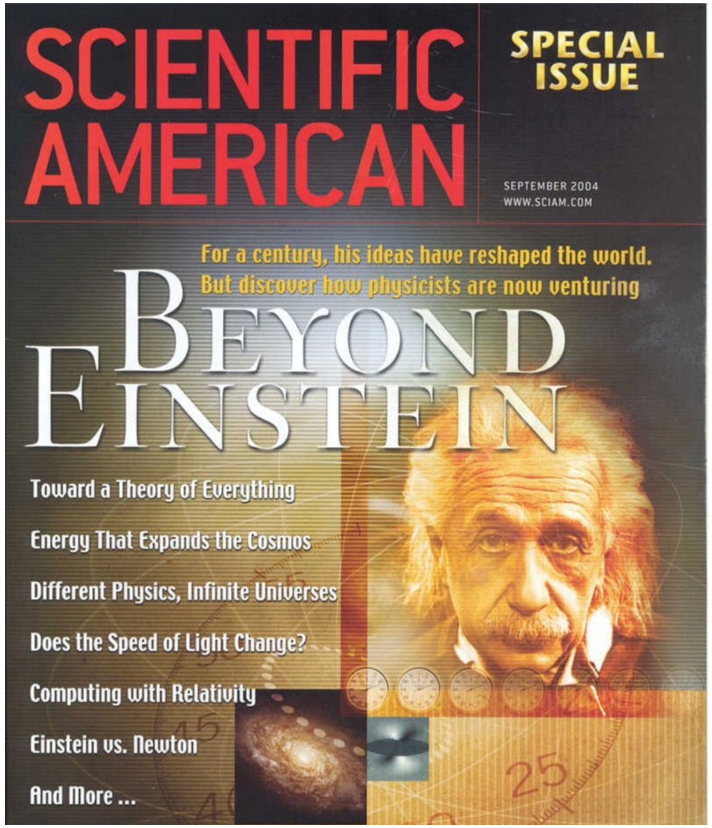
Tests of Lorentz and CPT Symmetry



outline

1. Introduction
2. Searches of Lorentz Violation
3. Searches of CPT Violation
4. Tests of quantum mechanics
5. Conclusion

Teppei Katori @teppeikatori
King's College London

Water Cherenkov Experiments for Precision Physics,
Jagiellonian University, Kraków, Poland, Sep. 18, 2025

Introduction

Lorentz violation

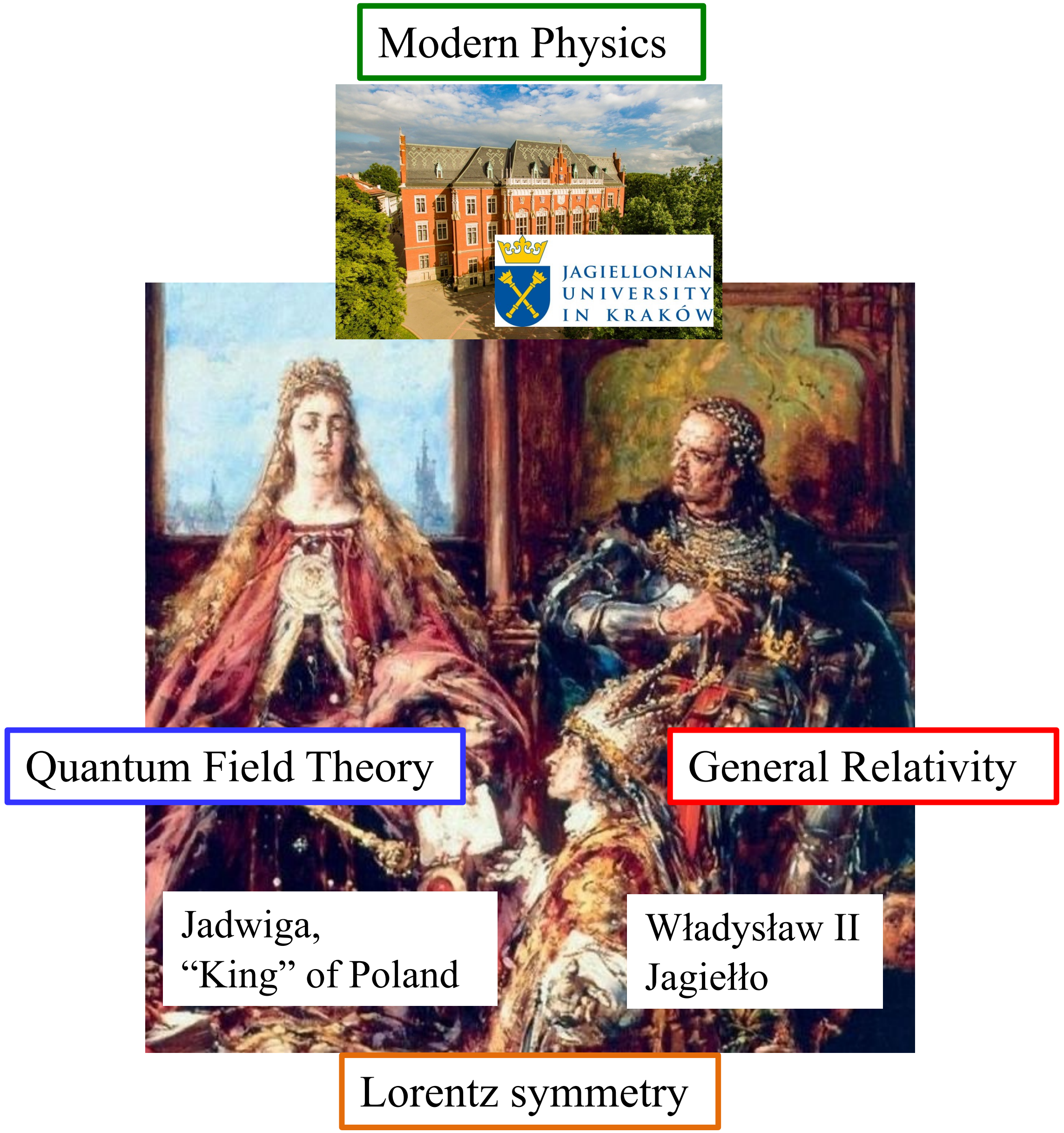
Quantum field theory and general relativity are the foundation of modern physics.

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



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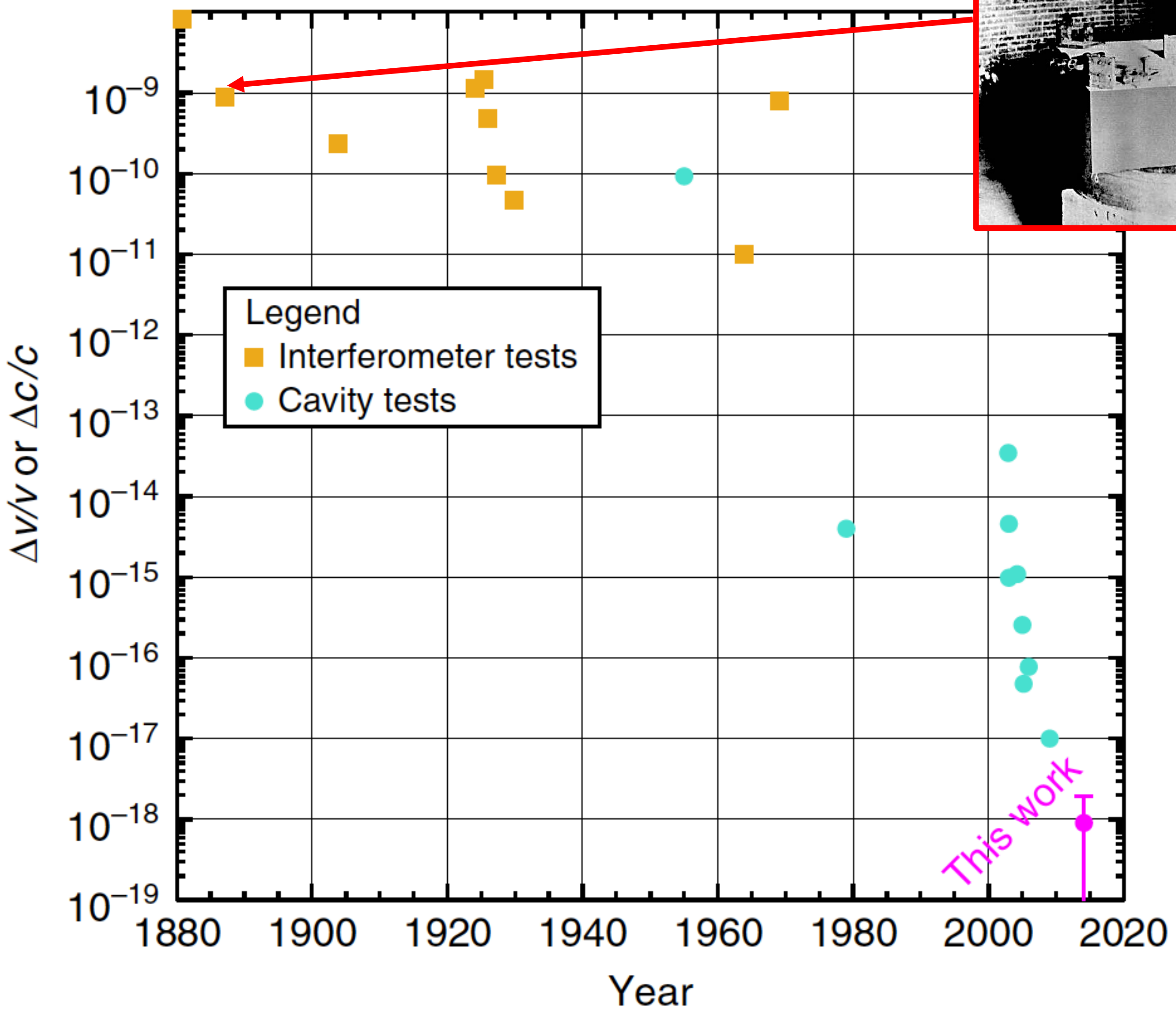
Nagel et al, Nature Comm., 6(2015)8174

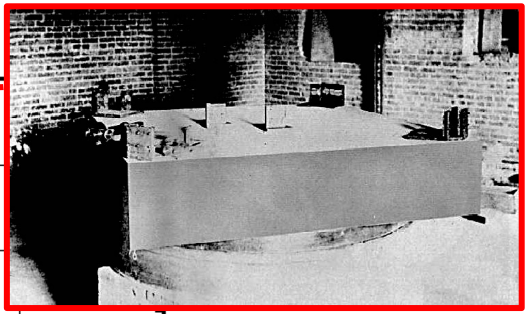
Searches of Lorentz violation

Lorentz symmetry is valid down to $\Delta c/c < 10^{-9}$

The experiment has been improved over 100 years.



Michelson-Morley experiment



[Nagel et al, Nature Comm., 6(2015)8174](#)

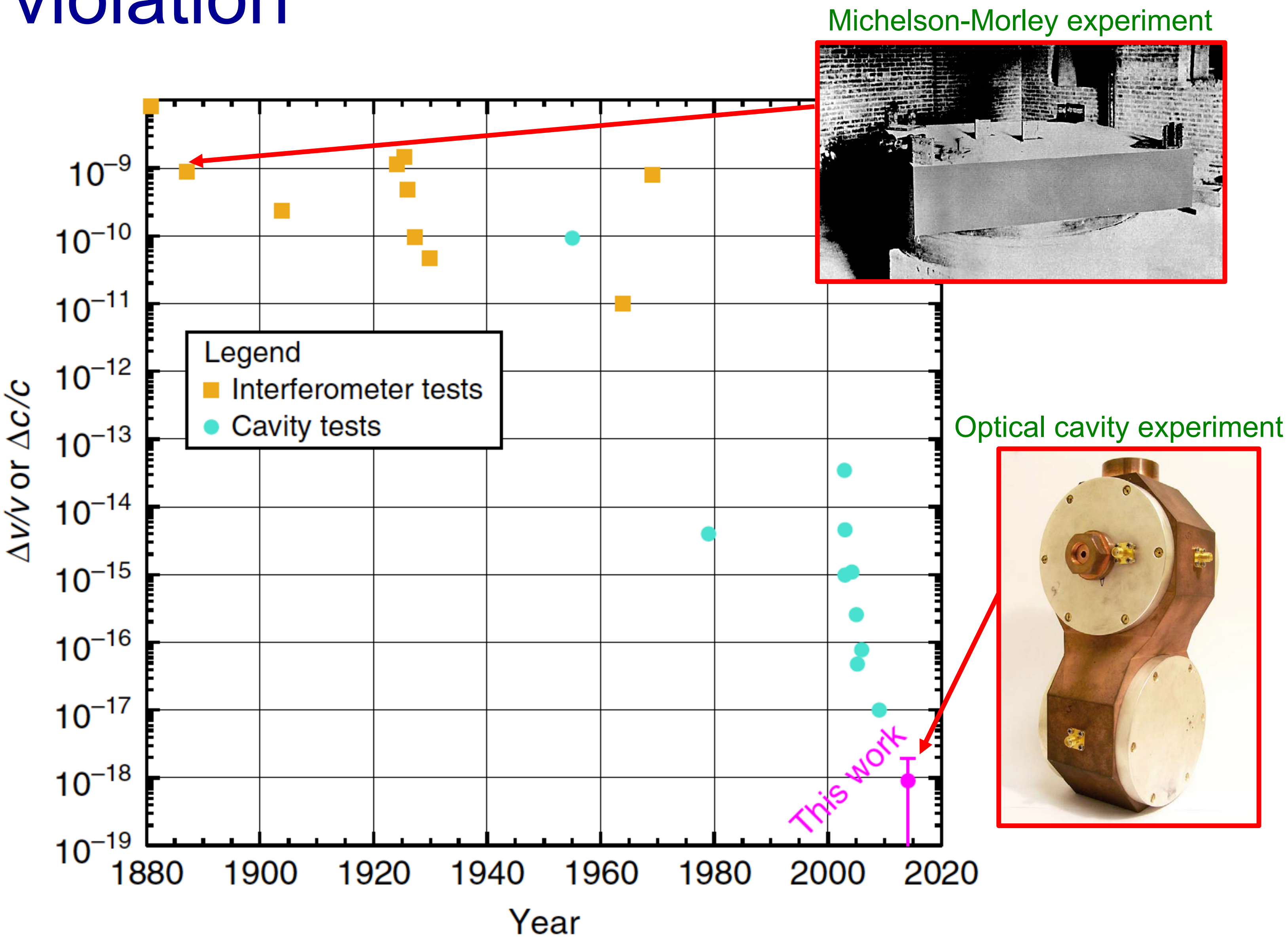
Searches of Lorentz violation

Lorentz symmetry is valid down to $\Delta c/c < 10^{-9}$

The experiment has been improved over 100 years.

Technology shift (interferometer → optical cavity) and $\Delta c/c < 10^{-18}$ (1 billion higher precision than M-M experiment)

Why we keep testing this?



Progress in Particle and Nuclear Physics 125 (2022) 103948

Quantum gravity

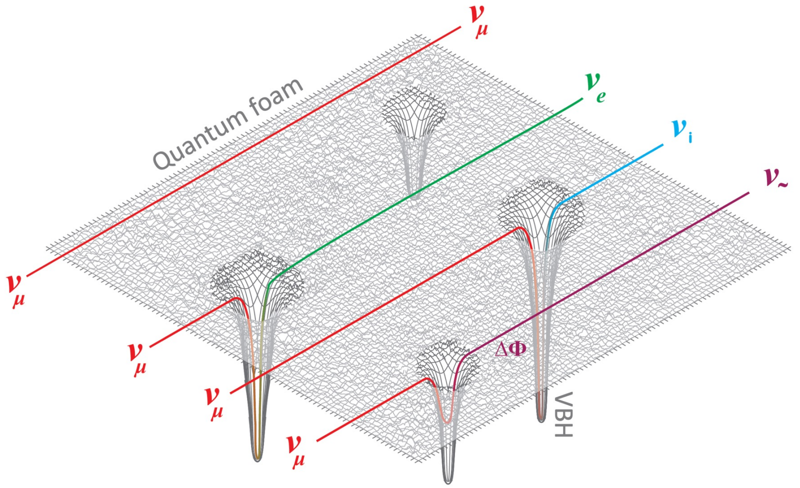
Searching Lorentz violation is well motivated

Lorentz violation in Planck scale theories
- string theory
- noncommutative field theory
- quantum loop gravity

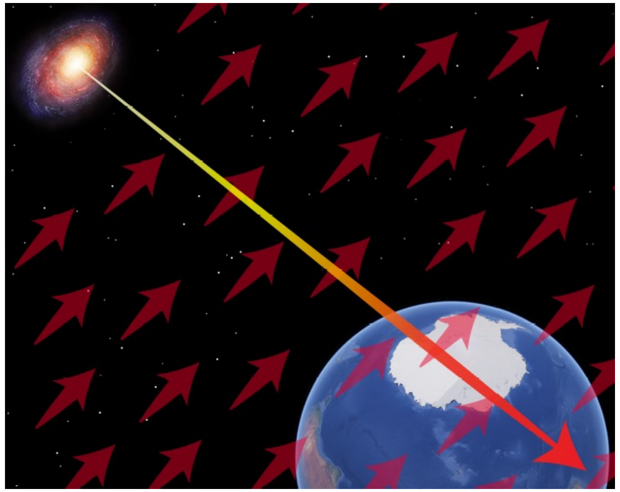
etc

Lorentz violation is seen as
- background field in vacuum (SME)
- spacetime fluctuation (quantum mechanics)

etc



Quantum foam
- quantum fluctuation of space-time



Standard Model Extension (SME)
- parameterize interactions with background field of the universe (æther)

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 the best probes of fundamental symmetry tests!

https://higgstan.com/

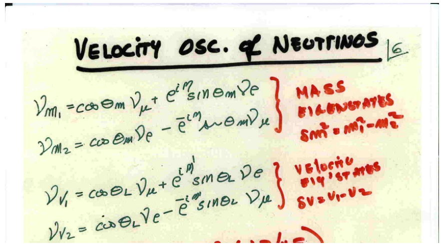
Searches of Lorentz violation

Glashow, Coleman, PLB405(1997)249
Kostelecký, Mewes PRD69(2004)016005

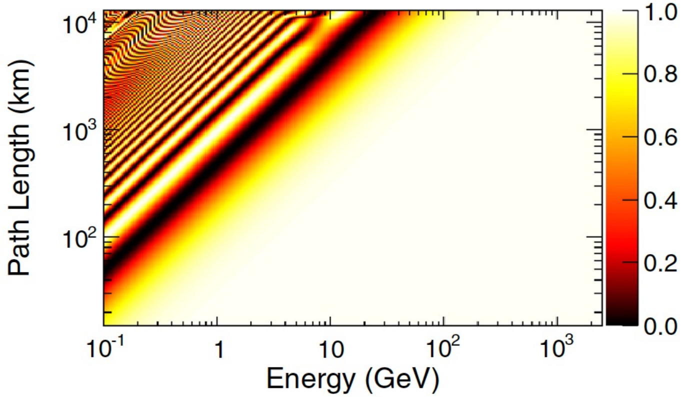
Lorentz violating neutrino oscillations

One of solutions of neutrino anomaly

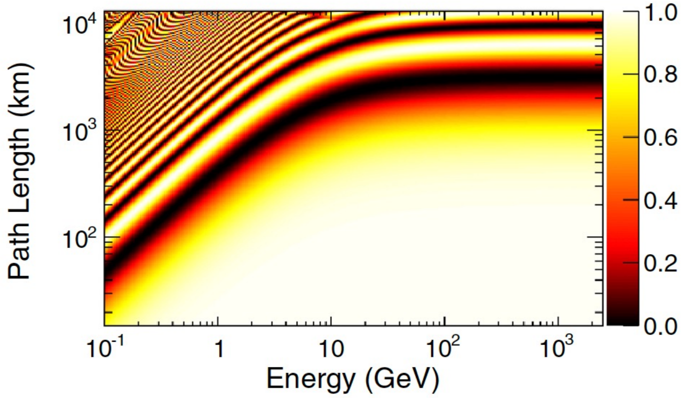
Glashow's talk, Neutrino 98



SuperK, PRD 91(2015)052003



(a) $\nu_\mu \to \nu_\mu$, No Lorentz violation



(b) $\nu_\mu \to \nu_\mu$, $a^T_{\mu\tau} = 10^{-22}$ GeV

Lorentz violating neutrino oscillation depend on L or LE, not L/E
→ Lorentz violation is small effect, if exists

Lorentz violating neutrino oscillations can be fully parameterized by the Standard-Model Extension (SME) Lagrangian

e.g.) SME Lagrangian for fermion

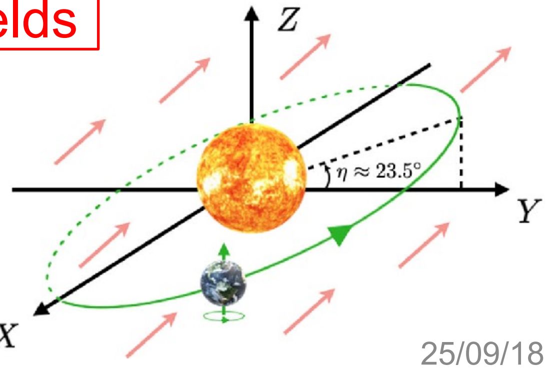
$$\mathcal{L} = i\bar{\psi}\gamma_\mu\partial^\mu\psi - m\bar{\psi}\psi + \bar{\psi}\gamma_\mu a^\mu\psi + \bar{\psi}\gamma_\mu c^{\mu\nu}\psi \cdots$$

Standard Model

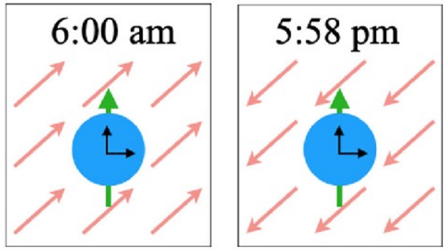
couplings with background fields

Physics of Lorentz violation
- Spectrum distortion,
- Sidereal time dependence

24h 00min 00sec: Solar day
23h 56min 4.1sec: Sidereal day



ZEUS, PRD107(2023)092008



Lorentz violation tests with neutrinos – Summary

Limits of all SME parameters are summarized in tables [ArXiv:0801.0287v17](https://arxiv.org/abs/0801.0287v17)

So far, there is no compelling evidence of Lorentz violation

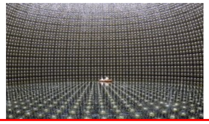
When do we find it???

28-page limits in neutrino sector LV...

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

Combination	Result	System	Ref.
$\mathcal{C}_{\mu e}$	$(-0.3 \pm 3.0) \times 10^{-20}$ GeV	T2K	[260]
$(\mathcal{A}_c)_{\mu e}$	$(0.3 \pm 3.2) \times 10^{-20}$ GeV	"	[260]
$(\mathcal{A}_s)_{\mu e}$	$(0.4 \pm 3.8) \times 10^{-20}$ GeV	"	[260]
$(\mathcal{B}_c)_{\mu e}$	$(-1.2 \pm 2.6) \times 10^{-20}$ GeV	"	[260]
$(\mathcal{B}_s)_{\mu e}$	$(2.0 \pm 3.1) \times 10^{-20}$ GeV	"	[260]
$\lvert(\mathcal{C})_{\bar{e}\bar{\mu}}\rvert^2$	$(10.7 \pm 2.6 \pm 1.3) \times (10^{-19}\ \text{GeV})^2$	LSND	[261]
$\lvert(\mathcal{C})_{\bar{e}\bar{\mu}}\rvert^2 + \frac{1}{2}\lvert(\mathcal{A}_s)_{\bar{e}\bar{\mu}}\rvert^2 + \frac{1}{2}\lvert(\mathcal{A}_c)_{\bar{e}\bar{\mu}}\rvert^2$	$(9.9 \pm 2.3 \pm 1.4) \times (10^{-19}\ \text{GeV})^2$	"	[261]
$\lvert(\mathcal{C})_{\bar{e}\bar{\mu}}\rvert^2 + \frac{1}{2}\lvert(\mathcal{A}_s)_{\bar{e}\bar{\mu}}\rvert^2 + \frac{1}{2}\lvert(\mathcal{A}_c)_{\bar{e}\bar{\mu}}\rvert^2 + \frac{1}{2}\lvert(\mathcal{B}_s)_{\bar{e}\bar{\mu}}\rvert^2 + \frac{1}{2}\lvert(\mathcal{B}_c)_{\bar{e}\bar{\mu}}\rvert^2$	$(10.5 \pm 2.4 \pm 1.4) \times (10^{-19}\ \text{GeV})^2$	"	[261]
$\lvert(a^{(3)}_{\text{eff}})^{e\tau}_{00}\rvert$	$< 6.5 \times 10^{-20}$ GeV	SNO	[251]
$\lvert(a^{(3)}_{\text{eff}})^{e\tau}_{10}\rvert$	$< 2.8 \times 10^{-21}$ GeV	"	[251]
$\lvert\text{Re}\,(a^{(3)}_{\text{eff}})^{e\tau}_{11}\rvert$	$< 1.5 \times 10^{-21}$ GeV	"	[251]
$\lvert\text{Im}\,(a^{(3)}_{\text{eff}})^{e\tau}_{11}\rvert$	$< 1.7 \times 10^{-21}$ GeV	"	[251]
$(a_R)^X_{\bar{e}\bar{\tau}}$	$(-5.6 \pm 8.0) \times 10^{-20}$ GeV	Daya Bay	[252]
$(a_R)^Y_{\bar{e}\bar{\tau}}$	$(-0.9 \pm 8.0) \times 10^{-20}$ GeV	"	[252]
$\text{Re}\,(a^T_{e\tau})$	$< 4.1 \times 10^{-23}$ GeV	Super-Kamiokande	[253]
$\text{Im}\,(a^T_{e\tau})$	$< 2.8 \times 10^{-23}$ GeV	"	[253]
$\lvert\text{Re}\,(a_L)^T_{e\tau}\rvert,\ \lvert\text{Im}\,(a_L)^T_{e\tau}\rvert$	$< 7.8 \times 10^{-20}$ GeV	Double Chooz	[256]
$\lvert\text{Re}\,(a_L)^X_{e\tau}\rvert,\ \lvert\text{Im}\,(a_L)^X_{e\tau}\rvert$	$< 4.4 \times 10^{-20}$ GeV	"	[256]
$\lvert\text{Re}\,(a_L)^Y_{e\tau}\rvert,\ \lvert\text{Im}\,(a_L)^Y_{e\tau}\rvert$	$< 9.0 \times 10^{-20}$ GeV	"	[256]
$\lvert\text{Re}\,(a_L)^Z_{e\tau}\rvert,\ \lvert\text{Im}\,(a_L)^Z_{e\tau}\rvert$	$< 2.7 \times 10^{-19}$ GeV	"	[256]
$\lvert -(a_L)^T_{e\tau} - 0.29(a_L)^Z_{e\tau} + 0.0042[-1.46(c_L)^{TT}_{e\tau} - 0.57(c_L)^{TZ}_{e\tau} + 0.38(c_L)^{ZZ}_{e\tau}]\ \text{GeV}\rvert$	$< 7.8 \times 10^{-20}$ GeV	"	[258]
$\lvert -0.91(a_L)^X_{e\tau} + 0.29(a_L)^Y_{e\tau} + 0.0042[-1.83(c_L)^{TX}_{e\tau} + 0.58(c_L)^{TY}_{e\tau} - 0.52(c_L)^{XZ}_{e\tau} + 0.16(c_L)^{YZ}_{e\tau}]\ \text{GeV}\rvert$	$< 6.6 \times 10^{-20}$ GeV	"	[258]
$\lvert 0.29(a_L)^X_{e\tau} + 0.91(a_L)^Y_{e\tau} + 0.0042[0.58(c_L)^{TX}_{e\tau} + 1.83(c_L)^{TY}_{e\tau} + 0.16(c_L)^{XZ}_{e\tau} + 0.52(c_L)^{YZ}_{e\tau}]\ \text{GeV}\rvert$	$< 7.0 \times 10^{-20}$ GeV	"	[258]
$\lvert 0.0042[0.26((c_L)^{XX}_{e\tau} - (c_L)^{YY}_{e\tau}) + 0.75(c_L)^{XY}_{e\tau}]\ \text{GeV}\rvert$	$< 5.4 \times 10^{-20}$ GeV	"	[258]
$\lvert 0.0042[0.38((c_L)^{XX}_{e\tau} - (c_L)^{YY}_{e\tau}) - 0.53(c_L)^{XY}_{e\tau}]\ \text{GeV}\rvert$	$< 5.4 \times 10^{-20}$ GeV	"	[258]
$\lvert(a_L)^T_{\mu\mu}\rvert$	$< 2 \times 10^{-7}$ GeV	Leptons, $SU(2)_L$ invariance	[239]*
$\lvert(a_L)^X_{\mu\mu}\rvert$	$< 4 \times 10^{-23}$ GeV	"	[239]*
$\lvert(a^{(3)}_{\text{eff}})^{\mu\mu}_{00}\rvert$	$< 8.2 \times 10^{-20}$ GeV	SNO	[251]
$\lvert(a^{(3)}_{\text{eff}})^{\mu\mu}_{10}\rvert$	$< 5.4 \times 10^{-21}$ GeV	"	[251]
$\lvert\text{Re}\,(a^{(3)}_{\text{eff}})^{\mu\mu}_{11}\rvert$	$< 2.9 \times 10^{-21}$ GeV	"	[251]
$\lvert\text{Im}\,(a^{(3)}_{\text{eff}})^{\mu\mu}_{11}\rvert$	$< 3.2 \times 10^{-21}$ GeV	"	[251]
$(a_R)^X_{\bar{\mu}\bar{\mu}}$	$(9 \pm 45) \times 10^{-20}$ GeV	Daya Bay	[252]
$(a_R)^Y_{\bar{\mu}\bar{\mu}}$	$(-9 \pm 45) \times 10^{-20}$ GeV	"	[252]
$\lvert(a_L)^0_{\mu\mu} - (a_L)^0_{\tau\tau}\rvert$	$< 1.9 \times 10^{-23}$ GeV	Super-Kamiokande	[262]*
$\lvert(a_L)^X_{\mu\mu}\rvert,\ \lvert(a_L)^Y_{\mu\mu}\rvert$	$< 4.8 \times 10^{-20}$ GeV	T2K	[263]
$\lvert(a_L)^0_{\mu\mu} - (a_L)^0_{\tau\tau}\rvert$	$< 6.3 \times 10^{-24}$ GeV	Super-Kamiokande	[264]*

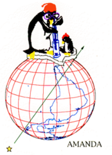
Spectral distortion



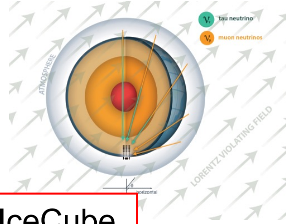
Super-Kamiokande
PRD91(2015)052003

Daya Bay

PRD98(2018)092013

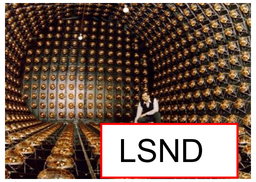


AMANDA
PRD79(2009)102005



IceCube
Nature Physics 14(2018)961

Sidereal variation



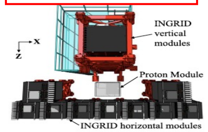
LSND
PRD72(2005)076004

MiniBooNE
PLB718(2013)1303

MINOS ND
PRL101(2008)151601

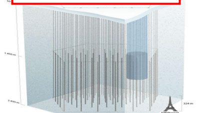
MINOS FD
PRL105(2010)151601

T2K ND



PRD95(2017)111101

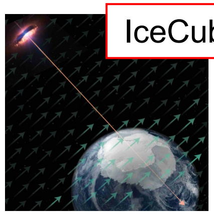
IceCube



PRD82(2010)112003

Double Chooz
PRD86(2013)112009

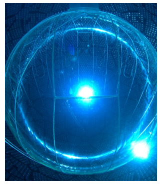
Flavor ratio



IceCube
Nature Physics, 18(2022)1287

Seasonal variation

SNO



PRD98(2018)112013

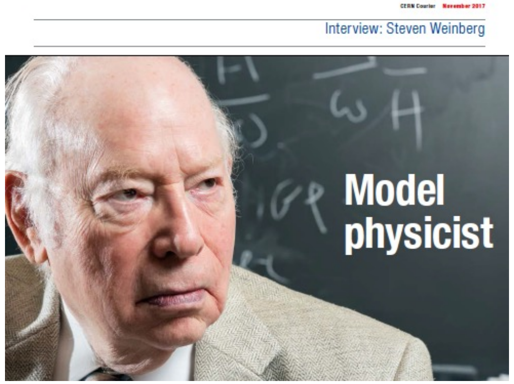
When do we find Lorentz violation???

Lorentz violation is motivated by Planck scale theories, so it is suppressed with the power of Planck mass ($\sim 10^{19}\ GeV$). In effective field theory, non-renormalizable operators are the signature of new physics, dimension analysis guides target sensitivity to look for Lorentz violation.

$$a^{(5)} \sim \frac{1}{M_{Pl}}, \qquad c^{(6)} \sim \left(\frac{1}{M_{Pl}}\right)^2, \qquad etc$$

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. Astrophysical signals have advantages to look for these operators.

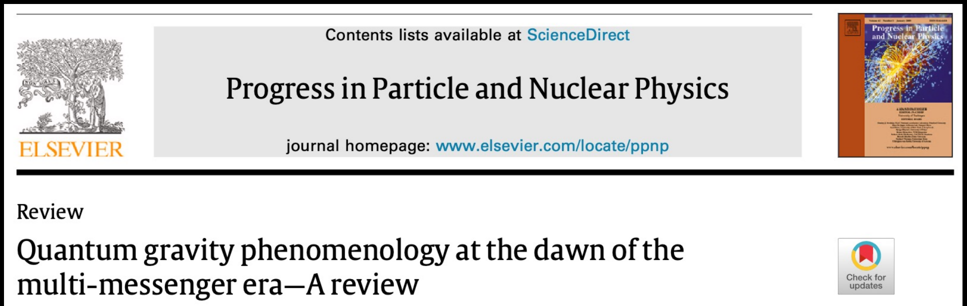


Steven Weinberg
(CERN Courier Nov. 2017)

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

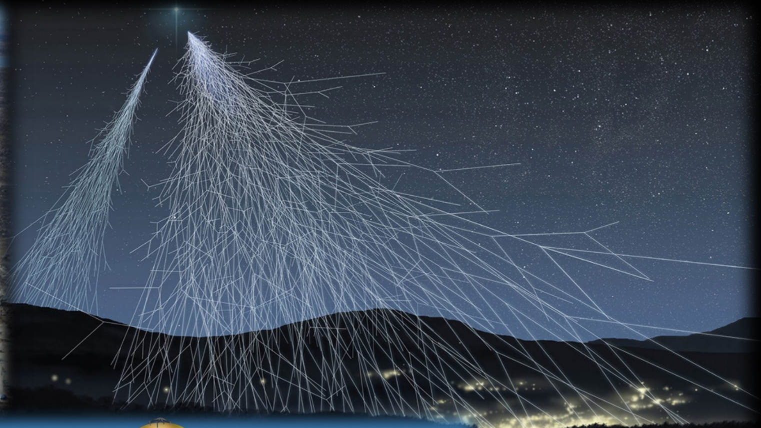
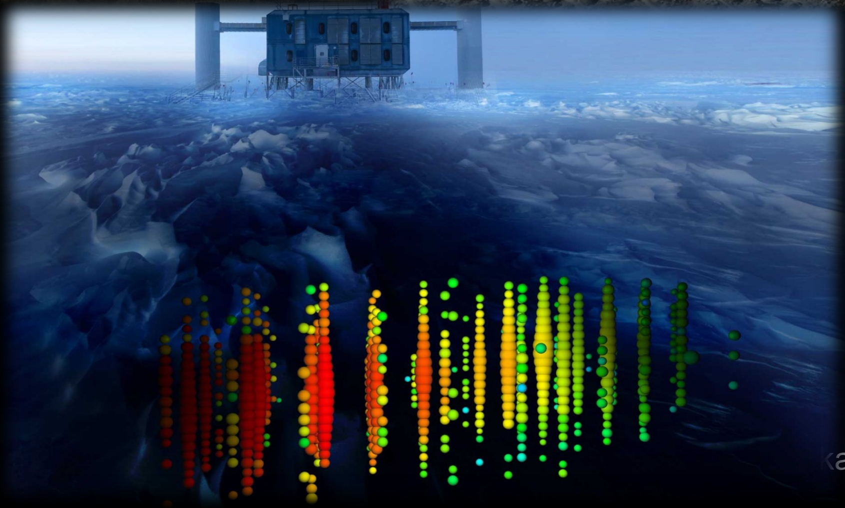
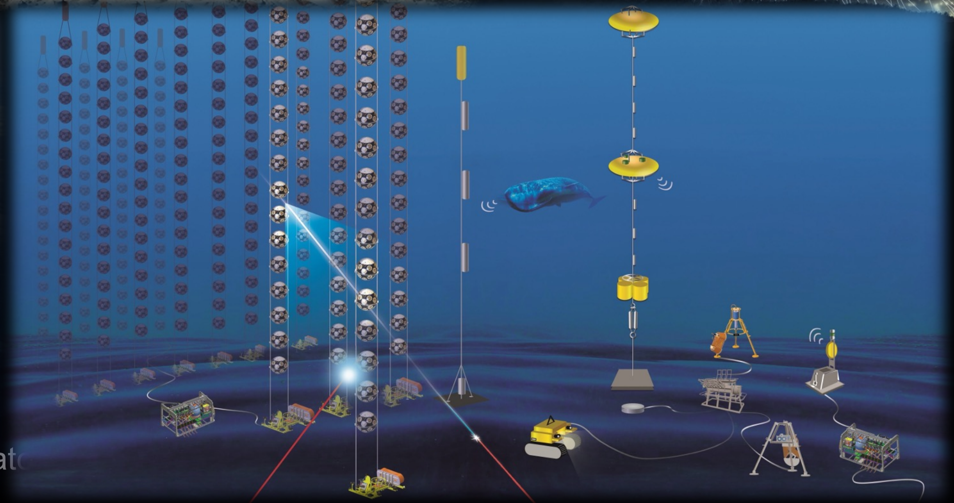
Progress in Particle and Nuclear Physics 125 (2022) 103948

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



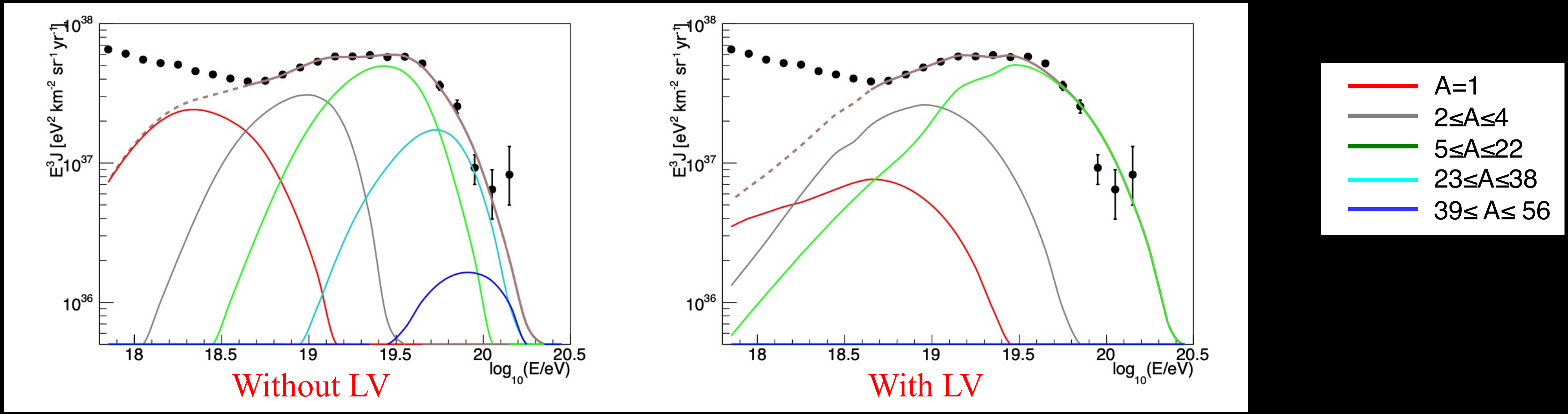
Auger, JCAP01(2022)023, and many others
HAWC, PRL124(2020)131101 and many others

Cut-off in high-energy cosmic ray spectrum

Lorentz violation = media in vacuum

- Attenuate high-energy cosmic rays

$$E^2 = p^2 + m^2 + a^{(5)}E^3 + c^{(6)}E^4 + \cdots$$



Auger UHECR spectrum

Stecker, et al, PRD91(2015)045009, and many others
KM3NeT, Nature 638(2025)376, ArXiv:2502.1207

Cut-off in high-energy cosmic ray spectrum

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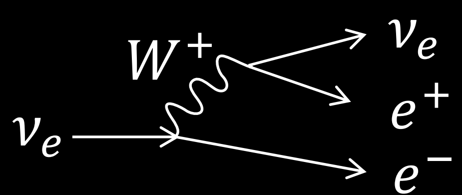
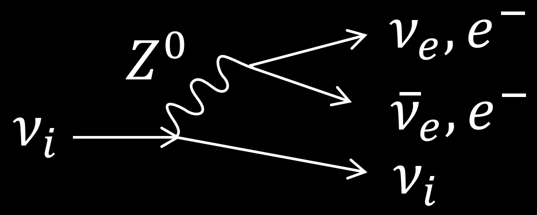
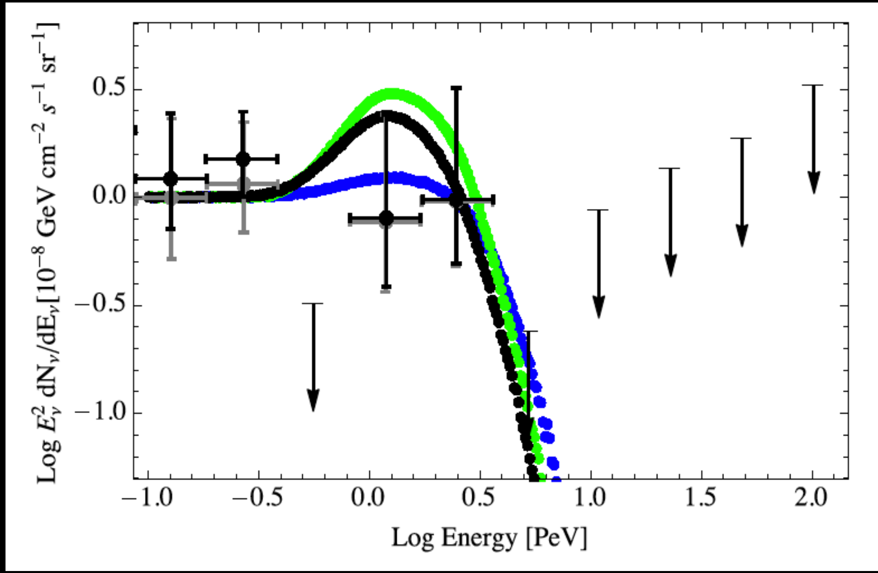
$$E^2 = p^2 + m^2 + a^{(5)}E^3 + c^{(6)}E^4 + \cdots$$



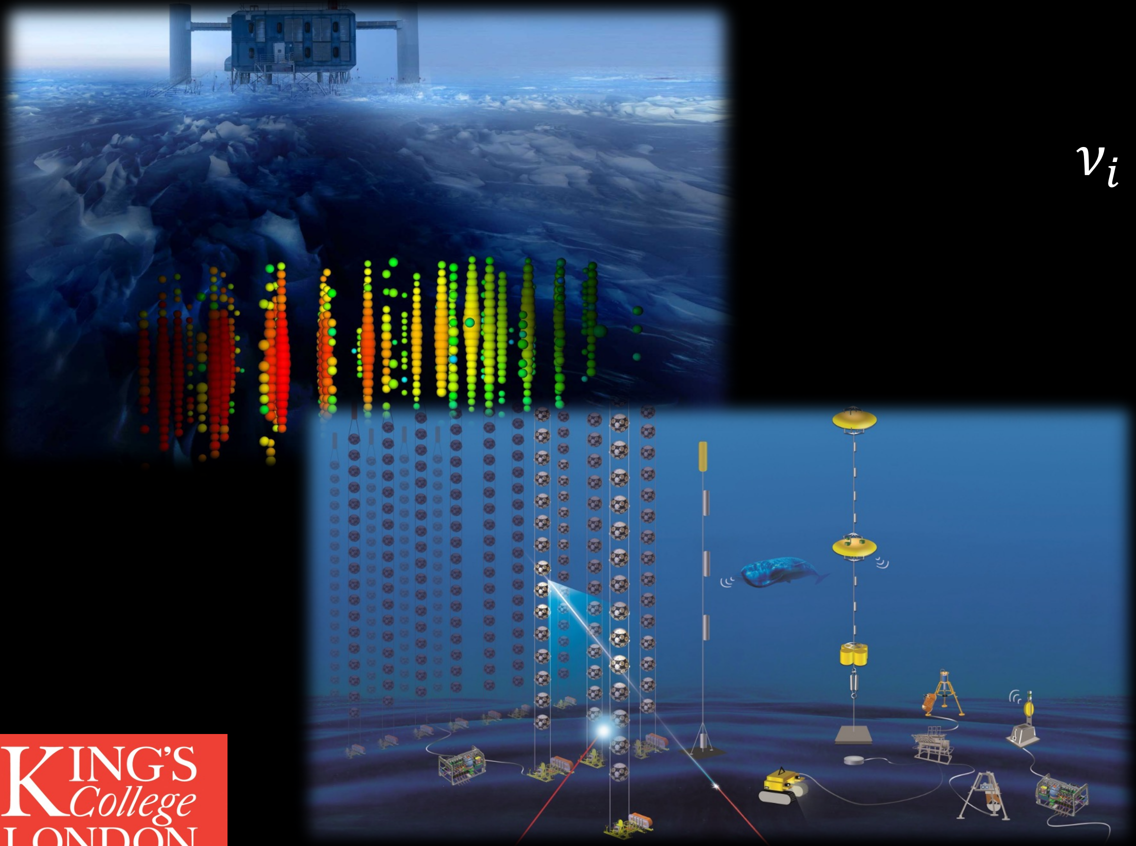
Vacuum pair emission



Neutrino splitting



IceCube neutrino spectrum distortion



Lorentz violating field cause radiation in vacuum

- High-energy neutrinos are attenuated
- KM3NeT 220 PeV neutrino (KM3-230213A)

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

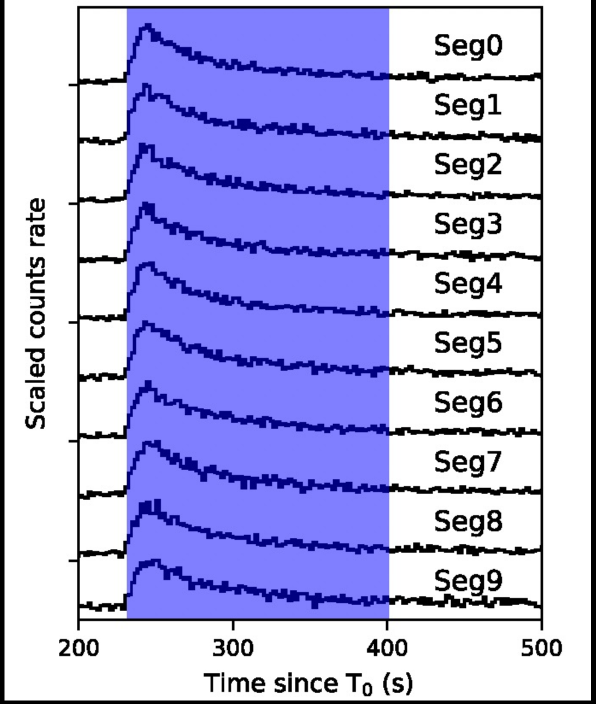
Amelino-Camelia et al, Nature 393(1998)763, LHASSO PRL133(2024)071501), and many others
Bustamante et al,PRD111(2025)12

Time-of-flight of high-energy cosmic rays

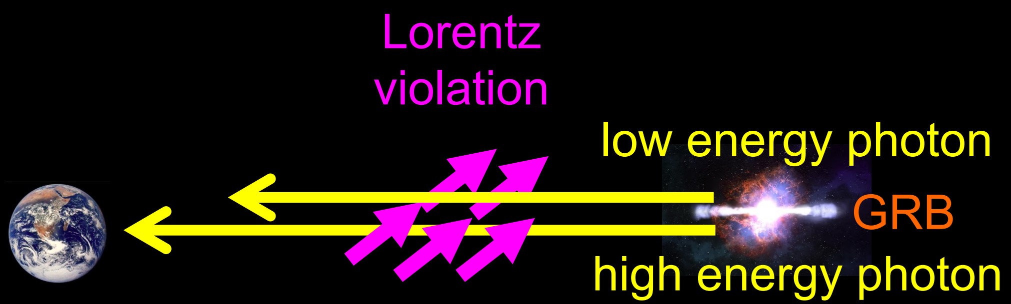
Lorentz violation = media in vacuum
- Anomalous time dependent effects

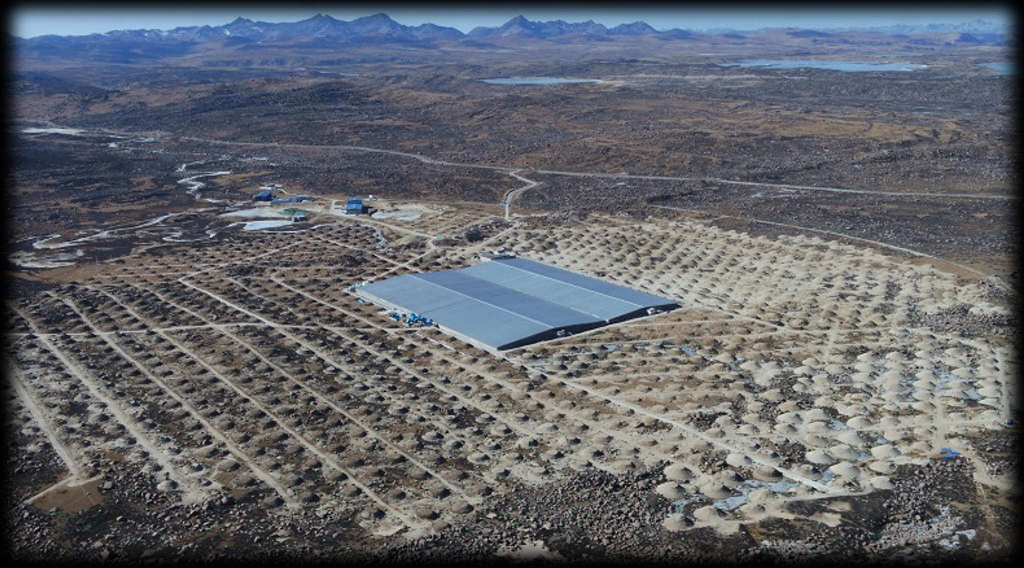
Gamma Ray Bursts
- Energy dependent light curve distortion

$$\delta v \sim E k_{00}^{(5)} + E^2 c_{00}^{(6)} + \cdots$$



LHASSO energy-dependent light curve of GRB221009A



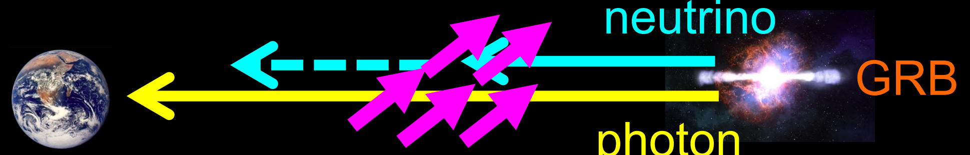


Time-of-flight of high-energy cosmic rays

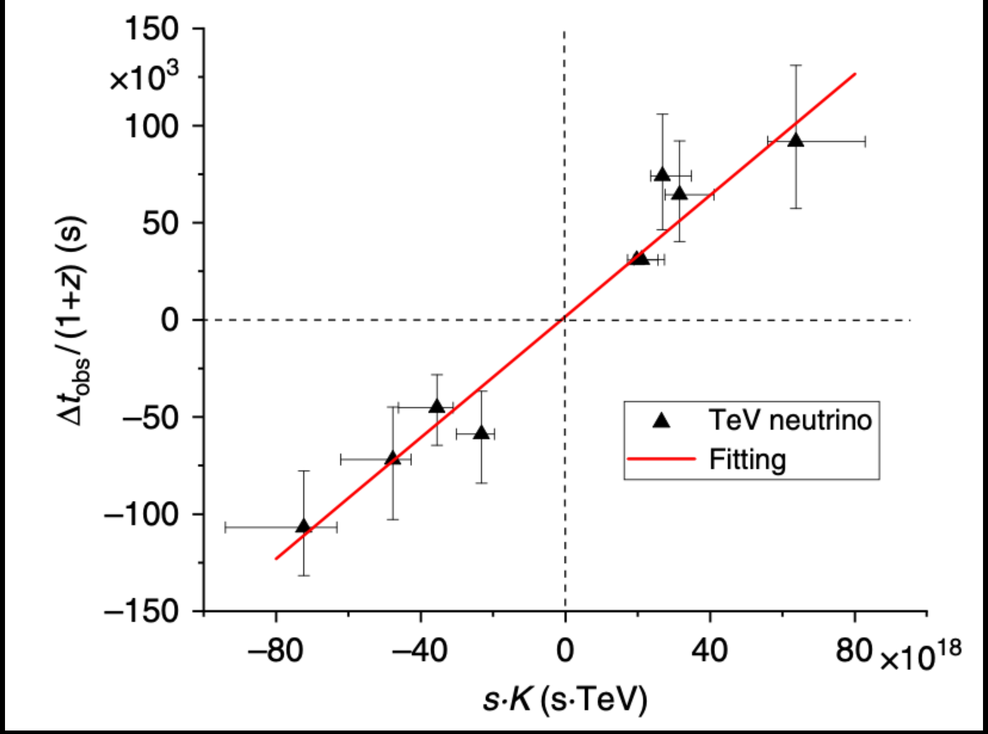
Lorentz violation = media in vacuum
- Anomalous time dependent effects

Gamma Ray Bursts
- Energy dependent light curve distortion
- Neutrino time-of-flight ($a^{(5)}$=CPT odd)

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



CPT odd Lorentz violation: $a^{(5)} \xleftrightarrow{\nu \leftrightarrow \bar{\nu}} -a^{(5)}$



IceCube-GRB coincidence candidates with Lorentz violation

IceCube, Nature Physics 18(2022)1287

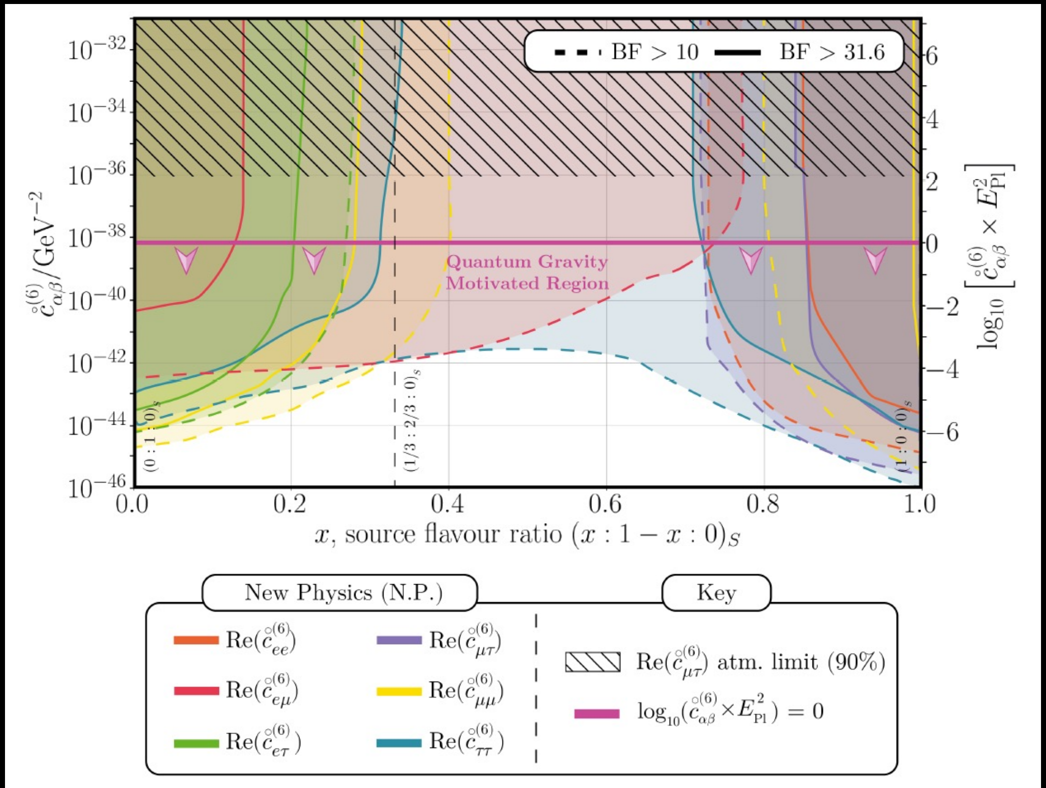
Anomalous neutrino flavour mixing

Lorentz violation = media in vacuum
- MSW-like effect in vacuum

Neutrino mixings are macroscopic quantum effects and sensitive to small effects.

Sensitive to the target region of Quantum Gravity ($< 1/M_{Pl}^2 \sim 10^{-38}\ GeV^{-2}$ for dim-6 operators)

IceCube Lorentz violation search through astrophysical neutrino flavour



Argüelles, Halzen, Kurahashi, PRX15 (2025) 030501

Future of high-energy neutrino astronomy

Higher energy gives better sensitivity to new physics?

Effective area of neutrino telescopes is limited
Cherenkov neutrino telescopes

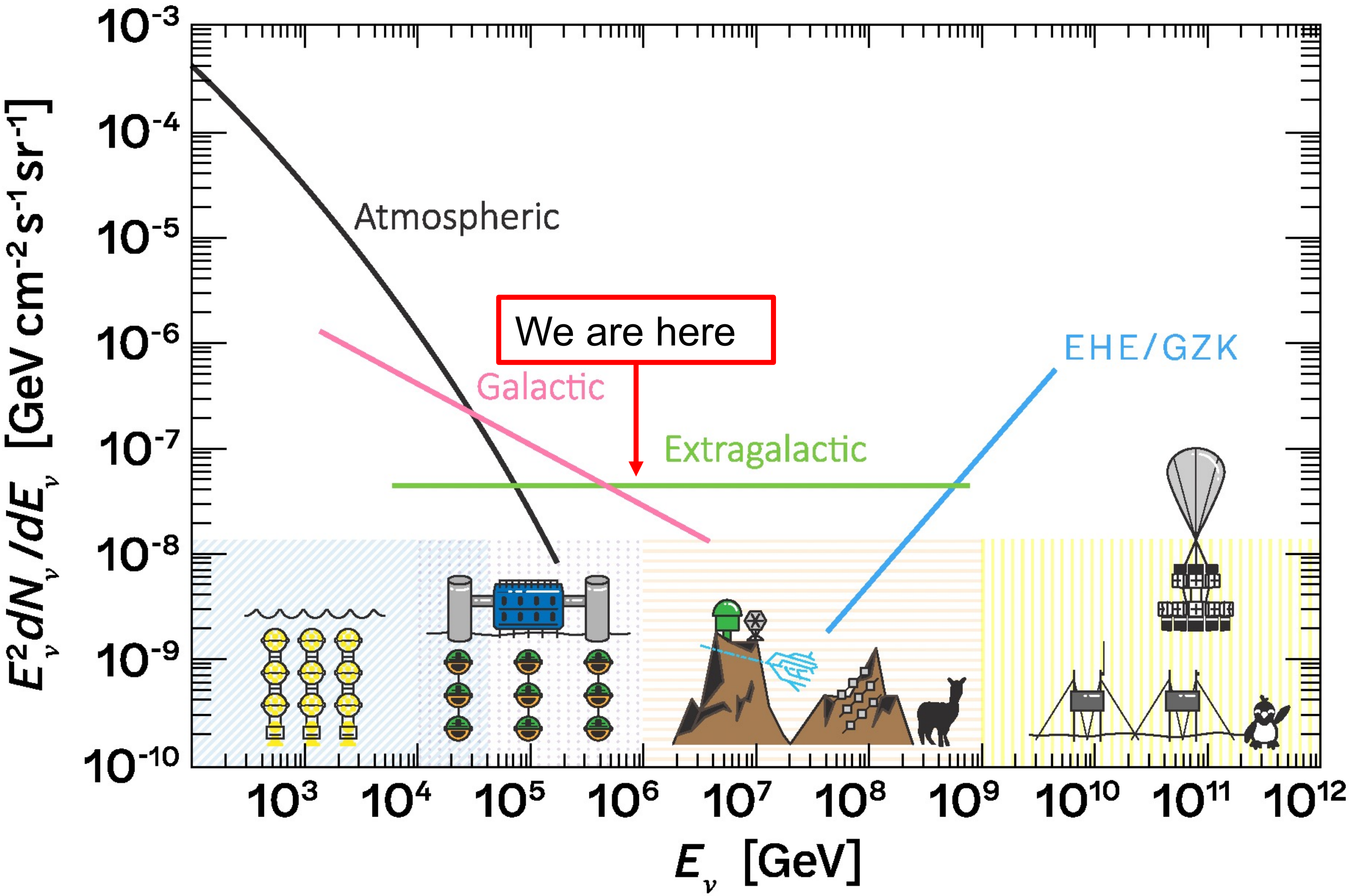
Future technologies;
- Radio telescope

PUEO, ARIANNA, RNO-G, IceCube-Gen2, TAROGE-M, Beacon, GRAND

- Air shower

Trinity, POEMMA, TAMBO, Auger/GCOS

etc

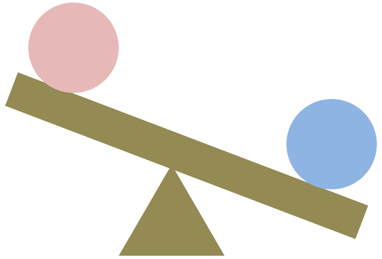


Searches of CPT violation

[Snowmass21 white paper, “Beyond the Standard Model effect with Neutrino Flavour”, EPJC83(2023)15](#)
[Barenboim et al., PLB780(2018)631](#)

Test of Direct CPT violation

$h_{eff} = \frac{M^2}{2E}$



$\bar{h}_{eff} = \frac{\bar{M}^2}{2E}$

Direct CPT violation

- Comparisons of particles and anti-particles
- $\left|\Delta m^2_{21} - \Delta \bar{m}^2_{21}\right| < 5.9\times10^{-5}\ \mathrm{eV}^2$
- $\left|\Delta m^2_{31} - \Delta \bar{m}^2_{31}\right| < 0.8 - 1.1\times10^{-3}\ \mathrm{eV}^2$

cf.) Kaon system

- $|m(K^o) - m(\overline{K^o})|/m(K^o) < 6\times10^{-19}\ \mathrm{GeV}$

→ $|m^2(K^o) - m^2(\overline{K^o})| < 0.25\ \mathrm{eV}^2$

cf.) Hydrogen-Antihydrogen charge/mass ratio (BASE) ,BASE, Nature 601(2022) 53

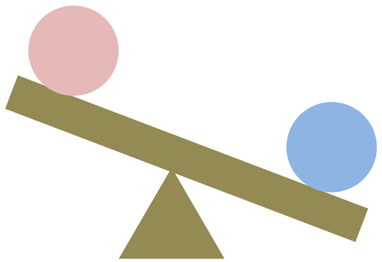
- $r_H < 2\times10^{-27}\ \mathrm{GeV}$

Neutrinos oscillation experiments provide the most precise direct CPT violation tests for elementary particles (Hyper-Kamiokande, JUNO, DUNE, etc)

Snowmass21 white paper, “Beyond the Standard Model effect with Neutrino Flavour”, EPJC83(2023)15
Greenberg, PRL89(2002)231602, Chaichian et al., PLB699(2011)177

Test of General CPT violation

$$h_{eff} = \frac{M^2}{2E} + a$$



$$\bar{h}_{eff} = \frac{M^2}{2E} - a$$

Lorentz and CPT violation

- Interactive local QFT
- CPT odd SME parameters ($a \overset{\nu \leftrightarrow \bar{\nu}}{\longleftrightarrow} -a$)
- High-precision LV test = High-precision CPT test

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CPT Violation Implies Violation of Lorentz Invariance

O.W. Greenberg*
Center for Theoretical Physics, Department of Physics, University of Maryland, College Park, Maryland 20742-4111
(Received 28 January 2002; published 18 November 2002)

A interacting theory that violates *CPT* invariance necessarily violates Lorentz invariance. On the other hand, *CPT* invariance is not sufficient for out-of-cone Lorentz invariance. Theories that violate *CPT* by having different particle and antiparticle masses must be nonlocal.

CPT violation with Lorentz invariant

- Non-local interaction
- Theoretical challenges

Contents lists available at ScienceDirect
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www.elsevier.com/locate/physletb

Particle-Antiparticle comparison remain an important test of CPT violation

CPT violation does not lead to violation of Lorentz invariance and vice versa

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[b] Dipartimento di Fisica, Università degli Studi di Ferrara, I-44100 Ferrara, Italy
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[d] Institute of Theoretical and Experimental Physics, 113259 Moscow, Russia

SuperK, PRD112(2025)012004
Olavarrieta et al.,ArXiv:2402.13308, IceCube, PRD111(2025)112001

Particle – Antiparticle comparison

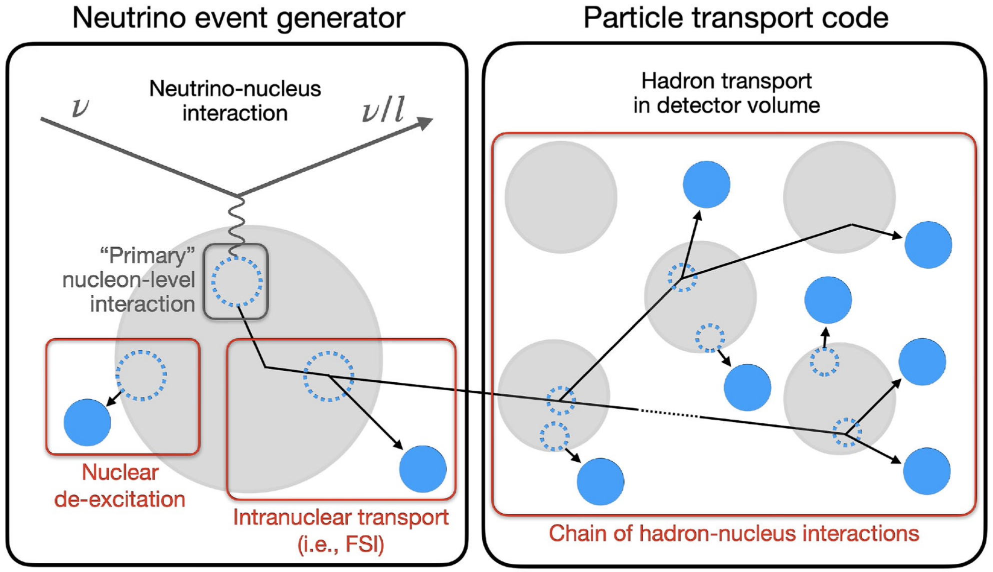
In general, charge separation of neutrinos are not easy for water Cherenkov detector

Low energy – Michel electron and nucleon multiplicity

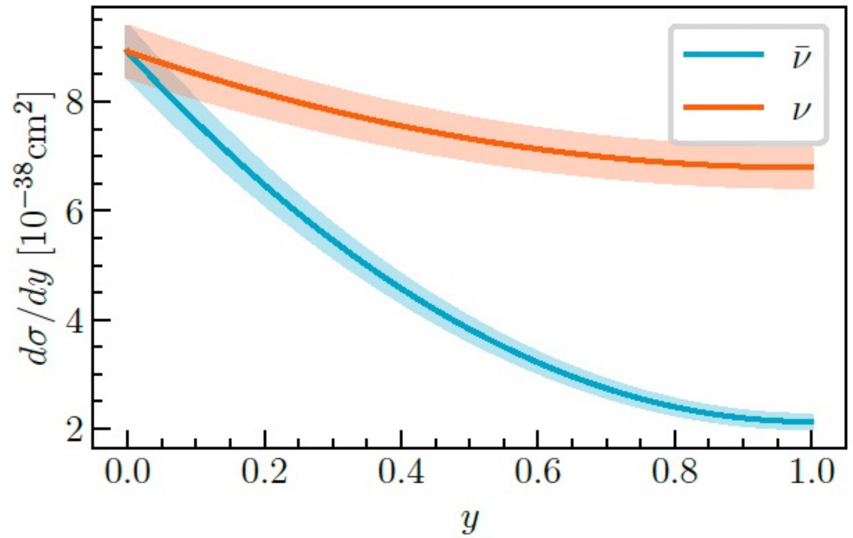
- $\nu_\mu + n \rightarrow \mu^- + p$ vs. $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
- $\nu_\mu + p \rightarrow \mu^- + \Delta^{++}$ vs. $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Delta^0$
- Timing, proton and neutron tagging
- Good nuclear physics for precise simulation

Medium energy – Inelasticity

- $\nu + X \rightarrow l + hadrons, y_{eff} = \frac{E_{had}}{E_{had}+E_{lep}}$
- Key to measure mass hierarchy with atmospheric neutrinos
- Good hadron physics for precise simulation



SuperK nucleon emission processes



DIS inelasticity distribution

Tests of Quantum Mechanics

Snowmass21 white paper, "Beyond the Standard Model effect with Neutrino Flavour", EPJC83(2023)15

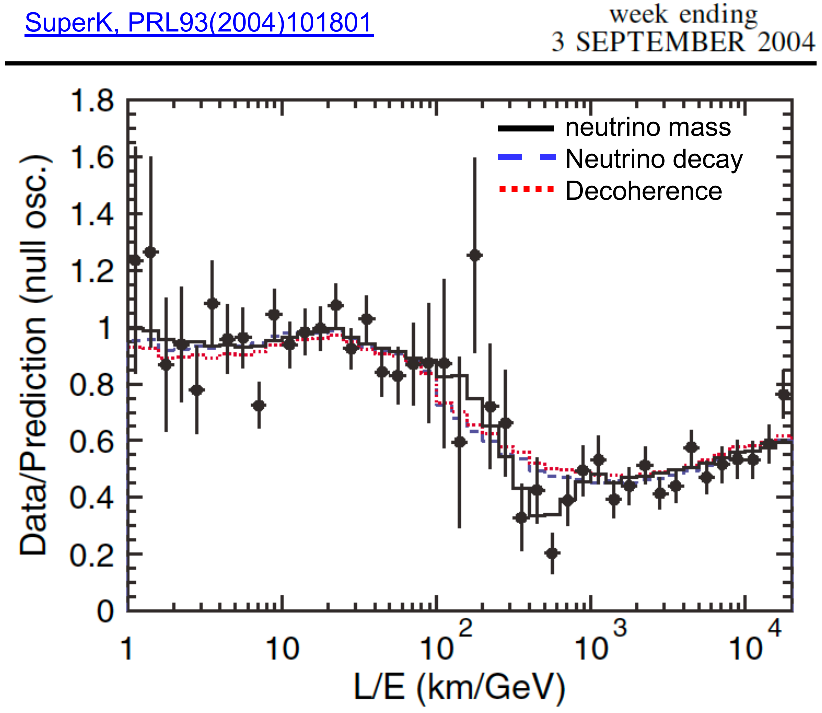
Test of Quantum Mechanics

Quantum decoherence

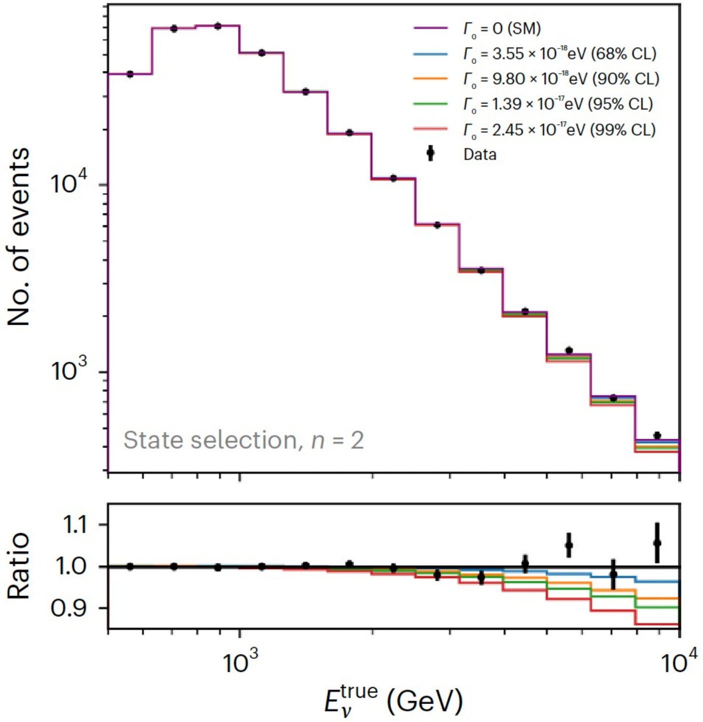
- One of solutions of neutrino anomaly
- Quantum decoherence dumps coherence, no oscillation

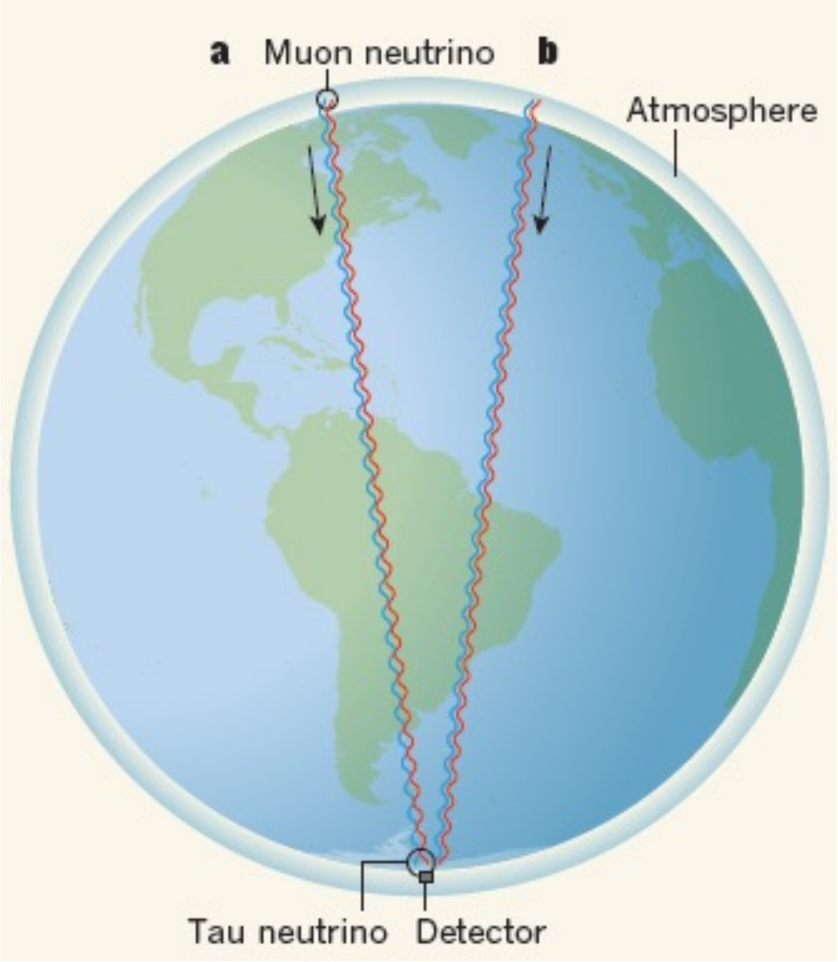
→ Quantum decoherence is small effect, if exists

SuperK, PRL93(2004)101801



IceCube, Nature Physics, 20 (2024) 913





IceCube, Nature Physics 14 (2018) 961

Snowmass21 white paper, “Beyond the Standard Model effect with Neutrino Flavour”, EPJC83(2023)15
Formaggio et al., PRL117(2016)050402, Groth et al, ArXiv:2504.05375, Minic, Takeuchi, Tze, PRD104(2021)L051301 and others

Test of Quantum Mechanics

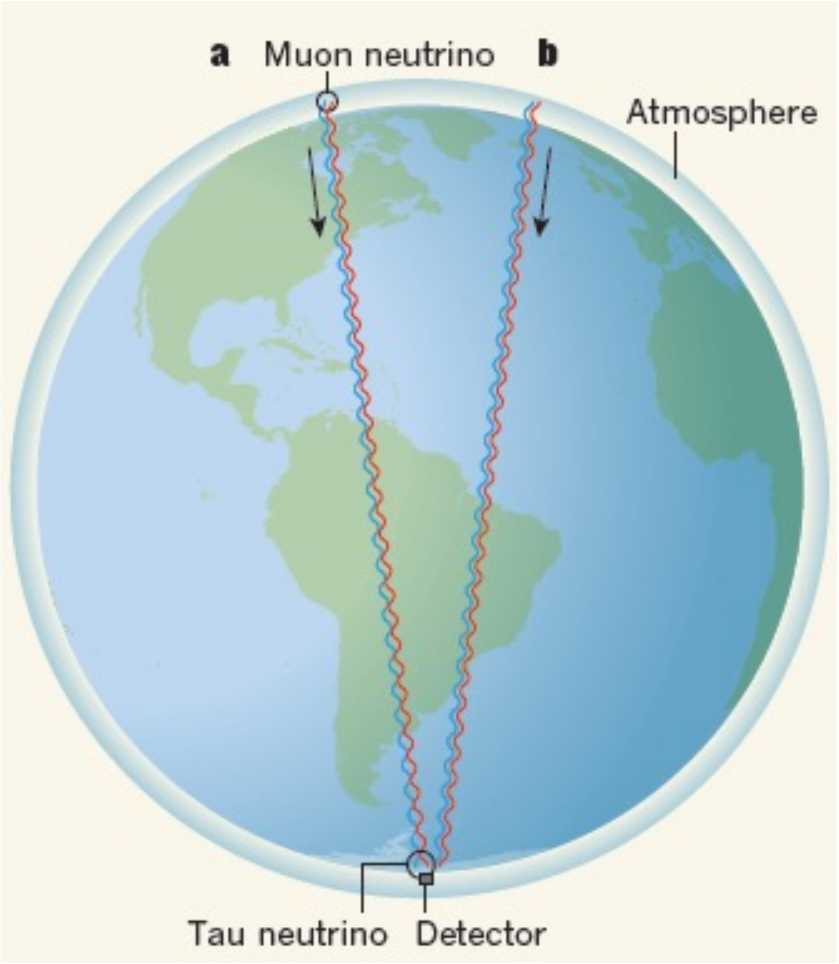
Quantum decoherence
- One of solutions of neutrino anomaly
- Quantum decoherence dumps coherence, no oscillation

→ Quantum decoherence is small effect, if exists

Atmospheric neutrino oscillation is the biggest interferometer on Earth to test quantum mechanics

Legget-Garg inequality - Correlation of time sequence
Nambu quantum mechanics - 2-dimensional phase rotation
etc

Active field but not many applications to neutrino physics yet



IceCube, Nature Physics 14 (2018) 961

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, but so far no compelling evidence of Lorentz violation

Astrophysical sources are powerful tools to look for Lorentz violation

Neutrino oscillations are one of the most precise test of CPT and quantum mechanics

Thank you for your attention!

Backup

Models of Lorentz violation

String theory, Kostelecký and Samuel, PRD39 (1989) 683
Ultra-light dark matter, Argüelles, Farrag, TK, ArXiv:2404.10926
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
Long range force, Bustamante, Agarwalla, PRL122(2019)061103
Torsion, Kostelecký, Russell, Tasson, PRL100(2008)111102

and many more!

Effective Lorentz violation (spontaneous Lorentz symmetry breaking) is compatible with Riemann geometry; however, Intrinsic Lorentz Violation is not

Finsler geometry Kostelecký and Li, PRD104 (2021) 044054 got lots of attention recently, to go beyond Riemann geometry

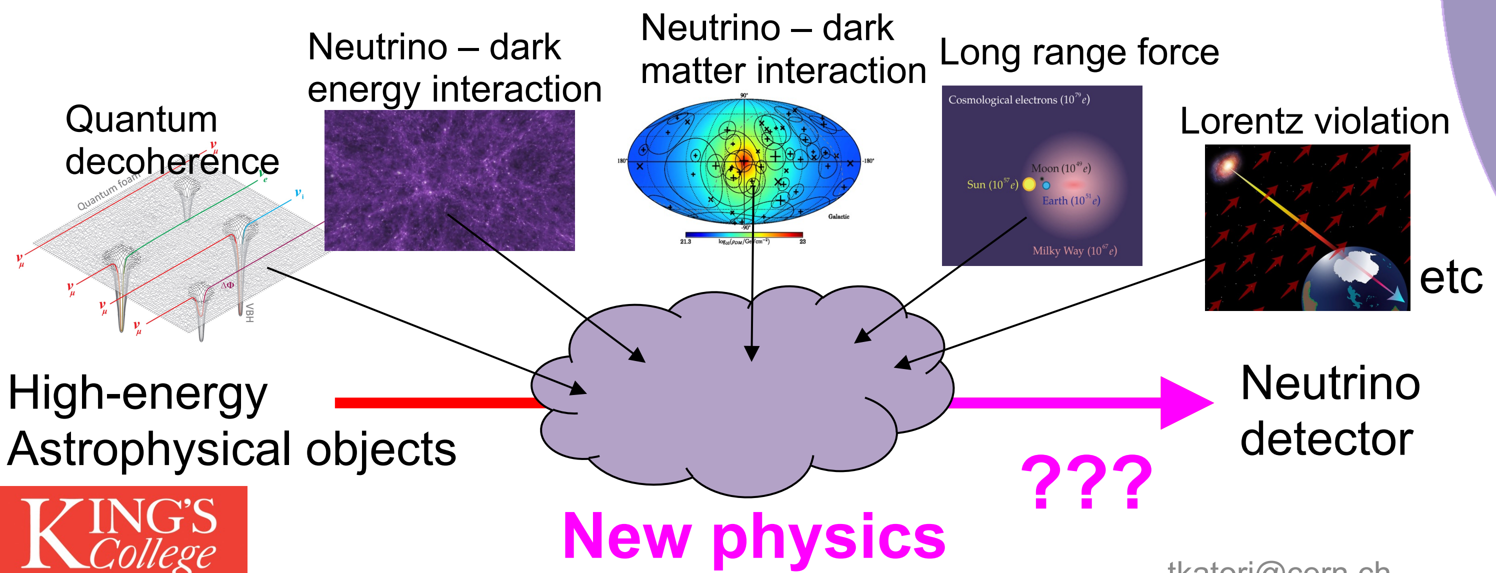
High-energy, long propagating neutrinos

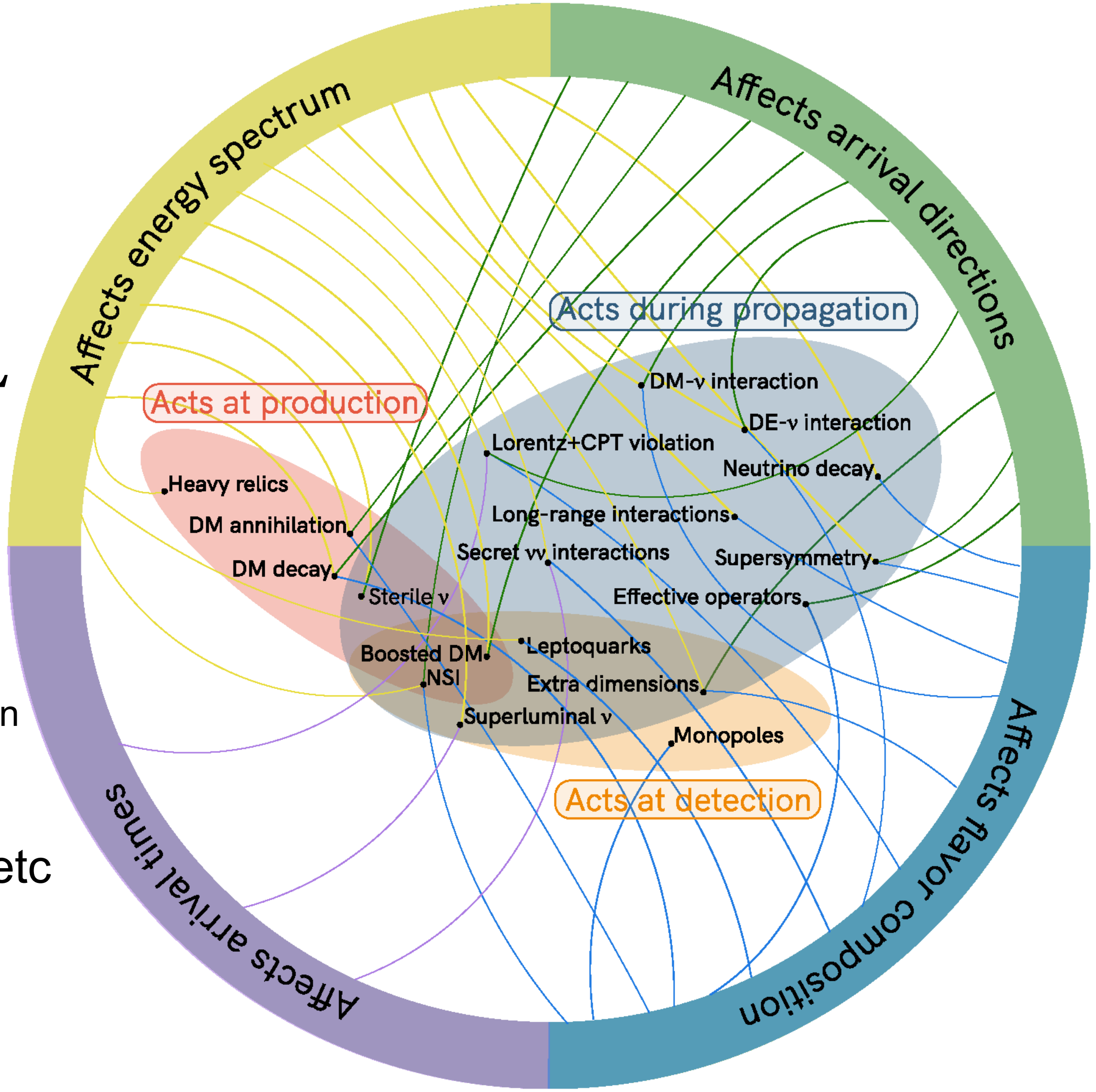
High-energy astrophysical neutrinos

- Long baseline accumulates new physics effect
- High energy enhances new physics 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





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)

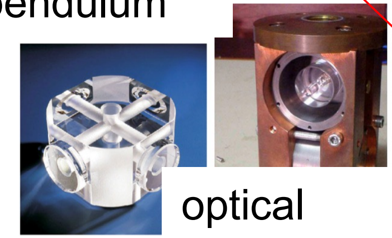
Lorentz violation limits from tabletop to cosmology

Physics MMA

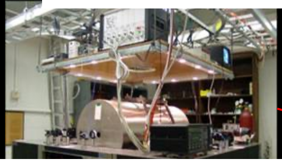
Lower dimension operators → searches by tabletop experiments
Higher dimension operators → searches by astrophysical observations

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

torsion pendulum

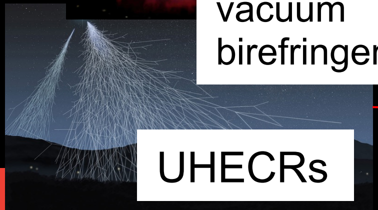


optical resonator



comagnetomator

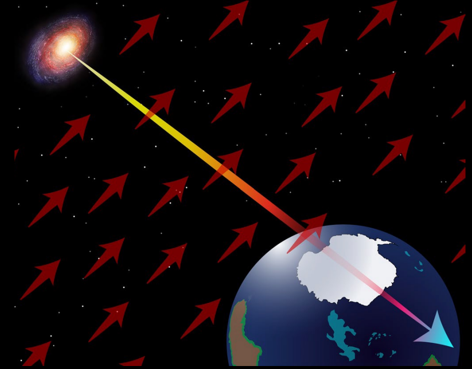
vacuum birefringence



UHECRs

dim.	method	type	sector	limits	ref.
$\mathring{a}^{(3)}$	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]
$\mathring{c}^{(4)}$	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]
$\mathring{a}^{(5)}$	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]
$\mathring{c}^{(6)}$	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

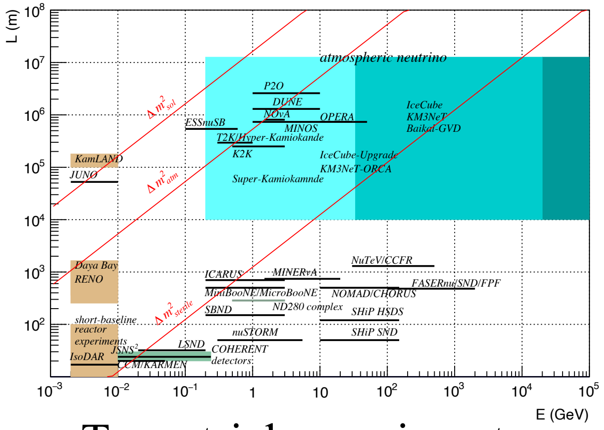
[1] IceCube, Nature Phys. 18, 1287 (2022) [2] WMAP, AstrophysJ.180, 330 (2009) [3] Allmendinger et al., PRL112, 110801 (2014) [4] Heckel et al., PRL97, 021603(2006) [5] Muon g-2, PRL100, 091602 (2008) [6] Kostelecký, Mewes,PRL110, 201601 (2013) [7] Kostelecký, Melissinos, Mewes, PLB 761, 1 (2016) [8] 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

L-E plot

High energy, long propagation experiments
- Neutrino telescopes [Snowmass, JHEA36(2022)55]

Neutrino telescopes for the ultra-high-energy neutrinos are not Cherenkov detector

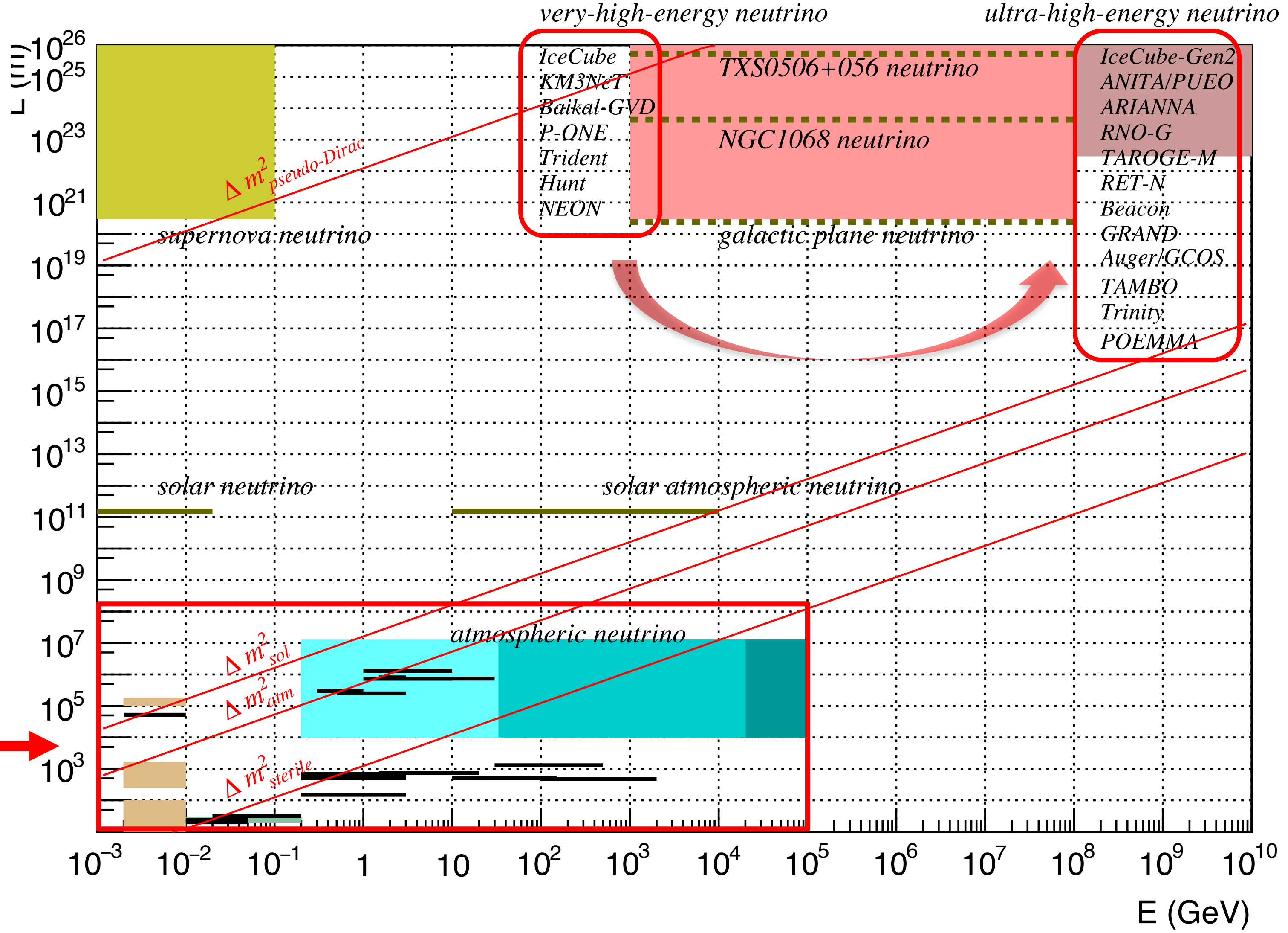
TeV-PeV → >100 PeV



Terrestrial experiments

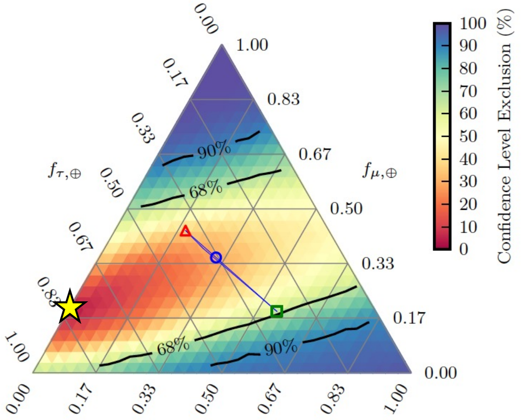
water and ice Cherenkov detectors

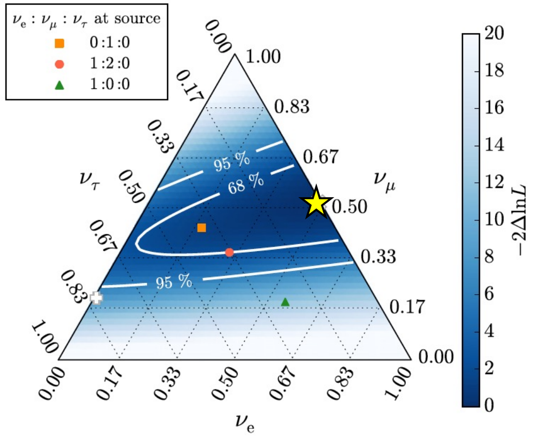
radio telescope, air shower array, etc



IceCube flavor ratio measurements

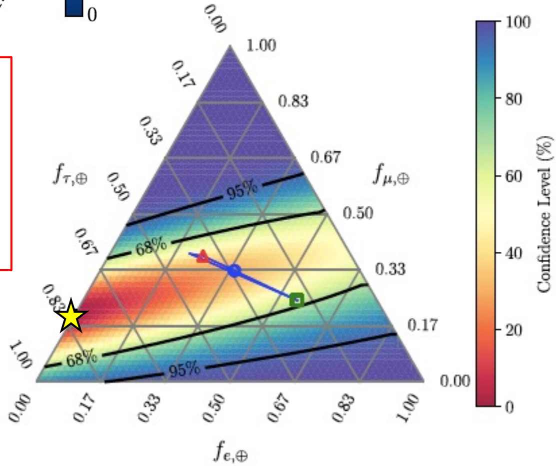
IceCube
1^{st} flavour ratio result
(0.0:0.2:0.8)

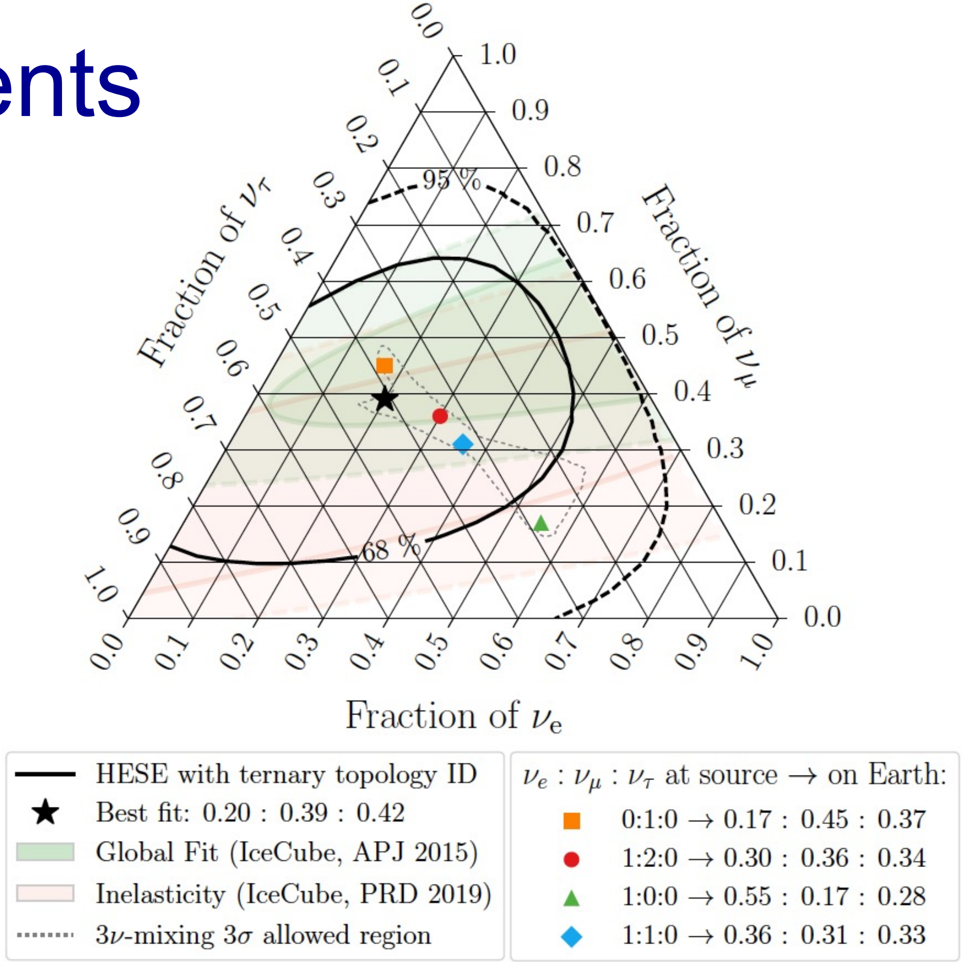




IceCube
2^{nd} flavour ratio result
(0.5:0.5:0.0)

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





2018 flavour ratio measurement

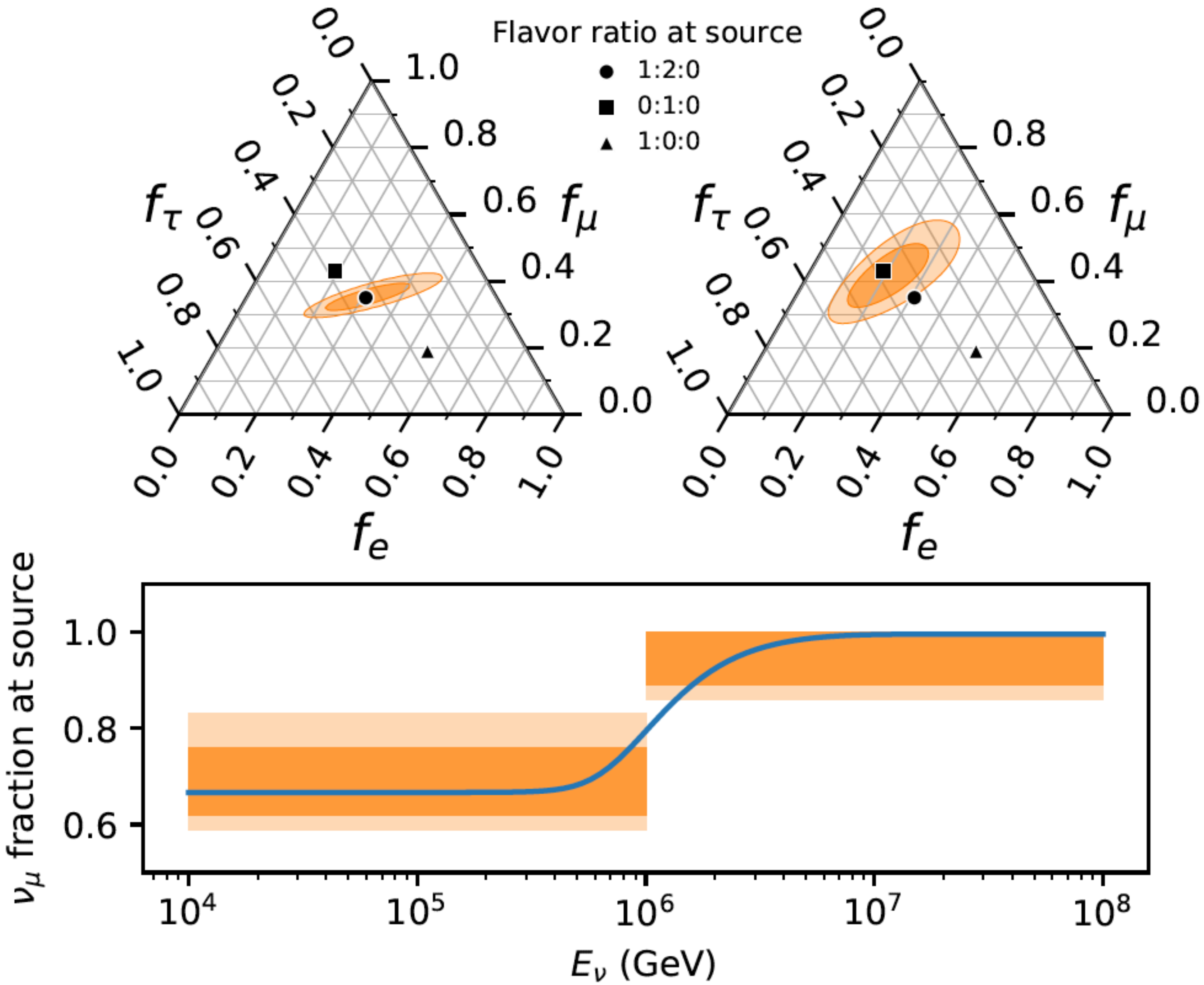
- Likelihood is very shallow and fit often confuses between ν_e and ν_τ
- Flavour ratio result has some power to distinguish ν_e and ν_τ

IceCube-Gen2, J.Phys.G48(2021)060501

Energy dependence of flavor ratio

Muon neutrino increases at higher energy

Future higher-statistics flavor measurement



Rasmussen, Lechner, Ackermann, Kowalski, Winter, PRD96(2017)083018

New physics flavor ratio predictions

New physics models have different flavor ratios

Effective operator
- It includes Lorentz violation
- Assuming all possible standard production models, $(\nu_e:\nu_\mu:\nu_\tau) = (x:1-x:0)$, it covers 2/3 of the phase space.