Beyond the Standard Model effects on neutrino flavor

Experimental overview and prospects:

High energies: neutrinos above the TeV scale

To be published, ArXiv:2203.10811

Teppei Katori
King's College London

Snowmass21 workshop, Seattle, July 24, 2022

KING'S College LONDON

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Snowmass White Paper:
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Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

C. A. Argüelles*[1], G. Barenboim*[2], M. Bustamante*[3], P. Coloma†*[4], P. B. Denton*[5], I. Esteban*[6,7], Y. Farzan*[8], E. Fernández Martínez*[4,9], D. V. Forero†*[10], A. M. Gago*[11], T. Katori†*[12], R. Lehnert*[13,14], M. Ross-Lonergan*[15], A. M. Suliga*[16,17], Z. Tabrizi*[18], L. Anchordoqui[19], K. Chakraborty[20], J. Conrad[21], A. Das[22], C. S. Fong[23], B. R. Littlejohn[24], M. Maltoni[4], D. Parno[25], J. Spitz[26], J. Tang[27], and S. Wissel[28]

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Beyond the Standard Model effects on Neutrino Flavor

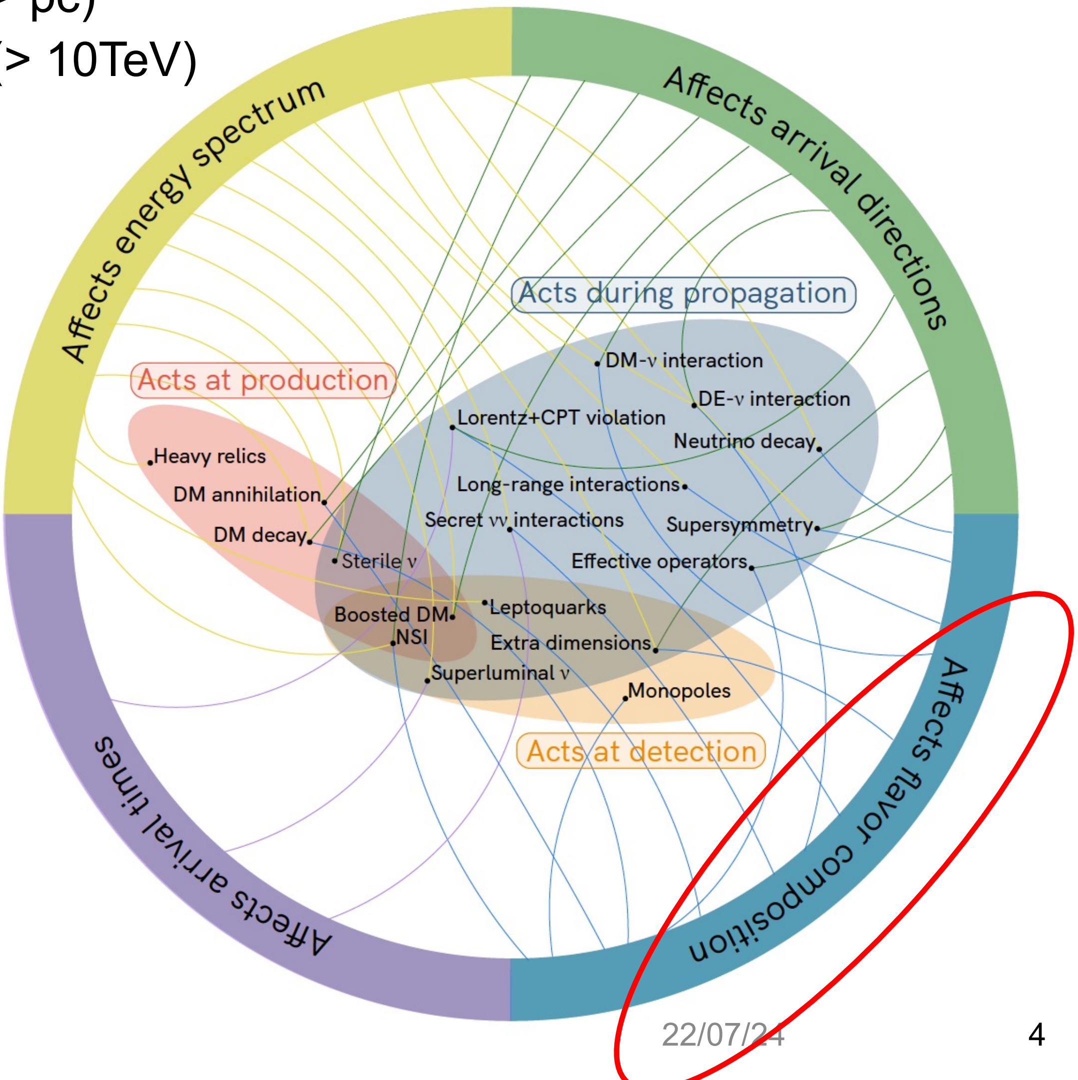
Natural place to look for new physics

1. Longest propagation distance (> pc)
2. Direct highest energy particles (> 10TeV)
3. Quantum mixing

“Neutrino flavour effect” covers many topics in particle physics!

We want to discover any of these!

- Lorentz and CPT violation
- Long-range interaction
- Dark matter-neutrino interaction
- Dark energy-neutrino interaction
- Neutrino self-interaction
- Non-standard interaction
- Neutrino decay
- Neutrino decoherence
- Sterile neutrinos
- Extra dimension, etc



Astrophysical neutrino flavour physics

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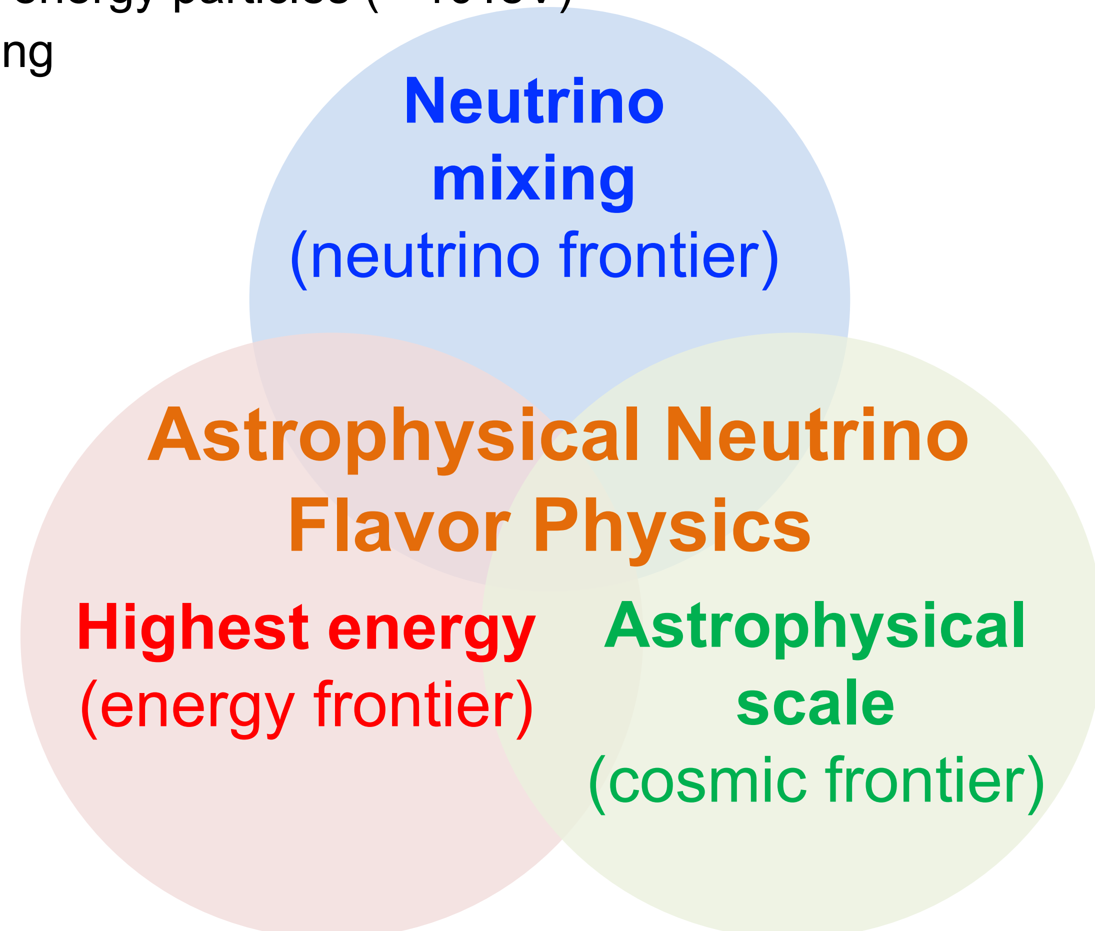

Astrophysical neutrino flavour physics

Flavour information is sensitive to the leading order of new physics

$$H = H_{SM} + H_{BSM}$$

$$P = |H_{SM}|^2 + |H_{SM} \cdot H_{BSM}| + |H_{BSM}|^2 + \cdots$$

We need high statistics flavour data to look for new physics

Astrophysical neutrino flavour physics

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$$H = H_{SM} + H_{BSM}$$

$$P = |H_{SM}|^2 + |H_{SM} \cdot H_{BSM}| + |H_{BSM}|^2 + \cdots$$

Standard neutrino Hamiltonian in vacuum

$$H_{SM} \sim \frac{m^2}{2E}$$

In highest energy, SM term is suppressed, BSM term becomes relatively larger

$$P = |H_{SM}|^2 + |H_{SM} \cdot H_{BSM}| + |H_{BSM}|^2 + \cdots$$

Higher-energy neutrinos have better sensitivity to new physics

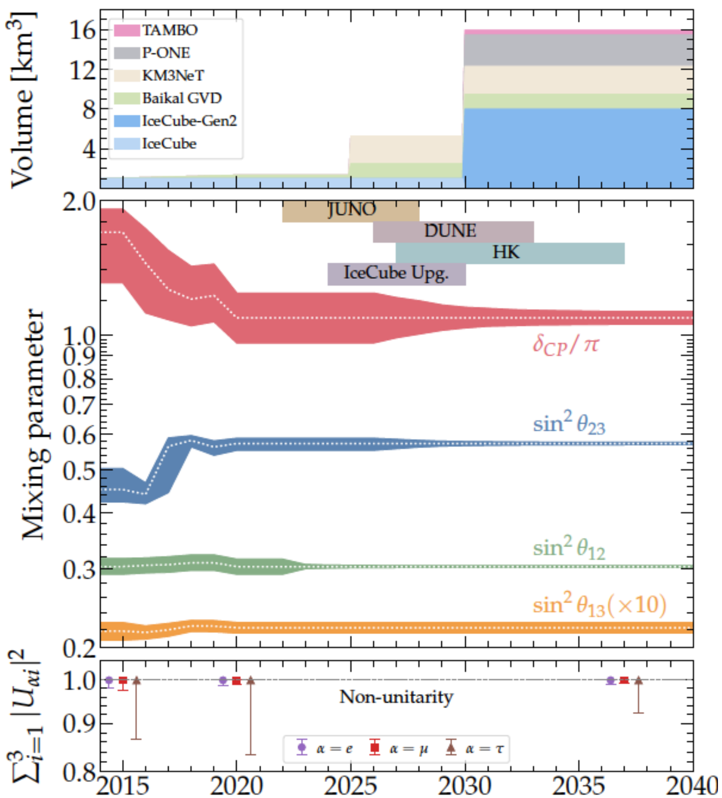
Song et al, JCAP04(2021)054

Astrophysical neutrino flavour physics

The goal is to find

$$P \neq P_{SM}(\Delta m^2 \pm \delta\Delta m^2, \theta \pm \delta\theta)$$

Sensitivity is improved by better oscillation parameter measurements



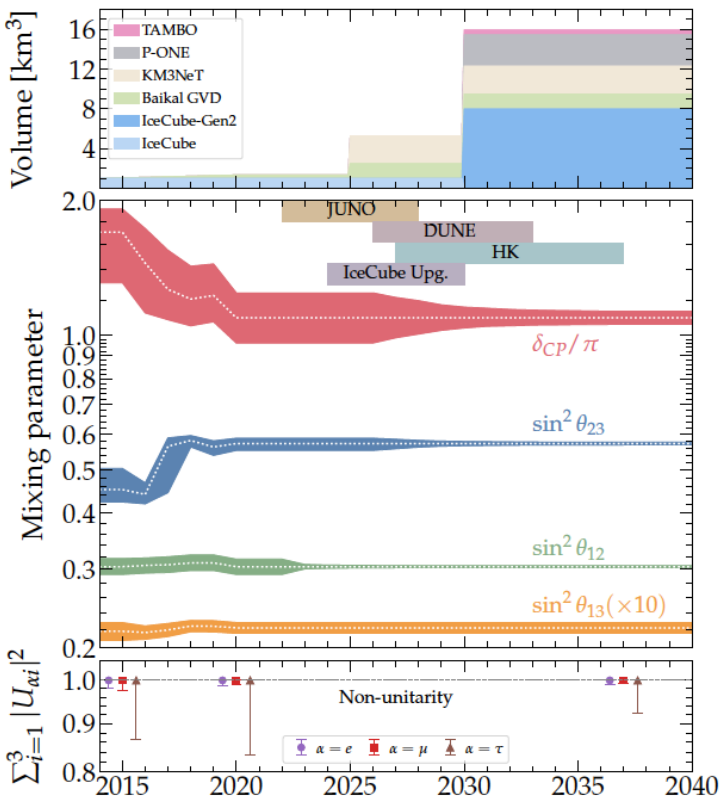
Song et al, JCAP04(2021)054

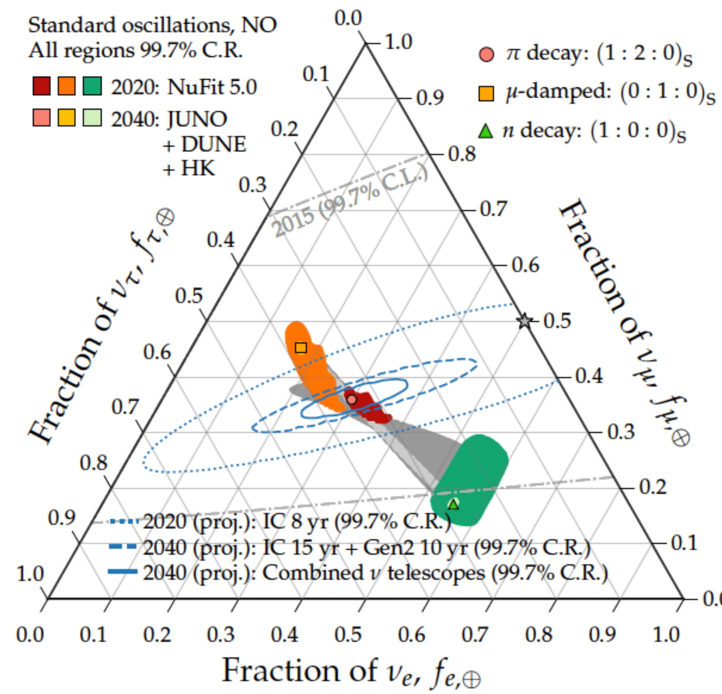
Astrophysical neutrino flavour physics

Astrophysical neutrino flavour simulation depends on astrophysical neutrino flavour assumption at the source

$$f_{\beta,\oplus} = \sum_{\beta}^{3} P_{\alpha\rightarrow\beta}(H_{SM}, H_{BSM}) \times f_{\alpha,S}$$

New physics sensitivity depends on astrophysical neutrino production model



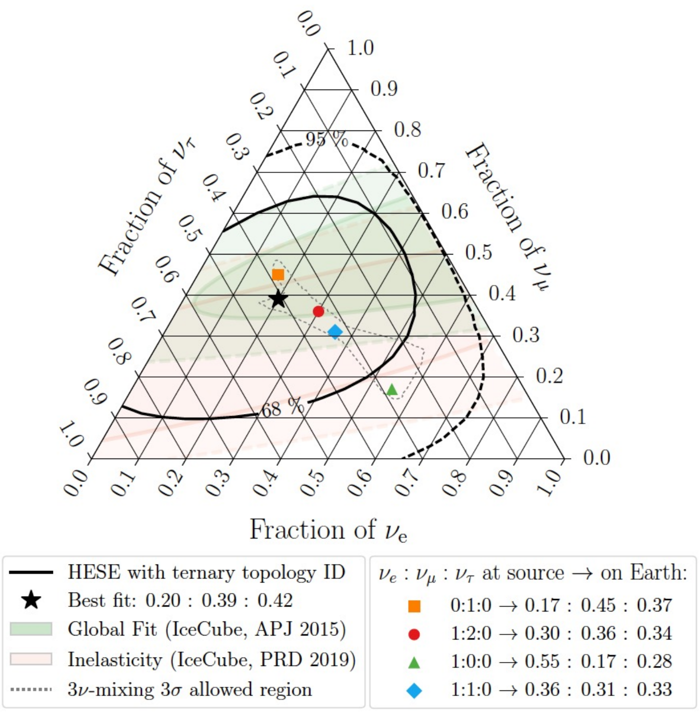


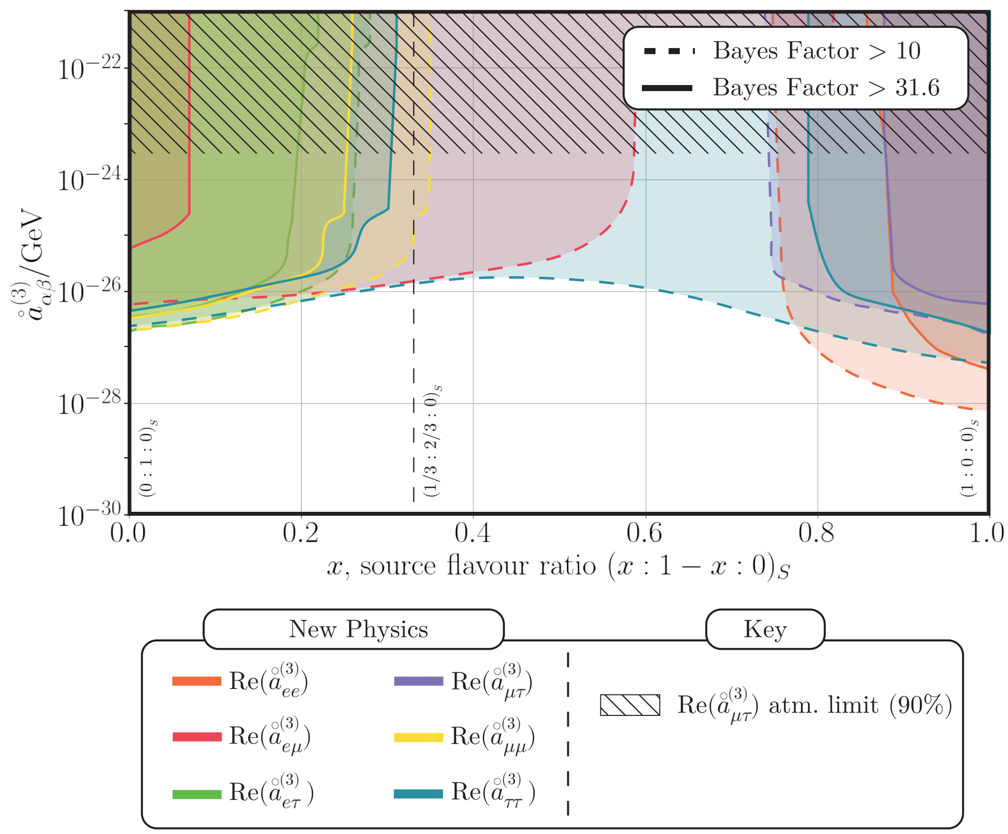
Astrophysical neutrino flavour physics (2022)

IceCube data allows almost all astrophysical neutrino flavour ratio

- New physics limits have astrophysical neutrino production model dependencies

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





Summary

Astrophysical neutrino flavour physics is a cross-frontier topic.

- Neutrino frontier, high-energy frontier, cosmic frontier

Very high discovery potential is supported by an interdisciplinary study

- Theory & experiment, particle physics & astrophysics

Snowmass white paper "Beyond the Standard Model effects on Neutrino Flavor", ArXiv:2203.10811

Summary

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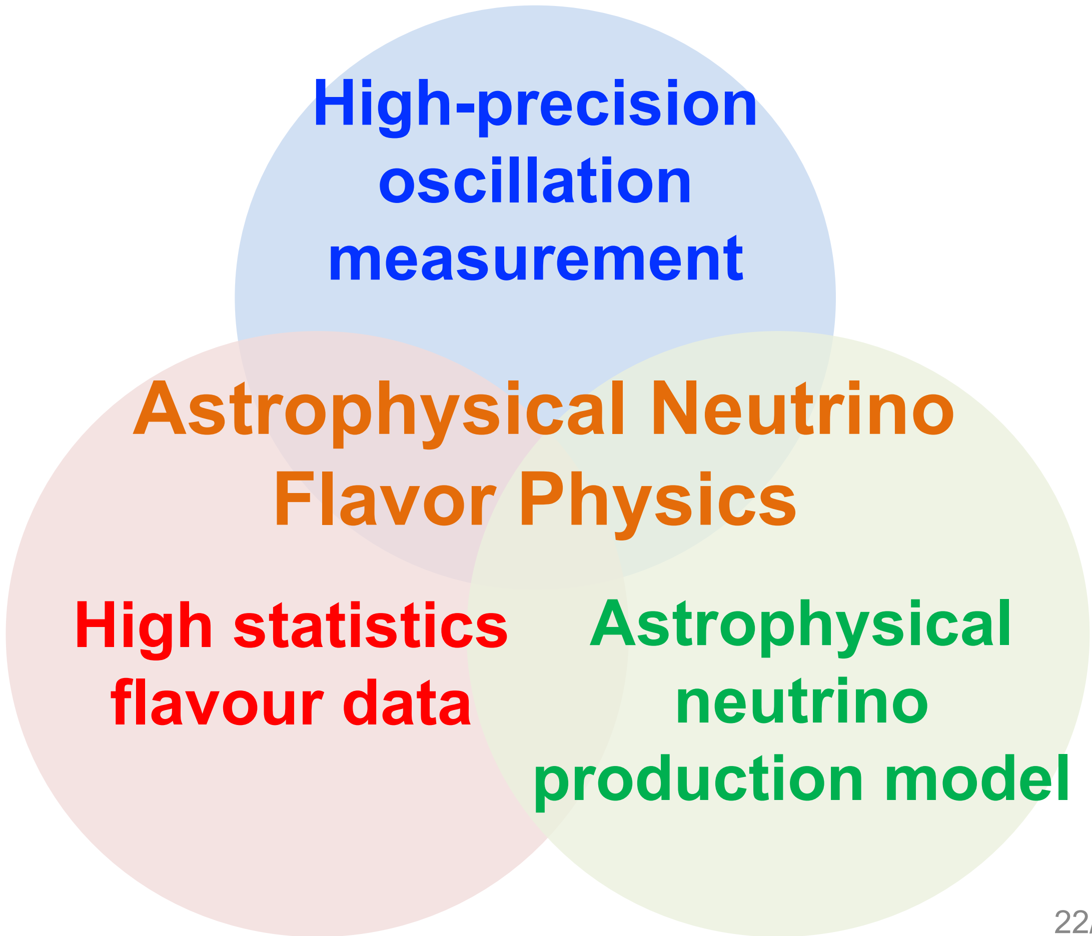

Summary

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Very high discovery potential is supported by an interdisciplinary study

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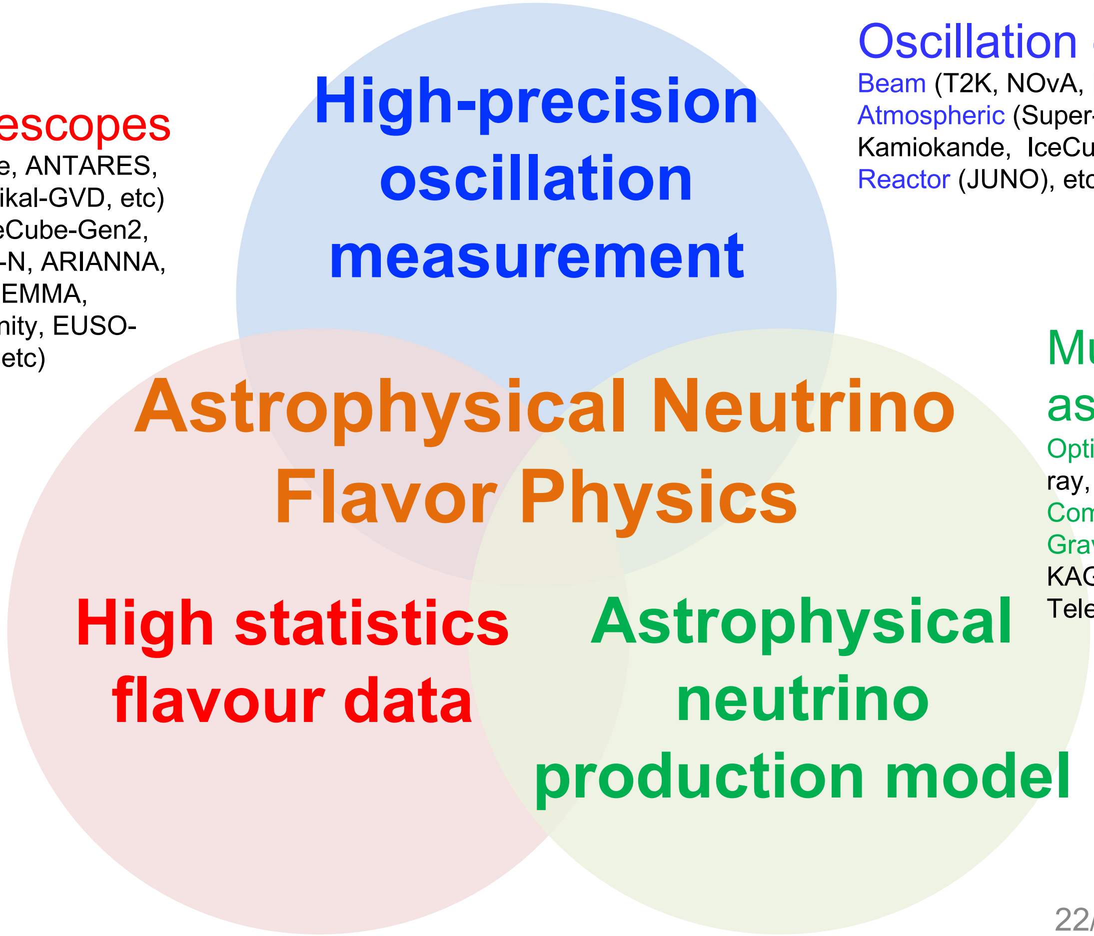
Neutrino telescopes

High-Energy (IceCube, ANTARES, KM3NeT, P-ONE, Baikal-GVD, etc)
Ultra-high-energy (IceCube-Gen2, TAMBO, Trinity, RET-N, ARIANNA, RNO-G, GRAND, POEMMA, BEACON, PUEO, Trinity, EUSO-SPB2, Auger/GCOS, etc)



Oscillation experiments

Beam (T2K, NOvA, DUNE, Hyper-Kamiokande)
Atmospheric (Super-Kamiokande, DUNE, Hyper-Kamiokande, IceCube-Upgrade, KM3NeT, INO)
Reactor (JUNO), etc

Multi-messenger astronomy

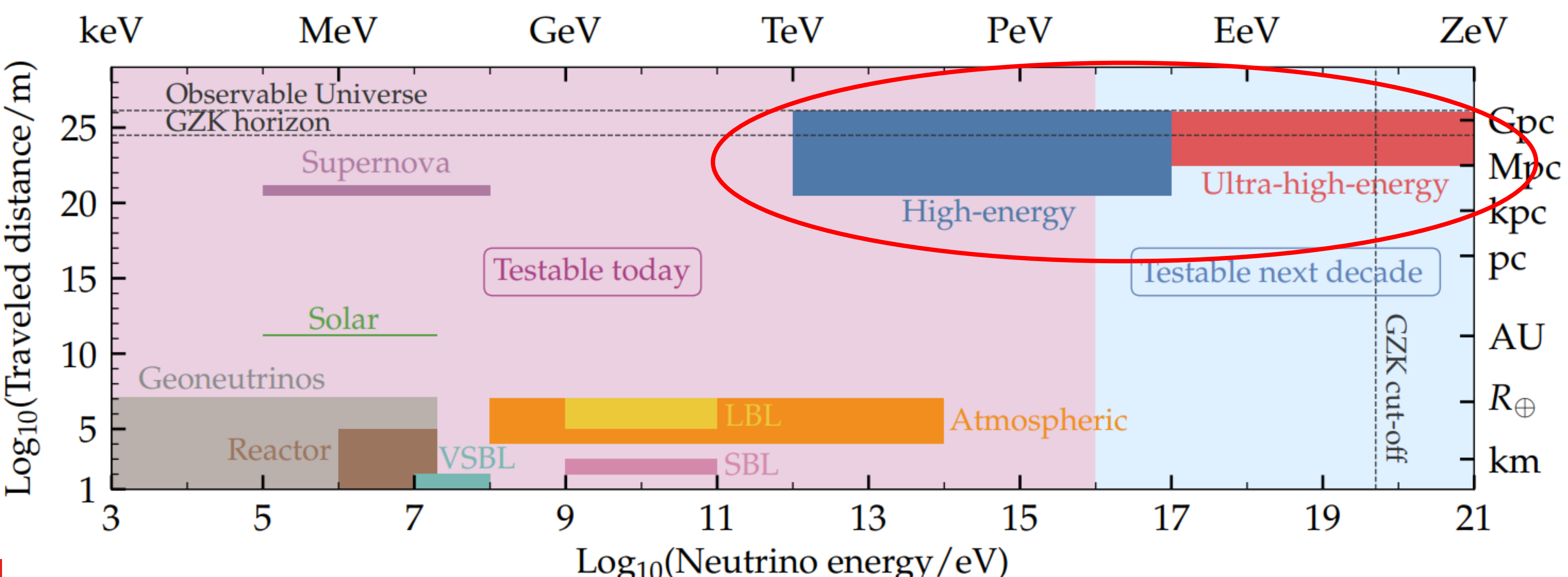
Optics (Radio, infrared, VIS, UV, X-ray, γ-ray)
Comic rays (Auger, TA, GCOS, etc)
Gravitational wave (LIGO, VARGO, KAGRA, LIGO-India, Einstein Telescope, LISA, etc)

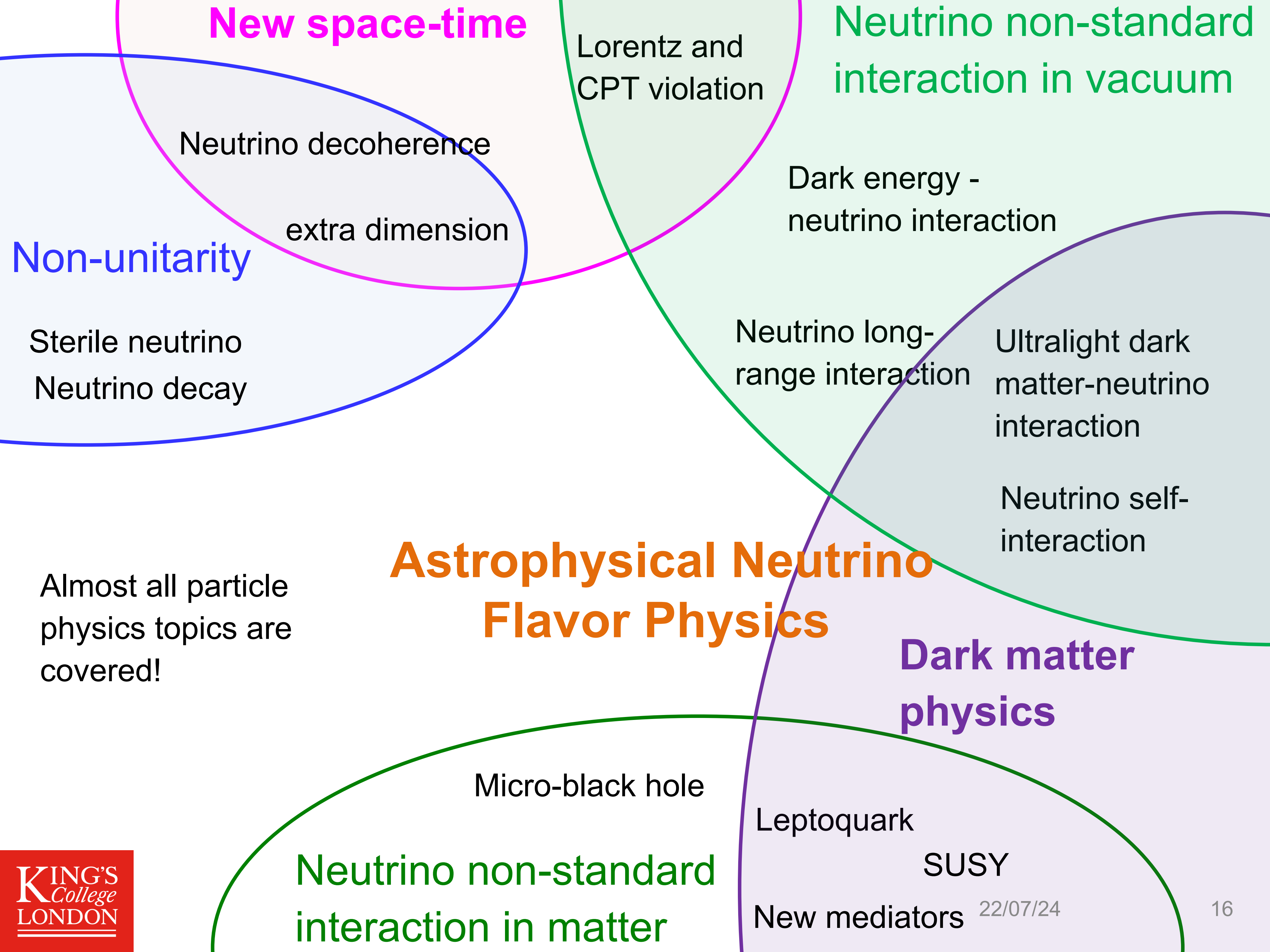
Backup

Beyond the Standard Model effects on Neutrino Flavor

Fundamental physics with high-energy cosmic neutrinos today and in the future

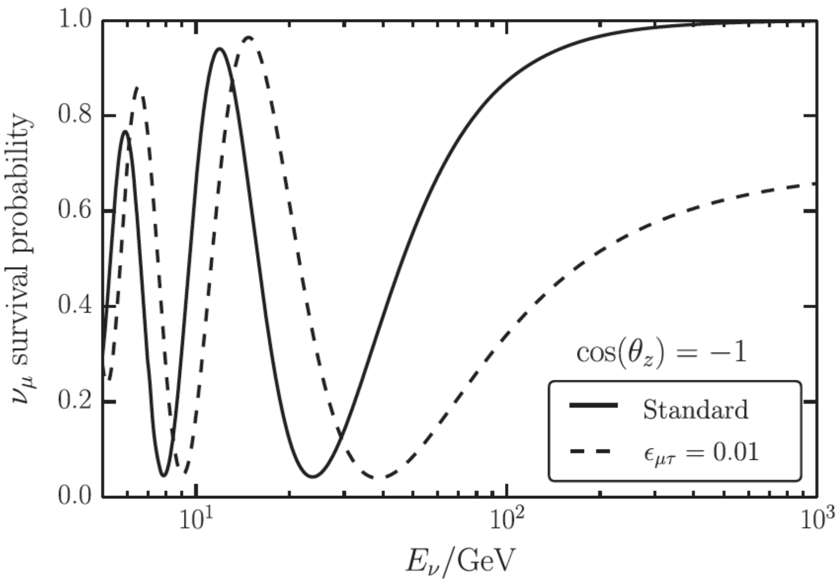
- Natural place to look for new physics
  1. Longest propagation distance (> pc)
  2. Direct highest energy particles (> 10TeV)
  3. Quantum mixing




New space-time
Lorentz and CPT violation
Neutrino non-standard interaction in vacuum
Neutrino decoherence
extra dimension
Non-unitarity
Dark energy - neutrino interaction
Sterile neutrino
Neutrino decay
Neutrino long-range interaction
Ultralight dark matter-neutrino interaction
Neutrino self-interaction
Astrophysical Neutrino Flavor Physics
Almost all particle physics topics are covered!
Dark matter physics
Micro-black hole
Leptoquark
SUSY
New mediators
Neutrino non-standard interaction in matter

Non-standard interactions

Atmospheric neutrinos cover ~100MeV - 20 TeV (conventional) coming from all direction (diffuse). However, direction is related to the propagation distance.
→ They are the highest energy particles (~20 TeV) with the longest baseline (12700km) propagating the high-density material (~13g/cm^3) on Earth.



$$h_{eff} \sim \frac{1}{2E} M^2 + V_{CC}, \quad P_{\alpha\beta} = \left| \langle \nu_\alpha | U(h_{eff}, t) | \nu_\beta \rangle \right|^2$$

$$M^2 = \begin{pmatrix} m_{ee}^2 & m_{e\mu}^2 & m_{\tau e}^2 \\ (m_{e\mu}^2)^* & m_{\mu\mu}^2 & m_{\mu\tau}^2 \\ (m_{\tau e}^2)^* & (m_{\mu\tau}^2)^* & m_{\tau\tau}^2 \end{pmatrix}, V_{CC} = \begin{pmatrix} \sqrt{2} G_F n_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Non-standard interaction limits in IceCube is order ~10^{-25} GeV

cf) The highest precision hydrogen 1S-2S transition (PRL107(2011)203001)
Fractional frequency uncertainty ~ 4x10^{-15} → new physics sensitivity ~10^{-23} GeV

Flavor new physics search with effective operators

Standard Model Extension (SME) is an effective field theory to look for Lorentz violation

$$L = \underbrace{i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi}_{\text{Standard Model}} + \underbrace{\bar{\psi}\gamma^{\mu}a_{\mu}\,\psi + \bar{\psi}\gamma^{\mu}c_{\mu\nu}\partial^{\nu}\psi \cdots}_{\text{New physics}}$$

Effective Hamiltonian can be written from here

$$h_{eff} \sim \underbrace{\frac{1}{2E}U^{\dagger}M^{2}U}_{\text{Standard Model}} + \underbrace{a^{(3)}_{\alpha\beta} - Ec^{(4)}_{\alpha\beta}}_{\text{New physics (renormalizable)}} + \underbrace{E^{2}a^{(5)}_{\alpha\beta} - E^{3}c^{(6)}_{\alpha\beta} \cdots}_{\text{higher dimension operator (non-renormalizable)}}$$

Astrophysical neutrino flavour sensitivity of dim-6 operator

goes beyond the natural scale $c^{(6)} \sim \frac{1}{M^2_{Planck}} \sim 10^{-38} GeV^{-2}$,

first time in any known scientific system

Flavor new physics search with effective operators

Neutrino oscillation formula is written with mixing matrix elements and eigenvalues

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

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

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

Astrophysical neutrino flux of flavour α at production is $\phi_\alpha^p(E) \sim \phi_\alpha^P \cdot E^{-\gamma}$. Since it's low statistics, we consider energy-averaged flavour composition β on Earth

$$\bar{\phi}_\beta^{\oplus} = \frac{1}{\Delta E}\int_{\Delta E} \sum_{\alpha} P_{\alpha\to\beta}(E,\infty)\, \phi_\alpha^p(E) dE$$

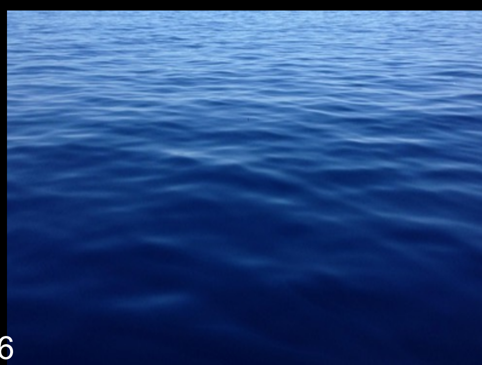
We take the fraction of this for each flavour.

$$f_\beta^{\oplus} = \frac{\bar{\phi}_\beta^{\oplus}}{\sum_{e,\mu,\tau} \bar{\phi}_\gamma^{\oplus}}$$

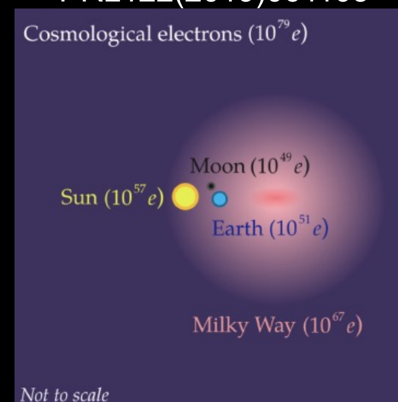
High-energy astrophysical neutrino flavour

High-energy particles (>60 TeV) propagating a long distance (>100 Mpc)
- Neutrinos can probe new physics in the universe

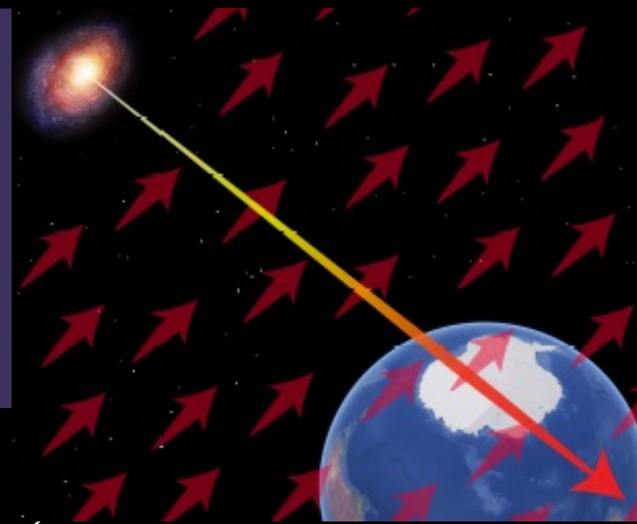
Quantum foam
Ellis,Mavromatos,Nanopoulos
PLB293(1992)37



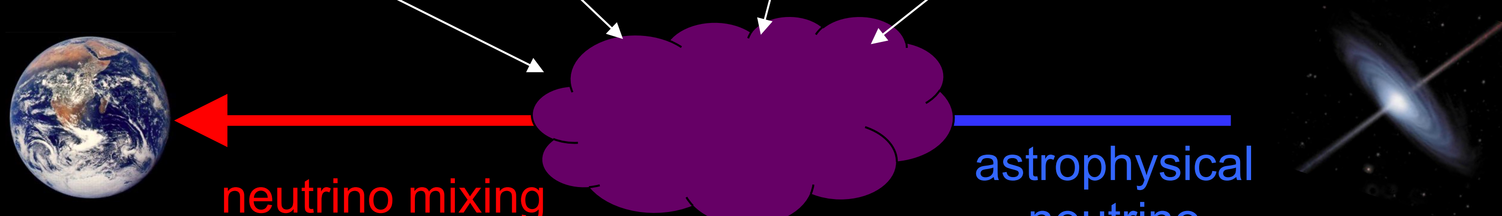
new long-range force
Bustamante,Agarwalla
PRL122(2019)061103



Lorentz violating field
Kostelecký Mewes,PRD69(2004)016005



Klop, Ando
PRD97(2018)063006
neutrino-dark energy coupling
etc...



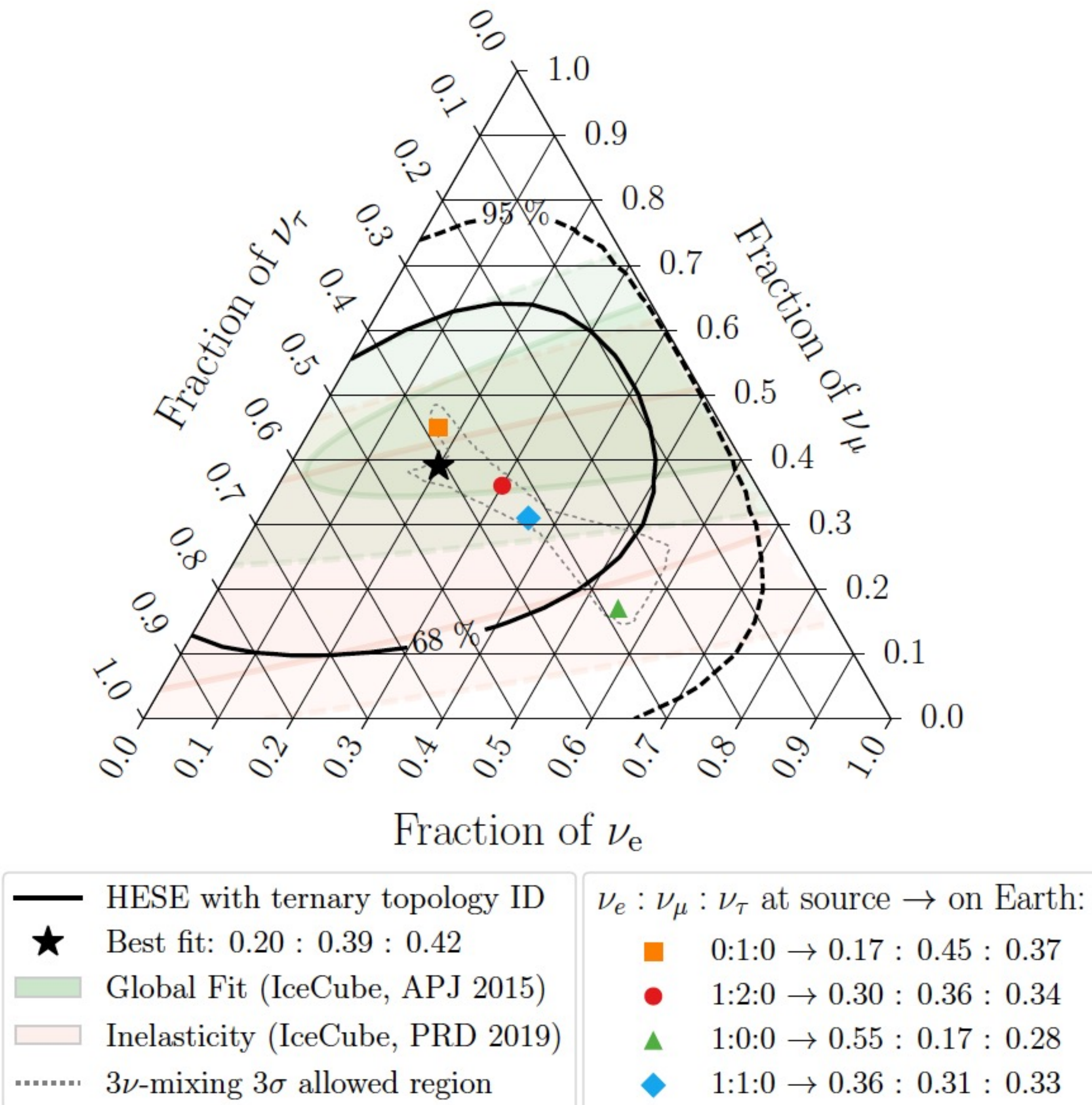
neutrino mixing

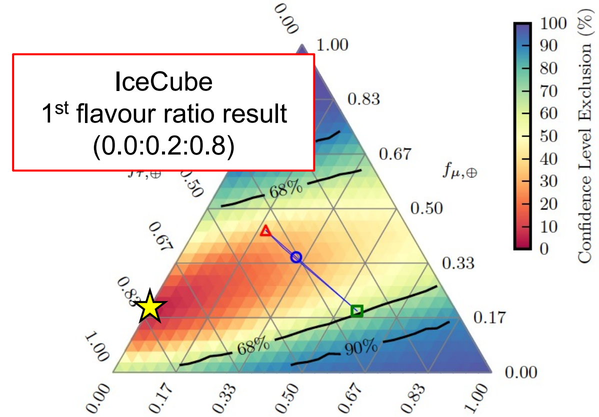
New physics

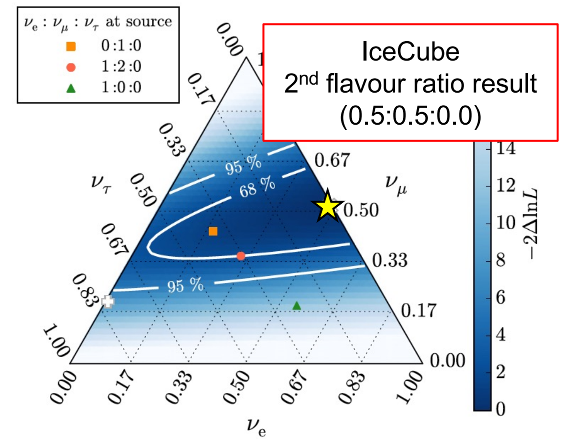
astrophysical neutrino

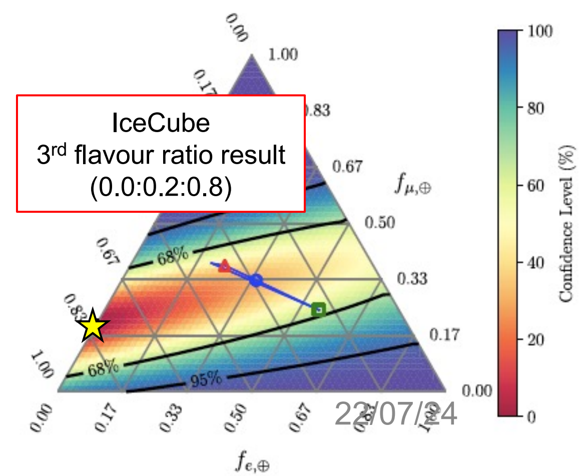
IceCube, PRL114(2015)171102, Astro.J.809:98(2015), PRD99(2019)032004, ArXiv:2011:03560

HESE 7.5-yr flavor ratio (2018)









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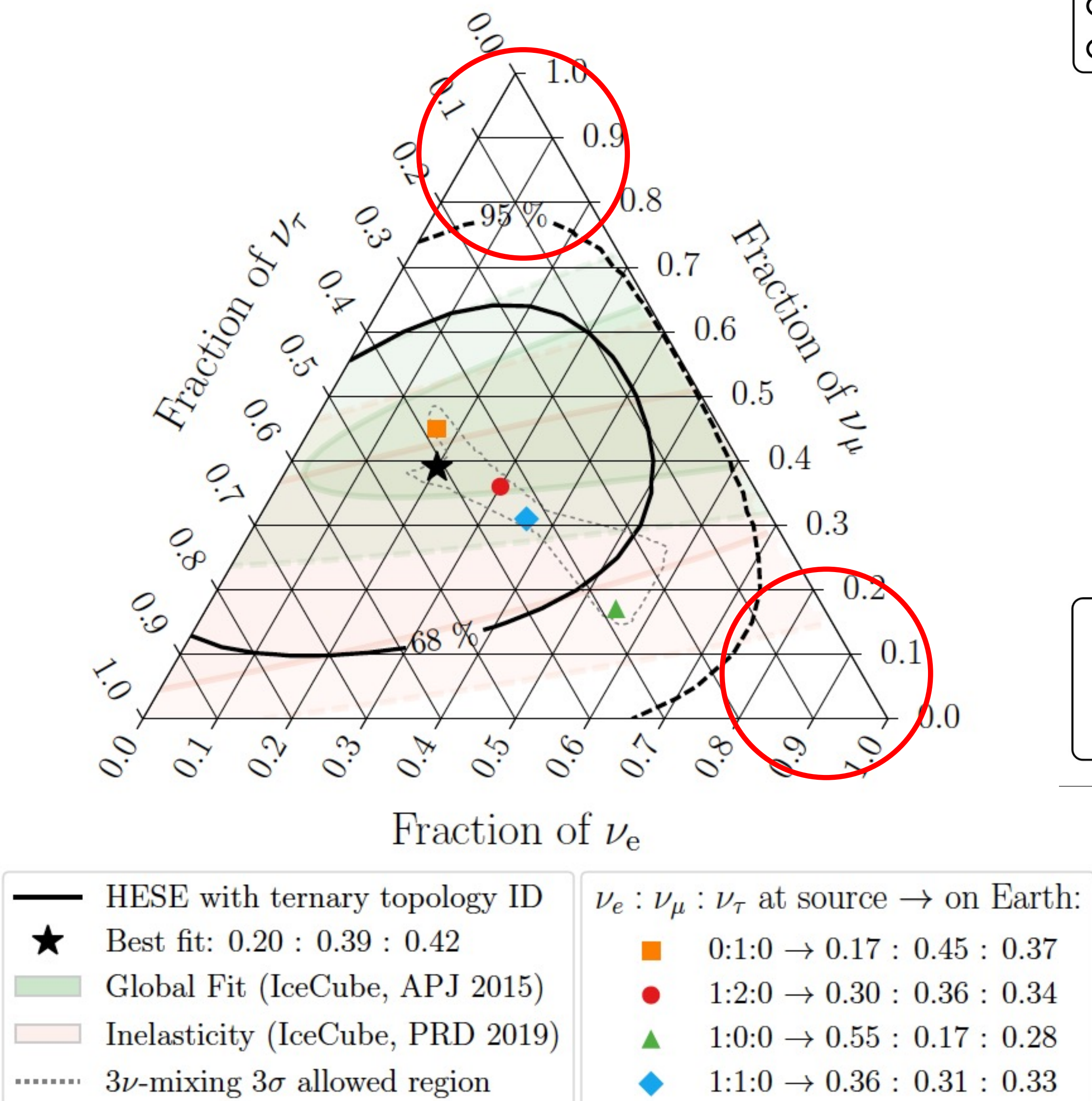
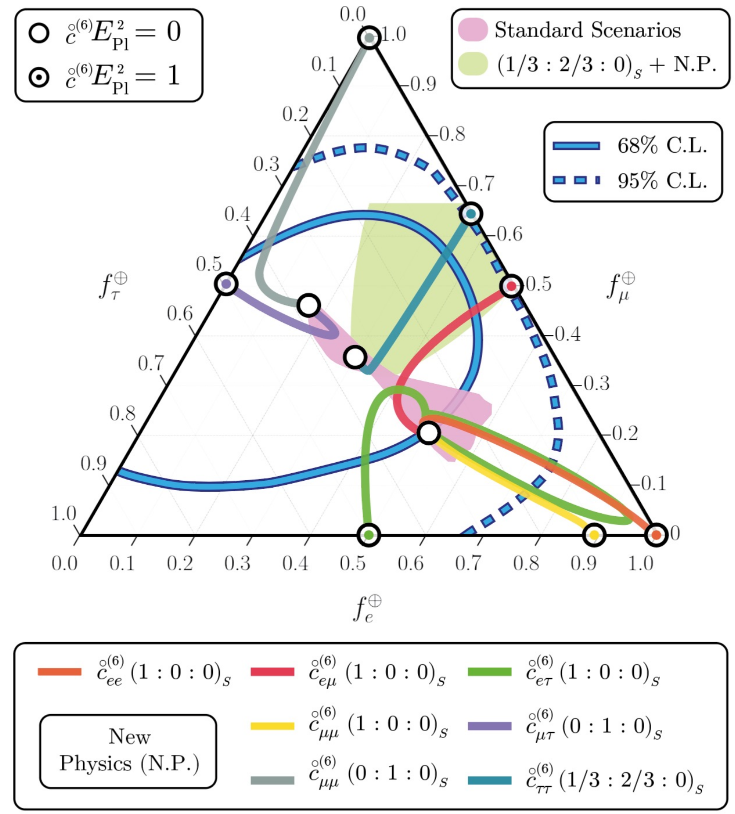




We are mainly testing scenarios where we assume astrophysical neutrino productions are dominated by ν_e or ν_μ

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

Neutrino interferometry – Atmospheric neutrinos

dim.	method	type	sector	limits	ref.
3	CMB polarization	astrophysical	photon	$\sim 10^{-43}$ GeV	[6]
	He-Xe comagnetometer	tabletop	neutron	$\sim 10^{-34}$ GeV	[10]
	torsion pendulum	tabletop	electron	$\sim 10^{-31}$ GeV	[12]
	muon g-2	accelerator	muon	$\sim 10^{-24}$ GeV	[13]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert$ $< 2.9 \times 10^{-24}$ GeV (99% C.L.) $< 2.0 \times 10^{-24}$ GeV (90% C.L.)	this work
4	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-38}$	[7]
	Laser interferometer	LIGO	photon	$\sim 10^{-22}$	[8]
	Sapphire cavity oscillator	tabletop	photon	$\sim 10^{-18}$	[5]
	Ne-Rb-K comagnetometer	tabletop	neutron	$\sim 10^{-29}$	[11]
	trapped Ca^{+} ion	tabletop	electron	$\sim 10^{-19}$	[14]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert$ $< 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work
5	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-34}$ GeV^{-1}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton	$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	[9]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert$ $< 2.3 \times 10^{-32}$ GeV^{-1} (99% C.L.) $< 1.5 \times 10^{-32}$ GeV^{-1} (90% C.L.)	this work
6	GRB vacuum birefringene	astrophysical	photon	$\sim 10^{-31}$ GeV^{-2}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton	$\sim 10^{-42}$ to 10^{-35} GeV^{-2}	[9]
	gravitational Cherenkov radiation	astrophysical	gravity	$\sim 10^{-31}$ GeV^{-2}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert$ $< 1.5 \times 10^{-36}$ GeV^{-2} (99% C.L.) $< 9.1 \times 10^{-37}$ GeV^{-2} (90% C.L.)	this work
7	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-28}$ GeV^{-3}	[7]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert$ $< 8.3 \times 10^{-41}$ GeV^{-3} (99% C.L.) $< 3.6 \times 10^{-41}$ GeV^{-3} (90% C.L.)	this work
8	gravitational Cherenkov radiation	astrophysical	gravity	$\sim 10^{-46}$ GeV^{-4}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert$ $< 5.2 \times 10^{-45}$ GeV^{-4} (99% C.L.) $< 1.4 \times 10^{-45}$ GeV^{-4} (90% C.L.)	this work

TABLE I: Comparison of attainable best limits of SME coefficients in various fields.

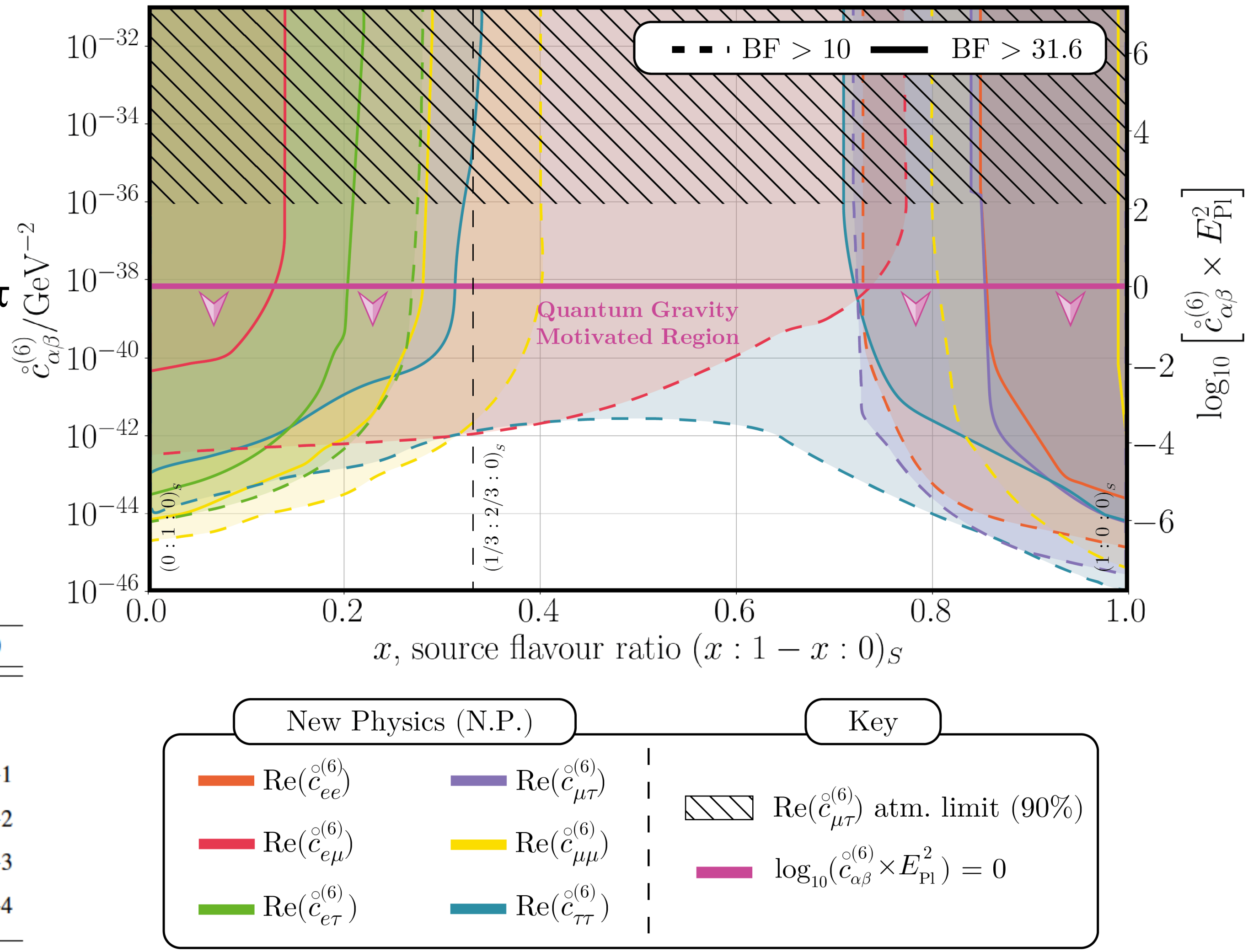
IceCube atmospheric neutrino limit, $c^{(6)} < 10^{-36} GeV^{-2}$
This is close to the target signal region, $c^{(6)} \sim 10^{-38} GeV^{-2}$

Neutrino interferometry – Atmospheric neutrinos

Strong limits on many parameters but they depend on the source flavour assumptions.

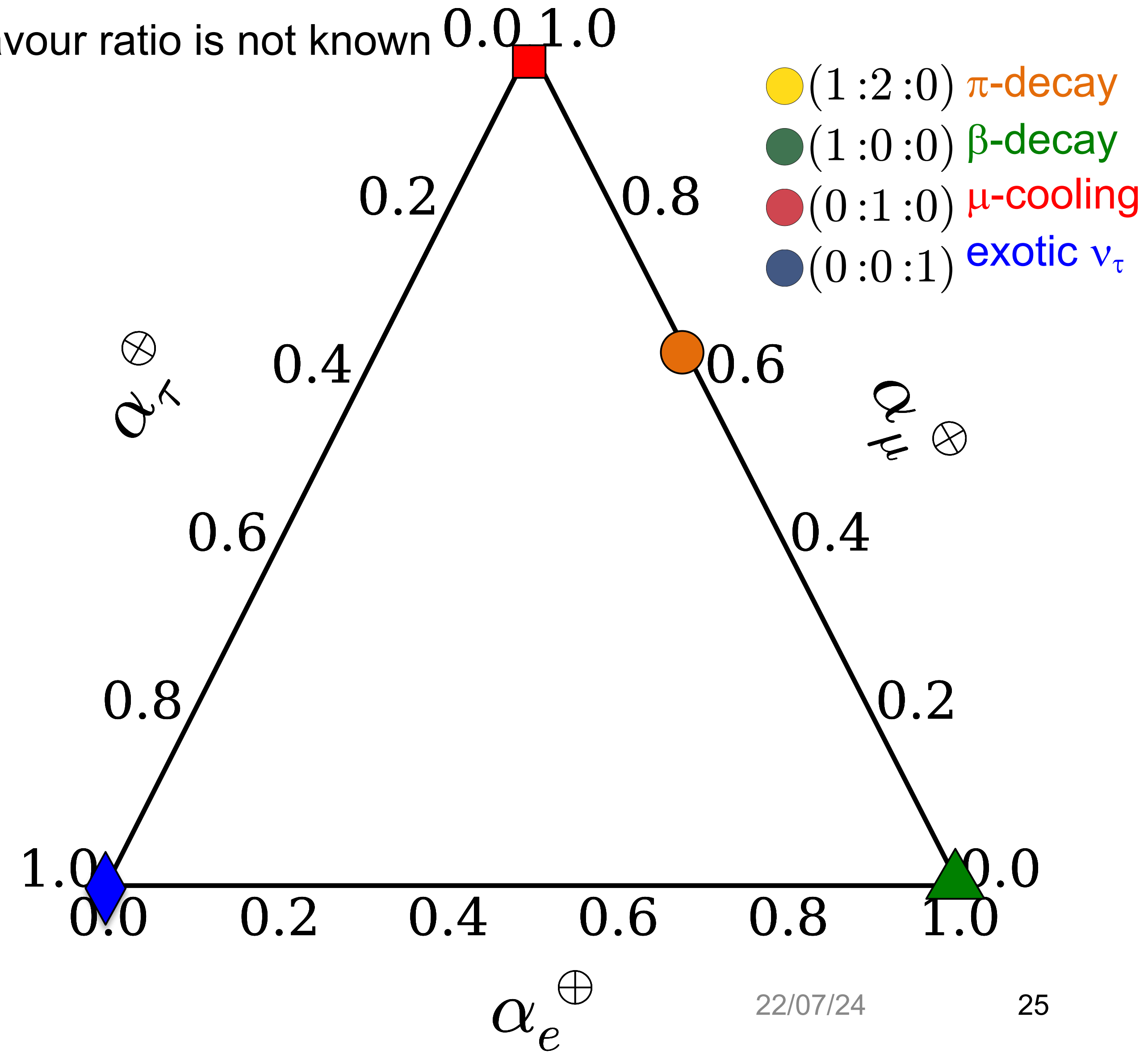
Substantial limits for $\tau\tau$ parameters are obtained through quantum Zeno effect

dim	coefficient	limit (BF> 10)
3	$\mathrm{Re}\,(\mathring{a}^{(3)}_{\tau\tau})$	2×10^{-26} GeV
4	$\mathrm{Re}\,(\mathring{c}^{(4)}_{\tau\tau})$	2×10^{-31}
5	$\mathrm{Re}\,(\mathring{a}^{(5)}_{\tau\tau})$	2×10^{-37} GeV^{-1}
6	$\mathrm{Re}\,(\mathring{c}^{(6)}_{\tau\tau})$	3×10^{-42} GeV^{-2}
7	$\mathrm{Re}\,(\mathring{a}^{(7)}_{\tau\tau})$	3×10^{-47} GeV^{-3}
8	$\mathrm{Re}\,(\mathring{c}^{(8)}_{\tau\tau})$	2×10^{-52} GeV^{-4}



Neutrino flavor ratio ($\nu_e : \nu_\mu : \nu_\tau$)

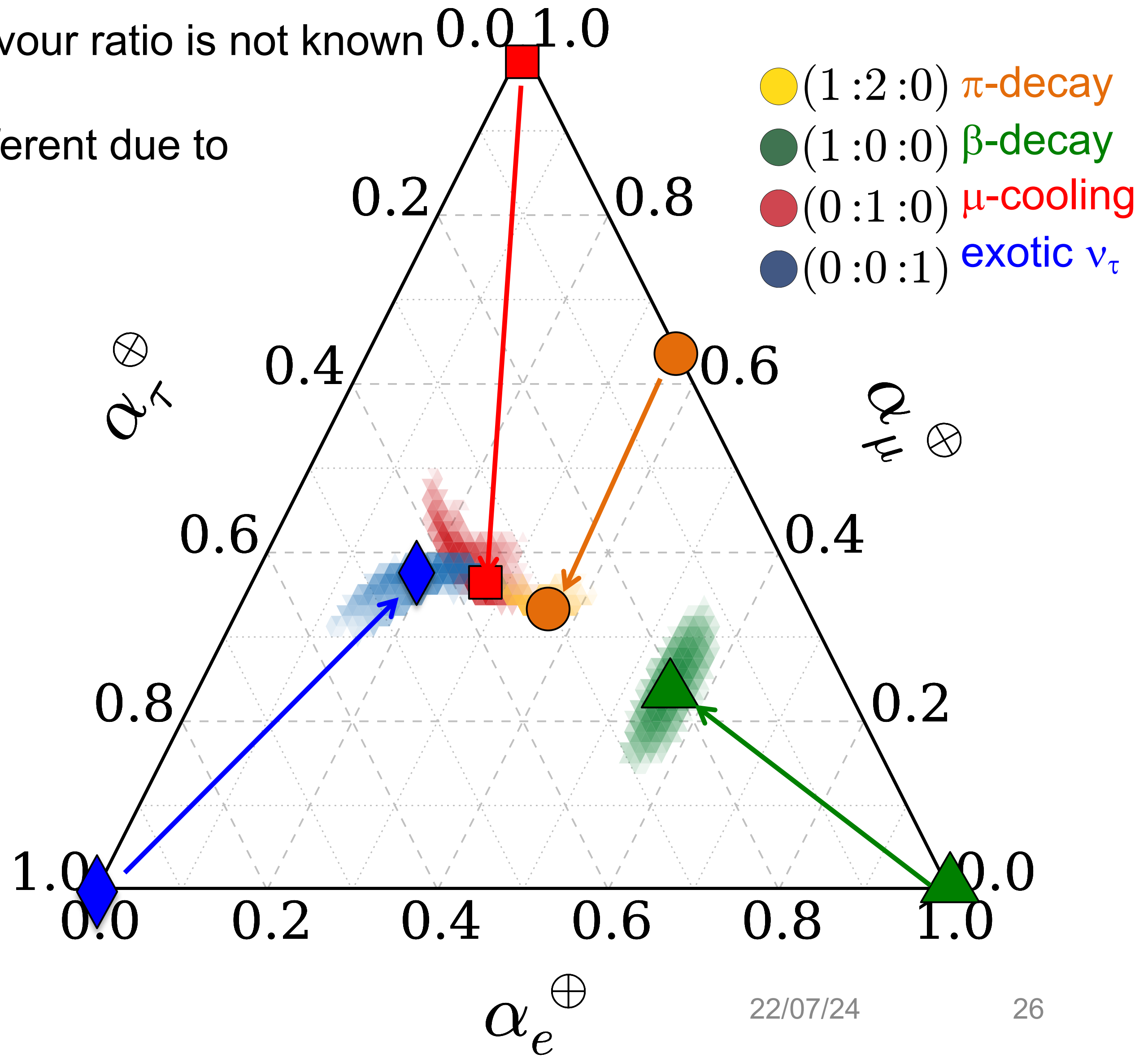
Astrophysical neutrino production mechanism is not known → production flavour ratio is not known



Neutrino flavor ratio ($\nu_e : \nu_\mu : \nu_\tau$)

Astrophysical neutrino production mechanism is not known → production flavour ratio is not known

Flavour ratio on Earth is different due to mixing by neutrino masses



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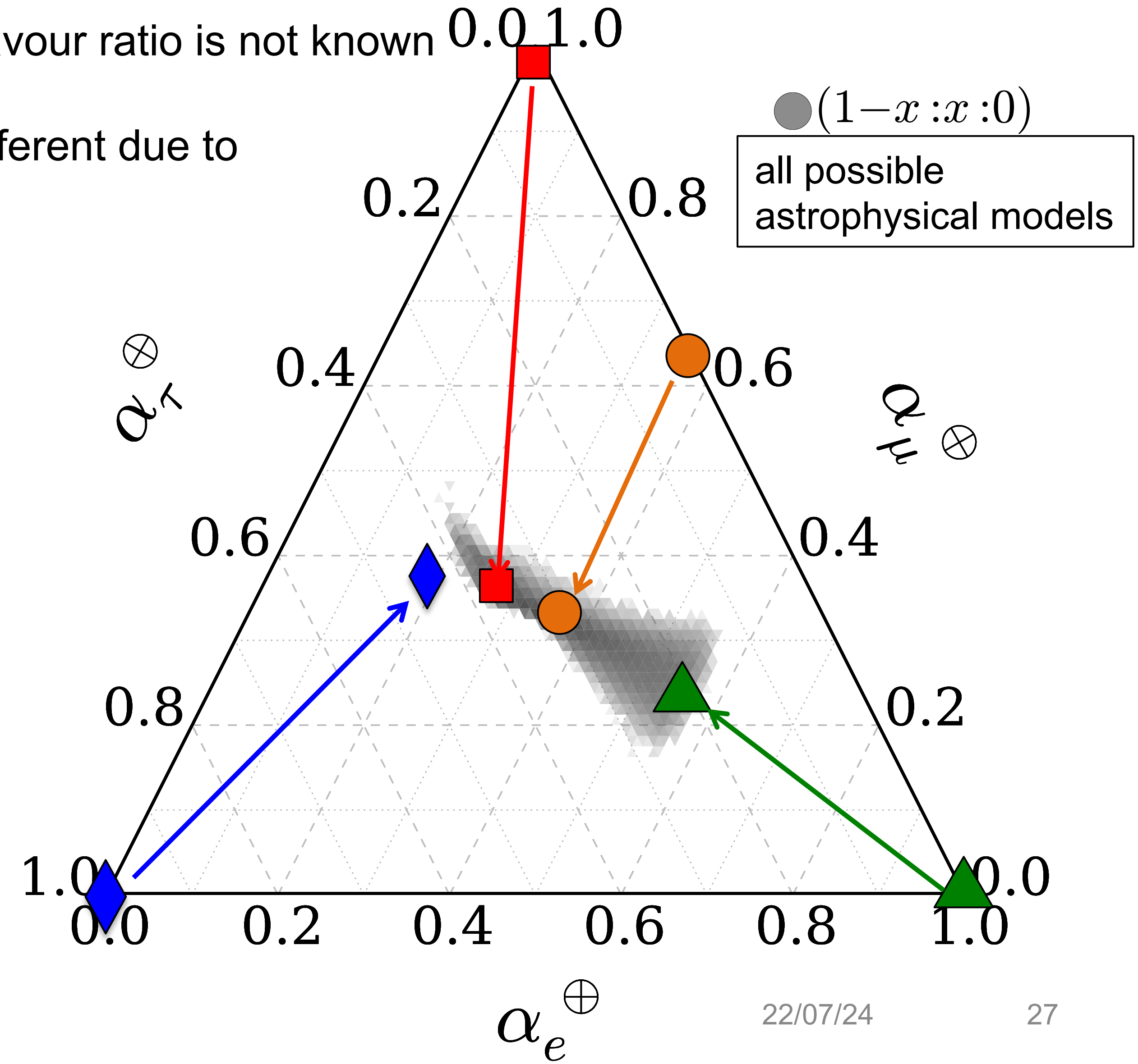
Flavour ratio on Earth is different due to mixing by neutrino masses

All possible flavour ratio is confined in a small space



Neutrino flavor ratio ($\nu_e : \nu_\mu : \nu_\tau$)

Astrophysical neutrino production mechanism is not known → production flavour ratio is not known

Flavour ratio on Earth is different due to mixing by neutrino masses

All possible flavour ratio is confined in a small space

e.g.) New physics just below the limit can produce any flavour ratio