Practical tests on the PMNS paradigm

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August 4-10, 2019
3 neutrinos and beyond @ Quy Nhon, Vietnam

1. Introduction

2. Scenarios beyond the PMNS paradigm

3. Tests Before HK & DUNE

4. Tests at HK & DUNE

5. Conclusions

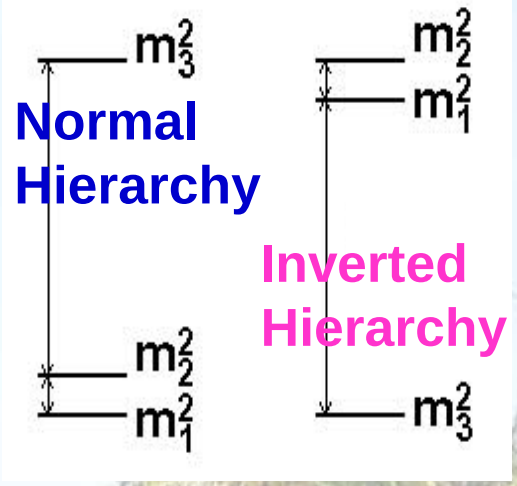
1. Introduction

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 (2012):

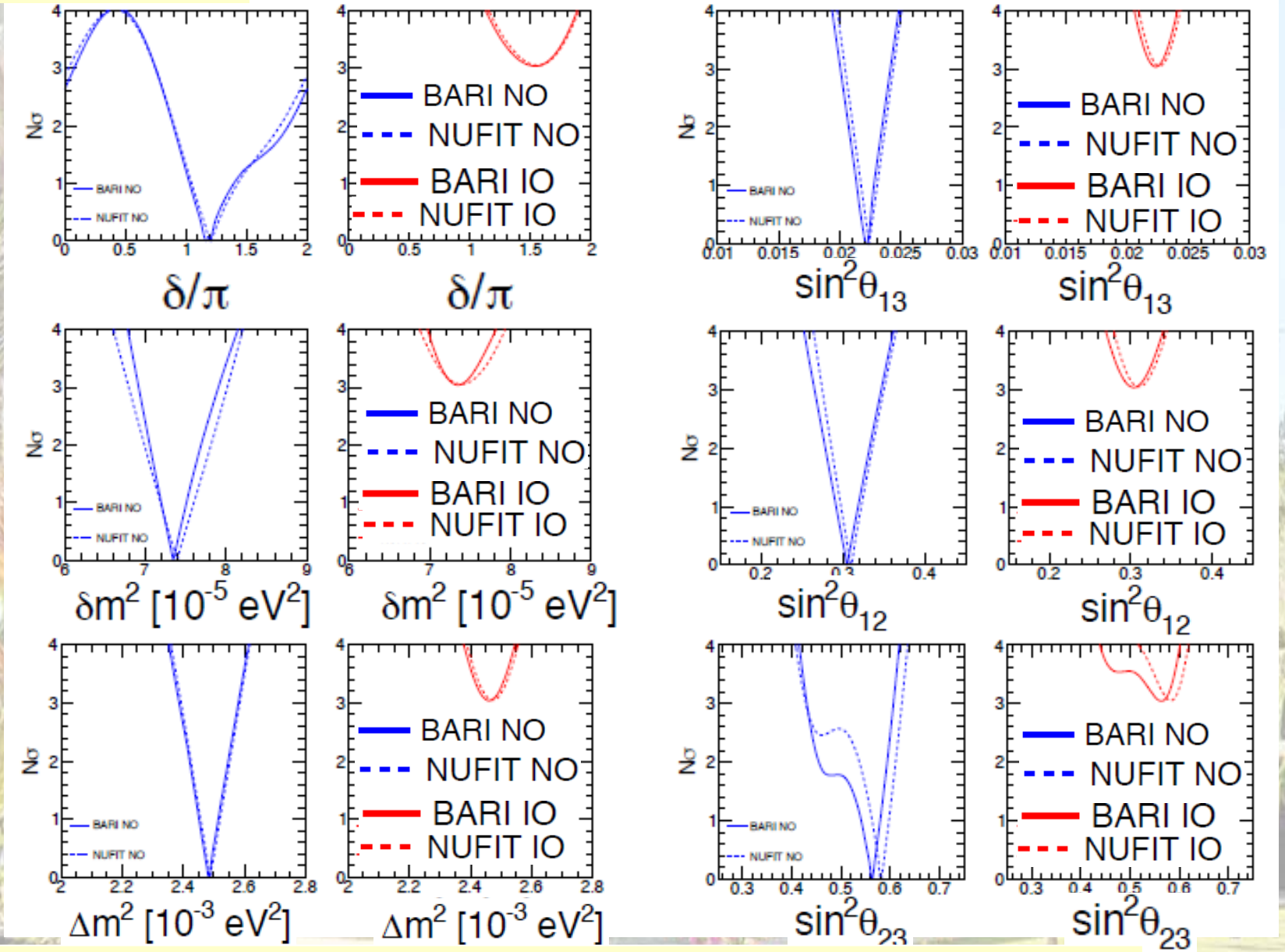
ν_{solar}+KamLAND (reactor) → $\theta_{12} \cong \frac{\pi}{6}, \Delta m_{21}^2 \cong 8 \times 10^{-5}\,\mathrm{eV}^2$

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

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

Status of 3ν fit

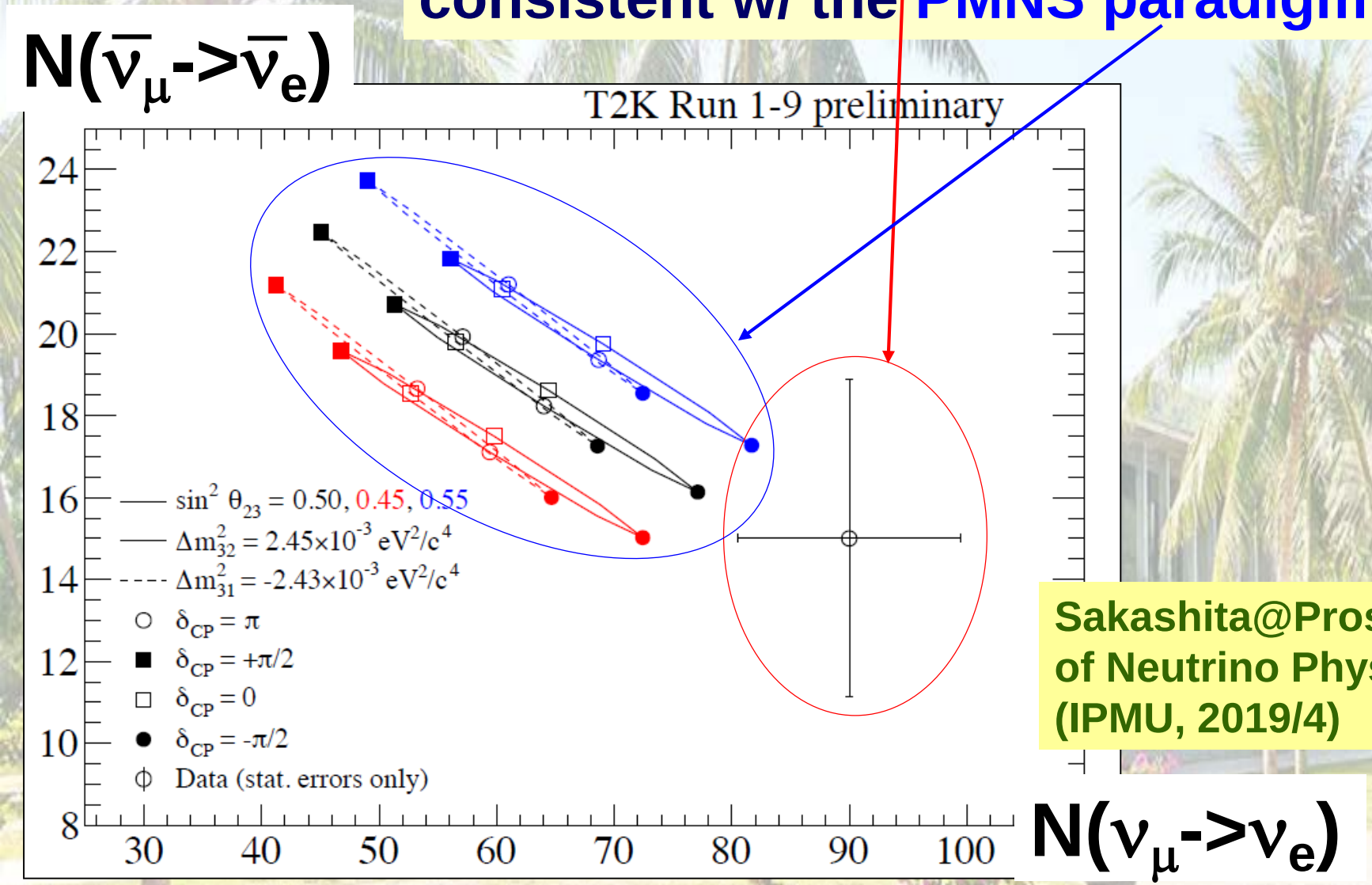
Lisi@Prospects of Neutrino Physics (IPMU, 2019/4)



NH(NO), δ~3π/2 is preferred over IH(IO), δ=0

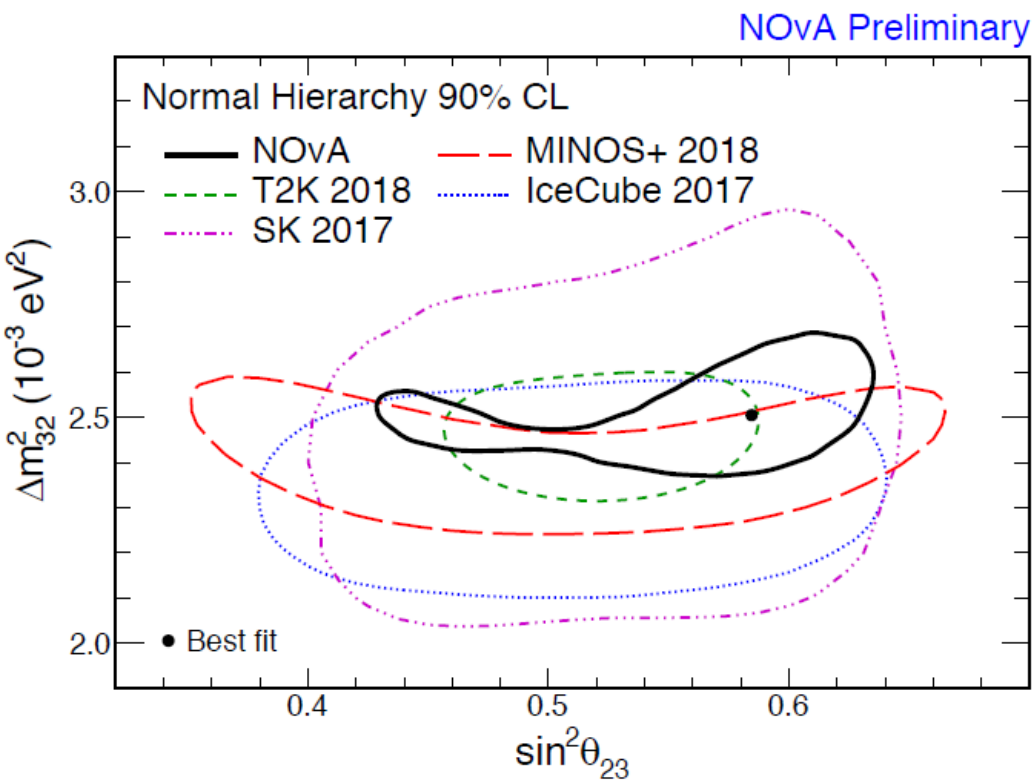
Potential problems with the PMNS paradigm

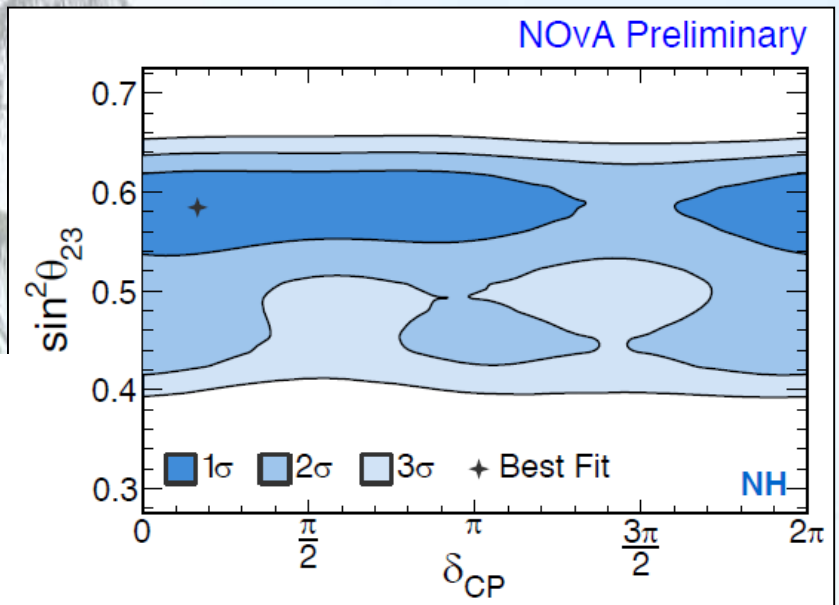
- T2K appearance data may not be consistent w/ the PMNS paradigm

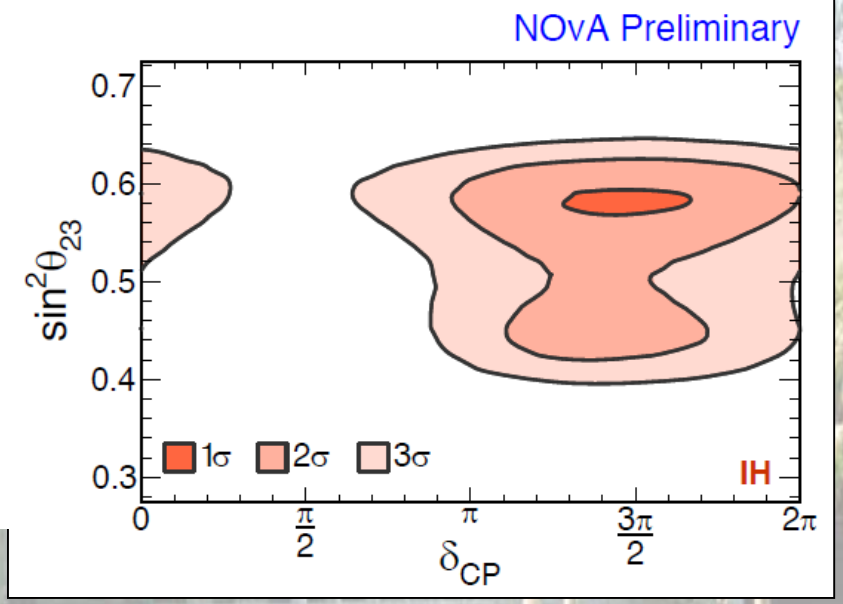


Sakashita@Prospects of Neutrino Physics (IPMU, 2019/4)

- **Consistency on θ_{23} & δ between Nova & T2K has to be yet seen**

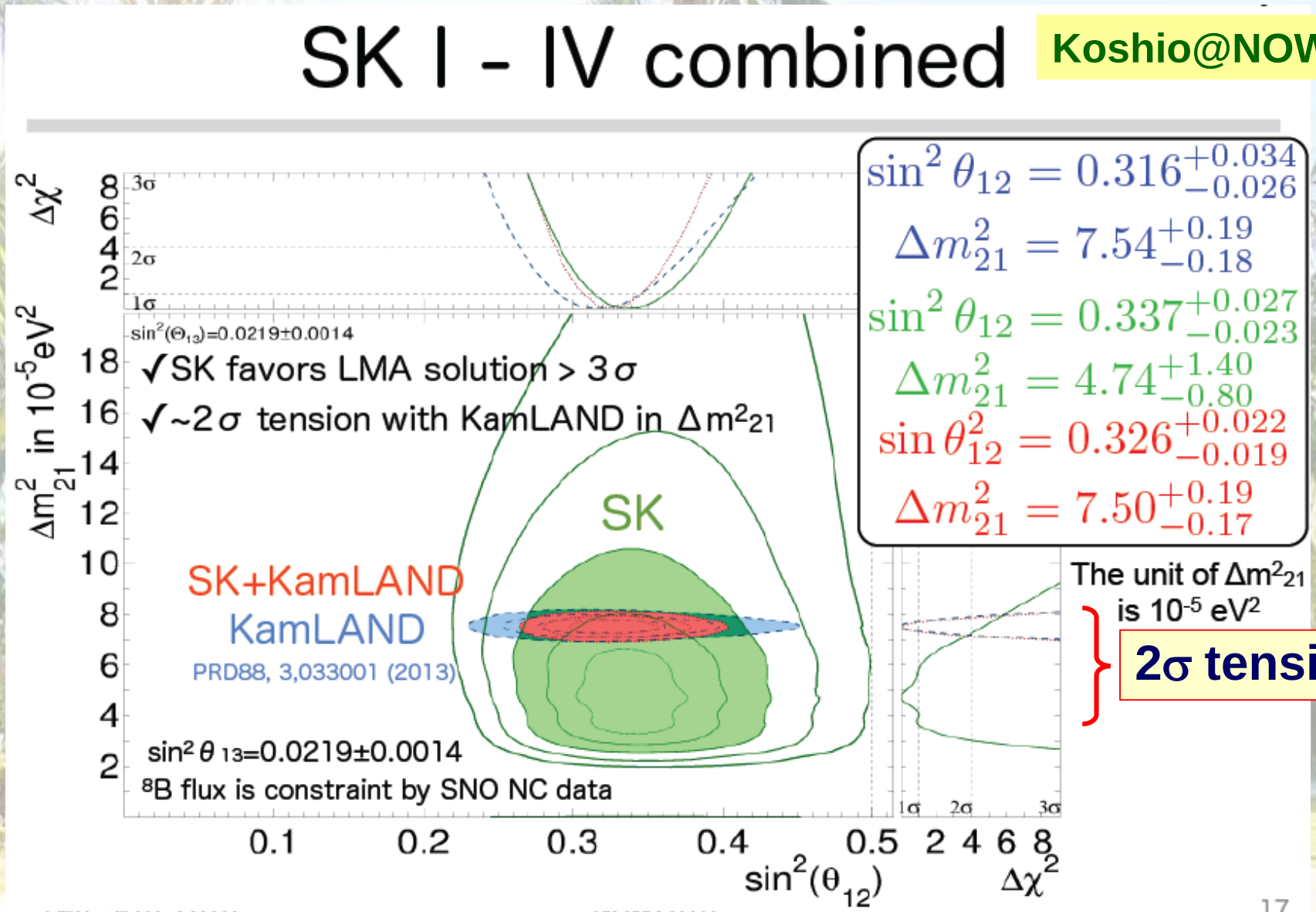






Bian@Prospects of Neutrino Physics (IPMU, 2019/4)

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



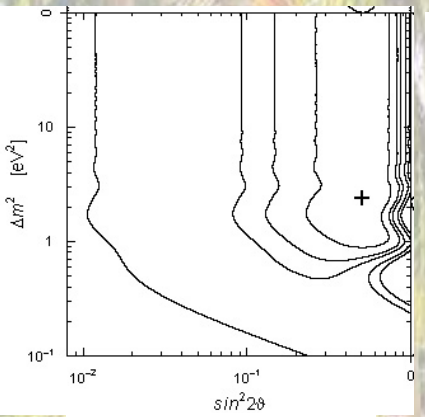
●Indication for Δm^2~O(1)eV^2

➢**LSND anomaly** $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

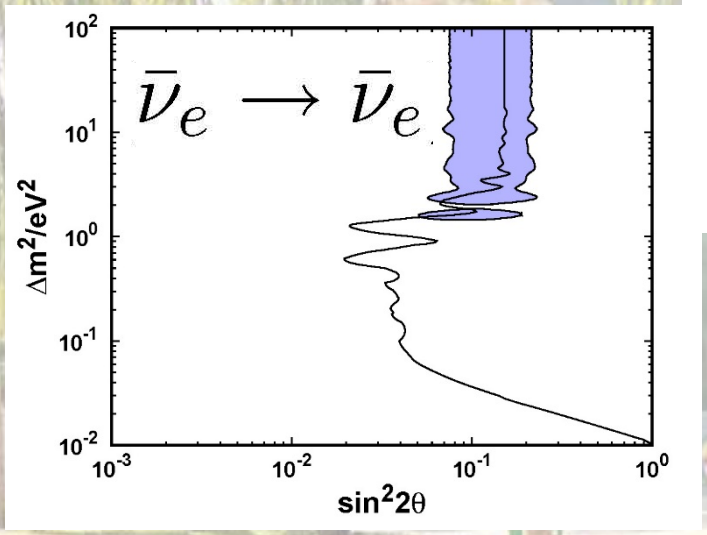
➢**MiniBooNE** $\nu_\mu \rightarrow \nu_e + \bar{\nu}_\mu \rightarrow \bar{\nu}_e$

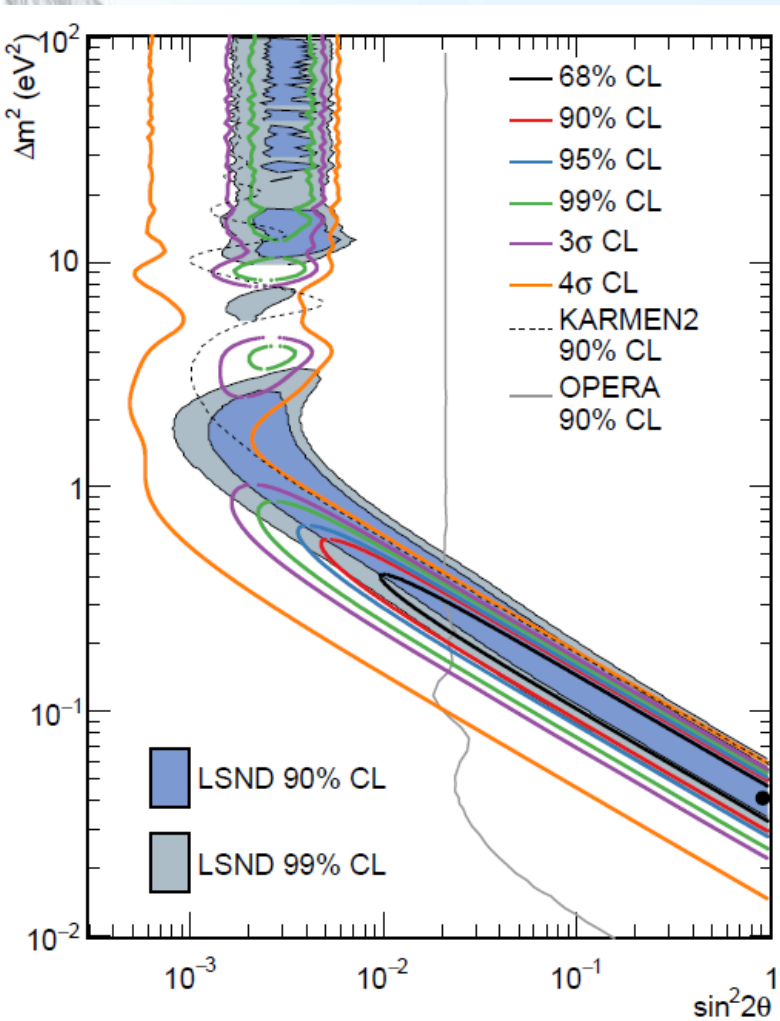
➢**Galium anomaly**

➢**Reactor anomaly**



ν_e->ν_e





2. Scenarios beyond the PMNS paradigm

Just like at B factories, 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 (beyond the PMNS paradigm).
→ Research on New Physics is important.

Test of the PMNS paradigm

Rather than looking for arbitrary possibilities of New Physics, here we discuss possible hints of the scenarios which have been discussed in the past.

List of popular NP in ν oscillation phenomenology

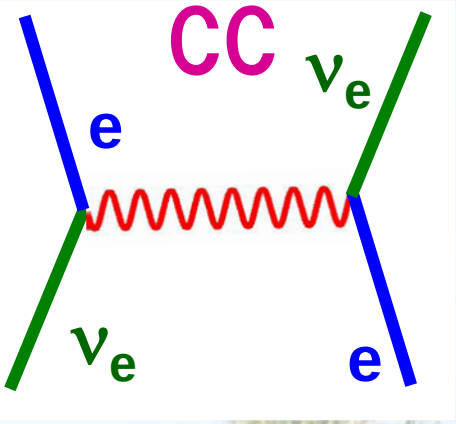
Scenario beyond SM+m_ν	Experimental indication ?	Phenomenological constraints on the magnitude of the effects
• Light sterile ν (ν_s)	Maybe	O(10%)
• Non Standard Interactions in propagation	Maybe	e-τ: O(100%) Others: O(1%)
Non Standard Interactions at production / detection	×	O(1%)
Unitarity violation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

In this talk, we will focus on these two because of potential experimental hints

●Features of light sterile ν (ν_s)

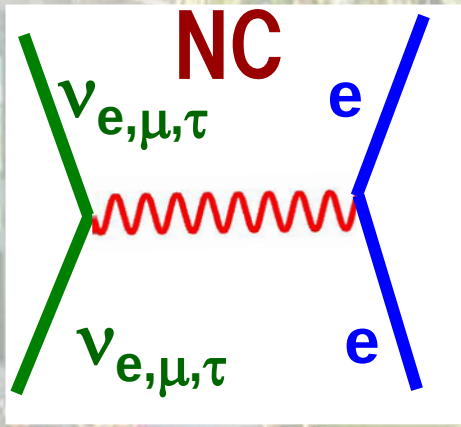
Interactions of active & sterile ν

	ν_e	ν_μ, ν_τ	ν_s
CC	✓	✕	✕
NC	✓	✓	✕
v	$A_e + A_n$	A_n	0



$$A_e = \sqrt{2} G_F N_e$$

$$A_n = -(1/\sqrt{2}) G_F N_n$$



Matter effect in the presence of sterile ν

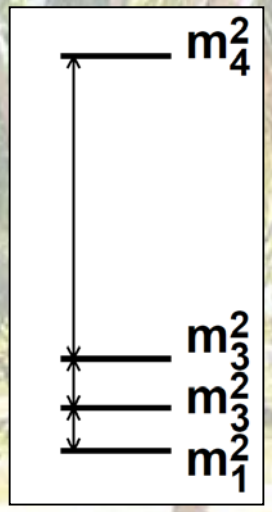
$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \left[U\begin{pmatrix}E_1 & 0 & 0 & 0\\ 0 & E_2 & 0 & 0\\ 0 & 0 & E_3 & 0\\ 0 & 0 & 0 & E_4\end{pmatrix}U^{-1} + \begin{pmatrix}A_e+A_n & 0 & 0 & 0\\ 0 & A_n & 0 & 0\\ 0 & 0 & A_n & 0\\ 0 & 0 & 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix}$$

The term which is proportional to identity can be ignored

$$U \equiv \begin{pmatrix}U_{e1} & U_{e2} & U_{e3} & U_{e4}\\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4}\\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4}\\ U_{s1} & U_{s2} & U_{s3} & U_{s4}\end{pmatrix}$$

$$A_e \equiv \sqrt{2}G_F N_e$$

$$A_n \equiv -\frac{G_F N_n}{\sqrt{2}}$$



$$= \left[U\begin{pmatrix}0 & 0 & 0 & 0\\ 0 & \Delta E_{21} & 0 & 0\\ 0 & 0 & \Delta E_{31} & 0\\ 0 & 0 & 0 & \Delta E_{41}\end{pmatrix}U^{-1} + \begin{pmatrix}A_e & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & \boxed{-A_n}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix}$$

ν_s has matter effect different from others

●Features of NSI 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

Modification of matter effect

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

NP

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

3. Tests Before HK & DUNE

(1) ν_s

To test the hypothesis of sterile ν, (i) we get the constraints on the extra mixing angles θ_{14} , θ_{24} , θ_{34} or (ii) we get the constraints on different matter effect.

$$U = \underbrace{R_{34}(\theta_{34},\delta_{34})R_{24}(\theta_{24},0)R_{14}(\theta_{14},\delta_{14})}_{\text{extra mixing angles}}\underbrace{R_{23}(\theta_{23},0)R_{13}(\theta_{13},\delta_{13})R_{12}(\theta_{12},0)}_{3\nu\text{ mixing angles}}$$

$$U_{e4} = e^{-i\delta_{14}} s_{14}$$
$$U_{\mu 4} = c_{14} s_{24}$$
$$U_{\tau 4} = c_{14} c_{24} e^{-i\delta_{34}} s_{34}$$
$$U_{s4} = c_{14} c_{24} c_{34}$$

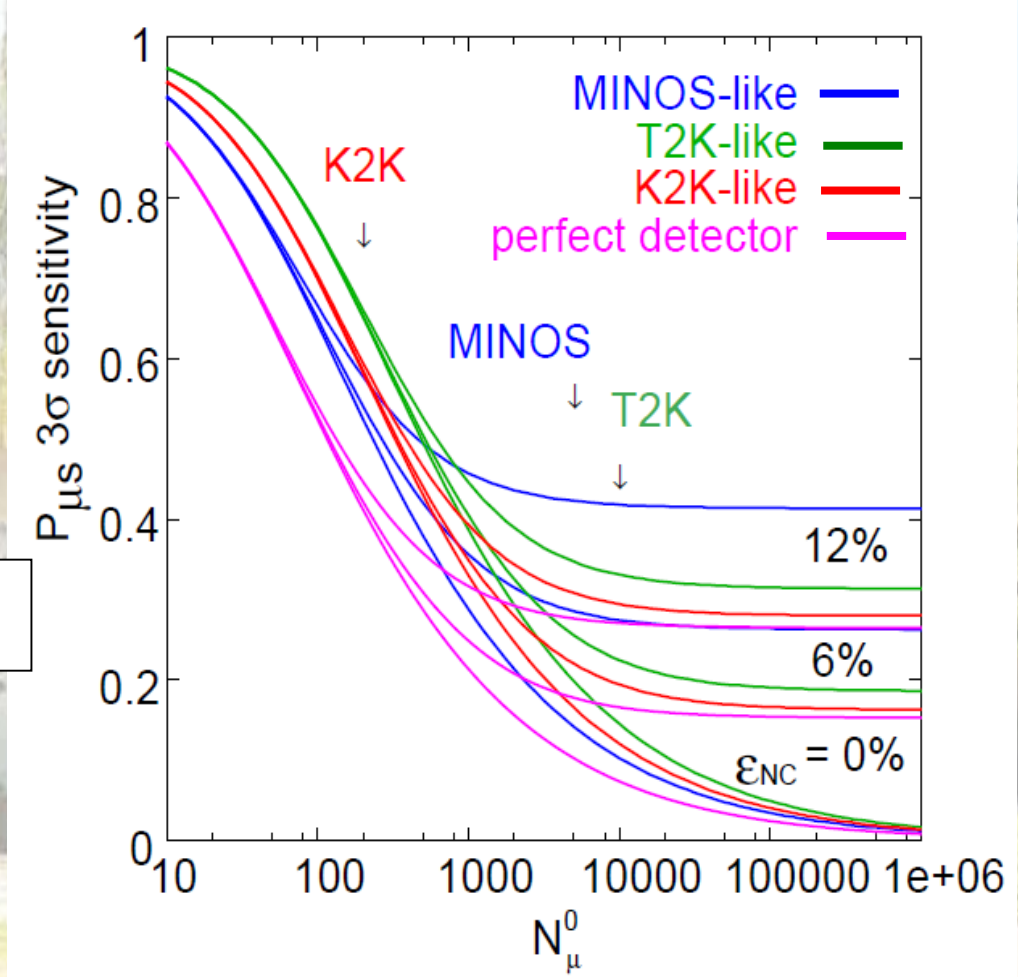
(1-1) Neutral current interactions of π^0 at T2K

By measuring #(π^0 ->2γ) due to NC, we can determine

$P(\nu_\mu \to \nu_e) + P(\nu_\mu \to \nu_\mu) + P(\nu_\mu \to \nu_\tau) = 1 - P(\nu_\mu \to \nu_s)$

Unfortunately, due to large statistical and systematic errors, precision is not so good:

$P(\nu_\mu \to \nu_s) \sim \sin^2 2\theta_{24} < 0.4$

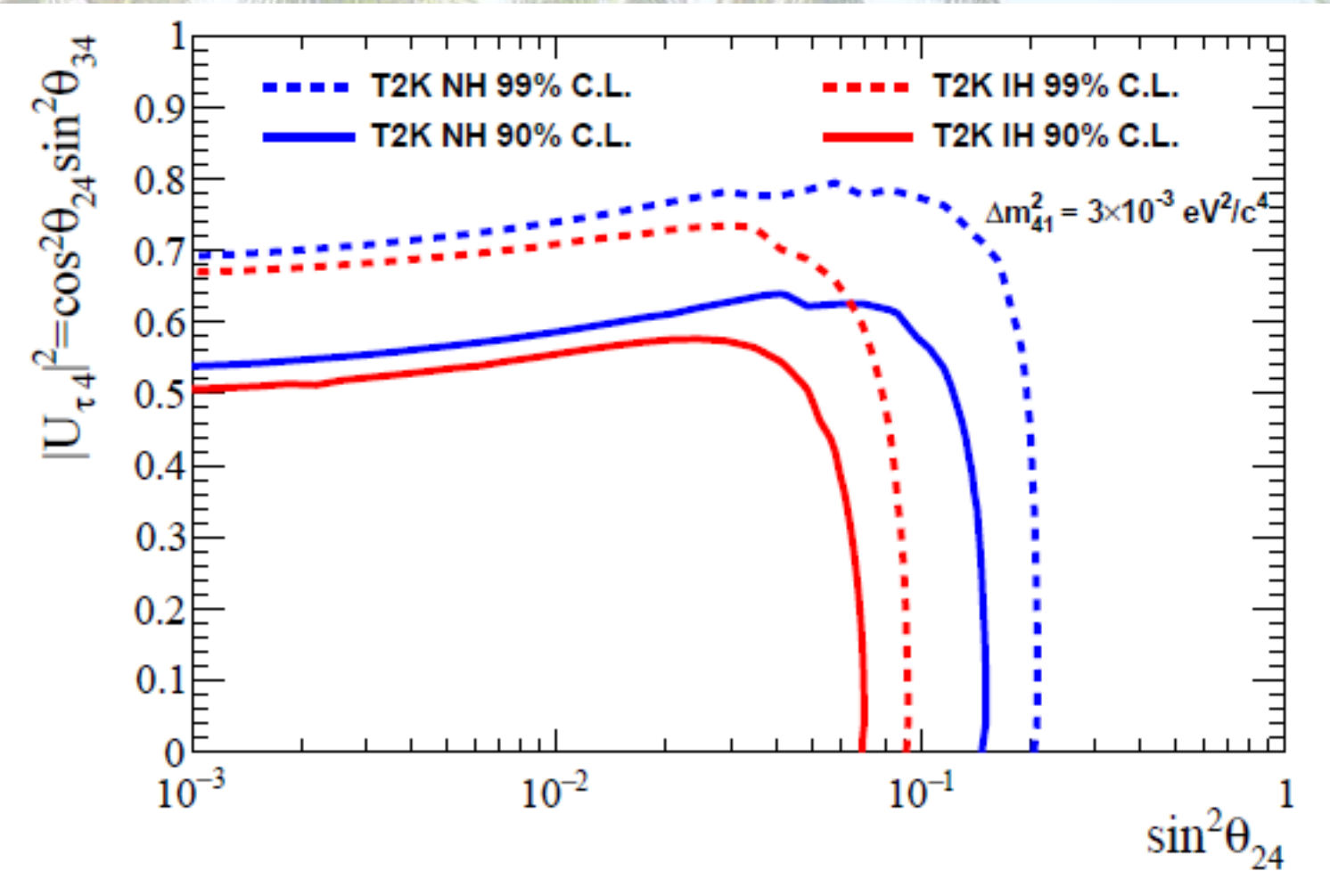


Barger, Geer, Whisnant, New J.Phys. 6 ('04) 135

(1-2) Appearance & disappearance probabilities at T2K

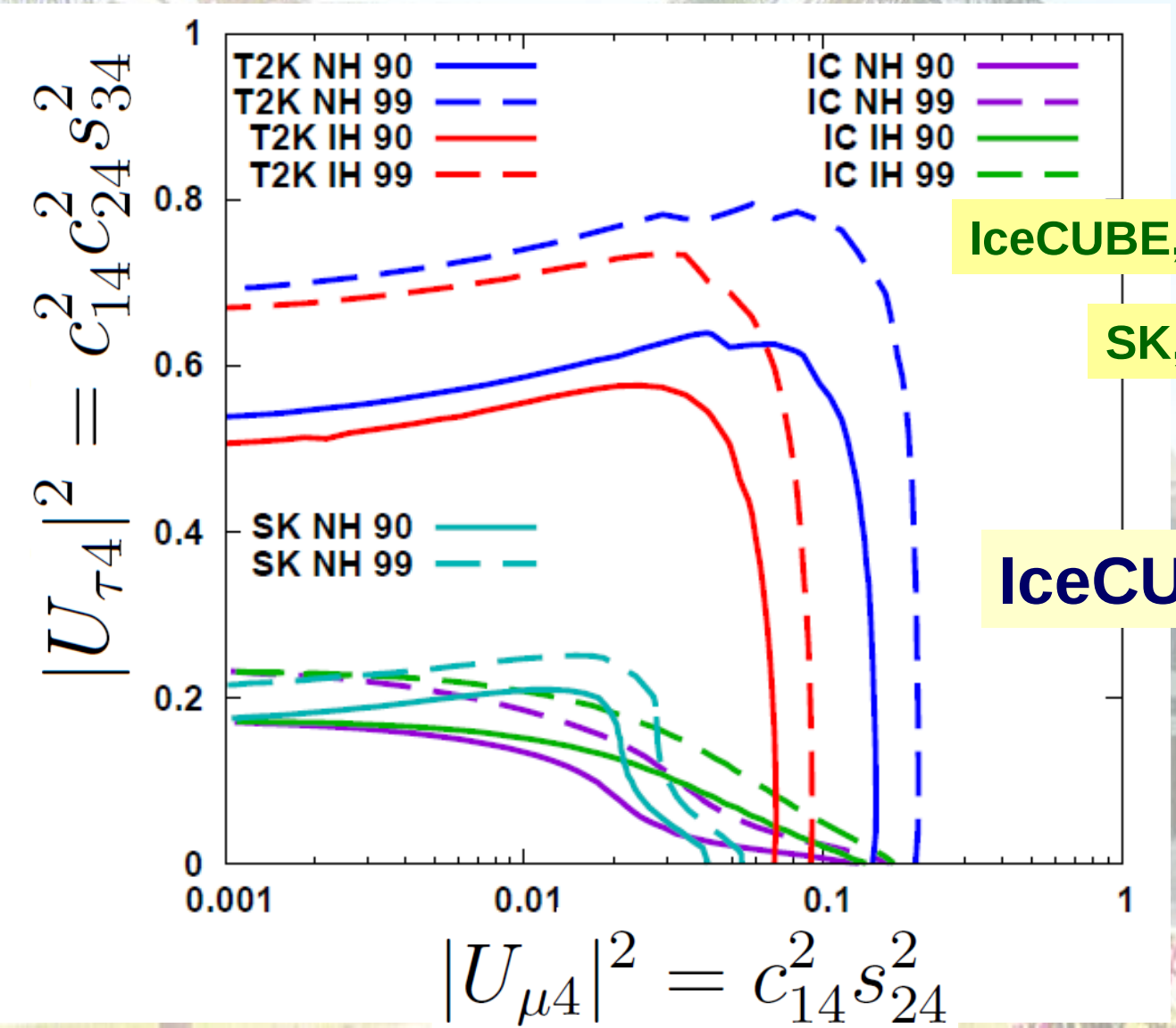
θ_{14} =0 is assumed

T2K, PRD99 ('19) 071103



(1-3) ν_{atm} (SK, IceCUBE)

more sensitive to matter effect than T2K



IceCUBE, PRD95 ('17) 112002

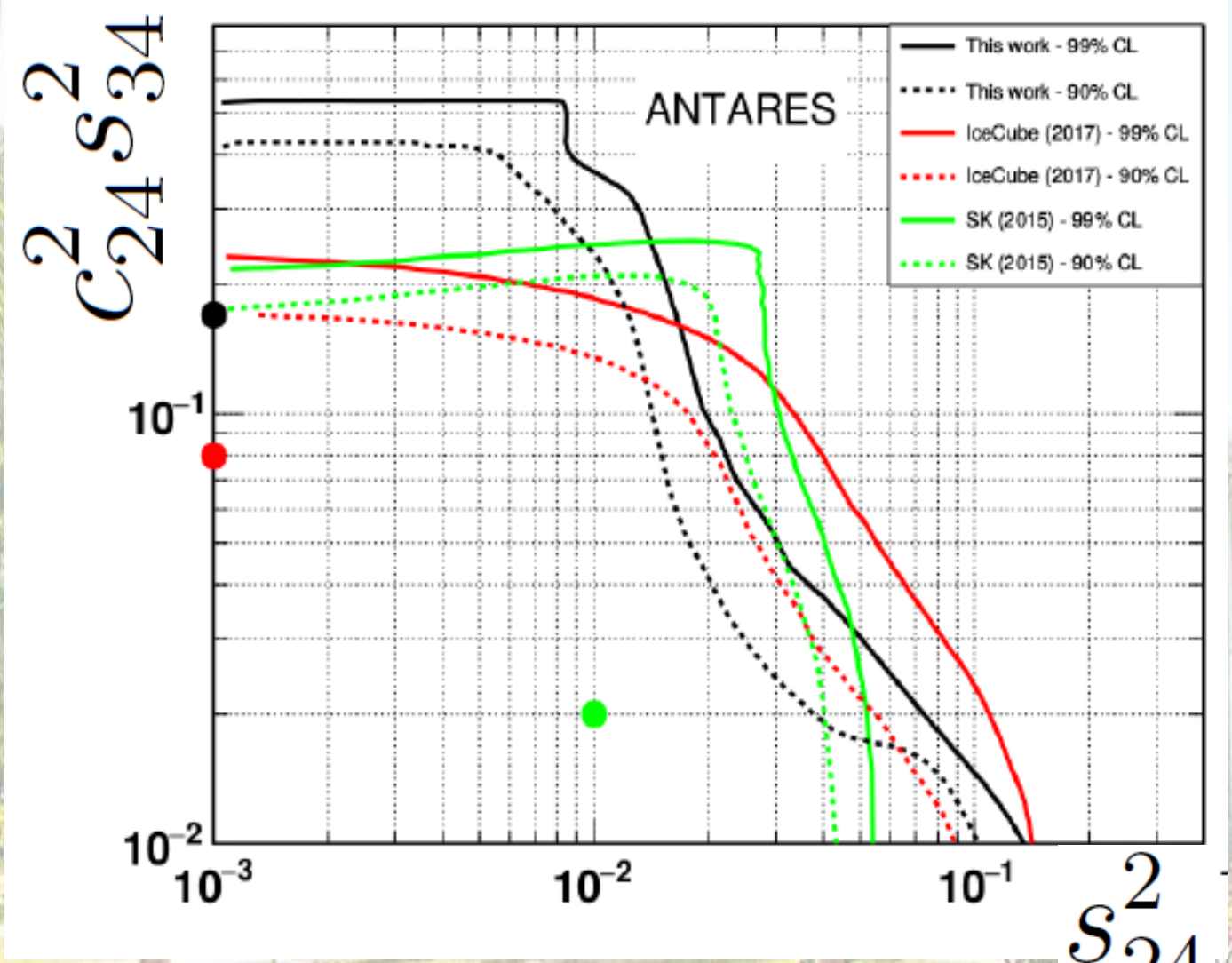
SK, PRD91 ('15) 052019

IceCUBE ~ SK >> T2K

(1-3) ν_{atm} (Antares)

Antares, PoS-NOW2018-008

Antares ~ IceCUBE ~ SK

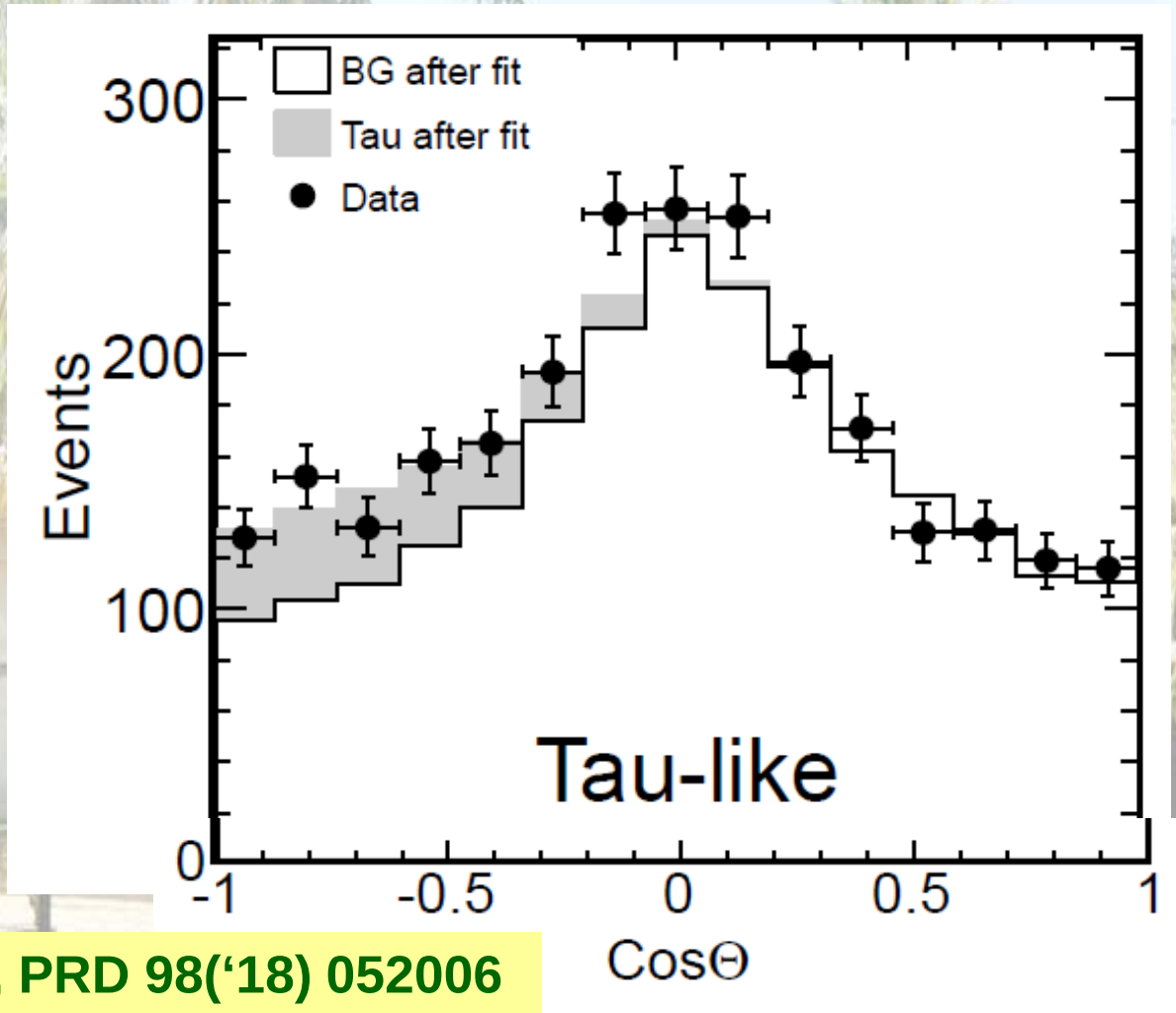


(1-4) SK ν_{atm} : τ appearance

$$U_{\mu 4} = c_{14} s_{24}$$
$$U_{\tau 4} = c_{14} c_{24} e^{-i\delta_{34}} s_{34}$$

$$P(\nu_\mu \to \nu_\tau) = 4\mathrm{Re}\left[U_{\mu 3} U^*_{\tau 3} (U^*_{\mu 3} U_{\tau 3} + U^*_{\mu 4} U_{\tau 4})\right] \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \cdots$$

Precise measurement of ν_τ is in principle important to constrain θ_{24} & θ_{34}, but it is challenging

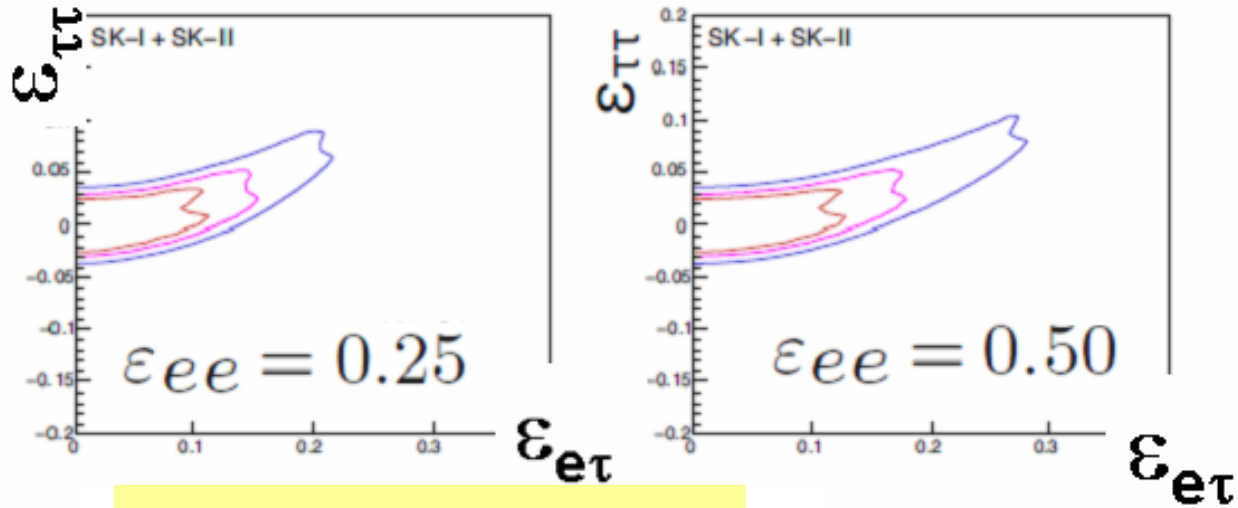


SK, PRD 98('18) 052006

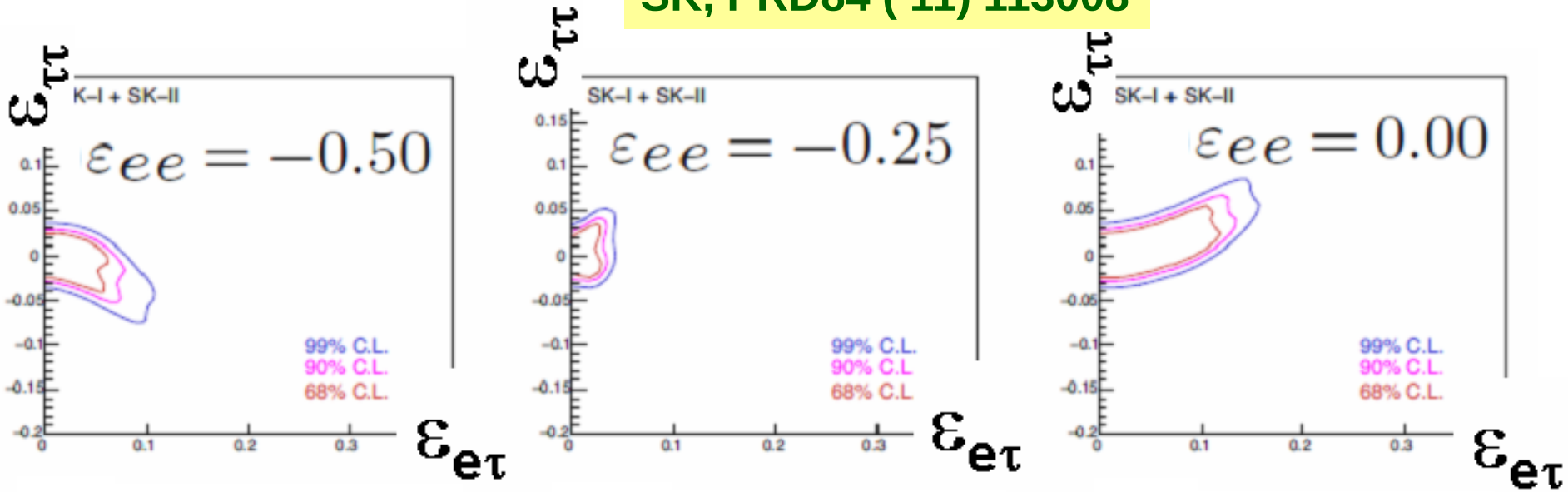
(2) NSI in propagation

(2-1) SK ν_{atm} : sensitive to matter effect

-> It is worth updating!



SK, PRD84 ('11) 113008

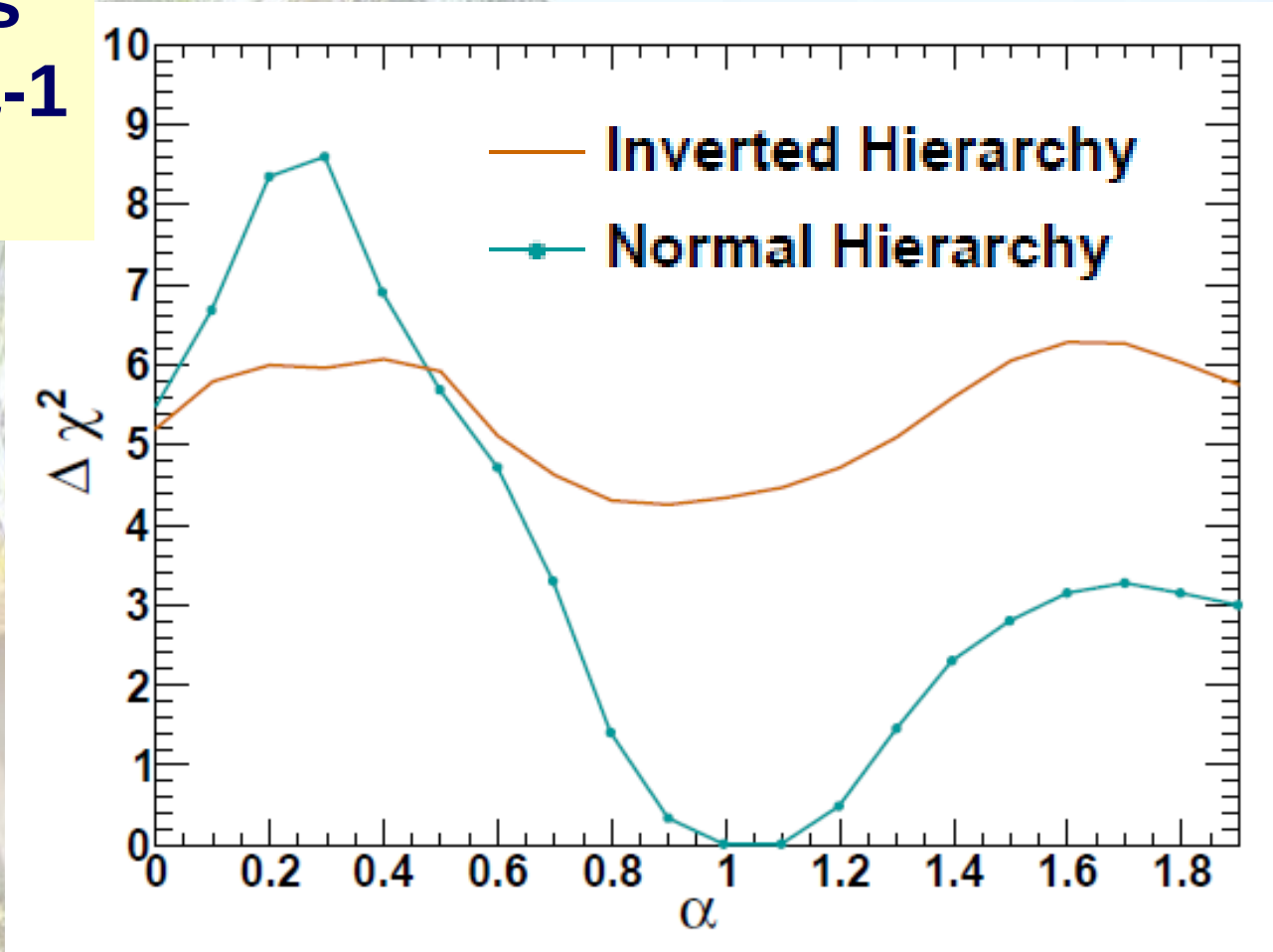


(2-2) SK ν_{atm} : rescale of matter effect A_e -> αA_e

$$A_e = \sqrt{2} G_F N_e$$

This corresponds to NSI with $\varepsilon_{ee} \equiv \alpha - 1$ other $\varepsilon_{\alpha\beta} = 0$

It is worth extending this analysis to: $-4 < \alpha - 1 < +4$



SK, PRD 97('18) 072001

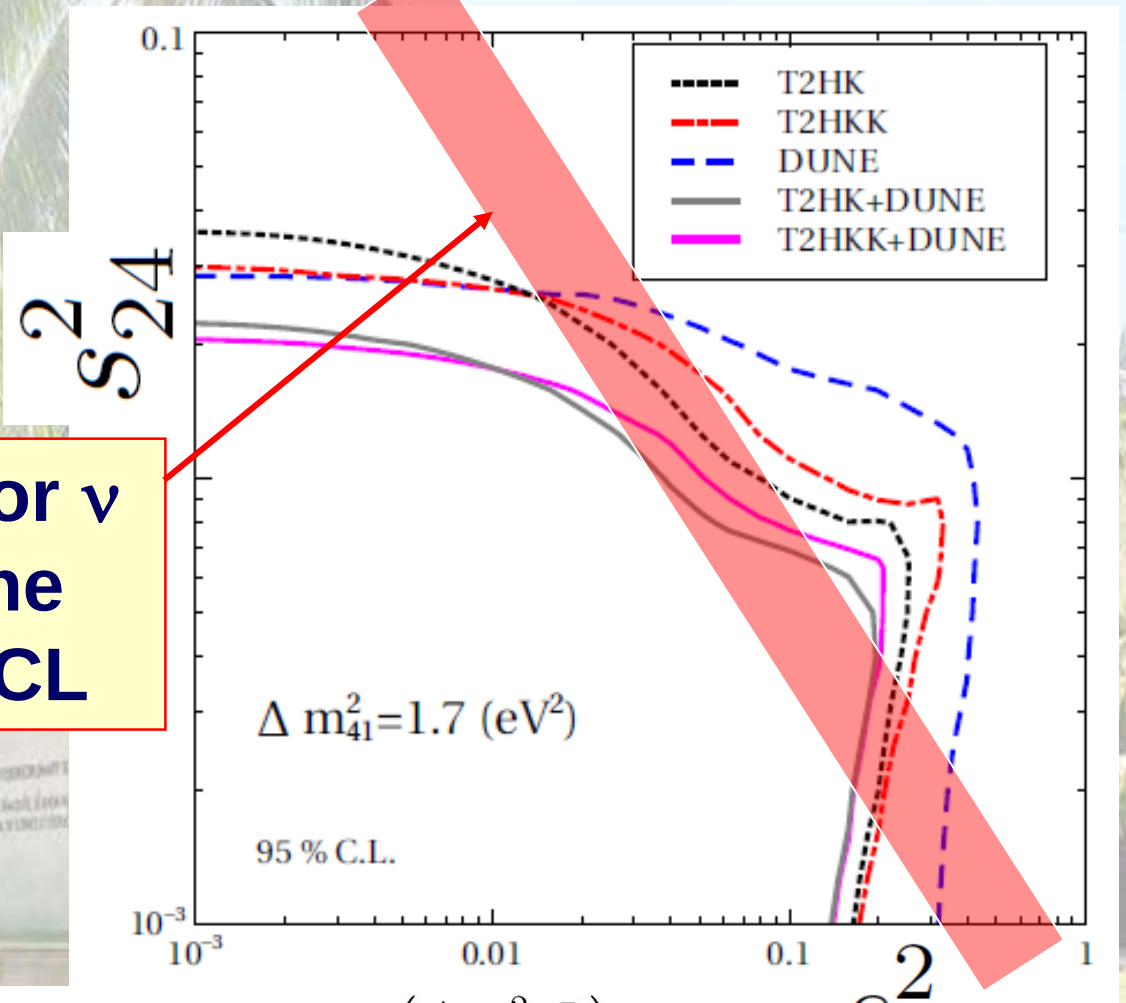
4. Tests at HK & DUNE

(1) ν_s (1-1) Accelerator ν (T2HK, T2HKK, DUNE)

Choubey-Dutta-Pramanik, Eur.Phys.J. C78 ('18) 339

$$\Delta m^2_{41}=1.7\ (\mathrm{eV}^2)$$

Combined accelerator ν can cover some of the LSND region @ 90%CL



$$P(\nu_\mu \to \nu_e) = 4\mathrm{Re}\left[U_{e3}U^*_{\mu3}(U^*_{e3}U_{\mu3} + \boxed{U^*_{e4}U_{\mu4}})\right]\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \cdots$$

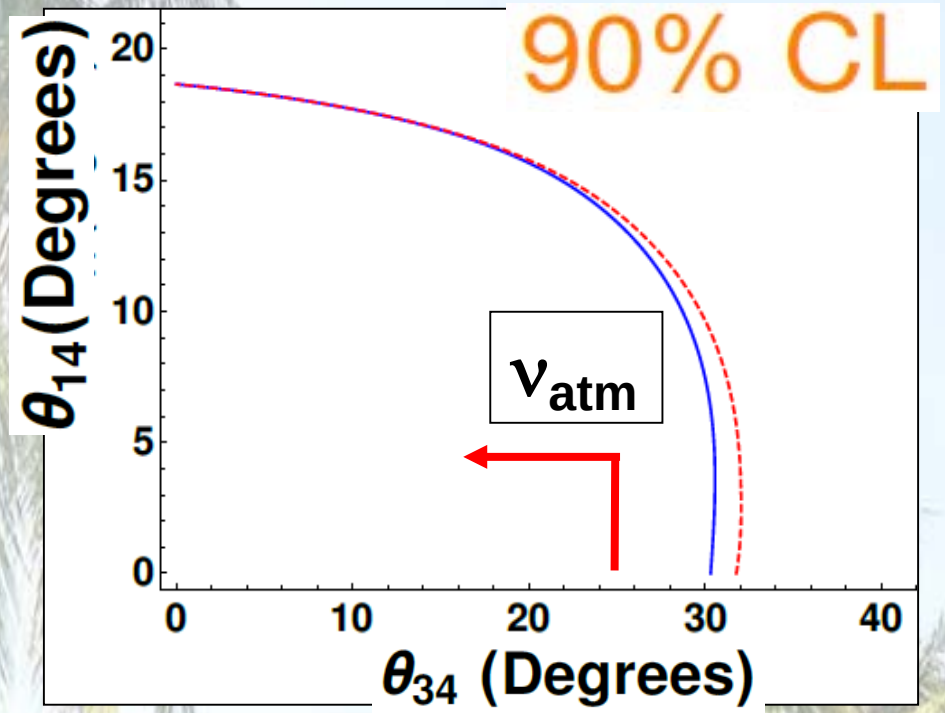
(1-2) Accelerator ν (DUNE w/ ν_τ)

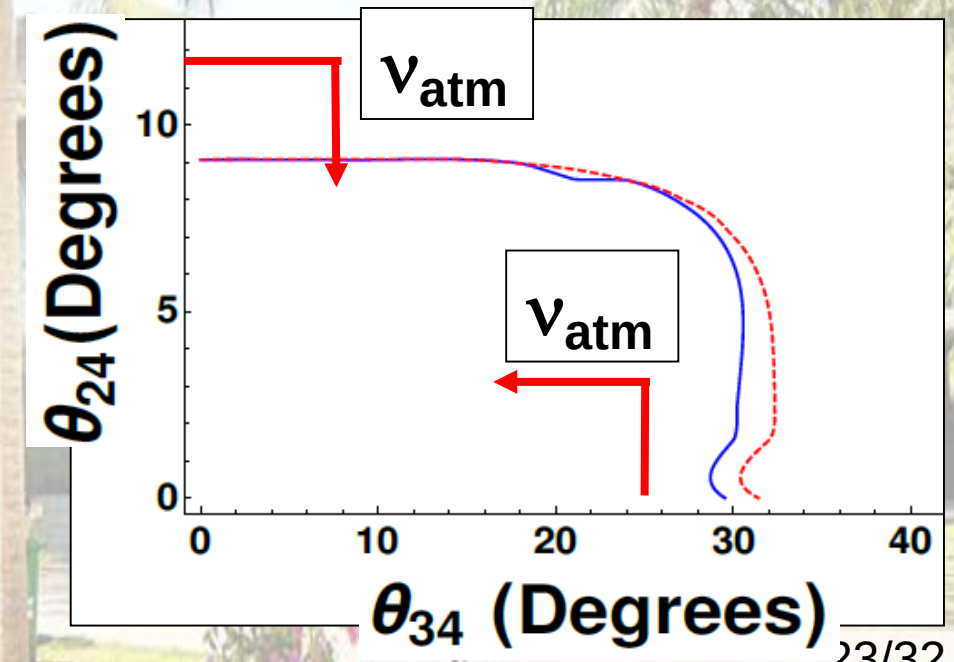
Ghoshal-Giarnetti-Meloni, arXiv:1906.06212v1

$\Delta m_{41}^2 = 1.0\ eV^2$

$\nu_\tau + \nu_\mu + \nu_e$ ———

$\nu_\mu + \nu_e$ - - - - -

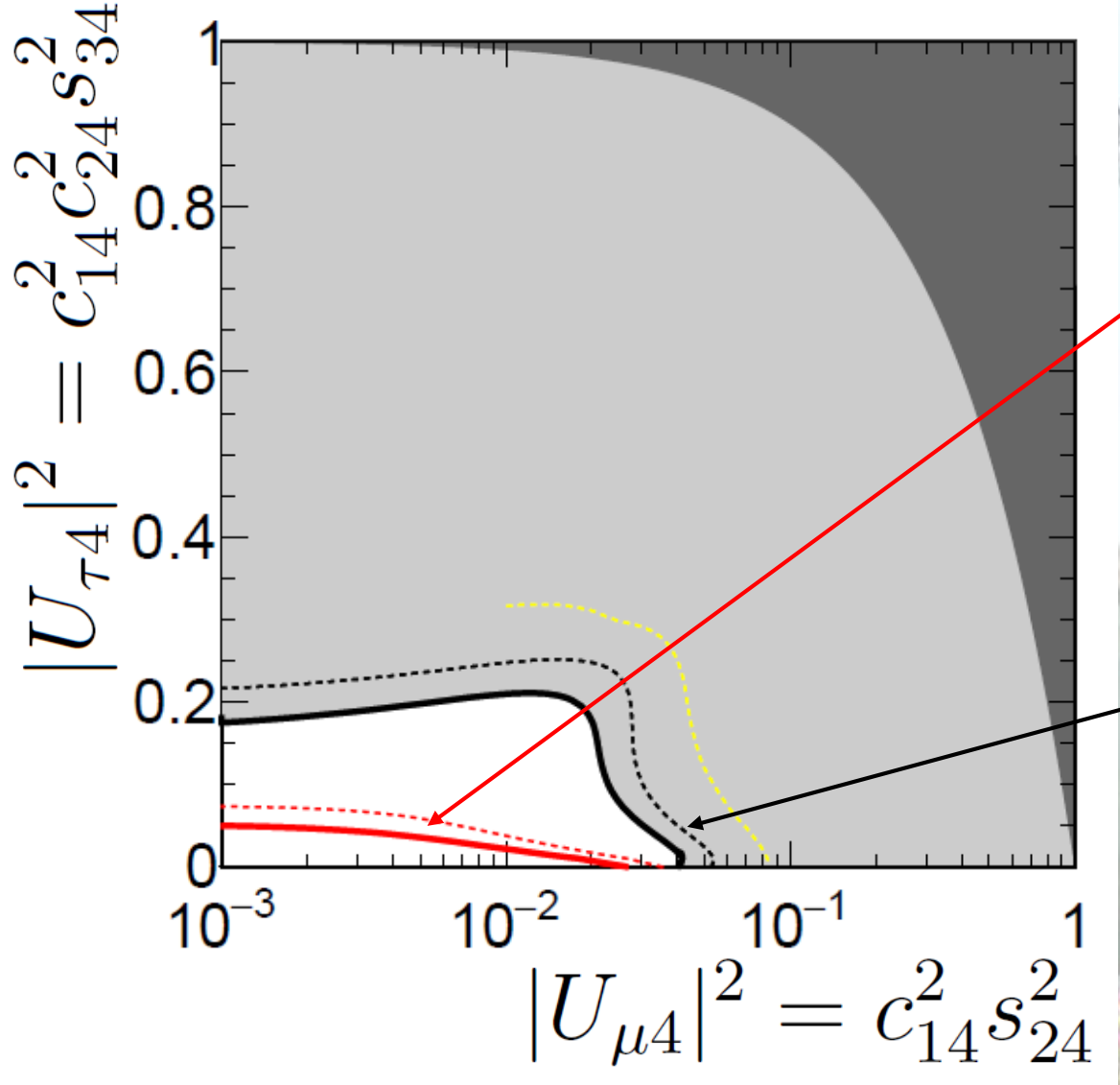




Accelerator ν has better (worse) sensitivity to θ_{24} (θ_{34}) than ν_{atm}

(1-3) HK ν_{atm}

HK, arXiv:1805.04163v2



HK Sensitivity to θ_{34} (θ_{24}) is (is not much) improved compared to SK:
90% CL (solid)
99% CL (dashed)

(2) NSI in propagation

In solar ν analysis, (ε_D, ε_N) was used:

$$U = R_{23}(\theta_{23}, 0) R_{13}(\theta_{13}, \delta_{13}) R_{12}(\theta_{12}, 0)$$

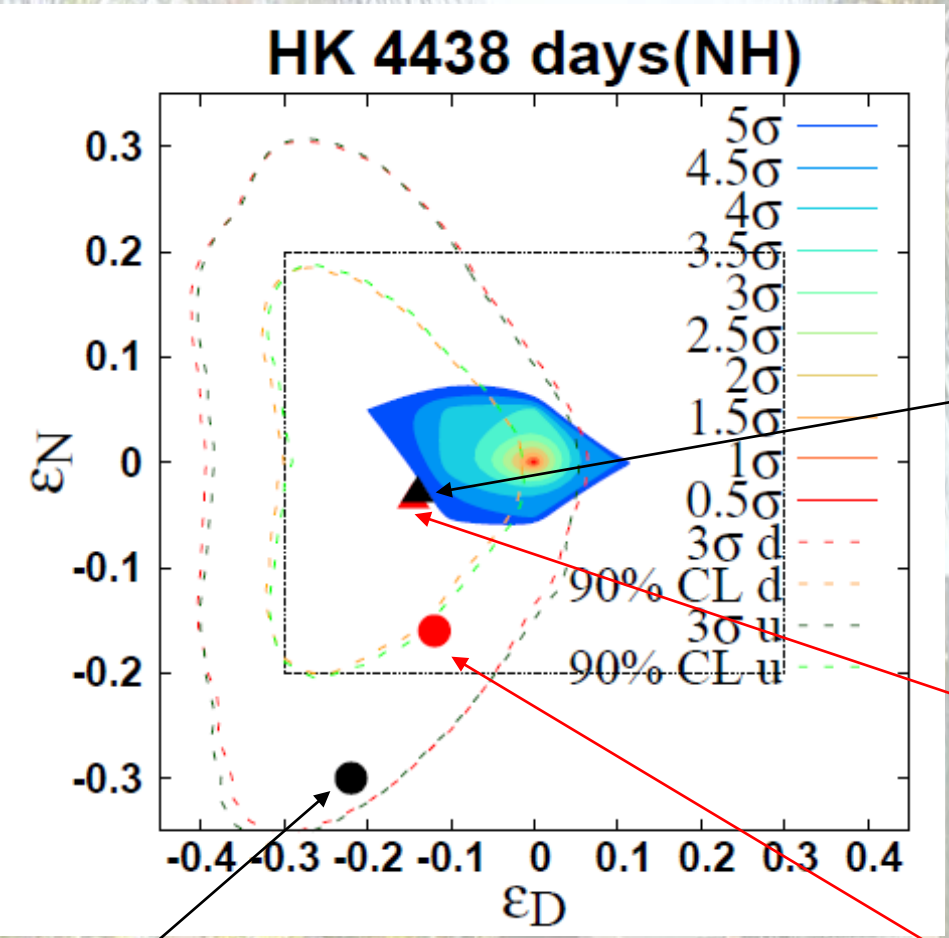
$$(\epsilon'_{\alpha\beta}) \equiv R_{13}^{-1}(\theta_{13}, \delta_{13})\, R_{23}^{-1}(\theta_{23}, 0)\ (\epsilon_{\alpha\beta})\ R_{23}(\theta_{23}, 0)\, R_{13}(\theta_{13}, \delta_{13})$$

$$\equiv \begin{pmatrix} \epsilon'_{11} & \epsilon'_{12} & \epsilon'_{13} \\ \epsilon'_{21} & \epsilon'_{22} & \epsilon'_{23} \\ \epsilon'_{31} & \epsilon'_{32} & \epsilon'_{33} \end{pmatrix} = \begin{pmatrix} \frac{\epsilon'_{11} + \epsilon'_{22}}{2} - \epsilon_D & \epsilon_N & \epsilon'_{13} \\ \epsilon_N^* & \frac{\epsilon'_{11} + \epsilon'_{22}}{2} + \epsilon_D & \epsilon'_{23} \\ \epsilon'_{31} & \epsilon'_{32} & \epsilon'_{33} \end{pmatrix}$$

-> Also for analysis of ν_{atm} & LBL, (ε_D, ε_N) will be used instead of $\varepsilon_{\alpha\beta}$.

(2-1) HK ν_{atm} (NH, Real ε_N)

Fukasawa-OY, NPB914 ('17) 99



HK ν_{atm} has sensitivity to some region of the ν_{solar} anomaly

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

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

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

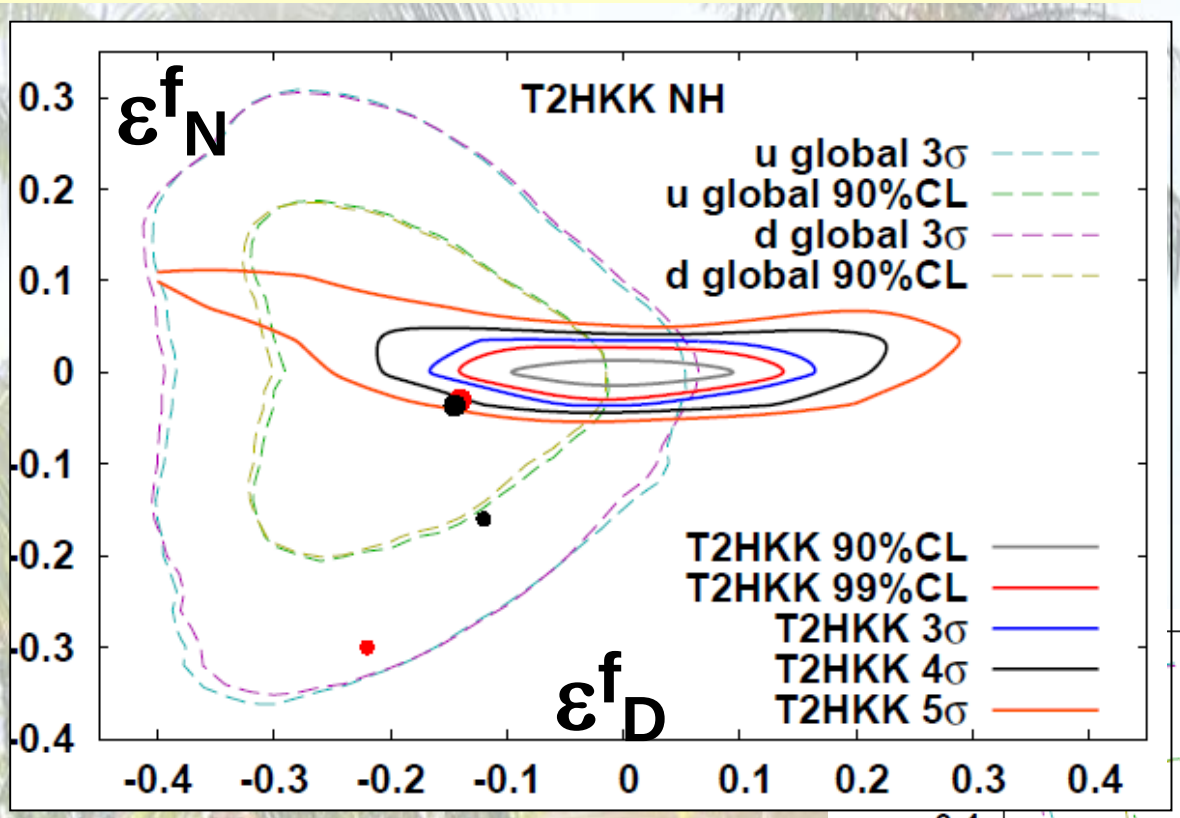
Best fit point of solar & KamLAND for f=d: significance:11σ

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

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

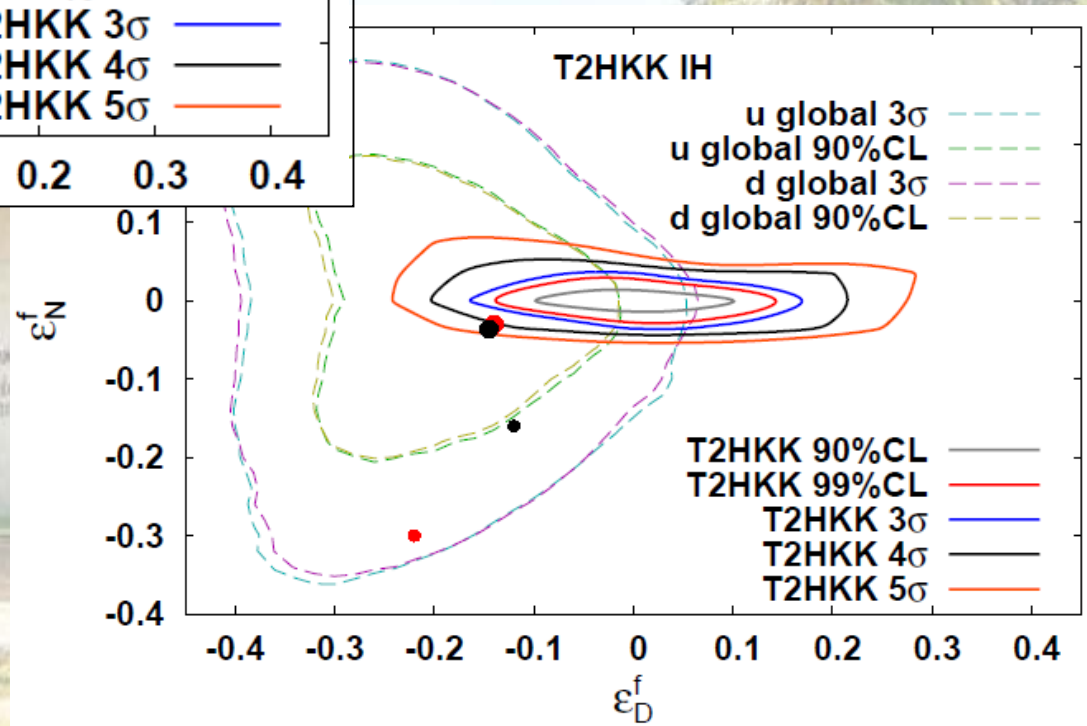
(2-2) Accelerator ν (T2HKK)

Ghosh & OY, arXiv:1709.08264



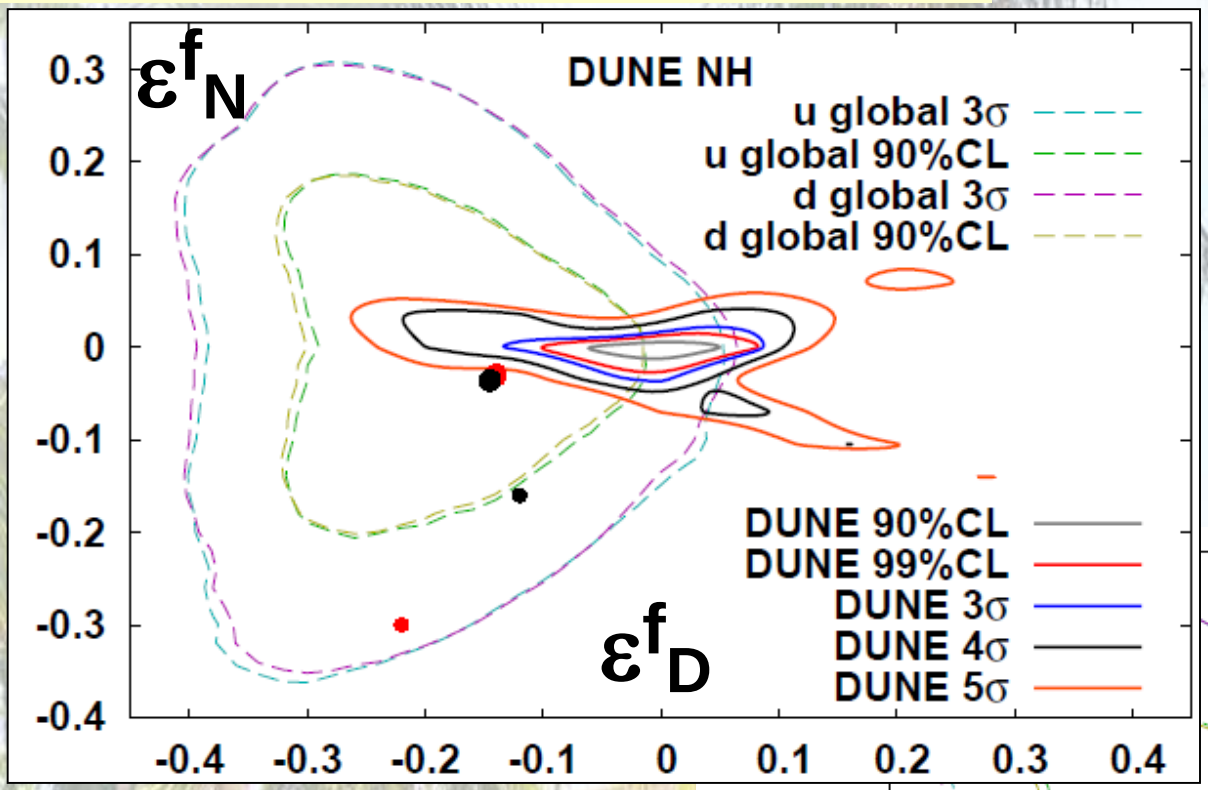
Excluded region by LBL is outside of the curve

δ(true) = -90°



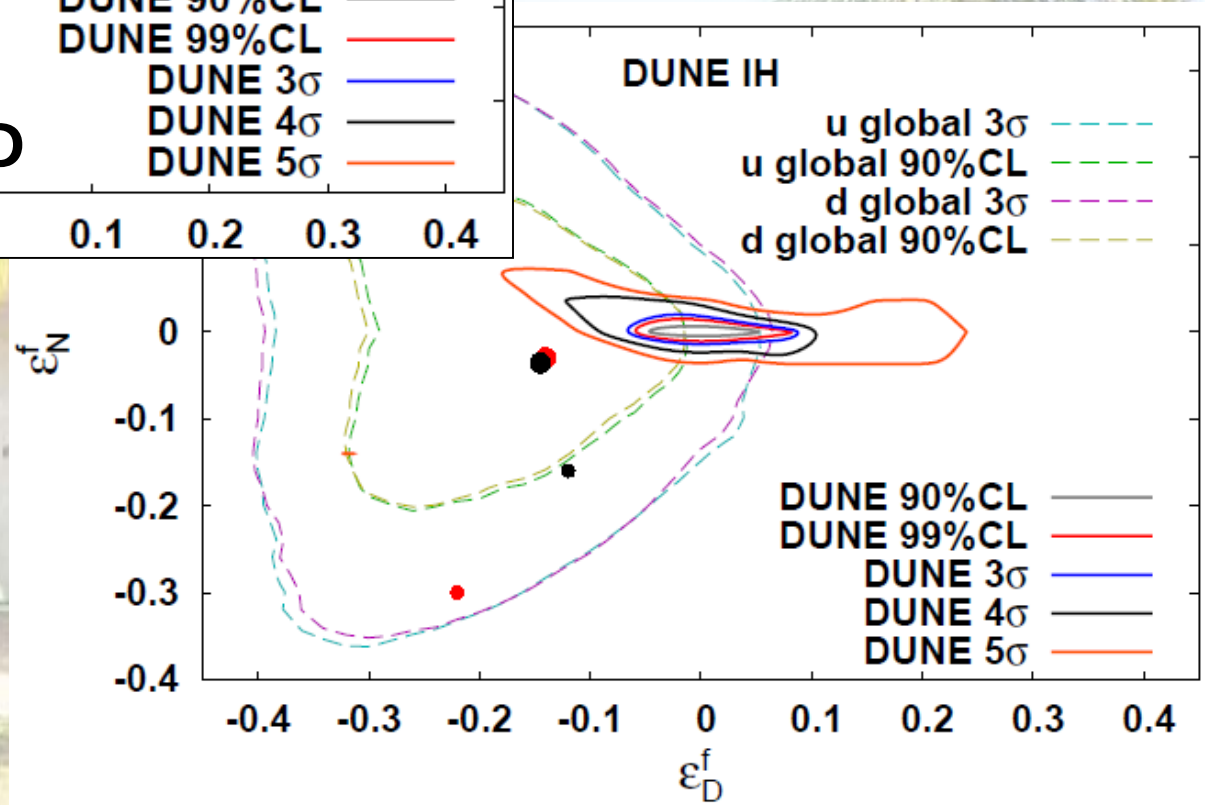
(2-3) Accelerator ν (DUNE)

Ghosh & OY, arXiv:1709.08264



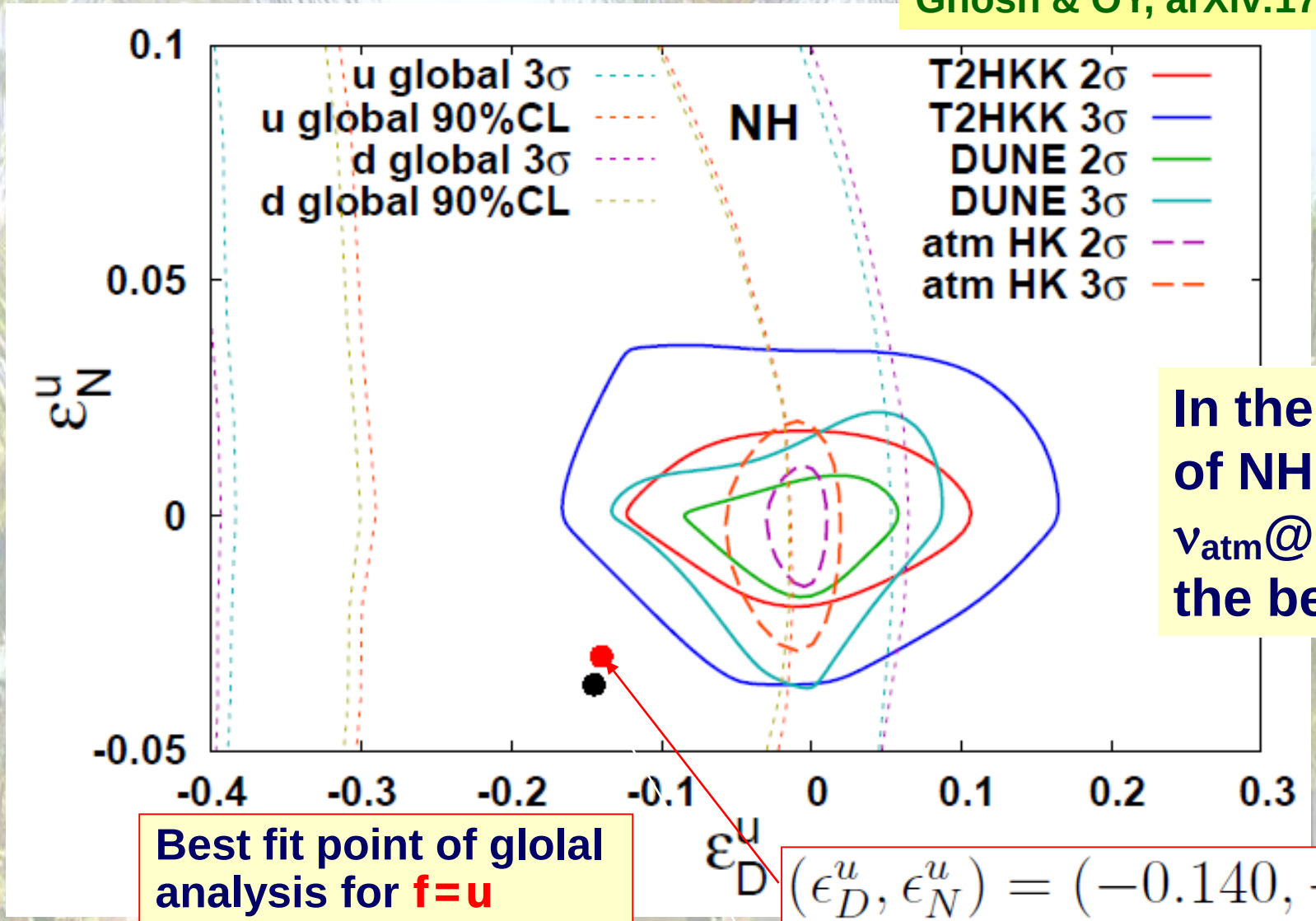
δ(true) = -90°

Sensitivity of DUNE is slightly better than T2HKK



●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**

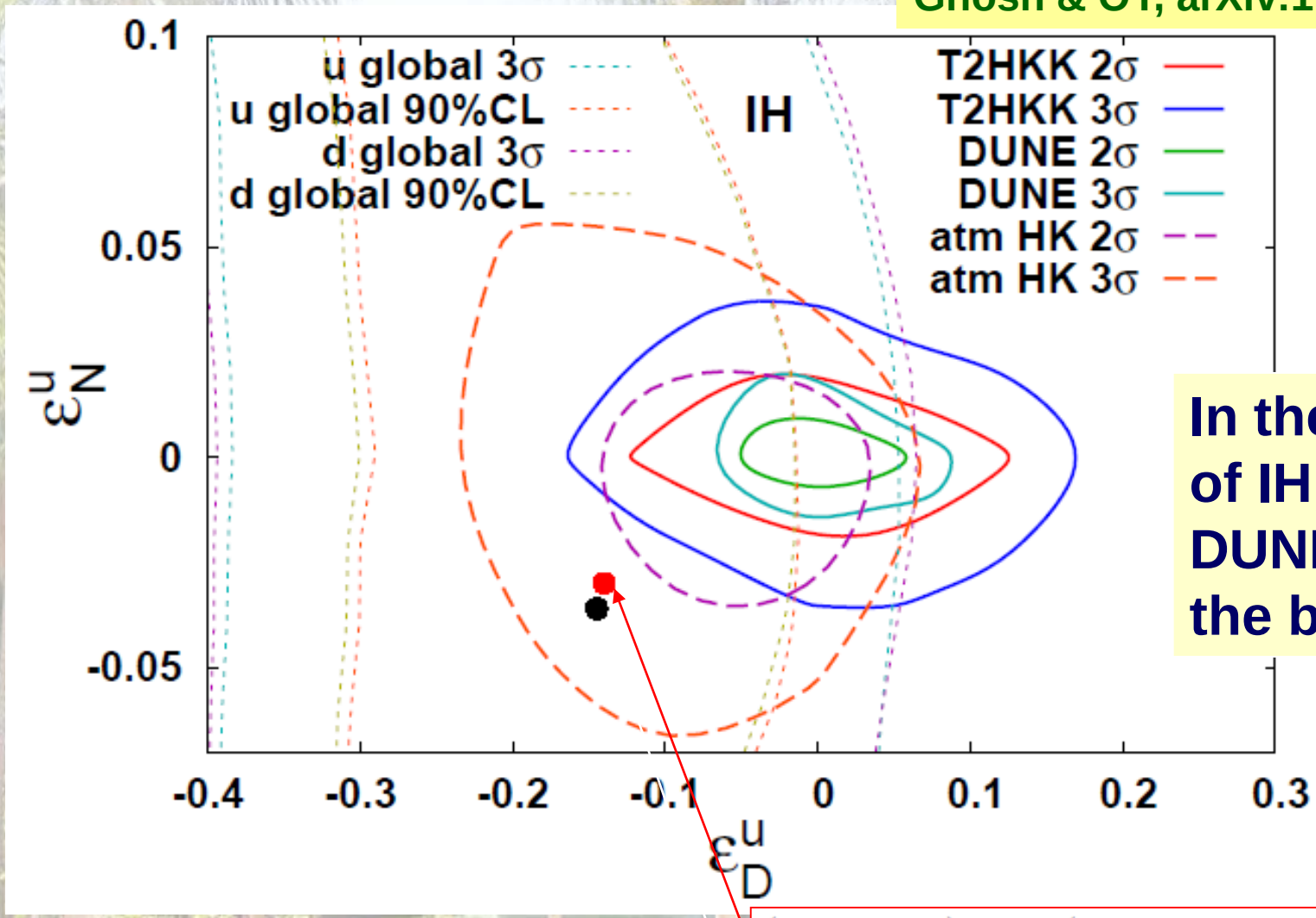
$$(\epsilon_D^u, \epsilon_N^u) = (-0.140, -0.030)$$

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

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

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

5. Conclusions (1)

- **The 3 mixing angles and the two mass squared differences have been determined in the PMNS paradigm.**
- **We still have to determine:**
  - **Mass hierarchy (important to determine δ)**
  - θ_{23}-$\pi/4$
  - δ
- **Currently there are several hints for deviation from the standard 3 flavor scenario. Research on sterile neutrinos and NSI is in progress and it may give us a hint for physics beyond the PMNS paradigm.**

5. Conclusions (2)

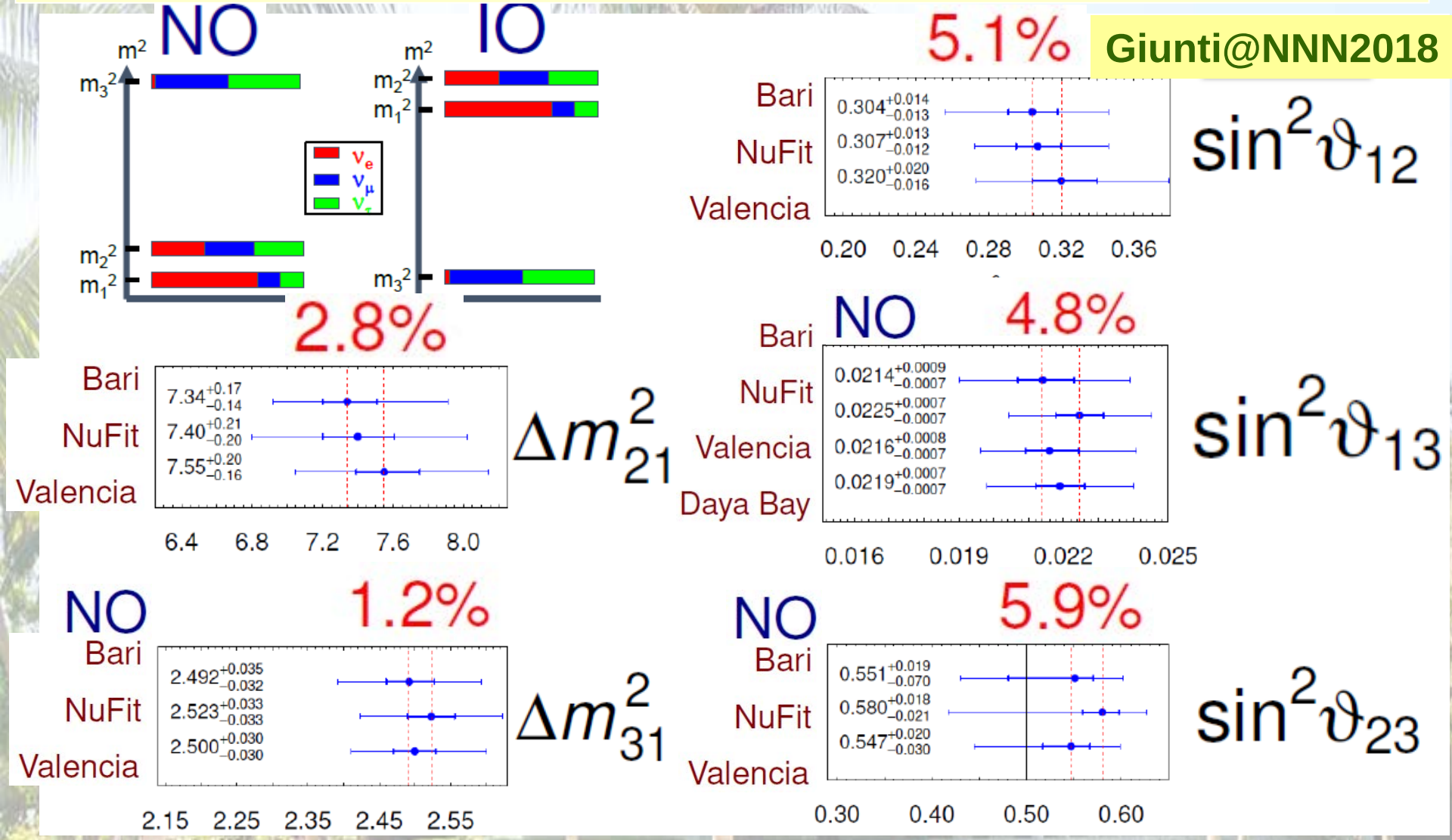
- The most popular scenarios beyond the PMNS paradigm are ν_s & NSI in propagation. Matter effect is important to search for both.

- Before HK & DUNE, ν_{atm} at HK and/or IceCUBE are powerful in constraining the two scenarios.

- After HK & DUNE, T2HK+DUNE is expected to cover some of the LSND region @90%CL (ν_s). ν_{atm}@HK, T2HKK, DUNE have sensitivity to some region of NSI which was suggested by ν_{solar}.

Backup slides

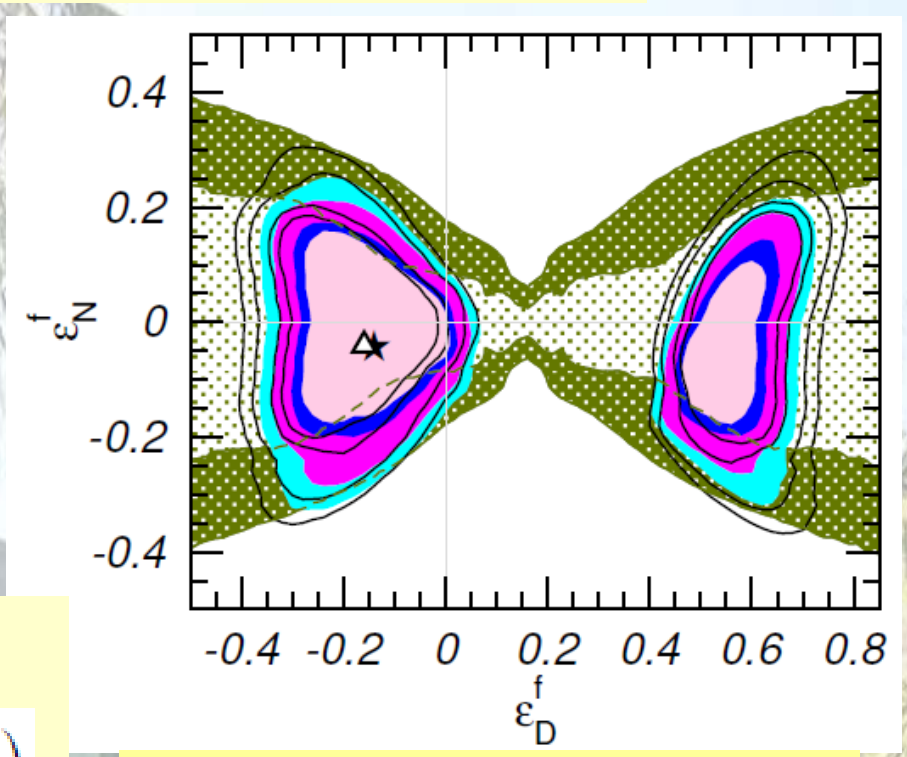
Allowed regions by different groups almost agree



There may be slight difference in θ_{23}-region

Motivation for Non Standard Interaction in ν propagation

- **There seem to be tension between solar ν & KamLAND data.**
  --> NSI may be necessary to explain data.



Best fit value of global fit

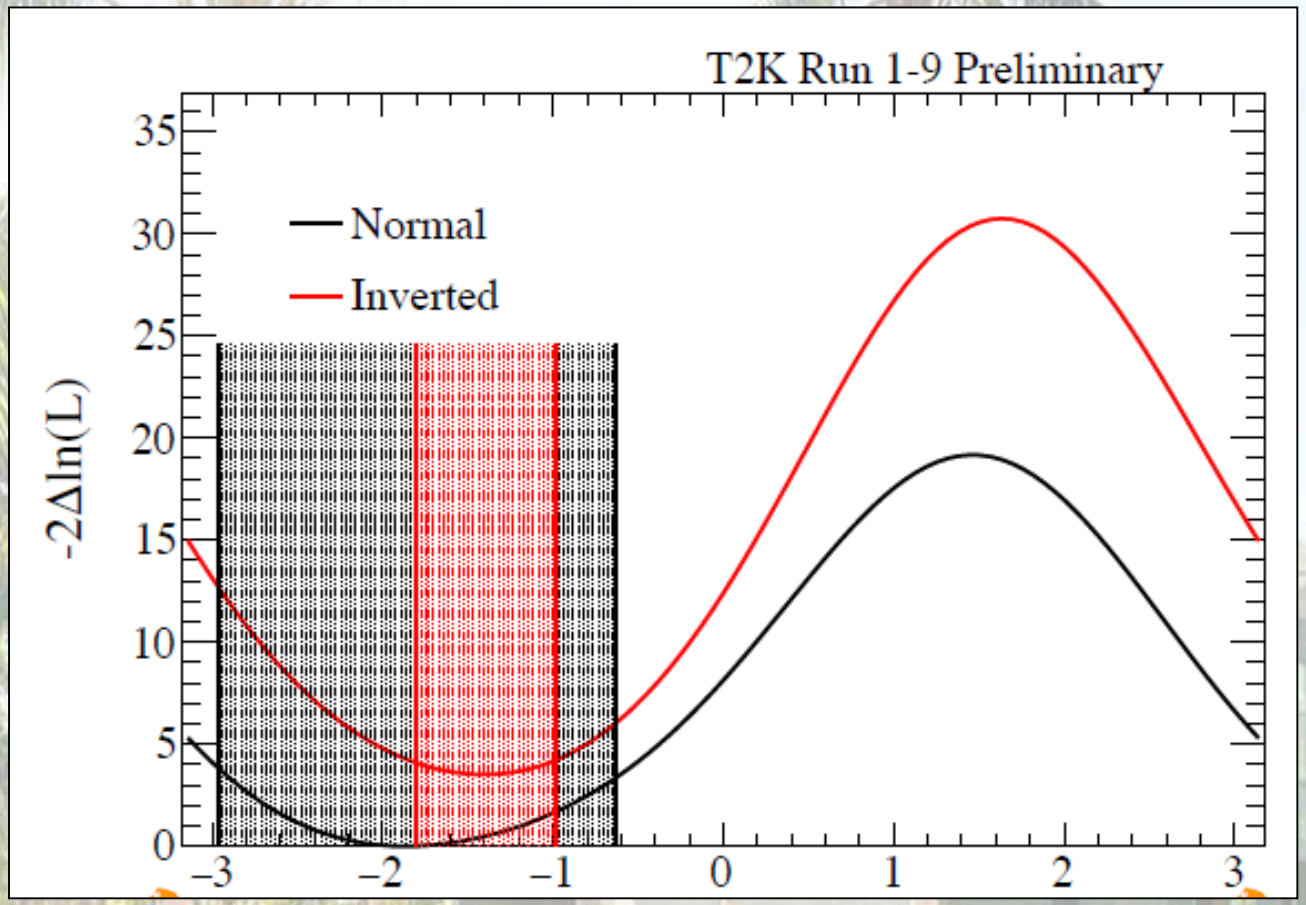
$$(\epsilon_D^u, \epsilon_N^u) = (-0.140, -0.030)$$

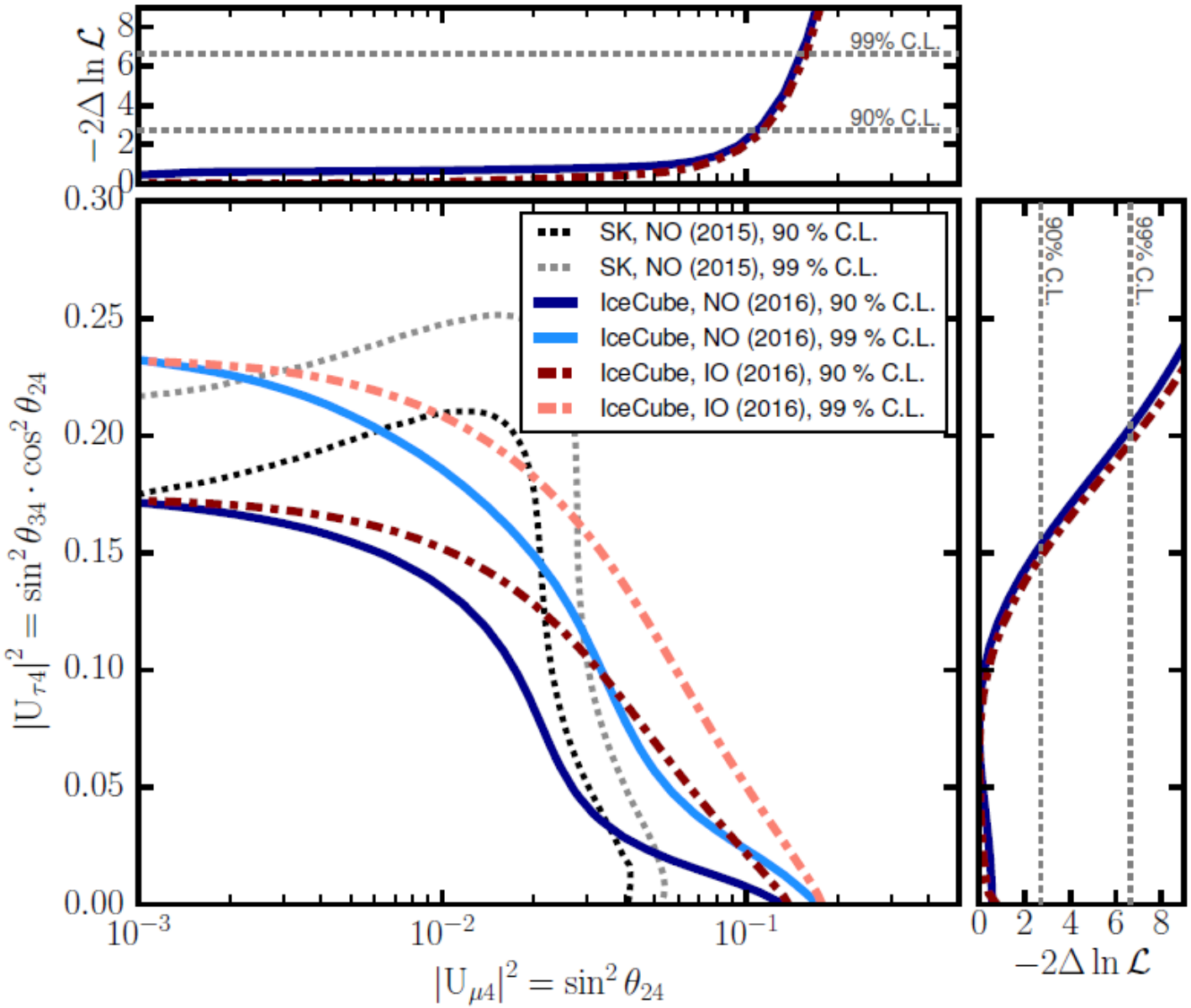
$$(\epsilon_D^d, \epsilon_N^d) = (-0.145, -0.036)$$

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

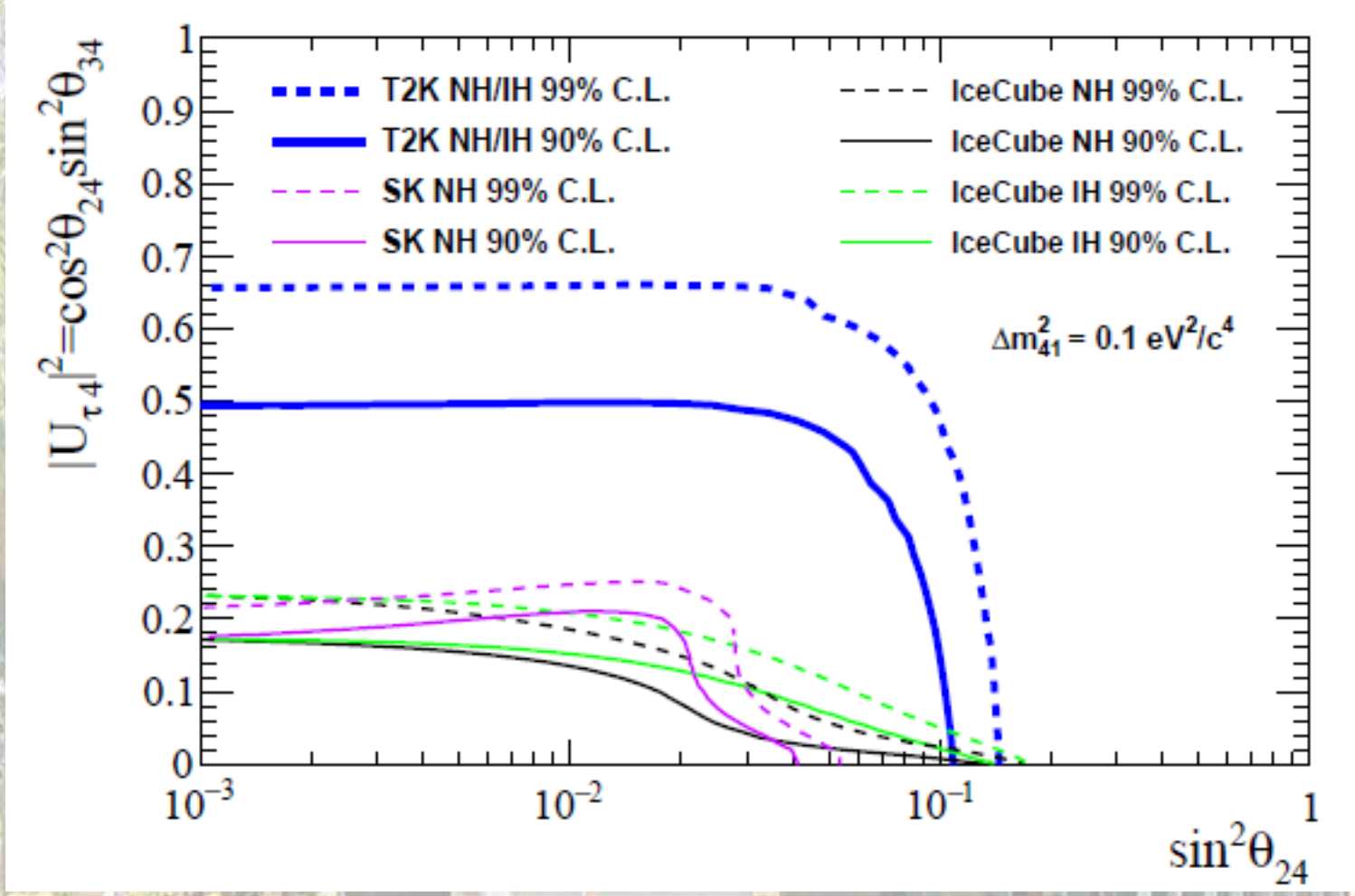
T2K results on ν_e appearance

Sakashita@Prospects of Neutrino Physics (IPMU, 2019/4)



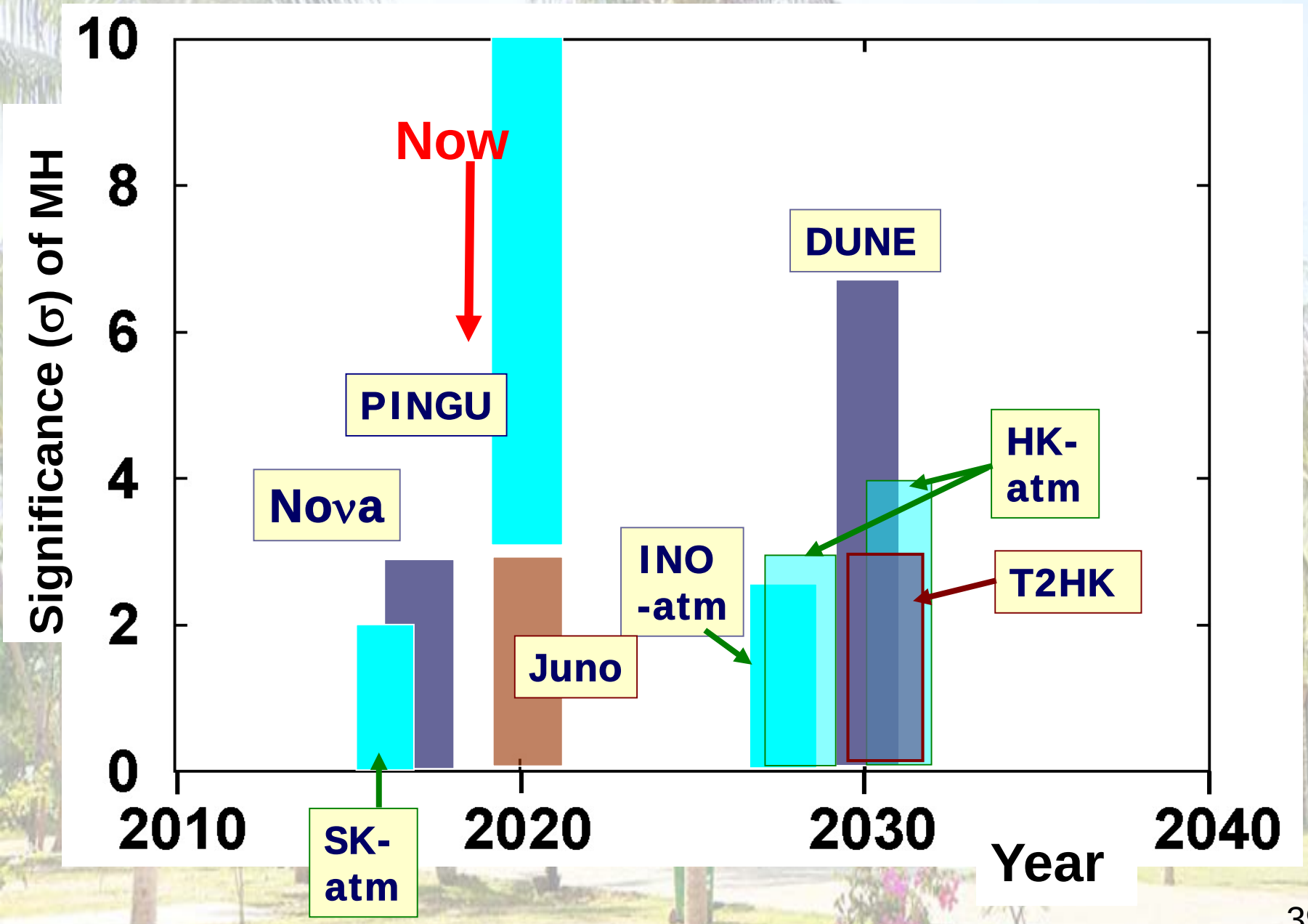


IceCUBE, PRD95 ('17) 112002



T2K, PRD99 ('19) 071103

Future exp. vs Mass Hierarchy



• Constraints on $\varepsilon_{\alpha\beta}$ for expts on Earth

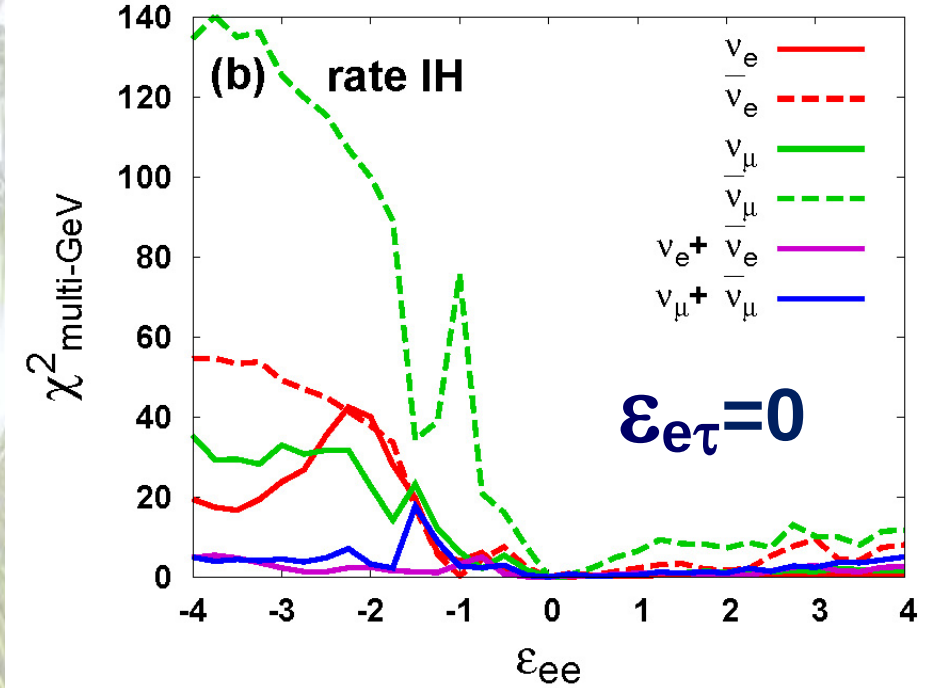
Davidson et al., JHEP 0303:011,2003; Berezhiani, Rossi, PLB535 ('02) 207; Barranco et al., PRD73 ('06) 113001; Barranco et al., arXiv:0711.0698

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

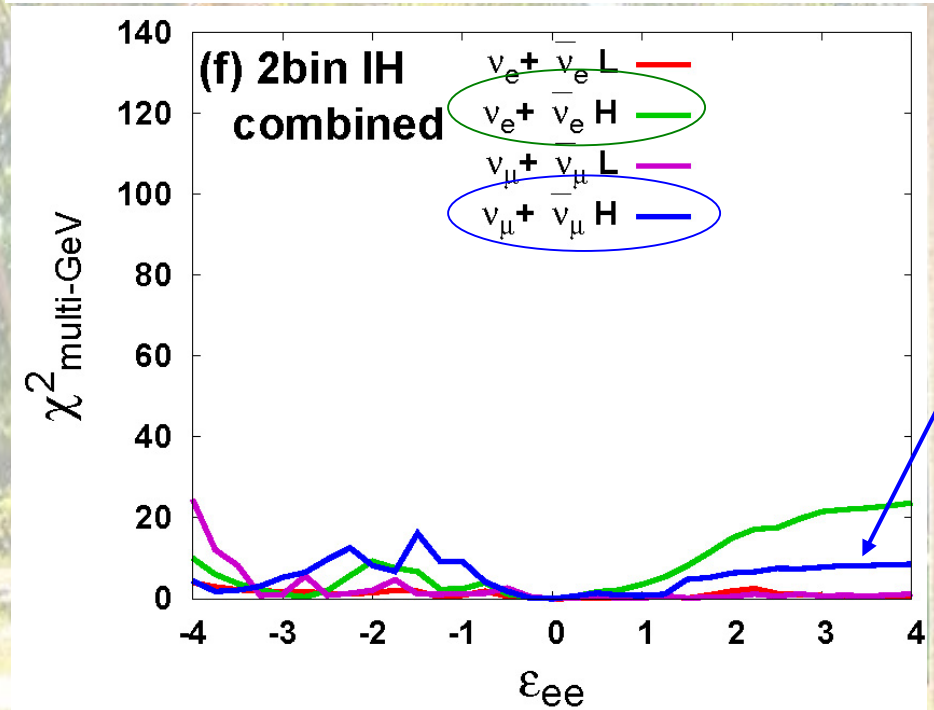
Constraints are weak

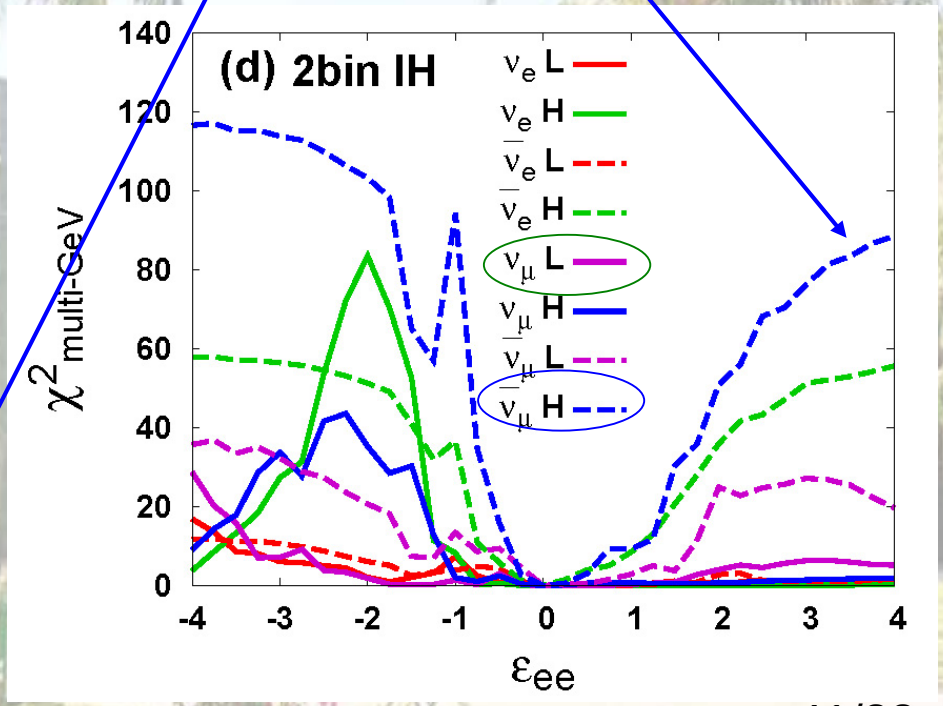
$$\begin{pmatrix} \boxed{|\epsilon_{ee}| \lesssim 4 \times 10^{0}} & |\epsilon_{e\mu}| \lesssim 3 \times 10^{-1} & \boxed{|\epsilon_{e\tau}| \lesssim 3 \times 10^{0}} \\ & |\epsilon_{\mu\mu}| \lesssim 7 \times 10^{-2} & |\epsilon_{\mu\tau}| \lesssim 3 \times 10^{-1} \\ & & \boxed{|\epsilon_{\tau\tau}|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

Behaviors of χ^2 (IH) for multi-GeV: $\nu+\bar{\nu}$ vs individual ν&$\bar{\nu}$ for $\varepsilon_{e\tau}=0$

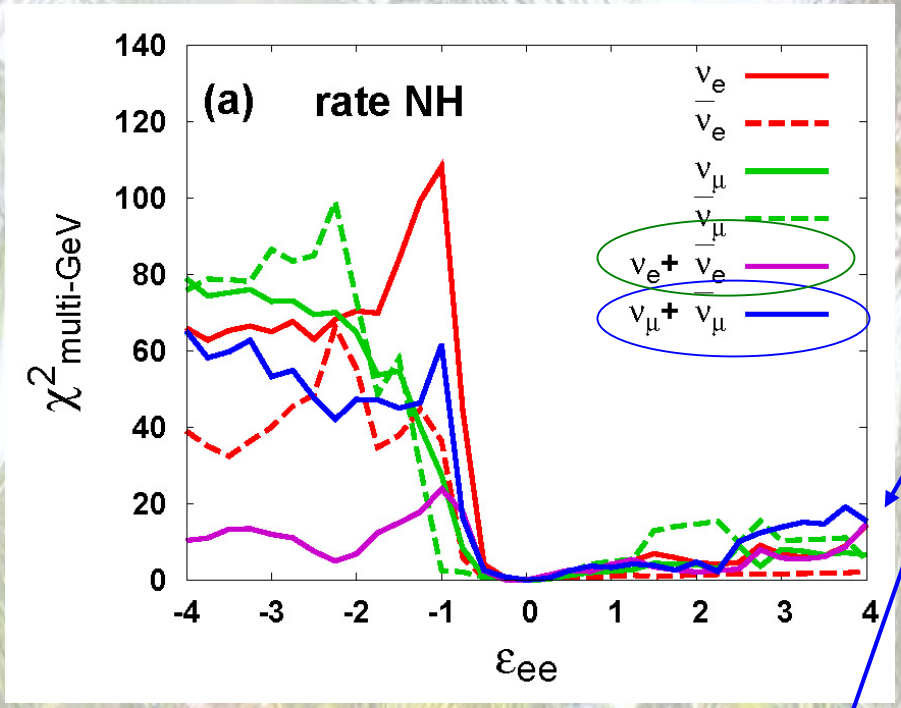


Destructive phenomenon between ν & $\bar{\nu}$ → Distinction between ν & $\bar{\nu}$ gives important information on ε_{ee}

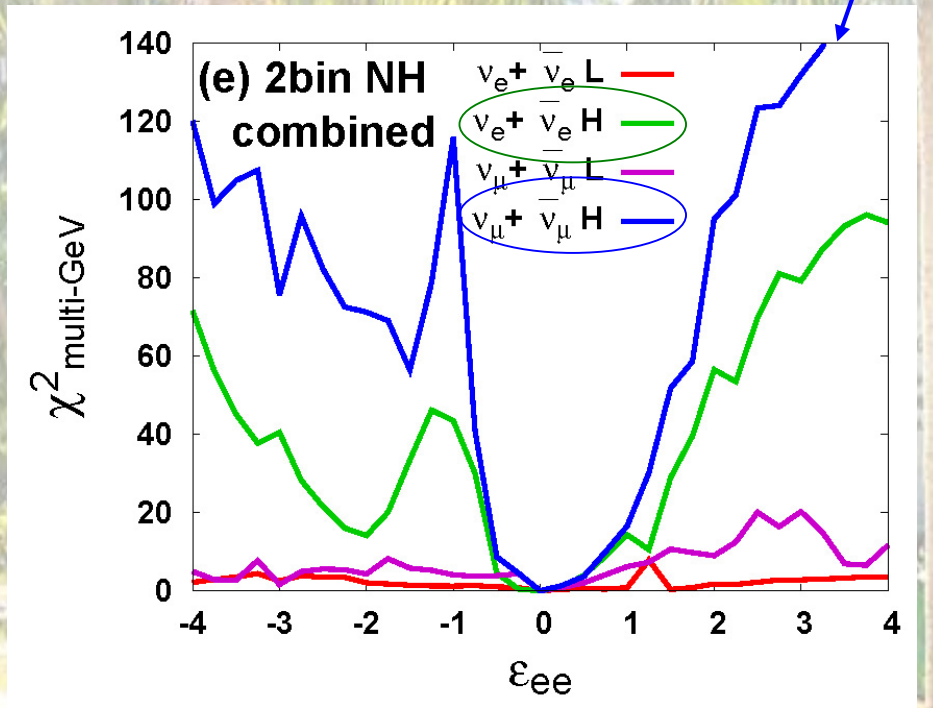


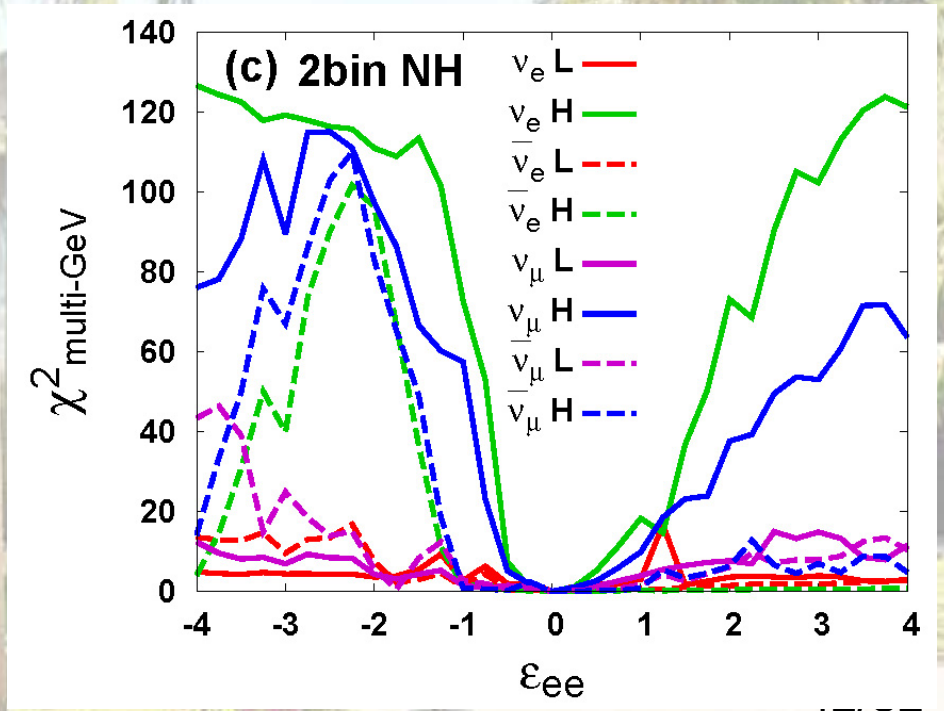


Behaviors of χ^2 (NH) for multi-GeV: Rate VS Spectrum for $\varepsilon_{e\tau}=0$



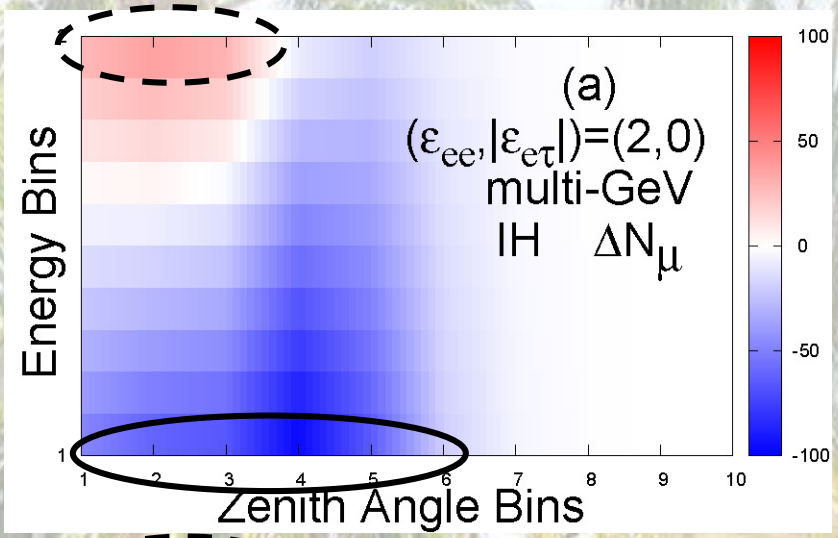
Destructive phenomenon between Low & High energy bins → Information on energy spectrum is important

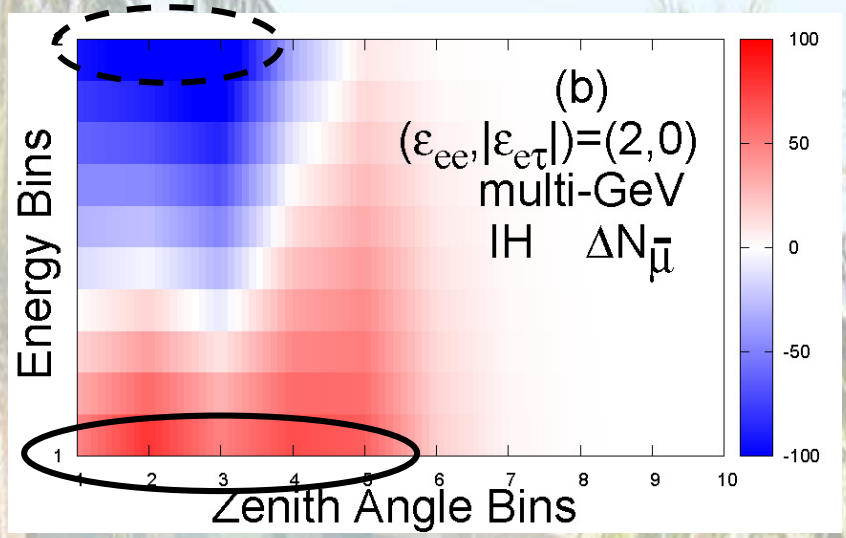


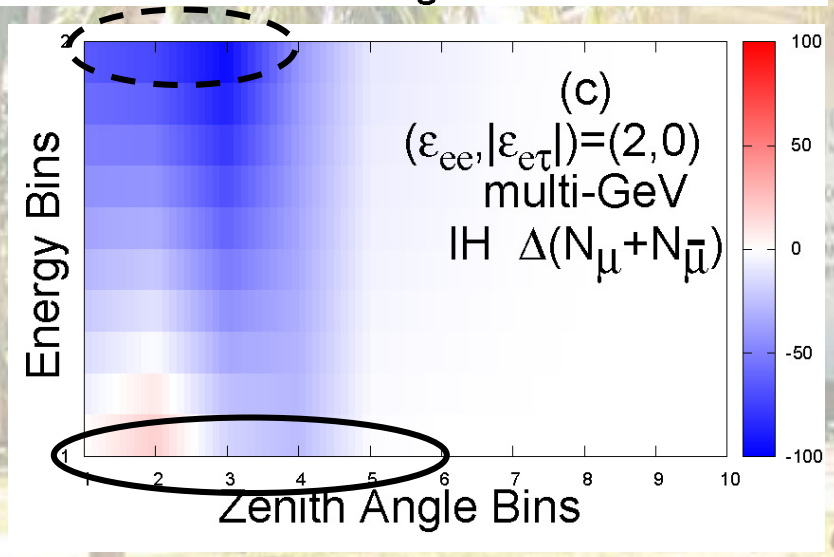


Behaviors of #(events) for multi-GeV: $\nu+\bar{\nu}$ vs individual ν&$\bar{\nu}$

Destructive phenomenon between ν & $\bar{\nu}$

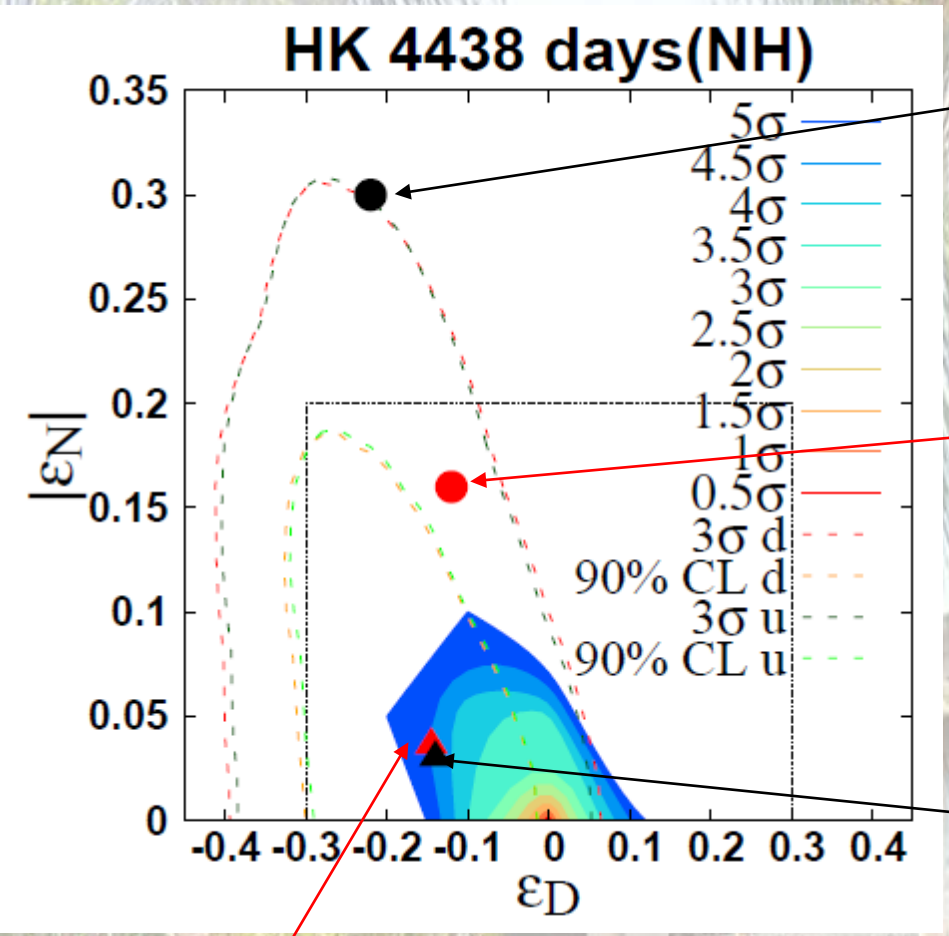






Theoretical understanding in terms of oscillation probabilities is under study.

Sensitivity of HK: (1) Complex $|\varepsilon_N|$ for NH



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

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

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

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

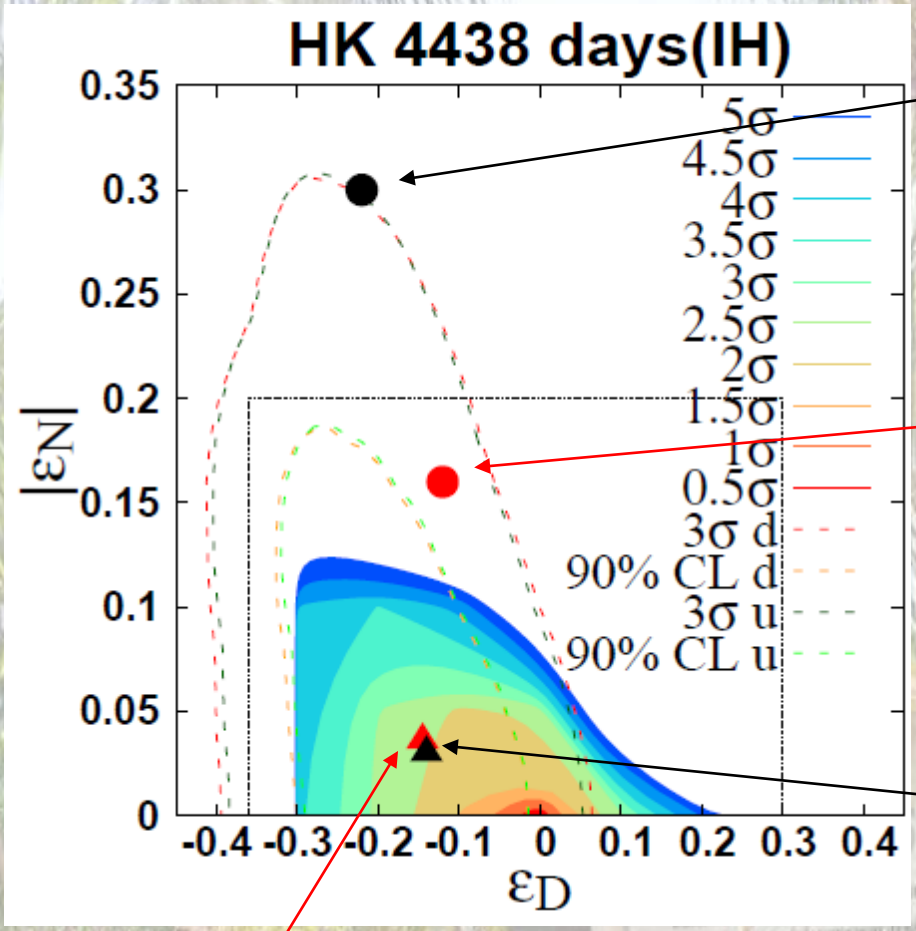
$$(\epsilon_D^u, \epsilon_N^u) = (-0.140, -0.030)$$

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

Sensitivity of HK: (1) Complex $|\varepsilon_N|$ for IH



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

Best fit point of solar & KamLAND for f=u: significance:35σ

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

Best fit point of solar & KamLAND for f=d: significance:8σ

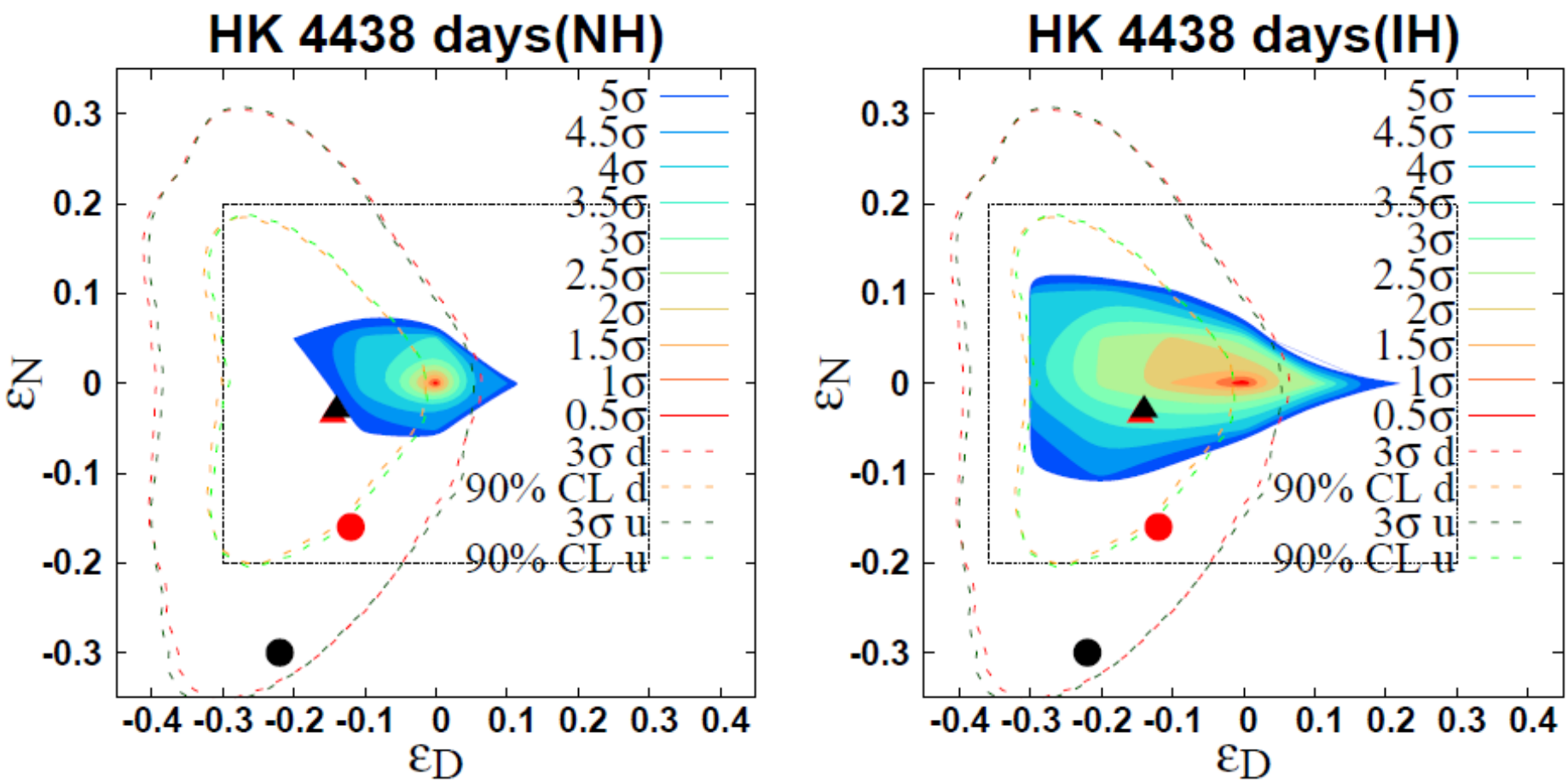
$$(\epsilon_D^u, \epsilon_N^u) = (-0.140, -0.030)$$

Best fit point of glolal analysis for f=u: significance:1.4σ

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

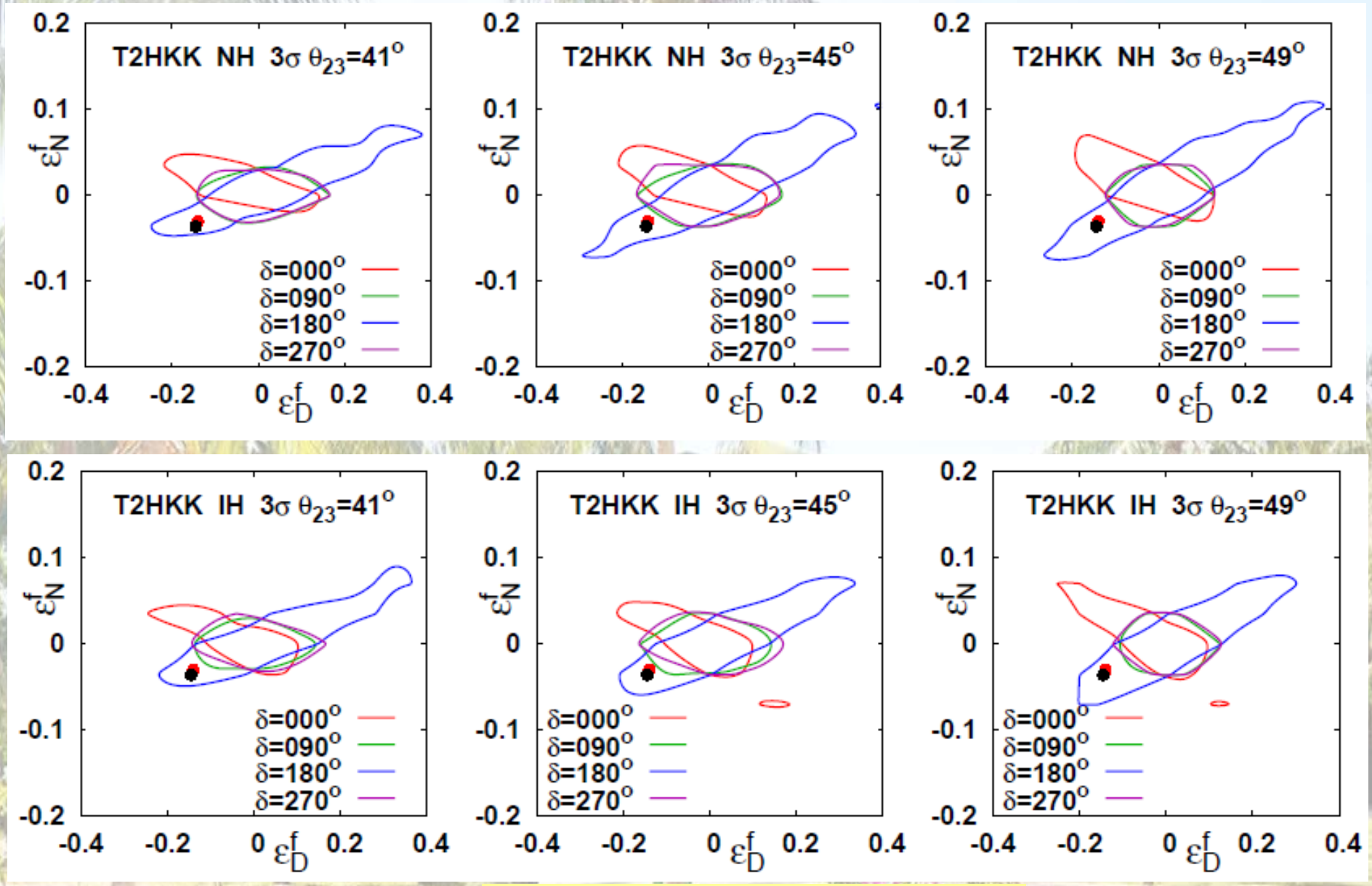
Best fit point of glolal analysis for f=d: significance:1.5σ

Sensitivity of HK: (2) Real $|\varepsilon_N|$



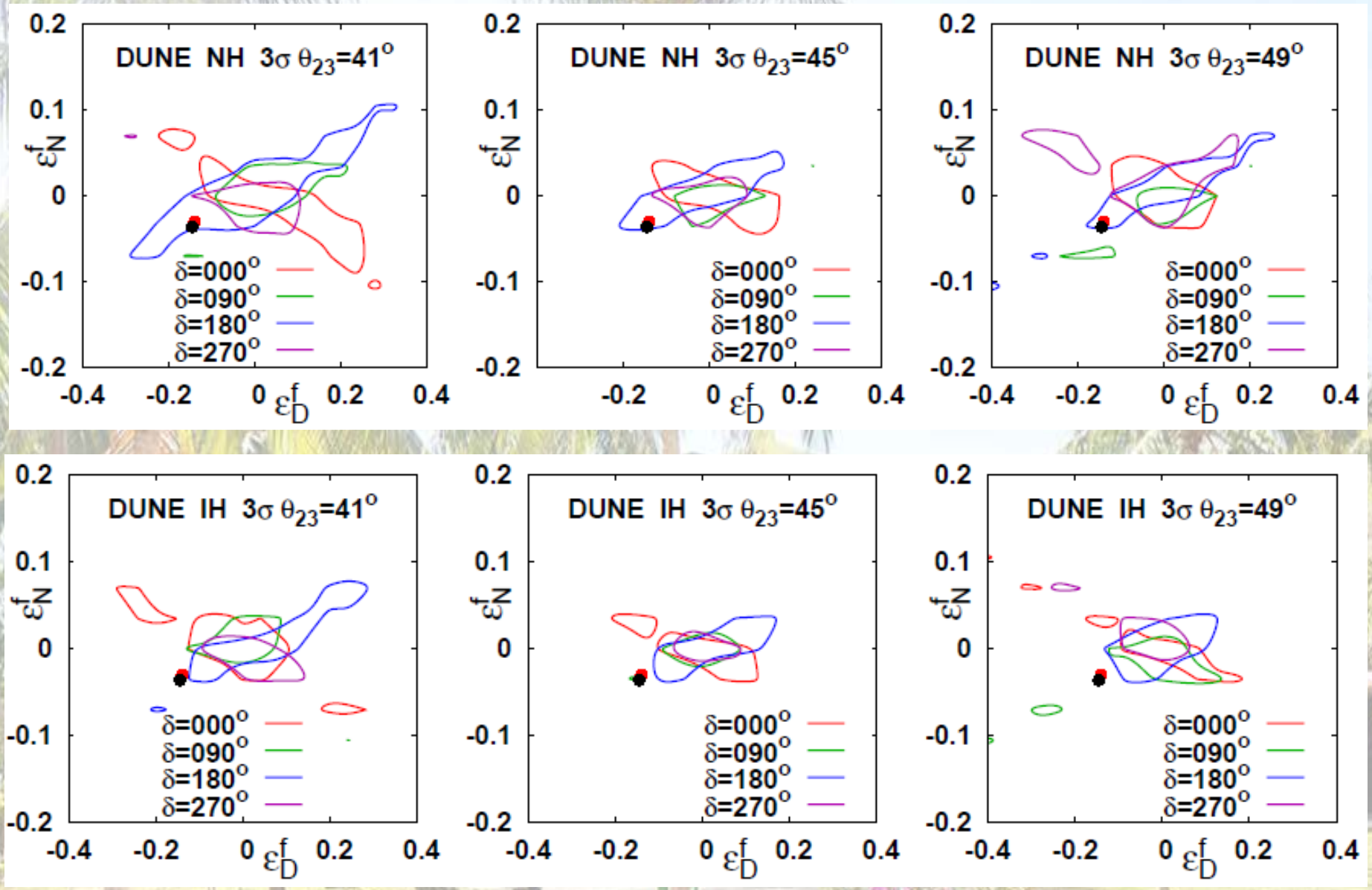
Allowed regions and significance are similar to the case for complex ε_N

●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