



# 问天之路：宇宙线叩开新物理之门

**Bo-Qiang Ma (马伯强)**

**Zhengzhou University/Peking University (郑州大学/北京大学)**

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In collaboration with Zhi Xiao, Lijing Shao, Shimin Yang, Lingli Zhou, Haowei Xu, Yunqi Xu, Nan Qin, Shu Zhang, Yue Liu, Yanqi Huang, Xinyi Zhang, Hao Li, Yingtian Chen, Chengyi Li, Jie Zhu, Ping He, Guangshuai Zhang, Luohan Wang, Hanlin Song, Qing Liu, Ruiqi Wang, .....

# 仰望星空：人类文明发展的精神坐标与探索轨迹



# **The highest energy particles can be observed by human being are from SKY**

- **Frontiers of human knowledge:**

**Cosmology, Astronomy, and Physics**



**AstroParticle Physics**

- **Particles from the Sky:**

Ultra-high energy cosmic rays (UHECRs) :  $10^{20}$  eV or higher

Cosmic photons from gamma ray bursts: multi-GeV to multi-TeV

Cosmic neutrinos with much higher energy: ~TeV to PeV

- **New physics from cosmic photons and neutrinos:**

**Lorentz violation**

**CPT violation**

**Axion**

**Sterile neutrino**

# Lorentz Transformation

$$\nabla^2 \phi - \frac{1}{c^2} \frac{\partial^2 \phi}{\partial t^2} = 0.$$

$$x'_1 = x_1,$$

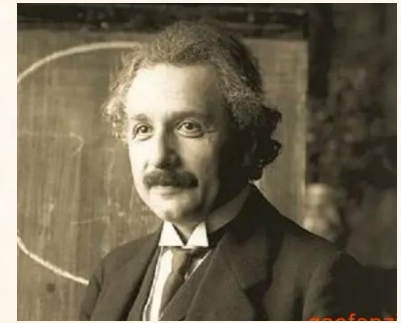
$$x'_2 = x_2,$$

$$x'_3 = \frac{x_3 - vt}{\sqrt{1 - v^2/c^2}},$$

$$t' = \frac{t - vx_3/c^2}{\sqrt{1 - v^2/c^2}},$$

$$\frac{\partial^2 \phi}{\partial x'^2_1} + \frac{\partial^2 \phi}{\partial x'^2_2} + \frac{\partial^2 \phi}{\partial x'^2_3} - \frac{1}{c^2} \frac{\partial^2 \phi}{\partial t'^2} = 0.$$

# Principles of Special Relativity



- Principle of Relativity: the equations describing the laws of physics have the same form in all admissible frames of reference.
- Principle of constant light speed: the speed of light is the same in all directions in vacuum in all reference frames, regardless whether the source of the light is moving or not.

# Triumphs of Einstein's Relativity

- One of the foundations of modern physics.
- Proved to be valid at very high precision.

Lorentz Invariance, the basic theoretical foundation of relativity, states that

the equations describing the laws of physics have the same form in all admissible reference frames.

So is there any reason that we seek for

Lorentz Violation ?

# LV as Window on the Nature of Space-Time

- The typical scale of quantum gravity is Planck scale

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

$$t_P \equiv \sqrt{G\hbar/c^5} \simeq 5.4 \times 10^{-44} \text{ s}$$

$$E_P = \sqrt{\hbar c^5/G} = 2.0 \times 10^9 \text{ J} \approx 1.22 \times 10^{19} \text{ GeV}$$

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

## Many possible ways for Lorentz violation

- spacetime foam [Ellis et al.'08, PLB]
- loop gravity [Alfaro et al.'00, PRL]
- torsion 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]

## Where to find Lorentz violation?

- Many theories predict new physics beyond conventional knowledge, so which one is correct?

**Any theory should be tested by experiments!**

- Where to do the experiments?

the effect is too tiny to be detected on Earth

- **Looking up at the Sky again:**

Cosmic photons from gamma ray bursts: 10~100 GeV or multi-TeV

Cosmic neutrinos with much higher energy: ~TeV-PeV

# Modified photon dispersion relation from LV

$$v(E) = c_0 \left( 1 - \xi \frac{E}{M_{\text{P}} c^2} - \zeta \frac{E^2}{M_{\text{P}}^2 c^4} \right)$$



$$\sqrt{\hbar c/G} \simeq 1.22 \times 10^{19} \text{ GeV}/c^2$$

Z.Xiao and B.-Q.Ma, PRD 80 (09) 116005, arXiv:0909.4927

See also, e.g.,

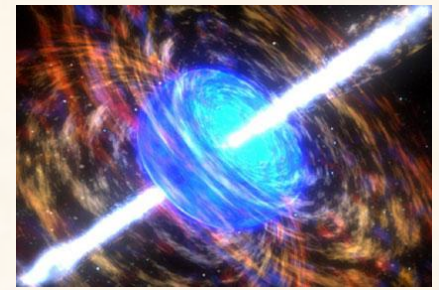
Jacobson et al.'06, Ann. Phys.

Kostelecky & Mewes'09, PRD

Mattingly'05, Living Rev. Rel.

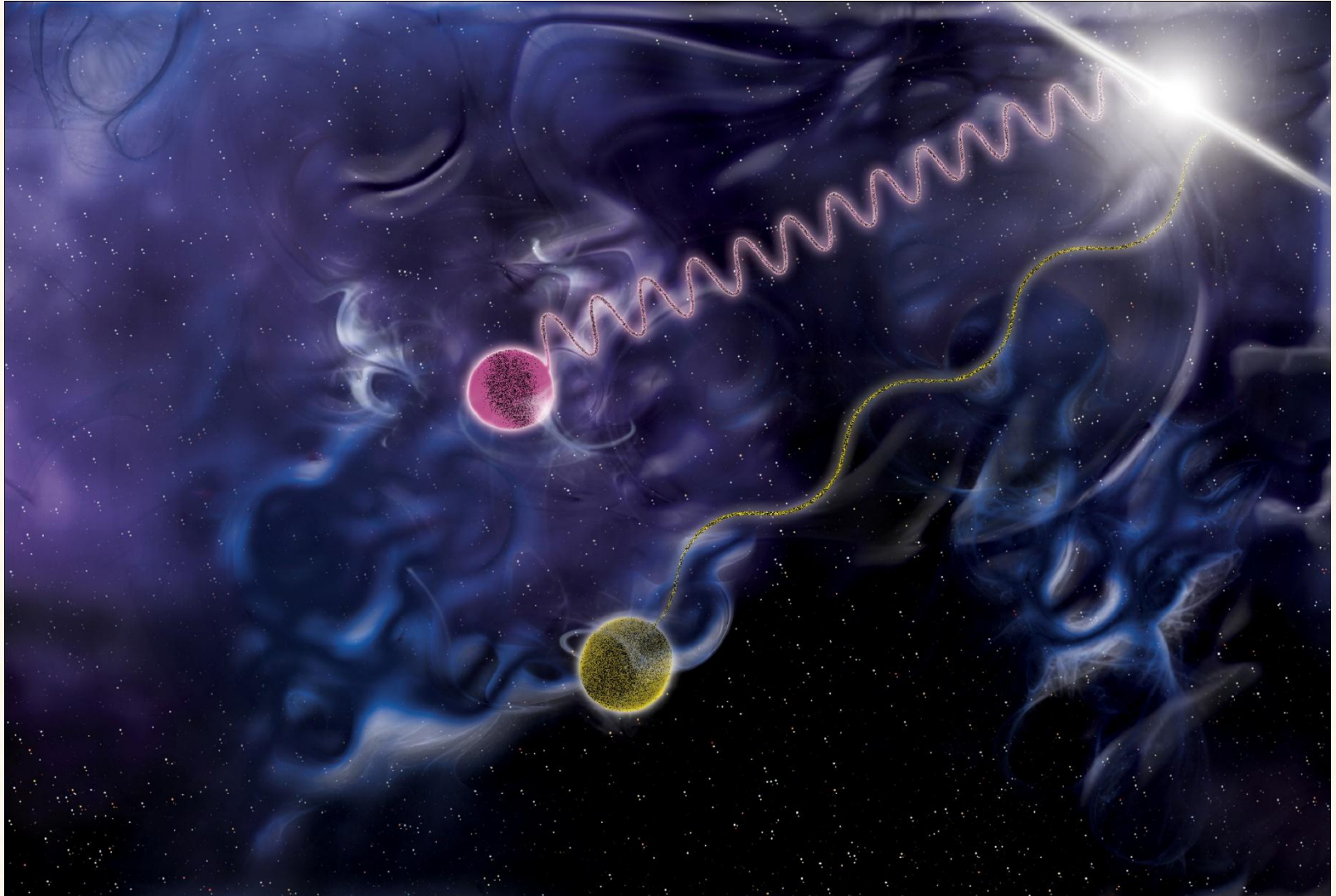
Amelino-Camelia & Smonlin'09, PRD

# Gammy-ray Bursts (GRBs)



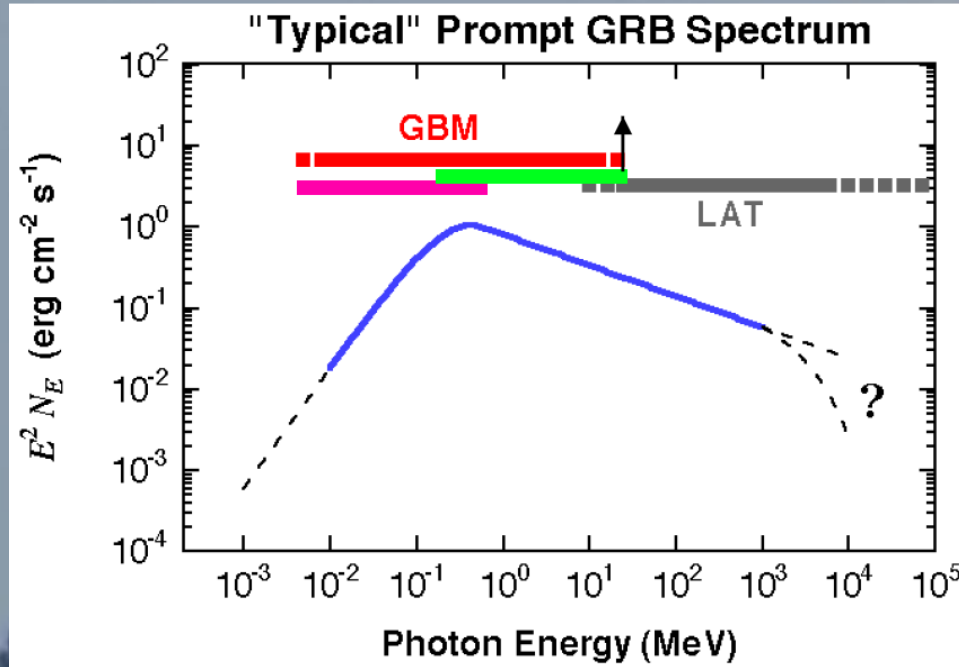
- The most energetic astrophysical process except the Big Bang
- 2 types
  - long GRBs: duration  $> 2$  s; collapses of massive rapidly rotating stars
  - short GRBs: duration  $< 2$  s; coalescence of two neutron stars or a neutron star and a black hole
- Long distance from detector:
  - $z \approx 2.15$  for long GRBs, several billion light-years
  - $z \approx 0.5$  for short GRBs
- Use GRBs to test LV [[Amelino-Camelia et al.'98, Nature](#)]

# ***Time-lag by GRB***

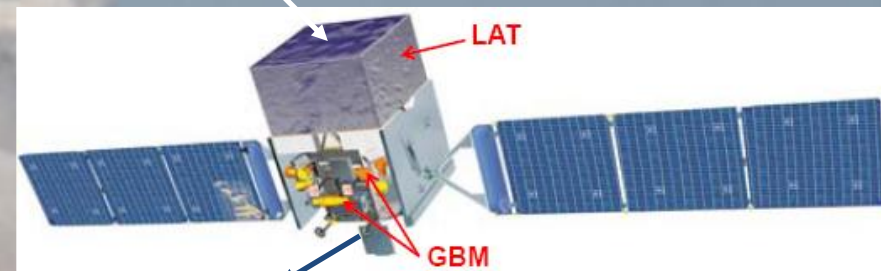


June 11, 2008

# Fermi instruments



~ 300 GeV



trigger photons ~ 0.1 MeV

# Model independent LV photon dispersion relation

$$\mathcal{E}^2 = \mathbf{p}^2 \left[ 1 - s_n \left( \frac{|\mathbf{p}|}{E_{\text{LV},n}} \right)^n \right]$$

$$v = 1 - s_n \frac{n+1}{2} \left( \frac{\mathcal{E}}{E_{\text{LV},n}} \right)^n$$

$n = 1$  or  $2$   linear and quadratic energy dependence

$s=1$  subluminal case;       $s=-1$  superluminal case

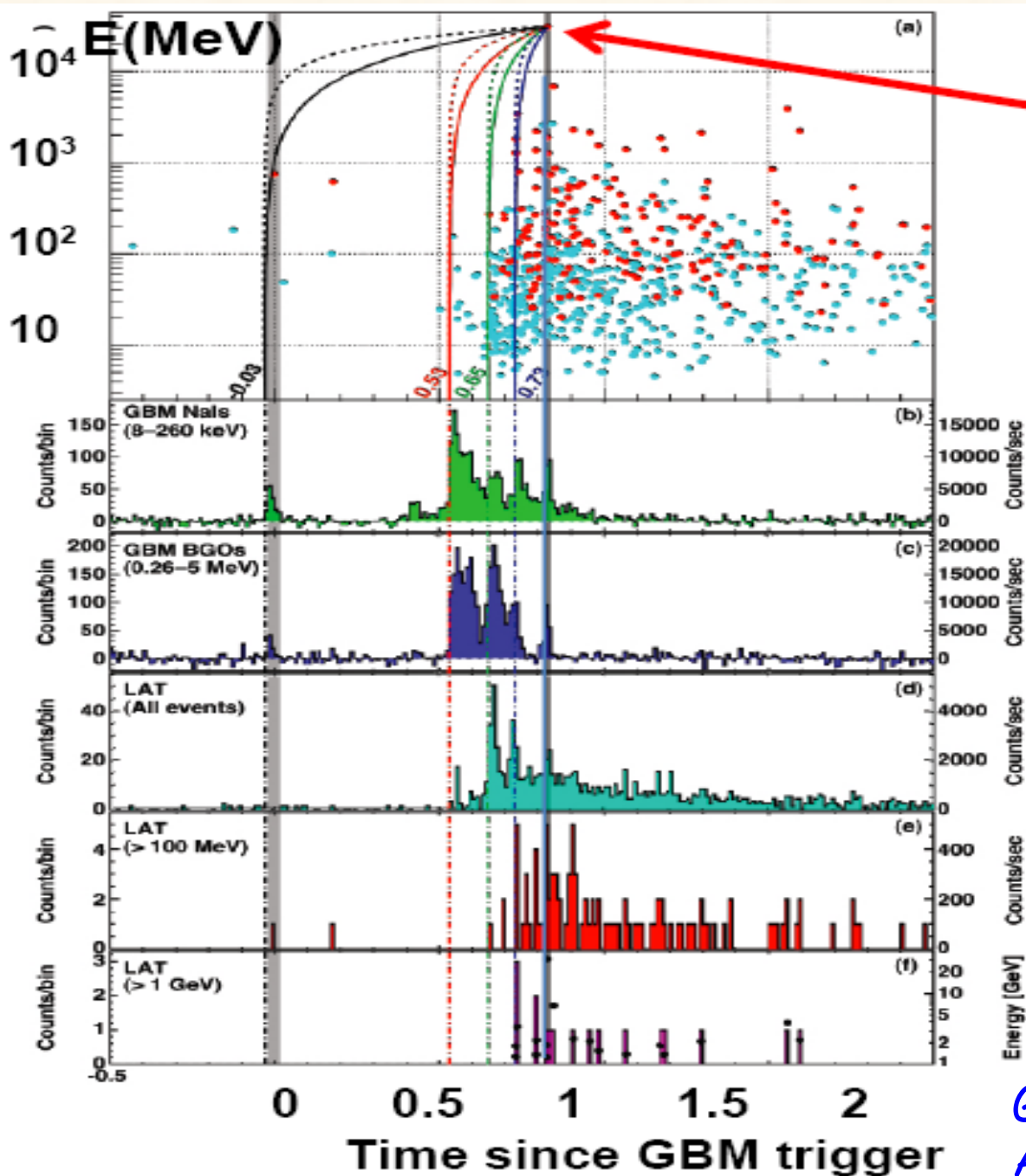
L.Shao and B.-Q.Ma, MPLA 25 (2010) 3251

See also, e.g.,

H.Xu, B.-Q.Ma, APP 82 (2016) 72, arXiv: 1607.03203

H.Xu, B.-Q.Ma, PLB 760 (2016) 602, arXiv: :1607.08043

H.Xu, B.-Q.Ma, JCAP 1801 (2018) 050, arXiv: 1801.08084



31 GeV

Time lags are affected both artificially and instrumentally

GRB090510  
Abdo et al.'09, Nature

# Early constraint from GRB090510 & Fermi-LAT data

Abdo et al. (Fermi), Nature 462 (2009) 331

a lower limit of  $1.2E_{\text{Planck}}$

Z.Xiao and B.-Q.Ma, PRD 80 (2009) 116005

$$M \sim 7.72 \times 10^{19} \text{ GeV} \quad 6.32M_{\text{Pl}}$$

Vasileiou et al., PRD 87 (2013) 122001

$$E_{\text{QG},1} > 7.6 \text{ times the Planck energy } (E_{\text{Pl}})$$

... ..

From Fermi Nature paper: we simply assume that it (high-energy photon) was emitted sometime during the relevant lower-energy emission episode.

# LV from energetic photons (multi-GeV) of GRBs

Z.Xiao and B.-Q.Ma, PRD 80 (2009) 116005, arXiv:0909.4927

L.Shao, Z.Xiao and B.-Q.Ma, APP 33 (2010) 312, arXiv:0911.2276

S.Zhang, B.-Q.Ma, APP 61 (2015) 108, arXiv:1406.4568

H.Xu, B.-Q.Ma, APP 82 (2016) 72, arXiv:1607.03203

H.Xu, B.-Q.Ma, PLB 760 (2016) 602, arXiv:1607.08043

H.Xu, B.-Q.Ma, JCAP 1801 (2018) 050, arXiv:1801.08084

Y.Liu, B.-Q.Ma, EPJC 78 (2018) 825, arXiv:1810.00636

J.Zhu, B.-Q.Ma, PLB 820 (2021) 136518 ... ..

H.Li, B.-Q. Ma, Science Bulletin 65 (2020) 262 arXiv:2012.06967 LV on AGN

.....

H.Song, B.-Q.Ma, PLB 856 (2024) 138951

H.Song, B.-Q.Ma, ApJ 983 (2025) 9 TeV&multi-TeV

H.Song, B.-Q.Ma, PRD 111 (2025) 103015 arXiv:2504.15685

.....

# Time lag by LV effect

- Expansion universe [\[Jacob & Piran'08, JCAP\]](#)

$$\Delta t_{\text{LV}} = \frac{1+n}{2H_0} \left( \frac{E_{\text{h}}^n - E_{\text{l}}^n}{M_{\text{QG}}^n c^{2n}} \right) \int_0^z \frac{(1+z')^n dz'}{h(z')}$$

$$M_{\text{QG,L}} = |\xi|^{-1} M_{\text{P}} \quad \text{and} \quad M_{\text{QG,Q}} = |\zeta|^{-1/2} M_{\text{P}}$$

$$h(z) = \sqrt{\Omega_{\Lambda} + \Omega_{\text{M}}(1+z)^3}$$

$$H_0 \simeq 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

$$\Omega_{\Lambda} \simeq 0.73 \quad \Omega_{\text{M}} \simeq 0.27$$

New derivation from Finsler geometry:

[J. Zhu, B.-Q. Ma, PRD 12 \(2022\) 124069.](#)

the  $\Delta t_{\text{obs}}/(1+z)$ - $K_n$  plot

**An intuitive way to perform analysis**

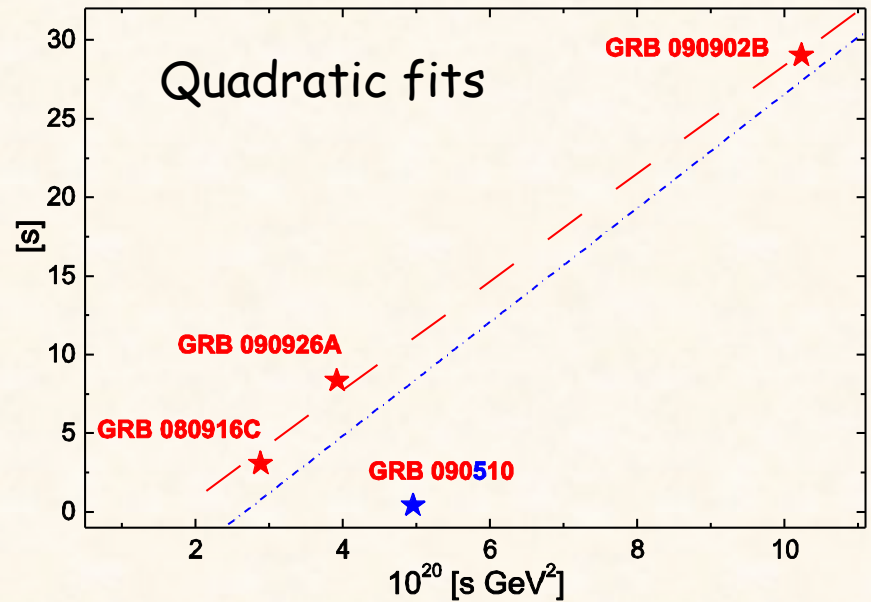
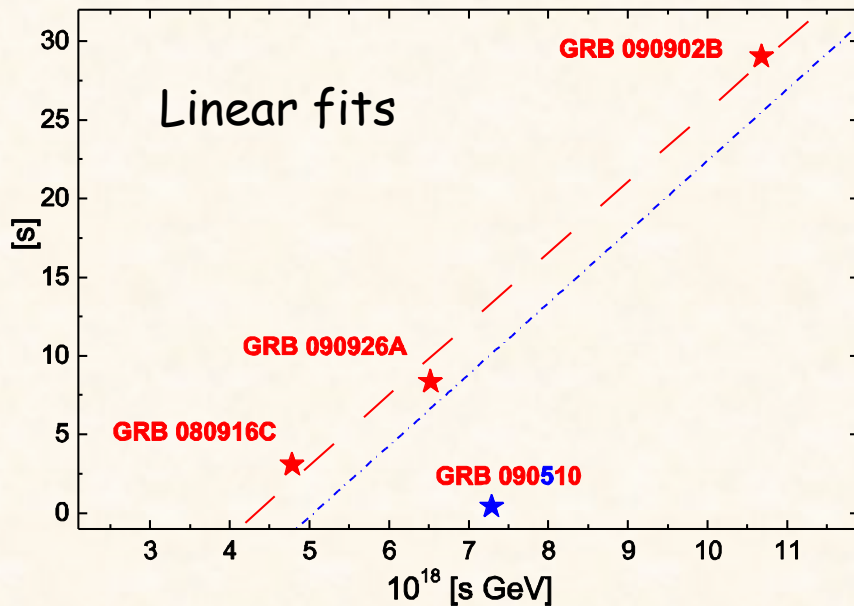
$$\Delta t_{\text{obs}} = \Delta t_{\text{LV}} + \Delta t_{\text{in}}(1+z)$$

$$\frac{\Delta t_{\text{obs}}}{1+z} = s_n \frac{K_n}{E_{\text{LV},n}^n} + \Delta t_{\text{in}}$$

$$K_n = \frac{1+n}{2H_0} \frac{E_{\text{high}}^n - E_{\text{low}}^n}{1+z} \int_0^z \frac{(1+z')^n dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}$$

$$\Delta t_{\text{LV}} = \frac{1+n}{2H_0} \left( \frac{E_{\text{h}}^n - E_{\text{l}}^n}{M_{\text{QG}}^n c^{2n}} \right) \int_0^z \frac{(1+z')^n dz'}{h(z')}$$

$$\Delta t_{\text{obs}} = \Delta t_{\text{LV}} + \Delta t_{\text{in}}(1+z)$$



$$M_{\text{QG,L}} = (2.2 \pm 0.2) \times 10^{17} \text{ GeV}/c^2 \text{ and } M_{\text{QG,Q}} = (5.4 \pm 0.2) \times 10^9 \text{ GeV}/c^2$$

$$M_{\text{QG,L}} = (2.2 \pm 0.9) \times 10^{17} \text{ GeV}/c^2 \text{ and } M_{\text{QG,Q}} = (5.3 \pm 0.8) \times 10^9 \text{ GeV}/c^2$$

S.Zhang, B.-Q.Ma, APP 61 (2015) 108, arXiv:1406:4568

## further development around 2015

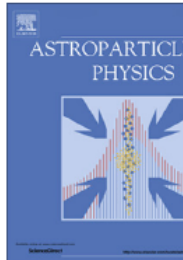
Astroparticle Physics 61 (2015) 108–112



Contents lists available at [ScienceDirect](#)

Astroparticle Physics

journal homepage: [www.elsevier.com/locate/astropart](http://www.elsevier.com/locate/astropart)



### Lorentz violation from gamma-ray bursts

Shu Zhang<sup>a</sup>, Bo-Qiang Ma<sup>a,b,c,d,\*</sup>

<sup>a</sup>School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

<sup>b</sup>Collaborative Innovation Center of Quantum Matter, Beijing, China

<sup>c</sup>Center for High Energy Physics, Peking University, Beijing 100871, China

<sup>d</sup>Center for History and Philosophy of Science, Peking University, Beijing 100871, China



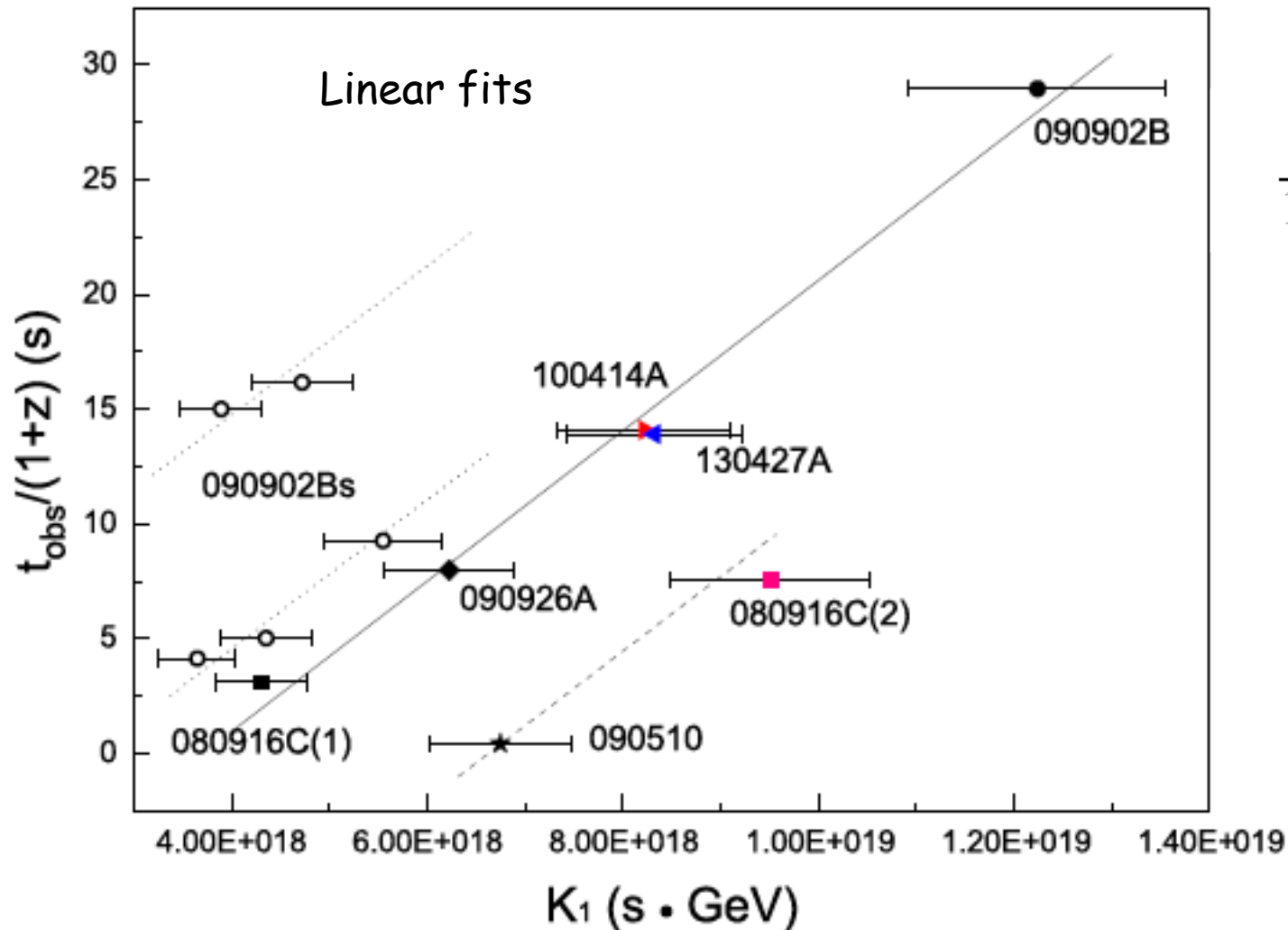
# Added data

Table 1: The data of the GRBs with high energy photons and known redshifts.

| GRB                  | $z$                 | $t_{\text{obs}}$ (s) | $E_{\text{obs}}$ (GeV) | $E_{\text{in}}$ (GeV) | $E_{\text{LV},1}$<br>( $\times 10^{17}$ GeV) | $\frac{t_{\text{obs}}}{1+z}$ (s) | $K_1$<br>( $\times 10^{18}$ s $\cdot$ GeV) |
|----------------------|---------------------|----------------------|------------------------|-----------------------|----------------------------------------------|----------------------------------|--------------------------------------------|
| 080916C(1)           | $4.35 \pm 0.15$     | 16.545               | 12.4                   | 66.3                  | $13.9 \pm 1.7$                               | 3.092                            | 4.30                                       |
| 090926A              | $2.1071 \pm 0.0001$ | 24.835               | 19.5                   | 60.6                  | $7.8 \pm 0.8$                                | 7.993                            | 6.23                                       |
| 100414A              | 1.368               | 33.365               | 29.7                   | 70.3                  | $5.8 \pm 0.6$                                | 14.090                           | 8.22                                       |
| 130427A <sup>a</sup> | $0.3399 \pm 0.0002$ | 18.644               | 72.6                   | 97.3                  | $6.0 \pm 0.7$                                | 13.915                           | 8.32                                       |
| 090902B              | 1.822               | 81.746               | 39.9                   | 112.6                 | $4.2 \pm 0.5$                                | 28.967                           | 12.24                                      |
| 090510               | $0.903 \pm 0.003$   | 0.828                | 29.9                   | 56.9                  | $155 \pm 17$                                 | 0.435                            | 6.75                                       |
| 080916C(2)           | $4.35 \pm 0.15$     | 40.509               | 27.4                   | 146.6                 | $12.6 \pm 1.4$                               | 7.572                            | 9.51                                       |
| 090902Bs             | 1.822               | 11.671               | 11.9                   | 33.6                  | $8.8 \pm 1.0$                                | 4.136                            | 3.65                                       |
|                      |                     | 14.166               | 14.2                   | 40.1                  | $8.7 \pm 1.0$                                | 5.020                            | 4.36                                       |
|                      |                     | 26.168               | 18.1                   | 51.1                  | $6.0 \pm 0.7$                                | 9.273                            | 5.55                                       |
|                      |                     | 42.374               | 12.7                   | 35.8                  | $2.6 \pm 0.3$                                | 15.016                           | 3.90                                       |
|                      |                     | 45.608               | 15.4                   | 43.5                  | $2.9 \pm 0.3$                                | 16.162                           | 4.72                                       |

<sup>a</sup>The data of this GRB are from the Pass 7 LAT reconstruction. The references for the redshifts of the GRBs are [18](GRB 080916C), [22](GRB 090510), [21](GRB 090902B), [19](GRB 090926A), [20](GRB 100414A), and [17](GRB 130427A).  $t_{\text{obs}}$  is the arrival time after the onset of the GRBs,  $E_{\text{obs}}$  is the measured energy of the photon,  $E_{\text{in}}$  is the intrinsic energy at the source of the GRBs, and  $E_{\text{LV},1}$  is the Lorentz violation parameter of the linear LV model without considering the intrinsic time lag. The standard errors of  $E_{\text{LV},1}$ 's are calculated with the consideration of the energy resolution of LAT [25] and the uncertainties of the cosmological parameters and the redshifts.  $K_1$  is the Lorentz violation factor with a unit as (s  $\cdot$  GeV)

## further development



$$\frac{t_{\text{obs}}}{1+z} = \frac{K_n}{E_{\text{LV},n}^n} + t_{\text{in}}$$

$$n=1$$

$$E_{\text{LV},1} = (3.05 \pm 0.19) \times 10^{17} \text{ GeV}$$

# Benchmark of low energy photons: trigger or peak?

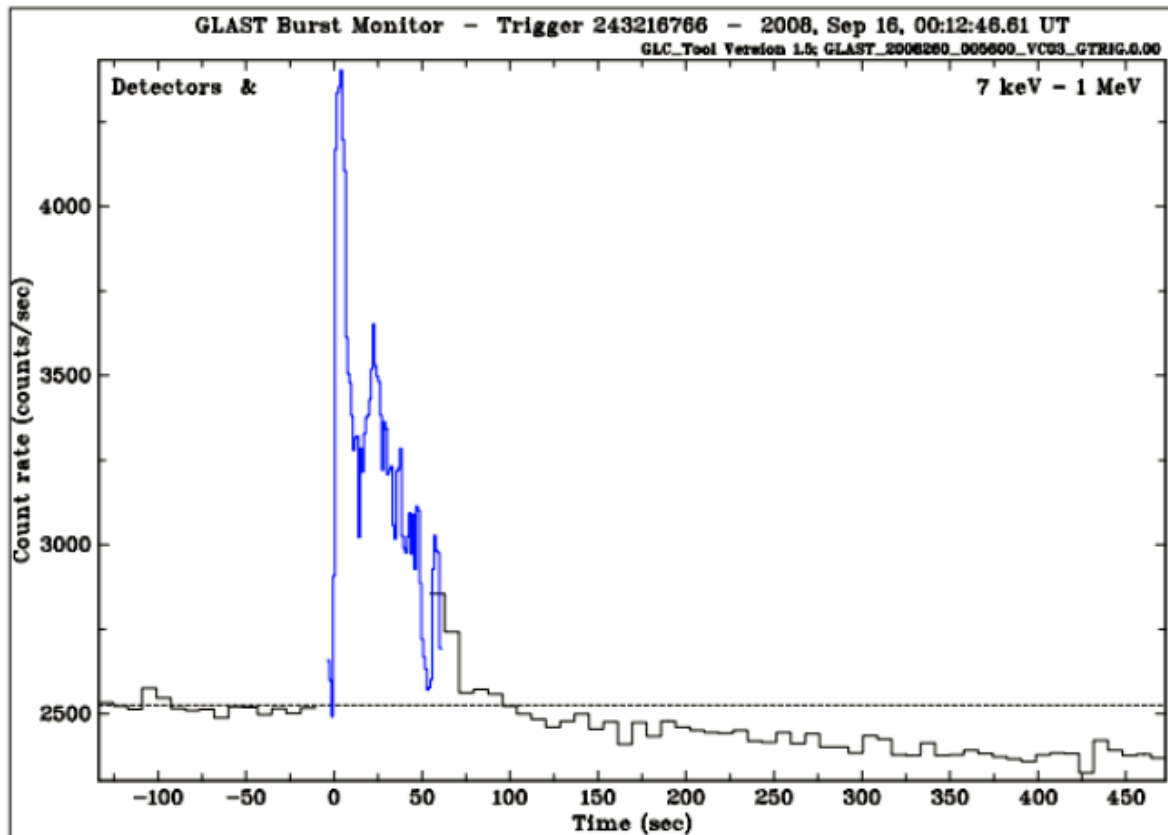
## Trigger:

- L.Shao, Z.Xiao and B.-Q.Ma, APP 33 (2010) 312, arXiv:0911.2276
- S.Zhang, B.-Q.Ma, APP 61 (2015) 108, arXiv:1406.4568

## The peak of low energy photons:

- H.Xu, B.-Q.Ma, APP 82 (2016) 72, arXiv: 1607.03203
- H.Xu, B.-Q.Ma, Phys.Lett.B 760 (2016) 602
- Y.Liu, B.-Q.Ma, EPJC 78 (2018) 825, arXiv: 1810.00636

# Benchmark of low energy photons: trigger or peak?



- H.Xu, B.-Q.Ma, APP 82 (2016) 72, arXiv: 1607.03203
- H.Xu, B.-Q.Ma, Phys.Lett.B 760 (2016) 602

- H.Xu, B.-Q.Ma, APP 82 (2016) 72, arXiv: 1607.03203

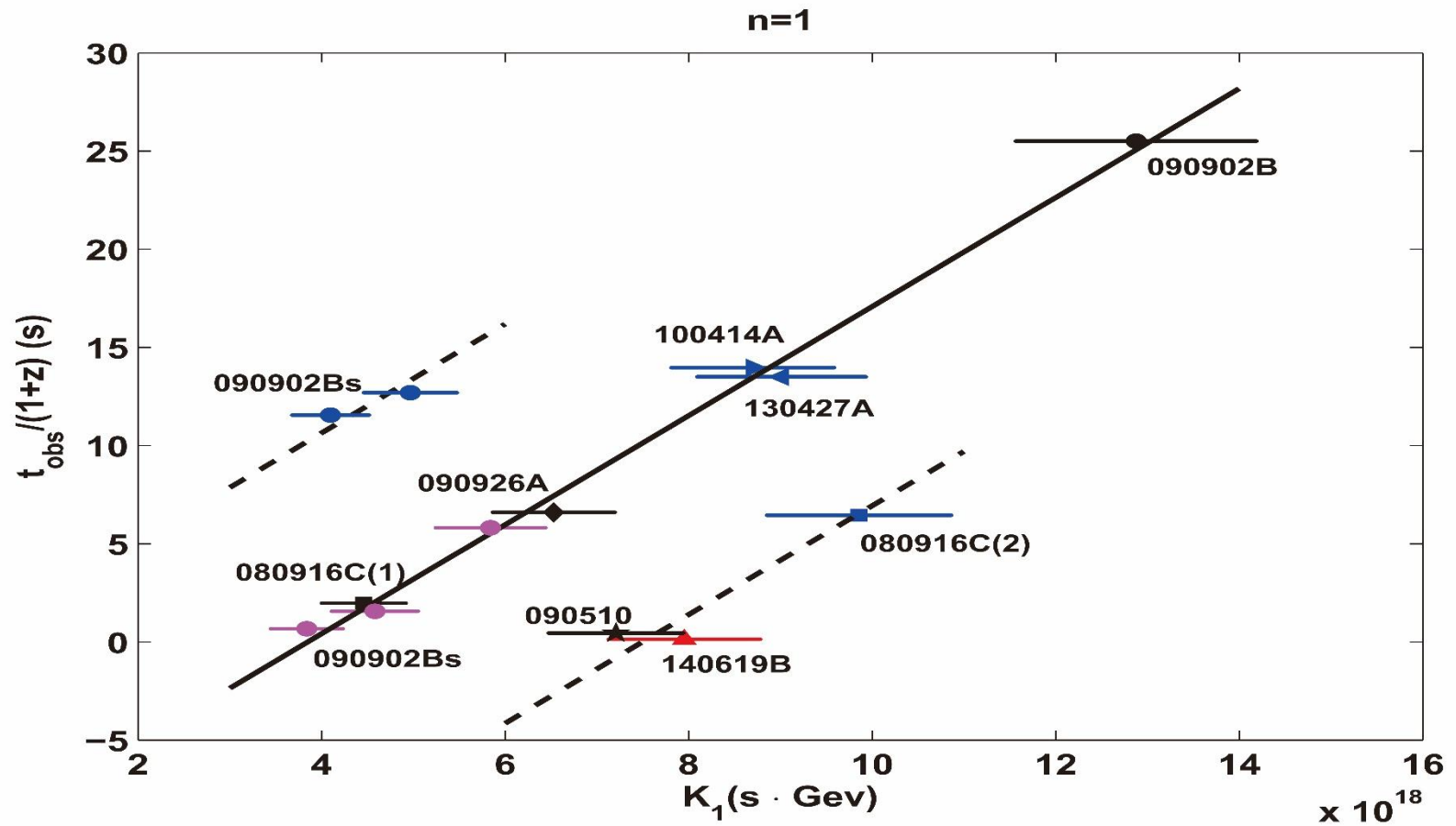
## New Analysis of Data

Table 1: The data of high energy photon events from GRBs with known redshifts.

| GRB        | $z$                 | $t_{\text{high}}$ (s) | $t_{\text{low}}$ (s) | $E_{\text{obs}}$ (GeV) | $E_{\text{source}}$ (GeV) | $\frac{\Delta t_{\text{obs}}}{1+z}$ (s) | $K_1$<br>( $\times 10^{18}$ s · GeV) |
|------------|---------------------|-----------------------|----------------------|------------------------|---------------------------|-----------------------------------------|--------------------------------------|
| 080916C(1) | $4.35 \pm 0.15$     | 16.545                | 5.984                | 12.4                   | 66.3                      | 1.974                                   | $4.46 \pm 0.45$                      |
| 080916C(2) | $4.35 \pm 0.15$     | 40.509                | 5.984                | 27.4                   | 146.6                     | 6.453                                   | $9.86 \pm 0.99$                      |
| 090510     | $0.903 \pm 0.003$   | 0.828                 | -0.032               | 29.9                   | 56.9                      | 0.452                                   | $7.21 \pm 0.73$                      |
| 090902B    | 1.822               | 81.746                | 9.768                | 39.9                   | 112.6                     | 25.506                                  | $12.9 \pm 1.3$                       |
| 090902Bs   | 1.822               | 11.671                | 9.768                | 11.9                   | 33.6                      | 0.674                                   | $3.84 \pm 0.39$                      |
|            |                     | 14.166                |                      | 14.2                   | 40.1                      | 1.559                                   | $4.58 \pm 0.47$                      |
|            |                     | 26.168                |                      | 18.1                   | 51.1                      | 5.812                                   | $5.84 \pm 0.59$                      |
|            |                     | 42.374                |                      | 12.7                   | 35.8                      | 11.554                                  | $4.10 \pm 0.42$                      |
|            |                     | 45.608                |                      | 15.4                   | 43.5                      | 12.700                                  | $4.97 \pm 0.51$                      |
| 090926A    | $2.1071 \pm 0.0001$ | 24.835                | 4.320                | 19.5                   | 60.6                      | 6.603                                   | $6.53 \pm 0.66$                      |
| 100414A    | 1.368               | 33.365                | 0.288                | 29.7                   | 70.3                      | 13.968                                  | $8.70 \pm 0.88$                      |
| 130427A    | $0.3399 \pm 0.0002$ | 18.644                | 0.544                | 72.6                   | 97.3                      | 13.509                                  | $9.02 \pm 0.91$                      |
| 140619B    | $2.67 \pm 0.37$     | 0.613                 | 0.096                | 22.7                   | 83.5                      | 0.141                                   | $7.96 \pm 0.82$                      |

- H.Xu, B.-Q.Ma, APP 82 (2016) 72, arXiv: 1607.03203

## New Results



- H.Xu, B.-Q.Ma, Phys.Lett.B 760 (2016) 602

## New GRB: 160509A

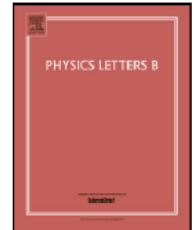
Physics Letters B 760 (2016) 602–604



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### Light speed variation from gamma ray burst GRB 160509A



Haowei Xu<sup>a</sup>, Bo-Qiang Ma<sup>a,b,c,d,\*</sup>

#### A B S T R A C T

It is postulated in Einstein's relativity that the speed of light in vacuum is a constant for all observers. However, the effect of quantum gravity could bring an energy dependence of light speed. Even a tiny speed variation, when amplified by the cosmological distance, may be revealed by the observed time lags between photons with different energies from astrophysical sources. From the newly detected long gamma ray burst GRB 160509A, we find evidence to support the prediction for a linear form modification of light speed in cosmological space.

- H.Xu, B.-Q.Ma, Phys.Lett.B 760 (2016) 602

## New GRB: 160509A

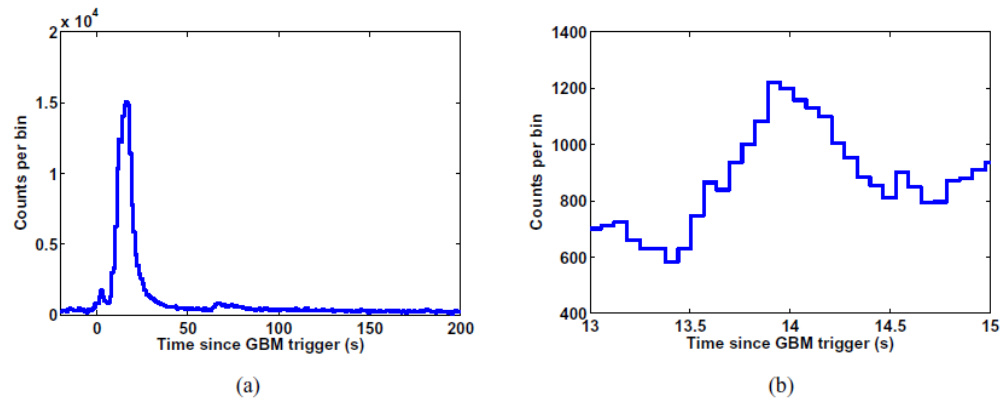


Figure 1: Light curves of the two brightest trigger detectors combined (GBM NaI-n0 and NaI-n3, 8 ~ 260 keV) for GRB 160509A. In the left panel (a), photon events are binned in 1 second intervals. In the right panel (b), photon events are binned in 0.064 seconds intervals to determine the peak of the main pulse as  $T_{\text{peak}} = 13.920$  s.

Table 1: Photons with energy higher than 1 GeV from GRB 160509A

| $E_{\text{obs}} / \text{GeV}$ | $t_{\text{arri}} / \text{s}$ | (RA, Dec)     |
|-------------------------------|------------------------------|---------------|
| 51.9                          | 76.506                       | (310.3, 76.0) |
| 2.33                          | 24.258                       | (313.2, 75.9) |
| 1.85                          | 87.039                       | (308.3, 73.9) |
| 1.52                          | 50.570                       | (328.8, 72.5) |
| 1.26                          | 49.155                       | (311.3, 75.8) |

- H.Xu, B.-Q.Ma, Phys.Lett.B 760 (2016) 602

## New GRB: 160509A

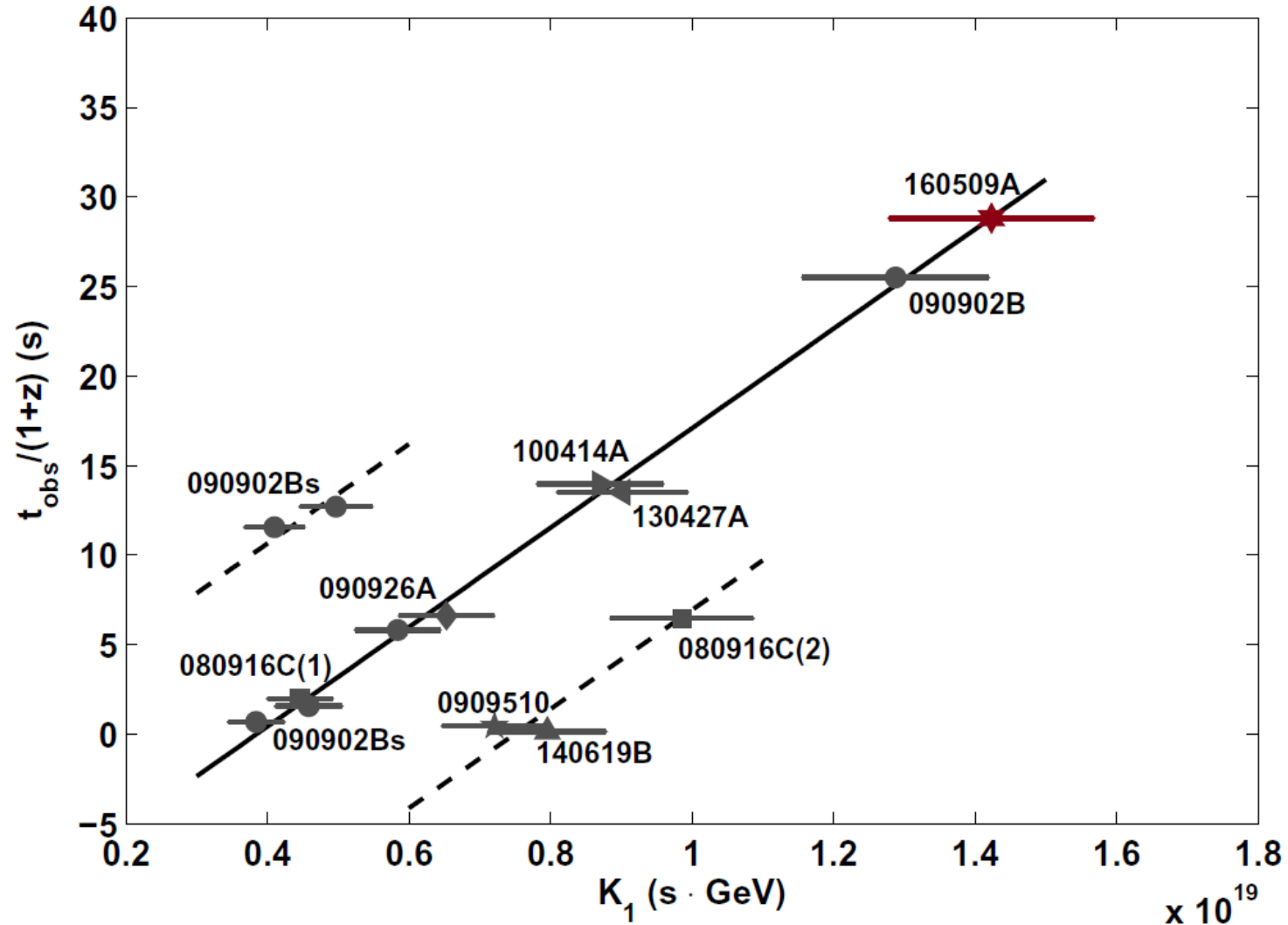
Table 2: Data of high energy photon event from GRB 160509A

| GRB     | $z$  | $t_{\text{high}}$ (s) | $t_{\text{low}}$ (s) | $E_{\text{obs}}$ (GeV) | $E_{\text{source}}$ (GeV) | $\frac{\Delta t_{\text{obs}}}{1+z}$ (s) | $K_1$ ( $\times 10^{18}$ s $\cdot$ GeV) |
|---------|------|-----------------------|----------------------|------------------------|---------------------------|-----------------------------------------|-----------------------------------------|
| 160509A | 1.17 | 76.506                | 13.920               | 51.9                   | 112.6                     | 28.812                                  | 14.2                                    |

Data of GRB 160509A.  $t_{\text{high}}$  and  $t_{\text{low}}$  denote the arrival time of the high energy photon event and the peak time of the main pulse of low energy photons respectively, with the trigger time of GBM as the zero point.  $E_{\text{obs}}$  and  $E_{\text{source}}$  are the energy measured by Fermi LAT and the intrinsic energy at the source of GRBs, with  $E_{\text{source}} = (1 + z)E_{\text{obs}}$ .  $K_1$  is the Lorentz violation factor with a unit of (s  $\cdot$  GeV) for  $n = 1$ .

- H.Xu, B.-Q.Ma, Phys.Lett.B 760 (2016) 602

## New GRB: 160509A



- H.Xu, B.-Q.Ma, Phys.Lett.B 760 (2016) 602

## **New GRB: 160509A**

we find evidence

to support the prediction for a linear form modification of light speed

$$v(E) = c(1 - E/E_{LV})$$

$$E_{LV} = 3.60 \times 10^{17} \text{ GeV}$$

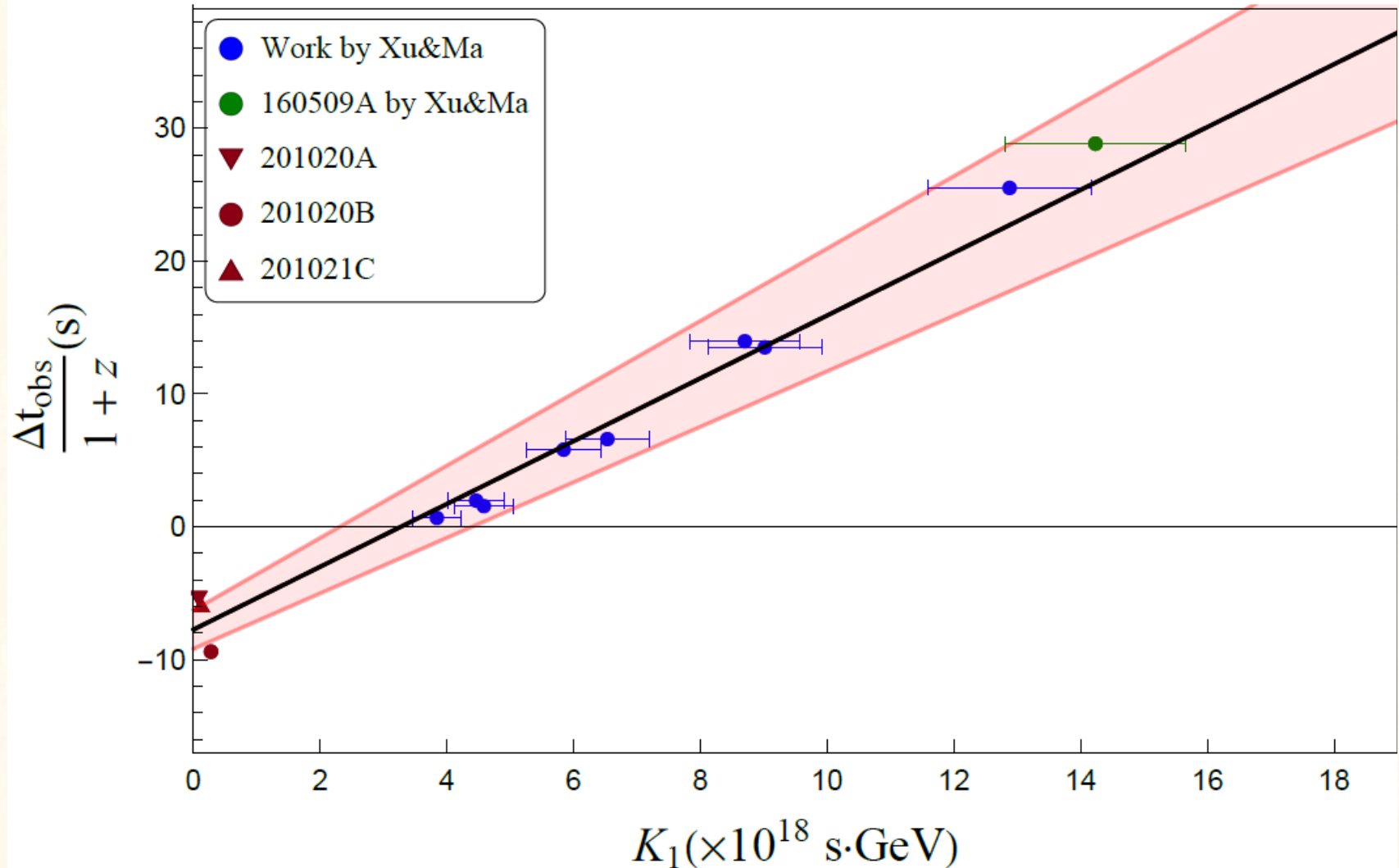
### A B S T R A C T

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It is postulated in Einstein's relativity that the speed of light in vacuum is a constant for all observers. However, the effect of quantum gravity could bring an energy dependence of light speed. Even a tiny speed variation, when amplified by the cosmological distance, may be revealed by the observed time lags between photons with different energies from astrophysical sources. From the newly detected long gamma ray burst GRB 160509A, we find evidence to support the prediction for a linear form modification of light speed in cosmological space.

- J.Zhu, B.-Q.Ma, Phys.Lett.B 820 (2021) 136518

## New GRBs: 201020A, 201020B, 201021C



- J.Zhu, B.-Q.Ma, Phys.Lett.B 820 (2021) 136518

## New GRBs: 201020A, 201020B, 201021C

Physics Letters B 820 (2021) 136518



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Physics Letters B

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Pre-burst events of gamma-ray bursts with light speed variation

Jie Zhu<sup>a</sup>, Bo-Qiang Ma<sup>a,b,c,\*</sup>



- Direct evidence for pre-burst stage of GRBs
- Support of light speed variation at  $E_{LV} = 3.60 \times 10^{17} \text{ GeV}$

- Y.Chen, B.-Q.Ma, JHEAp 32 (2021) 78-86

# Pre-burst of GRBs from machine learning

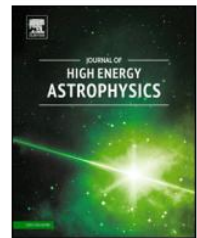
Journal of High Energy Astrophysics 32 (2021) 78–86



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Journal of High Energy Astrophysics

[www.elsevier.com/locate/jheap](http://www.elsevier.com/locate/jheap)



Novel pre-burst stage of gamma-ray bursts from machine learning

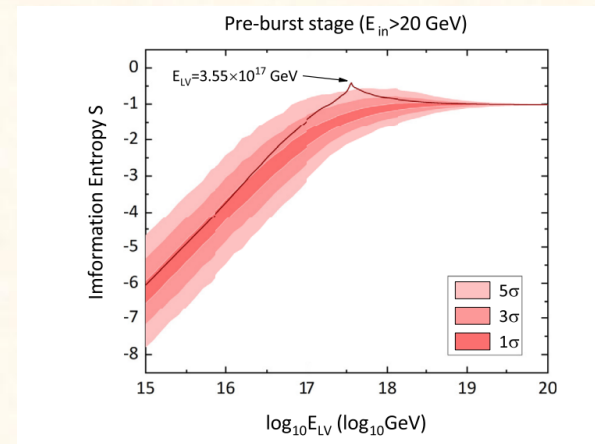
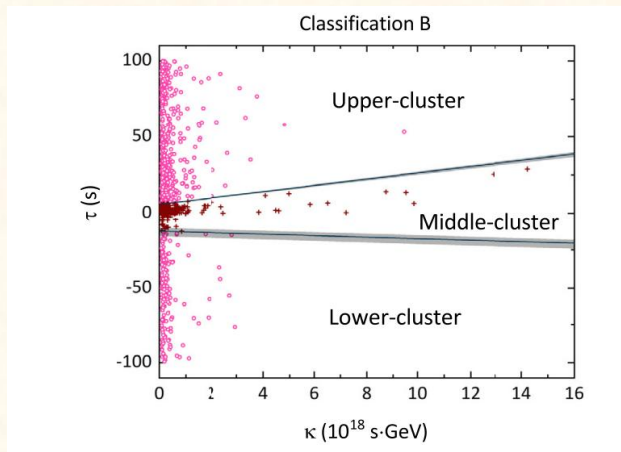
Yingtian Chen <sup>a,b</sup>, Bo-Qiang Ma <sup>a,c,d,e,\*</sup>



- Strong support for pre-burst stage of GRBs
- Support of light speed variation at  $E_{LV} = 3.60 \times 10^{17} \text{ GeV}$

- Y.Chen, B.-Q.Ma, JHEAp 32 (2021) 78-86

## Pre-burst of GRBs from machine learning



- Strong support for pre-burst stage of GRBs
- Support of light speed variation at  $E_{LV} = 3.60 \times 10^{17}$  GeV

- H.Song, B.-Q.Ma, Phys.Lett.B 856 (2024) 138951

## Refined model with intrinsic time delay

Letter

Energy-dependent intrinsic time delay of gamma-ray bursts on testing Lorentz invariance violation

Hanlin Song<sup>a</sup>, Bo-Qiang Ma<sup>a,b,\*</sup>

<sup>a</sup> School of Physics, Peking University, Beijing 100871, China

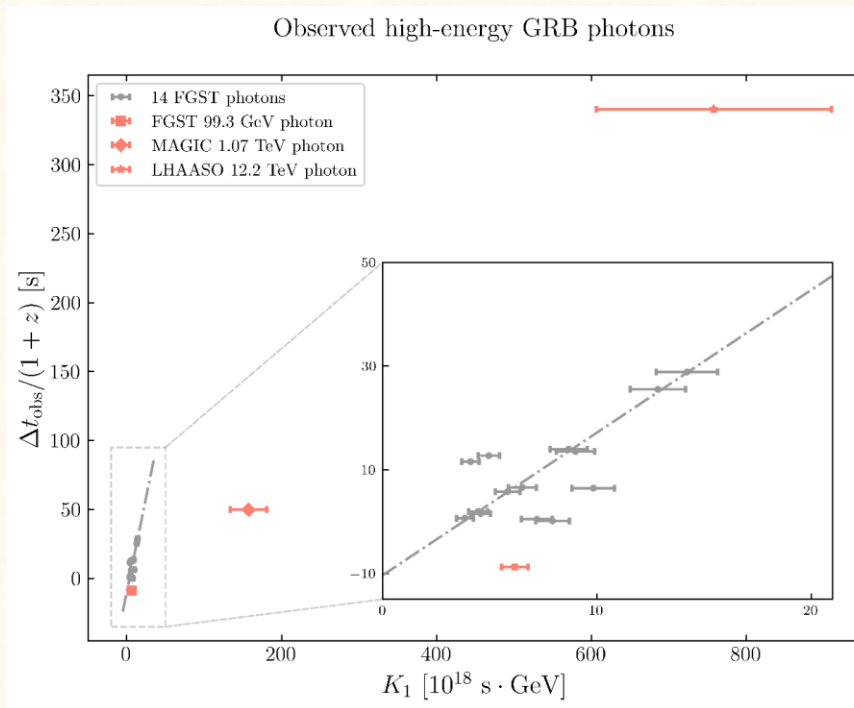
<sup>b</sup> Center for High Energy Physics, Peking University, Beijing 100871, China

$$\frac{\Delta t_{\text{obs}}}{1+z} = \Delta t_{\text{in,c}} + \alpha E_s + a_{\text{LV}} K_1$$

- Again showing a pre-burst stage of GRBs
- Support light speed variation at  $E_{\text{LV}} = 2.96^{+1.21}_{-0.70} \times 10^{17} \text{ GeV}$

- H.Song, B.-Q.Ma, ApJ 983 (2025) 9

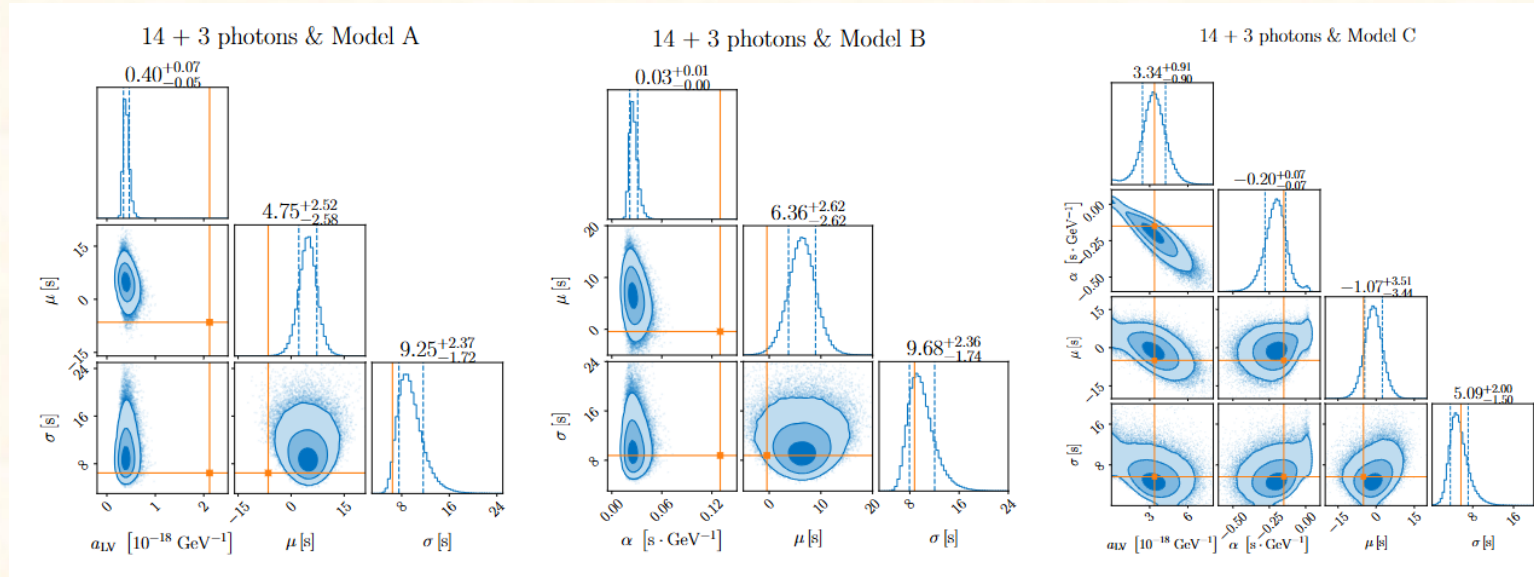
## Refined model analysis including TeV & multi-TeV data



- Again showing a pre-burst stage of GRBs
- Support of light speed variation at  $E_{\text{LV}} = 3.00^{+1.11}_{-0.64} \times 10^{17}$  GeV

- H.Song, B.-Q.Ma, PRD 111 (2025) 103015 arXiv:2504.15685

## Refined model analysis proved from Monte Carlo data



- Consistency between 14 dataset and 14+7 dataset with Model C
- Support of light speed variation at  $E_{LV} = 3.00^{+1.11}_{-0.64} \times 10^{17}$  GeV

# A brief summary of new results

Song, and Ma, (2024), *Phys.Lett.B*

Liu, Song, and Ma, (2024), *Res. Notes AAS*

Song, and Ma, (2025), *Phys.Dark Univ.*

Song, and Ma, (2025), *Astrophys.J.*

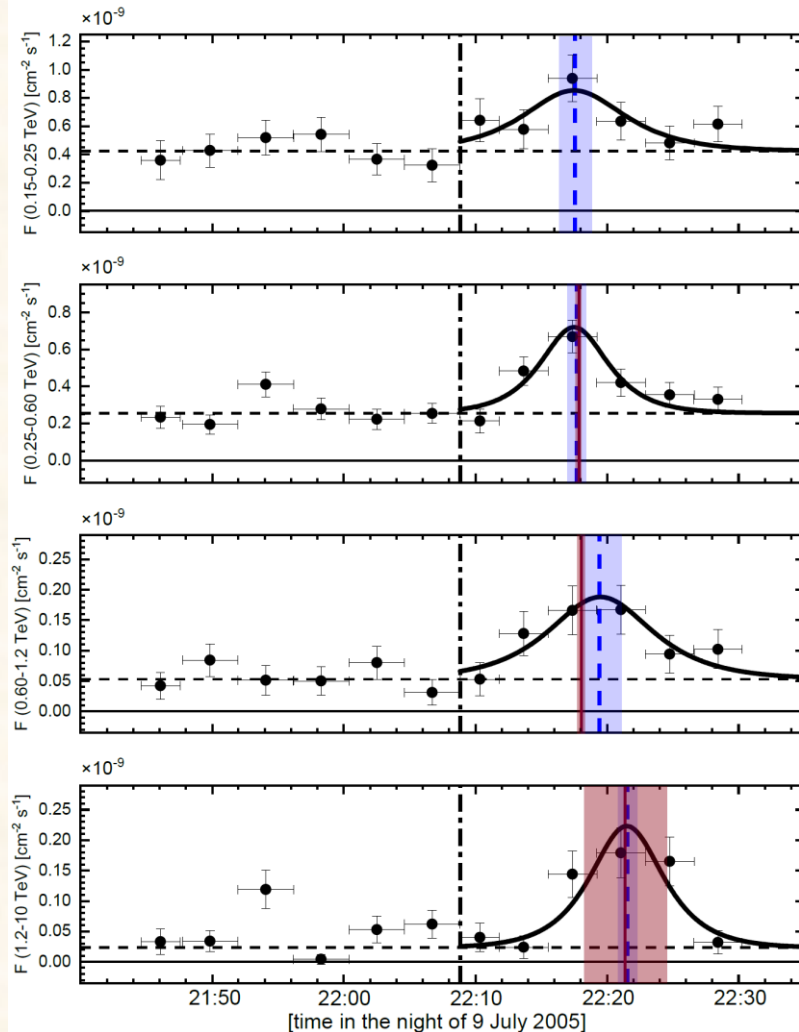
Song, and Ma, (2025), *Phys.Rev.D*

- Testing Lorentz invariance violation with Gamma-ray burst
  - Energy-dependent intrinsic time delay model
- **Consistent** results with **previous studies** on **GeV** photons
  - **Consistent** results in explaining **TeV** photons
  - **Hints for new physics at  $E_{LV} \sim 3 \times 10^{17}$  GeV**

**More data and stronger evidence will appear soon**

Carpet-3 300 TeV Photon Event as an Evidence for Lorentz Violation  
H. Song, B.-Q. Ma, arXiv: 2508.08984

# Light Speed Variation from AGN: Mrk501



Light curves (LC) binned in 4 minutes for the flare of Mrk 501 in the night on 9 July 2005 by MAGIC

**A shift of peak** by  $4 \pm 1$  minutes between bands 0.15-0.25 TeV and 1.2-10 TeV

$$E_{\text{LV}}^{\text{agn}} = 3.68_{-0.37}^{+0.46} \times 10^{17} \text{ GeV}$$



$$E_{\text{LV}}^{\text{grb}} = (3.60 \pm 0.26) \times 10^{17} \text{ GeV}$$

A support for the subluminal light speed variation from GRBs

## Prediction of Light speed variation from space-time foam

J.R. Ellis, N.E. Mavromatos, M. Westmuckett, Supersymmetric D-brane model of space-time foam, Phys. Rev. D 70 (2004) 044036, <https://doi.org/10.1103/PhysRevD.70.044036>, arXiv:gr-qc/0405066.

J.R. Ellis, N.E. Mavromatos, D.V. Nanopoulos, Derivation of a vacuum refractive index in a stringy space-time foam model, Phys. Lett. B 665 (2008) 412, <https://doi.org/10.1016/j.physletb.2008.06.029>, arXiv:0804.3566.

T. Li, N.E. Mavromatos, D.V. Nanopoulos, D. Xie, Time delays of strings in D-particle backgrounds and vacuum refractive indices, Phys. Lett. B 679 (2009) 407, <https://doi.org/10.1016/j.physletb.2009.07.062>, arXiv:0903.1303.

$$c_g = 1 - 2g_s \frac{\zeta_D |\mathbf{p}|}{M_s} \simeq 1 - \mathcal{O} \left( g_s \frac{n_D \mathcal{E}}{M_s} \right), \quad \langle\langle \lambda \rangle\rangle_D = \zeta_D > 0.$$

$$M_s \gtrsim 7.20 \times 10^{17} \zeta_D g_s \text{ GeV}$$



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Light speed variation in a string theory model for space-time foam

Chengyi Li <sup>a</sup>, Bo-Qiang Ma <sup>a,b,c,\*</sup>

# **The string theory model of space-time foam**

is consistent with current observations  
including a subluminal light speed variation around Planck scale  
and the LHAASO discovery of cosmic PeV photons

J.R. Ellis, N.E. Mavromatos, M. Westmuckett, Supersymmetric D-brane model of space-time foam, Phys. Rev. D 70 (2004) 044036, <https://doi.org/10.1103/PhysRevD.70.044036>, arXiv:gr-qc/0405066.

J.R. Ellis, N.E. Mavromatos, D.V. Nanopoulos, Derivation of a vacuum refractive index in a stringy space-time foam model, Phys. Lett. B 665 (2008) 412, <https://doi.org/10.1016/j.physletb.2008.06.029>, arXiv:0804.3566.

T. Li, N.E. Mavromatos, D.V. Nanopoulos, D. Xie, Time delays of strings in D-particle backgrounds and vacuum refractive indices, Phys. Lett. B 679 (2009) 407, <https://doi.org/10.1016/j.physletb.2009.07.062>, arXiv:0903.1303.



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Physics Letters B

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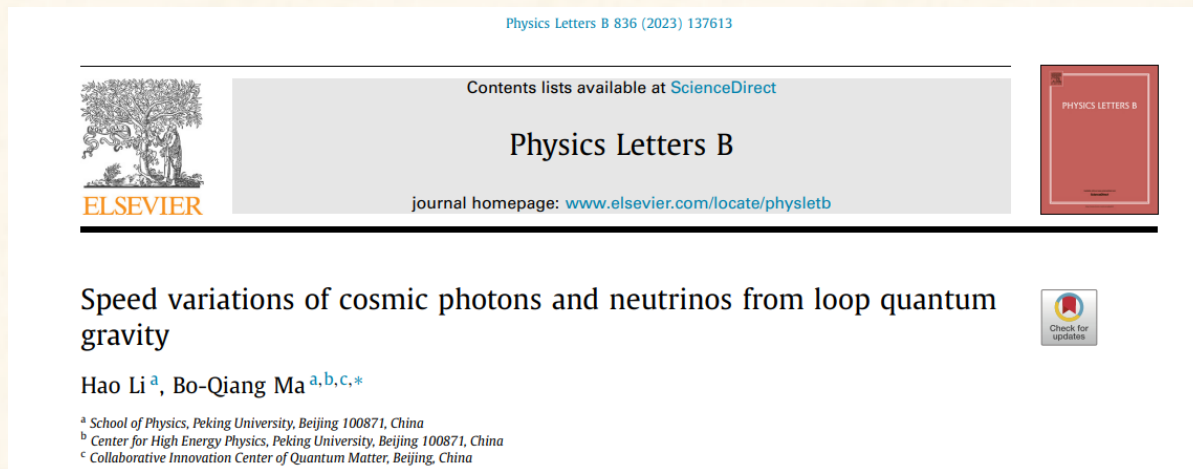


Light speed variation in a string theory model for space-time foam

Chengyi Li<sup>a</sup>, Bo-Qiang Ma<sup>a,b,c,\*</sup>

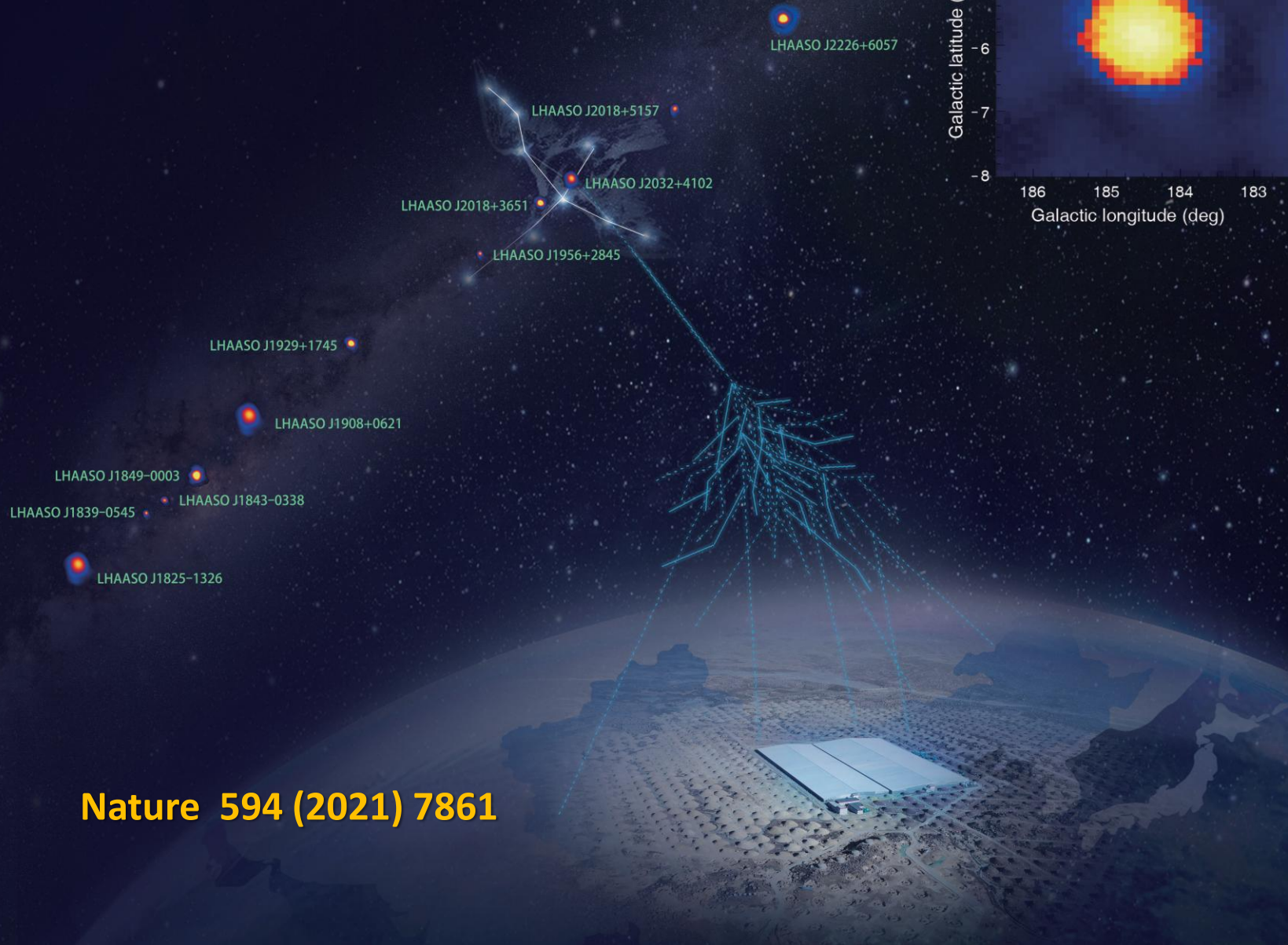
H.Li, B.-Q.Ma, PLB 836 (2023) 137613

# Speed variations of cosmic photons and neutrinos from loop quantum gravity



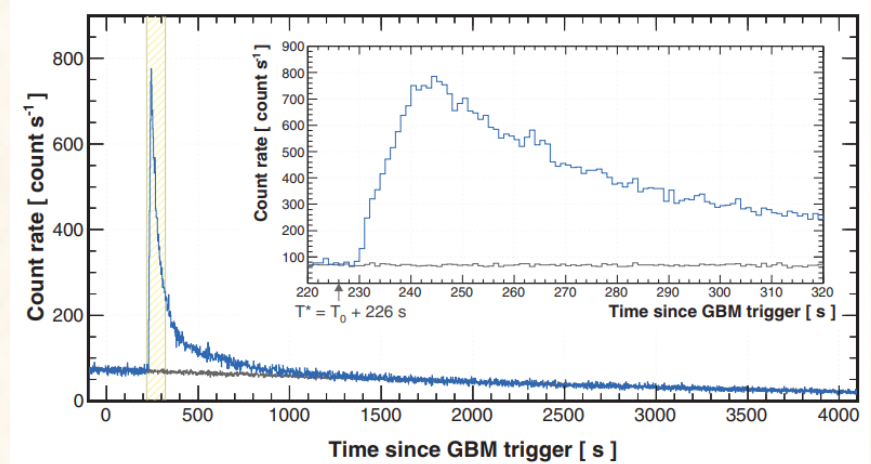
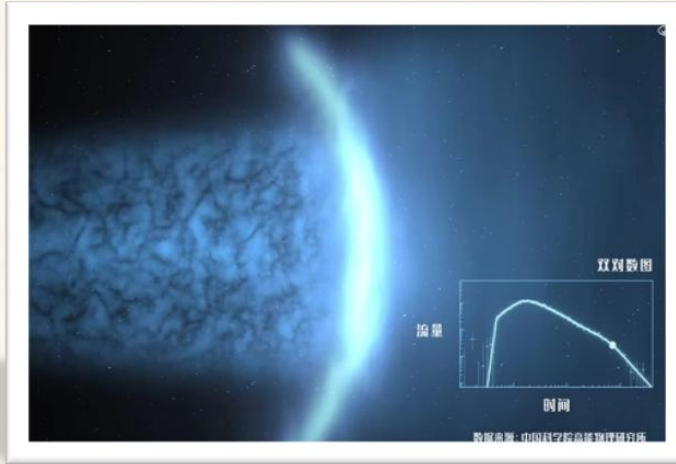
A consistent understanding of Lorentz violation features of cosmic photons and neutrinos from loop quantum gravity

# LHAASO discovery of PeV photons



Nature 594 (2021) 7861

# Newly observed GRB221009A



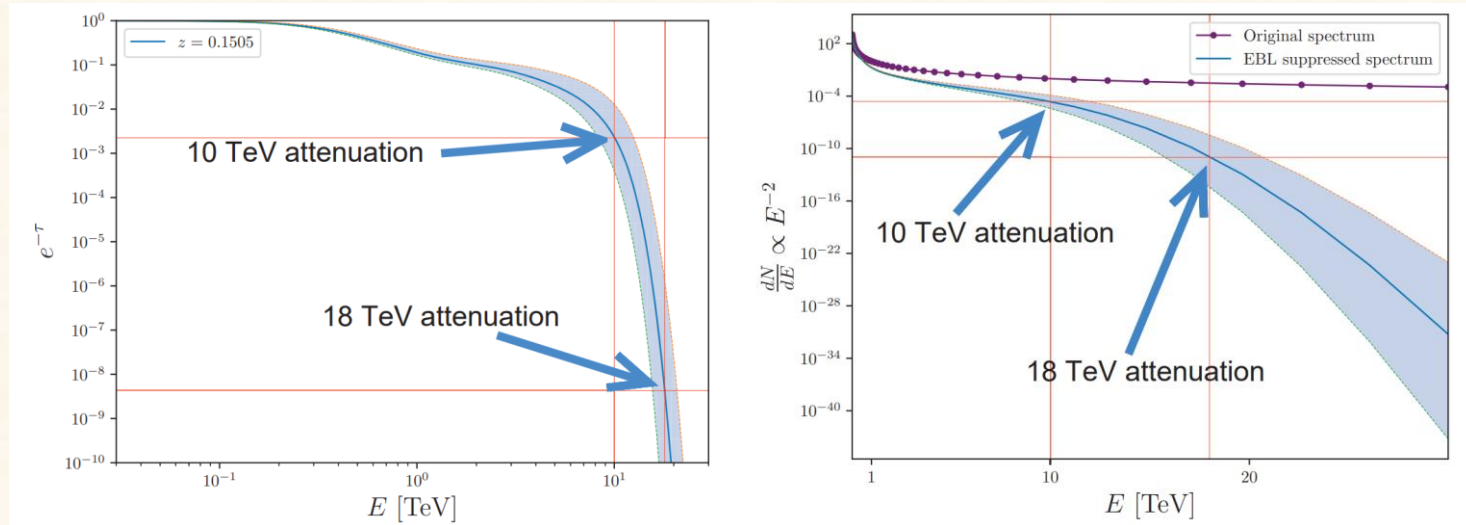
- Triggered by Fermi and Swift
- Very bright GRB with very short distance  
 $z=0.1505$  (2.4 billion light years)
- **LHAASO observation:** 64000 high energy events with energies larger than 200 GeV including photons with energy larger than 10 TeV.

**The first observation of GRB photons over 10 TeV.**

LHAASO, Science 380 (2023) 1390, June 8, 2023, arXiv:2306.06372

LHAASO, Sci. Adv. 9 (2023) adj2778, arXiv:2310.08845

# Newly observed GRB221009A



- Within standard model, extragalactic background light (EBL) could absorb cosmic photons severely and the flux is too weak to be observed.
- We suggest that Lorentz invariance violation induced threshold anomaly of  $\gamma\gamma \rightarrow e^-e^+$  process provides a candidate to explain the LHAASO observation of 18 TeV event.

H. Li and B.-Q. Ma, arXiv:2210.06338, APP 148 (2023) 102831

See also, H. Li and B.-Q. Ma, arXiv:2210.05563, EPJC 83 (2023) 192

## Axion-Photon Conversion of LHAASO Multi-TeV and PeV Photons

Guangshuai Zhang(张光帅)<sup>1</sup> and Bo-Qiang Ma(马伯强)<sup>1,2,3\*</sup>

- The axion-photon conversion allows extragalactic multi-TeV and PeV photons to propagate in the Universe for being detected on the Earth.
- The axion-photon conversation can serve as an **alternative mechanism** for the very-high-energy features of the newly observed gamma ray burst GRB 221009A.

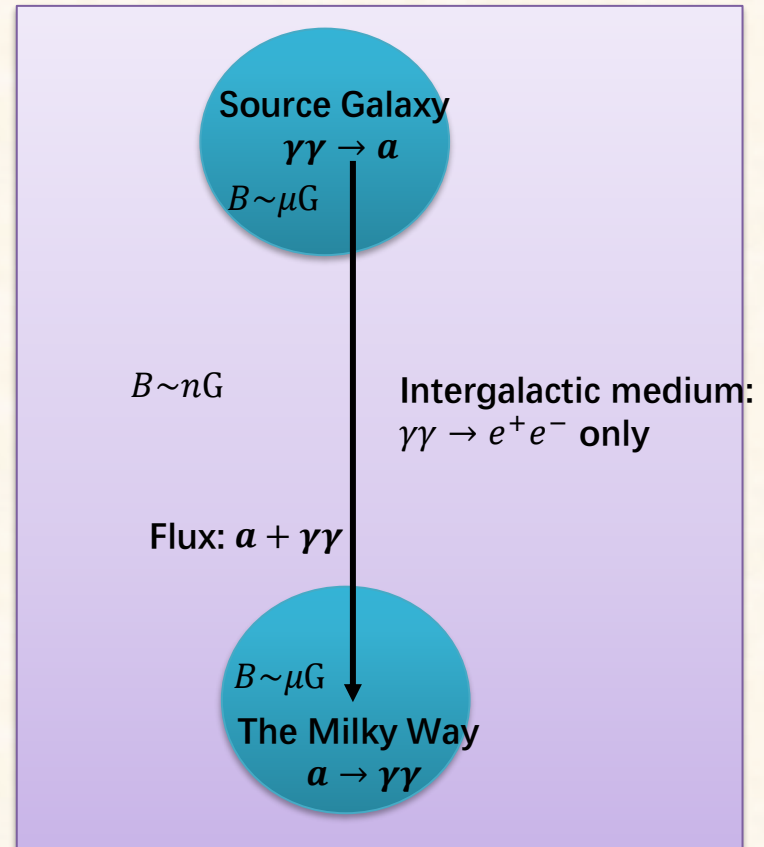
G. Zhang, B.-Q. Ma, arXiv: 2210.13120 , CPL 40 (2023) 011401

**An earlier work to indicate that LHAASO data on PeV photons and on multi-TeV photons from GRB221009A can be used for studying new physics of axions.**

# The picture of photon-axion conversion

The axion-photon conversion can explain the observation of VHE photons from GRB221009A, and provide constraints on the  $m_a$  and coupling constant  $g_{a\gamma}$  of axion-like-particles (ALPs).

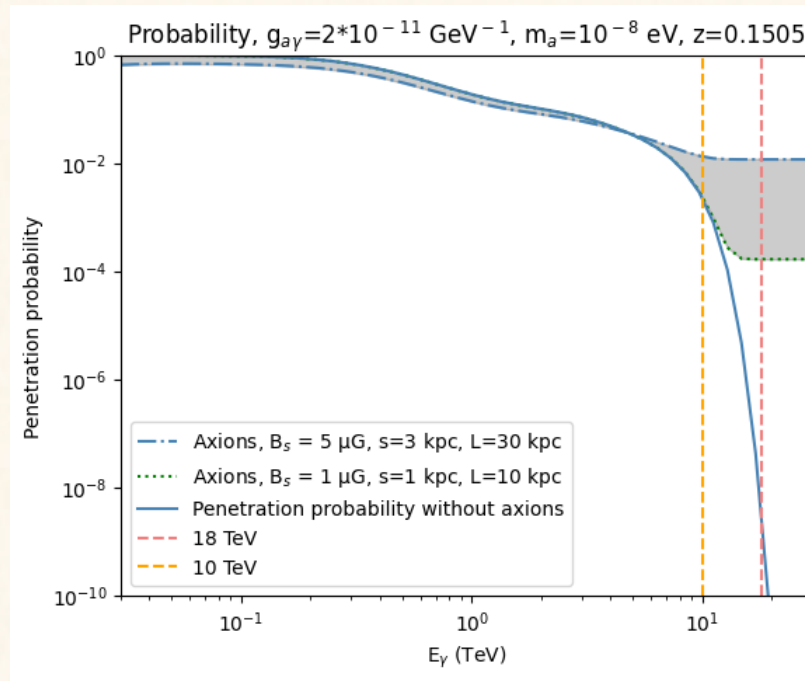
1. **GRB source frame magnetic fields:** Cellular model.
2. **Propagation in the intergalactic space :** no photon-ALP  $\gamma\gamma a$  conversion for the ALPs-photon mixed beams but only  $\gamma\gamma \rightarrow e^+e^-$ , putting constraints on  $m_a$  and  $g_{a\gamma}$ .
3. **Back conversion:** ALPs-photon conversion transforms some ALPs into photons in the magnetic field of Milky Way, making photons to be re-observable.



## Constraints on Axion Mass and Coupling Constant through LHAASO data

L. Wang, B.-Q. Ma, arXiv: 2304.01819, PRD 108 (2023) 023002

### Axion-Photon Conversion from GRB221009A



# Check New Physics with GRB221009A

The high energy features of GRB221009A need to be carefully examined to constrain possible new physics such as:

- Lorentz violation

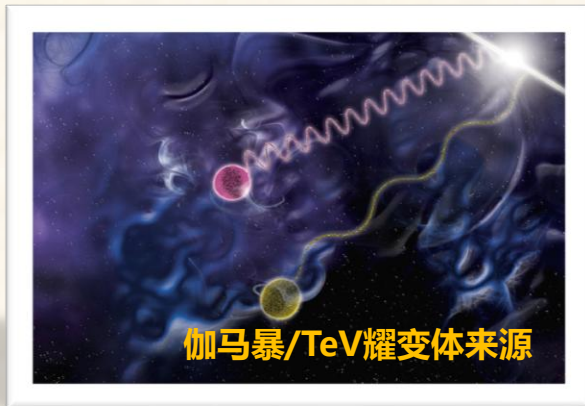
- Axion-photon conversion

- Sterile neutrino

# Searching for Lorentz Violation from Light-Speed Variation

- 以光速改变为例：

搜寻高能宇宙光子的飞行时间差



需要进一步开拓和深入

既往唯象分析建议光速可能改变的迹象

$$v(E) = c(1 - E/E_{LV}) \quad E_{LV}^{(\gamma)} \gtrsim 3.6 \times 10^{17} \text{ GeV}$$

L. Shao, Z. Xiao, B.-Q. Ma, APP 33 (2010) 312

S. Zhang, B.-Q. Ma, APP 61 (2015) 108

H. Xu, B.-Q. Ma, APP 82 (2016) 72

H. Xu, B.-Q. Ma, PLB 760 (2016) 602

H. Xu, B.-Q. Ma, JCAP 1801 (2018) 050

Y. Liu, B.-Q. Ma, EPJC 78 (2018) 825

J. Zhu, B.-Q. Ma, PLB 820 (2021) 136518

H. Li, B.-Q. Ma, Sci. Bull. 65 (2020) 262

.....

光子  
洛伦兹破缺

对中微子也可以开展类似研究

Y. Huang, B.-Q. Ma, Commun. Phys. 1 (2018) 62

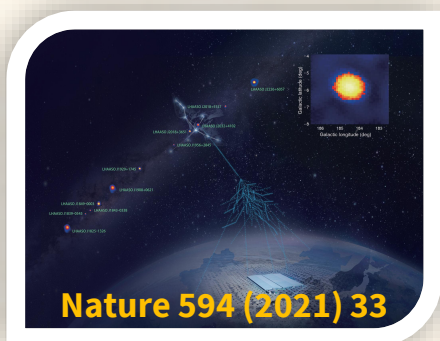
Y. Huang, H. Li, B.-Q. Ma, PRD 99 (2019) 123018

Y. Huang, B.-Q. Ma, Fund. Res. 4 (2024) 51

最早建议：G. Amelino-Camelia+, Nature 393 (1998) 763, 我组最早工作：Z. Xiao, B.-Q. Ma, PRD 80 (2009) 116005

# LHAASO discoveries set strong constraints on superluminal Lorentz violation

## 对粒子物理标准模型的精确检验



- LHAASO的最高能量 1.4 PeV 光子的突破性观测  
对光子超光速洛伦兹破缺给出极强约束

$$E_{LV}^{\gamma(\text{sup})} \gtrsim 2.7 \times 10^{24} \text{ GeV} \gg E_P$$

C. Li, B.-Q. Ma, PRD 104 (2021) 063012

C. Li, B.-Q. Ma, Sci. Bull. 66 (2021) 2254

## 光子/电子洛伦兹破缺参数的联合限制

P. He, B.-Q. Ma, PLB 829 (2022) 137034

P. He, B.-Q. Ma, PRD 108 (2023) 063006

- LHAASO对 1.1 PeV 蟹状星云辐射的首次测量  
对电子超光速洛伦兹破缺的强限制

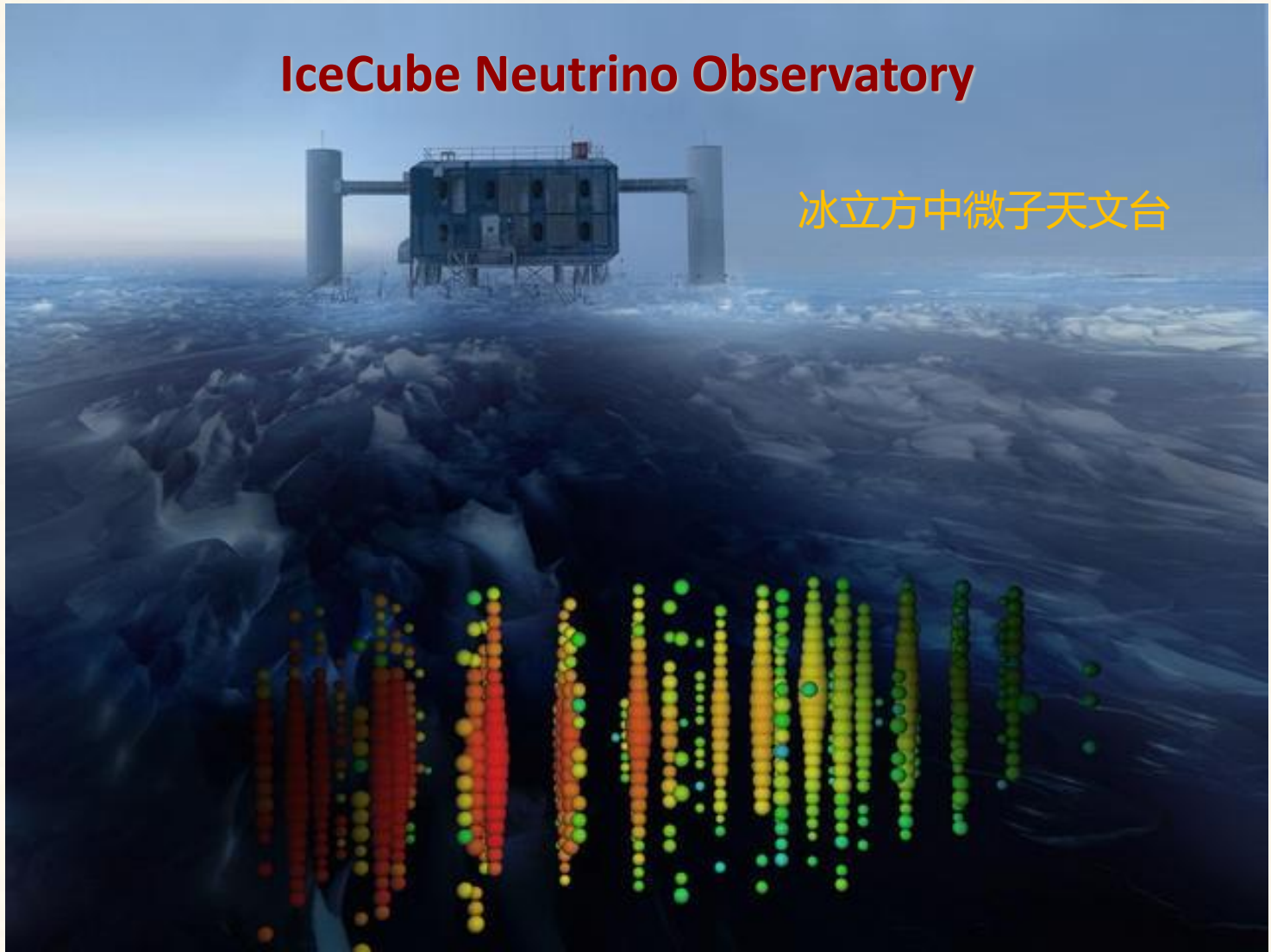
$$E_{LV}^{e(\text{sup})} \gtrsim \mathcal{O}(10^{26}) \text{ GeV} \gg E_P$$

C. Li, B.-Q. Ma, PLB 829 (2022) 137034



# IceCube Neutrino Observatory

冰立方中微子天文台



# IceCube Neutrinos

## —results reported by IceCube

- IceCube, *Astrophys.J.* 843 (2017) 2292
  - Y. Huang, B.-Q. Ma, *Comms.Phys.* 1 (2018) 62
- 
- More than ten years data taking: **energies > 30 TeV + 4 events of PeV**
  - Associated GRBs: narrow time window = within -100 to 300 seconds, some neutrinos compatible with **backgrounds**
  - Small flux to **rule out fireball models.**

# Advantages: from photons to neutrinos

- U. Jacob, T. Piran, Nat.Phys.3 (2007) 87
  - Y. Huang, B.-Q. Ma, Comms.Phys.1 (2018) 62
- 
- **Energy difference: photon < 100GeV, neutrino= TeV->PeV**
  - **Time difference: photon=a few seconds**  
**neutrino=a few hundred seconds -> months**
  - **Intrinsic time difference: can be safely neglected.**

# Reanalysis of TeV Events

## COMMUNICATIONS PHYSICS

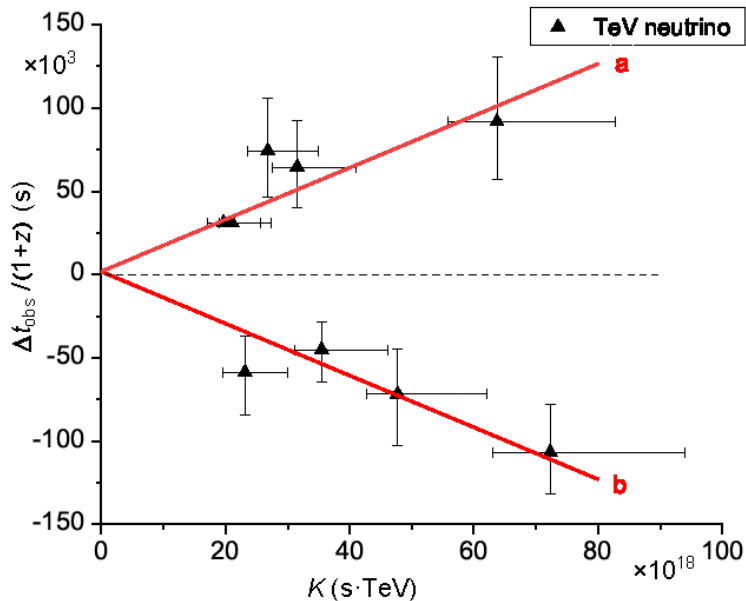
ARTICLE

DOI: 10.1038/s42005-018-0061-0

OPEN

Lorentz violation from gamma-ray burst neutrinos

Yanqi Huang<sup>1</sup> & Bo-Qiang Ma<sup>1,2,3</sup>



$$\left| \frac{\Delta t_{\text{obs}}}{1+z} - \Delta t_{\text{in}} \right| = \frac{K}{E_{\text{LV}}}$$

$$E_{\text{LV}} = (6.5 \pm 0.4) \times 10^{17} \text{ GeV}$$

Y. Huang, B.-Q. Ma, Comms.Phys.1 (2018) 62

# Reanalysis of TeV Events

## COMMUNICATIONS PHYSICS

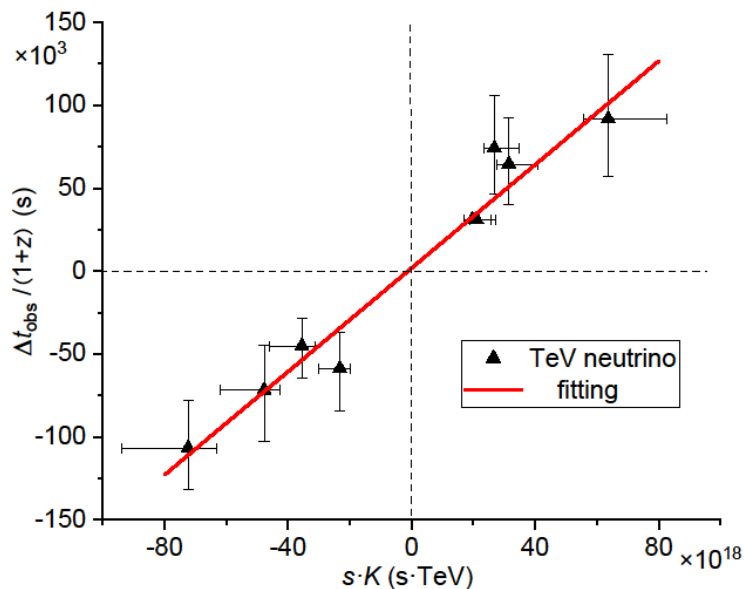
ARTICLE

DOI: 10.1038/s42005-018-0061-0

OPEN

Lorentz violation from gamma-ray burst neutrinos

Yanqi Huang<sup>1</sup> & Bo-Qiang Ma<sup>1,2,3</sup>



$$\frac{\Delta t_{\text{obs}}}{1+z} = \Delta t_{\text{in}} + s \frac{K}{E_{\text{LV}}}$$

$$s = \pm 1$$

# First Analysis of PeV Events

Y. Huang, B.-Q. Ma, Comms.Phys.1 (2018) 62

## COMMUNICATIONS PHYSICS

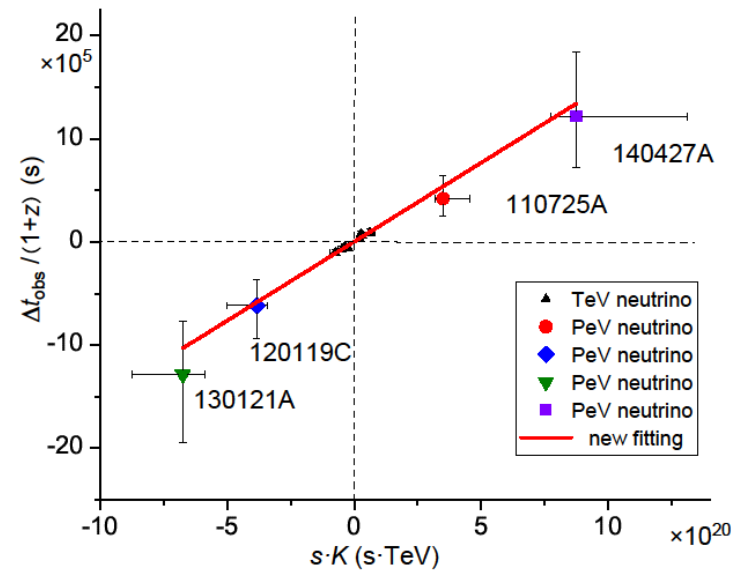
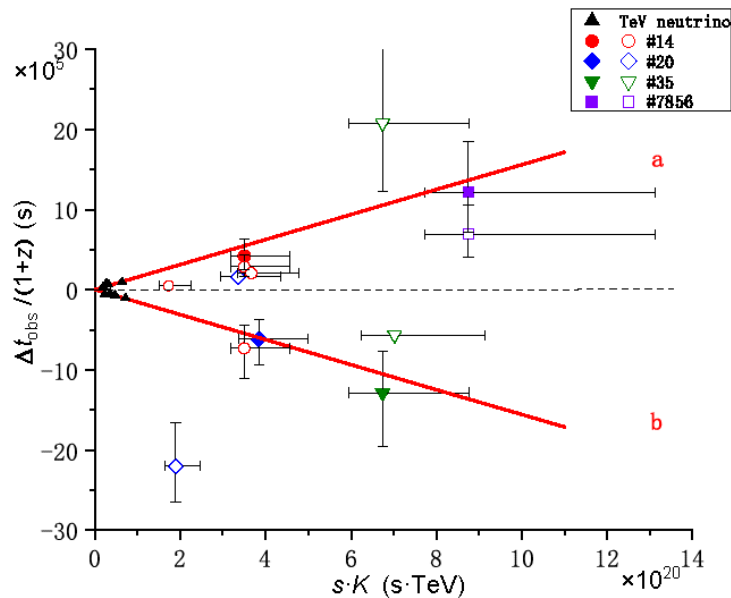
ARTICLE

DOI: 10.1038/s42005-018-0061-0

OPEN

### Lorentz violation from gamma-ray burst neutrinos

Yanqi Huang<sup>1</sup> & Bo-Qiang Ma<sup>1,2,3</sup>



# Association of IceCube Neutrinos with GRBs

Y. Huang, B.-Q. Ma, Comms.Phys.1 (2018) 62

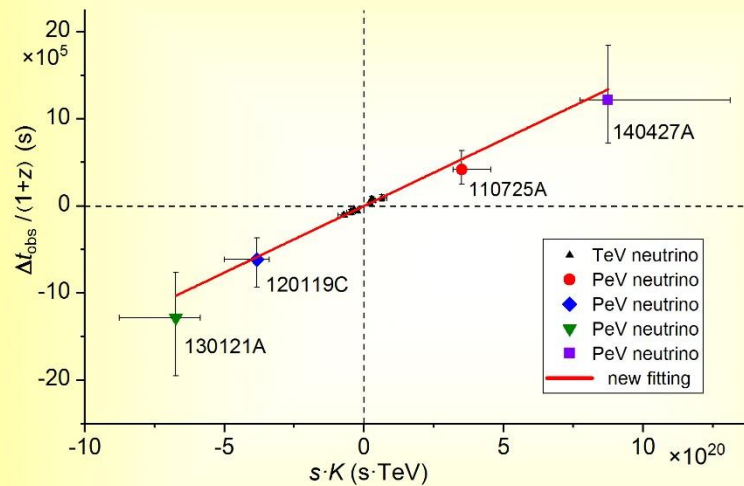
**Table 3 The properties of PeV neutrino events with associated GRB candidates**

|                          | $E$ (PeV)               | $\sigma$       | $\Delta\Psi$  | $z$      | $\Delta t_{\text{obs}}$ ( $10^3\text{s}$ ) | $\frac{\Delta t_{\text{obs}}}{1+z}$ ( $10^3\text{s}$ ) | $K$ ( $10^{18}\text{s} \cdot \text{TeV}$ ) |
|--------------------------|-------------------------|----------------|---------------|----------|--------------------------------------------|--------------------------------------------------------|--------------------------------------------|
| event #14                | $1.04^{+0.13}_{-0.14}$  | $13.2^\circ$   |               |          |                                            |                                                        |                                            |
| GRB 110725A <sup>c</sup> |                         | $9.06^\circ$   | $4.87^\circ$  | $2.15^b$ | 1320.217                                   | 419.1                                                  | 350.2                                      |
| GRB 110730A <sup>d</sup> |                         | $4.28^\circ$   | $5.6^\circ$   | $2.15^b$ | 907.885                                    | 288.2                                                  | 350.2                                      |
| GRB 110731A              |                         | $0.0001^\circ$ | $13.14^\circ$ | 2.83     | 782.096                                    | 204.2                                                  | 366.9                                      |
| GRB 110808B              |                         | $0.0693^\circ$ | $9.8^\circ$   | $0.5^b$  | 74.303                                     | 49.5                                                   | 172.8                                      |
| GRB 110905A              |                         | $0.0314^\circ$ | $14.9^\circ$  | $2.15^b$ | -2309.121                                  | -733.1                                                 | 350.2                                      |
| event #20                | $1.14^{+0.14}_{-0.138}$ | $10.7^\circ$   |               |          |                                            |                                                        |                                            |
| GRB 111229A <sup>d</sup> |                         | $0.0003^\circ$ | $18.9^\circ$  | 1.3805   | 384.970                                    | 161.7                                                  | 355.4                                      |
| GRB 120119C <sup>c</sup> |                         | $4.42^\circ$   | $36.9^\circ$  | $2.15^b$ | -1940.176                                  | -615.9                                                 | 383.9                                      |
| GRB 120210A              |                         | $5.51^\circ$   | $11.4^\circ$  | $0.5^b$  | -3304.901                                  | -2203.3                                                | 189.4                                      |
| event #35                | $2.00^{+0.24}_{-0.26}$  | $15.9^\circ$   |               |          |                                            |                                                        |                                            |
| GRB 120919A              |                         | $0.0863^\circ$ | $11.0^\circ$  | $2.15^b$ | 6539.722                                   | 2076.1                                                 | 674.3                                      |
| GRB 121229A <sup>d</sup> |                         | $0.0003^\circ$ | $12.1^\circ$  | 2.707    | -2091.621                                  | -564.2                                                 | 702.5                                      |
| GRB 130121A <sup>c</sup> |                         | $1.14^\circ$   | $6.55^\circ$  | $2.15^b$ | -4046.519                                  | -1284.6                                                | 674.3                                      |
| ATel #7856               | $2.6^{+0.3}_{-0.3}$     | $1^\circ$      |               |          |                                            |                                                        |                                            |
| GRB 140427A <sup>c</sup> |                         | $23.26^\circ$  | $25.8^\circ$  | $2.15^b$ | 3827.439                                   | 1215.1                                                 | 874.9                                      |
| GRB 140516B <sup>d</sup> |                         | $7.77^\circ$   | $8.63^\circ$  | $2.15^b$ | 2185.942                                   | 693.9                                                  | 874.9                                      |

The energy errors here are measurement uncertainties provided by the IceCube database. The column  $\sigma$  shows angular uncertainties of neutrino events and GRB candidates respectively. The angular separation  $\Delta\Psi$  is calculated from the differences between RA and Dec angles. For every one of the four events, there exists a candidate marked by <sup>c</sup> that satisfies the strict time criterion and is consistent with the regularity of the TeV neutrino. The mark <sup>d</sup> represents another option with a strong correlation

# CPT Violation from Cosmic Neutrinos:

Difference properties between neutrinos and antineutrinos.



Y. Huang, B.-Q. Ma, Comms.Phys.1 (2018) 62

<https://astronomycommunity.nature.com/users/179714-bo-qiang-ma/posts/39327-cpt-violation-from-cosmic-neutrinos>

## Testing Lorentz invariance and *CPT* symmetry using gamma-ray burst neutrinos

Xinyi Zhang<sup>1</sup> and Bo-Qiang Ma<sup>1,2,3,\*</sup>

<sup>1</sup>*School of Physics and State Key Laboratory of Nuclear Physics and Technology,  
Peking University, Beijing 100871, China*

<sup>2</sup>*Collaborative Innovation Center of Quantum Matter, Beijing, China*

<sup>3</sup>*Center for High Energy Physics, Peking University, Beijing 100871, China*



(Received 16 October 2018; published 25 February 2019)

- **We find that different neutrino/antineutrino propagation properties can be described with both Lorentz invariance and CPT symmetry violation.**
- **A viable way on testing the CPT symmetry violation between neutrinos and antineutrinos is suggested.**

Y. Huang, H.Li, B.-Q. Ma, PRD 99 (2019) 123018

**Consistent Lorentz violation features from near-TeV IceCube neutrinos**

Yanqi Huang,<sup>1</sup> Hao Li,<sup>1</sup> and Bo-Qiang Ma<sup>1,2,3,\*</sup>

<sup>1</sup>*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University,  
Beijing 100871, China*

<sup>2</sup>*Collaborative Innovation Center of Quantum Matter, Beijing, China*

<sup>3</sup>*Center for High Energy Physics, Peking University, Beijing 100871, China*

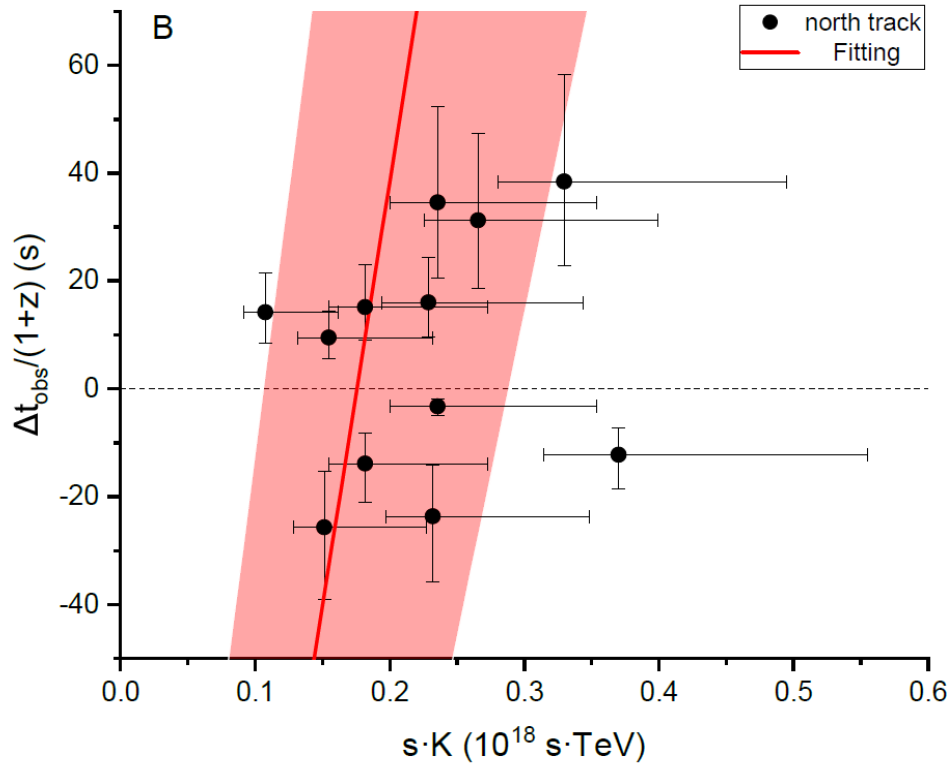


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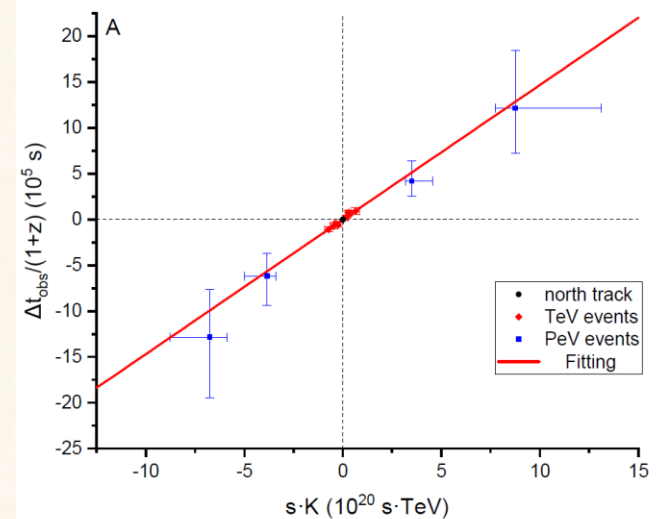
- **Previous association of 60 TeV to 2 PeV IceCube neutrinos with GRBs indicates Lorentz invariance and CPT symmetry violation.**
- **We find that another 12 northern hemisphere track events satisfy the same regularity at a lower energy scale around 1 TeV.**
- **Such a consistency over four orders of magnitude in energy provides a strong support of the revealed regularity.**

# 12 IceCube neutrinos near 1 TeV as new support to the TeV+PeV regularity

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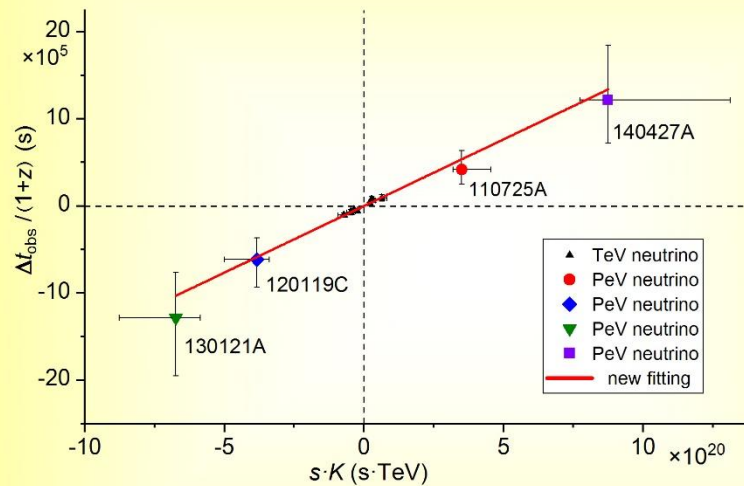


TeV + PeV + near-TeV neutrinos ( $r=0.99$ )



# CPT Violation from Cosmic Neutrinos:

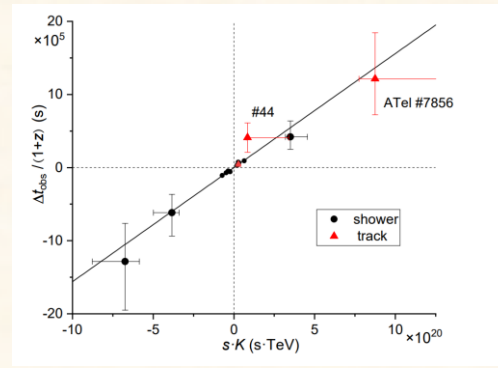
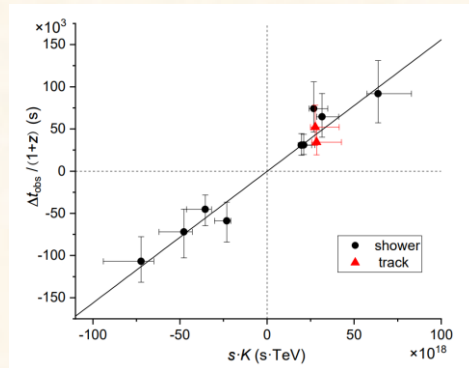
Difference properties between neutrinos and antineutrinos.



Y. Huang, B.-Q. Ma, Comms.Phys.1 (2018) 62

<https://communities.springernature.com/posts/cpt-violation-from-cosmic-neutrinos>

# Lorentz Violation of Cosmic Neutrinos: Association of IceCube Neutrino Events with GRBs



- We associate IceCube TeV and PeV neutrino events with gamma-ray bursts (GRBs).
- Among these 24 neutrino "shower" events above 60 TeV, 12 events are associated with GRBs.
- Track events are also associated with GRBs under the same Lorentz violation of neutrinos.
- The results support the Lorentz violation of neutrinos, indicating new physics beyond relativity.

## ABSTRACT

Based on the recent association of IceCube TeV and PeV neutrino events with gamma-ray bursts (GRBs) by considering the Lorentz violation of neutrinos, we provide a new estimate on the GRB neutrino flux with a more significant result compared to the previous constraint by the IceCube Collaboration. Among these 24 neutrino "shower" events above 60 TeV, 12 events are associated with GRBs. Such a result is compatible with the prediction from GRB fireball models. Analysis of track events provides a consistent result with the shower events to associate high energy cosmic neutrinos with GRBs under the same Lorentz violation features of neutrinos. We also make a background estimation and reveal GRBs as a significant source for the ultra-high energy IceCube neutrino events. Our work supports the Lorentz violation and  $CPT$ -violation of neutrinos, indicating new physics beyond relativity.



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Article

Ultra-high energy cosmic neutrinos from gamma-ray bursts

Yanqi Huang, Ph.D.<sup>a</sup>, Bo-Qiang Ma, Ph.D.<sup>a,b,c,\*</sup>

<sup>a</sup> School of Physics, Peking University, Beijing 100871, China

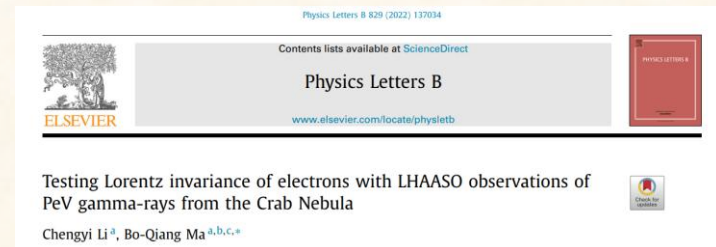
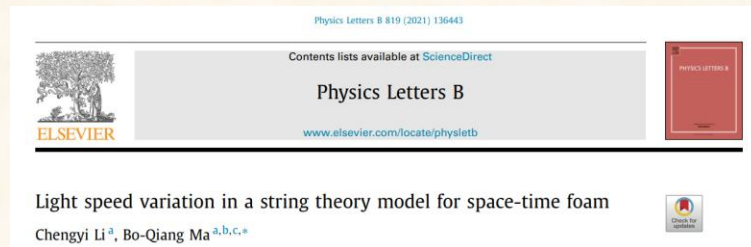
<sup>b</sup> Center for High Energy Physics, Peking University, Beijing 100871, China

<sup>c</sup> Collaborative Innovation Center of Quantum Matter, Beijing, China

C.Li and B.-Q.Ma, PLB 835 (2022) 137543, JHEP 03 (2023) 230

# The string theory model of space-time foam: Lorentz- and CPT-violating neutrinos from string/D-brane model

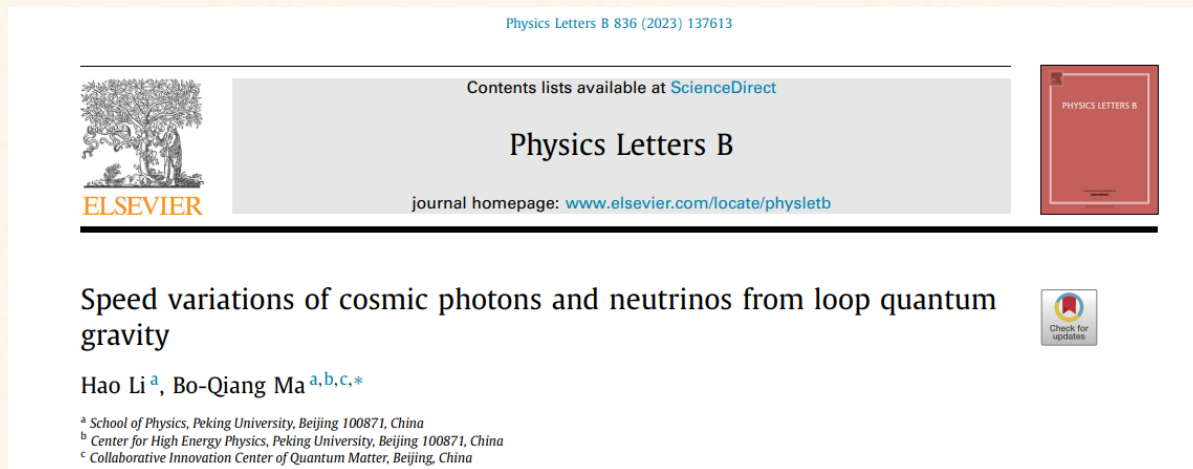
We show that the space-time foam model from string/D-brane theory predicts a scenario in which neutrinos can possess linearly energy dependent speed variation, together with an asymmetry between neutrinos and antineutrinos, indicating the possibility of Lorentz and CPT symmetry violation for neutrinos.



C.Li, B.-Q.Ma, PLB 819 (2021) 136443, PLB 829 (2022) 137034,  
PLB 835 (2022) 137543, JHEP 03 (2023) 230

H.Li, B.-Q.Ma, PLB 836 (2023) 137613

# Speed variations of cosmic photons and neutrinos from loop quantum gravity



A consistent understanding of Lorentz violation features of cosmic photons and neutrinos from loop quantum gravity

# Theoretical Studies on Lorentz Violation of Photons and Neutrinos

## 探索洛伦兹破缺与时空的新理论

### [弦理论]

C. Li, B.-Q. Ma, JHEP 03 (2023) 230  
C. Li, B.-Q. Ma, PLB 835 (2022) 137543  
C. Li, B.-Q. Ma, PLB 819 (2021) 136443

### [圈量子引力]

H. Li, B.-Q. Ma, PLB 836 (2023) 137613

### [Finsler几何]

J. Zhu, B.-Q. Ma, EPJC 83 (2023) 349  
J. Zhu, B.-Q. Ma, PRD 105 (2022) 12

### [标准模型拓展]

X. Zhang, B.-Q. Ma, PRD 99 (2019) 043013  
Z. Xiao, B.-Q. Ma, PRD 80 (2009) 116005  
L. Zhou, B.-Q. Ma, CPC 35 (2011) 987 .....



### - 基于弦理论的时空泡沫模型

对弦/D膜理论的时空泡沫 (D泡沫) 图景下  
粒子传播与反应行为的理论和唯象研究



### - 圈量子引力的半经典近似

对圈引力半经典 (WBSC) 近似下光子/中微  
子速度色散特征的研究, 及其唯象学应用



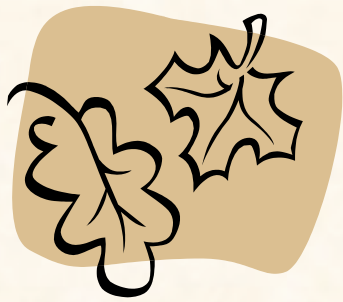
### - Finsler几何与宇宙学

考虑量子引力的有效描述, 在Finsler背景下对粒子  
测地轨迹及其传播时间差的理论计算



### - 类标准模型拓展的有效描述 (洛伦兹破缺矩阵)

标准模型拓展 (SME) 的理论和唯象讨论; 对标准模型  
补充 (SMS) 框架的原创性理论研究



## **Summary 1: cosmic photons**

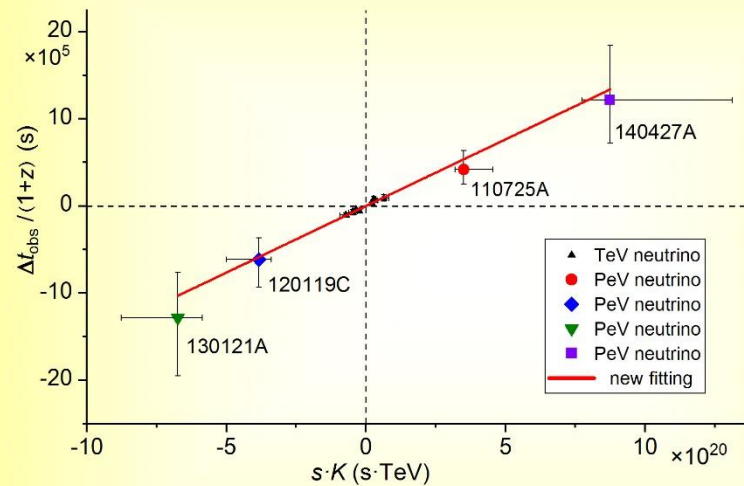
- **We analyse the data of energetic photons from gamma-ray bursts (GRBs).**
- **We unveil a surprising regularity behind the data of these energetic photons.**
- **We find events to support the energy-dependence of light speed, i.e., the Lorentz violation.**
- **The scenario is supported by new GRB 160509A, AGNs, and more recent data of GRB 221009A .....**

## Summary 2: ultrahigh energy cosmic neutrinos

- We associate IceCube TeV and PeV neutrino events with gamma-ray bursts (GRBs).
- We unveil a regularity of these energetic neutrinos indicting Lorentz violation, i.e., **new physics beyond relativity**.
- We suggest different propagation properties between neutrinos and antineutrinos, indicating **the CPT violation between neutrinos and antineutrinos**.
- The scenario of Lorentz- and CPT-violating neutrinos is consistent with the string theory model of space-time foam and loop quantum gravity.

# CPT Violation from Cosmic Neutrinos:

Difference properties between neutrinos and antineutrinos.



Y. Huang, B.-Q. Ma, Comms.Phys.1 (2018) 62

<https://communities.springernature.com/posts/cpt-violation-from-cosmic-neutrinos>

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# Association of 220 PeV Neutrino KM3-230213A with Gamma-Ray Bursts

Ruiqi Wang, Jie Zhu, Hao Li, and Bo-Qiang Ma

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[Research Notes of the AAS](#), [Volume 9](#), [Number 3](#)

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**DOI** 10.3847/2515-5172/adc452

*Thanks* 谢谢!