A Revisit of
Lorentz Invariance Violation

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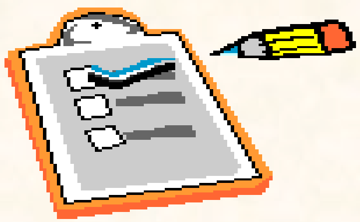
In collaboration with Zhi Xiao, Lijing Shao, Shimin Yang, Zhou Lingli, Yunqi Xu, Nan Qin



Outline

- Motivation: A probe on space-time
- Theories & A New Theory
- Phenomena: light speed anisotropy, neutrinos,
- Summary

The Nature of Space-Time

There are many issues concerning the nature of space-time in human history:

- Existence or Concept?
- Objective or Subjective?
- Continuous or Discrete?

Philosophy, Metaphysics, Art, Physics

Basic units of the universe: Planck Units

$$l_P = \sqrt{\frac{G\hbar}{c^3}} = 1.61624(8) \times 10^{-35}\, m$$

$$t_{\mathrm{P}} \equiv \sqrt{G\hbar/c^5} \simeq 5.4 \times 10^{-44}\ \mathrm{s}$$

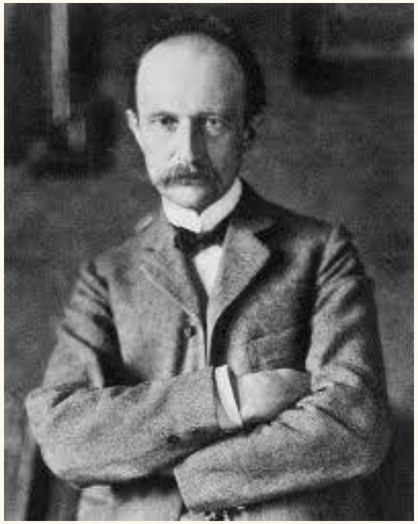
$$M_P = \sqrt{\frac{\hbar c}{G}} = 1.22089(6)\times 10^{19}\,\frac{\mathrm{GeV}}{\mathrm{c}^2} = 2.17644(11)\times 10^{-8}\,\mathrm{kg}$$

$$E_{\mathrm{P}} \equiv \sqrt{\hbar c^5/G} \simeq 2.0 \times 10^{9}\ \mathrm{J}$$

$$T_{\mathrm{P}} \equiv \sqrt{\hbar c^5/G k_B^2} \simeq 1.4 \times 10^{32}\ \mathrm{K}$$

Planck's *God-Given Unit System*

(Planck, 1899)



Planck, 1900

$$c,\ G,\ \hbar,\ k_B,\ \text{and}\ 1/4\pi\epsilon_0$$

units of length, mass, time, and temperature that would, independently of special bodies and substances, necessarily retain their significance for all times and all cultures, even extraterrestrial and extrahuman ones, and which may therefore be designated as natural units of measure. (Planck 1899, pp. 479–480)

Planck, M.: Über irreversible Strahlungsvorgänge. Sitzungsberichte der Königlich Preuischen Akademie der Wissenschaften zu Berlin **5**, 440 (1899)

A physical argument of discrete space-time

Y.Xu & B.-Q.Ma, MPLA 26 (2011) 2101, arXiv: 1106.1778

- From two known entropy constraints:

$$S_{\text{matter}} \leq 2\pi E R, \qquad S_{\text{matter}} \leq \frac{A}{4},$$

- Combined with black-body entropy

$$S = \frac{4}{45}\pi^2 T^3 V = \frac{16}{135}\pi^3 R^3 T^3.$$

- We arrive at a minimum value of space

$$R \geq \left(\frac{128}{3645\pi}\right)^{\frac{1}{2}} l_{\mathrm{P}} \simeq 0.1 l_{\mathrm{P}},$$

We reveal from physical arguments that space-time is discrete rather than continuous.

Proposal of a new fundamental length scale instead of the Newtonian constant

L.Shao & B.-Q.Ma, Sci.China Phys. Mech. Astro. 54 (2011) 1771, arXiv: 1006.3031

- If gravity is emergent, a new fundamental constant should be introduced to replace G.
- It is natural to suggest a fundamental length scale
- Such constant can be explained as the smallest length scale of quantum space-time.
- Its value can be measured through searches of Lorentz violation.

LV as Window on the Nature of Space-Time

- The typical scale of quantum gravity is Planck scale

$$l_P = \sqrt{\frac{G\hbar}{c^3}} = 1.61624(8) \times 10^{-35}\, m$$

$$t_{\mathrm{P}} \equiv \sqrt{G\hbar/c^5} \simeq 5.4 \times 10^{-44}\ \mathrm{s}$$

$$E_{\mathrm{P}} \equiv \sqrt{\hbar c^5/G} \simeq 2.0 \times 10^9\ \mathrm{J}$$

Lorentz Violation could be a relic probe for the nature of space-time & quantum gravity

Pioneers' study of Lorentz symmetry violation

The early discussion on the effects of Lorentz violation

- Dirac's æther and nonlinear electrodynamics
  P.A.M. Dirac, Nature **168**, 906 (1951).
- Goldstone boson associated to Spontaneous Lorentz symmetry breaking(SLSB)
  ▷Bjorken's earlier attempts: Photon as Goldstone boson associated to SLSB. J.D. Bjorken, Ann.Phys. **24**, 174 (1963).
  ▷Is Graviton also a Goldstone boson?
  P.R. Phillips, Phys. Rev. **146**, 966 (1966)....
- An universal length scale
  T.G. Pavlopoulos, Phys. Rev. **159**, 1106 (1967)
- Nielsen's renomalization group calculation of the beta-function for a non-covariant pure Yang-Mills theory
  H.B. Nielsen and M. Ninomiya, Nucl. Phys. B **141**, 153 (1978). ...

Many possible ways for Lorentz violation

- spacetime foam [Ellis et al.'08, PLB]
- loop gravity [Alfaro et al.'00, PRL]
- backgrounds in general gravity [Ni'75, PRL; Yan'83, TP,]
- vacuum condensate of antisymmetric tensor fields in string theory [Kostelecky & Samuel'89 & '91, PRL]
- double special relativity [Amelino-Camelia'02, Nature & '02 IJMPD]

The pioneering work to implement Lorentz-violation as field background

Wei-Tou Ni
Published in **Phys.Rev.Lett. 38 (1977) 301-304**

A review:

Wei-Tou Ni
Published in **Rept.Prog.Phys. 73 (2010) 056901**
e-Print: **arXiv:0912.5057**

Lorentz-violation as background fields

- It is useful to discuss various LV effects based on traditional techniques of effective field theory in particle physics.
- One can collect all possible background fields coupled with standard model particles, in a way such as standard model extension (SME).
- But such kind of works cannot be ranked as theory, but a platform for phenomenological applications to confront with data.

Human being needs fundamental theory for or against Lorentz-invariance violation.

- The total Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \delta\mathcal{L}, \tag{4}$$

where $\delta\mathcal{L}$ denotes tiny LV parts.

- take QED as example

$$\delta\mathcal{L}_{\rm QED} = \delta\mathcal{L}_{\rm photon} + \delta\mathcal{L}_{\rm electron}, \tag{5}$$

where

$$\delta\mathcal{L}_{\rm photon} \supset -\frac{1}{4}(k_F)_{\kappa\lambda\mu\nu}F^{\kappa\lambda}F^{\mu\nu} + \frac{1}{2}(k_{AF})_\kappa\epsilon^{\kappa\lambda\mu\nu}A_\lambda F_{\mu\nu}, \tag{6}$$

$$\begin{aligned}\delta\mathcal{L}_{\rm electron} \supset\ & \frac{1}{2}i\overline{\psi}(\widetilde{c}^{(\nu\mu)}\gamma_\nu + \widetilde{d}^{\nu\mu}\gamma_5\gamma_\nu + \frac{1}{2}\widetilde{g}^{\lambda\nu\mu}\sigma_{\lambda\nu})\overleftrightarrow{D}_\mu\,\psi \\ & -\overline{\psi}(\widetilde{b}_\mu\gamma_5\gamma^\mu + \frac{1}{2}\widetilde{H}_{\mu\nu}\sigma^{\mu\nu})\psi.\end{aligned} \tag{7}$$

Lagrangians in three SME frameworks: fermions

$$\mathcal{L} \rightarrow \mathcal{L} + \partial_i \Psi \epsilon \partial^i \Psi$$

S.R.Coleman and S.L.Glashow, PRD 59 (1999) 116008

$$\mathcal{L} = \frac{1}{2} i \overline{\nu}_A \gamma^\mu \overleftrightarrow{D_\mu} \nu_B \delta_{AB} + \frac{1}{2} i c^{\mu\nu}_{AB} \overline{\nu}_A \gamma^\mu \overleftrightarrow{D^\nu} \nu_B - a^\mu_{AB} \overline{\nu}_A \gamma^\mu \nu_B + \cdots$$

D.Colladay and V.A.Kostelecky, PRD 58, 116002 (1998)

$$\mathcal{L}_{\mathrm{F}} = \bar{\psi}_A (i\gamma^\alpha \partial_\alpha - m_A)\psi_A + i\Delta^{\alpha\beta}_{AA} \bar{\psi}_A \gamma_\alpha \partial_\beta \psi_A$$

Zhou L., B.-Q. Ma, MPLA 25, 2489 (2010); Chin.Phys.C 35, 987 (2011)

Three scenarios on how to understand and handle the backgrounds

- **Scenario I: fixed background scenario**

- **The backgrounds are taken as fixed parameters in any inertial frame of reference one decides to work. It means that there is an absolute background which is the same for any working reference frames such as earth-rest frame, sun-rest frame, or CMB frame.**
- **It can be adopted when one does not care about relations between different frames, or the situation could become very complicated with different formalisms in different frames.**
- **This scenario can apply as a practical tool for all of the three versions of SME: the simple Coleman-Glashow model, the minimal SME, and the SMS.**

S.R.Coleman and S.L.Glashow, PRD 59 (1999) 116008

Three scenarios on how to understand and handle the backgrounds

- **Scenario II: "new aether" scenario**

- **It means that there exists a privileged inertial frame of reference in which the the background can be considered as the ``new aether", i.e., the ``vacuum" at rest, which changes from one frame to another frame by Lorentz transformation.**

- **This scenario cannot apply directly to the Coleman-Glashow model, as the LV parameter is a scaler which should keep invariant in any working reference frame, but it can apply to the minimal SME and also to the SMS.**

V. A. Kostelecky, N. Russell, Rev. Mod. Phys. 83 (2011) 11

Three scenarios
on how to understand and handle the backgrounds

- **Scenario III: covariant scenario**

- **The background fields transform as tensors adhered with the corresponding standard model particles.**

- **The background fields are emergent and covariant with their standard model particles.**

- **This scenario cannot apply to the Coleman-Glashow model, but can apply to the minimal SME and also to the SMS.**

Zhou L., B.-Q.Ma, arXiv:1111.1574.

Some remarks on SME

- **The coefficients of background fields with standard model particles serve as LV parameters.**
- **The Lorentz-violation in SME is due to the existance of background fields, or in a sense of “new aether” as backgrounds.**
- **There is no Lorentz-violation for the whole system of standard-model-particles+backgrounds**

A New Theory: the replacement of basic principle in Special Relativity

- Principle of Relativity: the equations describing the laws of physics have the same form in all admissible frames of reference.

- Principle of physical invariance :

the equations describing the laws of physics have the same form in all admissible mathematical manifolds.

Zhou Lingli and B.-Q. Ma, MPLA 25 (2010) 2489, arXiv:1009.1331;
CPC 35 (2011) 987, arXiV: 1109.6387

A new theory of Lorentz violation

- **a replacement of the common derivative operators by covariant co-derivative ones**

$$\partial^\alpha \to M^{\alpha\beta}\partial_\beta, \quad D^\alpha \to M^{\alpha\beta}D_\beta,$$

- **The effective minimal Standard Model**

$$\begin{aligned}
\mathcal{L}_{SM} &= \mathcal{L}_G + \mathcal{L}_F + \mathcal{L}_{HG} + \mathcal{L}_{HF},\\
\mathcal{L}_G &= -\frac{1}{4}F^{a\alpha\beta}F^a_{\alpha\beta},\\
\mathcal{L}_F &= i\bar{\psi}\gamma^\alpha D_\alpha\psi,\\
\mathcal{L}_{HG} &= (D^\alpha\phi)^\dagger D_\alpha\phi + V(\phi),
\end{aligned}$$

- **A new standard model with supplementary terms**

$$\begin{aligned}
\mathcal{L}_{SMS} &= \mathcal{L}_{SM} + \mathcal{L}_{LV},\\
\mathcal{L}_{LV} &= \mathcal{L}_{GV} + \mathcal{L}_{FV} + \mathcal{L}_{HFV}
\end{aligned}$$

Zhou Lingli and B.-Q. Ma, MPLA 25 (2010) 2489, arXiv:1009.1331 ; CPC 35 (2011) 987, arXiv: 1109.6387

physical independence of mathematical background manifolds

The Lorentz invariance violation matrix

$$M^{\alpha\beta} = g^{\alpha\beta} + \Delta^{\alpha\beta},$$

$$\Delta^{\alpha\beta} = \begin{cases} 0 & \text{LI exact} \\ \to 0 & \text{LV small} \\ \text{otherwise} & \text{LV big} \end{cases}.$$

Zhou Lingli and B.-Q. Ma, MPLA 25 (2010) 2489

The Lorentz violation for protons from GZK cut-off

A special case is

$$\Delta^{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \xi & 0 & 0 \\ 0 & 0 & \xi & 0 \\ 0 & 0 & 0 & \xi \end{pmatrix},$$

$$E^2 = (1-\delta)\vec{p}^2 + m^2,$$
$$\delta = -\xi^2 + 2\xi.$$

$$\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 10^{-23} & 0 & 0 \\ 0 & 0 & 10^{-23} & 0 \\ 0 & 0 & 0 & 10^{-23} \end{pmatrix},$$

Zhou Lingli and B.-Q. Ma, MPLA 25 (2010) 2489

Photon speed in GRAAL experiment

The GRAAL facility of the European Synchrotron Radiation Facility (ESRF) in Grenoble.

In the head-on Compton scattering of the ultra-energy electrons and the low energy photons, the energy E of the scattered photon is given by

$$E = \frac{4\gamma^2 E_0}{1 + 4\gamma E_0/m_e + \theta^2\gamma^2}, \qquad (57)$$

The maximum energy E of the Compton scattered photons is called as the Compton Edge (CE). So

$$\delta x_{\mathrm{CE}} = \frac{4AE_0}{m_e}\delta\gamma = -\frac{4AE_0}{m_e}\beta^2\gamma^3\delta c, \qquad (58)$$

where $\gamma = (1-\beta^2)^{-1/2}$ is the Lorentz factor of the incident electron.

Zhou Lingli and B.-Q. Ma, arXiv:1009.1675, Astropart.Phys. 36 (2012) 37-41

Anisotropy of light speed

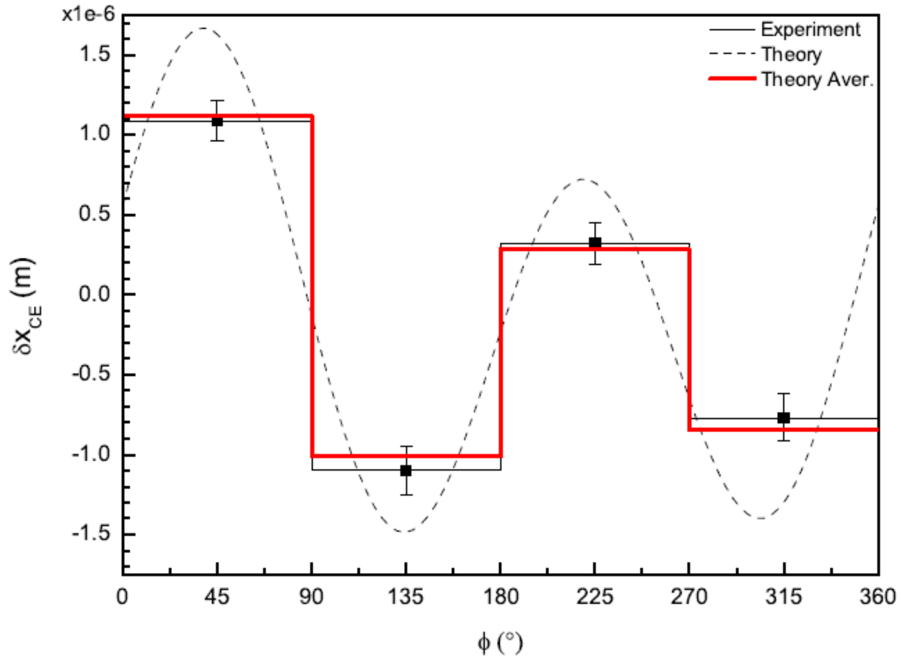


Fig. 1. δx_{CE} azimuthal distribution vs angles of the GRAAL data of the years 1998-2005 on a plane (x-y plane or $\theta = \pi/2$). $\xi = -2.89 \times 10^{-13}$, $\lambda = 6.53 \times 10^{-14}$.

Zhou Lingli and B.-Q. Ma, arXiv:1009.1675, Astropart.Phys. 36 (2012) 37-41

Anisotropy of light speed

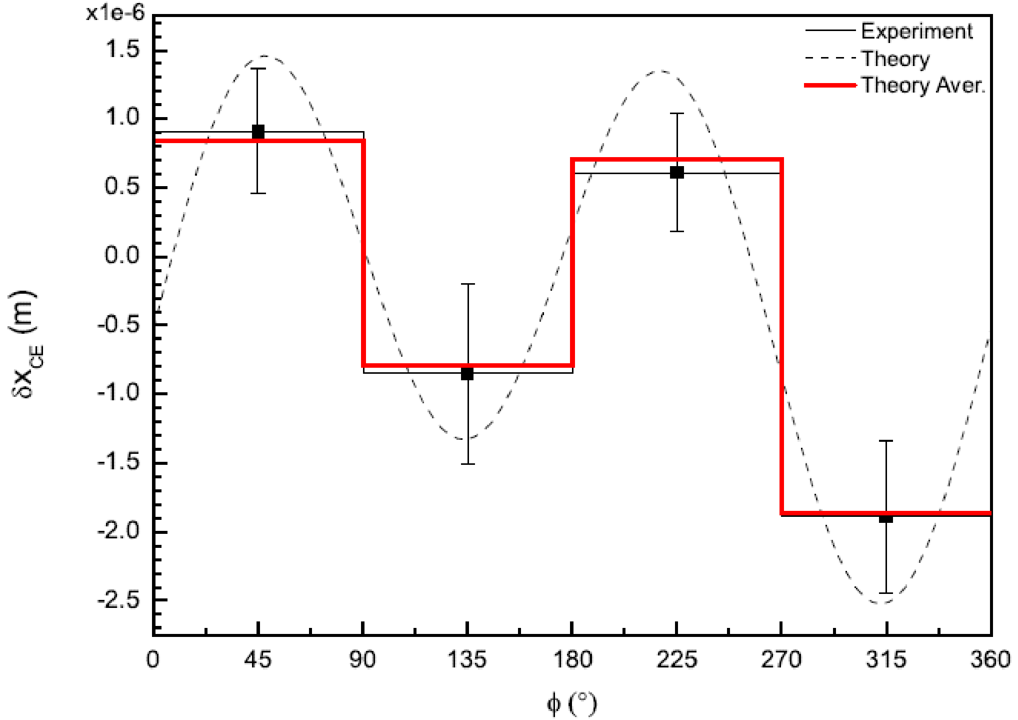


Fig. 2. $\delta x_{\rm CE}$ azimuthal distribution vs angles of the GRAAL data of the year 2008 on a plane (x-y plane or $\theta = \pi/2$). $\xi = -3.64 \times 10^{-13}$, $\lambda = 8.24 \times 10^{-14}$.

Zhou Lingli and B.-Q. Ma, arXiv:1009.1675, Astropart.Phys. 36 (2012) 37-41

The Lorentz violation for photons from comparison with SME constraints

- **There is no one-to-one correspondence between SMS and minimal SME.**
- **They could have an intersection.**
- **From the identity of the intersection for the two models, we get some constraints of SMS parameters from SME parameters.**

$$\Delta^{\alpha\beta}_{\text{photon}} = \begin{pmatrix} 3\Delta^{33}+10^{-17} & 10^{-5} & 10^{-5} & 10^{-6} \\ 10^{-9} & \Delta^{33}+10^{-17} & 10^{-9} & 10^{-9} \\ 10^{-9} & 10^{-9} & \Delta^{33}+10^{-17} & 10^{-9} \\ 10^{-9} & 10^{-8} & 10^{-8} & \Delta^{33} \end{pmatrix},$$

Zhou Lingli and B.-Q. Ma, arXiv:1110.1850

The phantom of the OPERA: superluminal neutrinos

- **We need to finger it out, whether it is a ghost or an angel of music.**

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THE PHANTOM OF THE OPERA: SUPERLUMINAL NEUTRINOS

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After the first release of the OPERA result, there have been many criticisms and doubts on the correctness of the experiment, such as whether the clocks at the two sides of CERN and LGNS are correctly adjusted by GPS technique as well as whether the distance between the two sides is properly measured, and whether the beam duration treatment of the data can introduce bias in the neutrino arrival time measurement. The OPERA collaboration repeated[11] the measurement over

as parameters. The velocity of a particle could be therefore superluminal or subluminal by adjusting the LV parameters. By confronting with the OPERA result, the LV parameters are estimated in Ref. 39 for the SMS framework and in Ref. 40 for the minimal SME.

First OPERA Paper

appeared in arXiv on September 23, 2011

arXiv:1109.4897 [hep-ex]
Title: Measurement of the neutrino velocity with the OPERA detector in the CNGS beam
Authors:OPERA

The OPERA neutrino experiment at the underground Gran Sasso Laboratory has measured the velocity of neutrinos from the CERN CNGS beam over a baseline of about 730 km with much higher accuracy than previous studies conducted with accelerator neutrinos. The measurement is based on high-statistics data taken by OPERA in the years 2009, 2010 and 2011. Dedicated upgrades of the CNGS timing system and of the OPERA detector, as well as a high precision geodesy campaign for the measurement of the neutrino baseline, allowed reaching comparable systematic and statistical accuracies. An early arrival time of CNGS muon neutrinos with respect to the one computed assuming the speed of light in vacuum of (60.7 \pm 6.9 (stat.) \pm 7.4 (sys.)) ns was measured. This anomaly corresponds to a relative difference of the muon neutrino velocity with respect to the speed of light (v-c)/c = (2.48 \pm 0.28 (stat.) \pm 0.30 (sys.)) \times 10-5.

Updated version of the OPERA Paper

arXiv:1109.4897v4 [hep-ex]; Published in **JHEP 1210 (2012) 093**

(Submitted on 22 Sep 2011 (v1), last revised 12 Jul 2012 (this version, v4))

Abstract: The OPERA neutrino experiment at the underground Gran Sasso Laboratory has measured the velocity of neutrinos from the CERN CNGS beam over a baseline of about 730 km. The measurement is based on data taken by OPERA in the years 2009, 2010 and 2011. Dedicated upgrades of the CNGS timing system and of the OPERA detector, as well as a high precision geodesy campaign for the measurement of the neutrino baseline, allowed reaching comparable systematic and statistical accuracies. An arrival time of CNGS muon neutrinos with respect to the one computed assuming the speed of light in vacuum of (6.5 +/-7.4(stat.)((+8.3)(-8.0)sys.))ns was measured corresponding to a relative difference of the muon neutrino velocity with respect to the speed of light (v-c)/c =(2.7 +/-3.1(stat.)((+3.4)(-3.3)(sys.))x10^(-6). The above result, obtained by comparing the time distributions of neutrino interactions and of protons hitting the CNGS target in 10.5 microseconds long extractions, was confrmed by a test performed at the end of 2011 using a short bunch beam allowing to measure the neutrino time of flight at the single interaction level.

New status of neutrino speed measurements

Table 1: Neutrino velocity of CNGS beam. Total standard deviation is used for weighted average: $\sigma = \sqrt{\sigma_{stat}^2 + \sigma_{sys}^2}$.

Collaboration	Superluminality δv
OPERA	$(2.7 \pm 3.1_{stat}{}^{+3.4}_{-3.3}{}_{sys}) \times 10^{-6}$
ICARUS	$(0.4 \pm 2.8_{stat} \pm 9.8_{sys}) \times 10^{-7}$
Borexino	$(-3.3 \pm 2.9_{stat} \pm 11.9_{sys}) \times 10^{-7}$
LVD	$(1.2 \pm 2.5_{stat} \pm 13.2_{sys}) \times 10^{-7}$
Weighted average	$(0.06 \pm 6.7) \times 10^{-7}$

Lagrangians in three SME frameworks

$$\mathcal{L} \to \mathcal{L} + \partial_i \Psi \epsilon \partial^i \Psi$$

S.R.Coleman and S.L.Glashow, PRD 59 (1999) 116008

$$\mathcal{L} = \frac{1}{2} i \overline{\nu}_A \gamma^\mu \overleftrightarrow{D_\mu} \nu_B \delta_{AB} + \frac{1}{2} i c^{\mu\nu}_{AB} \overline{\nu}_A \gamma^\mu \overleftrightarrow{D^\nu} \nu_B - a^\mu_{AB} \overline{\nu}_A \gamma^\mu \nu_B + \cdots$$

D.Colladay and V.A.Kostelecky, PRD 58, 116002 (1998)

$$\mathcal{L}_{\mathrm{F}} = \bar{\psi}_A (i\gamma^\alpha \partial_\alpha - m_A)\psi_A + i\Delta^{\alpha\beta}_{AA} \bar{\psi}_A \gamma_\alpha \partial_\beta \psi_A$$

Zhou L., B.-Q. Ma, MPLA 25, 2489 (2010); Chin.Phys.C 35, 987 (2011)

If the OPERA data were true

$$\mathcal{L}_{\mathrm{F}} = i\bar{\psi}_{\mathrm{A,L}}\gamma^{\alpha}\partial_{\alpha}\psi_{B,\mathrm{L}}\delta_{AB} + i\Delta^{\alpha\beta}_{\mathrm{L},AB}\bar{\psi}_{\mathrm{A,L}}\gamma_{\alpha}\partial_{\beta}\psi_{B,\mathrm{L}}$$
$$+ i\bar{\psi}_{\mathrm{A,R}}\gamma^{\alpha}\partial_{\alpha}\psi_{B,\mathrm{R}}\delta_{AB} + i\Delta^{\alpha\beta}_{\mathrm{R},AB}\bar{\psi}_{\mathrm{A,R}}\gamma_{\alpha}\partial_{\beta}\psi_{B,\mathrm{R}},$$

$$p^2 + g_{\alpha\mu}\Delta^{\alpha\beta}_{AA}\Delta^{\mu\nu}_{AA}p_{\beta}p_{\nu} + 2\Delta^{\alpha\beta}_{AA}p_{\alpha}p_{\beta} - m^2_A = 0.$$

$$\Delta^{\alpha\beta}_{AA} = \mathrm{diag}(\eta, \xi, \xi, \xi)$$

$$\frac{v-c}{c} = (2.48 \pm 0.28(\mathrm{stat.}) \pm 0.30(\mathrm{sys.})) \times 10^{-5},$$

$$\eta_{\nu_\mu} + \xi_{\nu_\mu} = (-2.48 \pm 0.28(\mathrm{stat.}) \pm 0.30(\mathrm{sys.})) \times 10^{-5}.$$

$|\xi_p| \leq 10^{-23}$ $|\xi_\gamma| \leq 10^{-14}$

Zhou Lingli and B.-Q. Ma, arXiv: 1109.6097

Constraints from all neutrino speed measurements

All the experiments above put a constraint on the superluminality δv of neutrinos, that is,

$$\delta v_\nu < 1 \times 10^{-9}. \tag{15}$$

With Eq. (12), the constraint on the speed anomaly of neutrinos means that the LV parameters η_ν and ξ_ν satisfy

$$|\eta_\nu + \xi_\nu| < 1 \times 10^{-9}. \tag{16}$$

Cherenkov analogous process

$$\nu_\mu \longrightarrow \begin{cases} \nu_\mu + \gamma & (a) \\ \nu_\mu + \nu_e + \overline{\nu}_e & (b) \\ \nu_\mu + e^+ + e^- & (c) \end{cases}$$

A.G. Cohen, S. L. Glashow, PRL 107 (2011) 181803 ; arXiv:1109.6562.

muon neutrinos with mean energy of 17.5 GeV

such superluminal neutrinos would lose energy rapidly

Thus we refute the superluminal interpretation of the OPERA result.

Constraints and tests of the superluminal neutrinos at OPERA

Xiao-Jun Bi, Peng-Fei Yin, Zhao-Huan Yu, and Qiang Yuan

Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

arXiv:1109.6667 [hep-ph]

$$E^2 = m^2 + |\vec{p}|^2 + \xi |\vec{p}|^2$$

the processes $\pi^+ \to \mu^+ + \nu_\mu$ and $\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$ are

forbiden

Further constraints on neutrino speed measurements

flying length and time. Nevertheless, we can take a more stringent constraint of $|\eta_\nu + \xi_\nu| < 0.85 \times 10^{-11}$ by combining the above analysis.

Summary

- Lorentz violation could provide a probe on the nature of space-time: Continuous or Discrete?
- The use of background fields coupled with SM-particles provides a platform to study the LV phenomenologically.
- We propose a new theory to implement the Lorentz-violation with Lorentz-violation matrix.
- Our theory can provide a description of light-speed anisotropy which seems to exist in data.
- Lorentz violation is being an active frontier both theoretically and experimentally.

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- **The background fields are emergent and covariant with their standard model particles.**

- **This scenario cannot apply to the Coleman-Glashow model, but can apply to the minimal SME and also to the SMS.**

Zhou L., B.-Q.Ma, arXiv:1111.1574.

The phantom of the OPERA

- Whether neutrinos are superluminal or not

is not a theoretical issue

...One does not know whether

the phantom is a ghost or an angel of music

until the end of the story...

The OPERA just begins,
we are still far from the end.

The phantom of the opera

歌剧魅影

夜半歌声

The phantom lover

Chinese version

歌剧魅影

Space-Time in Perspective

Space-Time: might be 3+1=4 dimensional or may have extra-dimensions

- **Space and time are dependent with each other.**
- **Both space and time are observer and object dependent:**

  Space-time are particle-type dependent and can be curved by the existence of matter.
- **Space and time might be discrete and such discreteness can be tested through experiments on Lorentz violation.**

Summary

- Researches on Lorentz violation have been active for many years.
- There might be some marginal evidences for Lorentz violation yet, but non of them can be considered as confirmed.
- The Lorentz violation study can bring conceptual revolution on the understanding of space-time for human being.
- Lorentz violation is being an active frontier both theoretically and experimentally.


Thanks!