极高能宇宙粒子与新物理探索

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2026年1月20日

海峡两岸粒子物理和宇宙学研讨会，广州

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, ……

Prof.W-Y. Pauchy Hwang

as a pioneer and guider to AstroParticle Physics

The highest energy particles

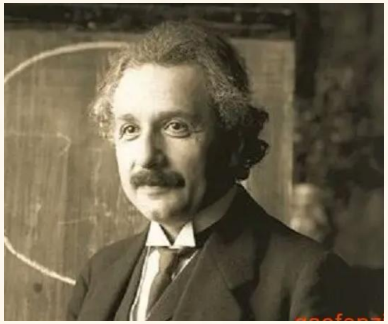
can be observed by human being are from SKY

- **Frontiers of human knowledge:**
  Cosmology, Astronomy, and Physics
  ⇨ **AstroParticle Physics**

- **Particles from the Sky:**
  Ultra-high energy comic 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

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

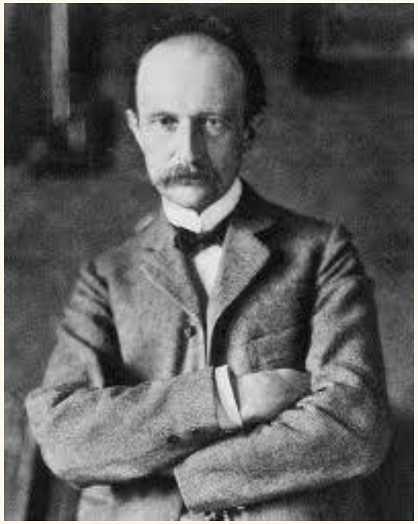
the equations describing the laws of physics have the same form in all admissible reference frames.

So is there any reason that we seek for

Lorentz Violation ?

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)

Basic units of the universe: Planck Units

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

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

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

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

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

A physical argument of discrete space-time

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

- From two known entropy constraints:

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

- 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

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

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

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

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

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

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 quantum gravity [Alfaro et al.'00, PRL]
- backgrounds in general gravity [Ni'75, PRL; Yan'83, TP, X.Xue]
- vacuum condensate of antisymmetric tensor fields in string theory [Kostelecky & Samuel'89 & '91, PRL]
- Doubly special relativity [Amelino-Camelia'02, Nature & '02 IJMPD]
- Finsler Geometry (Zhe Chang)

… …

For a recent review, see, P. He, B.-Q. Ma, Universe 8 (2022) 323.

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

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

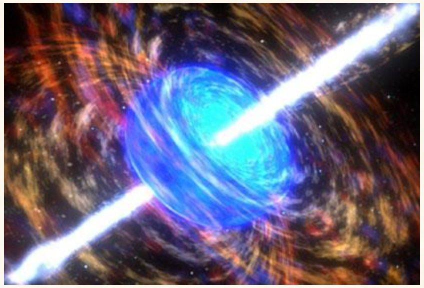
$$\sqrt{\hbar c/G} \simeq 1.22 \times 10^{19}\ \mathrm{GeV/c^2}$$

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)

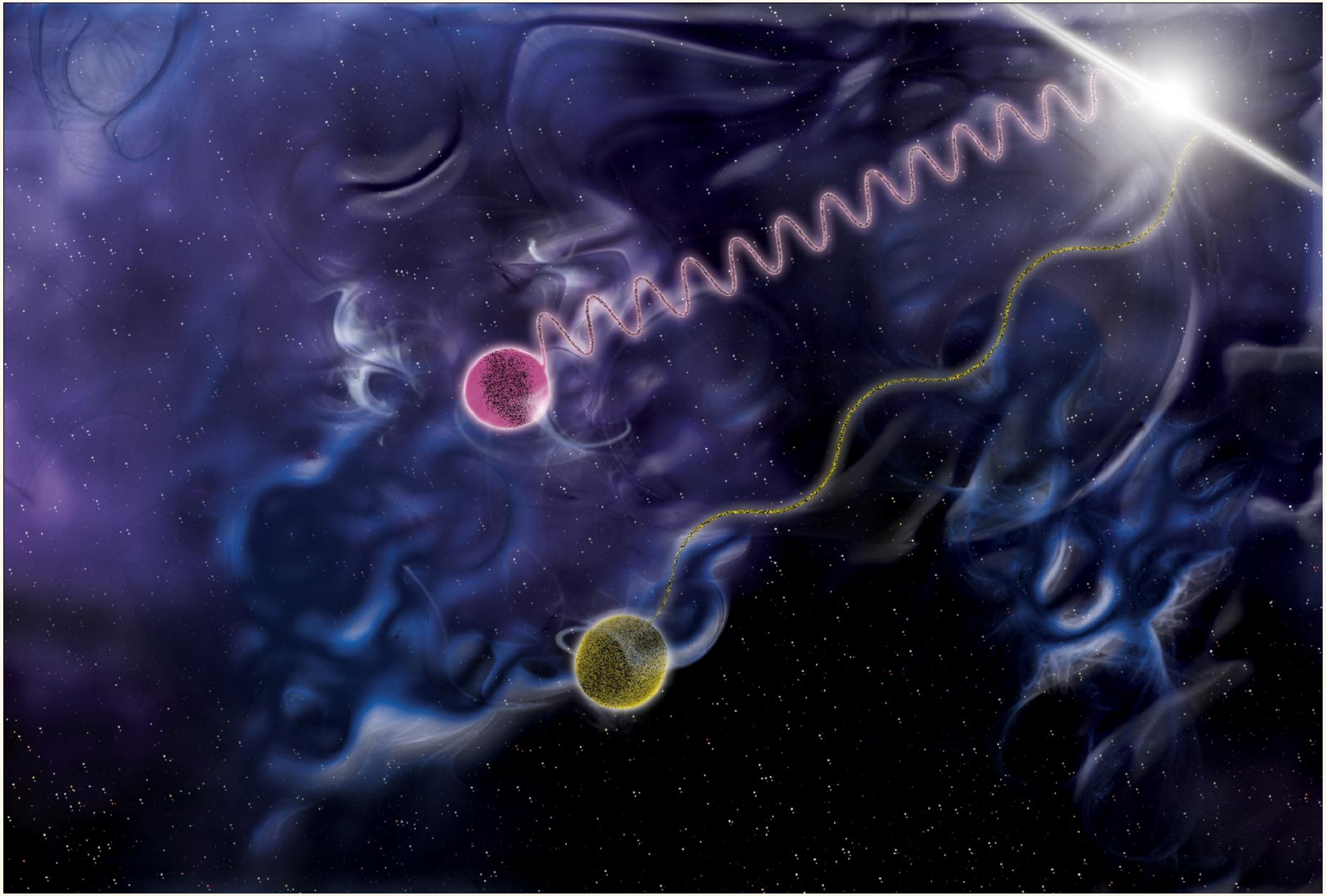


- The most energetic astrophysical process except the Big Bang
- 2 types
  - long GRBs: duration > 2 s; collapses of massive rapidly rotating stars
  - short GRBs: duration < 2 s; coalescence of two neutron stars or a neutron star and a black hole
- Long distance from detector:

  $z \approx 2.15$ for long GRBs, several billion light-years

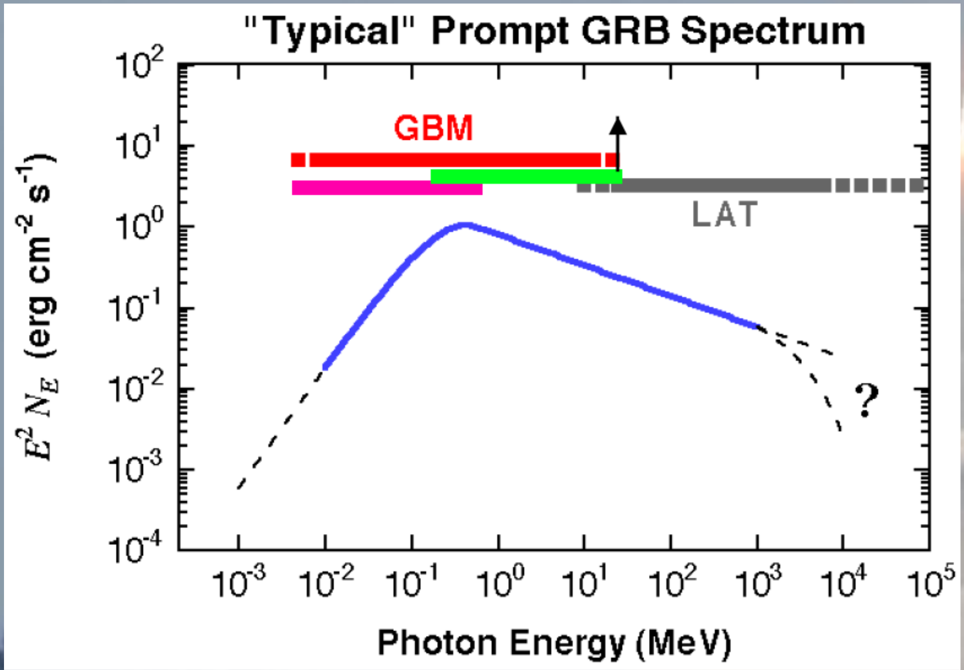
  $z \approx 0.5$ for short GRBs
- Use GRBs to test LV [Amelino-Camelia et al.'98, Nature]

Time-lag by GRB

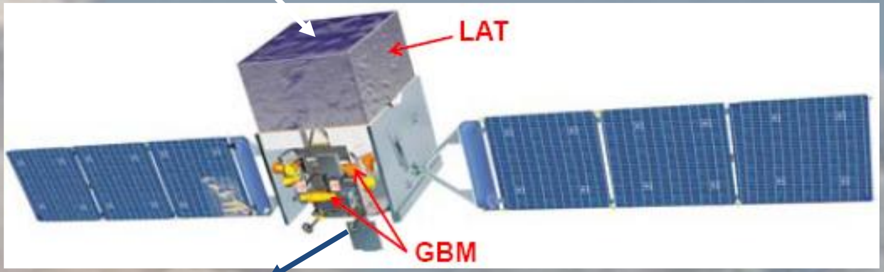


June 11, 2008

Fermi instruments



~ 300 GeV



trigger photons ~ 0.1 MeV

Model independent LV photon dispersion relation

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

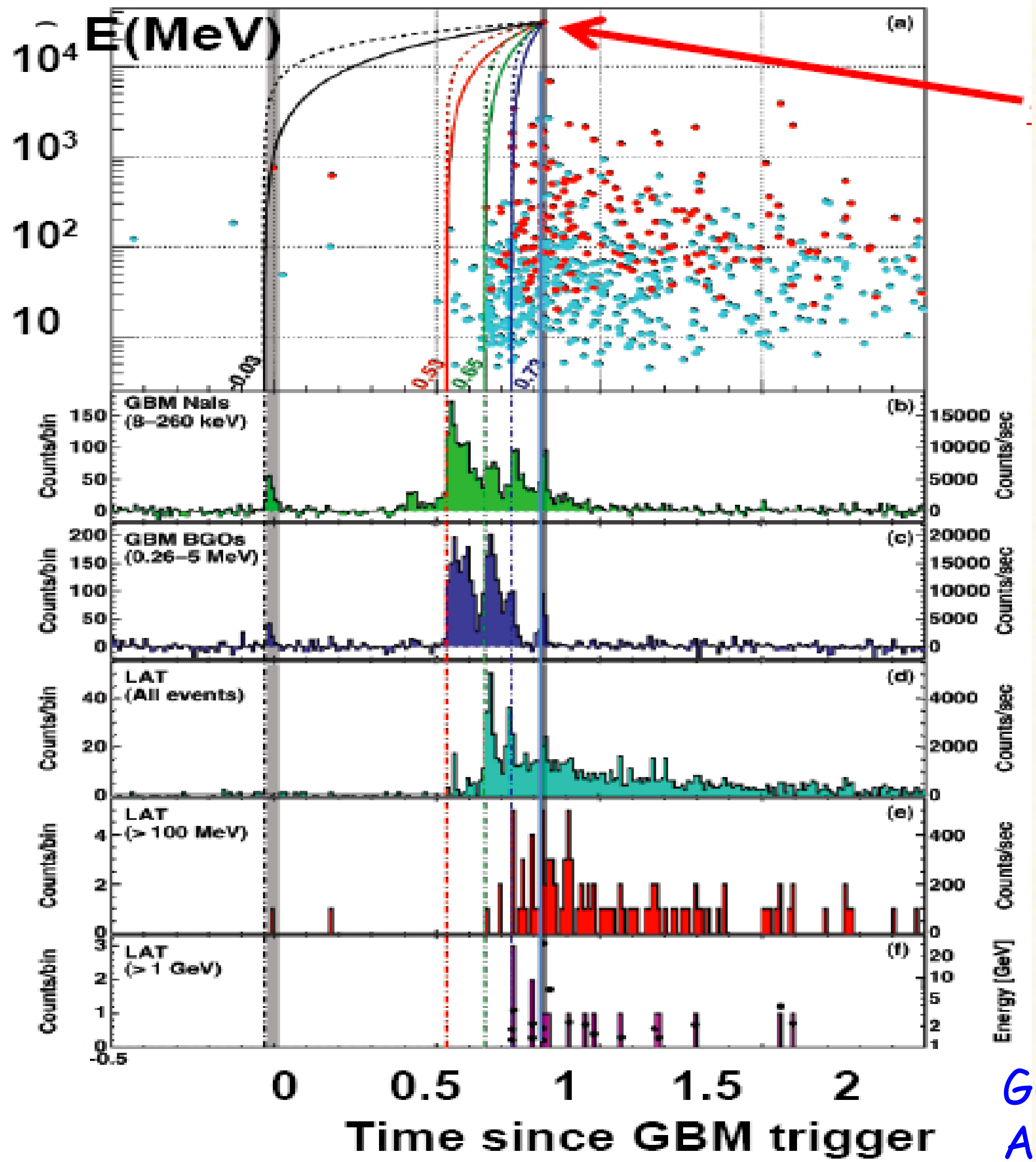
$$v = 1 - s_n \frac{n+1}{2} \left(\frac{\mathcal{E}}{E_{\mathrm{LV},n}} \right)^n$$

$n = 1$ 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



Time lags are affected both artificially and instrumentally

GRB090510
Abdo et al.'09, Nature

Early constraints from GRB090510 & Fermi-LAT data

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

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

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

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

Vasileiou et al., PRD 87 (2013) 122001

$E_{\mathrm{QG},1} > 7.6$ times the Planck energy (E_{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

H.Song, B.-Q. Ma, PLB (2025) 139959

……

Time lag by LV effect

- Expansion universe [Jacob & Piran'08, JCAP]

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

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

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

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

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

New derivation from Finsler geometry:

J. Zhu, B.-Q. Ma, PRD 12 (2022) 124069.

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

An intuitive way to perform analysis

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

$$\frac{\Delta t_{\rm obs}}{1+z} = s_n \frac{K_n}{E^n_{{\rm LV},n}} + \Delta t_{\rm in}$$

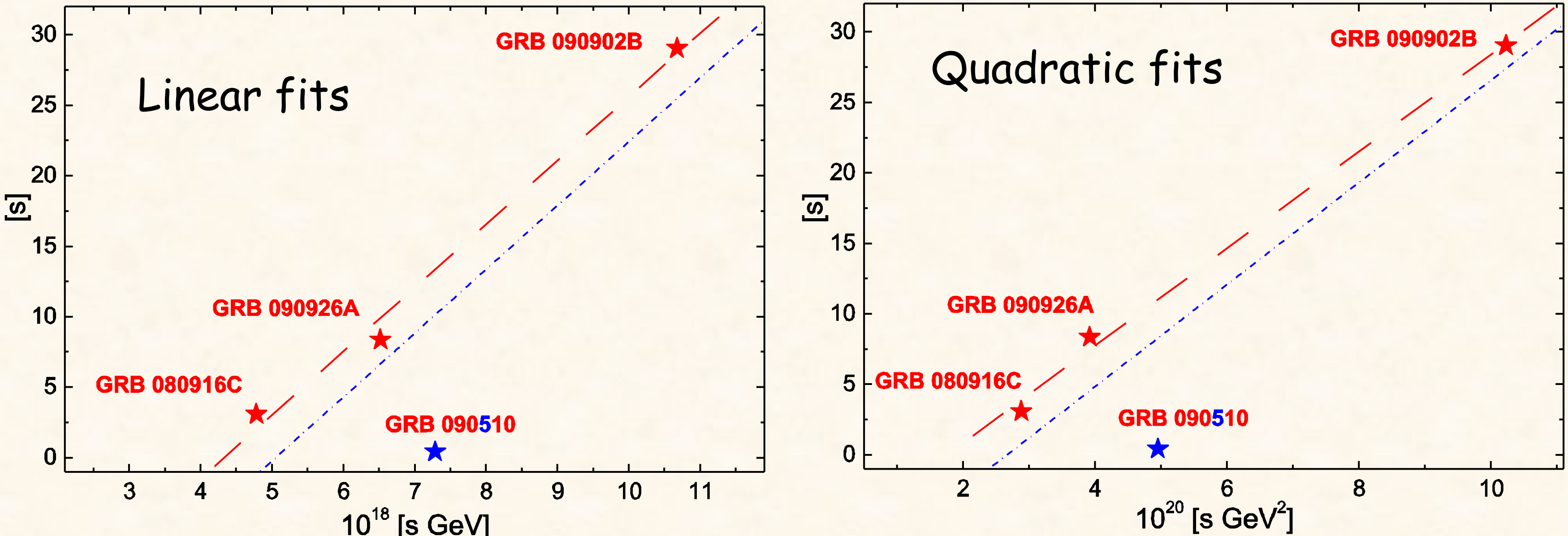
$$K_n = \frac{1+n}{2H_0} \frac{E^n_{\rm high} - E^n_{\rm low}}{1+z} \int_0^z \frac{(1+z')^n {\rm d}z'}{\sqrt{\Omega_{\rm m}(1+z')^3 + \Omega_\Lambda}}$$

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

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

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

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



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

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

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

further development around 2015

Astroparticle Physics 61 (2015) 108–112

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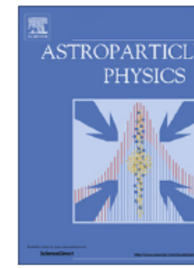
Astroparticle Physics

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



Lorentz violation from gamma-ray bursts

Shu Zhang [a], Bo-Qiang Ma [a,b,c,d,*]

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[b] Collaborative Innovation Center of Quantum Matter, Beijing, China
[c] Center for High Energy Physics, Peking University, Beijing 100871, China
[d] Center for History and Philosophy of Science, Peking University, Beijing 100871, China

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

Added data

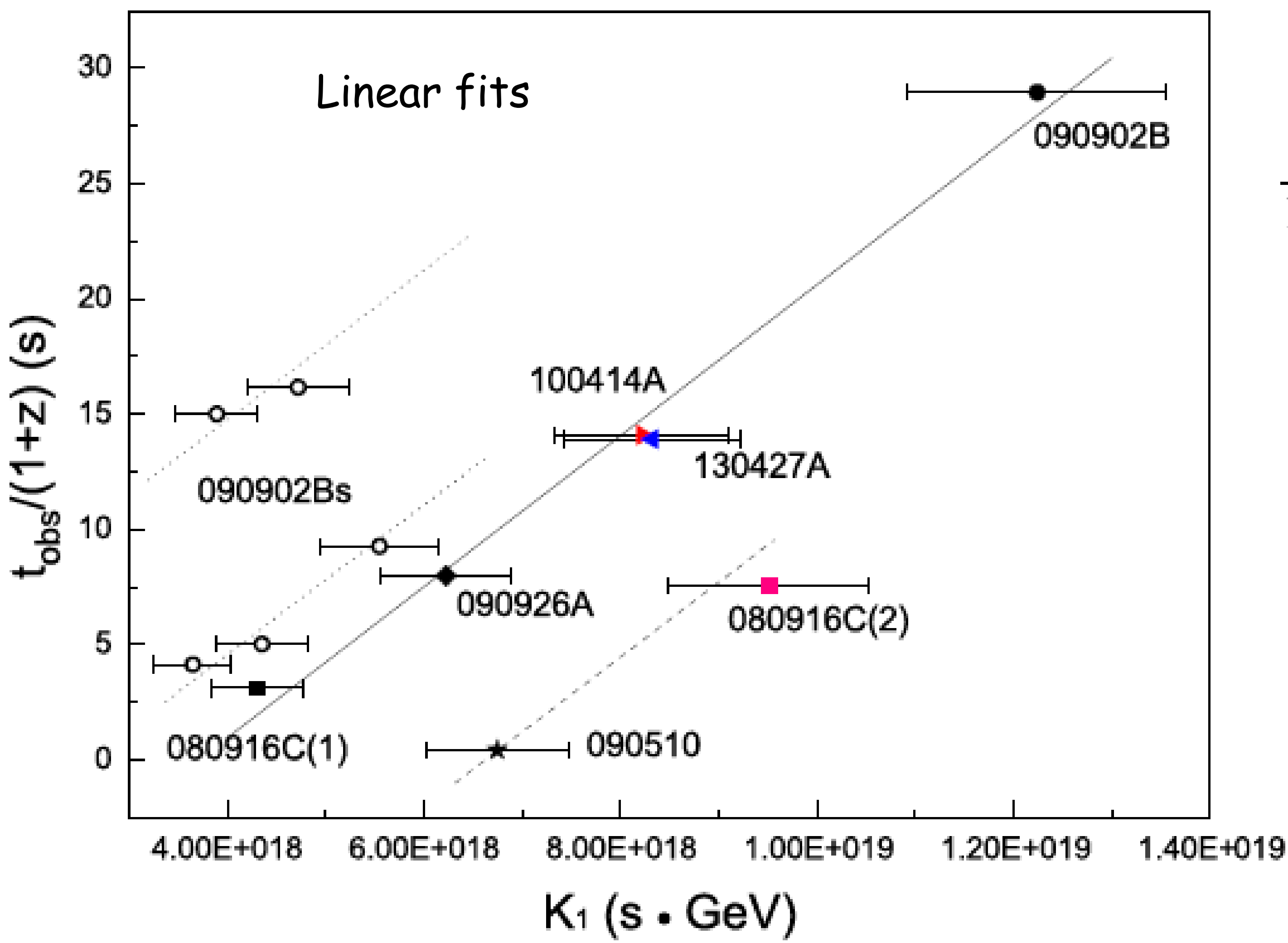
Table 1: The data of the GRBs with high energy photons and known redshifts.

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

[a]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_{obs} is the arrival time after the onset of the GRBs, E_{obs} is the measured energy of the photon, E_{in} is the intrinsic energy at the source of the GRBs, and $E_{LV,1}$ is the Lorentz violation parameter of the linear LV model without considering the intrinsic time lag. The standard errors of $E_{LV,1}$'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)

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

further development



$$\frac{t_{\rm obs}}{1+z} = \frac{K_{\rm n}}{E^{n}_{\rm LV,n}} + t_{\rm in}$$

n=1

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

Benchmark of low energy photons: trigger or peak?

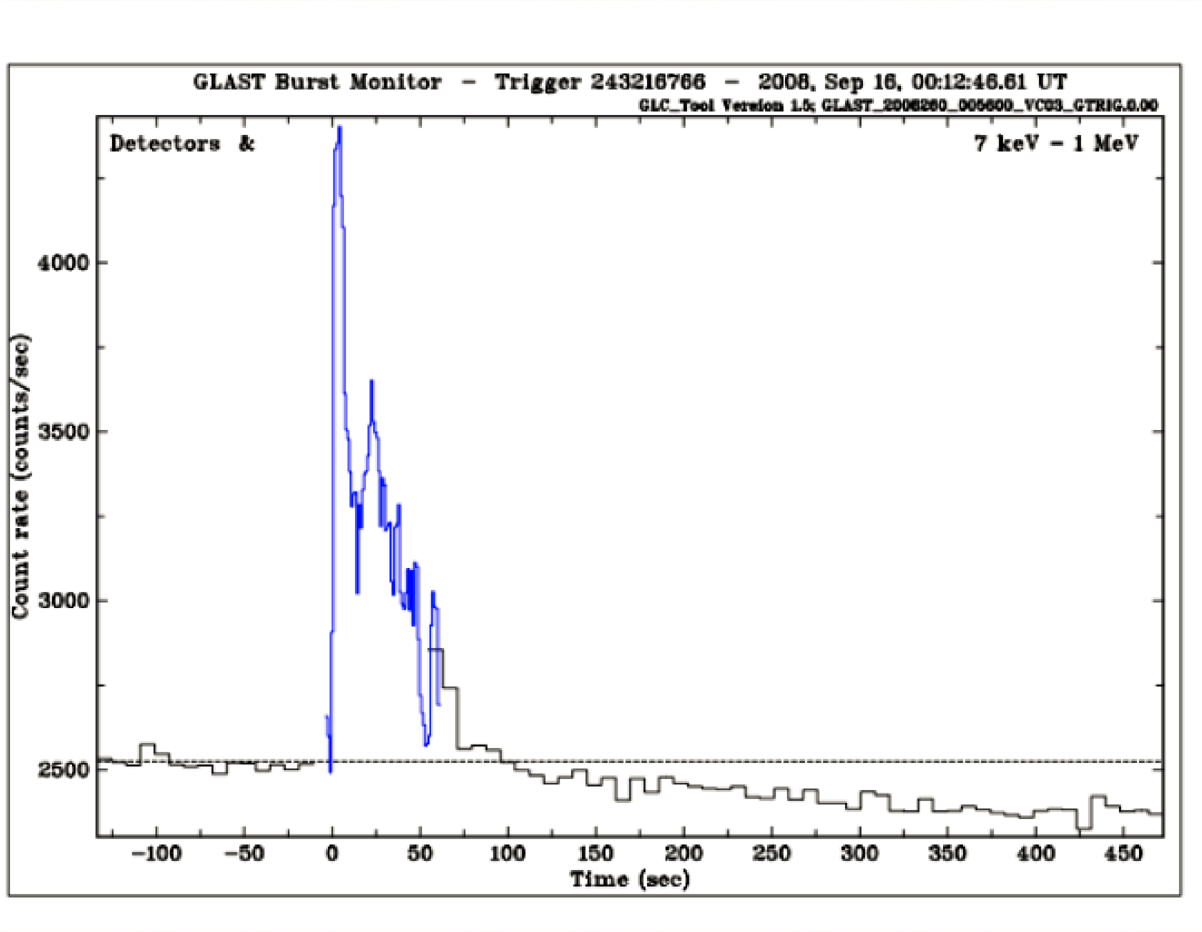
Trigger:

- 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

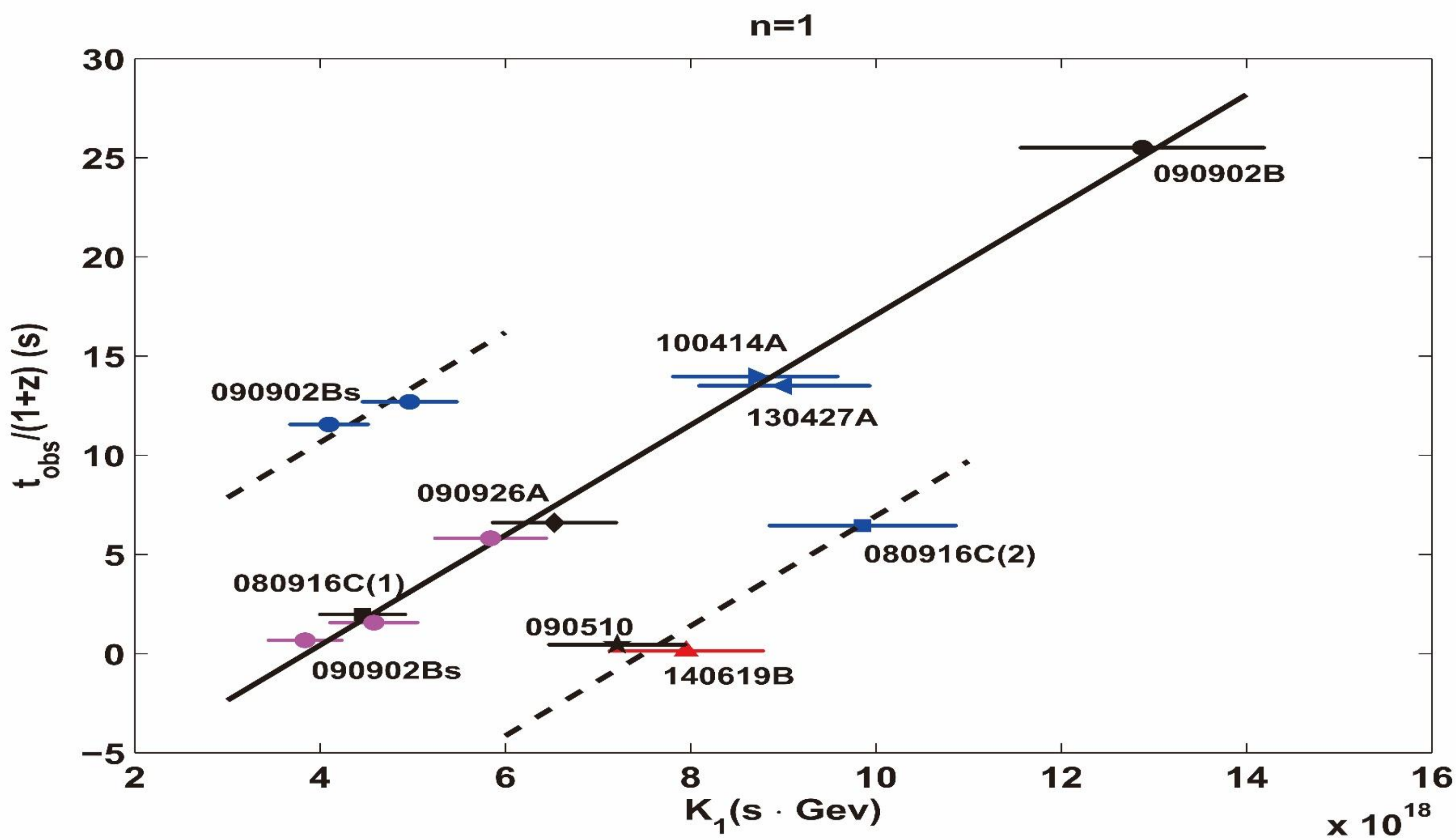
New Analysis of Data

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

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

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

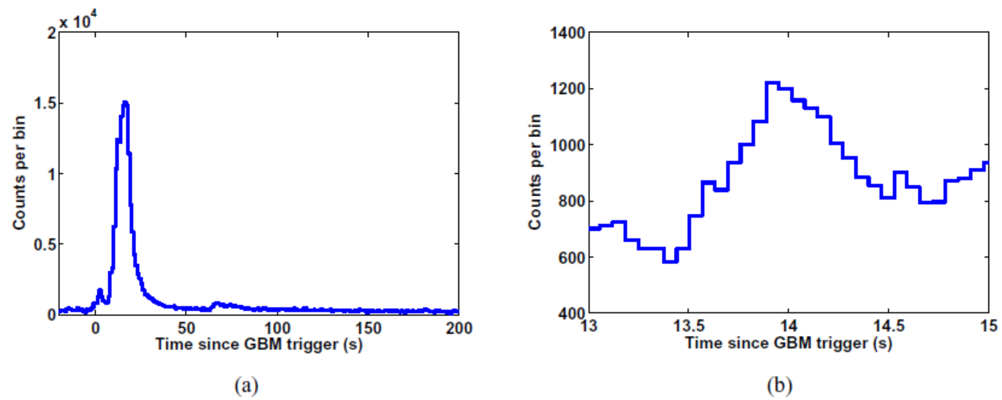


Figure 1: Light curves of the two brightest trigger detectors combined (GBM NaI-n0 and NaI-n3, 8 ~ 260 keV) for GRB 160509A. In the left panel (a), photon events are binned in 1 second intervals. In the right panel (b), photon events are binned in 0.064 seconds intervals to determine the peak of the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

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

$E_{\rm obs}$ / GeV	$t_{\rm arri}$ / 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

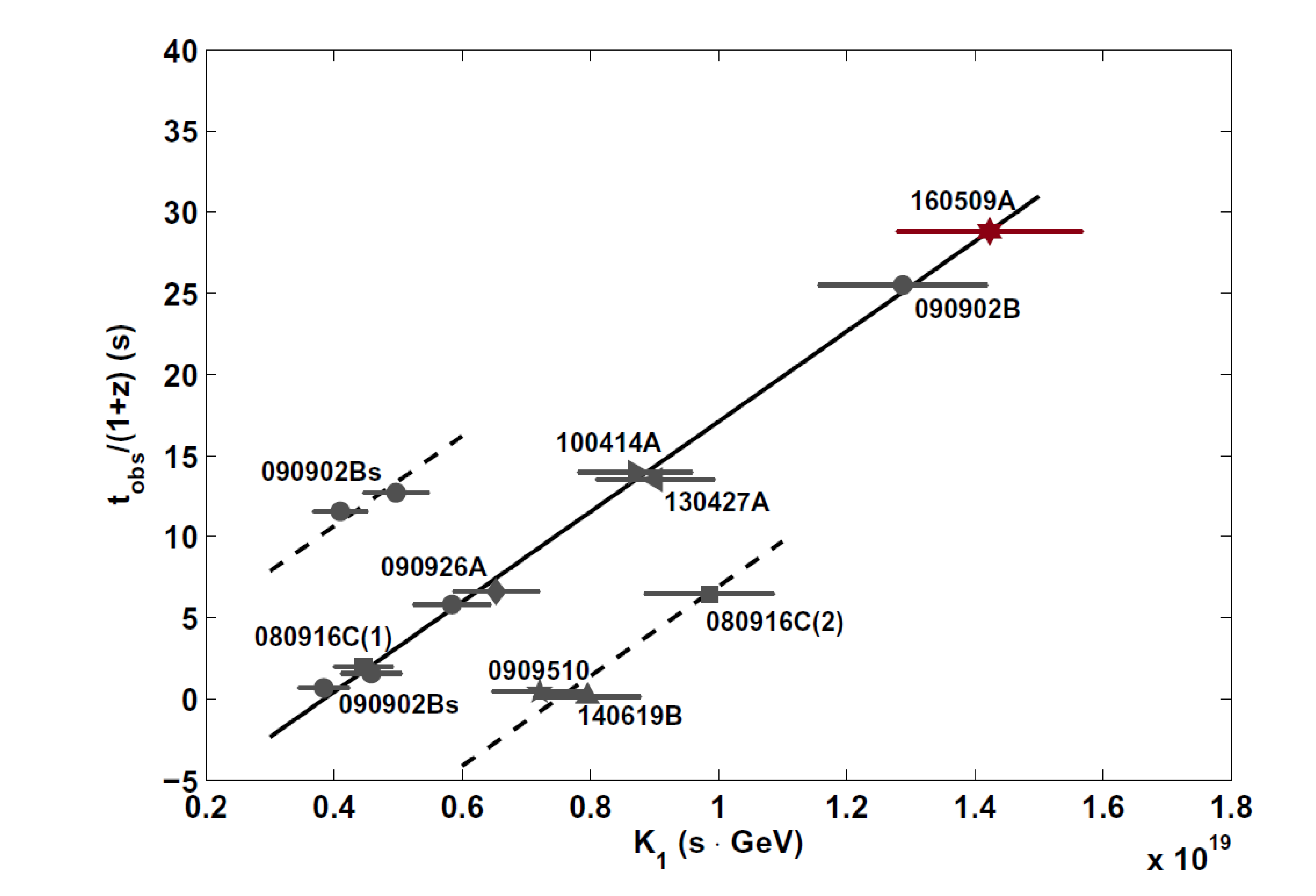
Table 2: Data of high energy photon event from GRB 160509A

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

Data of GRB 160509A. t_{high} and t_{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_{obs} and E_{source} are the energy measured by Fermi LAT and the intrinsic energy at the source of GRBs, with $E_{source} = (1 + z)E_{obs}$. K_1 is the Lorentz violation factor with a unit of (s · 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

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

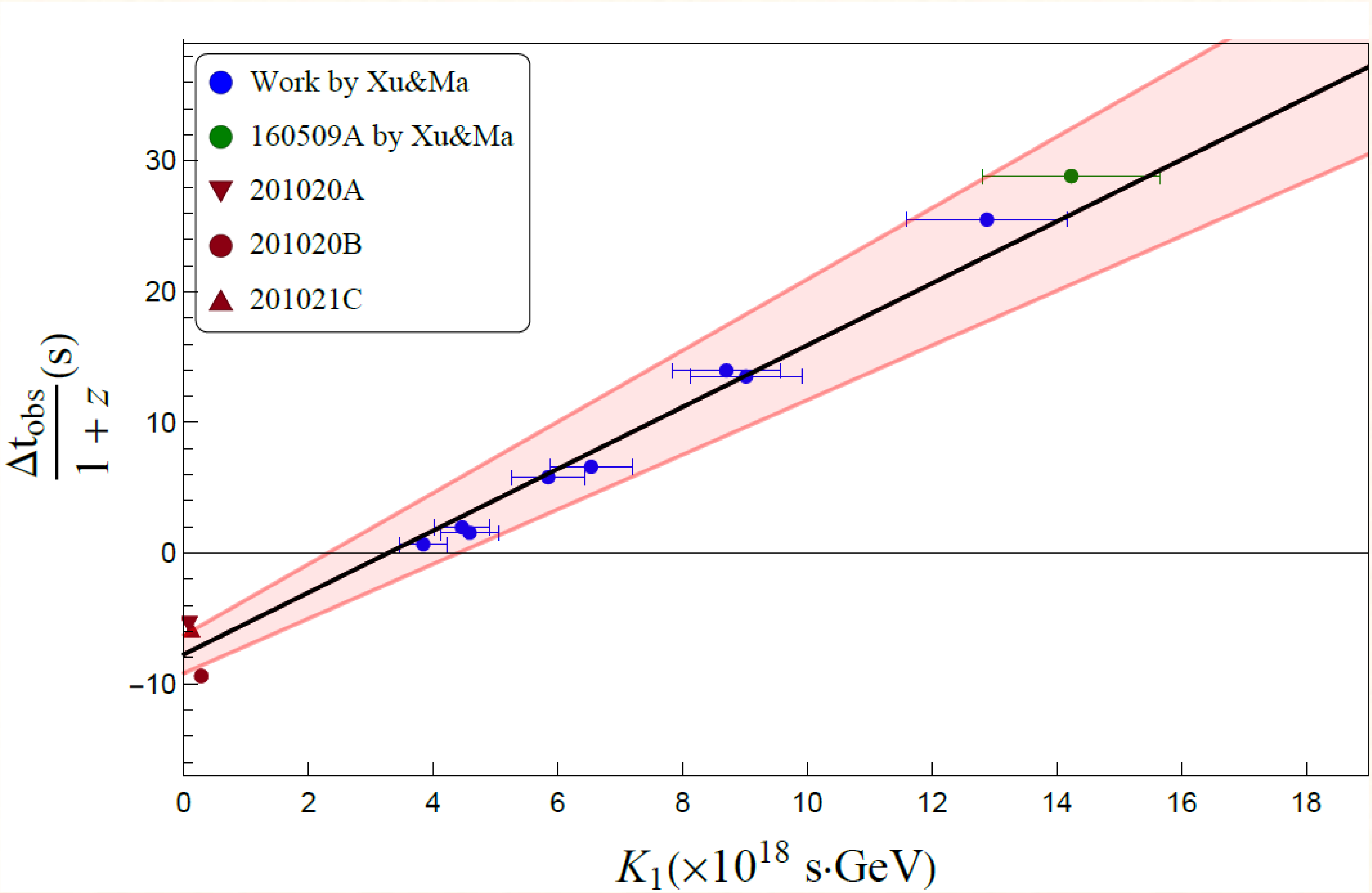
$$E_{\mathrm{LV}} = 3.60 \times 10^{17}\ \mathrm{GeV}$$

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.

- 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

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

Check for updates

Jie Zhu[a], Bo-Qiang Ma[a,b,c,*]

- **Direct evidence for pre-burst stage of GRBs**
- **Support of light speed variation at** $E_{LV} = 3.60 \times 10^{17}$ 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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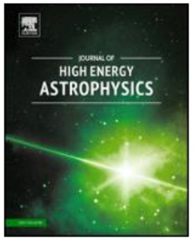
Journal of High Energy Astrophysics

www.elsevier.com/locate/jheap



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

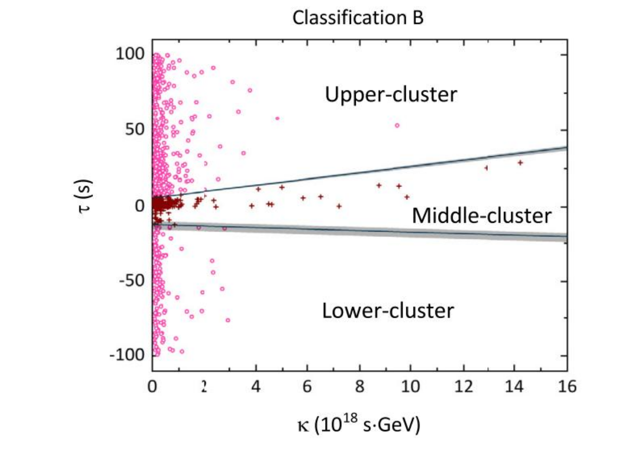
Check for updates

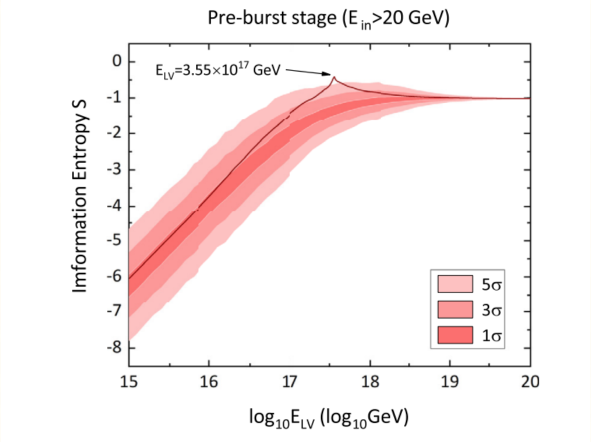
Yingtian Chen [a,b], Bo-Qiang Ma [a,c,d,e,*]

- **Strong support for pre-burst stage of GRBs**
- **Support of light speed variation at** $E_{\rm LV} = 3.60 \times 10^{17}$ 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** $E_{\rm LV} = 3.60 \times 10^{17}$ 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 [a], Bo-Qiang Ma [a,b,*]

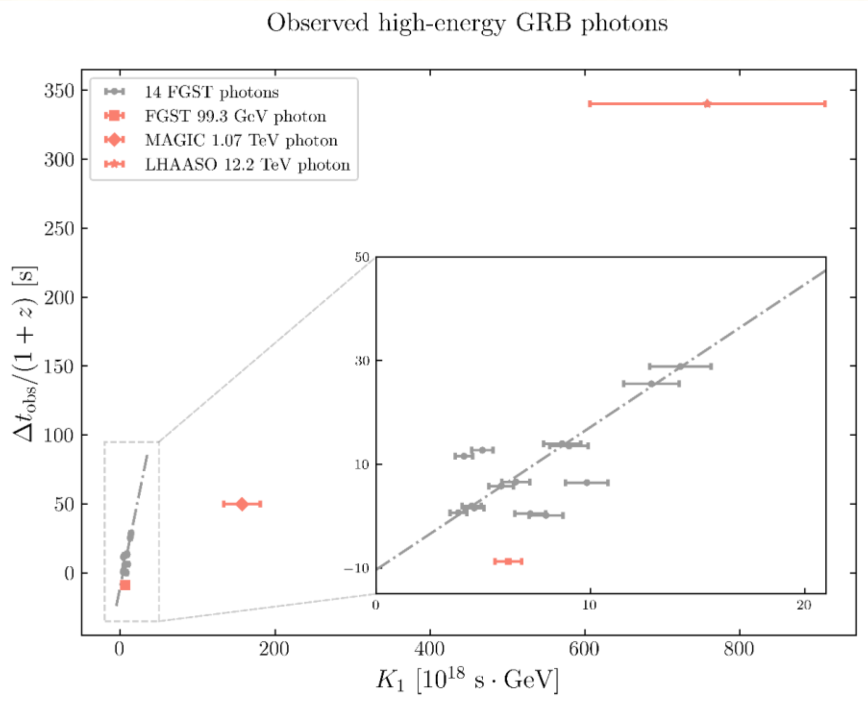
[a] School of Physics, Peking University, Beijing 100871, China
[b] Center for High Energy Physics, Peking University, Beijing 100871, China

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

- **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

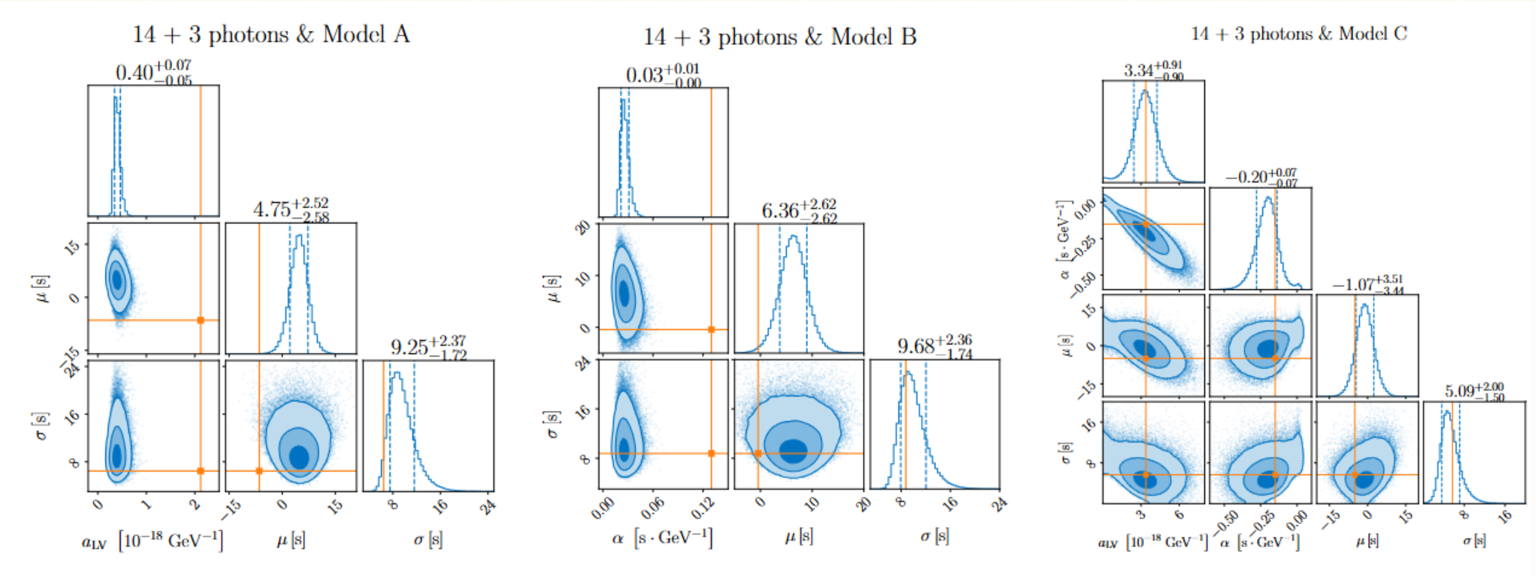
Refined model analysis including TeV & multi-TeV data



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

A brief summary of new results

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

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

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

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

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

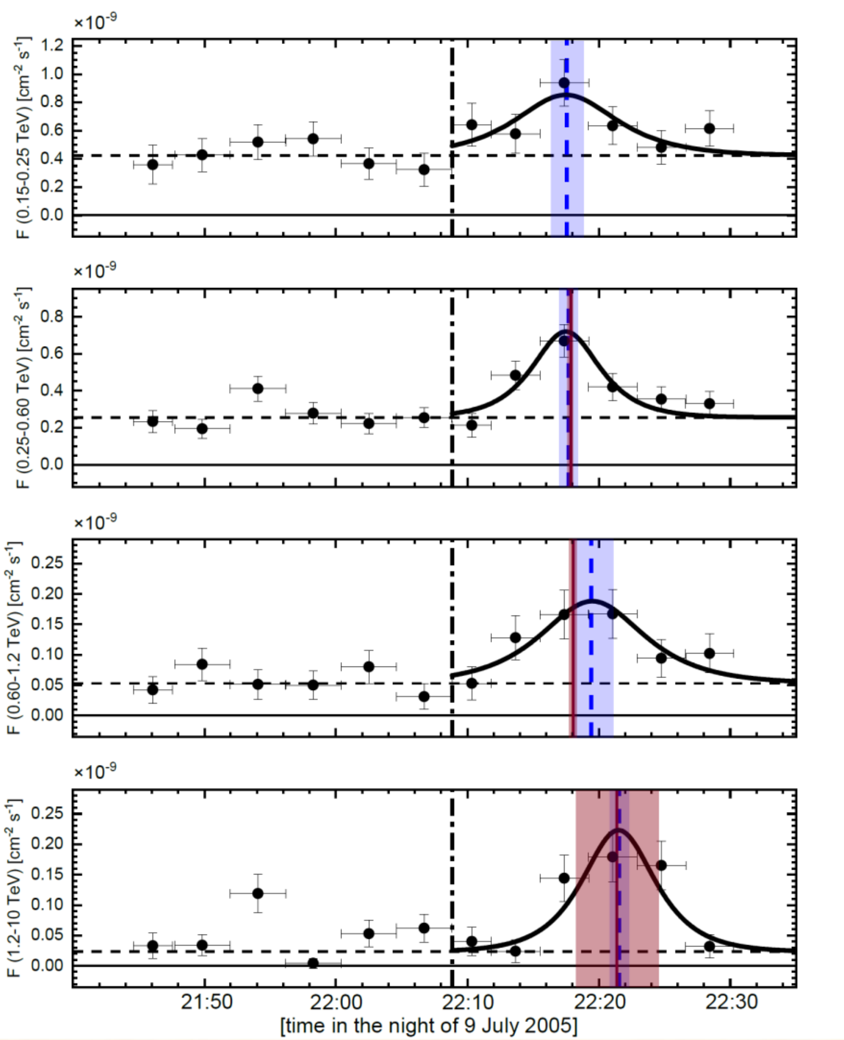
- Testing Lorentz invariance violation with Gamma-ray burst
- Energy-dependent intrinsic time delay model
- **Consistent** results with **previous studies** on **GeV** photons
- **Consistent** results in explaining **TeV** photons
- **Hints for new physics at $E_{LV} \sim 3 \times 10^{17}$ GeV**

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, PLB (2025) 139959, arXiv: 2508.08984

H. Li and B.-Q. Ma, Science Bulletin 65 (2020) 262

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±1 minutes between bands 0.15-0.25 TeV and 1.2-10 TeV

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

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

A support for the subluminal light speed variation from GRBs

C.Li, B.-Q.Ma, PLB 819 (2021) 136443, arXiv:2105.06515

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[a], Bo-Qiang Ma[a,b,c,*]

C.Li and B.-Q.Ma, PRD 104 (2021) 063012 & Science Bulletin 66 (2021) 2254

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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www.elsevier.com/locate/physletb
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Light speed variation in a string theory model for space-time foam

Chengyi Li[a], Bo-Qiang Ma[a,b,c,*]

C.Li, B.-Q.Ma, PLB (2021) 136443, arXiv:2105.06151

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

Speed variations of cosmic photons and neutrinos from loop quantum gravity

Physics Letters B 836 (2023) 137613

Contents lists available at ScienceDirect

Physics Letters B

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

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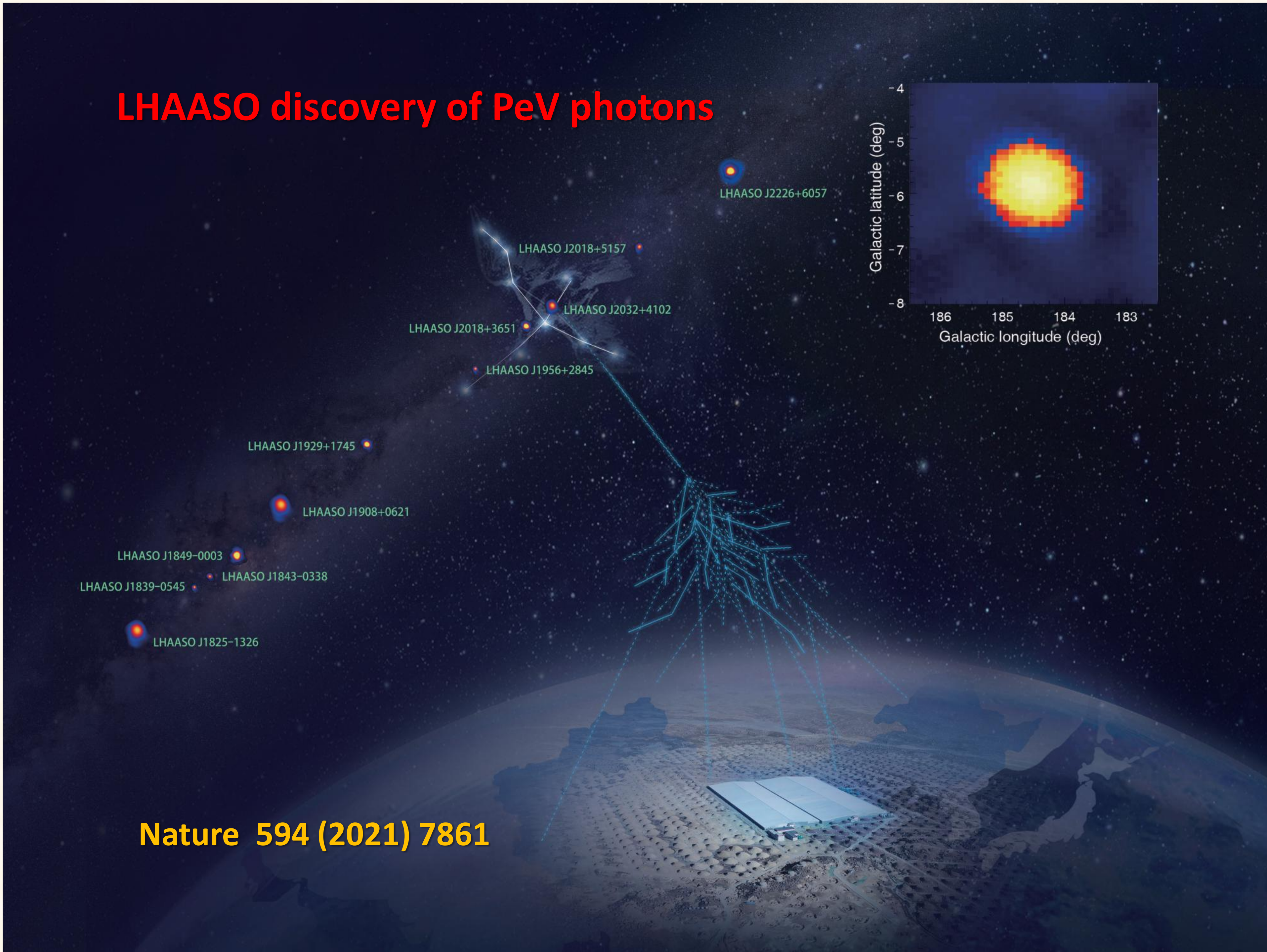
Speed variations of cosmic photons and neutrinos from loop quantum gravity

Hao Li [a], Bo-Qiang Ma [a,b,c,*]

[a] School of Physics, Peking University, Beijing 100871, China
[b] Center for High Energy Physics, Peking University, Beijing 100871, China
[c] Collaborative Innovation Center of Quantum Matter, Beijing, China

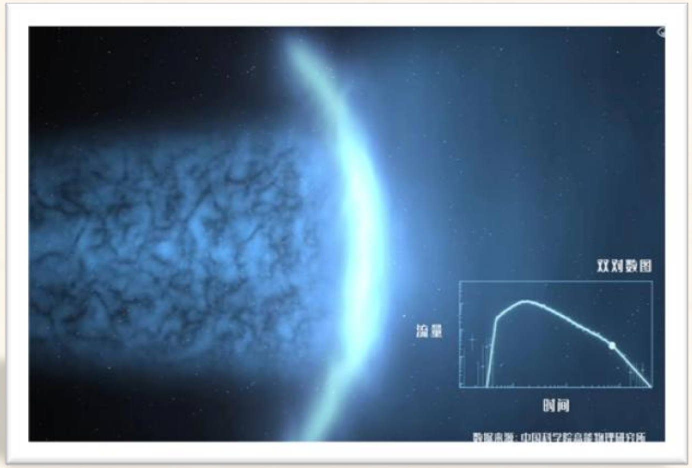
A consistent understanding of Lorentz violation features of cosmic photons and neutrinos from loop quantum gravity

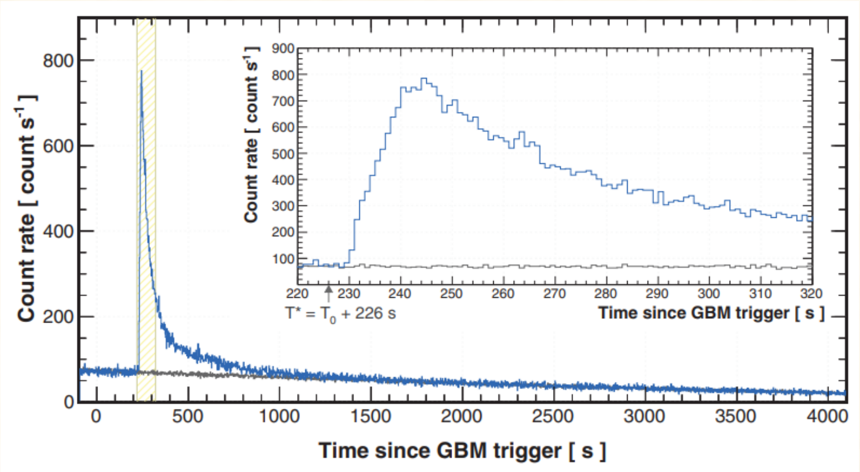
LHAASO discovery of PeV photons



Nature 594 (2021) 7861

Newly observed GRB221009A





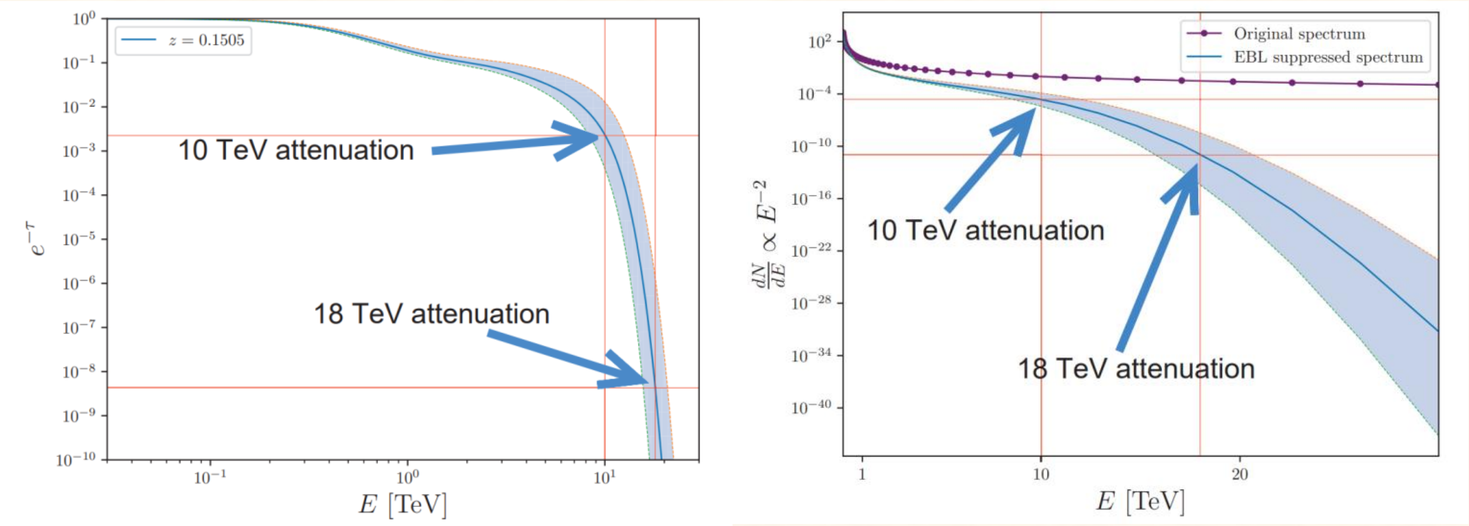
- Triggered by Fermi and Swift
- Very bright GRB with very short distance
  z=0.1505 (2.4 billion light years)
- LHAASO observation: 64000 high energy events with energies larger than 200 GeV including photons with energy larger than 10 TeV.

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 $\gamma\gamma \to e^- e^+$ 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

Chinese Physics Letters 40, 011401 (2023)

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

Guangshuai Zhang(张光帅)[1] and Bo-Qiang Ma(马伯强)[1,2,3*]

- 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.

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

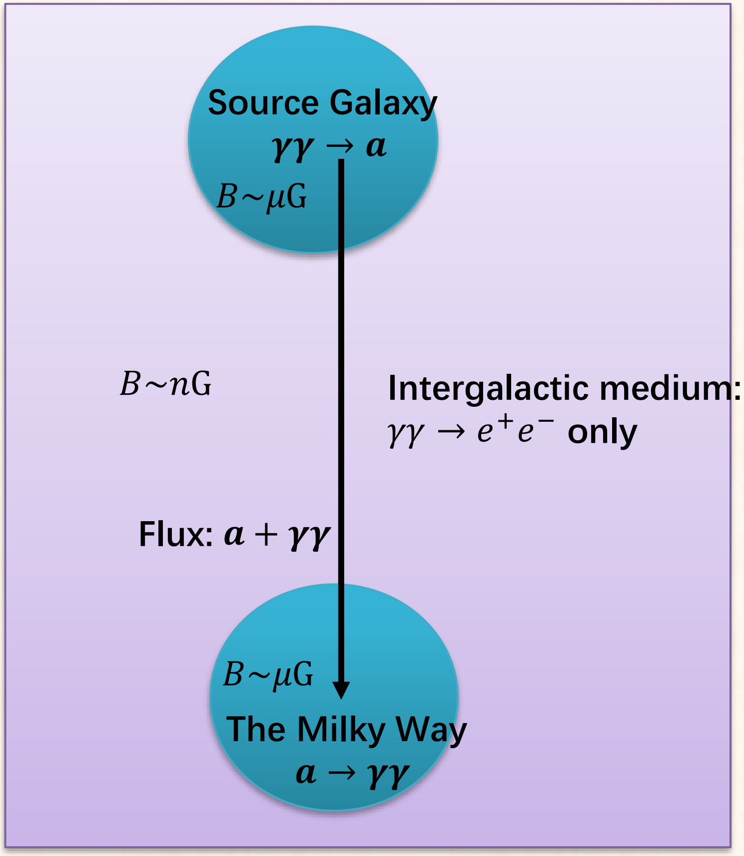
The picture of photon-axion conversion

The axion-photon convention 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 $\gamma\gamma a$ convention for the ALPs-photon mixed beams but only $\gamma\gamma \to e^+e^-$, putting constraints on m_a and $g_{a\gamma}$.

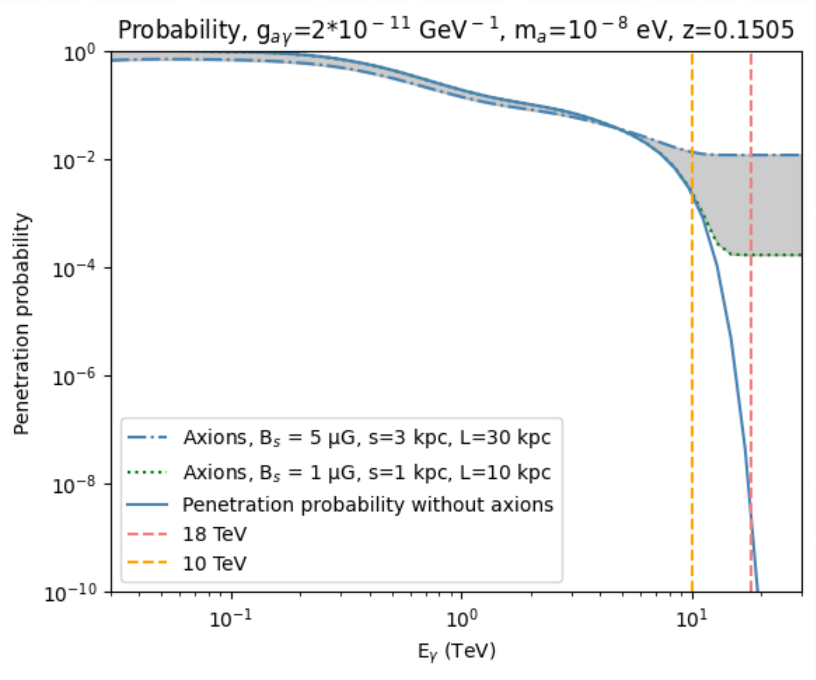
3. **Back conversion**: ALPs-photon conversion transforms some ALPs into photons in the magnetic field of Milky Way, making photons to be re-observable.



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

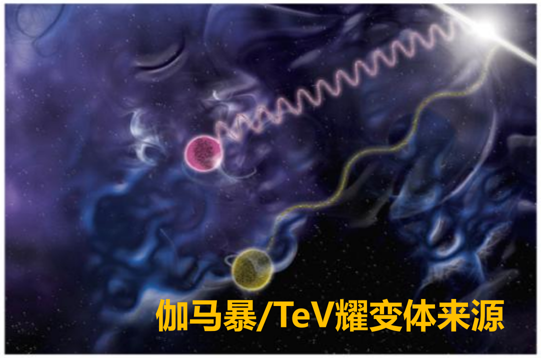
The high energy features of GRB221009A need to be carefully examined to constrain possible new physics such as:

- 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

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

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

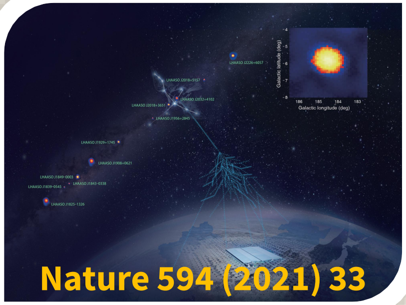
对中微子也可以开展类似研究

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

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

C. Li, B.-Q. Ma, PRD 104 (2021) 063012
C. Li, B.-Q. Ma, Sci. Bull. 66 (2021) 2254

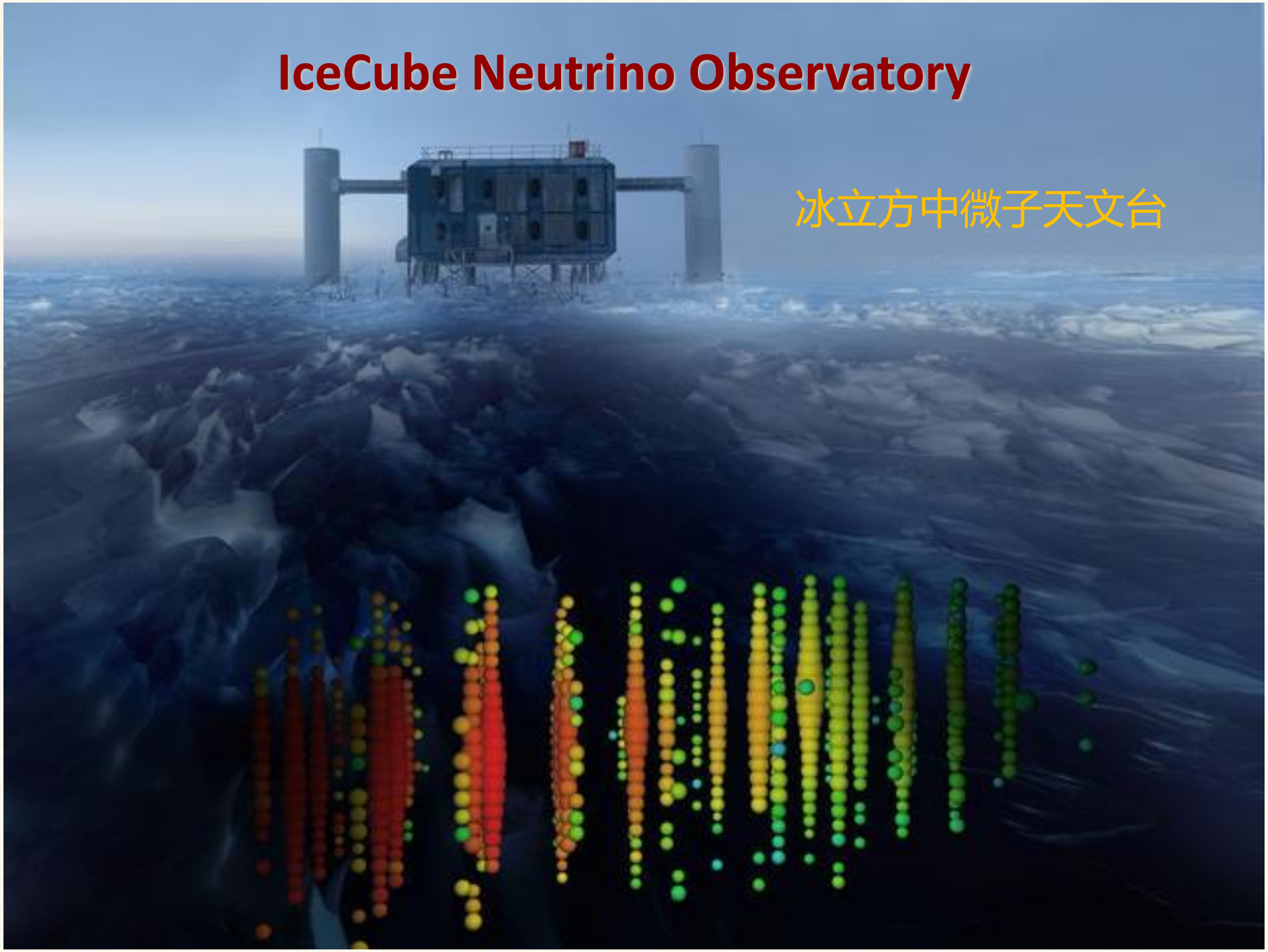
光子/电子洛伦兹破缺参数的联合限制

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

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

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->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

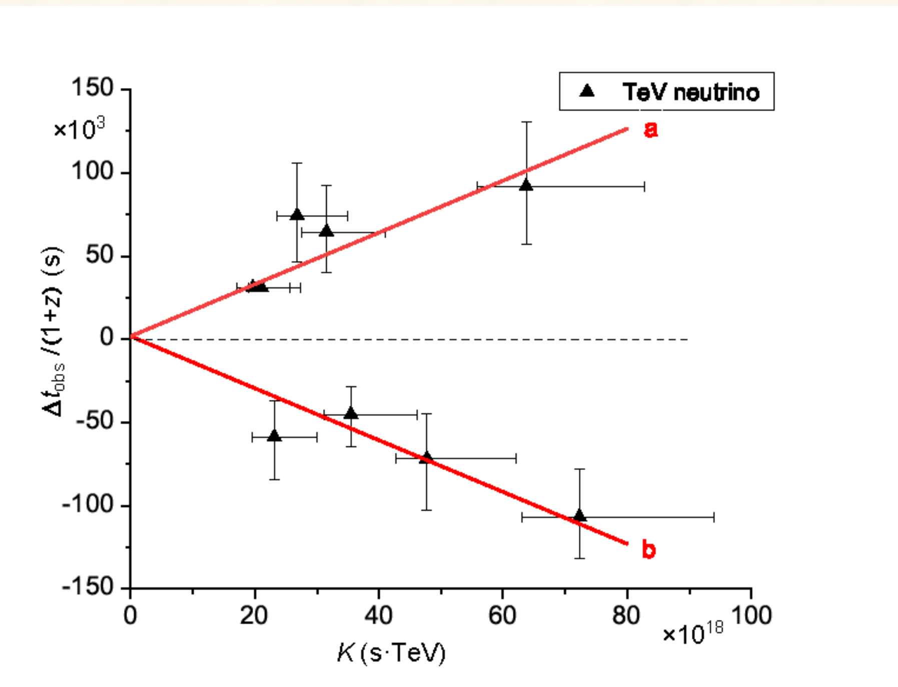
COMMUNICATIONS PHYSICS

ARTICLE

DOI: 10.1038/s42005-018-0061-0 OPEN

Lorentz violation from gamma-ray burst neutrinos

Yanqi Huang[1] & Bo-Qiang Ma[1,2,3]



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

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

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

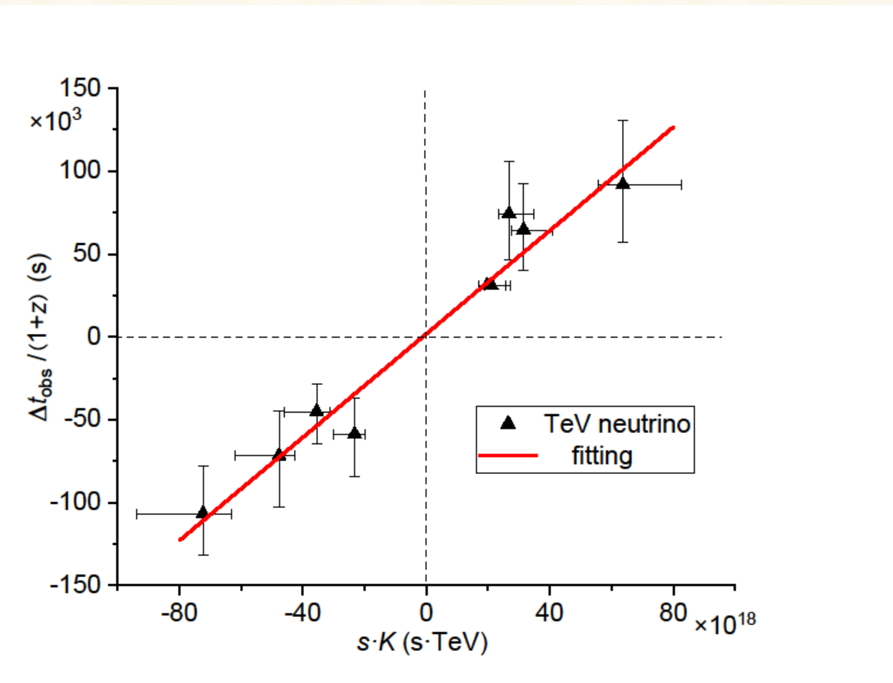
Reanalysis of TeV Events

COMMUNICATIONS
PHYSICS

ARTICLE
DOI: 10.1038/s42005-018-0061-0 OPEN

Lorentz violation from gamma-ray burst neutrinos

Yanqi Huang [1] & Bo-Qiang Ma [1,2,3]



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

$$s = \pm 1$$

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

First Analysis of PeV Events

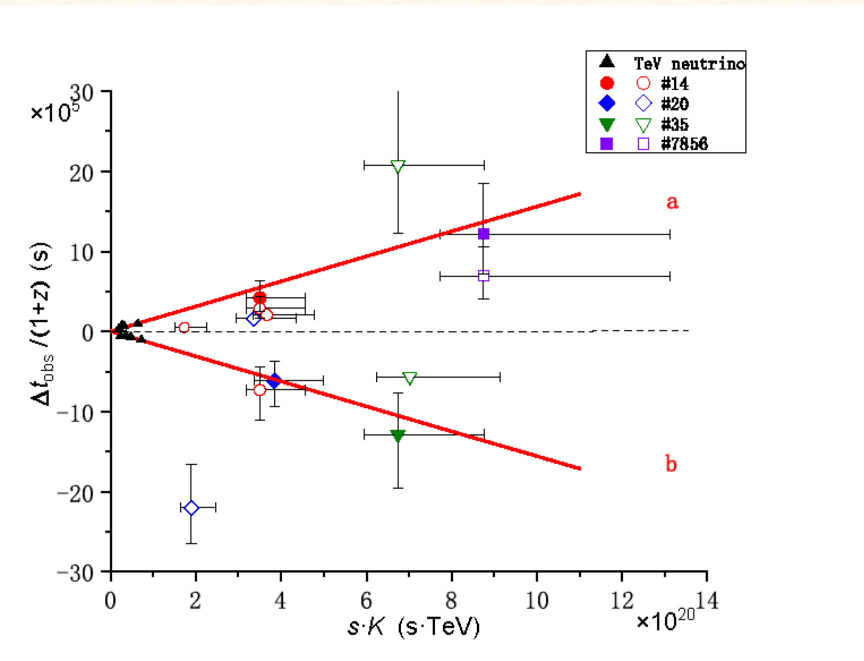
Y. Huang, B.-Q. Ma, Comms.Phys.1 (2018) 62

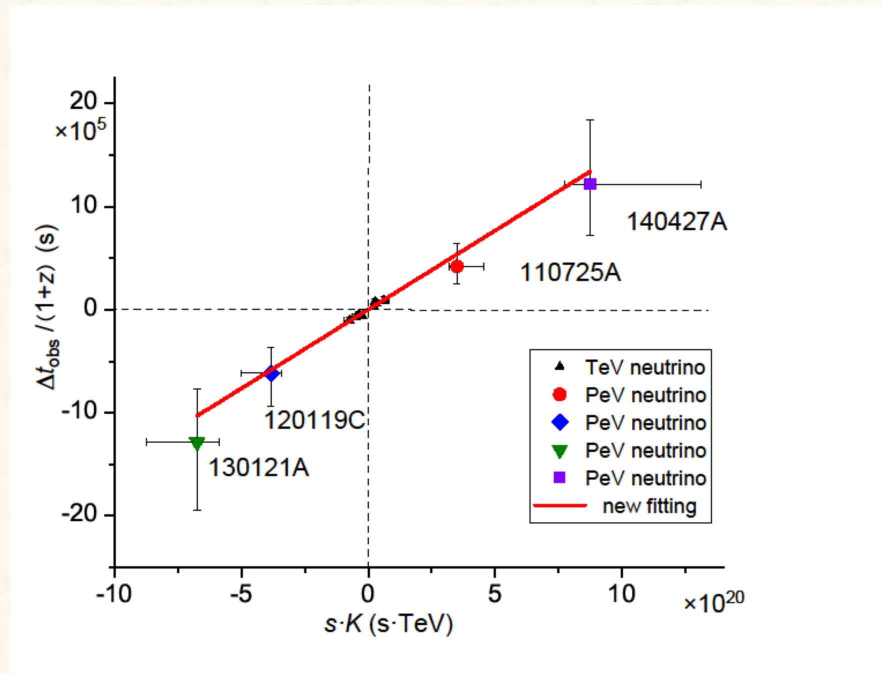
COMMUNICATIONS
PHYSICS

ARTICLE
DOI: 10.1038/s42005-018-0061-0 OPEN

Lorentz violation from gamma-ray burst neutrinos

Yanqi Huang[1] & Bo-Qiang Ma[1,2,3]





Association of IceCube Neutrinos with GRBs

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

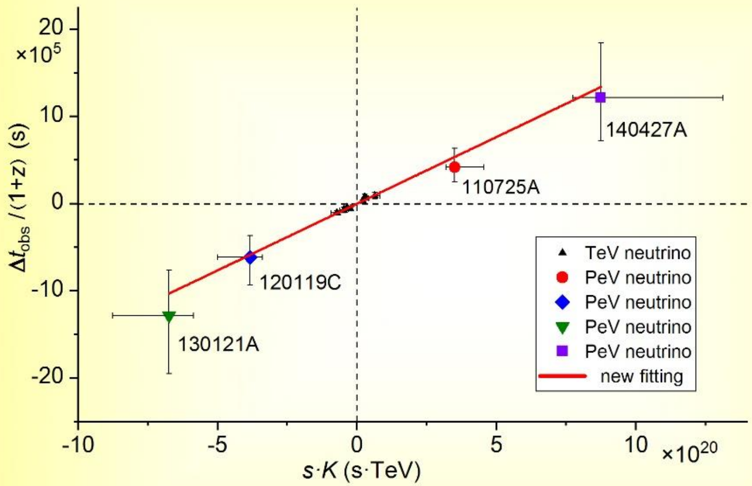
Table 3 The properties of PeV neutrino events with associated GRB candidates

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

The energy errors here are measurement uncertainties provided by the IceCube database. The column σ 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 [c] that satisfies the strict time criterion and is consistent with the regularity of the TeV neutrino. The mark [d] 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

PHYSICAL REVIEW D **99,** 043013 (2019)

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

Xinyi Zhang[1] and Bo-Qiang Ma[1,2,3,*]

[1]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
[2]*Collaborative Innovation Center of Quantum Matter, Beijing, China*
[3]*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.**

PHYSICAL REVIEW D **99,** 123018 (2019)

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

Consistent Lorentz violation features from near-TeV IceCube neutrinos

Yanqi Huang,[1] Hao Li,[1] and Bo-Qiang Ma[1,2,3,*]

[1]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*

[2]*Collaborative Innovation Center of Quantum Matter, Beijing, China*

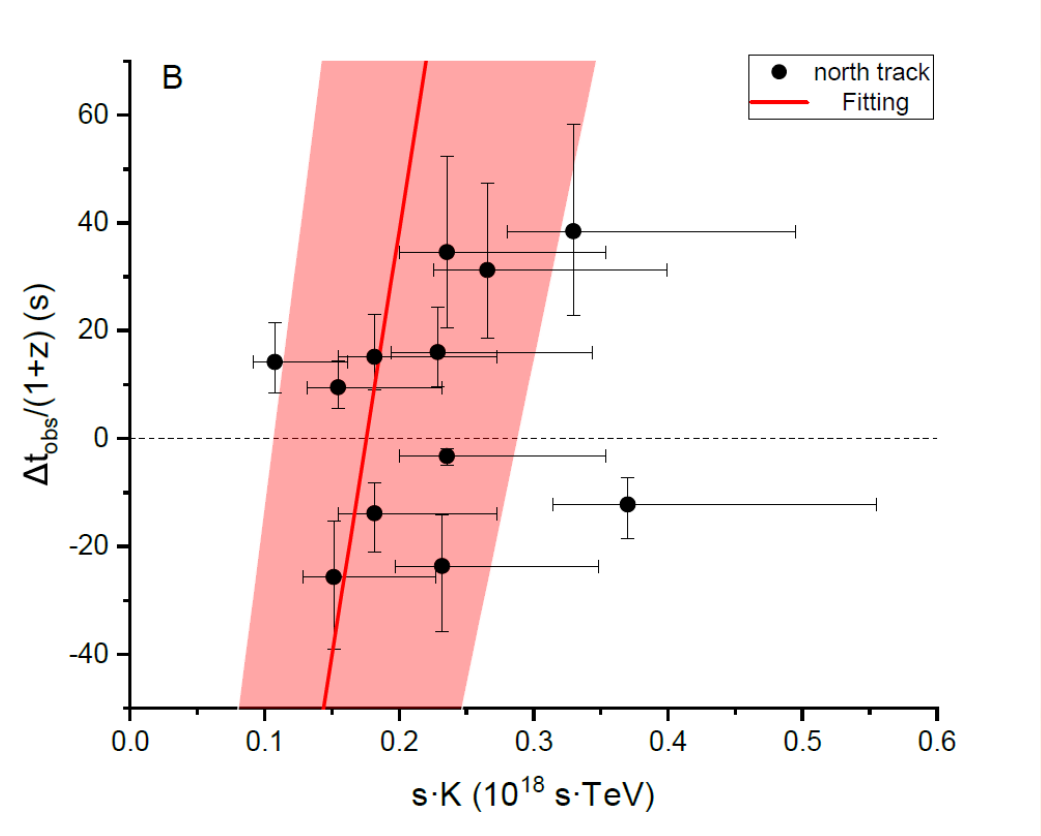
[3]*Center for High Energy Physics, Peking University, Beijing 100871, China*

(Received 31 January 2019; published 21 June 2019)

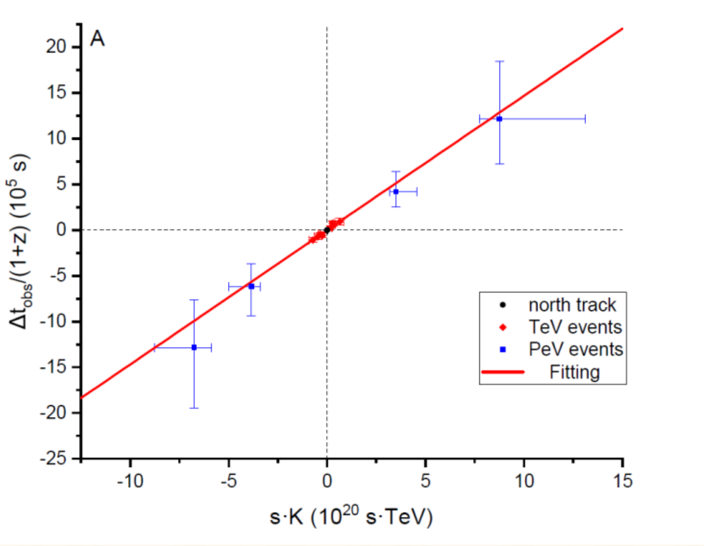
- **Previous association of 60 TeV to 2 PeV IceCube neutrinos with GRBs indicates Lorentz invariance and CPT symmetry violation.**
- **We find that another 12 northern hemisphere track events satisfy the same regularity at a lower energy scale around 1 TeV.**
- **Such a consistency over four orders of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

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

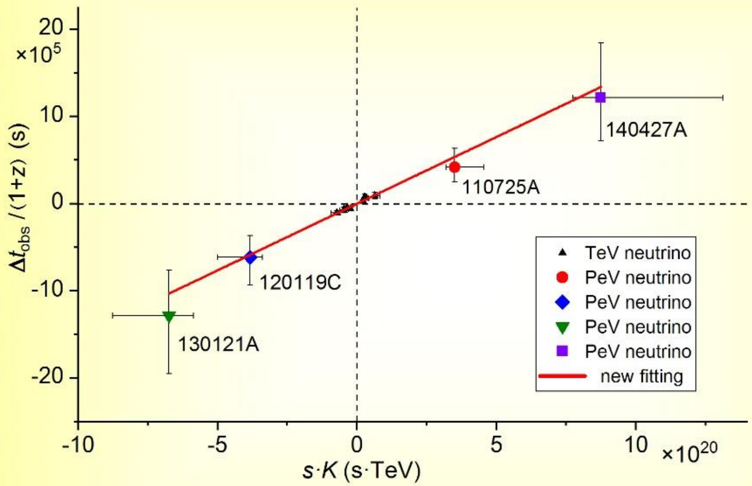


TeV + PeV + near-TeV neutrinos (r=0.99)



CPT Violation from Cosmic Neutrinos:

Difference properties between neutrinos and antineutrinos.



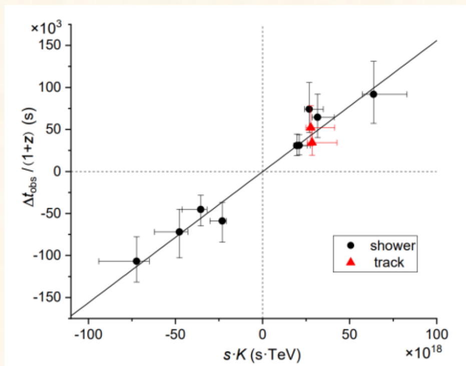
Y. Huang, B.-Q. Ma, Comms.Phys.1 (2018) 62

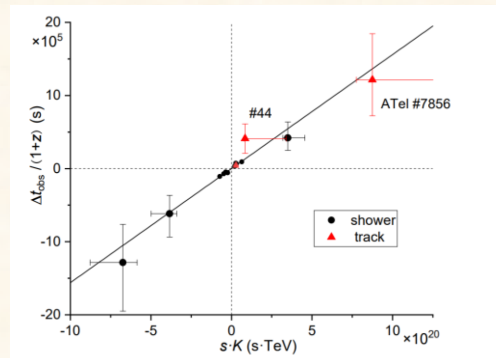
https://communities.springernature.com/posts/cpt-violation-from-cosmic-neutrinos

Y. Huang, B.-Q. Ma, Fundamental Research 4 (2024) 51 , arXiv:2211.00231

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.

Fundamental Research xxx (xxxx) xxx

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Article

Ultra-high energy cosmic neutrinos from gamma-ray bursts

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A B S T R A C T

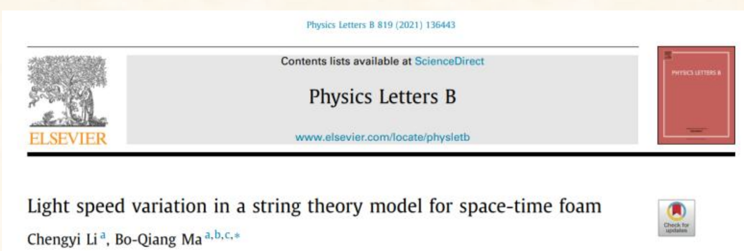
Based on the recent association of IceCube TeV and PeV neutrino events with gamma-ray bursts (GRBs) by considering the Lorentz violation of neutrinos, we provide a new estimate on the GRB neutrino flux with a more significant result compared to the previous constraint by the IceCube Collaboration. Among 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.

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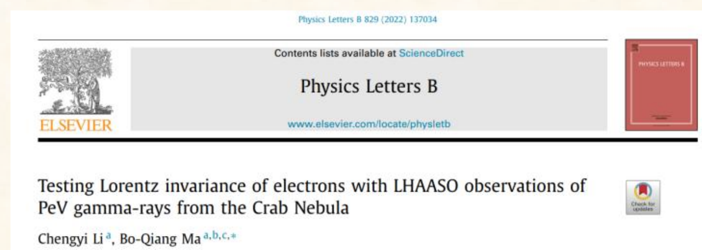
Light speed variation in a string theory model for space-time foam

Chengyi Li[a], Bo-Qiang Ma[a,b,c,*]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Testing Lorentz invariance of electrons with LHAASO observations of PeV gamma-rays from the Crab Nebula

Chengyi Li[a], Bo-Qiang Ma[a,b,c,*]

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

Physics Letters B 836 (2023) 137613

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Speed variations of cosmic photons and neutrinos from loop quantum gravity

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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]

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

- 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]

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

- 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]

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- 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

[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 ……

- 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

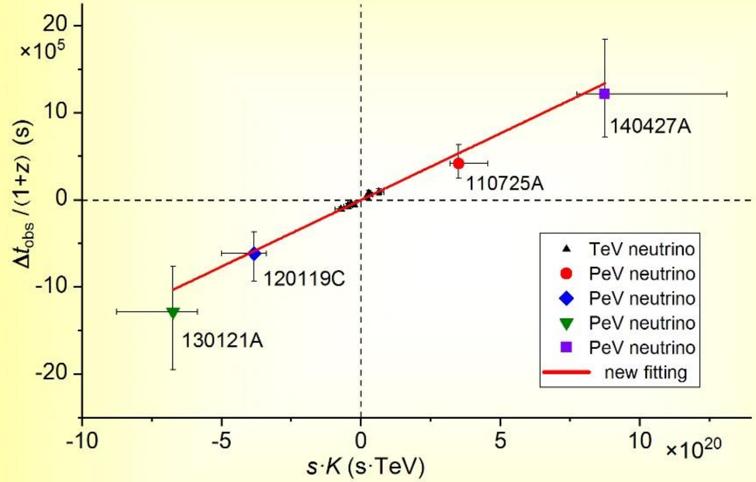
- We analyse the data of energetic photons from gamma-ray bursts (GRBs).
- We unveil a surprising regularity behind the data of these energetic photons.
- We find events to support the energy-dependence of light speed, i.e., the Lorentz violation.
- The scenario is supported by new GRB 160509A, AGNs,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

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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

Published March 2025 •

Research Notes of the AAS, Volume 9, Number 3

Citation Ruiqi Wang *et al* 2025 *Res. Notes AAS* **9** 65

DOI 10.3847/2515-5172/adc452


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