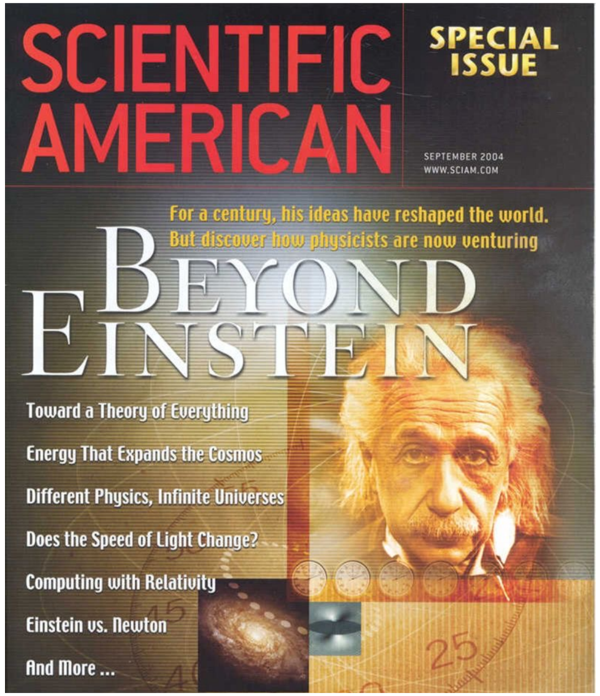
Tests of Spacetime Symmetry with Neutrinos

outline

1. Introduction
2. Tests of Lorentz violation with neutrinos
3. Tests of Lorentz violation with astrophysical neutrinos
4. Searches of ultralight dark matter with astrophysical neutrino flavor
5. Conclusion



Teppei Katori @teppeikatori
King's College London
Q-EYES 2025, KEK, Japan, Dec. 10, 2025

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Introduction

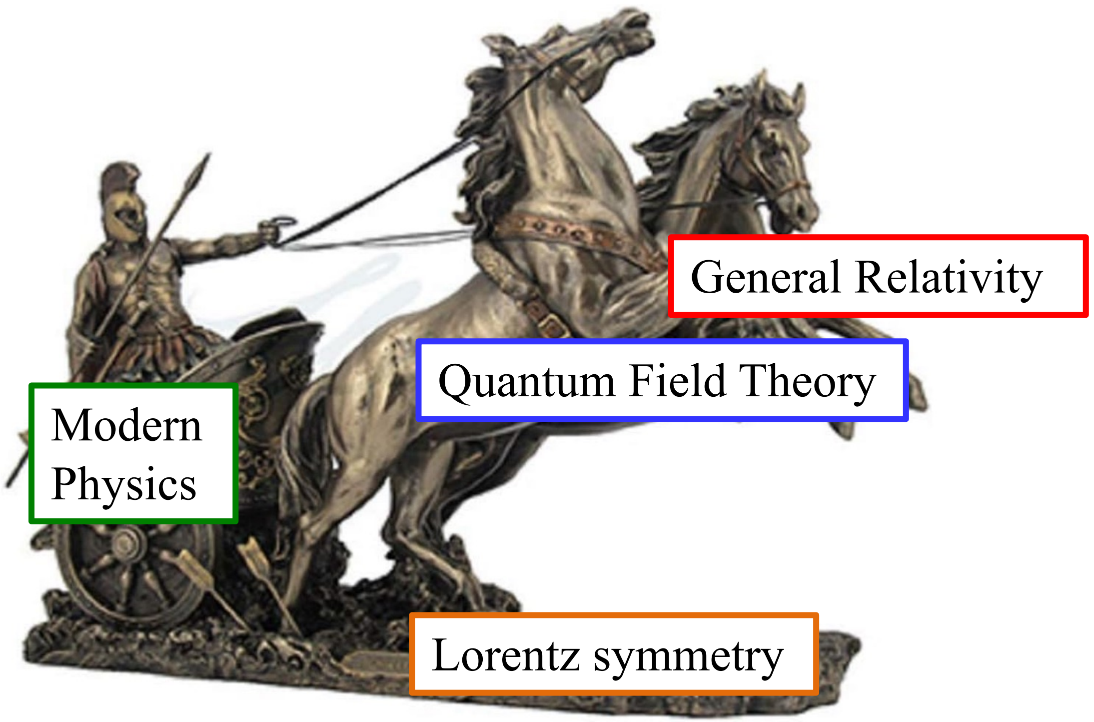
Lorentz violation

Quantum field theory and general relativity are the foundation of modern physics.

Special relativity is a basis for both quantum field theory and general relativity.

Special relativity is based on Lorentz symmetry

If the universe has a special direction, space doesn't have Lorentz symmetry and Lorentz transformation is violated → Lorentz violation



All fundamental physics phenomena must be experimentally tested including Lorentz symmetry

Parthey et al., PRL107(2011)203001

Fundamental Symmetry tests with Neutrinos

Atmospheric neutrinos
- Oscillation length L ~ 12700 km (at ~35 GeV)

→ the longest interferometer on earth

cf.) LIGO
- 4km arm + mirror ~ 1000 km equivalent

Astrophysical neutrinos
- energy reaches ~PeV

→ new physics sensitivity ~ 10^{-26} GeV

cf) High precision hydrogen 1S-2S transition

Fractional frequency uncertainty ~ 4×10^{-15}

→ new physics sensitivity ~10^{-23} GeV

Neutrinos are one of the best probes of fundamental symmetry tests!

https://higgstan.com/

Standard-Model Extension (SME)

Search of Lorentz violation is to find anomalous effects due to the couplings of background fields and ordinary fields (electrons, muons, neutrinos, etc)

SME is an effective field theory (EFT) framework to look for Lorentz violation

e.g.) vacuum Lagrangian for fermion

$$\mathcal{L} = i\bar{\psi}\gamma_\mu\partial^\mu\psi - m\bar{\psi}\psi + \bar{\psi}\gamma_\mu a^\mu\psi + \bar{\psi}\gamma_\mu c^{\mu\nu}\psi \cdots$$

Standard Model

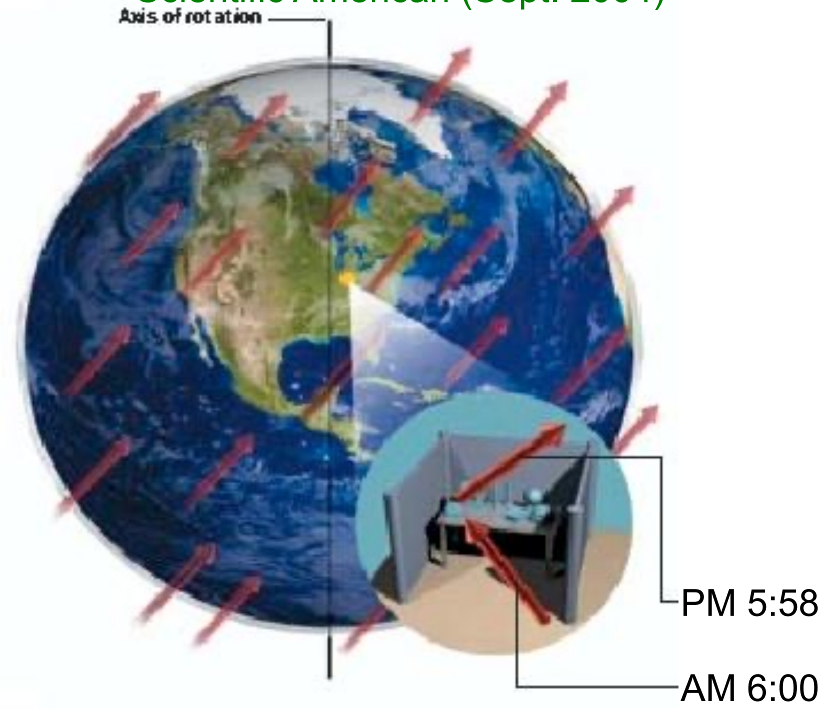
couplings with background fields

Physics of Lorentz violation

- Spectrum distortion,
- Sidereal time dependence,
- Anomalous flavour conversion,

etc

Scientific American (Sept. 2004)



Models of Lorentz violation

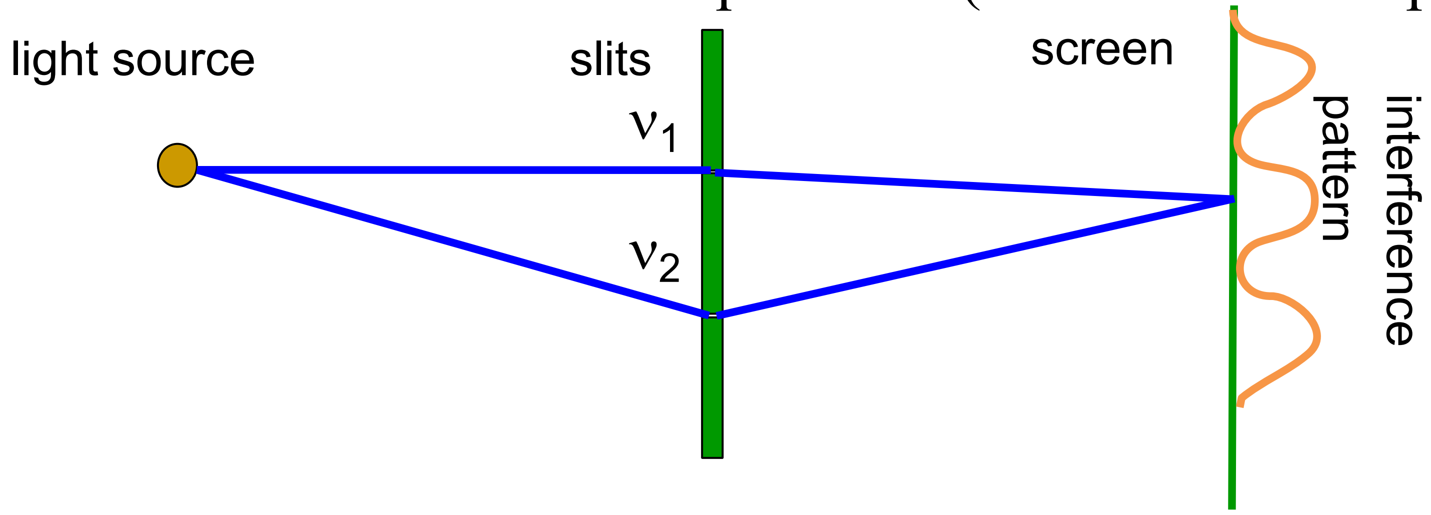
Long list of models including Lorentz violation

String theory, Kostelecký and Samuel, PRD39 (1989) 683
Ultra-light dark matter, Graham and Rajendran, PRD88 (2013) 035023
Quintessence, Ando, Kamionkowski, and Mocioiu, PRD80 (2009) 123522
Loop quantum gravity, Gambini and Pullin, PRD59 (1999) 124021
Non-commutative field theory, Carroll, Harvey, Kostelecký, Lane, Okamoto, PRL87 (2001) 141601
Hořava-Lifshitz gravity, Pospelov and Shang, PRD85 (2012) 105001
Lee-Wick theory, Myers and Pospelov, PRL90 (2003) 211601
etc

Tests of Lorentz Violation with Neutrinos

Neutrino oscillation experiments

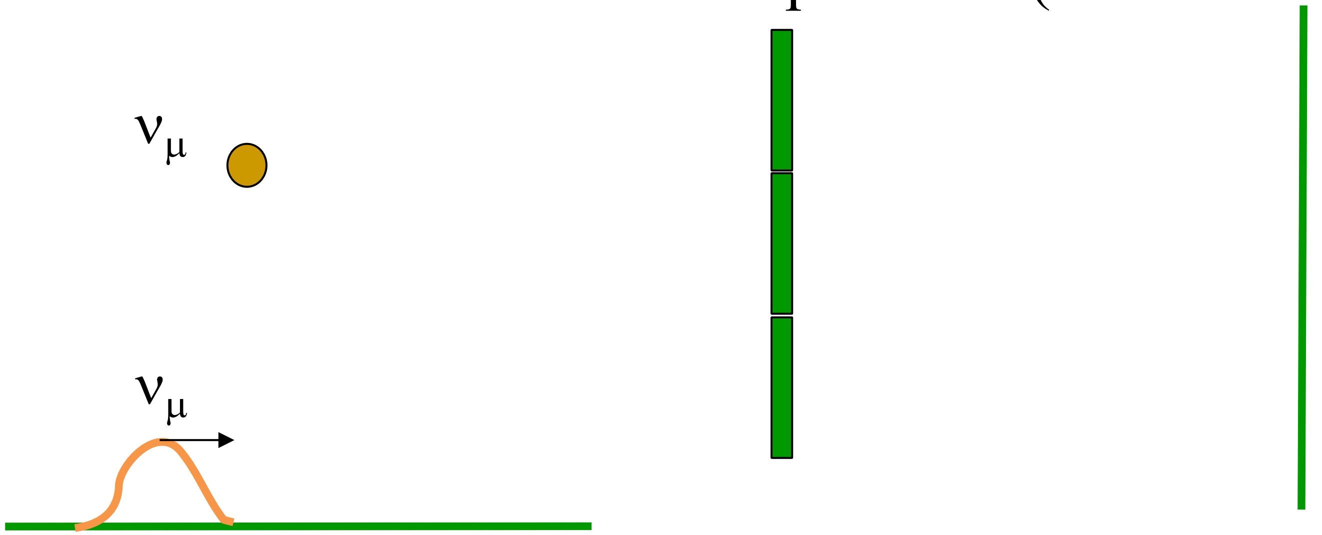
Neutrino oscillation is an interference experiment (cf. double slit experiment)



For double slit experiment, if path ν_1 and path ν_2 have different length, they have different phases and it causes interference.

Neutrino oscillation experiments

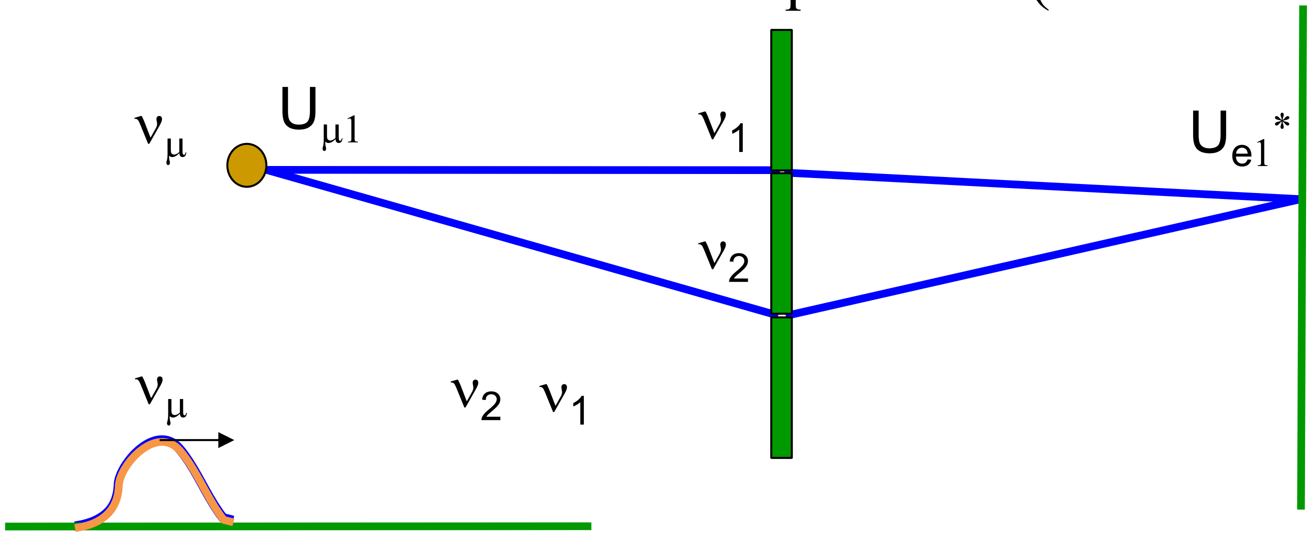
Neutrino oscillation is an interference experiment (cf. double slit experiment)



Neutrino flavour eigenstates are super-position of Hamiltonian eigenstates ν_1 and ν_2

Neutrino oscillation experiments

Neutrino oscillation is an interference experiment (cf. double slit experiment)

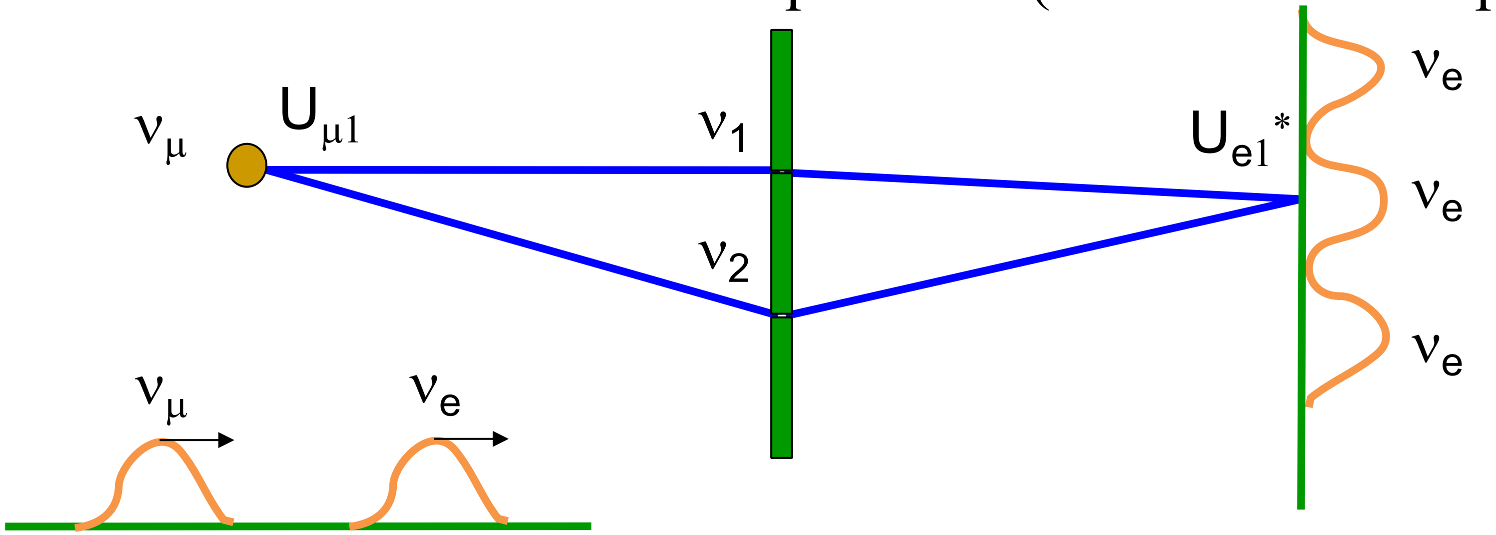


Neutrino flavour eigenstates are super-position of Hamiltonian eigenstates ν_1 and ν_2

Difference in velocities cause quantum interference

Neutrino oscillation experiments

Neutrino oscillation is an interference experiment (cf. double slit experiment)



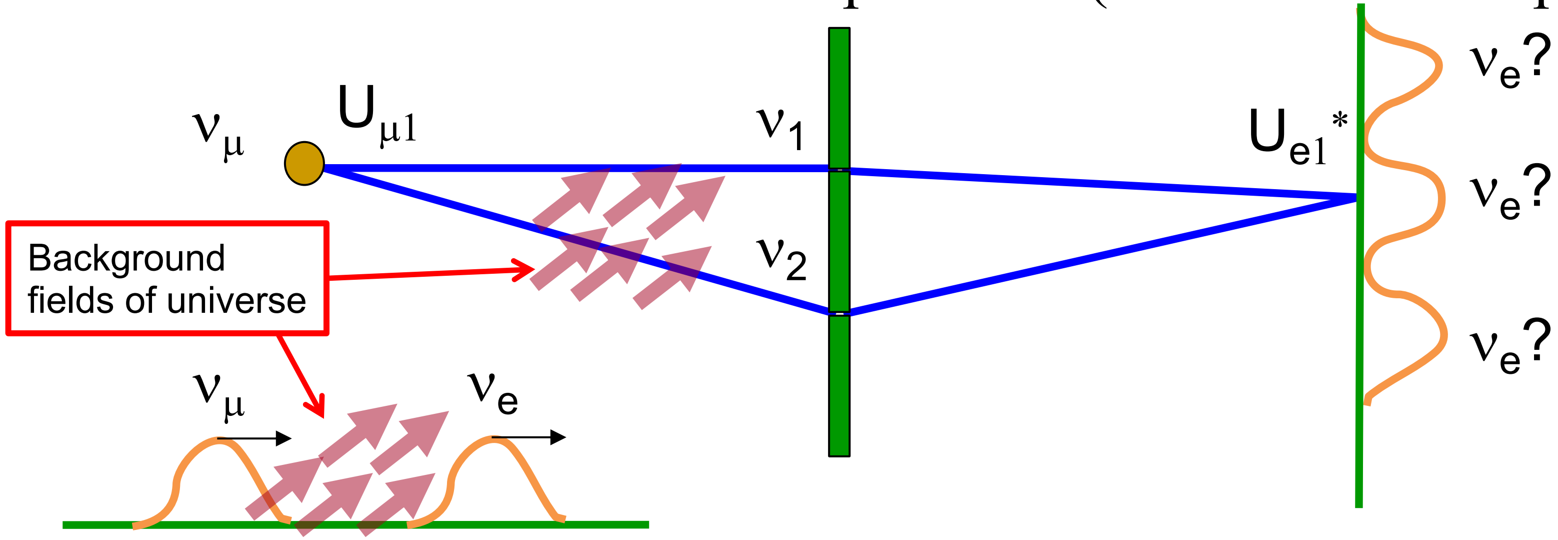
Neutrino flavour eigenstates are super-position of Hamiltonian eigenstates ν_1 and ν_2

Difference in velocities cause quantum interference

The detection may be different flavour (neutrino oscillations)

Neutrino oscillation experiments

Neutrino oscillation is an interference experiment (cf. double slit experiment)



Neutrino flavour eigenstates are super-position of Hamiltonian eigenstates ν_1 and ν_2

Difference in velocities cause quantum interference

The detection may be different flavour (neutrino oscillations)

Neutrino propagation may be affected by background fields

→ anomalous neutrino oscillation results

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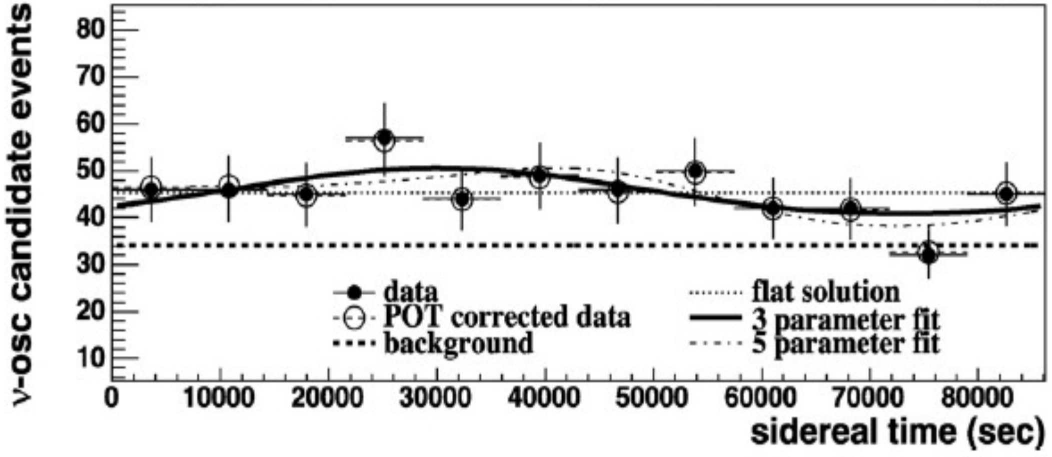
MiniBooNE ν_e appearance candidate data

Anomalous ν_e candidate low-energy excess

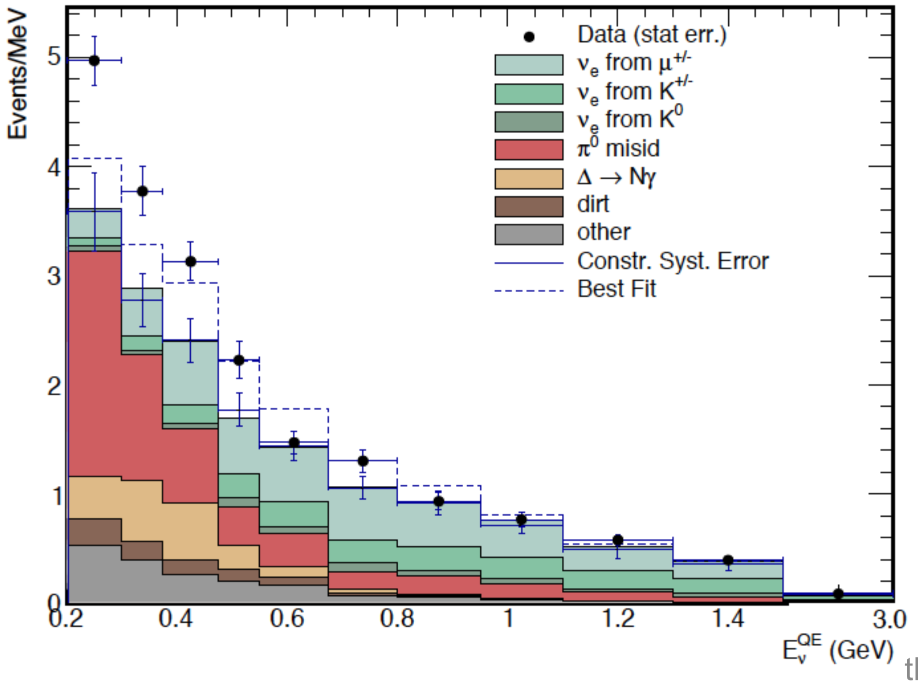
- Short baseline $\nu_\mu \rightarrow \nu_e$ oscillation experiment
- Data show no sidereal time dependent modulation

→ set limits on SME coefficients



ν_e excess sidereal time distribution

MiniBooNE low E ν_e excess



	ν-mode BF	2σ limit	$\bar{\nu}$-mode BF	2σ limit
$\lvert(\mathcal{C})_{e\mu}\rvert$	$3.1 \pm 0.6 \pm 0.9$	< 4.2	$0.1 \pm 0.8 \pm 0.1$	< 2.6
$\lvert(\mathcal{A}_s)_{e\mu}\rvert$	$0.6 \pm 0.9 \pm 0.3$	< 3.3	$2.4 \pm 1.3 \pm 0.5$	< 3.9
$\lvert(\mathcal{A}_c)_{e\mu}\rvert$	$0.4 \pm 0.9 \pm 0.4$	< 4.0	$2.1 \pm 1.2 \pm 0.4$	< 3.7

	SME coefficients combination (unit 10^{-20} GeV)
$\lvert(\mathcal{C})_{e\mu}\rvert$	$\pm[(a_L)^T_{e\mu} + 0.75(a_L)^Z_{e\mu}] - \langle E\rangle[1.22(c_L)^{TT}_{e\mu} + 1.50(c_L)^{TZ}_{e\mu} + 0.34(c_L)^{ZZ}_{e\mu}]$
$\lvert(\mathcal{A}_s)_{e\mu}\rvert$	$\pm[0.66(a_L)^Y_{e\mu}] - \langle E\rangle[1.33(c_L)^{TY}_{e\mu} + 0.99(c_L)^{YZ}_{e\mu}]$
$\lvert(\mathcal{A}_c)_{e\mu}\rvert$	$\pm[0.66(a_L)^X_{e\mu}] - \langle E\rangle[1.33(c_L)^{TX}_{e\mu} + 0.99(c_L)^{XZ}_{e\mu}]$

SME coefficients (Lorentz violation) limits

IceCube atmospheric neutrino spectrum distortion

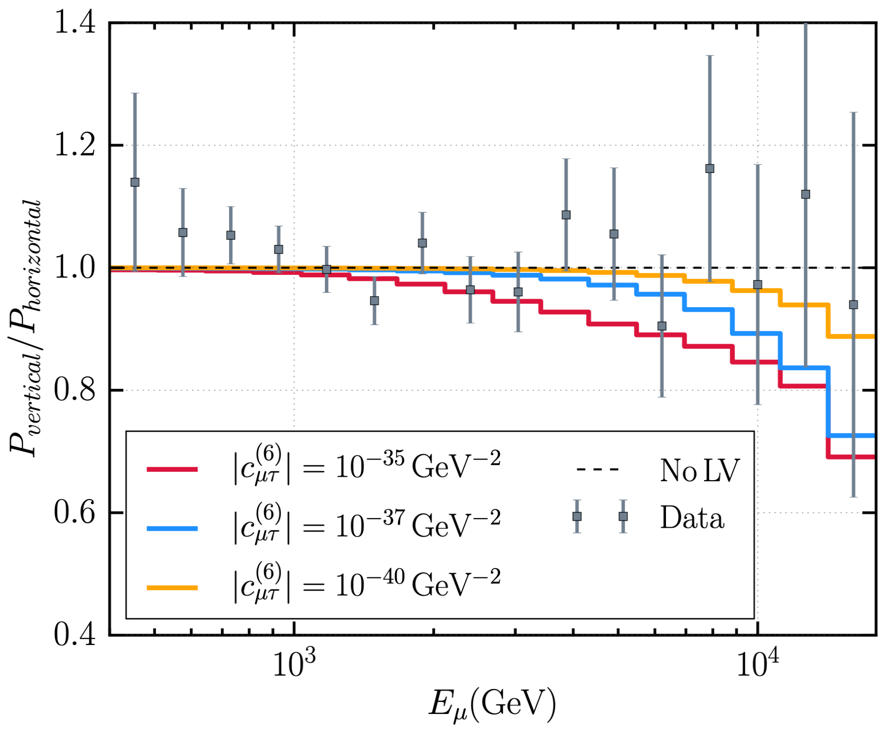
Anomalous ν_μ disappearance

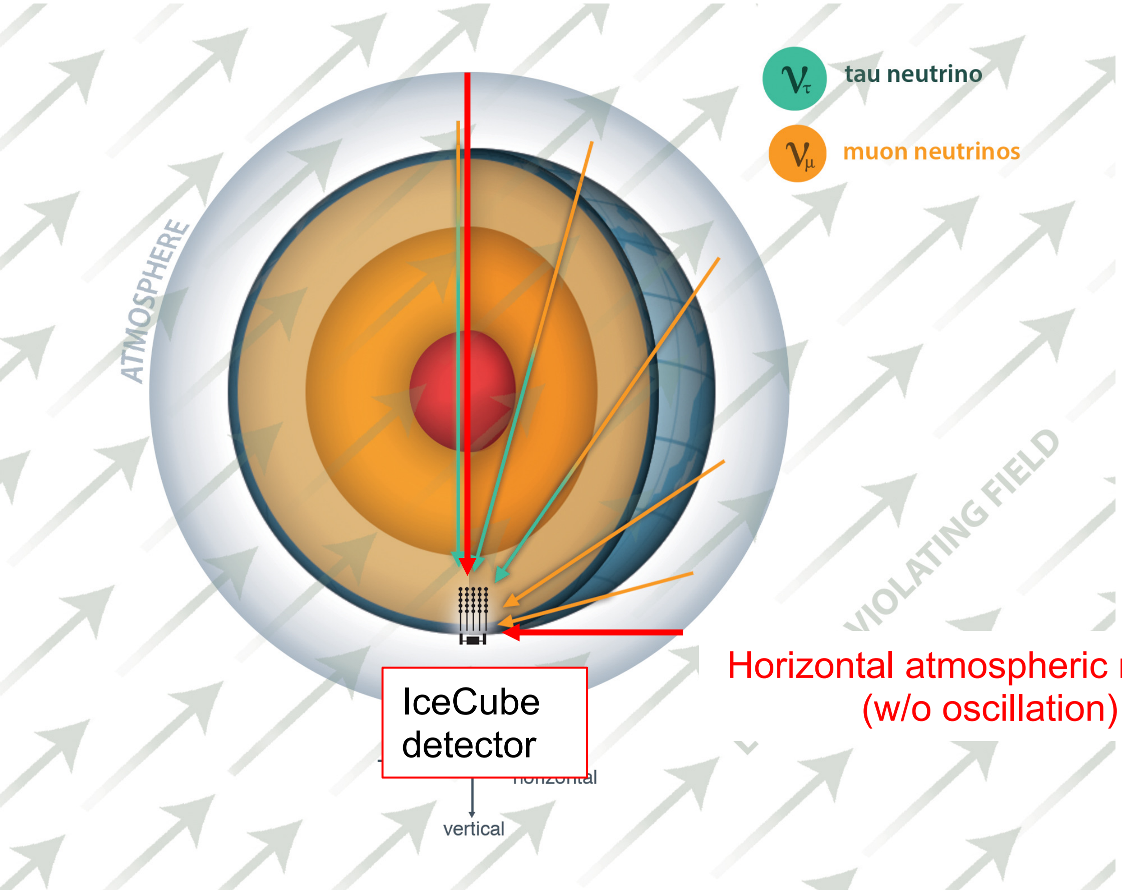
- Strong effect at high-energy and long propagation
- Data show no spectrum distortion

→ set limits on SME coefficients

Vertical atmospheric neutrino (w/ oscillation)

Atmospheric muon neutrino double ratio





Horizontal atmospheric neutrino (w/o oscillation)

Lorentz violation tests with neutrinos – Summary

Limits of all SME coefficients are summarized in tables [ArXiv:0801.0287v18](https://arxiv.org/abs/0801.0287v18)

So far, there is no compelling evidence of Lorentz violation

When do we find it???

~30-page limits in neutrino sector LV...

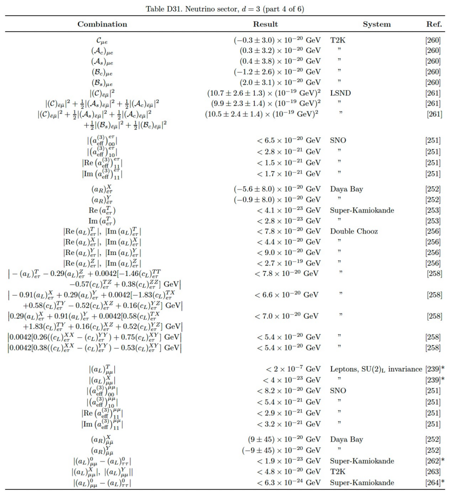
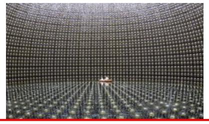


Table D31. Neutrino sector, $d=3$ (part 4 of 6)

Combination	Result	System	Ref.
$\mathcal{C}_{\mu e}$	$(-0.3\pm3.0)\times10^{-20}$ GeV	T2K	[260]
$(\mathcal{A}_c)_{\mu e}$	$(0.3\pm3.2)\times10^{-20}$ GeV	"	[260]
$(\mathcal{A}_s)_{\mu e}$	$(0.4\pm3.8)\times10^{-20}$ GeV	"	[260]
$(\mathcal{B}_c)_{\mu e}$	$(-1.2\pm2.6)\times10^{-20}$ GeV	"	[260]
$(\mathcal{B}_s)_{\mu e}$	$(2.0\pm3.1)\times10^{-20}$ GeV	"	[260]
$\lvert(\mathcal{C})_{\bar e\bar\mu}\rvert^2$	$(10.7\pm2.6\pm1.3)\times(10^{-19}\text{ GeV})^2$	LSND	[261]
$\lvert(\mathcal{C})_{\bar e\bar\mu}\rvert^2+\frac12\lvert(\mathcal{A}_s)_{\bar e\bar\mu}\rvert^2+\frac12\lvert(\mathcal{A}_c)_{\bar e\bar\mu}\rvert^2$	$(9.9\pm2.3\pm1.4)\times(10^{-19}\text{ GeV})^2$	"	[261]
$\lvert(\mathcal{C})_{\bar e\bar\mu}\rvert^2+\frac12\lvert(\mathcal{A}_s)_{\bar e\bar\mu}\rvert^2+\frac12\lvert(\mathcal{A}_c)_{\bar e\bar\mu}\rvert^2+\frac12\lvert(\mathcal{B}_s)_{\bar e\bar\mu}\rvert^2+\frac12\lvert(\mathcal{B}_c)_{\bar e\bar\mu}\rvert^2$	$(10.5\pm2.4\pm1.4)\times(10^{-19}\text{ GeV})^2$	"	[261]
$\lvert(a^{(3)}_{\text{eff}})^{e\tau}_{00}\rvert$	$<6.5\times10^{-20}$ GeV	SNO	[251]
$\lvert(a^{(3)}_{\text{eff}})^{e\tau}_{10}\rvert$	$<2.8\times10^{-21}$ GeV	"	[251]
$\lvert\text{Re}\,(a^{(3)}_{\text{eff}})^{e\tau}_{11}\rvert$	$<1.5\times10^{-21}$ GeV	"	[251]
$\lvert\text{Im}\,(a^{(3)}_{\text{eff}})^{e\tau}_{11}\rvert$	$<1.7\times10^{-21}$ GeV	"	[251]
$(a_R)^X_{\bar e\bar\tau}$	$(-5.6\pm8.0)\times10^{-20}$ GeV	Daya Bay	[252]
$(a_R)^Y_{\bar e\bar\tau}$	$(-0.9\pm8.0)\times10^{-20}$ GeV	"	[252]
$\text{Re}\,(a^T_{e\tau})$	$<4.1\times10^{-23}$ GeV	Super-Kamiokande	[253]
$\text{Im}\,(a^T_{e\tau})$	$<2.8\times10^{-23}$ GeV	"	[253]
$\lvert\text{Re}\,(a_L)^T_{e\tau}\rvert,\ \lvert\text{Im}\,(a_L)^T_{e\tau}\rvert$	$<7.8\times10^{-20}$ GeV	Double Chooz	[256]
$\lvert\text{Re}\,(a_L)^X_{e\tau}\rvert,\ \lvert\text{Im}\,(a_L)^X_{e\tau}\rvert$	$<4.4\times10^{-20}$ GeV	"	[256]
$\lvert\text{Re}\,(a_L)^Y_{e\tau}\rvert,\ \lvert\text{Im}\,(a_L)^Y_{e\tau}\rvert$	$<9.0\times10^{-20}$ GeV	"	[256]
$\lvert\text{Re}\,(a_L)^Z_{e\tau}\rvert,\ \lvert\text{Im}\,(a_L)^Z_{e\tau}\rvert$	$<2.7\times10^{-19}$ GeV	"	[256]
$\lvert-(a_L)^T_{e\tau}-0.29(a_L)^Z_{e\tau}+0.0042[-1.46(c_L)^{TT}_{e\tau}-0.57(c_L)^{TZ}_{e\tau}+0.38(c_L)^{ZZ}_{e\tau}]\text{ GeV}\rvert$	$<7.8\times10^{-20}$ GeV	"	[258]
$\lvert-0.91(a_L)^X_{e\tau}+0.29(a_L)^Y_{e\tau}+0.0042[-1.83(c_L)^{TX}_{e\tau}+0.58(c_L)^{TY}_{e\tau}-0.52(c_L)^{XZ}_{e\tau}+0.16(c_L)^{YZ}_{e\tau}]\text{ GeV}\rvert$	$<6.6\times10^{-20}$ GeV	"	[258]
$\lvert0.29(a_L)^X_{e\tau}+0.91(a_L)^Y_{e\tau}+0.0042[0.58(c_L)^{TX}_{e\tau}+1.83(c_L)^{TY}_{e\tau}+0.16(c_L)^{XZ}_{e\tau}+0.52(c_L)^{YZ}_{e\tau}]\text{ GeV}\rvert$	$<7.0\times10^{-20}$ GeV	"	[258]
$\lvert0.0042[0.26((c_L)^{XX}_{e\tau}-(c_L)^{YY}_{e\tau})+0.75(c_L)^{XY}_{e\tau}]\text{ GeV}\rvert$	$<5.4\times10^{-20}$ GeV	"	[258]
$\lvert0.0042[0.38((c_L)^{XX}_{e\tau}-(c_L)^{YY}_{e\tau})-0.53(c_L)^{XY}_{e\tau}]\text{ GeV}\rvert$	$<5.4\times10^{-20}$ GeV	"	[258]
$\lvert(a_L)^T_{\mu\mu}\rvert$	$<2\times10^{-7}$ GeV	Leptons, $SU(2)_L$ invariance	[239]*
$\lvert(a_L)^X_{\mu\mu}\rvert$	$<4\times10^{-23}$ GeV	"	[239]*
$\lvert(a^{(3)}_{\text{eff}})^{\mu\mu}_{00}\rvert$	$<8.2\times10^{-20}$ GeV	SNO	[251]
$\lvert(a^{(3)}_{\text{eff}})^{\mu\mu}_{10}\rvert$	$<5.4\times10^{-21}$ GeV	"	[251]
$\lvert\text{Re}\,(a^{(3)}_{\text{eff}})^{\mu\mu}_{11}\rvert$	$<2.9\times10^{-21}$ GeV	"	[251]
$\lvert\text{Im}\,(a^{(3)}_{\text{eff}})^{\mu\mu}_{11}\rvert$	$<3.2\times10^{-21}$ GeV	"	[251]
$(a_R)^X_{\bar\mu\bar\mu}$	$(9\pm45)\times10^{-20}$ GeV	Daya Bay	[252]
$(a_R)^Y_{\bar\mu\bar\mu}$	$(-9\pm45)\times10^{-20}$ GeV	"	[252]
$\lvert(a_L)^0_{\mu\mu}-(a_L)^0_{\tau\tau}\rvert$	$<1.9\times10^{-23}$ GeV	Super-Kamiokande	[262]*
$\lvert(a_L)^X_{\mu\mu}\rvert,\ \lvert(a_L)^Y_{\mu\mu}\rvert$	$<4.8\times10^{-20}$ GeV	T2K	[263]
$\lvert(a_L)^0_{\mu\mu}-(a_L)^0_{\tau\tau}\rvert$	$<6.3\times10^{-24}$ GeV	Super-Kamiokande	[264]*

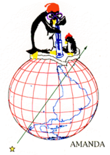
Spectral distortion



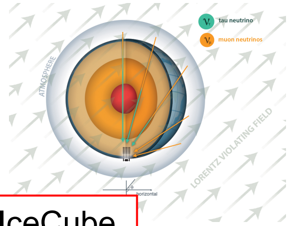
Super-Kamiokande
PRD91(2015)052003

Daya Bay

PRD98(2018)092013

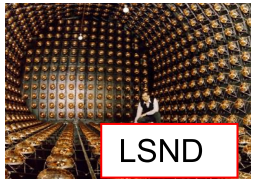


AMANDA
PRD79(2009)102005



IceCube
Nature Physics 14(2018)961

Sidereal variation



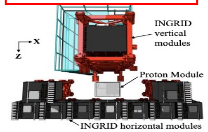
LSND
PRD72(2005)076004

MiniBooNE
PLB718(2013)1303

MINOS ND
PRL101(2008)151601

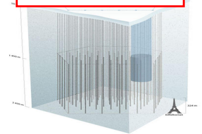
MINOS FD
PRL105(2010)151601

T2K ND



PRD95(2017)111101

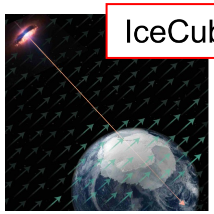
IceCube



PRD82(2010)112003

Double Chooz
PRD86(2013)112009

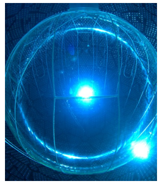
Flavor ratio



IceCube
Nature Physics, 18(2022)1287

Seasonal variation

SNO



PRD98(2018)112013

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When do we find Lorentz violation???

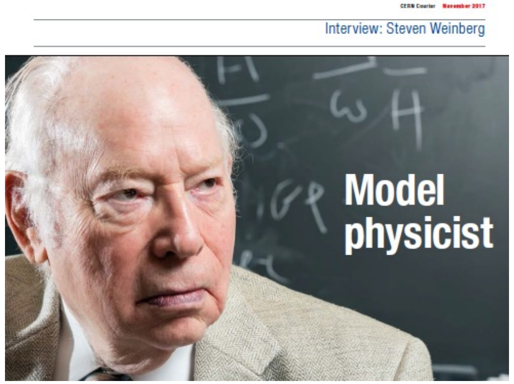
Lorentz violation is motivated by Planck scale theories, so it is suppressed with the power of Planck mass ($\sim 10^{19}\ GeV$)

$$\sim \frac{1}{M_{Pl}}, \left(\frac{1}{M_{Pl}}\right)^2, etc$$

In effective field theory, non-renormalizable operators are the signature of new physics, dimension analysis guides target sensitivity to look for Lorentz violation.

dimension-5 LV operator, $a^{(5)} < 10^{-19}\ GeV^{-1}$
dimension-6 LV operator, $c^{(6)} < 10^{-38}\ GeV^{-2}$
etc

These numbers can be used as a guidance to design new experiments



Steven Weinberg
(CERN Courier Nov. 2017)

"We don't know anything about non-renormalizable interaction terms, but I'll swear they are there!'

Tests of Lorentz violation with astrophysical neutrinos

Terrestrial experiments
- controlled, high-precision

So far, no compelling evidence of Lorentz violation

Atmospheric, astrophysical, and cosmological experiments
- not controlled, low-precision
- extreme systems (high energy, long propagation, etc)
- more sensitive to nonrenormalizable operators

Tests of Lorentz Violation with Astrophysical Neutrinos

Progress in Particle and Nuclear Physics 125 (2022) 103948

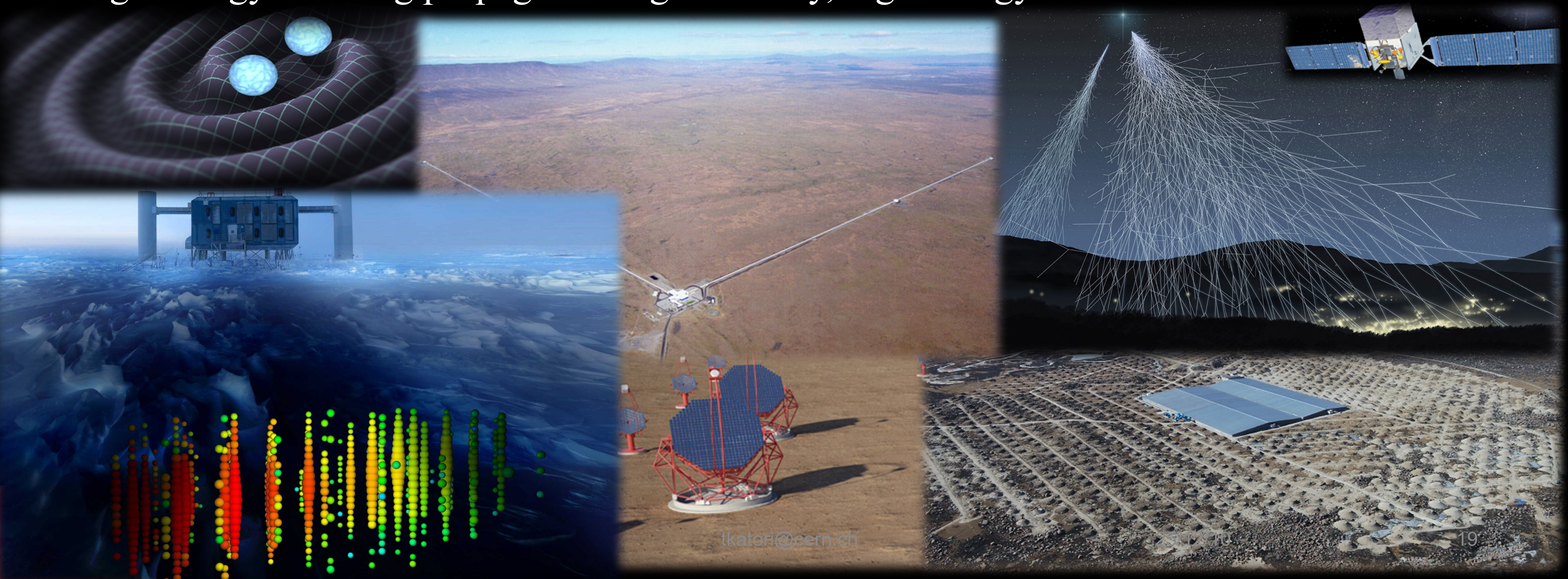
Lorentz violation in Astrophysics


Contents lists available at ScienceDirect
Progress in Particle and Nuclear Physics
journal homepage: www.elsevier.com/locate/ppnp

Review

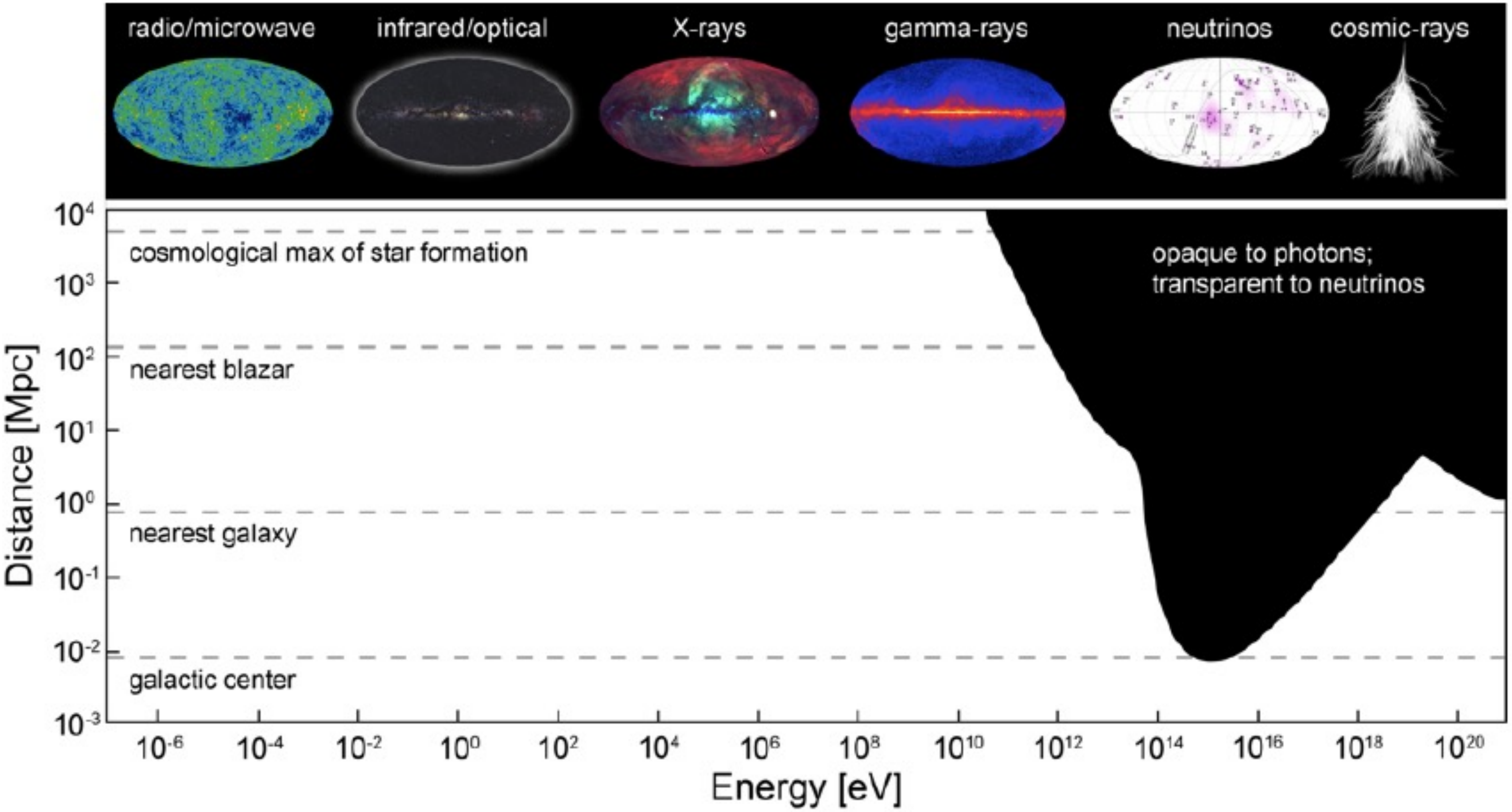
Quantum gravity phenomenology at the dawn of the multi-messenger era—A review

Highest energy particles – ultra-high-energy cosmic rays
Longest propagating waves – gravitational waves, cosmic microwave background
High-energy and long propagation – gamma-ray, high-energy neutrinos



High-energy astrophysical neutrinos

Neutrinos are the highest-energy (>100 TeV) longest-baseline (> Mpc) quantum system



Snowmass21, EPJC83(2023)15, Snowmass, JHEA36(2022)55, COST Action CA18108 PPNP125(2022)103948

High-energy, long propagating neutrinos

High-energy astrophysical neutrinos

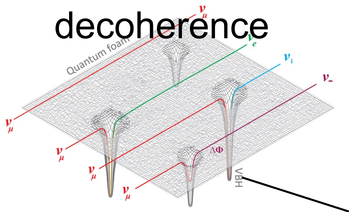
- Long baseline accumulates new physics effect
- High energy enhances new physics effect
- Quantum interference magnify a small effect

$$H \sim \frac{m^2}{2E} + V(new\ physics)$$

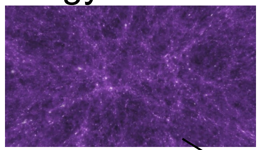
$$P \sim V(new\ physics) \cdot L$$

Energy spectrum, arrival time, flavor are affected by production, propagation, detection of neutrinos

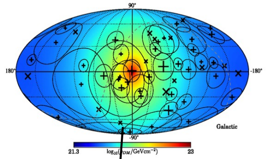
Quantum decoherence



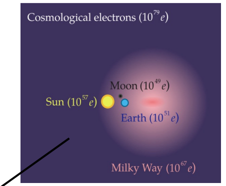
Neutrino – dark energy interaction



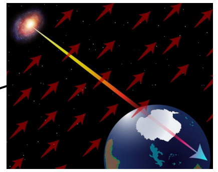
Neutrino – dark matter interaction



Long range force

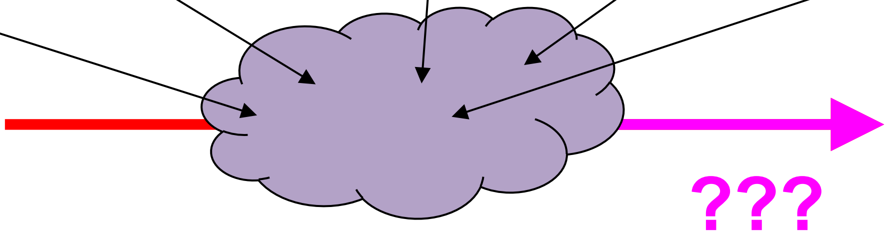


Lorentz violation



etc

High-energy Astrophysical objects



New physics

???

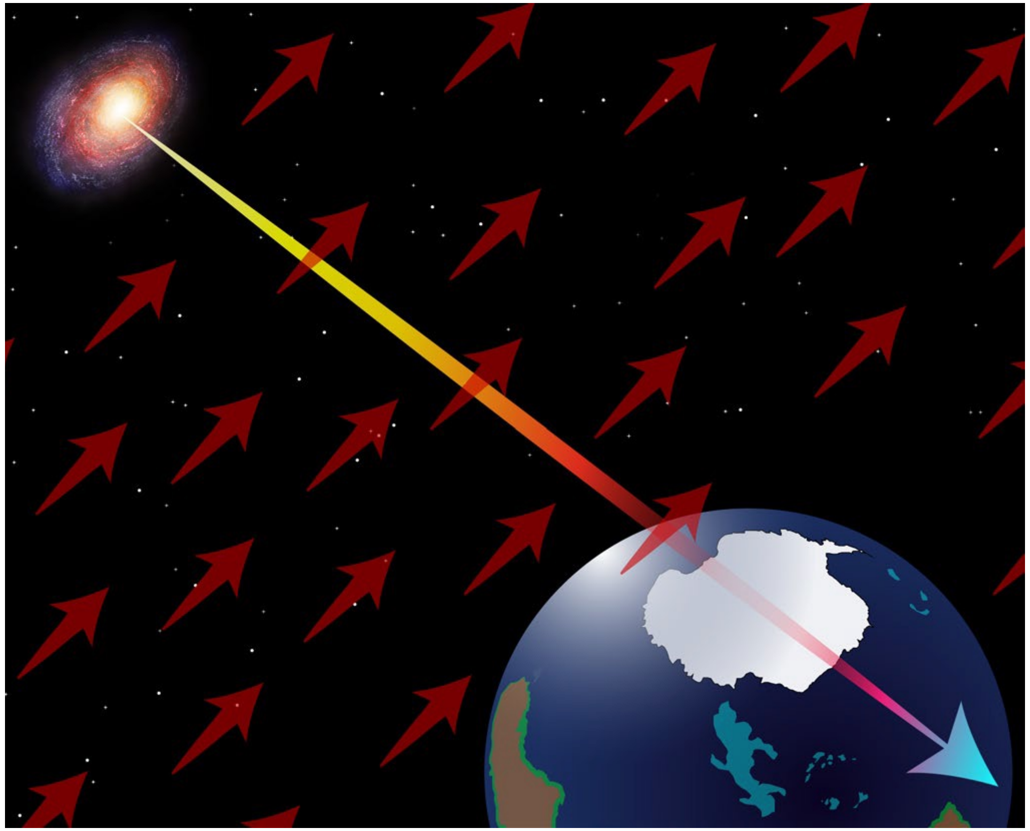
Neutrino detector

IceCube, Nature Physics(2022), (2024), Klop,Ando, PRD97(2018)063006,Argüelles,Kheirandish,Vincent, PRL119(2017)201801, Bustamante,Agarwalla, PRL122(2019)061103, Amelino-Camelia, ,Di Luca, Gubitosi, Rosati, D'Amico, Nature Astronomy (2023)

High-energy, long propagating neutrinos

Violation of Lorentz invariance

- Theoretically motivated (long list of models)
- Neutrino interacting with new fields in vacuum
- Matter potential in vacuum, but very small
- Energy spectrum, arrival time, flavor are affected
- Astrophysical neutrino flavor physics



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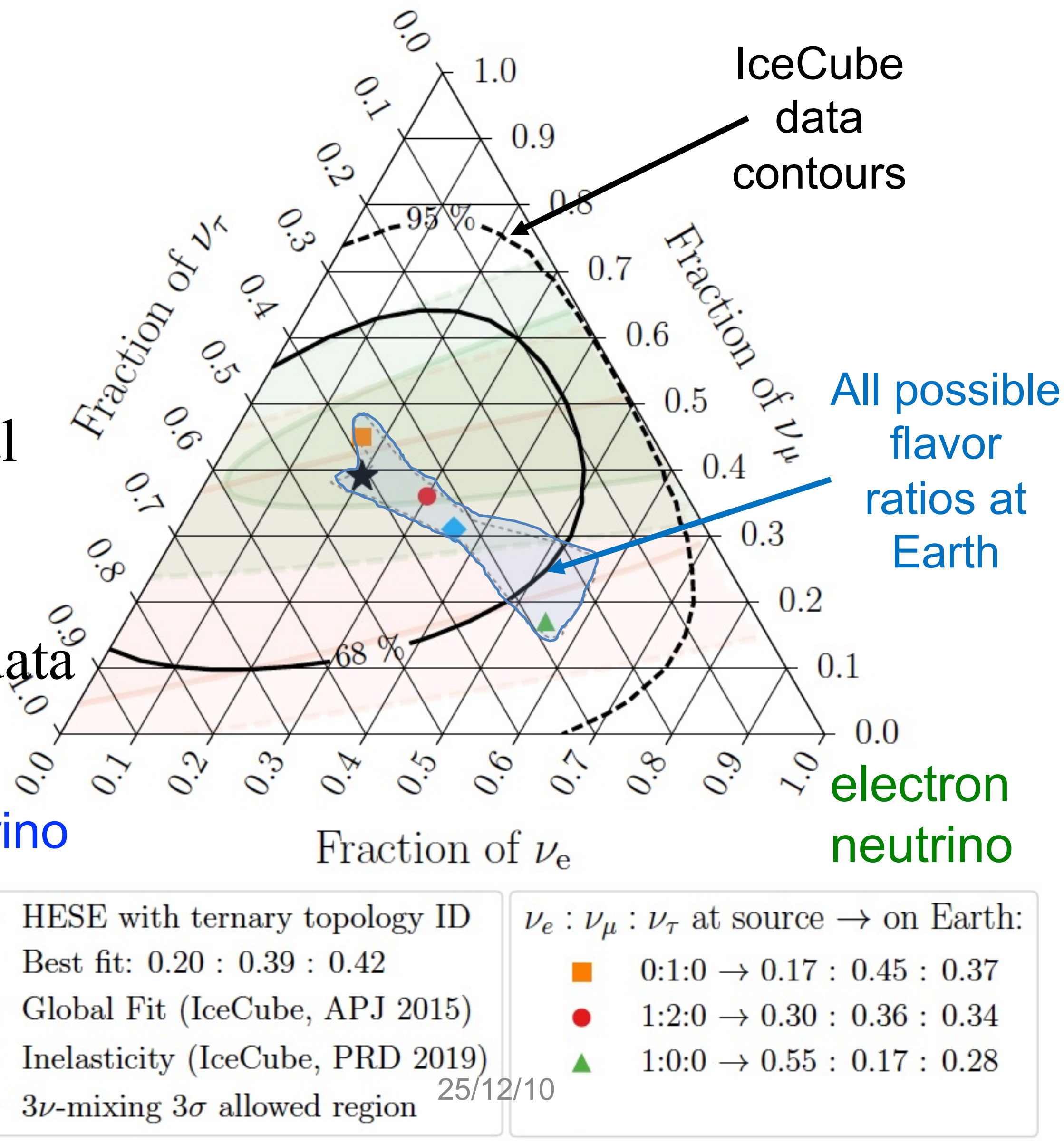
High-energy, long propagating neutrinos

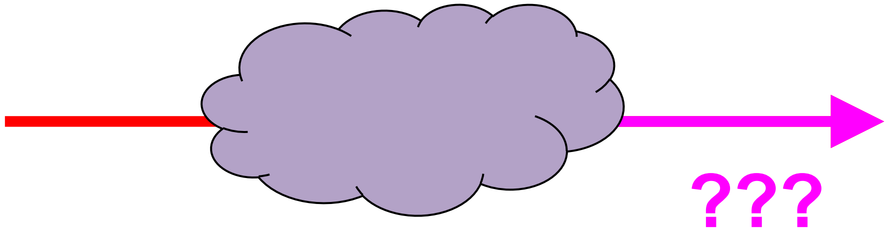
Astrophysical neutrino flavor physics

- Flavor triangle
- Spectrum integrated flavor ratio $(\nu_e : \nu_\mu : \nu_\tau)$
- Standard production models include ν_e and ν_μ
- Flavor ratio observables on Earth is different
- Deviation from this "island" is new physics signal

Data contour covers most of flavor triangle

- New physics cannot be discovered from current data
- Limits are set on vacuum operators





HESE 7.5-yr flavor Lorentz violation search

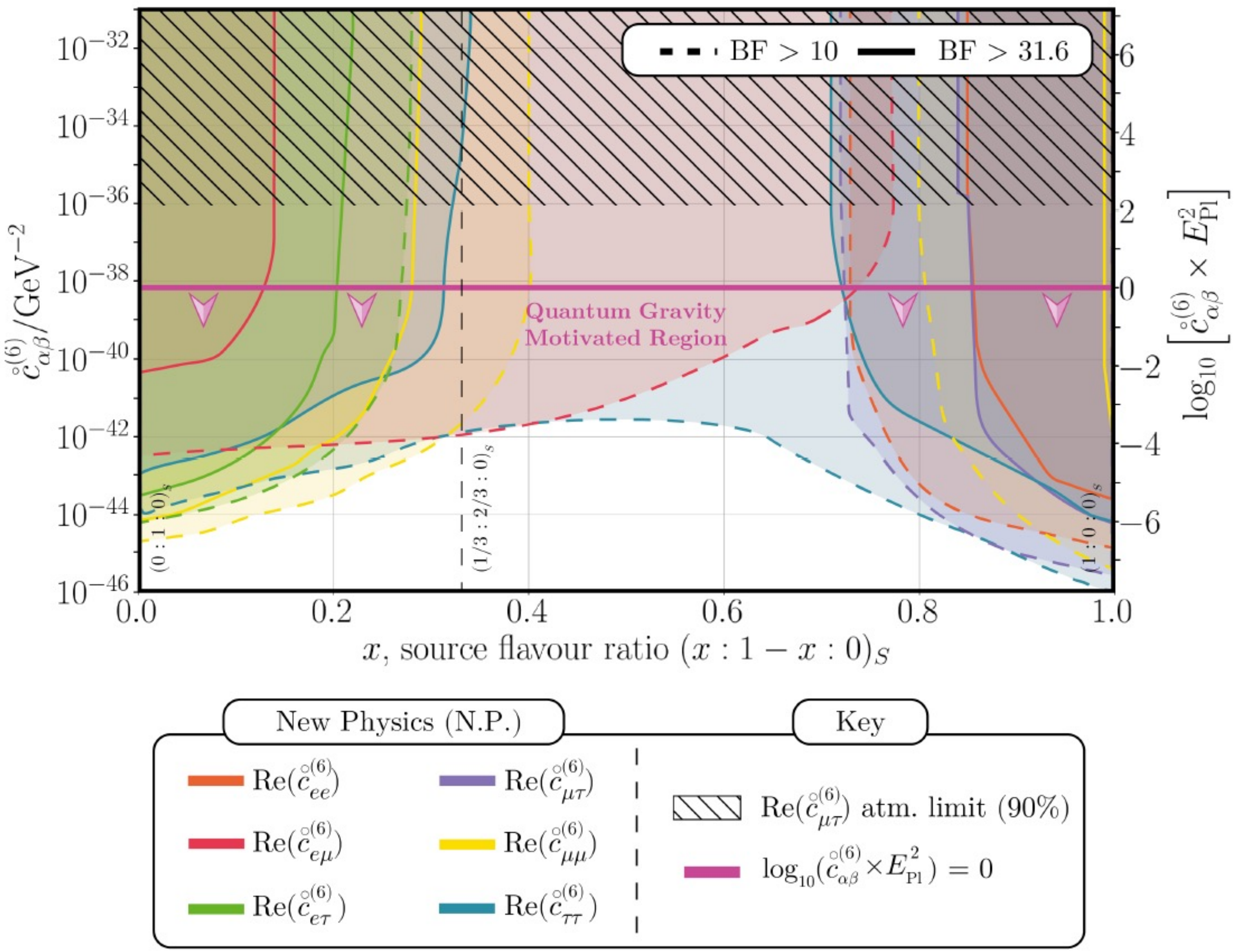
60 HESE events in 60 TeV – 2 PeV

IceCube data start to explore quantum gravity-motivated signal region for some parameters

$$c^{(6)} \leq \frac{1}{M_{Planck}^2} \sim 10^{-38} GeV^{-2}$$

dim	coefficient	limit (BF> 10.0)
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}

dim-6 new physics operator limit



tkatori@cern.ch

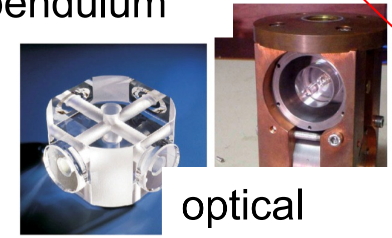
25/12/10

KING'S College LONDON

Lorentz violation limits from tabletop to cosmology

Physics MMA

torsion pendulum



optical resonator

comagnetomator

vacuum birefringence

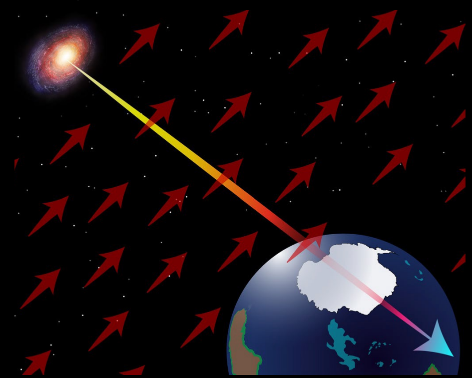
UHECRs

Lower dimension operators → searches by tabletop experiments
Higher dimension operators → searches by astrophysical observations

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

dim.	method	type	sector	limits	ref.
$\overset{\circ}{a}^{(3)}$	CMB polarization	astrophysical	photon	$\sim 10^{-43}$ GeV	[2]
	He-Xe comagnetometer	tabletop	neutron	$\sim 10^{-34}$ GeV	[3]
	torsion pendulum	tabletop	electron	$\sim 10^{-31}$ GeV	[4]
	muon g-2	accelerator	muon	$\sim 10^{-24}$ GeV	[5]
	neutrino mixing	astrophysical	neutrino	$\sim 10^{-26}$ GeV	[1]
$\overset{\circ}{c}^{(4)}$	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-38}$	[6]
	Laser interferometer	LIGO	photon	$\sim 10^{-22}$	[7]
	Sapphire cavity oscillator	tabletop	photon	$\sim 10^{-18}$	[8]
	Ne-Rb-K comagnetometer	tabletop	neutron	$\sim 10^{-29}$	[9]
	trapped Ca^{+} ion	tabletop	electron	$\sim 10^{-19}$	[10]
	neutrino mixing	astrophysical	neutrino	$\sim 10^{-31}$	[1]
$\overset{\circ}{a}^{(5)}$	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-34}$ GeV^{-1}	[6]
	ultra-high-energy cosmic ray	astrophysical	proton	$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	[11]
	neutrino mixing	astrophysical	neutrino	$\sim 10^{-37}$ GeV^{-1}	[1]
$\overset{\circ}{c}^{(6)}$	GRB vacuum birefringene	astrophysical	photon	$\sim 10^{-31}$ GeV^{-2}	[6]
	ultra-high-energy cosmic ray	astrophysical	proton	$\sim 10^{-42}$ to 10^{-35} GeV^{-2}	[11]
	gravitational Cherenkov radiation	astrophysical	gravity	$\sim 10^{-31}$ GeV^{-2}	[12]
	neutrino mixing	astrophysical	neutrino	$\sim 10^{-42}$ GeV^{-2}	[1]

Astrophysical neutrino flavour Lorentz violation limits



Weak interaction
+ Small mass
+ Quantum mixing
= macroscopic quantum system you cannot disturb

[1] IceCube, Nature Phys. 18, 1287 (2022) [2] WMAP, AstrophysJ.180, 330 (2009) [3] Allmendinger et al., PRL112, 110801 (2014) [4] Heckel et al., PRL97, 021603(2006) [5] Muon g-2, PRL100, 091602 (2008) [6] Kostelecký, Mewes,PRL110, 201601 (2013) [7] Kostelecký, Melissinos, Mewes, PLB 761, 1 (2016) [8] Nagel et al.,Nature Comm. 6, 8174(2015) [9] Smiciklas et al., PRL107, 171604 (2011) [10] Pruttivarasin et al., Nature 517, 592 [11] Maccione et al., JCAP 0904, 022 [12] Kostelecký, Tasson, PLB 749, 551

Tests of Lorentz Violation with Astrophysical Neutrinos – Summary

Astrophysical neutrinos have high potential to look for Lorentz violation. But there are many unknowns;

- Energy spectrum
- Production time
- Source information
- Foreground

etc

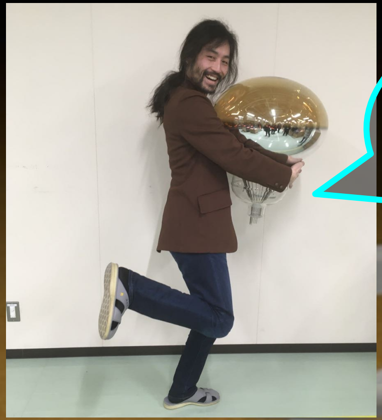
So far, astrophysical neutrino data are low statistics, and further data are needed to search Lorentz violation...

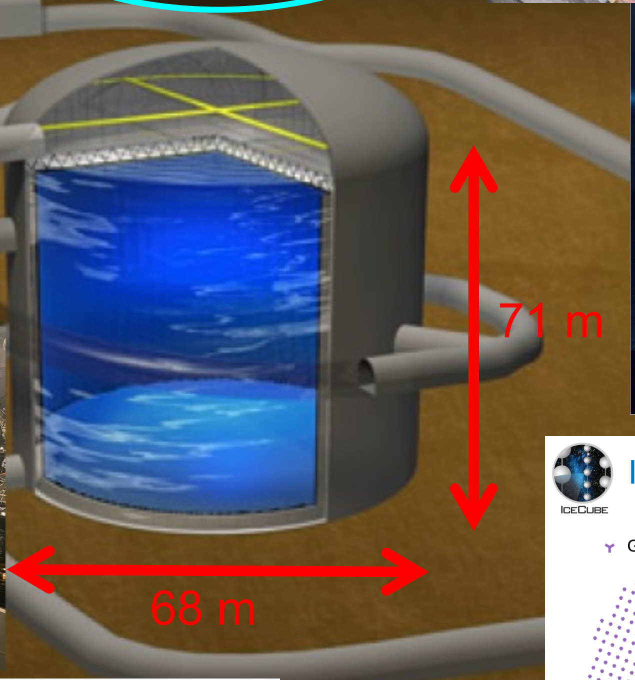
Hyper-Kamiokande, ArXiv:1805.04163 and IceCube-Gen2, J.Phys.G48(2021)060501

Hyper-Kamiokande and IceCube-Gen2

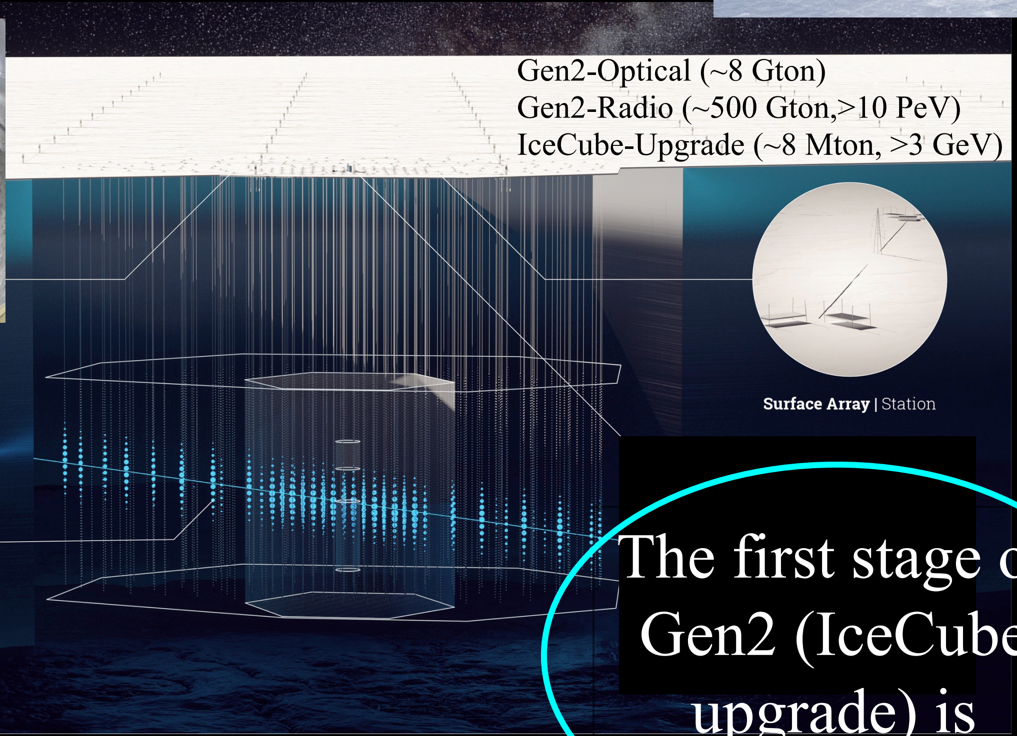
Summer
2024-2045
IceCube team

New international neutrino astronomy projects around the world

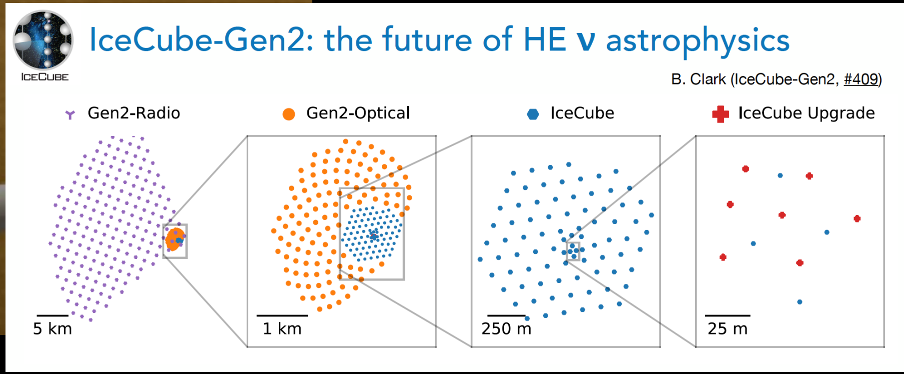




Hyper-K construction is ongoing



The first stage of Gen2 (IceCube upgrade) is ongoing



LONDON

Hyper-Kamiokande

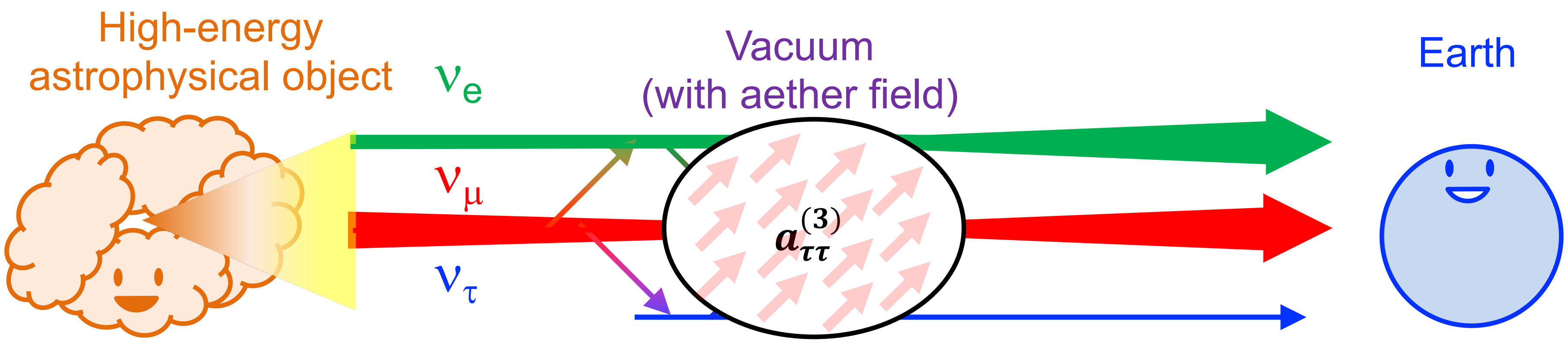
Searches of Ultralight Dark Matter with Astrophysical Neutrino Flavour

Astrophysical neutrino flavour physics

IceCube Lorentz violation analysis set a limit on $a_{\tau\tau}^{(3)}$

- Try to reinterpret this limit $a_{\tau\tau}^{(3)}$ as a limit of neutrino-ultralight dark matter interaction

$$h_{eff} \sim \frac{1}{2E} U^{\dagger} M^2 U + a_{\alpha\beta}^{(3)} \cdots \sim \frac{1}{2E} \begin{pmatrix} m_{ee}^2 & m_{e\mu}^2 & m_{\tau e}^2 \\ m_{e\mu}^{2*} & m_{\mu\mu}^2 & m_{\mu\tau}^2 \\ m_{\tau e}^{2*} & m_{\mu\tau}^{2*} & m_{\tau\tau}^2 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a_{\tau\tau}^{(3)} \end{pmatrix} \cdots$$



Astrophysical neutrino flavour physics

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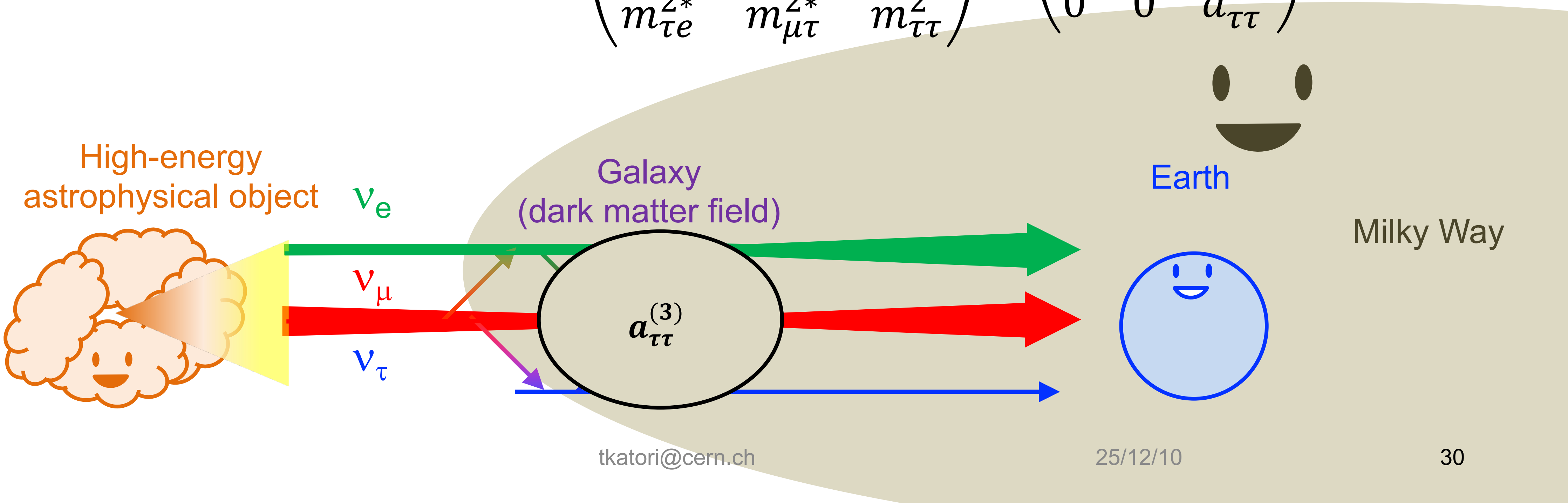
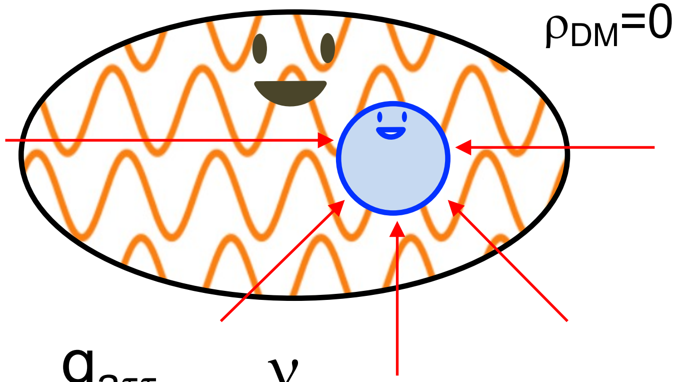
$$h_{eff} \sim \frac{1}{2E} U^{\dagger} M^2 U + a^{(3)}_{\alpha\beta} \cdots \sim \frac{1}{2E} \begin{pmatrix} m^2_{ee} & m^2_{e\mu} & m^2_{\tau e} \\ m^{2*}_{e\mu} & m^2_{\mu\mu} & m^2_{\mu\tau} \\ m^{2*}_{\tau e} & m^{2*}_{\mu\tau} & m^2_{\tau\tau} \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a^{(3)}_{\tau\tau} \end{pmatrix} \cdots$$



Ultralight dark matter coupling with neutrinos

Different dark matter models provide different effective Hamiltonian

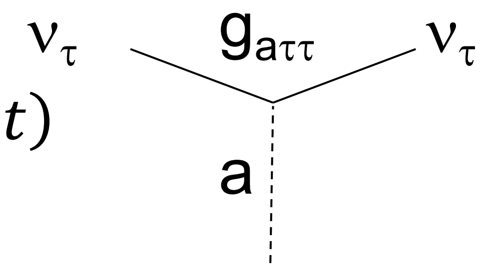
ρ_{DM}=0.3 GeV/m^3



ex) Relativistic ultra-light dark matter model

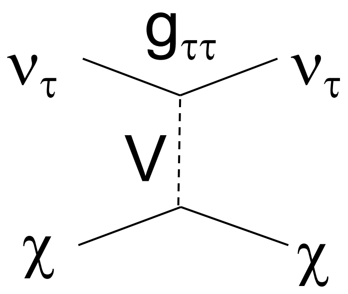
$$h_{eff} \sim \frac{1}{2E} U^{\dagger} M^2 U + V_{\tau\tau}$$

1. Axion dark matter model



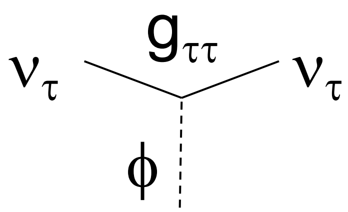
$$V_{\tau\tau}(t) = g_{a\tau\tau} m_a a_0 sin(m_a t)$$

2. Vector and axial vector dark matter coupling model



$$V_{\tau\tau}(t) = g_{\tau\tau}\sqrt{2\rho_{DM}}/m_A sin(m_A t)$$

(3. Scalar ultralight dark matter model correct neutrino mass)



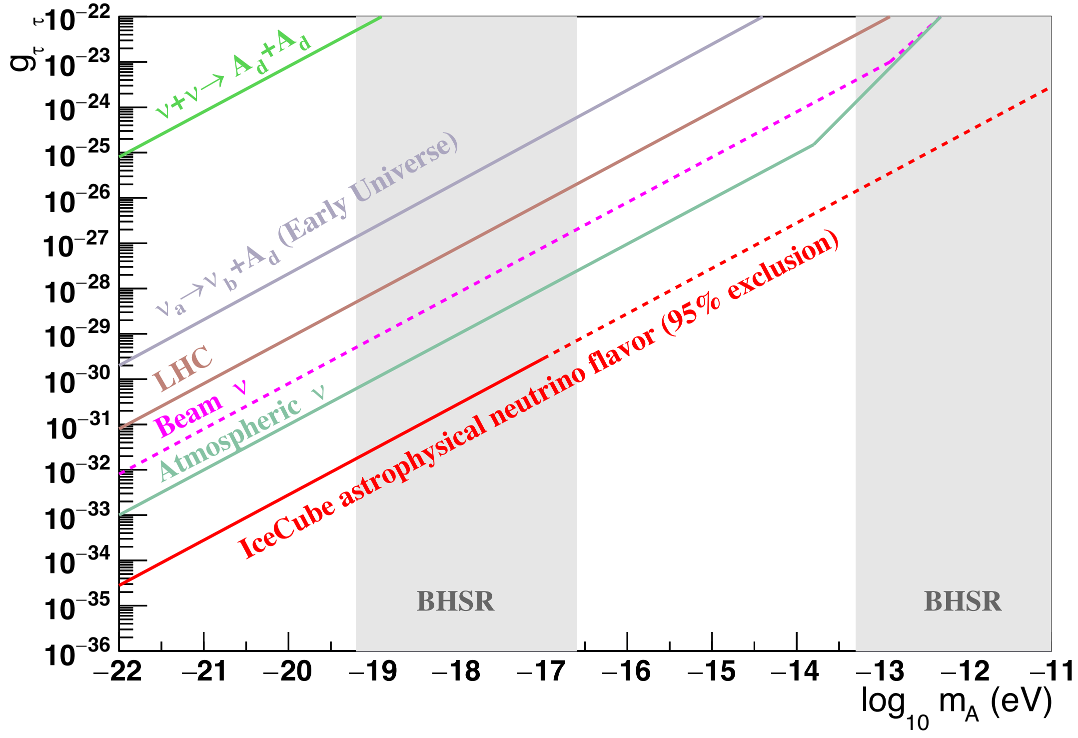
Krnjaic,Machado,Necib,PRD97(2018)075017

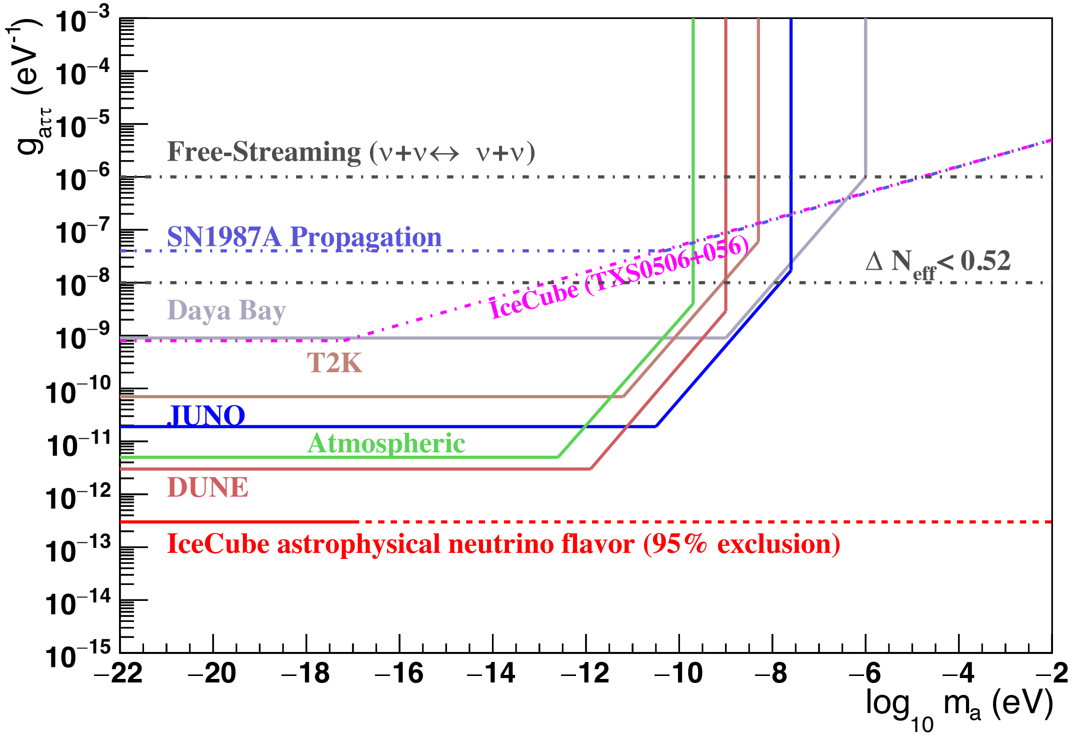
Brzeminski et al, JHEP08(2023)181, Huang and Nath, EPJC78(2018)922
Argüelles, TK, Farrag, ArXiv.2404.10926 (Submitted)

Ultralight dark matter coupling with neutrinos

Left: Vector and axial-vector coupling with dark matter: $g_{\tau\tau} < 3\times10^{-33}\left(\frac{m_{DM}}{10^{-20}eV}\right)$

Right: Axion dark matter coupling limit: $g_{a\tau\tau} < 3\times10^{-13}eV^{-1}\left(\frac{m_{DM}}{10^{-20}eV}\right)$





Bluhm, Kostelecky, Lane, Russell PRL 2002

Conclusion

Lorentz violation is motivated from Planck-scale theories

There is a worldwide effort to look for Lorentz violation, using various state-of-the-art techniques including neutrinos, but so far, no compelling evidence of Lorentz violation

Lorentz violation occurs in various models including ultralight dark matter

Thank you for your attention!

Backup

Flavor new physics search with effective operators

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

Standard Model | New physics

$$L = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi + \bar{\psi}\gamma^{\mu}a_{\mu}\,\psi + \bar{\psi}\gamma^{\mu}c_{\mu\nu}\partial^{\nu}\psi \cdots$$

Effective Hamiltonian can be written from here

Standard Model | New physics (renormalizable) | higher dimension operator (non-renormalizable)

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

$$E^{3}c^{(6)}_{\alpha\beta} = E^{3}\begin{pmatrix} c^{(6)}_{ee} & c^{(6)}_{e\mu} & c^{(6)}_{\tau e} \\ c^{(6)*}_{e\mu} & c^{(6)}_{\mu\mu} & c^{(6)}_{\mu\tau} \\ c^{(6)*}_{\tau e} & c^{(6)*}_{\mu\tau} & c^{(6)}_{\tau\tau} \end{pmatrix}$$

IceCube is sensitive to higher dimension operators

dimension-6 operator natural scale: $c^{(6)} \sim \frac{1}{M^{2}_{Planck}} \sim 10^{-38}GeV^{-2}$

Flavor new physics search with effective operators

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

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

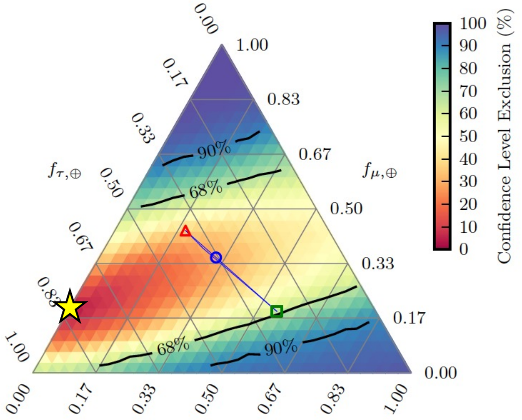
Finally, fraction of neutrino flavour b on the earth is

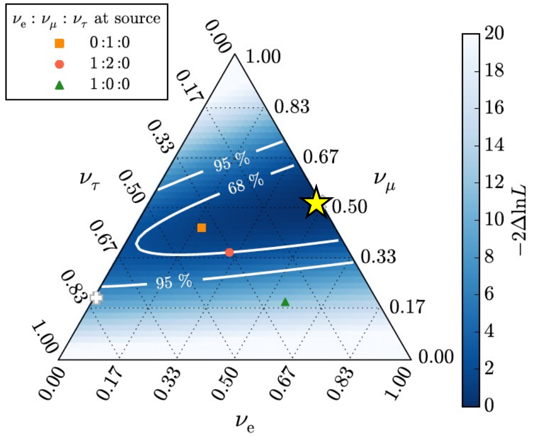
$$\alpha^{\oplus}_{\beta} \sim \int_{Emin}^{Emax} \sum_{\alpha} P_{\alpha\to\beta}(L\to\infty, E)\phi_\alpha(E)dE$$

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

IceCube flavor ratio measurements

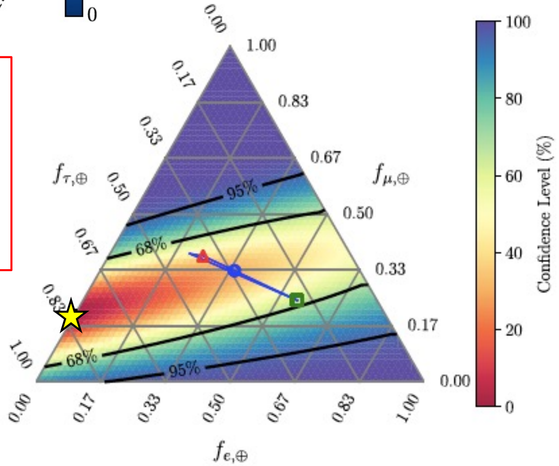
IceCube
1st flavour ratio result
(0.0:0.2:0.8)

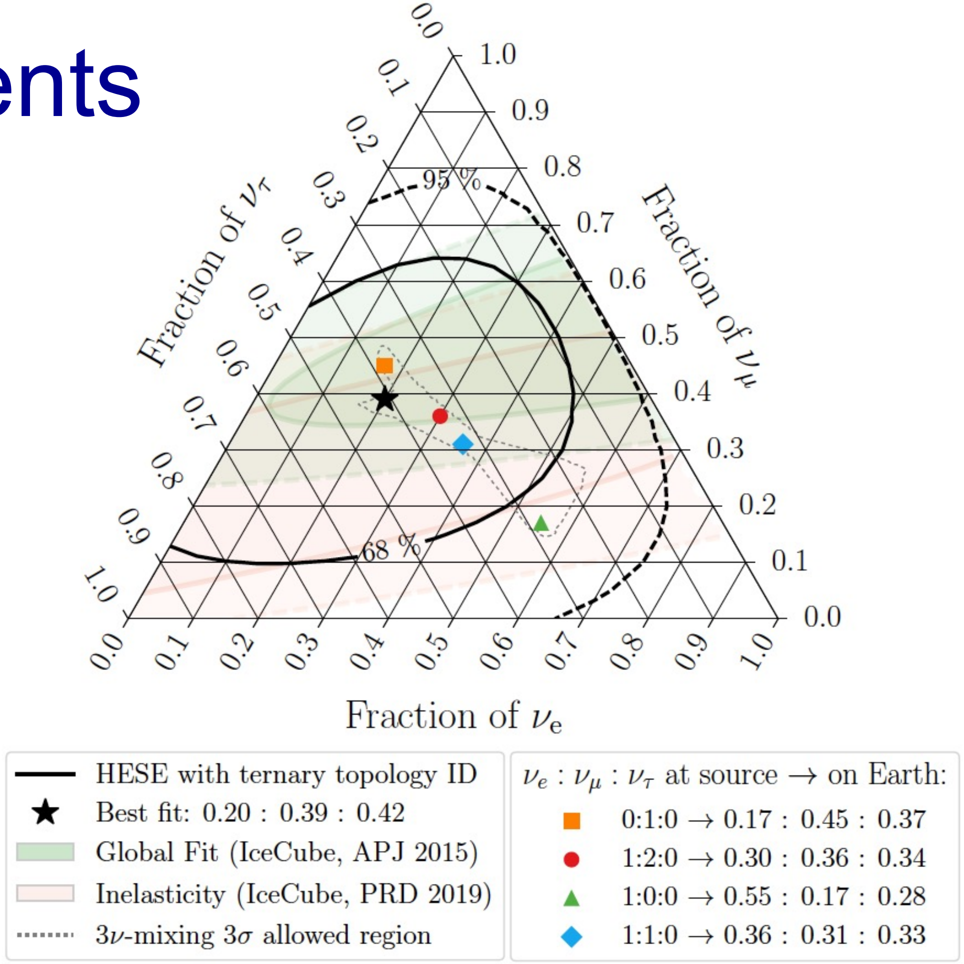




IceCube
2nd flavour ratio result
(0.5:0.5:0.0)

IceCube
3rd flavour ratio result
(0.0:0.2:0.8)





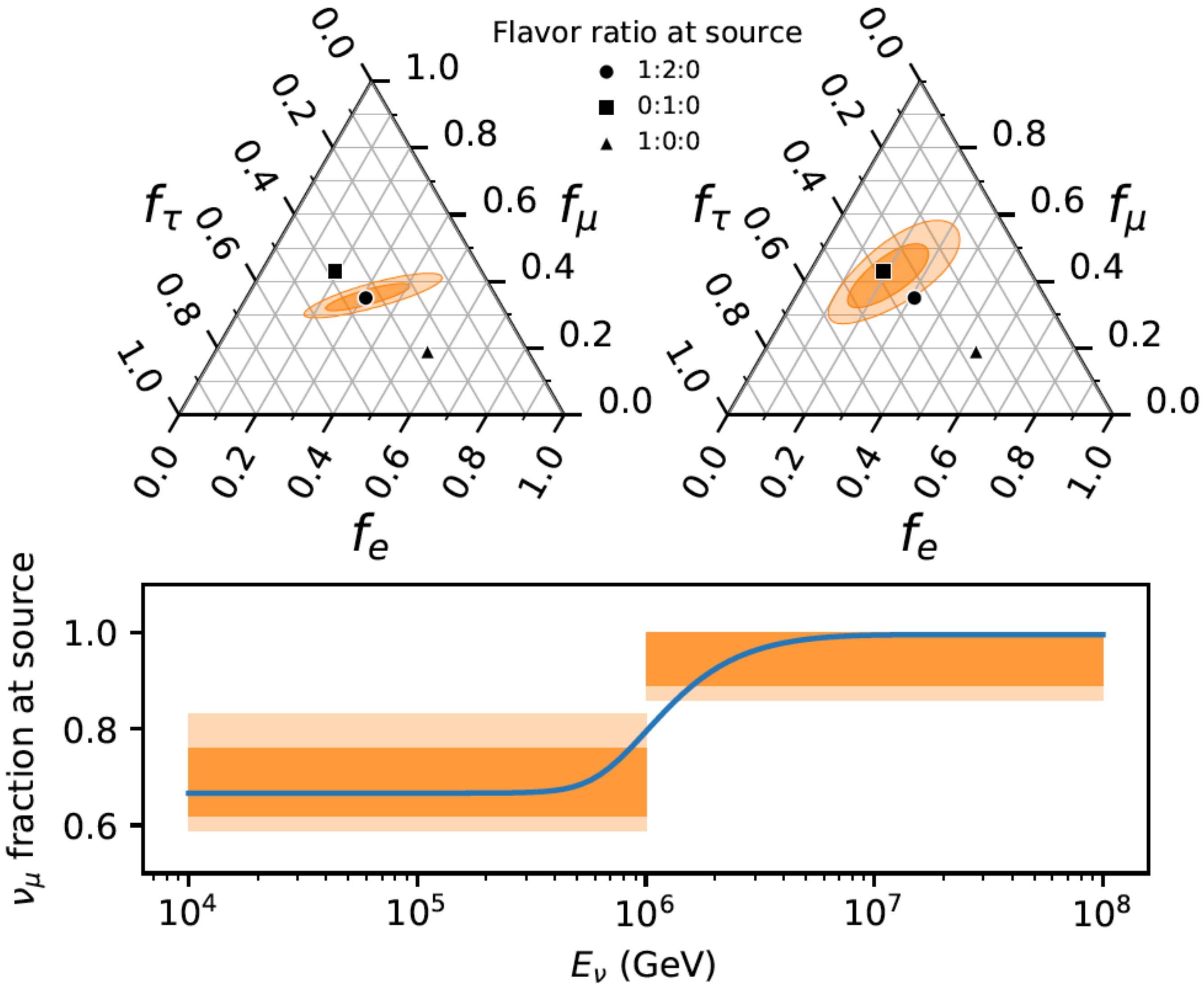
2018 flavour ratio measurement

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

Energy dependence of flavor ratio

Muon neutrino increases at higher energy

Future higher-statistics flavor measurement

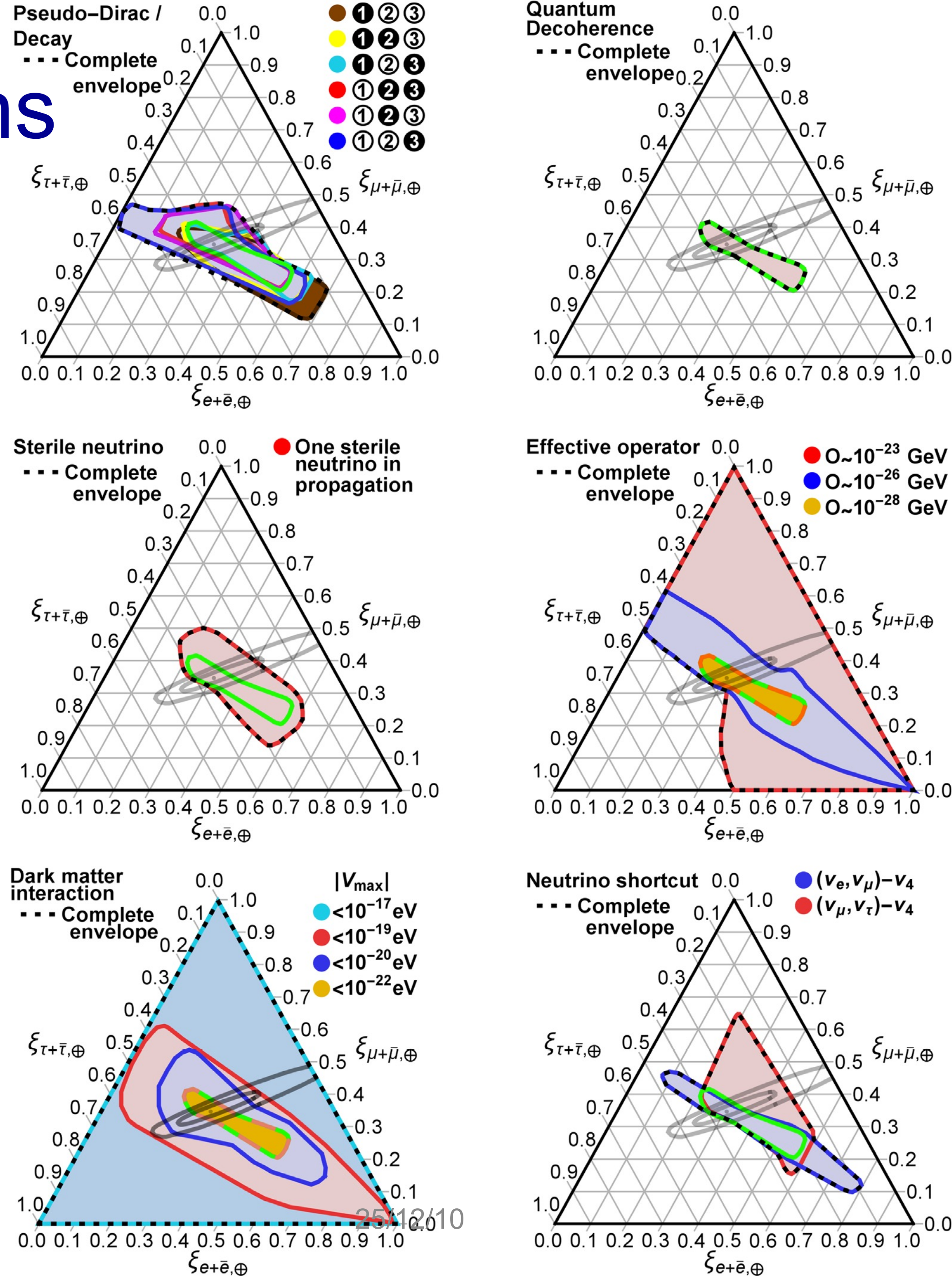


New physics flavor ratio predictions

New physics models have different flavor ratios

Effective operator

- It includes Lorentz violation
- Assuming all possible standard production models, (ν_e:ν_μ:ν_τ) = (x:1-x:0), it covers 2/3 of the phase space.



High-energy, long propagating neutrinos - summary

High energy astrophysical neutrinos have amazing new physics sensitivity, and it will increase more

Multi-messenger astronomy

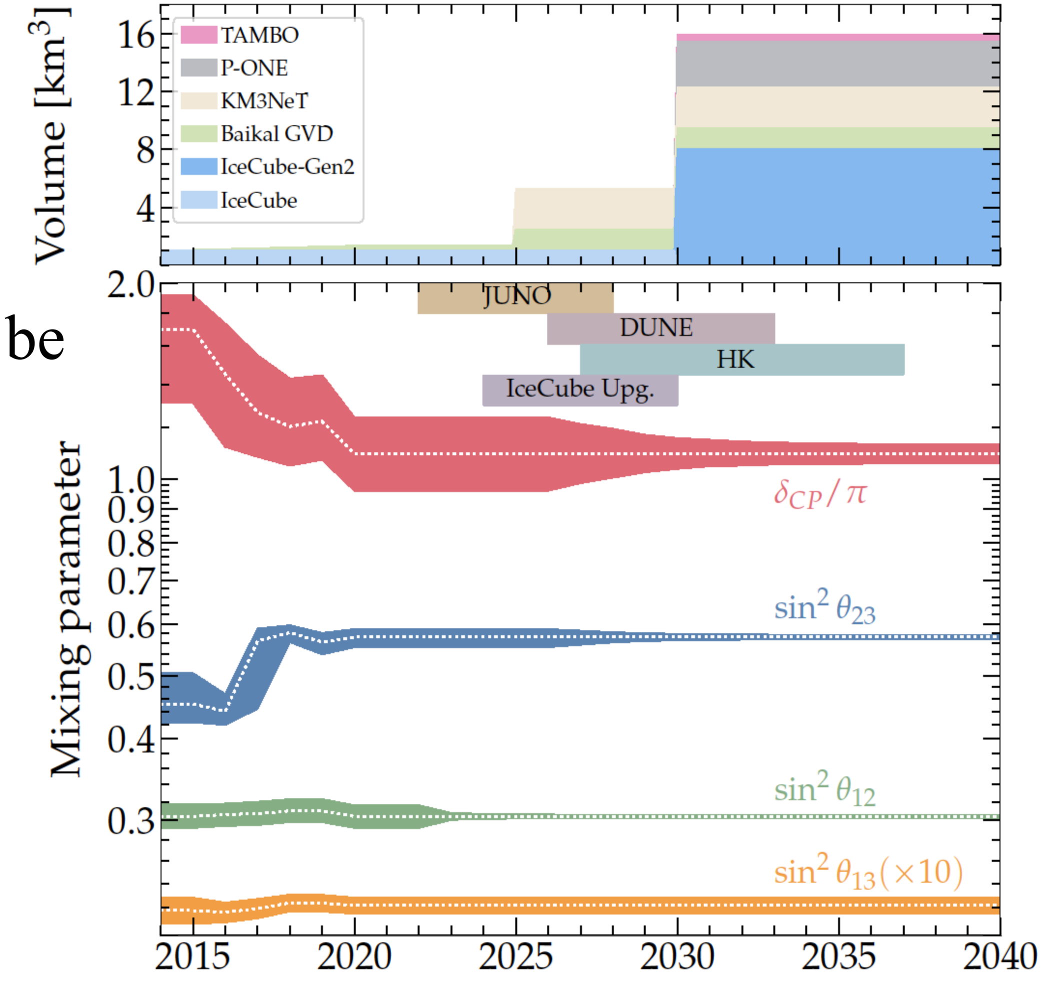
- High-energy astrophysical neutrino model errors will be reduced (spectrum, flavor, direction, time)

New neutrino telescopes

- Higher statistics to reach higher energy events

Neutrino physics

- Oscillation parameter errors will be reduced



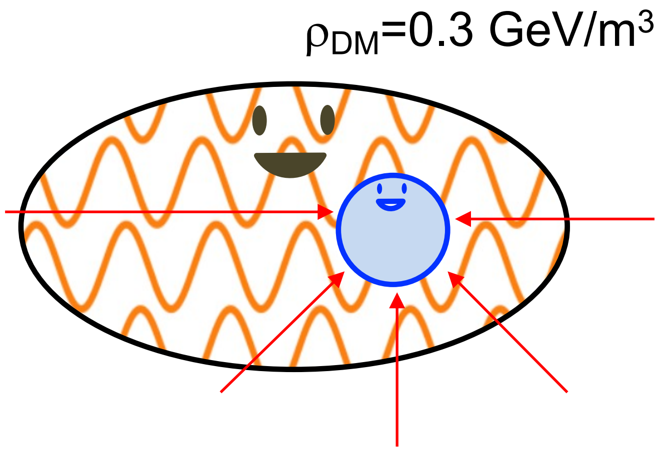
Time varying ultra-light dark matter coupling with neutrinos

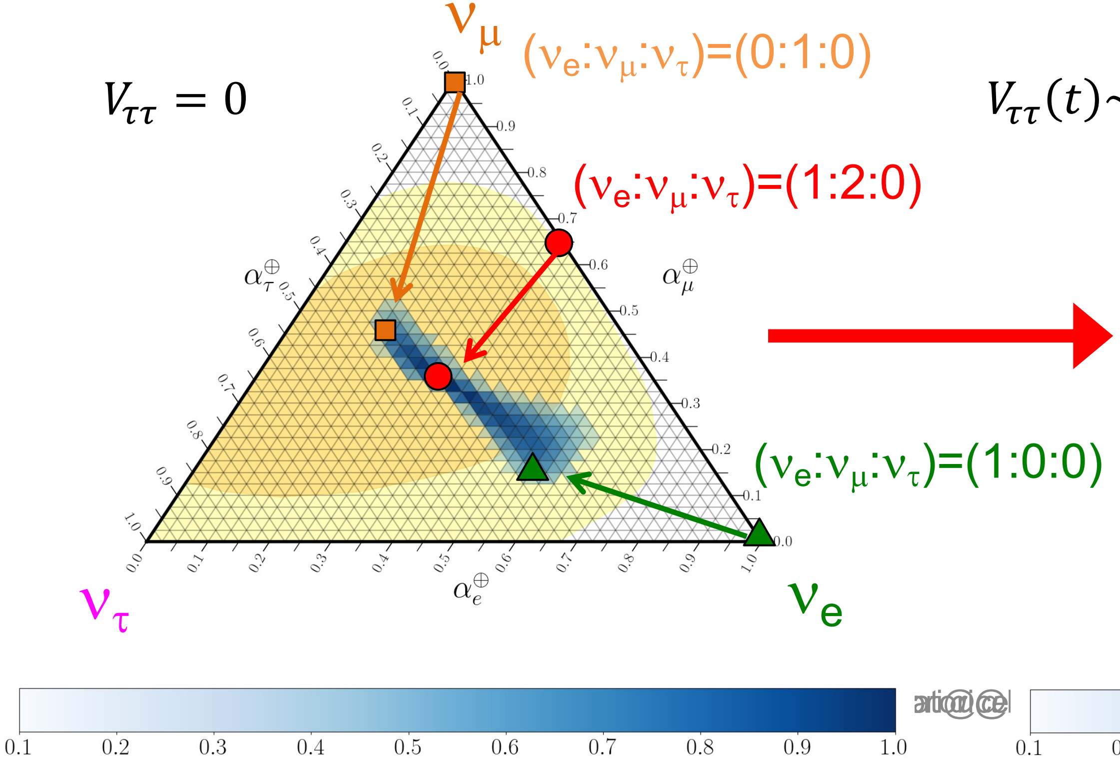
On average, dark matter potential is zero.

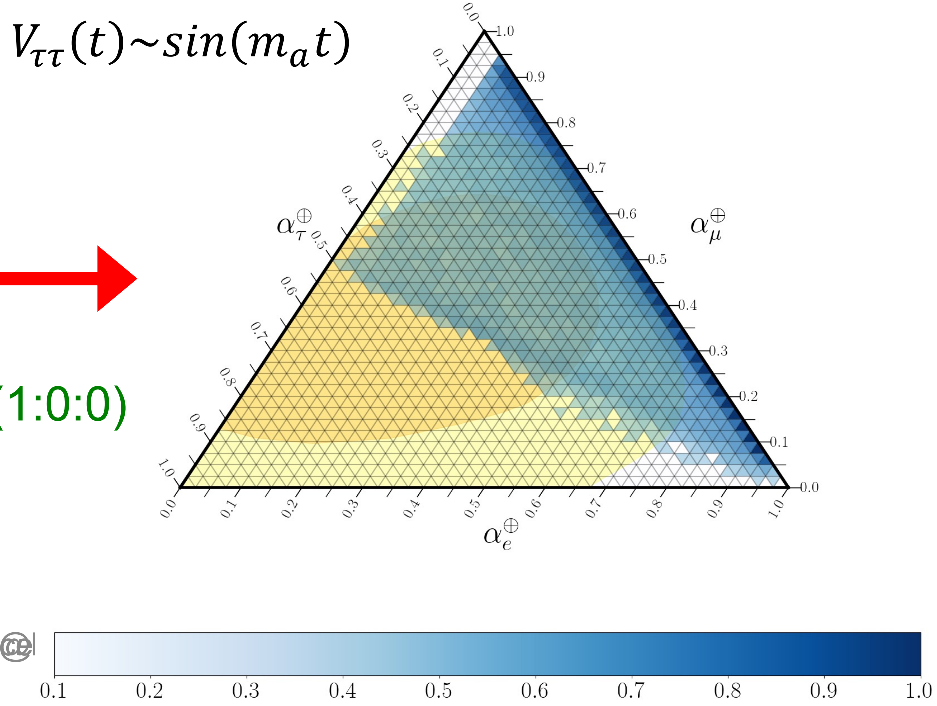
$$V_{\tau\tau}(t) = g_{a\tau\tau} m_a a_0 sin(m_a t) \xrightarrow{t\to\infty} 0$$

However, dark matter potential smear flavour ratio for each neutrino

We calculate flavour prediction points with oscillating dark matter potential which smears predicted flavour ratio





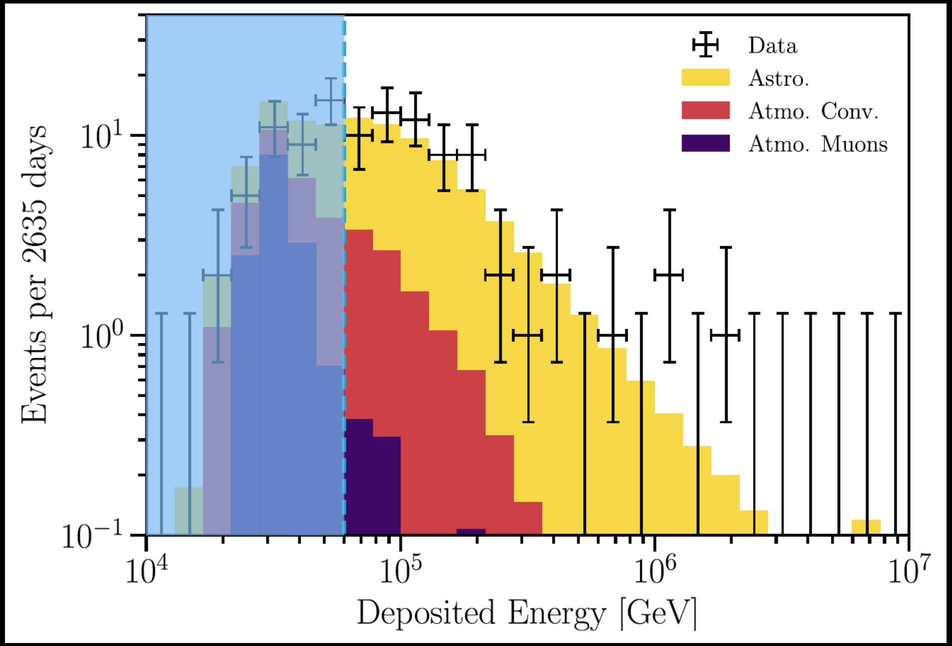


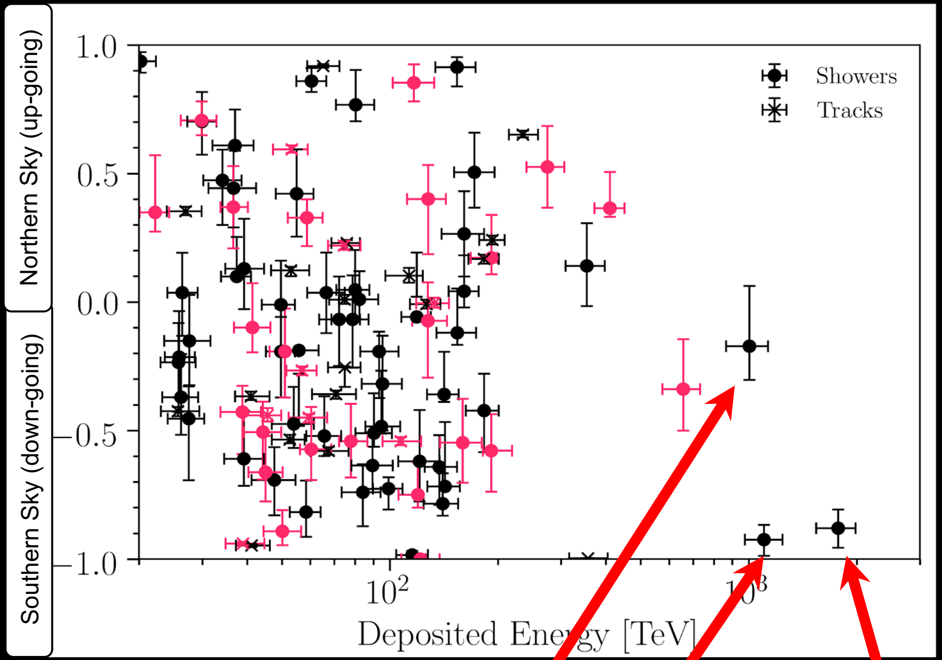
IceCube, PRD104(2021)022002

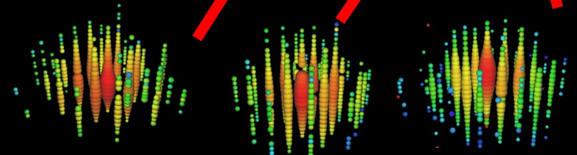
High-energy astrophysical neutrinos

60TeV- 2PeV astrophysical neutrinos are observed by IceCube Neutrino Observatory

high-energy starting event (HESE) sample



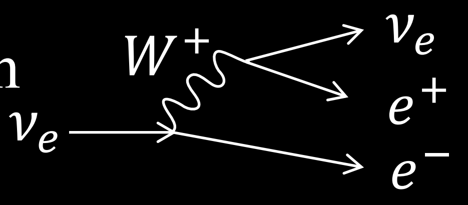




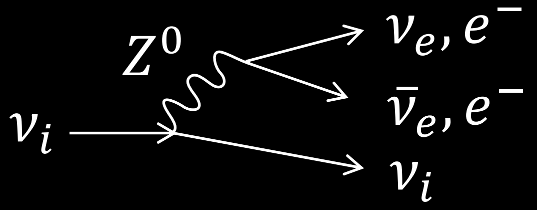
Stecker, et al, PRD91(2015)045009, and many others
KM3NeT, ArXiv:2502.1207

Test of Spacetime properties with Astrophysical neutrinos

Lorentz violation = Media in vacuum
- Spectrum distortion (energy)
- Time of Flight (time)
- Anomalous mixing (flavour)

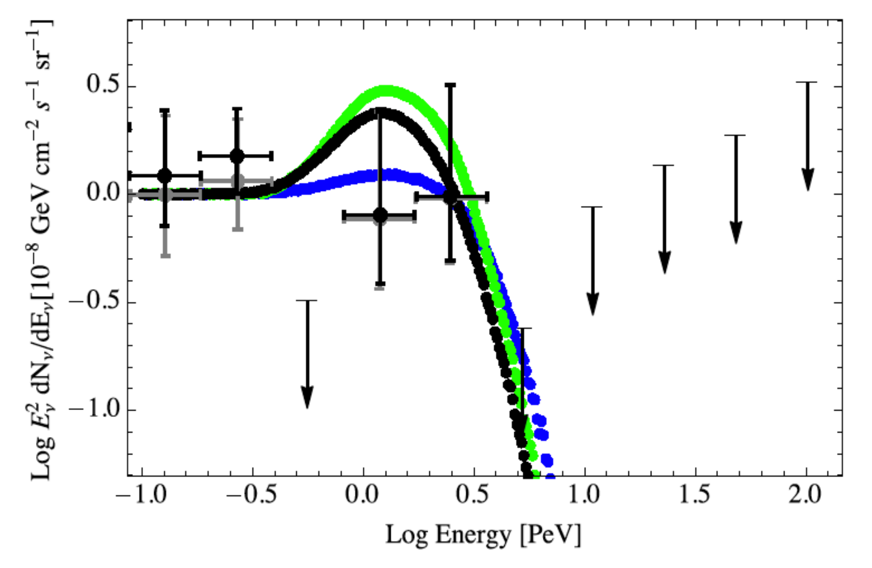


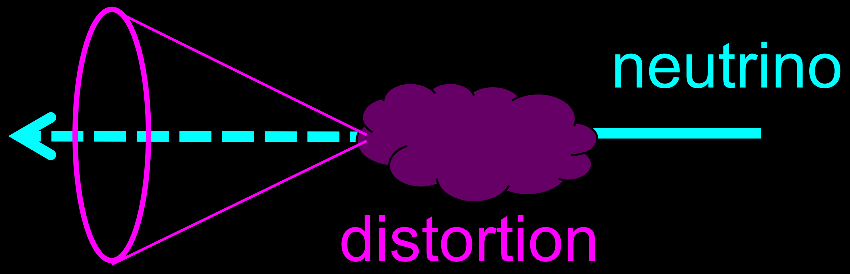
Vacuum pair emission

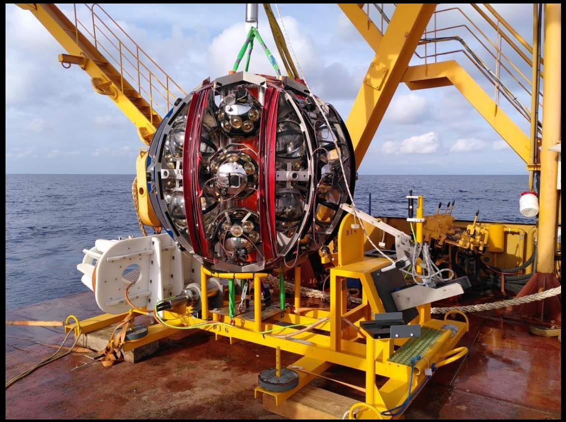


Neutrino splitting

Diffuse neutrino spectrum distortion







Lorentz violating field cause radiation in vacuum
- High-energy neutrinos are attenuated
- KM3NeT 220 PeV neutrino (KM3-230213A)

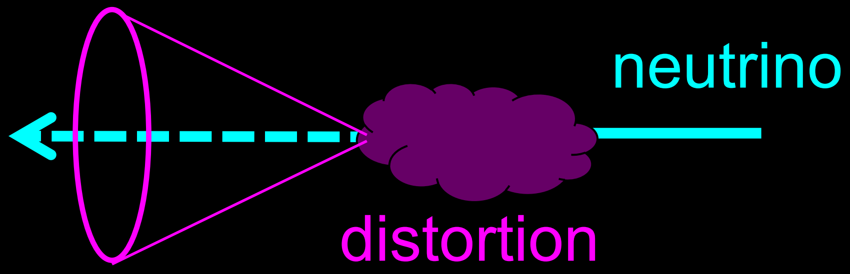
$$\delta \equiv c_\nu^2 - 1 < 4\times10^{-22}$$

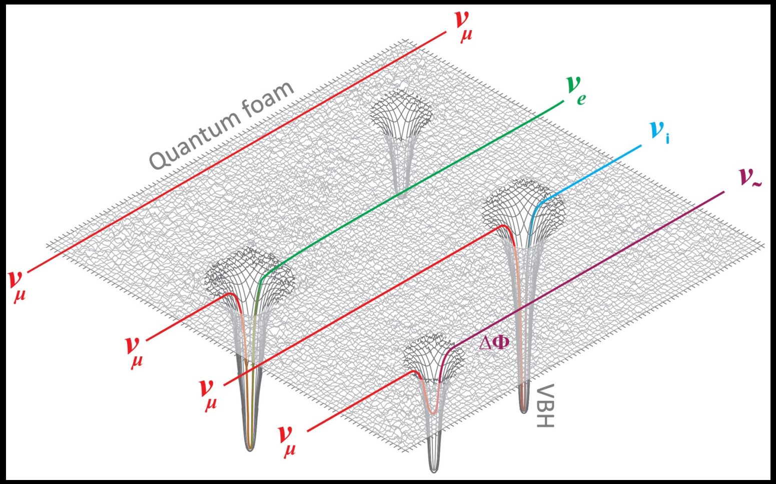
Stecker, et al, PRD91(2015)045009, and many others
KM3NeT, ArXiv:2502.1207, Ternes et al, arXiv:2503.04573

Test of Spacetime properties with Astrophysical neutrinos

Lorentz violation = Media in vacuum
- Spectrum distortion (energy)
- Time of Flight (time)
- Anomalous mixing (flavour)

Spectrum distortion happen by other scenarios
- "missing" neutrinos by micro black-hole (neutrino-loss quantum decoherence)
- Strong limits from SN1987A (cf. neutrino decay)





Lorentz violating field cause radiation in vacuum
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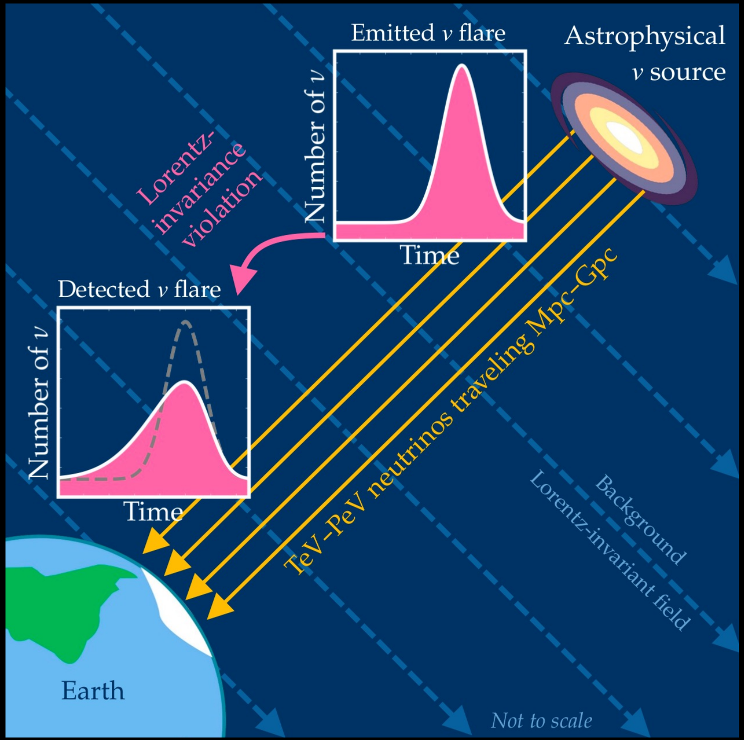
$$\delta \equiv c_v^2 - 1 < 4\times10^{-22}$$

Amelino-Camelia et al, Nature 393(1998)763, LHASSO PRL133(2024)071501)) and many others
Bustamante et al, ArXiv:2408.15949

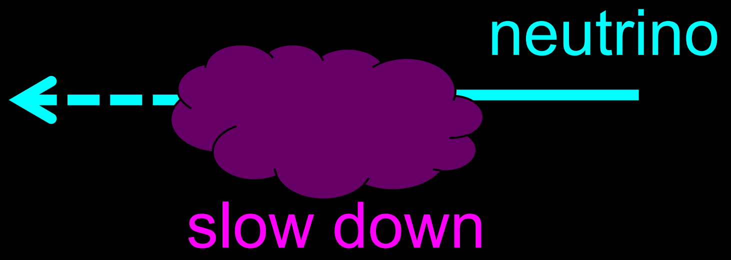
Test of Spacetime properties with Astrophysical neutrinos

New physics search
- Spectrum distortion (energy)
- Time of Flight (time)
- Anomalous mixing (flavour)



Modified dispersion due to quantum foam cause unexpected delay/advance for neutrinos
- Neutrino time-of-flight ($a^{(5)}$=CPT odd)

$$\delta v \sim E a^{(5)} + E^2 c^{(6)} + \cdots$$



Time distribution is modified due to Lorentz violation (energy-dependent)

Huang and Ma, Communications Physics1(2018)62, Amelino-Camelia et al, Nature Astronomy 7(2023)996 and many others

Test of Spacetime properties with Astrophysical neutrinos

New physics search
- Spectrum distortion (energy)
- Time of Flight (time)
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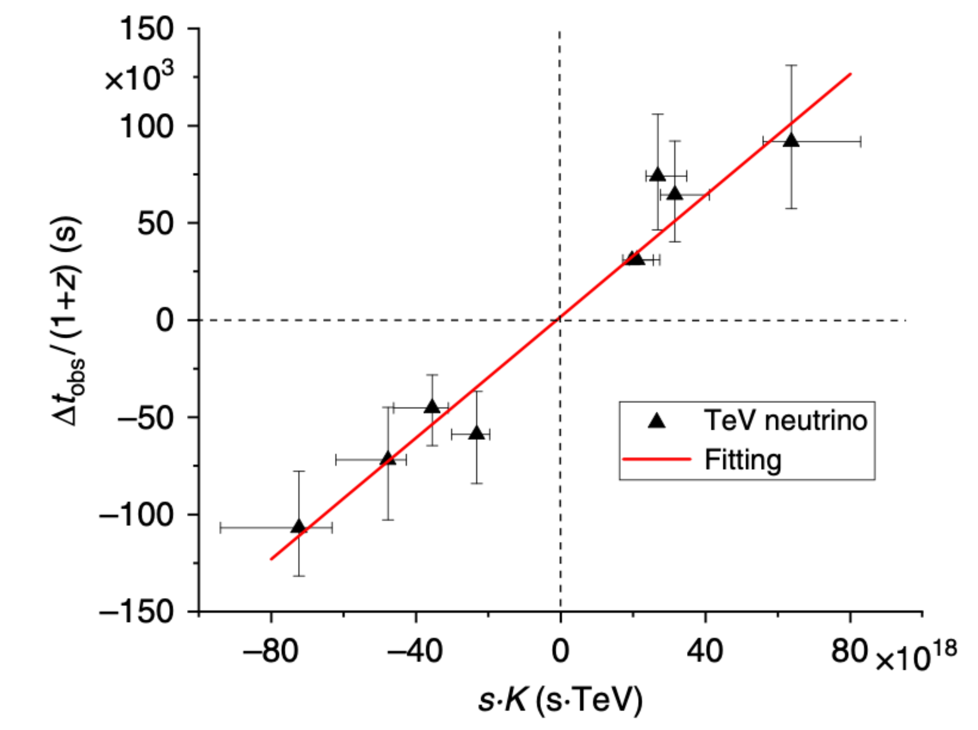

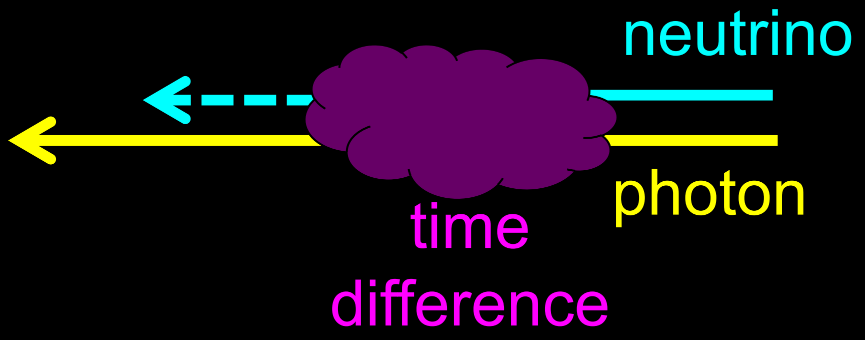

Neutrinos and gamma-ray bursts may have coincidence with Lorentz violation

IceCube, Nature Physics 18(2022)1287

Test of Spacetime properties with Astrophysical neutrinos

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Flavour effect
- Macroscopic quantum effect and sensitive to small effects
- Sensitive to the target signal region of Lorentz violation ($< 10^{-38}\ GeV^{-2}$ for dim-6 operators)