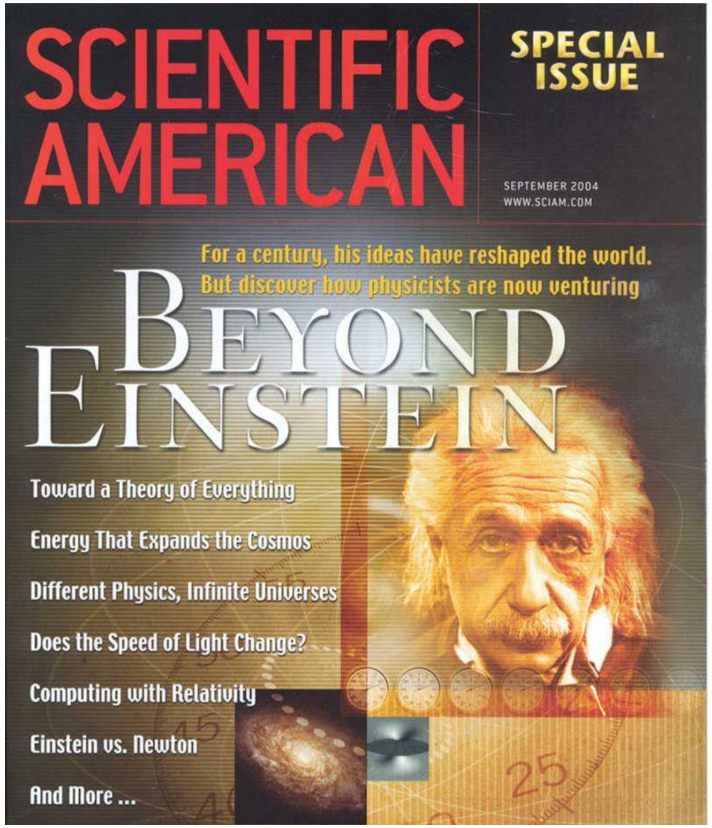
Modern Tests of Spacetime Symmetry

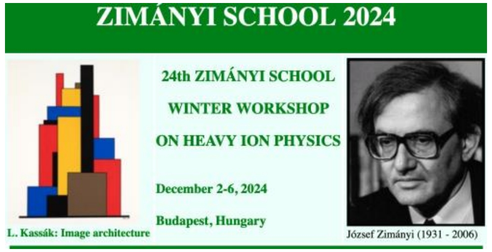


outline

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

Teppei Katori @teppeikatori
King's College London

Ortvay colloquium, Eötvös Loránd University
Budapest, Hungary, Dec 5, 2024



Introduction

(I want to say) Einstein is wrong!

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

Home Main Article Videos Q & A 中文版 conta

Special Relativity is Wrong

Latest Updates

This

List

baolujiang@gmail.com February 12, 2022 at 00:07

A website to disprove Special Relativity

To: Teppei Katori

- The two postulates

05: The main article is

24: Source Text for vi

18: Several Q&As are

armanettimaurizio@libero.it January 15, 2020 a

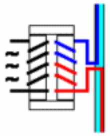
From Italy - OBJECT: here's how to overcome the speed of light.

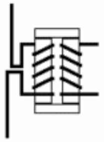
To: Teppei Katori

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





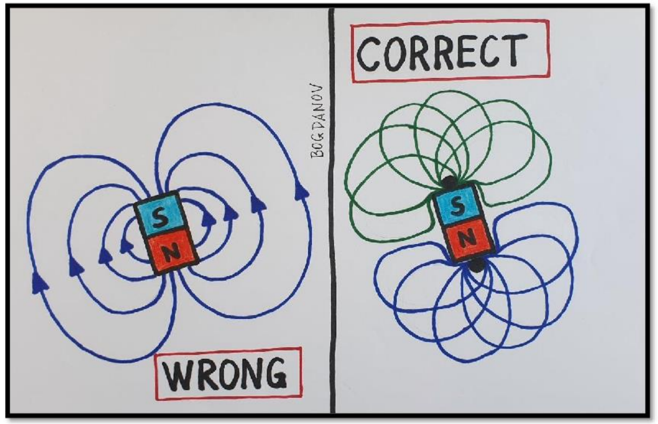
Cosmin Visan January 13, 2024 at 22:28

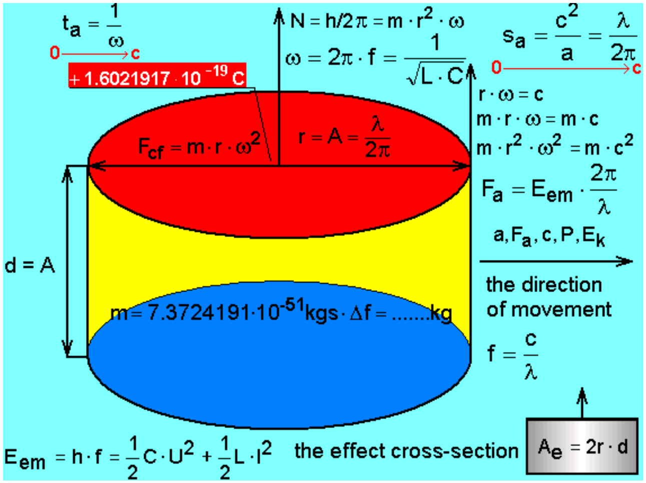
My theory of consciousness and meeting proposal

To: bozidar.butorac@kcl.ac.uk & 113 more

Details

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





KING'S College LONDON

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

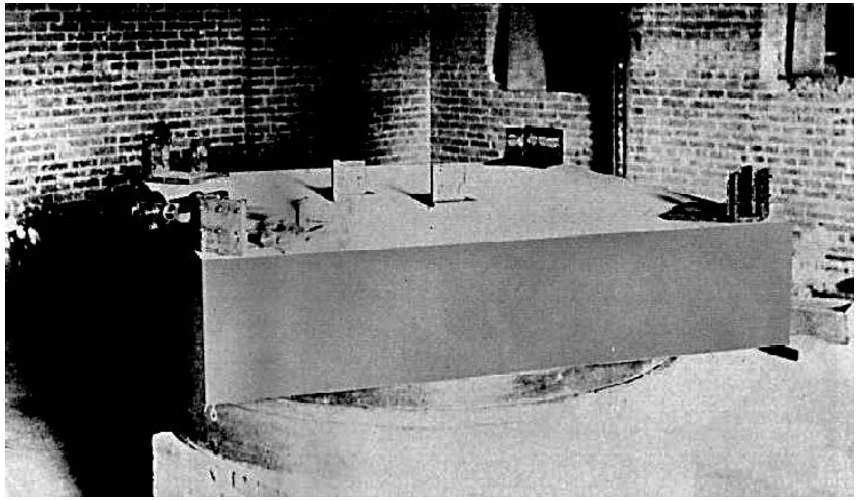
Lorentz symmetry is isotropy of the spacetime

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

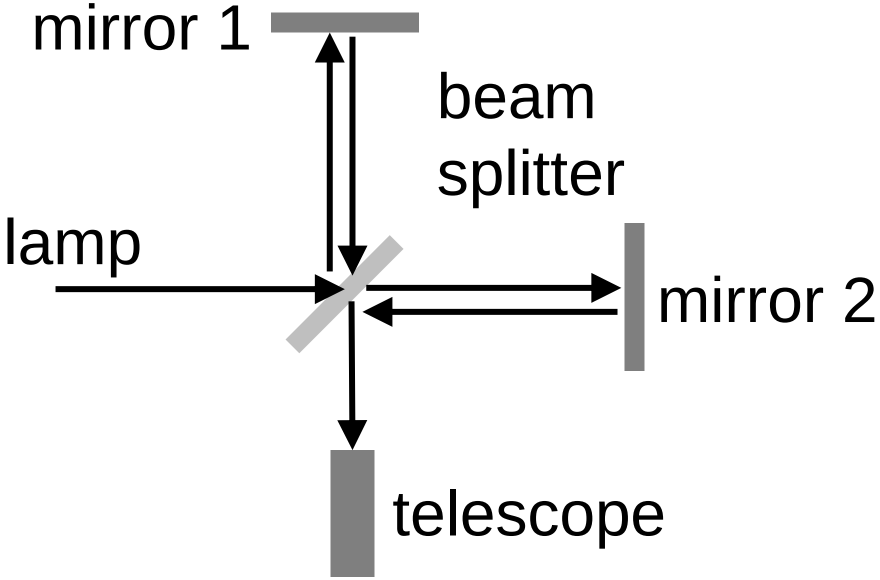
The experiment tried to measure the motion of the Earth relative to æther.



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

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

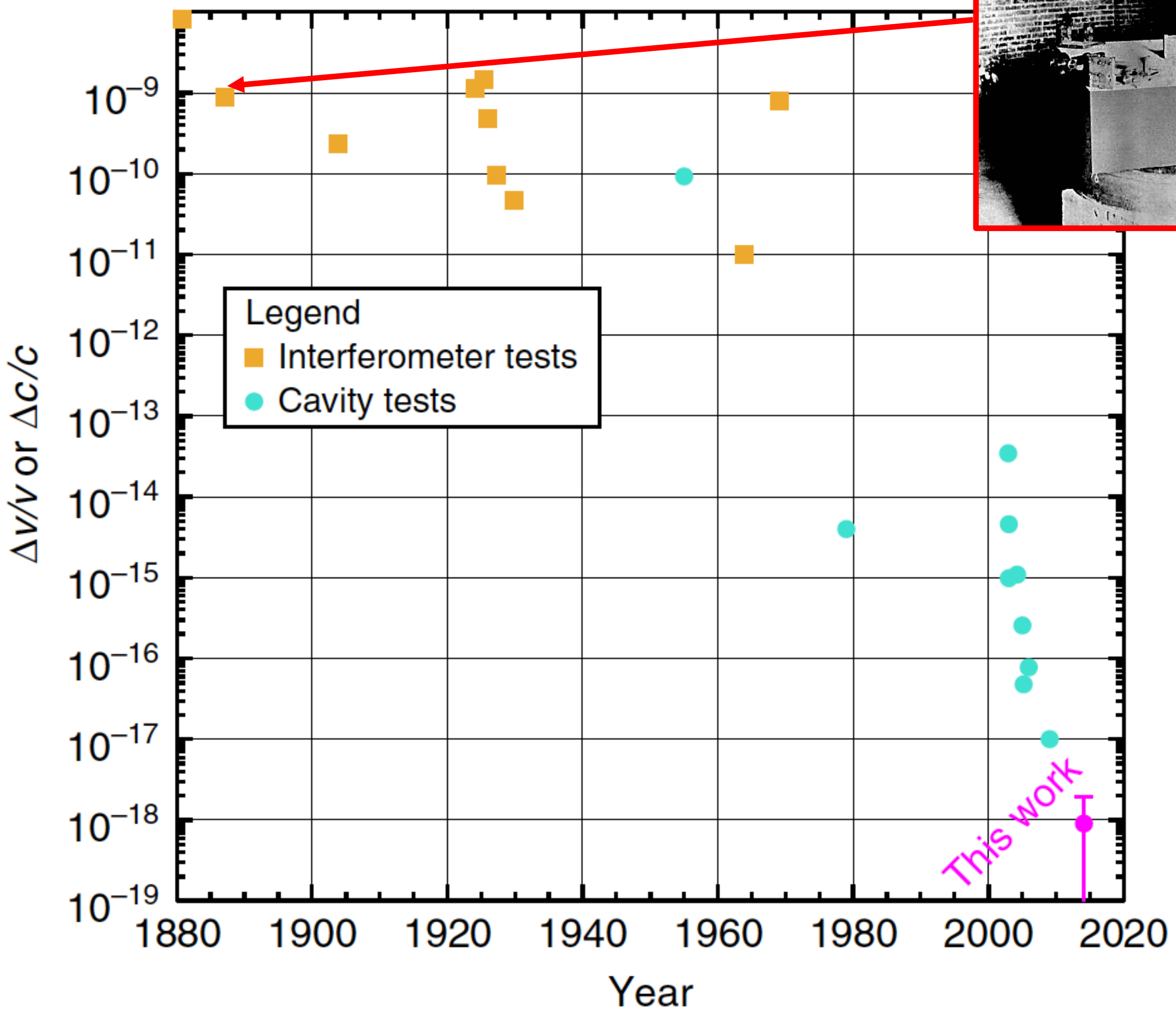
Lorentz symmetry is valid down to $\Delta c/c \sim 10^{-9}$

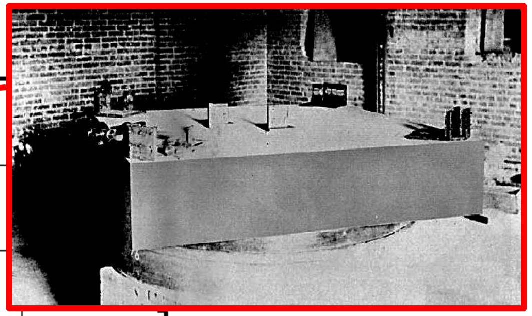


Nagel et al, Nature Comm., 6(2015)8174

Michelson-Morley experiment

The experiment has been improved over 100 years.



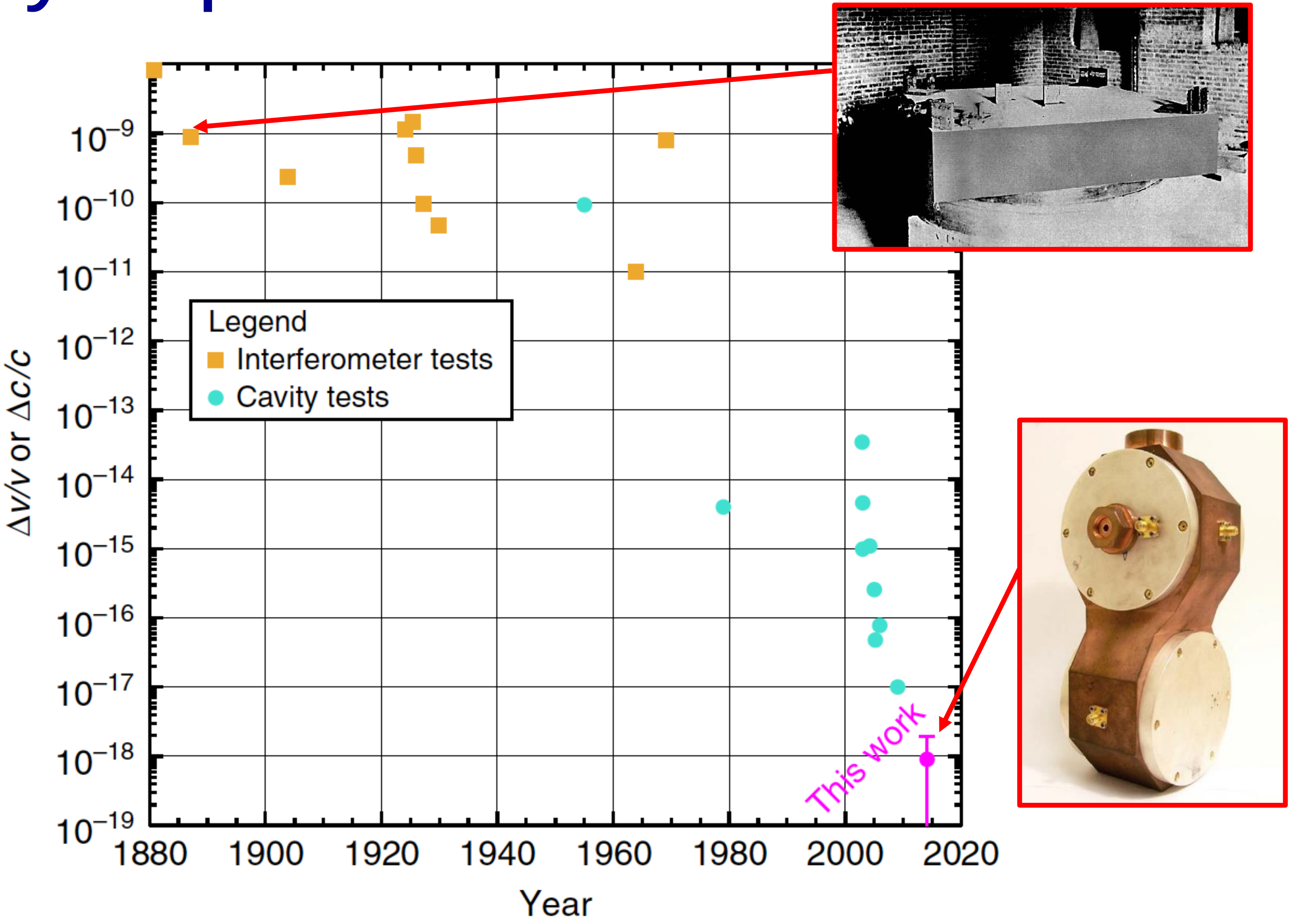


Nagel et al, Nature Comm., 6(2015)8174

Michelson-Morley experiment

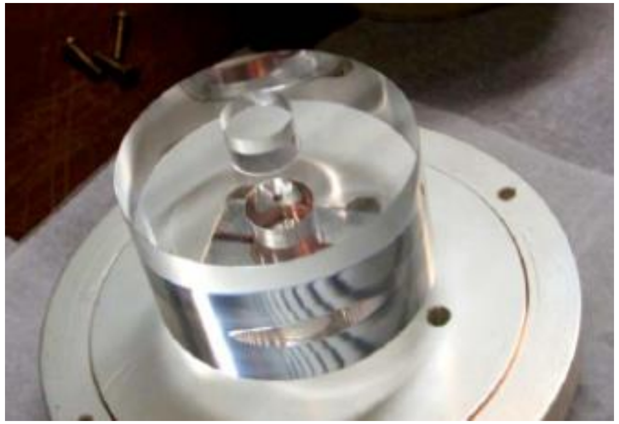
The experiment has been improved over 100 years.

Technology shift (interferometer → optical cavity) around 2000s



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

Optical cavity experiment

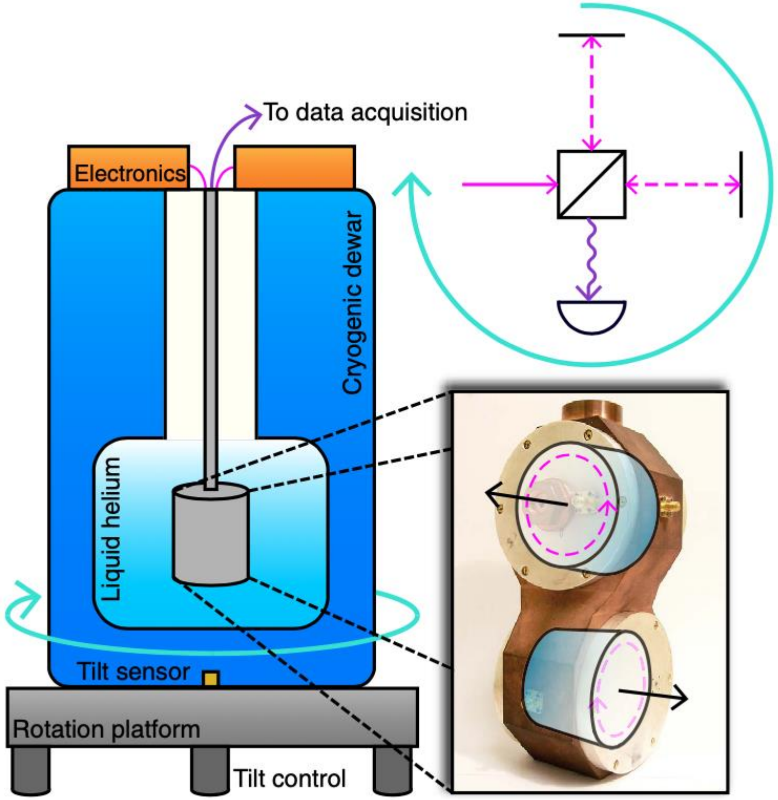


Modern Michelson-Morley experiment
- Saphire crystal resonator
- Whispering gallery mode
- Vacuum insulation, liquid helium cooling to 4K
- Turntable to actively rotate

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

Why we keep testing this?

Why do we expect Lorentz violation?



Quantum gravity

Searching Lorentz violation is well motivated

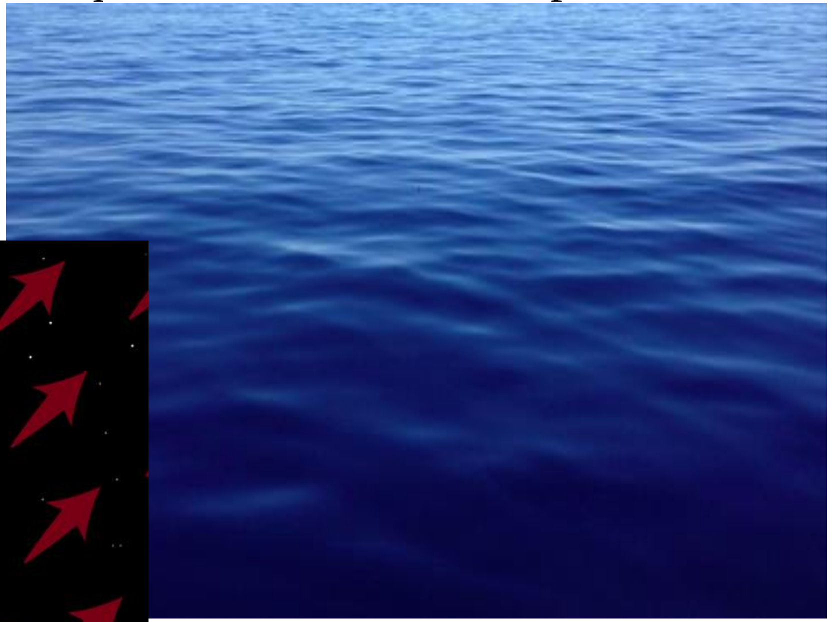
Lorentz violation in Planck scale theories
- string theory
- noncommutative field theory
- quantum loop gravity
- extra dimensions

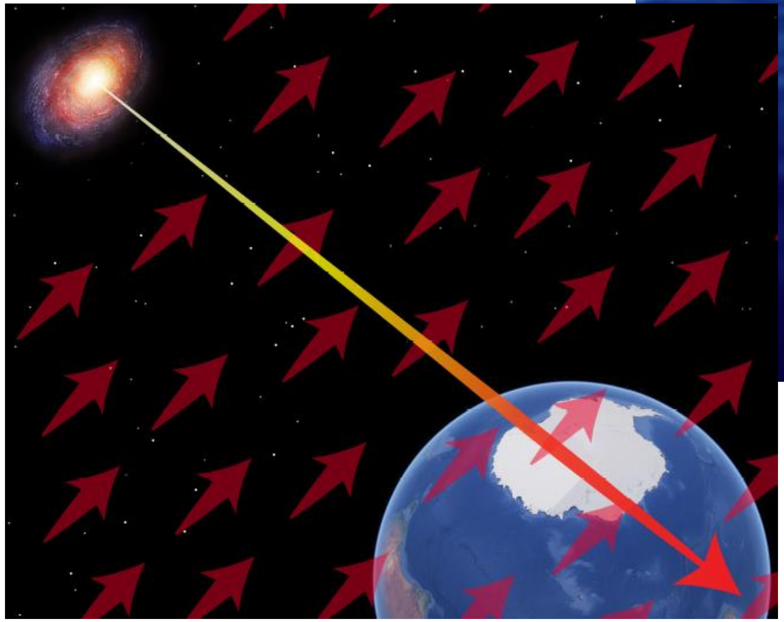
etc

Lorentz violation is seen as
- spacetime fluctuation
- background field in vacuum

etc

quantum foam
- quantum fluctuation of space-time





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

Quantum gravity

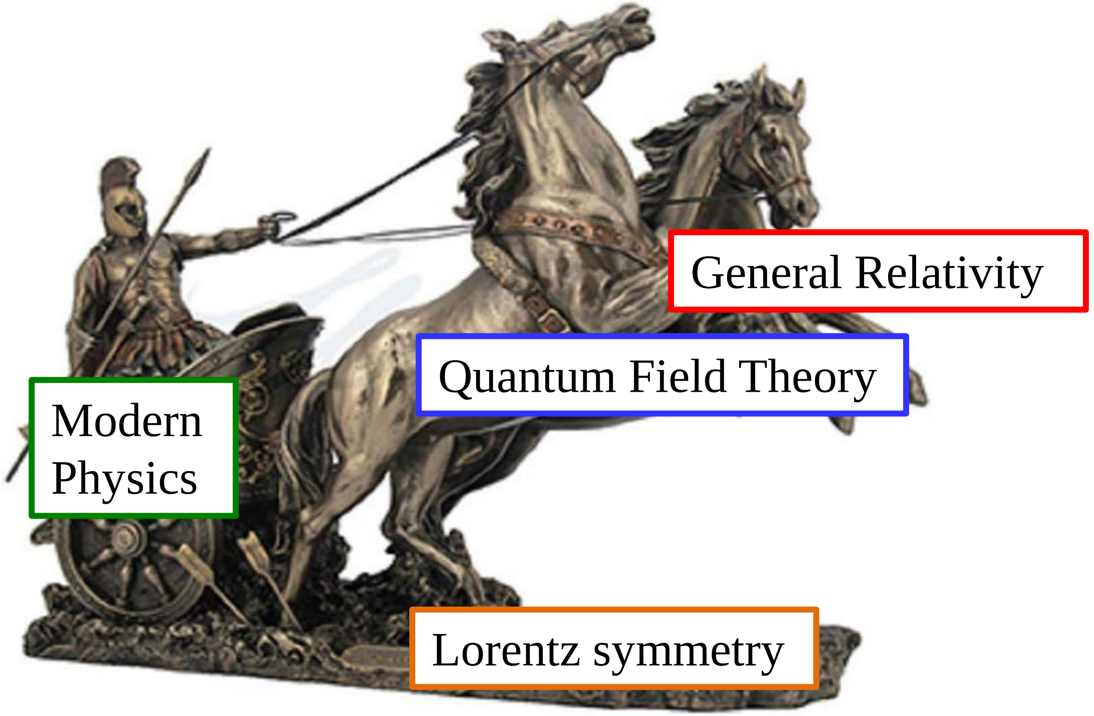
Searching Lorentz violation is well motivated

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?

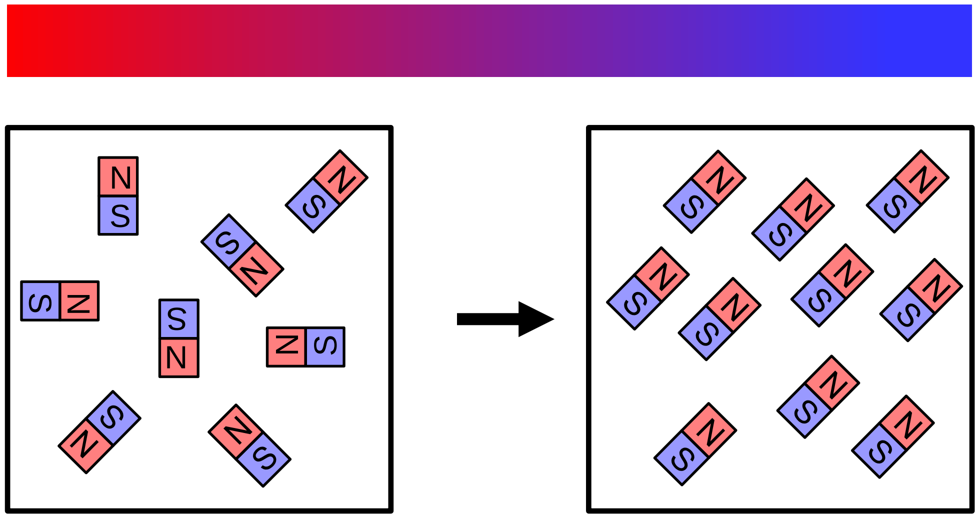
Lorentz symmetry could be spontaneously broken, if so, this doesn't violate existing framework of modern physics



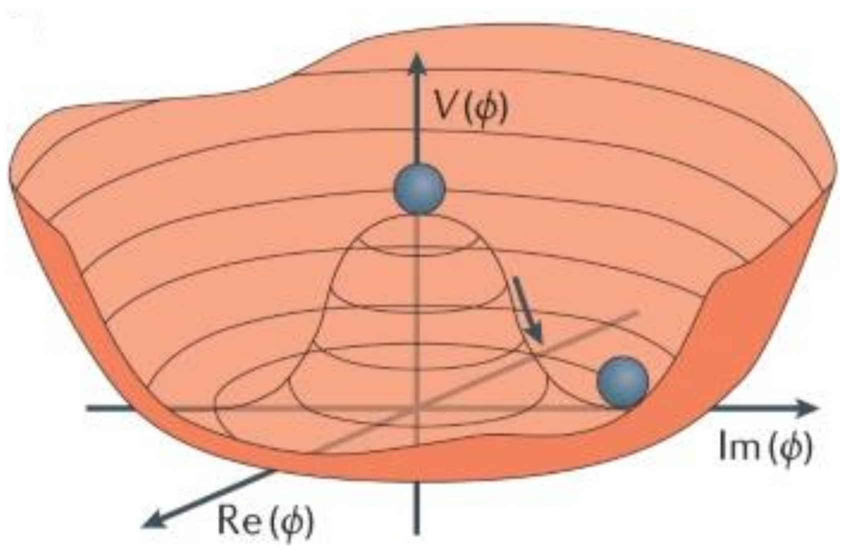
Spontaneous symmetry breaking

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

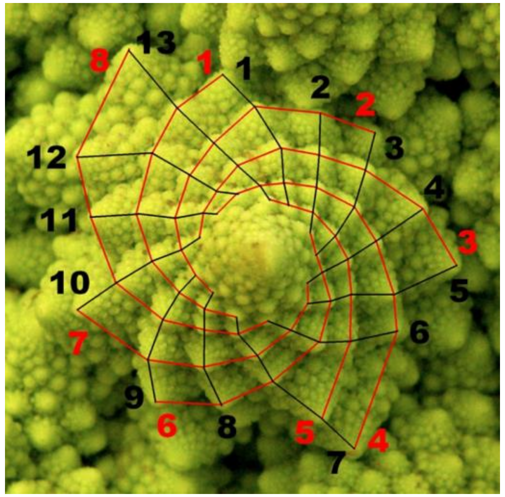


Spontaneous symmetry breaking

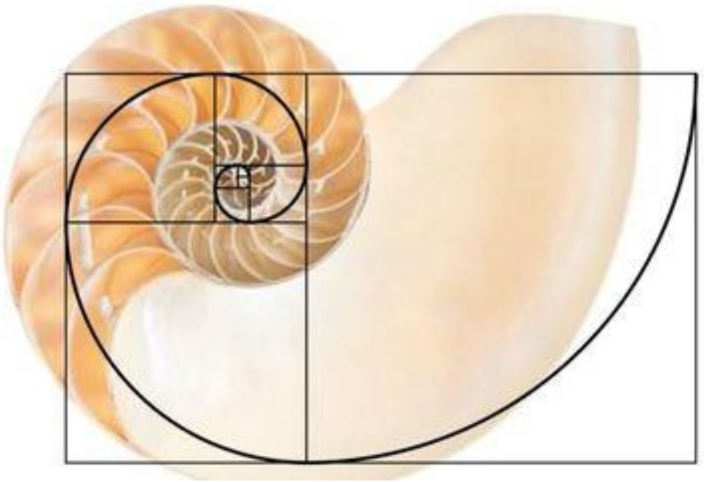
Searching Lorentz violation is well motivated

Math is a good approximation of nature
There is no perfect symmetry in nature, all somewhat broken

So why space-time symmetry is so 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

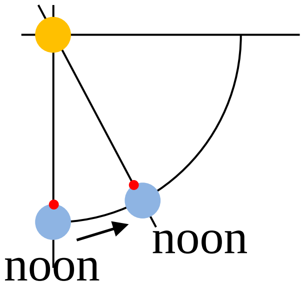
couplings with background fields

Physics of Lorentz violation

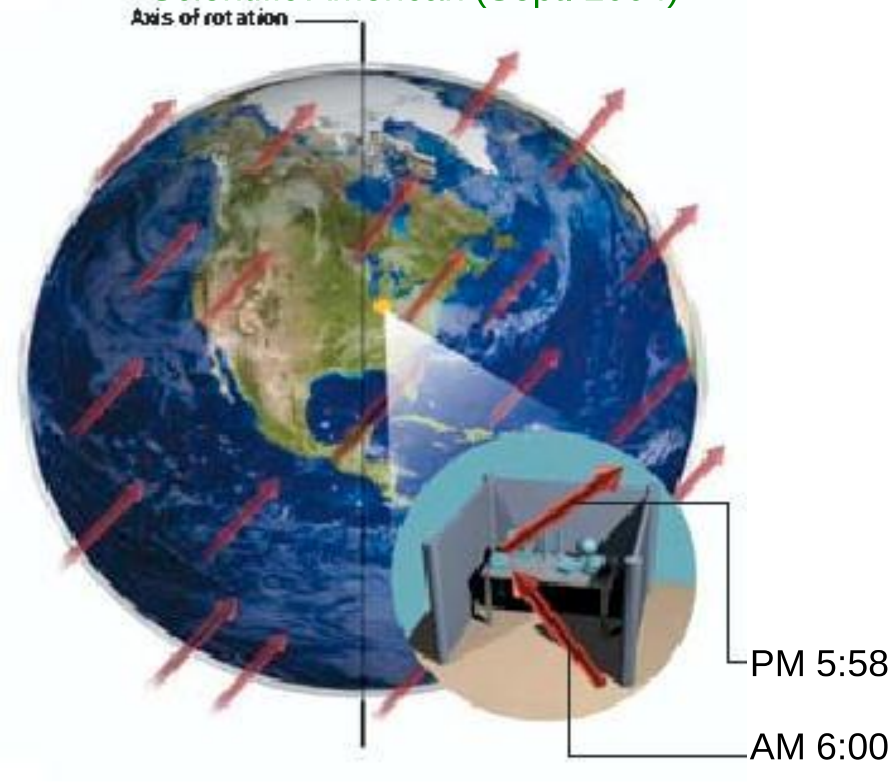
- Spectrum distortion,
- Sidereal time dependence, etc…

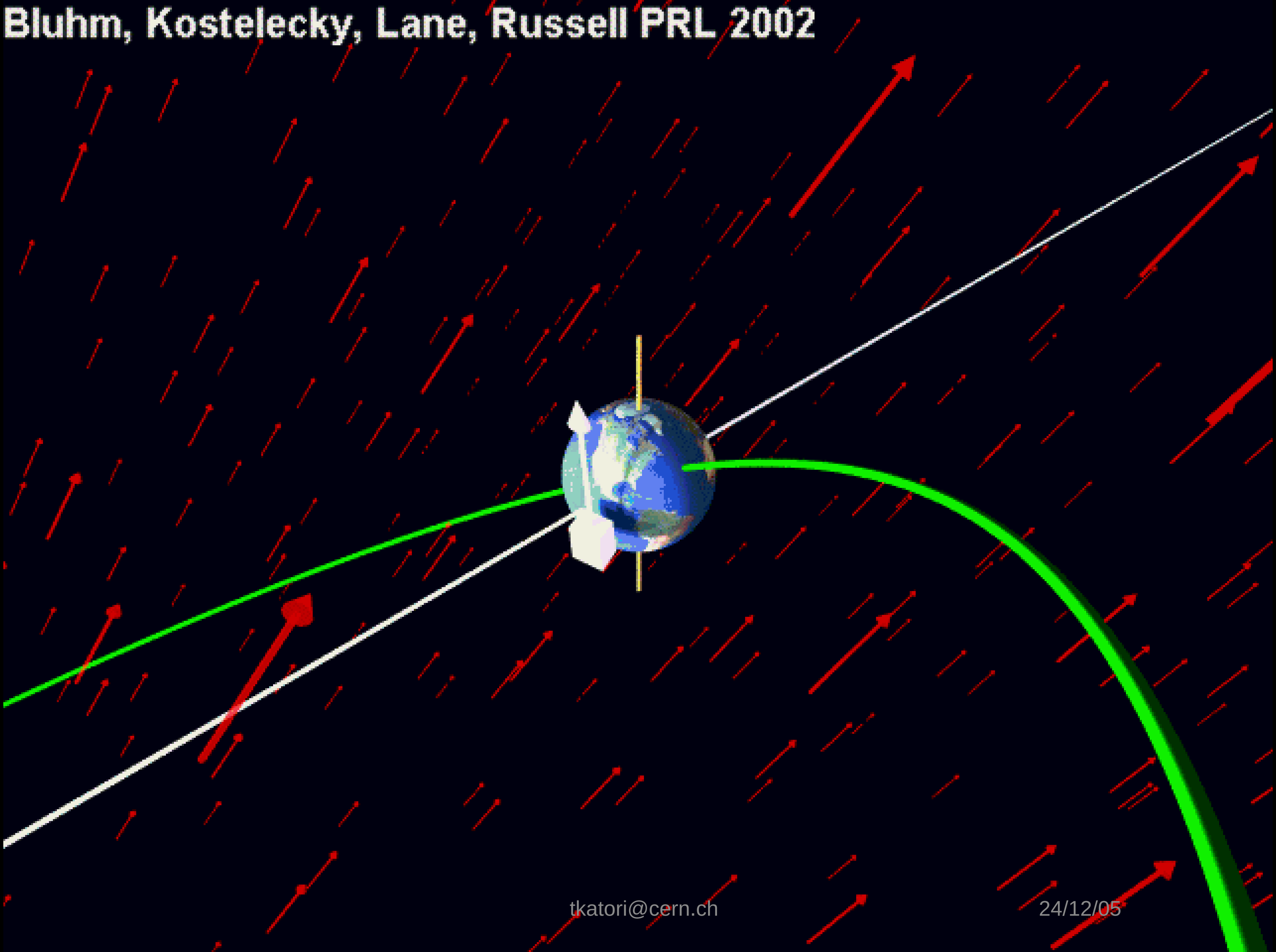
24h 00min 00sec: Solar day

23h 56min 4.1sec: Sidereal day



Scientific American (Sept. 2004)




Bluhm, Kostelecky, Lane, Russell PRL 2002

Tests of Lorentz violation

[EötWash, PRL85(2000)2869](#), [PRL100,(2008)041101](#)

Torsion pendulum

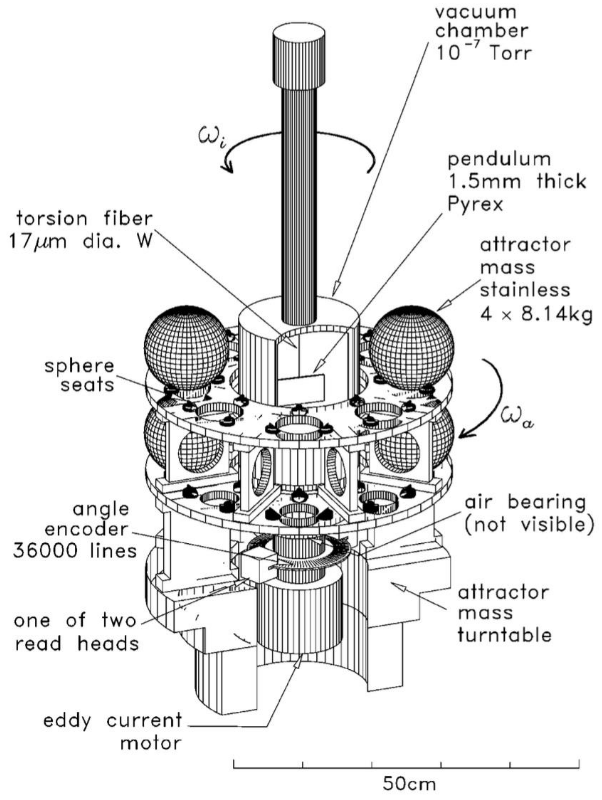
Eric G. Adelberger, University of Washington, Seattle

2025 recipient, Einstein Prize

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

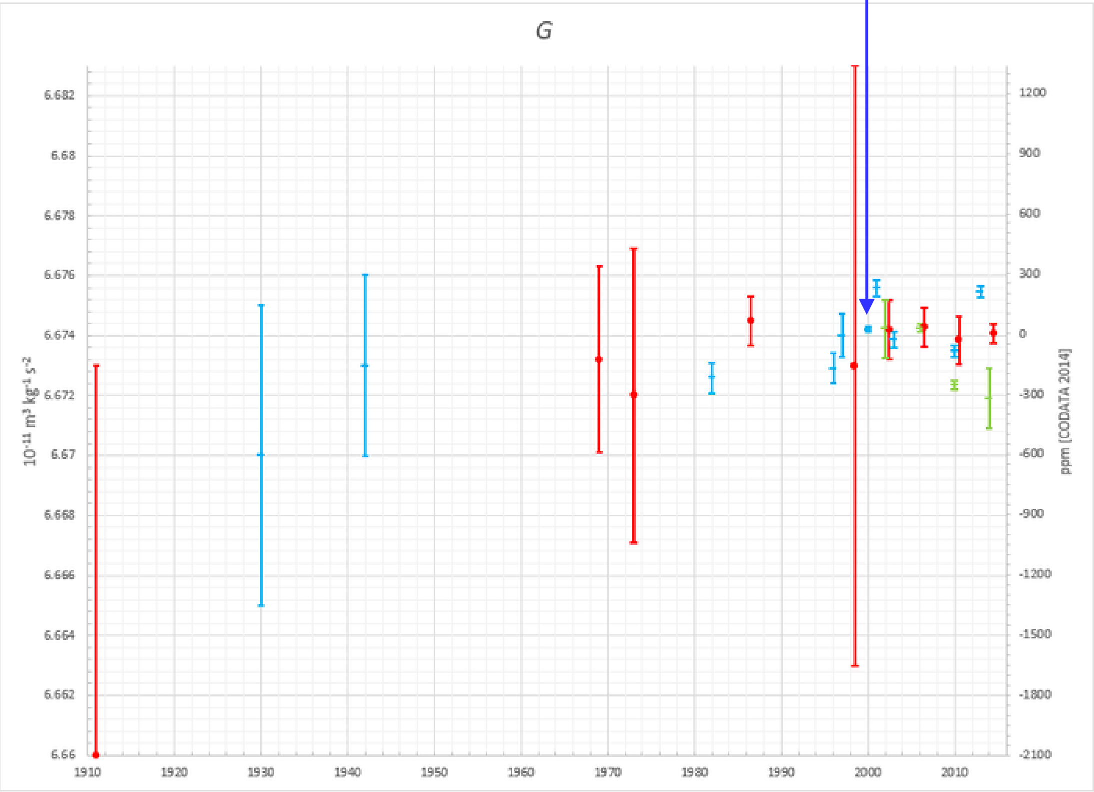
Eötvös experiment → EötWash experiment
- Modern torsion balance
- Newton constant
- Equivalent of Principle

etc



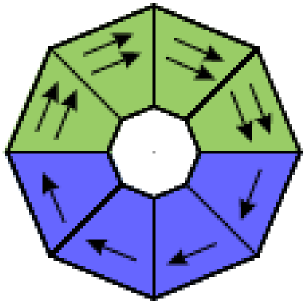
EötWash

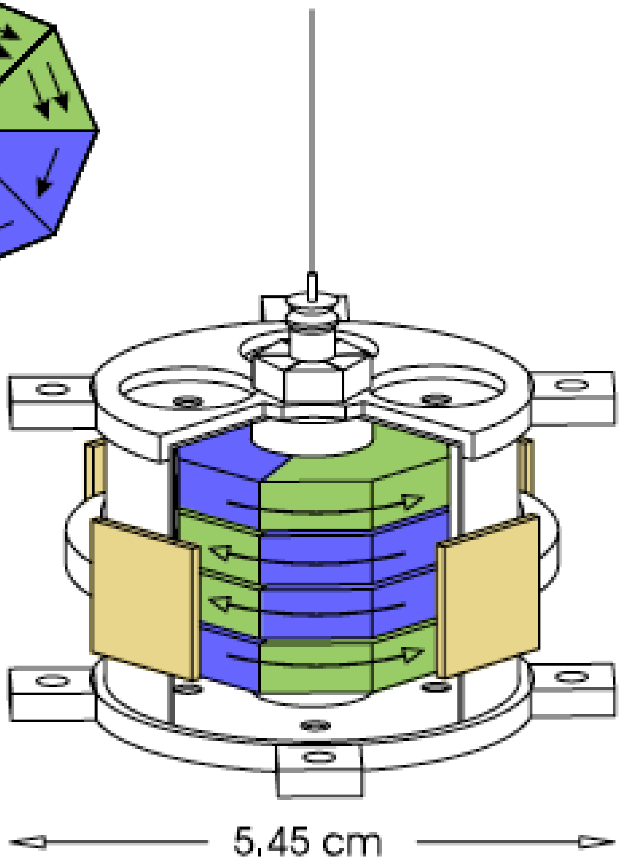
History of Newton constant measurement



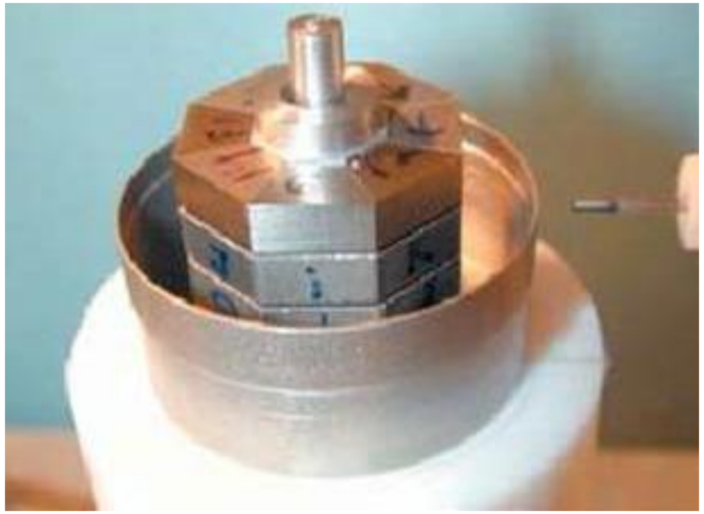
EötWash, PRL97(2006)021603 , PRL122(2019)231301

Torsion pendulum (electron)





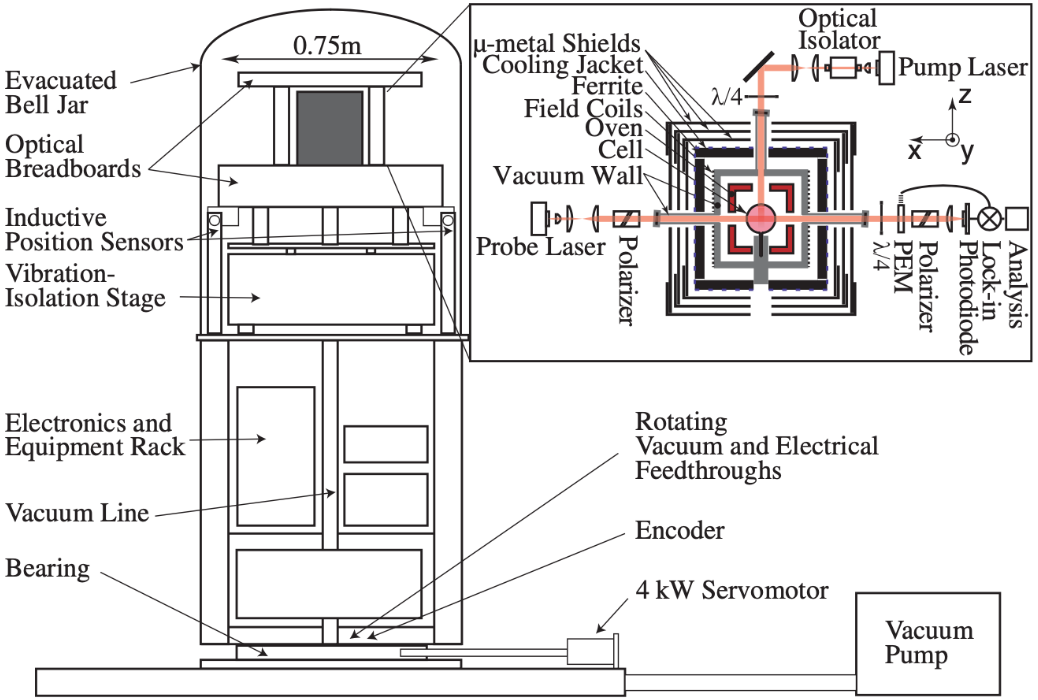
Electron spin – background field coupling
- AlNiCo: all magnetic field is from electron spin
- $SmCo_5$: electron orbital motion creates magnetic field
- Magnetize them to cancel magnetic field, so that the pendulum has net electron spin
- Look for coupling between electron spin and background field



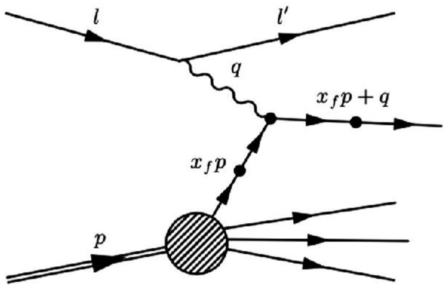
PRL105(2010)151604 and many others

Double gas maser (neutron)

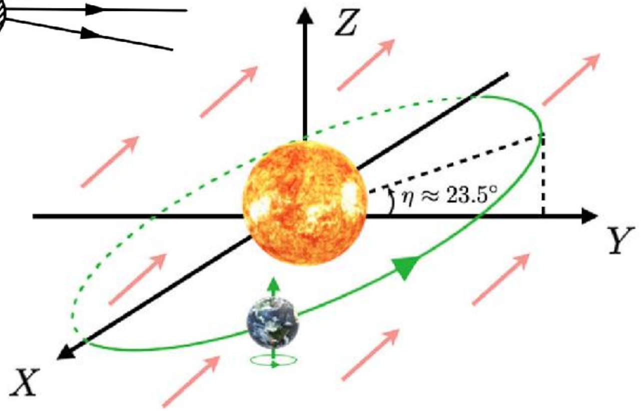
The most sensitive magnetometer
- Optical pump for Rb, K
- Spin transfer to noble gas (Xe, ^{3}He), monitor ^{3}He precession
- Look for coupling between neutron spin and background field

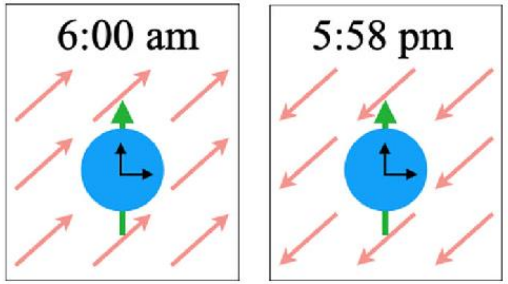


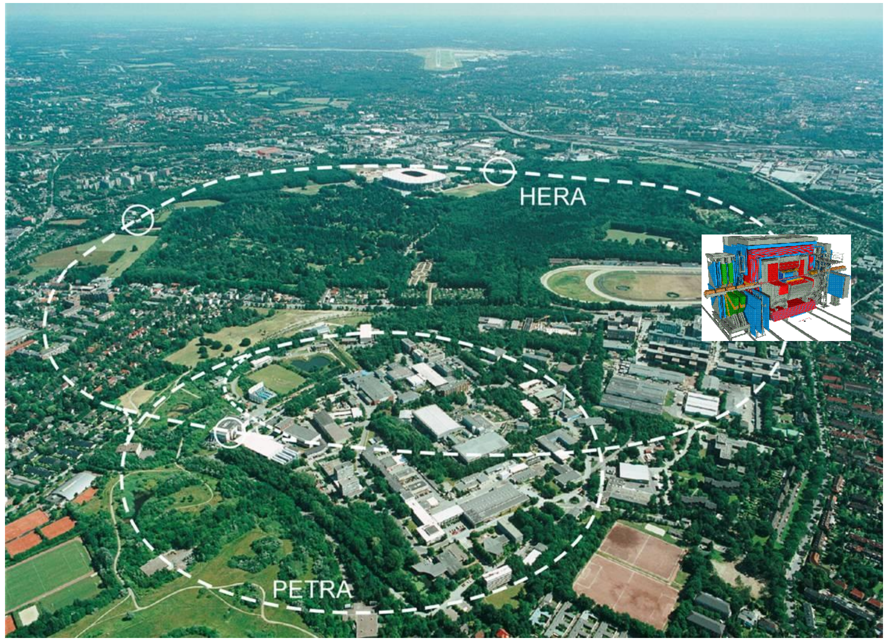
Collider physics (quarks)

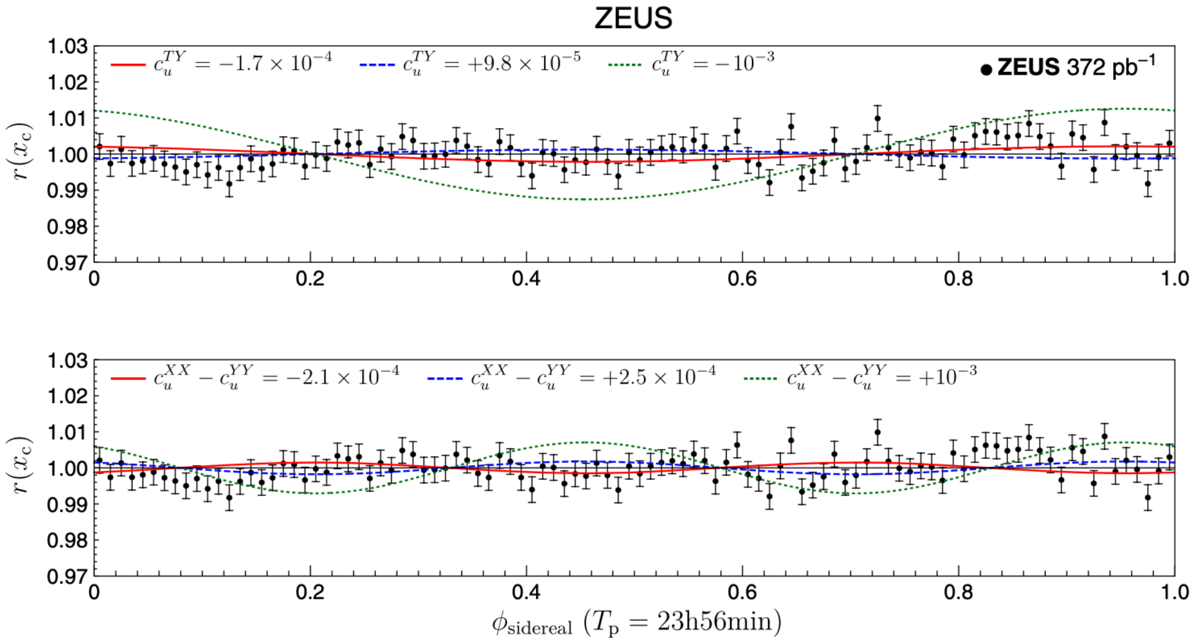


HERA p-e⁻ collider
- ZEUS deep-inelastic scattering data
- Monitor sidereal time dependence
- Similar tests are possible for other data





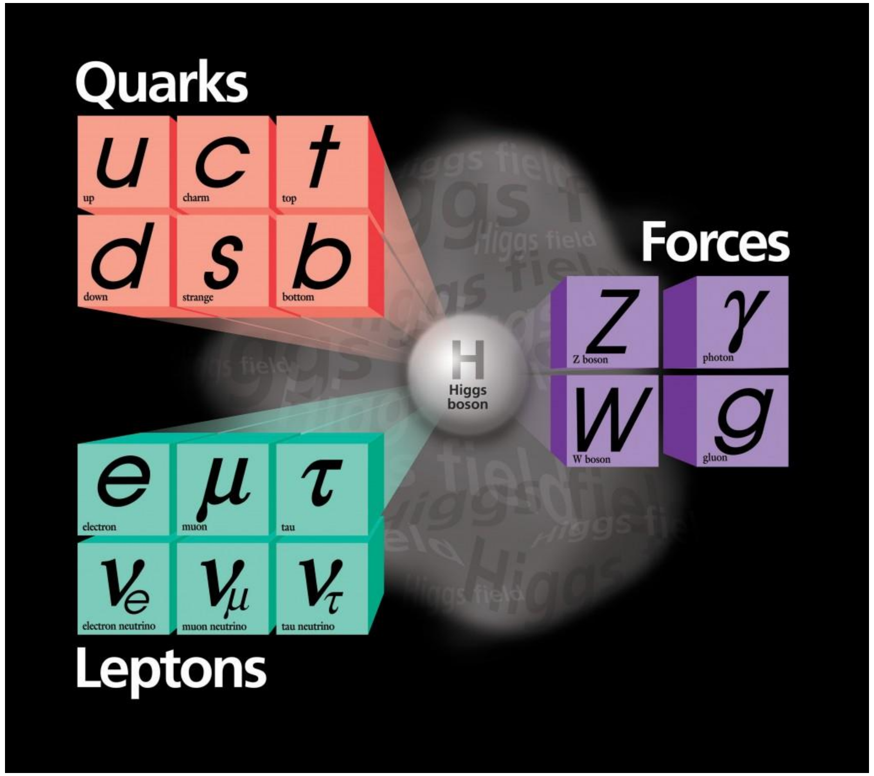




Neutrino physics

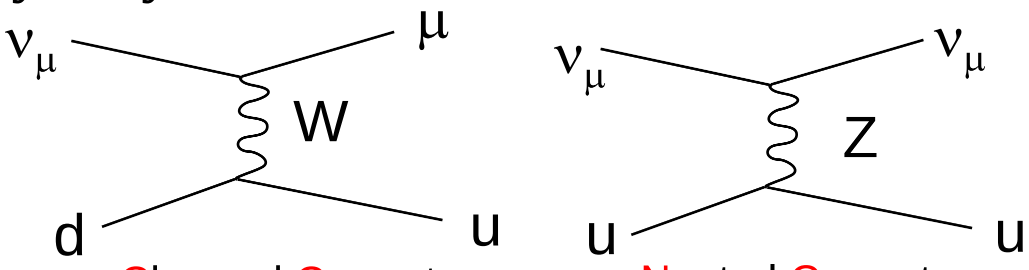
Neutrinos in the standard model

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.



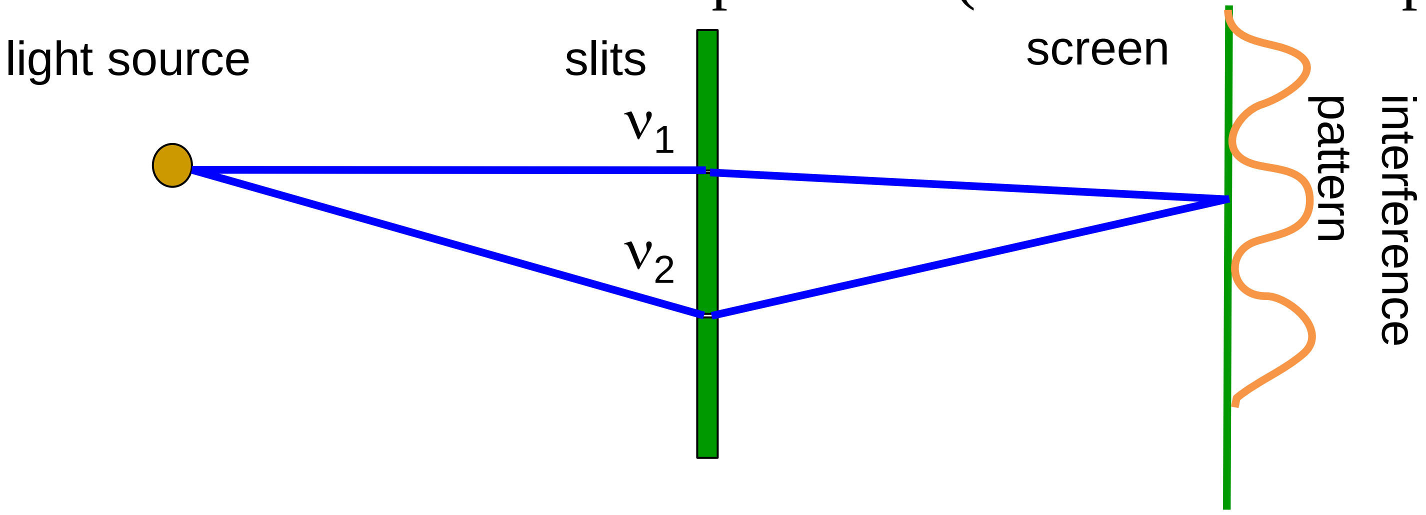
Charged Current (CC) interaction "W-boson exchange"

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

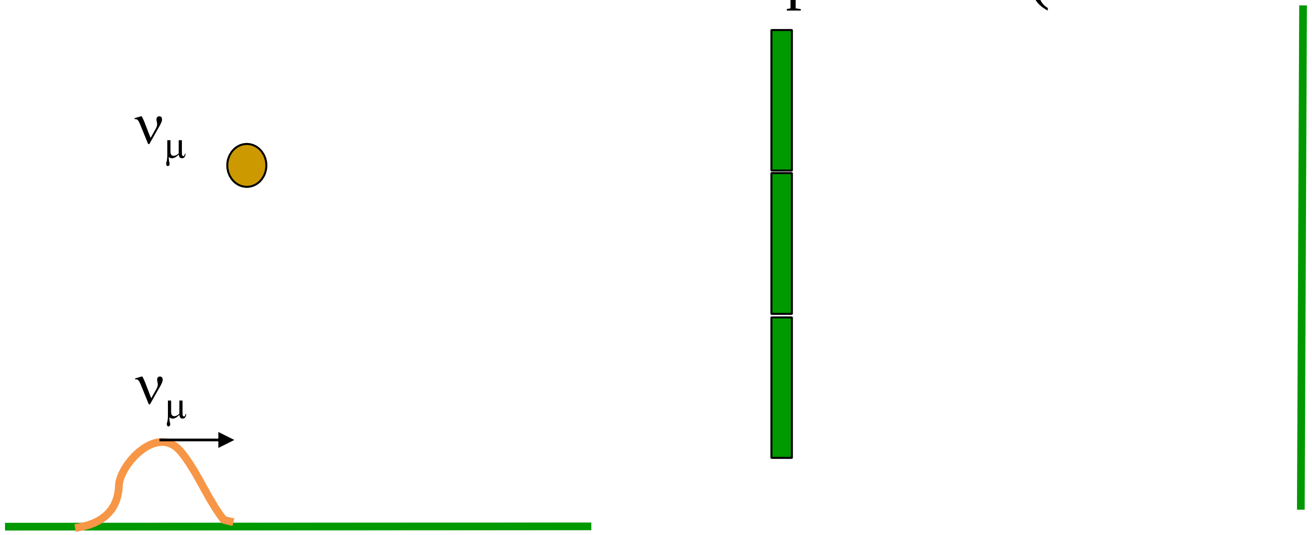
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

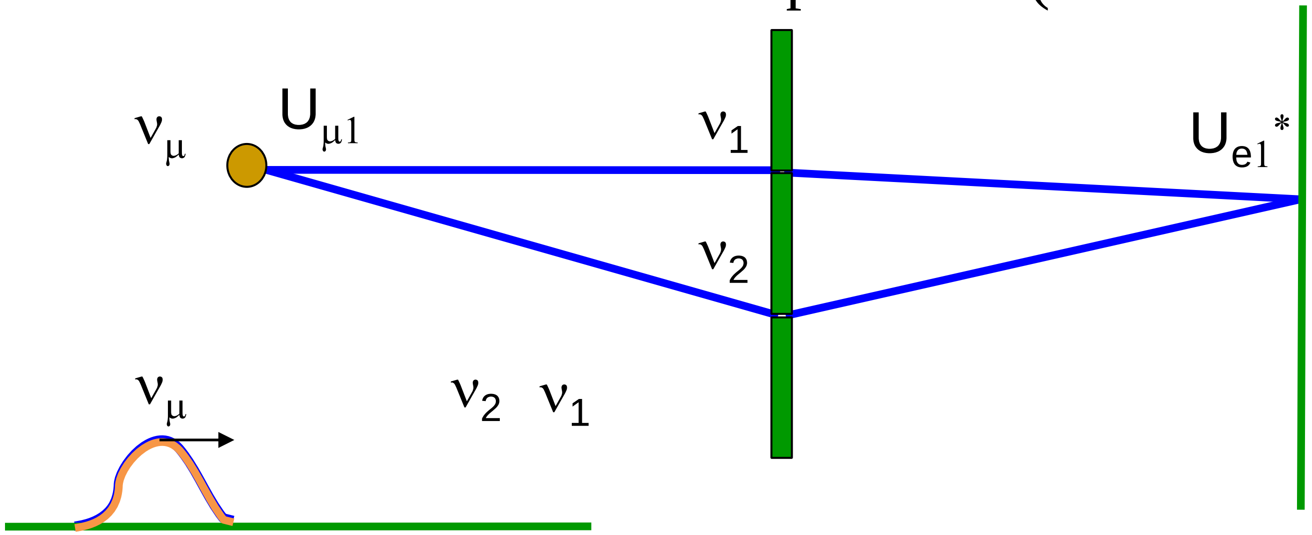
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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)

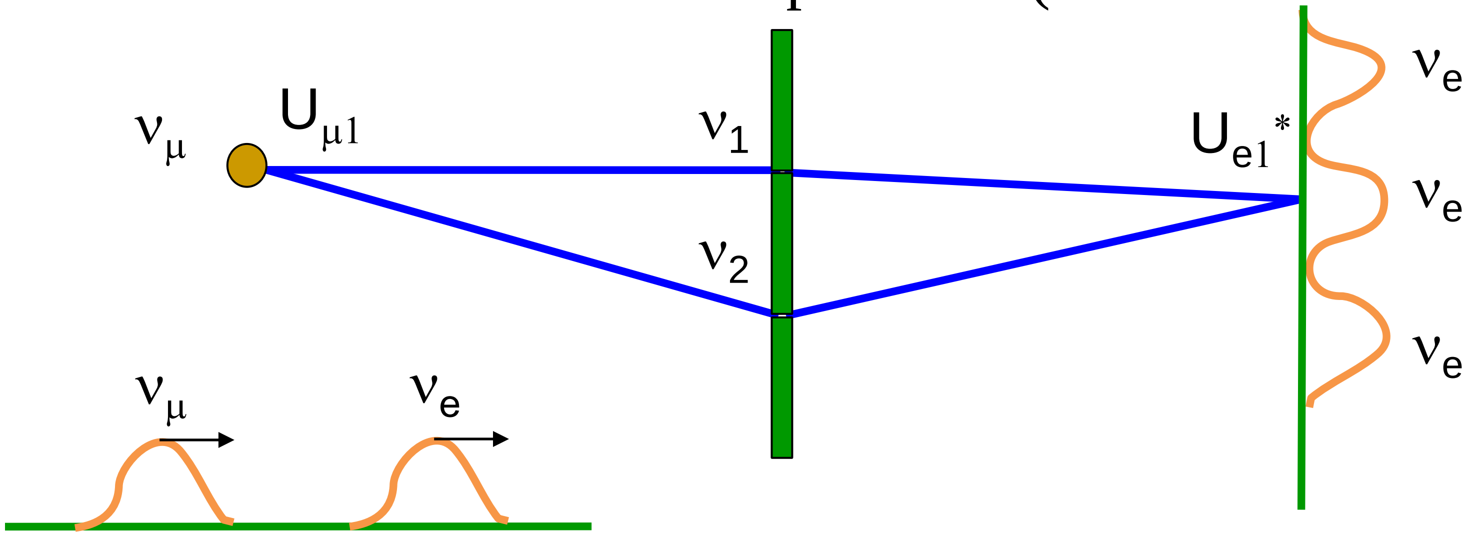


Neutrino flavour eigenstates are super-position of Hamiltonian eigenstates ν_1 and ν_2

Difference in velocities cause quantum interference

Neutrino oscillation experiments

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



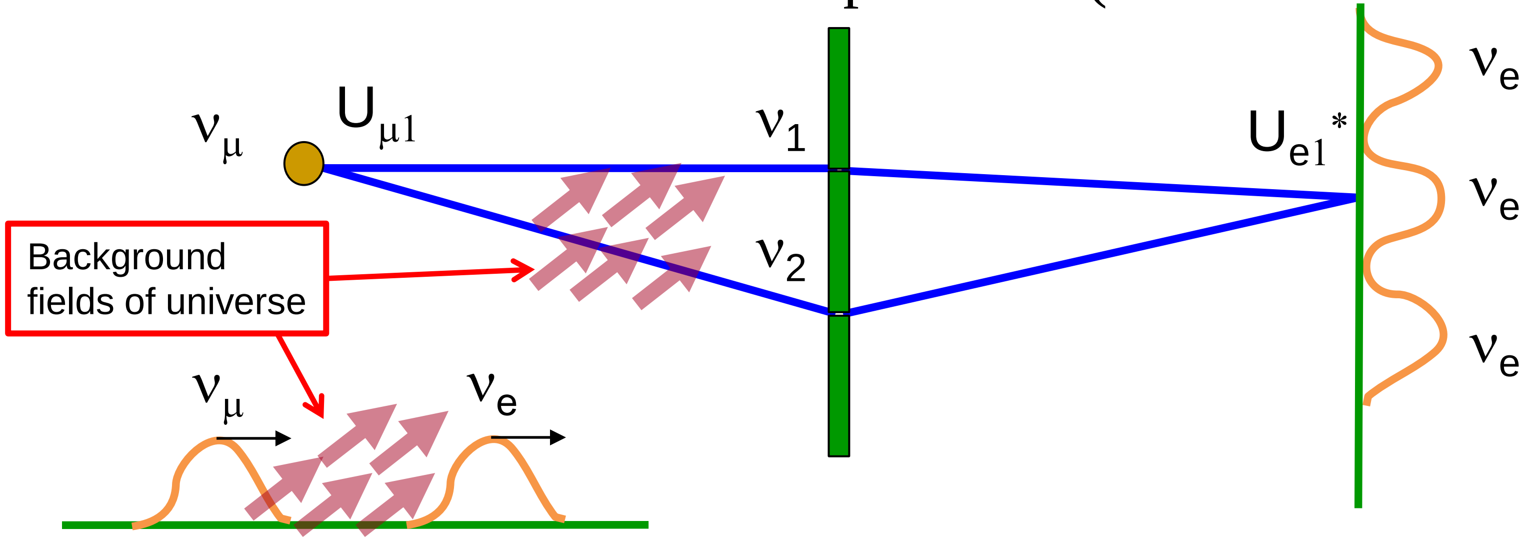
Neutrino flavour eigenstates are super-position of Hamiltonian eigenstates ν_1 and ν_2

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

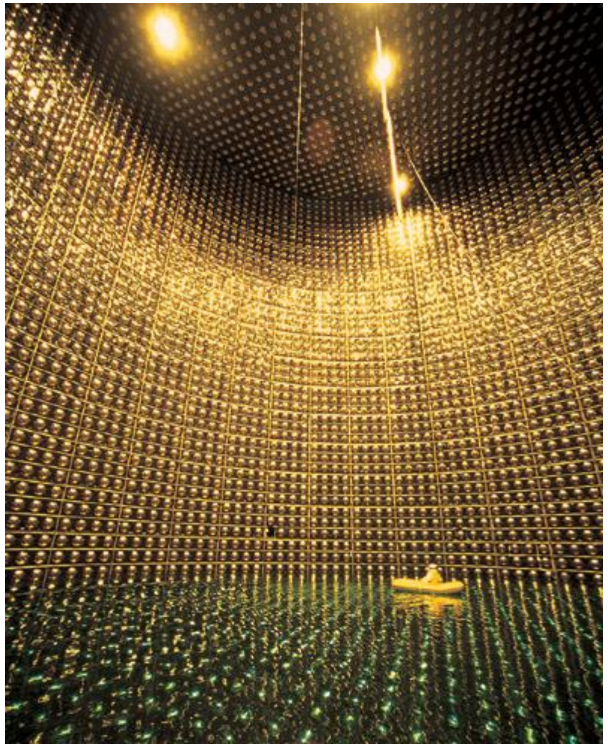
→ anomalous neutrino oscillation results

Neutrino oscillation experiments

Neutrino physics → Home of anomalies

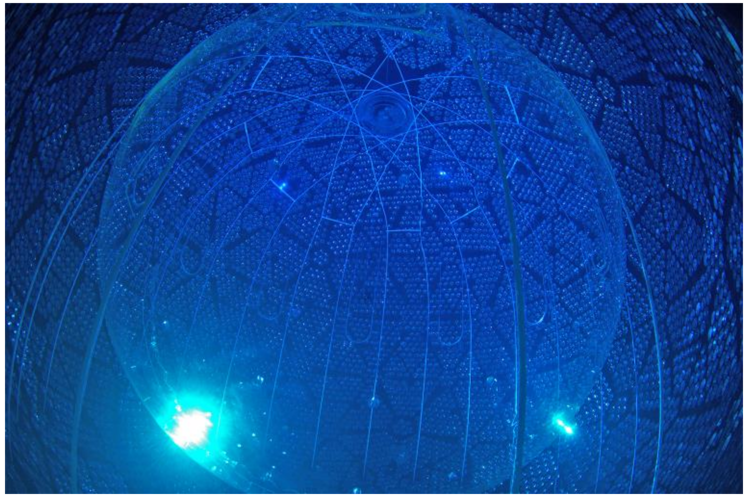
- Solar and atmospheric neutrino anomalies (Nobel prizes, 2002, 2015)

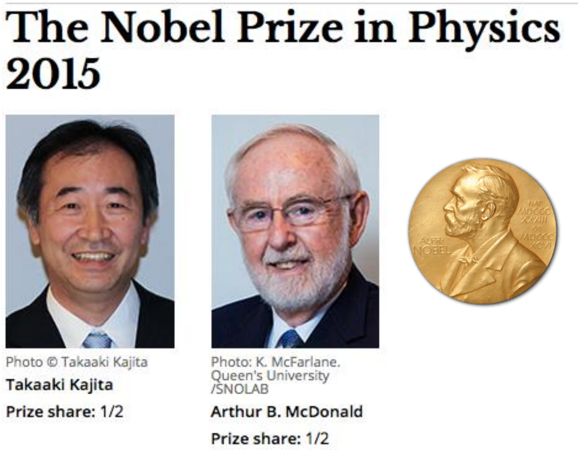
Super-Kamiokande detector

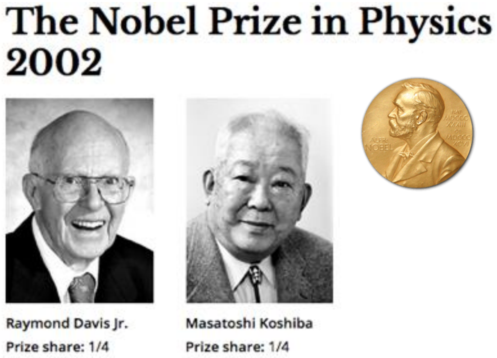


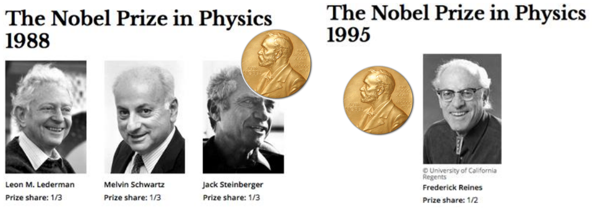
40m

SNO detector







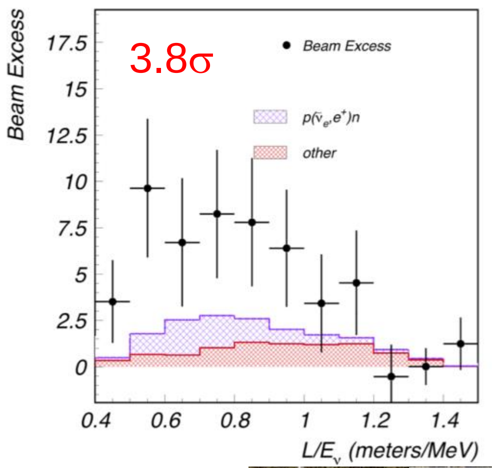


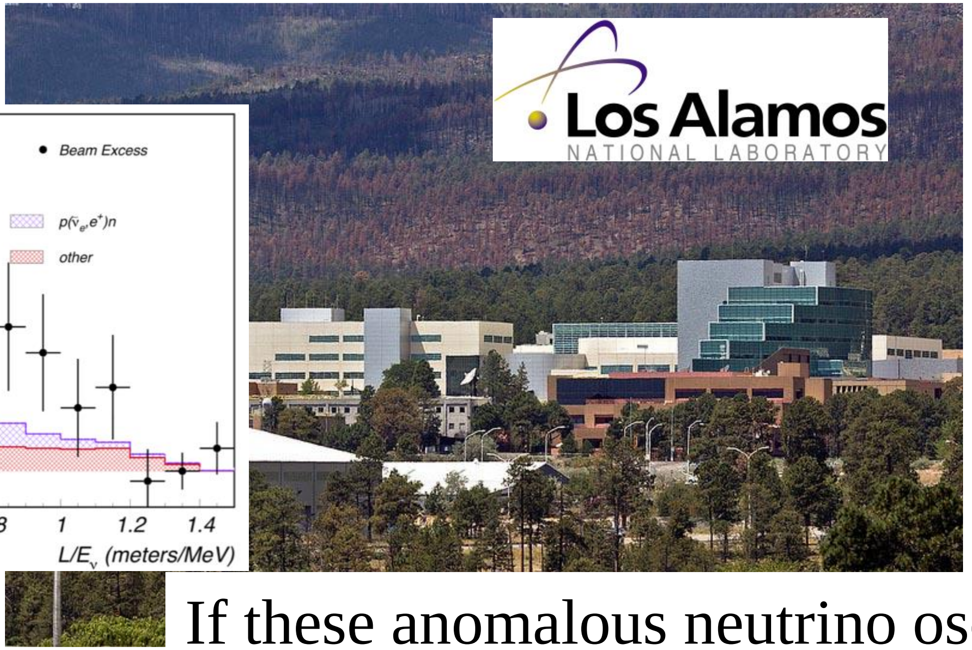
Neutrino oscillation experiments

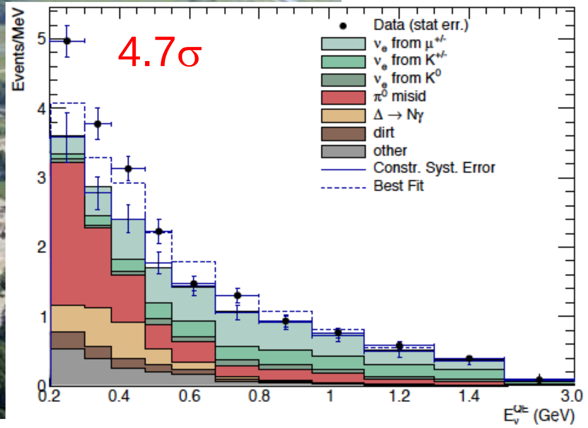
Neutrino physics → Home of anomalies

- ~~Solar and atmospheric neutrino anomalies~~ (Nobel prizes, 2001, 2015)
- ~~OPERA Neutrino-faster-than-Speed-of-Light~~ (detector problem)
- LSND excess
- MiniBooNE excess

LSND excess







MiniBooNE 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, 2001, 2015)
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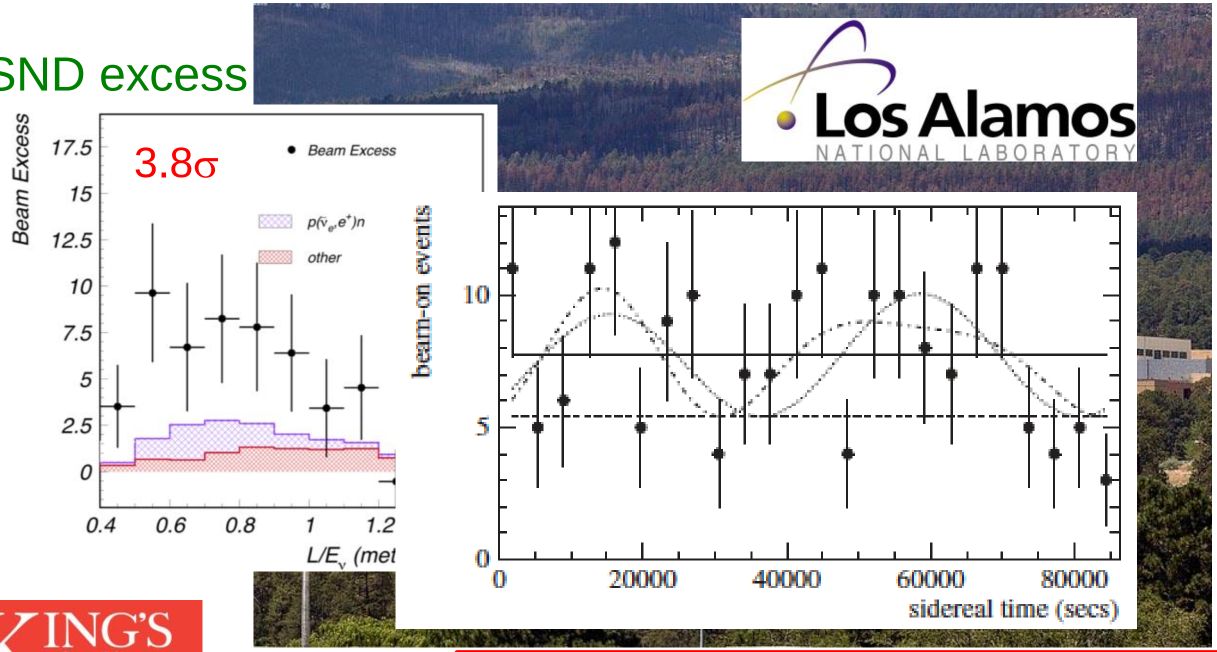
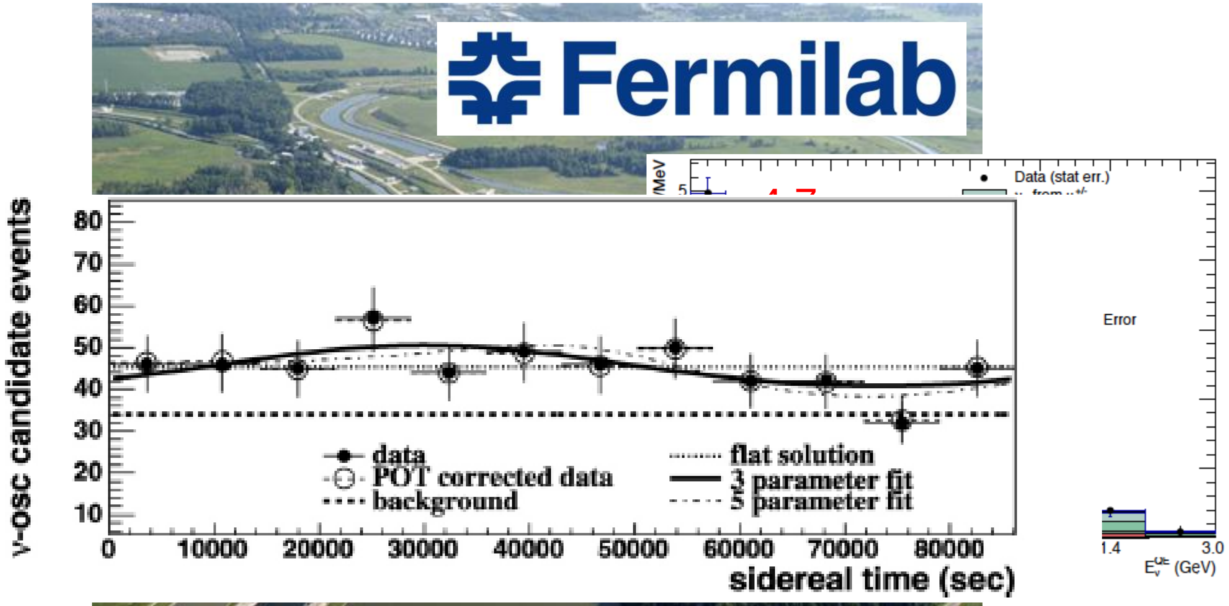
LSND excess





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

Combination	Result	System	Ref.
$(c_{\text{of}}^{(4)})_{00}$	$> -4 \times 10^{-19}$	IceCube	[275]*
$\lvert (c_{\text{of}}^{(4)})_{00} \rvert$	$< 7.1 \times 10^{-9}$	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]*
$\lvert (c_{\text{of}}^{(4)})_{10} \rvert$	$< 4.4 \times 10^{-9}$	SN1987A time of flight	[18]*

Table D15. Photon sector, $d = 3$

Combination	Result	System	Ref.
$\lvert k_{(V)00}^{(3)} \rvert$	$(7.32 \pm 2.94) \times 10^{-45}$ GeV	CMB polarization	[131], [132]*
$\lvert k_{(V)00}^{(3)} \rvert$	$< 1.54 \times 10^{-44}$ GeV	"	[133]*
$\lvert \mathbf{k_{AF}} \rvert$	$< 7.4 \times 10^{-45}$ GeV	"	[133]*
$\lvert \mathbf{k_{AF}} \rvert$	$< 1.03 \times 10^{-26}$ GeV	Satellites	[134]*
k_{AF}^Z	[illegible]	[illegible]	[illegible]]*
"	[illegible]	[illegible]	[illegible]]*
$\lvert k_{(V)10}^{(3)} \rvert$	[illegible]	[illegible]	[illegible]]*
$\lvert k_{(V)11}^{(3)} \rvert$	[illegible]	[illegible]	[illegible]]*
$k_{(V)10}^{(3)}$	[illegible]	[illegible]	[illegible]], [138]*

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

Combination	Result	System	Ref.
$\lvert \bar{c}_{0k}^{p} \rvert$	$< 1 \times 10^{-8}$	Binary pulsars	[75]*
$\lvert \bar{c}_{jk}^{p} \rvert$	$< 1 \times 10^{-11}$	"	[75]*
$\lvert \tilde{c}_Q \rvert$	$< 2 \times 10^{-11}$ 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]

able 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]

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When do we find Lorentz violation???

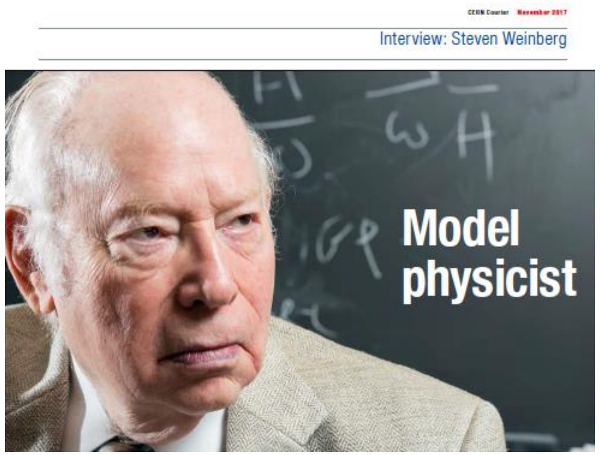
Lorentz violation is motivated by Planck scale theories, so it is suppressed with the power of Planck mass ($\sim 10^{19}\ GeV$)

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

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 $< 10^{-19}\ GeV^{-1}$
dimension-6 LV operator $< 10^{-38}\ GeV^{-2}$
etc

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



Steven Weinberg
(CERN Courier Nov. 2017)

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

Tests of Lorentz violation – 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

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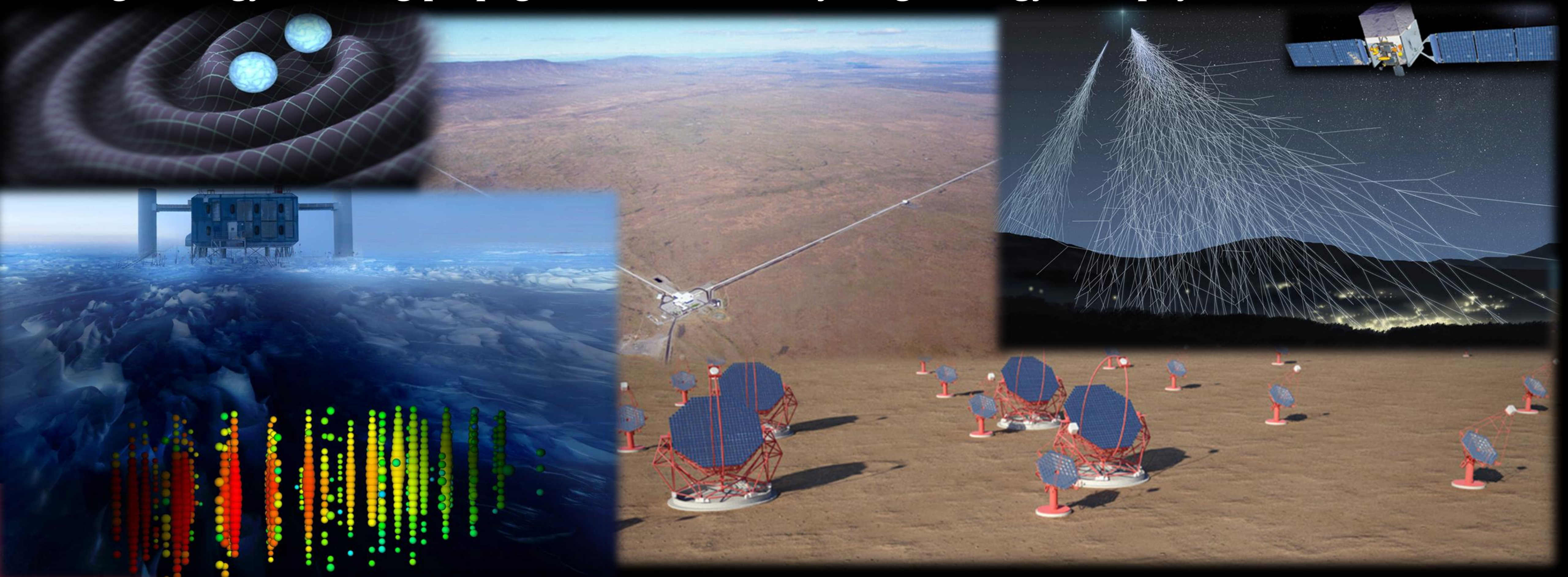
Review

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

Highest energy particles – Ultra-high-energy cosmic rays

Longest propagating particles – Gravitational waves, cosmic microwave background

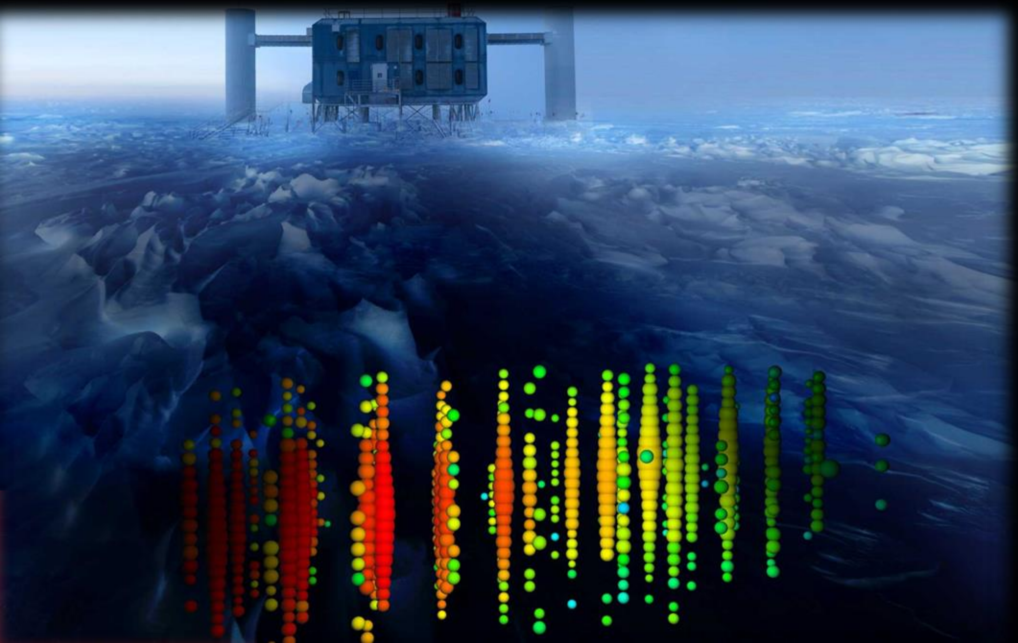
High-energy and long propagation – Gamma-ray, High-energy astrophysical neutrinos

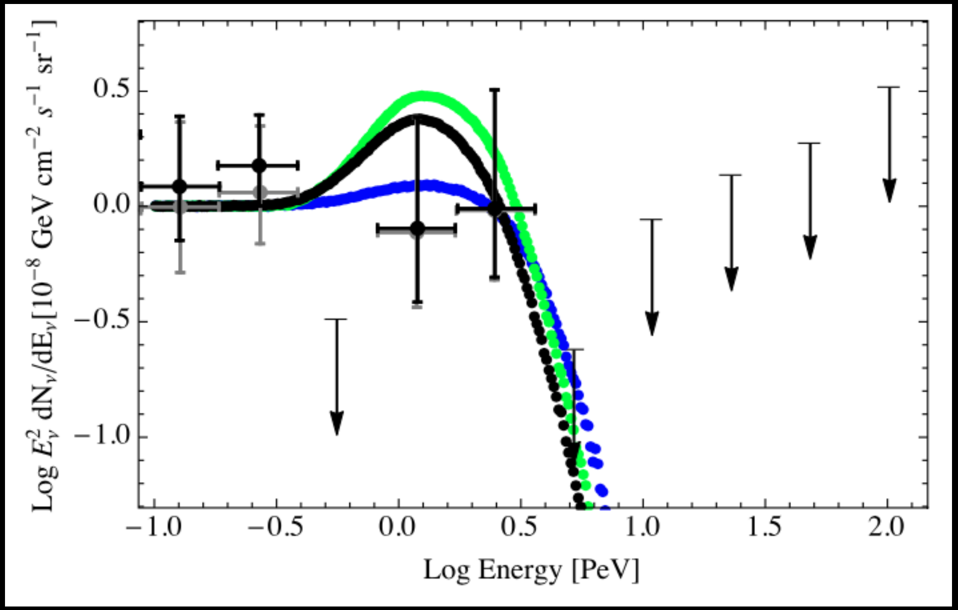


Cut-off in high-energy cosmic ray spectrum

Lorentz violation = media in vacuum

- Attenuate high-energy cosmic rays?

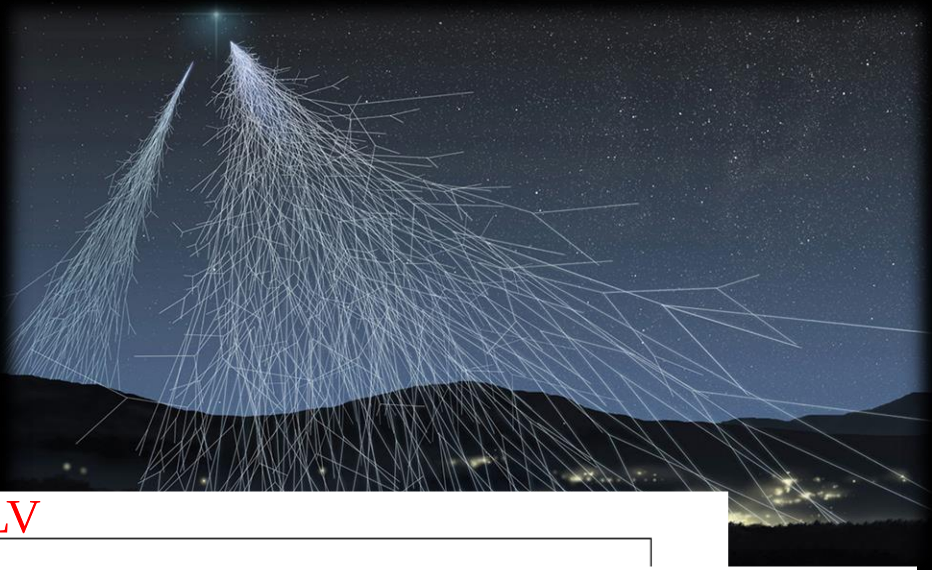


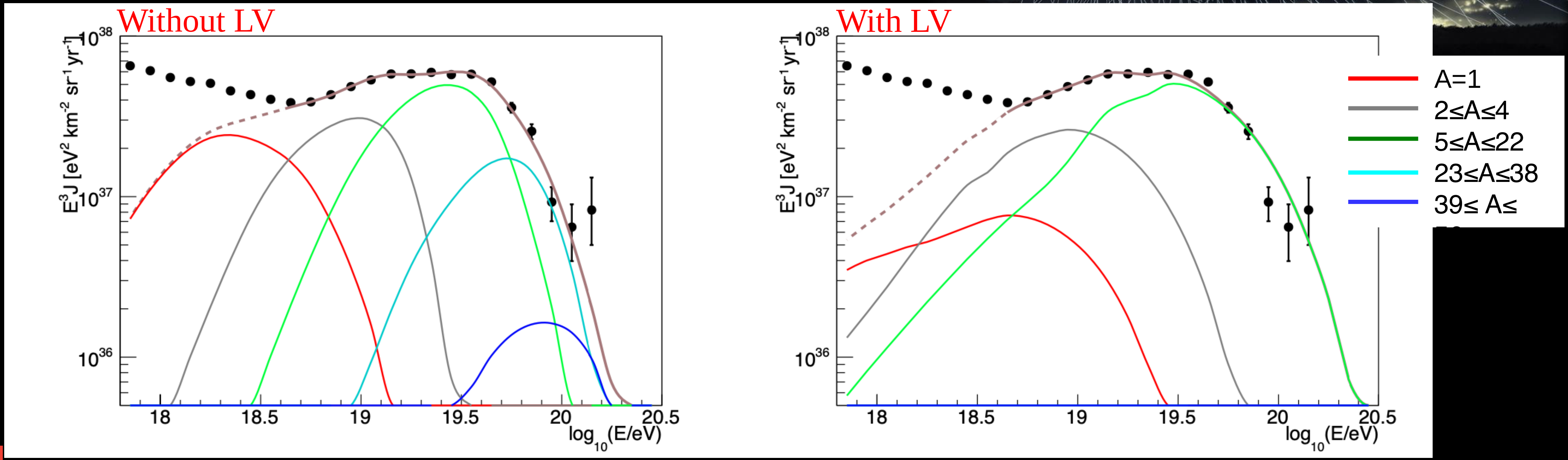


High-energy astrophysical neutrino spectrum

Cut-off in high-energy cosmic ray spectrum

Lorentz violation = media in vacuum
- Attenuate high-energy cosmic rays?





Ultra-high-energy cosmic ray spectrum

Time delay of high-energy cosmic rays

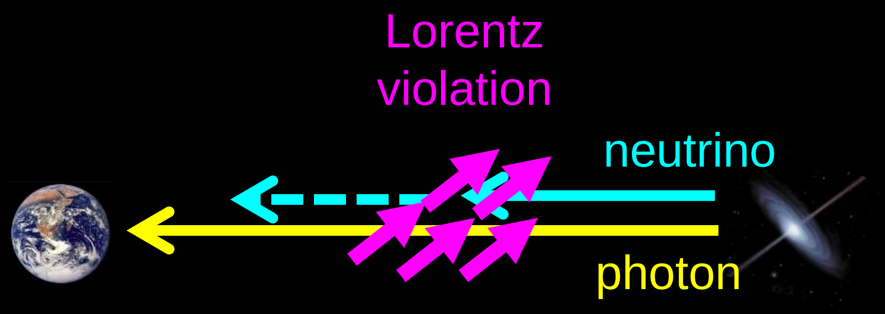
Lorentz violation = media in vacuum
 - Time difference between photons and neutrinos?

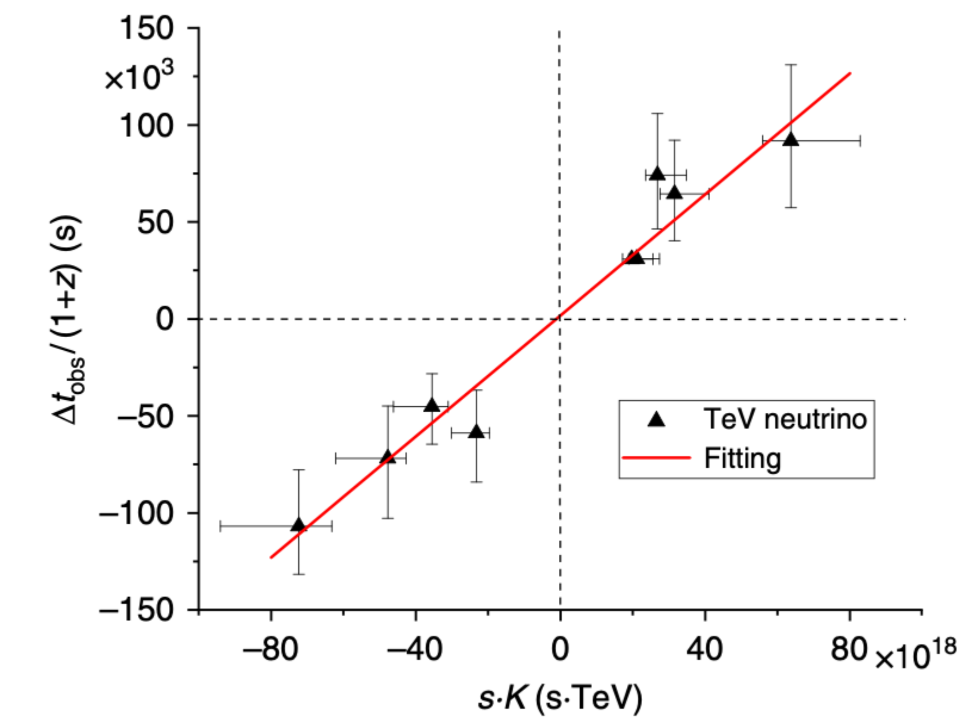
Gamma Ray Bursts
 - Not identified as point neutrino sources
 - Time delay or advance proportion to neutrino energy and sign may fit with data

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



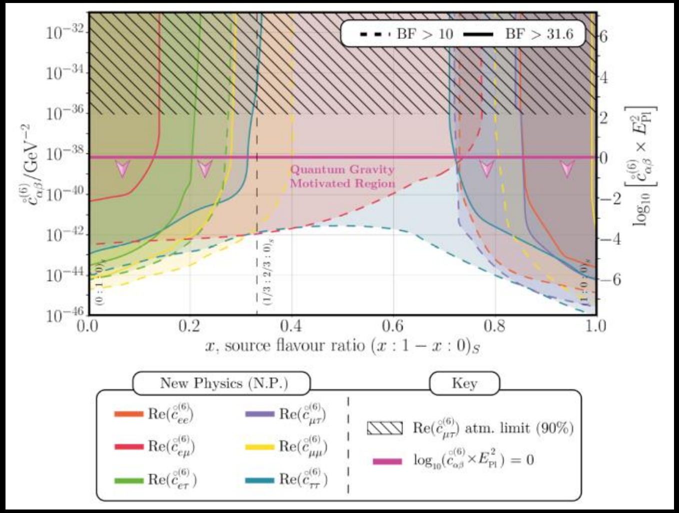


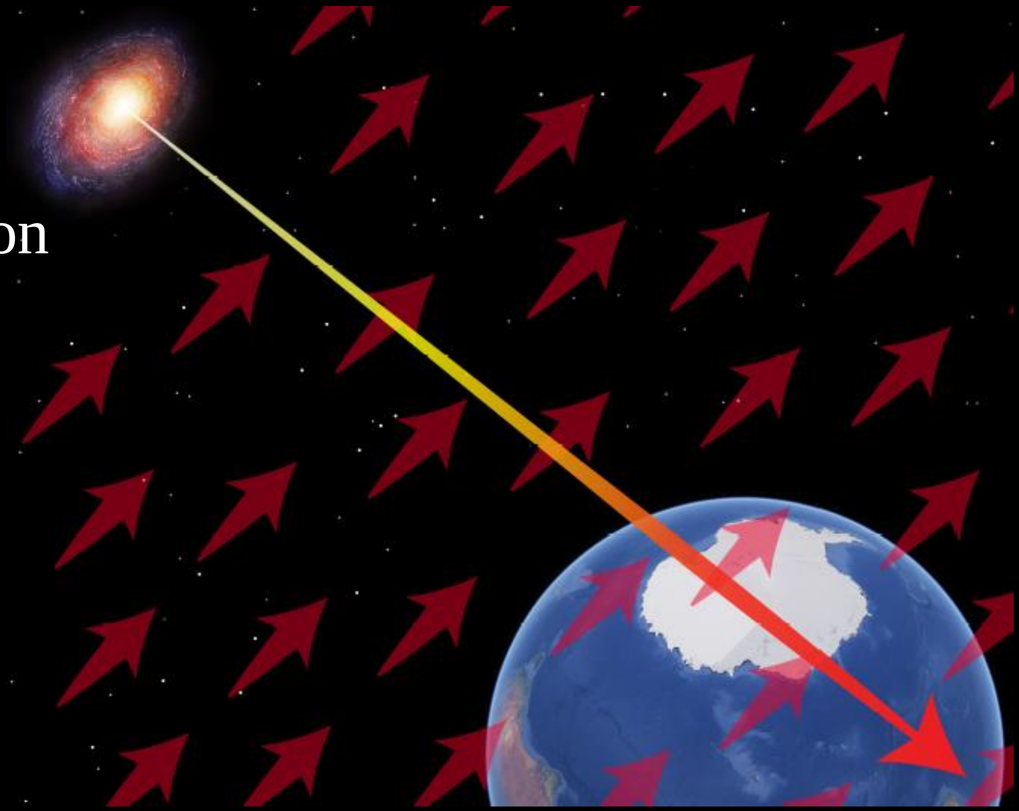
IceCube, Nature Physics 18(2022)1287

Anomalous neutrino mixings in vacuum

Lorentz violation = media in vacuum
 - Neutrino oscillations are affected by media
 - If the universe is saturated with background field, they would affect flavours of astrophysical neutrinos

Sensitive to the target signal region of Lorentz violation ($< 10^{-38}\ GeV^{-2}$ for dimension-6 operators), no anomalous neutrino oscillation is discovered yet





Neutrino astronomy – Summary

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

- Energy spectrum
- Sources (5 known sources, Sun, SN1987, TXS0506+056, NGC1068, Galactic plane)
- Flavour structure

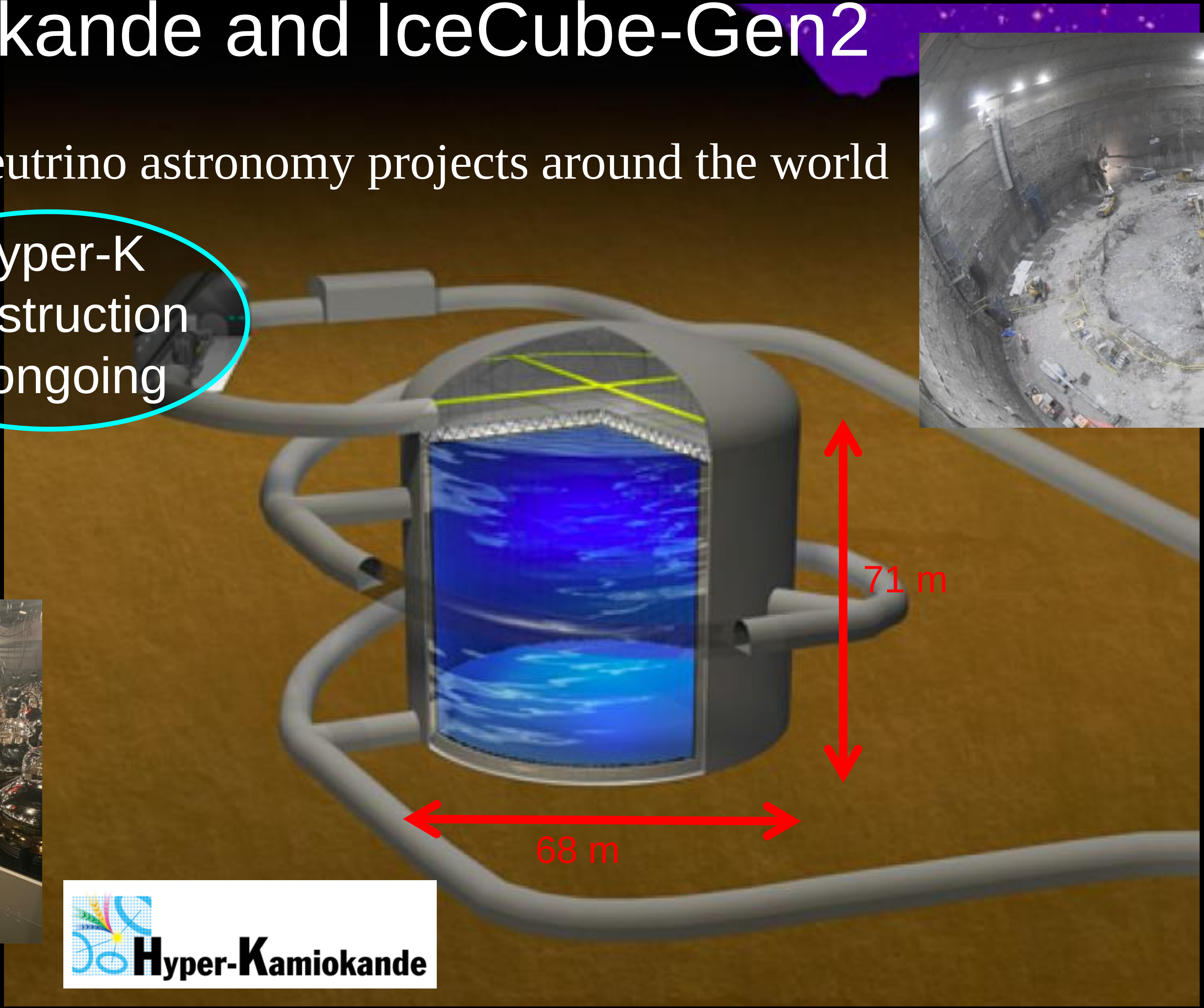
So far, astrophysical neutrino data are low statistics and further data are needed to search Lorentz violation

Hyper-Kamiokande, ArXiv:1805.04163

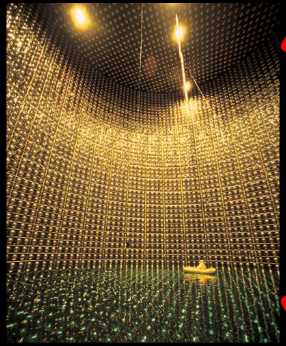
Hyper-Kamiokande and IceCube-Gen2

New international neutrino astronomy projects around the world

Hyper-K construction is ongoing



Super-Kamiokande

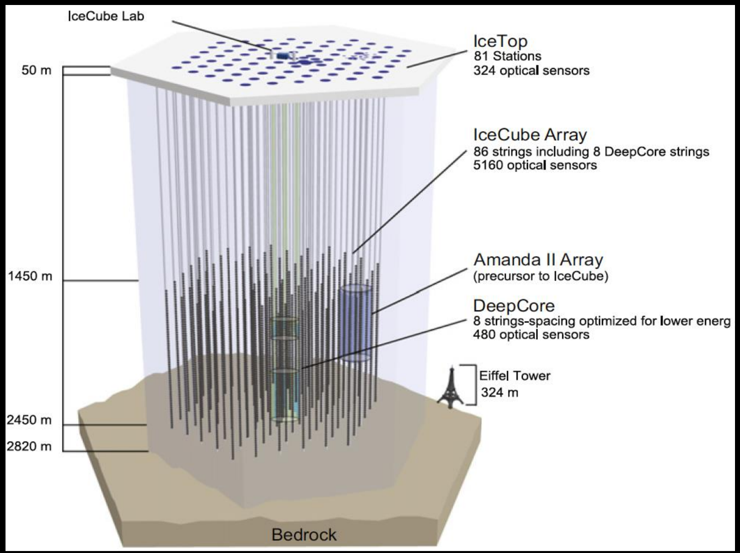


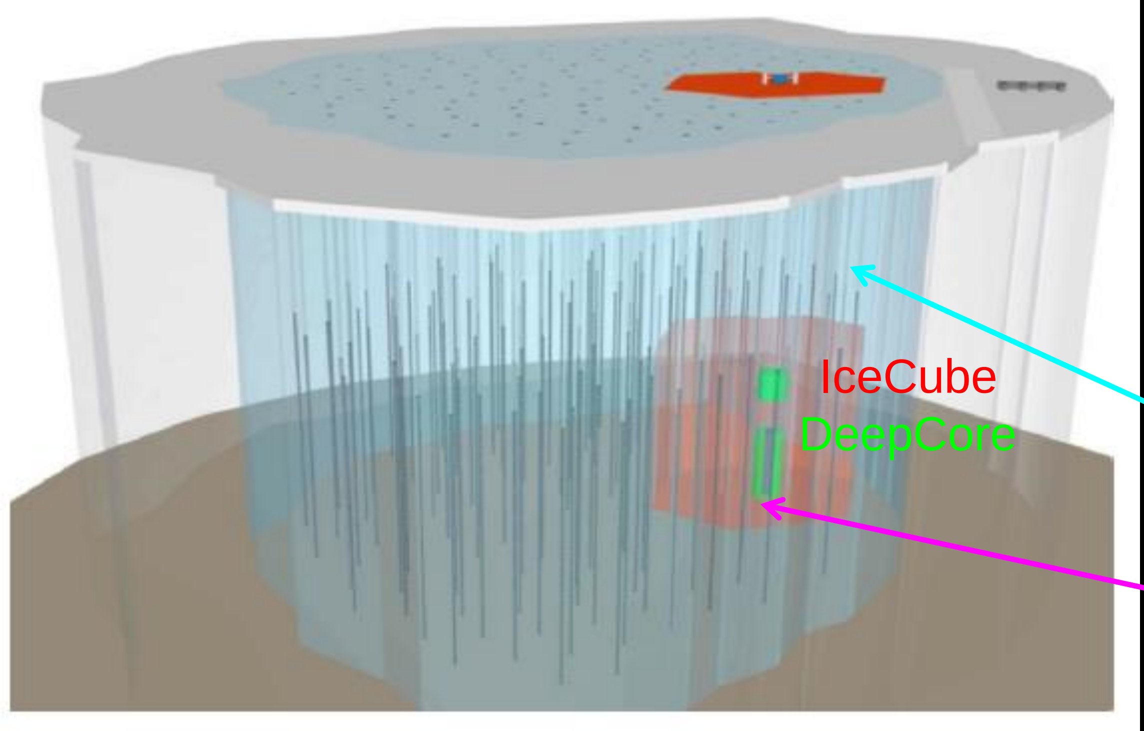
40m

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

Hyper-Kamiokande and IceCube-Gen2

New international neutrino astronomy projects around the world



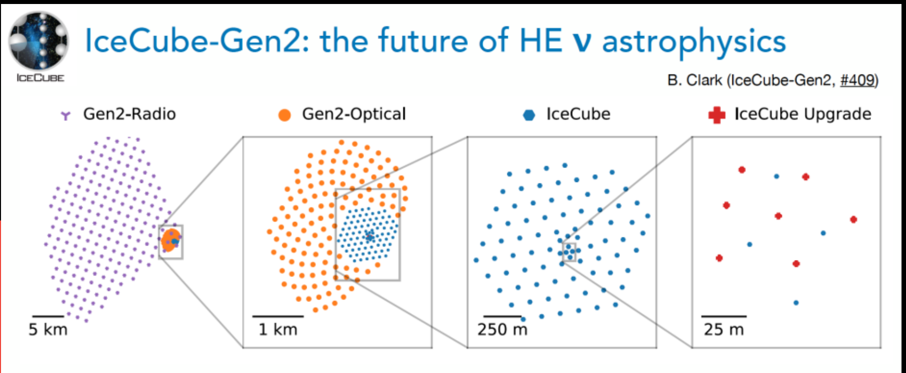


IceCube (~1Gton)

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

Neutrino oscillation and neutrino astronomy are powerful tools to look for Lorentz violation

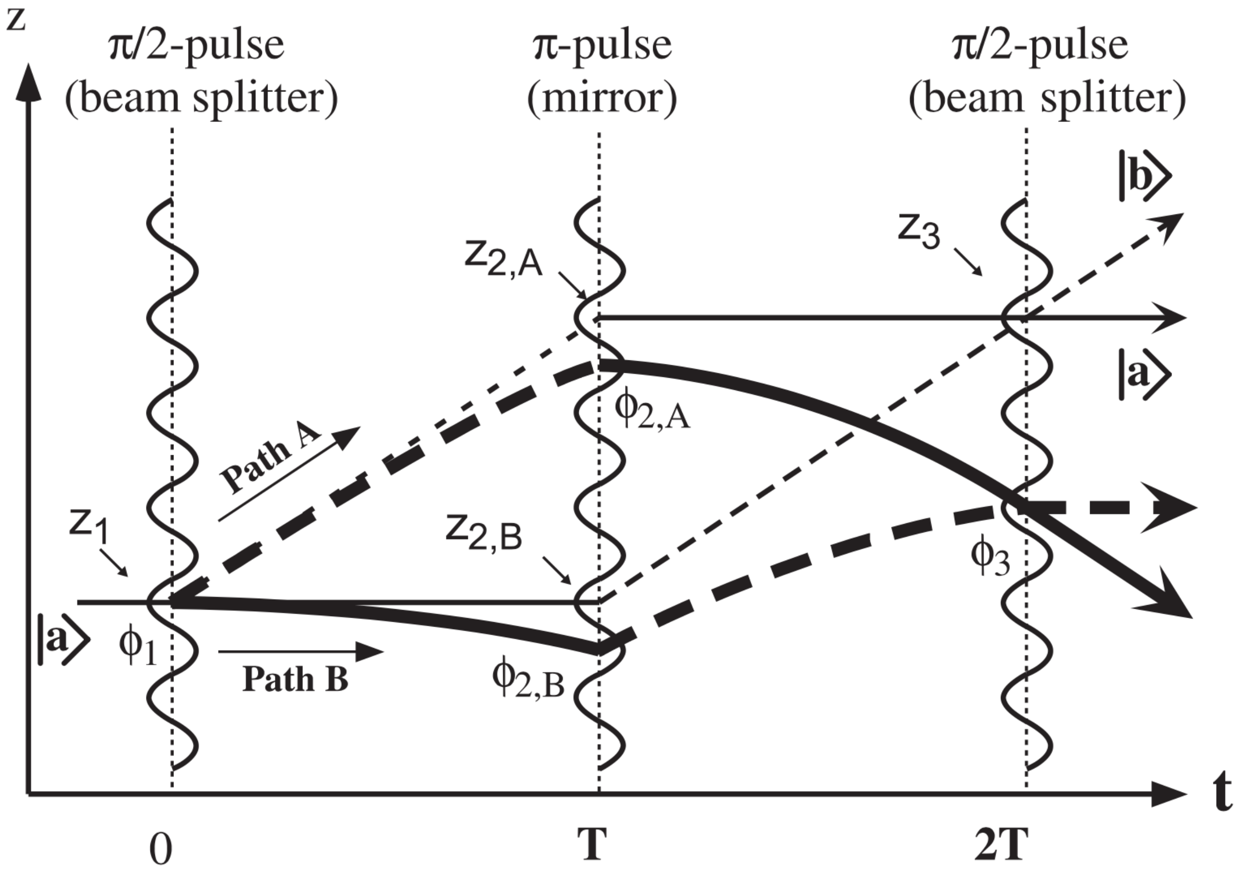
Merry Christmas!

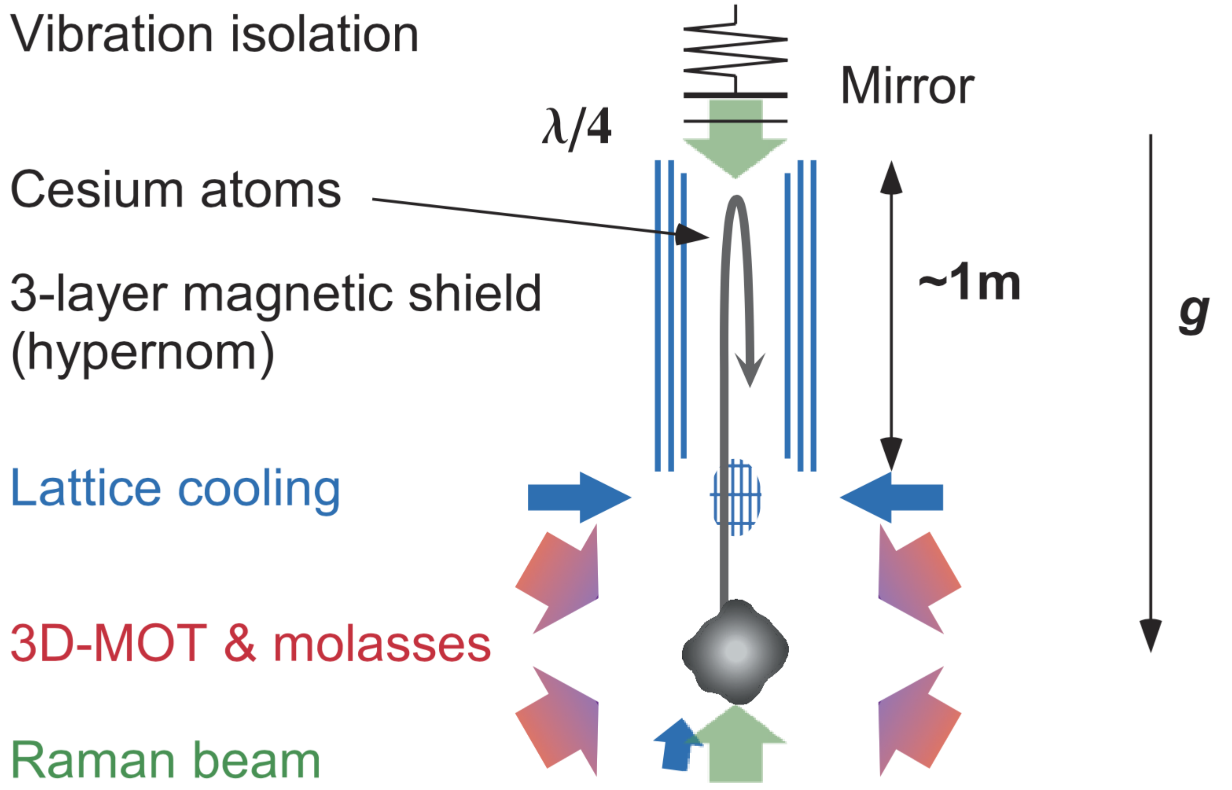
Backup

Müller et al., PRL100(2008)031101 and others

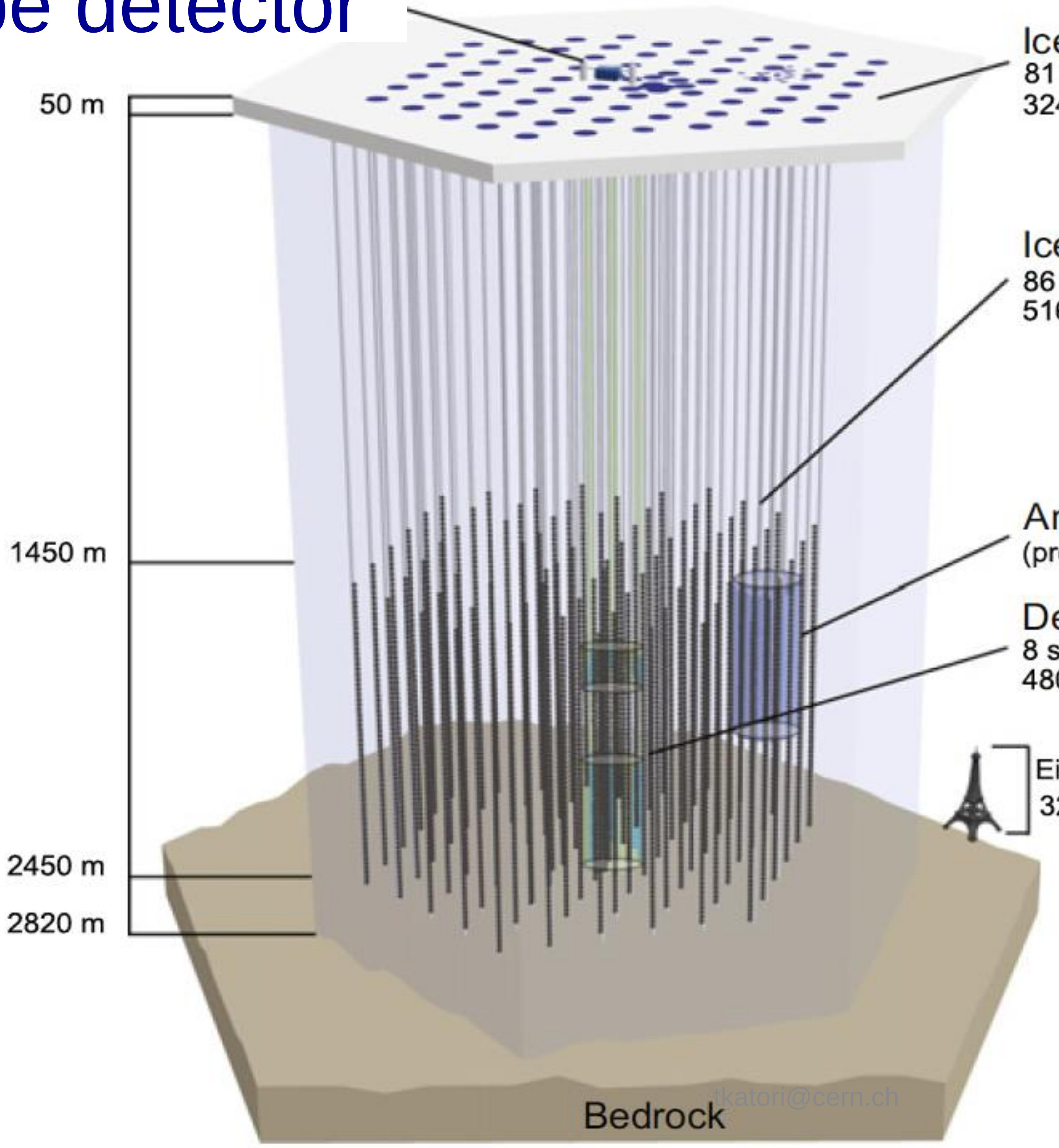
Gravity test

Matter wave interferometer

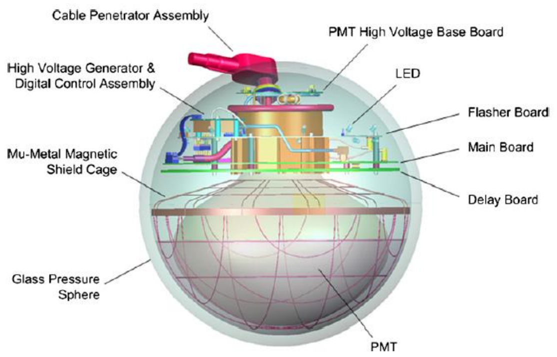




IceCube detector

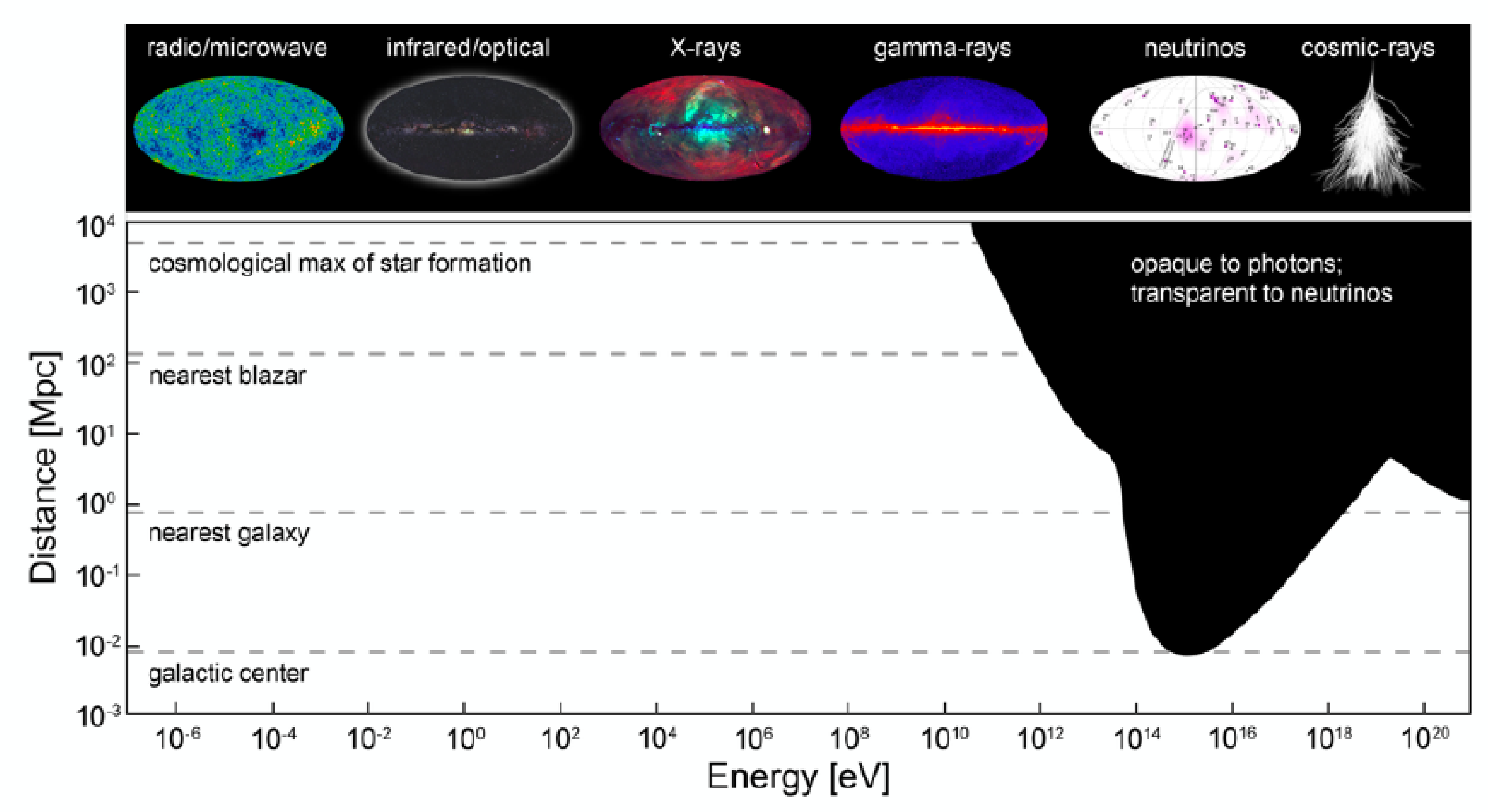


digital optical module (DOM)



High-energy astrophysical neutrinos

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



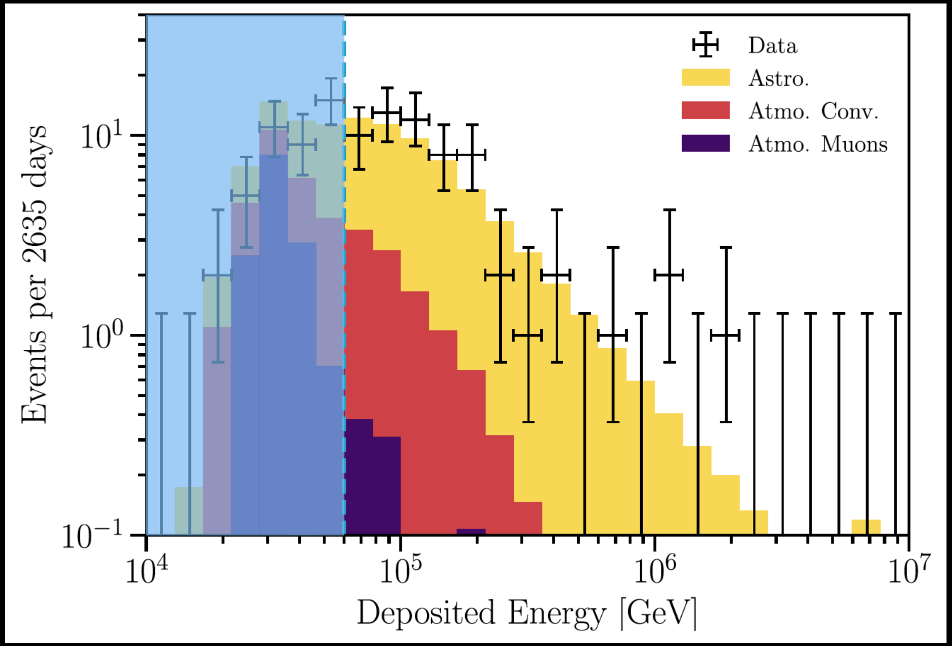
IceCube, PRD104(2021)022002

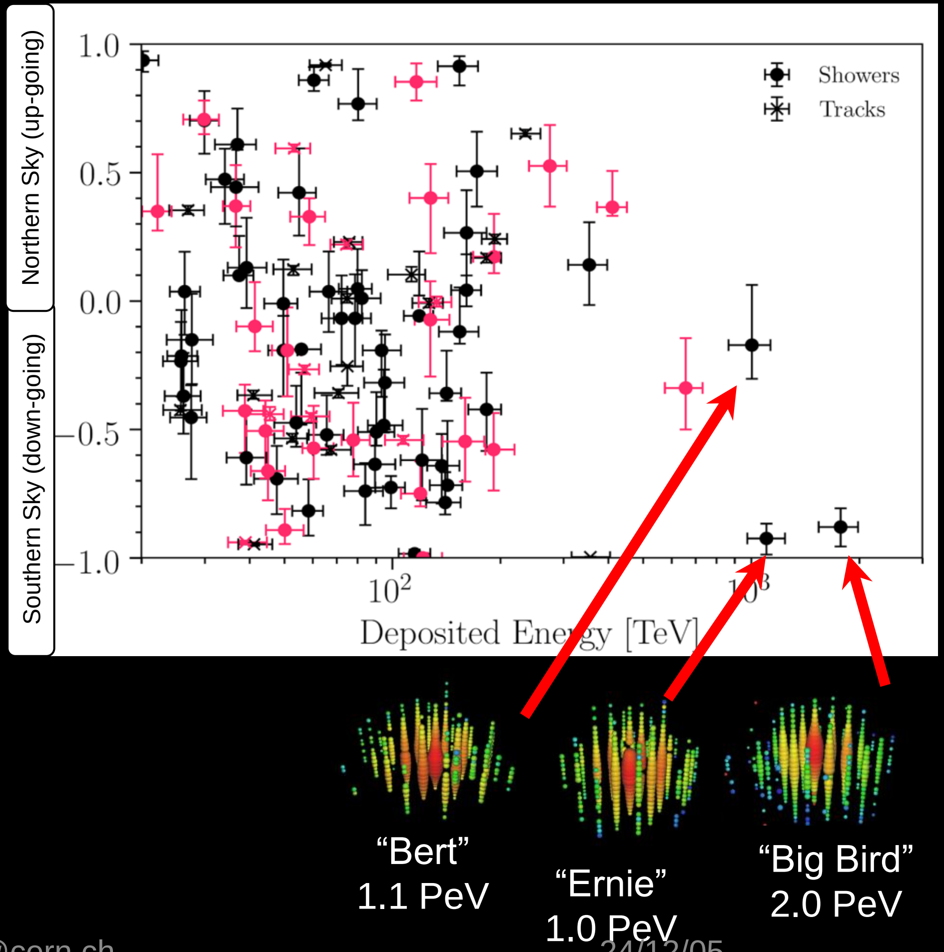
High-energy astrophysical neutrinos

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

high-energy starting event (HESE) sample

2. Hig





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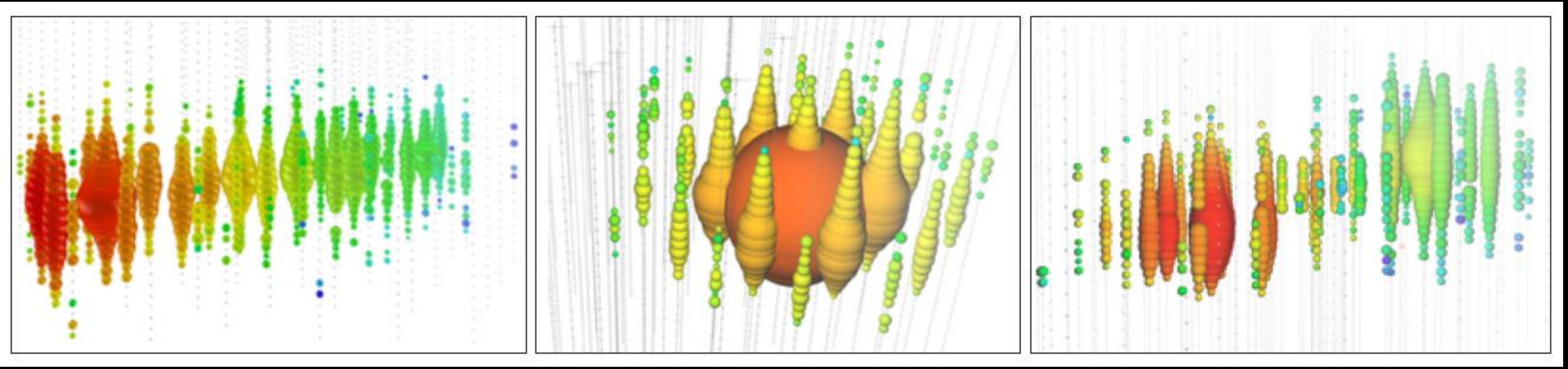
IceCube event morphology

Track
ν_μCC
$\nu_\mu + N \to \mu + X$

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

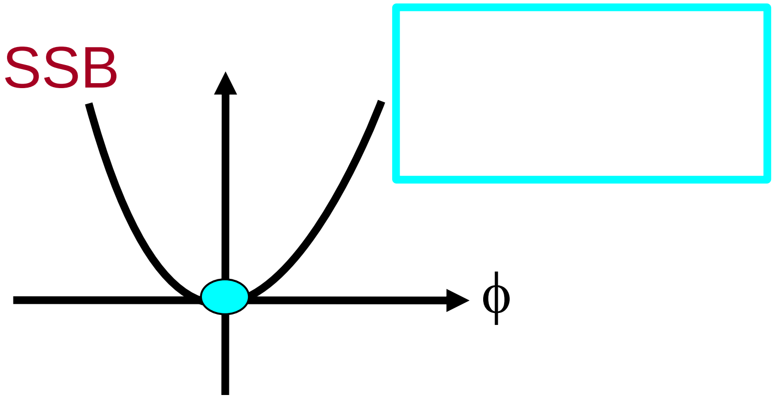
Double cascade
ν_τCC (L~50m•E/PeV)
$\nu_\tau + N \to \tau + X$
$\tau \to X'$

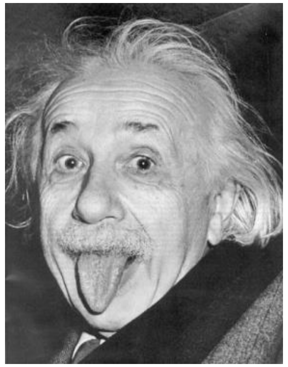


Spontaneous symmetry breaking (SSB)

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





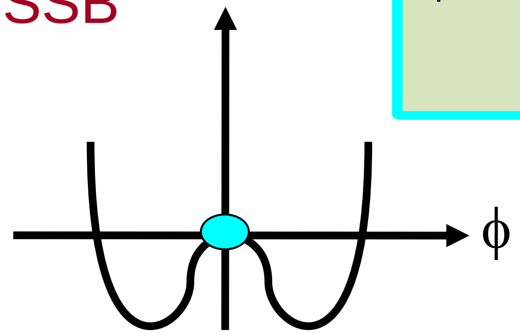
$$L = \frac{1}{2}\left(\partial_\mu\phi\right)^2 - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4$$

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

SSB



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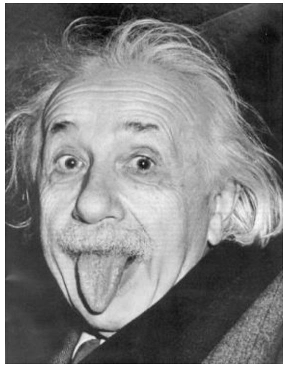


Particle acquires
mass term!

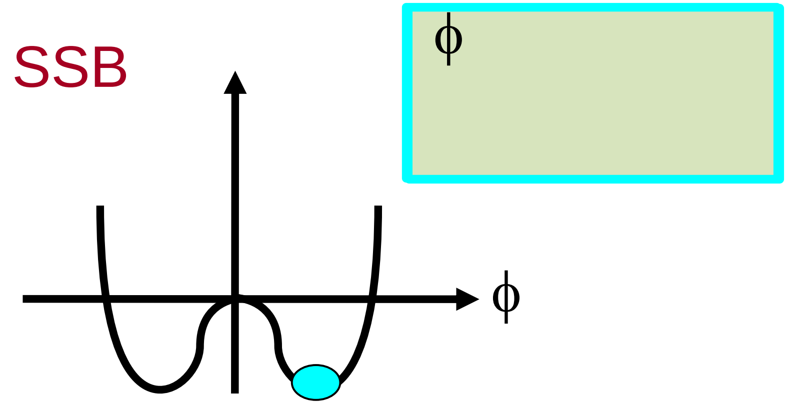
$$L = \frac{1}{2}\left(\partial_{\mu}\phi\right)^{2} - \frac{1}{2}\mu^{2}\phi^{2} - \frac{1}{4}\lambda\phi^{4}$$

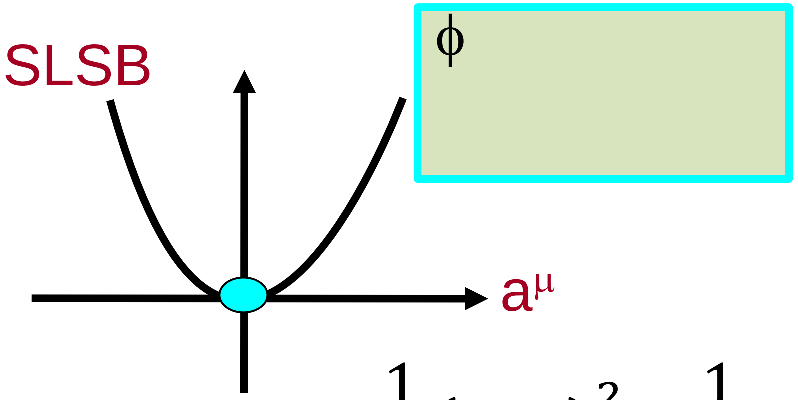
Spontaneous Lorentz symmetry breaking (SLSB)

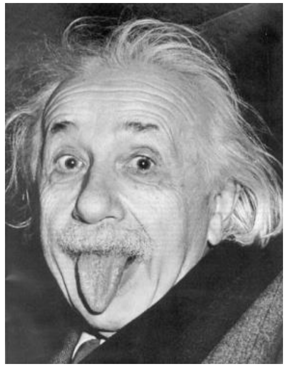
vacuum Lagrangian for fermion $L = i\bar{\psi}\gamma_{\mu}\partial^{\mu}\psi - m\bar{\psi}\psi$

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







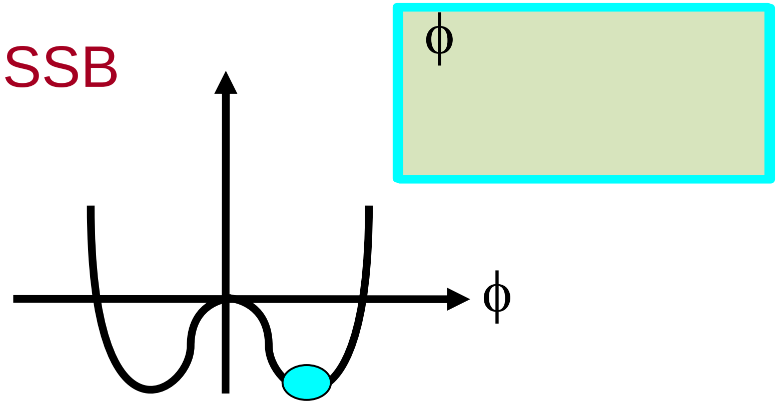
$$L = \frac{1}{2}\left(\partial_{\mu}\phi\right)^{2} - \frac{1}{2}\mu^{2}\phi^{2} - \frac{1}{4}\lambda\phi^{4}$$

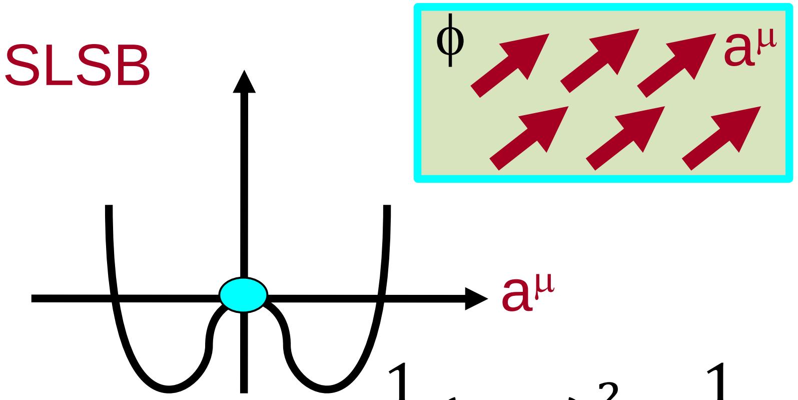
Spontaneous Lorentz symmetry breaking (SLSB)

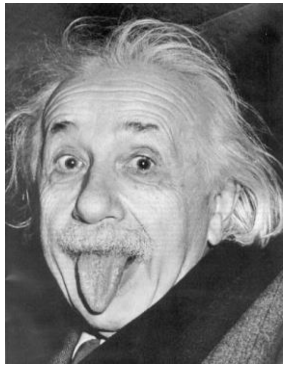
vacuum Lagrangian for fermion $L = i\bar{\psi}\gamma_\mu\partial^\mu\psi - m\bar{\psi}\psi + \bar{\psi}\gamma_\mu a^\mu\psi$

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





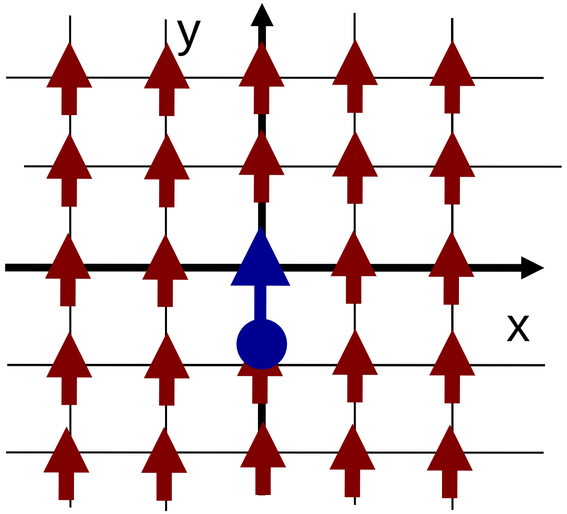


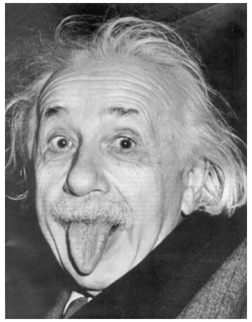
Lorentz symmetry is spontaneously broken!

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

Particle and Observer Lorentz transformation

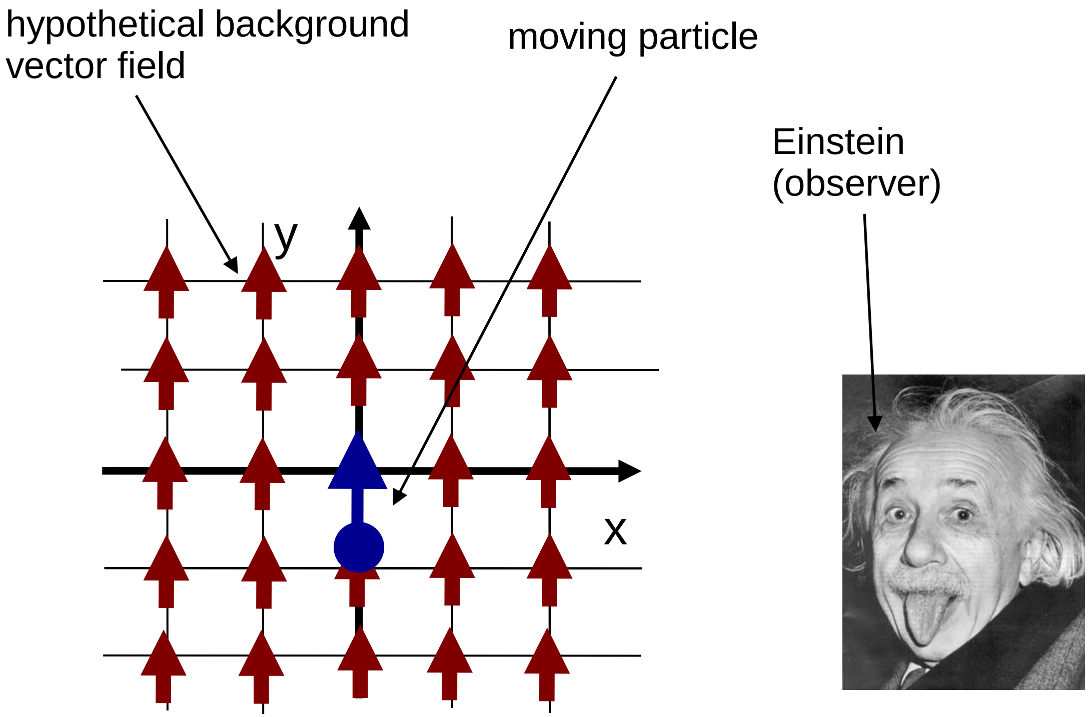
$$\overline{Y}(x) g_m a^m Y(x)$$





Particle and Observer Lorentz transformation

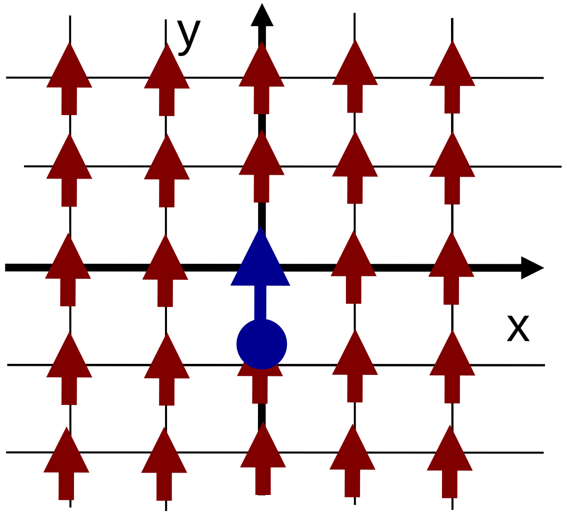
$$\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x)$$

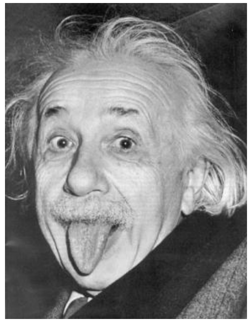


Particle and Observer Lorentz transformation

Under the particle Lorentz transformation:

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





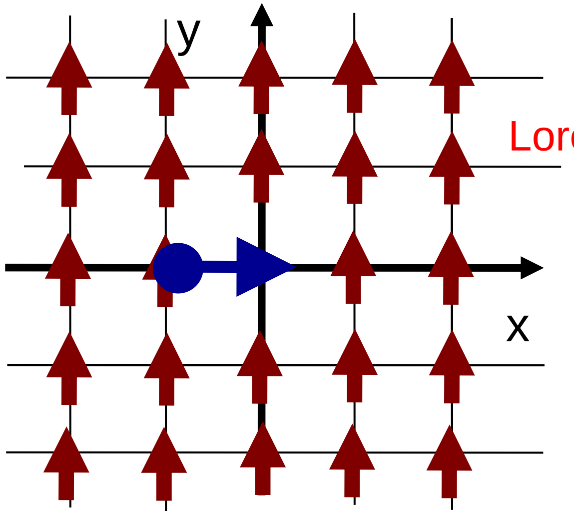
Particle and Observer Lorentz transformation

Under the particle Lorentz transformation:

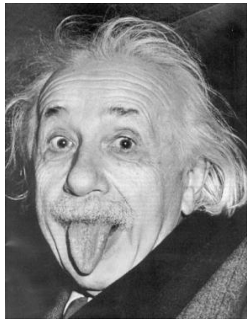
$$\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x) \rightarrow U[\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x)]U^{-1}$$

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

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



Lorentz violation!



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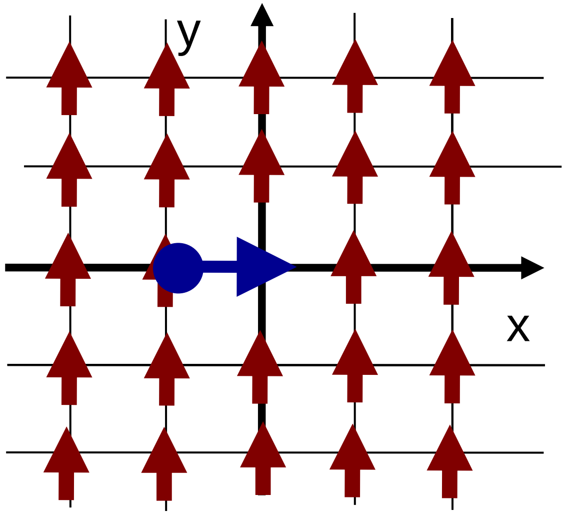
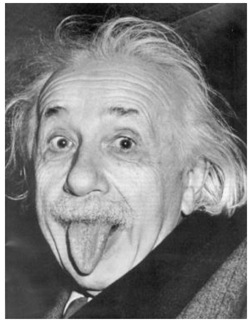
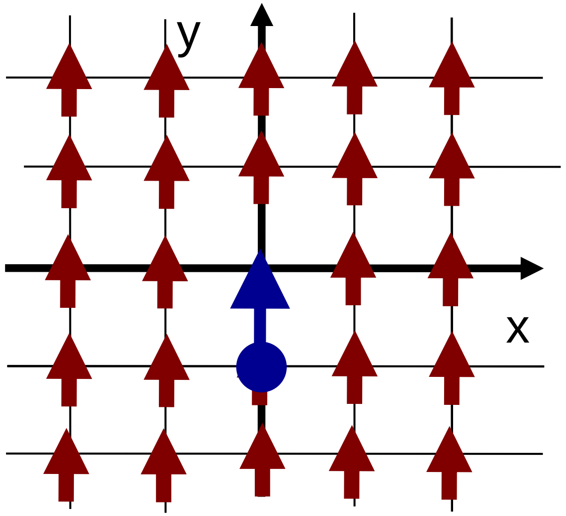




Under the observer Lorentz transformation:

$$\bar{Y}(x) g_m a^m Y(x)$$



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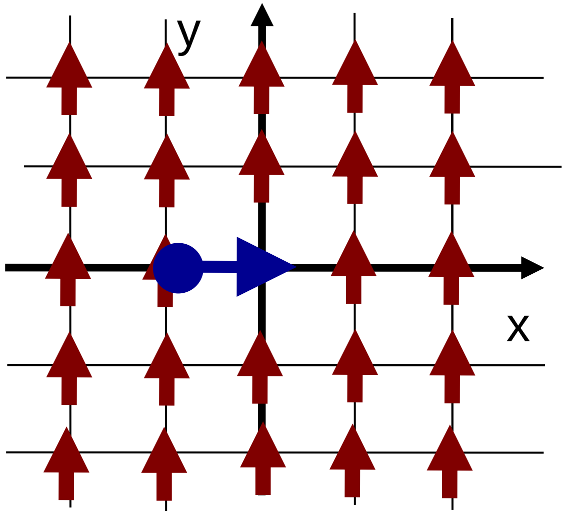
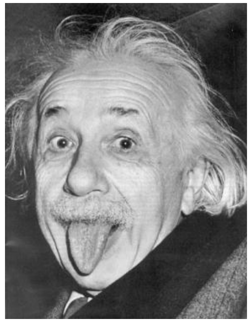
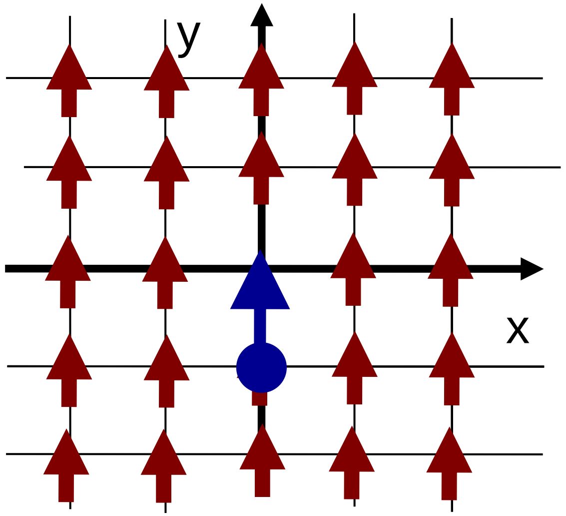




Under the observer Lorentz transformation:

$$\overline{Y}(x)g_m a^m Y(x)$$

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



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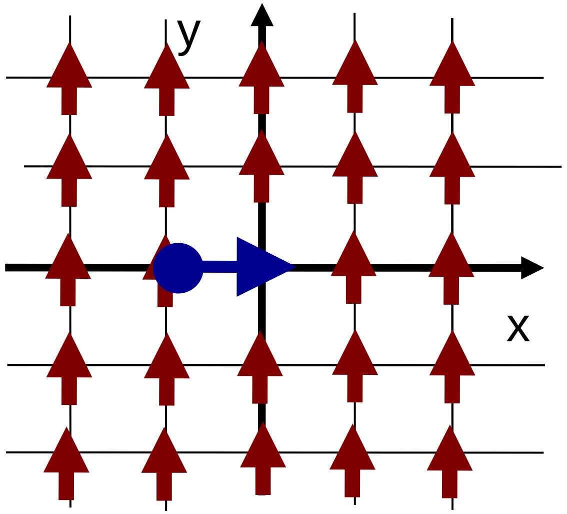
$$\neq \overline{\Psi}(\Lambda x)\gamma_\mu a^\mu \Psi(\Lambda x)$$

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



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