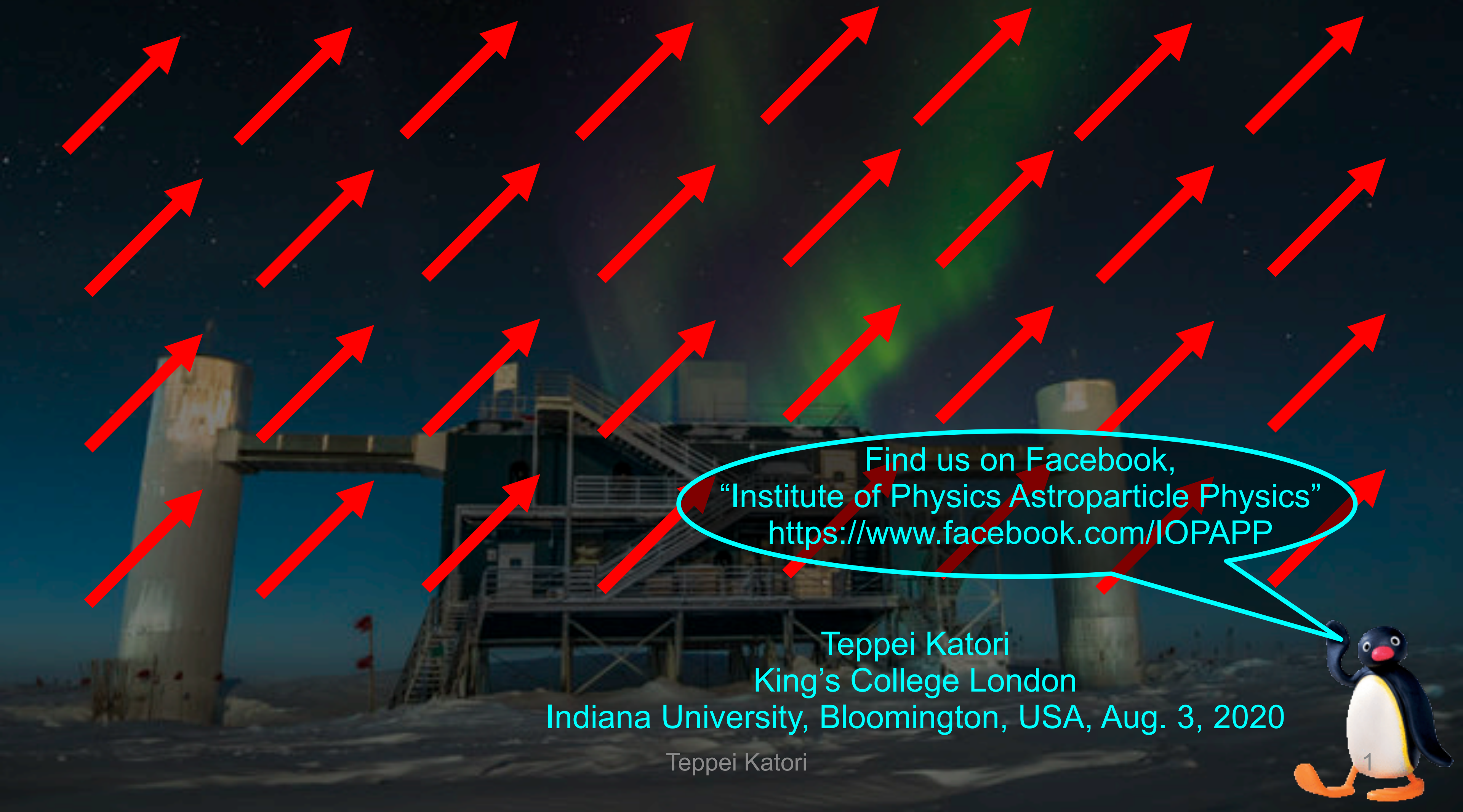
Lorentz Violation with Astrophysical Neutrino Flavor

IceCube, To be published (2020)



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Teppei Katori
King’s College London
Indiana University, Bloomington, USA, Aug. 3, 2020

Summary

This is the preliminary results of Lorentz violation search from the High Energy Starting Event sample in IceCube (HESE-7.5yr, to be published 2020).

Currently, our search of Lorentz violation is very limited cases, and unfortunately, so far, we don't find Lorentz violation. However, our approach is very promising for future searches in IceCube (for example, dim-6 LV limit reaches down to ~$10^{-42\text{-}46}$ GeV^{-2})

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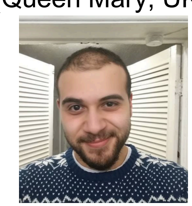


Tianlu Yuan
(UW-Madison)

Kareem's award-winning Neutrino 2020 movie
https://www.youtube.com/watch?v=wA1n3u5Ujgo

1. Introduction

2. Astrophysical neutrinos

3. Flavour ratio

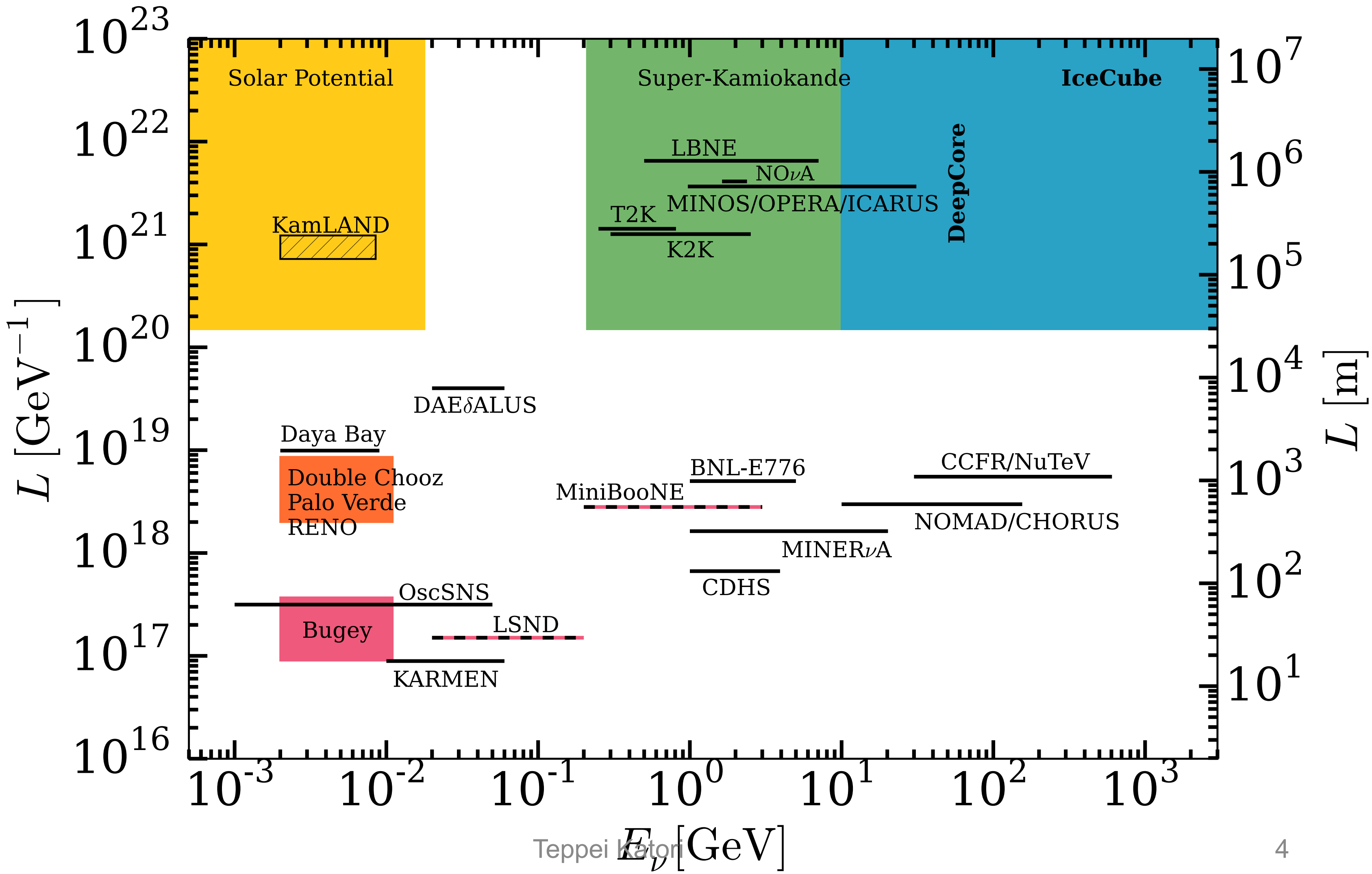
4. Lorentz violation limit

5. Conclusion

Kostelecký and Mewes, PRD69(2004)016005
Argüelles, INVISIBLE2015

1. Lorentz violation with neutrino oscillation

Neutrino oscillation is natural interferometer
→ Longer baseline and higher-energy is more sensitive to smaller parameters



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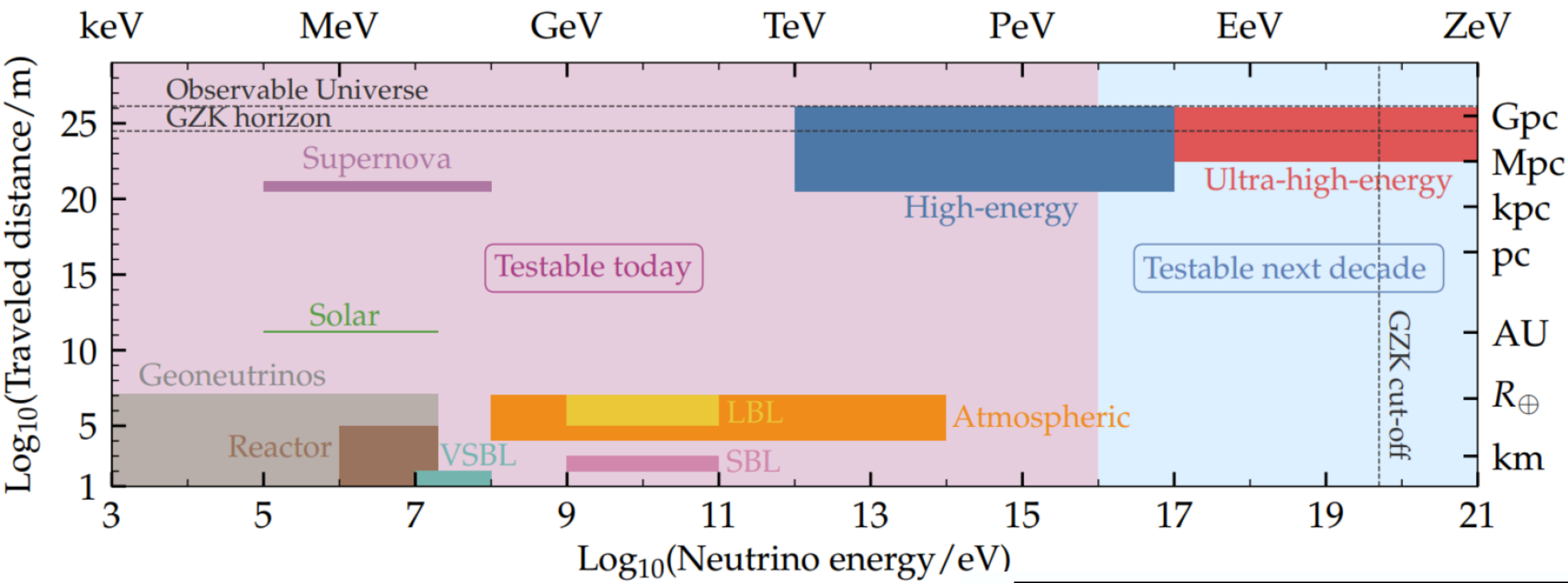
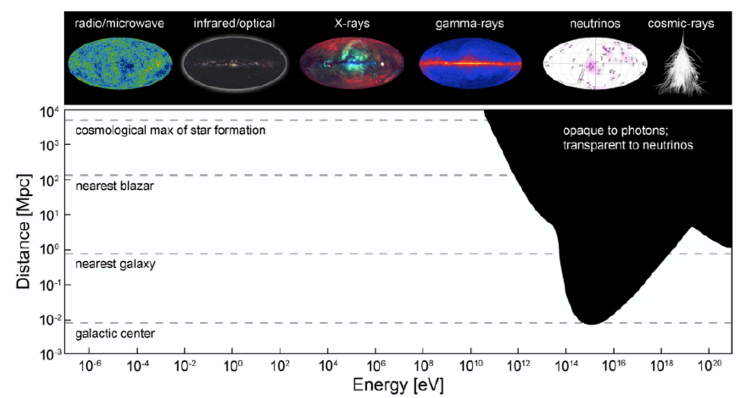


Astrophysical neutrinos are the highest energy particles to propagate the longest distance in the universe

↓

Sensitive to higher order operators



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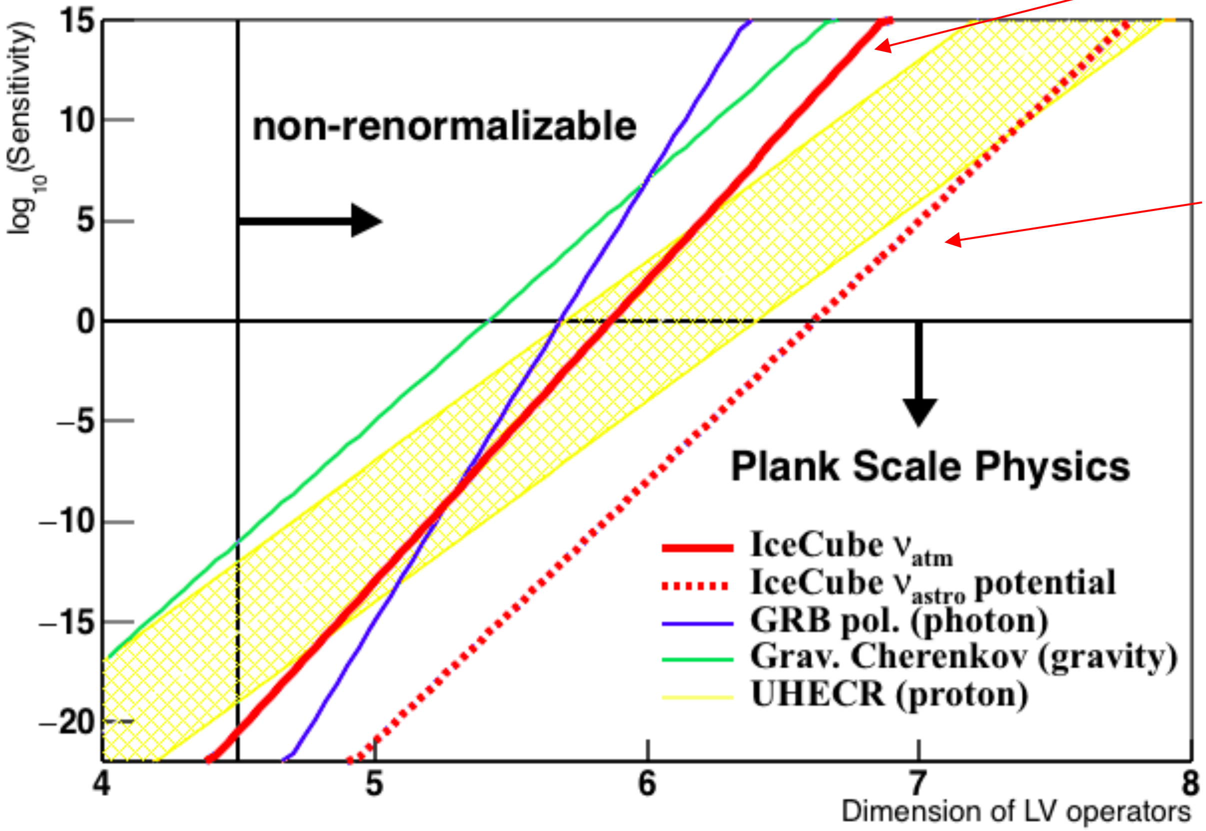
1. Astrophysical neutrino flavour sensitivity of new physics

Combination of longer baseline and higher energy makes extra-terrestrial neutrino to be the most sensitive source of fundamental physics.

Lorentz violation sensitivity (normalized with M_{Planck})

IceCube atmospheric neutrino LV sensitivity
Nature Physics 14(2018)961



IceCube astrophysical neutrino LV sensitivity

IceCube dim-6 LV operator search can go beyond any existing tests, and reach quantum gravity frontier ($\sim 1/M_{Planck}^2 \sim 10^{-38}$ GeV^{-2})

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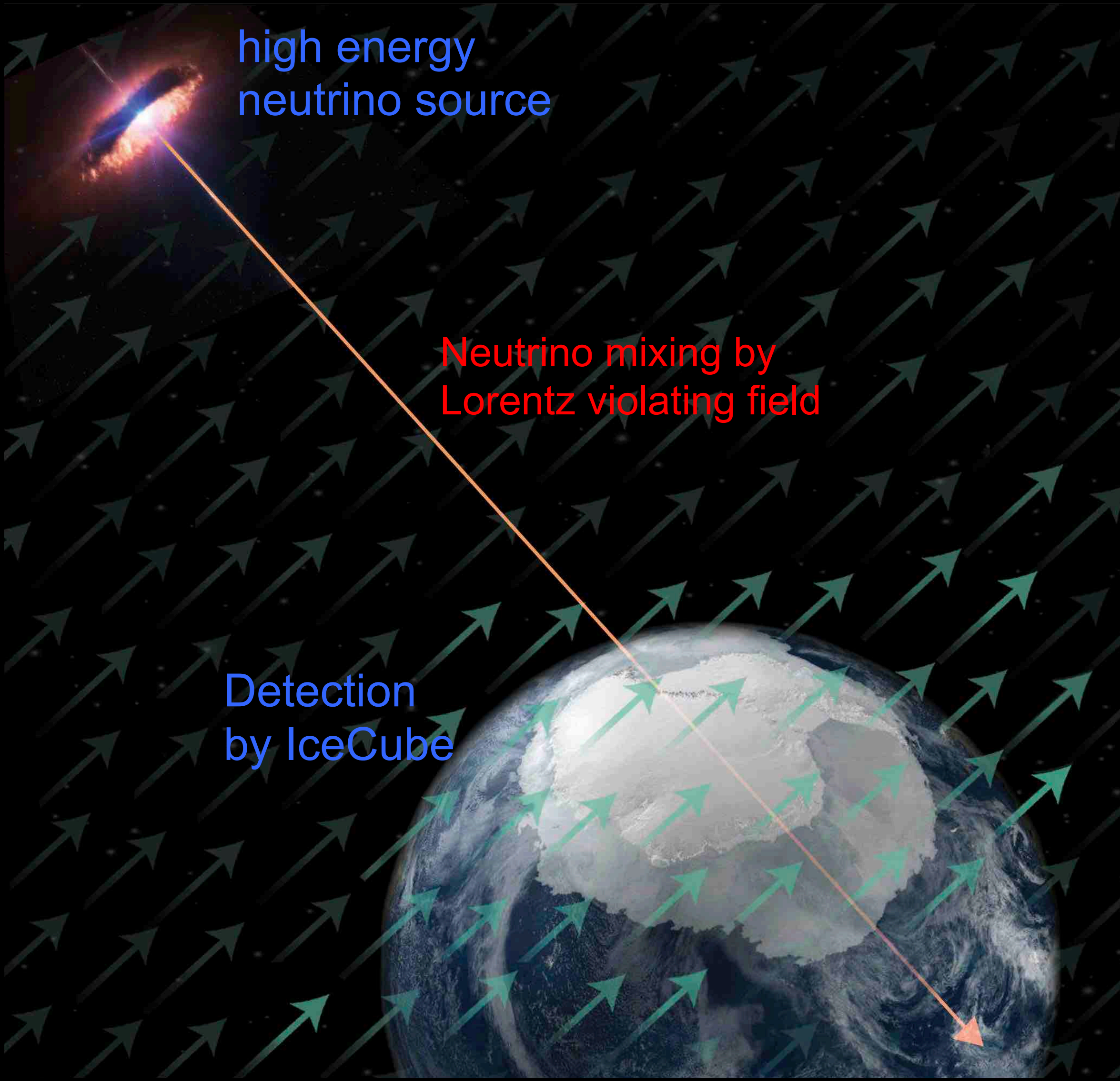
1. Neutrino interferometry – Astrophysical high-energy neutrinos

Neutrinos propagate over ~Gpc

Although neutrinos lose coherence, any extra interaction modify neutrino mixings.

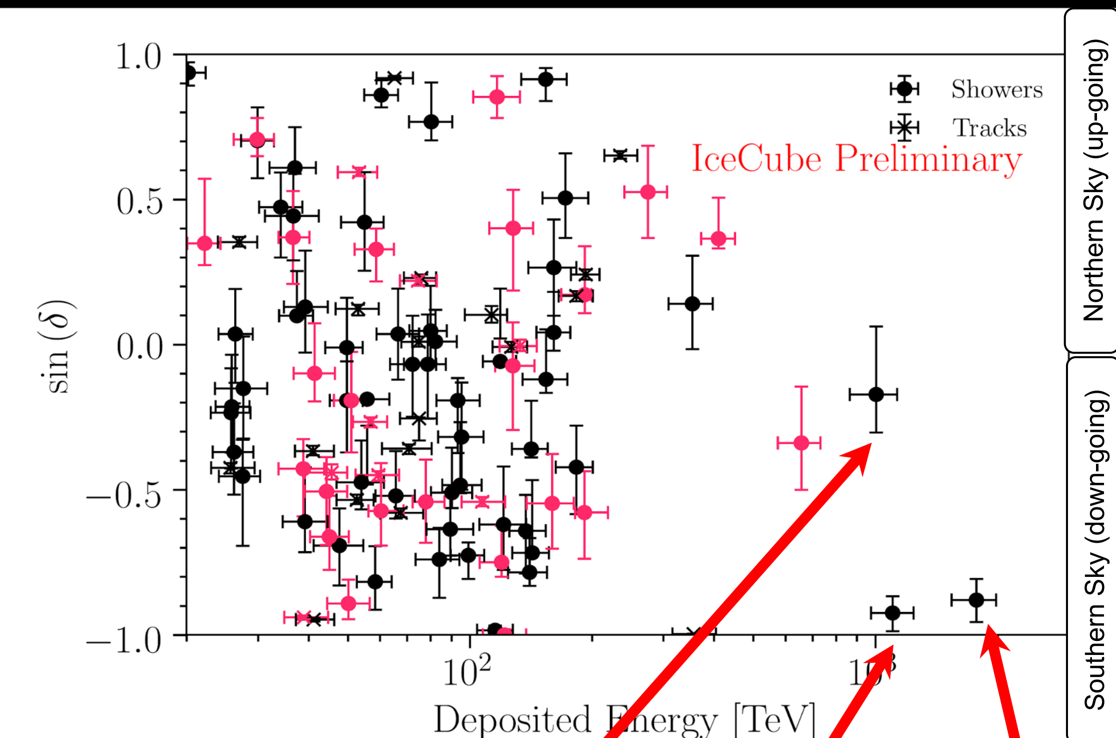
Information of small Lorentz violation is encoded on neutrino mixing probability, so by measuring astrophysical neutrino flavours, you can explore Lorentz violation

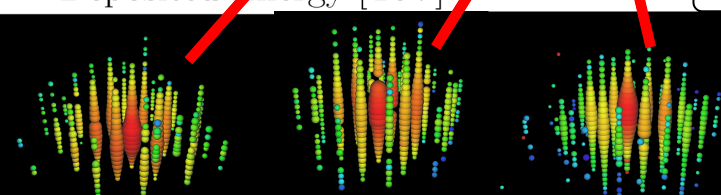


IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

2. Astrophysical Very-High-Energy Neutrinos

First observation (2013) by IceCube Neutrino Observatory
- 60-2000 TeV neutrinos

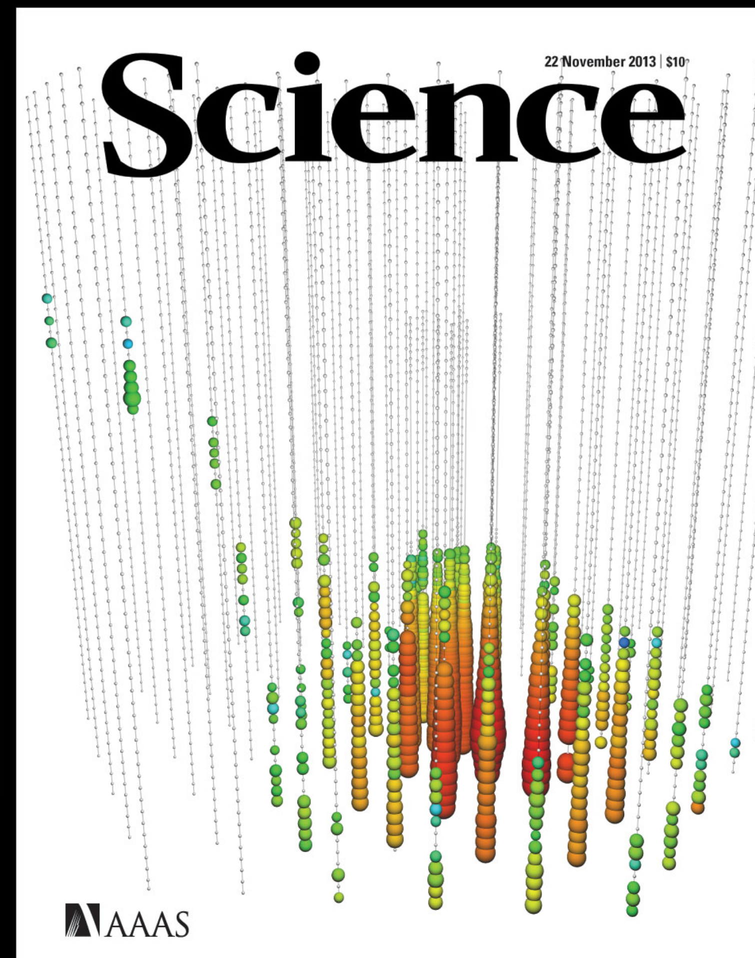




"Bert"
1.1 PeV

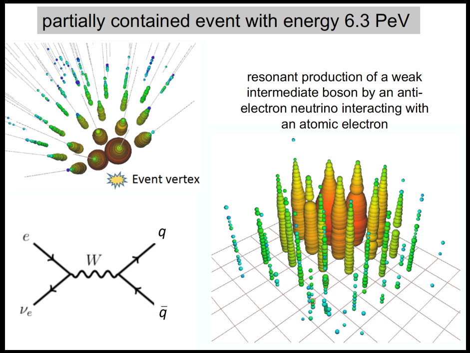
"Ernie"
1.0 PeV

"Big Bird"
2.0 PeV



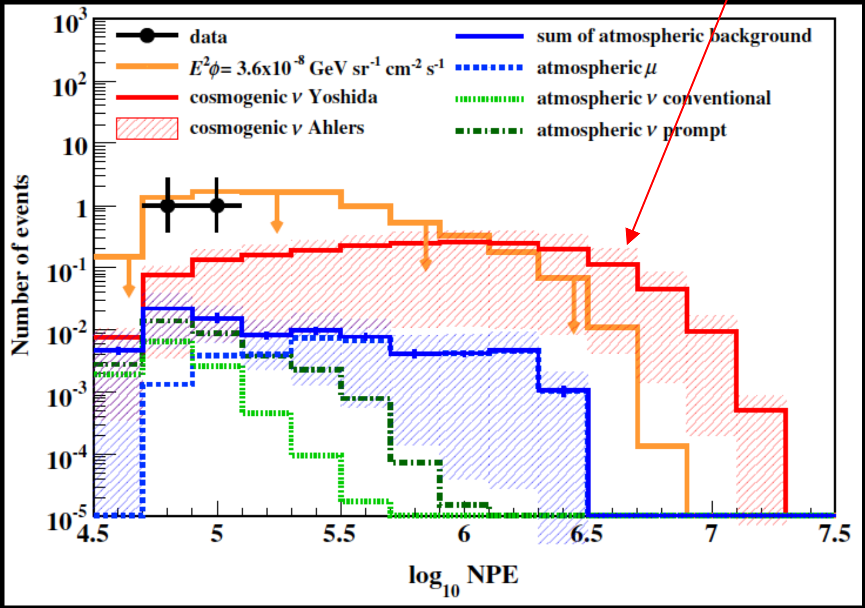
2. Astrophysical Very-High-Energy Neutrinos

First Glashow resonance
(Santander, Neutrino 2020)

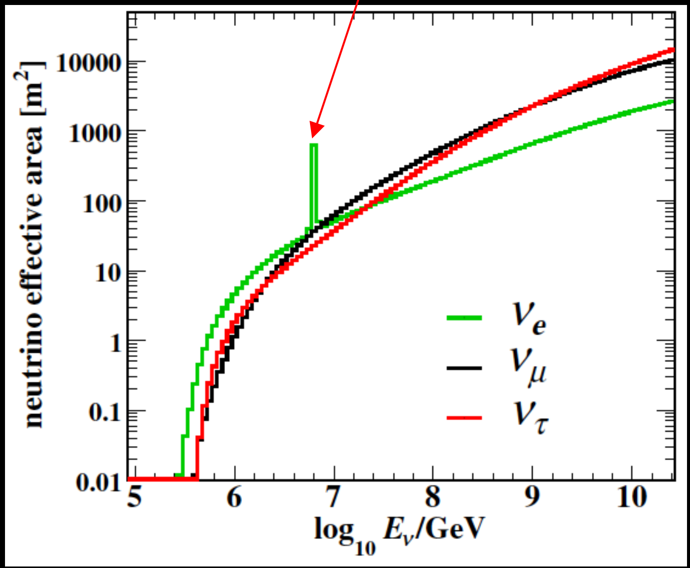


First observation (2013) by IceCube Neutrino Observatory
- 60-2000 TeV neutrinos
- Unlikely from Glashow resonance or GZK neutrinos

$$p + \gamma \to \Delta \to \pi \to \nu$$



$$\bar{\nu}_e(6.2PeV) + e \to W$$



IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

2. Astrophysical Very-High-Energy Neutrinos

First observation (2013) by IceCube Neutrino Observatory
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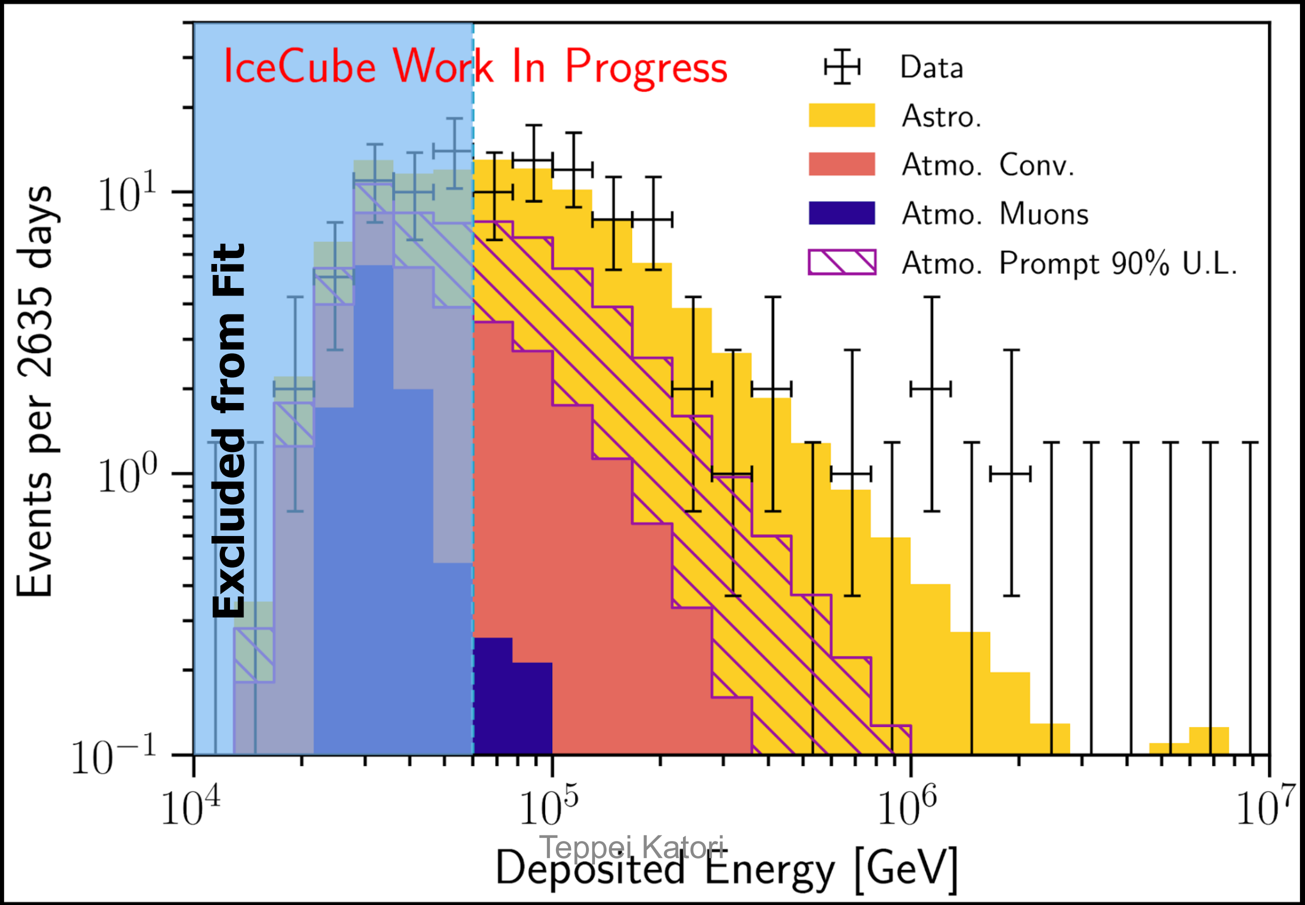
- Unlikely from Glashow resonance or GZK neutrinos
- Unlikely from atmospheric neutrinos



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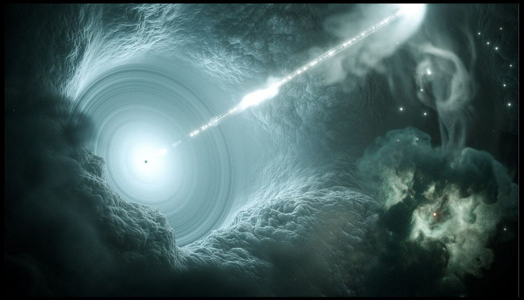
IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

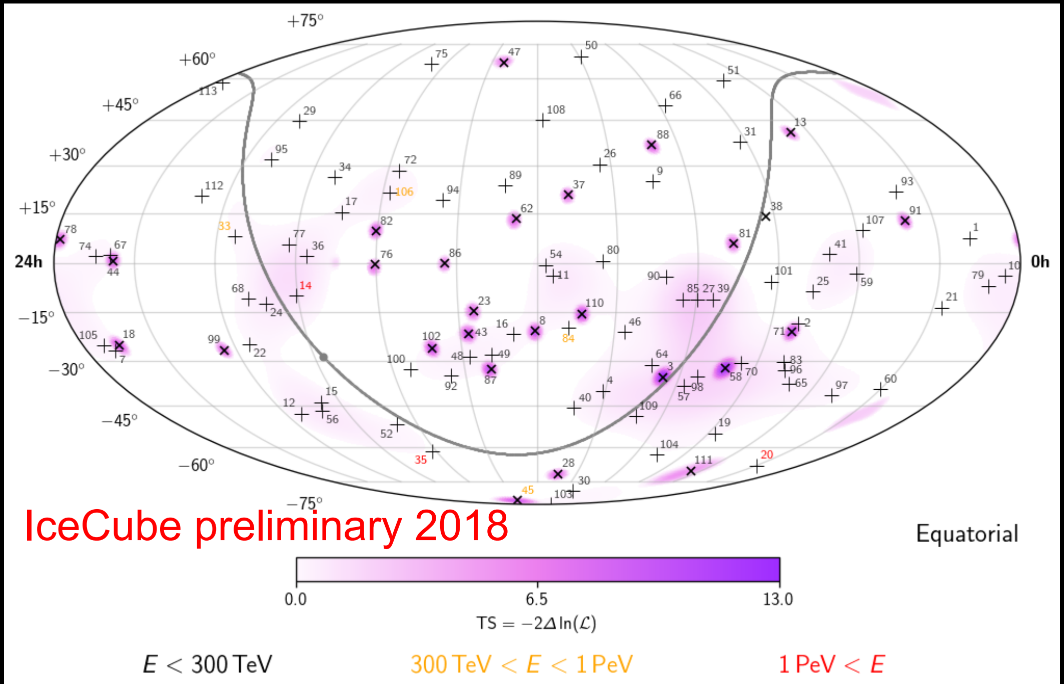
2. Astrophysical Very-High-Energy Neutrinos

Evidence of Blazar Neutrino
- IC170922A
- TXS 0506+056



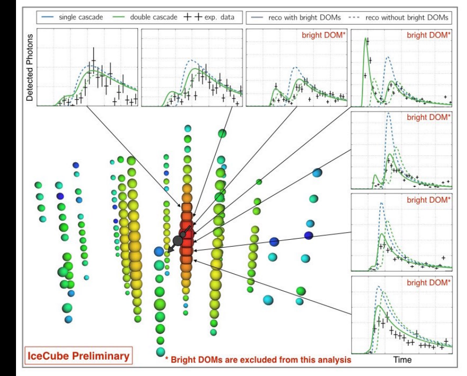
IceCube, Science361(2018)147
IceCube et al,(2018)eaat1378

First observation (2013) by IceCube Neutrino Observatory
- 60-2000 TeV neutrinos
- Unlikely from Glashow resonance or GZK neutrinos
- Unlikely from atmospheric neutrinos
- Sources are mostly unknown (diffuse)



IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

2. Astrophysical Very-High-Energy Neutrinos



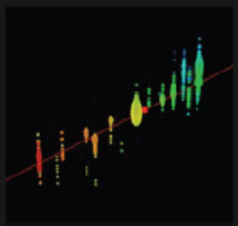
First astrophysical tau neutrino (Santander, Neutrino 2020)

First observation (2013) by IceCube Neutrino Observatory
- 60-2000 TeV neutrinos
- Unlikely from Glashow resonance or GZK neutrinos
- Unlikely from atmospheric neutrinos
- Sources are mostly unknown (diffuse)
- Shower topology is dominant

ID	Deposited energy (TeV)	Event type
1	$47.6^{+6.5}_{-5.4}$	Shower
2	117^{+15}_{-15}	Shower
3	$78.7^{+10.8}_{-8.7}$	Track
4	165^{+20}_{-15}	Shower
5	$71.4^{+9.0}_{-9.0}$	Track
6	$28.4^{+2.7}_{-2.5}$	Shower
7	$34.3^{+3.5}_{-4.3}$	Shower
8	$32.6^{+10.3}_{-11.1}$	Track
9	$63.2^{+7.1}_{-8.0}$	Shower
10	$97.2^{+10.4}_{-12.4}$	Shower
11	$88.4^{+12.5}_{-10.7}$	Shower
12	104^{+13}_{-13}	Shower
13	253^{+26}_{-22}	Track
14	1041^{+132}_{-144}	Shower
15	$57.5^{+8.3}_{-7.8}$	Shower
16	$30.6^{+3.6}_{-3.5}$	Shower
17	200^{+27}_{-27}	Shower
18	$31.5^{+4.6}_{-3.3}$	Track
19	$71.5^{+7.0}_{-7.2}$	Shower
20	1141^{+143}_{-133}	Shower
21	$30.2^{+3.5}_{-3.3}$	Shower
22	220^{+21}_{-24}	Shower
23	$82.2^{+8.6}_{-8.4}$	Track
24	$30.5^{+3.2}_{-2.6}$	Shower
25	$33.5^{+4.9}_{-5.0}$	Shower
26	210^{+29}_{-26}	Shower
27	$60.2^{+5.6}_{-5.6}$	Shower
28	$46.1^{+5.7}_{-4.4}$	Track

Hill, Neutrino 2014

CC Muon Neutrino

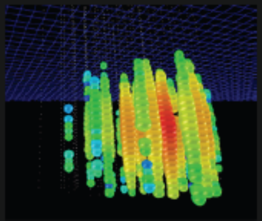


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution

Neutral Current / Electron Neutrino



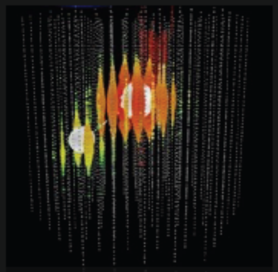
$$\nu_e + N \rightarrow e + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100 TeV)

CC Tau Neutrino

time

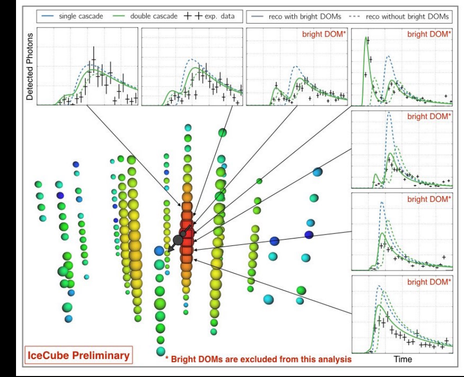


$$\nu_\tau + N \rightarrow \tau + X$$

"double-bang" and other signatures (simulation)

IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

2. Astrophysical Very-High-Energy Neutrinos



First astrophysical tau neutrino
(Santander, Neutrino 2020)

First observation (2013) by IceCube Neutrino Observatory
- 60-2000 TeV neutrinos
- Unlikely from Glashow resonance or GZK neutrinos
- Unlikely from atmospheric neutrinos
- Sources are mostly unknown (diffuse)
- Shower topology is dominant
- Production flavour structure unknown

Naively
- Any astrophysical VHE neutrino production flavour (without new physics) makes roughly $\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$ on the earth (later)
- At very high energy, $\sigma(CC) \sim 3\sigma(NC)$
- Track : Shower ~ 1 : 3 ($N_T/N_S \sim 0.33$)

Data
- $N_T/N_S \sim 0.3$ → any production models are compatible with data

Signal of Lorentz violation is anomalous neutrino mixing, but we don't know much about astrophysical neutrino flavour production

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1. Introduction

2. Astrophysical neutrinos

3. Flavour ratio

4. Lorentz violation limit

5. Conclusion

Kostelecký and Mewes, PRD85(2012)096005

3. Astrophysical neutrino flavour with Lorentz violation

We start from isotropic model of nonminimal SME

$$h_{eff} \sim \frac{1}{2E} U^\dagger M^2 U + a^{(3)}_{\alpha\beta} - E c^{(4)}_{\alpha\beta} + E^2 a^{(5)}_{\alpha\beta} - E^3 c^{(6)}_{\alpha\beta} + E^4 a^{(7)}_{\alpha\beta} - E^5 c^{(8)}_{\alpha\beta} \cdots$$

dim-6 isotropic SME (d=6)

$$E^3 c^{(6)}_{\alpha\beta} = E^3 \frac{1}{\sqrt{4\pi}} \left(c^{(6)}_{\alpha\beta} \right)_{00} = E^3 \begin{pmatrix} c^{(6)}_{ee} & c^{(6)}_{e\mu} & c^{(6)}_{\tau e} \\ c^{(6)*}_{e\mu} & c^{(6)}_{\mu\mu} & c^{(6)}_{\mu\tau} \\ c^{(6)*}_{\tau e} & c^{(6)*}_{\mu\tau} & c^{(6)}_{\tau\tau} \end{pmatrix} = E^3 c^{(6)} \widetilde{U}^\dagger_6 O_6 \widetilde{U}_6$$

scale

O(1) diagonal element

mixing matrix

and so on…

We test dim-3 to dim-8 operators one by one to find nonzero scale (or set limit on scale)

$$h_{eff} \sim \frac{1}{2E} U^\dagger M^2 U - E^3 c^{(6)}_{\alpha\beta} = V^\dagger(E) \Delta V(E)$$

$$V(E) = \begin{pmatrix} V_{e1}(E) & V_{e2}(E) & V_{e3}(E) \\ V_{\mu 1}(E) & V_{\mu 2}(E) & V_{\mu 3}(E) \\ V_{\tau 1}(E) & V_{\tau 2}(E) & V_{\tau 3}(E) \end{pmatrix}, \qquad \Delta = \begin{pmatrix} \lambda_1(E) & 0 & 0 \\ 0 & \lambda_2(E) & 0 \\ 0 & 0 & \lambda_3(E) \end{pmatrix}$$

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We start from isotropic model of nonminimal SME

$$h_{eff} \sim \frac{1}{2E} U^\dagger M^2 U + a^{(3)}_{\alpha\beta} - E c^{(4)}_{\alpha\beta} + E^2 a^{(5)}_{\alpha\beta} - E^3 c^{(6)}_{\alpha\beta} + E^4 a^{(7)}_{\alpha\beta} - E^5 c^{(8)}_{\alpha\beta} \cdots$$

Neutrino oscillation formula is written with mixing matrix elements and eigenvalues

$$P_{\alpha\to\beta}(E,L) = 1 - 4\sum_{i>j} Re\left(V^*_{\alpha i} V^*_{\beta i} V_{\alpha j} V_{\beta j}\right) sin^2\left(\frac{\lambda_i - \lambda_j}{2} L\right) + 2\sum_{i>j} Im\left(V^*_{\alpha i} V^*_{\beta i} V_{\alpha j} V_{\beta j}\right) sin\left((\lambda_i - \lambda_j)L\right)$$

However, astrophysical neutrinos propagate O(100Mpc) → lost coherence

$$P_{\alpha\to\beta}(E,\infty) \sim 1 - 2\sum_{i>j} Re\left(V^*_{\alpha i} V^*_{\beta i} V_{\alpha j} V_{\beta j}\right) = \sum_i |V_{\alpha i}|^2 \left|V_{\beta i}\right|^2$$

→ Information of small Lorentz violation is encoded on neutrino mixing probability, so by measuring astrophysical neutrino flavours, you can explore Lorentz violation

The experimental observable is the flavor ratio, where flux spectrum is integrated, and overall normalization is removed

$$\bar{\phi}^{\oplus}_\beta = \frac{1}{|\Delta E|} \int_{\Delta E} \sum_\alpha \bar{P}_{\nu_\alpha \to \nu_\beta}(E) \phi^i_\alpha(E) dE, \qquad \alpha^{\oplus}_\beta = \bar{\phi}^{\oplus}_\beta / \sum_\gamma \bar{\phi}^{\oplus}_\gamma .$$

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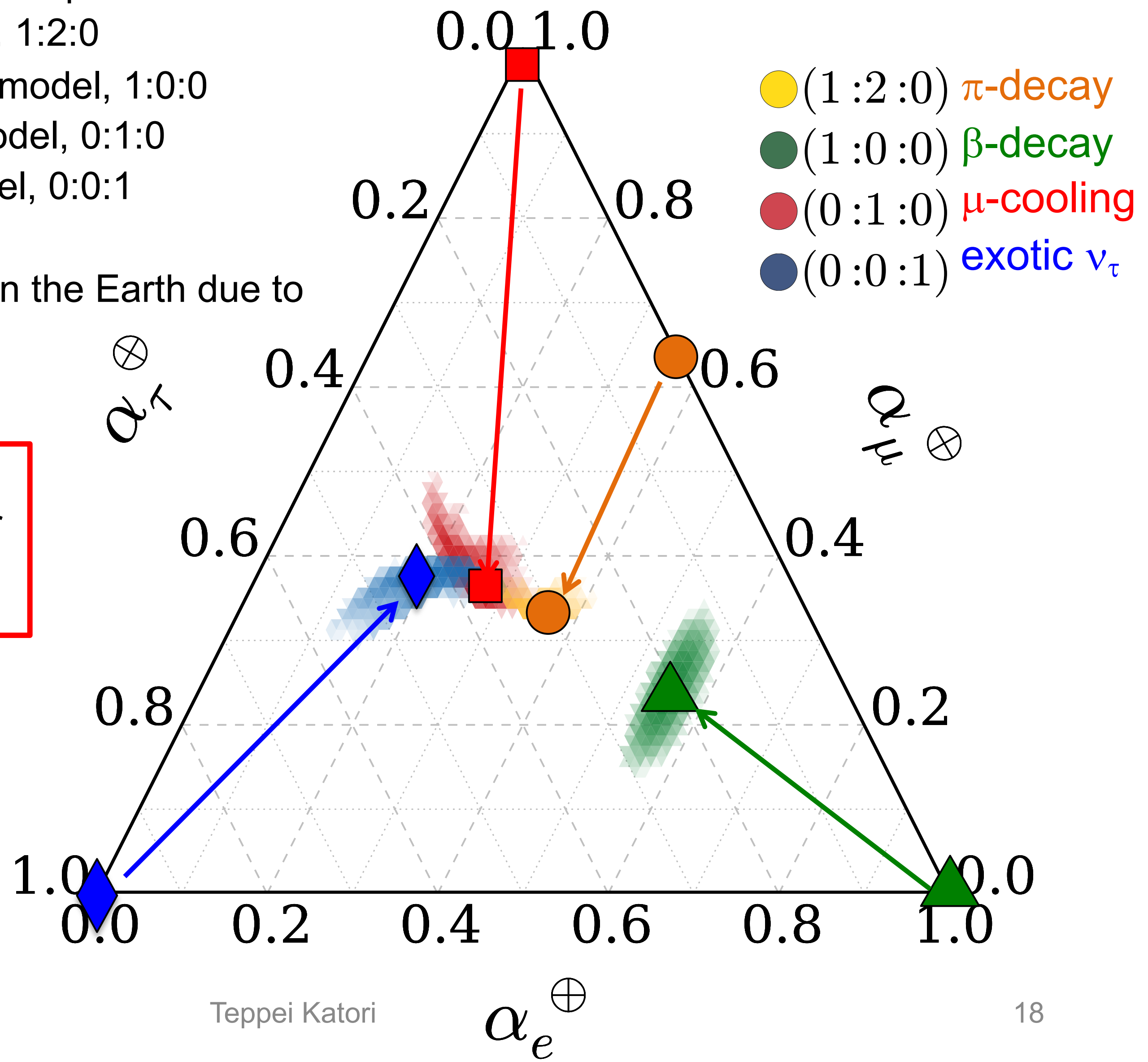
3. Flavour ratio

There are 3 astrophysical neutrino production models
- i. pion decay dominant model, 1:2:0
- ii. electron neutrino dominant model, 1:0:0
- iii. muon neutrino dominant model, 0:1:0
- iv. tau neutrino dominant model, 0:0:1

Initial flavour ratio is modified on the Earth due to neutrino mixing

The main focus is the ratio of astrophysical neutrino flavour

$$\nu_e : \nu_\mu : \nu_\tau$$



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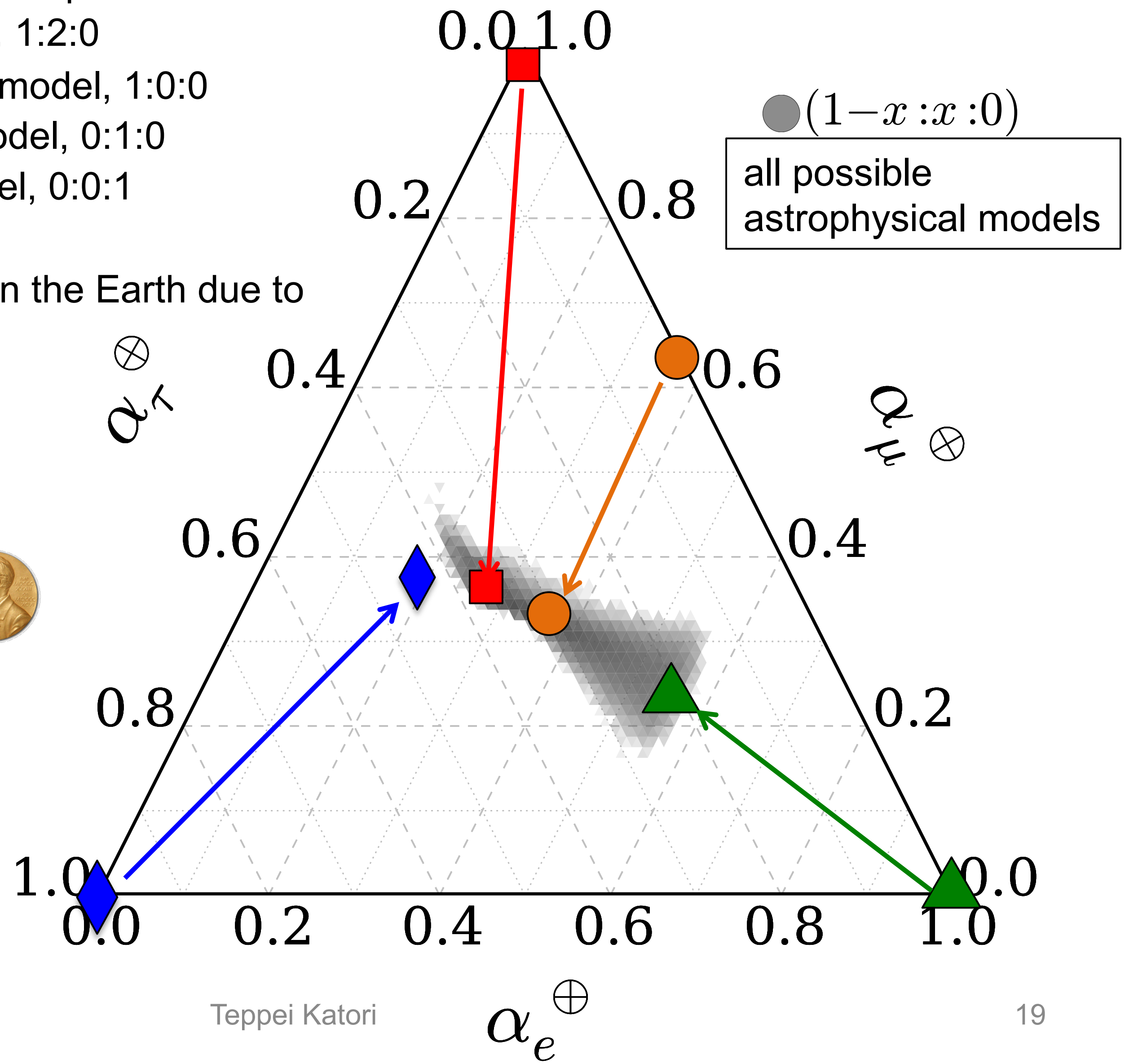
Initial flavour ratio is modified on the Earth due to neutrino mixing

All possible flavour ratio is confined in a small space.

If you measure flavour ratio outside of this, you win!



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Initial flavour ratio is modified on the Earth due to neutrino mixing

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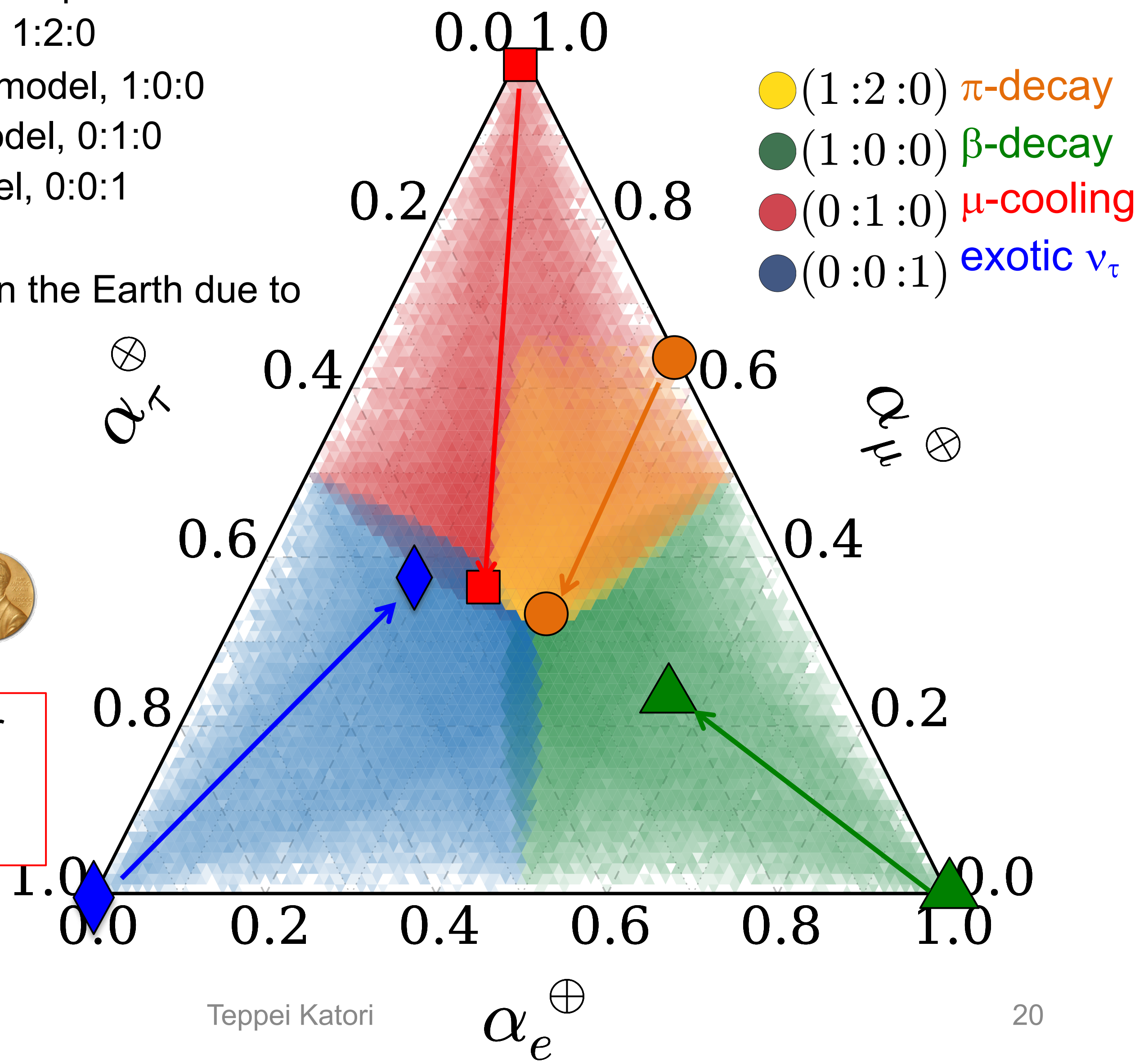
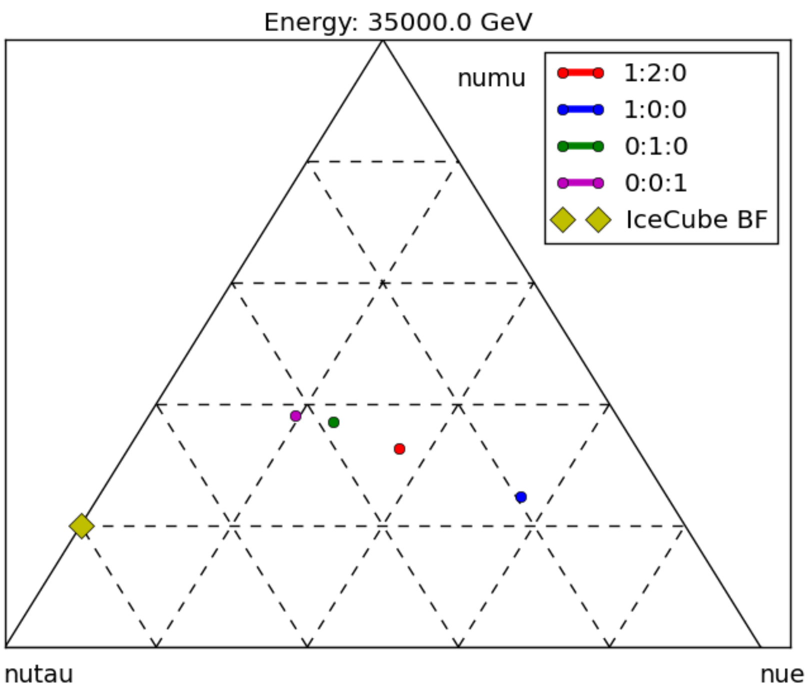
E.g.) dim-4 new physics operator ~ 10^{-28} (just below IceCube atmospheric neutrino limit)

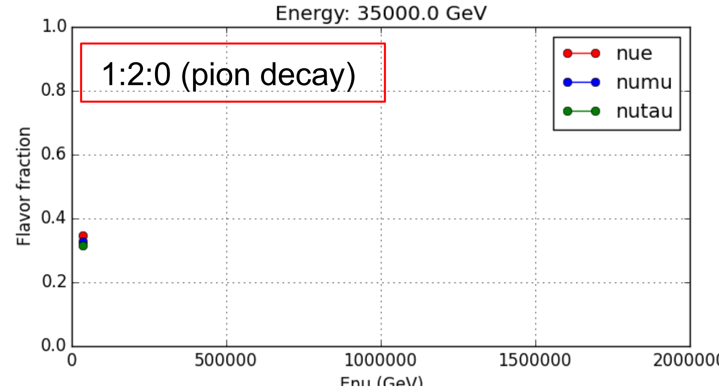


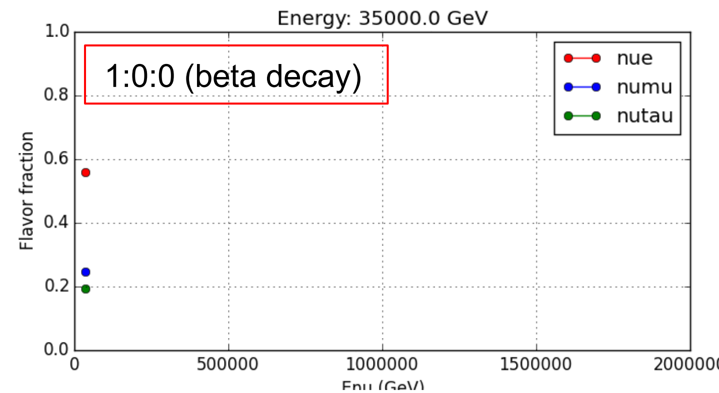
3. Neutrino flavour ratio with new physics

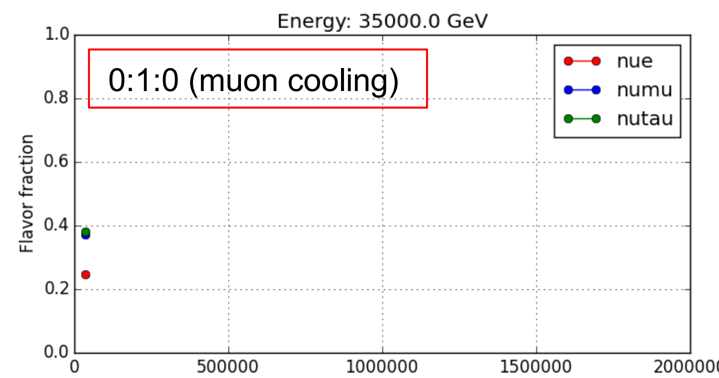
An example Hamiltonian with new physics term
(~10^{-28} CPT even Lorentz violation)

$$h_{eff} = \frac{1}{2E}\begin{pmatrix} m_{ee}^2 & m_{e\mu}^2 & m_{e\tau}^2 \\ m_{e\mu}^{2*} & m_{\mu\mu}^2 & m_{\mu\tau}^2 \\ m_{e\tau}^{2*} & m_{\mu\tau}^{2*} & m_{\tau\tau}^2 \end{pmatrix} + E\cdot\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & c_{\mu\tau} \\ 0 & c_{\mu\tau} & c_{\tau\tau} \end{pmatrix}$$









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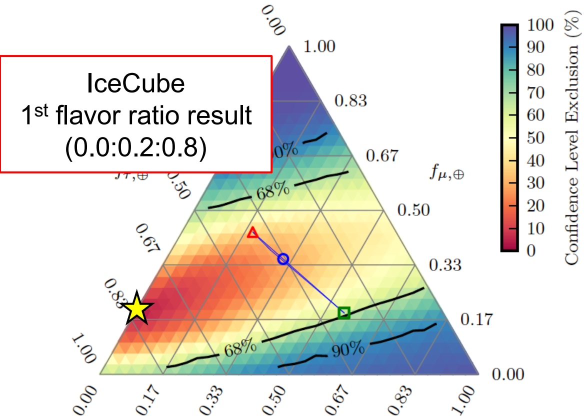
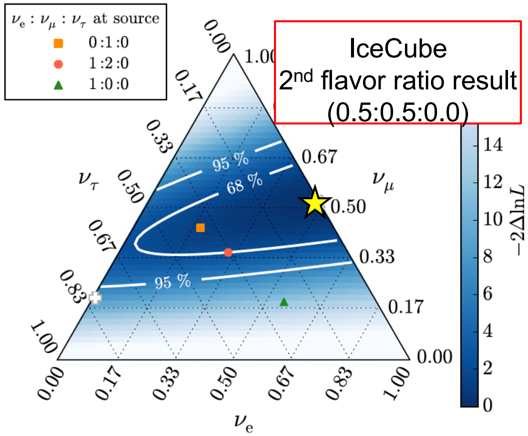
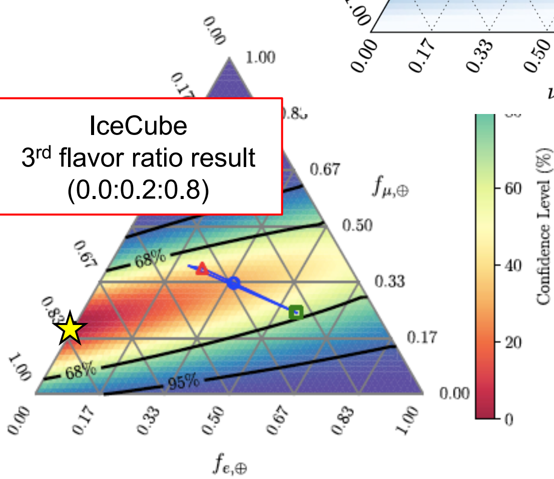
Taboada (IceCube), Neutrino 2018
IceCube, PRL114(2015)171102, Astro.J.809:98(2015), PRD99(2019)032004

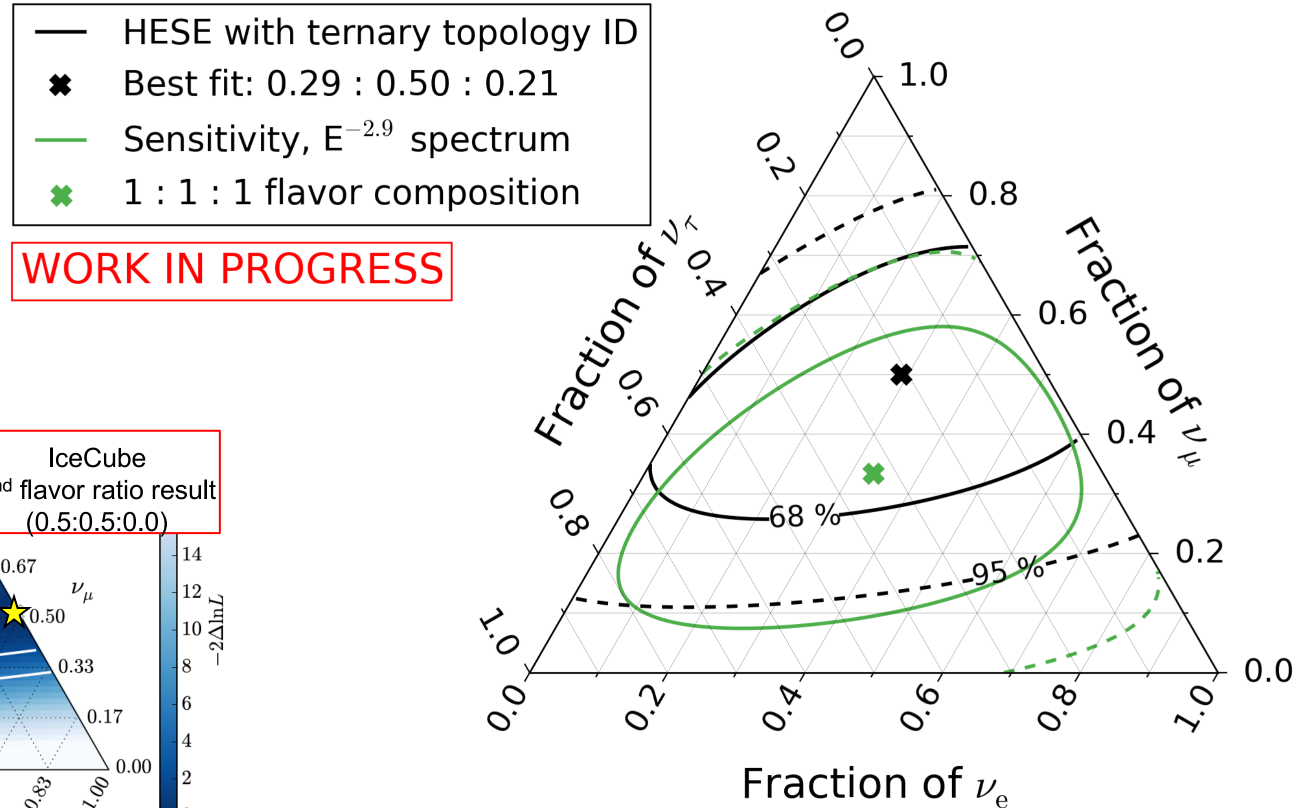
IceCube preliminary

4. HESE 7.5-yr data (2018)









New flavour ratio measurement

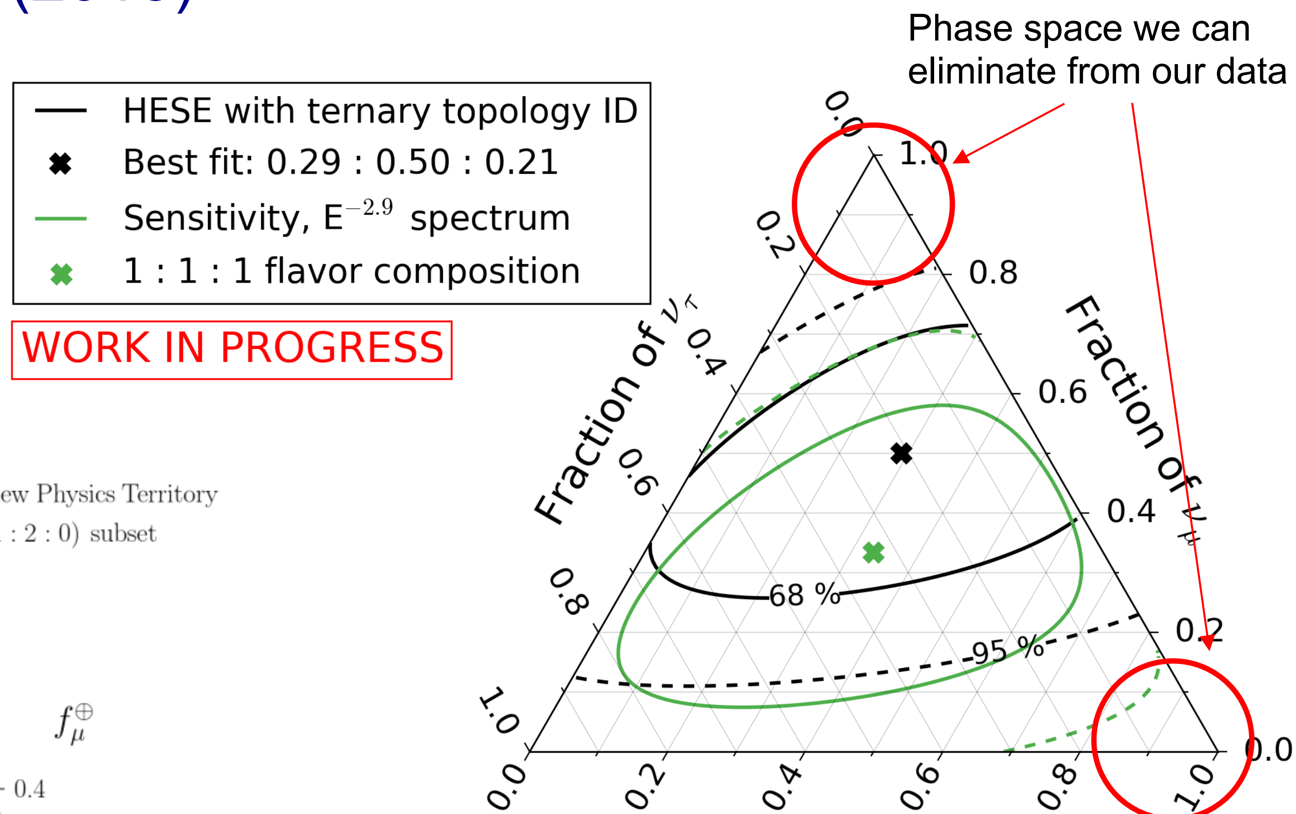
- Likelihood is very shallow and fit often confuses between ν_e and ν_τ
- New flavour ratio result has some power to distinguish ν_e and ν_τ

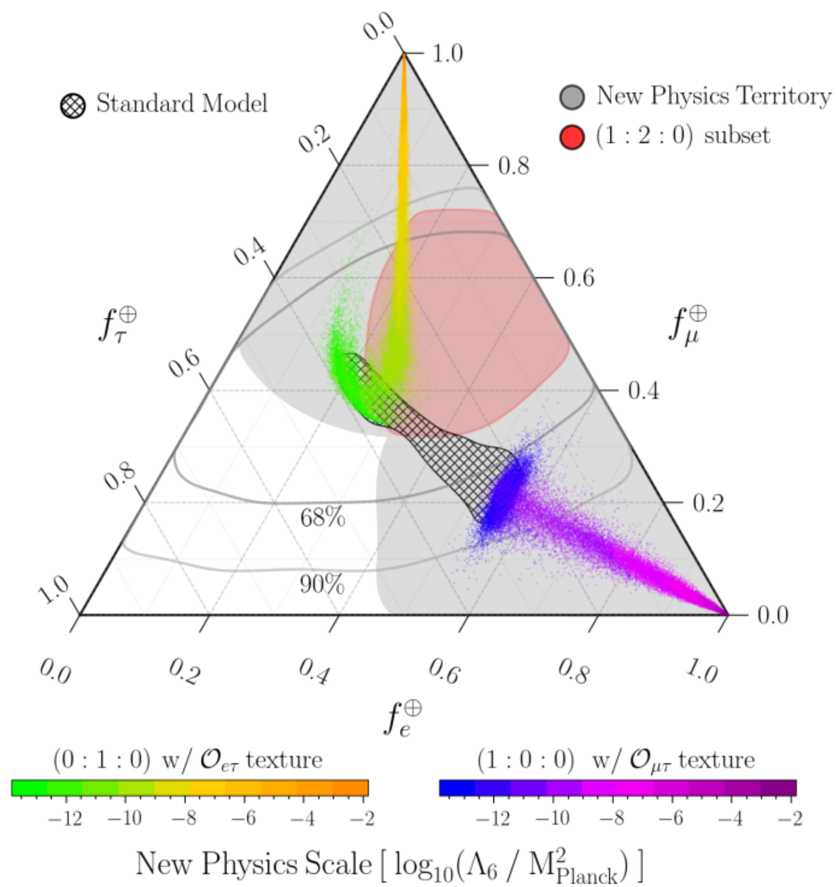
Taboada (IceCube), Neutrino 2018
IceCube, PRL114(2015)171102, Astro.J.809:98(2015), PRD99(2019)032004

4. HESE 7.5-yr data (2018)

IceCube preliminary

We can exclude models if Lorentz violation make flavour ratios at those corners





1. Astrophysical neutrino is pre-dominantly produced as muon neutrinos (~0:1:0), and new physics causes ν_e-ν_τ transition (nonzero $c^{(6)}_{\tau e}$)

2. Astrophysical neutrino is pre-dominantly produced as electron neutrinos (~1:0:0), and physics causes ν_μ-ν_τ transition (nonzero $c^{(6)}_{\mu\tau}$)

IceCube preliminary

4. Astrophysical Neutrino Flavour Lorentz Violation search

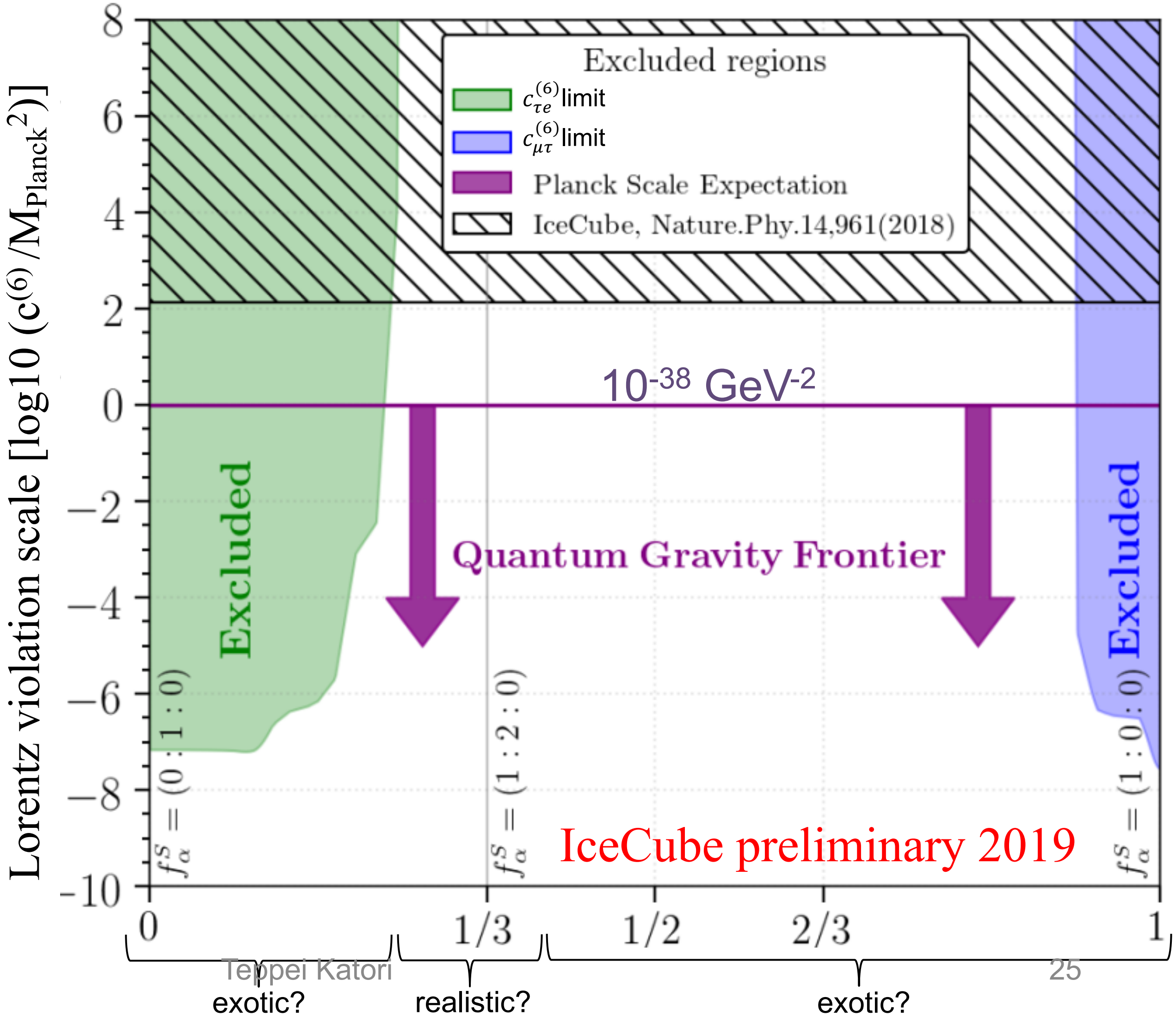
We start to exclude possible new physics in Planck scale signal region
- This moment, we focus to search max e↔τ mixing or max μ↔τ mixing by LV

- dim-3 LV limit ~ 10^{-26} GeV
- dim-4 LV limit ~ 10^{-32}
- dim-5 LV limit ~10^{-40} GeV^{-1}
- dim-6 LV limit ~10^{-46} GeV^{-2}
- dim-7 LV limit ~10^{-51} GeV^{-3}
- dim-8 LV limit ~10^{-58} GeV^{-4}

We start to explore quantum gravity-motivated region, but so far, we didn't discover LV

1. No Lorentz violation
2. Improve flavour ratio LV search analysis

2 is the answer!



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Conclusion

Neutrino interferometry is a powerful technique to look for new physics if new physics couple with neutrinos and they cause neutrino mixings.

Astrophysical neutrino mixing sensitivity reaches to naïve expectation of Planck scale physics. However, at this moment, the sensitivity is limited and we didn't discover Lorentz violation.

We need more statistics, better systematics constraint, and better particle identification algorithm to find Lorentz violation.

IceCube-Gen2 collaboration

Thank you for your attention!