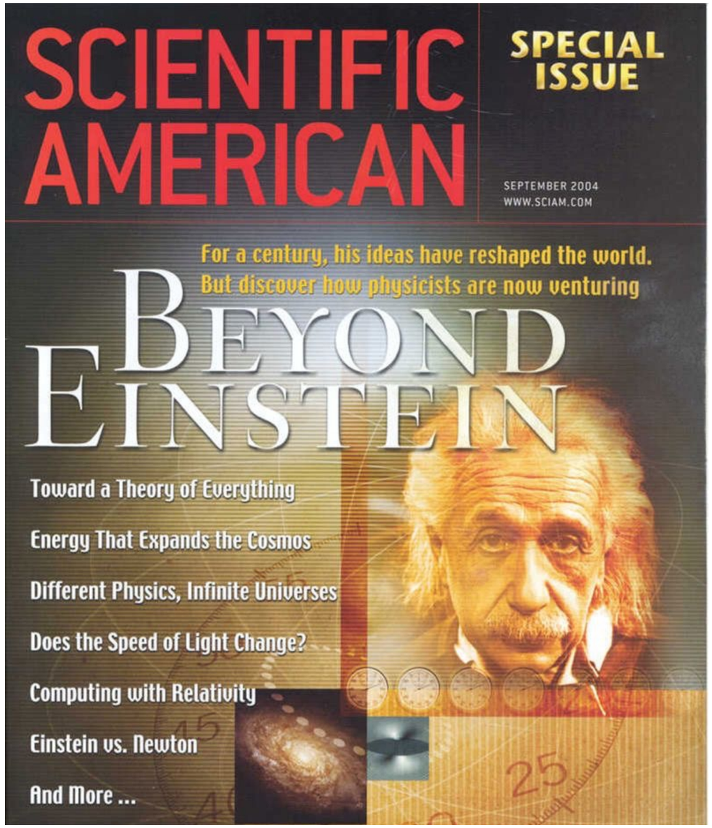
Tests of Spacetime Symmetry with Neutrinos



outline

1. Introduction
2. Tests of Lorentz violation with neutrinos
3. Tests of Lorentz violation with astrophysical neutrinos
4. Conclusion

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King's College London
Neutrino Conference 2025, ICISE, Quy Nhon, Vietnam, July 23, 2025

Introduction

Theory of Special Relativity

Einstein and Lorentz

Special relativity is a basis of both quantum field theory and general relativity

Special relativity is based on Lorentz symmetry

Lorentz symmetry is isotropy of spacetime

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

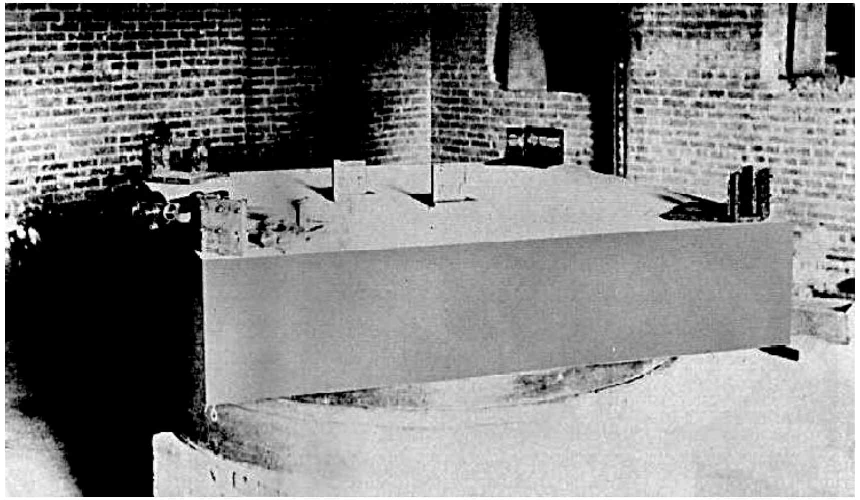
Michelson-Morley experiment

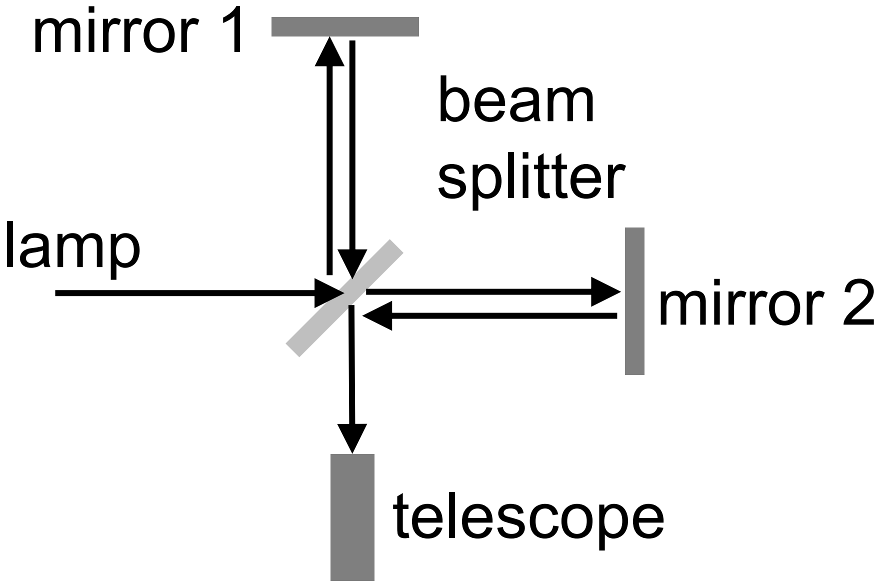
The experiment tried to measure the motion of the Earth relative to æther.

The experiment shows the speed of light is constant regardless the motion of the Earth.

This result suggests the isotropy of spacetime, and Lorentz symmetry.

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

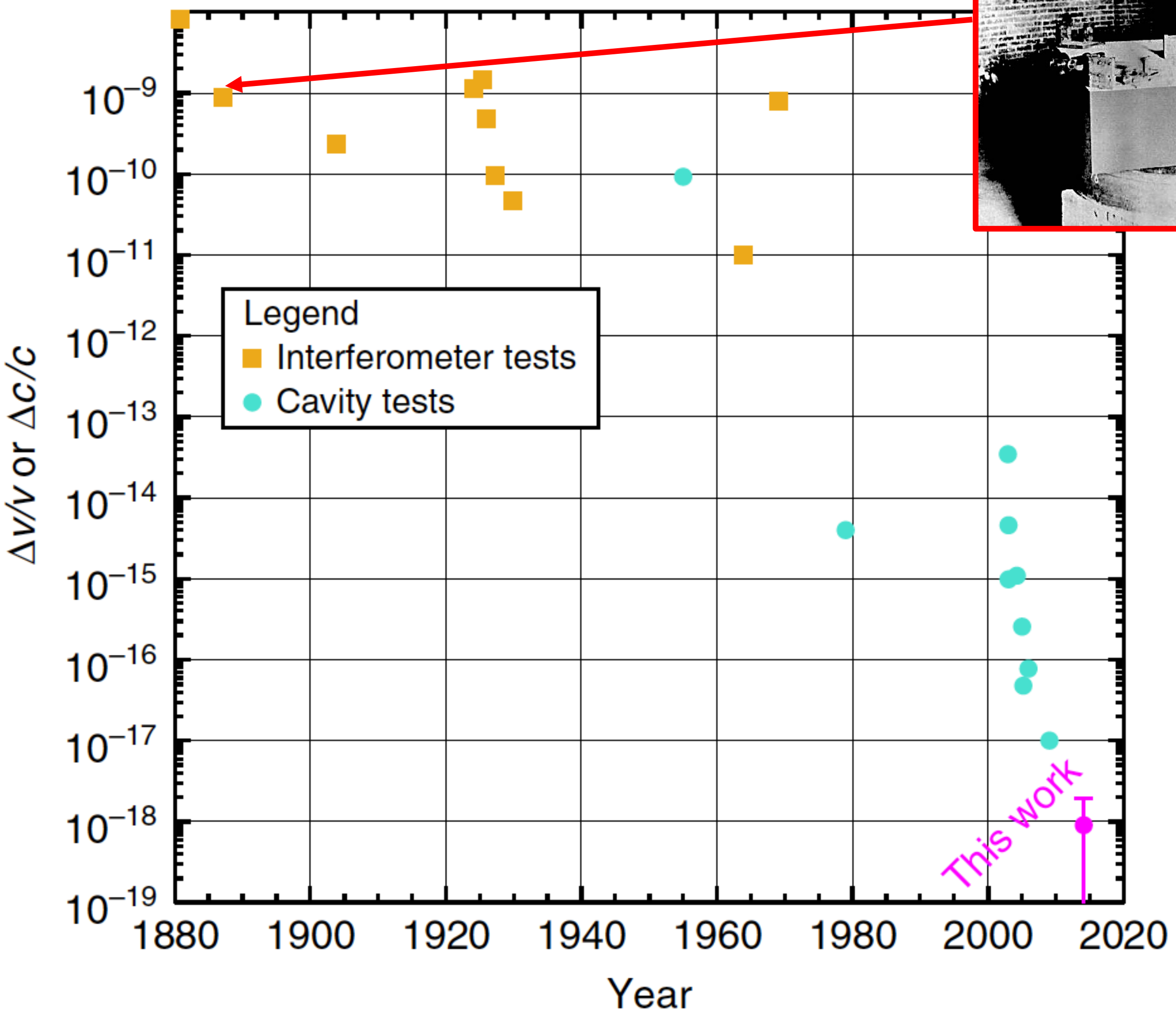


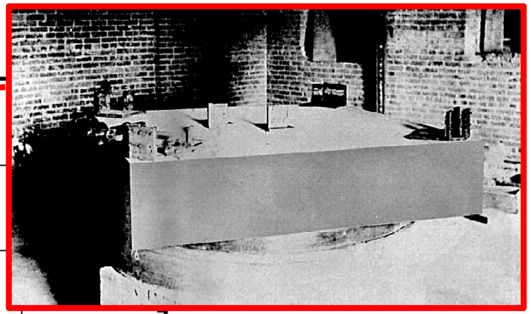


Nagel et al, Nature Comm., 6(2015)8174

Michelson-Morley experiment

The experiment has been improved over 100 years.





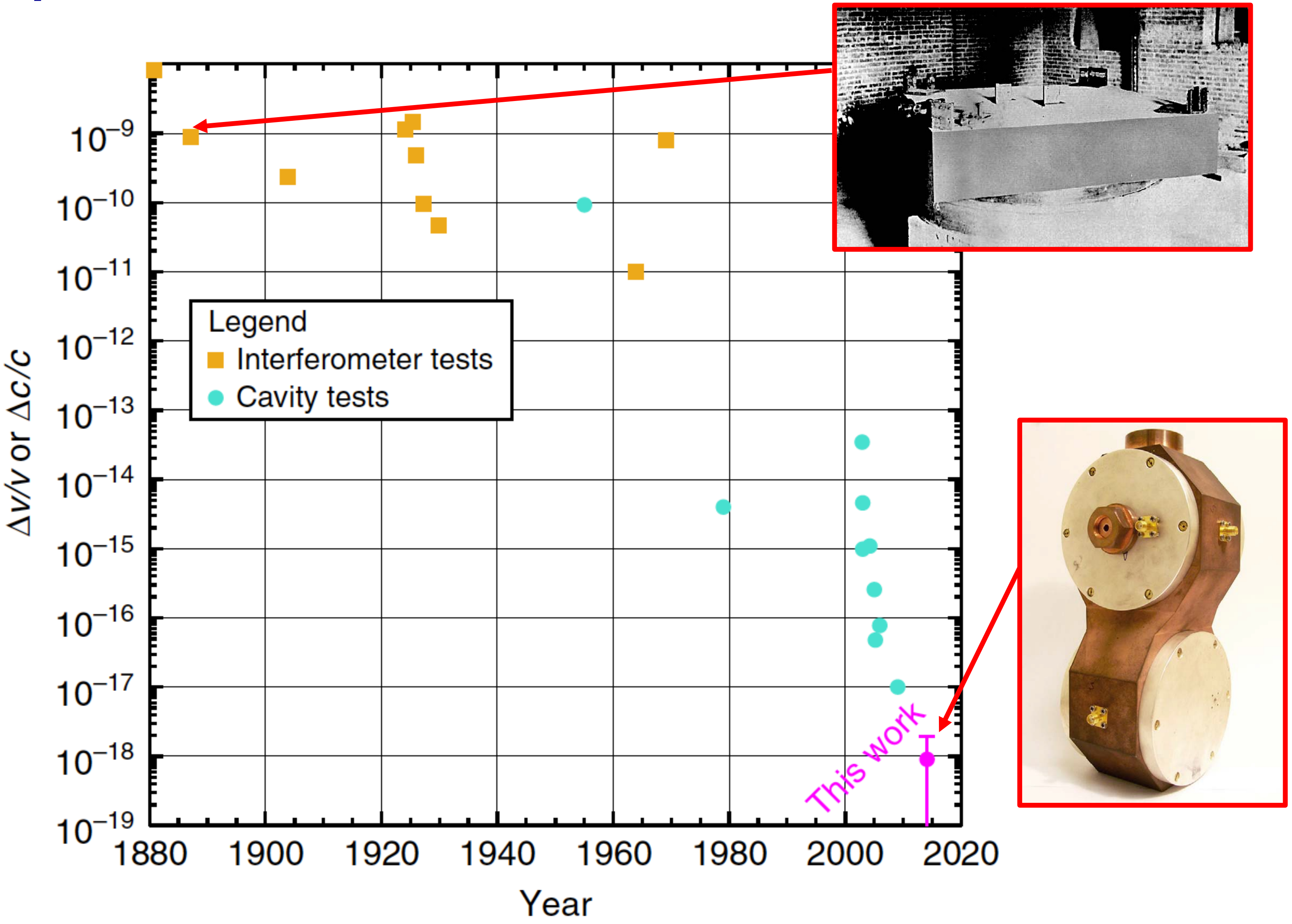
Michelson-Morley experiment

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?

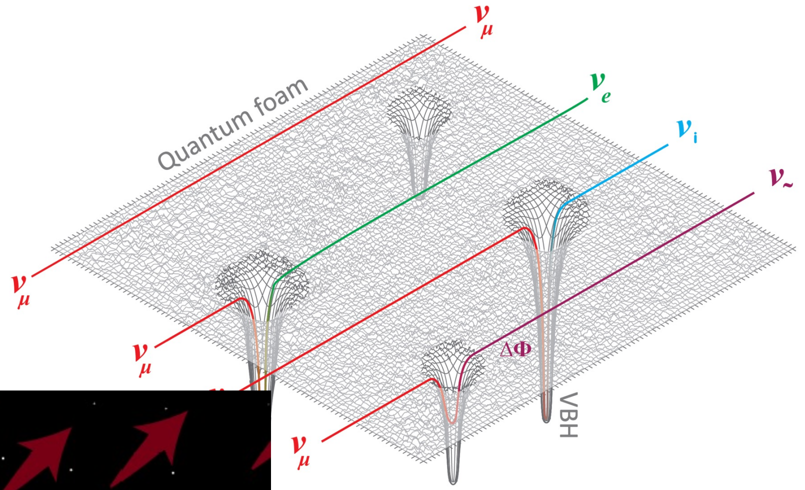
Why do we expect Lorentz violation?



Progress in Particle and Nuclear Physics 125 (2022) 103948

Quantum gravity

Quantum foam
- quantum fluctuation of space-time



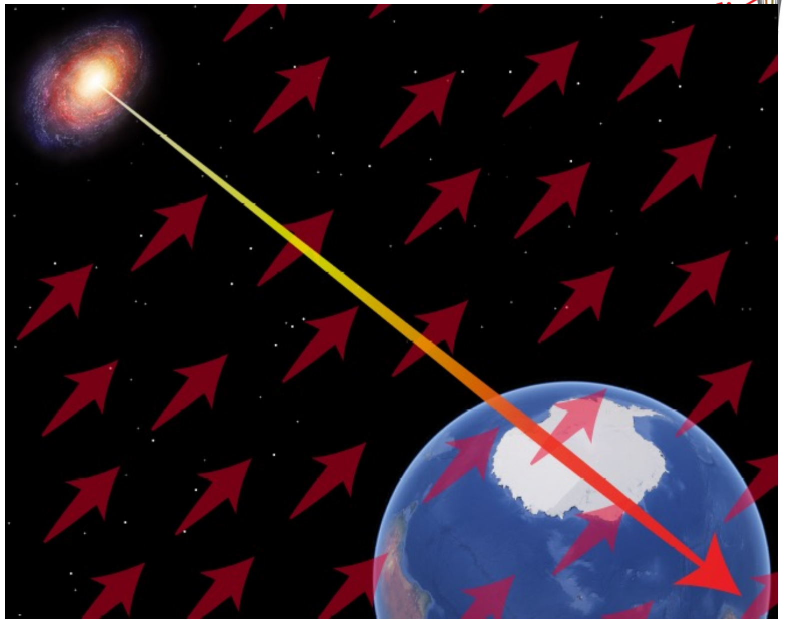
Searching Lorentz violation is well motivated

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

etc

Lorentz violation is seen as
- spacetime fluctuation (Lindblad eqn.)
- background field in vacuum (SME)

etc



Lorentz violating field
- background field of the universe (æther)

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Standard-Model Extension (SME)

Alan Kostelecky, Indiana University

2025 recipient, Norman F. Ramsey Prize

For the development of the Standard Model Extension and for its application to, and inspiration for, a broad set of precision measurement tests across various physical systems, some of which have reached Planck-scale sensitivity.

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

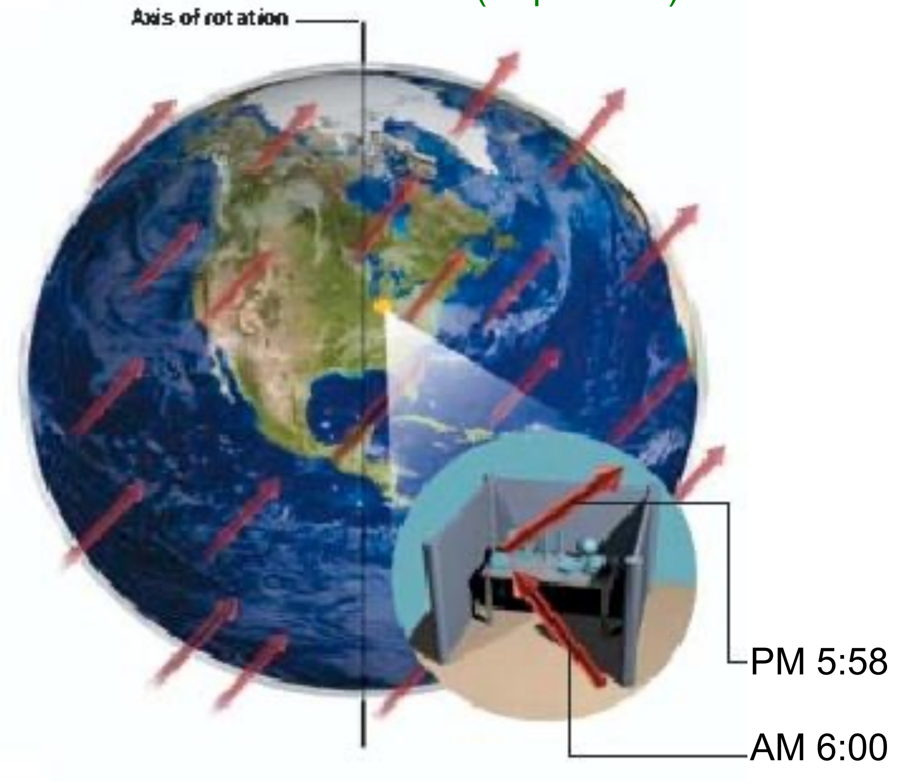
SME is an effective field theory (EFT) framework to look for Lorentz violation

e.g.) vacuum Lagrangian for fermion

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

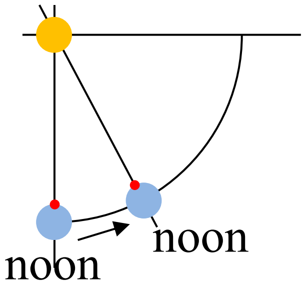
Standard Model | couplings with background fields

Scientific American (Sept. 2004)



Physics of Lorentz violation

- Spectrum distortion,
- Sidereal time dependence, etc…



24h 00min 00sec: Solar day

23h 56min 4.1sec: Sidereal day

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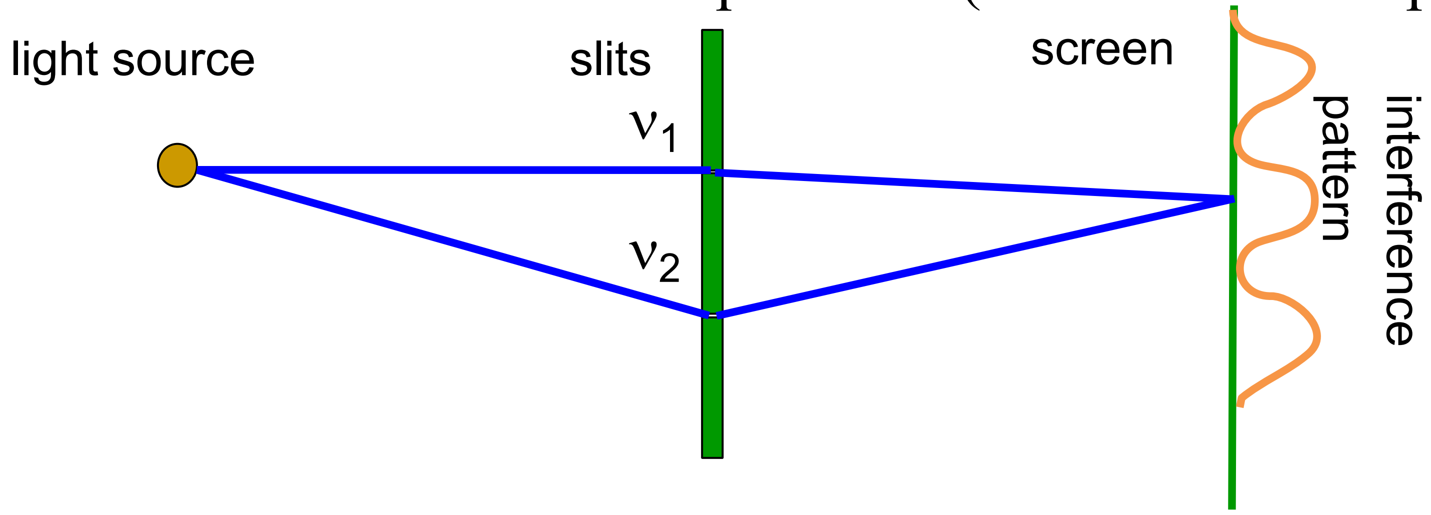
Tests of Lorentz Violation with Neutrinos

Neutrino oscillation experiments

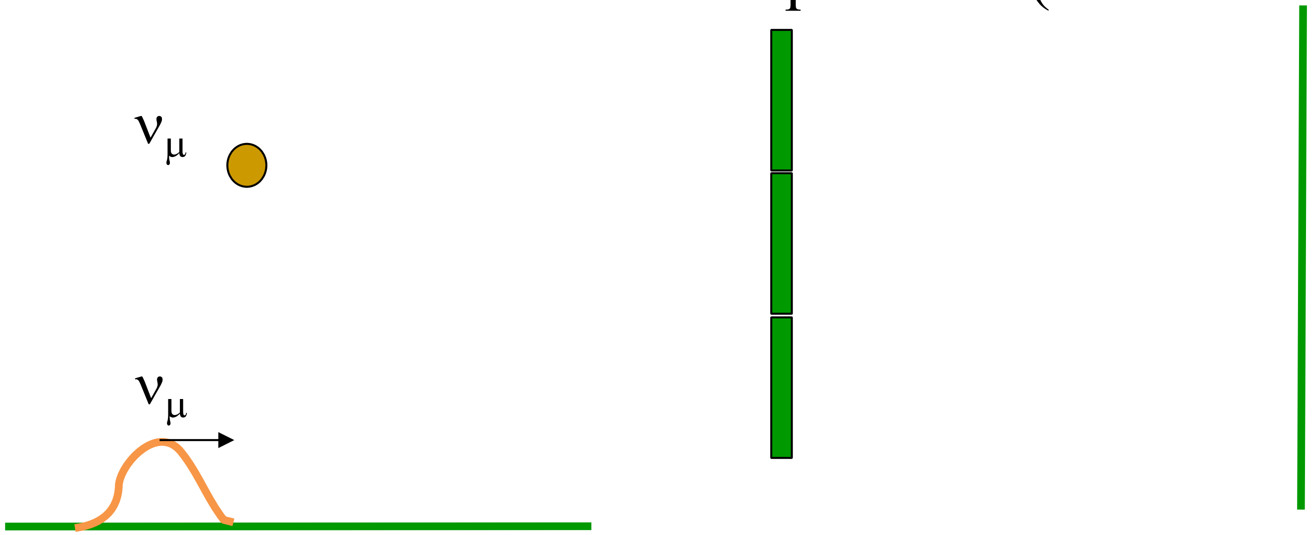
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

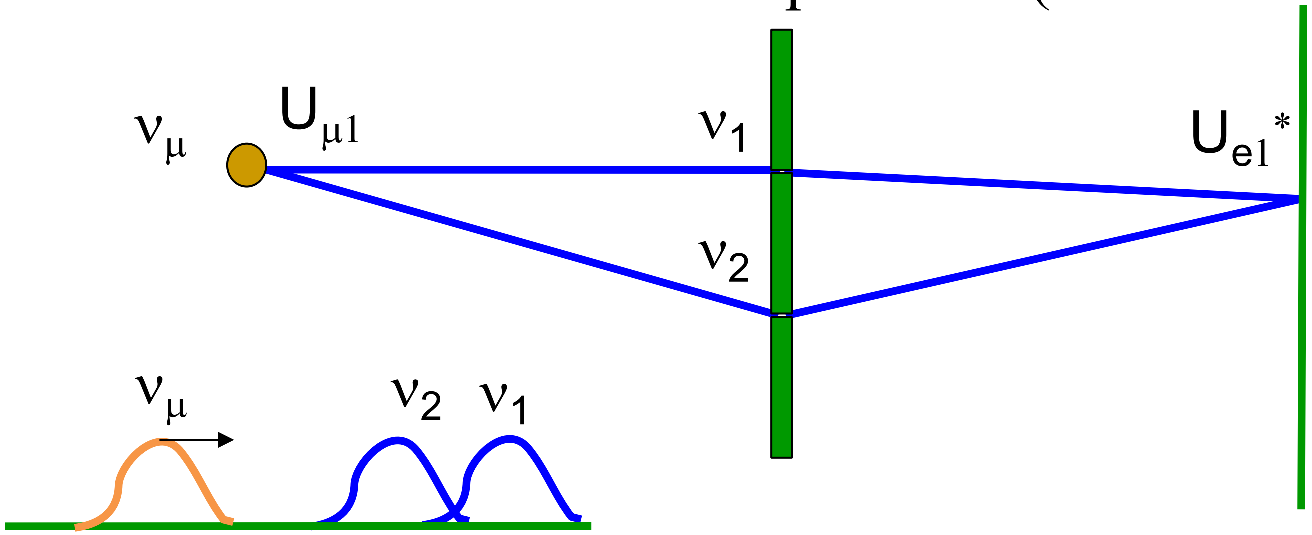
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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)

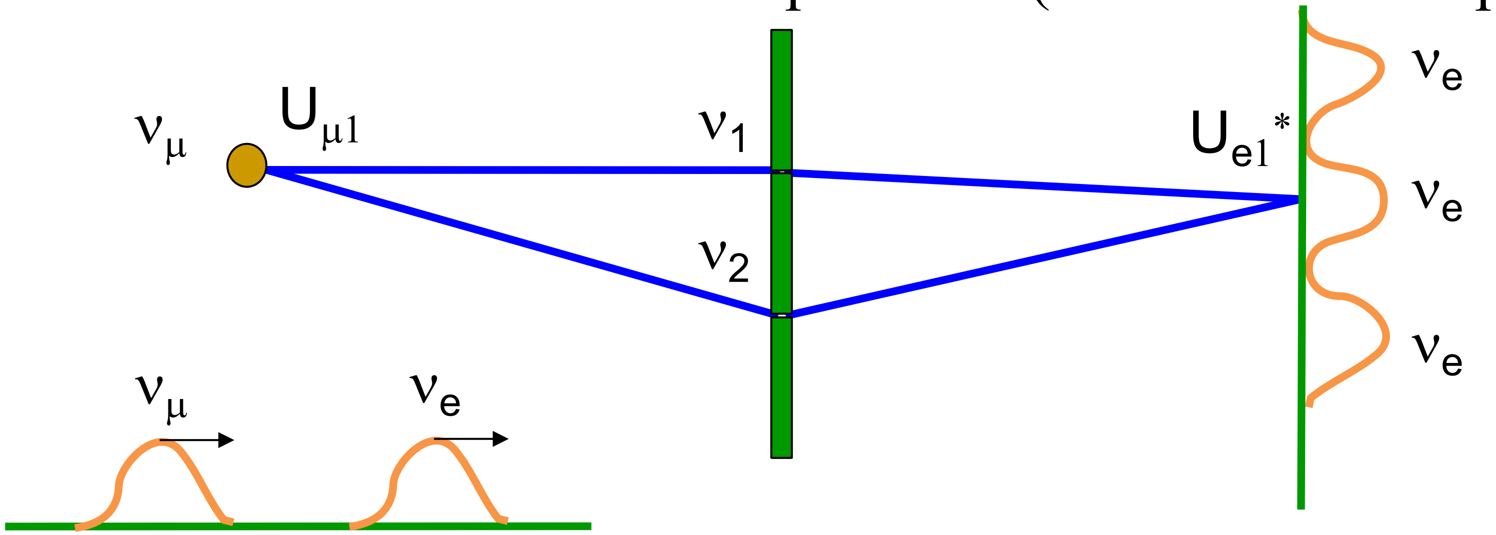


Neutrino flavour eigenstates are super-position of Hamiltonian eigenstates ν_1 and ν_2

Difference in velocities cause quantum interference

Neutrino oscillation experiments

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



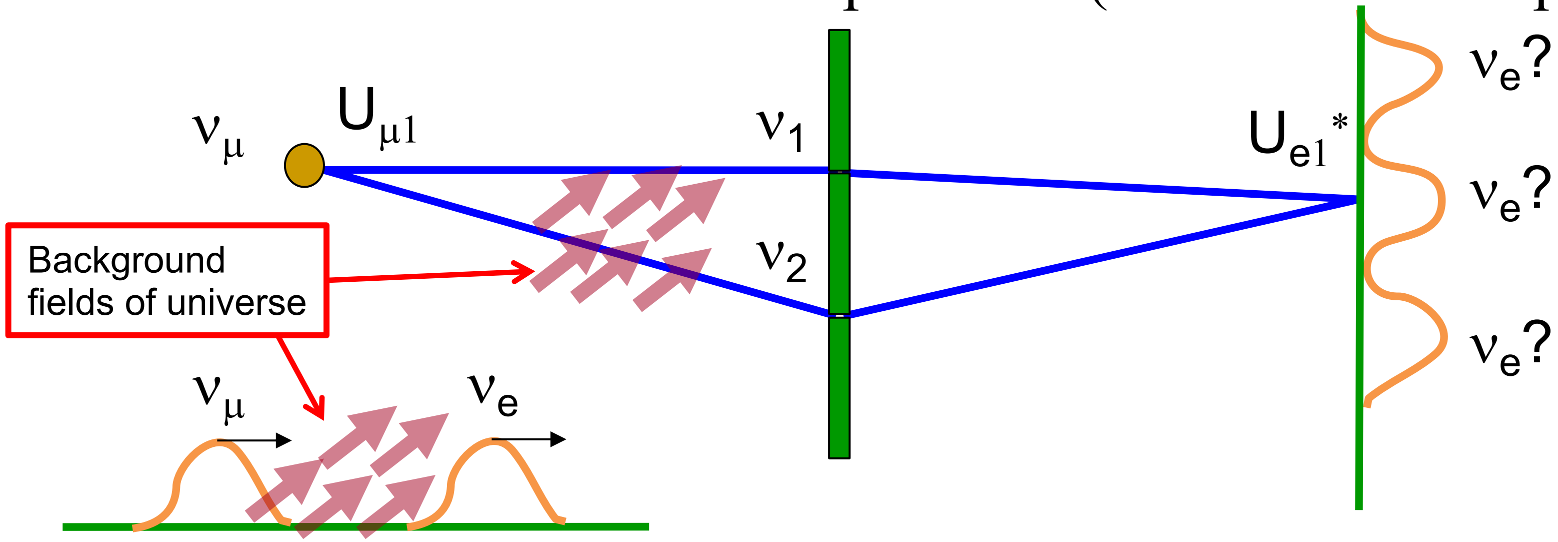
Neutrino flavour eigenstates are super-position of Hamiltonian eigenstates ν_1 and ν_2

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

MiniBooNE ν_e appearance candidate data

	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

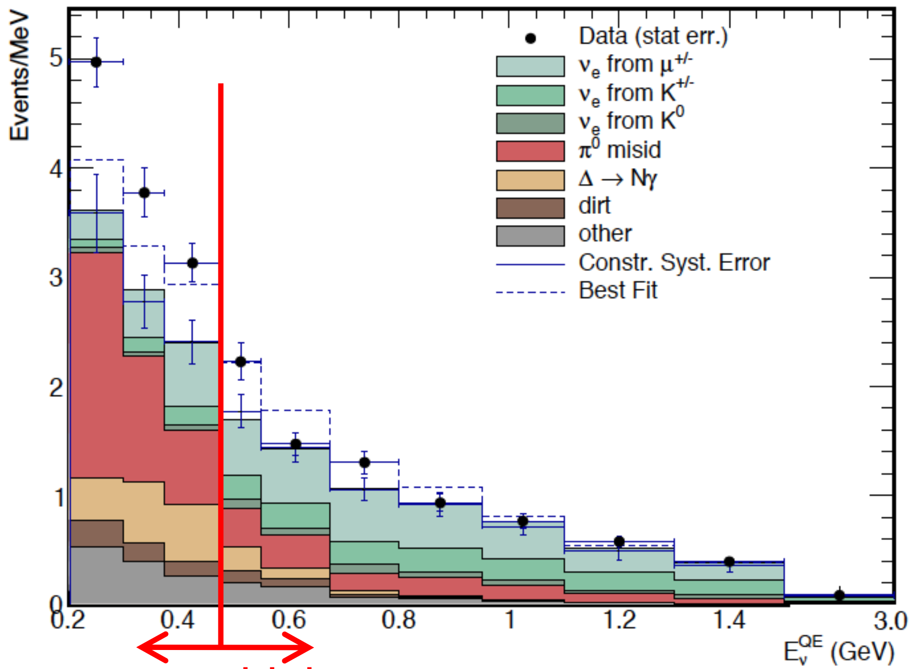
	SME coefficients combination (unit 10^{-20} GeV)
$\lvert(\mathcal{C})_{e\mu}\rvert$	$\pm[(a_L)^T_{e\mu} + 0.75(a_L)^Z_{e\mu}] - \langle E\rangle[1.22(c_L)^{TT}_{e\mu} + 1.50(c_L)^{TZ}_{e\mu} + 0.34(c_L)^{ZZ}_{e\mu}]$
$\lvert(\mathcal{A}_s)_{e\mu}\rvert$	$\pm[0.66(a_L)^Y_{e\mu}] - \langle E\rangle[1.33(c_L)^{TY}_{e\mu}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

Anomalous ν_e candidate low-energy excess

- Can that be Lorentz violation?

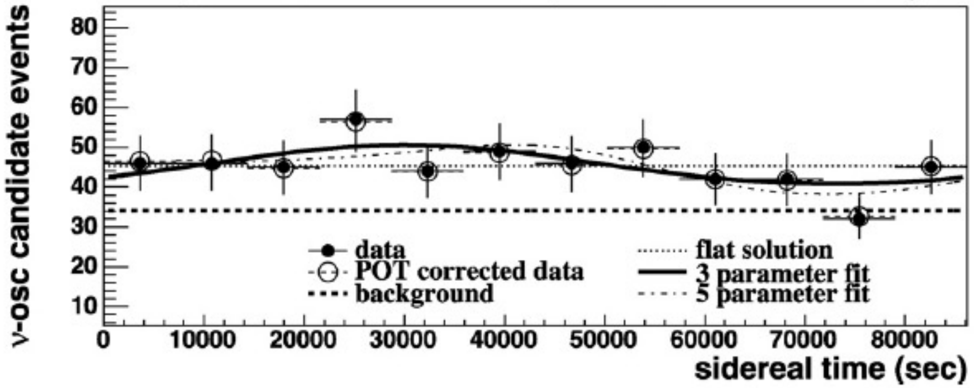
→ no sidereal time dependent modulation, unlikely Lorentz violation

MiniBooNE low E ν_e excess

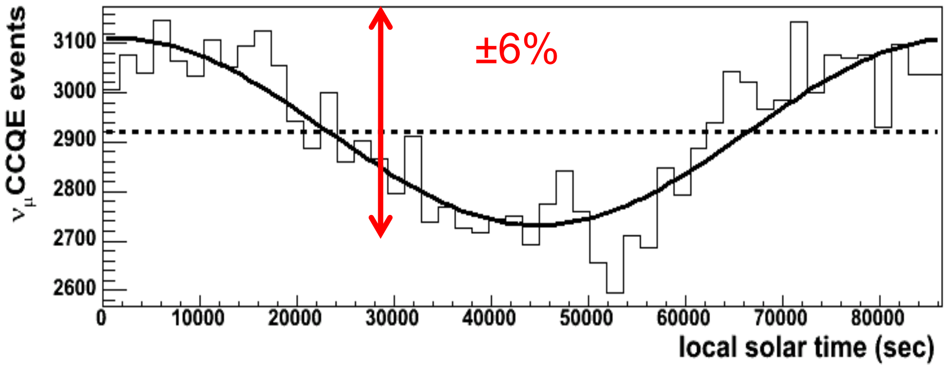


low energy   high energy

Neutrino mode ν_e candidate data sidereal time distribution



ν_μCCQE events day-night distribution



Lorentz violation tests with neutrinos – Summary

Limits of all SME parameters are summarized in tables [ArXiv:0801.0287v17]

So far, there is no compelling evidence of Lorentz violation

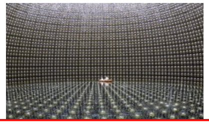
When do we find it???

28-page limits only in neutrino sector...

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]*

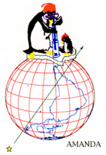
Spectral distortion



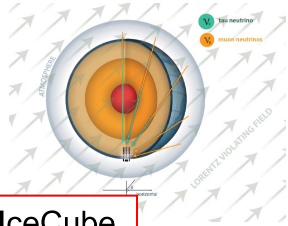
Super-Kamiokande
PRD91(2015)052003

Daya Bay

PRD98(2018)092013

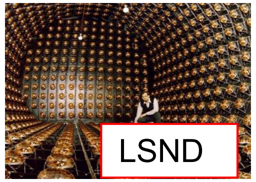


AMANDA
PRD79(2009)102005



IceCube
Nature Physics 14(2018)961

Sidereal variation



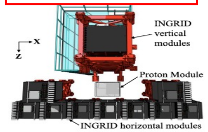
LSND
PRD72(2005)076004

MiniBooNE
PLB718(2013)1303

MINOS ND
PRL101(2008)151601

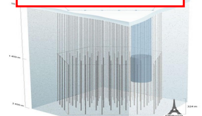
MINOS FD
PRL105(2010)151601

T2K ND



PRD95(2017)111101

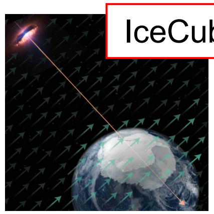
IceCube



PRD82(2010)112003

Double Chooz
PRD86(2013)112009

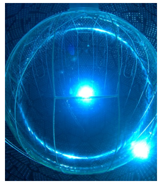
Flavor ratio



IceCube
Nature Physics, 18(2022)1287

Seasonal variation

SNO



PRD98(2018)112013

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When do we find Lorentz violation???

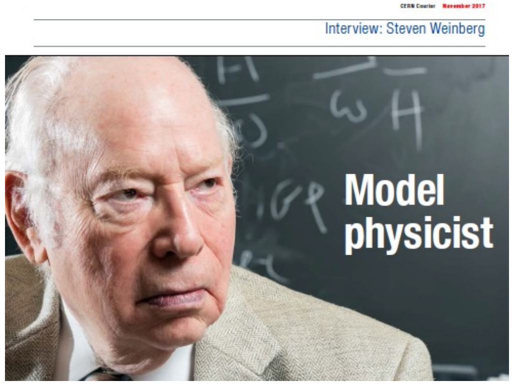
Lorentz violation is motivated by Planck scale theories, so it is suppressed with the power of Planck mass ($\sim 10^{19}\ GeV$)

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

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!'

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Tests of Lorentz violation with astrophysical neutrinos

Terrestrial experiments
- controlled, high-precision

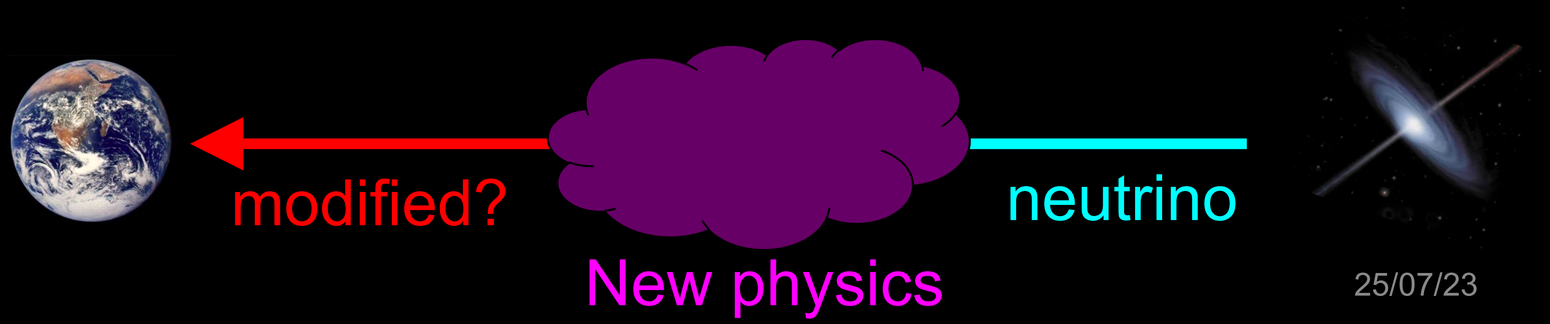
So far, no compelling evidence of Lorentz violation

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

Astrophysical neutrinos

Long, straight trajectory propagation in vacuum
- Astrophysical neutrinos are sensitive to tiny space-time effects



Snowmass21 white paper, "Beyond the Standard Model effect with Neutrino Flavour", EPJC83(2023)15
"Quantum gravity phenomenology at the dawn of the multi-messenger era", Prog. Partt. Nucl.Phys. 125 (2022) 103948

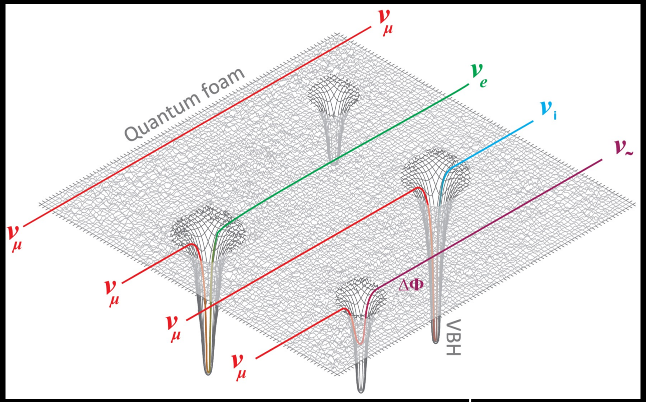
Astrophysical neutrinos

Long, straight trajectory propagation in vacuum
- Astrophysical neutrinos are sensitive to tiny space-time effects

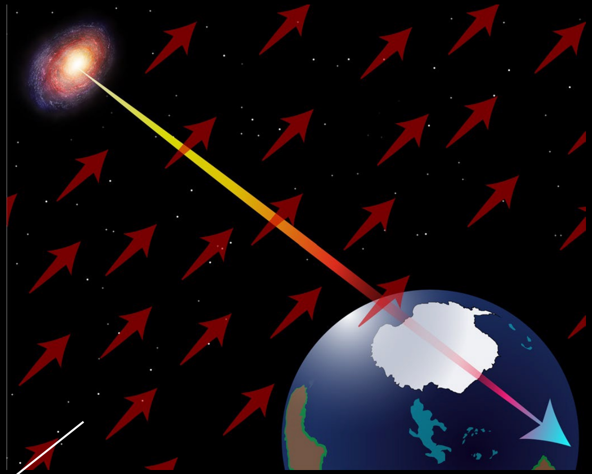
Long list of new models to affect astrophysical neutrino propagation
- Long range force
- Neutrino-dark matter coupling
- Neutrino-dark energy coupling

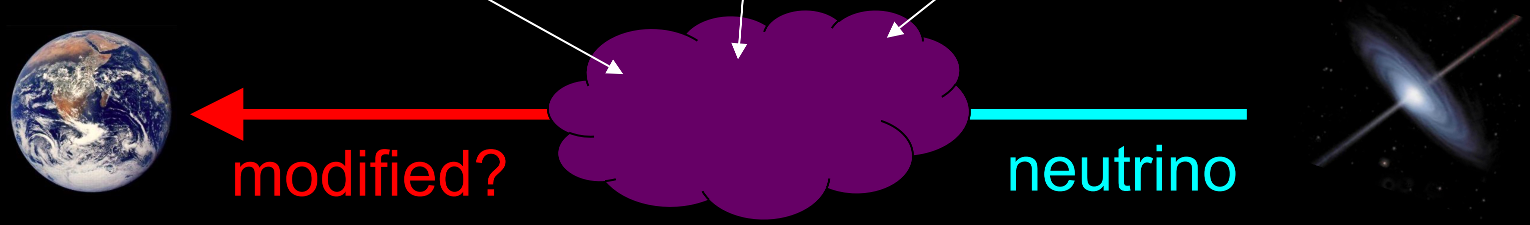
etc

Quantum foam



Lorentz violating field

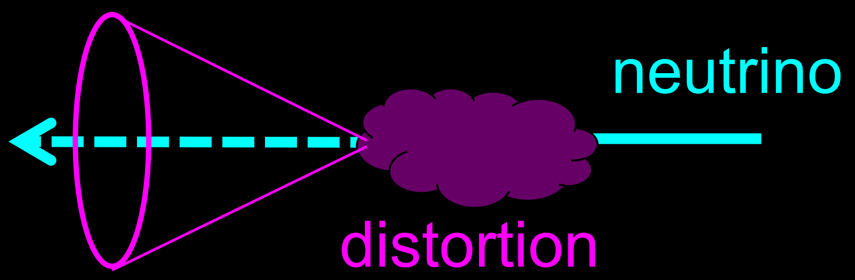


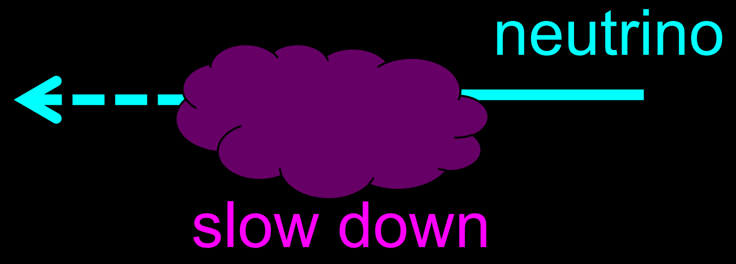


New physics

Test of Spacetime properties with Astrophysical neutrinos

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



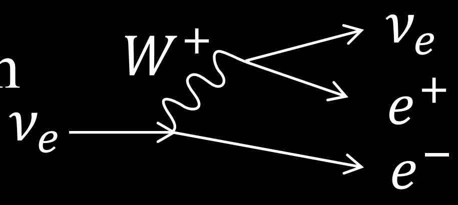


Stecker, et al, PRD91(2015)045009, and many others
KM3NeT, ArXiv:2502.1207

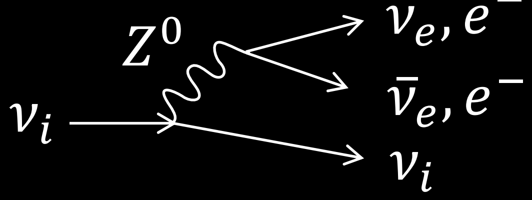
Test of Spacetime properties with Astrophysical neutrinos

Lorentz violation = Media in vacuum

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

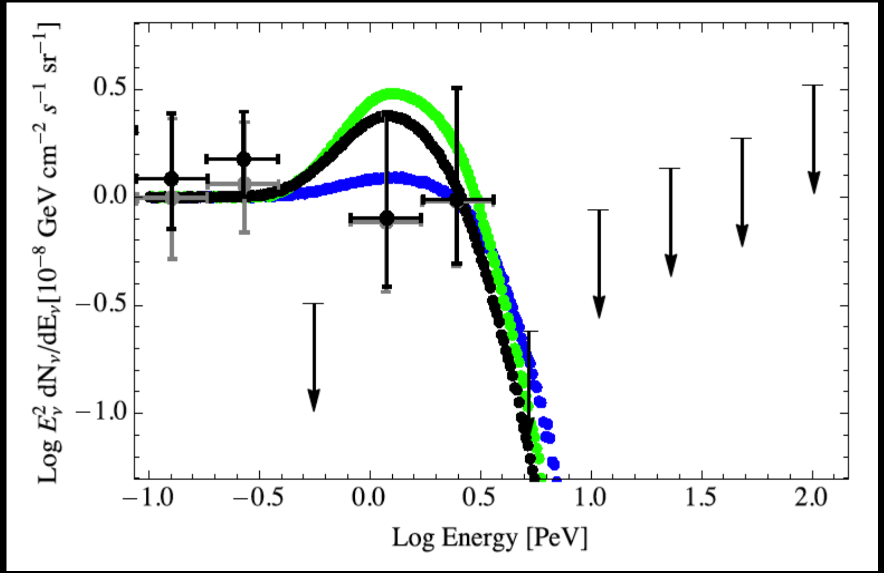


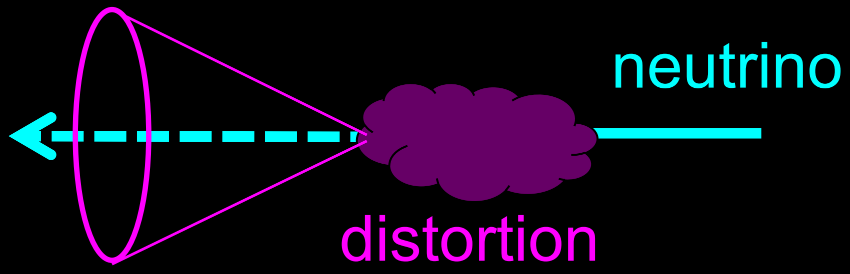
Vacuum pair emission



Neutrino splitting

Diffuse neutrino spectrum distortion

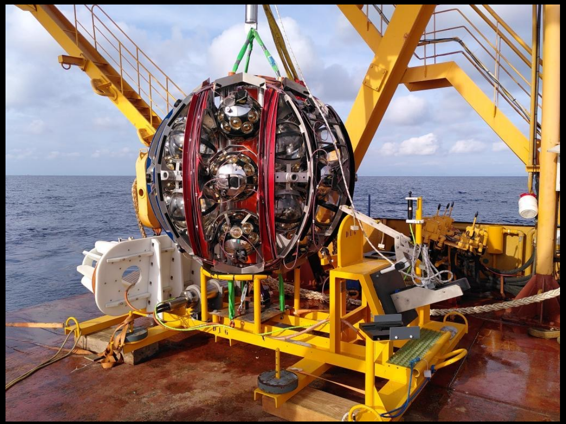




Lorentz violating field cause radiation in vacuum

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

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



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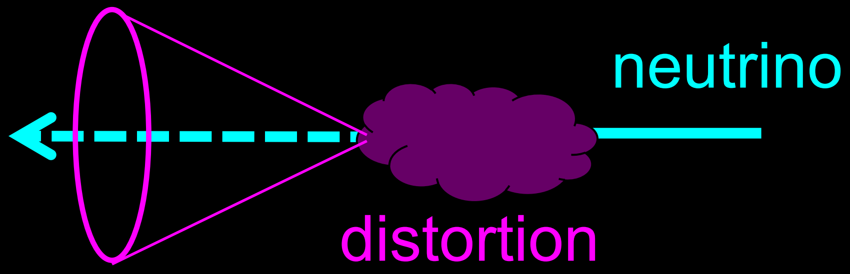
Stecker, et al, PRD91(2015)045009, and many others
KM3NeT, ArXiv:2502.1207, Ternes et al, arXiv:2503.04573

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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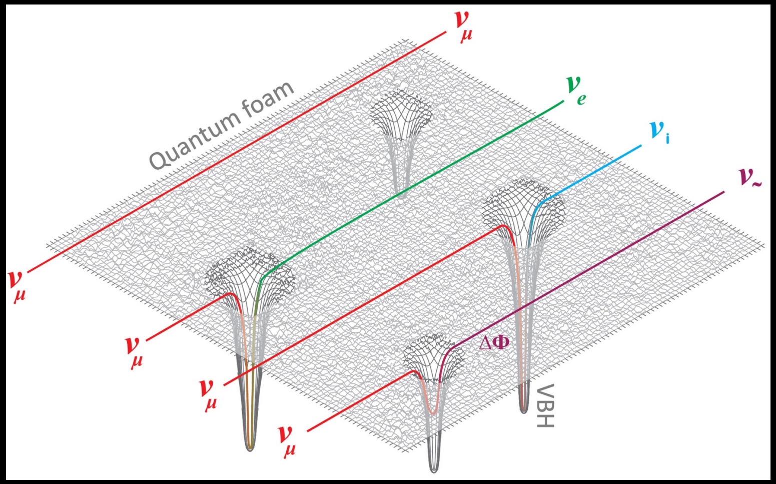


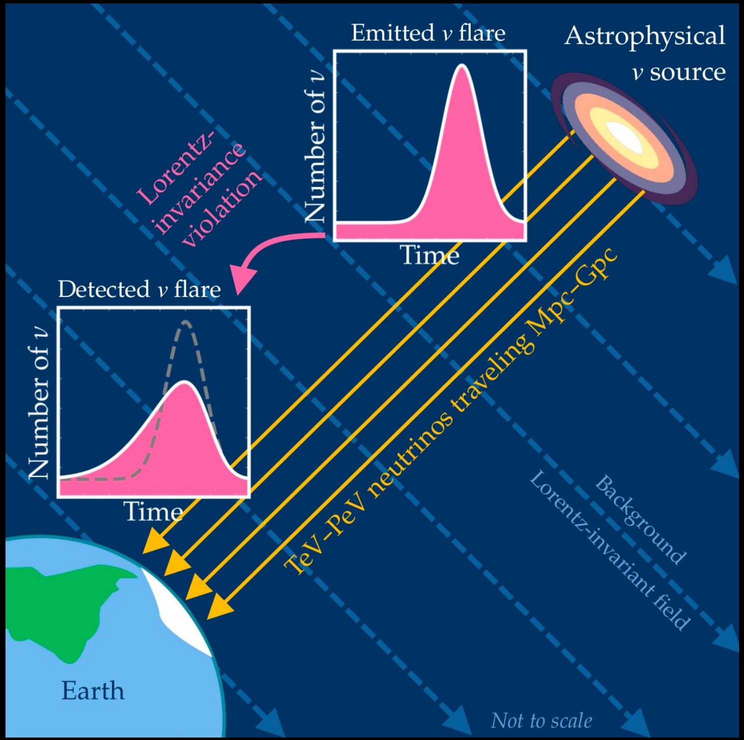
Amelino-Camelia et al, Nature 393(1998)763, LHASSO PRL133(2024)071501)) and many others
Bustamante et al, ArXiv:2408.15949

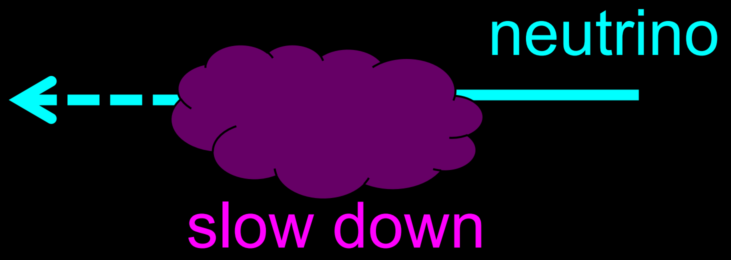
Test of Spacetime properties with Astrophysical neutrinos

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)
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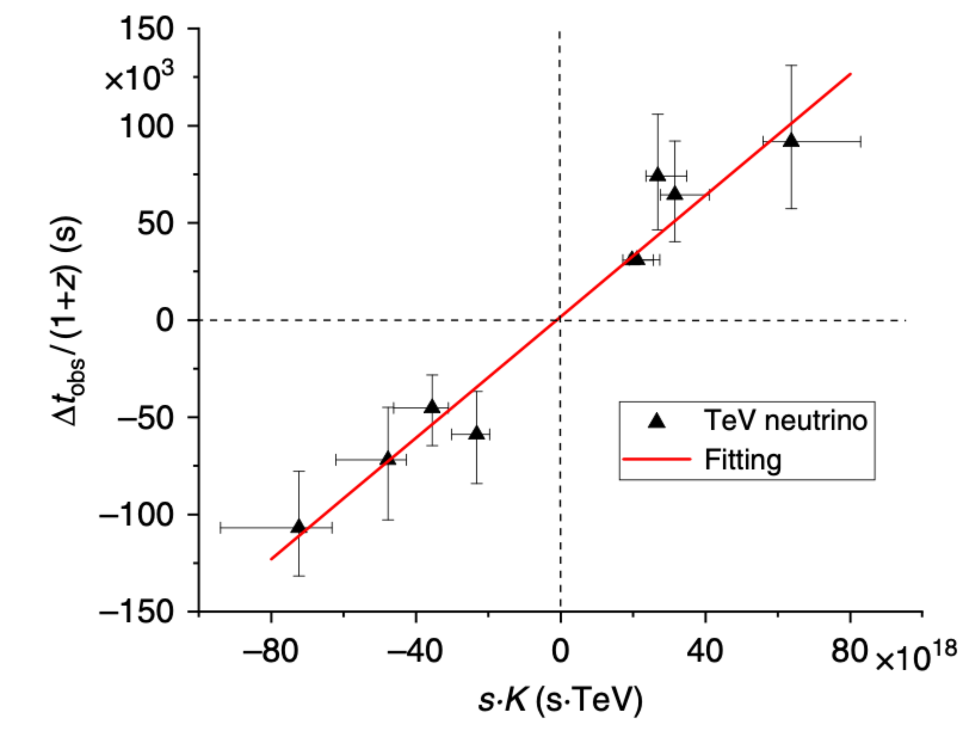
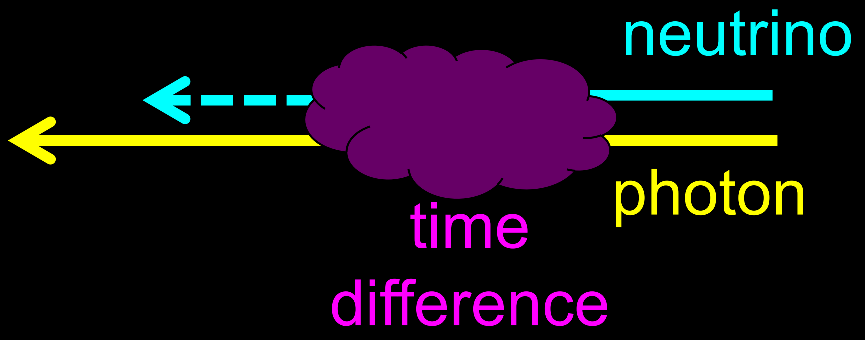




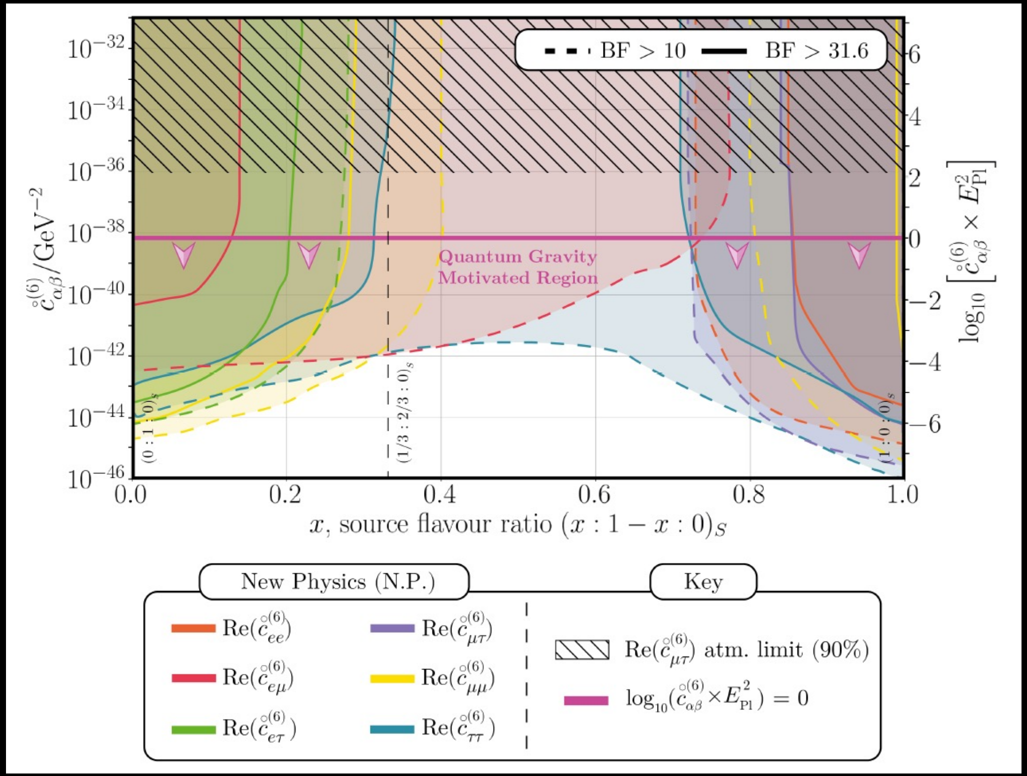
Neutrinos and gamma-ray bursts may have coincidence with Lorentz violation

IceCube, Nature Physics 18(2022)1287

Test of Spacetime properties with Astrophysical neutrinos

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

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)



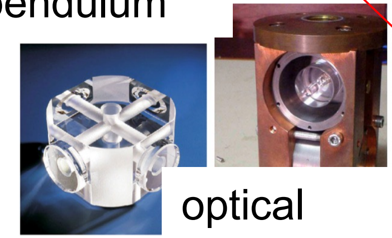
Lorentz violation limits from tabletop to cosmology

Physics MMA

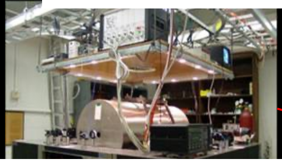
Lower dimension operators → searches by tabletop experiments
Higher dimension operators → searches by astrophysical observations

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

torsion pendulum

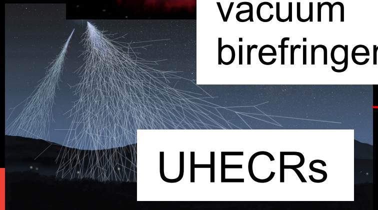


optical resonator



comagnetomator

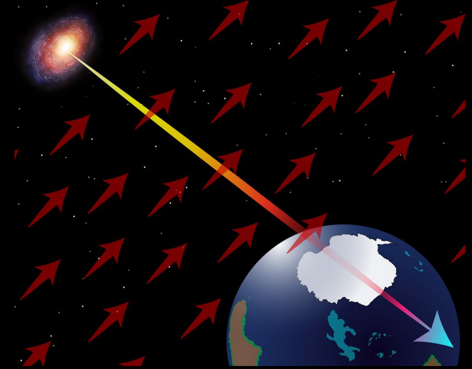
vacuum birefringence



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

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

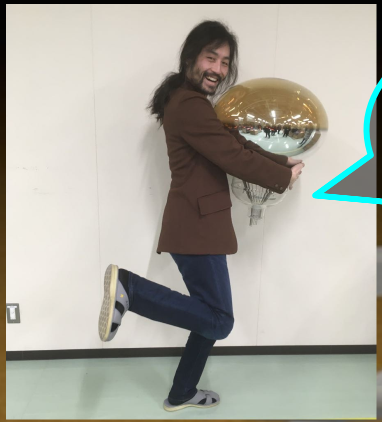
So far, astrophysical neutrino data are low statistics, and further data are needed to search Lorentz violation...

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

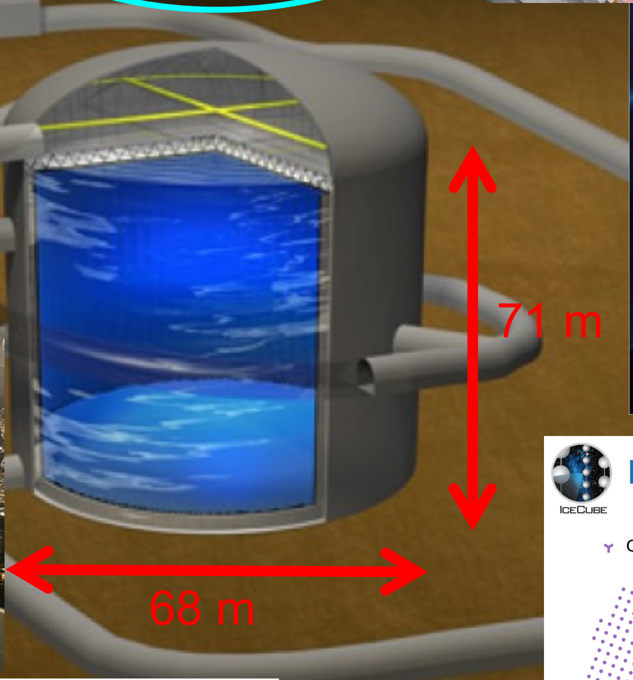
Hyper-Kamiokande and IceCube-Gen2

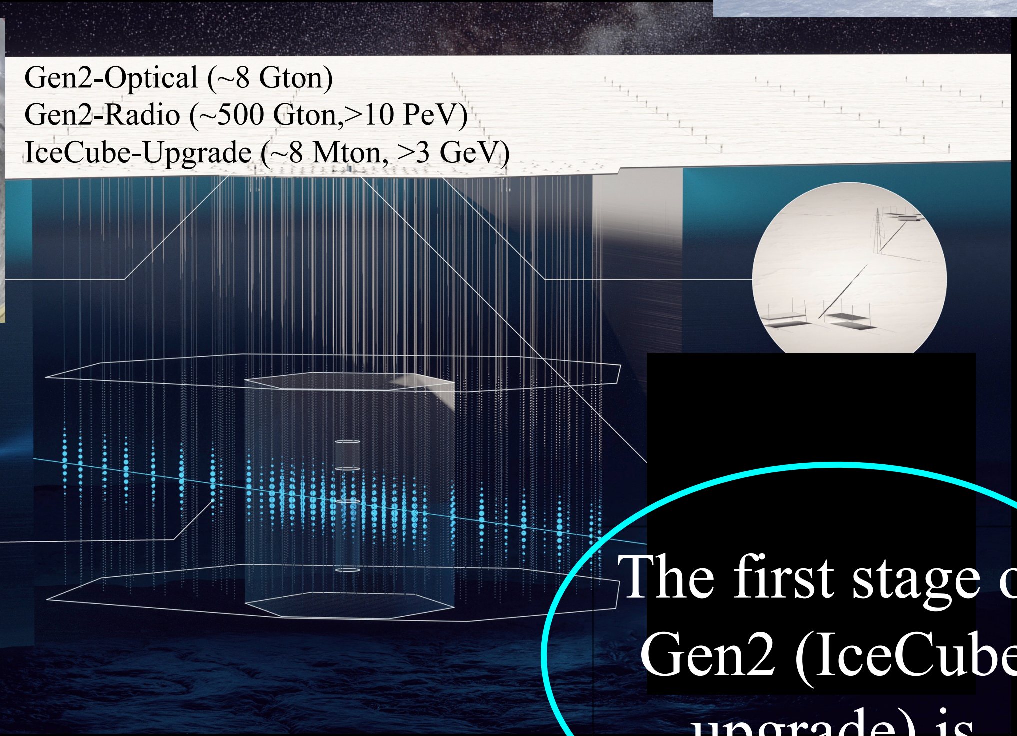
Summer 2024-2045 IceCube team

New international neutrino astronomy projects around the world

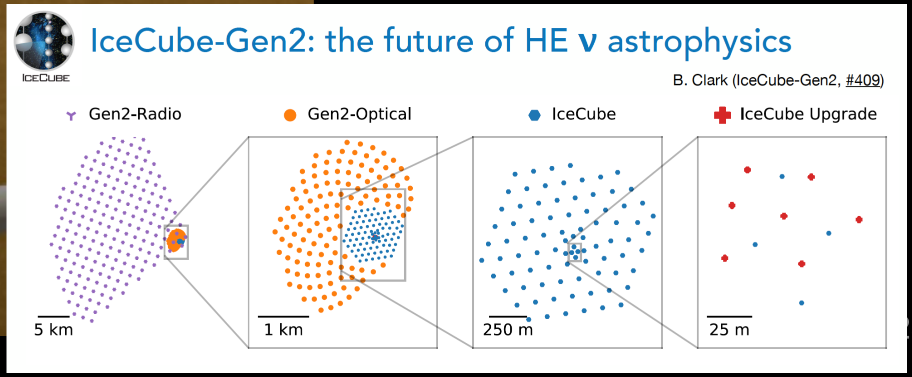


Hyper-K construction is ongoing





The first stage of Gen2 (IceCube upgrade) is ongoing



Hyper-Kamiokande

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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

Astrophysical neutrinos are powerful tools to look for Lorentz violation

Thank you for your attention!

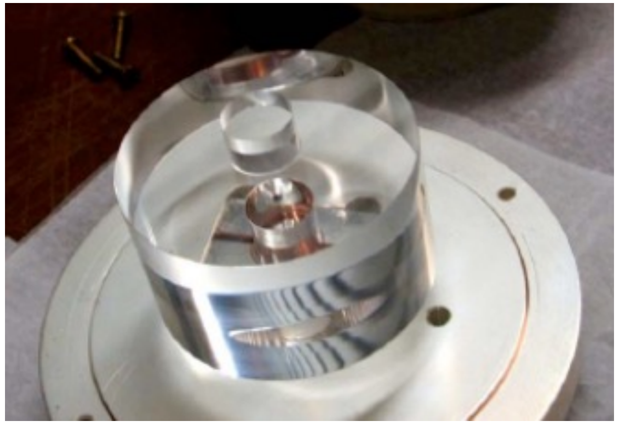
Backup

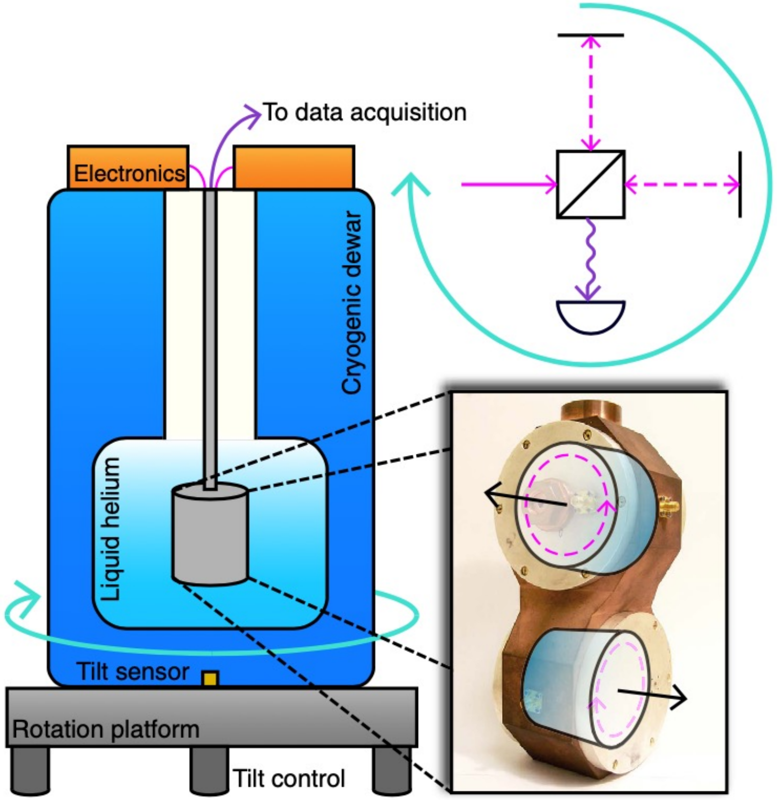
Nagel et al, Nature Comm., 6(2015)8174

Optical cavity experiment

Modern Michelson-Morley experiment
- Saphire crystal resonator
- Whispering gallery mode
- Vacuum insulation, liquid helium cooling to 4K
- Turntable to actively rotate

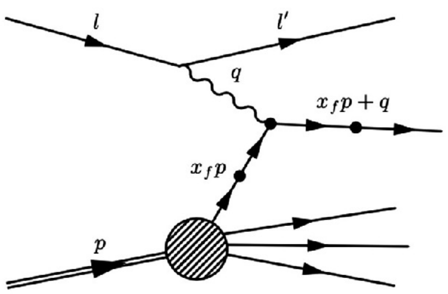
This experiment is sensitive to the anisotropy of speed of light down to $\Delta c/c \sim 10^{-18}$





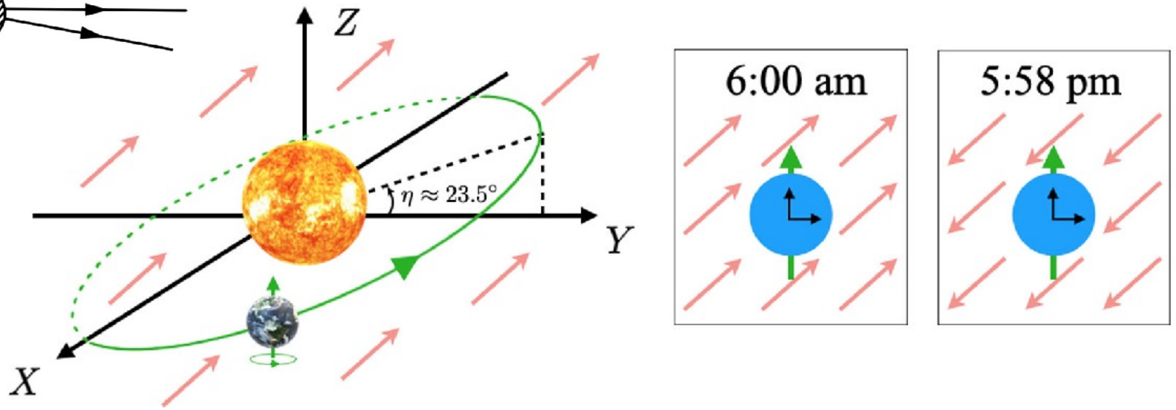
ZEUS, PRD107(2023)092008 and many others

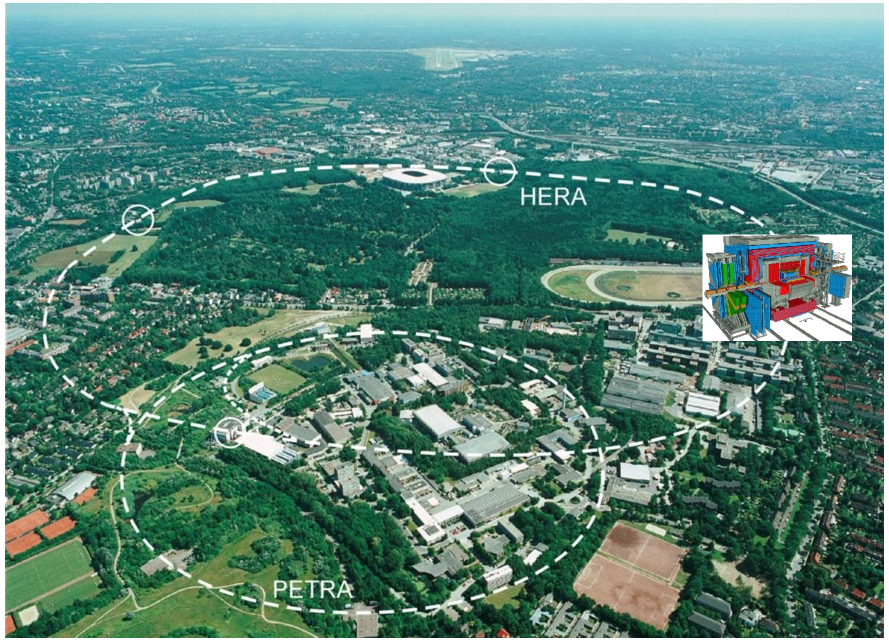
Collider physics (quarks)

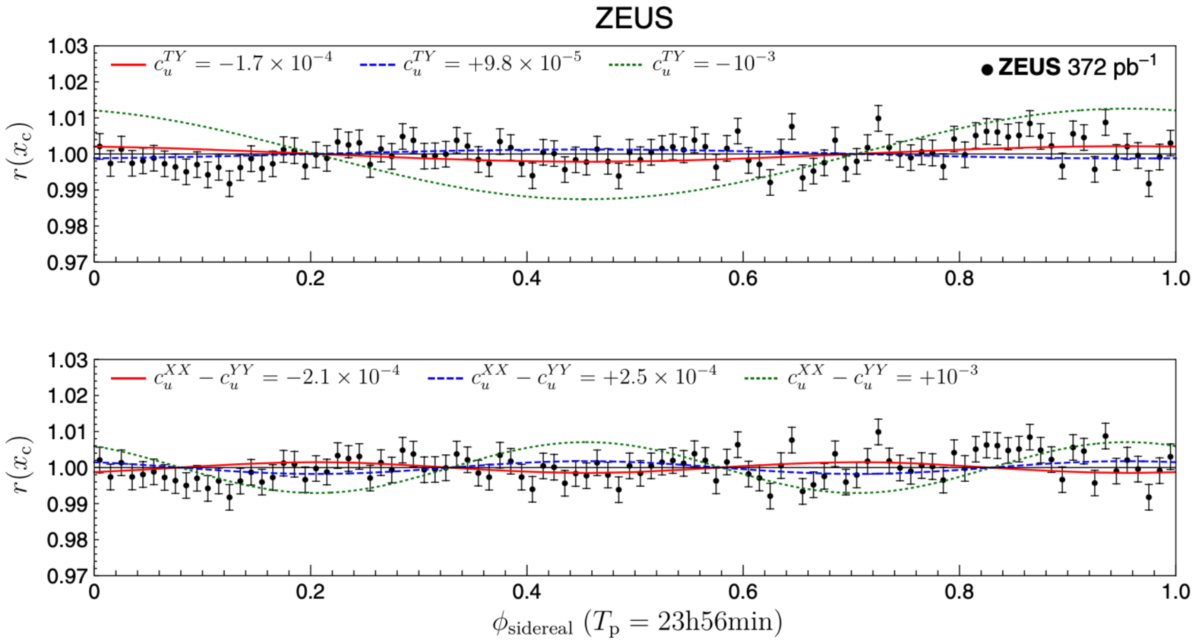


HERA p-e$^-$ collider

- ZEUS deep-inelastic scattering data
- Monitor sidereal time dependence
- LV tests of quarks







Models of 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
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

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

High-energy, long propagating neutrinos

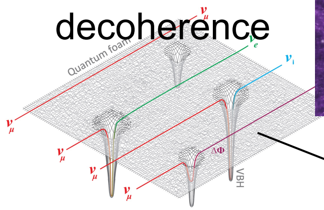
High-energy astrophysical neutrinos

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

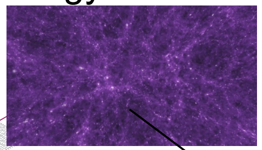
$$H\sim\frac{m^2}{2E}+V(new\ physics),P\sim V(new\ physics)\cdot L$$

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

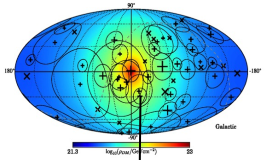
Quantum decoherence



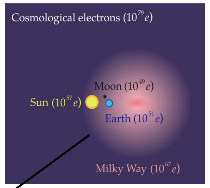
Neutrino – dark energy interaction



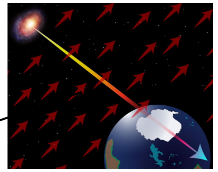
Neutrino – dark matter interaction



Long range force

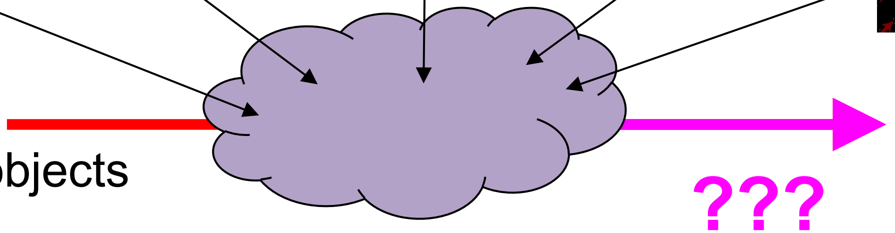


Lorentz violation



etc

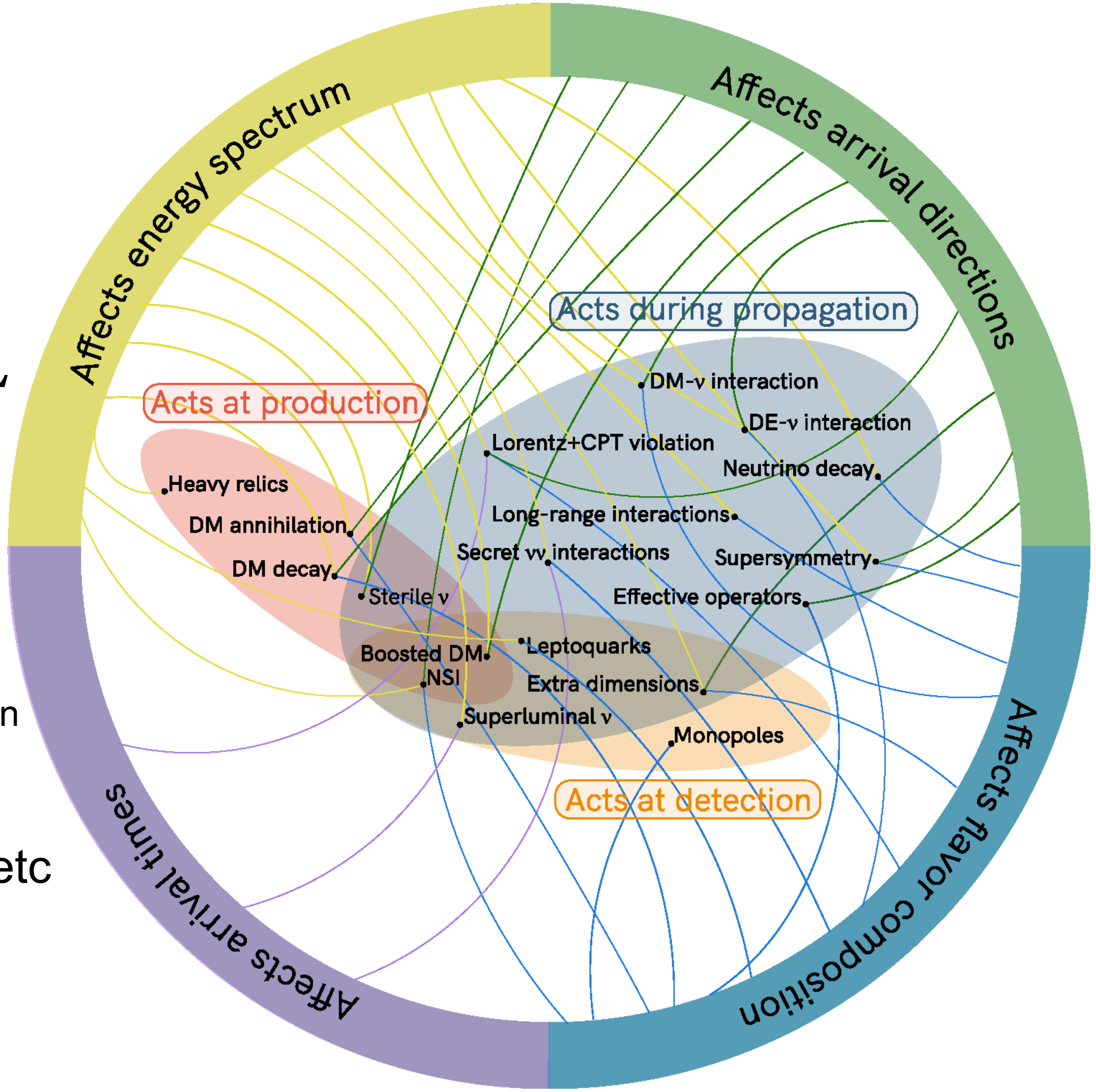
High-energy Astrophysical objects



Neutrino detector

???

New physics



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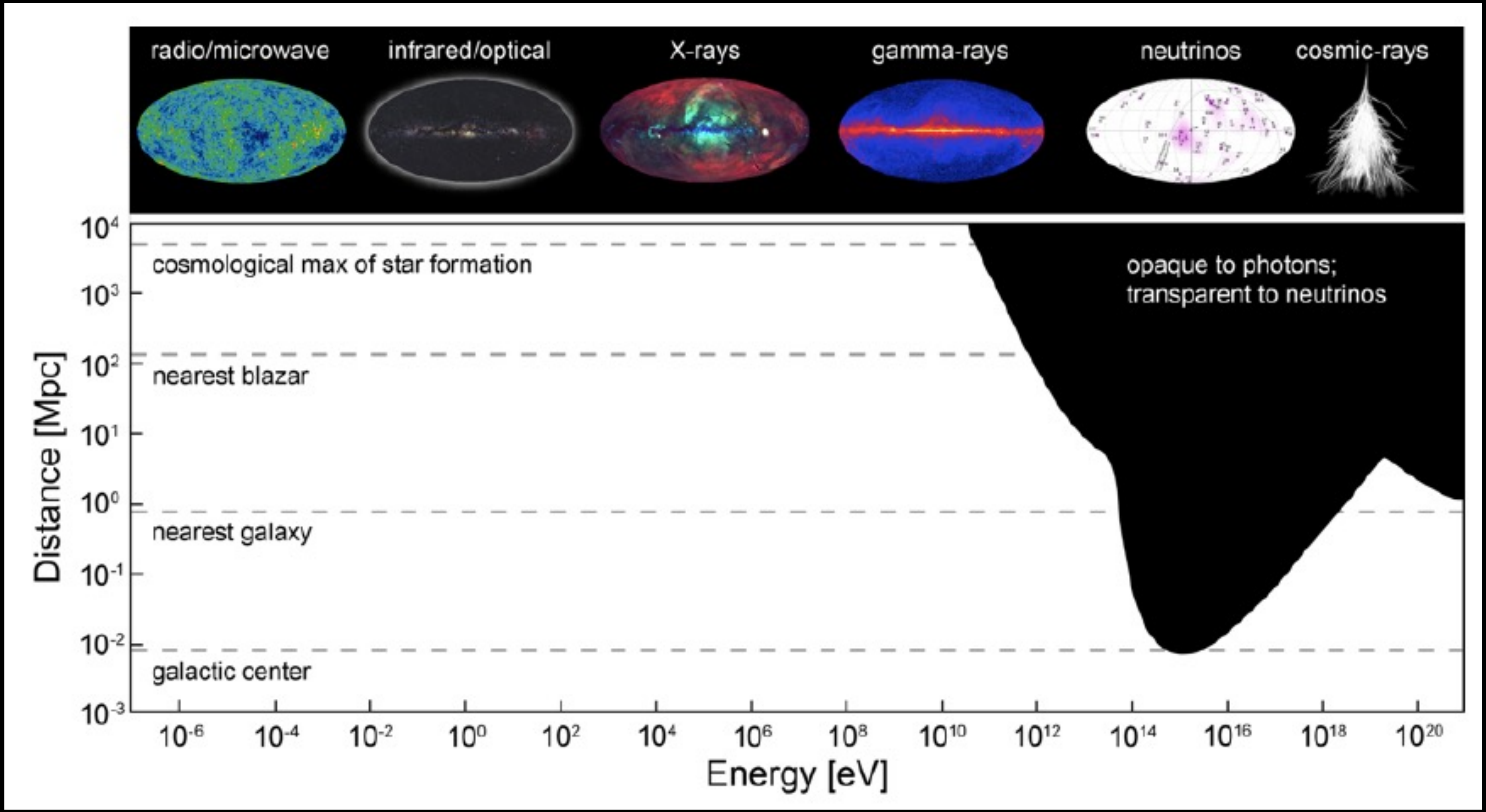
IceCube, Nature Physics(2022), (2024), Klop,Ando, PRD97(2018)063006,Argüelles,Kheirandish,Vincent, PRL119(2017)201801, Bustamante,Agarwalla, PRL122(2019)061103, Amelino-Camelia, ,Di Luca, Gubitosi, Rosati, D'Amico, Nature Astronomy (2023)

High-energy astrophysical neutrinos

Above ~100 TeV, neutrinos are only particles pointing to their high-energy sources

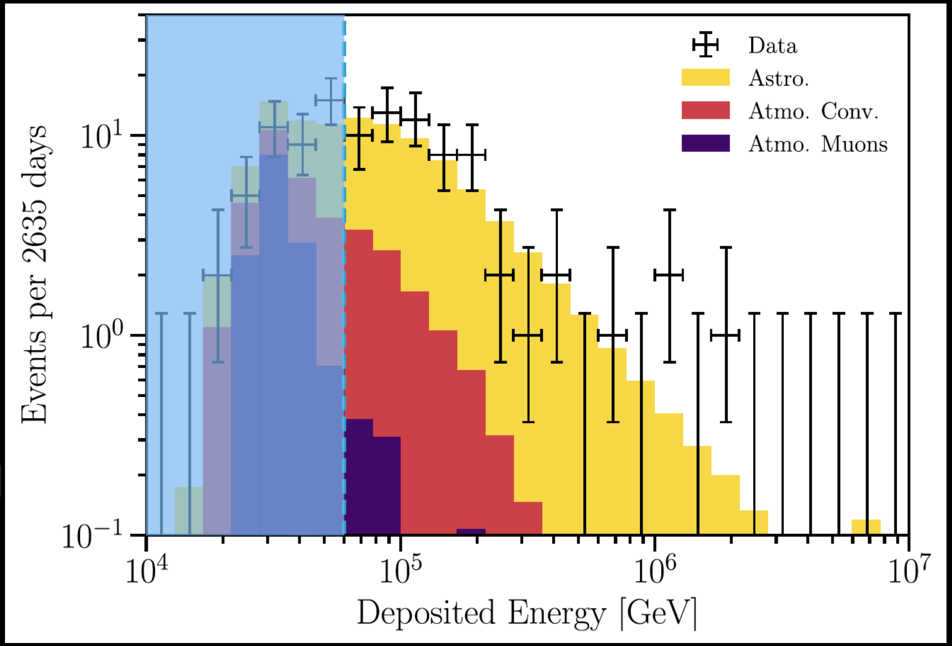


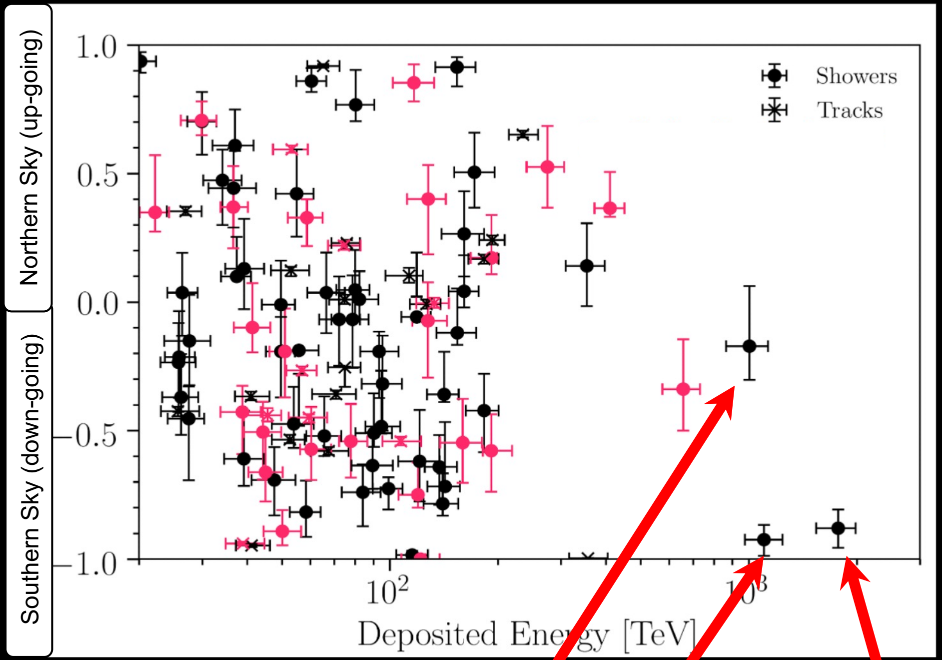
High-energy astrophysical neutrinos

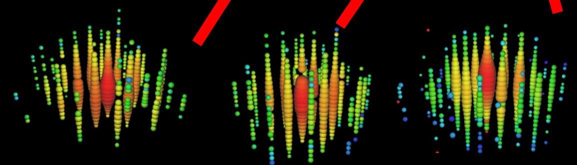
60TeV- 2PeV astrophysical neutrinos are observed by IceCube Neutrino Observatory

high-energy starting event (HESE) sample

2. Hig







“Bert”
1.1 PeV

“Ernie”
1.0 PeV

“Big Bird”
2.0 PeV

IceCube, Nature Phys. 18, 1287 (2022), IceCube, PRD104,(2021)022002, EPJC82(2022)1031

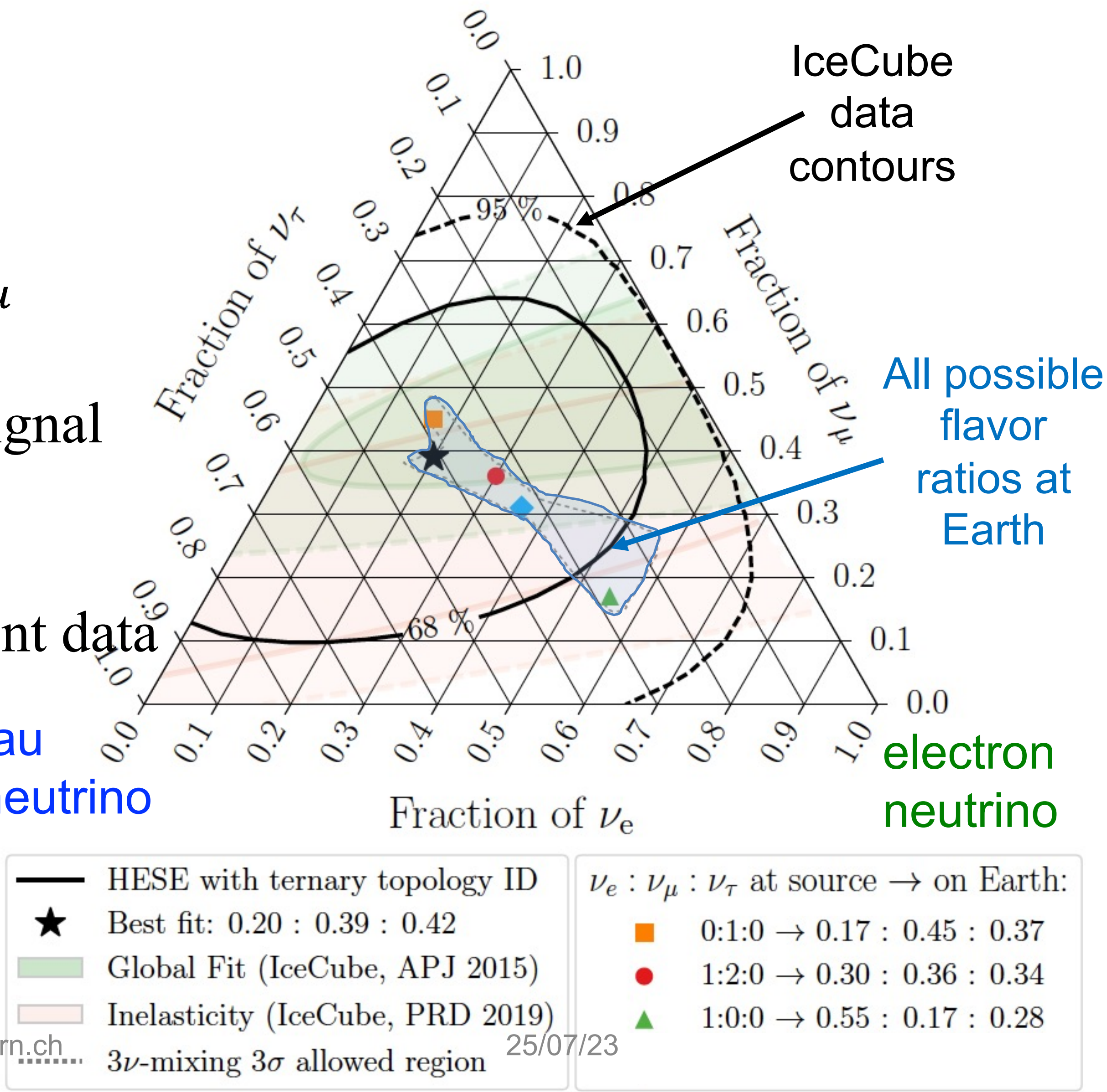
High-energy, long propagating neutrinos

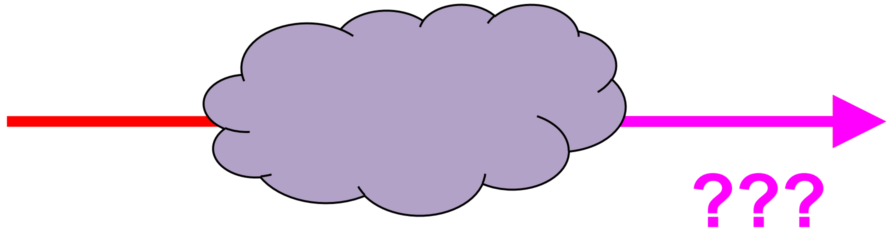
Astrophysical neutrino flavor physics

- 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

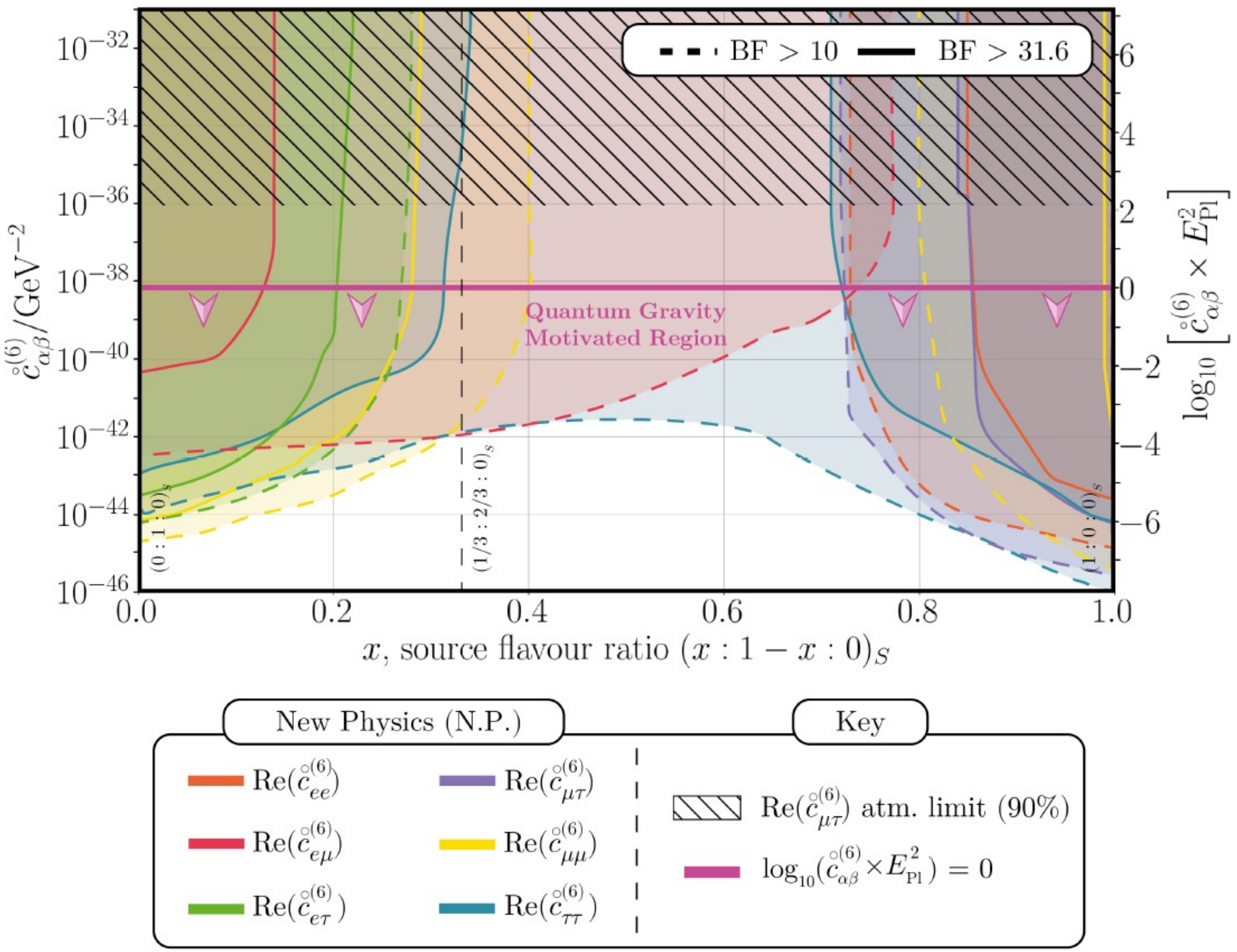
dim-6 new physics operator limit

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



Mewes and Kostelecký, PRD85(2012)096005

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)

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

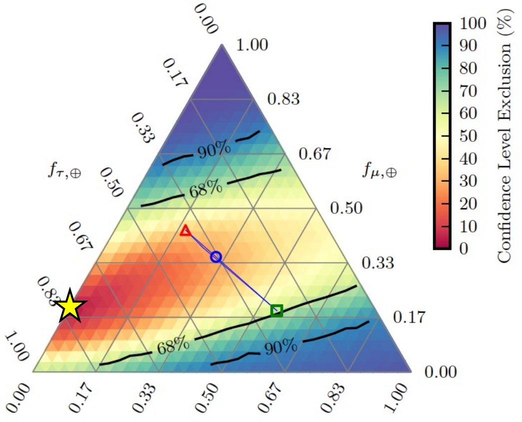
$$E^{3}c_{\alpha\beta}^{(6)} = E^{3}\begin{pmatrix} c_{ee}^{(6)} & c_{e\mu}^{(6)} & c_{\tau e}^{(6)} \\ c_{e\mu}^{(6)*} & c_{\mu\mu}^{(6)} & c_{\mu\tau}^{(6)} \\ c_{\tau e}^{(6)*} & c_{\mu\tau}^{(6)*} & c_{\tau\tau}^{(6)} \end{pmatrix}$$

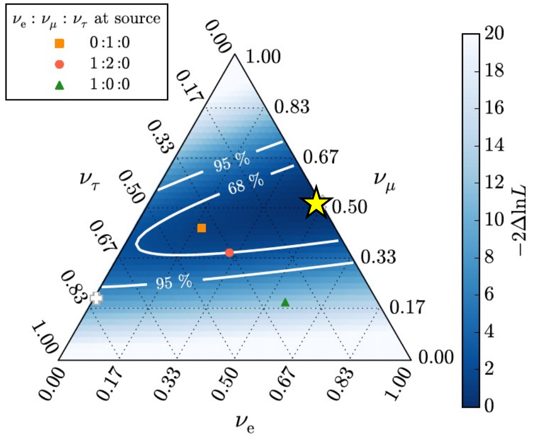
IceCube is sensitive to higher dimension operators

dimension-6 operator natural scale: $c^{(6)}\sim\frac{1}{M_{Planck}^{2}}\sim10^{-38}GeV^{-2}$

IceCube flavor ratio measurements

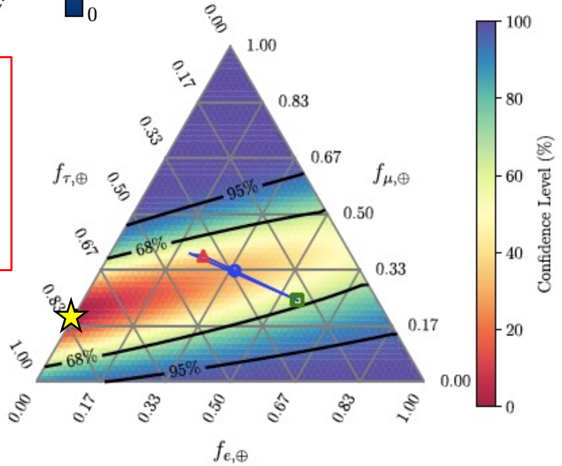
IceCube
1st flavour ratio result
(0.0:0.2:0.8)

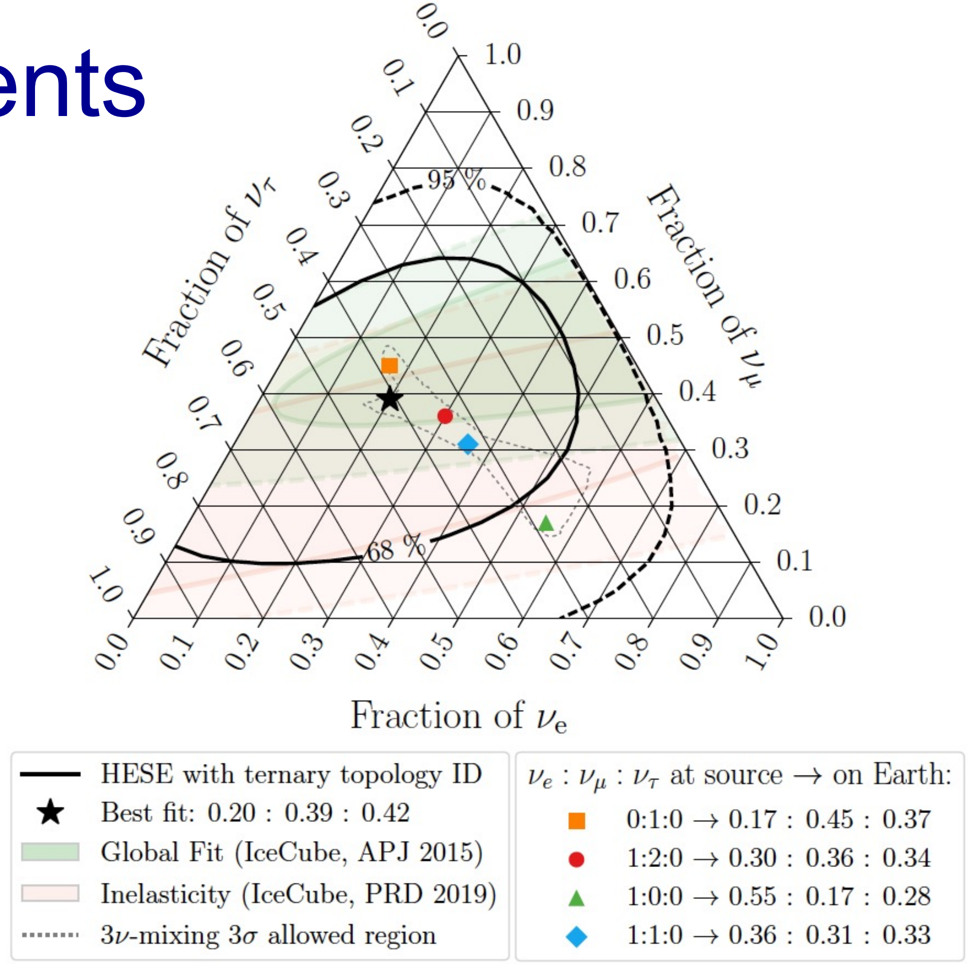




IceCube
2nd flavour ratio result
(0.5:0.5:0.0)

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





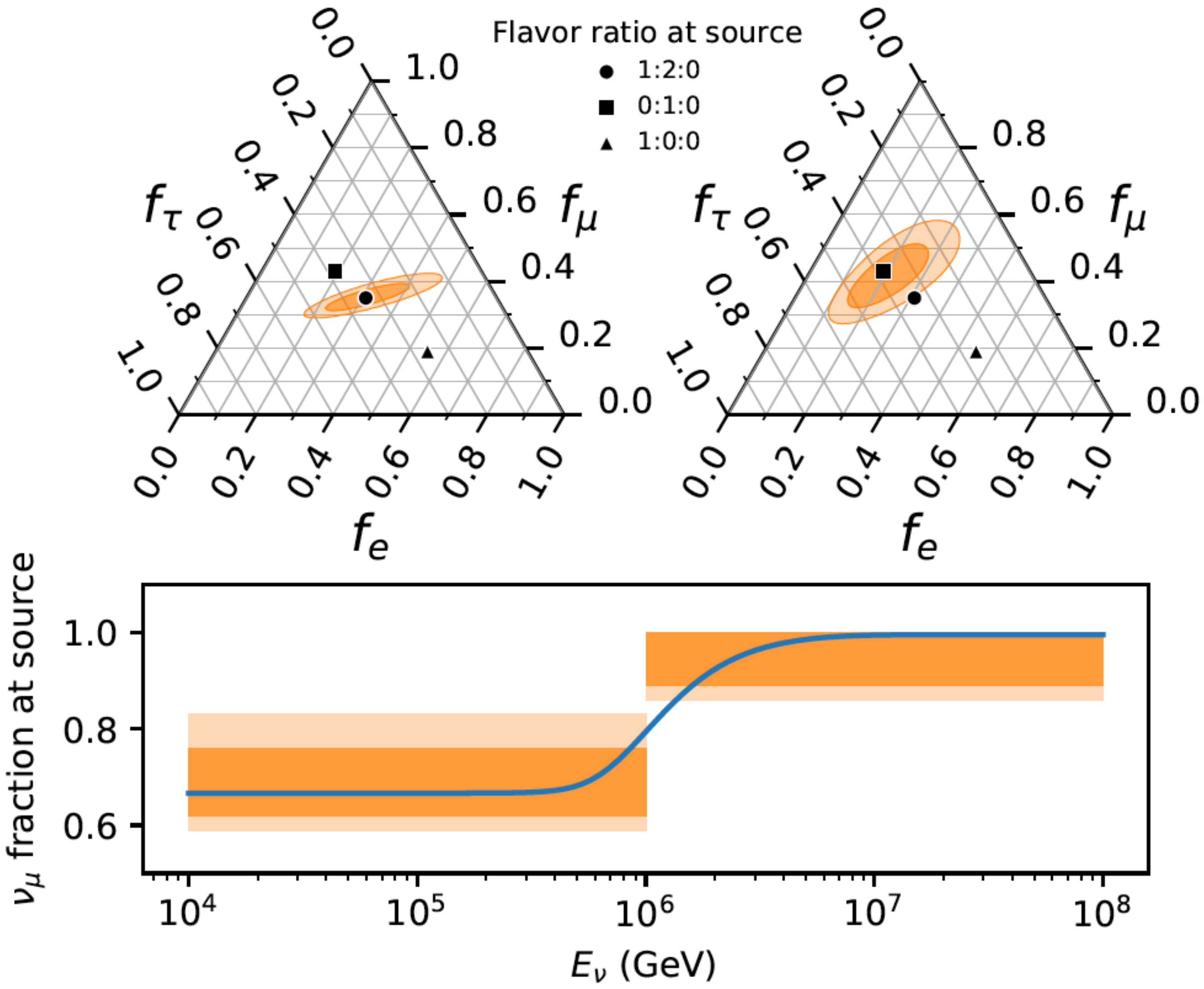
2018 flavour ratio measurement

- 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



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.