CONSTRAINING THE FLAVOR STRUCTURE OF LORENTZ VIOLATION HAMILTONIAN WITH THE MEASUREMENT OF ASTROPHYSICAL NEUTRINO FLAVOR COMPOSITIONS

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arXiv: 1704.04027

OUTLINE

- Introduction
- Lorentz violation effects to neutrino flavor transitions
- Lorentz violation and the current IceCube results on astrophysical neutrino flavor compositions
- IceCube-Gen2 and its potential of constraining Lorentz Violation Hamiltonian
- Summary

INTRODUCTION

- Flavor discrimination

Probe the flavor transition, ex: ν oscillation, ν decay, Lorentz Violation(LV)

$\Phi_e^0 : \Phi_\mu^0 : \Phi_\tau^0$ ⟷ $\Phi_e : \Phi_\mu : \Phi_\tau$

Generate the source

detected at the Earth

$$(\Phi_e:\Phi_\mu:\Phi_\tau)=P_{\alpha\beta}(\Phi_e^0:\Phi_\mu^0:\Phi_\tau^0)$$

INTRODUCTION

- There are two types of astrophysical sources in proton-proton collision and proton-γ collision:

- $PP \rightarrow (\pi^+, \pi^-, \pi^0) + X$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$(\nu_e, \nu_\mu, \nu_\tau) = (\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau) \approx (1,2,0)$$

1. π source(1/3,2/3,0)
2. μ damped source(0,1,0)

- $P\gamma \rightarrow \Delta^+ \rightarrow n\pi^+$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

$$(\nu_e, \nu_\mu, \nu_\tau) \approx (1,1,0)$$
$$(\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau) \approx (0,1,0)$$

1. π source(1/3,2/3,0)
2. μ damped source(0,1,0)

J. P. Rachen and P. Meszaros, 1998
T. Kashti and E. Waxman, Phy. Rev. Lett. 2005

- We shall focus on pion source from pp collision

$$(\nu_e, \nu_\mu, \nu_\tau) = (\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau) \approx (1/3, 2/3, 0)$$

- Defining neutrino flavor fraction:

$$f_\alpha^0 = \Phi^0(\nu_\alpha)/(\Phi^0(\nu_e) + \Phi^0(\nu_\mu) + \Phi^0(\nu_\tau))$$

↑ total flux of neutrinos and anti-neutrinos at the source

Hence

$$(f_e^0, f_\mu^0, f_\tau^0) = (1/3, 2/3, 0)$$

$$f_\alpha = \Phi(\nu_\alpha)/(\Phi(\nu_e) + \Phi(\nu_\mu) + \Phi(\nu_\tau))$$

total flux of neutrinos
and anti-neutrinos at
the terrestrial detector

$$f_\alpha = P_{\alpha\beta} f_\beta^0 \qquad P_{\alpha\beta} = P(\nu_\beta \to \nu_\alpha)$$

with $(f_e^0, f_\mu^0, f_\tau^0) = (1/3, 2/3, 0)$

$$f_e = 1/3 + (P_{e\mu} - P_{e\tau})/3$$
$$f_\mu = 1/3 + (P_{\mu\mu} - P_{\mu\tau})/3$$
$$f_\tau = 1/3 + (P_{\mu\tau} - P_{\tau\tau})/3$$

A test of μτ symmetry breaking

LV EFFECTS TO NEUTRINO FLAVOR TRANSITION

- For neutrinos, the general form of LV Hamiltonian

$$\mathbf{H}^{\nu}_{LV} = \frac{p_\lambda}{E}\begin{pmatrix} a^{\lambda}_{ee} & a^{\lambda}_{e\mu} & a^{\lambda}_{e\tau} \\ a^{\lambda*}_{e\mu} & a^{\lambda}_{\mu\mu} & a^{\lambda}_{\mu\tau} \\ a^{\lambda*}_{e\tau} & a^{\lambda*}_{\mu\tau} & a^{\lambda}_{\tau\tau} \end{pmatrix} - \frac{p^\rho p^\lambda}{E}\begin{pmatrix} c^{\rho\lambda}_{ee} & c^{\rho\lambda}_{e\mu} & c^{\rho\lambda}_{e\tau} \\ c^{\rho\lambda*}_{e\mu} & c^{\rho\lambda}_{\mu\mu} & c^{\rho\lambda}_{\mu\tau} \\ c^{\rho\lambda*}_{e\tau} & c^{\rho\lambda*}_{\mu\tau} & c^{\rho\lambda}_{\tau\tau} \end{pmatrix}$$

- For rotationally invariant LV effects

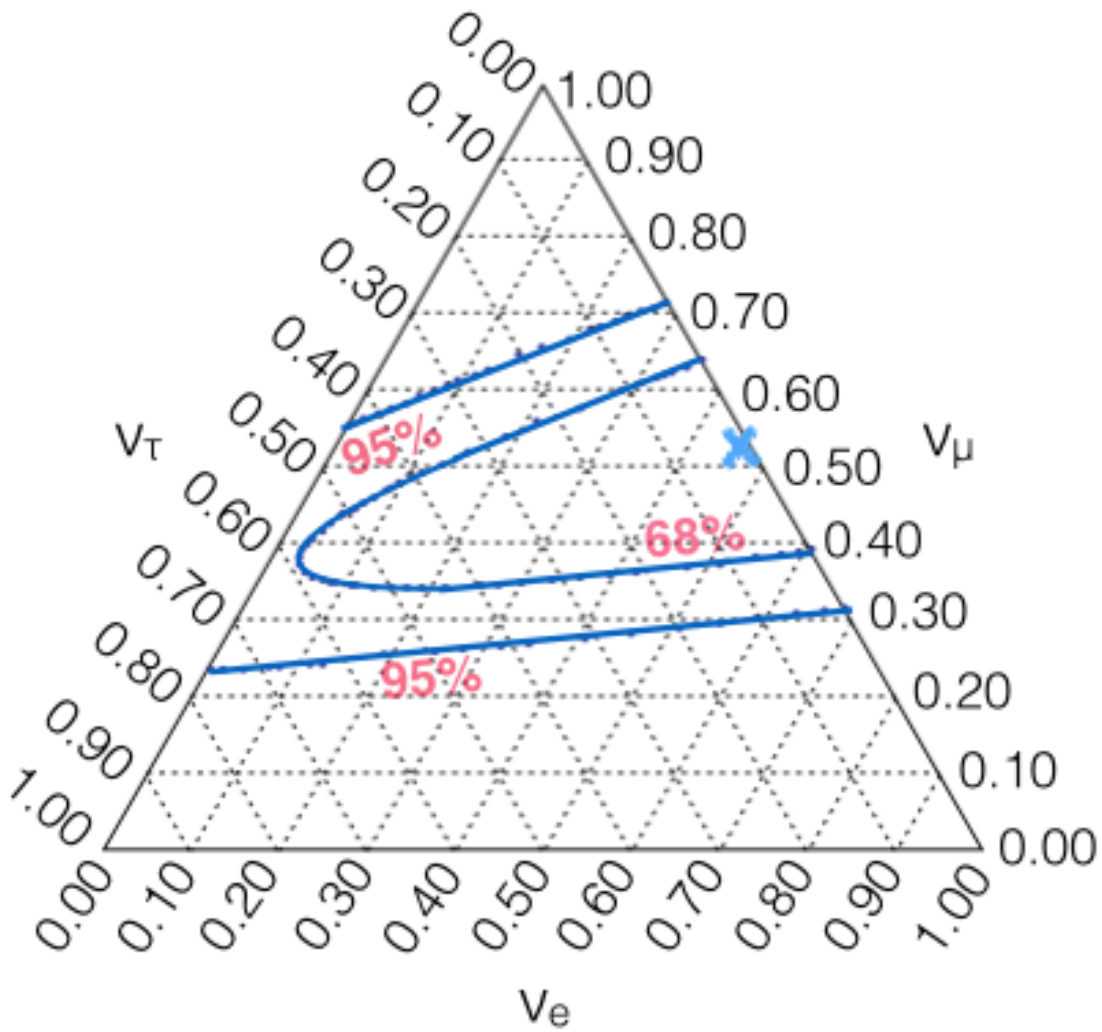
$$\mathbf{H}^{\nu}_{LV} = \begin{pmatrix} a^{T}_{ee} & a^{T}_{e\mu} & a^{T}_{e\tau} \\ a^{T*}_{e\mu} & a^{T}_{\mu\mu} & a^{T}_{\mu\tau} \\ a^{T*}_{e\tau} & a^{T*}_{\mu\tau} & a^{T}_{\tau\tau} \end{pmatrix} - \frac{4E}{3}\begin{pmatrix} c^{TT}_{ee} & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ c^{TT*}_{e\mu} & c^{TT}_{\mu\mu} & c^{TT}_{\mu\tau} \\ c^{TT*}_{e\tau} & c^{TT*}_{\mu\tau} & c^{TT}_{\tau\tau} \end{pmatrix}$$

$$\mathbf{H}^{\bar{\nu}}_{LV} = -\begin{pmatrix} a^{T}_{ee} & a^{T}_{e\mu} & a^{T}_{e\tau} \\ a^{T*}_{e\mu} & a^{T}_{\mu\mu} & a^{T}_{\mu\tau} \\ a^{T*}_{e\tau} & a^{T*}_{\mu\tau} & a^{T}_{\tau\tau} \end{pmatrix}^{*} - \frac{4E}{3}\begin{pmatrix} c^{TT}_{ee} & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ c^{TT*}_{e\mu} & c^{TT}_{\mu\mu} & c^{TT}_{\mu\tau} \\ c^{TT*}_{e\tau} & c^{TT*}_{\mu\tau} & c^{TT}_{\tau\tau} \end{pmatrix}^{*}$$

Sun-centered celestial equatorial frame (T,X,Y,Z) Let us first focus on $a^{T}_{\alpha\beta}$

Teppei Katori, V. Alan Kostelecký, and Rex Tayloe, Phys. Rev. D **74**, 105009(2006)
V. Alan Kostelecký and Matthew Mewes, Phys. Rev. D **69**, 016005(2004)

LORENTZ VIOLATIONS AND CURRENT ICECUBE RESULTS ON ASTROPHYSICAL NEUTRINO FLAVOR COMPOSITION



- E_ν is between 25 TeV and 2.8 PeV

  $H_{SM} \approx \Delta m^2_{31}/2E_\nu$

  Hence H_{SM} is between

  5×10^{-26} GeV

  and

  4.5×10^{-28} GeV

Can Lorentz Violation play role in this data?

M. G. Aartsen *et al.* (IceCube Collaboration), Astrophys.J. 809 (2015) no.1, 98

CURRENT BOUNDS ON LORENTZ VIOLATION PARAMETERS

Super-K's result: K. Abe et al. (Super-Kamiokande Collaboration),Phys. Rev. D **91**, 052003(2015)

LV parameter		Limit at 95% C.L.	Best fit	No LV $\Delta\chi^2$	Previous limit
$e\mu$	$\mathrm{Re}(a^T)$	1.8×10^{-23} GeV	1.0×10^{-23} GeV	1.4	4.2×10^{-20} GeV [1]
	$\mathrm{Im}(a^T)$	1.8×10^{-23} GeV	4.6×10^{-24} GeV		
	$\mathrm{Re}(c^{TT})$	8.0×10^{-27}	1.0×10^{-28}	0.0	9.6×10^{-20} [1]
	$\mathrm{Im}(c^{TT})$	8.0×10^{-27}	1.0×10^{-28}		
$e\tau$	$\mathrm{Re}(a^T)$	4.1×10^{-23} GeV	2.2×10^{-24} GeV	0.0	7.8×10^{-20} GeV [2]
	$\mathrm{Im}(a^T)$	2.8×10^{-23} GeV	1.0×10^{-28} GeV		
	$\mathrm{Re}(c^{TT})$	9.3×10^{-25}	1.0×10^{-28}	0.3	1.3×10^{-17} [2]
	$\mathrm{Im}(c^{TT})$	1.0×10^{-24}	3.5×10^{-25}		
$\mu\tau$	$\mathrm{Re}(a^T)$	6.5×10^{-24} GeV	3.2×10^{-24} GeV	0.9	...
	$\mathrm{Im}(a^T)$	5.1×10^{-24} GeV	1.0×10^{-28} GeV		
	$\mathrm{Re}(c^{TT})$	4.4×10^{-27}	1.0×10^{-28}	0.1	...
	$\mathrm{Im}(c^{TT})$	4.2×10^{-27}	7.5×10^{-28}		

$H_{SM} < 5 \times 10^{-26}$ GeV

Significant room for H_{LV} to play an important role

V. Alan Kostelecký and Neil Russell, Rev. Mod. Phys. **83**, 11(2016)
[1]T. Katori(MiniBooNE Collaboration), Mod. Phys. Lett. A 27, 1230024(2012)
[2]T. Katori and J. Spitz, in CPT and Lorentz Symmetry VI(World scientific, Singapore, 2014)

SIMPLE LORENTZ VIOLATION HAMILTONIAN

$$\mathbf{H}^{\nu}_{LV} = \begin{pmatrix} 0 & 0 & a_{e\tau} \\ 0 & 0 & 0 \\ a^*_{e\tau} & 0 & 0 \end{pmatrix} \Rightarrow \quad P = \begin{pmatrix} 1/2 & 0 & 1/2 \\ 0 & 1 & 0 \\ 1/2 & 0 & 1/2 \end{pmatrix}$$

Recall: $(\Phi_e:\Phi_\mu:\Phi_\tau)=P_{\alpha\beta}(\Phi_e^0:\Phi_\mu^0:\Phi_\tau^0)$

$(P_{e\mu}-P_{e\tau})=(P_{\mu\tau}-P_{\tau\tau})= -1/2$

$(P_{\mu\mu}-P_{\mu\tau})=1$

$(f_e,f_\mu,f_\tau)=(1/6,2/3,1/6)$

Large breaking of $\mu\tau$ symmetry

SIMPLE LORENTZ VIOLATION HAMILTONIAN

$$\mathbf{H}^{\nu}_{LV} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & a^T_{\mu\mu} & 0 \\ 0 & 0 & a^T_{\tau\tau} \end{pmatrix} \Rightarrow \mathbf{P} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$, $a_{\mu\mu}^T \neq a_{\tau\tau}^T$

Recall: $(\Phi_e:\Phi_\mu:\Phi_\tau)=P_{\alpha\beta}(\Phi_e^0:\Phi_\mu^0:\Phi_\tau^0)$

$(P_{e\mu}-P_{e\tau})=0$

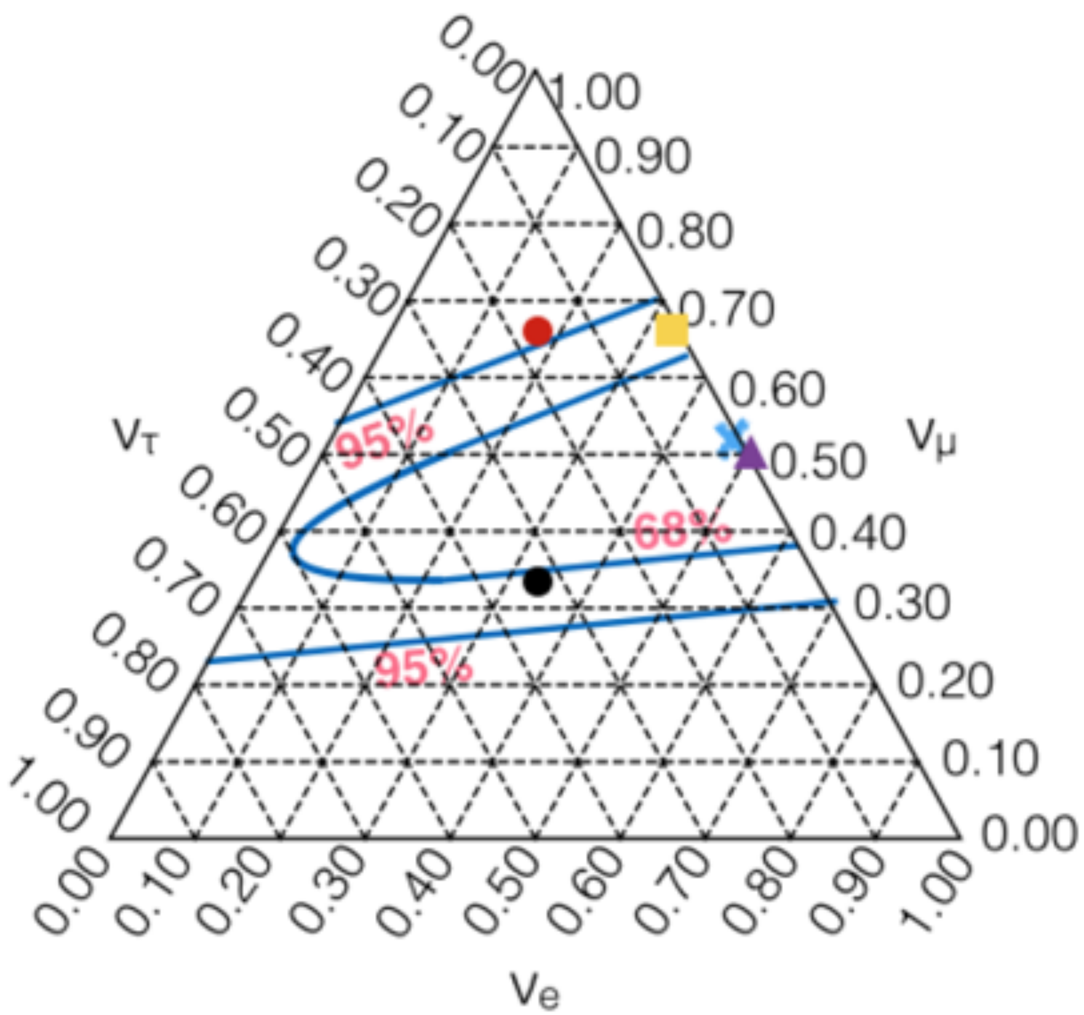
$(P_{\mu\mu}-P_{\mu\tau})=1$

$(P_{\mu\tau}-P_{\tau\tau})= -1$

Large breaking of $\mu\tau$ symmetry

$(f_e,f_\mu,f_\tau)=(1/3,2/3,0)$

COMPARISONS OF SPECIAL CASES WITH RECENT ICECUBE MEASUREMENT OF ASTROPHYSICAL NEUTRINO FLAVOR COMPOSITION



RED: $a_{e\tau}^{T}$, $a_{e\tau}^{T*} \neq 0$

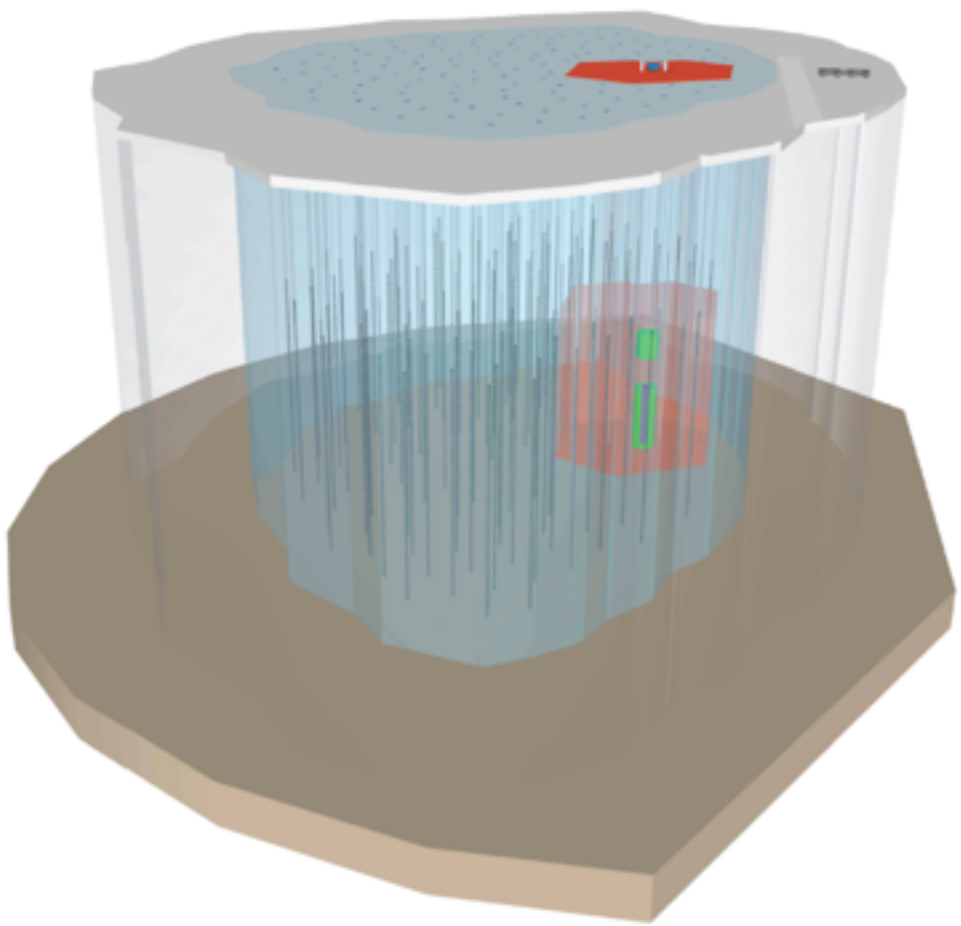
Yellow: $a_{\mu\mu}^{T}$, $a_{\tau\tau}^{T} \neq 0$

Purple: $a_{e\mu}^{T}$, $a_{e\mu}^{T*} \neq 0$

Black: $a_{\mu\tau}^{T}$, $a_{\mu\tau}^{T*} \neq 0$

All cases fall into 2σ region as other elements grow from zero

ICECUBE-GEN2 AND ITS POTENTIAL OF CONSTRAINING LORENTZ VIOLATION HAMILTONIAN

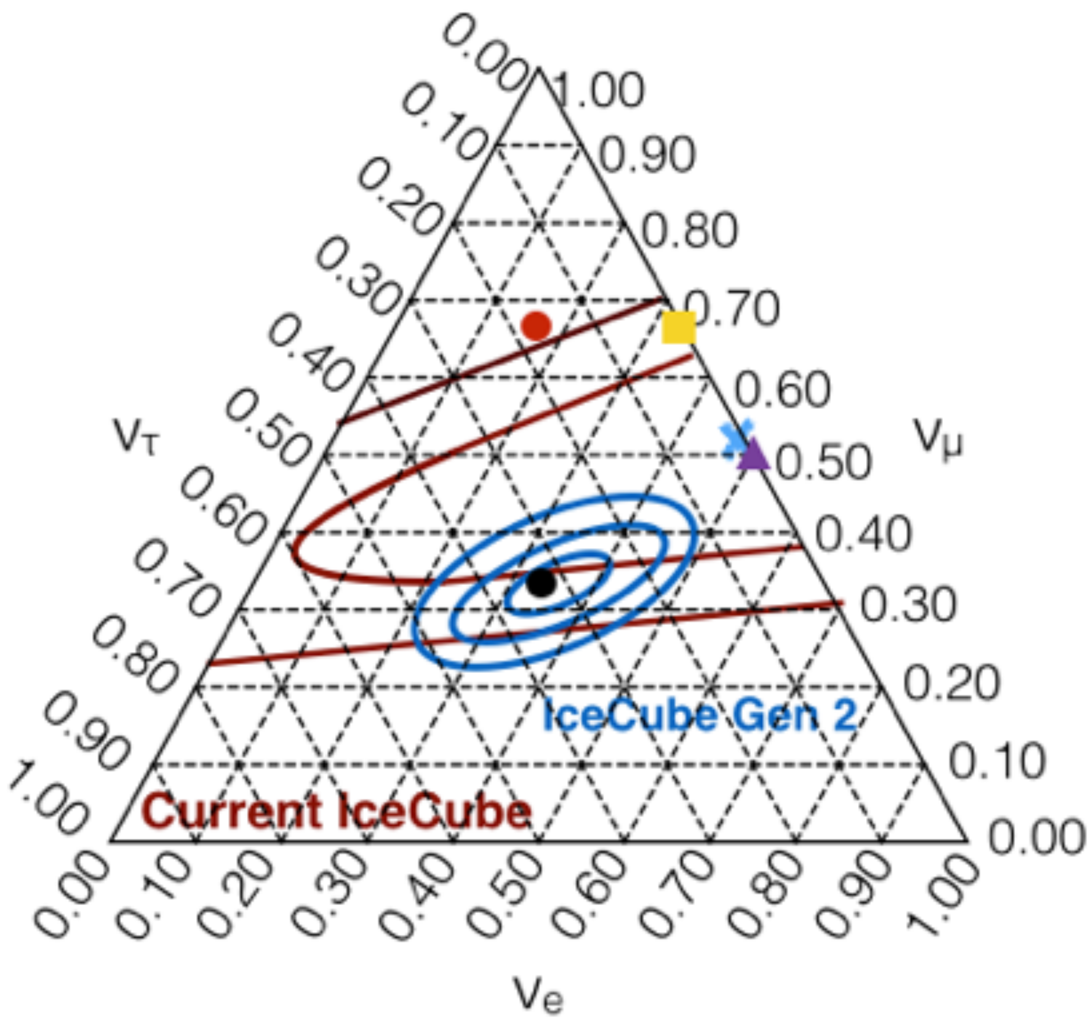


IceCube Collaboration (M.G. Aartsen (Adelaide U.) et al.), arXiv:1412.5106

~10 km^3 instrumented volume
~250 m spacing of photo sensors

- A possible IceCube-Gen2 configuration
- IceCube, in red, and the infill sub-detector DeepCore, in green.
- blue volume shows the full instrumented next-generation detector, with PINGU displayed in grey as a denser infill extension within DeepCore.

SENSITIVITIES OF ICECUBE-GEN2 ON ASTROPHYSICAL NEUTRINO FLAVOR COMPOSITIONS



$$\Phi_\nu(E) = \Phi_0 \left(\frac{100\ \text{TeV}}{E}\right)^\gamma$$

γ=2.2±0.2

Φ_0=(5.1±0.8) x 10^{-18}GeV^{-1}cm^{-2}s^{-1}sr^{-1}

Pion source from pp collision is assumed

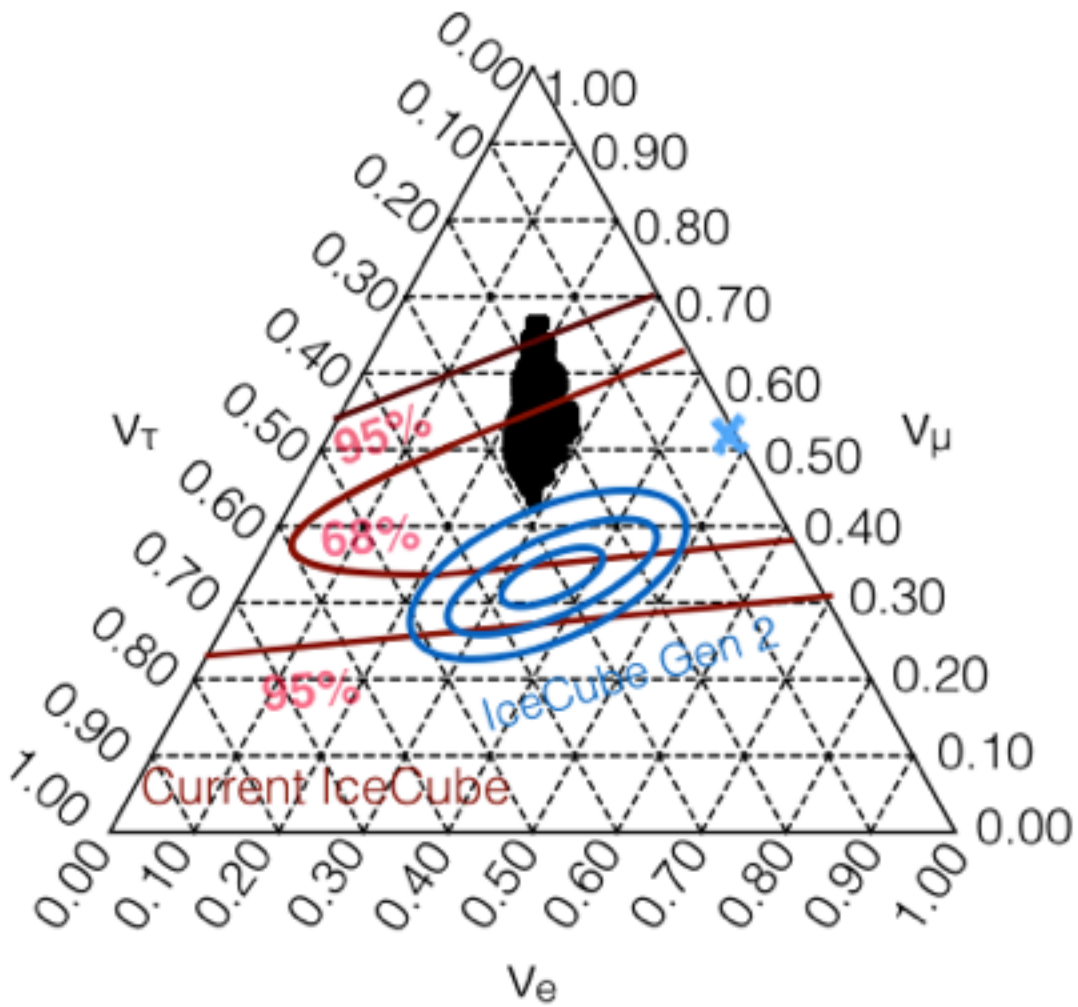
E_{th}=100 TeV

10 years of exposure

1σ, 2σ, and 3σ regions

I. M. Shoemaker and K. Murase, Phys. Rev. D 93 085004 (2016) IceCube-Gen2 regions

SK 95% C.L. limits: $Re(a_{e\tau}^T) < 4.1\times10^{-23}$ GeV $Im(a_{e\tau}^T) < 2.8\times10^{-23}$ GeV

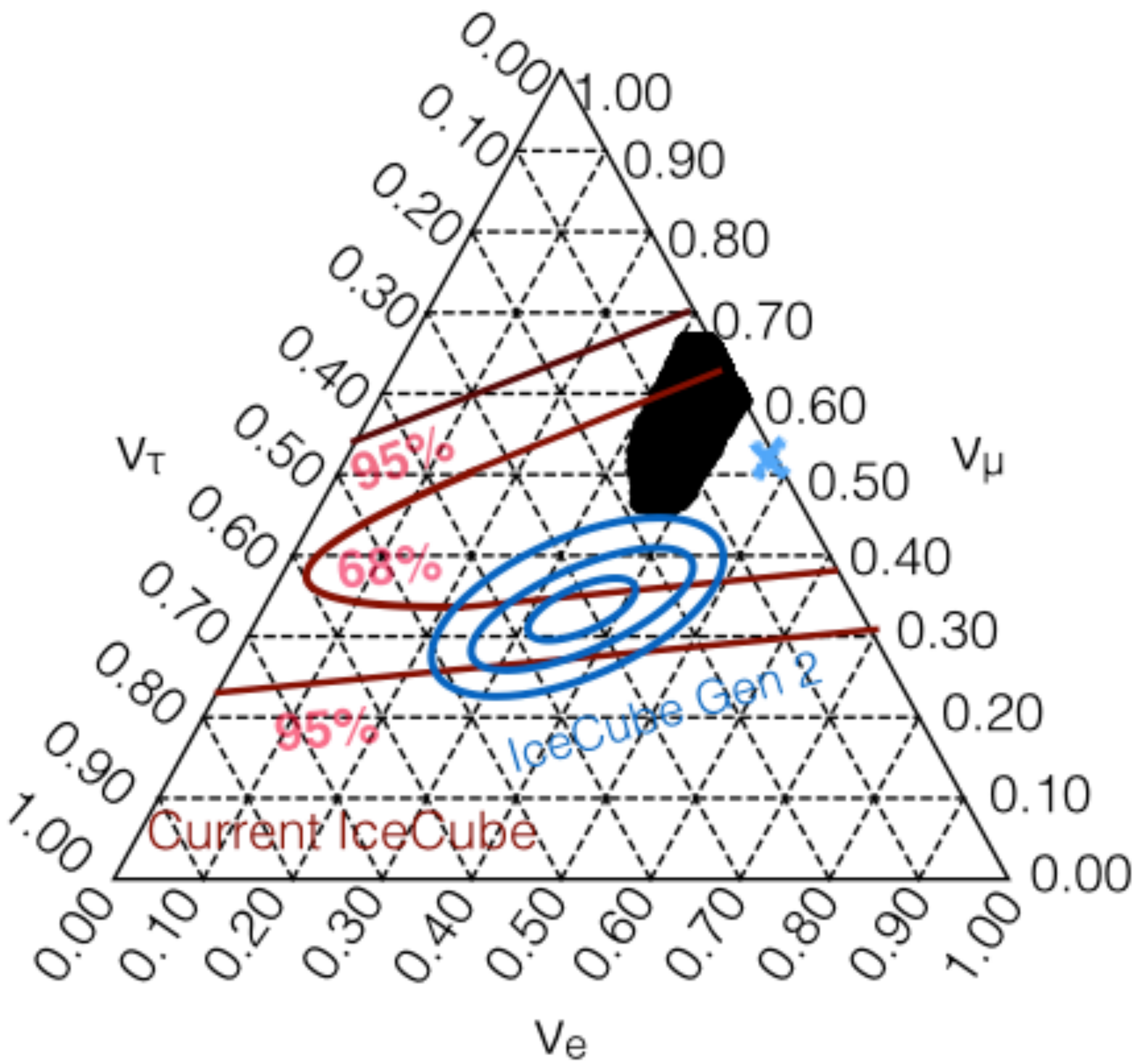


$$\mathbf{H}^{\nu}_{LV} = \begin{pmatrix} 0 & 0 & a_{e\tau} \\ 0 & 0 & 0 \\ a^{*}_{e\tau} & 0 & 0 \end{pmatrix}$$

Allow other elements to grow from zero and include the contribution from H_{SM}

The parameter ranges in the table predict the black region of flavor fraction—disfavored at 3σ.

$\lvert a^T_{e\tau}\rvert$	5×10^{-24} GeV	5×10^{-25} GeV
$\lvert a^T_{e\mu}\rvert/\lvert a^T_{e\tau}\rvert$	$(0, 0.42)$	$(0, 0.39)$
$\lvert a^T_{\mu\tau}\rvert/\lvert a^T_{e\tau}\rvert$	$(0, 0.42)$	$(0, 0.39)$
$\lvert a^T_{\mu\mu}\rvert/\lvert a^T_{e\tau}\rvert$	$(0, 0.50)$	$(0, 0.45)$
$\lvert a^T_{\tau\tau}\rvert/\lvert a^T_{e\tau}\rvert$	$(0, 0.50)$	$(0, 0.45)$



$$\mathbf{H}^{\nu}_{LV} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & a^T_{\mu\mu} & 0 \\ 0 & 0 & a^T_{\tau\tau} \end{pmatrix}$$

Allow other elements to grow from zero and include the contribution from H_{SM}

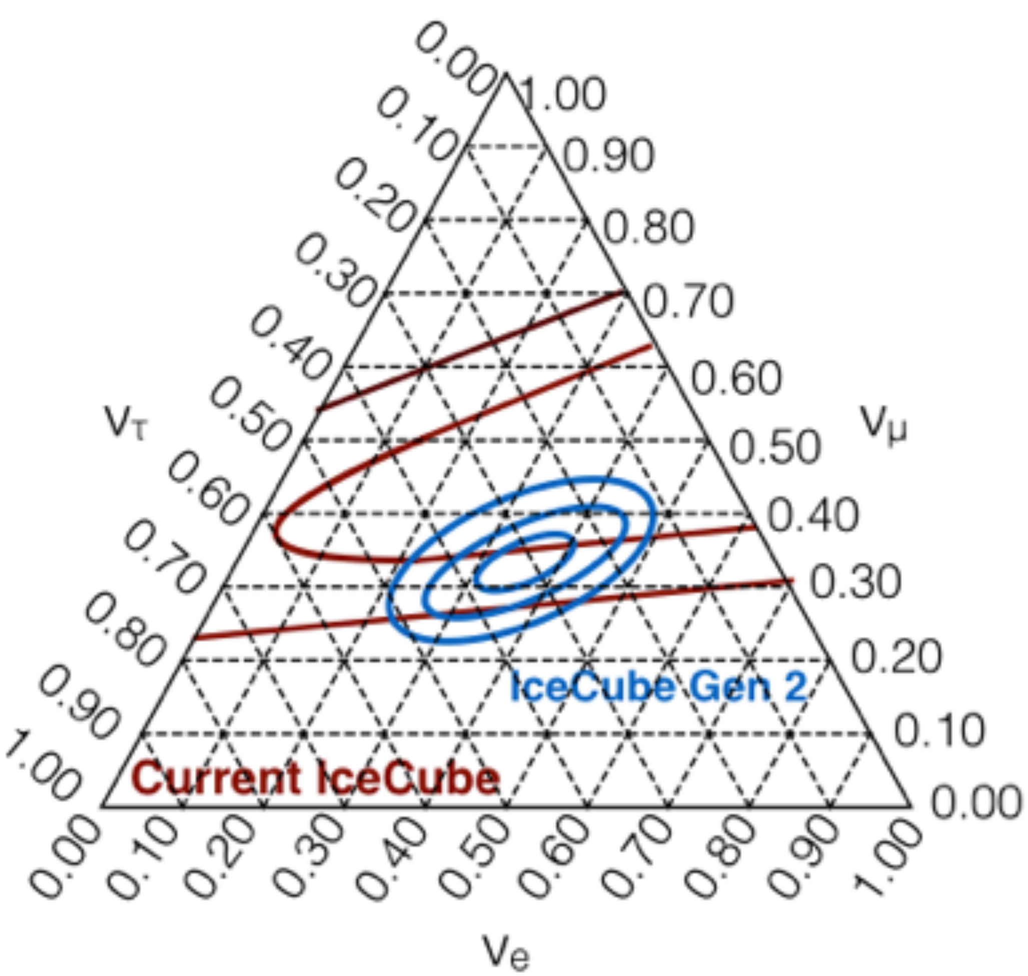
The parameter ranges in the table predict the black region of flavor fraction—disfavored at 3σ.

$a^T_{\mu\mu} = 2a^T_{\tau\tau}$	5×10^{-24} GeV	5×10^{-25} GeV
$\lvert a^T_{e\mu}\rvert / \lvert a^T_{\mu\mu}\rvert$	$(0, 0.40)$	$(0, 0.39)$
$\lvert a^T_{e\tau}\rvert / \lvert a^T_{\mu\mu}\rvert$	$(0, 0.40)$	$(0, 0.39)$
$\lvert a^T_{\mu\tau}\rvert / \lvert a^T_{\mu\mu}\rvert$	$(0, 0.40)$	$(0, 0.39)$

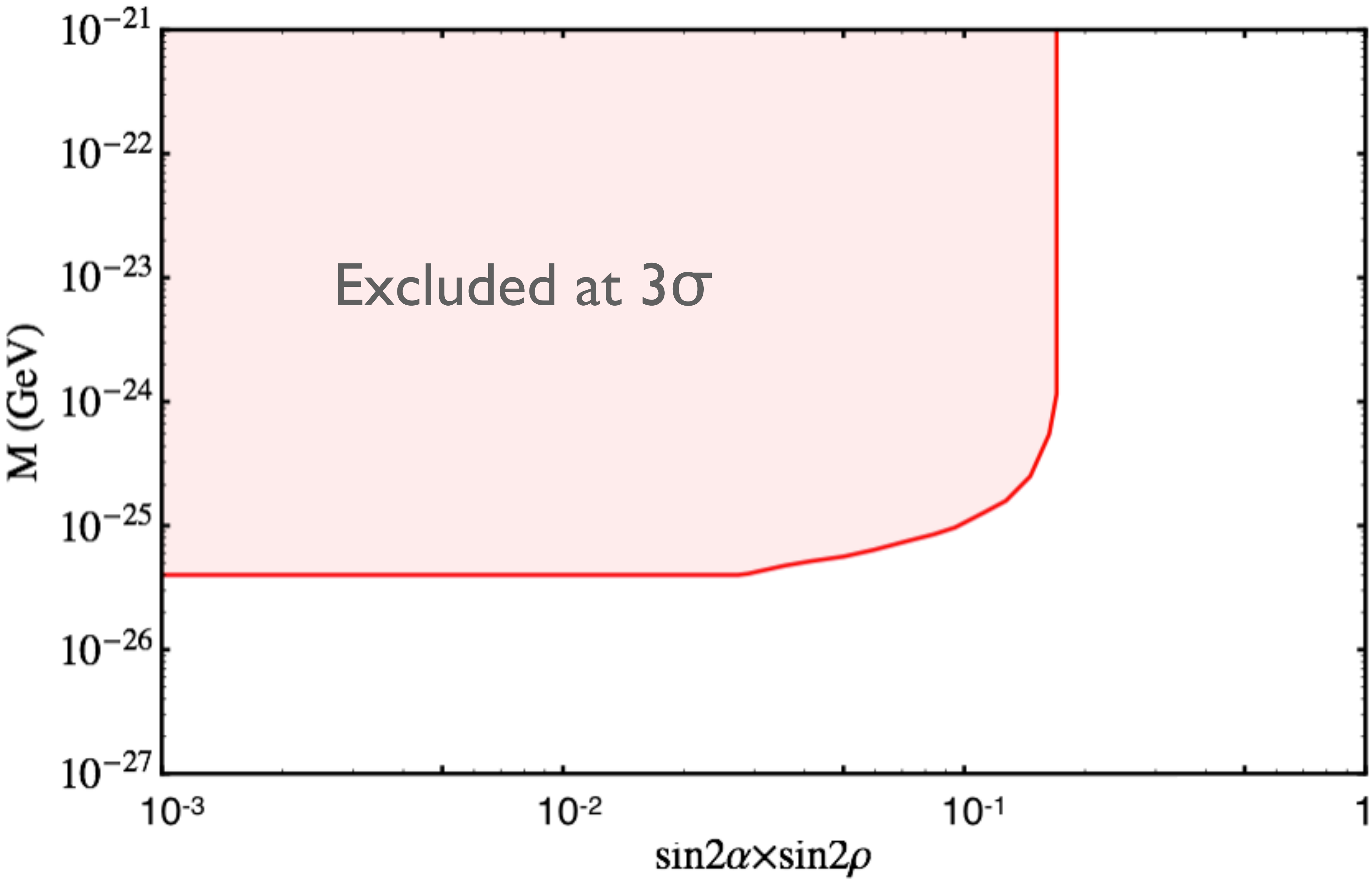
H=H$_{SM}$+H$_{LV}$

$$\mathbf{H}^{\nu}_{LV} = \begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ a^{T*}_{e\mu} & a^T_{\mu\mu} & a^T_{\mu\tau} \\ a^{T*}_{e\tau} & a^{T*}_{\mu\tau} & a^T_{\tau\tau} \end{pmatrix}$$

$$= M \begin{pmatrix} 0 & cos\rho e^{i\sigma} & sin\rho e^{i\lambda} \\ cos\rho e^{-i\sigma} & 0 & 0 \\ sin\rho e^{-i\lambda} & 0 & 0 \end{pmatrix} - M \begin{pmatrix} \gamma & 0 & 0 \\ 0 & cos2\alpha & sin2\alpha e^{i\beta} \\ 0 & sin2\alpha e^{-i\beta} & -cos2\alpha \end{pmatrix}$$



Increasing M until the predicted flavor fraction is out of the IceCube Gen2 3σ region.



For most values of sin2α x sin2ρ, the energy scale M is constrained to be less than few times 10^{-26} GeV

Constraint on $C_{\alpha\beta}^{TT}$

$-4EC_{\alpha\beta}^{TT}/3$ replaces $a_{\alpha\beta}^{T}$ when the latter is turn off.

if the constraint on M, which is made of $a_{\alpha\beta}^{T}$, is few times 10^{-26} GeV, the corresponding constraint on M' (dimensionless quantity made of $C_{\alpha\beta}^{TT}$) is about 10^{-31} with E chosen as 100 TeV(Threshold energy).

K. Abe et al. (Super-Kamiokande Collaboration), Phys. Rev. D **91**, 052003(2015)

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$e\tau$	$\mathrm{Re}(a^T)$	4.1×10^{-23} GeV	2.2×10^{-24} GeV	0.0	7.8×10^{-20} GeV [2]
	$\mathrm{Im}(a^T)$	2.8×10^{-23} GeV	1.0×10^{-28} GeV		
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$\mu\tau$	$\mathrm{Re}(a^T)$	6.5×10^{-24} GeV	3.2×10^{-24} GeV	0.9	...
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	$\mathrm{Re}(c^{TT})$	4.4×10^{-27}	1.0×10^{-28}	0.1	...
	$\mathrm{Im}(c^{TT})$	4.2×10^{-27}	7.5×10^{-28}		

SUMMARY

- We have introduced Lorentz violation Hamiltonian in neutrino sector.
- Previous experimental search on Lorentz violation with neutrino is introduced. Previous best limit by Super-Kamiokande experiment is summarized.
- We have shown that Lorentz violating Hamiltonian with parameters in the above SK limits can change significantly the flavor transition probabilities of high energy astrophysical neutrinos in TeV to PeV energy range.
- For the pion source induced from pp collisions, Lorentz violating Hamiltonian with large $\mu\tau$ symmetry breaking effect is more stringently constrained.
- We show that IceCube-Gen2 can place stringent constraints on the Lorentz violating Hamiltonian.