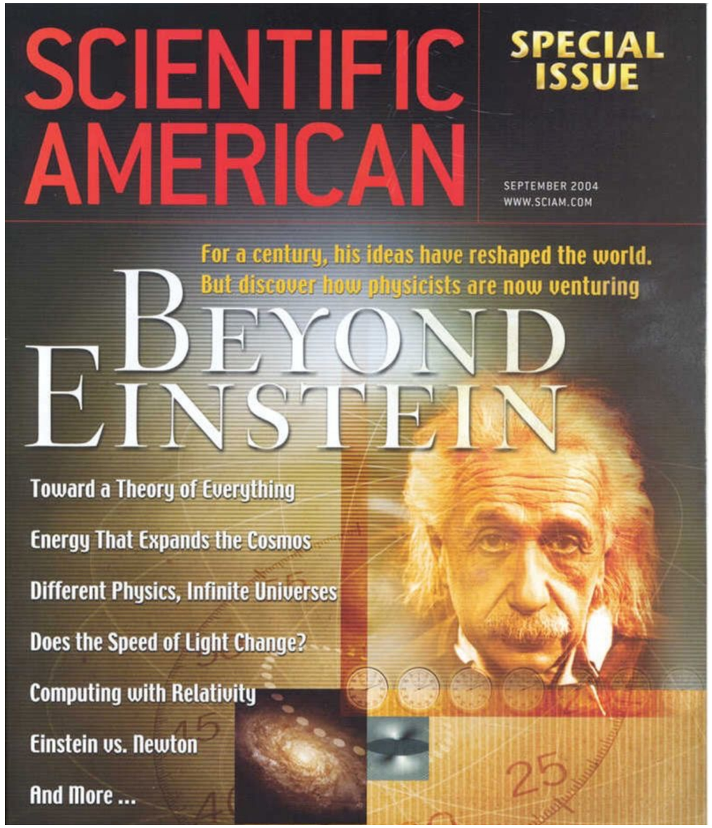
Modern Tests of Spacetime Symmetry

outline

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



Teppei Katori @teppeikatori
King's College London
GSSI Astroparticle colloquium
L'Aquila, Italy, Jan 15, 2025

KING'S College LONDON

Introduction

I want to say Einstein is wrong!

How to disprove Einstein's theory **scientifically**???

baolujiang@gmail.com February 12, 2022 at 00:07
A website to disprove Special Relativity
To: Teppei Katori

Hom

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

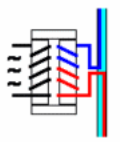
- *2022-10-22: Section 'On velocity addition' is added to the end of th main article.*
- *2021-11-21: Several Q&As are added.*
- *05: The main article is*
- *24: Source Text for vi*
- *18: Several Q&As are*

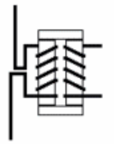
armanettimaurizio@libero.it January 15, 2020 a
From Italy - OBJECT: here's how to overcome the speed of light.
To: Teppei Katori

TO THE PERSONAL ATTENTION OF PROF. TEPPEI KATORI

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

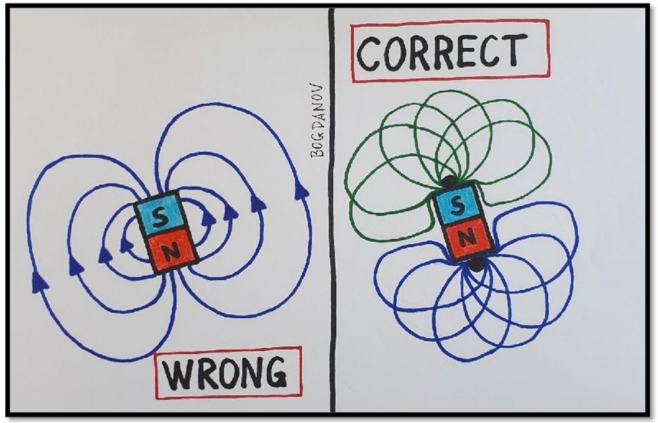
I can demonstrate under scientific control and in a repeatable
the speed of light. The brain has the energetic power of instantar
the problem was to prove it scientifically, today it is possible, I ca

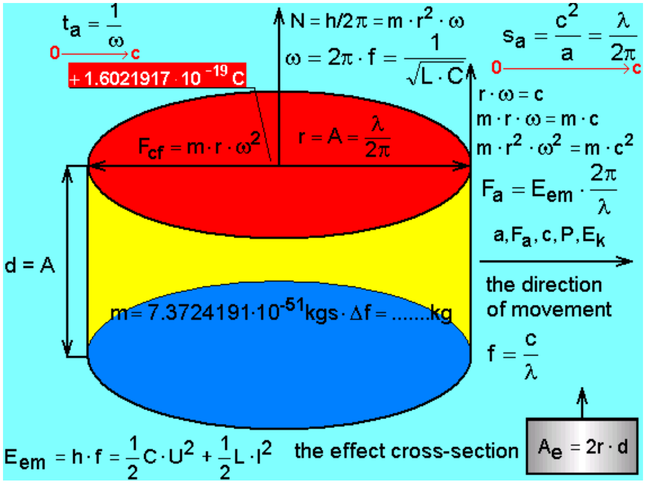




Cosmin Visan January 13, 2024 at 22:28
My theory of consciousness and meeting proposal
To: bozidar.butorac@kcl.ac.uk & 113 more
Details

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





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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

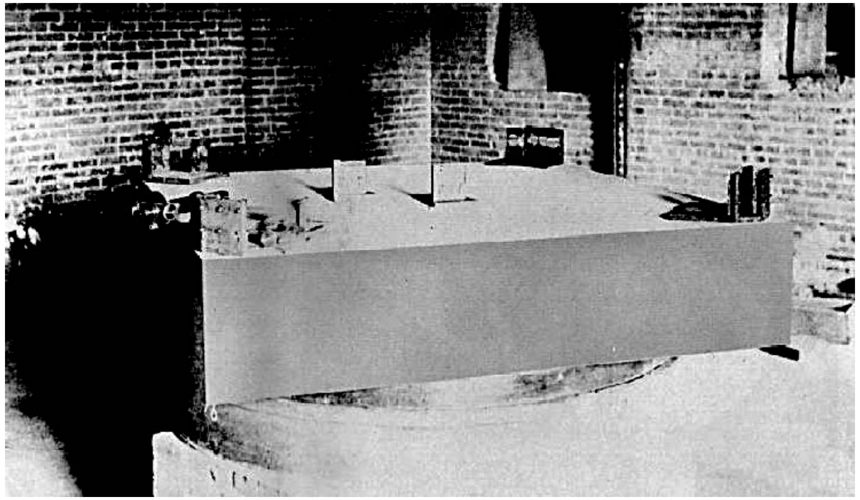
Michelson-Morley experiment

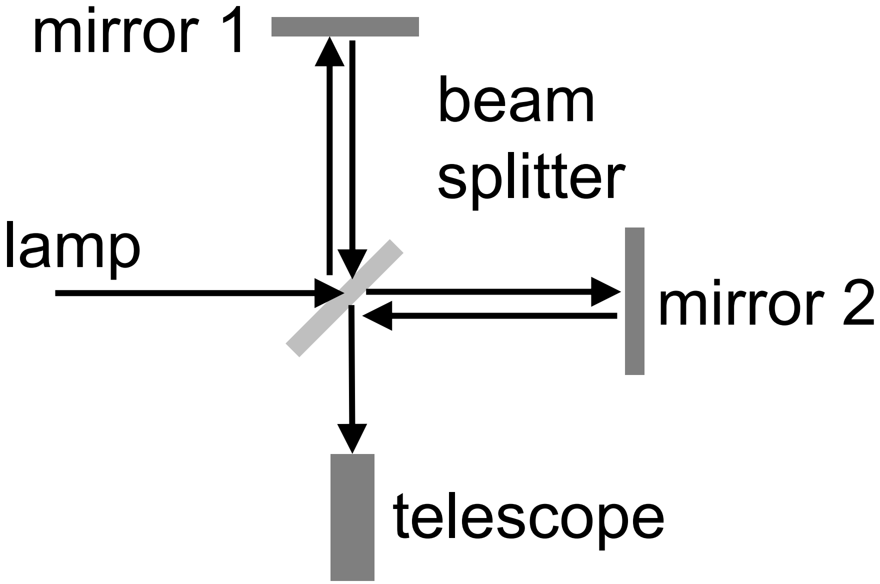
The experiment tried to measure the motion of the Earth relative to æther.

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 $\Delta c/c \sim 10^{-9}$

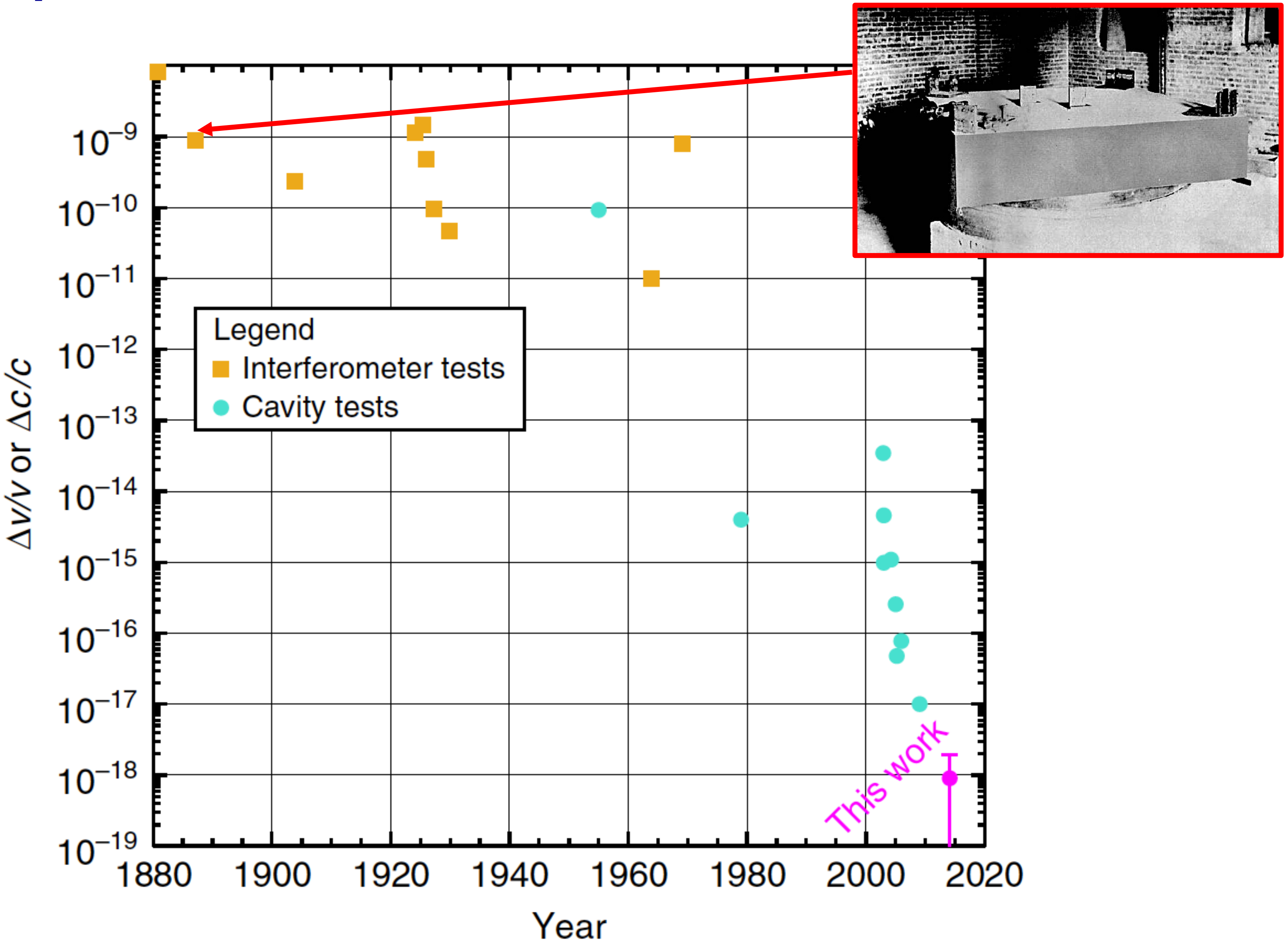




Nagel et al, Nature Comm., 6(2015)8174

Michelson-Morley experiment

The experiment has been improved over 100 years.

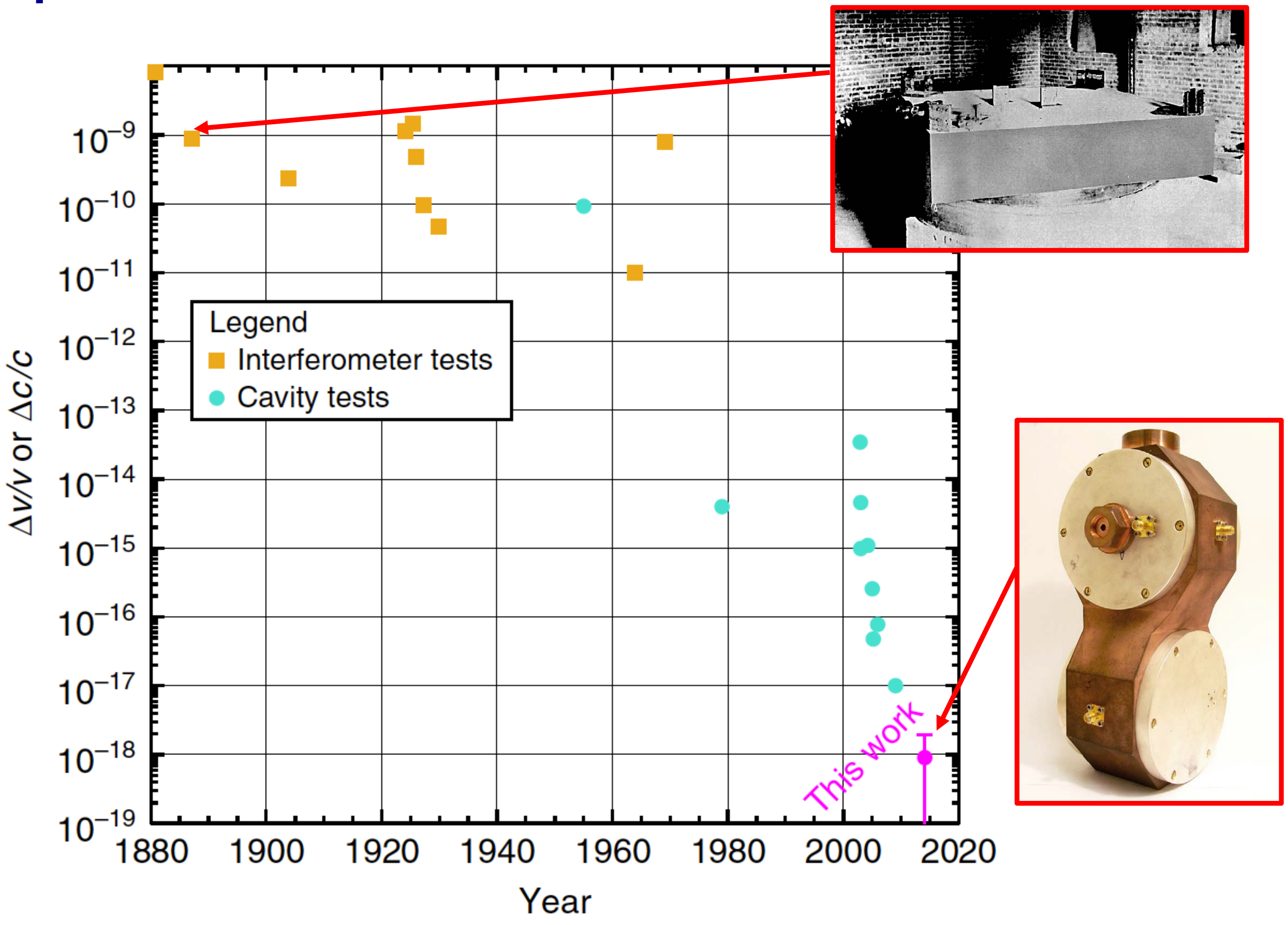


Nagel et al, Nature Comm., 6(2015)8174

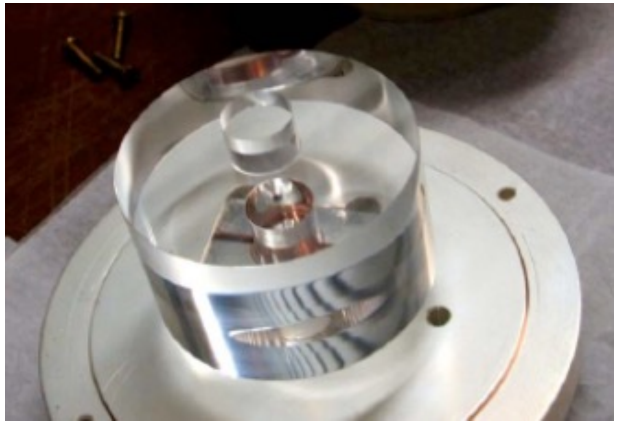
Michelson-Morley experiment

The experiment has been improved over 100 years.

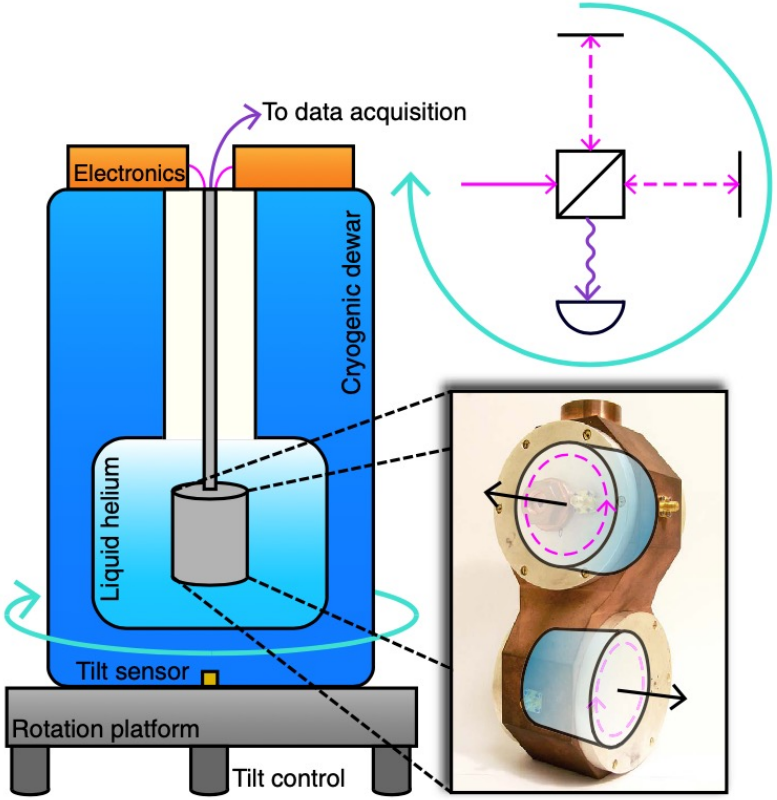
Technology shift (interferometer → optical cavity) around 2000s



Optical cavity experiment



Modern Michelson-Morley experiment
- 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 $\Delta c/c \sim 10^{-18}$

Why we keep testing this?

Why do we expect Lorentz violation?

Progress in Particle and Nuclear Physics 125 (2022) 103948

Quantum gravity

Searching Lorentz violation is well motivated

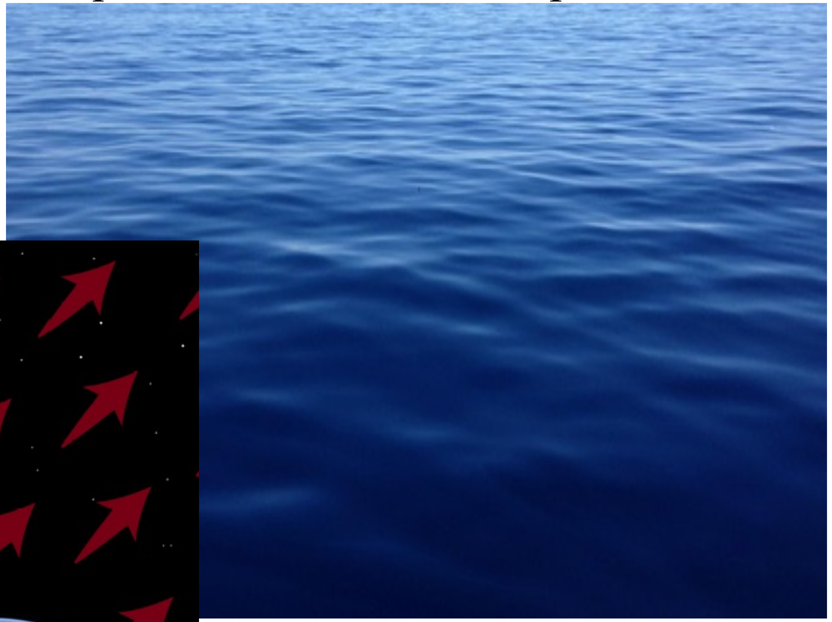
Lorentz violation in Planck scale theories
- string theory
- noncommutative field theory
- quantum loop gravity

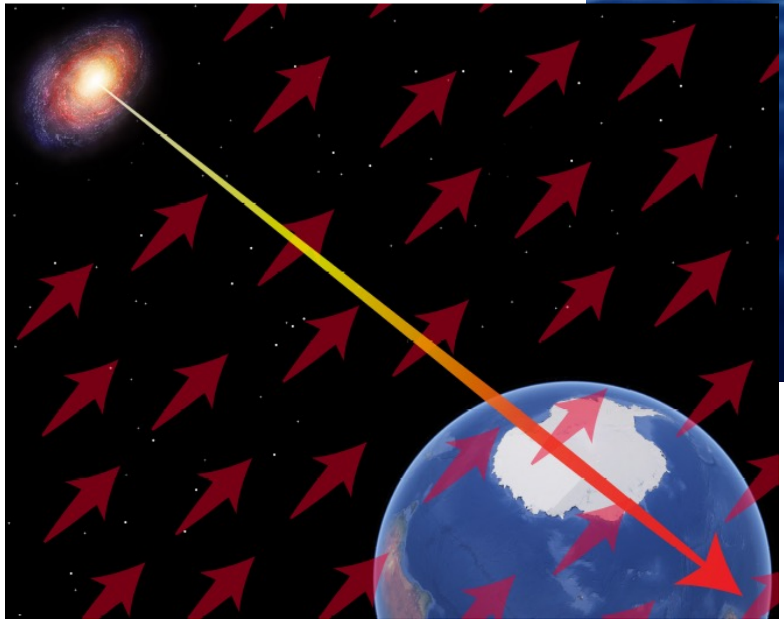
etc

Lorentz violation is seen as
- 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

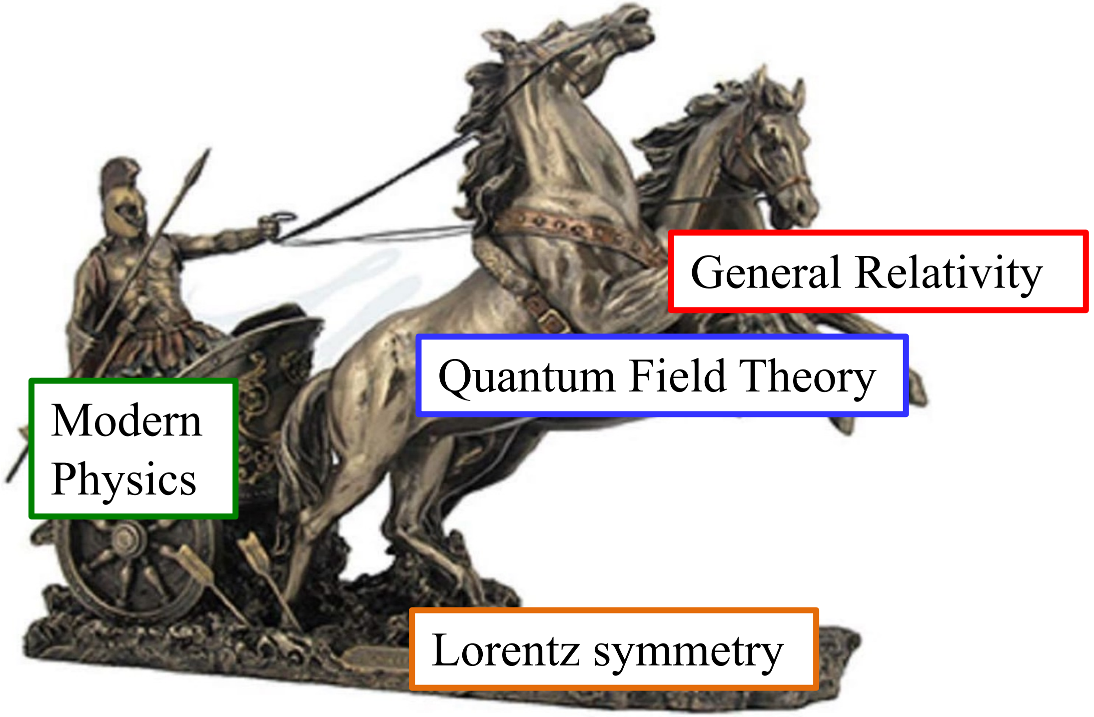
Searching Lorentz violation is well motivated

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

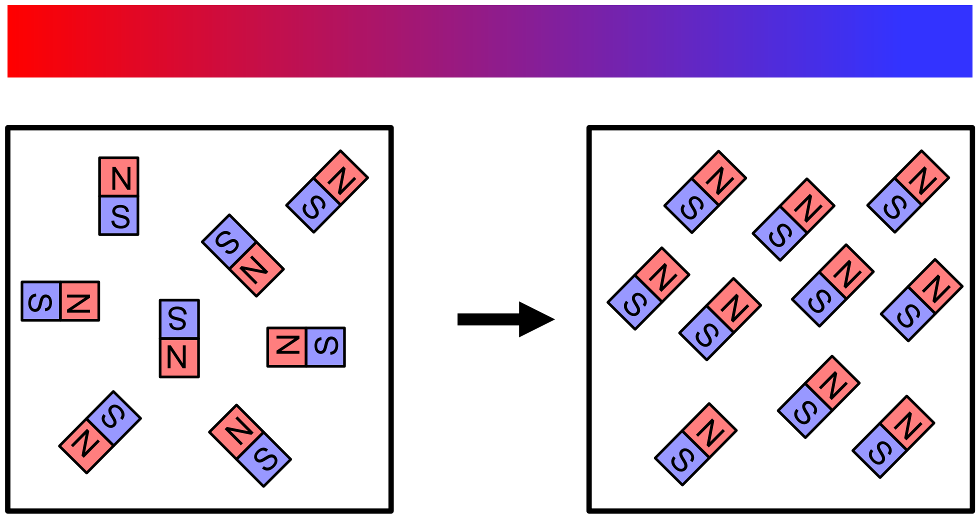


Spontaneous symmetry breaking

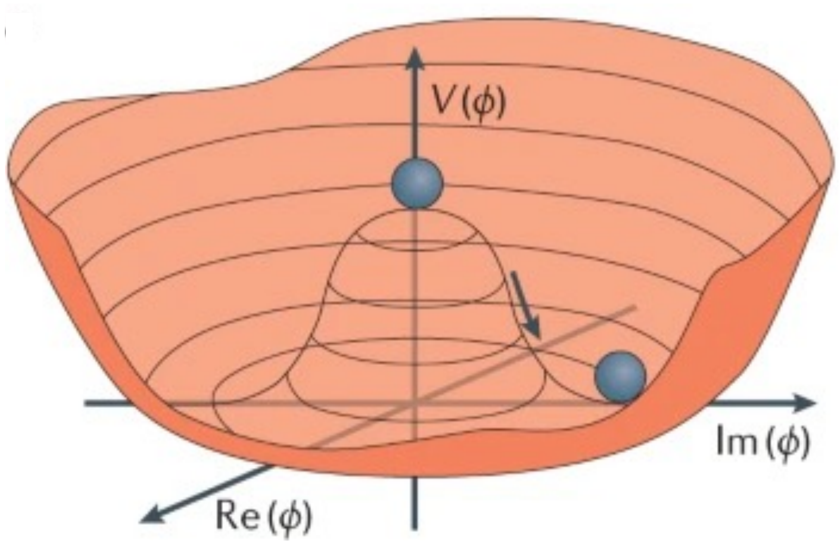
Searching Lorentz violation is well motivated

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

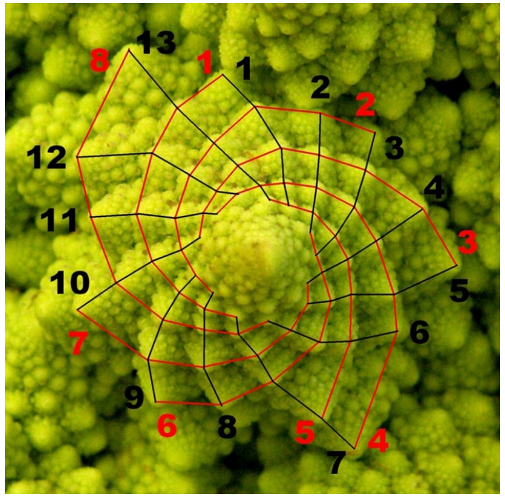


Spontaneous symmetry breaking

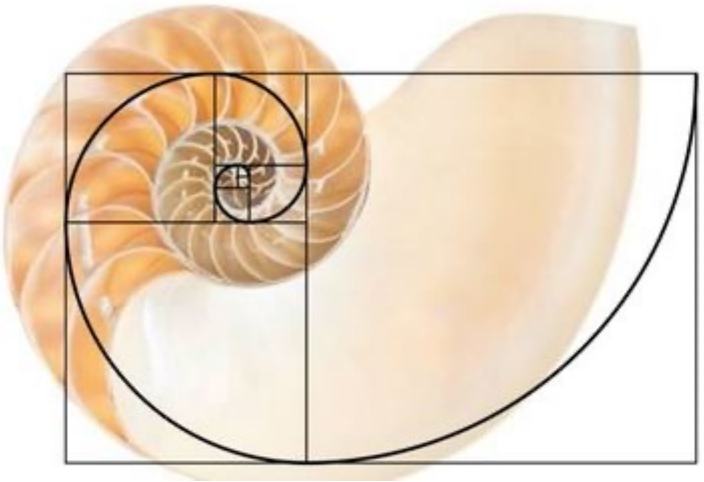
Searching Lorentz violation is well motivated

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)

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 framework to look for Lorentz violation

e.g.) vacuum Lagrangian for fermion

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

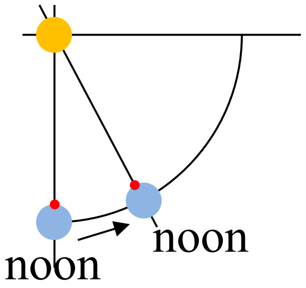
Standard Model

couplings with background fields

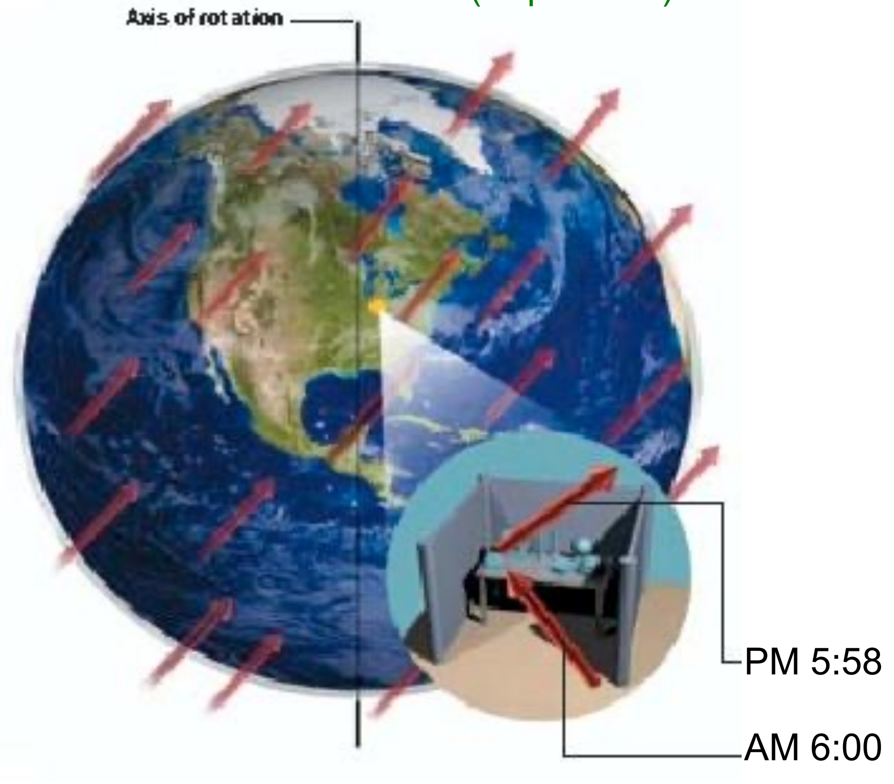
Physics of Lorentz violation

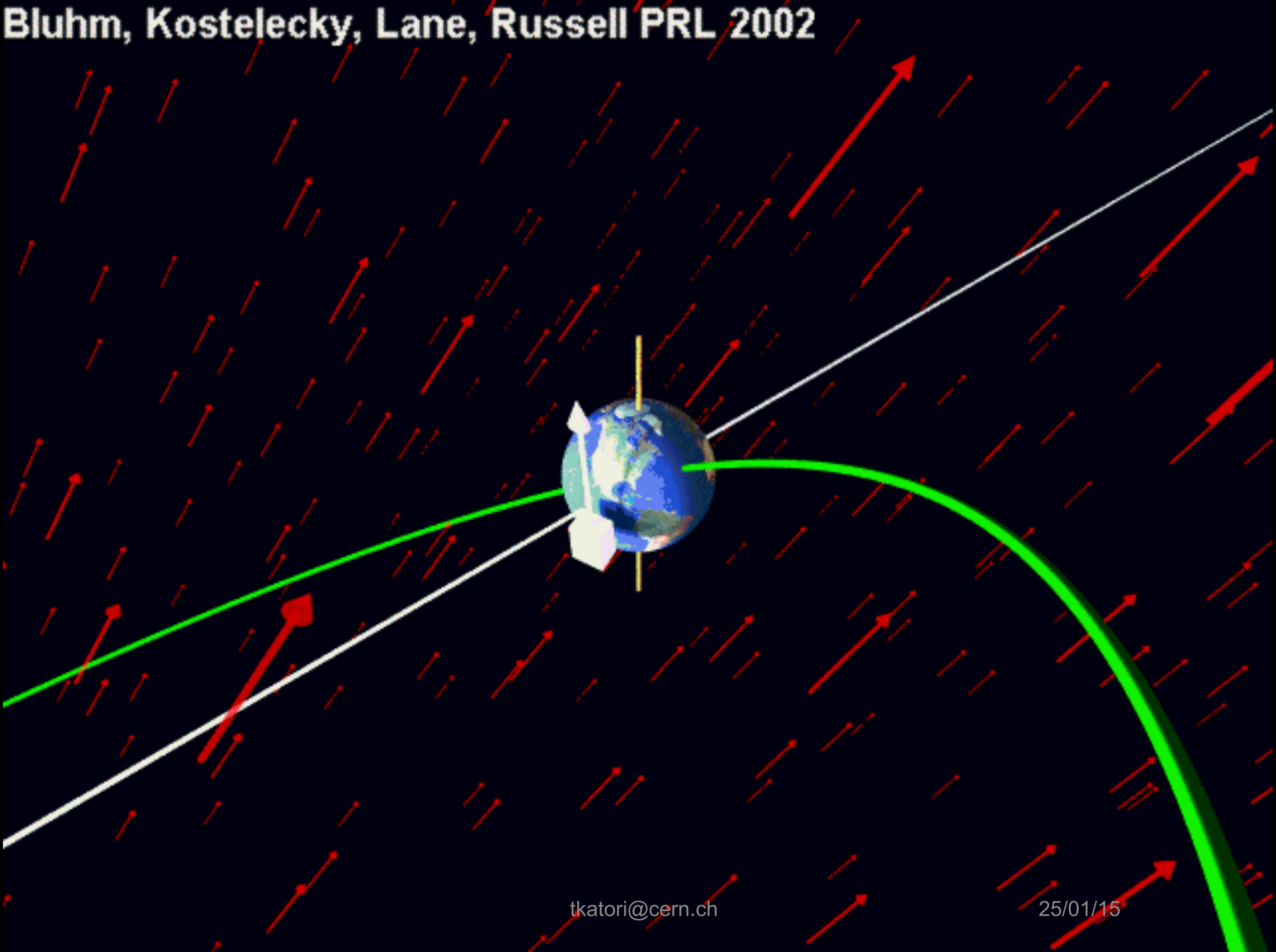
- Spectrum distortion,
- Sidereal time dependence, etc…

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



Scientific American (Sept. 2004)




Bluhm, Kostelecky, Lane, Russell PRL 2002

Tests of Lorentz violation

EötWash, PRL97(2006)021603 , PRL122(2019)231301

Torsion pendulum (electron)

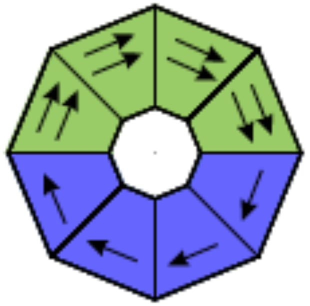
Eric G. Adelberger, University of Washington, Seattle

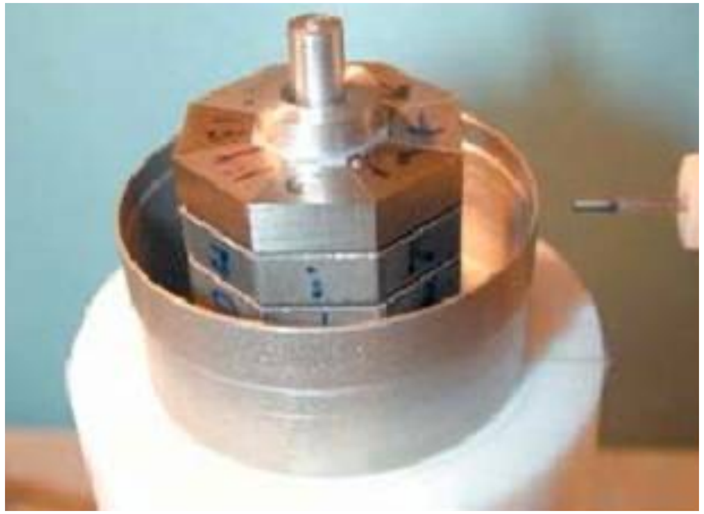
2025 recipient, Einstein Prize

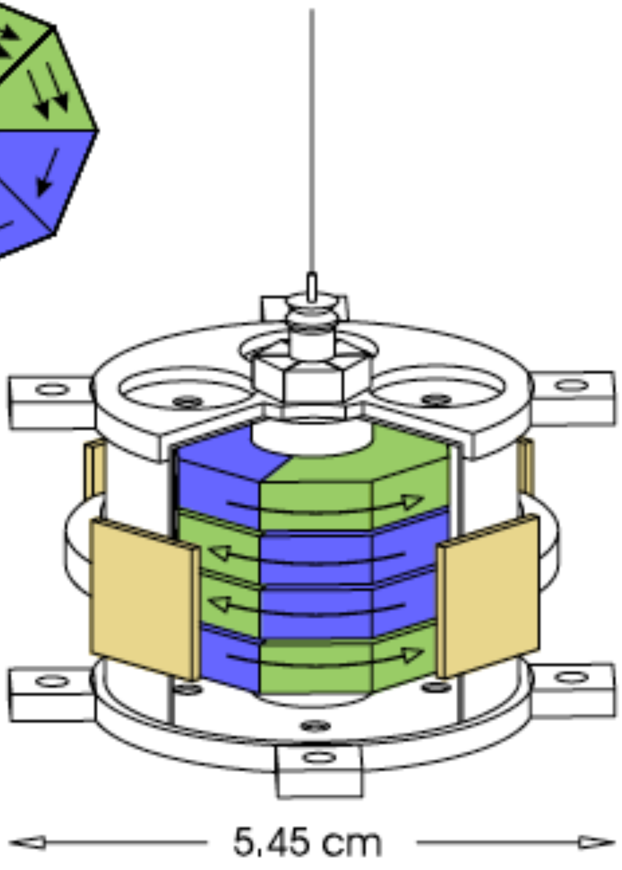
For outstanding contributions to experimental gravity using precision torsion-balance measurements, which have profound implications for fundamental physics.

Modern torsion balance

- AlNiCo: all magnetic field is from electron spin
- $SmCo_5$: 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



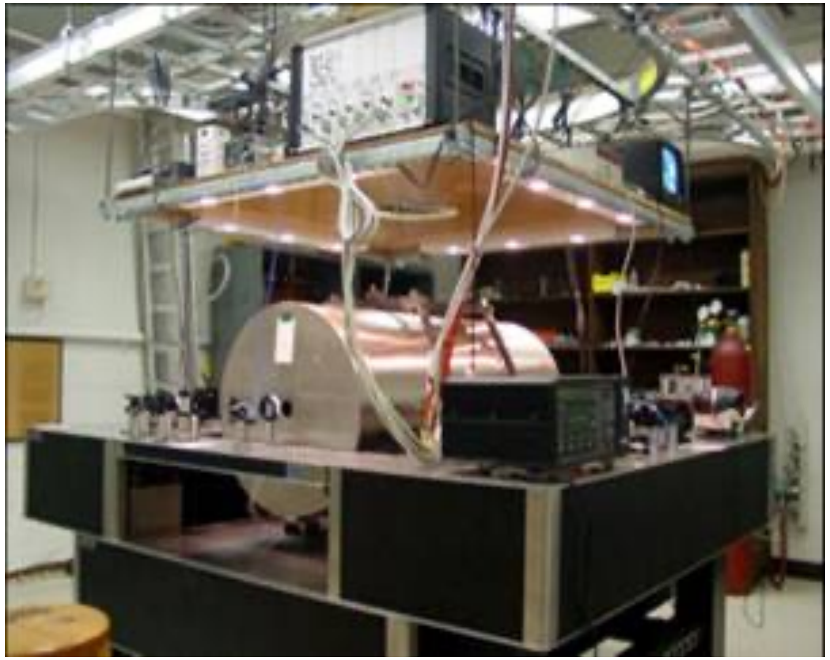


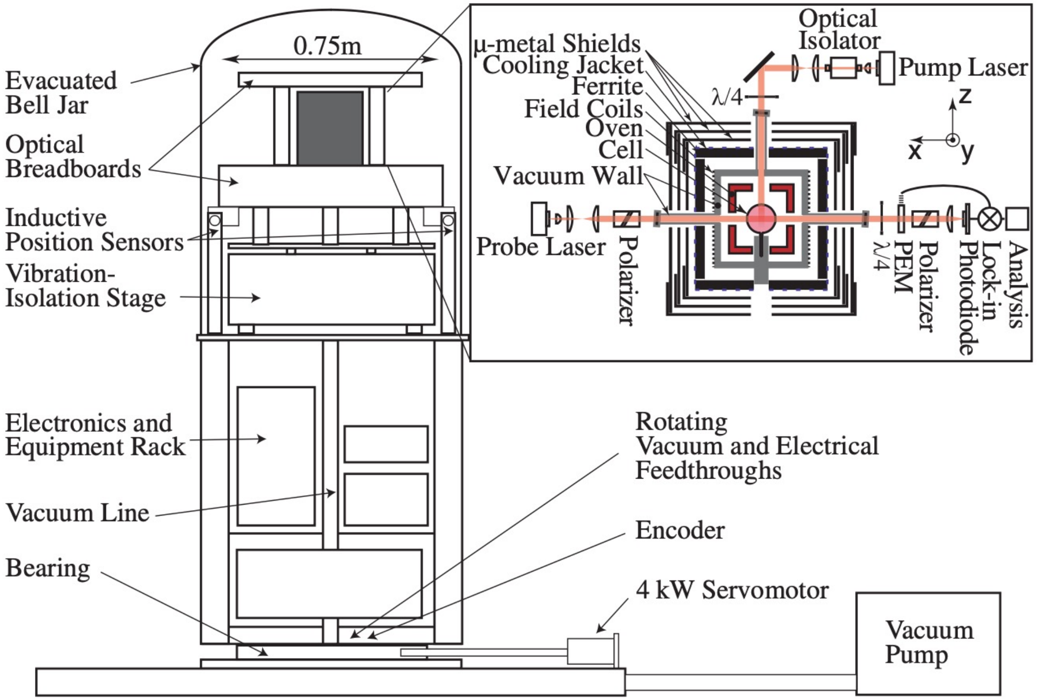


PRL105(2010)151604 and many others

Double gas maser (neutron)

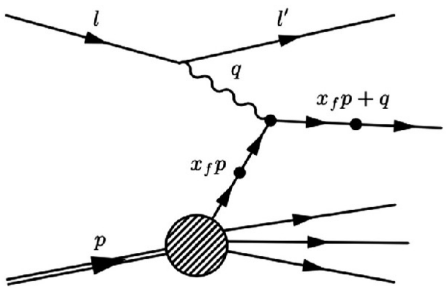
The most sensitive magnetometer
- Optical pump for Rb, K
- Spin transfer to noble gas (Xe, ^{3}He), monitor ^{3}He precession
- Look for coupling between neutron spin and background field



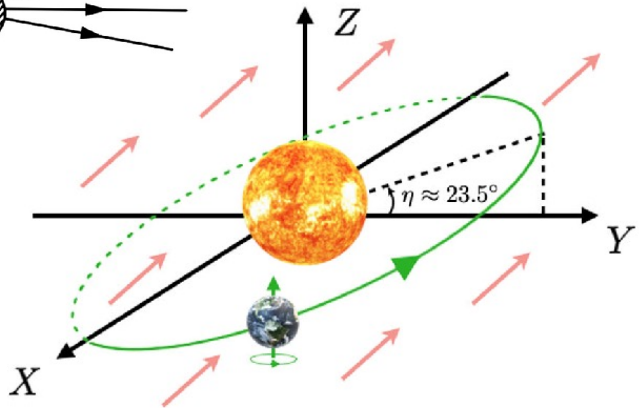


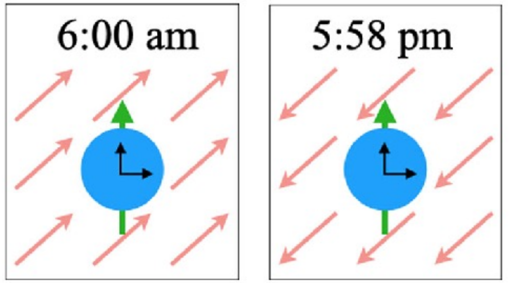
ZEUS, PRD107(2023)092008 and many others

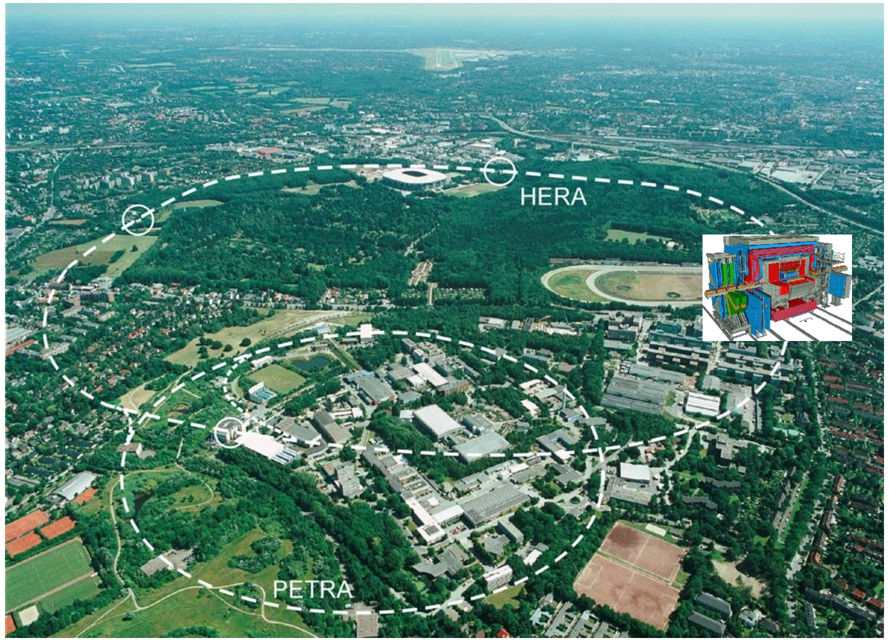
Collider physics (quarks)

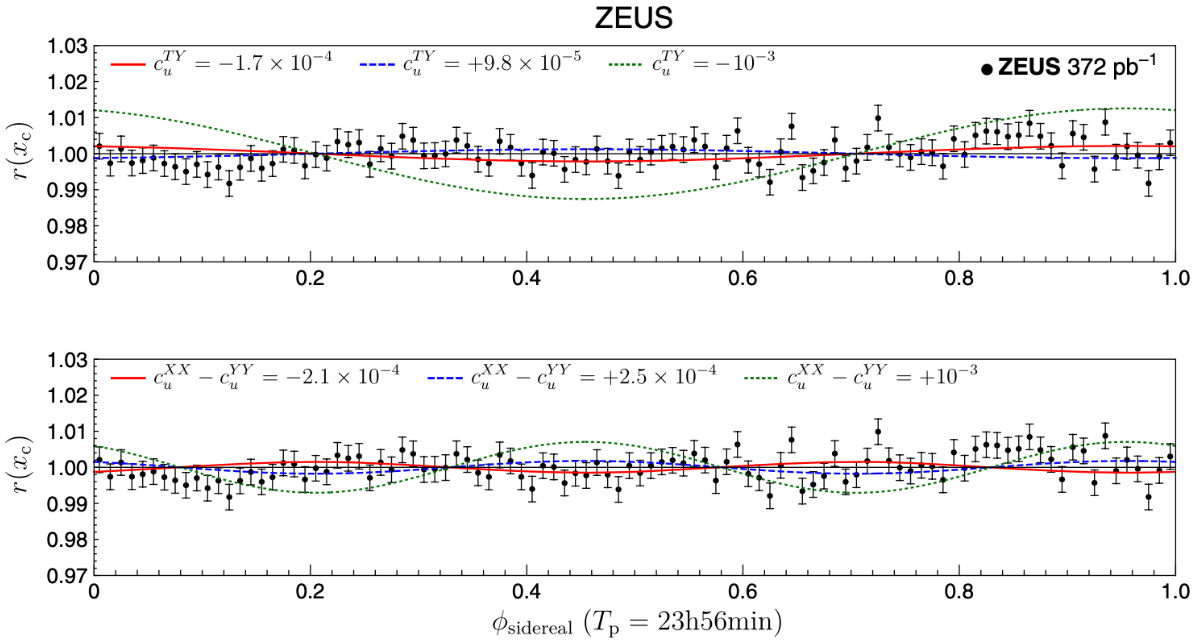


HERA p-e$^-$ collider
- ZEUS deep-inelastic scattering data
- Monitor sidereal time dependence
- Similar tests are possible for other data





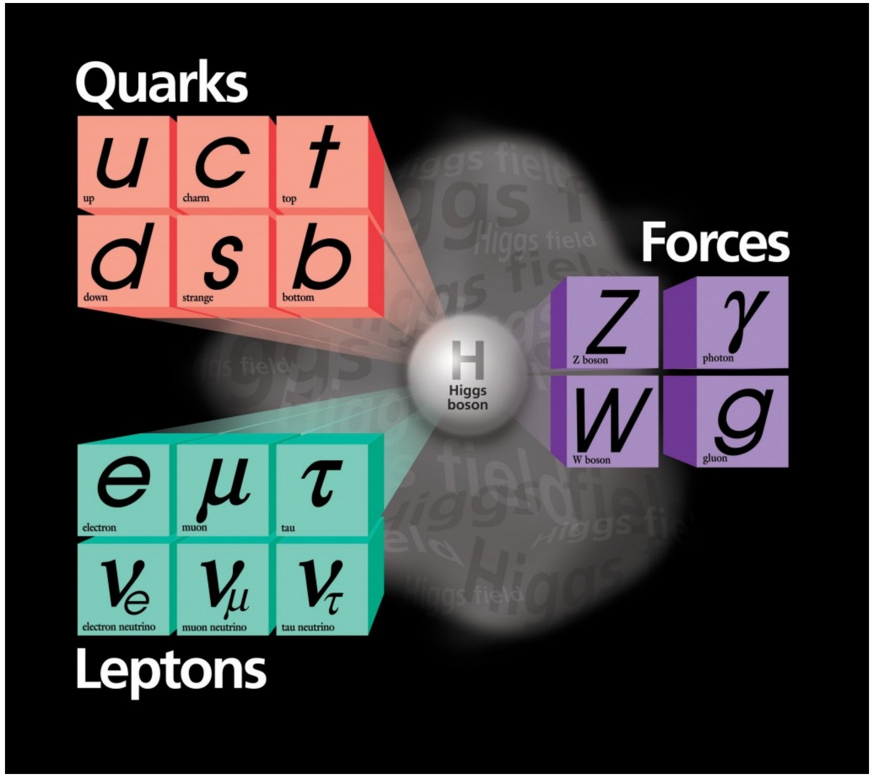




Neutrino physics

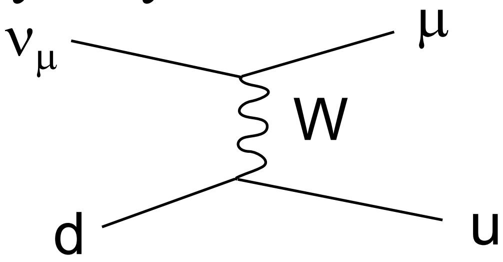
Neutrinos in the standard model

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

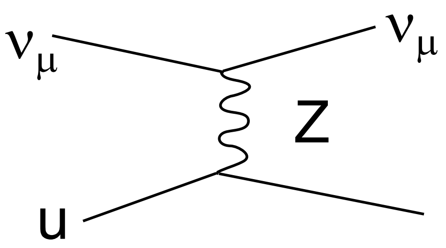


Neutrinos are special because,

1. they only interact with weak nuclear force.



Charged Current (CC) interaction
"W-boson exchange"

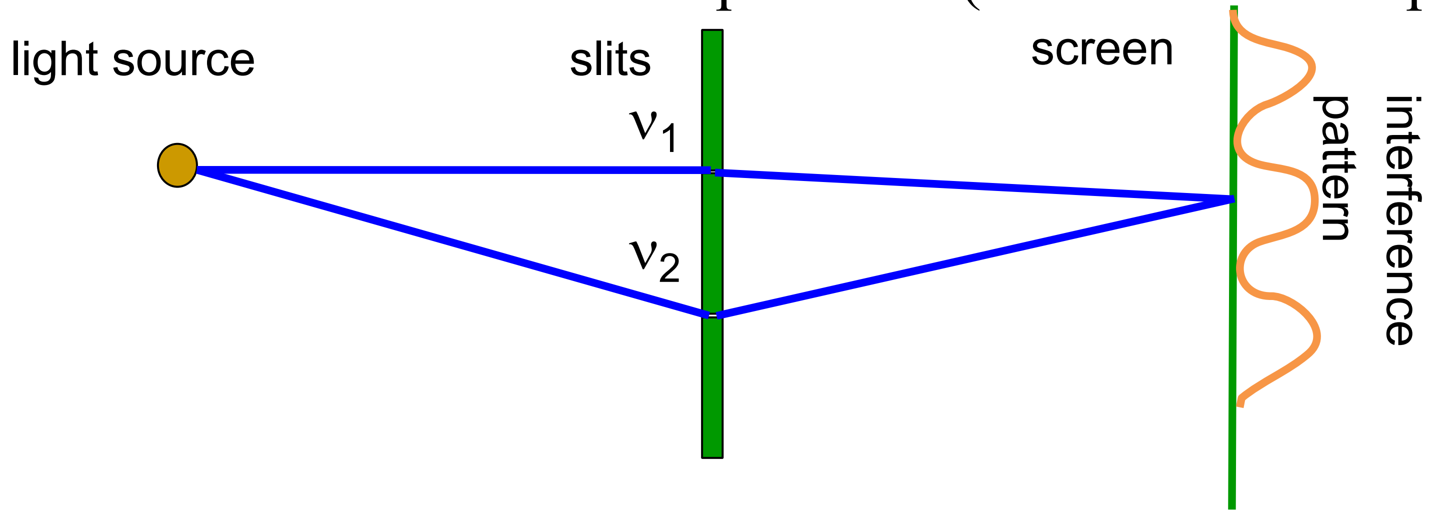


Neutral Current (NC) interaction
"Z-boson exchange"

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

Neutrino oscillation experiments

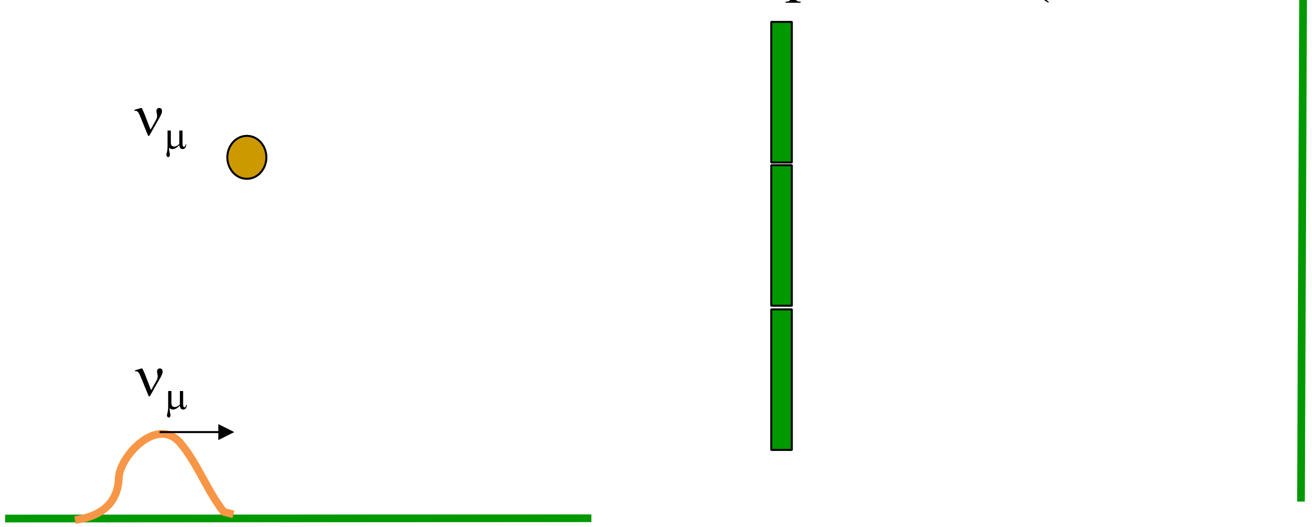
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

Neutrino oscillation experiments

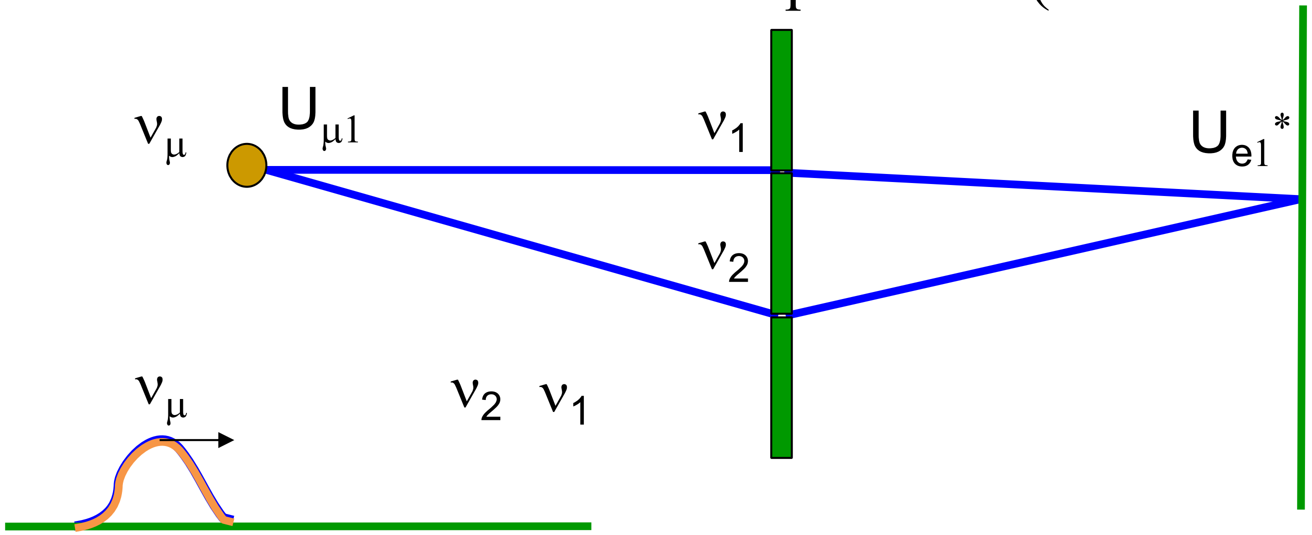
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

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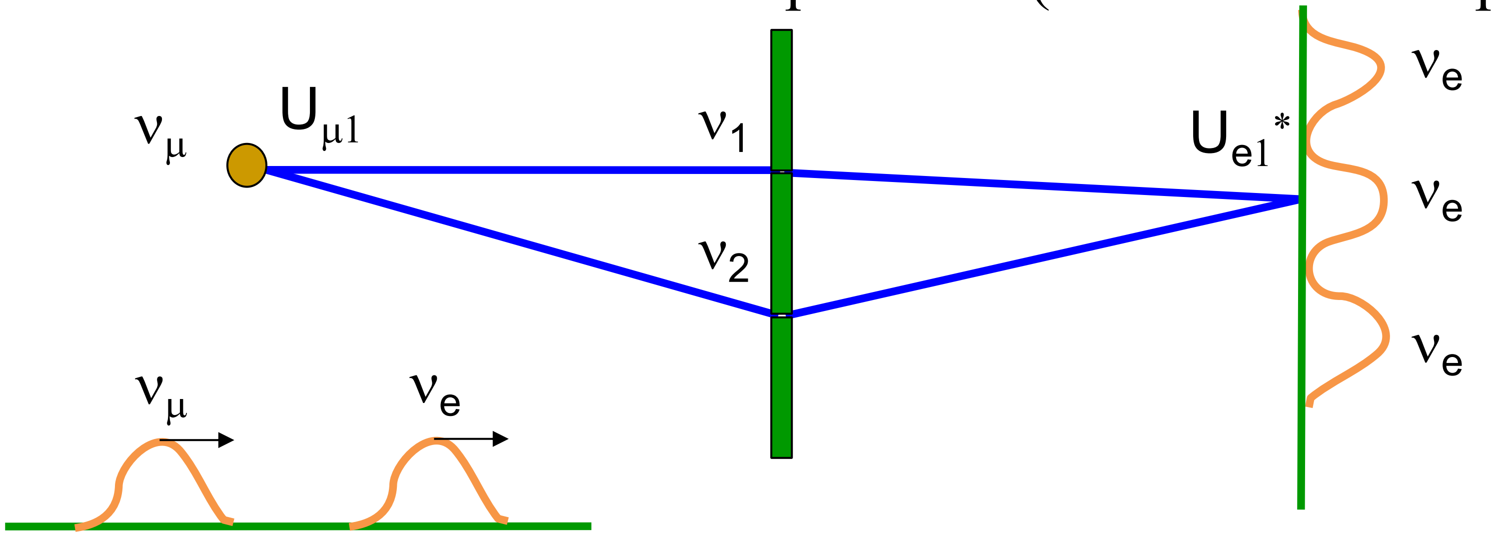


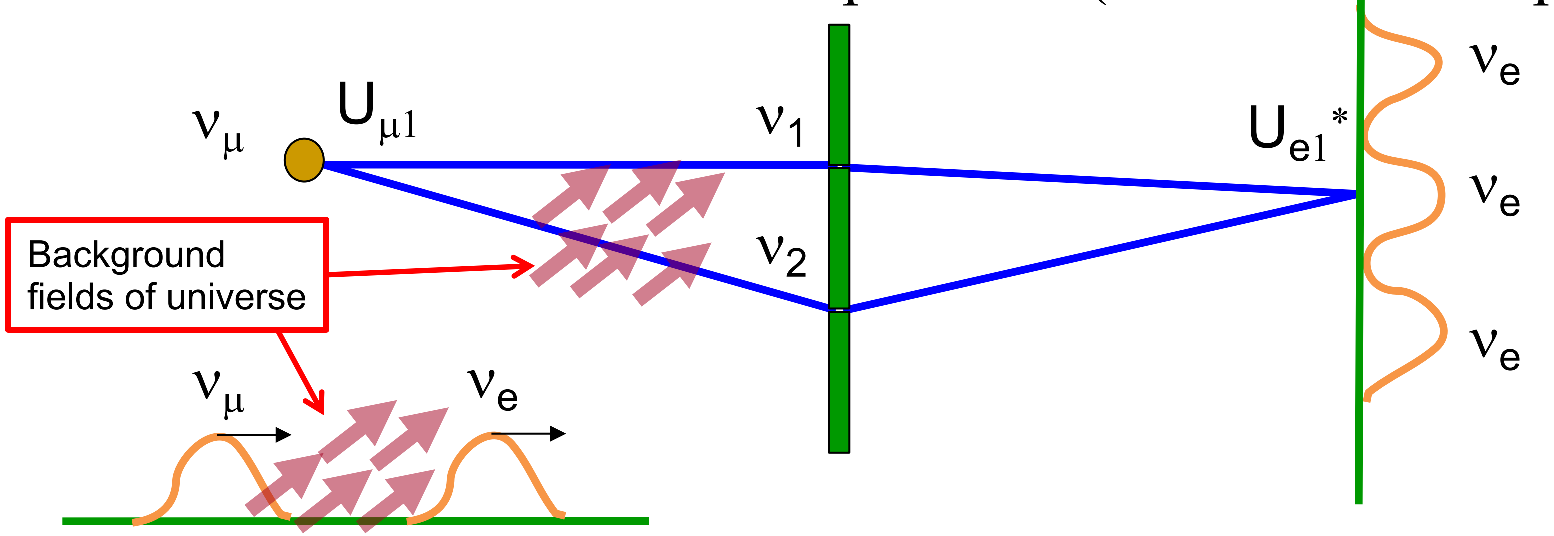
Neutrino flavour eigenstates are super-position of Hamiltonian eigenstates ν_1 and ν_2

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

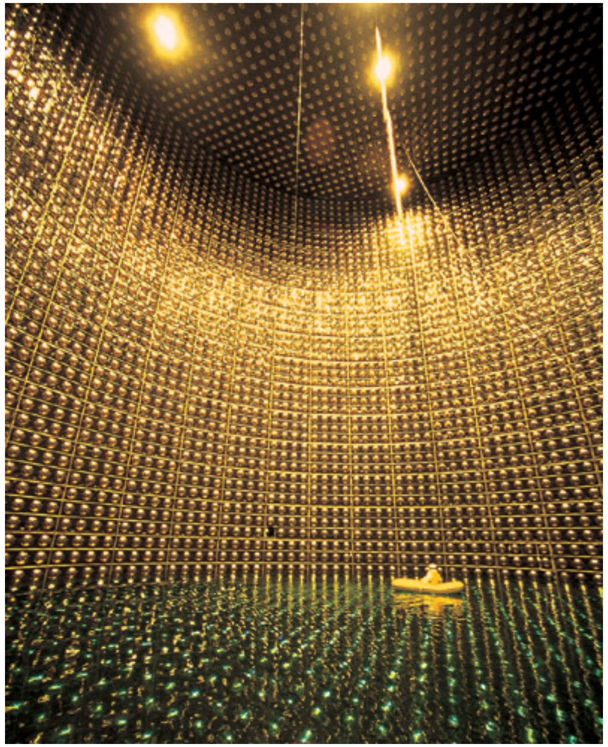
→ anomalous neutrino oscillation results

Neutrino oscillation experiments

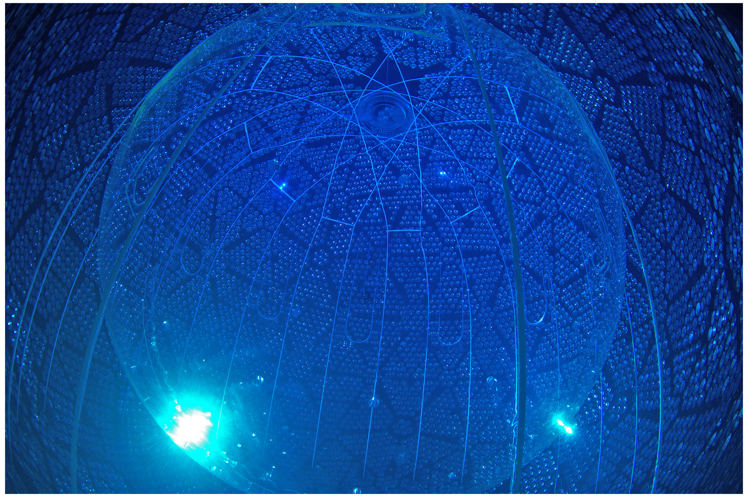
Neutrino physics → Home of anomalies

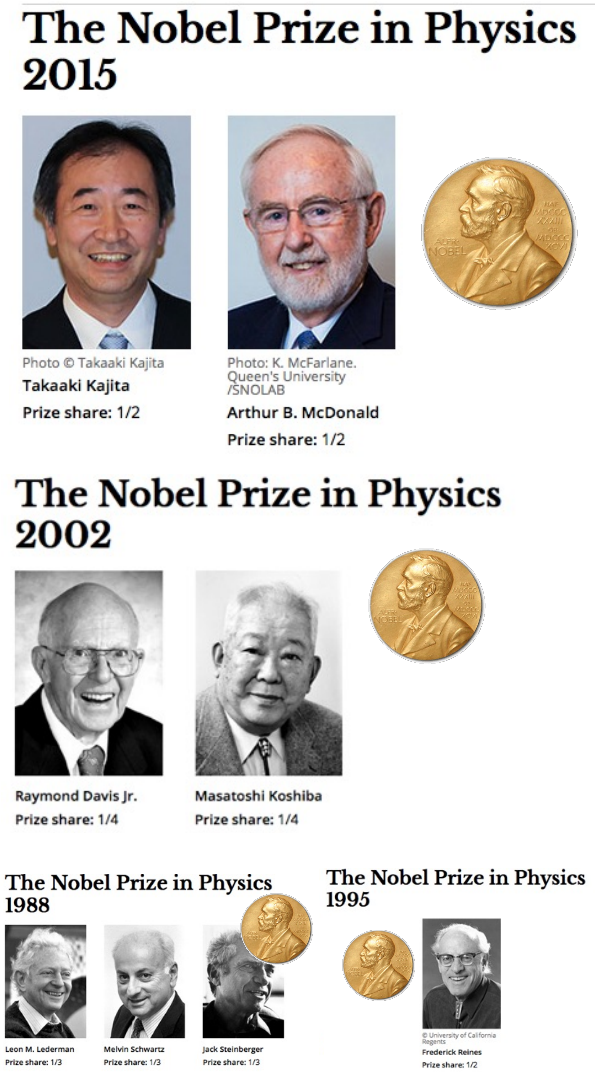
- Solar and atmospheric neutrino anomalies (Nobel prizes, 2002, 2015)

Super-Kamiokande detector



SNO detector



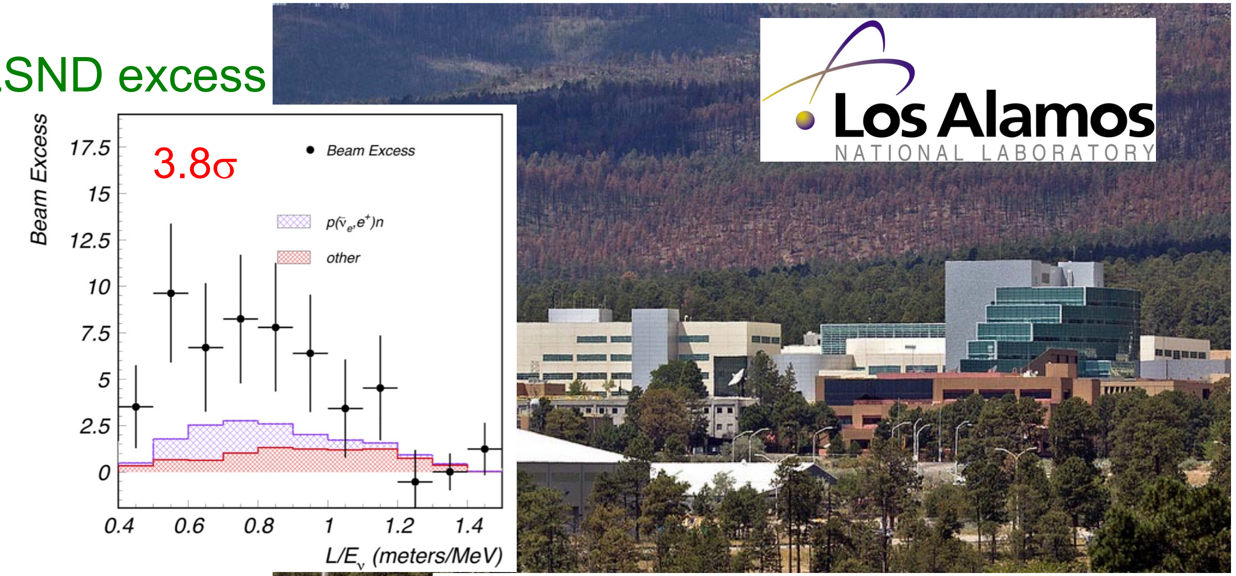


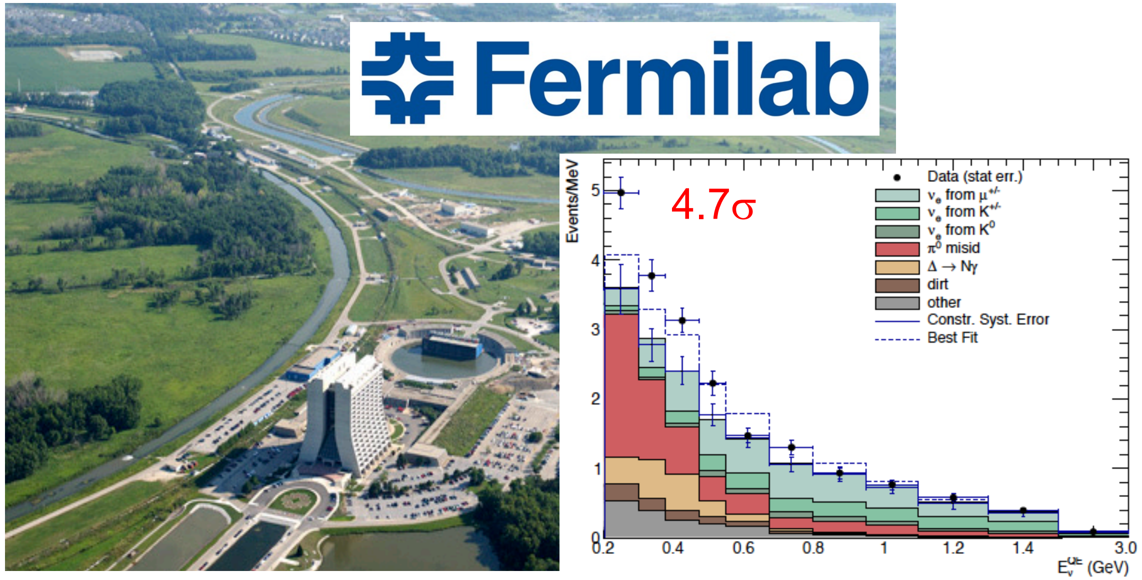
LSND, PRD64(2001)112007, MiniBooNE, PRL121(2018)22180

Neutrino oscillation experiments

Neutrino physics → Home of anomalies
- ~~Solar and atmospheric neutrino anomalies~~ (Nobel prizes, 2001, 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

MiniBooNE excess

LSND, PRD72(2005)076004, MiniBooNE, PLB718(2013)1303, TK, MPLA27(2012)1230024

Neutrino oscillation experiments

Neutrino physics → Home of anomalies
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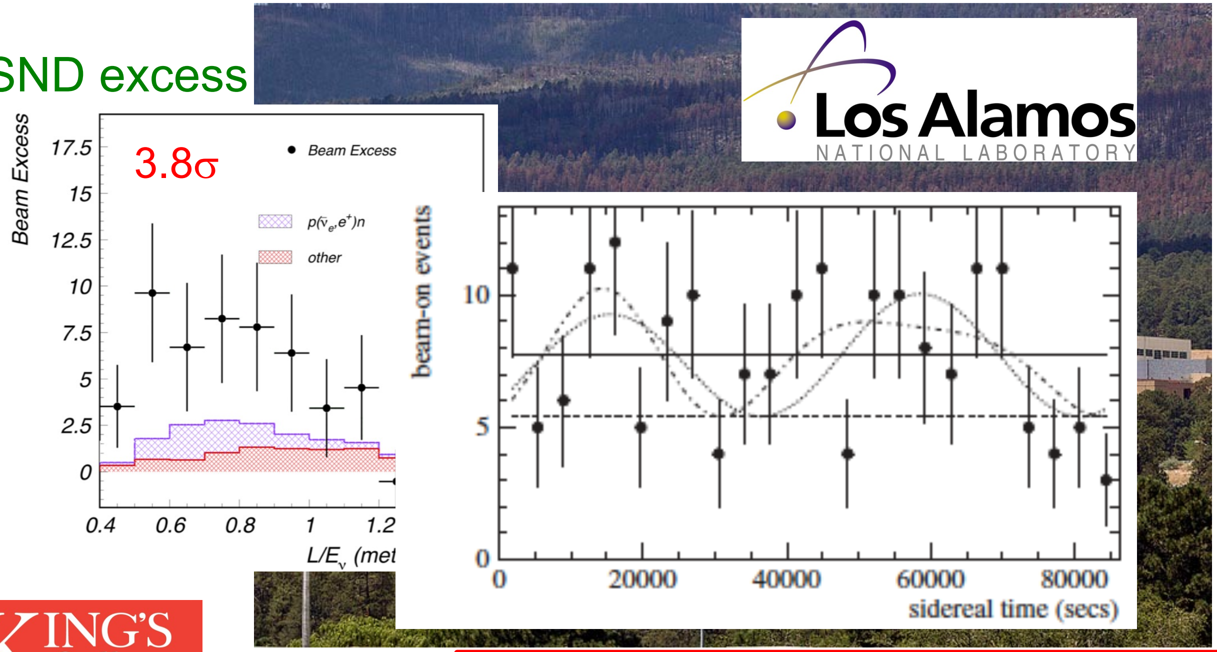
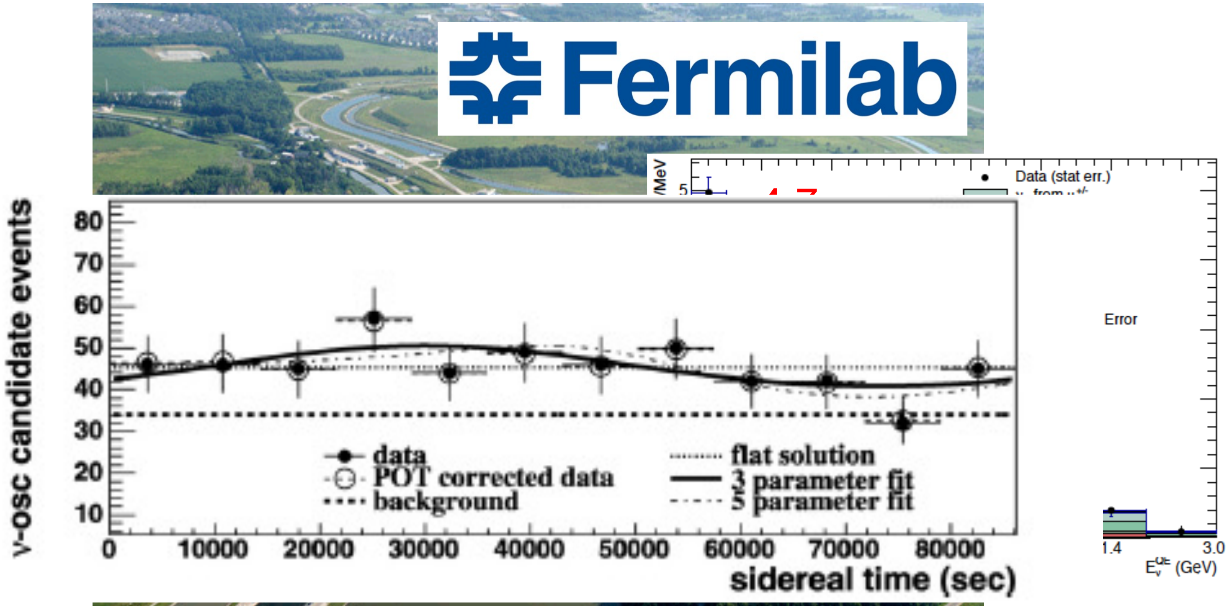
LSND excess





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.
$\vert k^{(3)}_{(V)00}\vert$	$(7.32 \pm 2.94) \times 10^{-45}$ GeV	CMB polarization	[131], [132]*
$\vert k^{(3)}_{(V)00}\vert$	$< 1.54 \times 10^{-44}$ GeV	”	[133]*
$\vert \mathbf{k_{AF}}\vert$	$< 7.4 \times 10^{-45}$ GeV	”	[133]*
$\vert \mathbf{k_{AF}}\vert$	$< 1.03 \times 10^{-26}$ GeV	Satellites	[134]*
k^Z_{AF}	[illegible]	[illegible]	[illegible]]*
”	[illegible]	[illegible]	[illegible]]*
$\vert k^{(3)}_{(V)10}\vert$	[illegible]	[illegible]	[illegible]]*
$\vert k^{(3)}_{(V)11}\vert$	[illegible]	[illegible]	[illegible]]*
$k^{(3)}_{(V)10}$	[illegible]	[illegible]	[illegible]], [138]*

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

Combination	Result	System	Ref.
$\vert\bar{c}^p_{0k}\vert$	$< 1 \times 10^{-8}$	Binary pulsars	[75]*
$\vert\bar{c}^p_{jk}\vert$	$< 1 \times 10^{-11}$	”	[75]*
$\vert\tilde{c}_Q\vert$	$< 2 \times 10^{-11}$ 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.
$(c^{(4)}_{\text{of}})_{00}$	$> -4 \times 10^{-19}$	IceCube	[275]*
$\vert(c^{(4)}_{\text{of}})_{00}\vert$	$< 7.1 \times 10^{-9}$	SN1987A time of flight	[18]*
”	$< 1.4 \times 10^{-4}$	Fermilab time of flight	[18]*
$(c^{(4)}_{\text{of}})_{00}$	$-8.4 \pm 1.1^{+1.2}_{-0.9} \times 10^{-5}$	OPERA time of flight	[18]*
”	$-1.8 \pm 1.0 \times 10^{-4}$	MINOS time of flight	[18]*
$(c^{(4)}_{\text{of}})_{10}$	$(-1 \text{ to } 4) \times 10^{-17}$	IceCube	[275]*
$\vert(c^{(4)}_{\text{of}})_{10}\vert$	$< 4.4 \times 10^{-9}$	SN1987A time of flight	[18]*

ıble 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]

KING'S College LONDON

When do we find Lorentz violation???

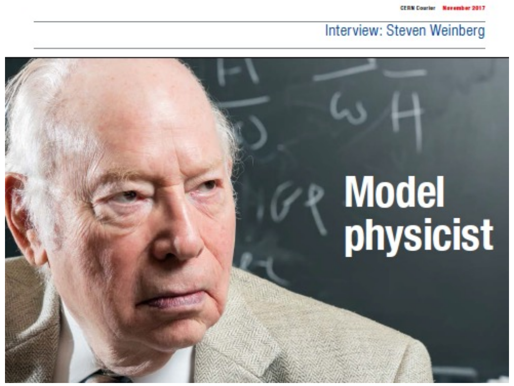
Lorentz violation is motivated by Planck scale theories, so it is suppressed with the power of Planck mass ($\sim 10^{19}\ GeV$)

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

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 – 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

Progress in Particle and Nuclear Physics 125 (2022) 103948

Lorentz violation in Astrophysics


Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

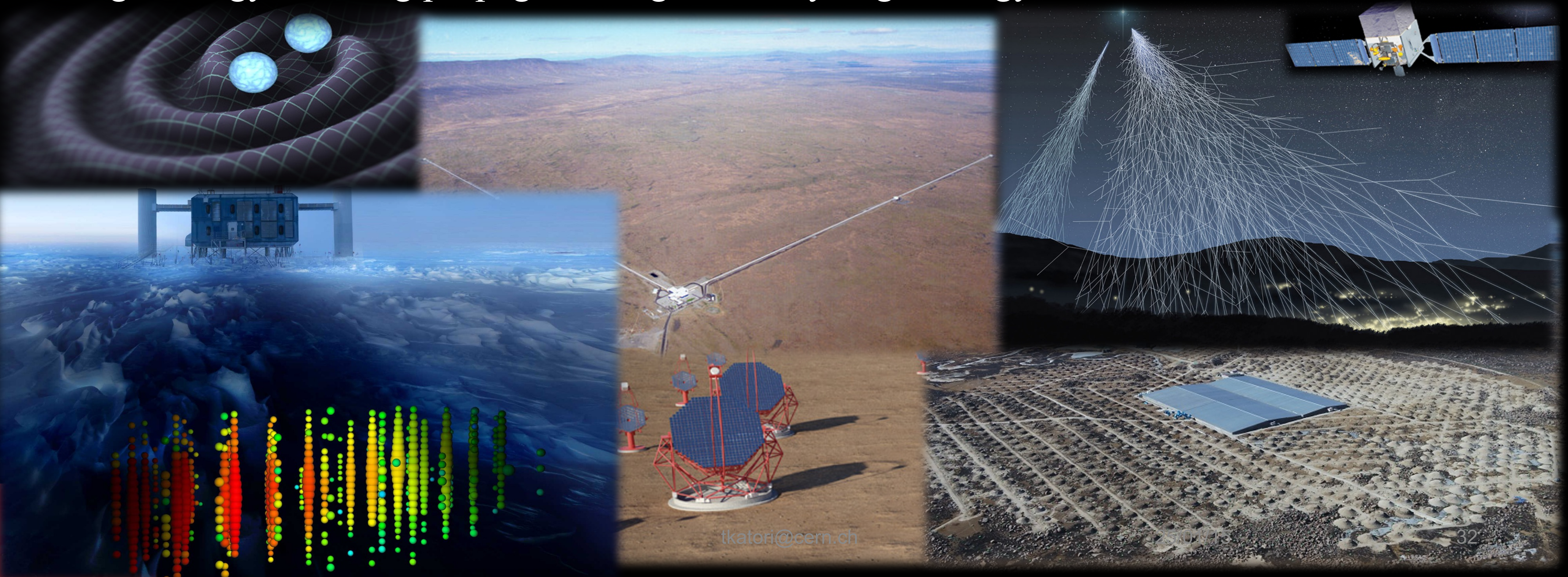
journal homepage: www.elsevier.com/locate/ppnp

ELSEVIER

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



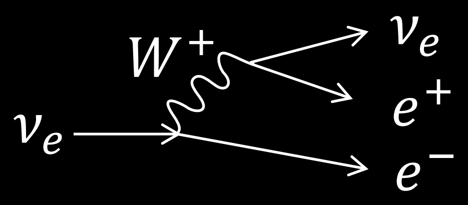
Stecker, et al, PRD91(2015)045009, and many others

Cut-off in high-energy cosmic ray spectrum

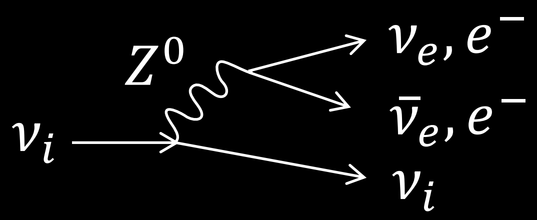
Lorentz violation = media in vacuum

- Attenuate high-energy cosmic rays

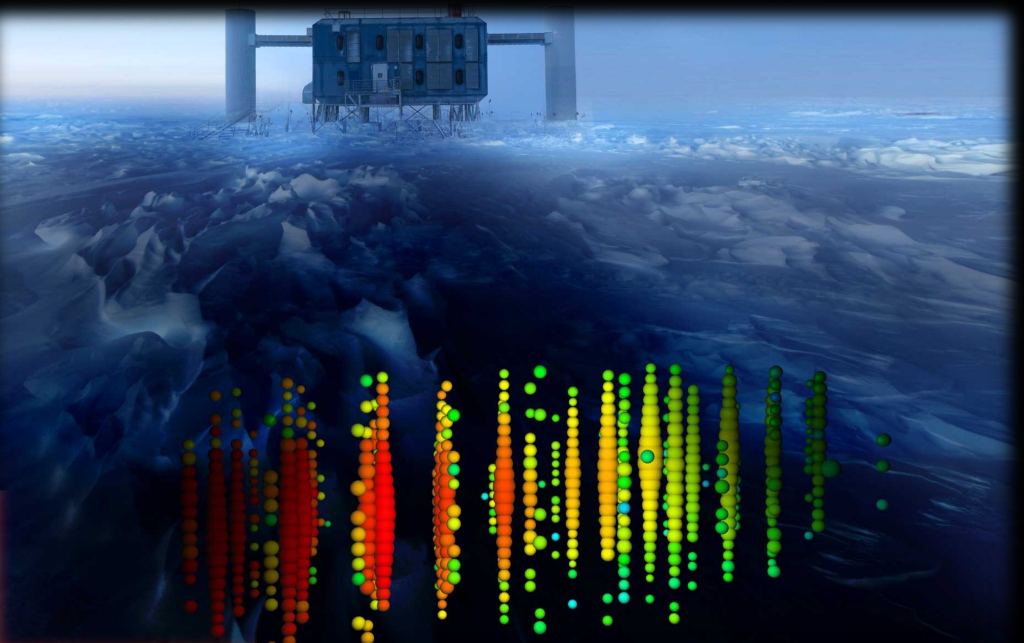
$$E^2 = p^2 + m^2 + a^{(5)}E^3 + c^{(6)}E^4 + \cdots$$

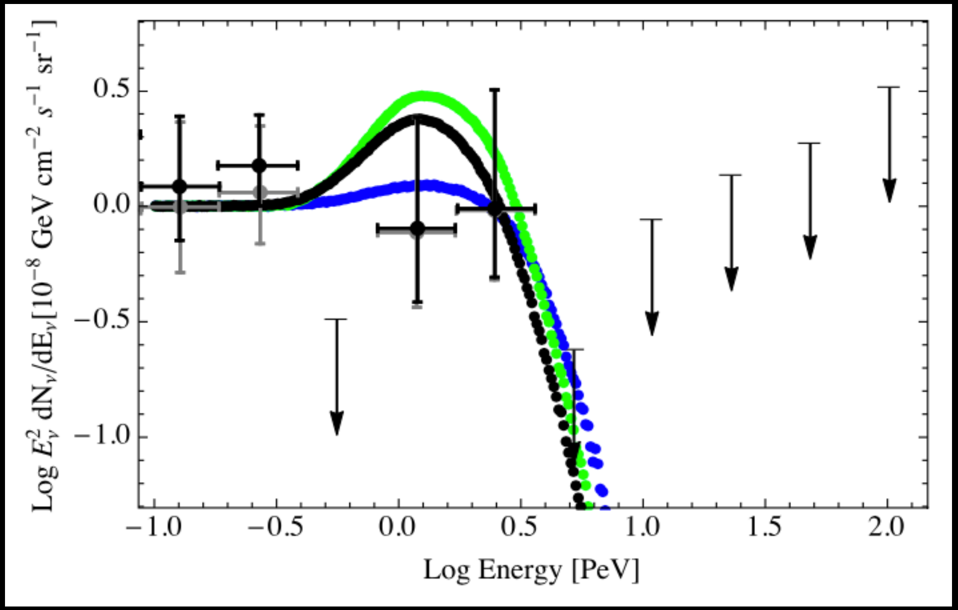


Vacuum pair emission



Neutrino splitting





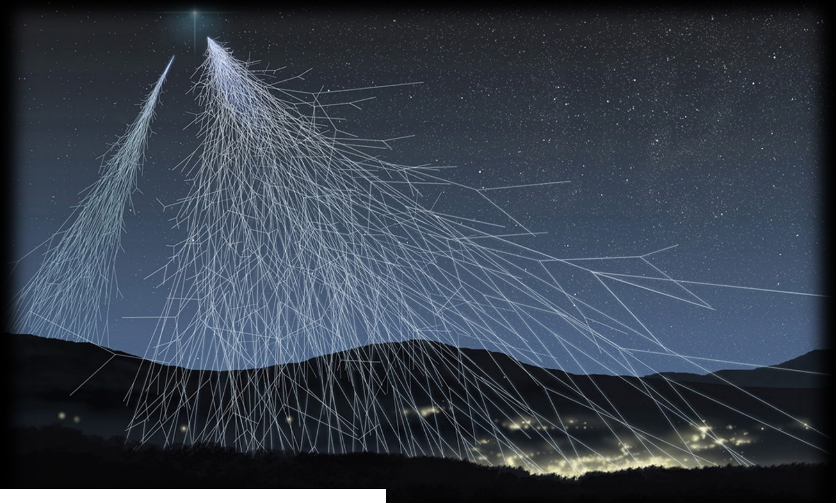
IceCube High-energy neutrino spectrum

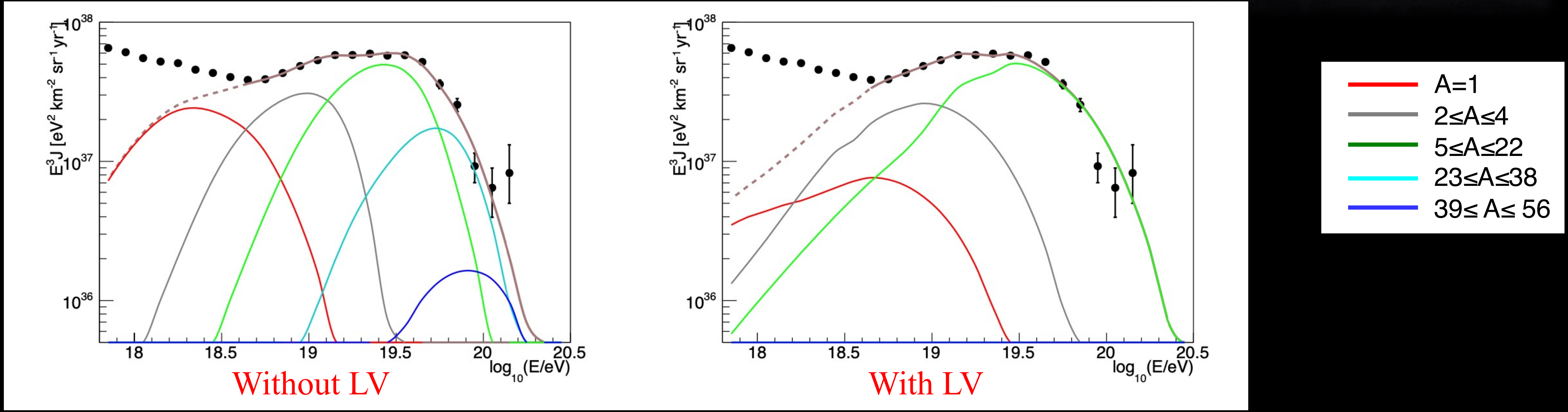
Cut-off in high-energy cosmic ray spectrum

Lorentz violation = media in vacuum

- Attenuate high-energy cosmic rays

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





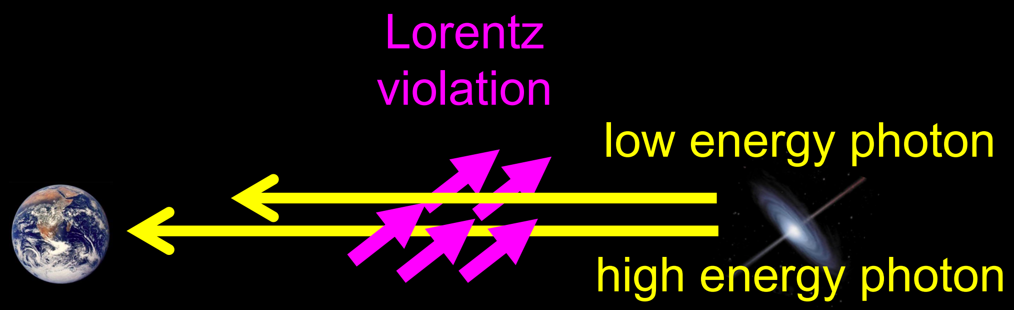
Auger UHECR spectrum

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

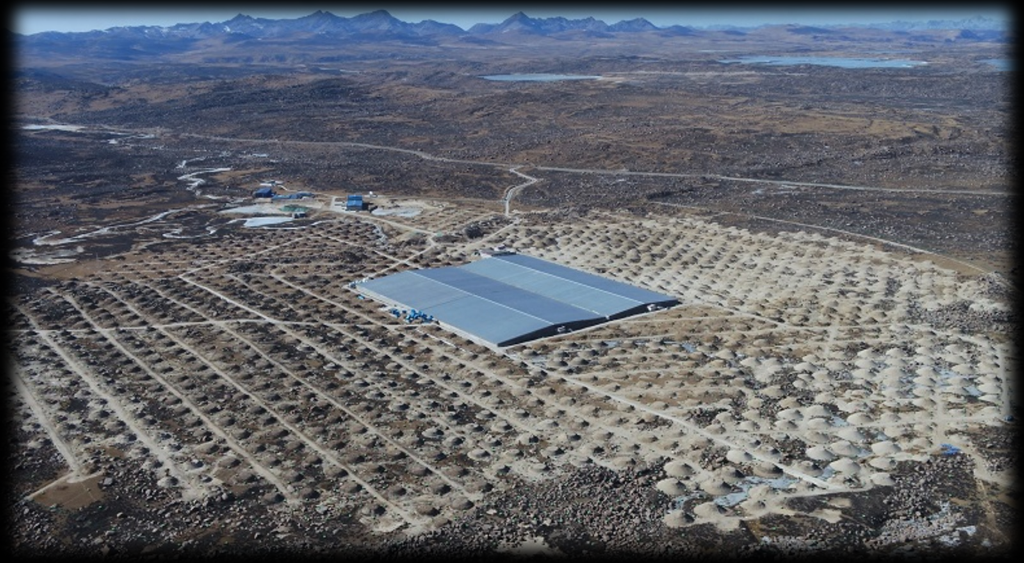
$$\delta v \sim E k_{00}^{(5)} + E^2 c_{00}^{(6)} + \cdots$$



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)



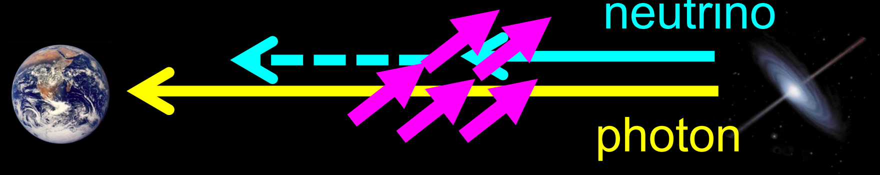
Huang and Ma, Communications Physics1(2018)62, Amelino-Camelia et al, Nature Astronomy 7(2023)996 and many others

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)

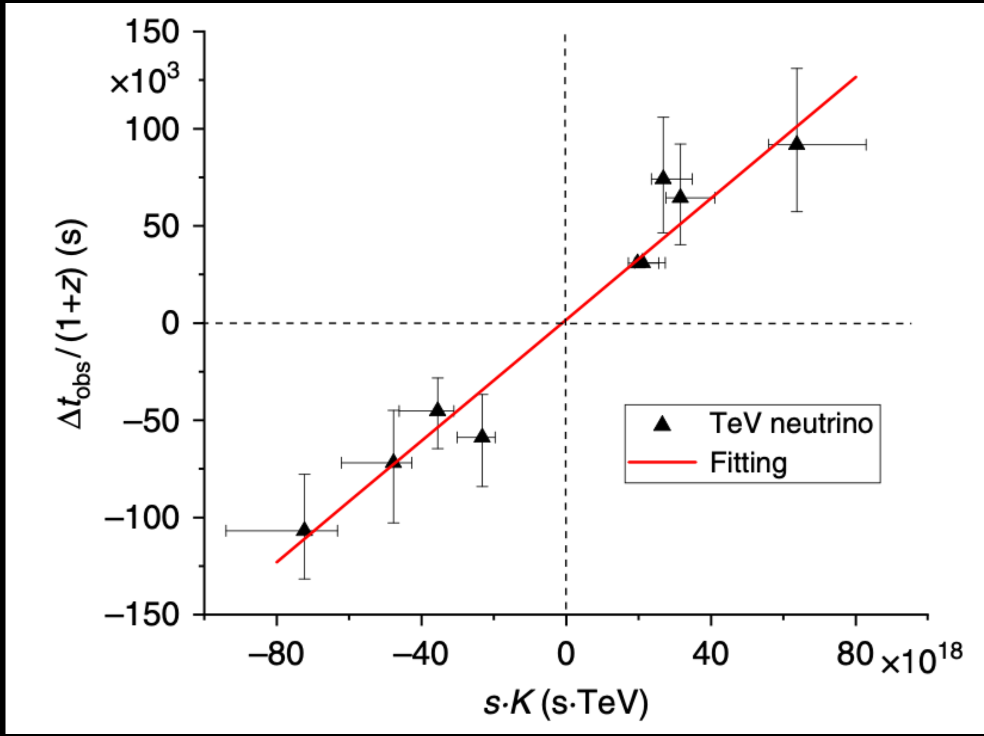
$$\delta v \sim E a^{(5)} + E^2 c^{(6)} + \cdots$$



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

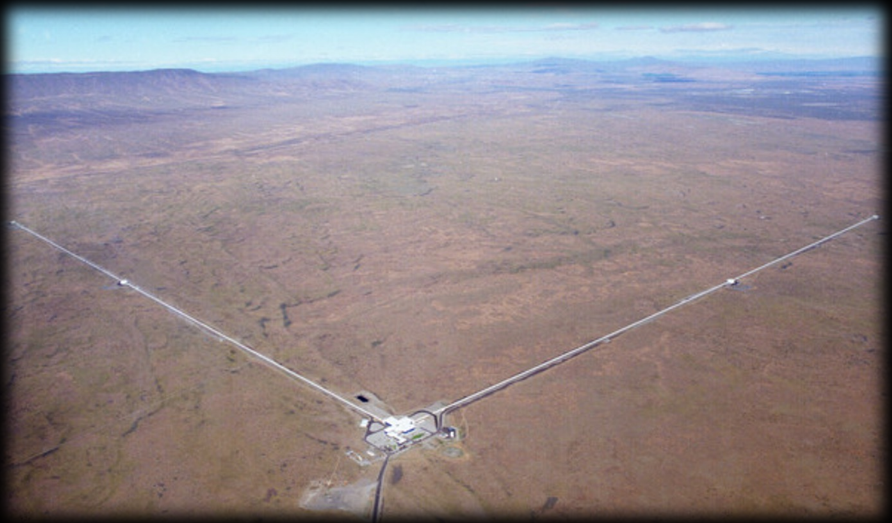


IceCube-GRB coincidence candidates with Lorentz violation

Gravity sector

Lorentz Violation ~ quantum gravity phenomenology
- New focus (EFT is difficult for gravity)

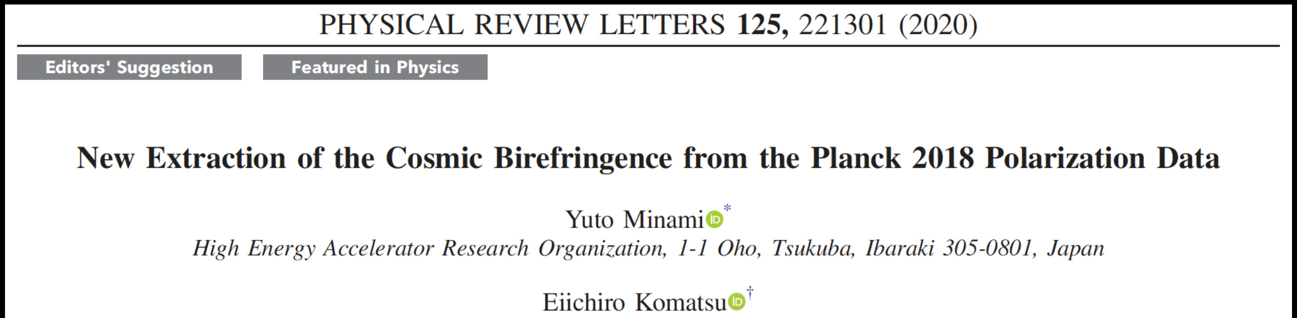
LIGO-VIRGO
- Gravitational waves LIGO, Virgo, Fermi, INTEGRAL, 2017 ApJL **848** L13
- Michelson-Morley interferometer PLB761(2016)1



Cosmic rays
- Gravitational Cherenkov radiation PLB 749 (2015) 551

Terrestrial experiments
- Matter wave interferometer PRL100(2008)031101 and many others

Vacuum birefringence


PHYSICAL REVIEW LETTERS **125**, 221301 (2020)

Editors' Suggestion | Featured in Physics

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

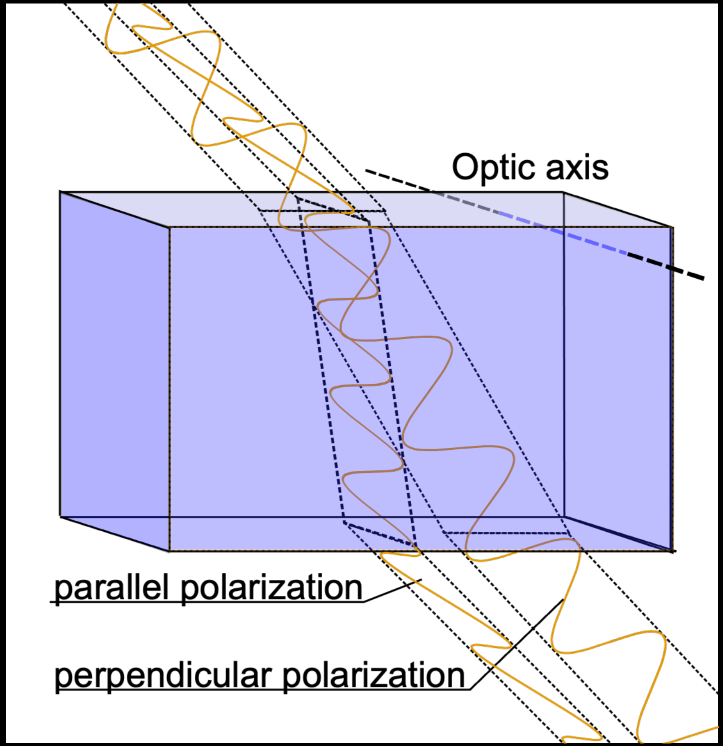
Yuto Minami*
High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Eiichiro Komatsu†

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)



IceCube, Nature Physics 18(2022)1287

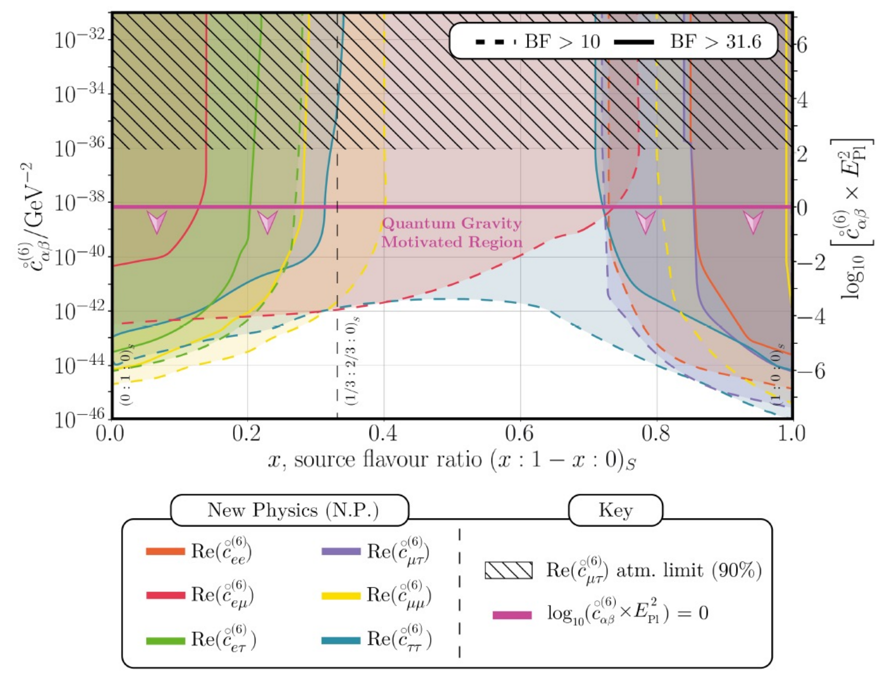
Anomalous neutrino flavour

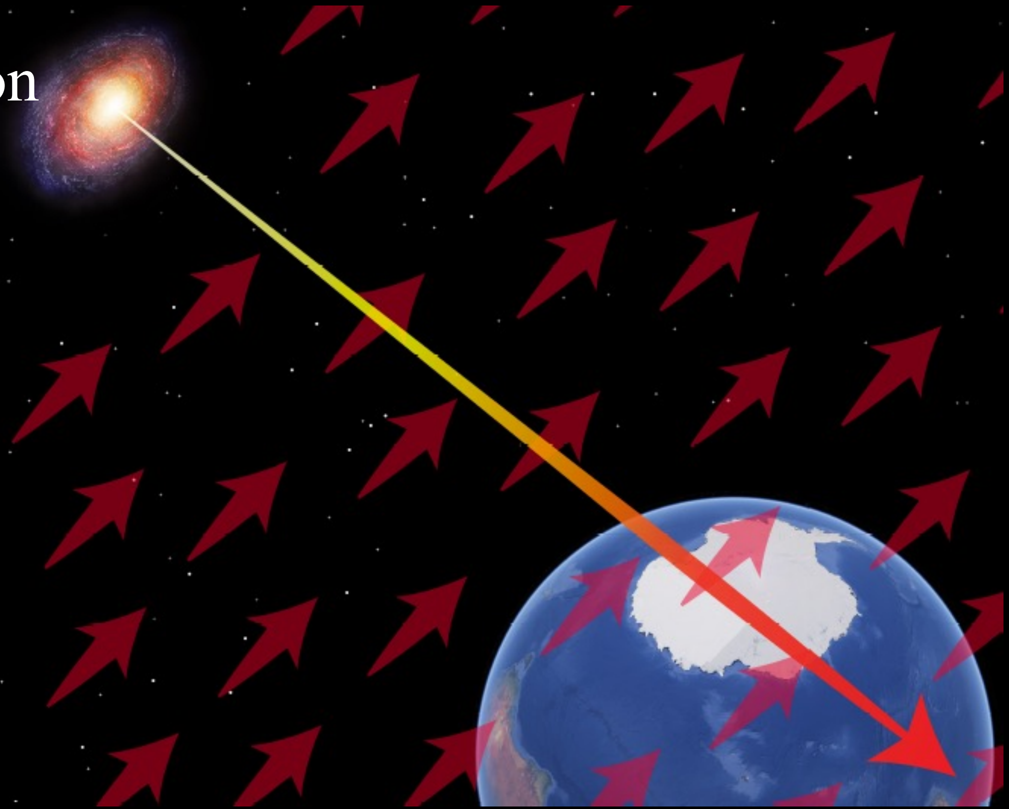
Lorentz violation = media in vacuum
 - MSW-like effect in vacuum

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

No Lorentz violation discovered

Sensitivity is neutrino production model dependent





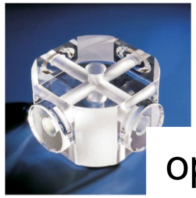
High-energy, long propagating neutrinos

Physics MMA

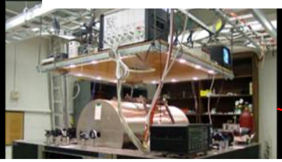
Lower dimension operators → searches by tabletop experiments
Higher dimension operators → searches by astrophysical observations

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

torsion pendulum

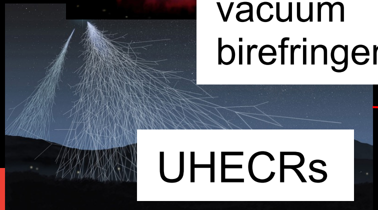


optical resonator



comagnetomator

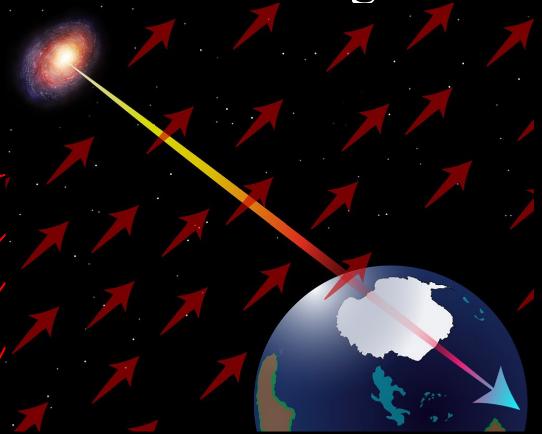
vacuum birefringence



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 mixing



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

King's College London

[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 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

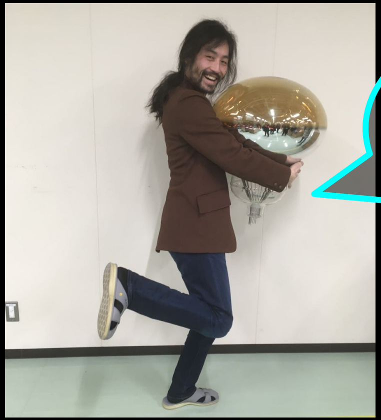
etc

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

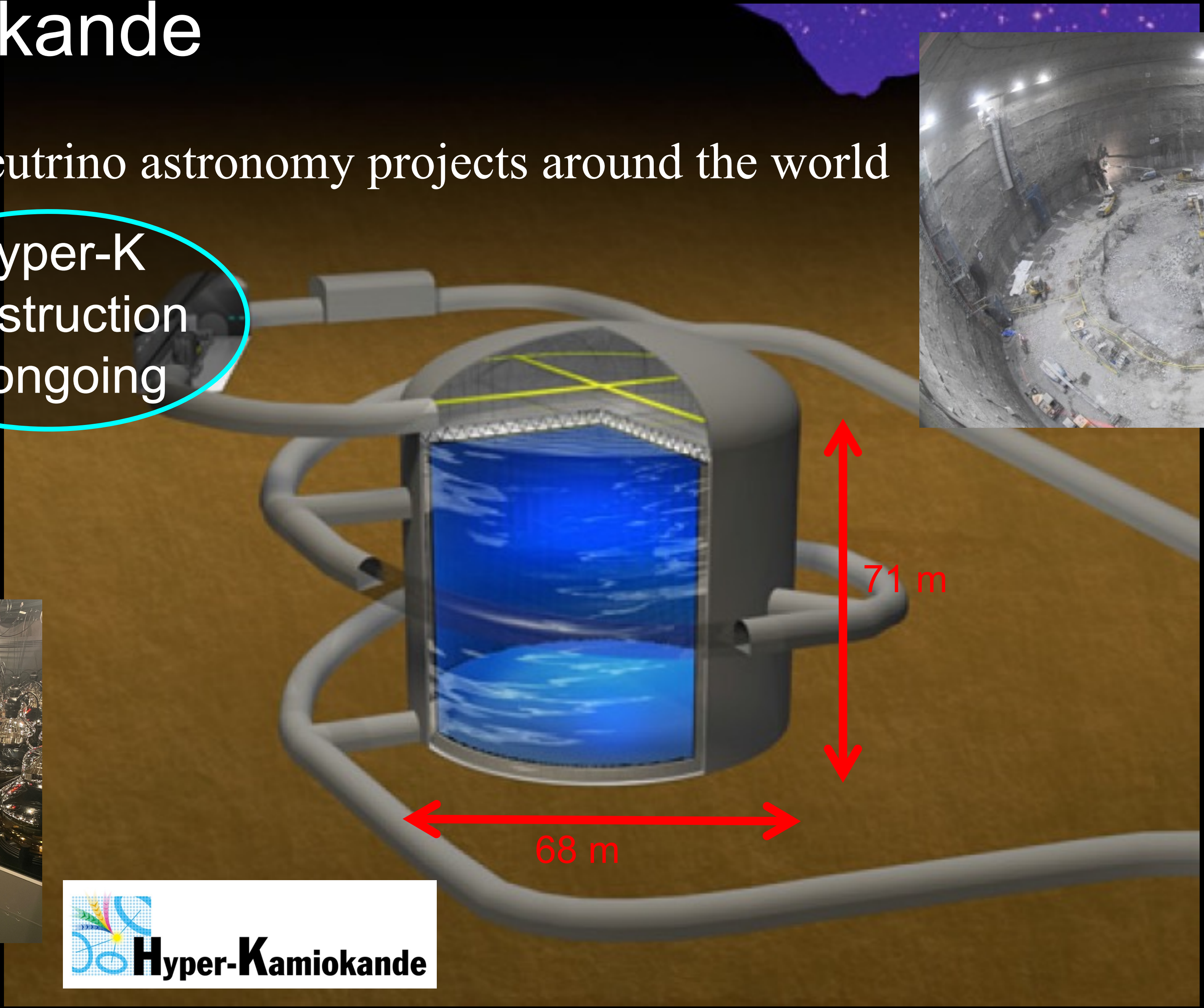
Hyper-Kamiokande, ArXiv:1805.04163

Hyper-Kamiokande

New international neutrino astronomy projects around the world

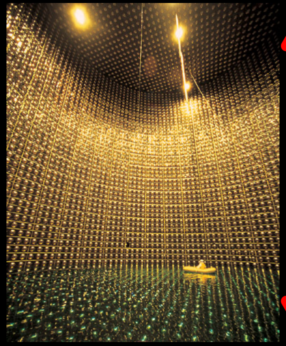


Hyper-K construction is ongoing



Hyper-Kamiokande

Super-Kamiokande

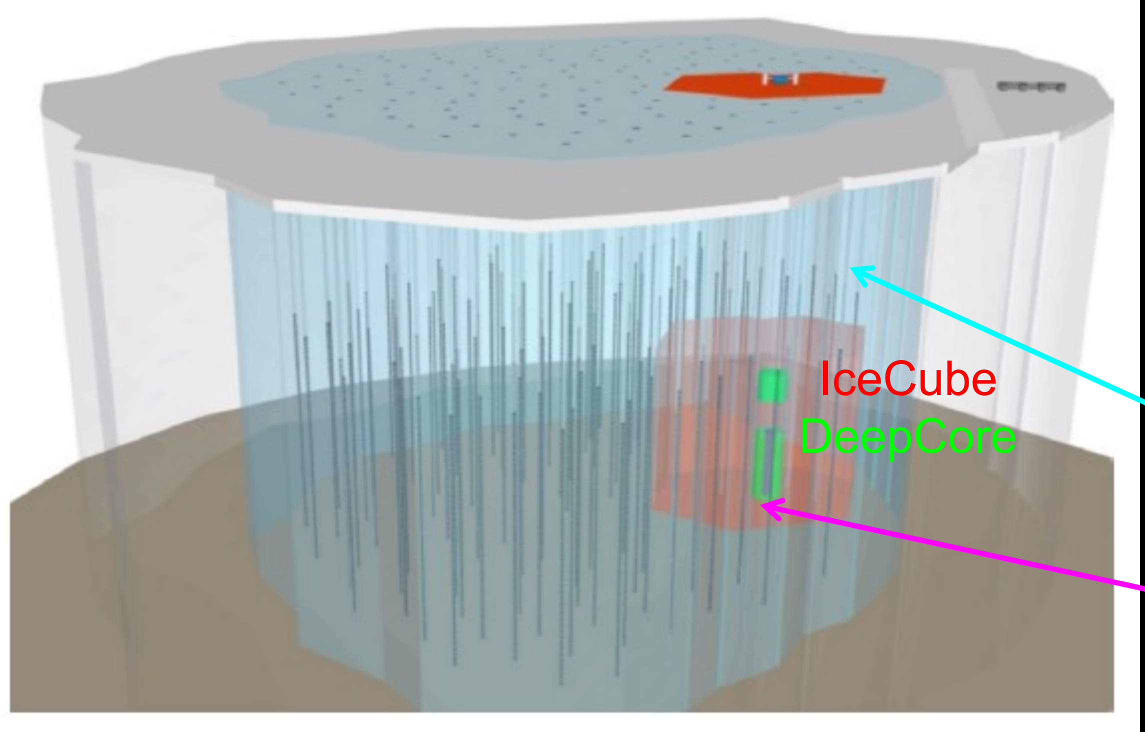


IceCube-Gen2, J.Phys.G48(2021)060501

IceCube-Gen2

New international neutrino astronomy projects around the world

Summer 2024-2045 IceCube team

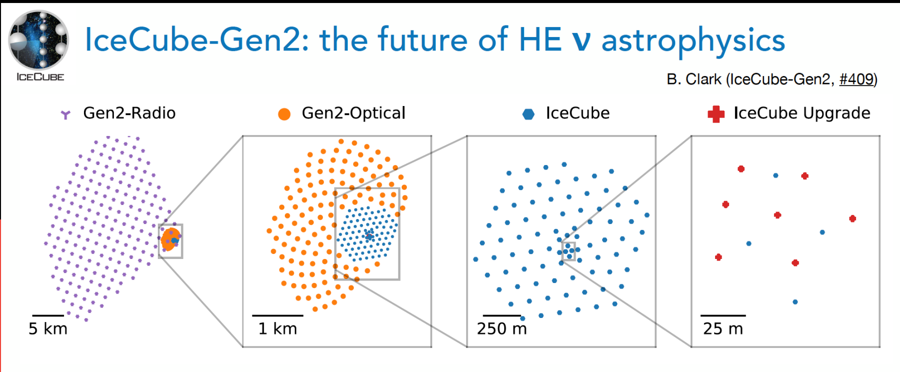


IceCube (~1Gton)

Gen2-Optical (~8 Gton)

DeepCore (>7 GeV)

IceCube-Upgrade (>3GeV)



The first stage of Gen2 (IceCube upgrade) is ongoing

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 observations are powerful tools to look for Lorentz violation

Thank you for your attention!

Backup

Models of Lorentz violation

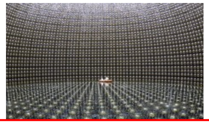
String theory, Kostelecký and Samuel, PRD39 (1989) 683
Ultra-light dark matter, Graham and Rajendran, PRD88 (2013) 035023
Quintessence, Ando, Kamionkowski, and Mocioiu, PRD80 (2009) 123522
Loop quantum gravity, Gambini and Pullin, PRD59 (1999) 124021
Non-commutative field theory, Carroll, Harvey, Kostelecký, 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

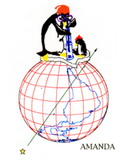


Super-Kamiokande

PRD91(2015)052003

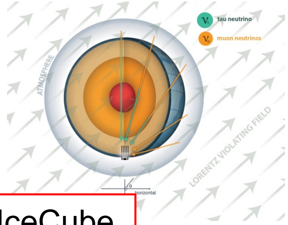
Daya Bay

PRD98(2018)092013



AMANDA

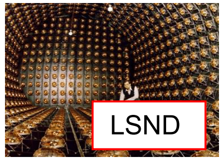
PRD79(2009)102005



IceCube

Nature Physics 14(2018)961

Sidereal variation



LSND

PRD72(2005)076004

MiniBooNE

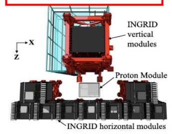
PLB718(2013)1303

MINOS ND

PRL101(2008)151601

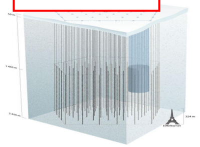
MINOS FD

PRL105(2010)151601



T2K ND

PRD95(2017)111101



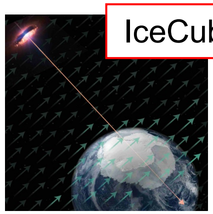
IceCube

PRD82(2010)112003

Double Chooz

PRD86(2013)112009

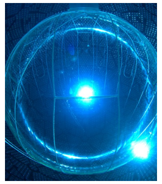
Flavor ratio



IceCube

Nature Physics, 18(2022)1287

Seasonal variation



SNO

PRD98(2018)112013

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

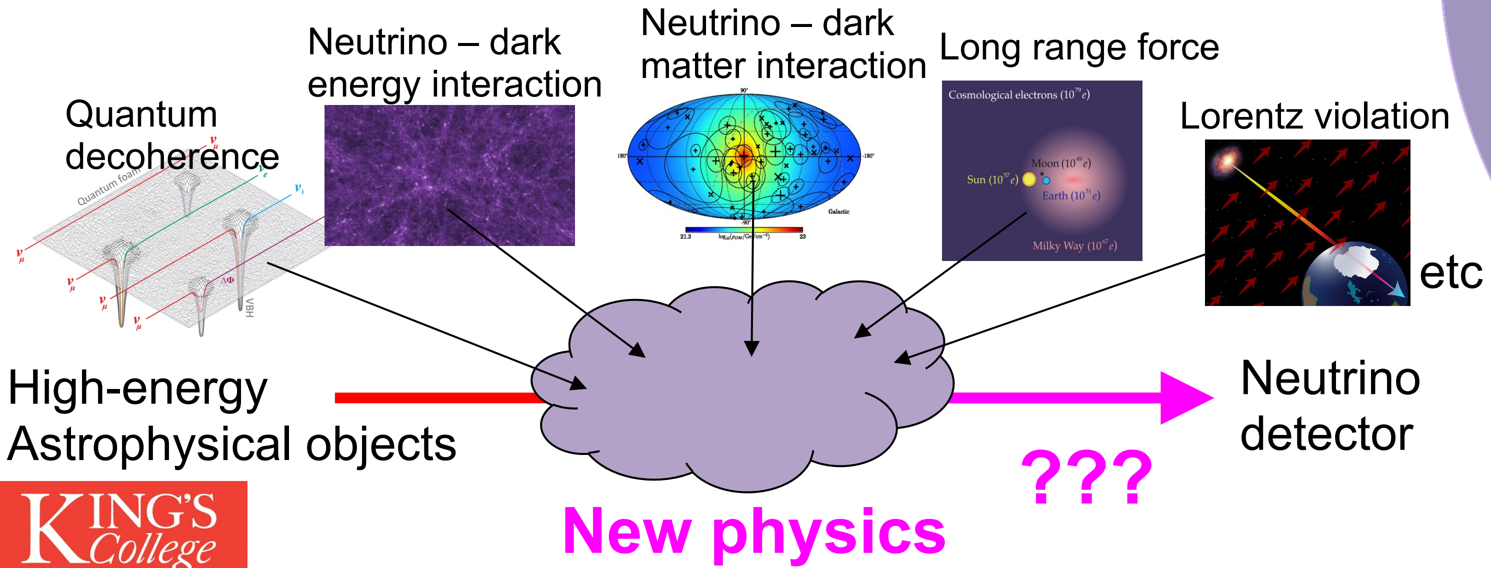
High-energy, long propagating neutrinos

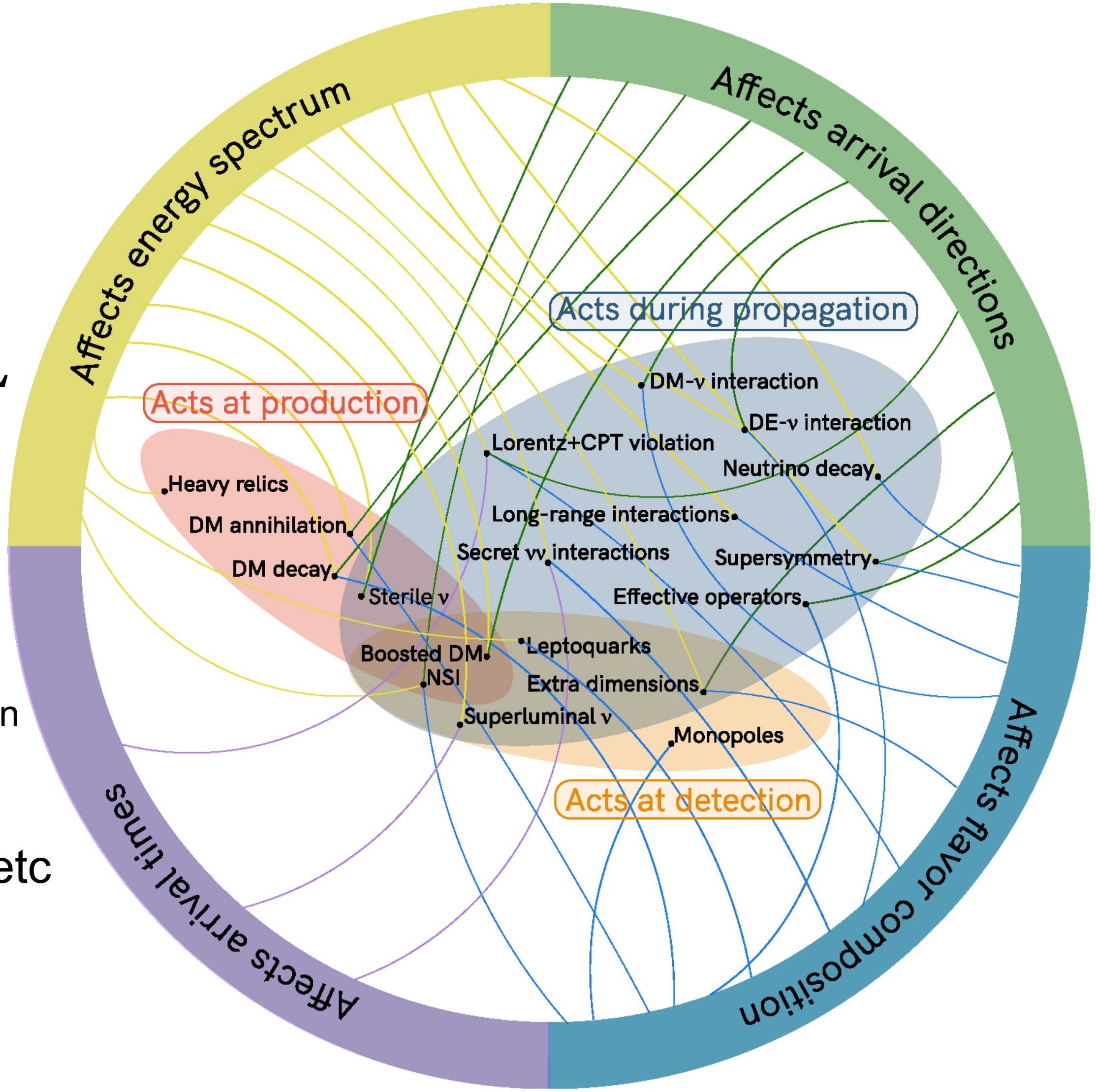
High-energy astrophysical neutrinos

- 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

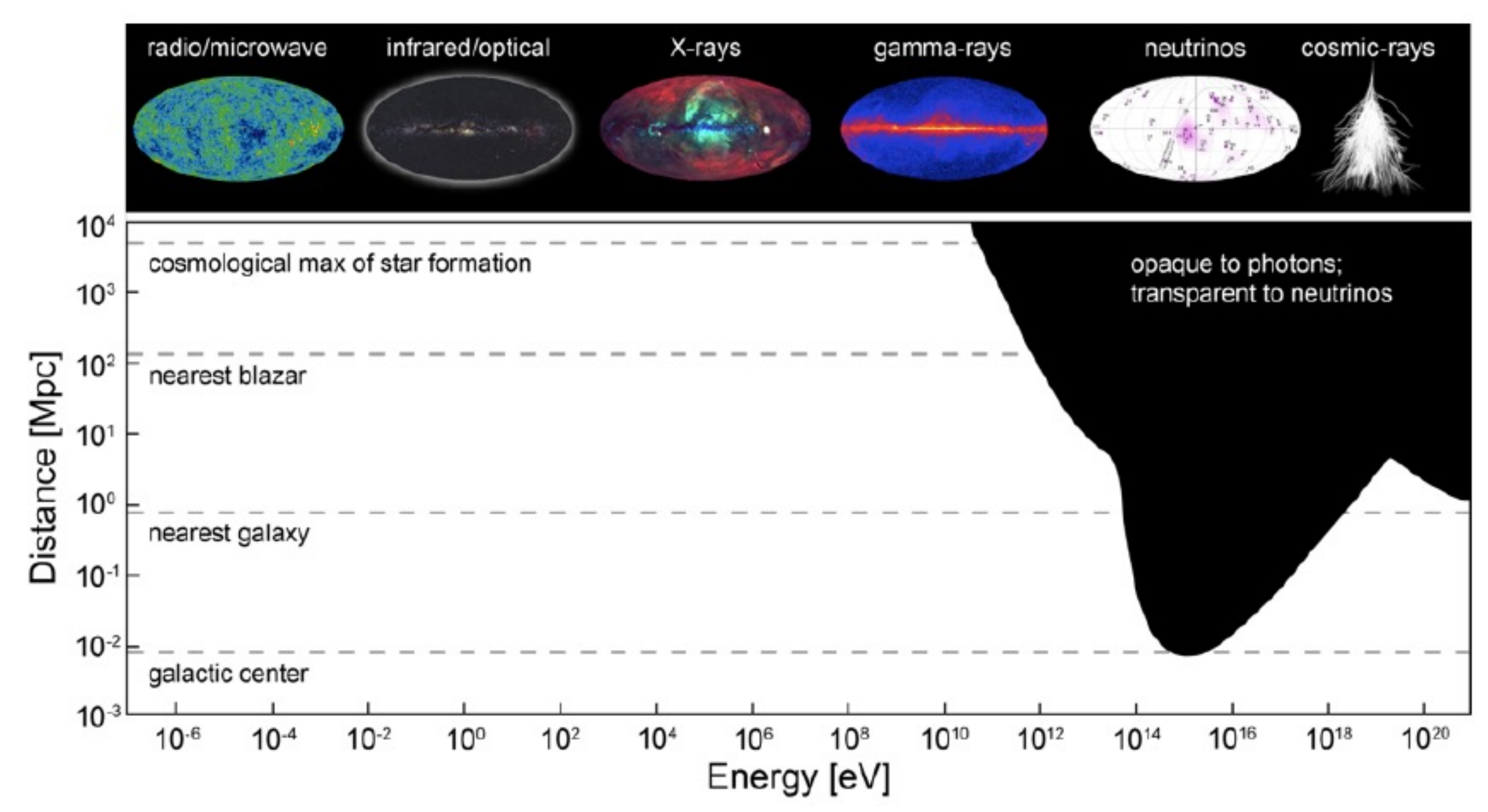




IceCube, Nature Physics(2022), (2024), Klop,Ando, PRD97(2018)063006,Argüelles,Kheirandish,Vincent, PRL119(2017)201801, Bustamante,Agarwalla, PRL122(2019)061103, Amelino-Camelia, ,Di Luca, Gubitosi, Rosati, D'Amico, Nature Astronomy (2023)

High-energy astrophysical neutrinos

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

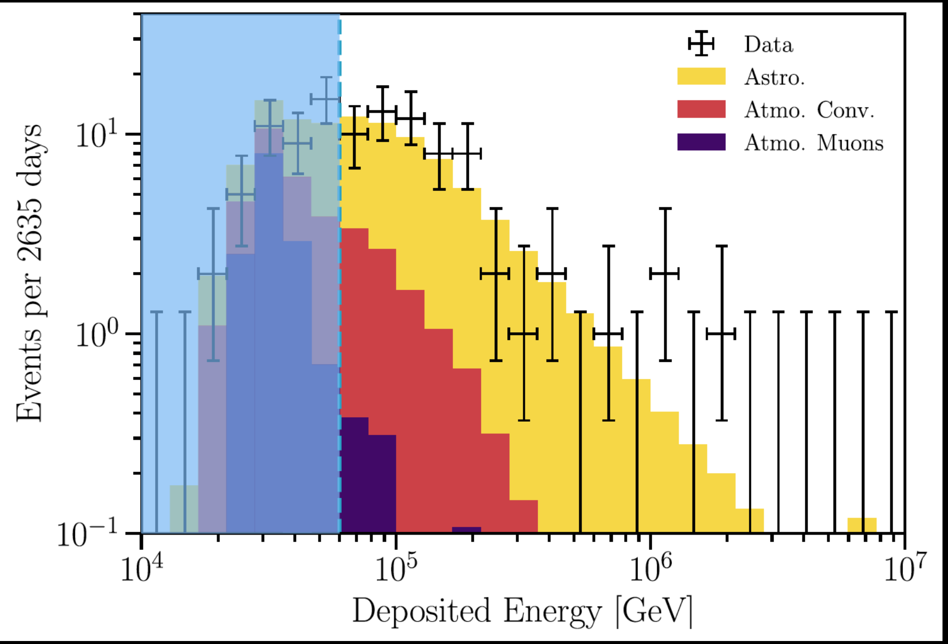


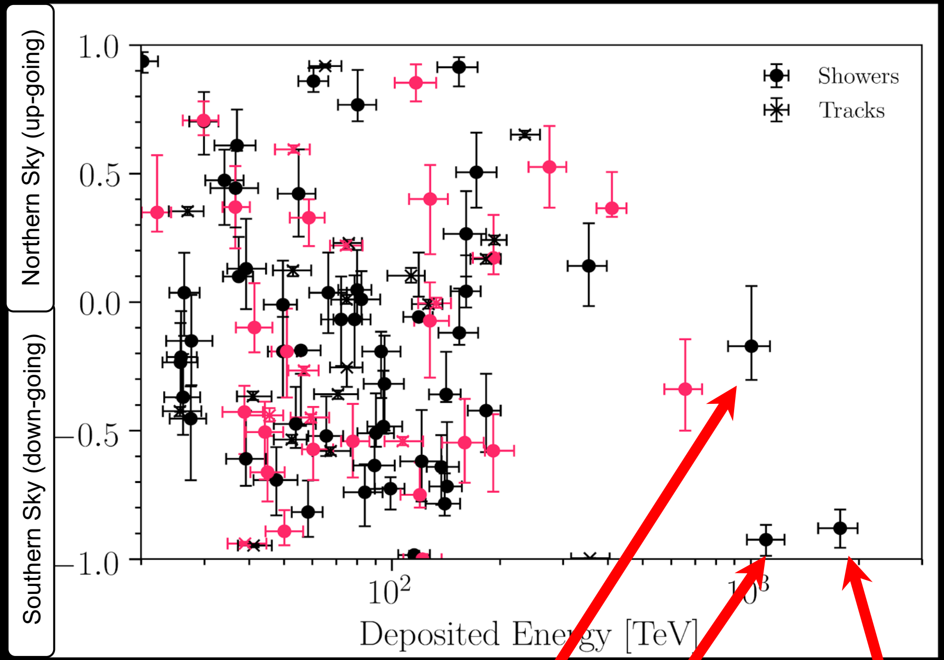
High-energy astrophysical neutrinos

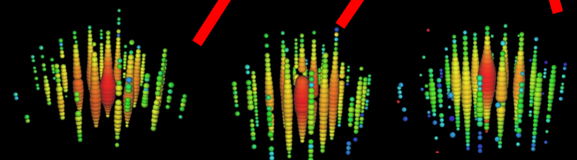
60TeV- 2PeV astrophysical neutrinos are observed by IceCube Neutrino Observatory

high-energy starting event (HESE) sample

2. Hig







"Bert"
1.1 PeV

"Ernie"
1.0 PeV

"Big Bird"
2.0 PeV

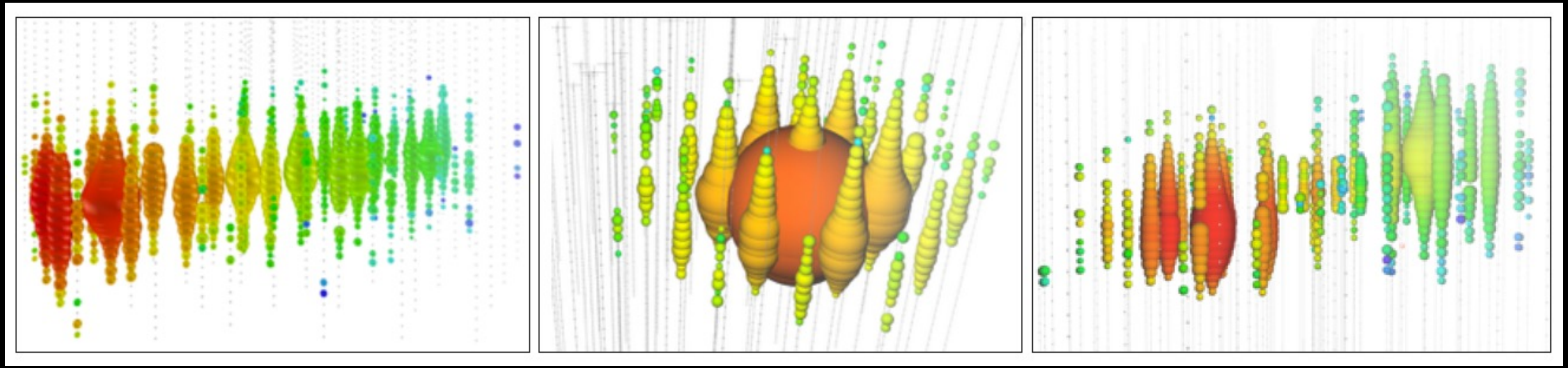
IceCube-Gen2, J.Phys.G48(2021)060501

IceCube event morphology

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

Cascade
ν_eCC, ν_τCC, NC
$$\nu_e + N \rightarrow e + X$$
$$\nu_\tau + N \rightarrow \tau + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

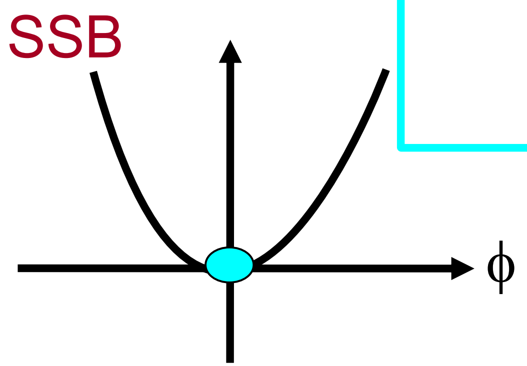
Double cascade
ν_τCC (L~50m•E/PeV)
$$\nu_\tau + N \rightarrow \tau + X$$
$$\tau \rightarrow X'$$

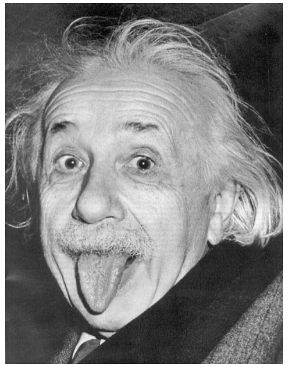


Spontaneous symmetry breaking (SSB)

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





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

Kostelecký and Samuel,PRD39(1989)683

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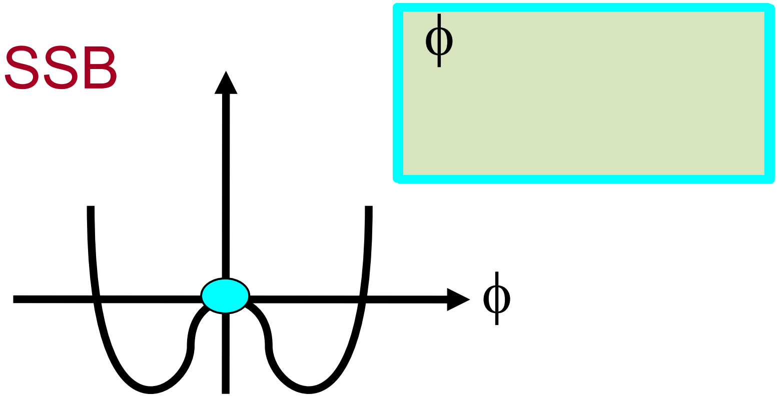
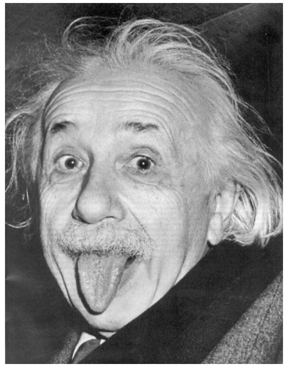




Particle acquires mass term!

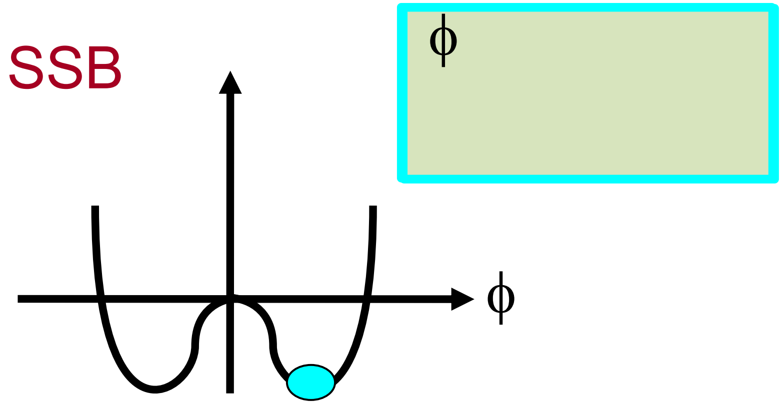
$$L = \frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4$$

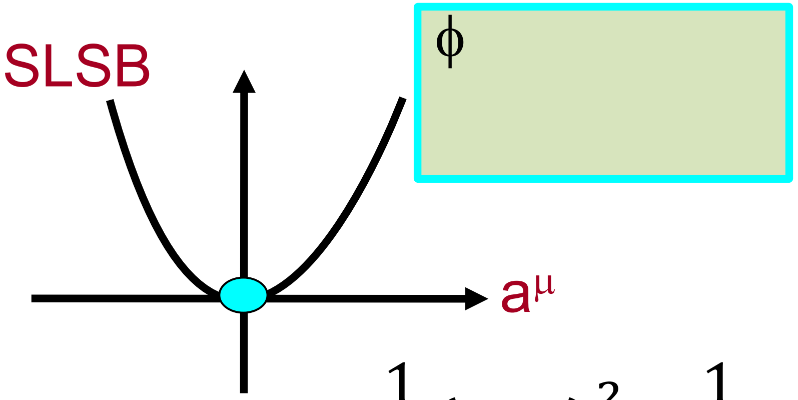
Spontaneous Lorentz symmetry breaking (SLSB)

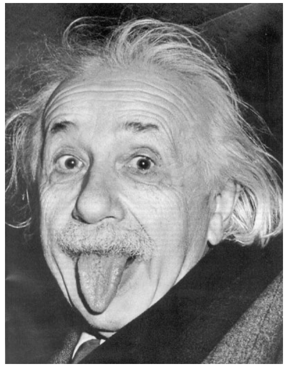
vacuum Lagrangian for fermion $L = i\bar{\psi}\gamma_\mu \partial^\mu \psi - m\bar{\psi}\psi$

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







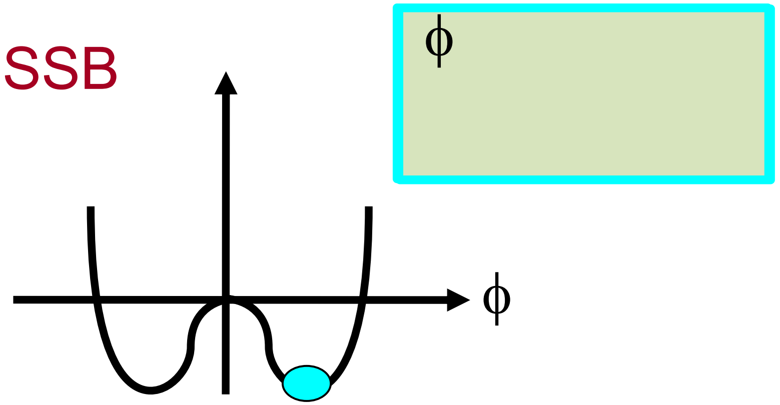
$$L = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4$$

Kostelecký and Samuel,PRD39(1989)683

Spontaneous Lorentz symmetry breaking (SLSB)

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



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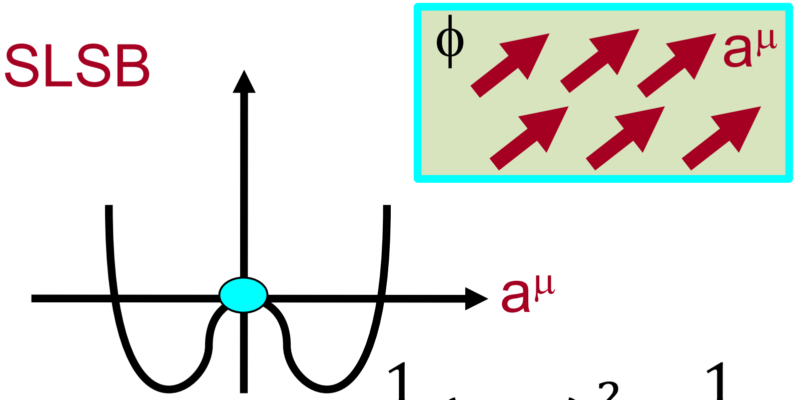
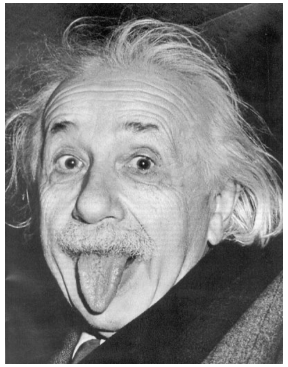


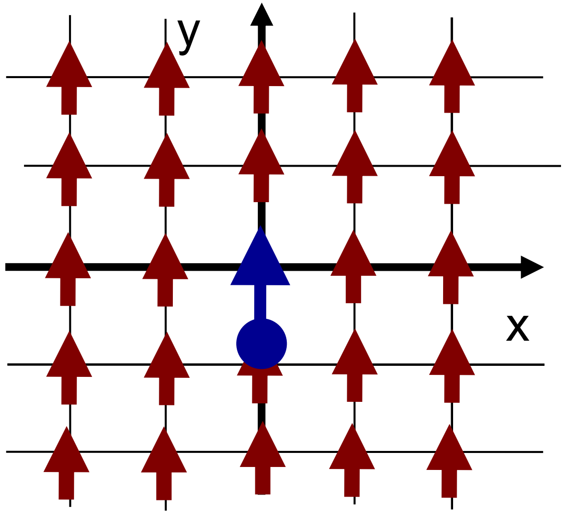


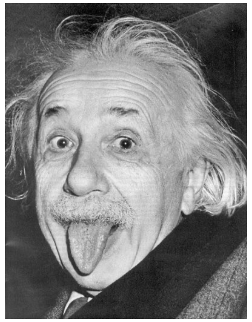
Lorentz symmetry is spontaneously broken!

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

Particle and Observer Lorentz transformation

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





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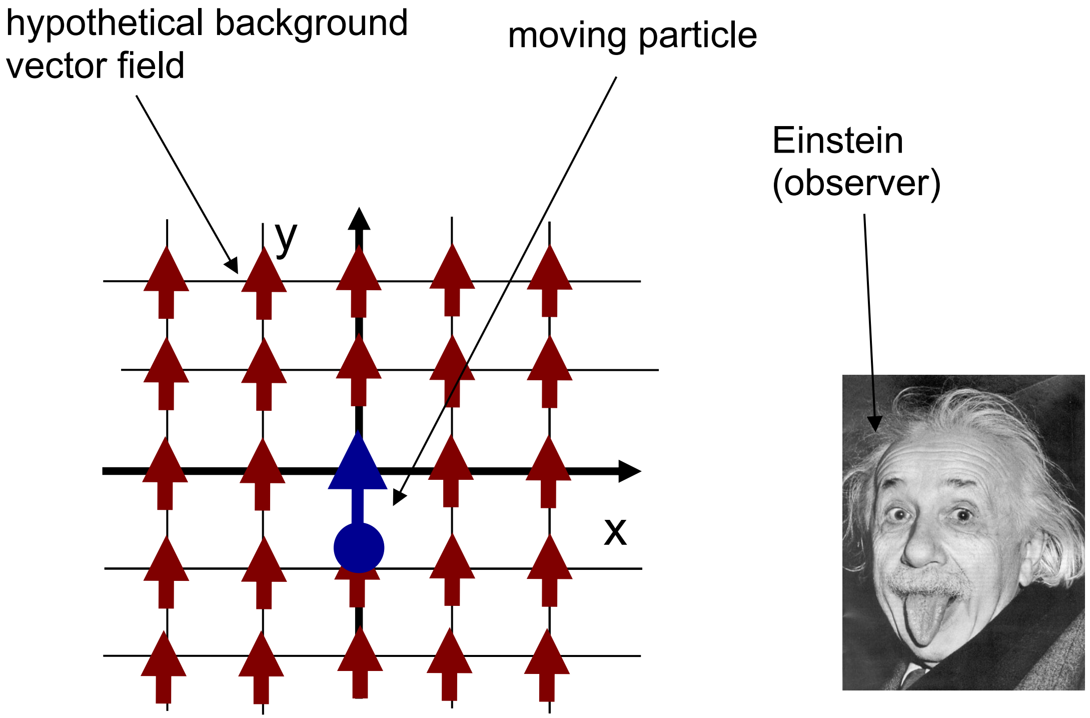
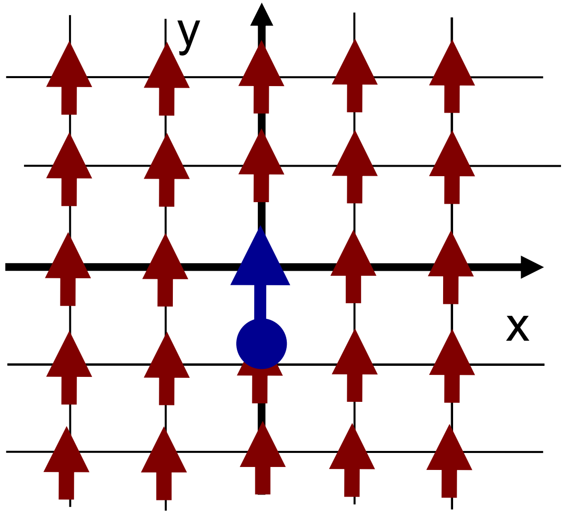
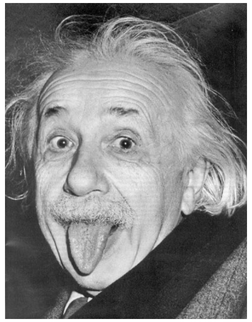


Particle and Observer Lorentz transformation

Under the particle Lorentz transformation:

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





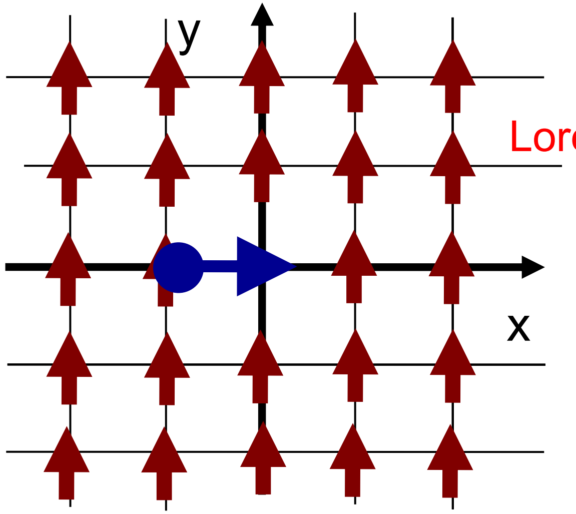
Particle and Observer Lorentz transformation

Under the particle Lorentz transformation:

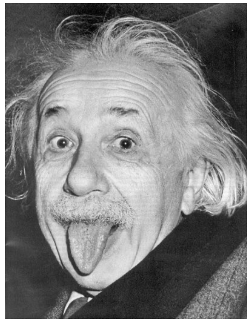
$$\overline{\Psi}(x)\gamma_{\mu}a^{\mu}\Psi(x) \rightarrow U[\overline{\Psi}(x)\gamma_{\mu}a^{\mu}\Psi(x)]U^{-1}$$

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

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



Lorentz violation!



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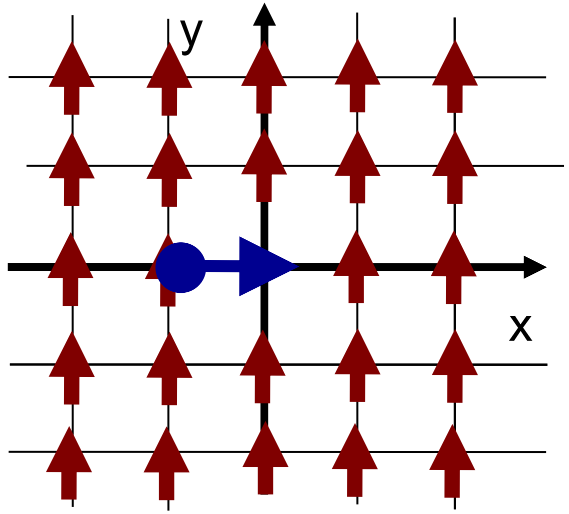
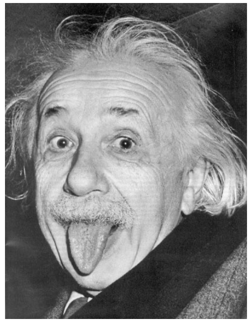
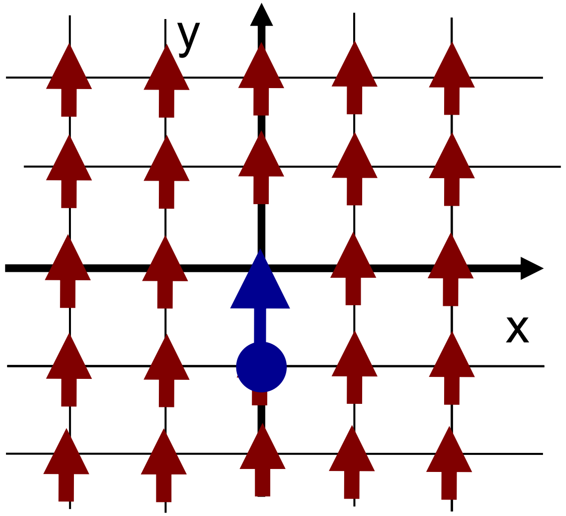


Under the observer Lorentz transformation:

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





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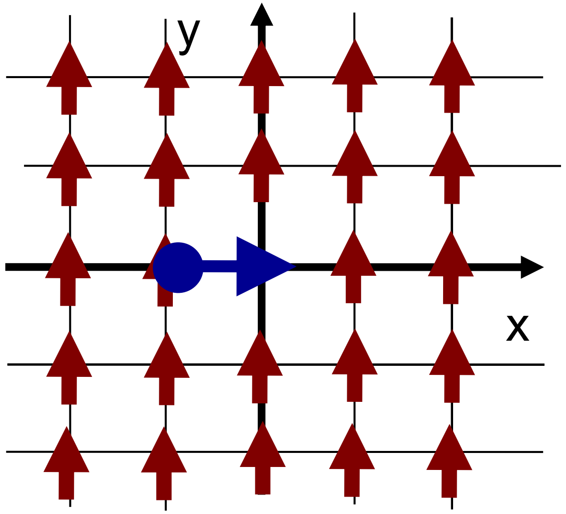
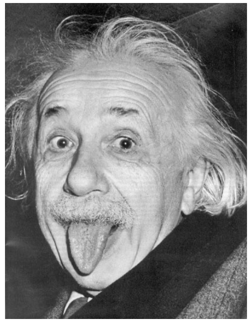
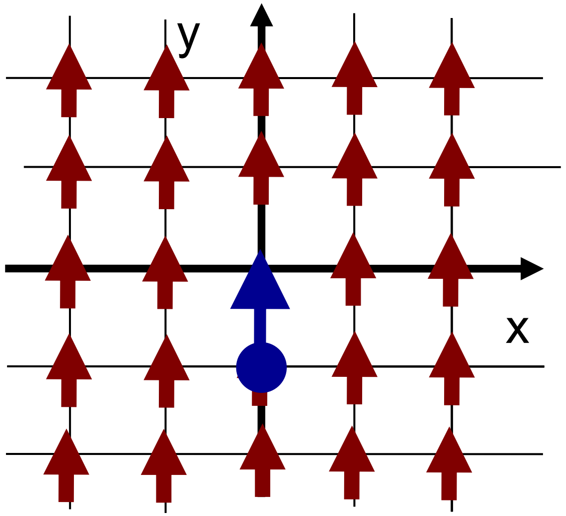


Under the observer Lorentz transformation:

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

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





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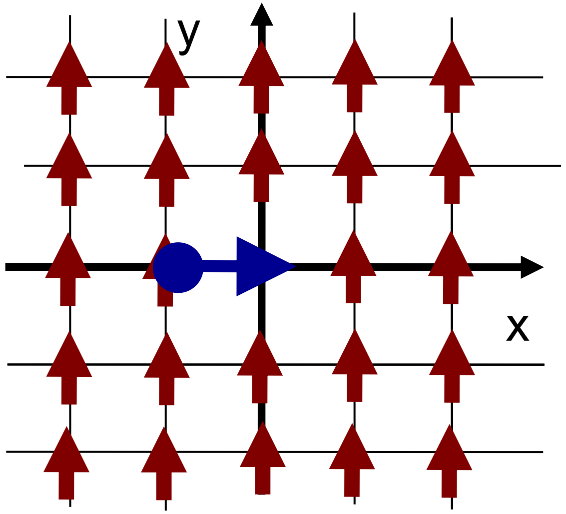
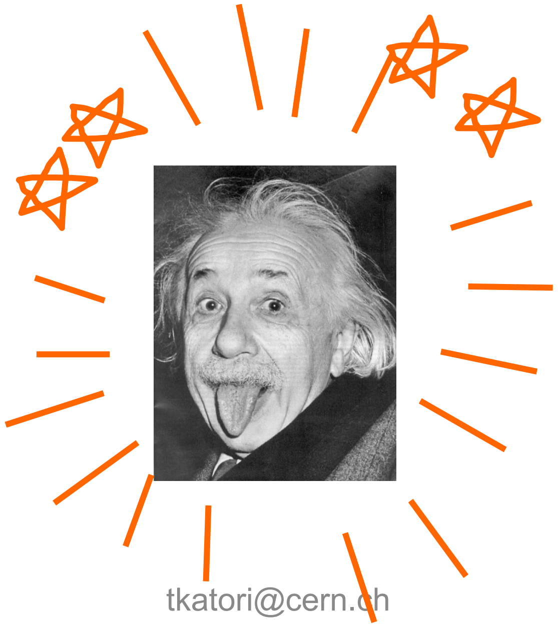


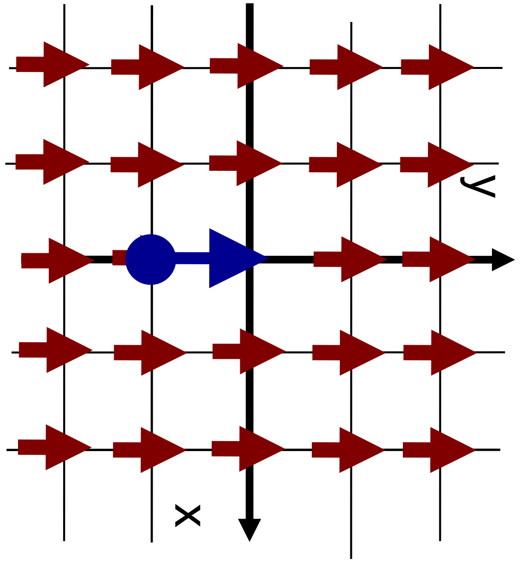
Under the observer Lorentz transformation:

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

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

all observers agree for all observations



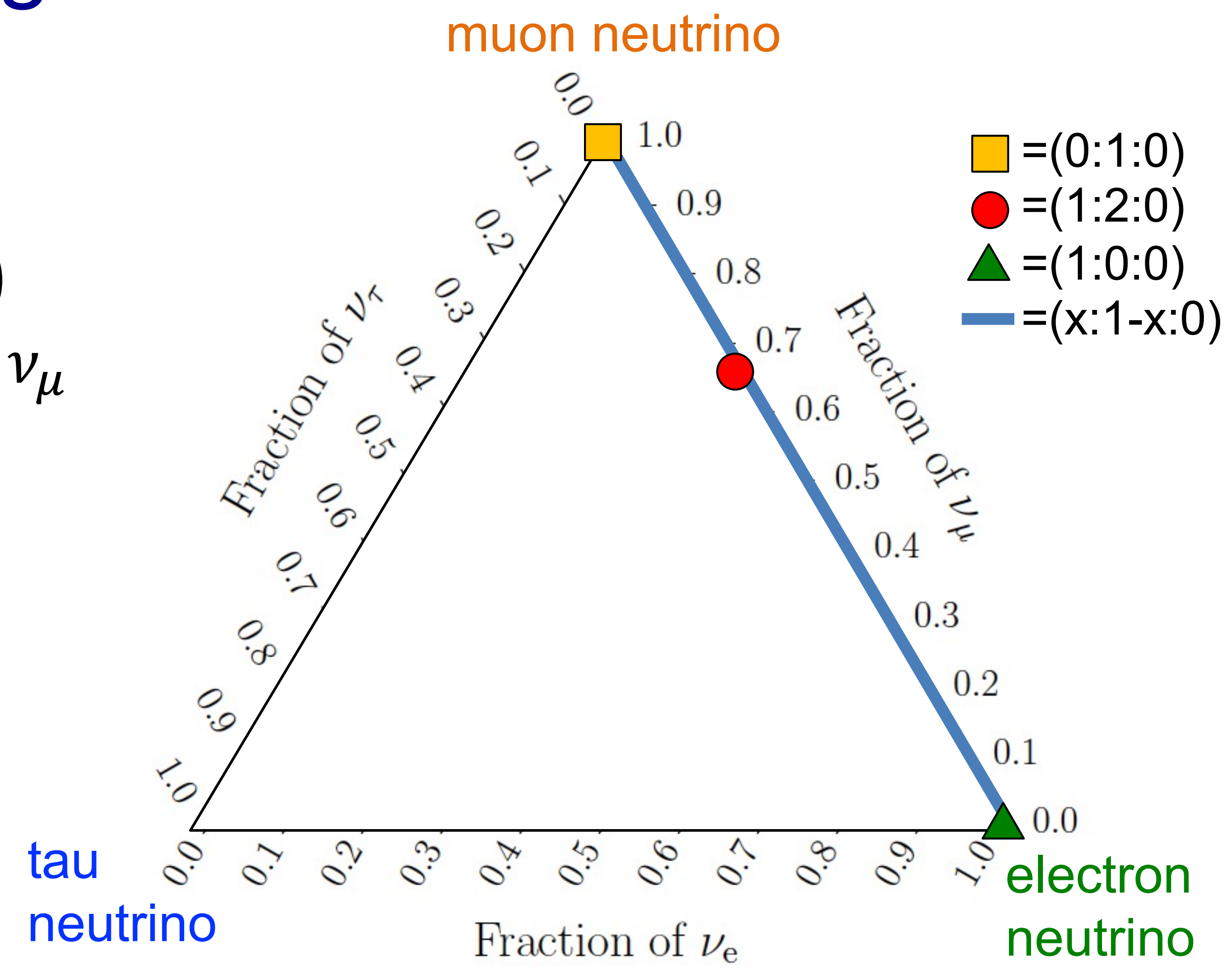


IceCube, Nature Phys. 18, 1287 (2022)

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



KING'S College LONDON

IceCube, Nature Phys. 18, 1287 (2022)

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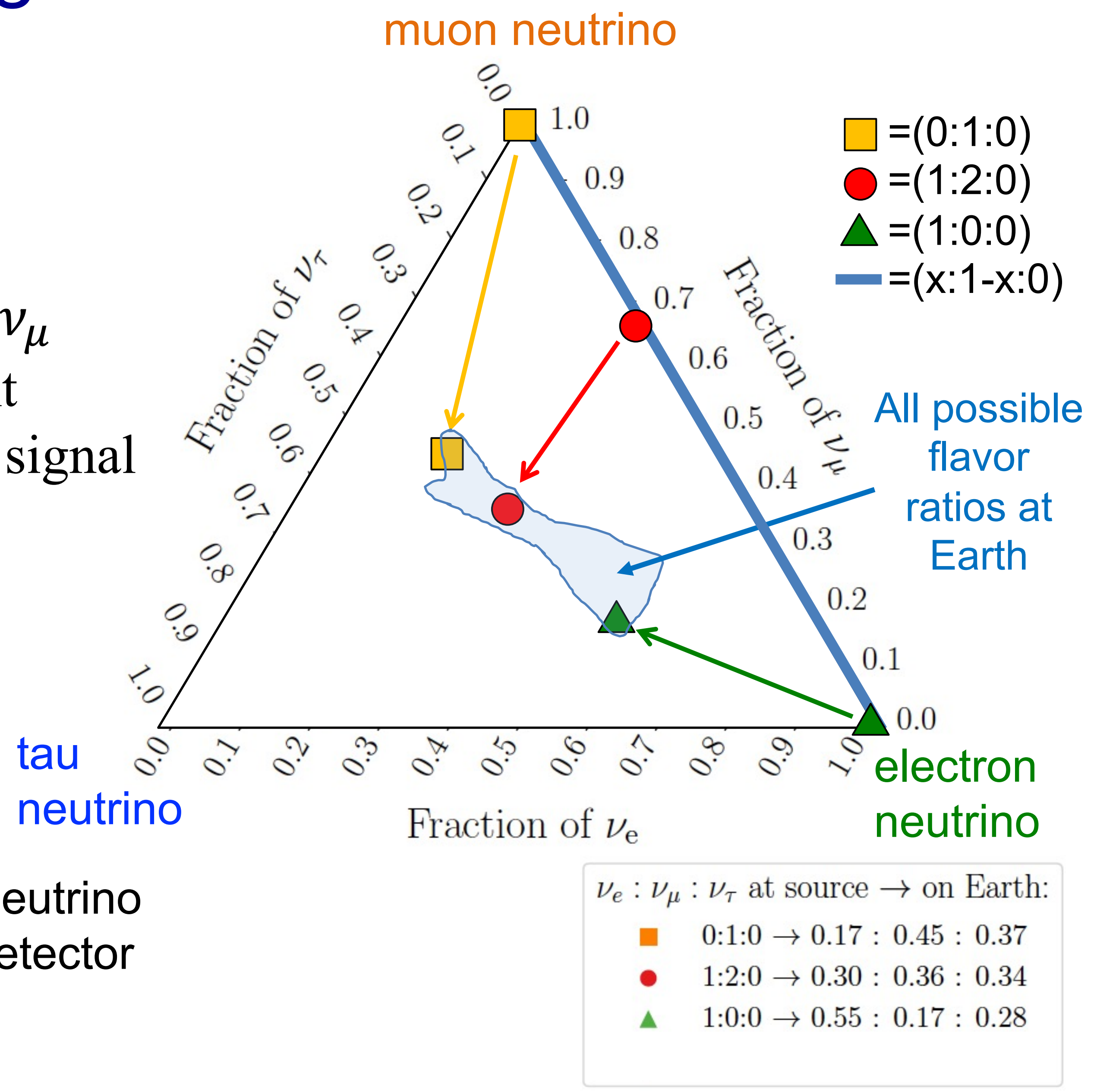
- Deviation from this "island" is new physics signal



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

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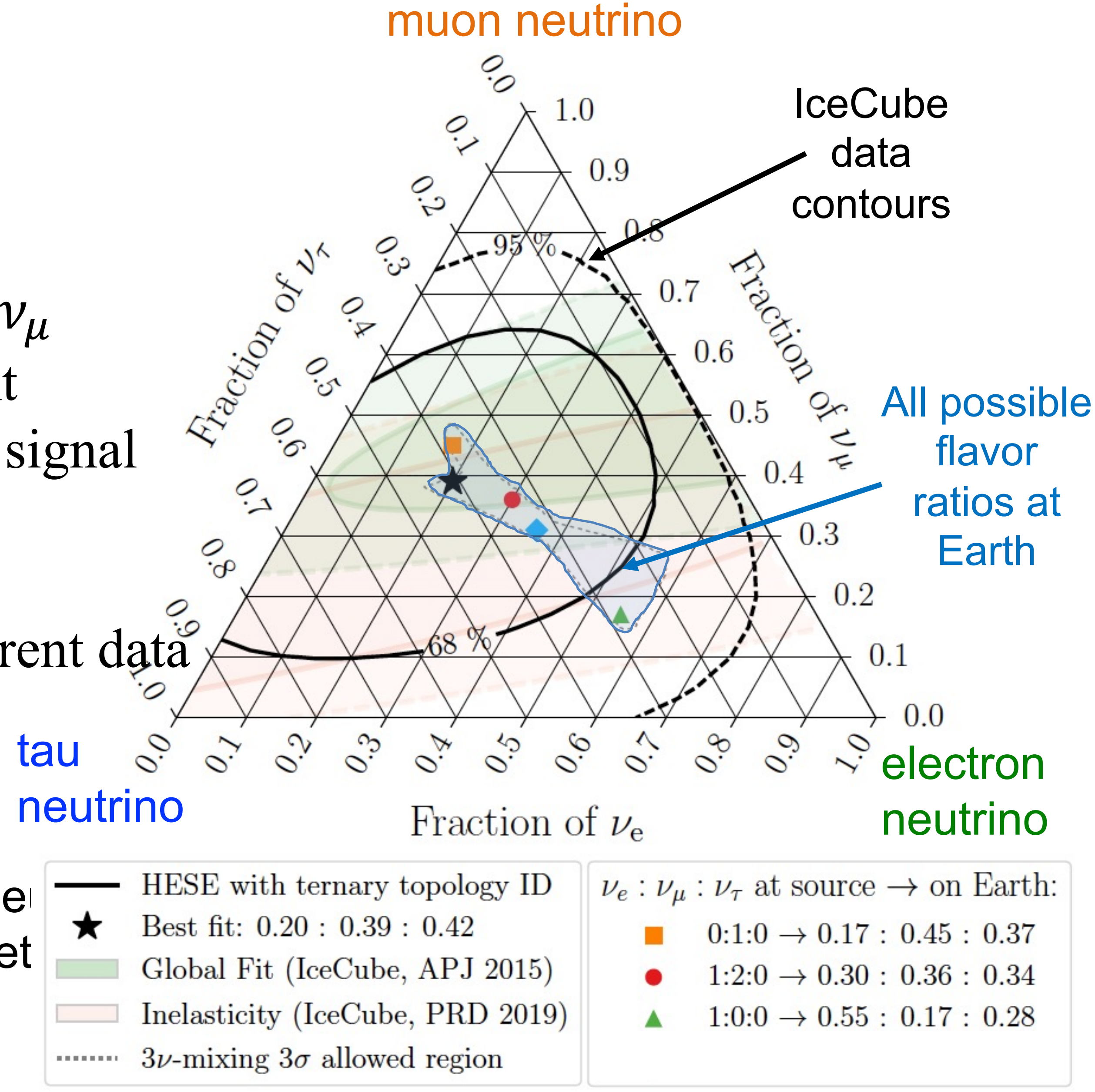
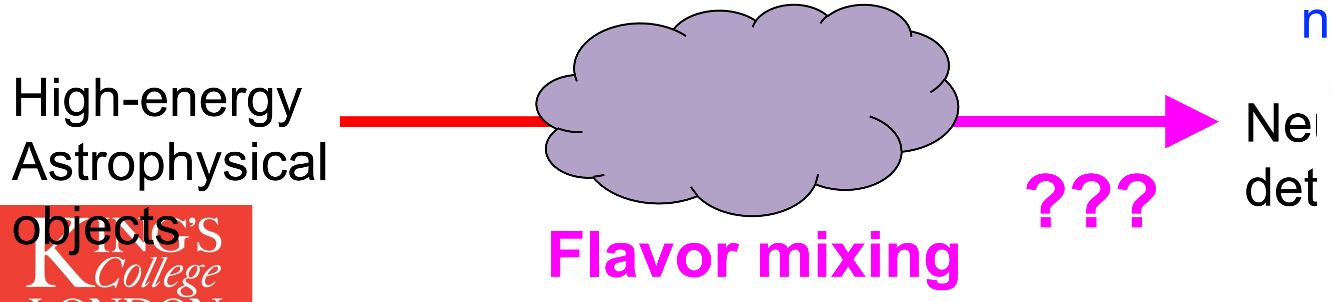
Data contour covers most of flavor triangle

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





IceCube, Nature Physics18(2023)1287

HESE 7.5-yr flavor Lorentz violation search

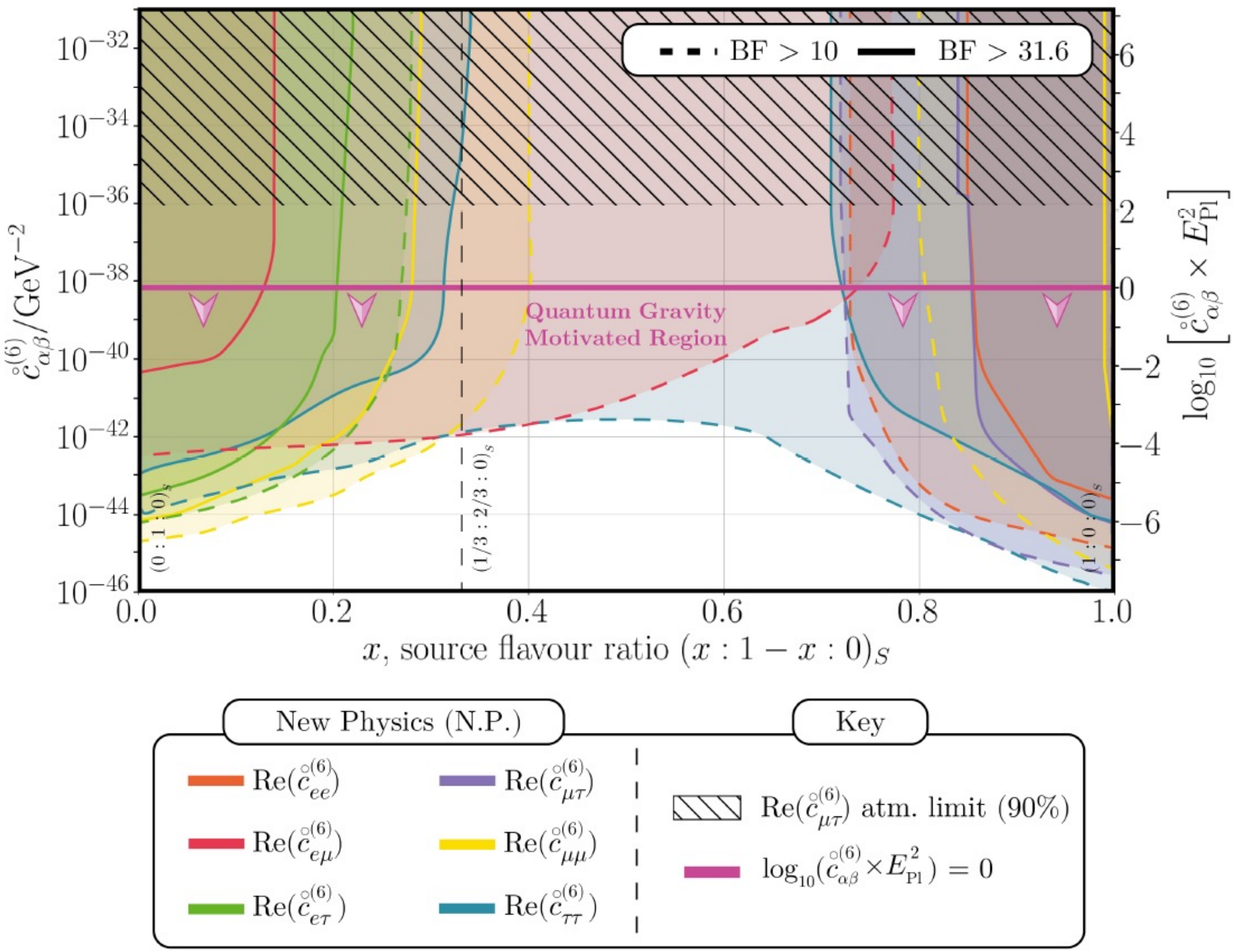
60 HESE events in 60 TeV – 2 PeV

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

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

dim	coefficient	limit (BF> 10.0)
3	$\mathrm{Re}\,(\mathring{a}^{(3)}_{\tau\tau})$	2×10^{-26} GeV
4	$\mathrm{Re}\,(\mathring{c}^{(4)}_{\tau\tau})$	2×10^{-31}
5	$\mathrm{Re}\,(\mathring{a}^{(5)}_{\tau\tau})$	2×10^{-37} GeV^{-1}
6	$\mathrm{Re}\,(\mathring{c}^{(6)}_{\tau\tau})$	3×10^{-42} GeV^{-2}
7	$\mathrm{Re}\,(\mathring{a}^{(7)}_{\tau\tau})$	3×10^{-47} GeV^{-3}
8	$\mathrm{Re}\,(\mathring{c}^{(8)}_{\tau\tau})$	2×10^{-52} GeV^{-4}

dim-6 new physics operator limit



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)

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

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

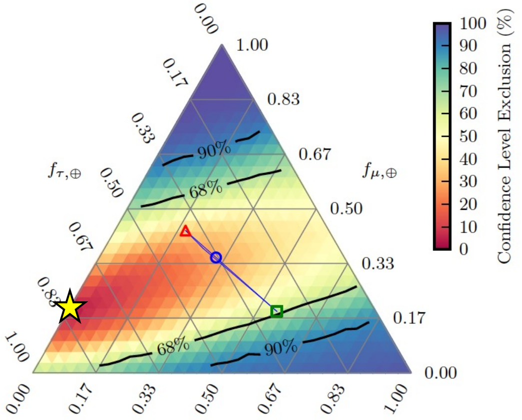
IceCube is sensitive to higher dimension operators

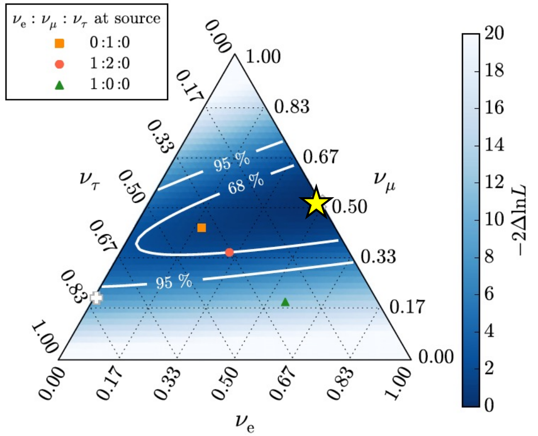
dimension-6 operator natural scale: $c^{(6)} \sim \frac{1}{M^{2}_{Planck}} \sim 10^{-38}GeV^{-2}$

IceCube, PRL114(2015)171102, Astro.J.809:98(2015), PRD99(2019)032004, EPJC82(2022) 1031

IceCube flavor ratio measurements

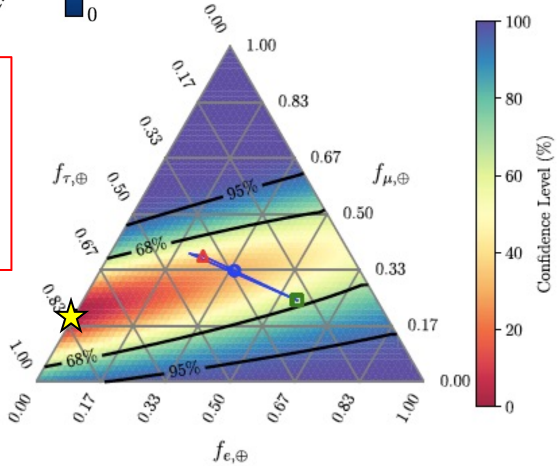
IceCube
1st flavour ratio result
(0.0:0.2:0.8)

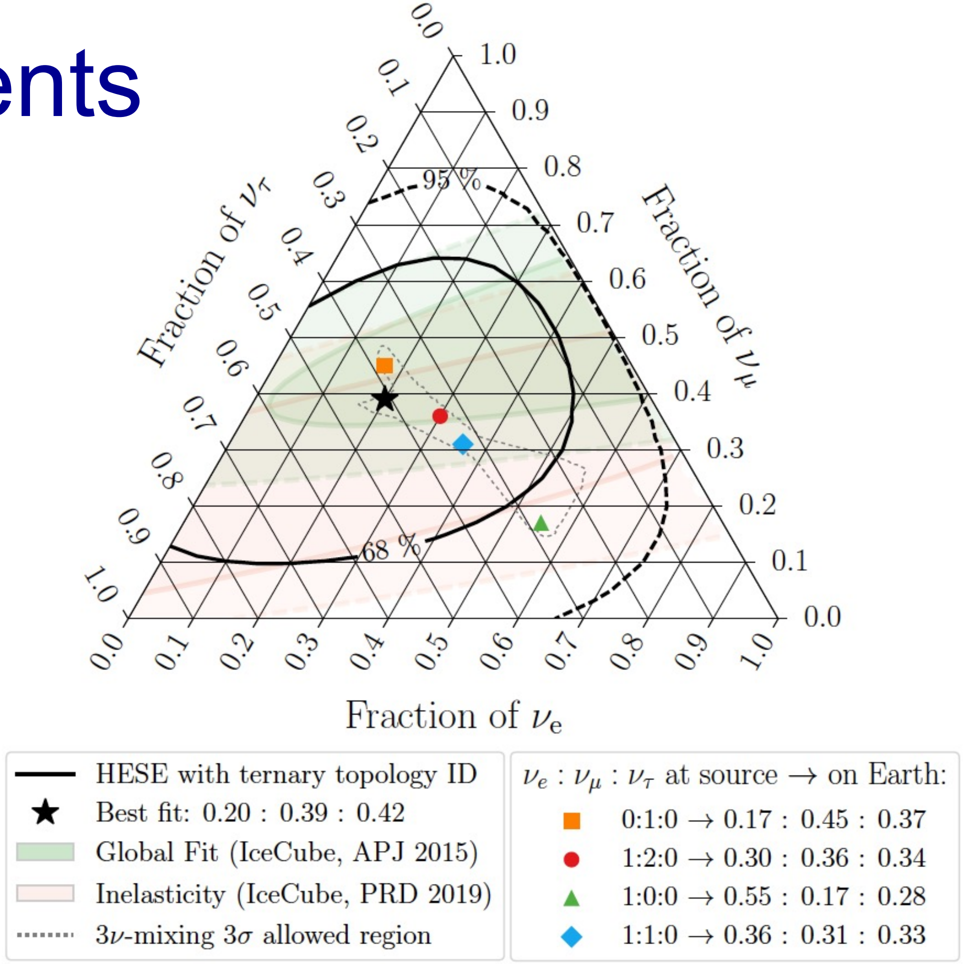




IceCube
2nd flavour ratio result
(0.5:0.5:0.0)

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





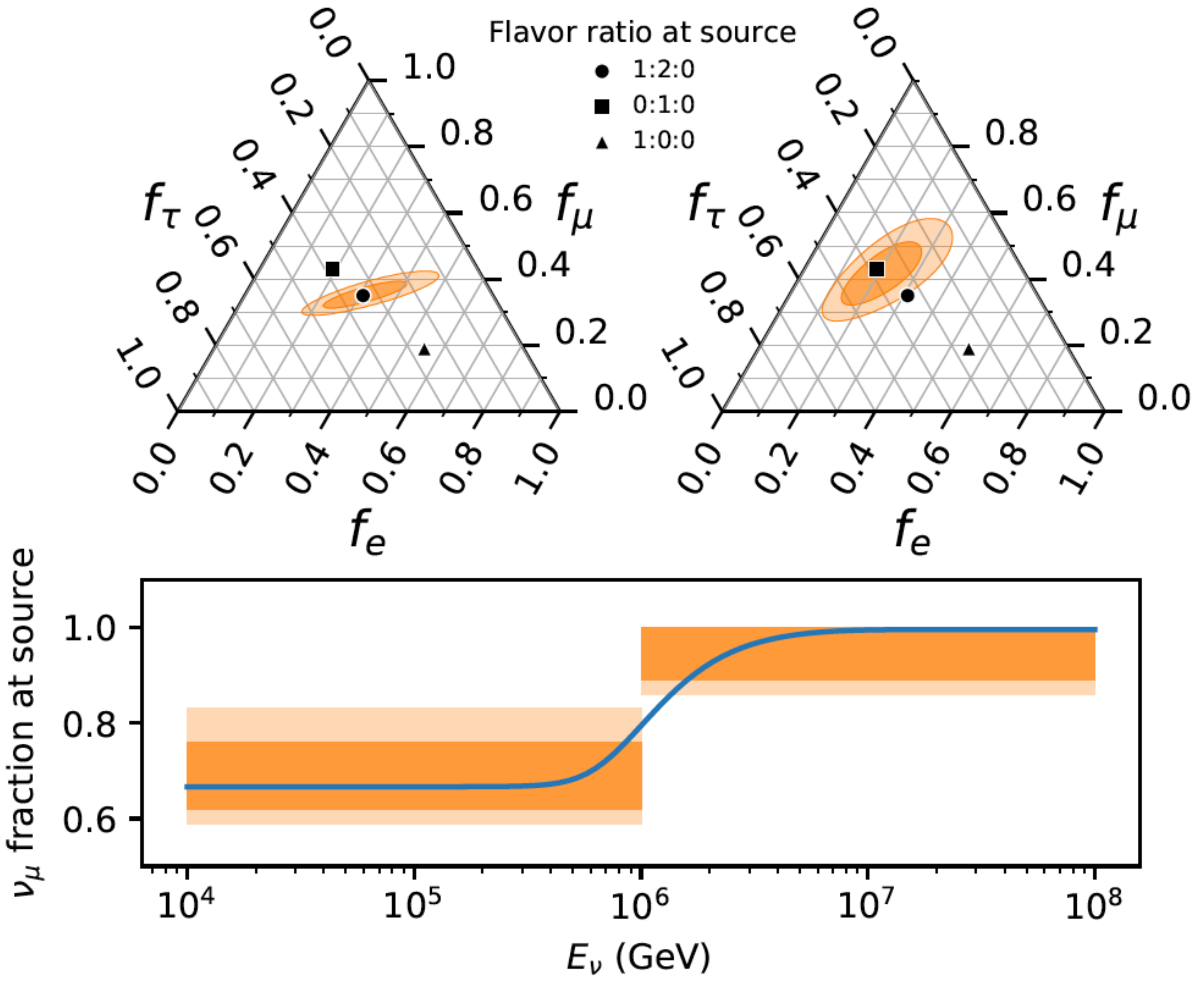
2018 flavour ratio measurement

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

Energy dependence of flavor ratio

Muon neutrino increases at higher energy

Future higher-statistics flavor measurement



New physics flavor ratio predictions

New physics models have different flavor ratios

Effective operator

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