

Modern Tests of Spacetime Symmetry

outline

1. Introduction
2. Tests of Lorentz violation
3. Tests Lorentz violation in astrophysics



Teppei Katori  @teppeikatori
King's College London

Neutrino Group seminar, Ruđer Bošković Institute, Zagreb, April 10, 2025

Introduction

I want to say Einstein is wrong!

How to disprove Einstein's theory
scientifically???

A **armanettimaurizio@libero.it**
From Italy - OBJECT: here's how to overcome the speed of light.
To: Teppei Katori

January 15, 2020 at 10:05

B **baoluijiang@gmail.com**
A website to disprove Special Relativity
To: Teppei Katori

February 12, 2022 at 00:07

Home

Special Relativity is Wrong

This website is dedicated to proving that **Special Relativity is Wrong**.

Listed below are the major sections in our article:

- [Why is Special Relativity wrong?](#)
- [What is Special Relativity?](#)
- [The two postulates](#)

Latest Updates

- 2022-10-22: Section 'On velocity addition' is added to the end of the main article.
- 2021-11-21: Several Q&As are added.

05: The main article is

24: [Source Text](#) for vi

18: Several Q&As are

CV **Cosmin Visan**
My theory of consciousness and meeting proposal
To: bozidar.butorac@kcl.ac.uk & 113 more

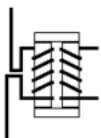
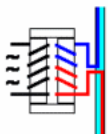
January 13, 2024 at 22:28

[Details](#)

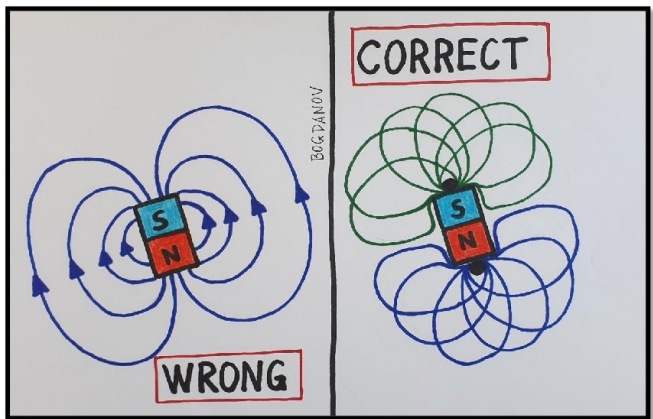
TO THE PERSONAL ATTENTION OF PROF. TEPPEI KATORI

OBJECT: here's how to overcome the speed of light.

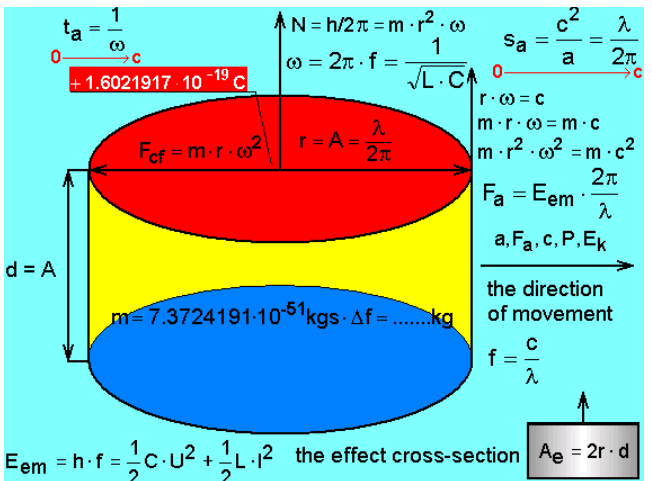
I can demonstrate under scientific control and in a repeatable the speed of light. The brain has the energetic power of instantar the problem was to prove it scientifically, today it is possible, I ca



The True Pattern of Magnetic Field looks nothing like we are used to!



tkatori@cern.ch



25/04/10

3

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

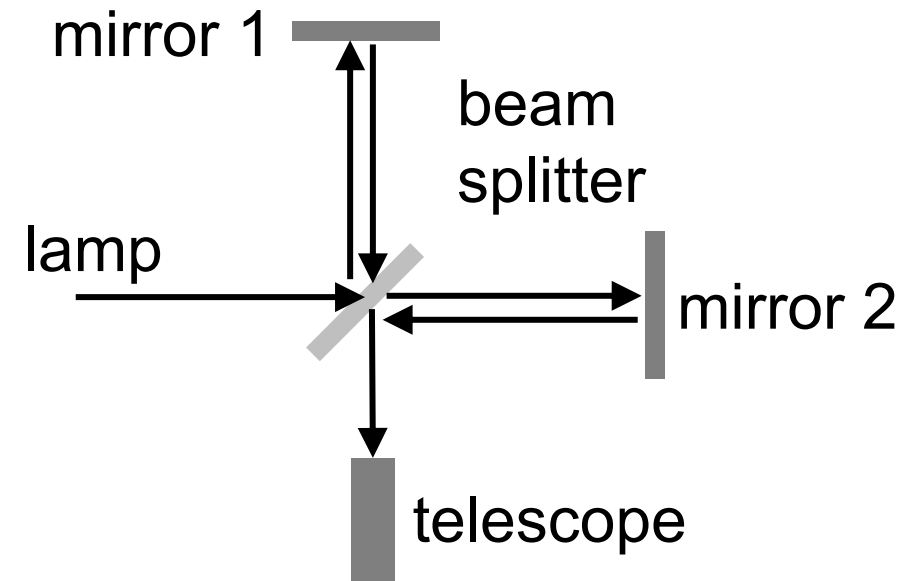
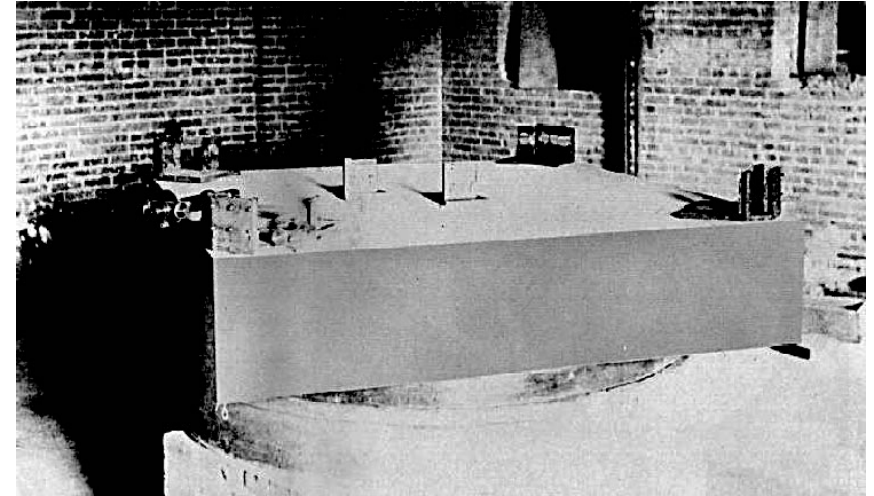
Michelson-Morley experiment

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.

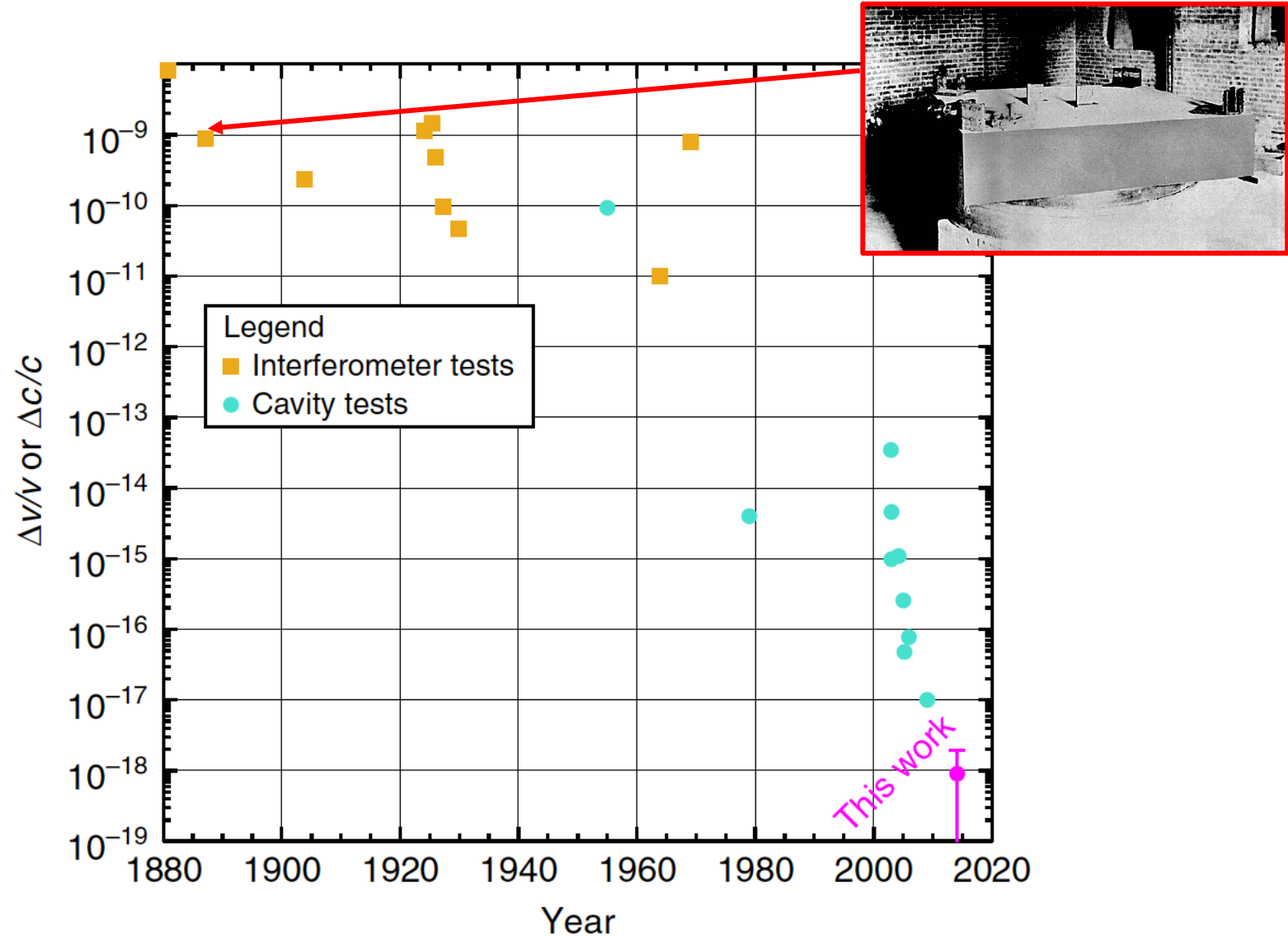
This result suggests the isotropy of spacetime, and Lorentz symmetry.

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



Michelson-Morley experiment

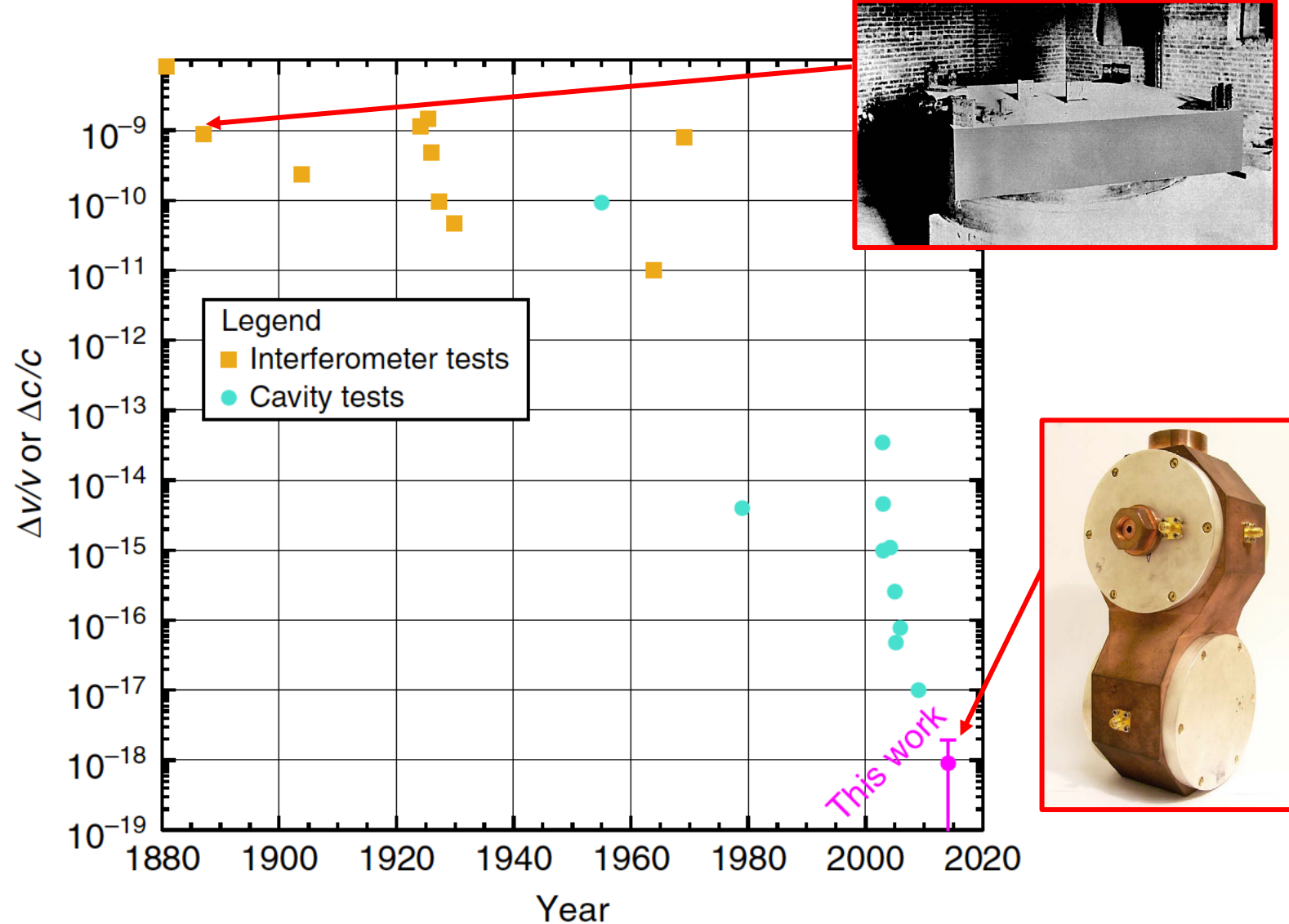
The experiment has been improved over 100 years.



Michelson-Morley experiment

The experiment has been improved over 100 years.

Technology shift
(interferometer → optical
cavity) around 2000s



Optical cavity experiment

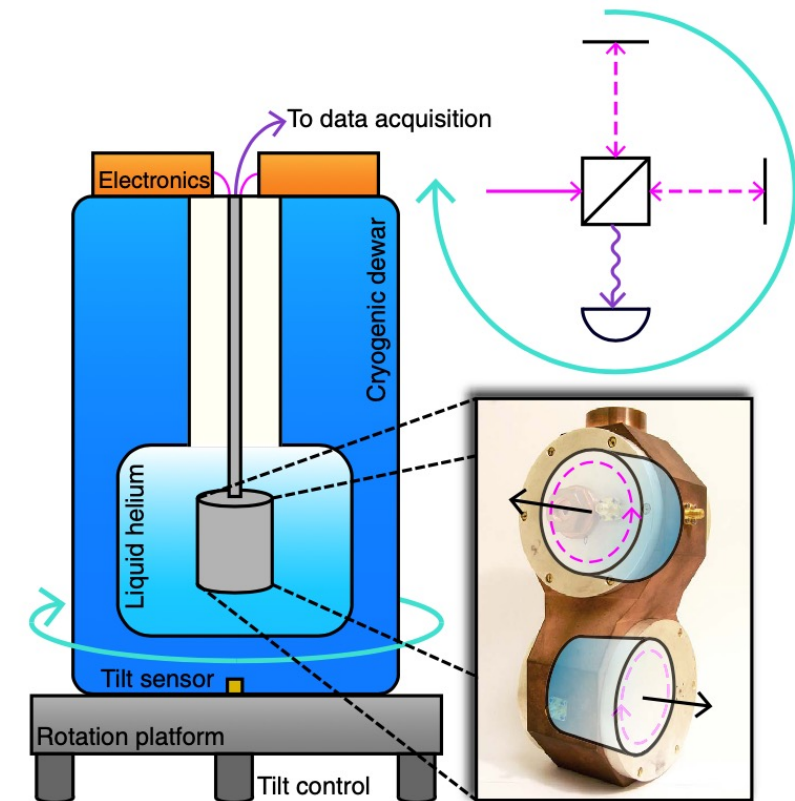
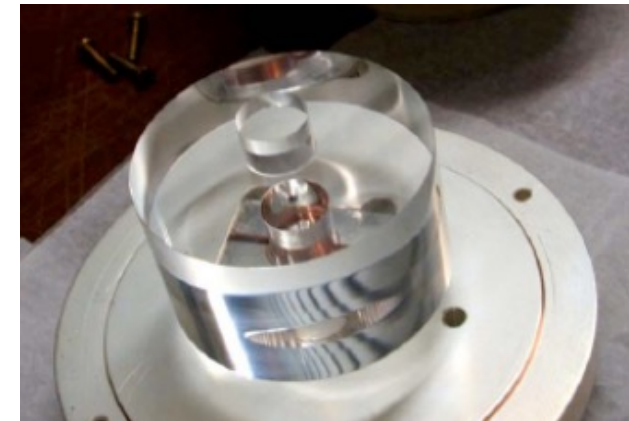
Modern Michelson-Morley experiment

- Sapphire 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 $\Delta c/c \sim 10^{-18}$

Why we keep testing this?

Why do we expect Lorentz violation?



Quantum gravity

Searching Lorentz violation is well motivated

Lorentz violation in Planck scale theories

- string theory
- noncommutative field theory
- quantum loop gravity

etc

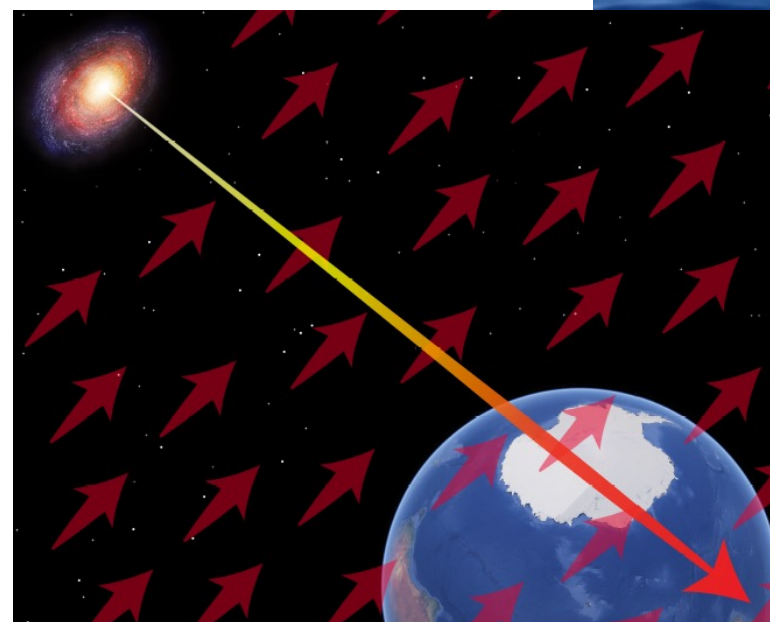
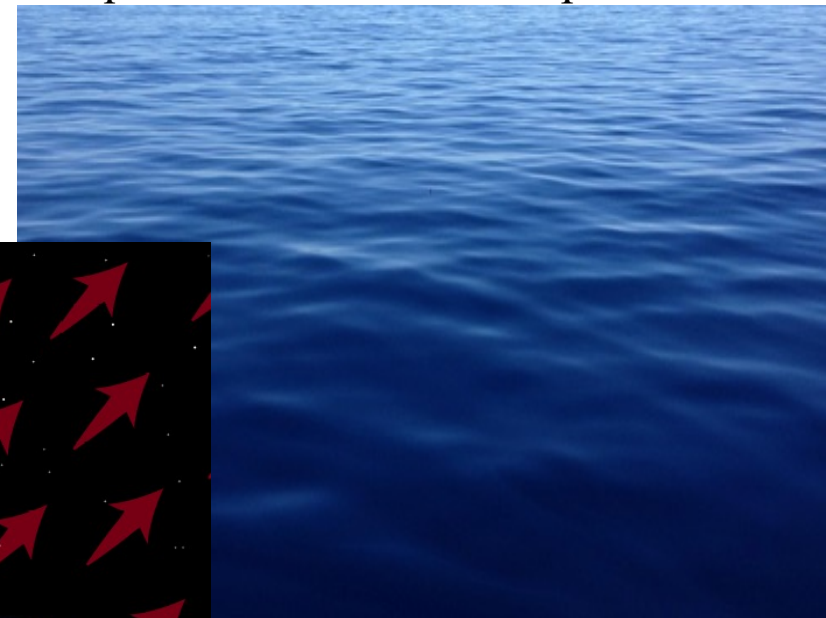
Lorentz violation is seen as

- spacetime fluctuation
- background field in vacuum (EFT)

etc

quantum foam

- quantum fluctuation of space-time



Lorentz violating field

- background field of the universe (æther)

Quantum gravity

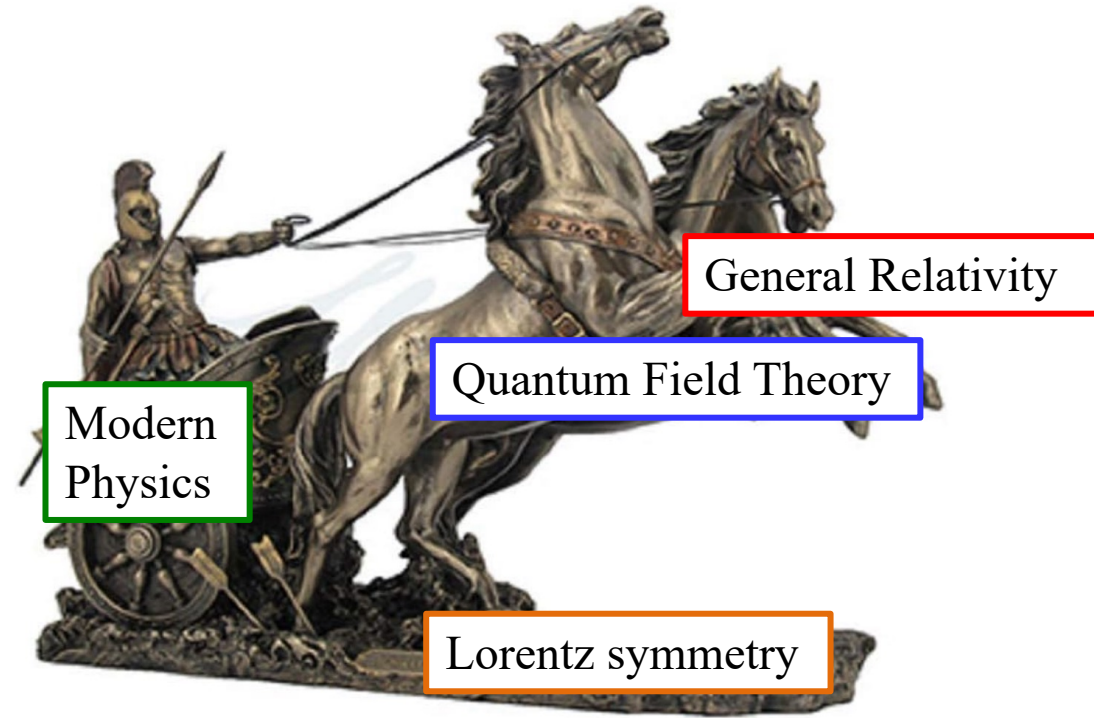
Searching Lorentz violation is well motivated

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

Lorentz symmetry is a basis for both quantum field theory and general relativity

How to formulate Lorentz violation in our theories?

Lorentz symmetry could be **spontaneously broken**, if so, this doesn't violate existing framework of modern physics



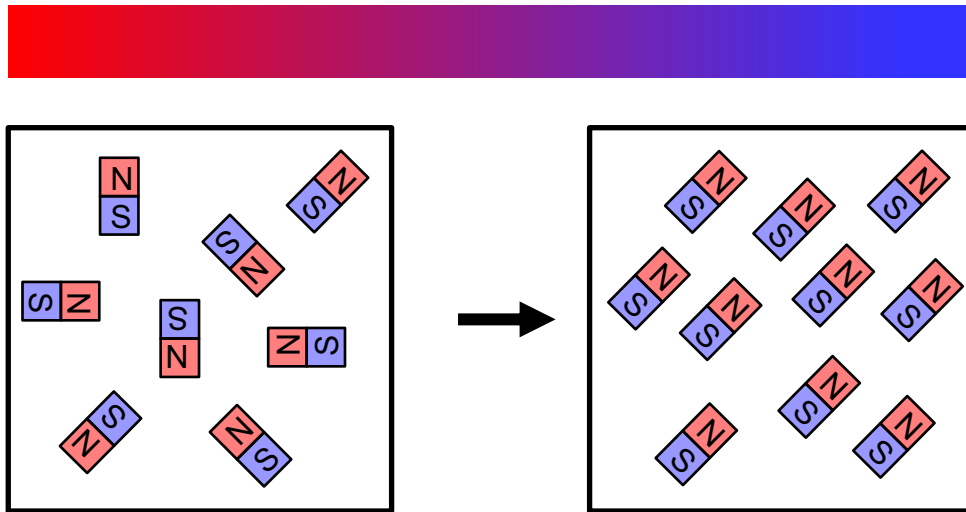
Spontaneous symmetry breaking

Searching Lorentz violation is well motivated

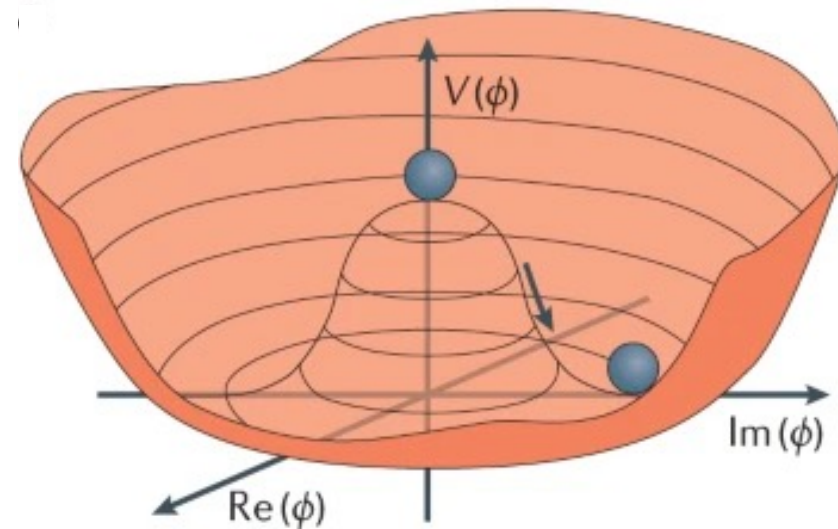
Nature has many examples of spontaneous symmetry breaking

- Condensed matter (magnetization, crystallization, etc)
- Phase transition in vacuum (Higgs mechanism, **spontaneous Lorentz symmetry breaking**)

Magnetization



Higgs mechanism



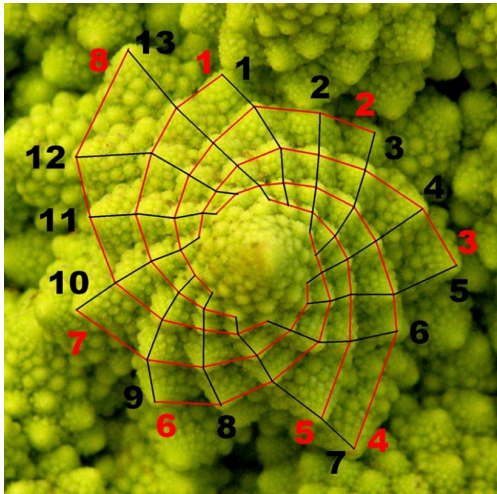
Spontaneous symmetry breaking

Searching Lorentz violation is well motivated

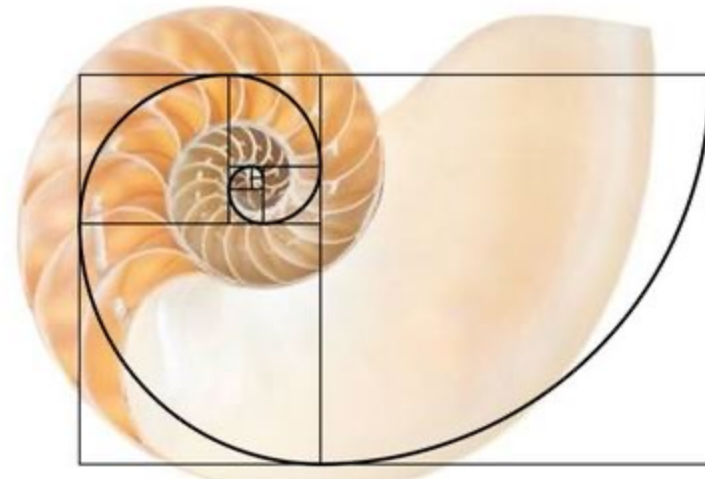
Math is a good approximation of nature

There is no perfect symmetry in nature, all somewhat broken

So why spacetime symmetry is perfect?!



Fibonacci number and broccoli



Golden ratio and seashell

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 framework to look for Lorentz violation

e.g.) vacuum Lagrangian for fermion

$$\mathcal{L} = \underbrace{i\bar{\psi}\gamma_{\mu}\partial^{\mu}\psi - m\bar{\psi}\psi}_{\text{Standard Model}} + \underbrace{\bar{\psi}\gamma_{\mu}a^{\mu}\psi + \bar{\psi}\gamma_{\mu}c^{\mu\nu}\psi}_{\text{couplings with background fields}} \dots$$

Standard Model

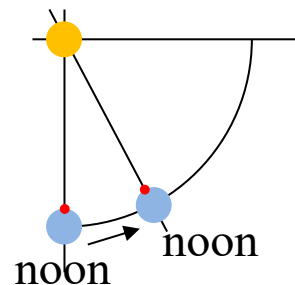
couplings with background fields

Physics of Lorentz violation

- Spectrum distortion,
- **Sidereal time dependence**, etc...

24h 00min 00sec: Solar day

23h 56min 4.1sec: Sidereal day



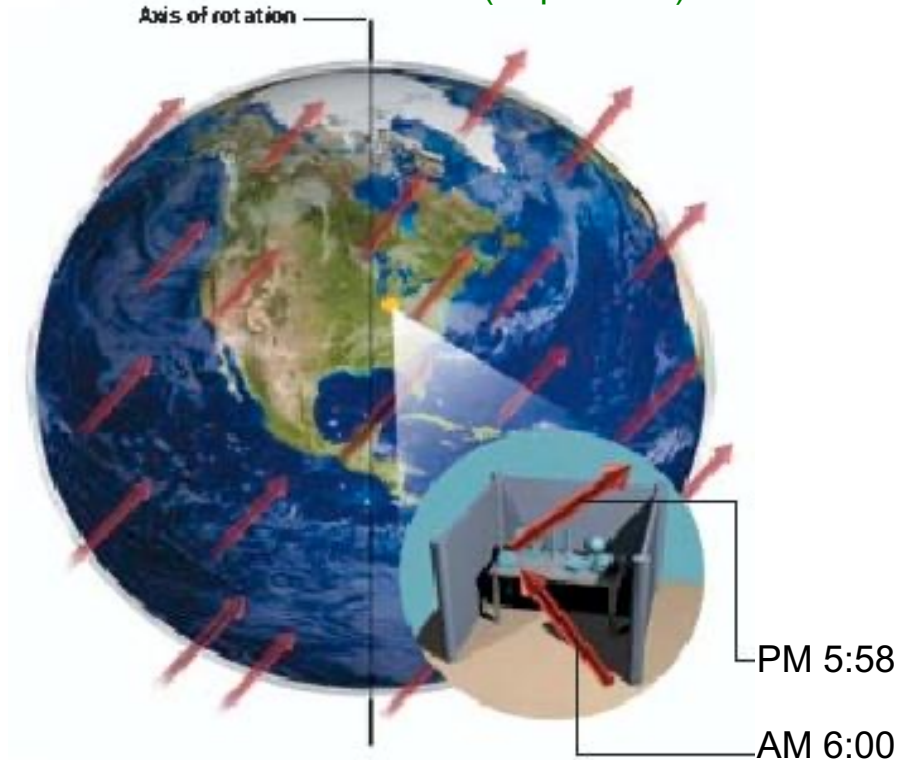
tkatori@cern.ch

Alan Kostelecky, Indiana University

2025 recipient, Norman F. Ramsey Prize

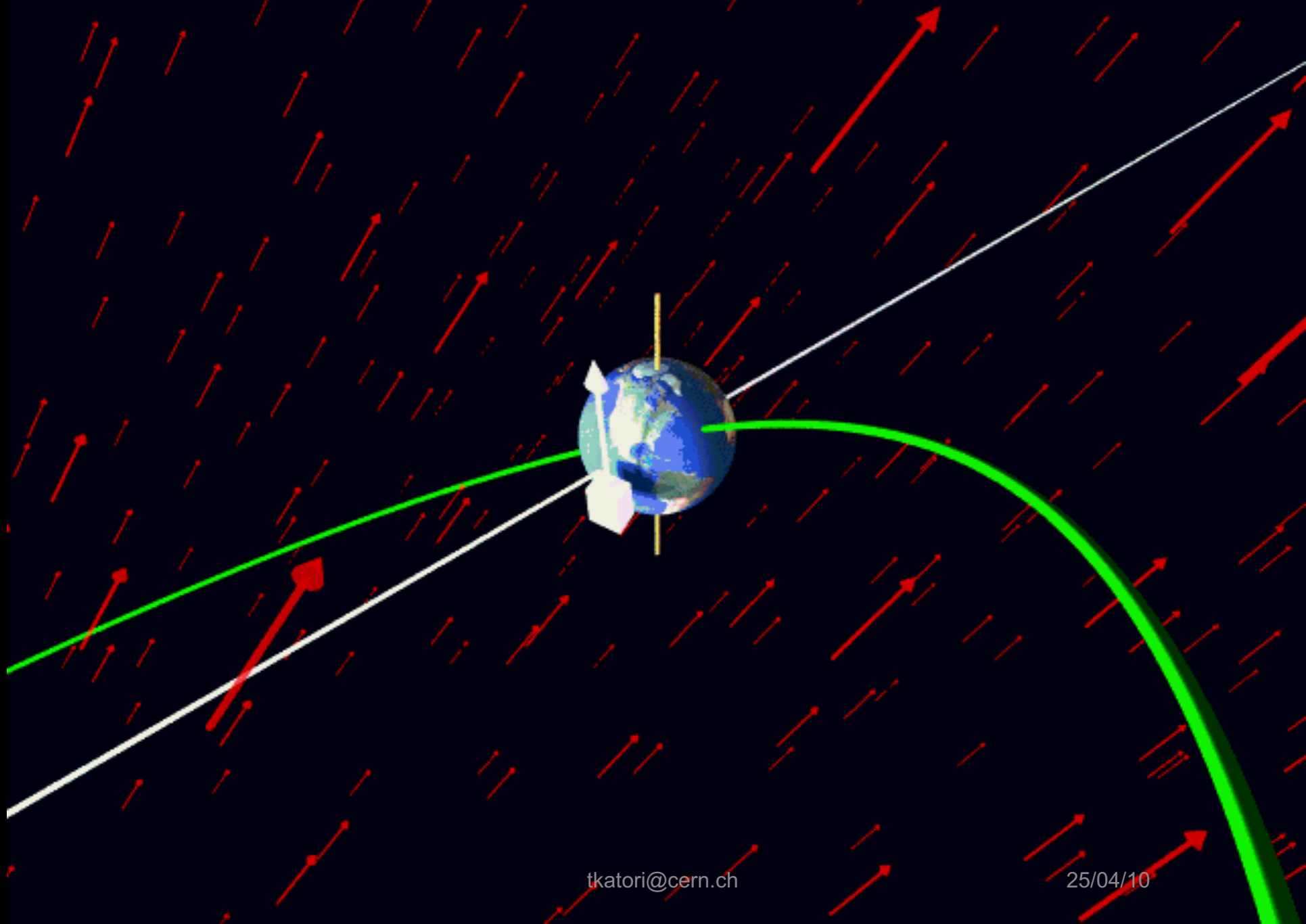
For the development of the Standard Model Extension and for its application to, and inspiration for, a broad set of precision measurement tests across various physical systems, some of which have reached Planck-scale sensitivity.

Scientific American (Sept. 2004)



25/04/10

13

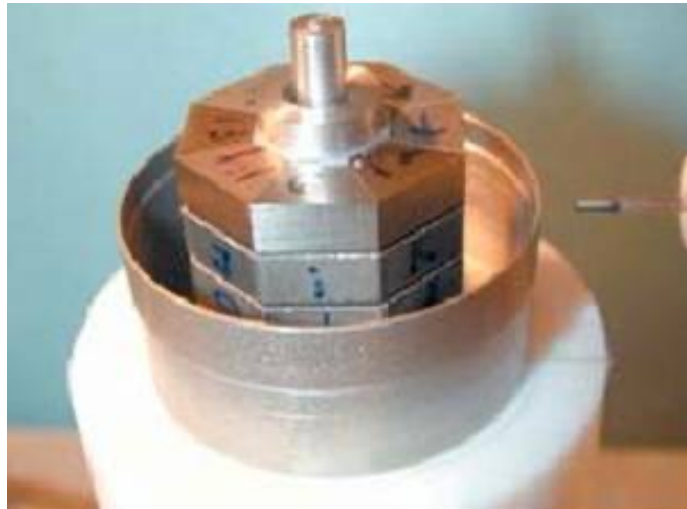


Tests of Lorentz violation

Torsion pendulum (electron)

Modern torsion balance

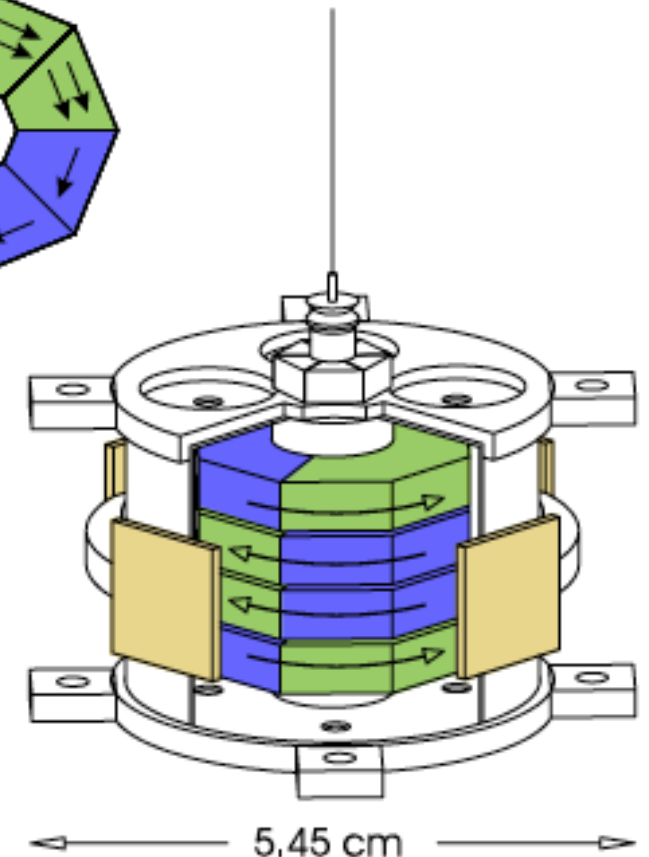
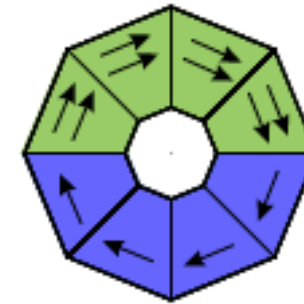
- AlNiCo: all magnetic field is from electron spin
- SmCo₅: electron orbital motion creates magnetic field
- Magnetize them to cancel magnetic field, so that the pendulum has net electron spin
- Look for coupling between electron spin and background field



Eric G. Adelberger, University of Washington, Seattle

2025 recipient, Einstein Prize

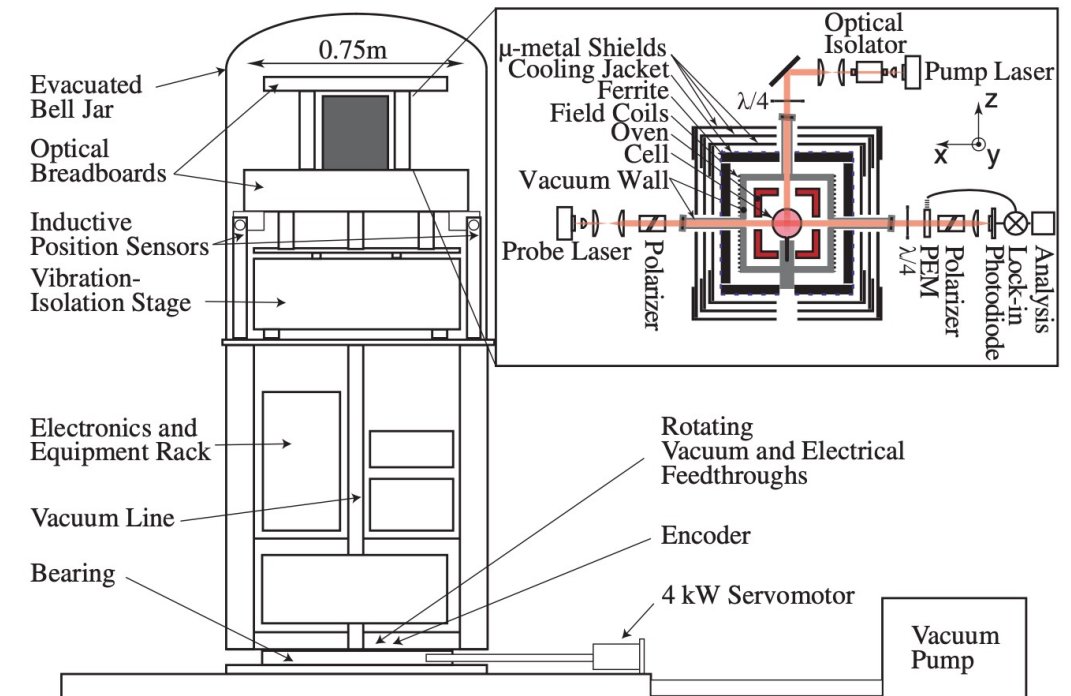
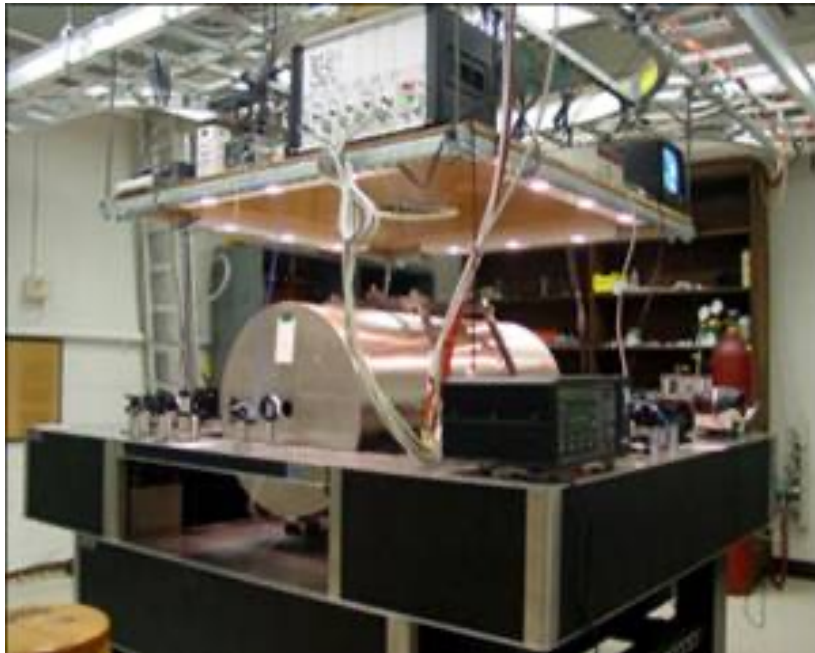
For outstanding contributions to experimental gravity using precision torsion-balance measurements, which have profound implications for fundamental physics.



Double gas maser (neutron)

The most sensitive magnetometer

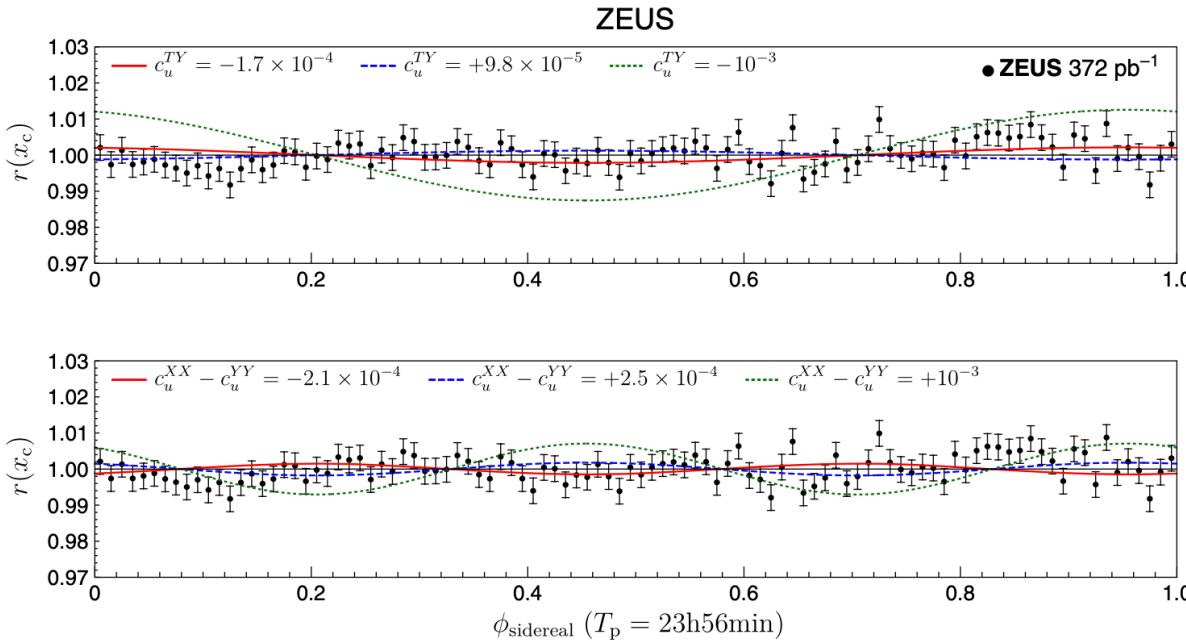
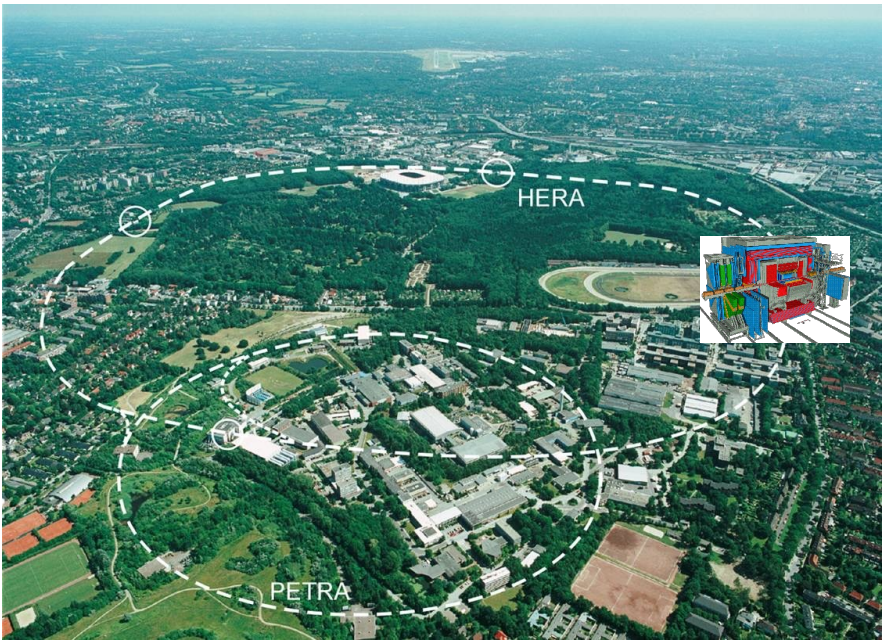
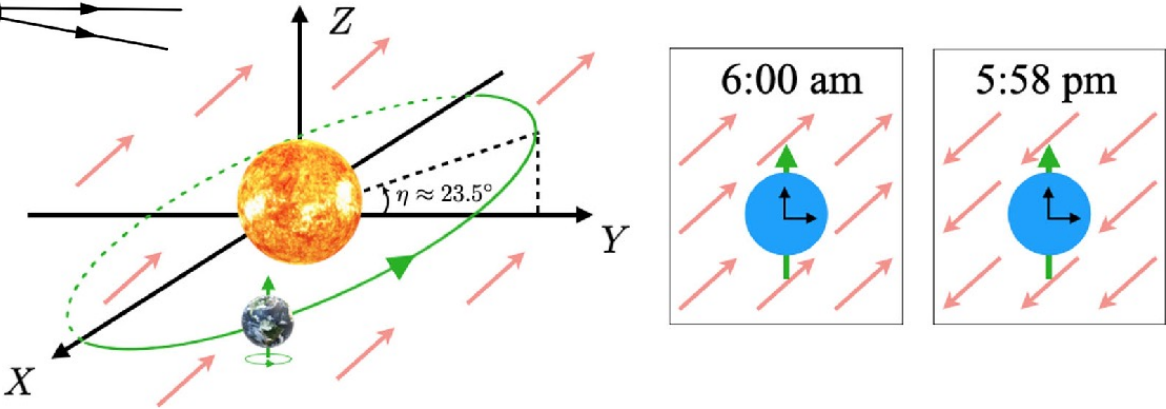
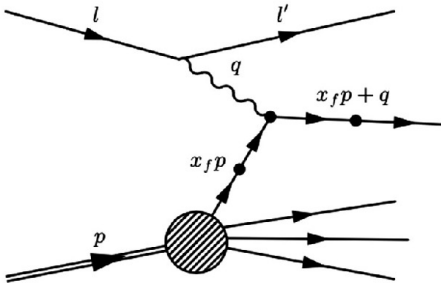
- Optical pump for Rb, K
- Spin transfer to noble gas (Xe, ^3He), monitor ^3He precession
- Look for coupling between neutron spin and background field



Collider physics (quarks)

HERA p-e⁻ collider

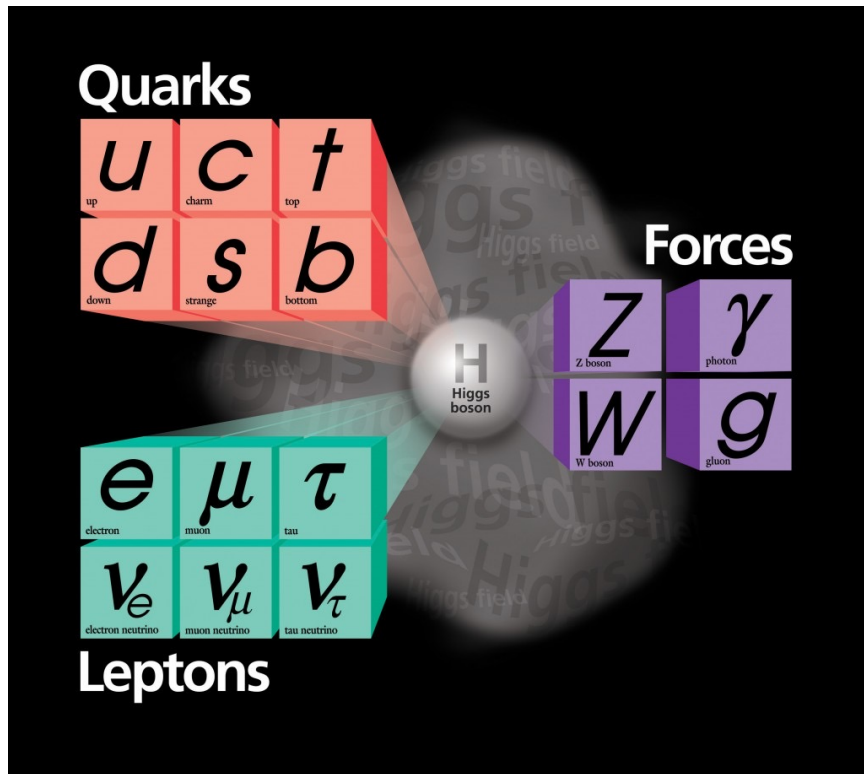
- ZEUS deep-inelastic scattering data
- Monitor sidereal time dependence
- Similar tests are possible for other data



Neutrino physics

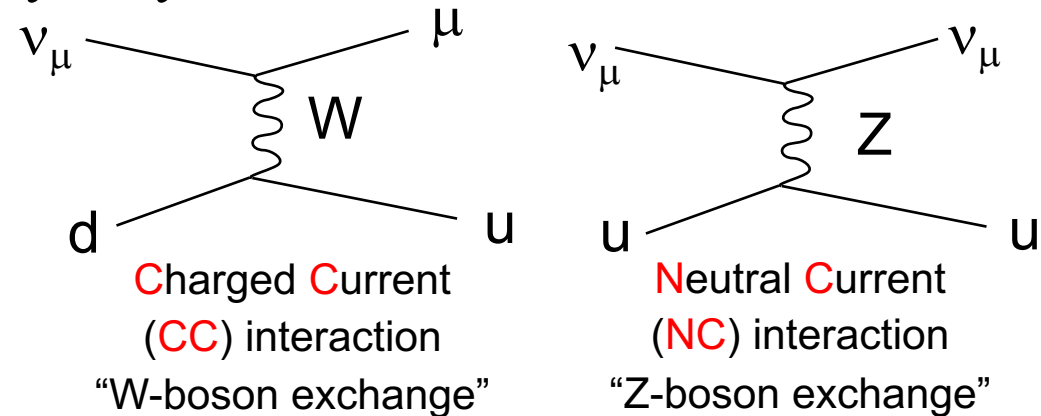
Neutrinos in the standard model

The standard model describes 6 quarks and 6 leptons and 3 types of force carriers.



Neutrinos are special because,

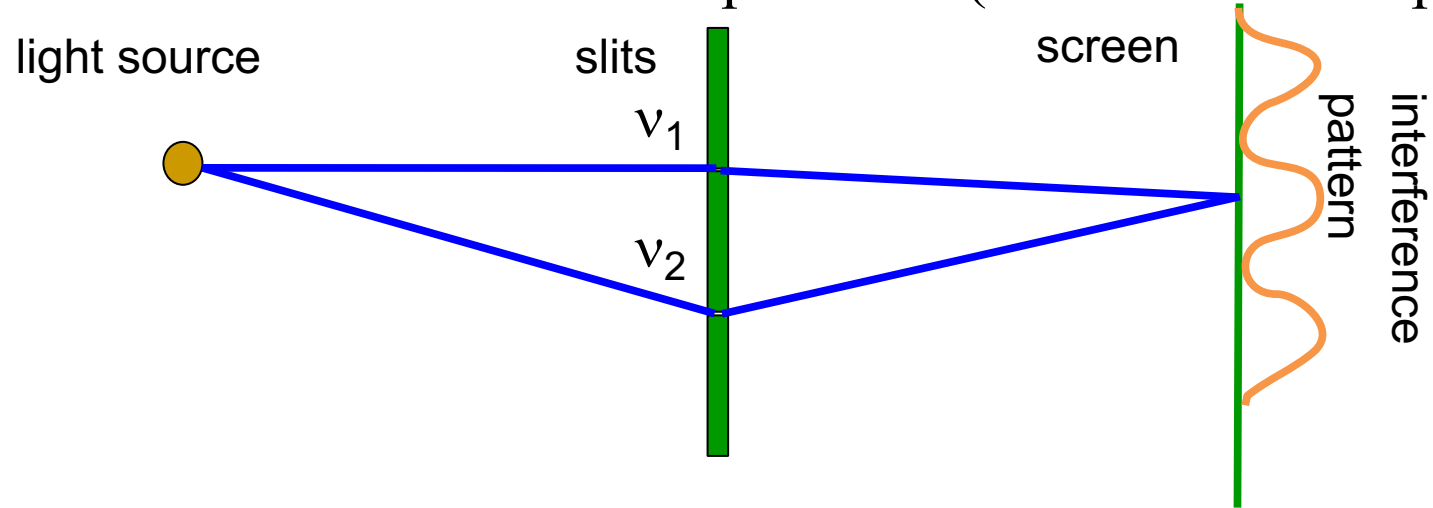
1. they only interact with weak nuclear force.



2. interaction eigenstate is not Hamiltonian eigenstate, and propagation of neutrinos changes their species (flavours), called **neutrino oscillation**.

Neutrino oscillation experiments

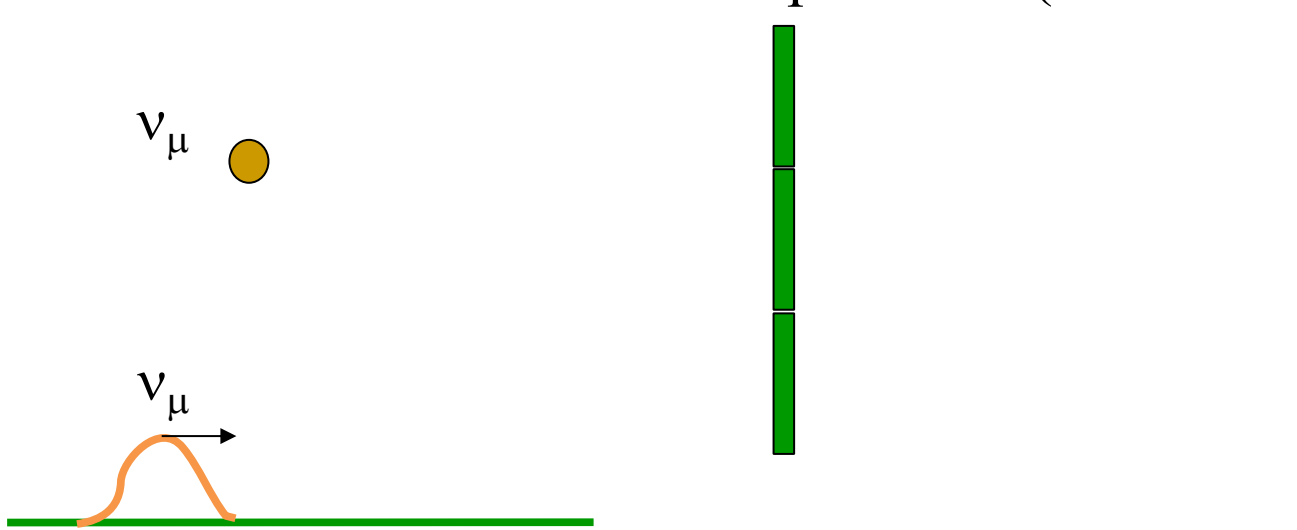
Neutrino oscillation is an interference experiment (cf. double slit experiment)



For double slit experiment, if path v_1 and path v_2 have different length, they have different phases and it causes interference.

Neutrino oscillation experiments

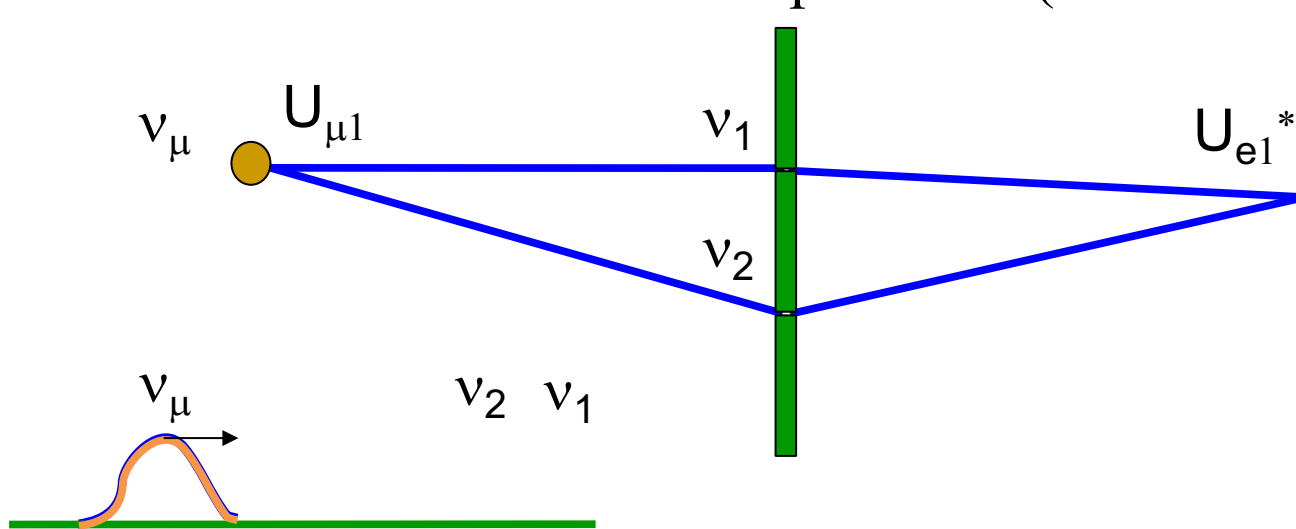
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

Neutrino oscillation experiments

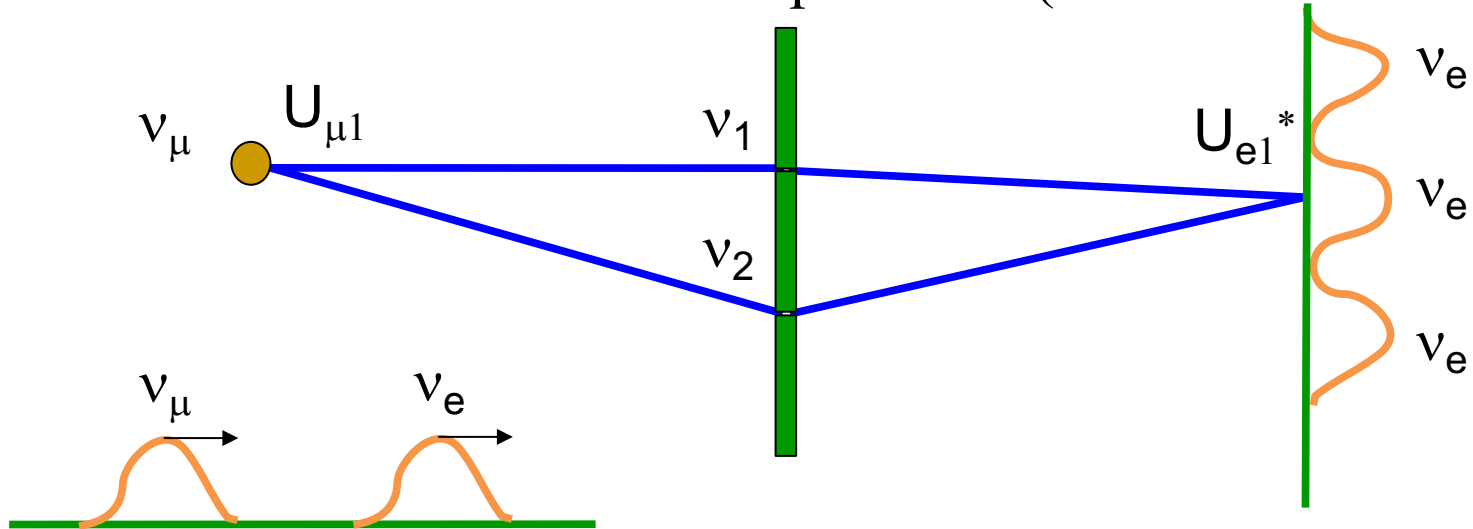
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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)



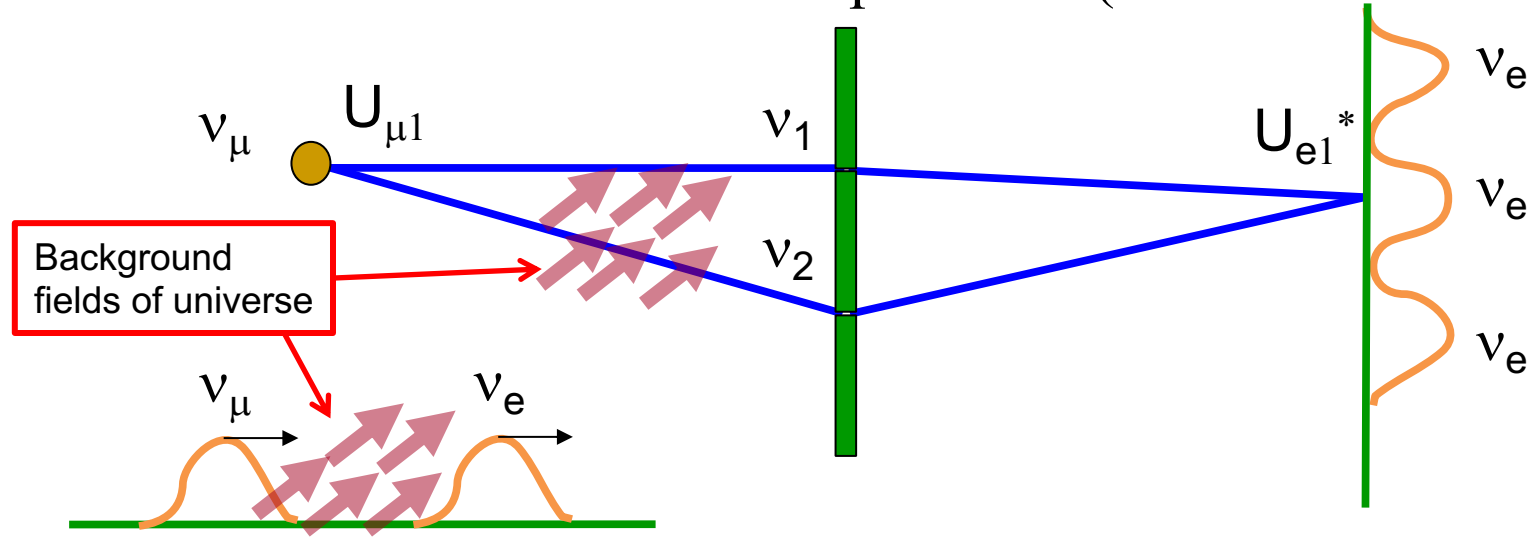
Neutrino flavour eigenstates are super-position of Hamiltonian eigenstates ν_1 and ν_2

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

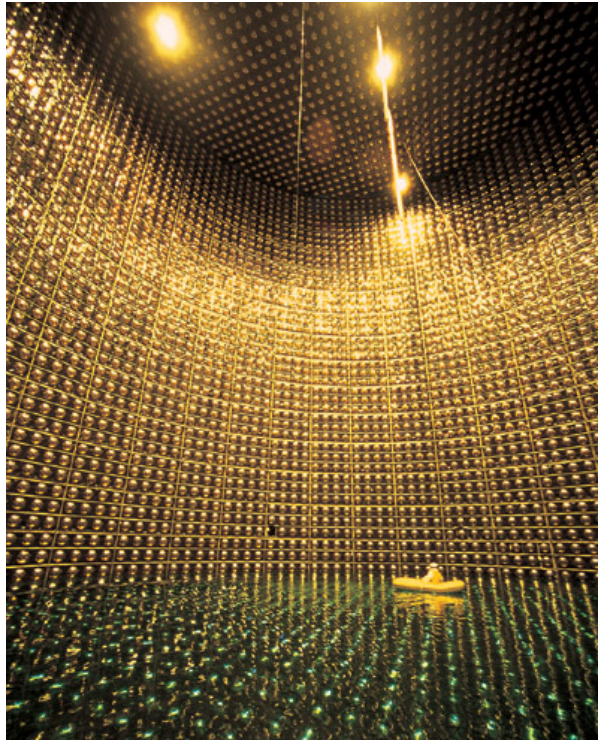
→ anomalous neutrino oscillation results

Neutrino oscillation experiments

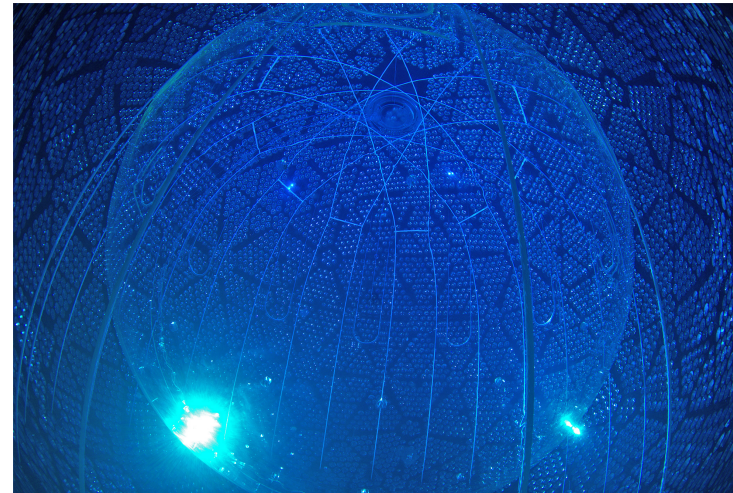
Neutrino physics → Home of anomalies

- Solar and atmospheric neutrino anomalies (Nobel prizes, 2002, 2015)

Super-Kamiokande detector



SNO detector



The Nobel Prize in Physics 2015



Photo © Takaaki Kajita
Takaaki Kajita
Prize share: 1/2



Photo: K. McFarlane,
Queen's University
/SNOLAB
Arthur B. McDonald
Prize share: 1/2



The Nobel Prize in Physics 2002



Raymond Davis Jr.
Prize share: 1/4



Masatoshi Koshihara
Prize share: 1/4



The Nobel Prize in Physics 1988



Leon M. Lederman
Prize share: 1/3



Melvin Schwartz
Prize share: 1/3



Jack Steinberger
Prize share: 1/3



The Nobel Prize in Physics 1995



Frederick Reines
Prize share: 1/2



Raymond Davis Jr.
Prize share: 1/2

Neutrino oscillation experiments

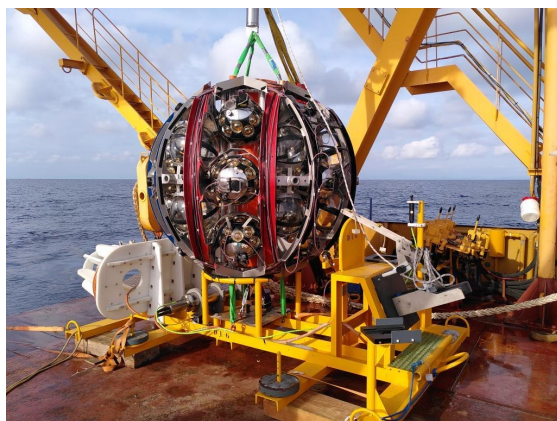
Neutrino physics → Home of anomalies

- ~~Solar and atmospheric neutrino anomalies~~ (Nobel prizes, 2002, 2015)
- OPERA Neutrino-faster-than-Speed-of-Light

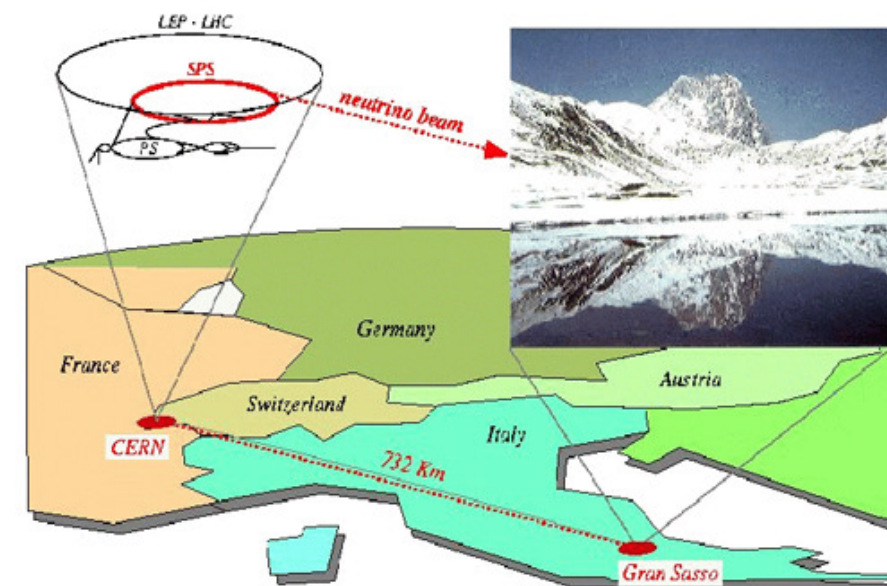
$$\delta \equiv c_v^2 - 1 \sim 5 \times 10^{-5}$$

KM3NeT 220 PeV neutrino (KM3-230213A)

$$\delta \equiv c_v^2 - 1 < 4 \times 10^{-22}$$



CERN to Gran Sasso Neutrino Beam

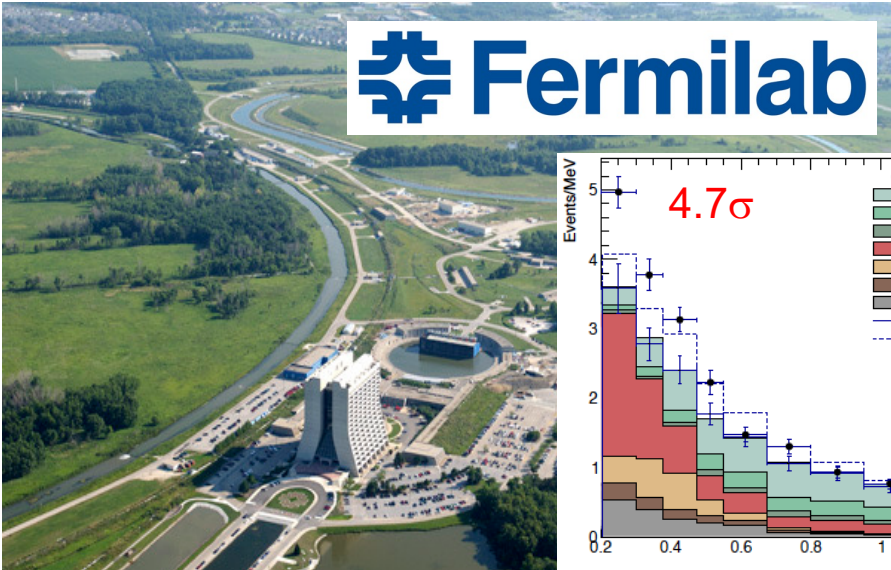
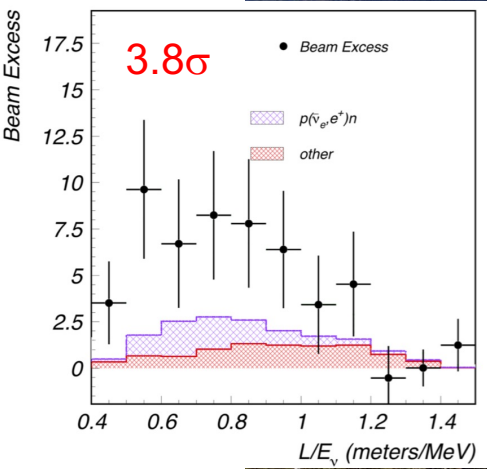


Neutrino oscillation experiments

Neutrino physics → Home of anomalies

- ~~Solar and atmospheric neutrino anomalies~~ (Nobel prizes, 2002, 2015)
- ~~OPERA Neutrino faster than Speed of Light~~ (detector problem)
- LSND excess
- MiniBooNE excess

LSND excess



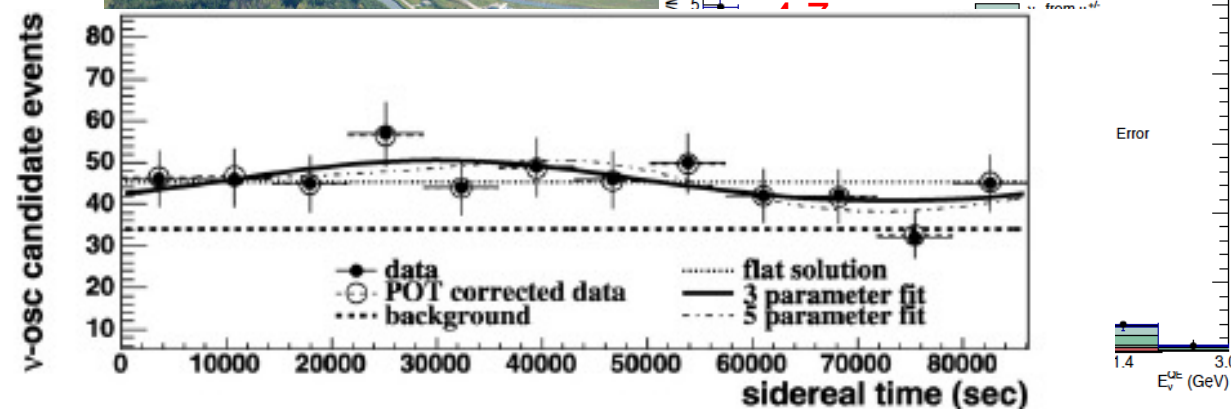
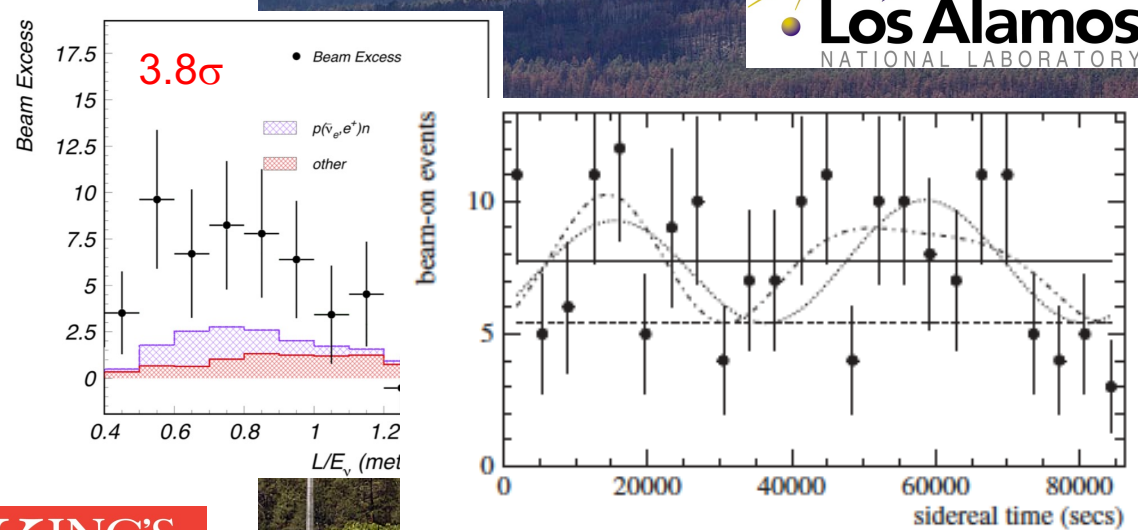
If these anomalous neutrino oscillation data are due to Lorentz violation, data may show sidereal time dependence

Neutrino oscillation experiments

Neutrino physics → Home of anomalies

- ~~Solar and atmospheric neutrino anomalies~~ (Nobel prizes, 2002, 2015)
- ~~OPERA Neutrino faster than Speed of Light~~ (detector problem)
- ~~LSND excess~~ (not Lorentz violation)
- ~~MiniBooNE excess~~ (not Lorentz violation)

LSND excess



MiniBooNE excess

Lorentz violation cannot explain these excesses simultaneously

Tests of Lorentz violation – Summary

Limits of SME parameters are summarized in tables

<https://arxiv.org/abs/0801.0287v17>

So far, there is no compelling evidence of Lorentz violation

Table D15. Photon sector, $d = 3$

Combination	Result	System	Ref.
$ k_{(V)00}^{(3)} $	$(7.32 \pm 2.94) \times 10^{-45}$ GeV	CMB polarization	[131], [132]*
$ k_{(V)00}^{(3)} $	$< 1.54 \times 10^{-44}$ GeV	"	[133]*
$ k_{AF} $	$< 7.4 \times 10^{-45}$ GeV	"	[133]*
$ k_{AF} $	$< 1.03 \times 10^{-26}$ GeV	Satellites	[134]*
k_{AF}^Z			[134]*

Table D10. Proton sector, $d = 4$ (part 2 of 2)

Combination	Result	System	Ref.
$ k_{(V)10}^{(3)} $			[75]*
$ k_{(V)11}^{(3)} $			[75]*
$k_{(V)10}^{(3)}$			[75]*
$ \tilde{c}_{0k}^p $	$< 1 \times 10^{-8}$	Binary pulsars	[75]*
$ \tilde{c}_{jk}^p $	$< 1 \times 10^{-11}$	"	[75]*
$ \tilde{c}_Q $	$< 2 \times 10^{-11}$ GeV	Relativistic Li ions	[72]
$\tilde{c}_{TT}$	$(0.24 \pm 0.30) \times 10^{-6}$	Nuclear binding energy	[76]
"	$(-3.3 \pm 3.5) \times 10^{-6}$	Cs interferometer	[77]
$\tilde{c}_Q$	$(-0.3 \pm 2.2) \times 10^{-22}$ GeV	Cs fountain	[105]
$\tilde{c}_-$	$(-1.8 \pm 2.8) \times 10^{-25}$ GeV	"	[105]

Table D32. Neutrino sector, $d = 4$ (part 1 of 13)

Combination	Result	System	Ref.
$(c_{\text{of}}^{(4)})_{00}$	$> -4 \times 10^{-19}$	IceCube	[275]*
$ (c_{\text{of}}^{(4)})_{00} $	$< 7.1 \times 10^{-9}$	SN1987A time of flight	[18]*
"	$< 1.4 \times 10^{-4}$	Fermilab time of flight	[18]*
$(c_{\text{of}}^{(4)})_{00}$	$-8.4 \pm 1.1^{+1.2}_{-0.9} \times 10^{-5}$	OPERA time of flight	[18]*
"	$-1.8 \pm 1.0 \times 10^{-4}$	MINOS time of flight	[18]*
$(c_{\text{of}}^{(4)})_{10}$	$(-1 \text{ to } 4) \times 10^{-17}$	IceCube	[275]*
$ (c_{\text{of}}^{(4)})_{10} $	$< 4.4 \times 10^{-9}$	SN1987A time of flight	[18]*

Table D12. Neutron sector, $d = 3, 4$ (part 2 of 2)

Result	System	Ref.
$< (3 \pm 27 \pm 27) \times 10^{-14}$	Macroscopic matter	[123]*
$< 1 \times 10^{-8}$	Binary pulsars	[75]*
$< 1 \times 10^{-11}$	"	[75]*
$(-4 \pm 6) \times 10^{-6}$	Gravimetry	[124]*
$(-1 \pm 1) \times 10^{-5}$	"	[124]*
$(-1 \pm 1) \times 10^{-5}$	"	[124]*
$(-1.8 \pm 2.2) \times 10^{-14}$ GeV	Quartz oscillators	[125]
$(1.1 \pm 1.4) \times 10^{-6}$	Nuclear binding energy	[76]
$(7.6 \pm 6.7) \times 10^{-6}$	Cs interferometer	[77]
$(4.8 \pm 4.4) \times 10^{-29}$	Ne/Rb/K magnetometer	[107]
$(-2.8 \pm 3.4) \times 10^{-29}$	"	[107]

When do we find Lorentz violation???

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

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

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

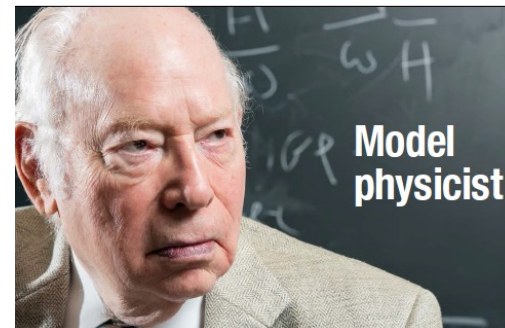
dimension-5 LV operator, $a^{(5)} < 10^{-19} \text{ GeV}^{-1}$

dimension-6 LV operator, $c^{(6)} < 10^{-38} \text{ GeV}^{-2}$

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 – Astrophysics

Terrestrial experiments

- controlled, high-precision
- various systems (optics, pendulum, gas, particle physics, etc)

So far, no compelling evidence of Lorentz violation

Astrophysical and cosmological experiments

- not controlled, low-precision
- extreme systems (highest energy, longest distance, etc)
- **more sensitive to nonrenormalizable operators**

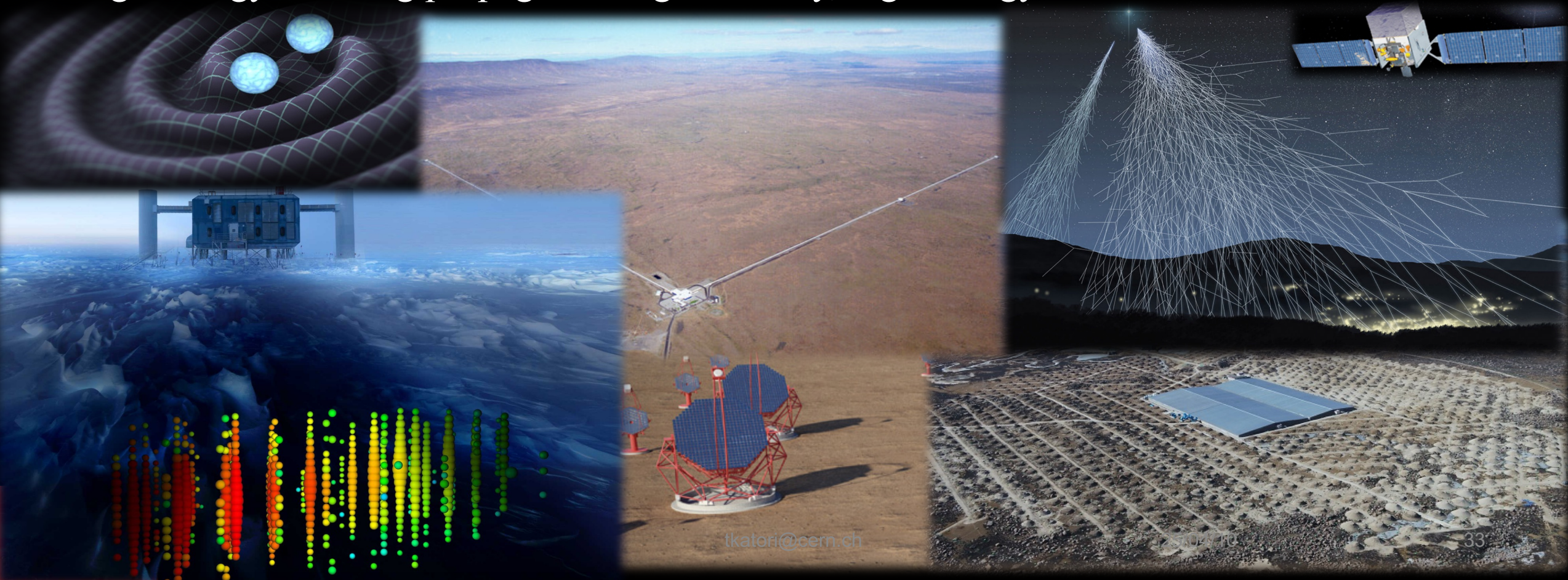
Tests of Lorentz violation in Astrophysics

Lorentz violation in Astrophysics

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

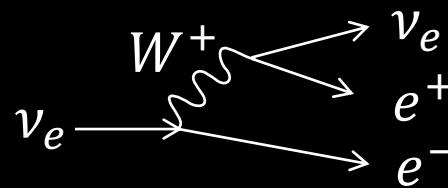


Cut-off in high-energy cosmic ray spectrum

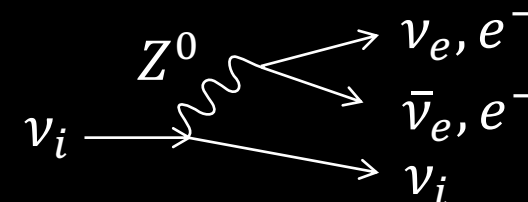
Lorentz violation = media in vacuum

- Attenuate high-energy cosmic rays

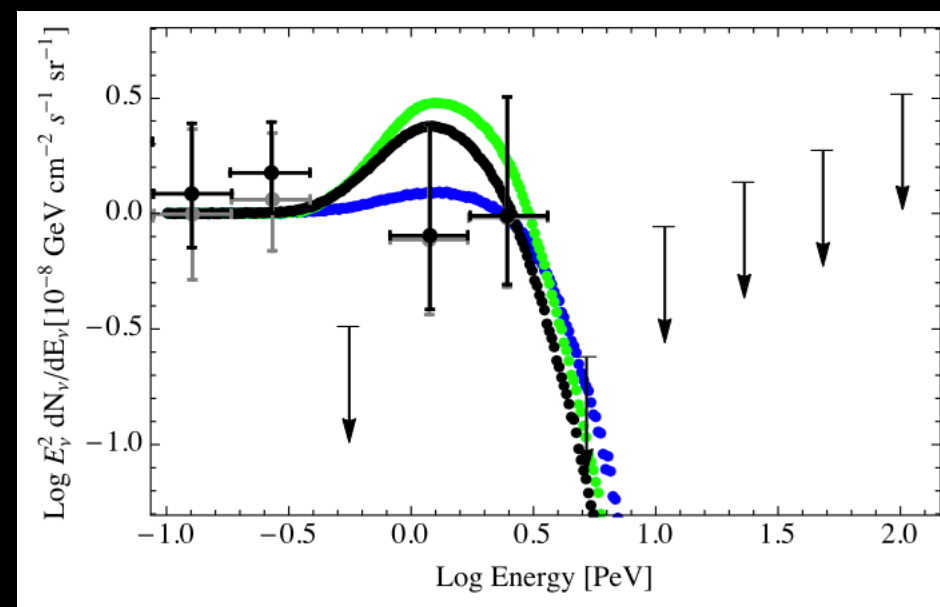
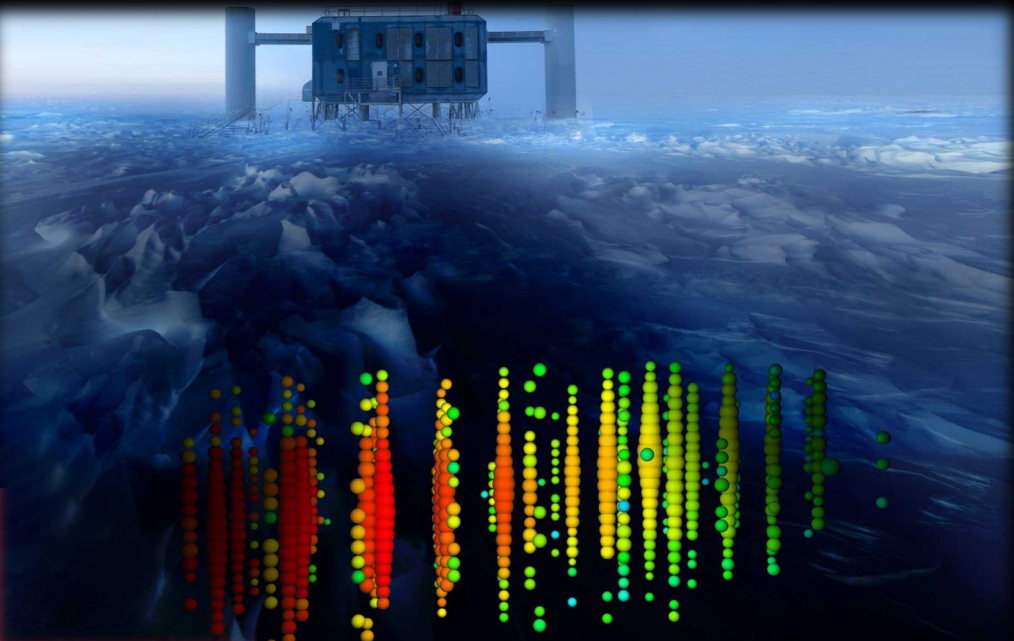
$$E^2 = p^2 + m^2 + a^{(5)}E^3 + c^{(6)}E^4 + \dots$$



Vacuum pair emission



Neutrino splitting



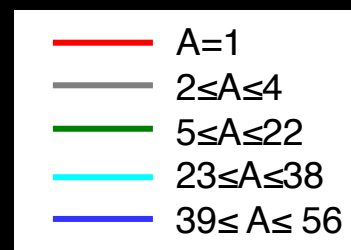
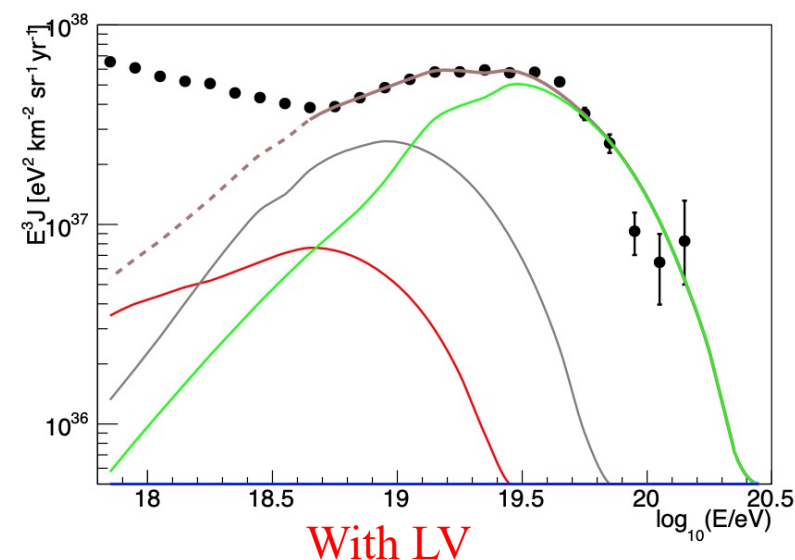
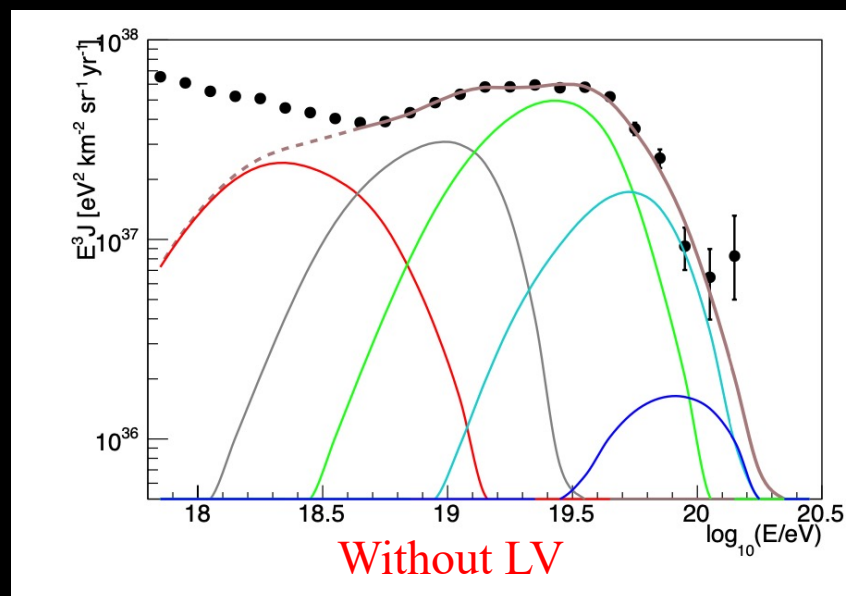
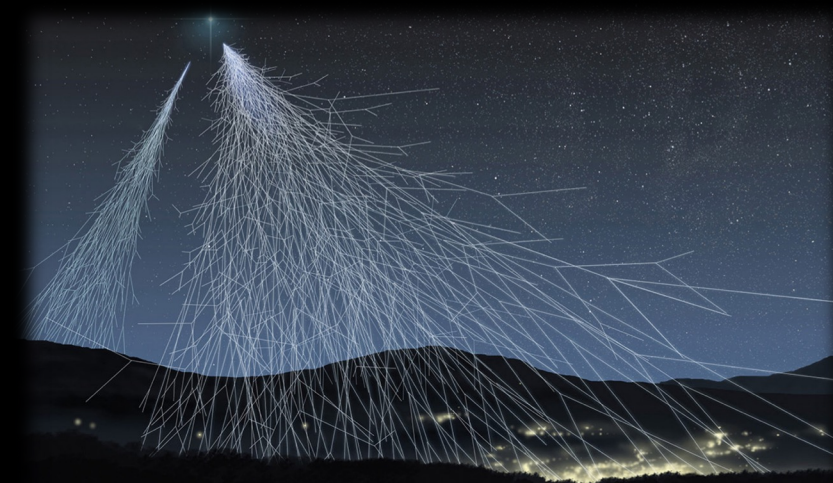
IceCube High-energy neutrino spectrum

Cut-off in high-energy cosmic ray spectrum

Lorentz violation = media in vacuum

- Attenuate high-energy cosmic rays

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



Auger UHECR spectrum

Time-of-flight of high-energy cosmic rays

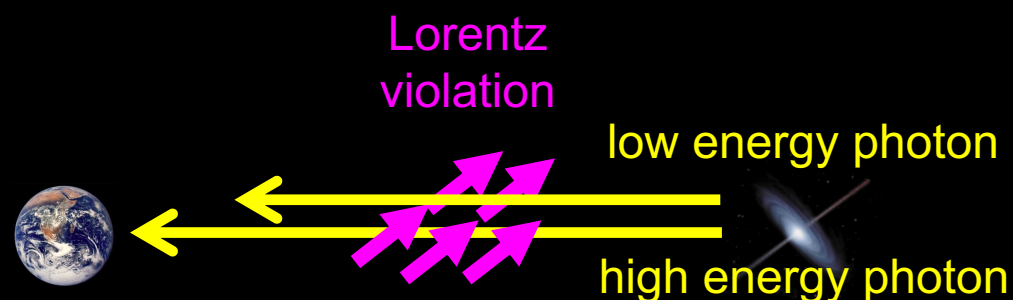
Lorentz violation = media in vacuum

- Anomalous time dependent effects

Gamma Ray Bursts

- Energy dependent light curve distortion

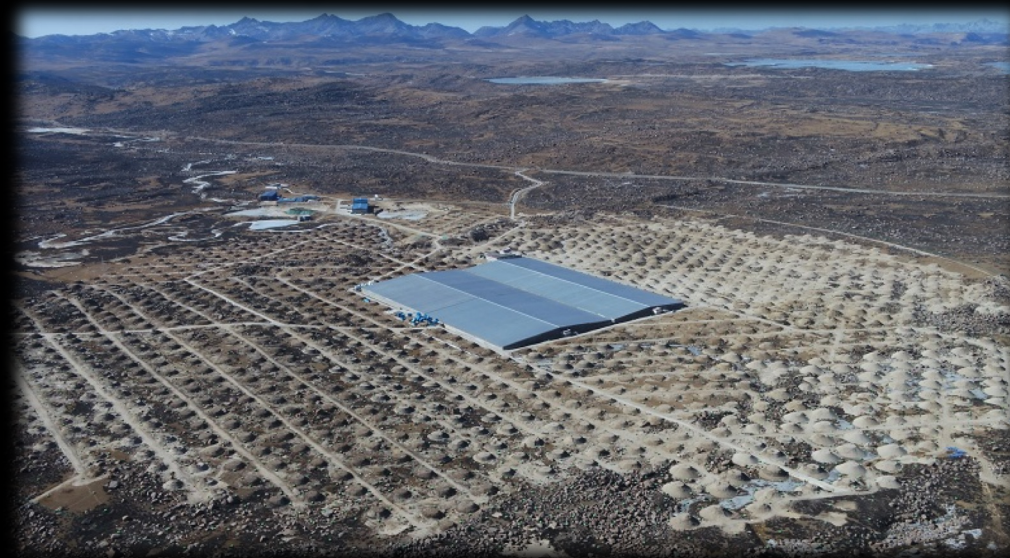
$$\delta v \sim E k_{00}^{(5)} + E^2 c_{00}^{(6)} + \dots$$



Tests of quantum gravity from observations of γ -ray bursts

G. Amelino-Camelia, John Ellis, N. E. Mavromatos,
D. V. Nanopoulos & Subir Sarkar

Nature 393, 763–765 (1998)



Time-of-flight of high-energy cosmic rays

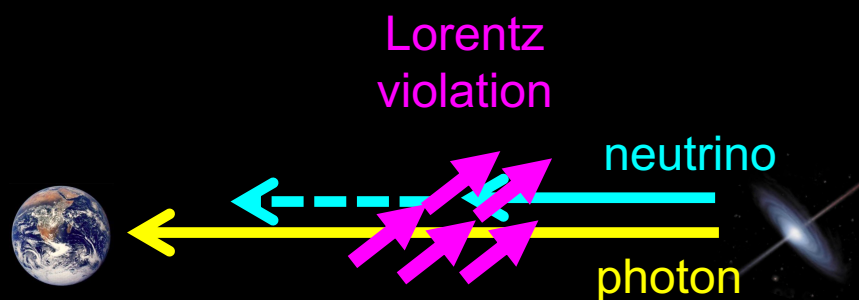
Lorentz violation = media in vacuum

- Anomalous time dependent effects

Gamma Ray Bursts

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

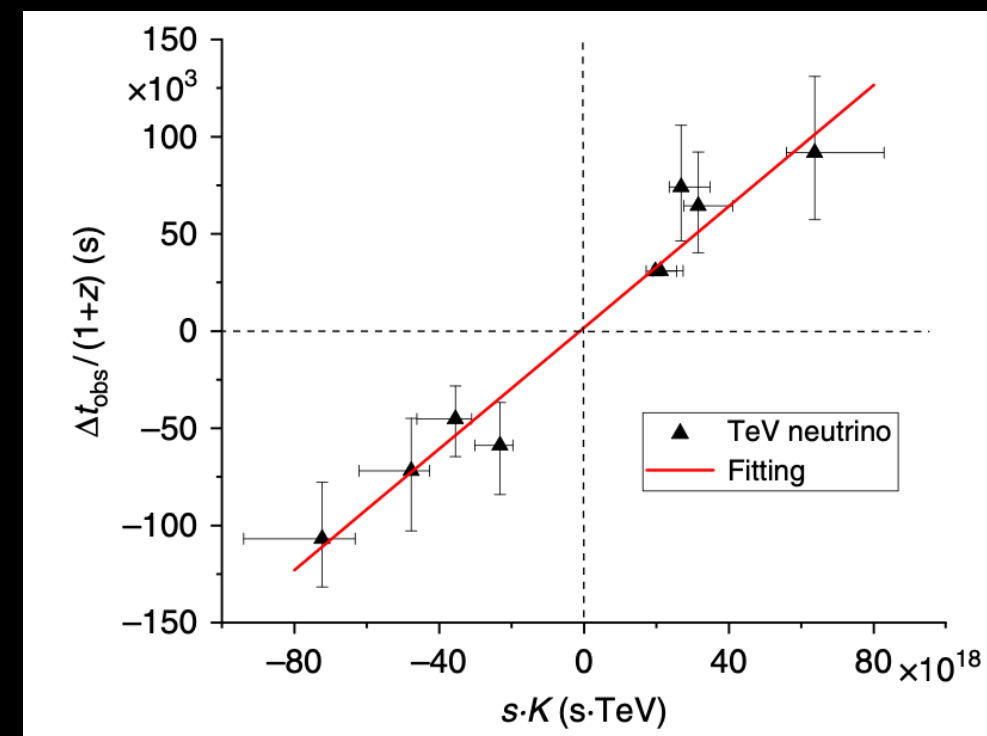
$$\delta v \sim E a^{(5)} + E^2 c^{(6)} + \dots$$



Could quantum gravity slow down neutrinos?

[Giovanni Amelino-Camelia](#) , [Maria Grazia Di Luca](#), [Giulia Gubitosi](#), [Giacomo Rosati](#)
& [Giacomo D'Amico](#)

[Nature Astronomy](#) 7, 996–1001 (2023) | [Cite this article](#)



IceCube-GRB coincidence candidates with Lorentz violation

Gravity sector

Lorentz Violation ~ quantum gravity phenomenology

- New focus (EFT is difficult for gravity)

LIGO-VIRGO

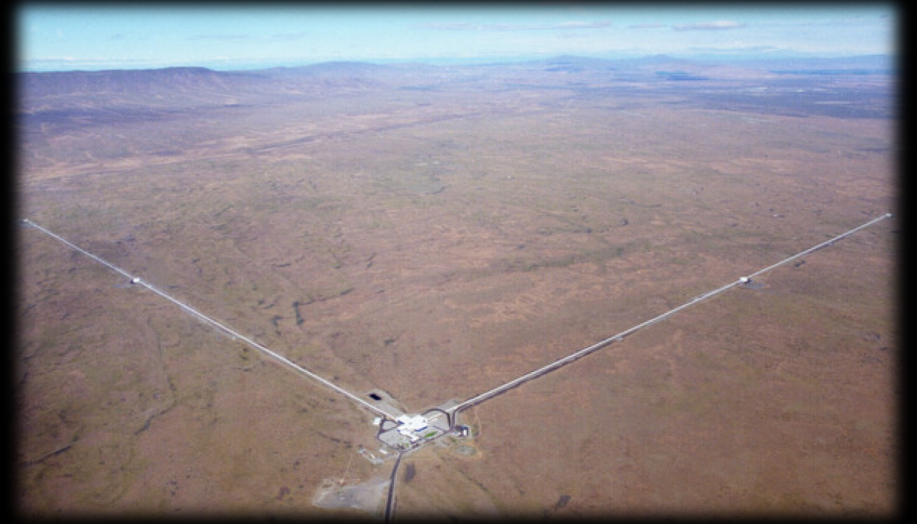
- Gravitational waves [LIGO, Virgo, Fermi, INTEGRAL, 2017 ApJL 848 L13](#)
- Michelson-Morley interferometer [PLB761\(2016\)1](#)

Cosmic rays

- Gravitational Cherenkov radiation [PLB 749 \(2015\) 551](#)

Terrestrial experiments

- Matter wave interferometer [PRL100\(2008\)031101](#) and many others



Vacuum birefringence

Lorentz violation = media in vacuum
→ Additional source of polarization

GRB polarization [PRL110, 201601 \(2013\)](#) and others
- Strong sensitivity on higher dimension operators

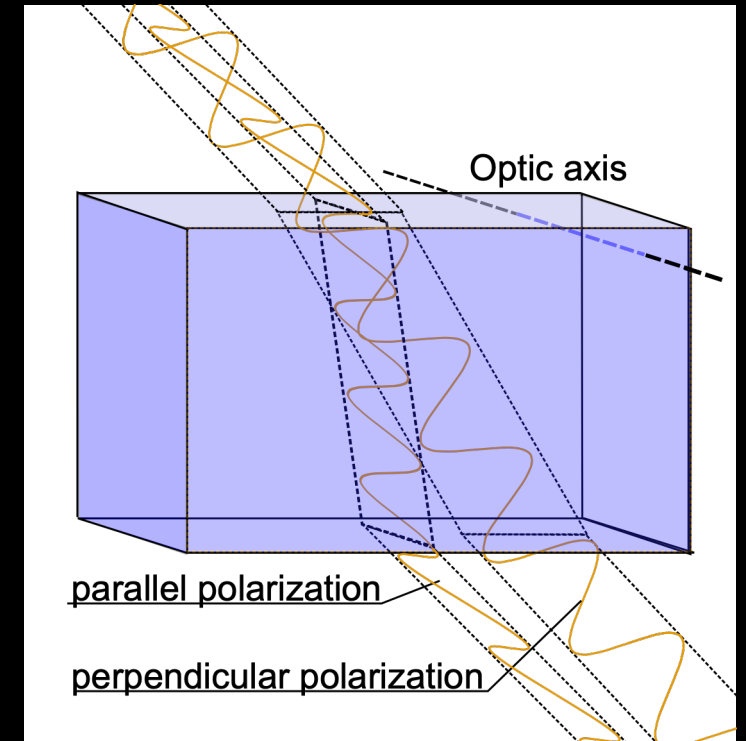
CMB polarization [PRL125 \(2020\) 22, 221301](#)
- The longest distance
- Strongest sensitivity to dimension-3 operator
- Mild tension? (2.4σ)

New Extraction of the Cosmic Birefringence from the Planck 2018 Polarization Data

Yuto Minami^{*}

High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Eiichiro Komatsu[†]



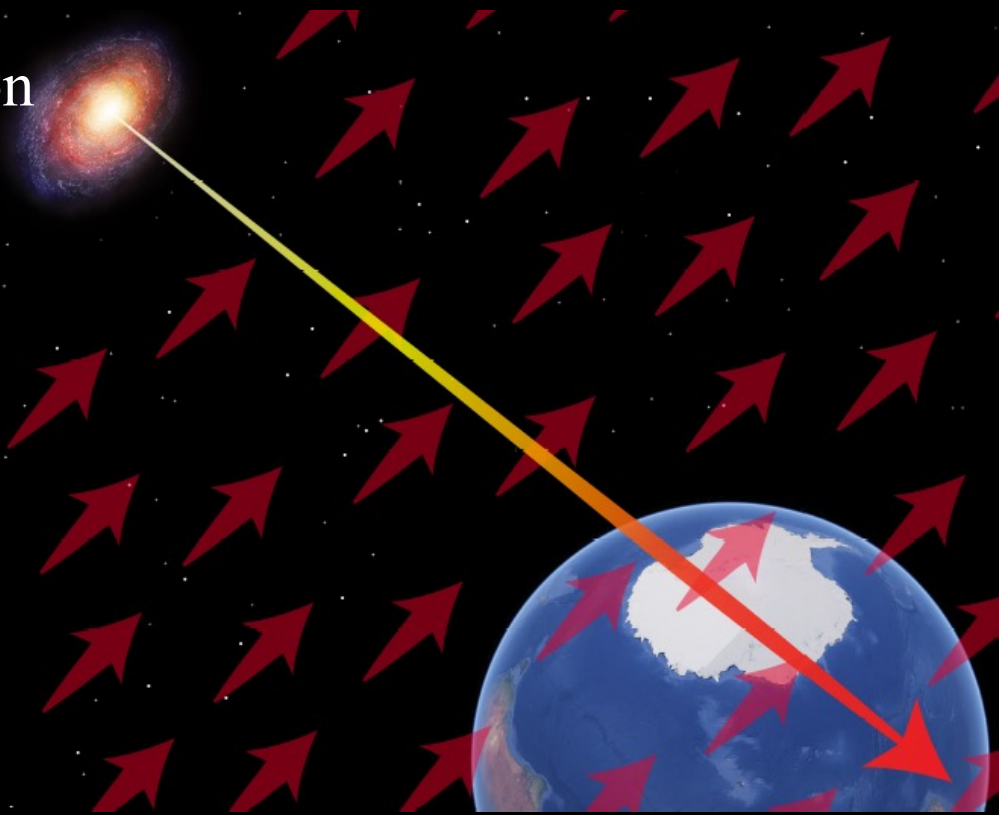
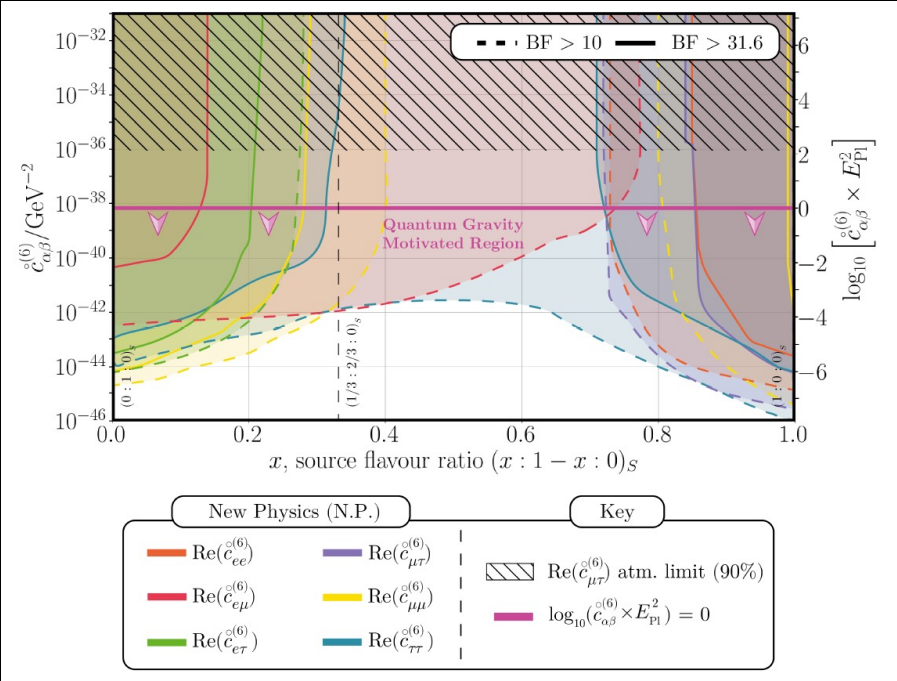
Anomalous neutrino flavour

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

Sensitive to the target signal region of Lorentz violation
($< 10^{-38} \text{ GeV}^{-2}$ for dimension-6 operators)

No Lorentz violation
discovered

Sensitivity is neutrino
production model
dependent



High-energy, long propagating neutrinos

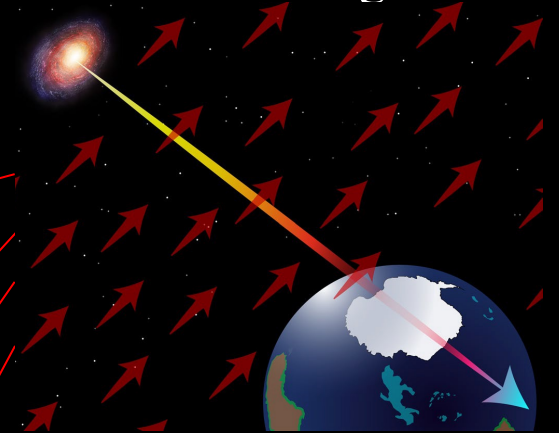


Physics MMA

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

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

Astrophysical neutrino flavour mixing



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



torsion pendulum



optical resonator



comagnetometer



vacuum birefringence



UHECRs

dim.	method	type	sector	limits	ref.
$\frac{1}{a^{(3)}}$	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]
$\frac{1}{c^{(4)}}$	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]
$\frac{1}{a^{(5)}}$	neutrino mixing	astrophysical	neutrino	$\sim 10^{-31}$	[1]
	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]
$\frac{1}{c^{(6)}}$	neutrino mixing	astrophysical	neutrino	$\sim 10^{-37}$ GeV ⁻¹	[1]
	GRB vacuum birefringence	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]

[1] IceCube, Nature Phys. 18, 1287 (2022) [2] WMAP, Astrophys.J. 180, 330 (2009) [3] Allmendinger et al., PRL 112, 110801 (2014) [4] Heckel et al., PRL 97, 021603(2006) [5] Muon g-2, PRL 100, 091602 (2008) [6] Kostelecký, Mewes, PRL 110, 201601 (2013) [7] Kostelecký, Melissinos, Mewes, PLB 761, 1 (2016) [8] Nagel et al., Nature Comm. 6, 8174(2015) [9] Smicklas et al., PRL 107, 171604 (2011) [10] Prutivarasin et al., Nature 517, 592 [11] Maccione et al., JCAP 0904, 022 [12] Kostelecký, Tasson, PLB 749, 551

Tests of Lorentz Violation in Astrophysics – Summary

Astrophysics has a high potential to look for Lorentz violation. But there are many unknowns;

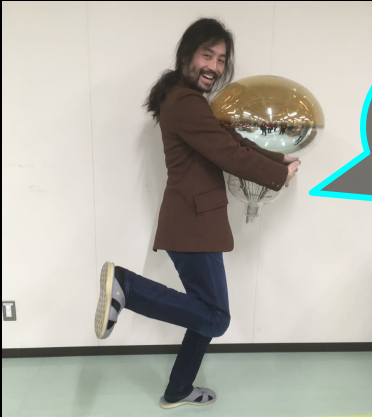
- Energy spectrum
- Production time
- Source information
- Foreground

etc

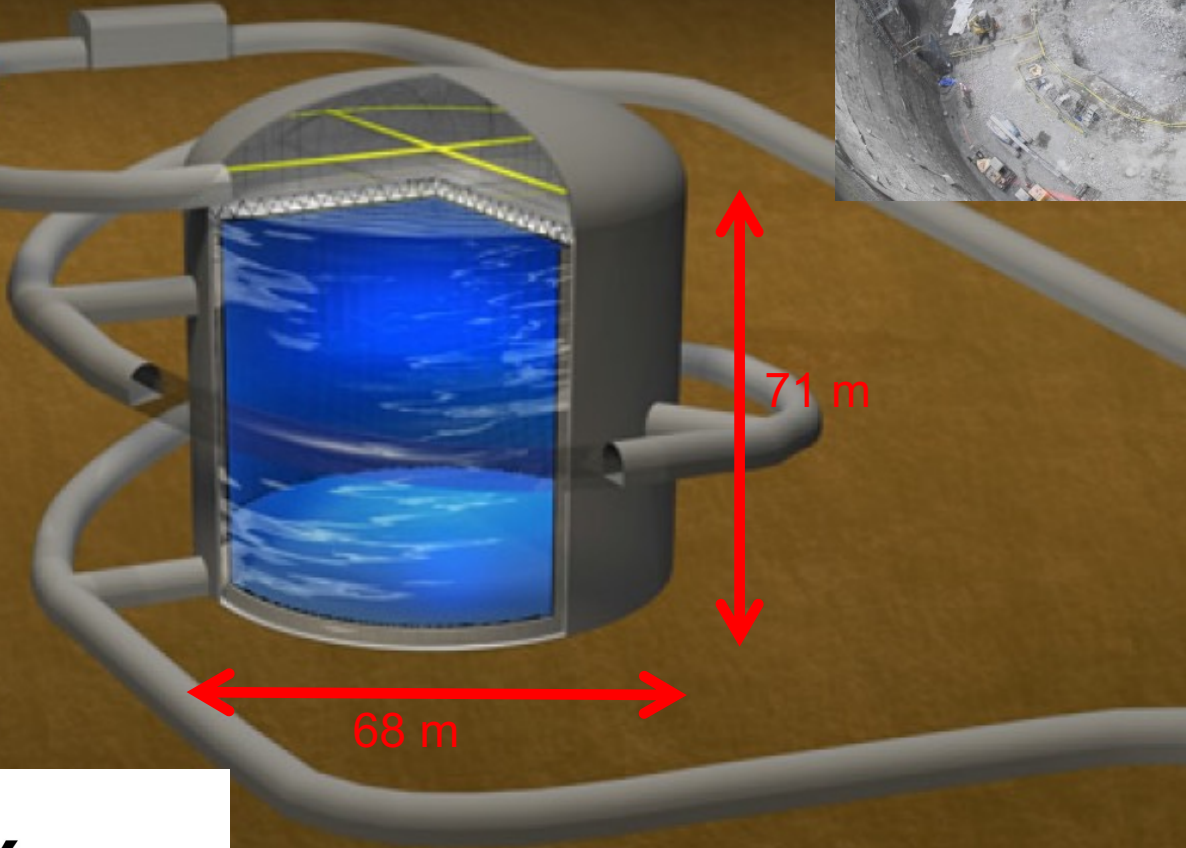
So far, astrophysical neutrino data are low statistics and further data are needed to search Lorentz violation...

Hyper-Kamiokande

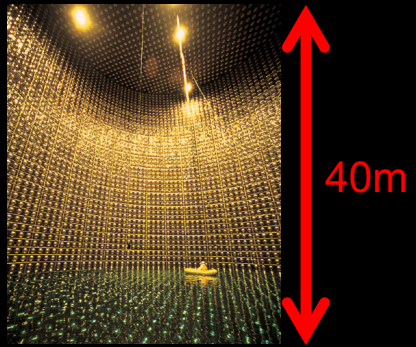
New international neutrino astronomy projects around the world



Hyper-K
construction
is ongoing

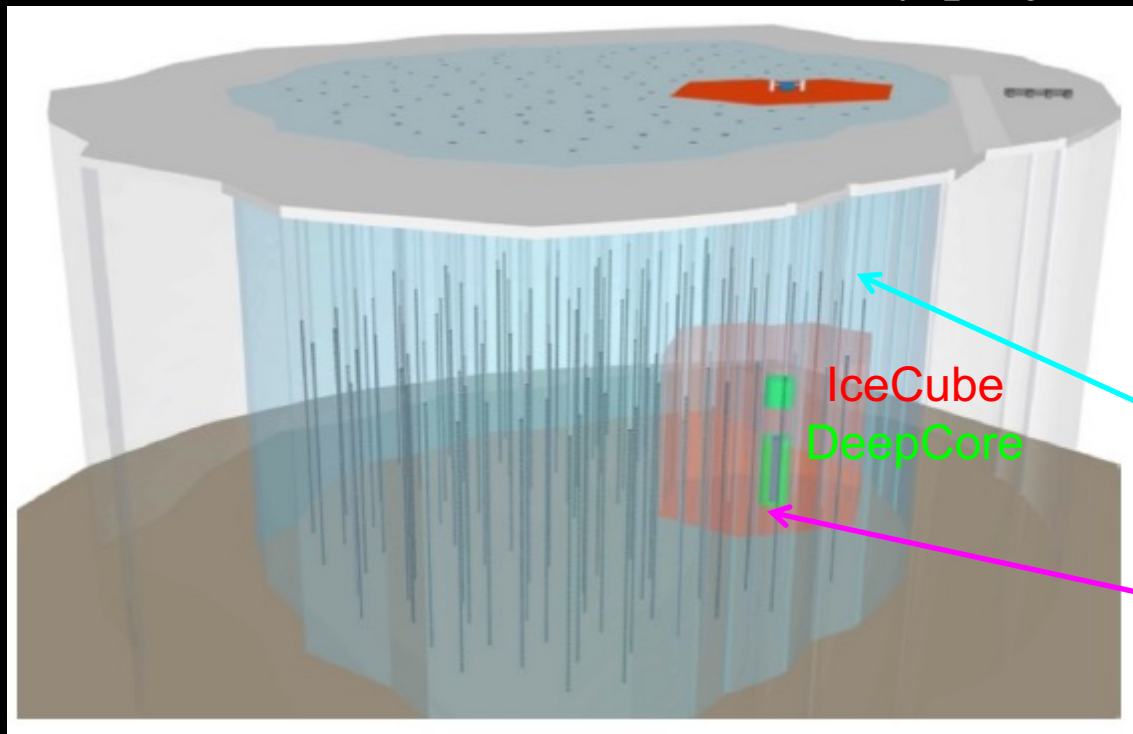


Super-Kamiokande



IceCube-Gen2

New international neutrino astronomy projects around the world



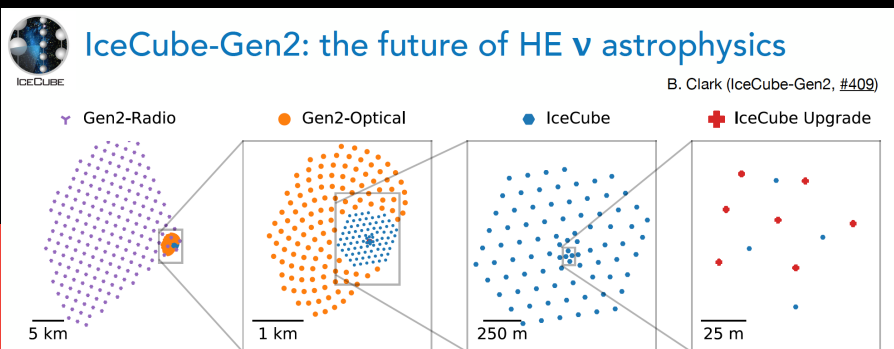
Summer 2024-2045 IceCube team

IceCube (~ 1 Gton)

Gen2-Optical (~ 8 Gton)

DeepCore (>7 GeV)

IceCube-Upgrade (>3 GeV)



The first stage of Gen2
(IceCube upgrade) is ongoing



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 observations are powerful tools to look for Lorentz violation

Thank you for your attention!



Backup

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](#)

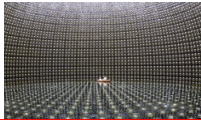
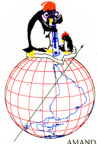
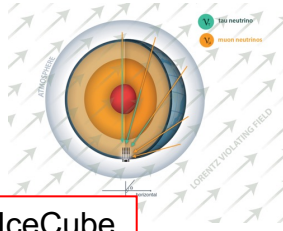
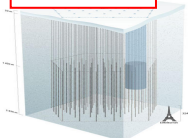
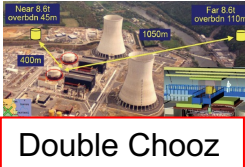
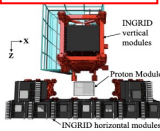
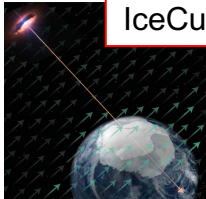
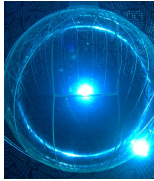
Lee-Wick theory, [Myers and Pospelov, PRL90 \(2003\) 211601](#)

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

Lorentz violation tests with neutrinos

Spectral distortion	Sidereal variation
 Super-Kamiokande PRD91(2015)052003  AMANDA PRD79(2009)102005  IceCube Nature Physics 14(2018)961	Daya Bay  PRD98(2018)092013  MINOS ND PRL101(2008)151601  IceCube PRD82(2010)112003  LSND PRD72(2005)076004  MINOS FD PRL105(2010)151601  Double Chooz PRD86(2013)112009  MiniBooNE PLB718(2013)1303  T2K ND PRD95(2017)111101
Flavor ratio	Seasonal variation
 IceCube Nature Physics, 18(2022)1287	SNO  PRD98(2018)112013

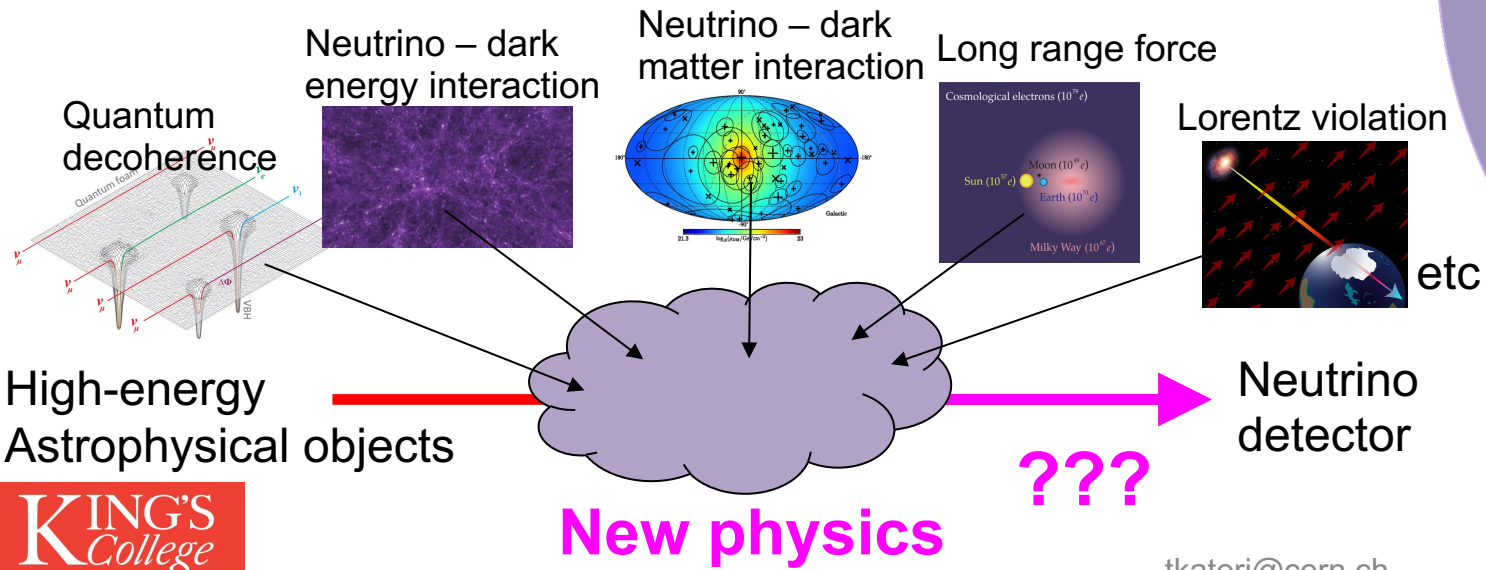
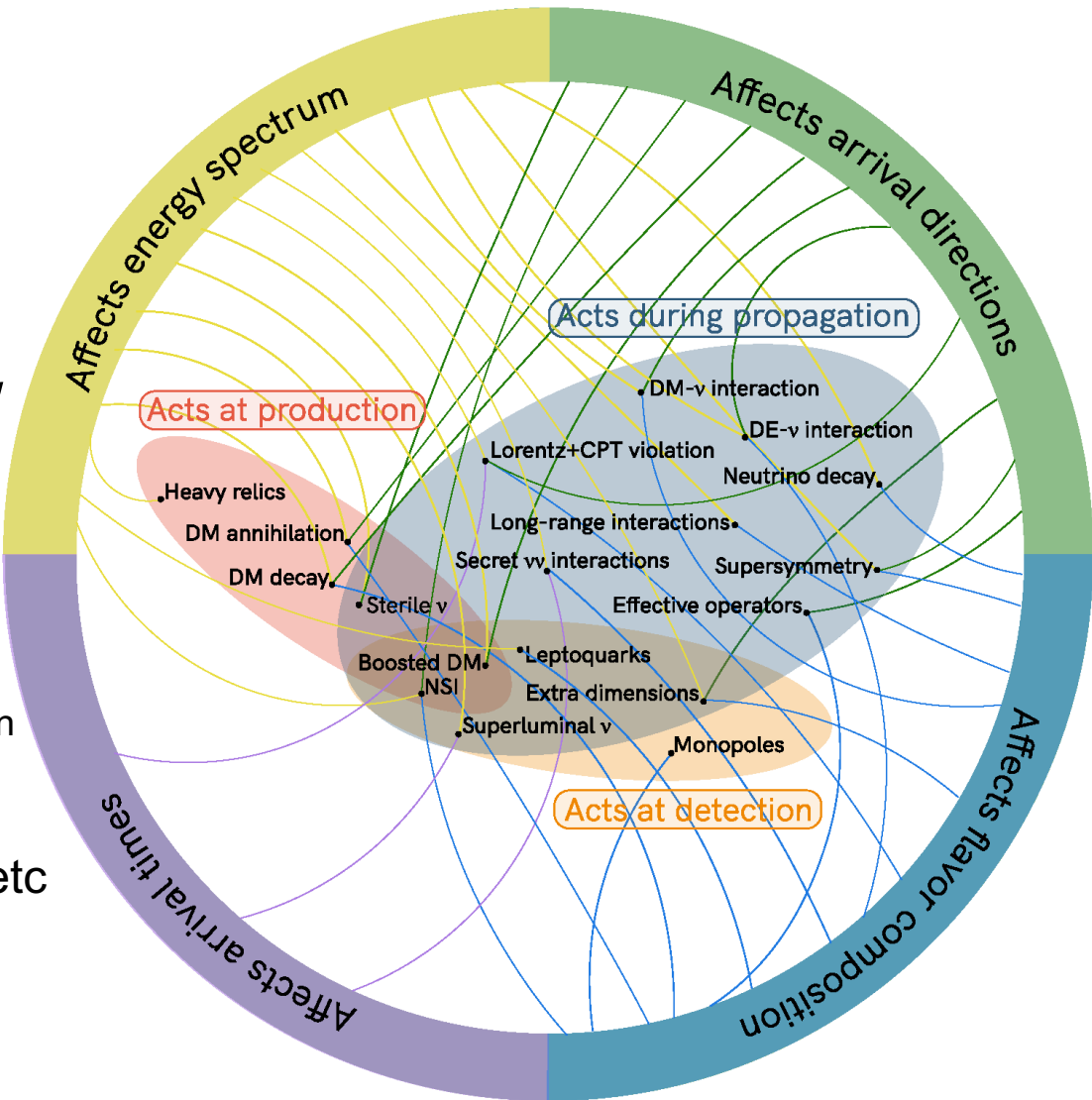
High-energy, long propagating neutrinos

High-energy astrophysical neutrinos

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

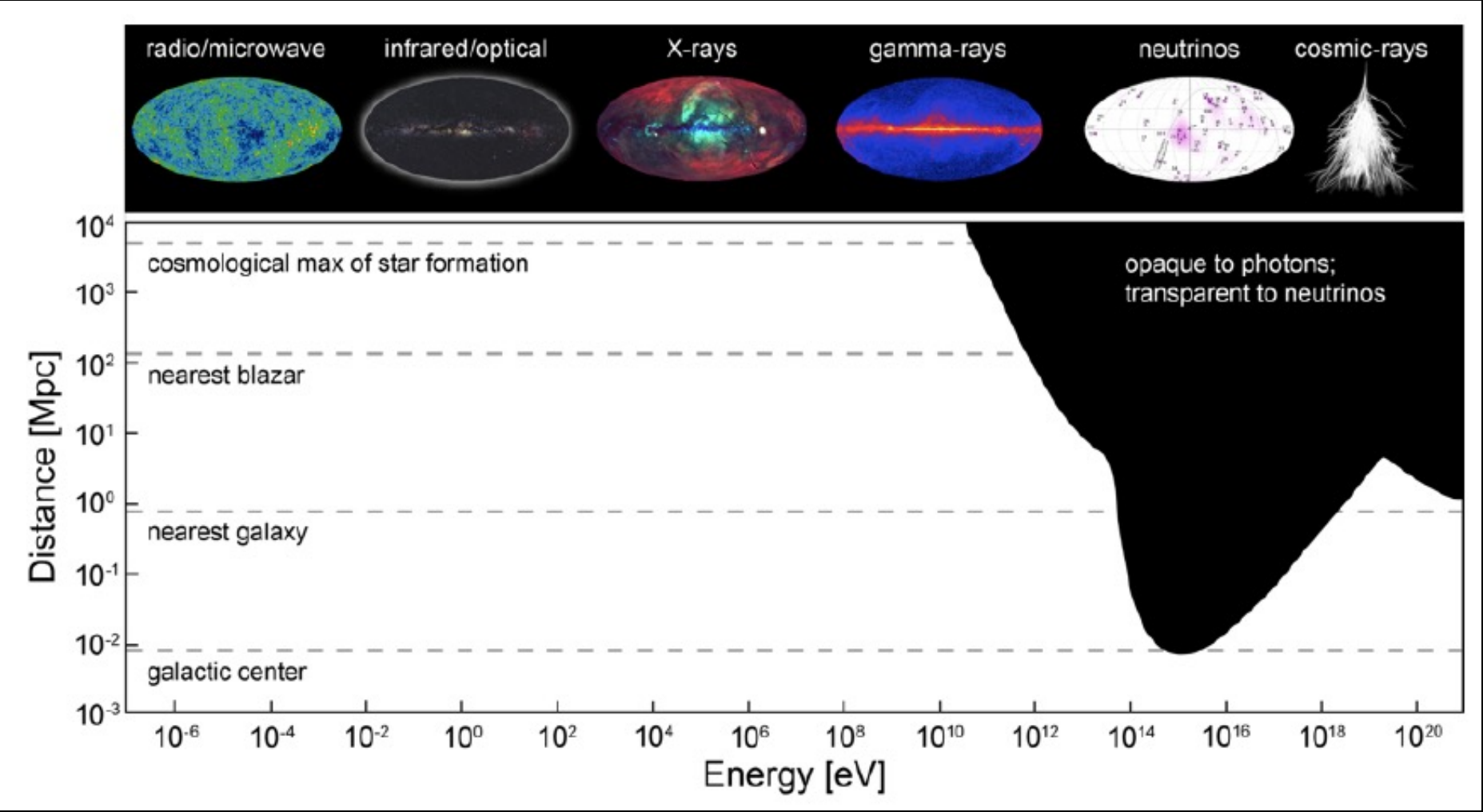
$$H \sim \frac{m^2}{2E} + V(\text{new physics}), P \sim V(\text{new physics}) \cdot L$$

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



High-energy astrophysical neutrinos

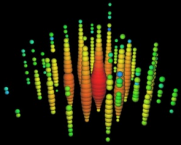
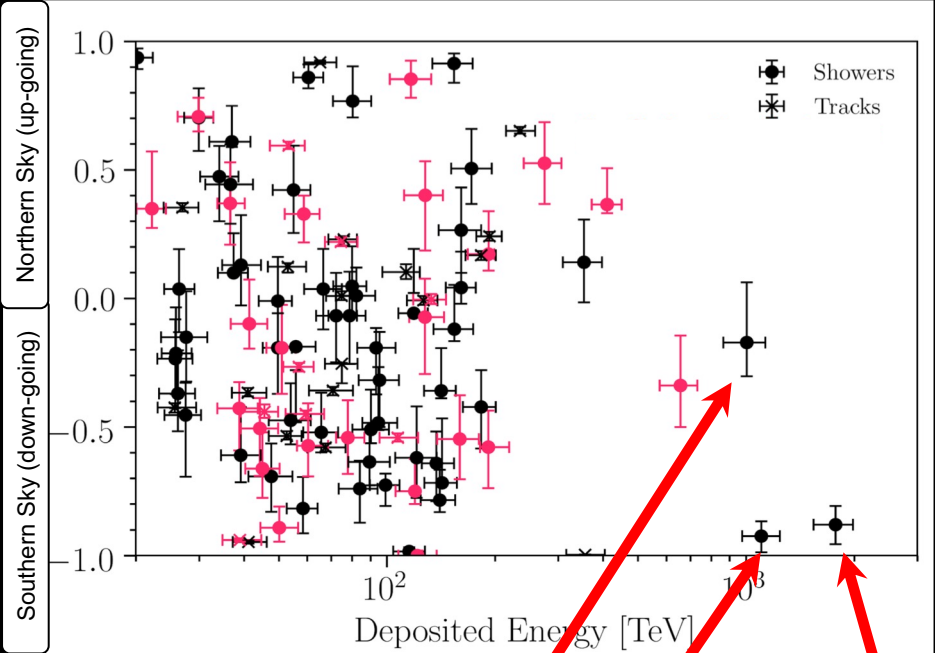
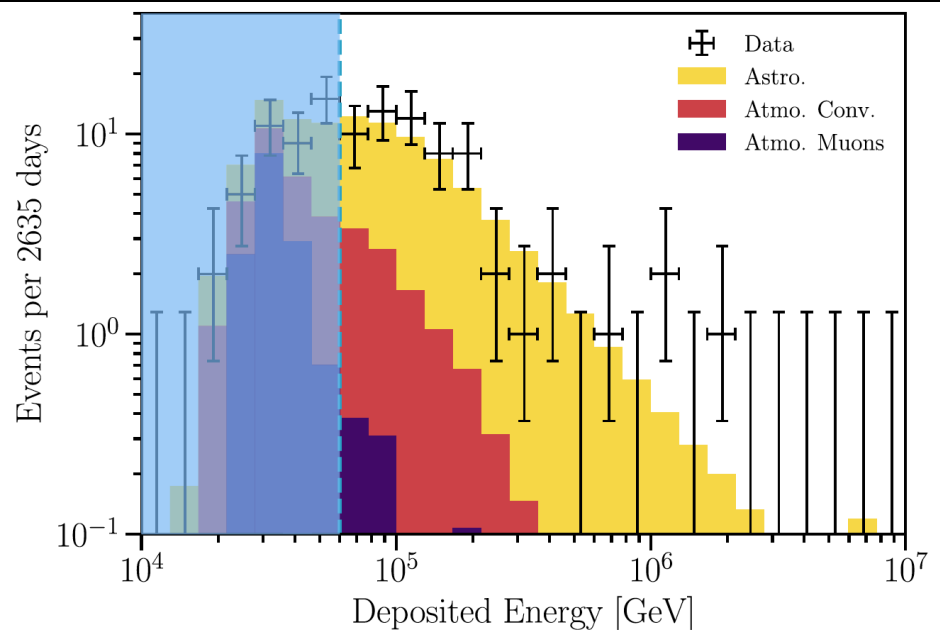
Above ~ 100 TeV, neutrinos are only particles pointing to their high-energy sources



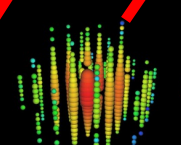
High-energy astrophysical neutrinos

60TeV- 2PeV astrophysical neutrinos are observed by IceCube Neutrino Observatory
high-energy starting event (HESE) sample

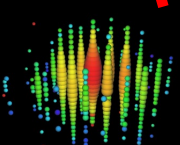
2. Hig



“Bert”
1.1 PeV



“Ernie”
1.0 PeV



“Big Bird”
2.0 PeV

25/04/10

IceCube event morphology

Track

ν_μ CC

$$\nu_\mu + N \rightarrow \mu + X$$

Cascade

ν_e CC, ν_τ CC, NC

$$\nu_e + N \rightarrow e + X$$

$$\nu_\tau + N \rightarrow \tau + X$$

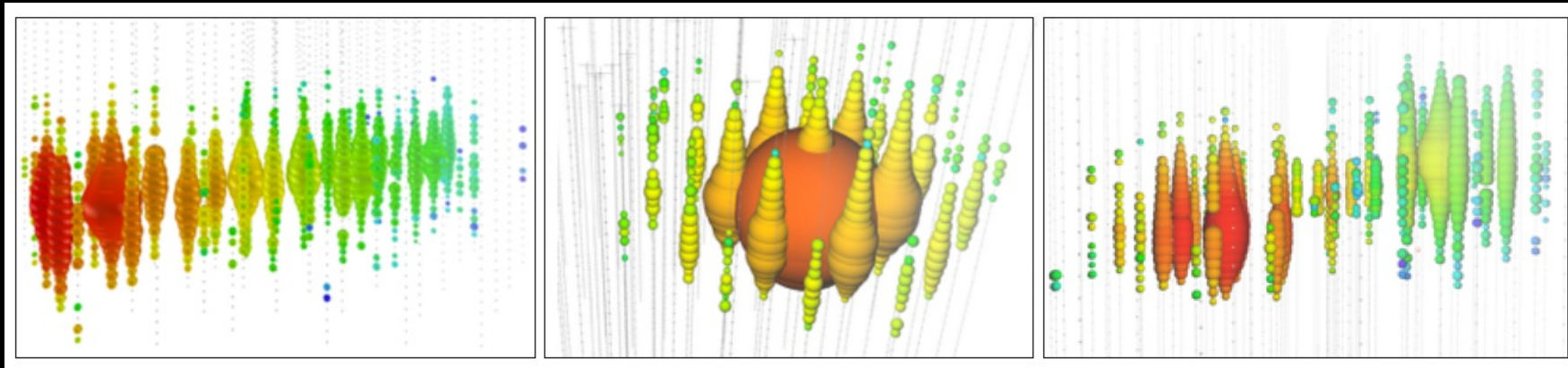
$$\nu_x + N \rightarrow \nu_x + X$$

Double cascade

ν_τ CC ($L \sim 50 \text{m} \cdot E/\text{PeV}$)

$$\nu_\tau + N \rightarrow \tau + X$$

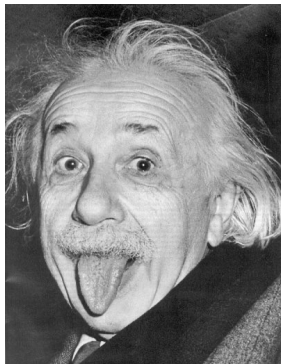
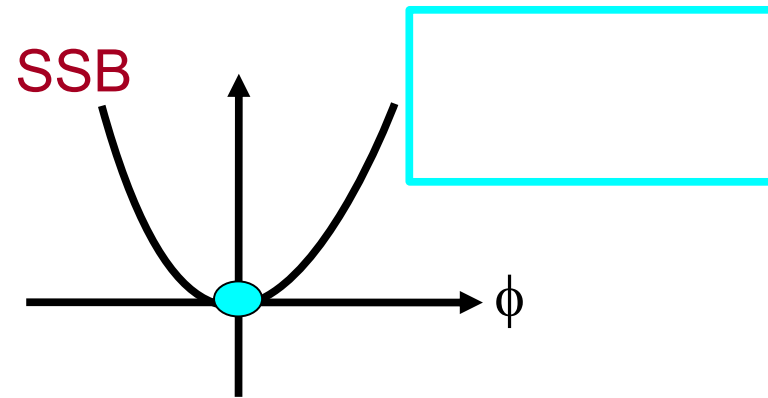
$$\tau \rightarrow X'$$



Spontaneous symmetry breaking (SSB)

$$\text{vacuum Lagrangian for fermion } L = i\bar{\psi}\gamma_{\mu}\partial^{\mu}\psi$$

In the Standard Model, a phase transition of a scalar field gives nonzero field value in vacuum

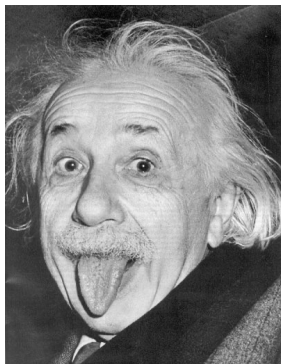
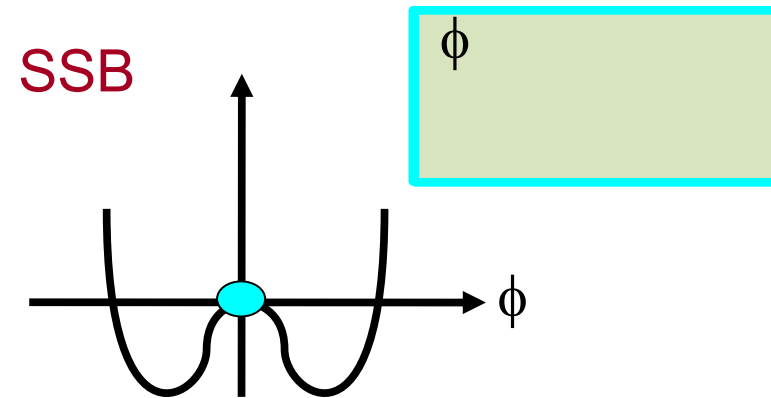


$$L = \frac{1}{2}(\partial_{\mu}\phi)^2 - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4$$

Spontaneous symmetry breaking (SSB)

vacuum Lagrangian for fermion $L = i\bar{\psi}\gamma_{\mu}\partial^{\mu}\psi - m\bar{\psi}\psi$

In the Standard Model, a phase transition of a scalar field gives nonzero field value in vacuum



Particle acquires mass term!

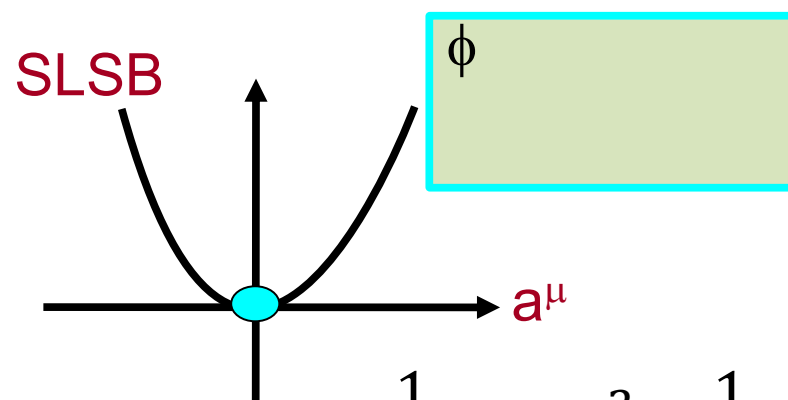
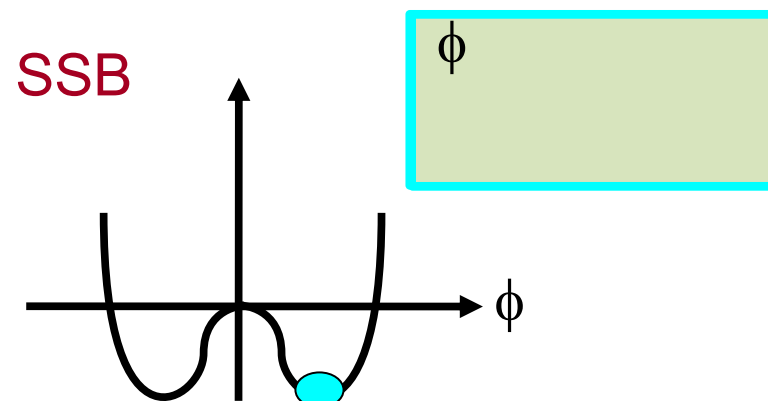
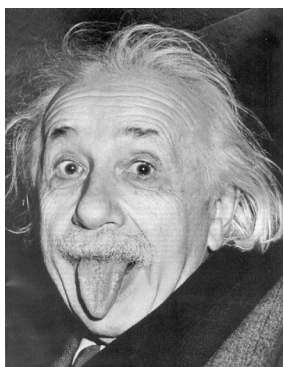
$$L = \frac{1}{2}(\partial_{\mu}\phi)^2 - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4$$

Spontaneous Lorentz symmetry breaking (SLSB)

$$\text{vacuum Lagrangian for fermion } L = i\bar{\psi}\gamma_{\mu}\partial^{\mu}\psi - m\bar{\psi}\psi$$

In the Standard Model, a phase transition of a scalar field gives nonzero field value in vacuum

In String Theory, a vector field can be frozen in vacuum by spontaneous symmetry broken



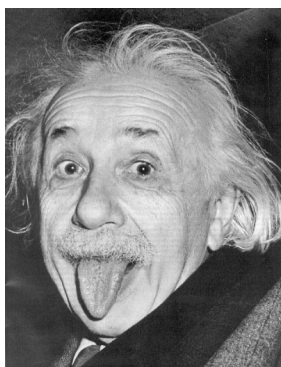
$$L = \frac{1}{2}(\partial_{\mu}\phi)^2 - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4$$

Spontaneous Lorentz symmetry breaking (SLSB)

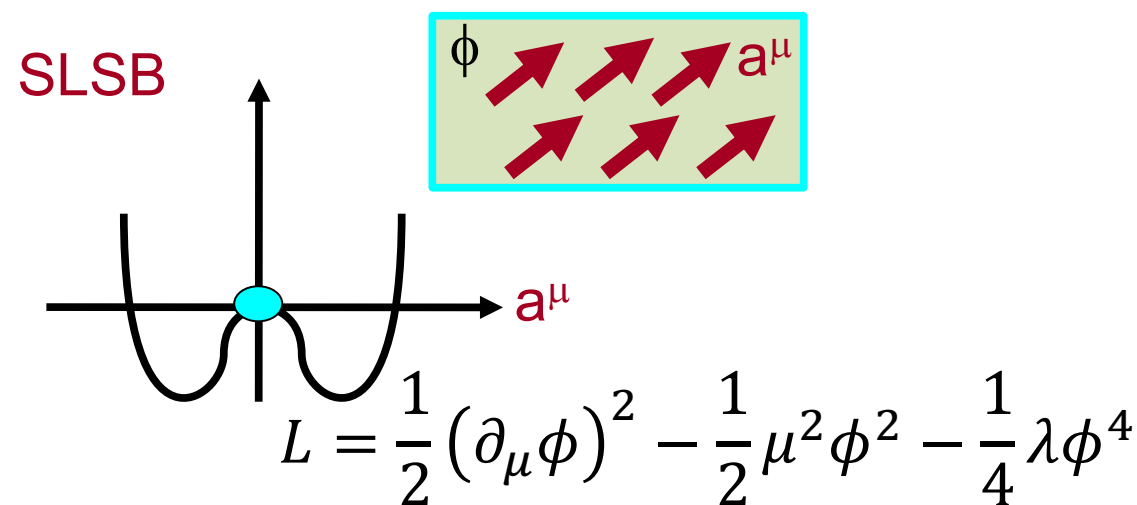
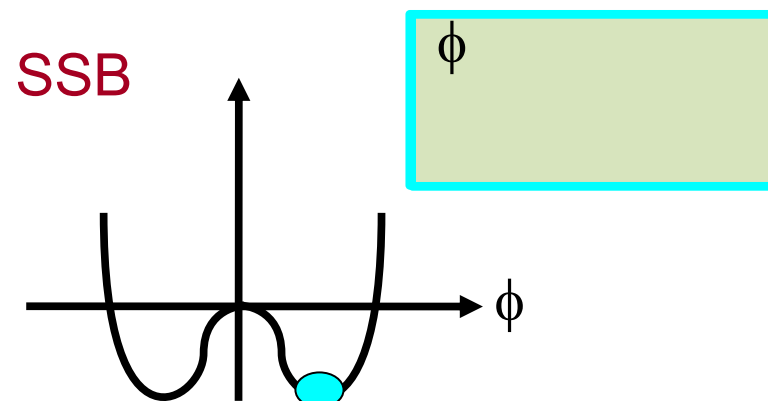
$$\text{vacuum Lagrangian for fermion } L = i\bar{\psi}\gamma_{\mu}\partial^{\mu}\psi - m\bar{\psi}\psi + \bar{\psi}\gamma_{\mu}a^{\mu}\psi$$

In the Standard Model, a phase transition of a scalar field gives nonzero field value in vacuum

In String Theory, a vector field can be frozen in vacuum by spontaneous symmetry broken

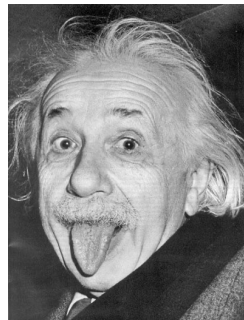
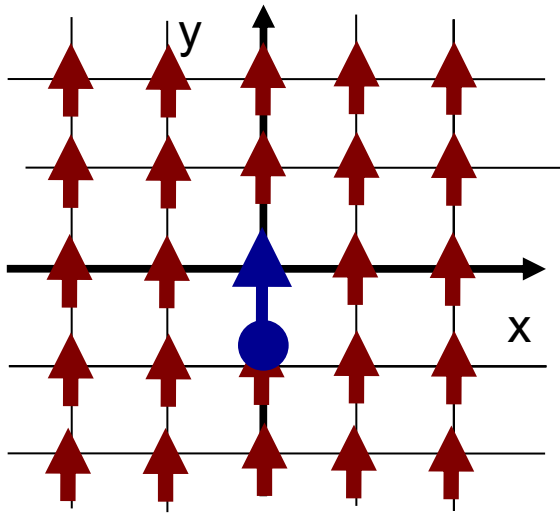


Lorentz symmetry
is spontaneously
broken!



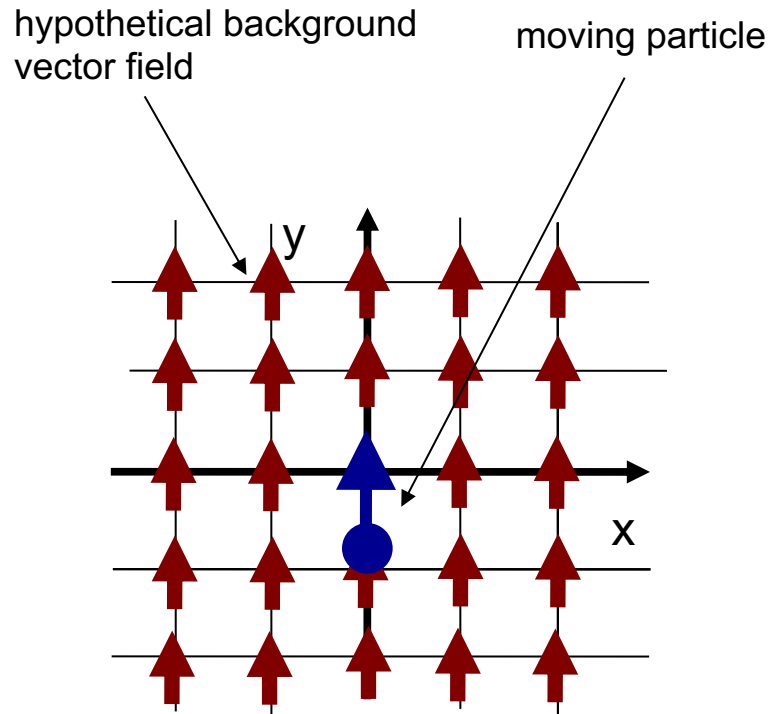
Particle and Observer Lorentz transformation

$$\bar{\Psi}(x)\gamma_{\mu}a^{\mu}\Psi(x)$$

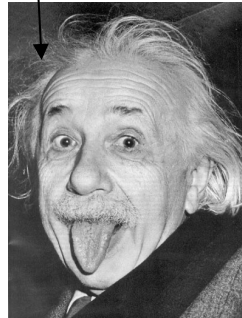


Particle and Observer Lorentz transformation

$$\bar{\Psi}(x)\gamma_{\mu}a^{\mu}\Psi(x)$$



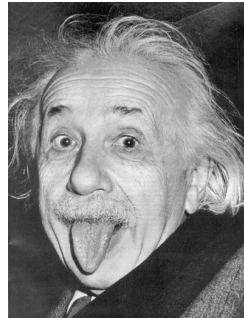
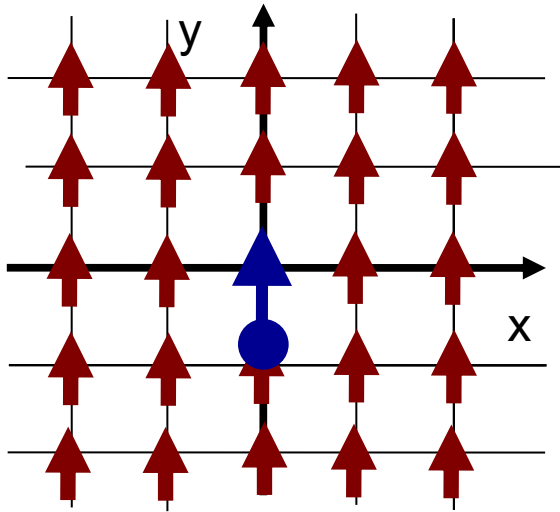
Einstein
(observer)



Particle and Observer Lorentz transformation

Under the **particle** Lorentz transformation:

$$U \bar{\Psi}(x) \gamma_{\mu} a^{\mu} \Psi(x) U^{-1}$$

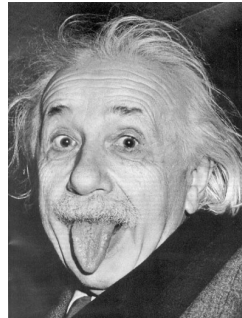
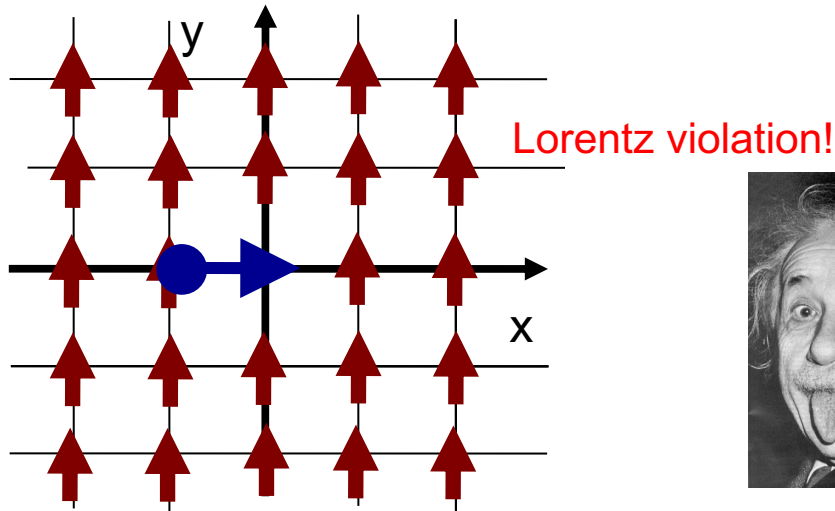


Particle and Observer Lorentz transformation

Under the **particle** Lorentz transformation:

$$\bar{\Psi}(x)\gamma_{\mu}a^{\mu}\Psi(x) \rightarrow U[\bar{\Psi}(x)\gamma_{\mu}a^{\mu}\Psi(x)]U^{-1}$$
$$\neq \bar{\Psi}(\Lambda x)\gamma_{\mu}a^{\mu}\Psi(\Lambda x)$$

Lorentz violation is observable
when a particle is moving in the
fixed coordinate space



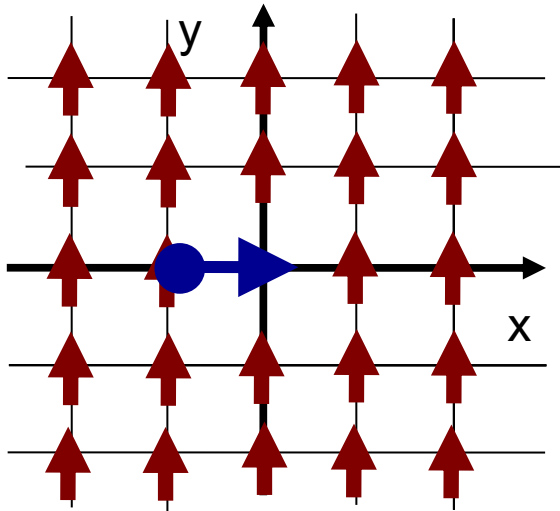
Particle and Observer Lorentz transformation

Under the **particle** Lorentz transformation:

$$\bar{\Psi}(x)\gamma_{\mu}a^{\mu}\Psi(x) \rightarrow U[\bar{\Psi}(x)\gamma_{\mu}a^{\mu}\Psi(x)]U^{-1}$$

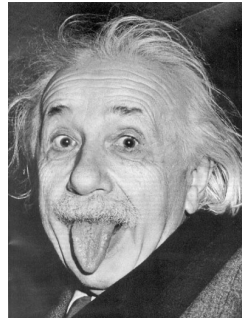
$$\neq \bar{\Psi}(\Lambda x)\gamma_{\mu}a^{\mu}\Psi(\Lambda x)$$

Lorentz violation is observable
when a particle is moving in the
fixed coordinate space

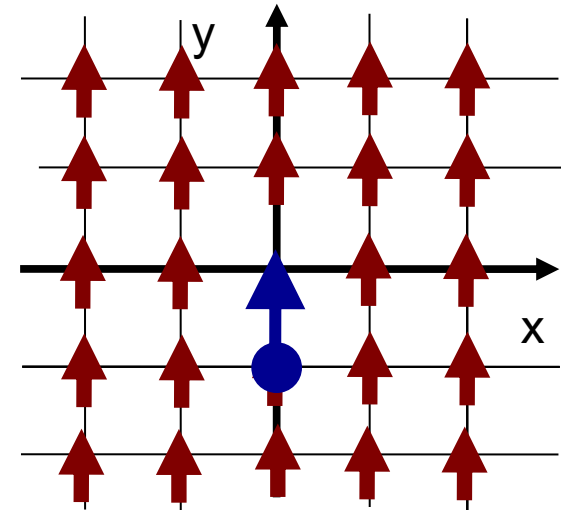


Under the **observer** Lorentz transformation:

$$\bar{\Psi}(x)\gamma_{\mu}a^{\mu}\Psi(x)$$



tkatori@cern.ch



25/04/10

61

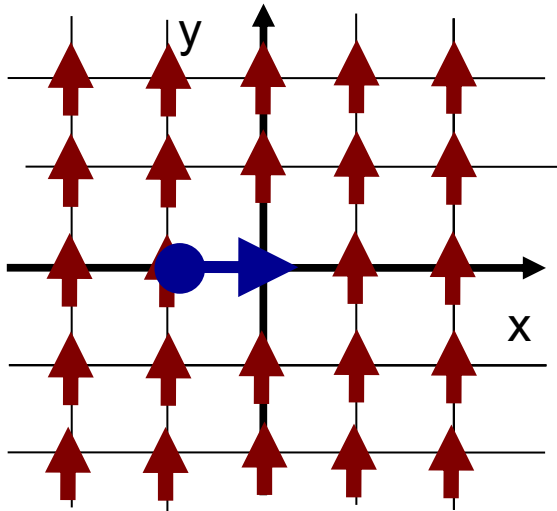
Particle and Observer Lorentz transformation

Under the **particle** Lorentz transformation:

$$\bar{\Psi}(x)\gamma_{\mu}a^{\mu}\Psi(x) \rightarrow U[\bar{\Psi}(x)\gamma_{\mu}a^{\mu}\Psi(x)]U^{-1}$$

$$\neq \bar{\Psi}(\Lambda x)\gamma_{\mu}a^{\mu}\Psi(\Lambda x)$$

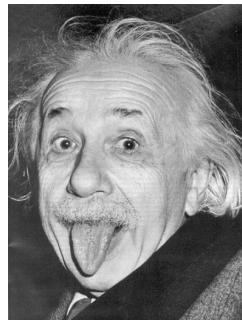
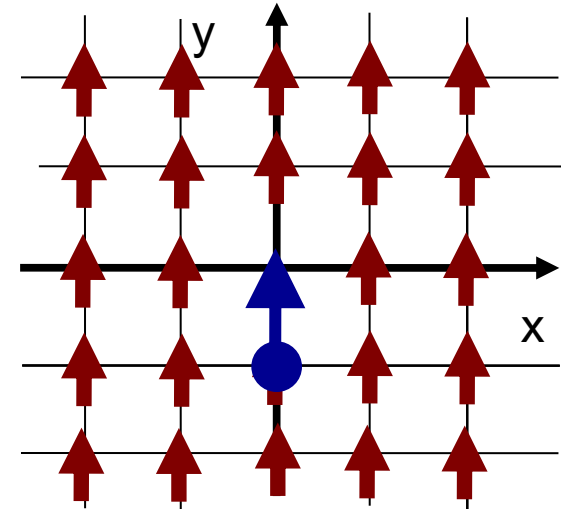
Lorentz violation is observable
when a particle is moving in the
fixed coordinate space



Under the **observer** Lorentz transformation:

$$\bar{\Psi}(x)\gamma_{\mu}a^{\mu}\Psi(x)$$

$$x \rightarrow \Lambda^{-1}x$$



tkatori@cern.ch

25/04/10

62

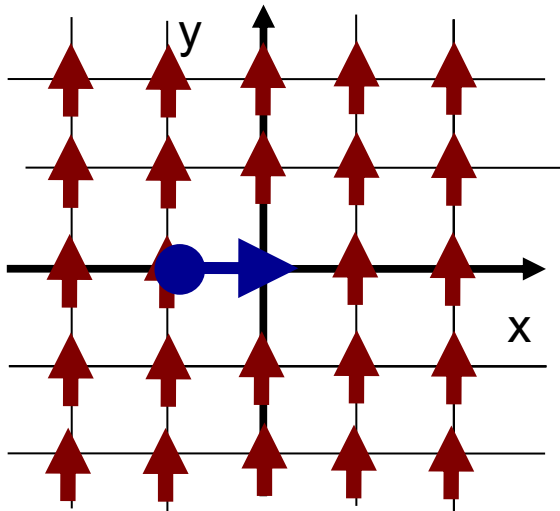
Particle and Observer Lorentz transformation

Under the **particle** Lorentz transformation:

$$\bar{\Psi}(x)\gamma_{\mu}a^{\mu}\Psi(x) \rightarrow U[\bar{\Psi}(x)\gamma_{\mu}a^{\mu}\Psi(x)]U^{-1}$$

$$\neq \bar{\Psi}(\Lambda x)\gamma_{\mu}a^{\mu}\Psi(\Lambda x)$$

Lorentz violation is observable
when a particle is moving in the
fixed coordinate space

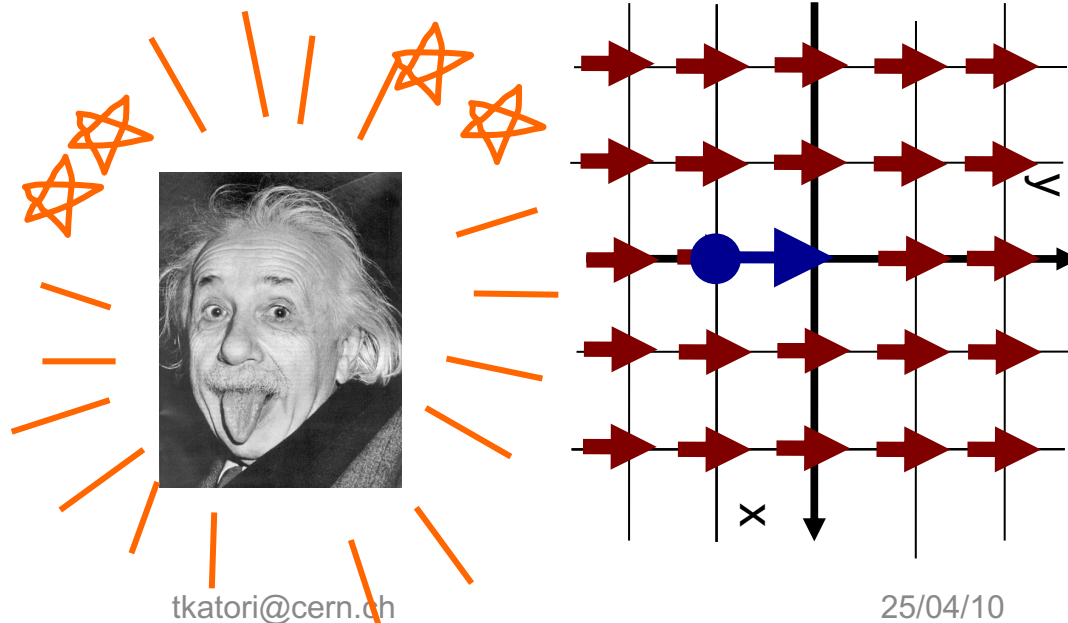


Under the **observer** Lorentz transformation:

$$\bar{\Psi}(x)\gamma_{\mu}a^{\mu}\Psi(x) \xrightarrow{\Lambda^{-1}} \bar{\Psi}(\Lambda^{-1}x)\gamma_{\mu}a^{\mu}\Psi(\Lambda^{-1}x)$$

Lorentz violation cannot be generated
by observers motion (coordinate
transformation is unbroken)

all observers agree for all observations



tkatori@cern.ch

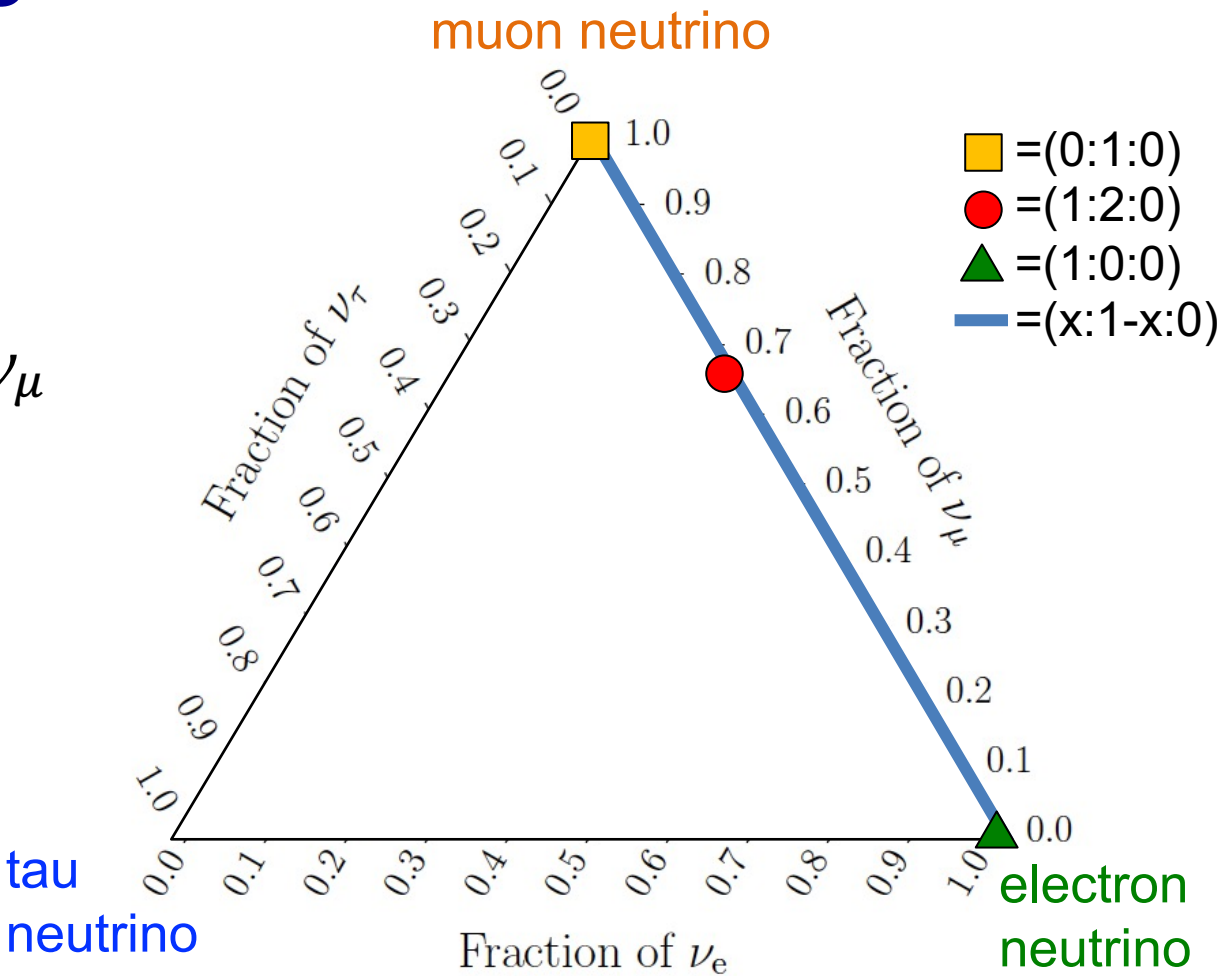
25/04/10

63

High-energy, long propagating neutrinos

Astrophysical neutrino flavor physics

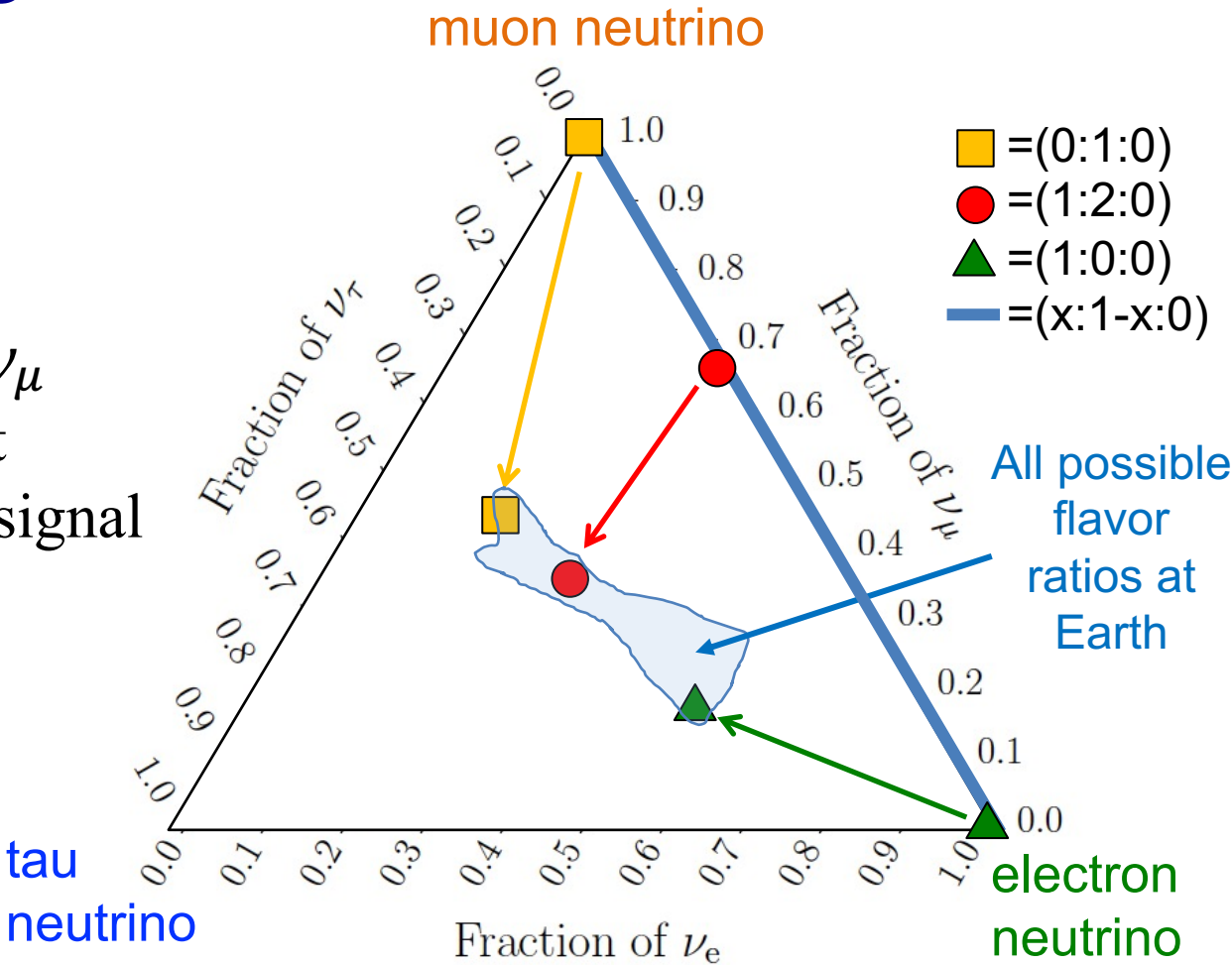
- Flavor triangle
- Spectrum integrated flavor ratio ($\nu_e:\nu_\mu:\nu_\tau$)
- Standard production models include ν_e and ν_μ



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



$\nu_e : \nu_\mu : \nu_\tau$ at source $\rightarrow$ on Earth:

■	0:1:0 $\rightarrow$ 0.17 : 0.45 : 0.37
●	1:2:0 $\rightarrow$ 0.30 : 0.36 : 0.34
▲	1:0:0 $\rightarrow$ 0.55 : 0.17 : 0.28

25/04/10



tkatori@cern.ch

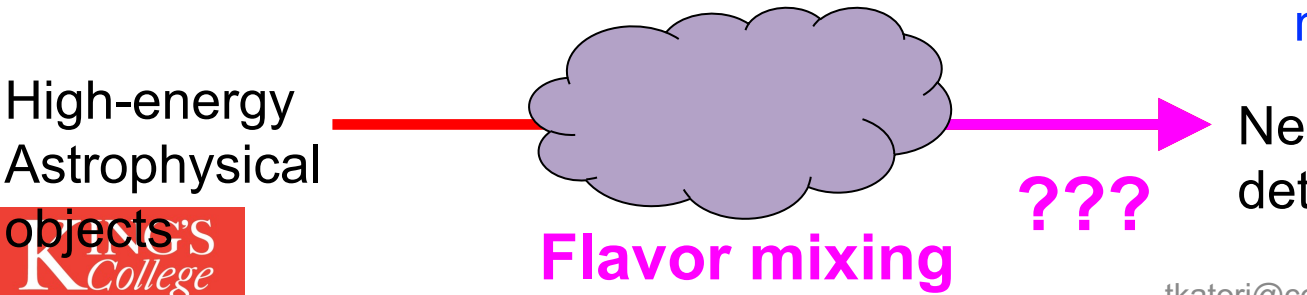
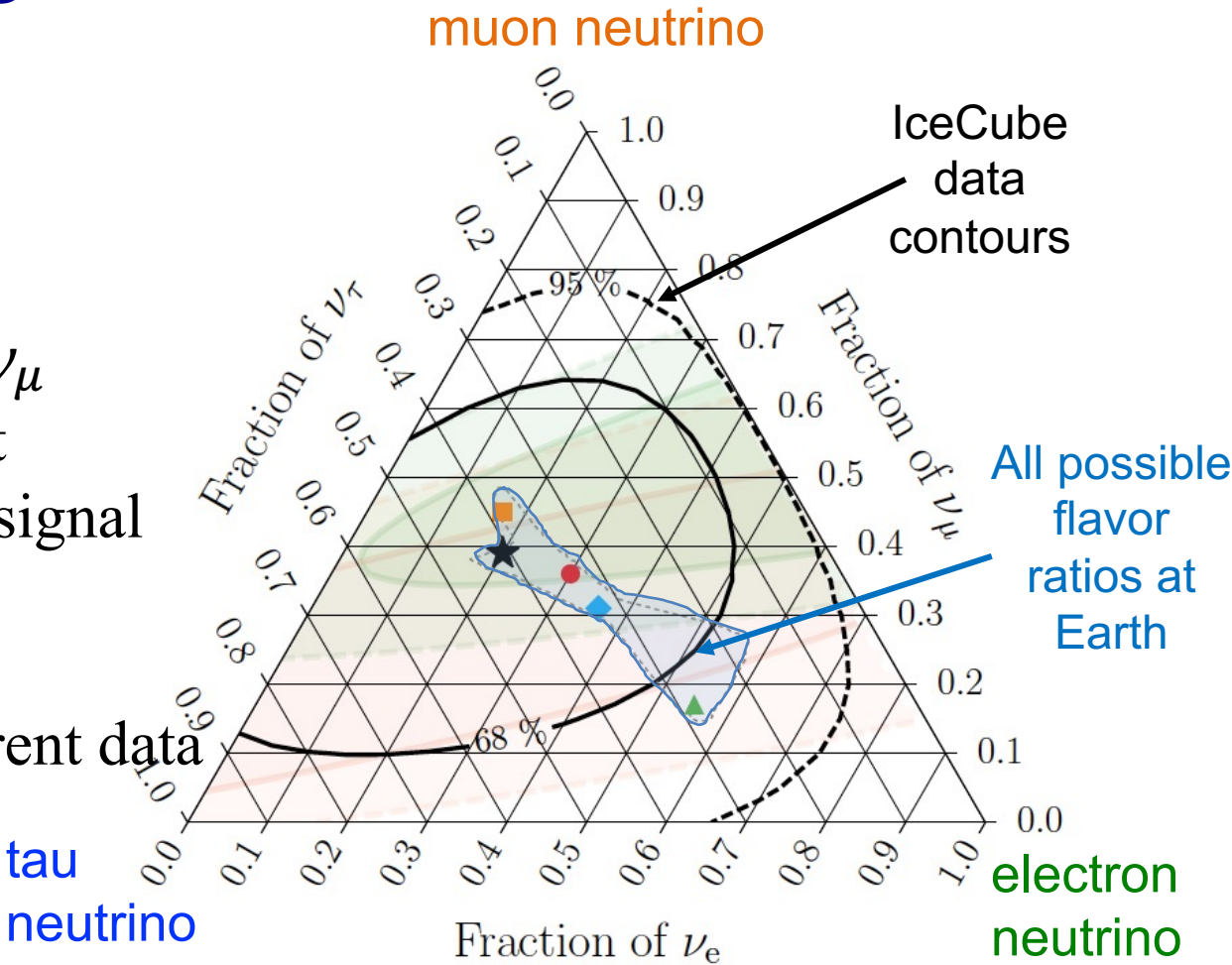
High-energy, long propagating neutrinos

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 with ternary topology ID	$\nu_e : \nu_\mu : \nu_\tau$ at source $\rightarrow$ on Earth:
★	Best fit: 0.20 : 0.39 : 0.42	0:1:0 $\rightarrow$ 0.17 : 0.45 : 0.37
■	Global Fit (IceCube, APJ 2015)	1:2:0 $\rightarrow$ 0.30 : 0.36 : 0.34
■	Inelasticity (IceCube, PRD 2019)	1:0:0 $\rightarrow$ 0.55 : 0.17 : 0.28
■	3ν-mixing 3σ allowed region	

HESE 7.5-yr flavor Lorentz violation search

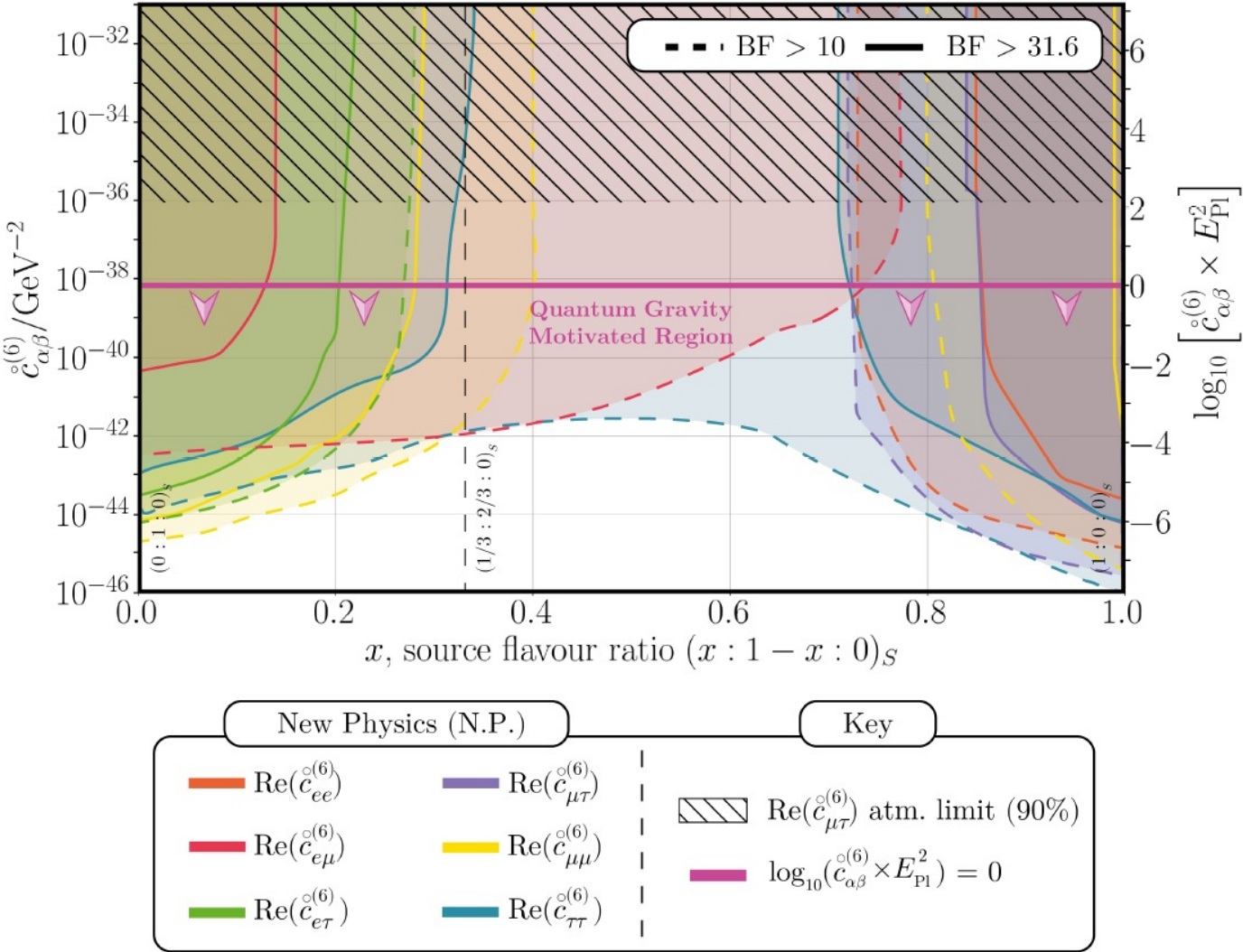
dim-6 new physics operator limit

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



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

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

Effective Hamiltonian can be written from here

Standard Model

New physics (renormalizable)

higher dimension operator (non-renormalizable)

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

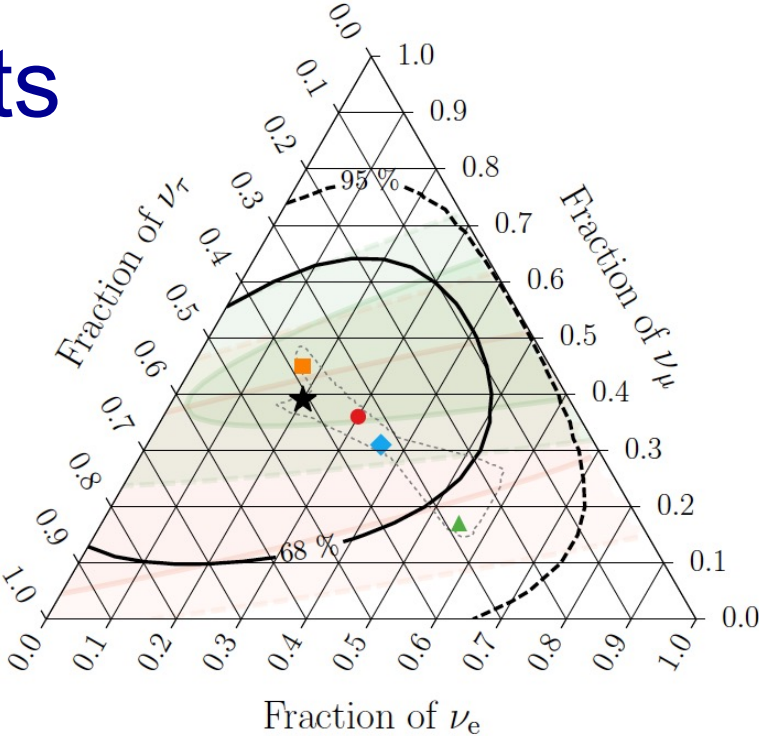
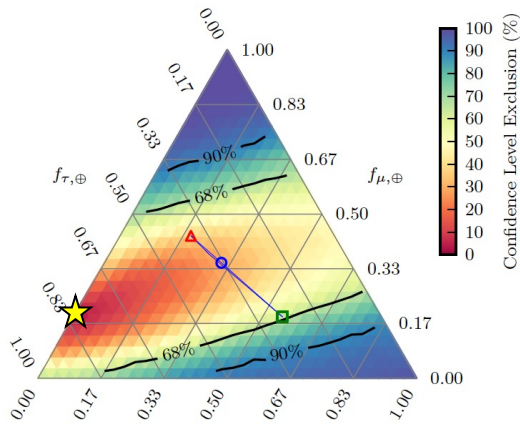
$E^3 c_{\alpha\beta}^{(6)} = E^3 \begin{pmatrix} c_{ee}^{(6)} & c_{e\mu}^{(6)} & c_{\tau e}^{(6)} \\ c_{e\mu}^{(6)*} & c_{\mu\mu}^{(6)} & c_{\mu\tau}^{(6)} \\ c_{\tau e}^{(6)*} & c_{\mu\tau}^{(6)*} & c_{\tau\tau}^{(6)} \end{pmatrix}$

IceCube is sensitive to higher dimension operators

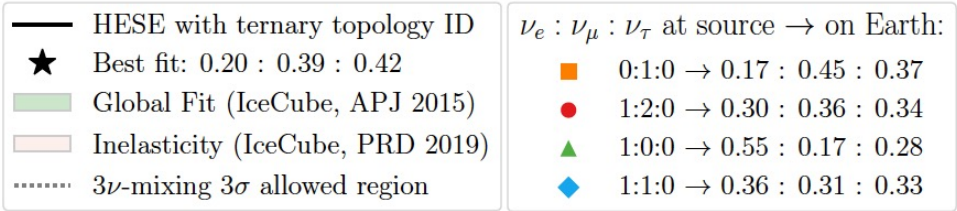
dimension-6 operator natural scale: $c^{(6)} \sim \frac{1}{M_{Planck}^2} \sim 10^{-38} GeV^{-2}$

IceCube flavor ratio measurements

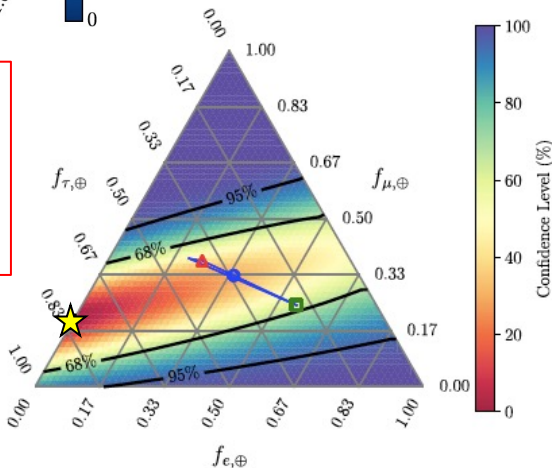
IceCube
1st flavour ratio result
(0.0:0.2:0.8)



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



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



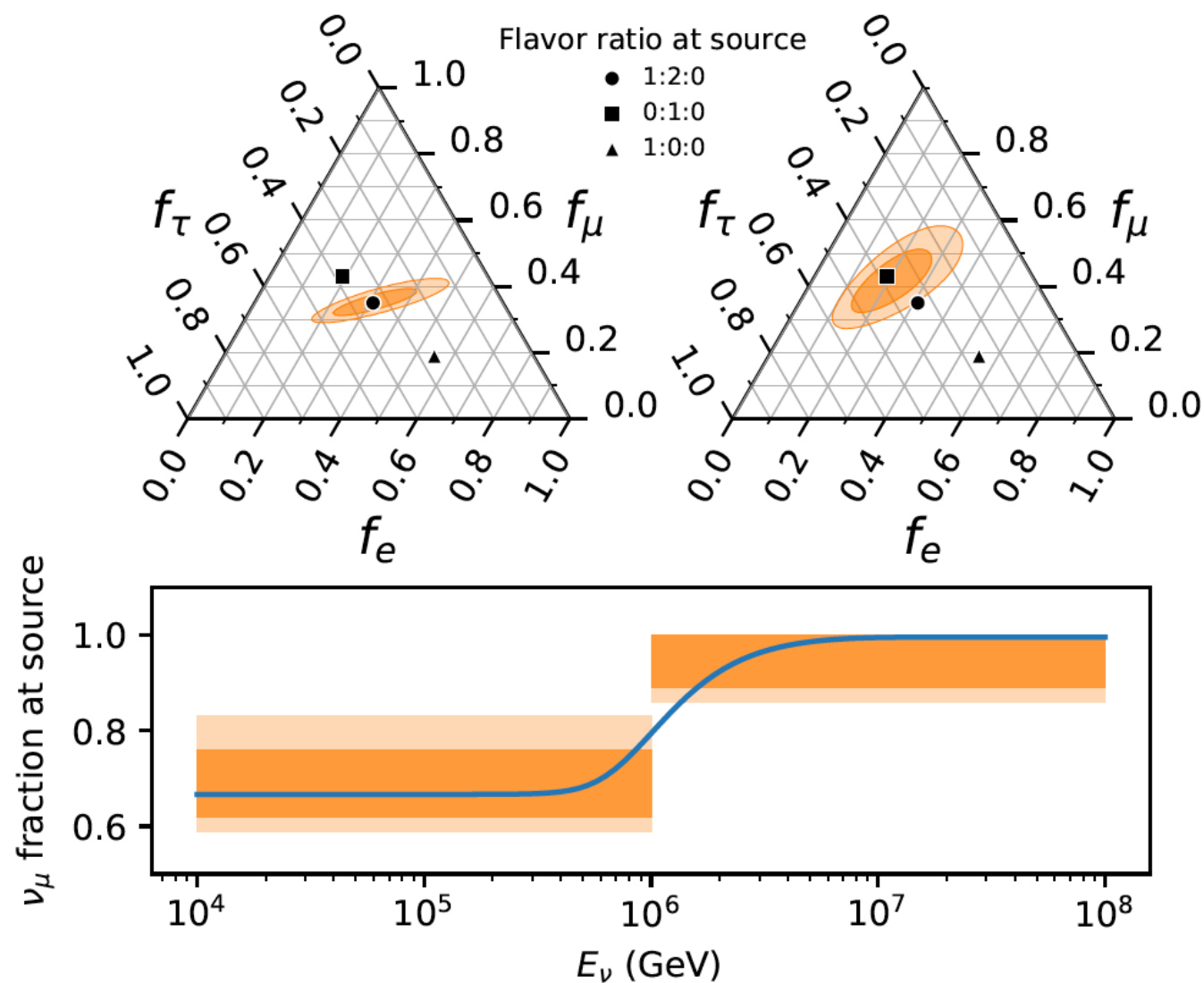
2018 flavour ratio measurement

- 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



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.

