

# Sensitivity of T2KK to non-standard interactions

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**In collaboration with Haruna OKI**

**1. Introduction**

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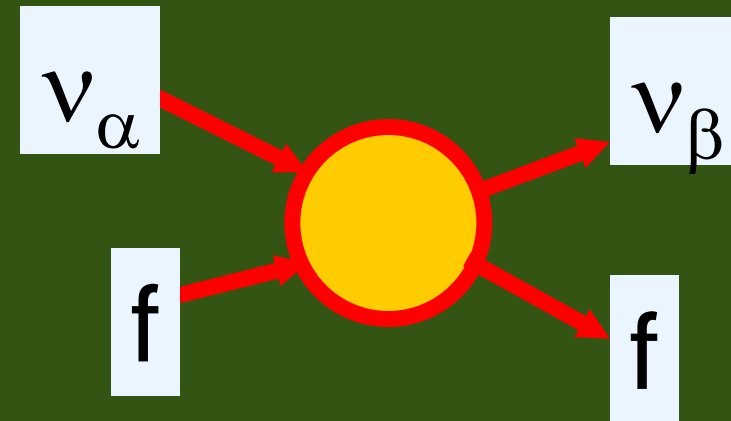
# 1. Motivation for research on **New Physics**

**High precision** measurements of  $\nu$  oscillation in future experiments can be used to probe **physics beyond SM** by looking at deviation from **SM**+ $m_\nu$ .

→ Research on **New Physics** is important.

Phenomenological **New Physics** considered in this talk: 4-fermi exotic interactions:

$$\mathcal{L}_{eff} = G_{NP}^{\alpha\beta} \bar{\nu}_\alpha \gamma^\mu \nu_\beta \bar{f} \gamma_\mu f'$$



neutral current  
non-standard  
interaction

# ● NP in propagation (NP matter effect)

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \left[ U \text{diag}(E_1, E_2, E_3) U^{-1} + A \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix} \right] \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$A \equiv \sqrt{2} G_F N_e \quad N_e \equiv \text{electron density}$$

**NP**

# ● Constraints on $\epsilon_{\alpha\beta}$

Davidson et al., JHEP 0303:011,2003; Berezhiani, Rossi, PLB535 ('02) 207; Barranco et al., PRD73 ('06) 113001; Barranco et al., arXiv:0711.0698

Biggio et al., JHEP 0908, 090 (2009) w/o 1-loop arguments

related to each other by  $\nu_{\text{atm}}$

can be improved by  $\nu_{\text{atm}}$

$$\left( \begin{array}{l} |\epsilon_{ee}| \lesssim 4 \times 10^0 \\ |\epsilon_{e\mu}| \lesssim 3 \times 10^{-1} \\ |\epsilon_{e\tau}| \lesssim 3 \times 10^0 \\ |\epsilon_{\mu\mu}| \lesssim 7 \times 10^{-2} \\ |\epsilon_{\mu\tau}| \lesssim 3 \times 10^{-1} \\ |\epsilon_{\tau\tau}| \lesssim 2 \times 10^1 \end{array} \right)$$

## 2. High energy behavior of $\nu_{\text{atm}}$ data & NSI

### ● Standard case with $N_\nu=2$

$$1 - P(\nu_\mu \rightarrow \nu_\mu) = \sin^2 2\theta_{\text{atm}} \sin^2 \left( \frac{\Delta m_{\text{atm}}^2 L}{4E} \right) \propto \frac{1}{E^2}$$

### ● Standard case with $N_\nu=3$

$$1 - P(\nu_\mu \rightarrow \nu_\mu) \sim \left( \frac{\Delta m_{31}^2}{2AE} \right)^2 \left[ \sin^2 2\theta_{23} \left( \frac{c_{13}^2 AL}{2} \right)^2 + s_{23}^2 \sin^2 2\theta_{13} \sin^2 \left( \frac{AL}{2} \right) \right] \propto \frac{1}{E^2}$$

### ● Deviation of $1-P(\nu_\mu \rightarrow \nu_\mu)$ due to NP contradicts with data

$$1 - P(\nu_\mu \rightarrow \nu_\mu) \simeq \mathbf{C}_0 + \frac{\mathbf{C}_1}{E} + \frac{c_{20}L^2 + c_{21} \sin^2(c_{22}L)}{E^2}$$

→ High  $\nu_{\text{atm}}$  data gives constraints on NP:

$$|\mathbf{C}_0| \ll 1, |\mathbf{C}_1| \ll 1$$

● with NP

$$1 - P(\nu_\mu \rightarrow \nu_\mu) \simeq \mathbf{c}_0 + \frac{\mathbf{c}_1}{E} + \frac{c_{20}L^2 + c_{21} \sin^2(c_{22}L)}{E^2}$$

$$|\mathbf{c}_0| \ll 1 \rightarrow |\varepsilon_{e\mu}| \ll 1, |\varepsilon_{\mu\mu}| \ll 1, |\varepsilon_{\mu\tau}| \ll 1$$

$|\varepsilon_{\mu\tau}| \ll 1$ : Already shown by Fornengo et al. PRD65, 013010, '02;  
Gonzalez-Garcia&Maltoni, PRD70, 033010, '04; Mitsuka@nufact08

$|\varepsilon_{\mu\mu}| \ll 1$ : Already shown from other expts. by Davidson et al.  
JHEP 0303:011, '03

$|\varepsilon_{e\mu}| \ll 1$ : New observation (analytical consideration only)

$$|\mathbf{c}_1| \ll 1 \rightarrow |\varepsilon_{\tau\tau} - |\varepsilon_{e\tau}|^2 / (1 + \varepsilon_{ee})| \ll 1$$

Already shown by  
Friedland-Lunardini,  
PRD72:053009, '05

- Summary of the constraints on  $\epsilon_{\alpha\beta}$

To a good approximation, we are left with 3 independent variables  $\epsilon_{ee}$ ,  $|\epsilon_{e\tau}|$ ,  $\arg(\epsilon_{e\tau})$ :

$$A \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix}$$

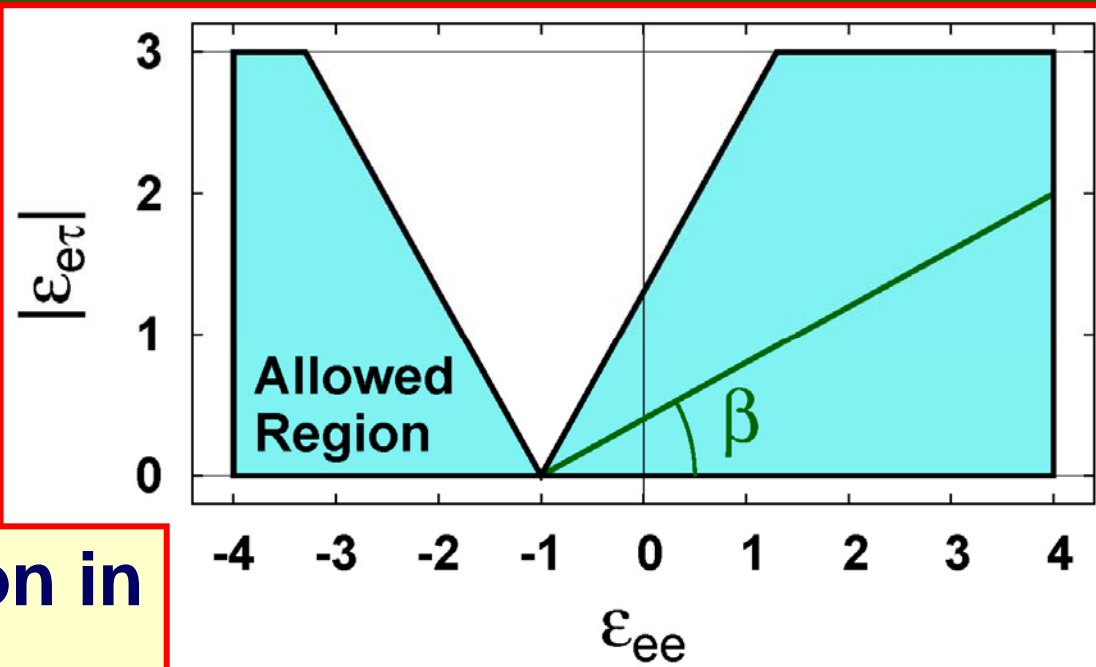


$$A \begin{pmatrix} 1 + \epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^* & 0 & |\epsilon_{e\tau}|^2 / (1 + \epsilon_{ee}) \end{pmatrix}$$

Furthermore,  $\nu_{atm}$  data implies

$$\tan\beta = |\epsilon_{e\tau}| / (1 + \epsilon_{ee}) < 1.3$$

Friedland-Lunardini,  
PRD72:053009,'05



Allowed region in  
 $(\epsilon_{ee}, |\epsilon_{e\tau}|)$

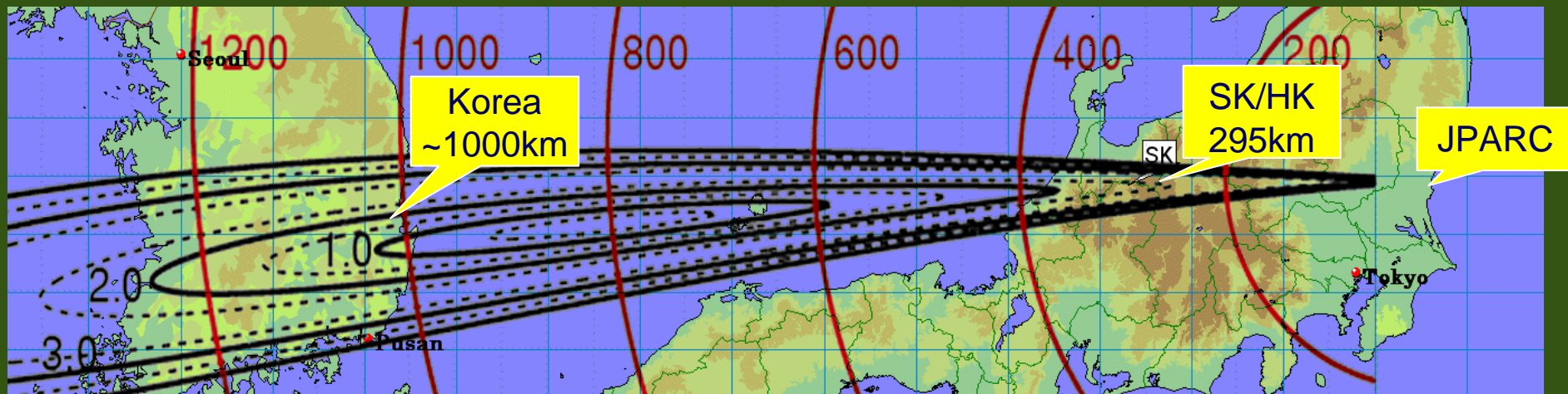
### 3. Sensitivity to NSI of propagation at T2KK

T2KK proposal with baselines  $L=295\text{km}$ ,  $1050\text{km}$   
→  $L=1050\text{km}$  is sensitive to the matter effect

	$ \Delta m^2_{31} L/4E$	$ \Delta m^2_{21} L/4E$	$AL/2E$
$L=295\text{km}$	$\sim 1$	$\sim 0.04$	$\sim 0.06$
$L=1050\text{km}$	$\sim 5$	$\sim 0.1$	$\sim 0.3$



dependence on  $A$  &  $\Delta m^2_{21}$  at  $L=1050\text{km}$  is non-negligible





# Outline of our Analysis

$$A \equiv \sqrt{2}G_F n_e$$

Our ansatz

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \left\{ U_{MNS}^{-1} \text{diag} \left( \frac{m_1^2}{2E}, \frac{m_2^2}{2E}, \frac{m_3^2}{2E} \right) U_{MNS} + A \begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^* & 0 & \frac{|\epsilon_{e\tau}|^2}{1+\epsilon_{ee}} \end{pmatrix} \right\} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

Black : standard

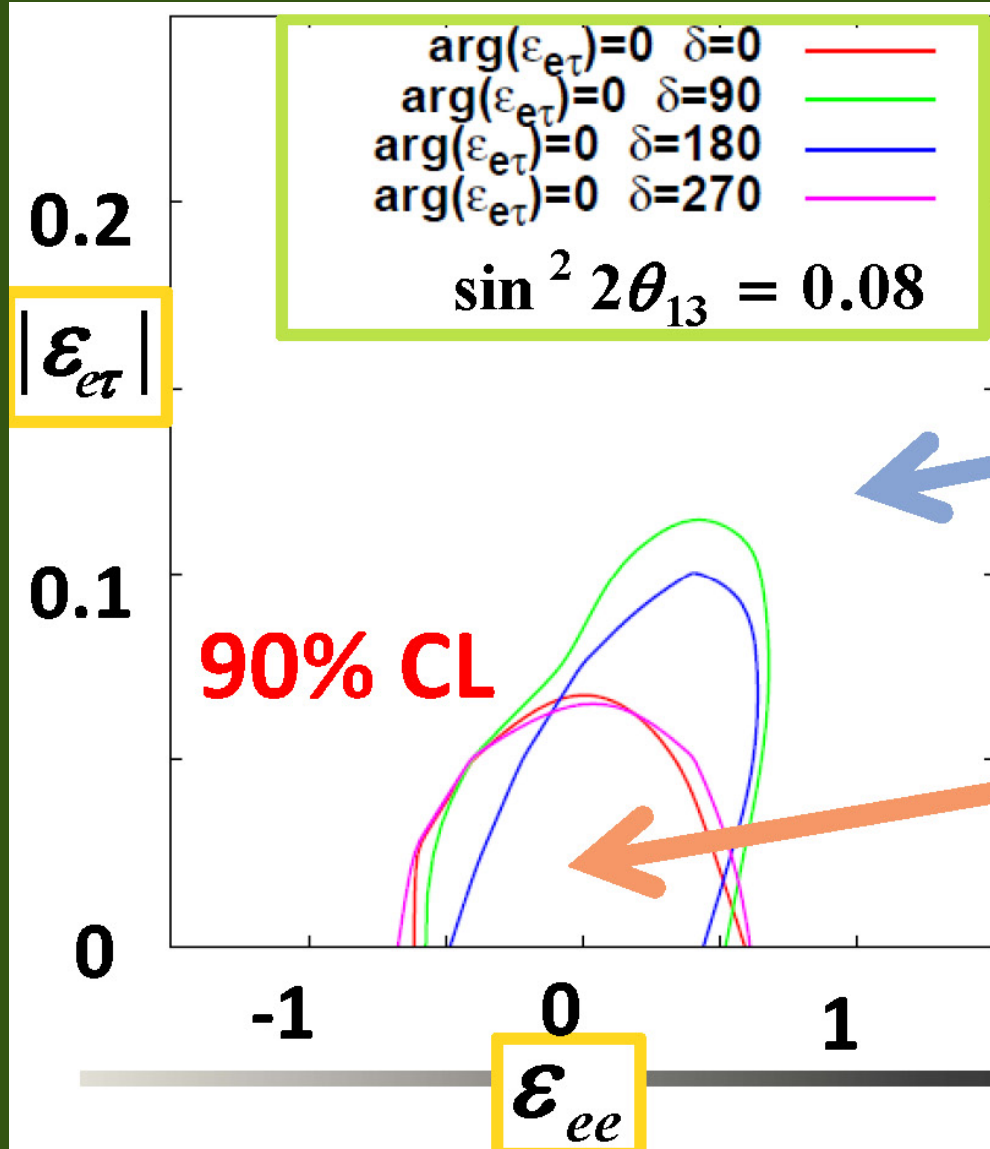
Red : non-standard

$$\Delta\chi^2(\text{NSI}) = \min_{\text{std parameters}} \sum_i \frac{(N_i^0(\text{NSI}) - N_i(\text{std}))^2}{\sigma_i^2} + \Delta\chi^2_{\text{prior}}$$

$$\Delta\chi^2_{\text{prior}} \equiv \frac{(\sin^2 2\theta_{23} - \sin^2 2\theta_{23}^{\text{best}})^2}{(\delta \sin^2 2\theta_{23})^2} + \frac{(\Delta m_{31}^2 - \Delta m_{31}^{2\text{best}})^2}{(\delta \Delta m_{31}^2)^2} + \frac{(\sin^2 2\theta_{13} - \sin^2 2\theta_{13}^{\text{best}})^2}{(\delta \sin^2 2\theta_{13})^2}$$

$\Delta\chi^2 > 4.6$ : Deviation of NSI from  $\nu\text{SM}$  is significant compared with errors (at 90% CL of 2 degrees of freedom  $\epsilon_{ee}, |\epsilon_{e\tau}|$ )

# Sensitivity to $\varepsilon_{ee}$ , $|\varepsilon_{e\tau}|$



Marginalized over  $\theta_{13}$ ,  
 $\theta_{23}$ ,  $|\Delta m_{31}^2|$ ,  $\text{sign}(\Delta m_{31}^2)$

- **Outside of the curves :**  
Effects of NSI can be distinguished from the standard case.
- **Inside of the curves :**  
Effects of NSI are not significant.

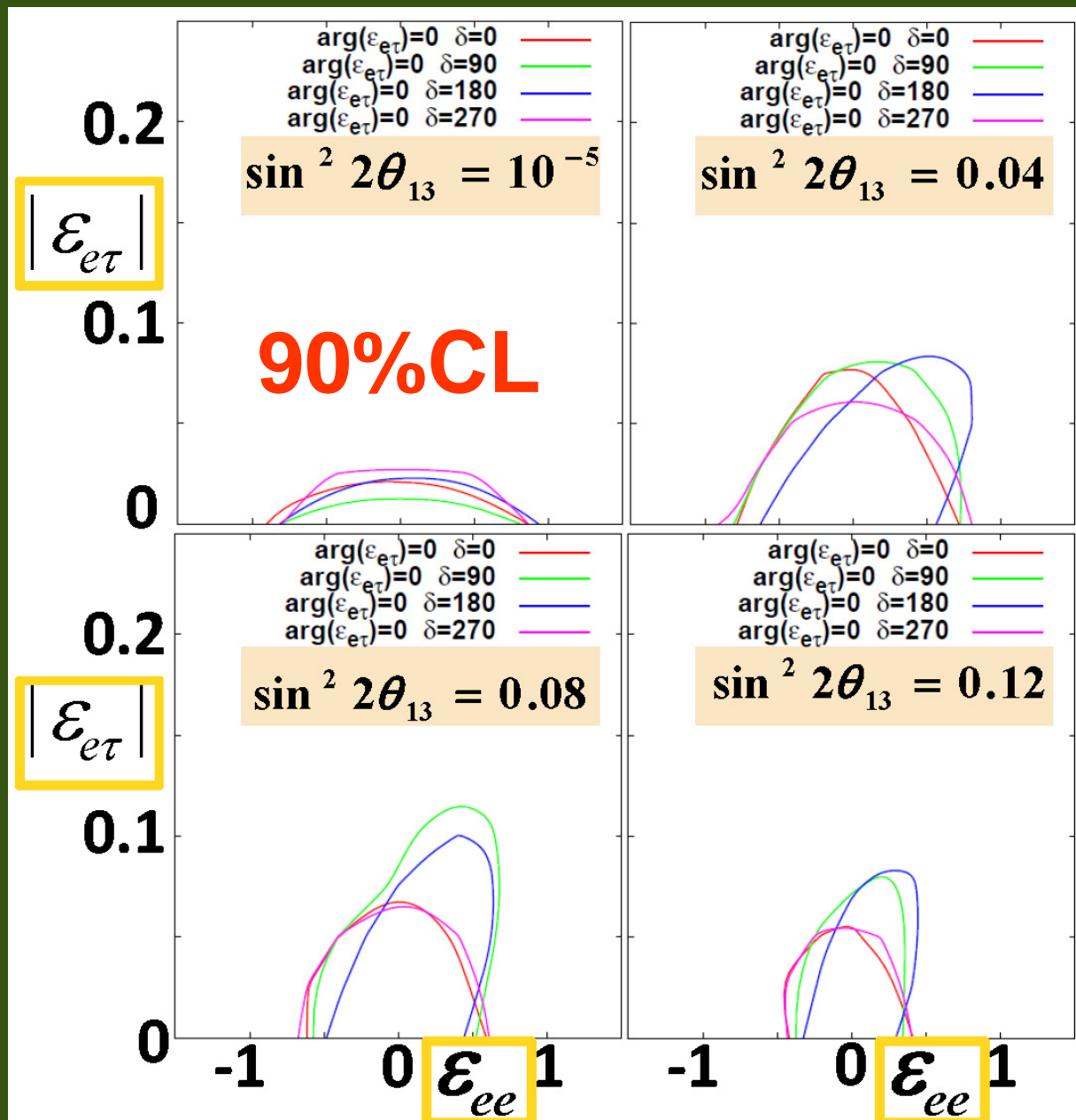
- Dependence on phases  $\delta$  and  $\arg(\varepsilon_{e\tau})$

$$P(\nu_\mu \rightarrow \nu_e) \cong P_0(\nu_\mu \rightarrow \nu_e) \Big|_{\Delta m_{21}^2=0} + \Delta m_{21}^2 P_1(\nu_\mu \rightarrow \nu_e)$$

Function of  
 $\delta + \arg(\varepsilon_{e\tau})$

Approximately  
function of  
 $\arg(\varepsilon_{e\tau})$  only

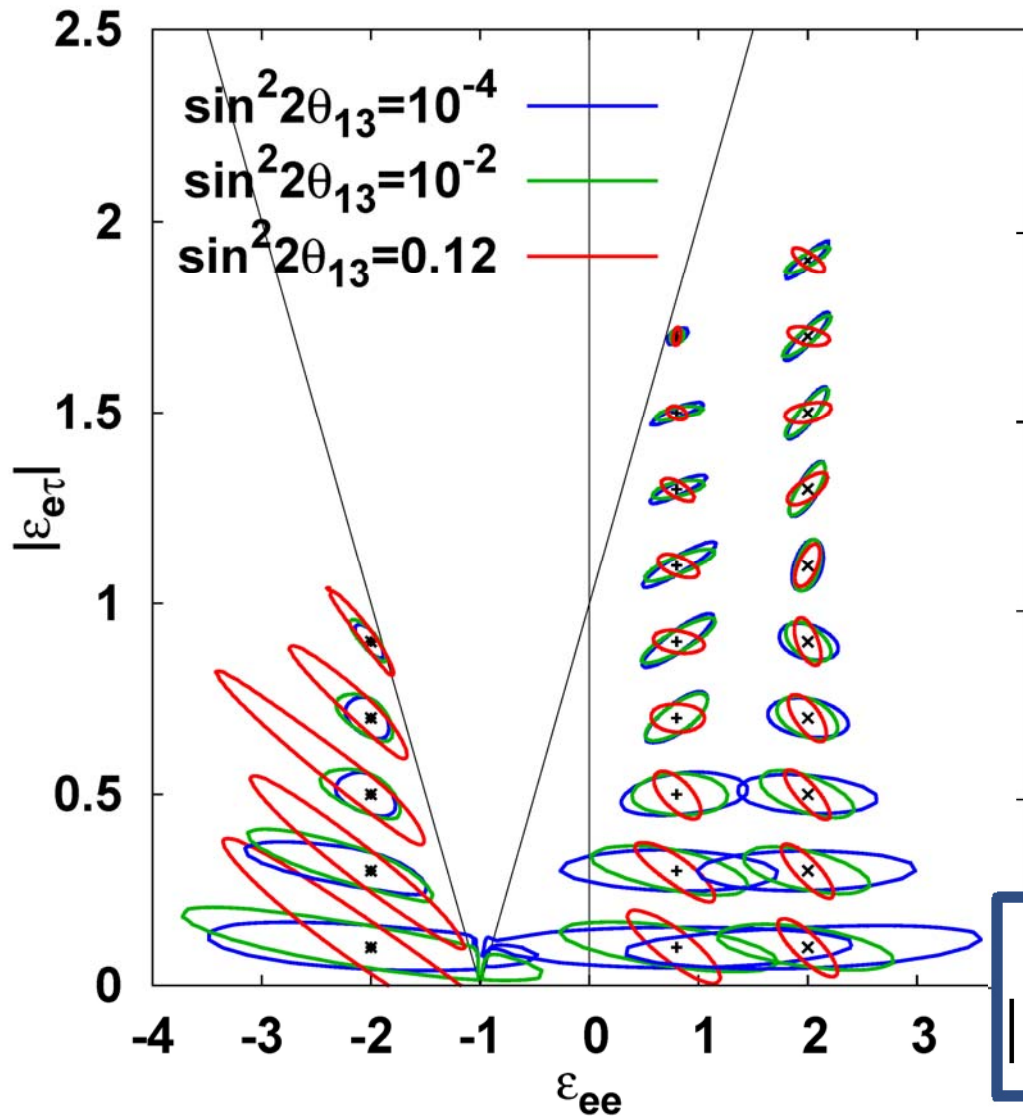
# Sensitivity to $\epsilon_{ee}$ , $|\epsilon_{e\tau}|$ for various $\theta_{13}$



regions depend on  $\theta_{13}, \delta, \arg(\epsilon_{e\tau})$

$$\begin{array}{l}
 |\epsilon_{ee}| < 4 \\
 |\epsilon_{e\tau}| < 3 \\
 \downarrow \\
 |\epsilon_{ee}| \gtrsim 1 \\
 |\epsilon_{e\tau}| \gtrsim 0.2
 \end{array}$$

# Precision of $\epsilon_{ee}, |\epsilon_{e\tau}|$



$|\epsilon_{e\tau}| \geq 0.5$   
 $\epsilon_{ee}, |\epsilon_{e\tau}|$   
 determined  
 separately



$\epsilon_{ee}$  not determined  
 $|\epsilon_{e\tau}|$  determined (if  $> 0.1$ )

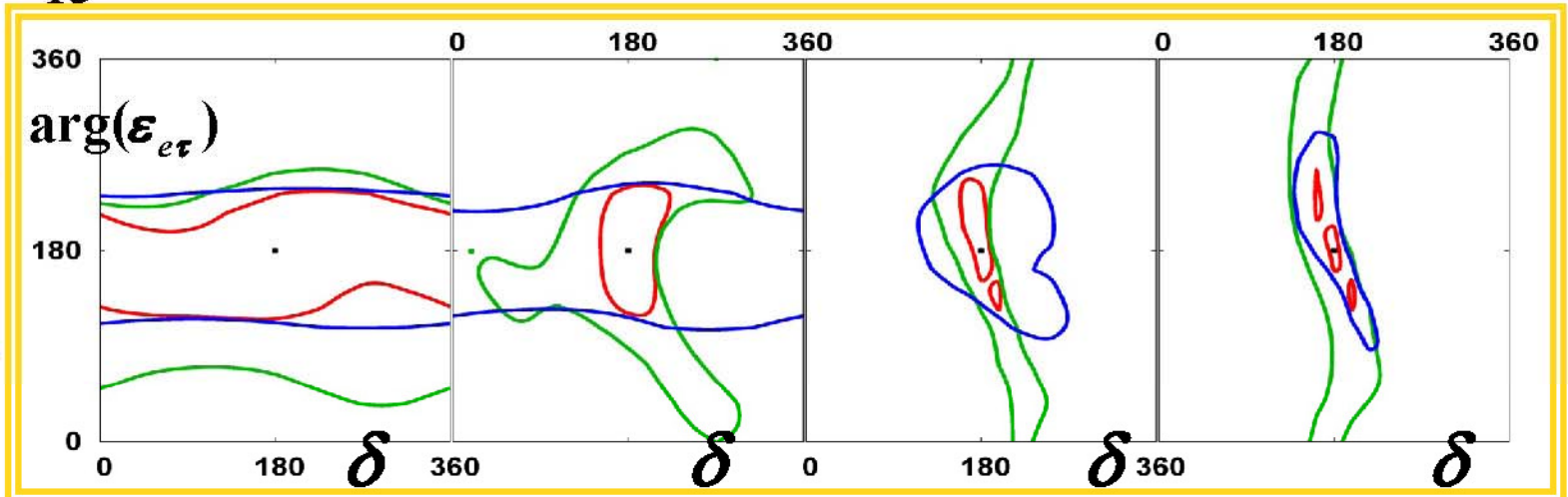
# Sensitivity to $\delta$ and $\arg(\varepsilon_{e\tau})$

Kamioka+Korea —  
 Kamioka —  
 Korea —

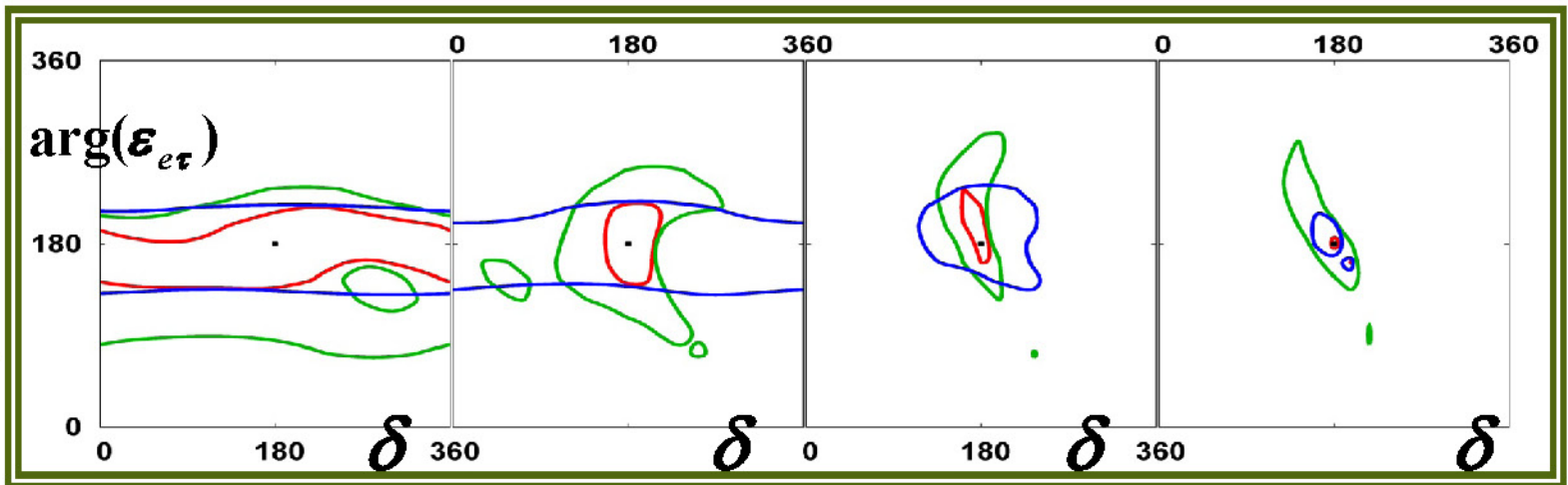
- Correlation of measured  $\arg(\varepsilon_{e\tau})$  and  $\delta$

$\sin^2 2\theta_{13} = 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 0.12$

$\varepsilon_{ee} = 0.8$   
 $|\varepsilon_{e\tau}| = 0.2$



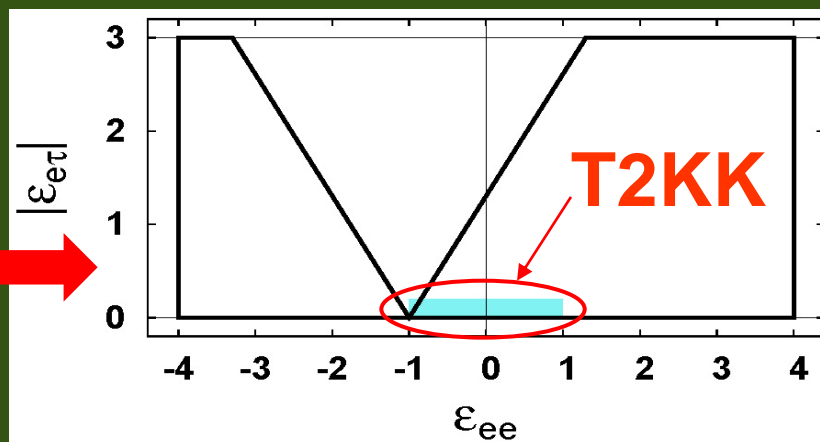
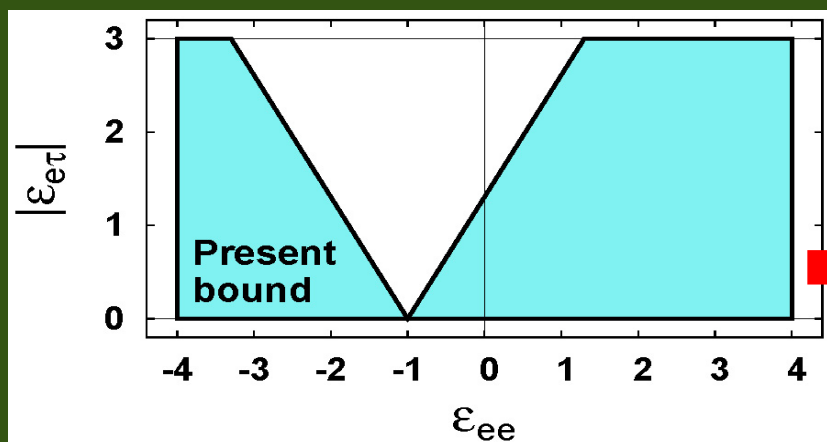
$\varepsilon_{ee} = 0.8$   
 $|\varepsilon_{e\tau}| = 0.4$



- If  $(\varepsilon_{ee}, |\varepsilon_{e\tau}|, s_{13})$  are large, we can determine  $\arg(\varepsilon_{e\tau}), \delta$

## 4. Conclusions (1)

- We studied phenomenological sensitivity to NSI in propagation of the T2KK proposal
- Under the assumptions  $\epsilon_{e\mu} = \epsilon_{\mu\mu} = \epsilon_{\mu\tau} = 0$  &  $\epsilon_{\tau\tau} = |\epsilon_{e\tau}|^2 / (1 + \epsilon_{ee})$ , we found that T2KK can restrict the NSI parameters  $|\epsilon_{ee}| \lesssim 1, |\epsilon_{e\tau}| \lesssim 0.2$



- If  $\epsilon_{ee}$ ,  $|\epsilon_{e\tau}|$  and  $S_{13}$  are large, then T2KK can determine  $\epsilon_{ee}$ ,  $|\epsilon_{e\tau}|$ ,  $\delta$  and  $\arg(\epsilon_{e\tau})$  separately.



## 4. Conclusions (2)

- We provided an analytical argument on the oscillation probability for high energy atmospheric neutrinos that  $|\varepsilon_{\mu\alpha}| \ll 1$  &  $|\varepsilon_{\tau\tau} - |\varepsilon_{e\tau}|^2 / (1 + \varepsilon_{ee})| \ll 1$  must hold.

- Deviation of  $1 - P(\nu_\mu \rightarrow \nu_\mu)$  from the standard case in high energy  $\nu_{\text{atm}}$  data gives strong constraints on **New Physics**.

→ It would be great if we can constrain/determine  $c_0, c_1, c_{2j}$  ( $j=0,1,2$ ) in high energy  $\nu_{\text{atm}}$  data:

$$1 - P(\nu_\mu \rightarrow \nu_\mu) \simeq c_0 + \frac{c_1}{E} + \frac{c_{20}L^2 + c_{21} \sin^2(c_{22}L)}{E^2}$$

**Is it possible at SK, IceCube, HK?**



**Backup slides**

● **O(1)**

$$1 - P(\nu_\mu \rightarrow \nu_\mu) \simeq c_0 + \frac{c_1}{E} + \frac{c_{20}L^2 + c_{21} \sin^2(c_{22}L)}{E^2}$$

$$c_0 \simeq 4\tilde{X}_1^{\mu\mu} \tilde{X}_2^{\mu\mu} \sin^2\left(\frac{\Delta\tilde{E}_{21}L}{2}\right) + 4\tilde{X}_3^{\mu\mu} \sin^2\left(\frac{(1 + \epsilon_{ee} + \epsilon_{\tau\tau})AL}{2}\right)$$

$$4\tilde{X}_1^{\mu\mu} \tilde{X}_2^{\mu\mu} \simeq 1 - \frac{1 + \epsilon_{ee} + \epsilon_{\tau\tau}}{(1 + \epsilon_{ee})|\epsilon_{\mu\tau}|^2 + \epsilon_{\tau\tau}|\epsilon_{e\mu}|^2 - 2\text{Re}(\epsilon_{e\mu}\epsilon_{\mu\tau}(\epsilon_{e\tau})^*)} \left(\frac{|\epsilon_{e\mu}|^2 + |\epsilon_{\mu\mu}|^2 + |\epsilon_{\mu\tau}|^2}{1 + \epsilon_{ee} + \epsilon_{\tau\tau}} - \epsilon_{\mu\mu}\right)^2$$

$$4\tilde{X}_3^{\mu\mu} \simeq 4\frac{|\epsilon_{e\mu}|^2 + |\epsilon_{\mu\mu}|^2 + |\epsilon_{\mu\tau}|^2}{(1 + \epsilon_{ee} + \epsilon_{\tau\tau})^2} - 4\frac{(1 + \epsilon_{ee})|\epsilon_{\mu\tau}|^2 + \epsilon_{\tau\tau}|\epsilon_{e\mu}|^2 - 2\text{Re}(\epsilon_{e\mu}\epsilon_{\mu\tau}(\epsilon_{e\tau})^*)}{(1 + \epsilon_{ee} + \epsilon_{\tau\tau})^3}$$

$$\Delta\tilde{E}_{21} \simeq 2A \left[ \frac{(1 + \epsilon_{ee})|\epsilon_{\mu\tau}|^2 + \epsilon_{\tau\tau}|\epsilon_{e\mu}|^2 - 2\text{Re}(\epsilon_{e\mu}\epsilon_{\mu\tau}(\epsilon_{e\tau})^*)}{1 + \epsilon_{ee} + \epsilon_{\tau\tau}} \right]$$

→  $|\epsilon_{e\mu}| \ll 1, |\epsilon_{\mu\mu}| \ll 1, |\epsilon_{\mu\tau}| \ll 1$

$|\epsilon_{\mu\tau}| \ll 1$ : Already shown by **Fornengo et al. PRD65, 013010, '02**

$|\epsilon_{\mu\mu}| \ll 1$ : Already shown by **Davidson et al. JHEP 0303:011, '03**

$|\epsilon_{e\mu}| \ll 1$ : **New observation**

- **O(1/E)**

$$1 - P(\nu_\mu \rightarrow \nu_\mu) \simeq c_0 + \frac{c_1}{E} + \frac{c_{20}L^2 + c_{21} \sin^2(c_{22}L)}{E^2}$$

$$\frac{c_1}{E} \simeq -2s_{23}^2(\epsilon_{ee} + \epsilon_{\tau\tau})(1 + \epsilon_{ee} + \epsilon_{\tau\tau})A\zeta \frac{\Delta m_{31}^2}{E} \sin^2 \left[ \frac{A\zeta}{2(1 + \epsilon_{ee} + \epsilon_{\tau\tau})} \right]$$

$$\zeta \equiv \epsilon_{\tau\tau} - |\epsilon_{e\tau}|^2 / (1 + \epsilon_{ee})$$

$$\rightarrow \left| \epsilon_{\tau\tau} - |\epsilon_{e\tau}|^2 / (1 + \epsilon_{ee}) \right| \ll 1$$

Already shown by **Friedland-Lunardini, PRD72:053009,'05**

- **To summarize**

$$A \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix}$$



$$A \begin{pmatrix} 1 + \epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^* & 0 & |\epsilon_{e\tau}|^2 / (1 + \epsilon_{ee}) \end{pmatrix}$$

# ● T violation : standard vs NP (1)

$$\begin{aligned} \text{Im}(\tilde{X}_1^{\mu e} \tilde{X}_2^{\mu e*}) &= \frac{-1}{(\Delta\tilde{E}_{21})^2 \Delta\tilde{E}_{31} \Delta\tilde{E}_{32}} \text{Im} \left[ \left\{ Y_3^{\mu e} - (\tilde{E}_2 + \tilde{E}_3) Y_2^{\mu e} \right\} \left\{ Y_3^{\mu e} - (\tilde{E}_3 + \tilde{E}_1) Y_2^{\mu e} \right\}^* \right] \\ &= \frac{-1}{\Delta\tilde{E}_{21} \Delta\tilde{E}_{31} \Delta\tilde{E}_{32}} \text{Im} \{ Y_3^{\mu e} (Y_2^{\mu e})^* \}. \end{aligned}$$

$$Y_2^{\mu e} = (U\mathcal{E}U^{-1} + \mathcal{A})_{\mu e} = (U\mathcal{E}U^{-1})_{\mu e}$$

$$Y_3^{\mu e} = \left[ (U\mathcal{E}U^{-1} + \mathcal{A})^2 \right]_{\mu e} = (U\mathcal{E}^2U^{-1})_{\mu e} + (U\mathcal{E}U^{-1})_{\mu e} \mathcal{A}_{ee} + (U\mathcal{E}U^{-1})_{\mu\tau} \mathcal{A}_{\tau e},$$

$$\begin{aligned} \text{Im} \{ Y_3^{\mu e} (Y_2^{\mu e})^* \} &= \text{Im} \left[ (U\mathcal{E}U^{-1})_{\mu e}^* \left\{ (U\mathcal{E}^2U^{-1})_{\mu e} + (U\mathcal{E}U^{-1})_{\mu\tau} \mathcal{A}_{\tau e} \right\} \right] \\ &= \text{Im} \{ Y_3^{\mu e} (Y_2^{\mu e})^* \}_{\text{std}} + \text{Im} \{ Y_3^{\mu e} (Y_2^{\mu e})^* \}_{\text{NP}}, \end{aligned}$$

## ● T violation : standard vs NP (2)

$$\begin{aligned}
 \text{Im} \{Y_3^{\mu e} (Y_2^{\mu e})^*\}_{\text{std}} &\equiv \text{Im} \left[ (U\mathcal{E}U^{-1})_{\mu e}^* (U\mathcal{E}^2U^{-1})_{\mu e} \right] \\
 &= \text{Im} \left[ \{(\Delta E_{31})^2 X_3^{\mu e} + (\Delta E_{21})^2 X_2^{\mu e}\} \{ \Delta E_{31} (X_3^{\mu e})^* + \Delta E_{21} (X_2^{\mu e})^* \} \right] \\
 &= \Delta E_{21} \Delta E_{31} \Delta E_{32} \text{Im} (X_3^{\mu e} (X_2^{\mu e})^*) \\
 &= \Delta E_{21} \Delta E_{31} \Delta E_{32} \frac{1}{8} c_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin \delta
 \end{aligned}$$

$$\begin{aligned}
 \text{Im} \{Y_3^{\mu e} (Y_2^{\mu e})^*\}_{\text{NP}} &\equiv \text{Im} \left\{ (U\mathcal{E}U^{-1})_{\mu e}^* (U\mathcal{E}U^{-1})_{\mu\tau} \mathcal{A}_{\tau e} \right\} \\
 &= \text{Im} \left[ A(\epsilon_{e\tau})^* \{ \Delta E_{31} (X_3^{\mu e})^* + \Delta E_{21} (X_2^{\mu e})^* \} (\Delta E_{31} X_3^{\mu\tau} + \Delta E_{21} X_2^{\mu\tau}) \right] \\
 &= A|\epsilon_{e\tau}| \left[ (\Delta E_{31})^2 \text{Im} \{ (X_3^{\mu e})^* X_3^{\mu\tau} e^{2i\gamma} \} \right. \\
 &\quad \left. + \Delta E_{31} \Delta E_{21} \text{Im} \{ (X_3^{\mu e})^* X_2^{\mu\tau} e^{2i\gamma} + (X_2^{\mu e})^* X_3^{\mu\tau} e^{2i\gamma} \} \right. \\
 &\quad \left. + (\Delta E_{21})^2 \text{Im} \{ (X_2^{\mu e})^* X_2^{\mu\tau} e^{2i\gamma} \} \right] \\
 &\simeq A \Delta E_{31} \Delta E_{21} |X_2^{\mu e}| |X_3^{\mu\tau}| \text{Im}(\epsilon_{e\tau})
 \end{aligned}$$

$$\frac{\text{Im} \{Y_3^{\mu e} (Y_2^{\mu e})^*\}_{\text{NP}}}{\text{Im} \{Y_3^{\mu e} (Y_2^{\mu e})^*\}_{\text{std}}} \simeq \frac{A|\epsilon_{e\tau}| \sin(\arg(\epsilon_{e\tau}))}{\Delta E_{32} s_{13} \sin \delta} \sim \frac{A}{\Delta E_{32}} \frac{|\epsilon_{e\tau}|}{s_{13}} \sim \frac{10|\epsilon_{e\tau}|}{s_{13}}$$

- T violating part : standard vs NP

$$\frac{(\text{T violation})_{\text{NP}}}{(\text{T violation})_{\text{std}}} \cong \frac{AE |\varepsilon_{e\tau}| \sin(\arg(\varepsilon_{e\tau}))}{|\Delta m_{31}^2| s_{13} \sin \delta} \cong \frac{10 |\varepsilon_{e\tau}|}{s_{13}} \bullet \frac{\sin(\arg(\varepsilon_{e\tau}))}{\sin \delta}$$