Sensitivity of T2HKK to non-standard flavor-dependent interactions

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Ghosh & OY, arXiv:1709.08264

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1. Introduction

Framework of 3 flavor ν oscillation

Mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Functions of mixing angles θ_{12}, θ_{23}, θ_{13}, and CP phase δ

All 3 mixing angles have been measured

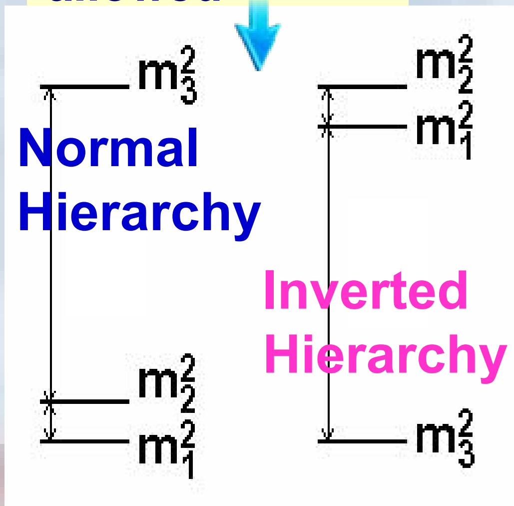
ν_{solar}+KamLAND (reactor) → $\theta_{12} \cong \frac{\pi}{6}, \Delta m^2_{21} \cong 8 \times 10^{-5} eV^2$

ν_{atm}, K2K,T2K,MINOS,Nova (accelerators) → $\theta_{23} \cong \frac{\pi}{4}, |\Delta m^2_{32}| \cong 2.5 \times 10^{-3} eV^2$

DCHOOZ+Daya Bay+Reno (reactors), T2K+MINOS+Nova → $\theta_{13} \cong \pi / 20$

Next task is to measure $\mathrm{sign}(\Delta m^2_{31})$, $\pi/4-\theta_{23}$ and δ

Both hierarchy patterns are allowed



Proposed experiments

- T2HK(JP, JPARC-->HK) L=295km, E~0.6GeV
- T2HHK(JP, JPARC-->Korea) L=1100km, E~1GeV
- DUNE (US, FNAL-->Homestake, SD) , L=1300km, E~2GeV

$$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu + \overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$$

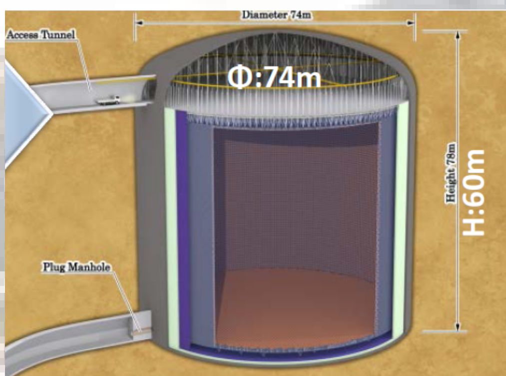
These experiments are expected to measure $\mathrm{sign}(\Delta m^2_{31})$, $\pi/4-\theta_{23}$ and δ

Future plan: T2HK

- **Phase 2**

0.75MW ν beam ⇒ Hyperkamiokande
(50 times K2K) (10 times SK)

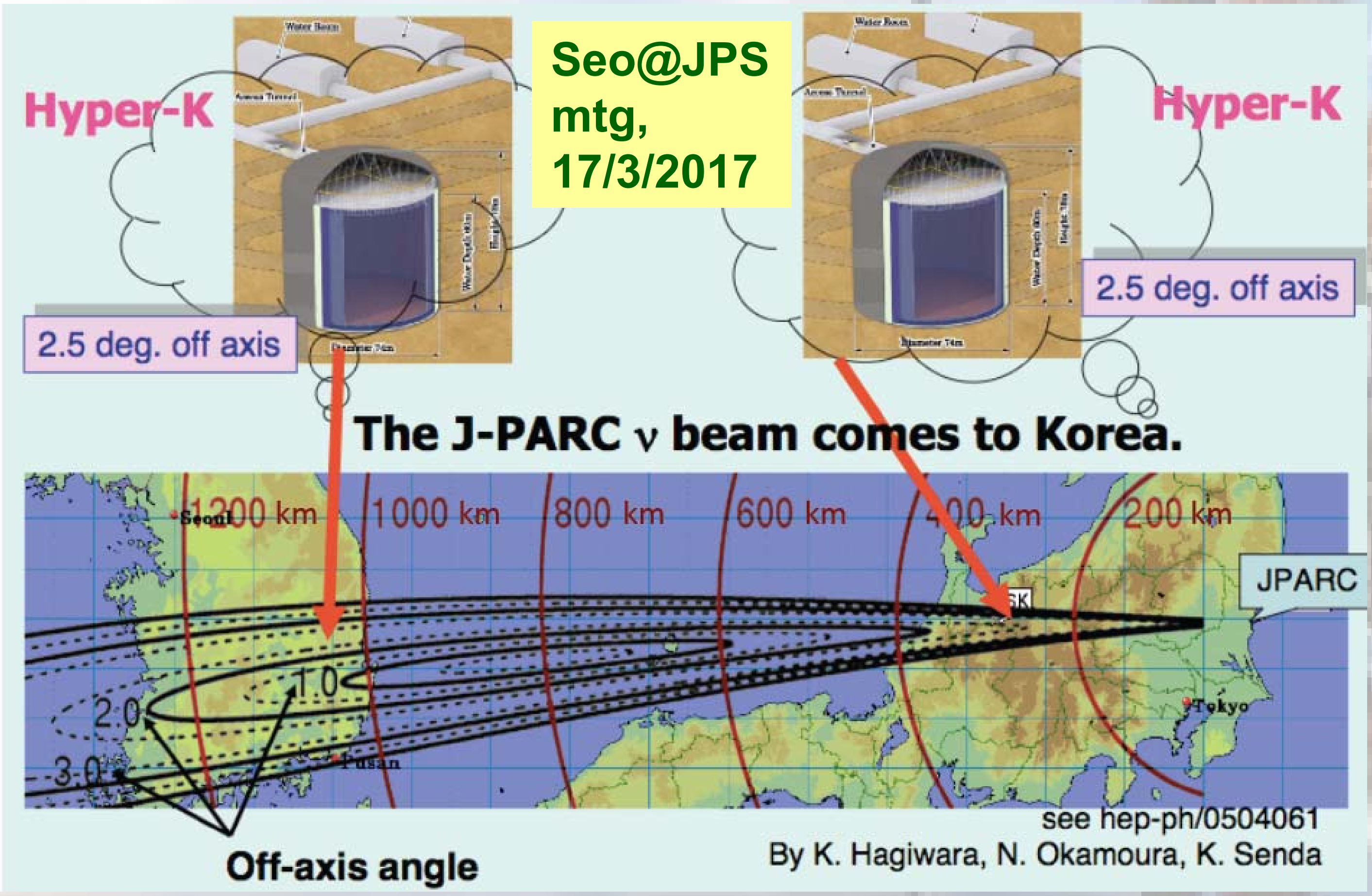
- **Extension of T2K**
- **Measurement of CP phase δ**



Hyper-kamiokande

Future plan: T2HKK

Recent revival of old T2KK idea in 2005:
T2HKK proposal w/ baselines L=295km, 1100km
→L=1100km is sensitive to the matter effect

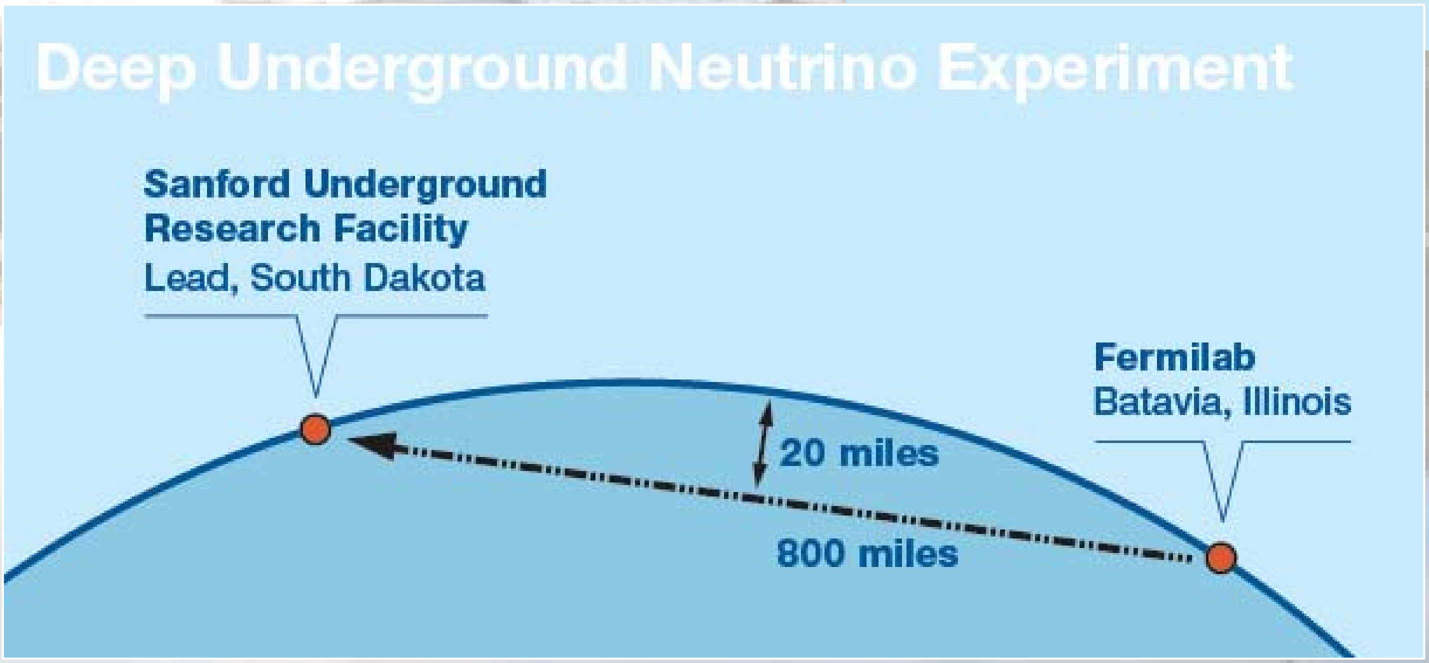


Seo@JPS mtg, 17/3/2017

Future plan: DUNE

2.3MW ν beam@Fermilab
$\Rightarrow$ 40-kt Liquid Argon detector @ Sanford Underground RF

E $\sim$ 2GeV, L $\sim$ 1300km



Motivation for research on New Physics

High precision measurements of ν oscillation in future experiments can be used to probe **physics beyond SM** by looking at deviation from SM+m_ν (like at B factories).

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

List of New Physics discussed in ν phenomenology

Scenario beyond SM+m_ν	Experimental indication ?	Phenomenological constraints on the magnitude of the effects
Light sterile ν	Maybe	O(10%)
NSI at production / detection	×	O(1%)
NSI in propagation	Maybe	e-τ: O(100%) Others: O(1%)
Unitarity violation due to heavy particles	×	O(0.1%)

NSI: discussed in this talk

In the mean time we have had some possible tensions among the data within the standard oscillation scenario:

- ν_{solar} - KamLAND: Δm^2_{21} → NSI or sterile ν
- NOvA - T2K: θ_{23} → ??
- LSND-MiniBooNE anomaly, Reactor anomaly, Gallium anomaly → sterile ν

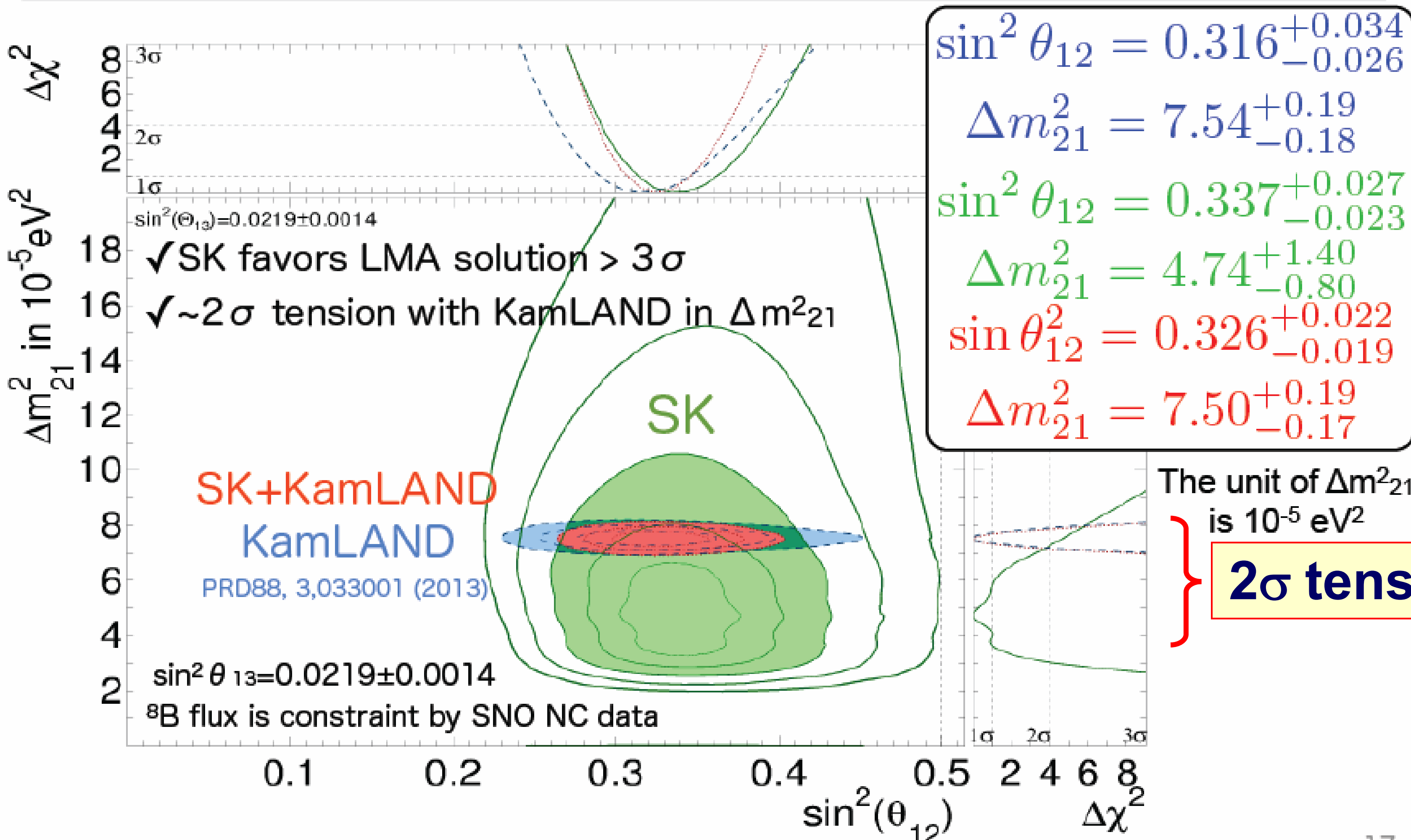
NSI: motivation to this talk

sterile ν : not directly related to this talk

- **Tension between Δm^2_{21}(solar) & Δm^2_{21}(KamLAND)**

SK I - IV combined

Koshio@ NOW2016



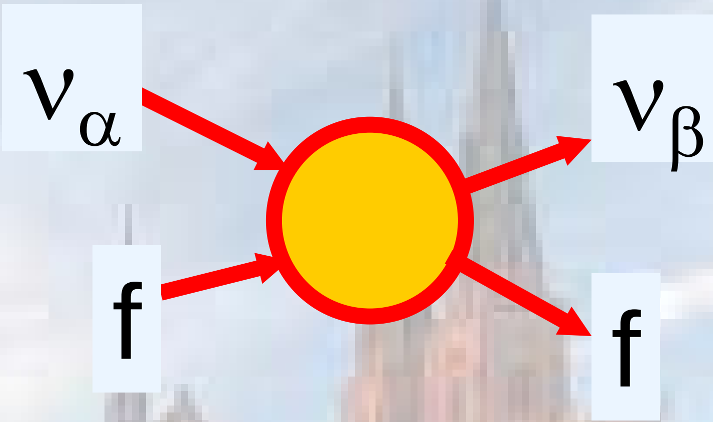
The unit of Δm^2_{21} is 10^{-5} eV^2

2σ tension

2. Nonstandard Interaction in propagation

Phenomenological New Physics considered in this talk: 4-fermi Non Standard 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

f = e, u or d

Modification of matter effect

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

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

NP

Observation of matter effect needs large L

ν oscillation in matter (in two flavor toy case)

$$P(\nu_\mu \to \nu_e) = \left(\frac{\Delta E}{\Delta \tilde{E}}\right)^2 \sin^2 2\theta \sin^2\left(\frac{\Delta \tilde{E} L}{2}\right)$$

$$\Delta E \equiv \Delta m^2 / 2E$$

$$\Delta \tilde{E} \equiv \left[(\Delta E \cos 2\theta - A)^2 + (\Delta E \sin 2\theta)^2\right]^{1/2}$$

$$A \equiv \sqrt{2} G_F n_e(x)$$

$$\tan 2\tilde{\theta} \equiv \frac{\Delta E \sin 2\theta}{\Delta E \cos 2\theta - A}$$

Matter effect becomes most conspicuous if $\Delta E \cos 2\theta = A$ is satisfied ($\tilde{\theta} = \pi/2$). In this case, the baseline length L has to be large:

$$\pi = \Delta \tilde{E} L = \Delta E \sin 2\theta L = A L \tan 2\theta$$

→L > π/A > O(1000km)

● Constraints on $\varepsilon_{\alpha\beta}$ from non-oscillation experiments

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)

Constraints are weak

$$\begin{pmatrix} |\epsilon_{ee}| \lesssim 4\times 10^{0} & |\epsilon_{e\mu}| \lesssim 3\times 10^{-1} & |\epsilon_{e\tau}| \lesssim 3\times 10^{0} \\ & |\epsilon_{\mu\mu}| \lesssim 7\times 10^{-2} & |\epsilon_{\mu\tau}| \lesssim 3\times 10^{-1} \\ & & |\epsilon_{\tau\tau}| \lesssim 2\times 10^{1} \end{pmatrix}$$

● **Some model predicts large NSI** (new gauge boson mass is of O(10MeV) and SU(2) invariance is broken): Farzan, PLB748 ('15) 311; Farzan-Shoemaker, JHEP,1607 ('16)033; Farzan-Heeck, PRD94 ('16) 053010.

• NSI for solar ν: $\varepsilon_{\alpha\beta}$ vs (ε_D, ε_N)

Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152

In solar ν analysis, Δm_{31}^2 -> infinity, H -> H^{eff}

$$H^{\rm eff} = \frac{\Delta m_{21}^2}{4E}\begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix}$$

$$+ \begin{pmatrix} c_{13}^2 A & 0 \\ 0 & 0 \end{pmatrix} + A \sum_{f=e,u,d} \frac{N_f}{N_e} \begin{pmatrix} -\epsilon_D^f & \epsilon_N^f \\ \epsilon_N^{f*} & \epsilon_D^f \end{pmatrix}$$

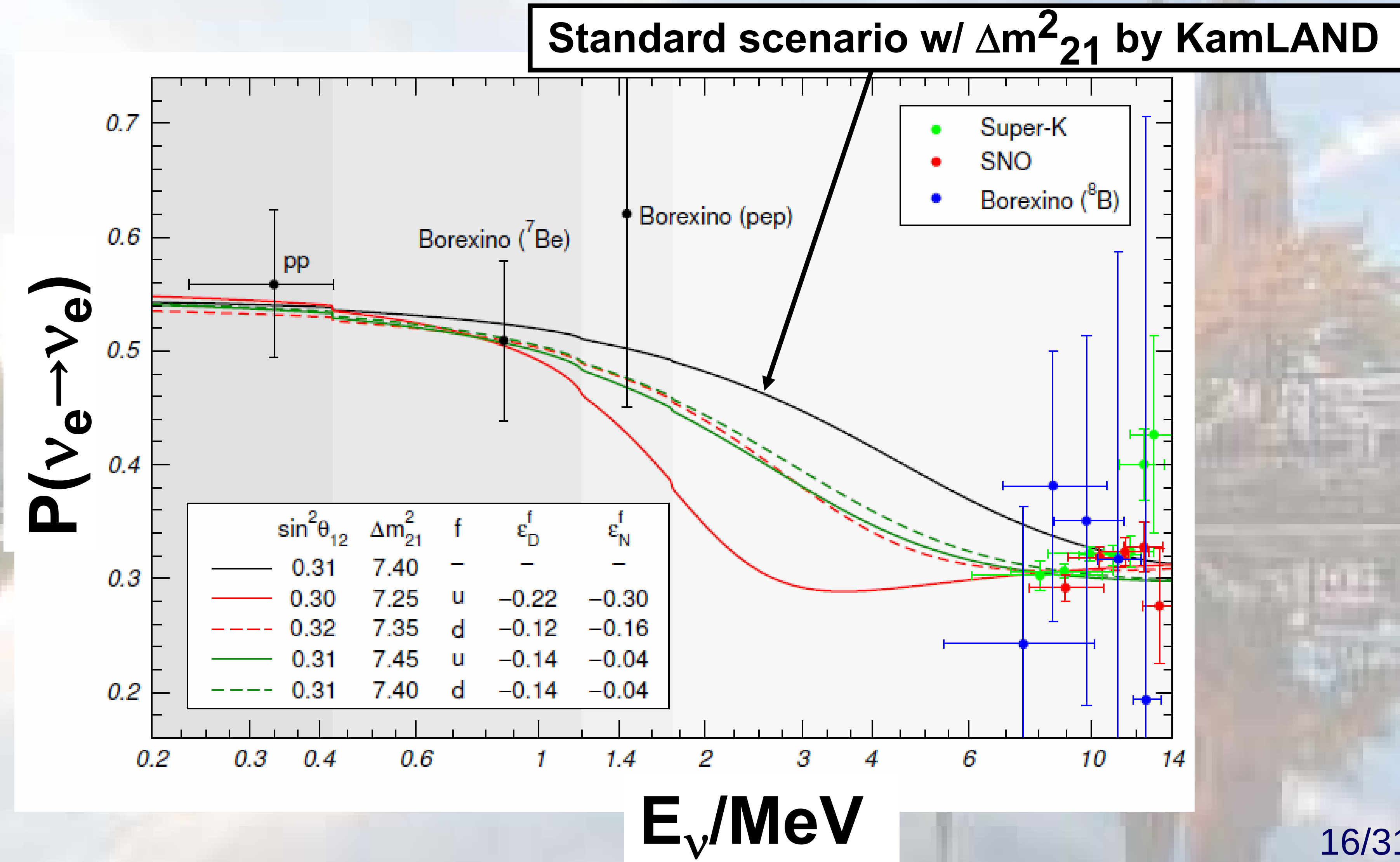
$$\begin{aligned}
\epsilon_D^f &= c_{13}s_{13}{\rm Re}\left[e^{i\delta_{\rm CP}}\left(s_{23}\epsilon_{e\mu}^f + c_{23}\epsilon_{e\tau}^f\right)\right] - \left(1+s_{13}^2\right)c_{23}s_{23}{\rm Re}\left[\epsilon_{\mu\tau}^f\right] \\
&\quad -\frac{c_{13}^2}{2}\left(\epsilon_{ee}^f - \epsilon_{\mu\mu}^f\right) + \frac{s_{23}^2 - s_{13}^2 c_{23}^2}{2}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right) \\
\epsilon_N^f &= c_{13}\left(c_{23}\epsilon_{e\mu}^f - s_{23}\epsilon_{e\tau}^f\right) + s_{13}e^{-i\delta_{\rm CP}}\left[s_{23}^2\epsilon_{\mu\tau}^f - c_{23}^2\epsilon_{\mu\tau}^{f*} + c_{23}s_{23}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right)\right]
\end{aligned}$$

f = e, u or d

ε^f_{ee}, $|\varepsilon^f_{e\tau}|$, $\varepsilon^f_{\tau\tau}$ have to be solved from (ε^f_D, ε^f_N)

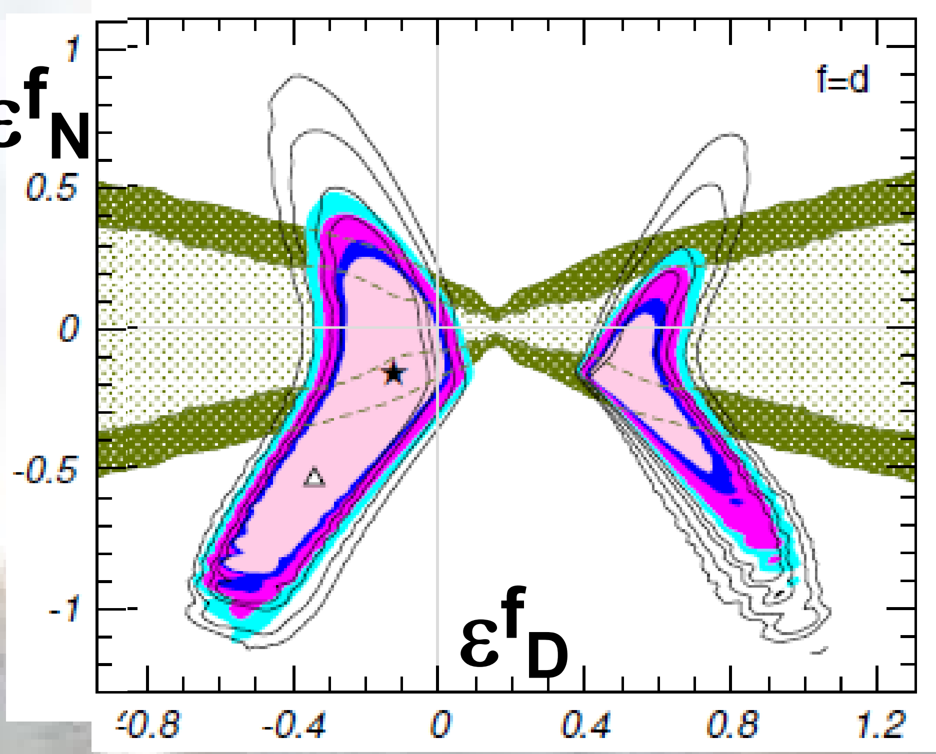
Tension between solar ν & KamLAND data comes from little observation of upturn by SK & SNO

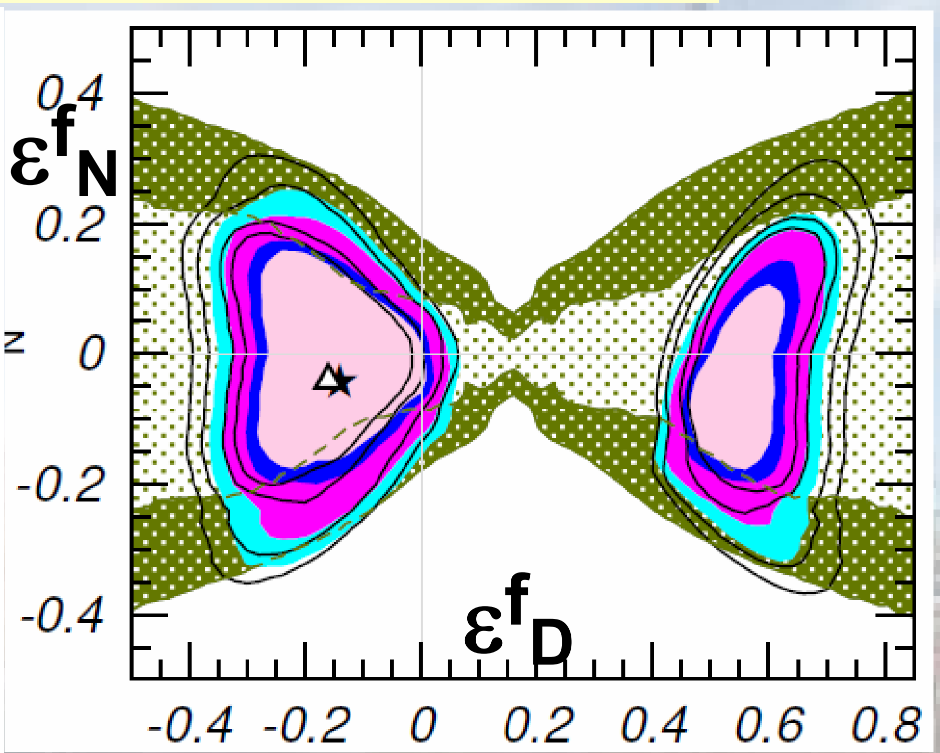
Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152



Tension between solar ν & KamLAND can be solved by NSI

Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152





Best fit value of solar-KL

$$(\epsilon^u_D, \epsilon^u_N) = (-0.22, -0.30)$$

$$(\epsilon^d_D, \epsilon^d_N) = (-0.12, -0.16)$$

Best fit value of global fit

$$(\epsilon^u_D, \epsilon^u_N) = (-0.140, -0.030)$$

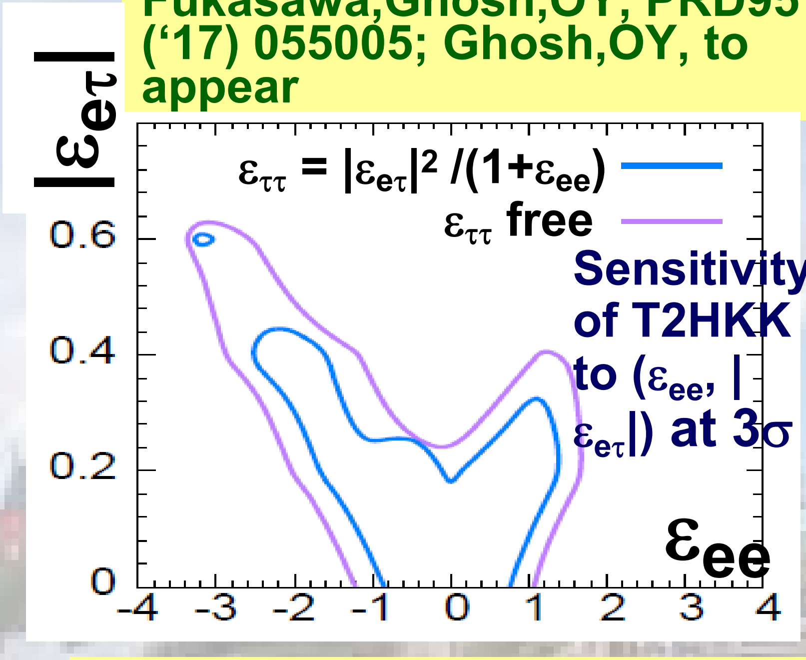
$$(\epsilon^d_D, \epsilon^d_N) = (-0.145, -0.036)$$

3. Sensitivity to NSI of propagation at T2HKK

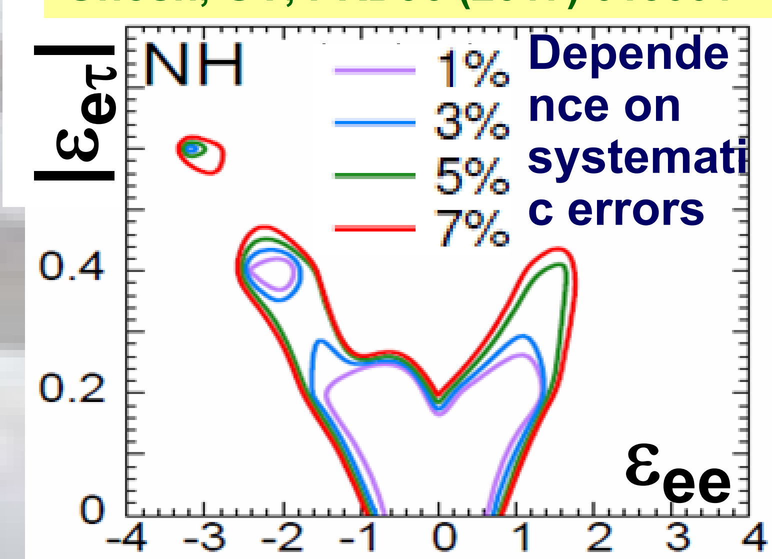
3.0 Motivation of our work

All the works on the sensitivity to NSI was expressed in terms of $\varepsilon_{\alpha\beta}$ typically in (ε_D, ε_N)-plane
-> Whether the LBL experiments have sensitivity to the region suggested by the solar tension is not clear.
-> Sensitivity given in (ε_D, ε_N)-plane is desired.

Fukasawa,Ghosh,OY, PRD95 ('17) 055005; Ghosh,OY, to appear



Ghosh, OY, PRD96 (2017) 013001



3.1 Outline of our Analysis

Strategy of our analysis:

- **We assume $\varepsilon_{\alpha\beta}$(true) = 0 and minimize χ^2 (ε^f_D(test), ε^f_N(test)) by varying other $\varepsilon_{\alpha\beta}$(test).**

We compare the sensitivities of

T2HKK, DUNE, HK(ν_{atm})

$L=1100\,\mathrm{km}$ (T2HKK)

$L=1300\,\mathrm{km}$ (DUNE)

$10\,\mathrm{km} < L < 13000\,\mathrm{km}$ (HK(ν_{atm}))

Relation between $\varepsilon_{\alpha\beta}$ & (ε_D, ε_N)

We treat $\varepsilon^f_{\tau\tau}$, $|\varepsilon^f_{e\tau}|$, ε^f_{ee} as dependent variables:

$$|\epsilon^f_{e\tau}| = \frac{1}{c_{13}c_{23}\sin(\phi_{13}+\delta_{CP})}\left(-F\sin\delta_{CP}+G\cos\delta_{CP}\right)$$

$$\epsilon^f_{\tau\tau} = \frac{2}{s_{13}\sin 2\theta_{23}\ \sin(\phi_{13}+\delta_{CP})}\left(F\sin\phi_{13}+G\cos\phi_{13}\right)$$

$$\begin{aligned} F \equiv\ & \epsilon^f_N - c_{13}c_{23}\,|\epsilon^f_{e\mu}|\,\cos\phi_{12} \\ & - s_{13}|\epsilon^f_{\mu\tau}|\left\{s^2_{23}\cos(\phi_{23}-\delta_{CP}) - c^2_{23}\cos(\phi_{23}+\delta_{CP})\right\} \\ G \equiv\ & -c_{13}c_{23}\,|\epsilon^f_{e\mu}|\,\sin\phi_{12} \\ & - s_{13}|\epsilon^f_{\mu\tau}|\left\{s^2_{23}\sin(\phi_{23}-\delta_{CP}) + c^2_{23}\sin(\phi_{23}+\delta_{CP})\right\} \end{aligned}$$

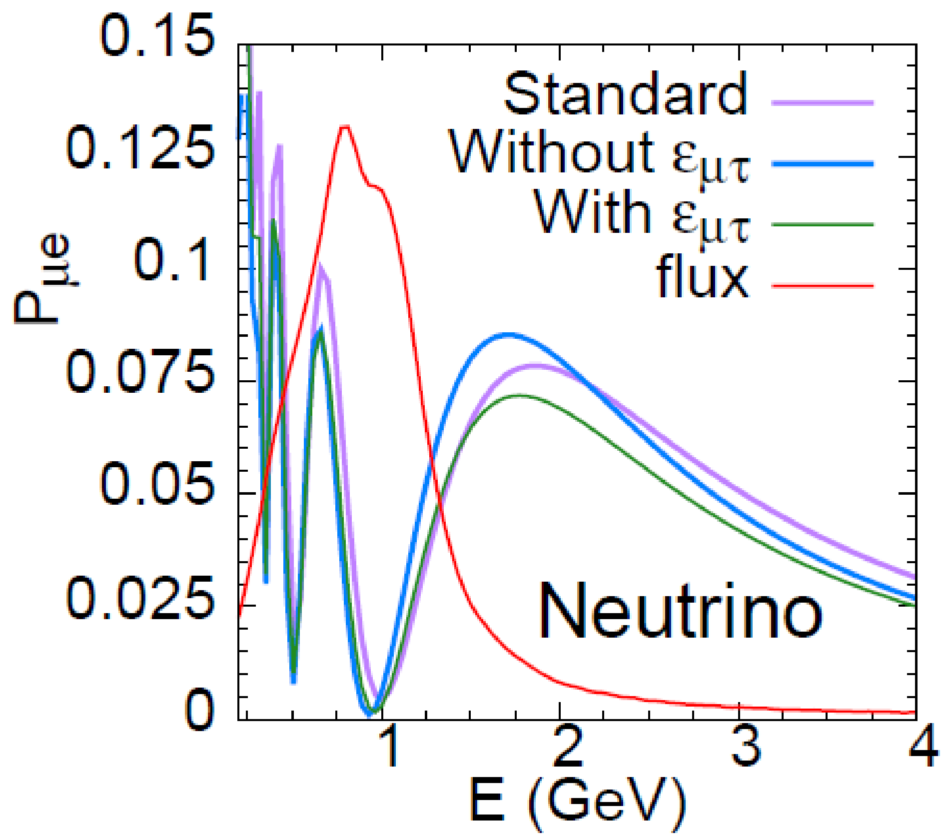
ϕ_{12} =arg($\varepsilon^f_{e\mu}$), ϕ_{13} =arg($\varepsilon^f_{e\tau}$), ϕ_{23} =arg($\varepsilon^f_{\mu\tau}$)

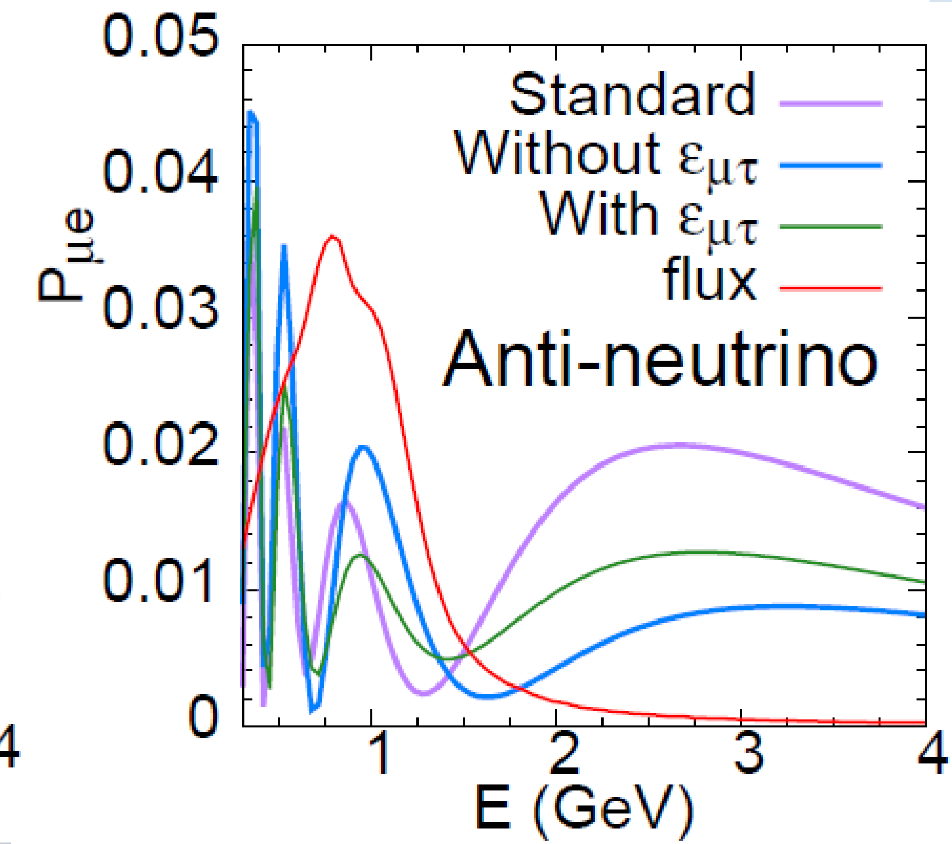
$$
\begin{aligned}
\epsilon^f_{ee} = \frac{2}{c^2_{13}} \Big\{ & \frac{s_{23}}{2} \sin 2\theta_{13} |\epsilon^f_{e\mu}| \cos(\delta_{\rm CP} + \phi_{12}) \\
& + \frac{c_{23}}{2} \sin 2\theta_{13} |\epsilon^f_{e\tau}| \cos(\delta_{\rm CP} + \phi_{13}) \\
& - \left(1 + s^2_{13}\right) c_{23} s_{23} |\epsilon^f_{\mu\tau}| \cos(\phi_{23}) \\
& - \epsilon^f_D + \frac{s^2_{23} - s^2_{13} c^2_{23}}{2} \epsilon^f_{\tau\tau} \Big\}
\end{aligned}
$$

ϕ_{12} =arg($\varepsilon^f_{e\mu}$), ϕ_{13} =arg($\varepsilon^f_{e\tau}$), ϕ_{23} =arg($\varepsilon^f_{\mu\tau}$)

In principle we could take into account $\varepsilon^f_{e\mu}$, but contribution from $\varepsilon^f_{e\mu}$ turns out to be small, so we put $\varepsilon^f_{e\mu}$ =0 for simplicity

ϵ_{ee}	$\lvert\epsilon_{e\tau}\rvert$	$\epsilon_{\tau\tau}$	δ_{CP}	θ_{23}	$\arg(\epsilon_{e\tau})$	$\lvert\epsilon_{\mu\tau}\rvert$	$\arg(\epsilon_{\mu\tau})$	$\lvert\epsilon_{e\mu}\rvert$	$\arg(\epsilon_{e\mu})$	χ^2
0.846	0.123	-0.021	-90	47	0	0	0	0	0	25.46
1.128	0.108	0.511	-90	45	30	0.15	90	0	0	17.54
0.917	0.146	0.114	-90	47	0	0	0	0.03	30	24.61





-> Independent variables to be marginalized over:
Δm^2_{32}, θ_{23}, δ, $|\varepsilon^f_{\mu\tau}|$, ϕ_{13}

$$\chi^2 = \min_{\xi_k,\ \text{osc. param}} \left(\chi^2_{\text{stat}} + \sum_k \xi_k^2 + \chi^2_{\text{prior}} \right)$$

$$\chi^2_{\text{stat}} = 2 \sum_i \left\{ \tilde{N}_i^{\text{test}} - N_i^{\text{true}} - N_i^{\text{true}} \log \left(\frac{\tilde{N}_i^{\text{test}}}{N_i^{\text{true}}} \right) \right\}$$

Pull variables for systematic errors

$$\tilde{N}_i^{\text{test}} \equiv \left(1 + \sum_k c_i^k \xi_k \right) N_i^{\text{test}}$$

$$\chi^2_{\text{prior}} = 2.7 \left(\frac{|\epsilon_{e\mu}|}{0.15} \right)^2 + 2.7 \left(\frac{|\epsilon_{\mu\tau}|}{0.15} \right)^2$$

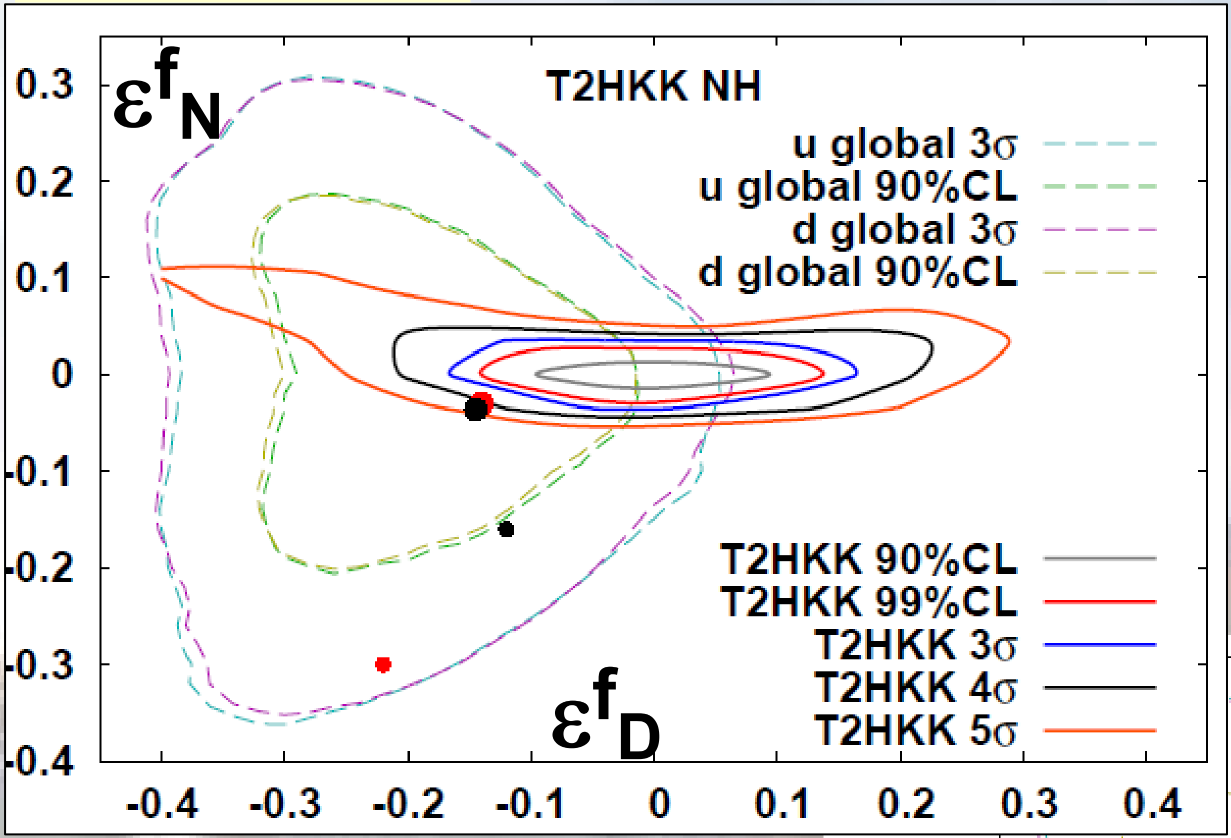
$$|\epsilon^f_{e\mu}| < 0.05, \quad |\epsilon^f_{\mu\tau}| < 0.05 \qquad \epsilon_{\alpha\beta} = 3\, \epsilon^f_{\alpha\beta}$$

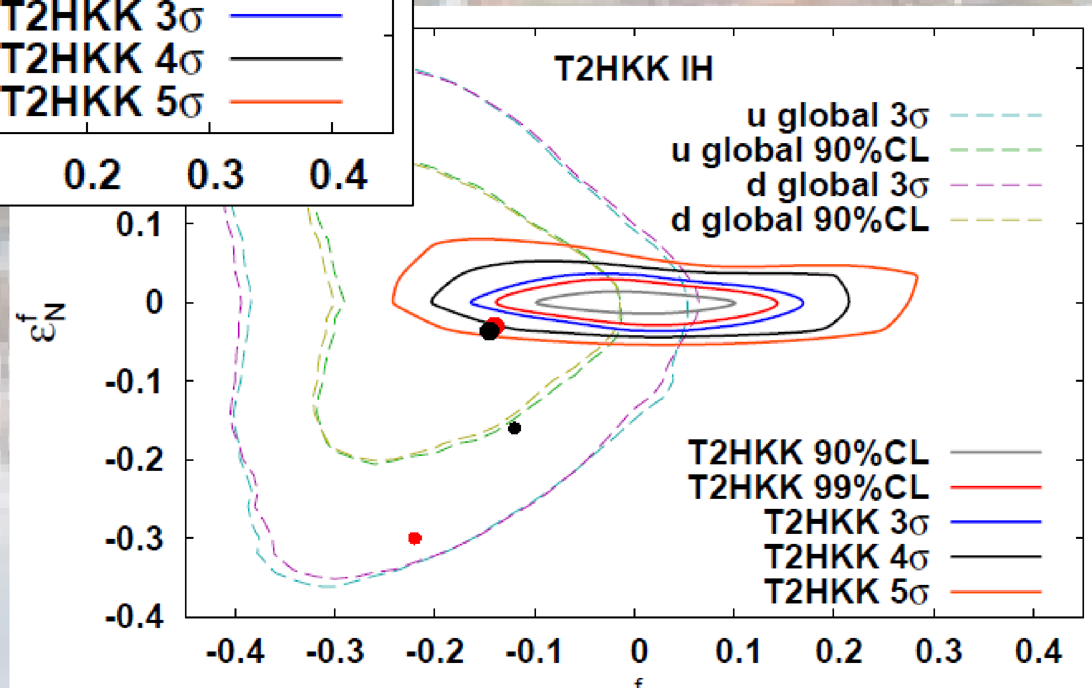
3.2 Results

δ(true) = -90°

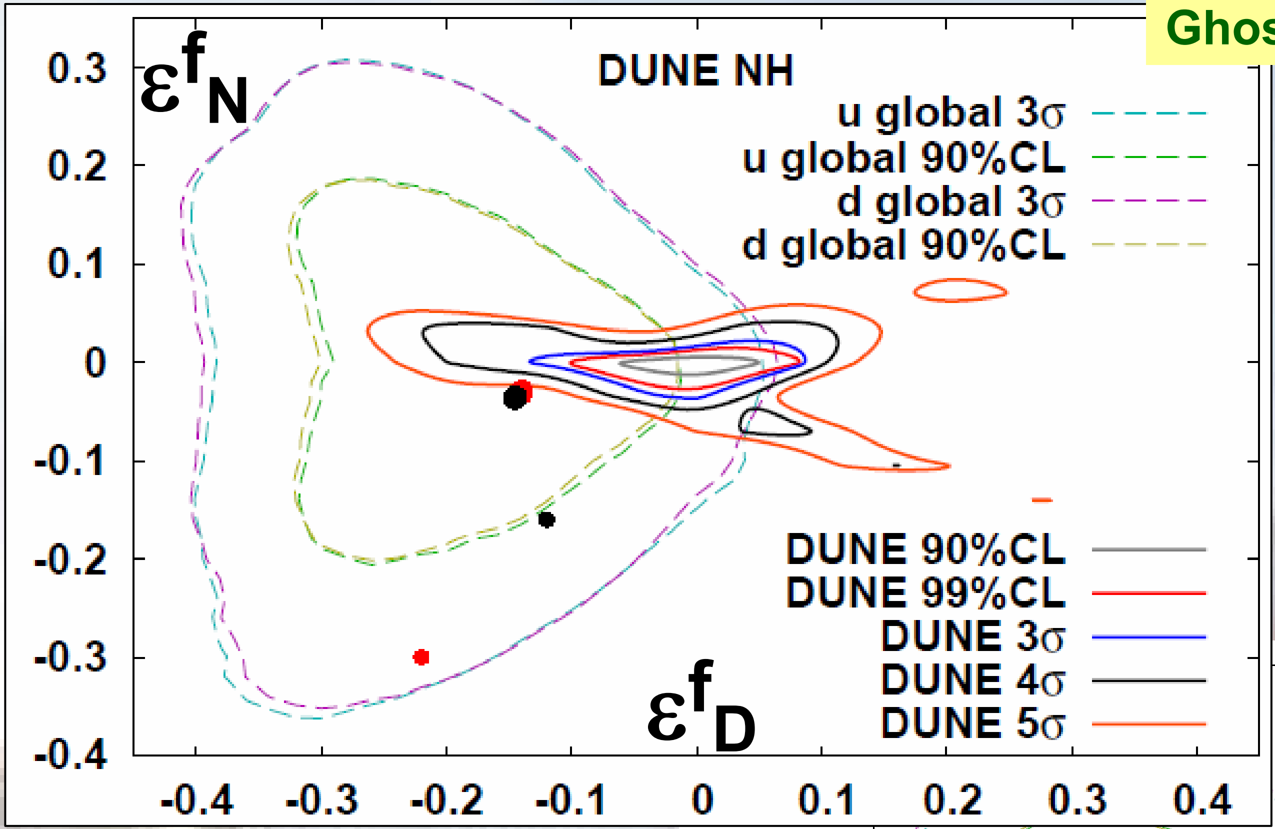
Ghosh & OY, arXiv:1709.08264

Excluded region by LBL is outside of the curve



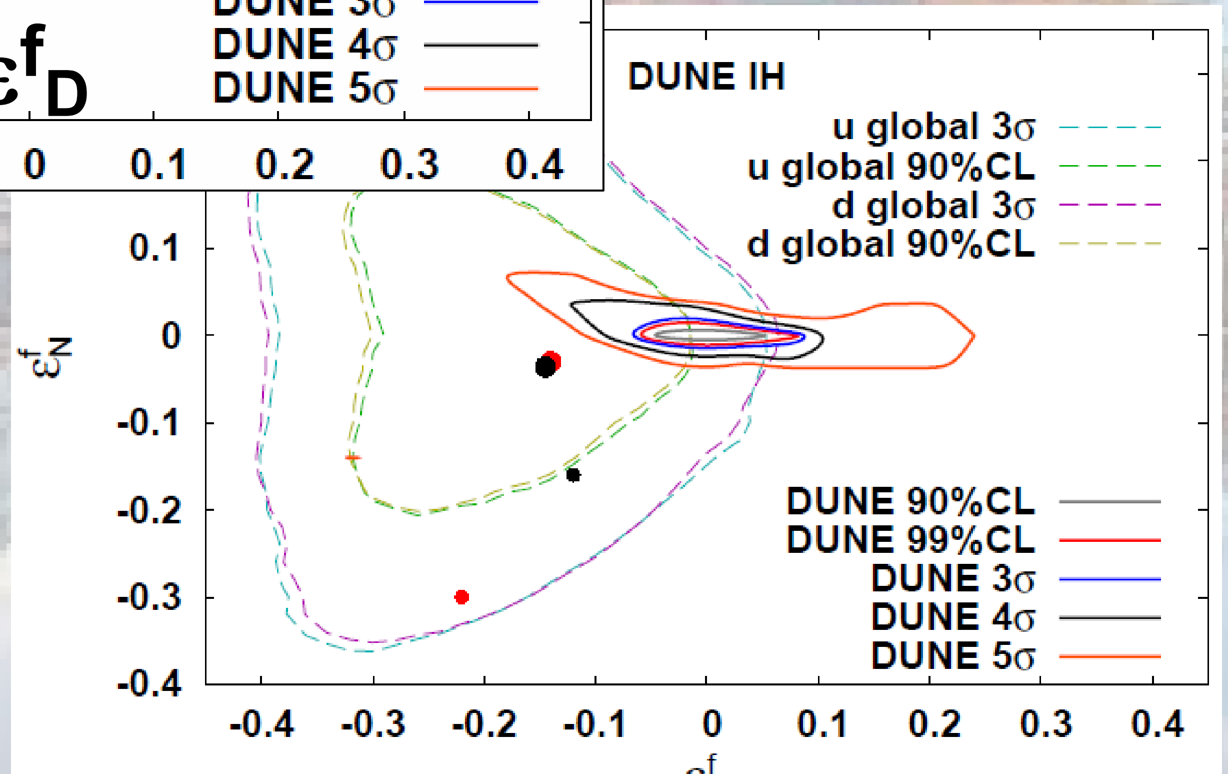


Ghosh & OY, arXiv:1709.08264



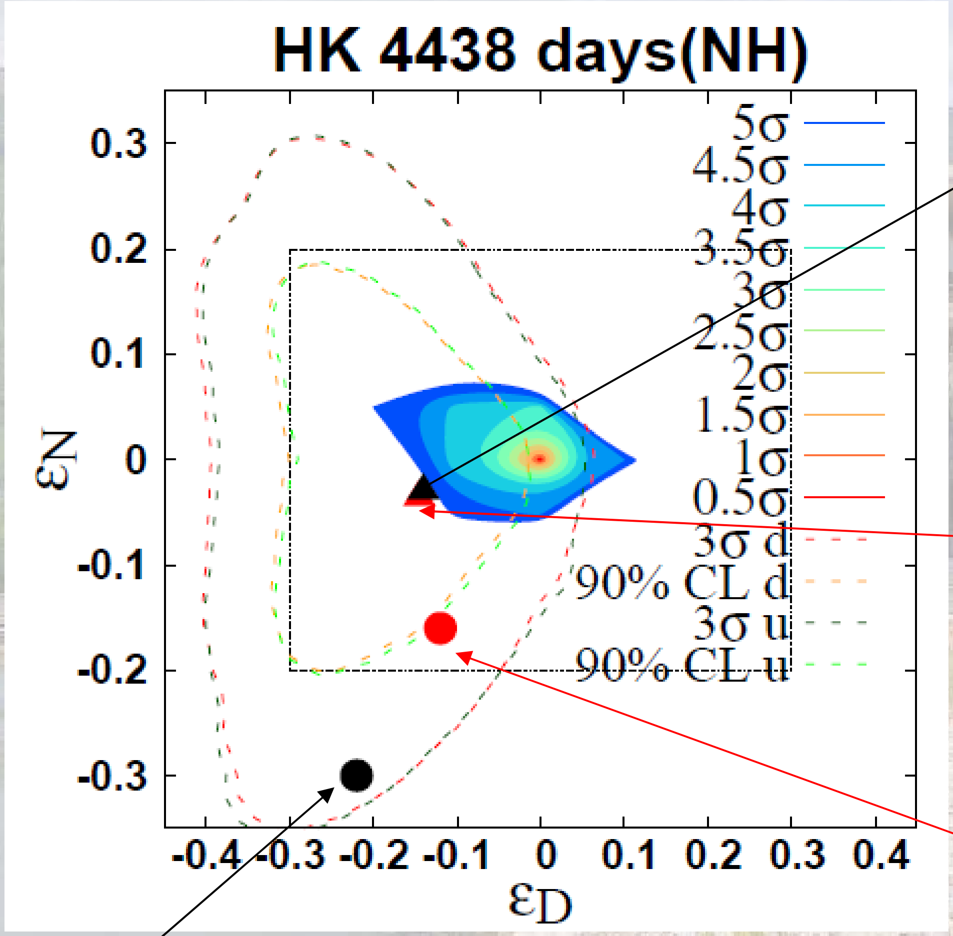
δ(true) = -90°

Sensitivity of DUNE is slightly better than T2HKK



Sensitivity of ν_{atm} at HK : Real ε_N

OY@nufact2016



$$(\epsilon_D^u, \epsilon_N^u) = (-0.140, -0.030)$$

Best fit point of glolal analysis for f=u: significance:5σ

$$(\epsilon_D^d, \epsilon_N^d) = (-0.145, -0.036)$$

Best fit point of glolal analysis for f=d: significance:5σ

$$(\epsilon_D^d, \epsilon_N^d) = (-0.12, -0.16)$$

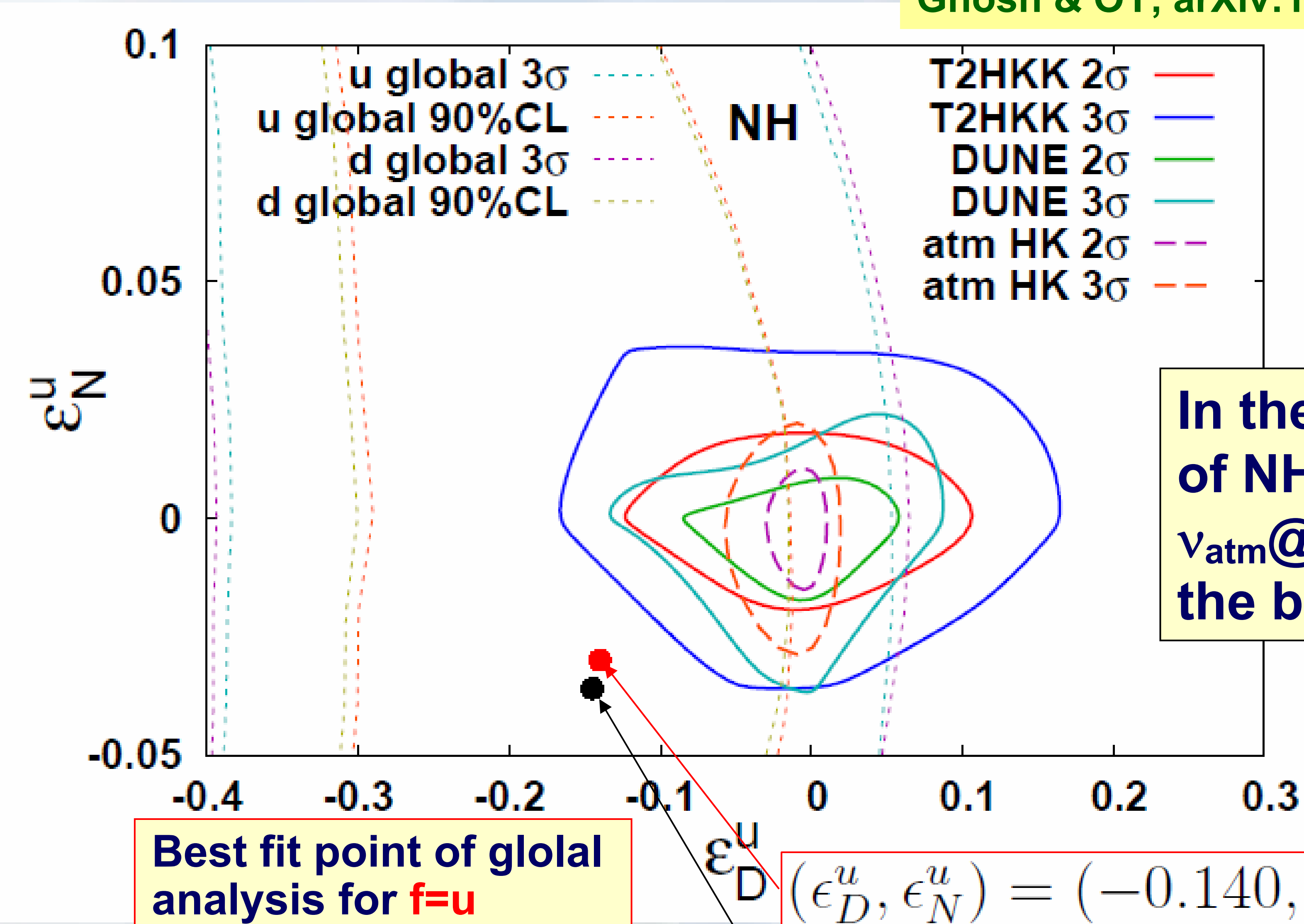
Best fit point of solar & KamLAND for f=d: significance:11σ

$$(\epsilon_D^u, \epsilon_N^u) = (-0.22, -0.30)$$

Best fit point of solar & KamLAND for f=u: significance:38σ

●Comparison of sensitivity T2HKK, DUNE, ν_{atm}@HK

Ghosh & OY, arXiv:1709.08264



In the case of NH, ν_{atm}@HK is the best

Best fit point of glolal analysis for **f=u**

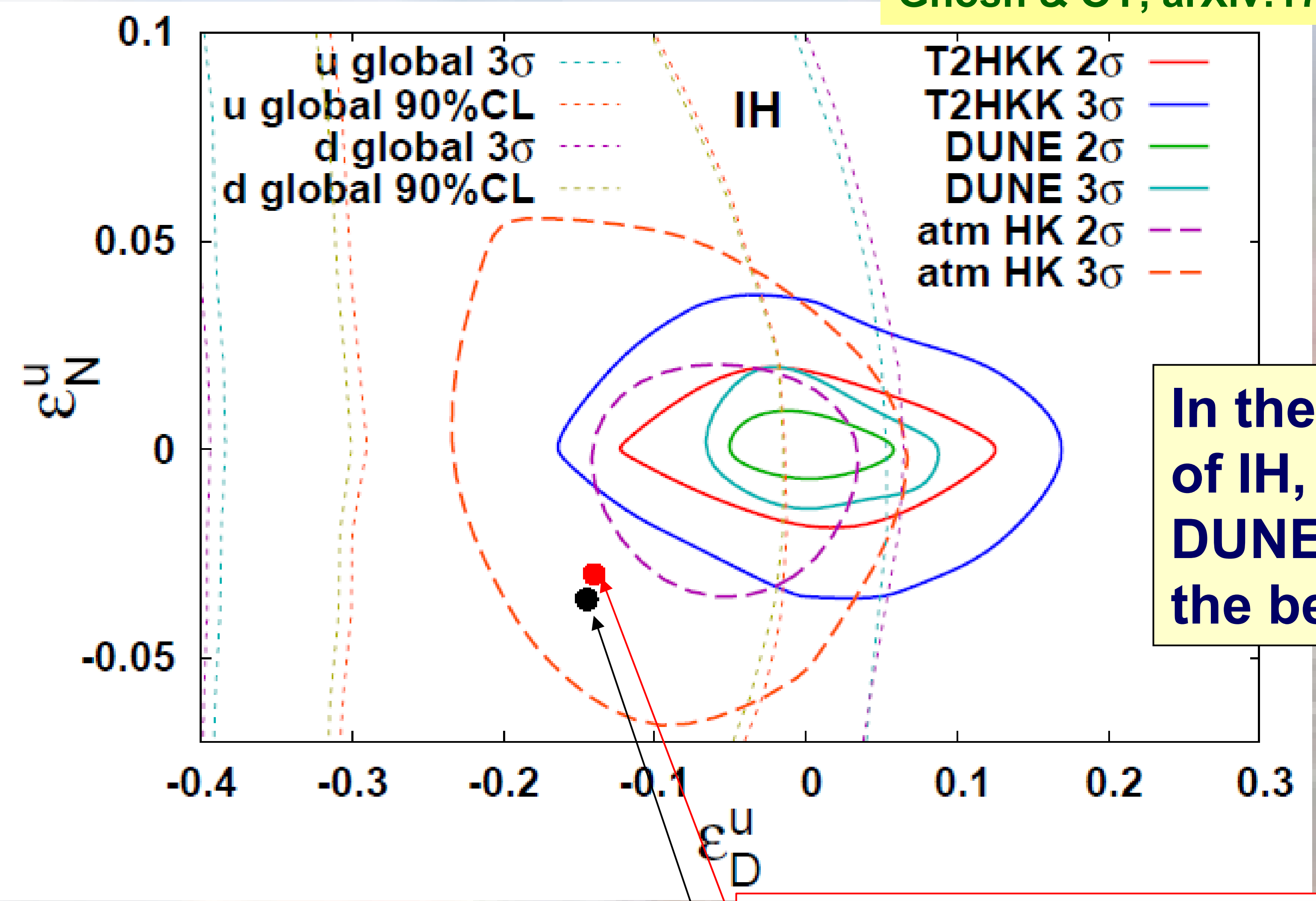
$$(\epsilon_D^u, \epsilon_N^u) = (-0.140, -0.030)$$

Best fit point of glolal analysis for f=d

$$(\epsilon_D^d, \epsilon_N^d) = (-0.145, -0.036)$$

●Comparison of sensitivity T2HKK, DUNE, ν_{atm}@HK

Ghosh & OY, arXiv:1709.08264

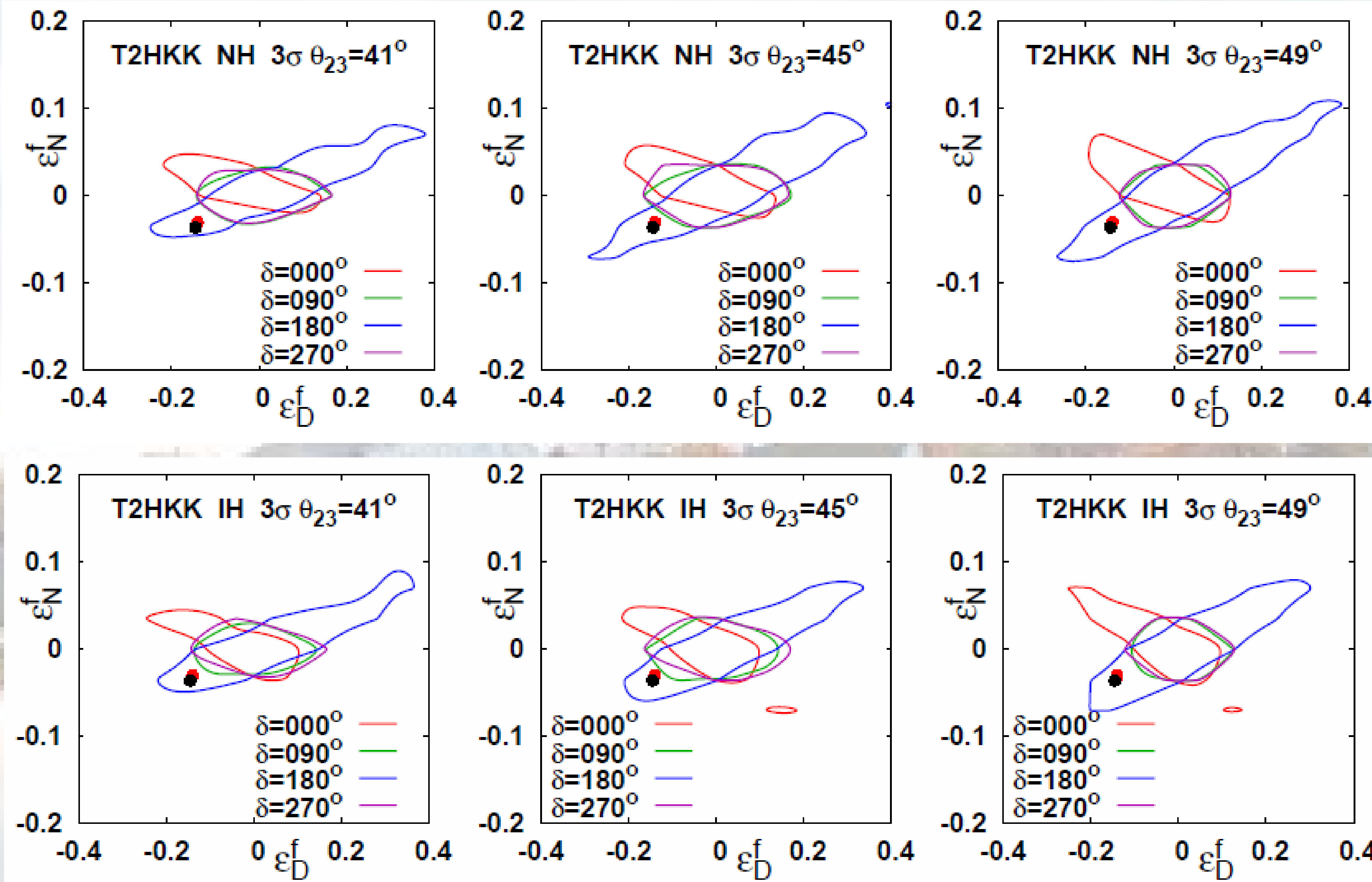


In the case of IH, DUNE is the best

$$(\epsilon^u_D, \epsilon^u_N) = (-0.140, -0.030)$$

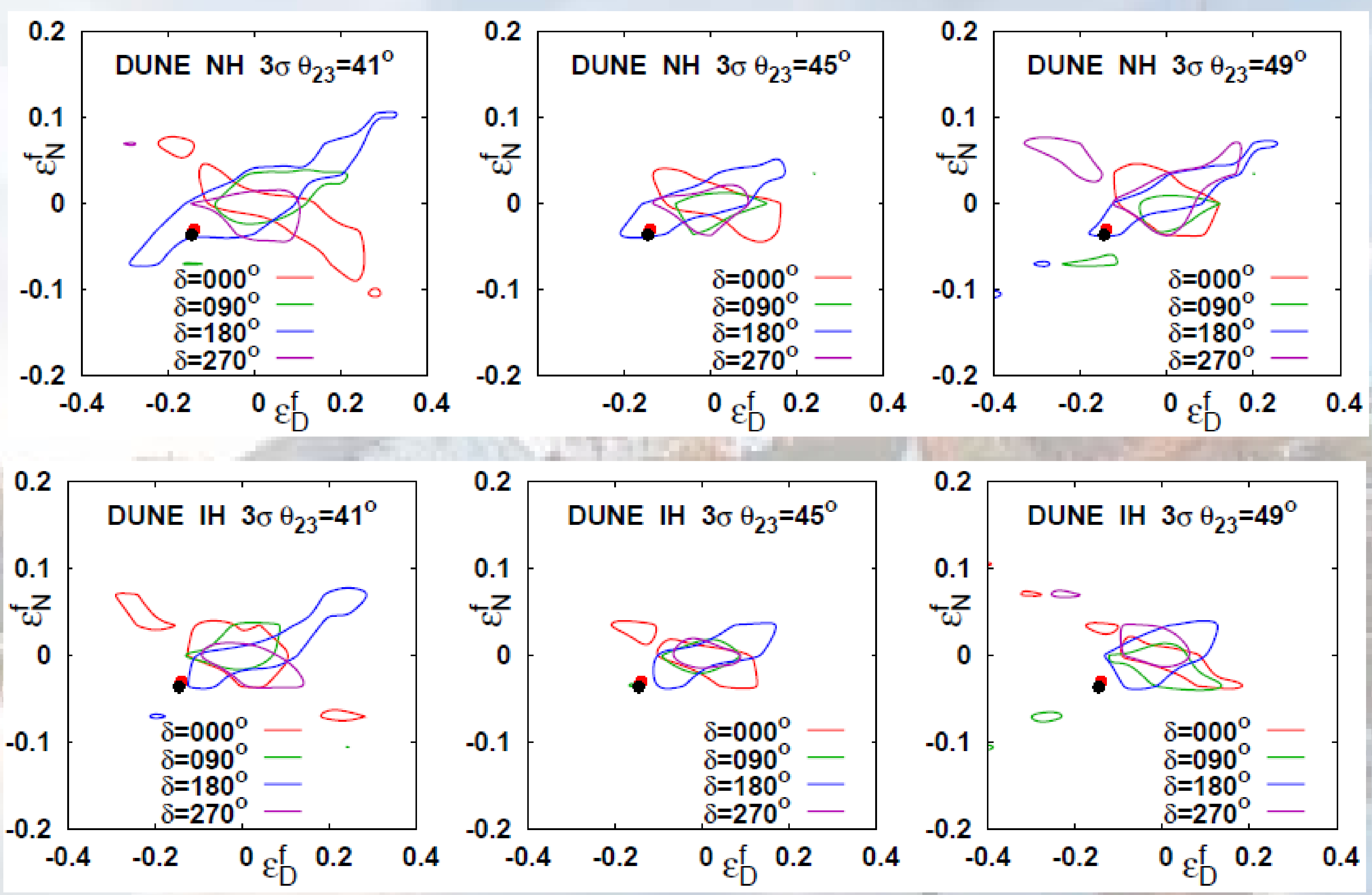
$$(\epsilon^d_D, \epsilon^d_N) = (-0.145, -0.036)$$

●Dependence of T2HKK on θ_{23}(true) & δ(true)



Ghosh & OY, arXiv:1709.08264

●Dependence of DUNE on θ_{23}(true) & δ(true)



Ghosh & OY, arXiv:1709.08264

4. Conclusions

- T2HKK and DUNE have sensitivity to NSI and they cover some of the allowed region in the (ϵ^f_D, ϵ^f_N)-plane suggested by the solar ν tension for δ(true) = -90^o.
- Sensitivity of DUNE is slightly better than that of T2HKK because DUNE uses information of wide E_ν spectrum.
- Dependence of T2HKK on θ_{23}(true) & δ(true) was found and if δ(true) = 180^o, then significance of the best-fit point becomes lower.

Backup slides

T2HKK:Appearance probability at L=1050km