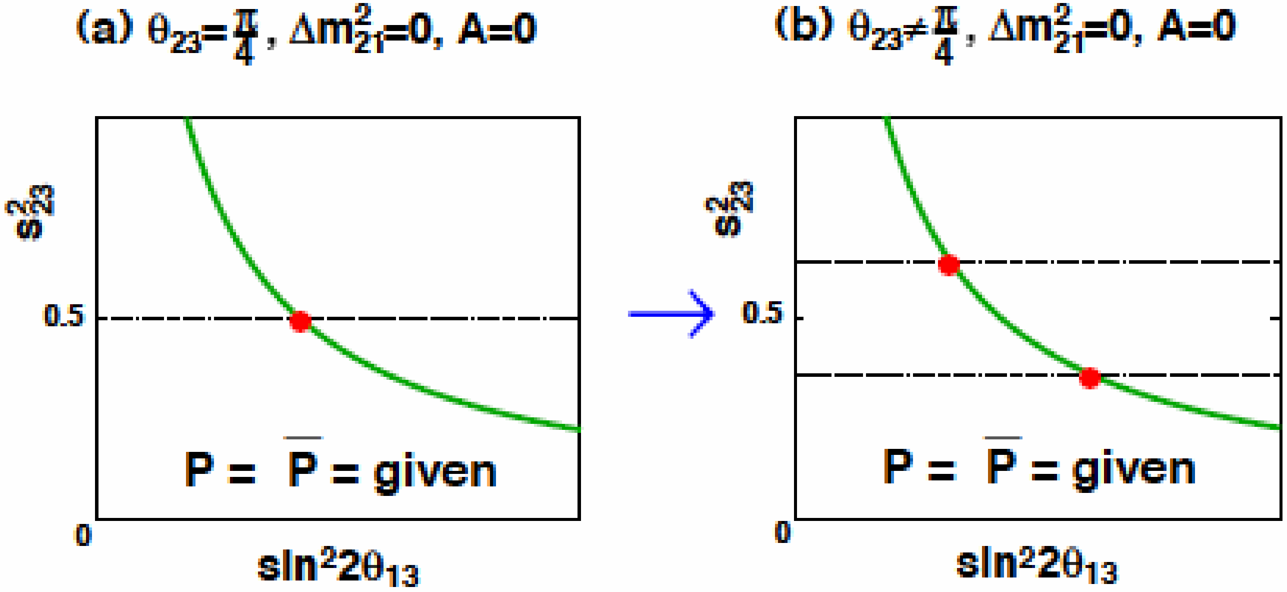


- Intrinsic degeneracy; $\delta_2=\pi-\delta_1$
- sign(Δm^2)-δ degeneracy arises because P is approx. invariant under:
- $\Delta m^2 \longrightarrow -\Delta m^2$
- $\delta \longrightarrow \pi-\delta$

MN JHEP01

ov onference

θ_{23} octant degeneracy

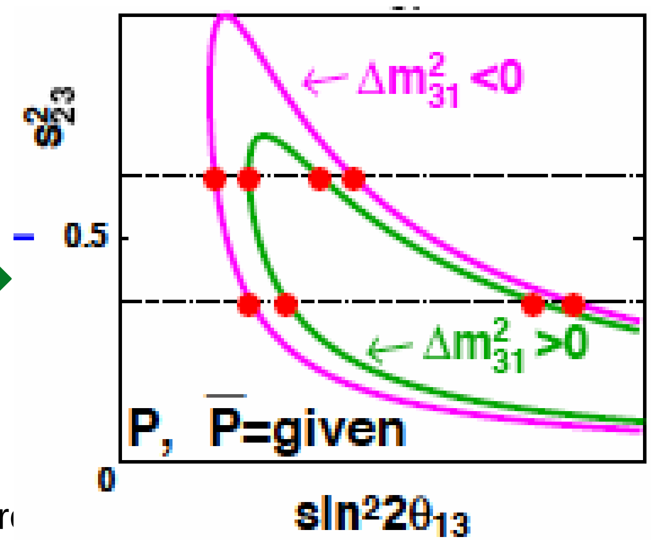


OY Nufact03

$P\mu e = \sin^2 2\theta_{13} \ \mathrm{x}\ s^2_{23}$

Solar Δm^2 on

Matter effect on

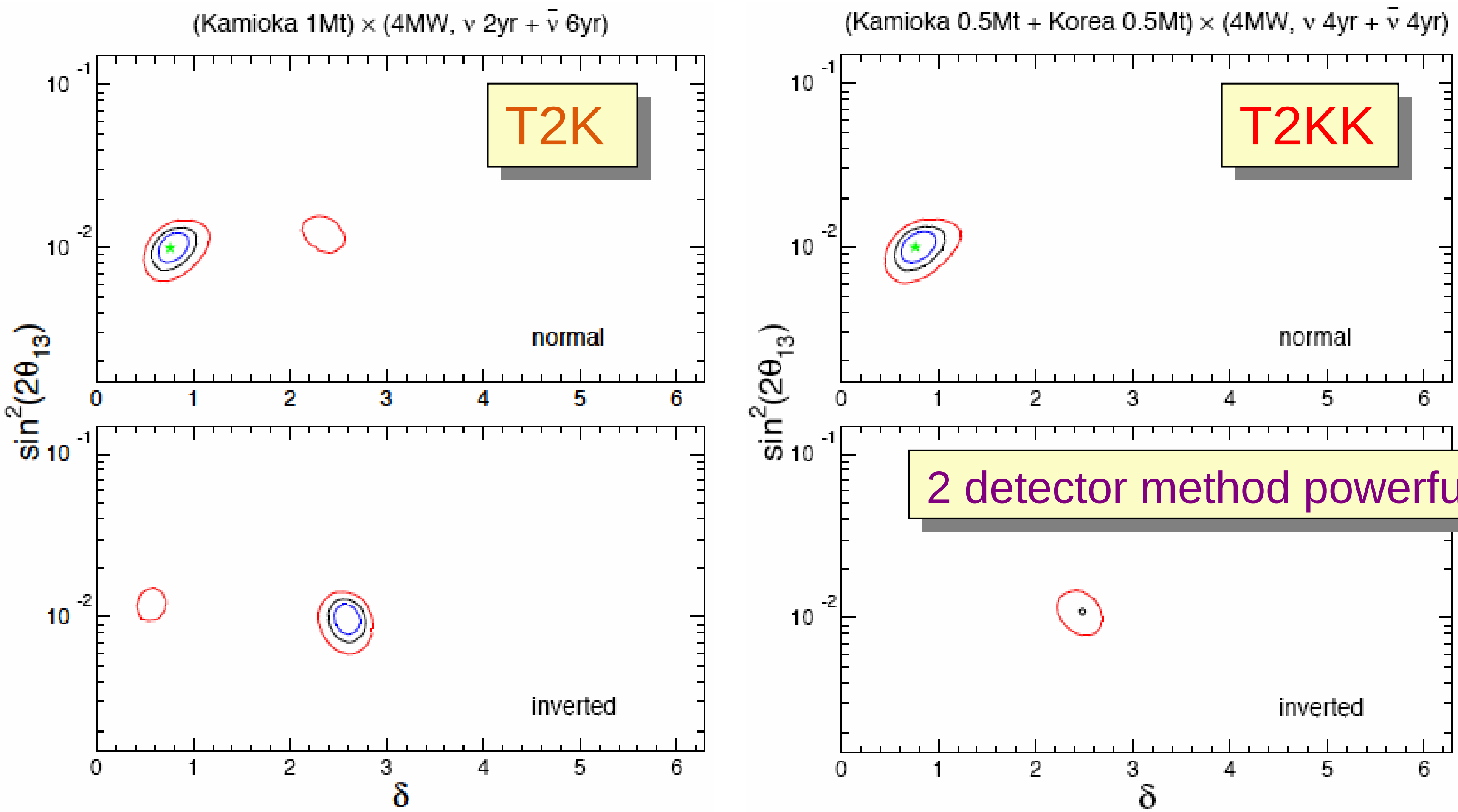


Altogether, 2 x 2 x 2 = 8-fold degeneracy

Two detector method is powerful

Spectral information solves intrinsic degeneracy

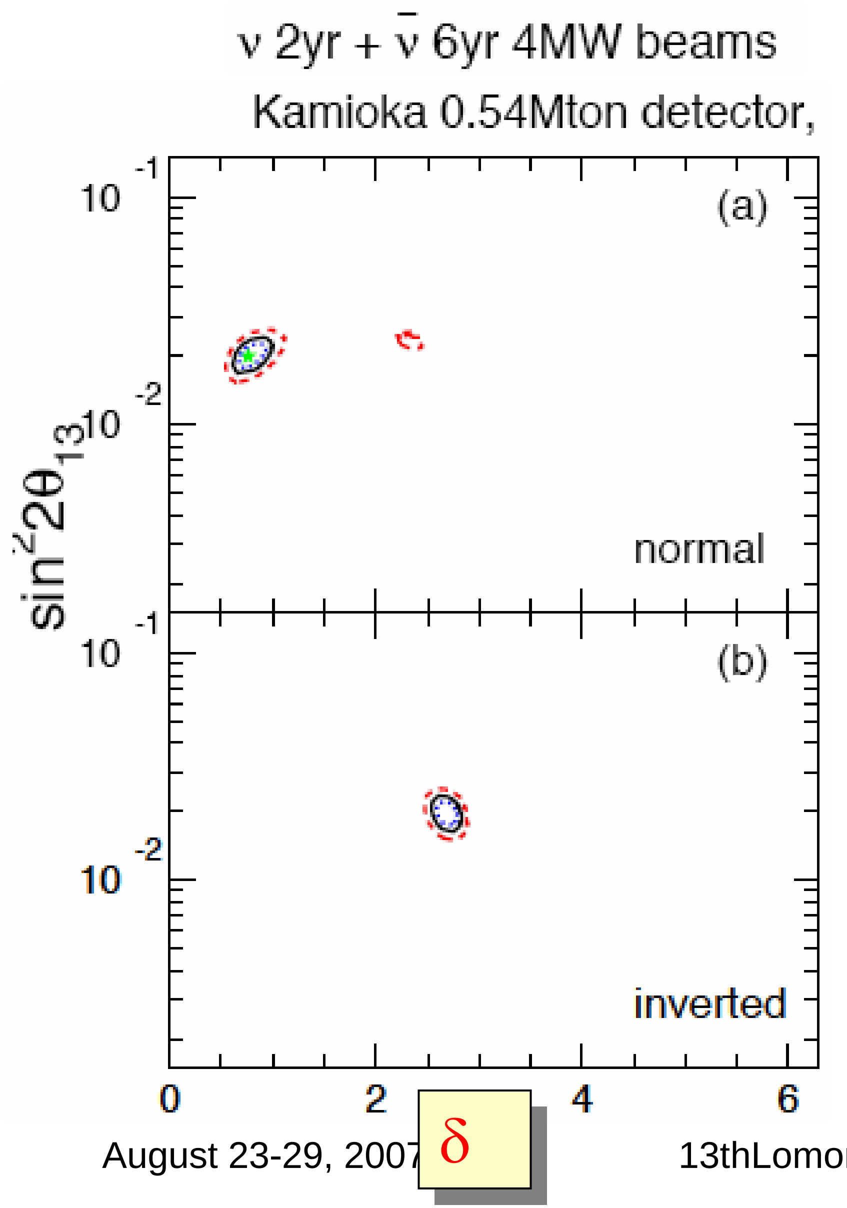
from 1000 page Ishitsuka file

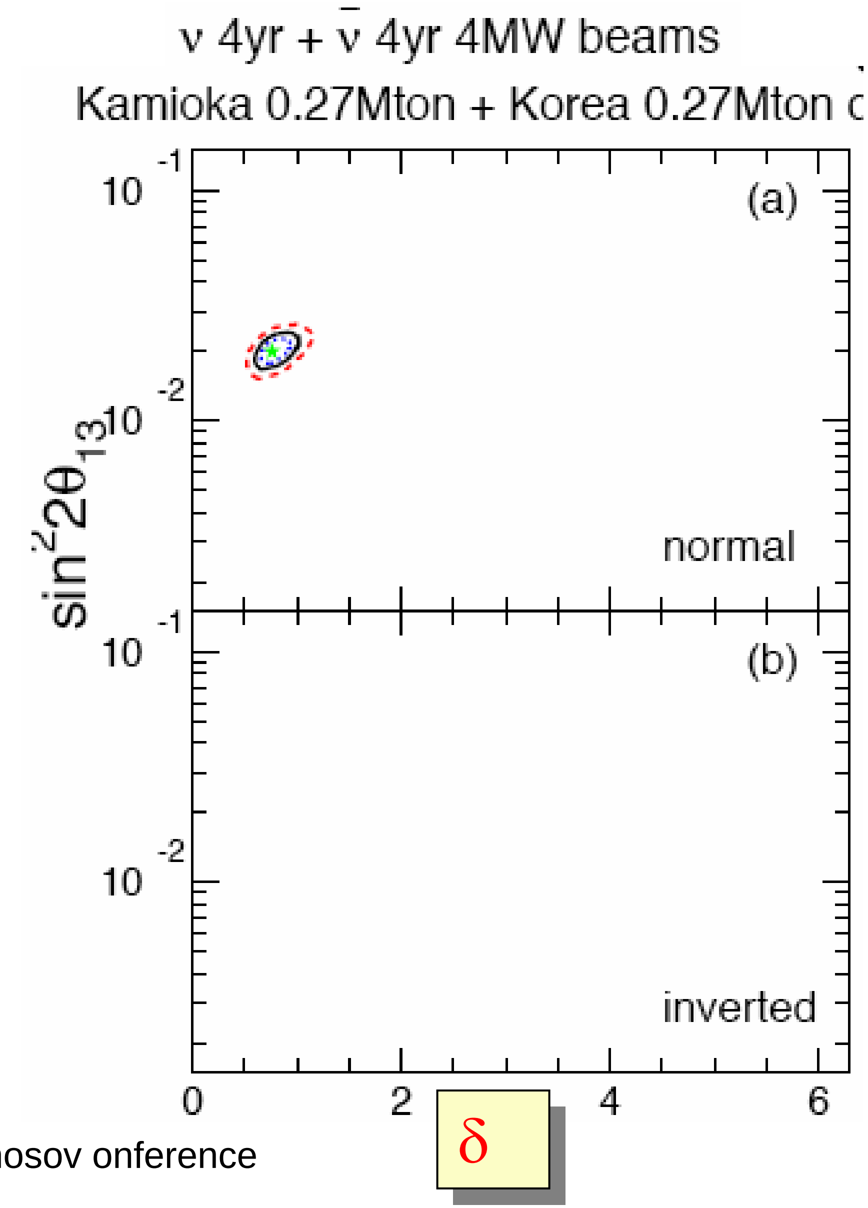


August 23-29,

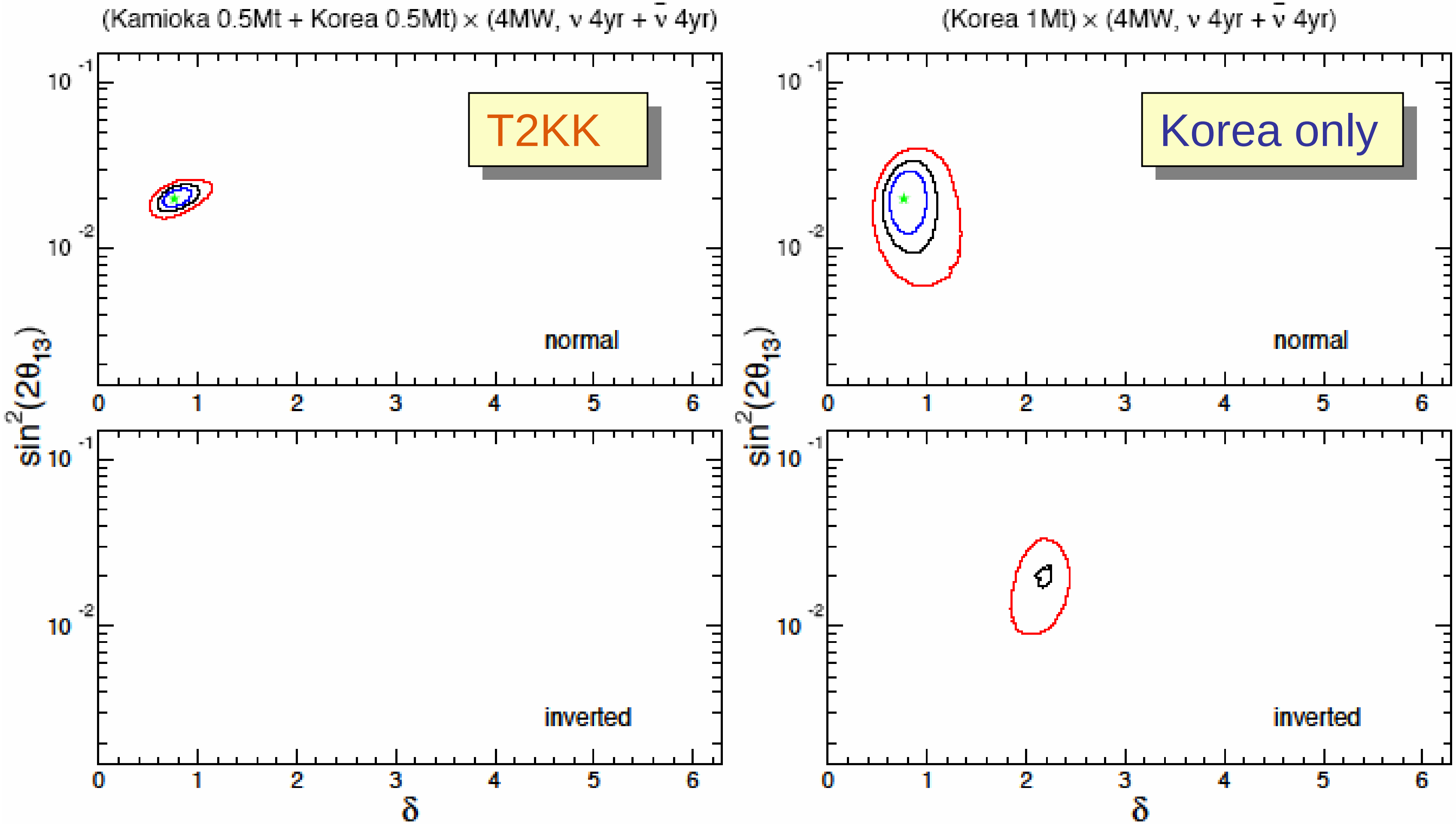
SK momentum resolution ~30 MeV at 1 GeV

T2K(0.54 Mt) vs. T2KK(0.27+0.27 Mt)





It is not quite only the matter effect

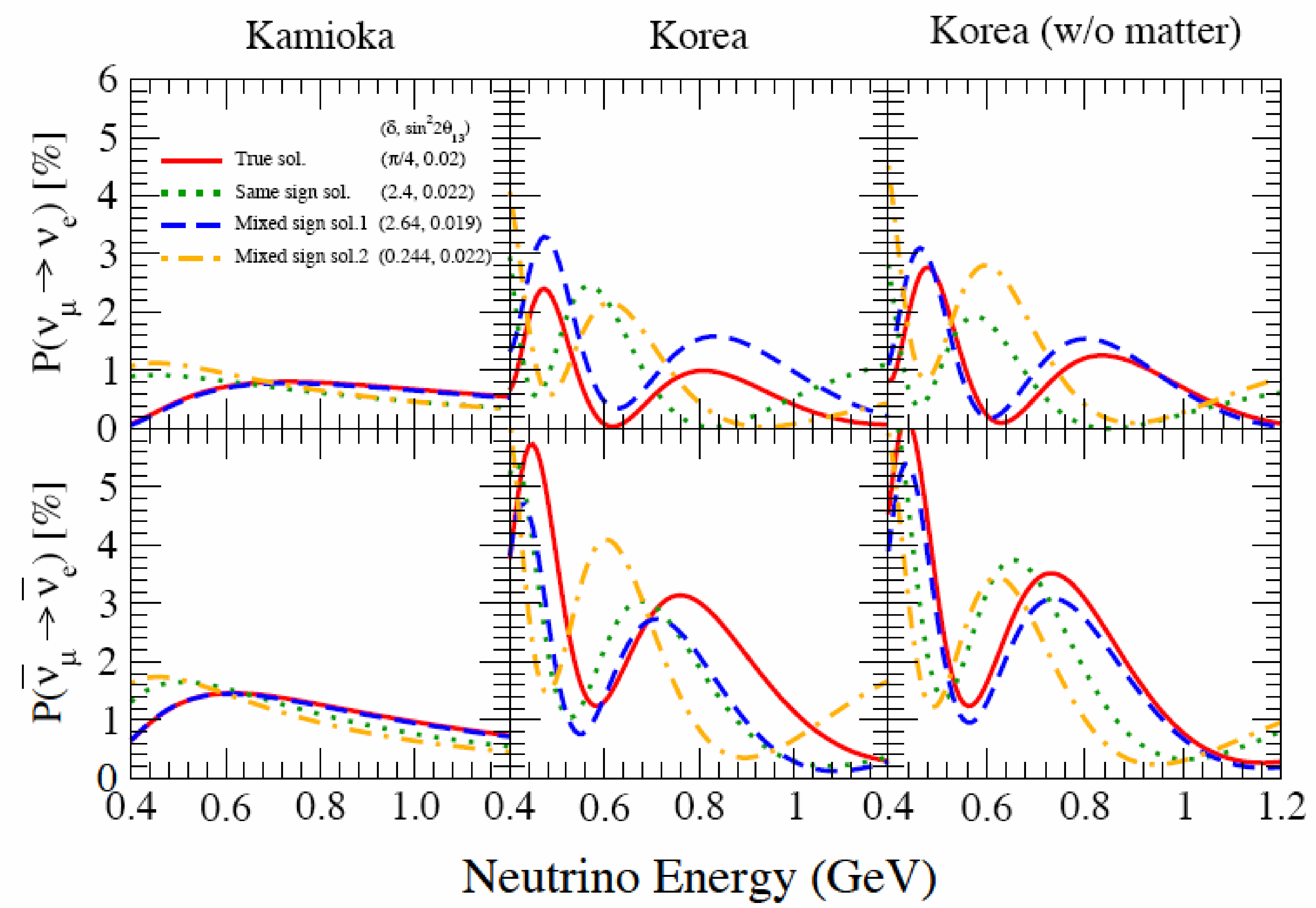


- With the same input parameter and Korean detector of 0.54 Mt the sign-Δm^2 degeneracy is NOT completely resolved

2 identical detector method powerful !

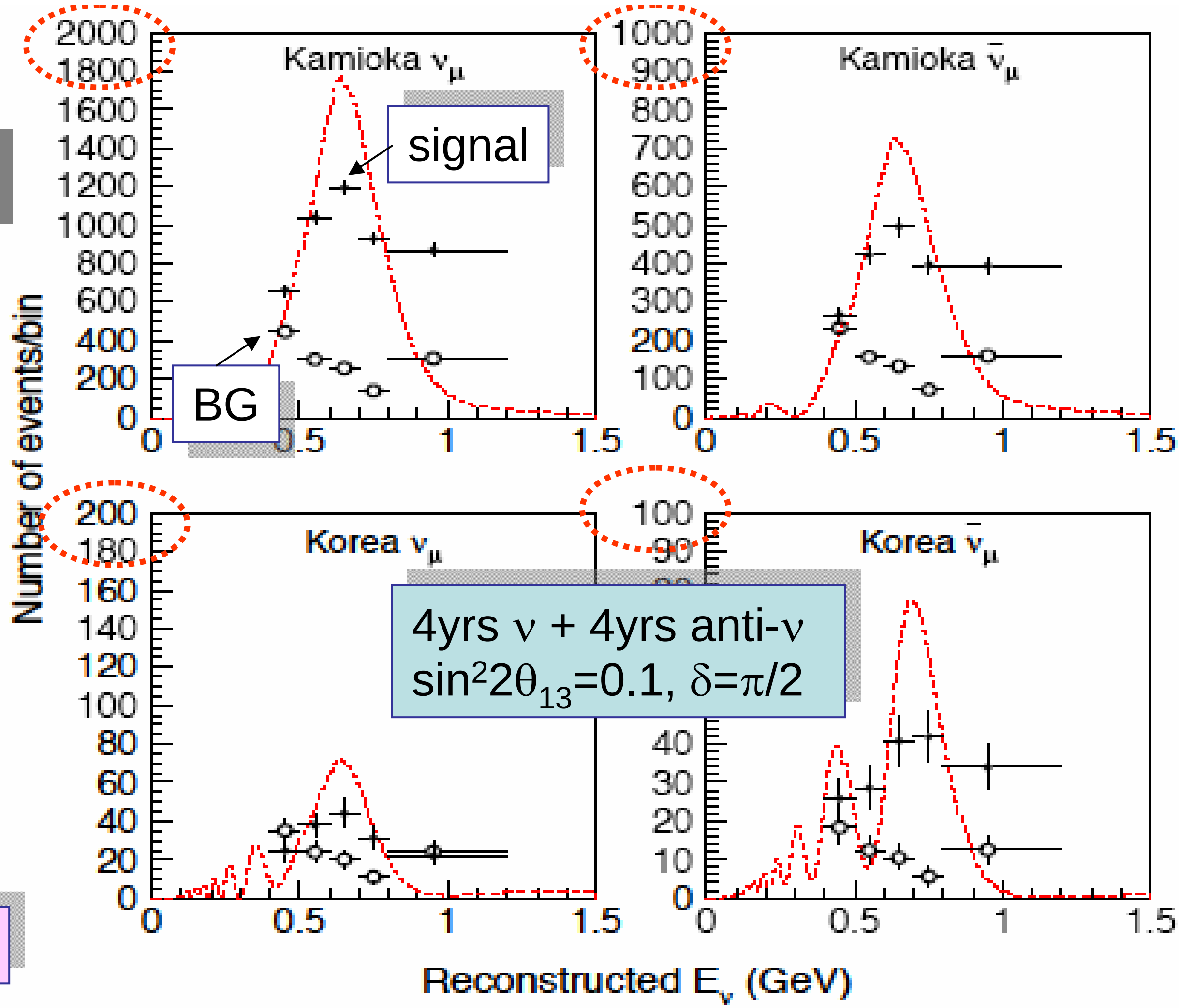
Let us resolve degeneracy

Difference in P should solve the degeneracy



Kajita in NOVE2006

Expected signal, BG and χ^2



ν and anti-ν
×
Kamioka and Korea

5 energy bins

syst. Errors:

5% BG (overall)
5% BG (energy dep.)
5% signal efficiency

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

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

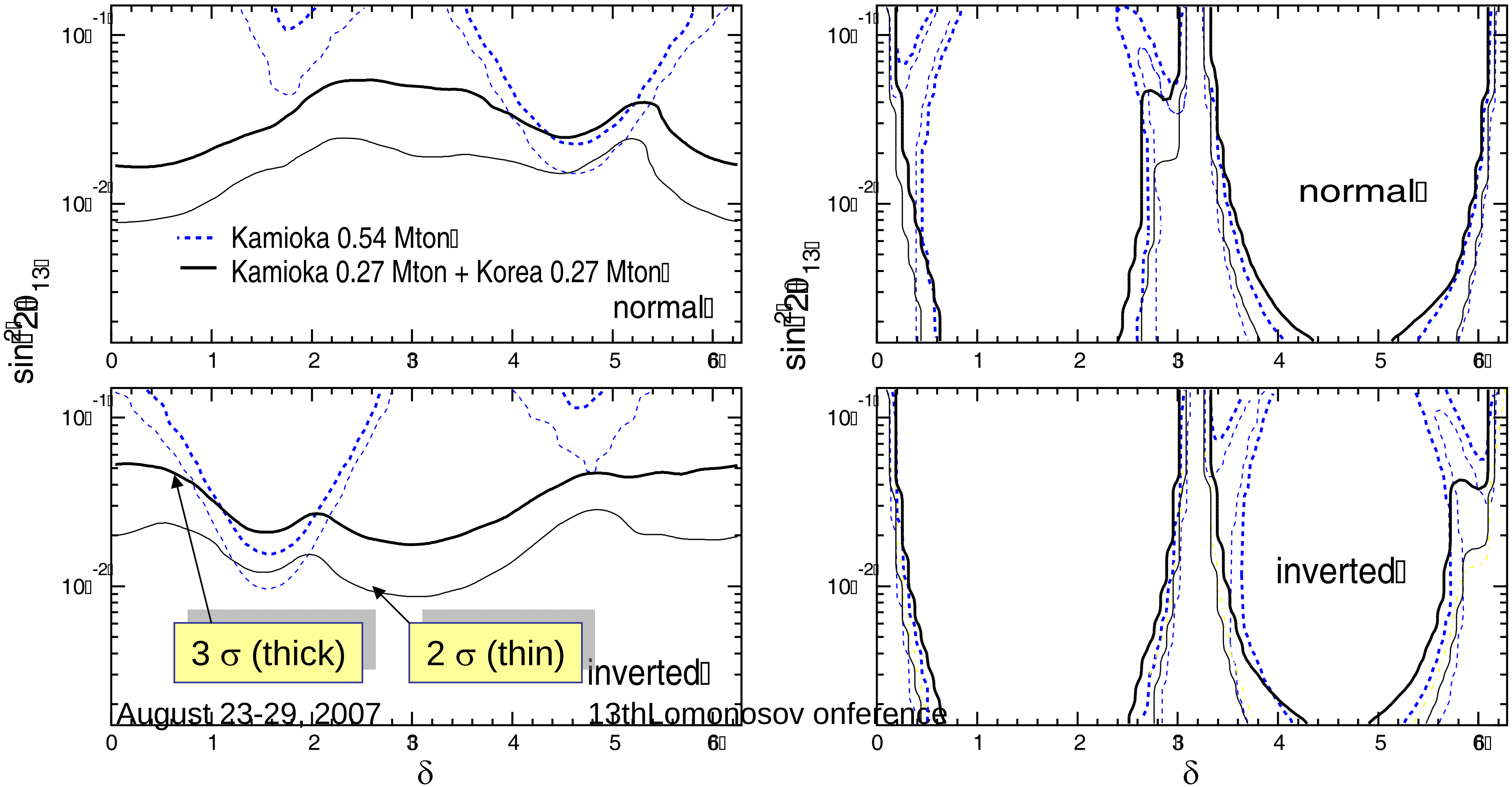
T2KK vs. T2K II Comparison

hep-ph/0504026

Total mass of the detectors = 0.54 Mton fid. mass
4 years neutrino beam + 4 years anti-neutrino beam

Mass hierarchy

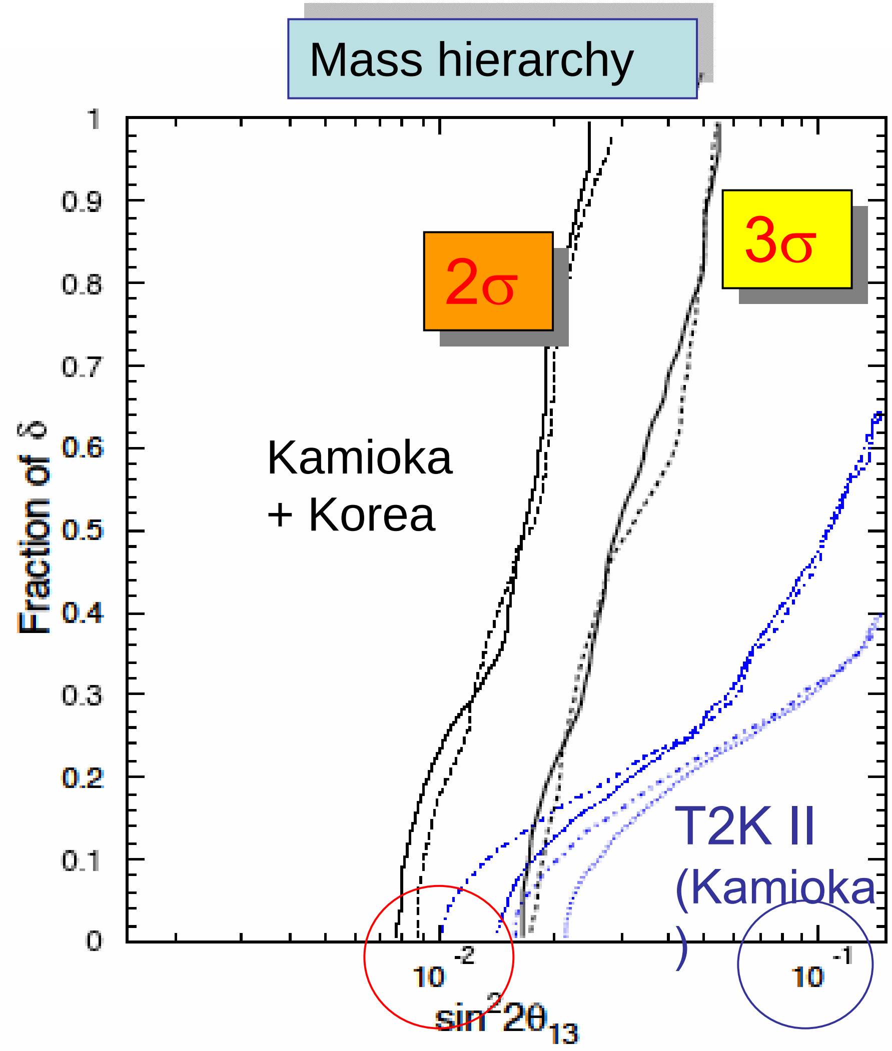
CP violation (sinδ≠0)

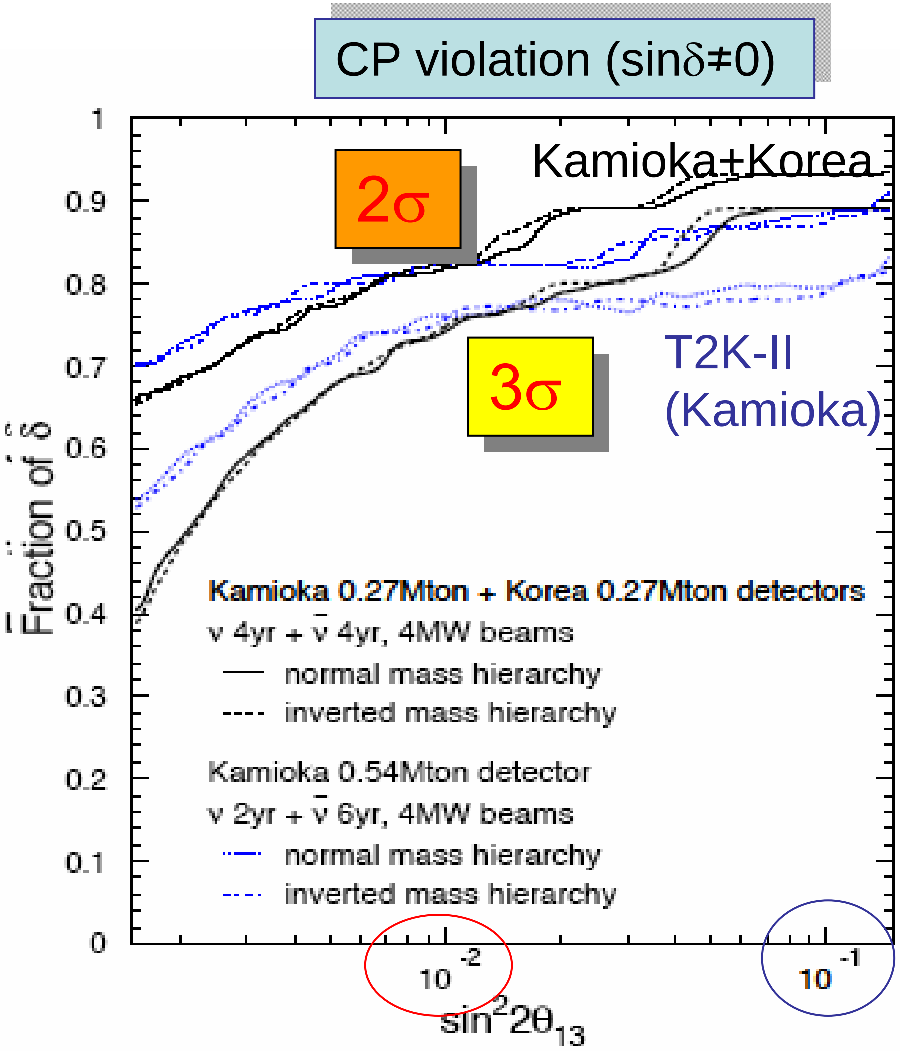


Expected sensitivity (2)

hep-ph/0504026

Total mass of the detectors = 0.54 Mton fid. mass
4 years neutrino beam + 4 years anti-neutrino beam





How to solve θ_{23} octant degeneracy

Strategy: Look for terms which depend on θ_{23} but not through the form $s_{23}^2 \times \sin^2 2\theta_{13}$

- Detect solar Δm^2 term $\sim c_{23}^2$
- Requires very long baseline
- well controlled systematic error plus statistics
- Powerful at small θ_{13}

- Combining reactor measurement of θ_{13}
- Requires great precision in reactor θ_{13} measurement
- Powerful at large θ_{13}

#4. Sensitive to solar n oscillation; good for octant degeneracy

- Detect the effect of the solar term using a far detector in Korea, which has a longer baseline.

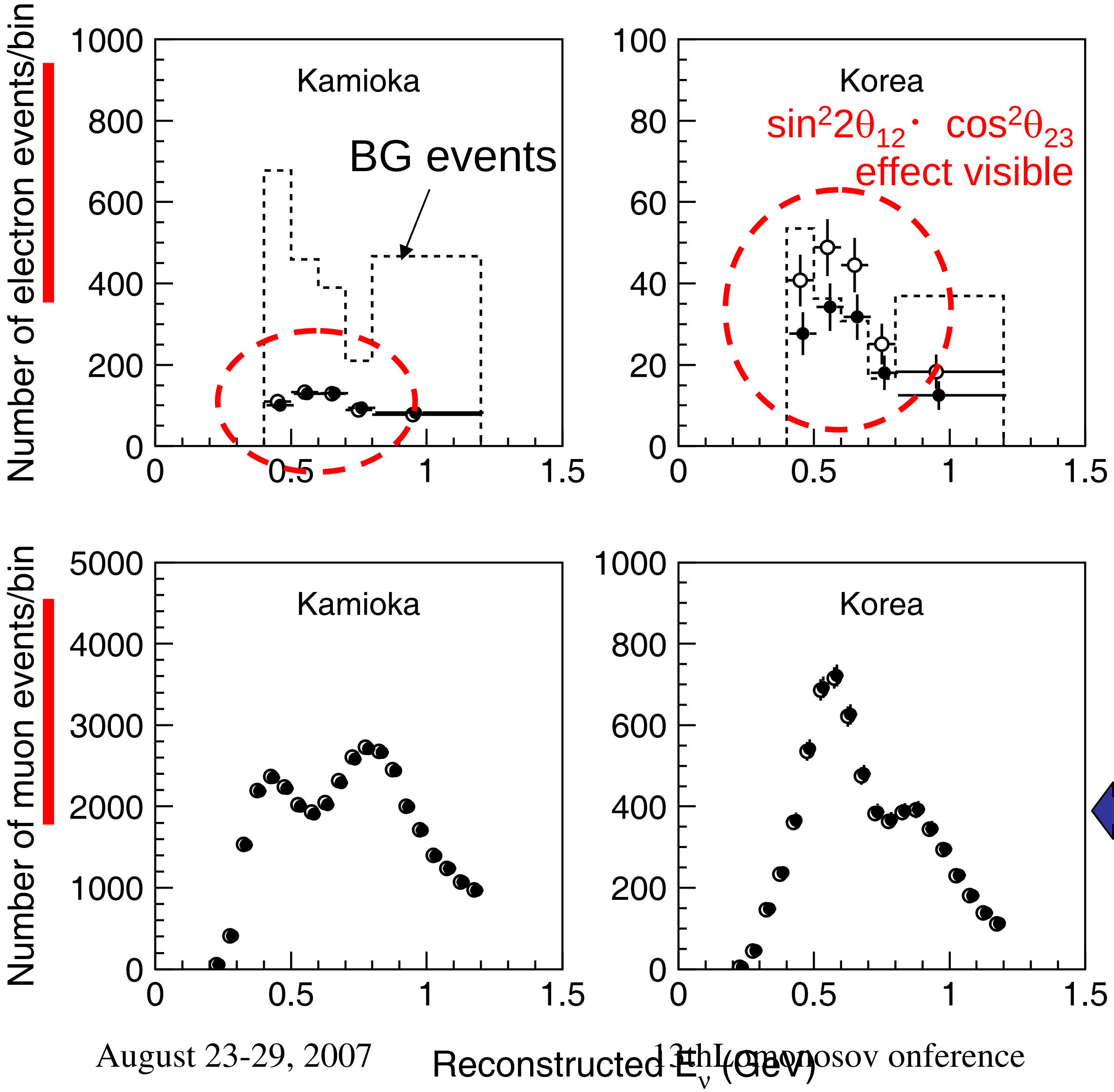
solar term

$$
\begin{aligned}
P[\nu_\mu(\bar{\nu}_\mu) \to \nu_{\mathrm{e}}(\bar{\nu}_e)] &= \boxed{\underline{c_{23}^2} \sin^2 2\theta_{12} \left(\frac{\Delta m_{21}^2 L}{4E}\right)^2} \\
&+ \underline{\sin^2 2\theta_{13}}\,\underline{s_{23}^2} \left[\sin^2 \left(\frac{\Delta m_{31}^2 L}{4E}\right) - \frac{1}{2} s_{12}^2 \left(\frac{\Delta m_{21}^2 L}{2E}\right) \sin \left(\frac{\Delta m_{31}^2 L}{2E}\right) \right. \\
&\qquad \left. \pm \left(\frac{4E\,\underline{a(x)}}{\Delta m_{31}^2}\right) \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E}\right) \mp \frac{\underline{a(x)}L}{2} \sin \left(\frac{\Delta m_{31}^2 L}{2E}\right) \right] \\
&+ 2\underline{J_r} \left(\frac{\Delta m_{21}^2 L}{2E}\right) \left[\underline{\cos\delta} \sin \left(\frac{\Delta m_{31}^2 L}{2E}\right) \mp 2 \underline{\sin\delta} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E}\right) \right].
\end{aligned}
$$

$a(x) = \sqrt{2} G_F N_e(x)$, $N_e(x)$: electron number density

$J_r \;\; (= c_{12} s_{12} c_{13}^2 s_{13} c_{23} s_{23})$: reduced Jarlskog factor

Effect of the solar term



○$\sin^2\theta_{23} = 0.4$,
$\sin^2 2\theta_{13} = 0.01$

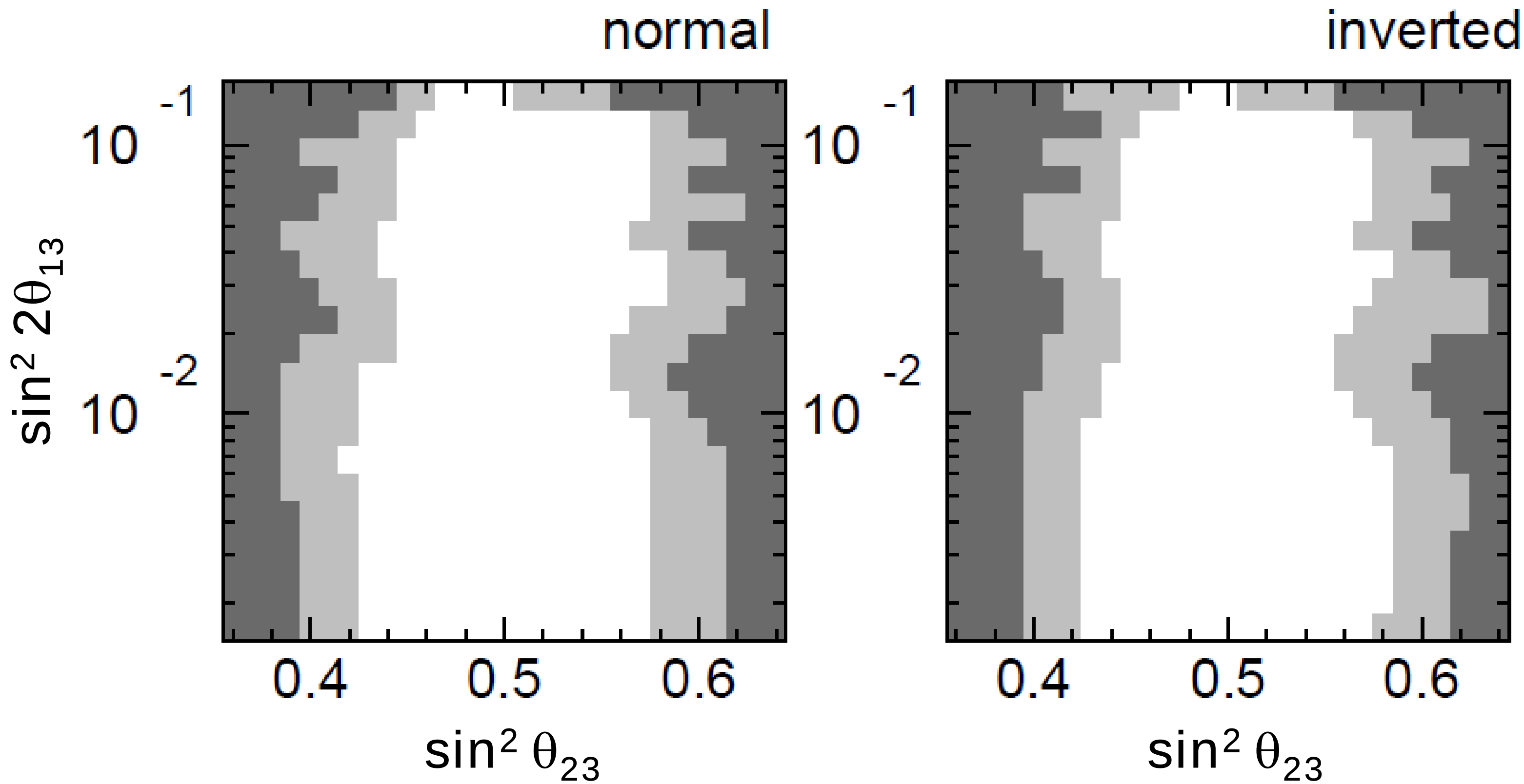
●$\sin^2\theta_{23} = 0.6$,
$\sin^2 2\theta_{13} = 0.0067$

(These parameters are chosen to so that $\sin^2\theta_{23}\cdot \sin^2 2\theta_{13}$ is equal.)

Δm^2: positive
$\delta=\pi 3/4$

Included in this analysis, since θ_{23} is relevant.

Sensitivity to θ_{23} octant



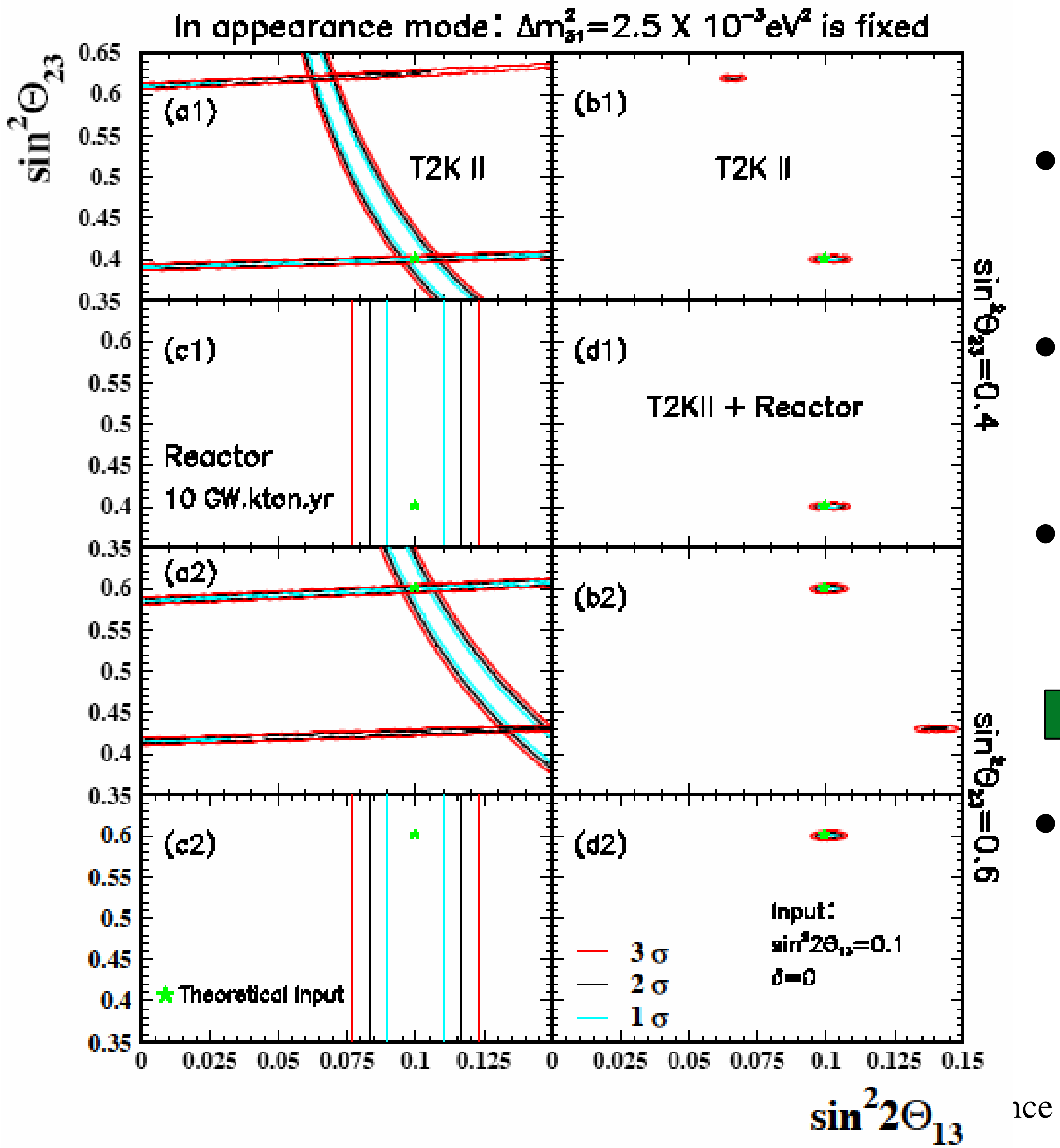
can determine θ_{23} octant
for any δ by

$> 3\sigma$

$2 \sim 3\sigma$

If $\sin^2 \theta_{23} < 0.42$ or > 0.58 ($\sin^2 2\theta_{23} = 0.974$), θ_{23} octant can be determined by $> 2\sigma$ even at very small $\sin^2 2\theta_{13}$.

Reactor + accelerator method



MSYIS 02

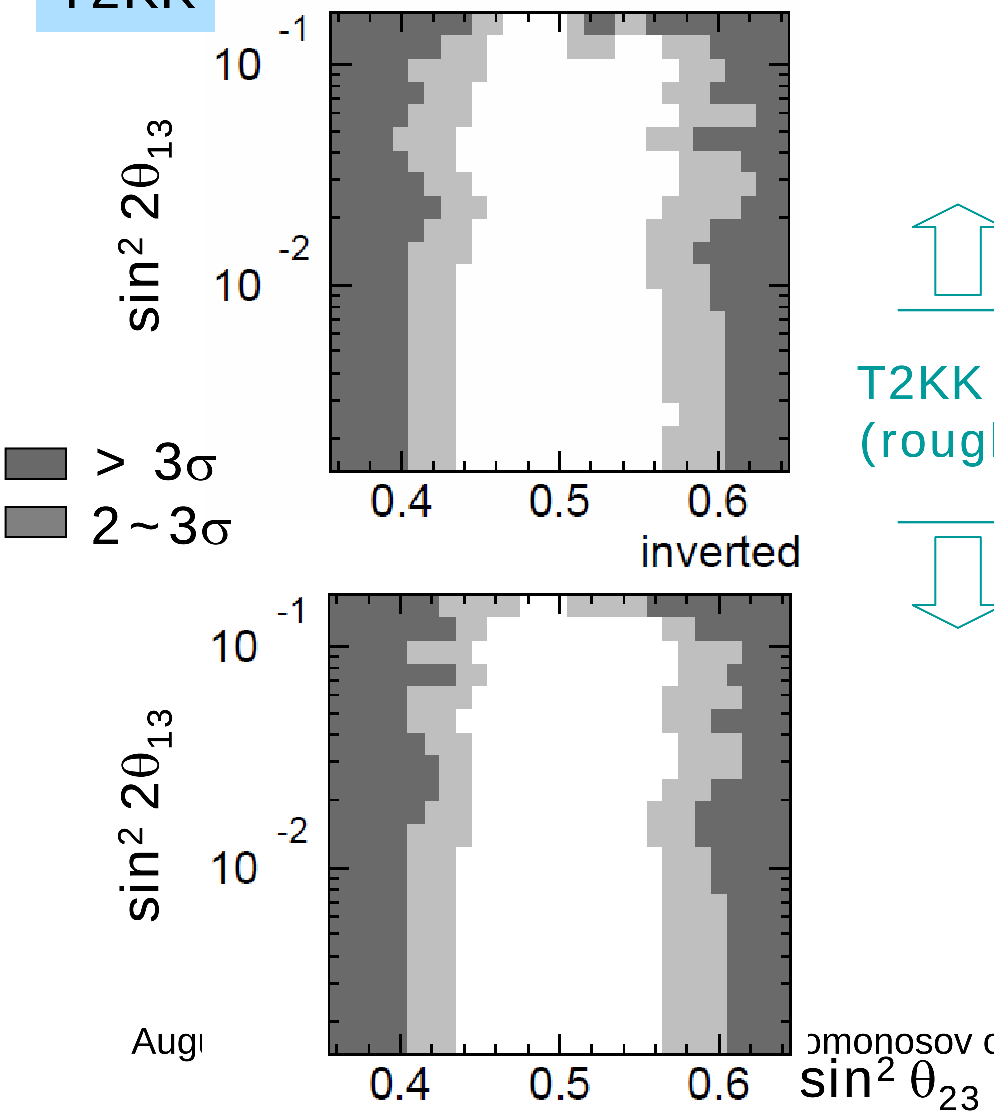
- Acc-disappearance => s^2_{23}=0.4 or 0.6
- Acc-appearance => $s^2_{23}\sin^2 2\theta_{13}$ = 0.06
- Reactor => $\sin^2 2\theta_{13}$ = 0.1

- Solves θ_{23} degeneracy

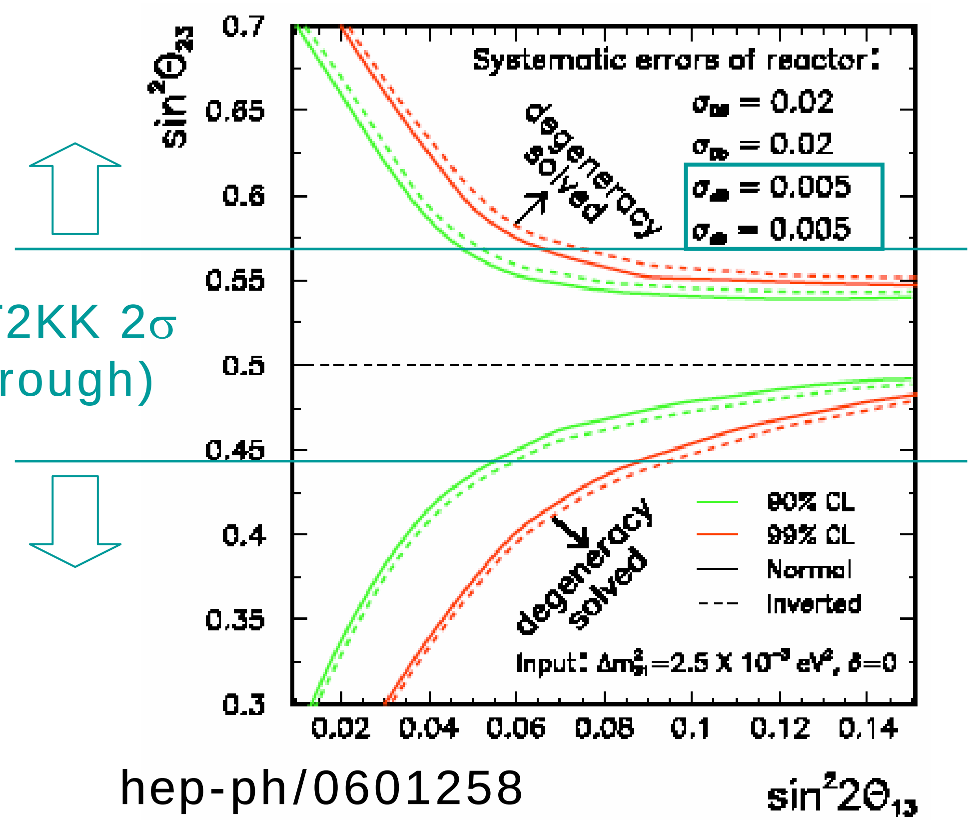
Sensitivity comparison with T2K+Reactor

$\delta=0$ assumed

T2KK



T2K-II + phase II reactor



hep-ph/0601258

T2KK has better sensitivity at $\sin^2 2\theta_{13} < 0.06\sim0.07$.

In a nutshell, 8 fold degeneracy can be resolved by T2KK because ..

- intrinsic degeneracy is resolved by spectrum information
- sign-Δm^2 degeneracy is solved with matter effect + 2 identical detector comparison
- θ_{23} octant degeneracy is solved by identifying the solar oscillation effect in T2KK

More physics capabilities ?

T2KK can do more physics

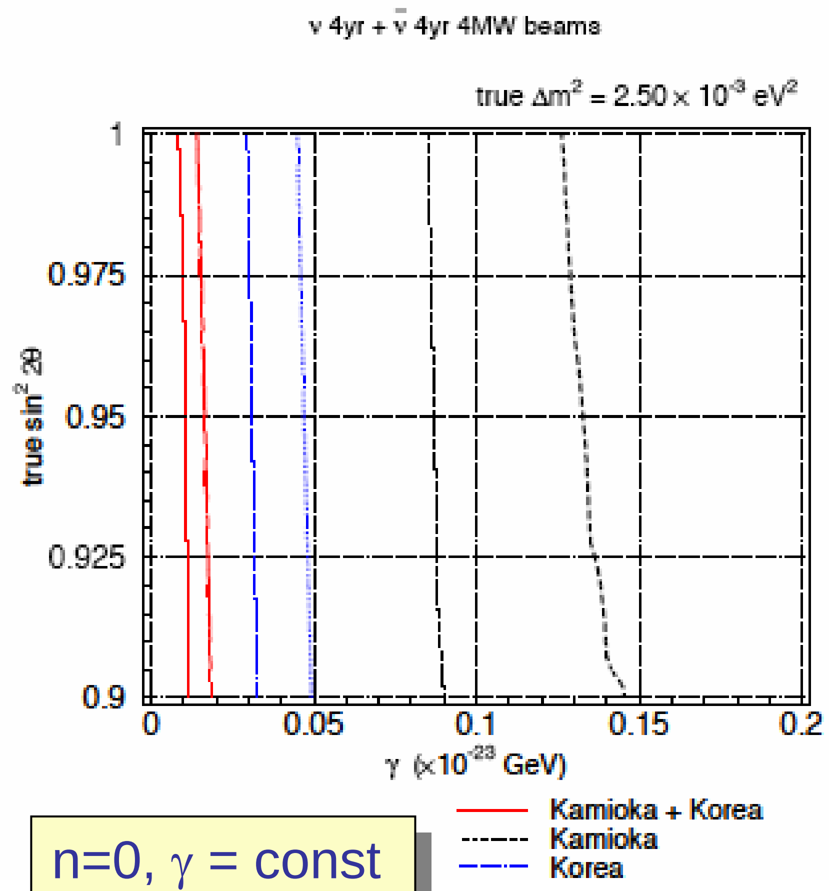
- T2KK can do more exotic physics like quantum decoherence, Lorentz violation, non-standard neutrino interactions etc.
- Let discuss ``quantum decoherence'' as an example:

$$P(\nu_\mu \to \nu_\mu) = 1 - \frac{1}{2}\sin^2 2\theta \left[1 - e^{-\gamma(E)L}\cos\left(\frac{\Delta m^2 L}{2E}\right)\right]$$

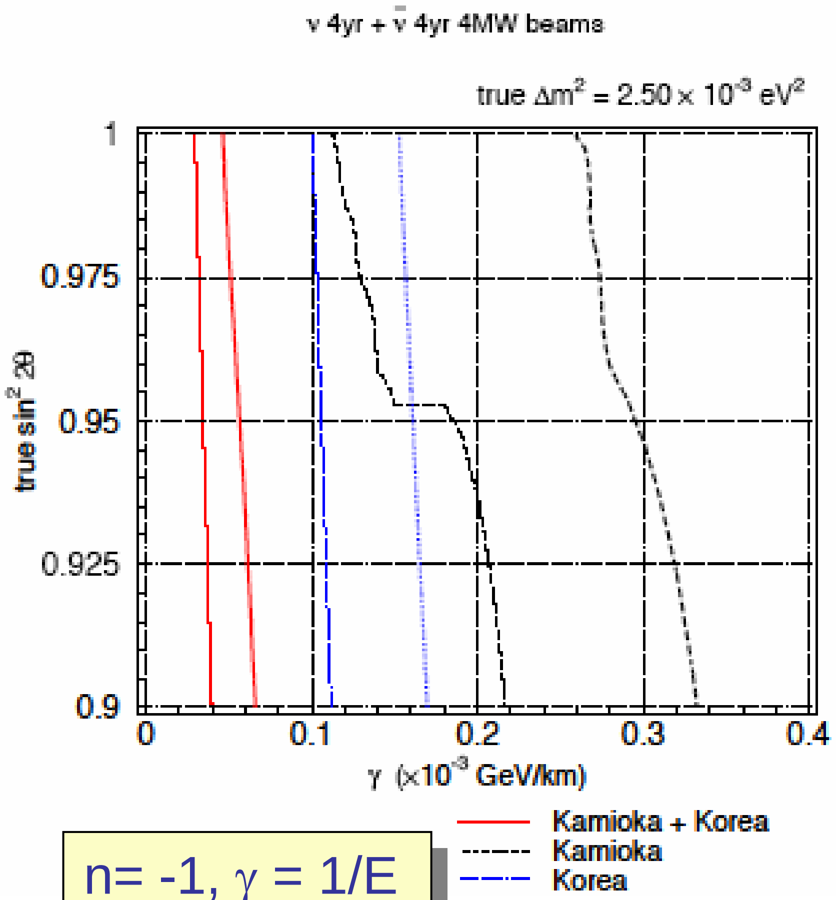
$$\gamma(E) = \gamma_0 \left(\frac{E}{\mathrm{GeV}}\right)^n \quad (\text{with } n = 0, 2, -1)$$

Fogli et al.,
Benatti et al.

T2KK vs. Kamioka or Korea-only



n=0, γ = const



n= -1, γ = 1/E

T2KK improve the current bound by more than 2 orders of magnitude !

Conclusion

- T2KK=Tokai to Kamioka Korea setting is powerful because of 2 identical detectors systematic errors cancel

confirmed !

- strategy for resolving 8 fold parameter degeneracy in situ is formulated
- More physics

Unique among various proposals !

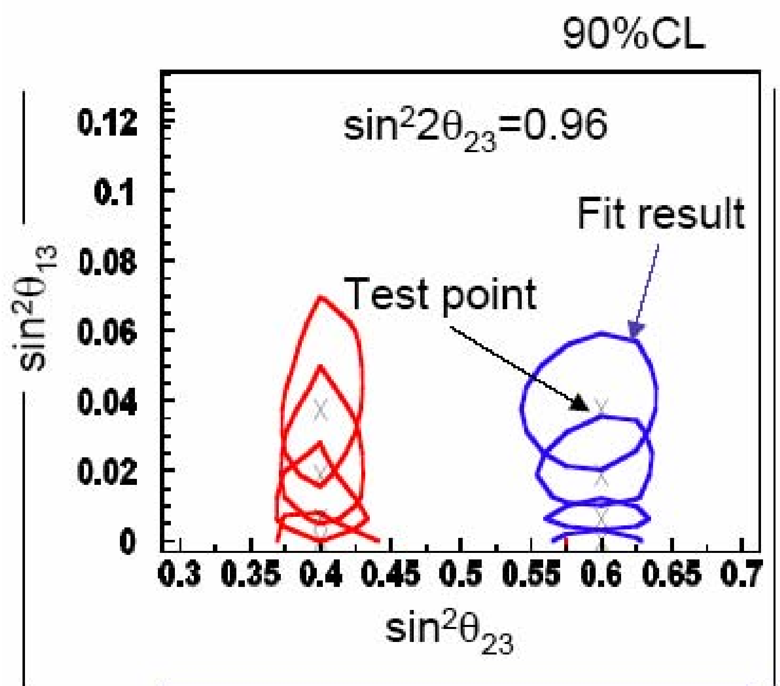
Atm ν; powerful way for octant degene.

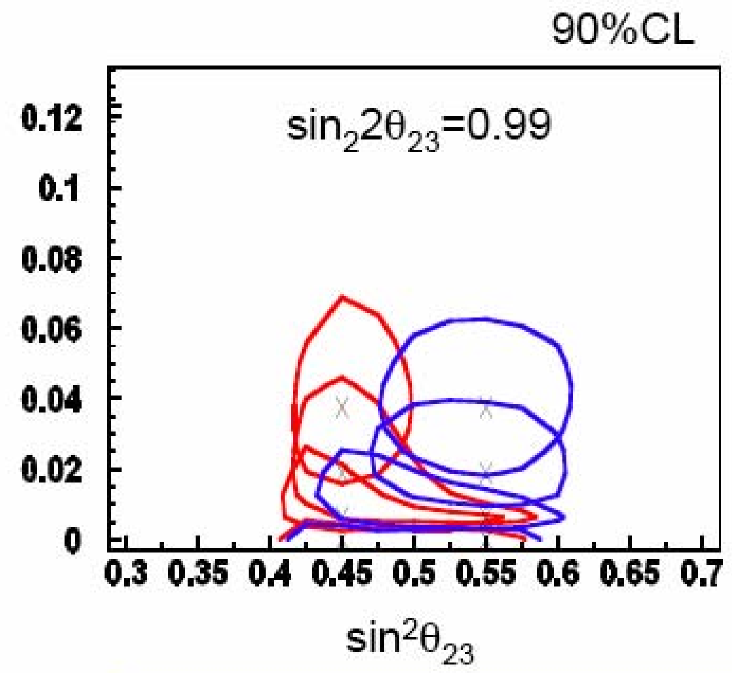
T.Kajita@NNN05

Discrimination between $\theta_{23} > \pi/4$ and $< \pi/4$ with the (12) and (13) terms

1.8Mtonyr = 3.3 yrs HK

$s^2\theta_{23}=0.40 \sim 0.60$
$s^2\theta_{13}=0.00 \sim 0.04$
$\delta cp=45^o$





Discrimination between $\theta_{23} > \pi/4$ and $< \pi/4$ is possible for all θ_{13}.

Discrimination between $\theta_{23} > \pi/4$ and $< \pi/4$ is marginally possible only for $\theta_{13} > 0.04$.

T2KK can resolve ν mass hierarchy with bonus of better CP sensitivity at large θ_{13}