Neutrino Interferometry for New Physics Search

TK, MPLA27(2012)1230024
IceCube, Nature Physics 14(2018)961
IceCube, To be published (2019)

Motivation
- String theory
- Loop quantum gravity
- Horava-Lifshitz gravity
- Lee-Wick theory
- Non-commutative field theory
- Supersymmetry
- etc

Physics
- Lorentz violating field
- Quantum foam
- Neutrino-dark matter coupling
- Neutrino-dark energy coupling
- Neutrino-torsion coupling
- Neutrino velocity $\neq$ c
- Violation of equivalent principle
- etc

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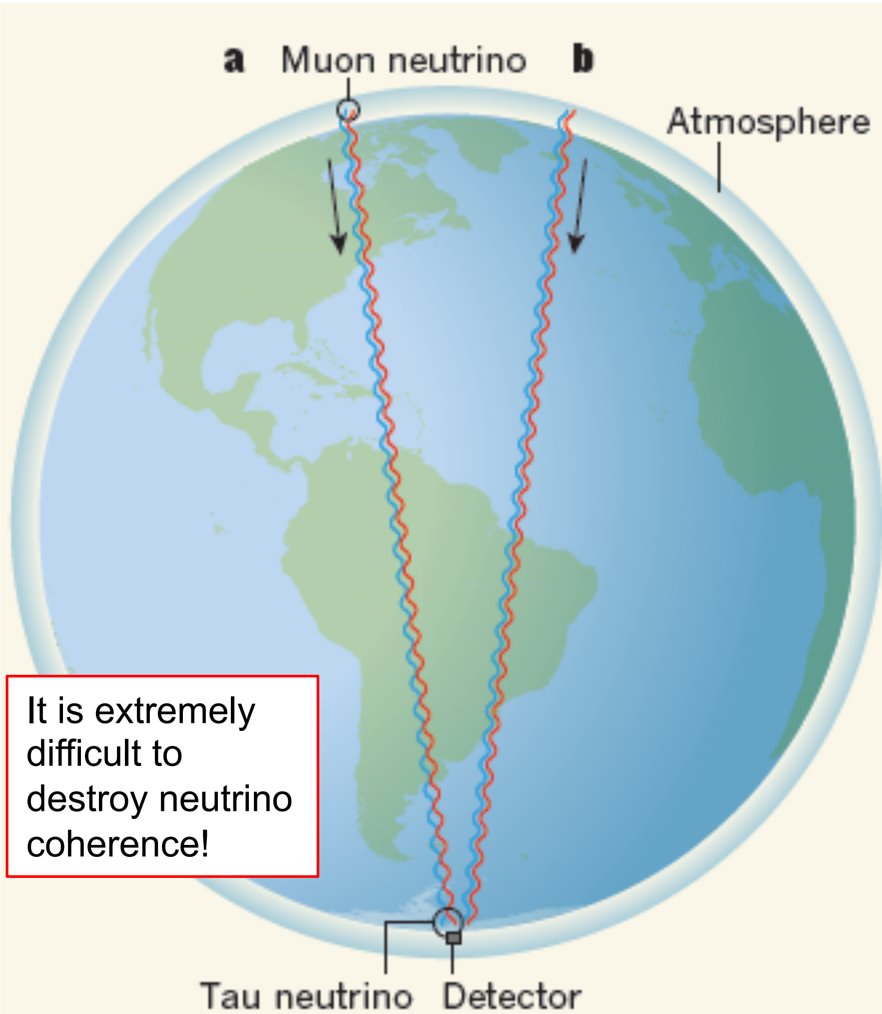
Teppei Katori
Queen Mary University of London
Quantum Sensors, King’s College London, UK, March 6, 2019

IceCube, Nature Physics 14 (2018) 961
Mewes, Nature 560 (2018) 316

Neutrino interferometry – Atmospheric neutrinos



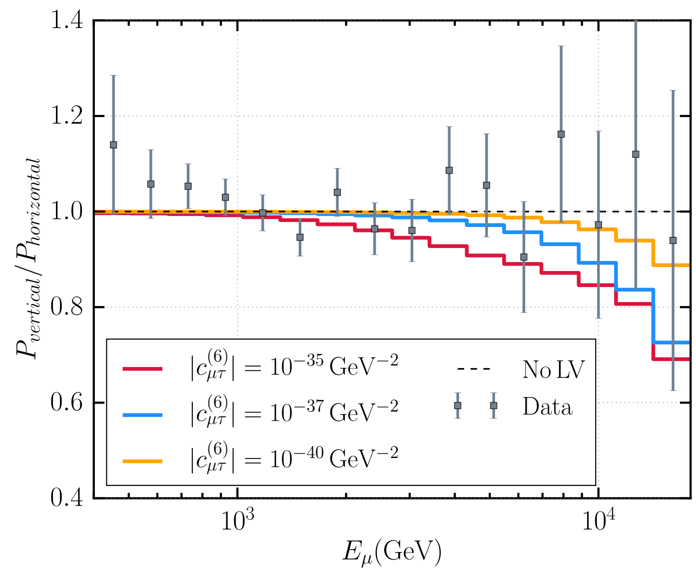
It is extremely difficult to destroy neutrino coherence!

Neutrino oscillation is a nature interferometer. Any extra interactions in the Lagrangian contribute the phase shift

For 20 TeV up-going atmospheric neutrinos (L~12700km), detectable phase shift by neutrino is

$$\bar{\psi} a^{\mu} \gamma_{\mu} \psi \ , \qquad a \sim 10^{-24}\ GeV$$

If anomalous coupling with neutrinos in vacuum cause a phase shift in similar order, we can see it from spectrum distortion of atmospheric neutrinos



Effective Hamiltonian with new physics operators

$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \dots$$

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Atomic experiments have strong limits on lower order couplings (renormalizable). Neutrino oscillations are doing good

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Astrophysical observations have strong limits on higher order couplings non-renormalizable). Neutrino oscillations are better tools there

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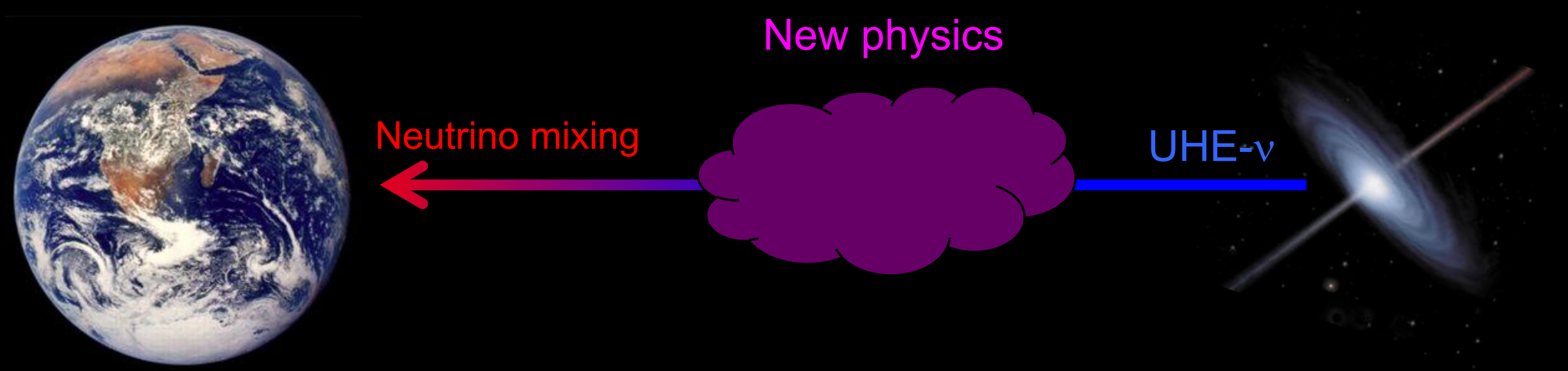
Argüelles, TK, Salvado,PRL115(2015)161303
Diaz et al, PRD85(2013)096005, Ellis et al, PLB789(2018)352

Neutrino interferometry – Astrophysical high-energy neutrinos

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

Vacuum Cherenkov radiation and Blazar neutrino ToF can limit new physics of neutrino.

Neutrino mixing properties of astrophysical neutrinos can push this limit further.
- In principle, we can do it without knowing neutrino flavours at the production
- This is the most sensitive, as long as we assume new physics cause neutrino mixing



Neutrino interferometry - Astrophysical high-energy neutrinos

Any new physics can end up in the effective Hamiltonian

$$h_{eff} = \frac{1}{2E} U^\dagger M^2 U + \sum_n \left(\frac{E}{\Lambda_n} \right)^n \tilde{U}_n^\dagger O_n \tilde{U}_n = V^\dagger \Delta V$$

neutrino oscillation formula

$$P_{\alpha\to\beta}(L) = 1 - 4 \sum_{i>j} \mathrm{Re}(V_{\alpha i}^* V_{\beta i}^* V_{\alpha j} V_{\beta j}) \sin^2\left(\frac{\Delta_{ij}}{2} L \right) + 2 \sum_{i>j} \mathrm{Im}(V_{\alpha i}^* V_{\beta i}^* V_{\alpha j} V_{\beta j}) \sin\left(\Delta_{ij} L \right)$$

neutrino mixing formula

$$P_{\alpha\to\beta}(L \to \infty) \sim 1 - 2 \sum_{i>j} \mathrm{Re}(V_{\alpha i}^* V_{\beta i}^* V_{\alpha j} V_{\beta j}) = \sum_i |V_{\alpha i}|^2 |V_{\beta i}|^2$$

Information of small contamination of new physics appears on neutrino flavour mixings

At high energy, neutrino mass term is suppressed

Neutrino interferometry - Astrophysical high-energy neutrinos

There are 3 astrophysical neutrino production models

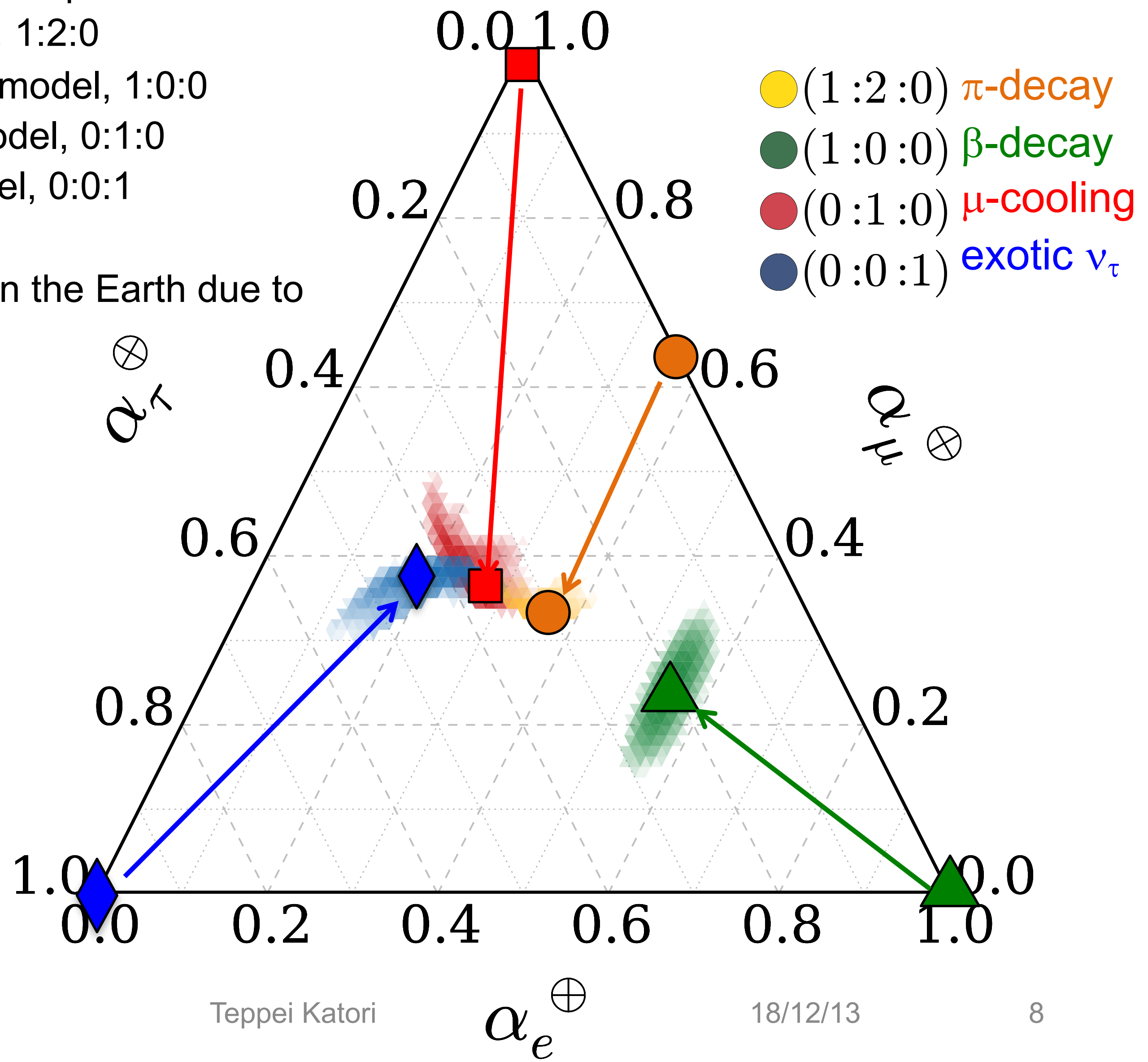
i. pion decay dominant model, 1:2:0

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



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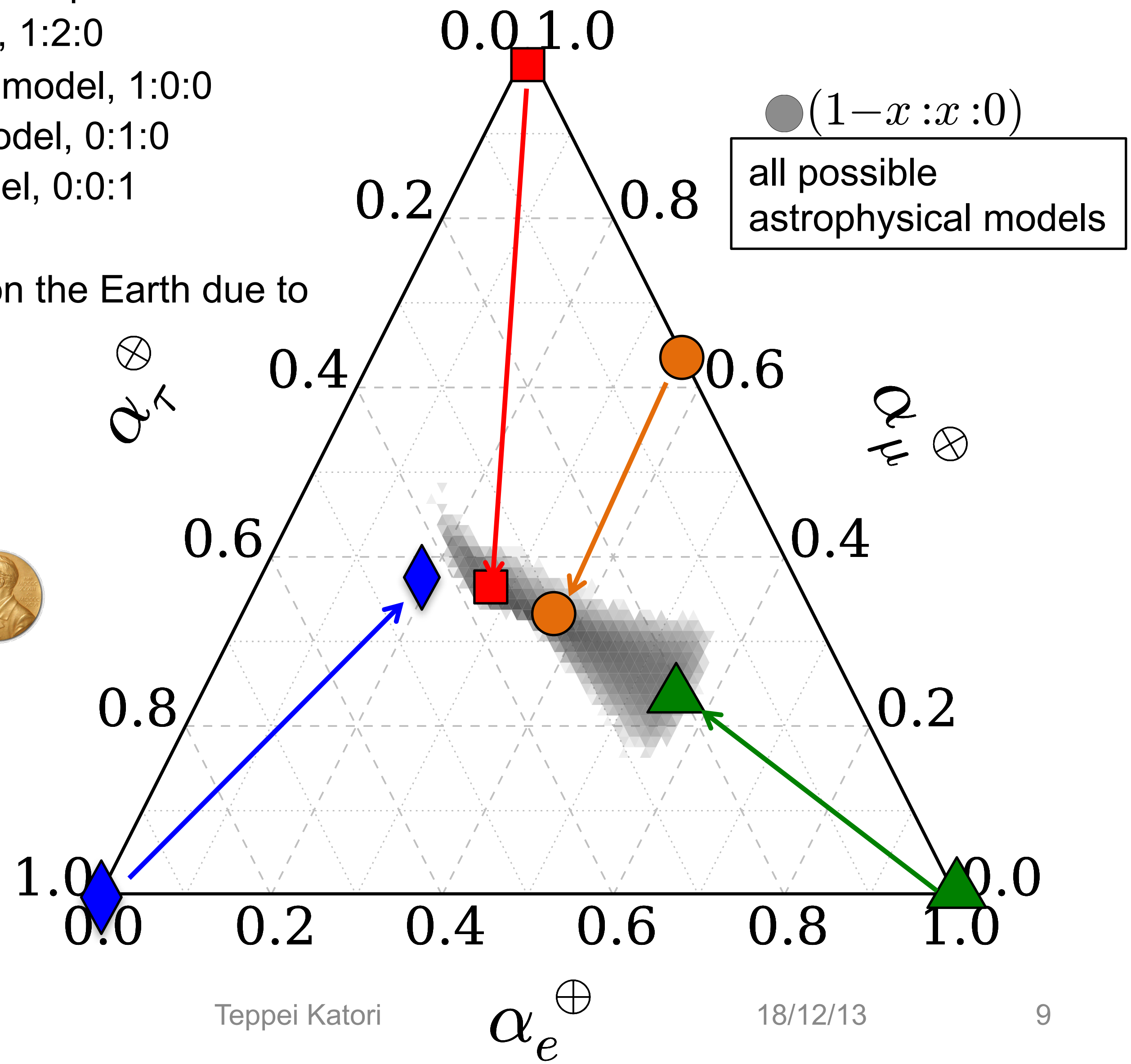
All possible flavour ratio is confined in a small space.

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



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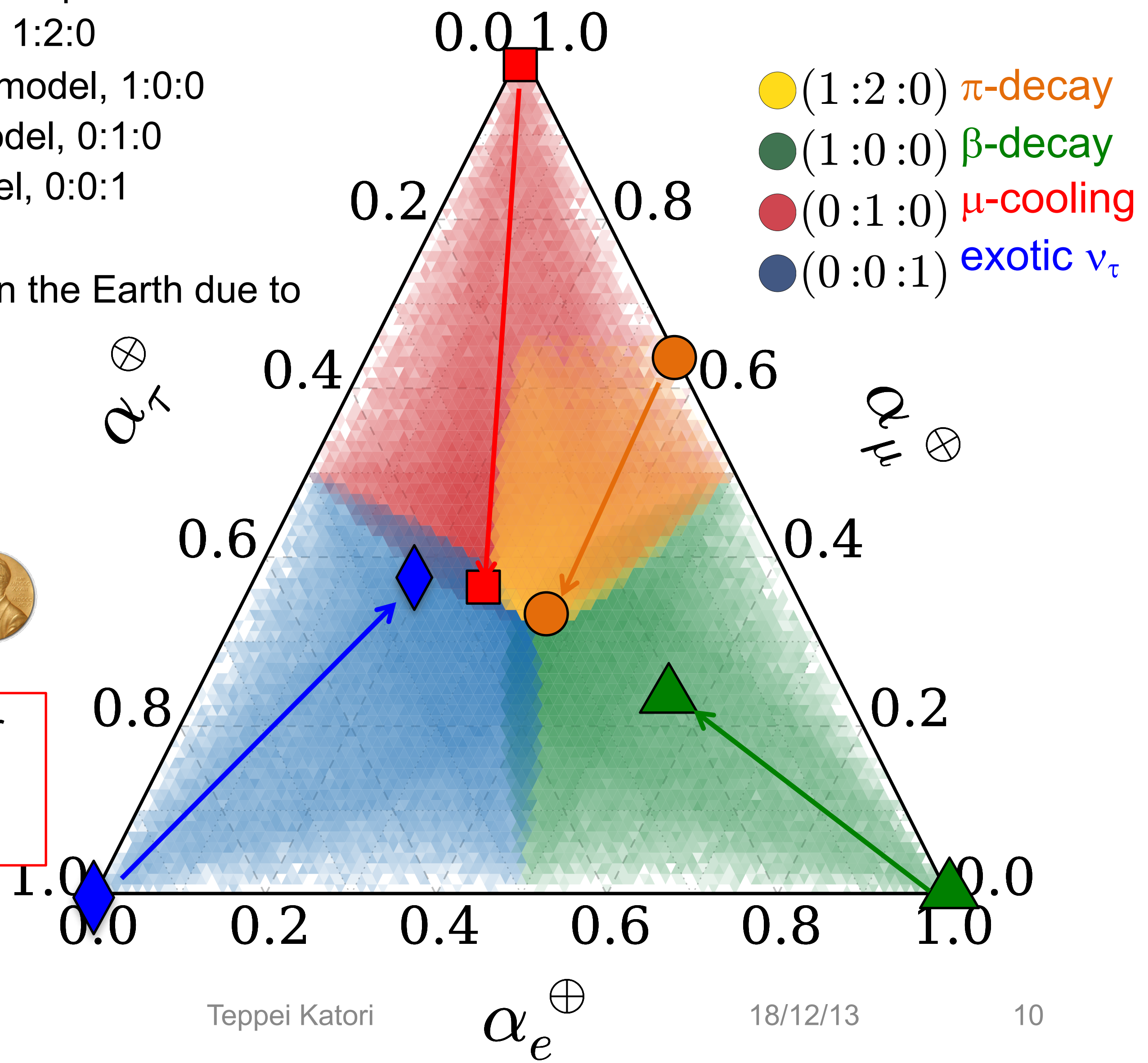
E.g.) dim-3 new physics operator ~ 10^{-24} GeV (just below IceCube atmospheric neutrino limit)

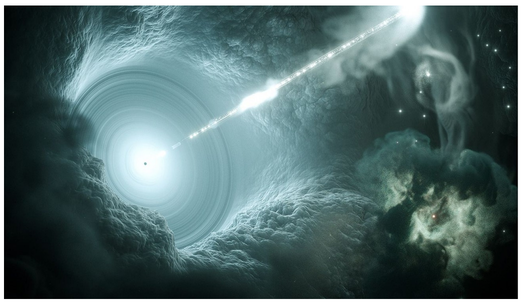


IceCube preliminary

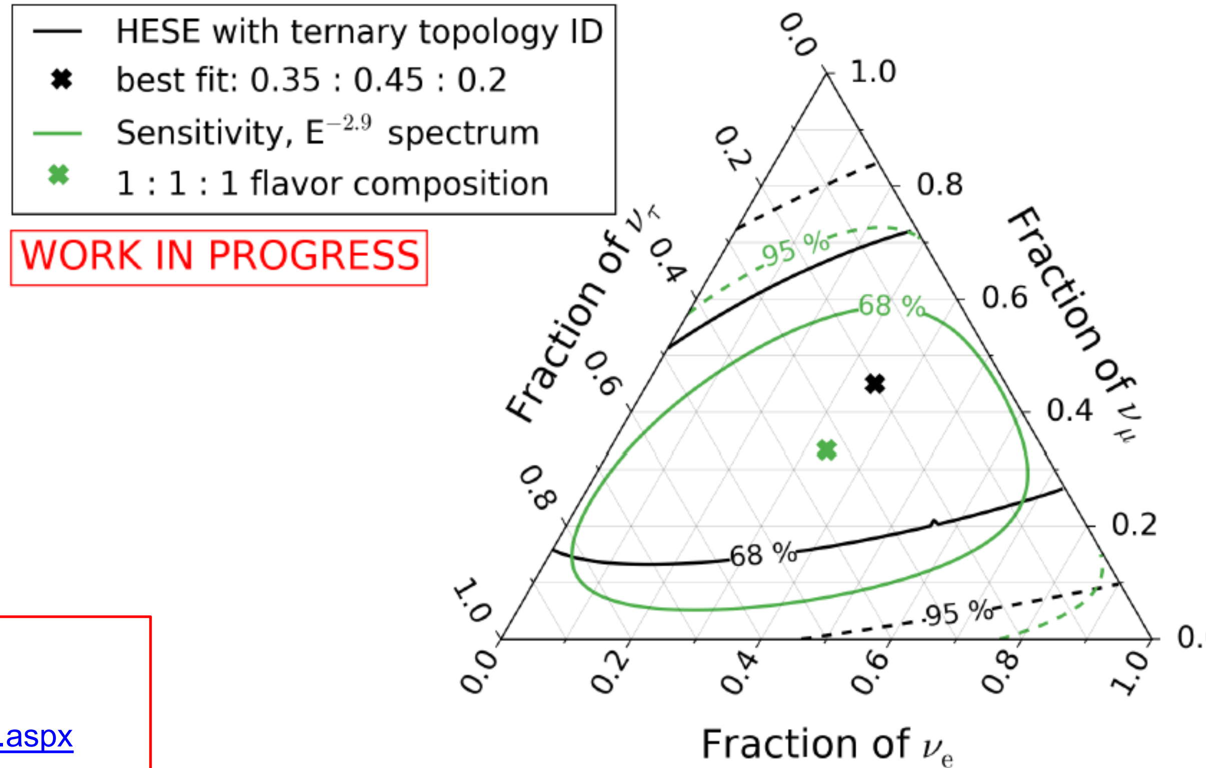
New IceCube data (2018)

Blazar neutrino

- IC170922A and TXS 0506+056
- Optical coincidence
- Clustering from this direction



IceCube, Science361(2018)147



New flavour ratio measurement

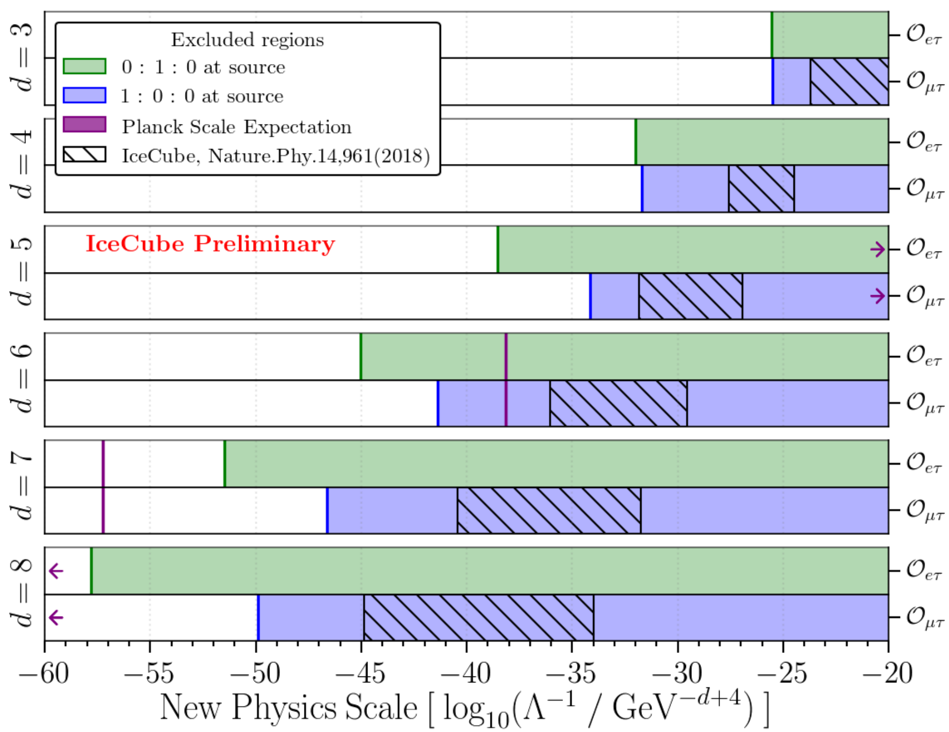
- Likelihood is very shallow and fit confuse between ν_e and ν_τ
- New flavour ratio result has some power to distinguish between ν_e and ν_τ

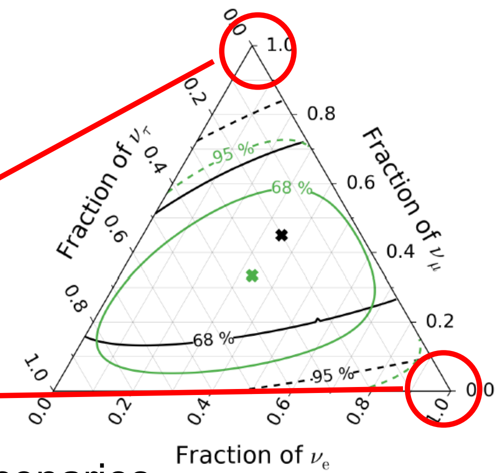
IceCube preliminary

IceCube flavor ratio test for new physics (to be published)

We start to exclude possible new physics in Planck scale signal region

- This moment, we can exclude only 2 scenarios
- dimnesion-3 vacuum operator limit ($\bar{\psi} a^{\mu} \gamma_{\mu} \psi, \bar{\psi} b^{\mu} \gamma_{\mu} \gamma_5 \psi$) ~ 10^{-25} GeV
- dimnesion-4 vacuum operator limit ($\bar{\psi} c^{\mu\nu} \gamma_{\mu} \partial_{\nu} \psi, \bar{\psi} d^{\mu\nu} \gamma_{\mu} \gamma_5 \partial_{\nu} \psi$) ~ 10^{-33}
- dimension-6 vacuum operator limit ~10^{-40} GeV^{-2}





Tested scenarios

1. Astrophysical neutrino is pre-dominantly produced as muon neutrinos (0:1:0), and new physics causes ν_e-ν_τ transition
2. Astrophysical neutrino is pre-dominantly produced as electron neutrinos (1:0:0), and new physics causes ν_μ-ν_τ transition

Conclusion

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

Spectrum distortion of atmospheric neutrino is used to look for new physics.

Astrophysical neutrino mixing sensitivity reaches to naïve expectation of Planck scale. However, in this moment, the sensitivity is limited. We need more statistics and better particle identification algorithm to find new physics.

Thank you for your attention!

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