



Lorentz violation from cosmic photons and neutrinos

Bo-Qiang Ma (马伯强)

Peking University (北京大学)

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and Consequences in Accelerators and Cosmology**

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,.....

The highest energy particles

can be observed by human being is from SKY

- Frontiers of human knowledge:
Cosmology, Astronomy, and Physics
- The combination of cosmology, astrophysics, and particle physics → cosmology & particle astrophysics
CosPA -- by Pauchy Hwang
- Better understanding of the universe:
from most small to most big → connecting quarks to the cosmos
- New physics from cosmic photons and neutrinos:
Lorentz violation

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 for 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]
- backgrounds in general gravity [Ni'75, PRL; Yan'83, TP,]
- vacuum condensate of antisymmetric tensor fields in string theory [Kostelecky & Samuel'89 & '91, PRL]
- double special relativity [Amelino-Camelia'02, Nature & '02 IJMPD]

Pioneers' study of Lorentz symmetry violation

The early discussion on the effects of Lorentz violation

- **Dirac's æther and nonlinear electrodynamics**

P.A.M. Dirac, *Nature* **168**, 906 (1951).

- **Goldstone boson associated to Spontaneous Lorentz symmetry breaking(SLSB)**

▷Bjorken's earlier attempts: Photon as Goldstone boson associated to SLSB. J.D. Bjorken, *Ann.Phys.* **24**, 174 (1963).

▷Is Graviton also a Goldstone boson?

P.R. Phillips, *Phys. Rev.* **146**, 966 (1966)...

- **An universal length scale**

T.G. Pavlopoulos, *Phys. Rev.* **159**, 1106 (1967)

- **Nielsen's renormalization group calculation of the beta-function for a non-covariant pure Yang-Mills theory**

H.B. Nielsen and M. Ninomiya, *Nucl. Phys. B* **141**, 153 (1978). ...

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

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



- Principle of physical invariance :
the equations describing the laws of physics have the same form in all **admissible mathematical manifolds.**

A new theory of Lorentz violation

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

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

- The effective minimal Standard Model

$$\mathcal{L}_{SM} = \mathcal{L}_G + \mathcal{L}_F + \mathcal{L}_{HG} + \mathcal{L}_{HF},$$

$$\mathcal{L}_G = -\frac{1}{4} F^{a\alpha\beta} F_{\alpha\beta}^a,$$

$$\mathcal{L}_F = i\bar{\psi}\gamma^\alpha D_\alpha\psi,$$

$$\mathcal{L}_{HG} = (D^\alpha\phi)^\dagger D_\alpha\phi + V(\phi),$$

- A new standard model with supplementary terms

$$\mathcal{L}_{SMS} = \mathcal{L}_{SM} + \mathcal{L}_{LV},$$

$$\mathcal{L}_{LV} = \mathcal{L}_{GV} + \mathcal{L}_{FV} + \mathcal{L}_{HFV}$$

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

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 higher

Cosmic neutrinos with much higher energy: ~TeV-PeV

LV from energetic photons 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](#)

.....

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 [[Piran'05, Rev. Mod. Phys.](#)]
 - 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
- use GRBs to test LV [[Amelino-Camelia et al.'98, Nature](#)]



Formulas in our analysis of LV parameter

linear and quadratic energy dependence

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

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

- 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, Phys.Lett.B 760 (2016) 602
- H.Xu, B.-Q.Ma, JCAP 1801 (2018) 050

Time lag by LV effect

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

$$\Delta t_{\text{LV}} = \frac{1+n}{2H_0} \left(\frac{E_h^n - E_1^n}{M_{\text{QG}}^n c^{2n}} \right) \int_0^z \frac{(1+z')^n dz'}{h(z')}$$

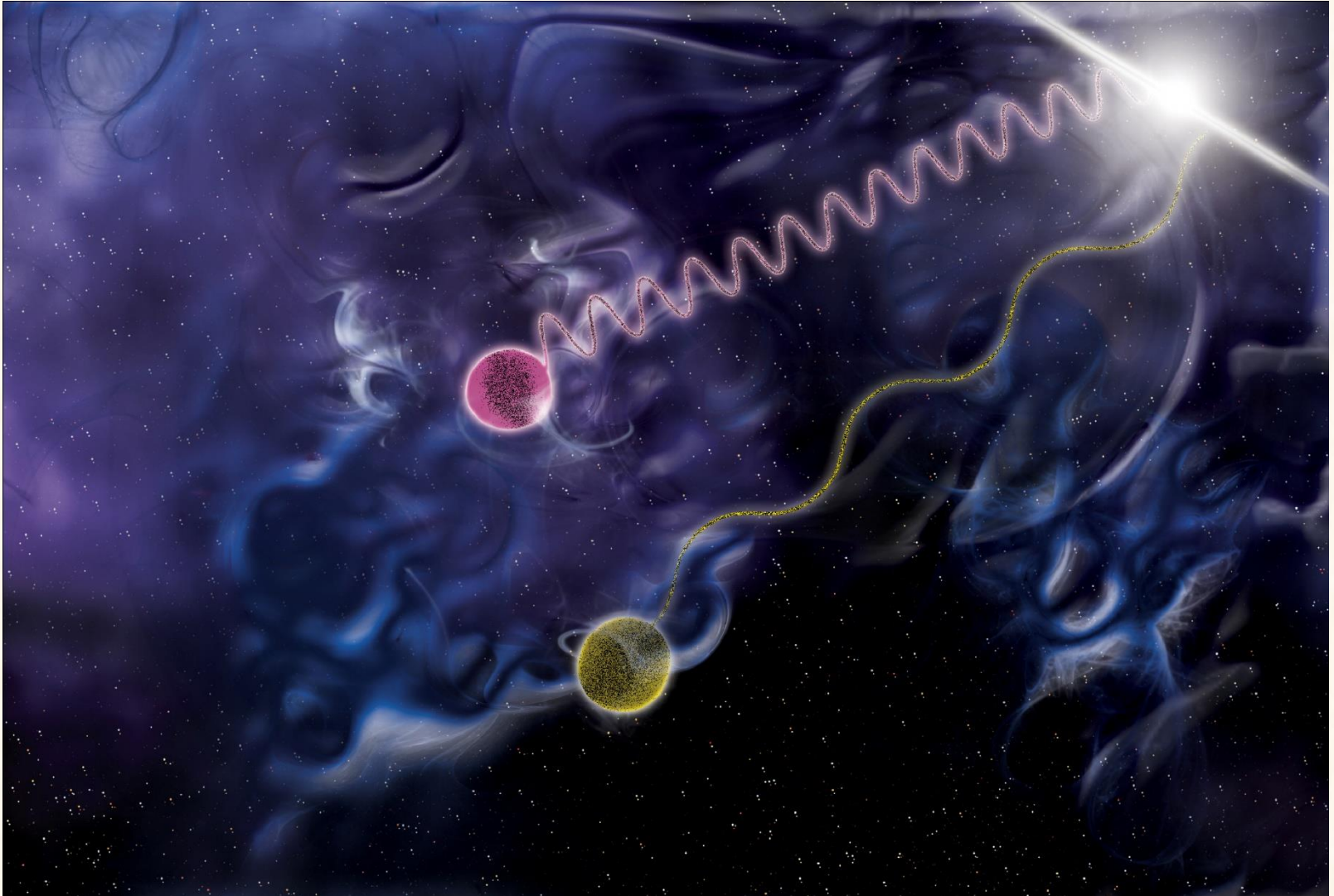
$$M_{\text{QG,L}} = |\xi|^{-1} M_{\text{P}} \quad \text{and} \quad M_{\text{QG,Q}} = |\zeta|^{-1/2} M_{\text{P}}$$

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

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

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

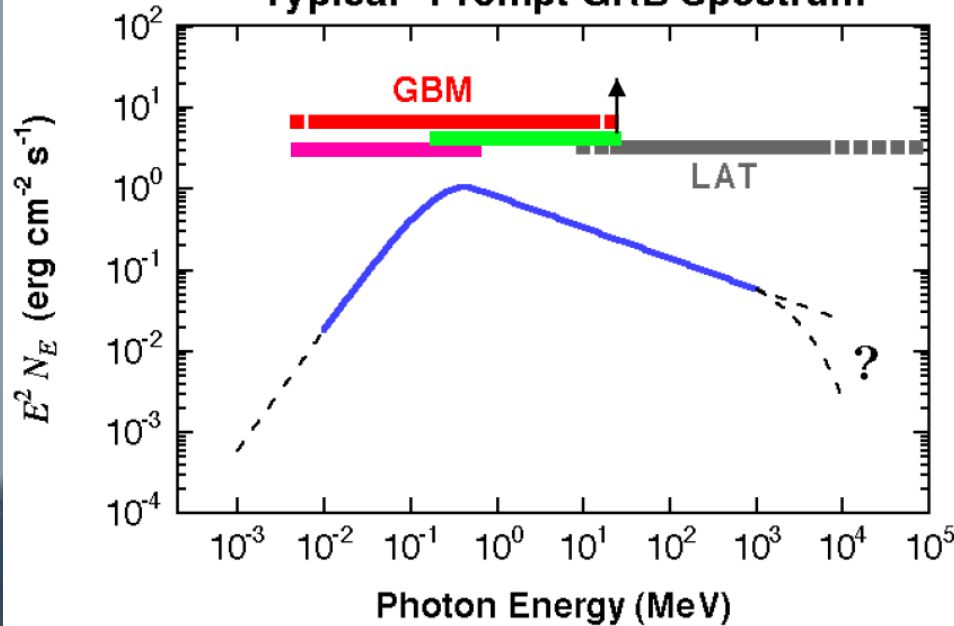
Time-lag by GRB



June 11, 2008

Fermi instruments

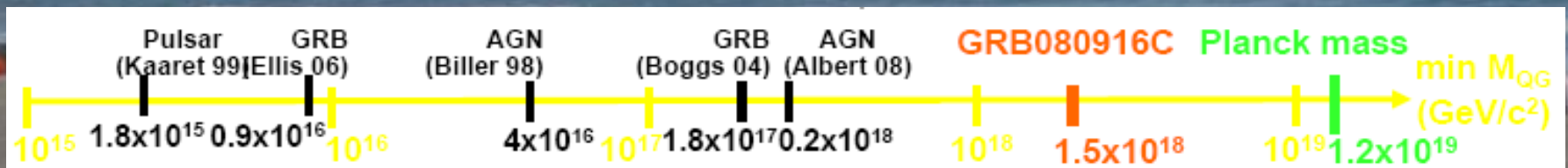
"Typical" Prompt GRB Spectrum



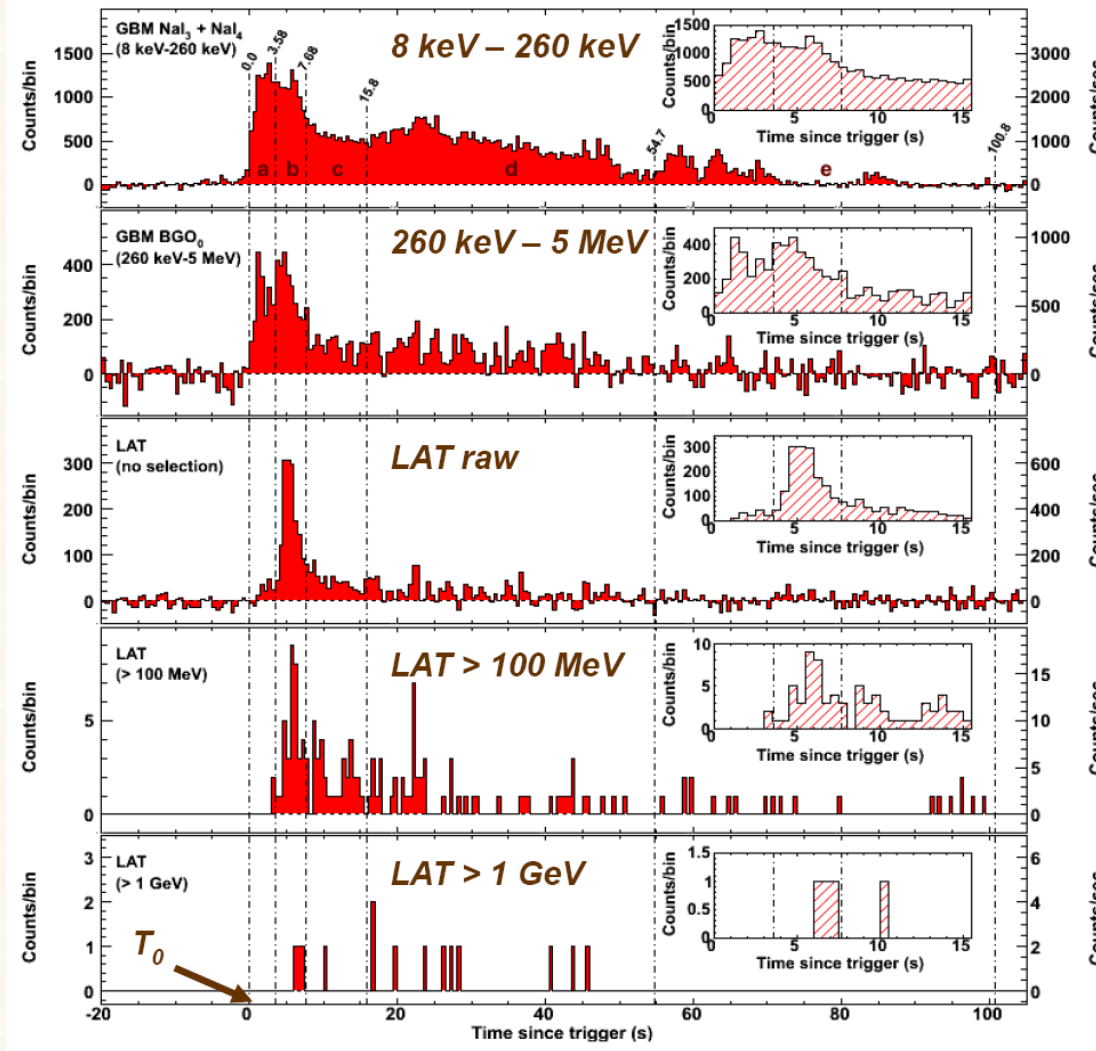
~ 300 GeV



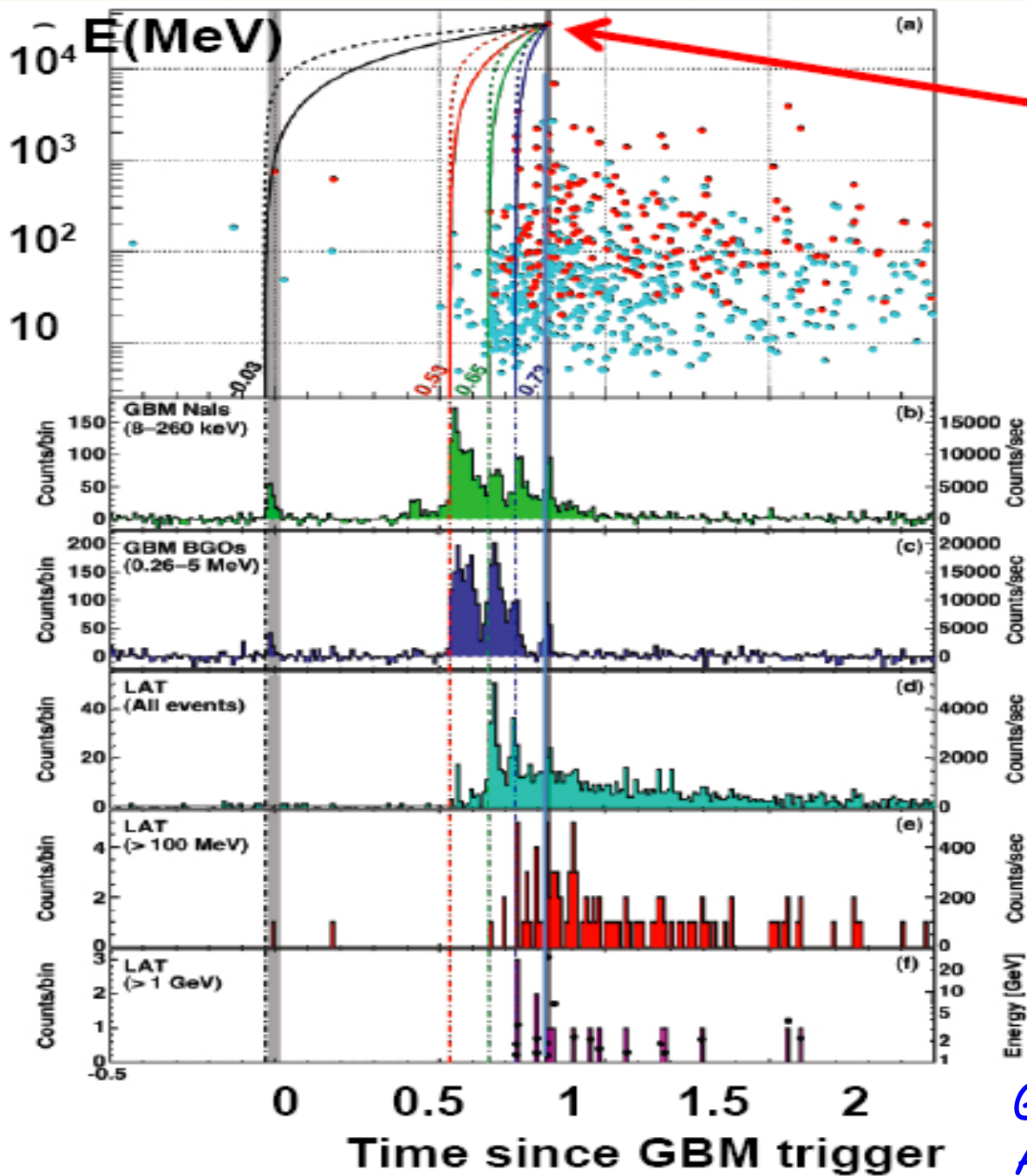
trigger photons ~ 0.1 MeV



Lag determinations



GRB080916C -- Abdo et al.'09, Science




31 GeV

Time lags are affected both artificially and instrumentally


GRB090510
Abdo et al.'09, Nature

Four Fermi observations

the arrival of the highest energy photon to GBM trigger



GRBs	z	E (GeV)	Δt_{obs} (s)	$M_{\text{QG,L}}$ (GeV/c ²)	$M_{\text{QG,Q}}$ (GeV/c ²)
080916C [19]	4.35 [21]	13.22	16.54	1.5×10^{18}	9.7×10^9
090510 [20]	0.903 [22]	31	0.829	1.7×10^{19}	3.4×10^{10}
090902B [23]	1.822 [24]	33.4	82	3.7×10^{17}	5.9×10^9
090926A [25]	2.1062 [26]	19.6	26	7.8×10^{17}	6.8×10^9


$$\Delta t_{\text{obs}} = \Delta t_{\text{LV}}$$

$$M_{\text{QG,L}} \sim (4.9 \pm 8.1) \times 10^{18} \text{ GeV}$$

$$M_{\text{QG,Q}} \sim (1.4 \pm 1.3) \times 10^{10} \text{ GeV}$$

Separation of astrophysical time lags from LV delay

- imperfect knowledge of radiation mechanism of GRBs
- a survey of GRBs at different redshifts
 - the time lag induced by LV accumulates with propagation distance
 - the **intrinsic source** induced time lag is likely to be a distance independent quantity
- A robust survey [Ellis et al.'06 & 08, *Astropart. Phys.*]

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

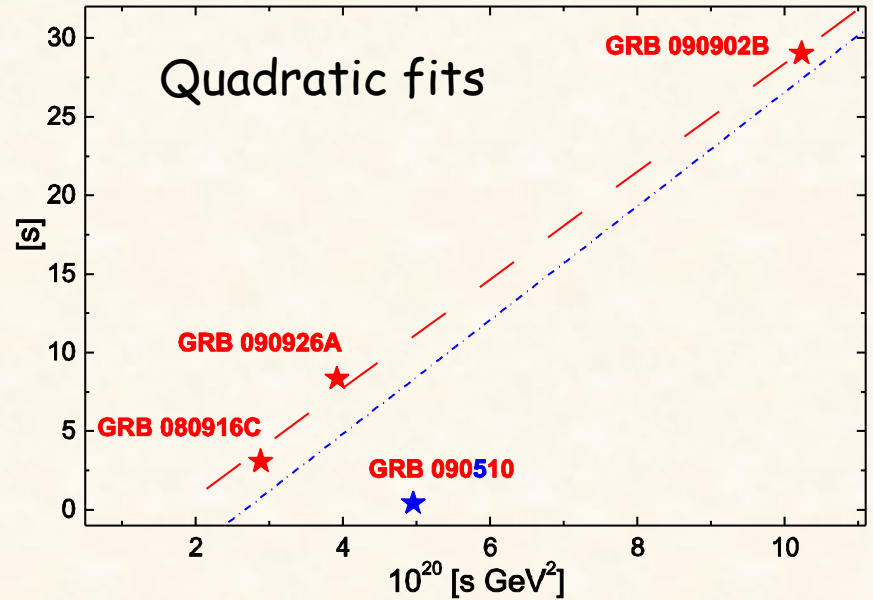
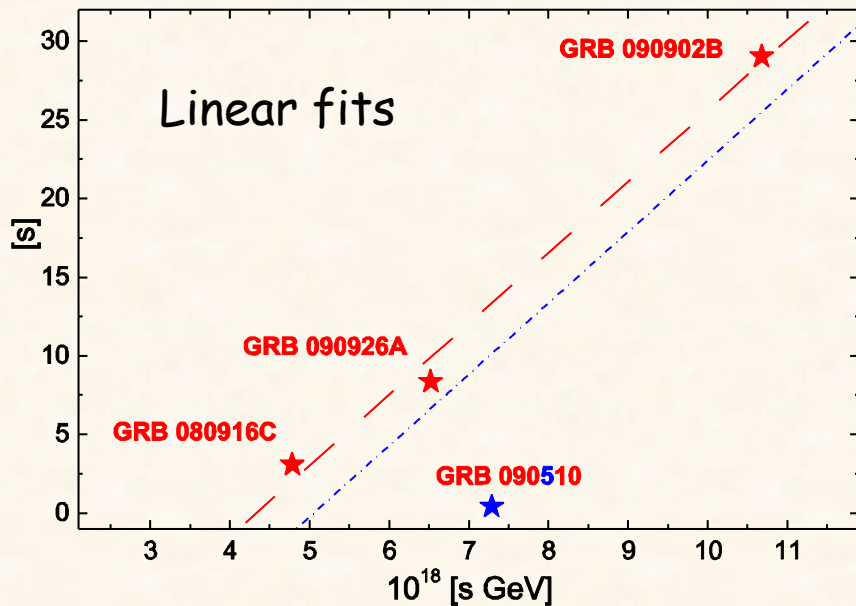
An intuitive way to perform analysis

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

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

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

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



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

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

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

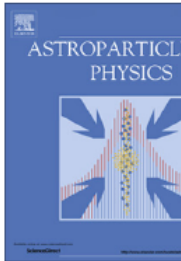
further development

Astroparticle Physics 61 (2015) 108–112

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



Lorentz violation from gamma-ray bursts

Shu Zhang^a, Bo-Qiang Ma^{a,b,c,d,*}

^aSchool of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

^bCollaborative Innovation Center of Quantum Matter, Beijing, China

^cCenter for High Energy Physics, Peking University, Beijing 100871, China

^dCenter for History and Philosophy of Science, Peking University, Beijing 100871, China



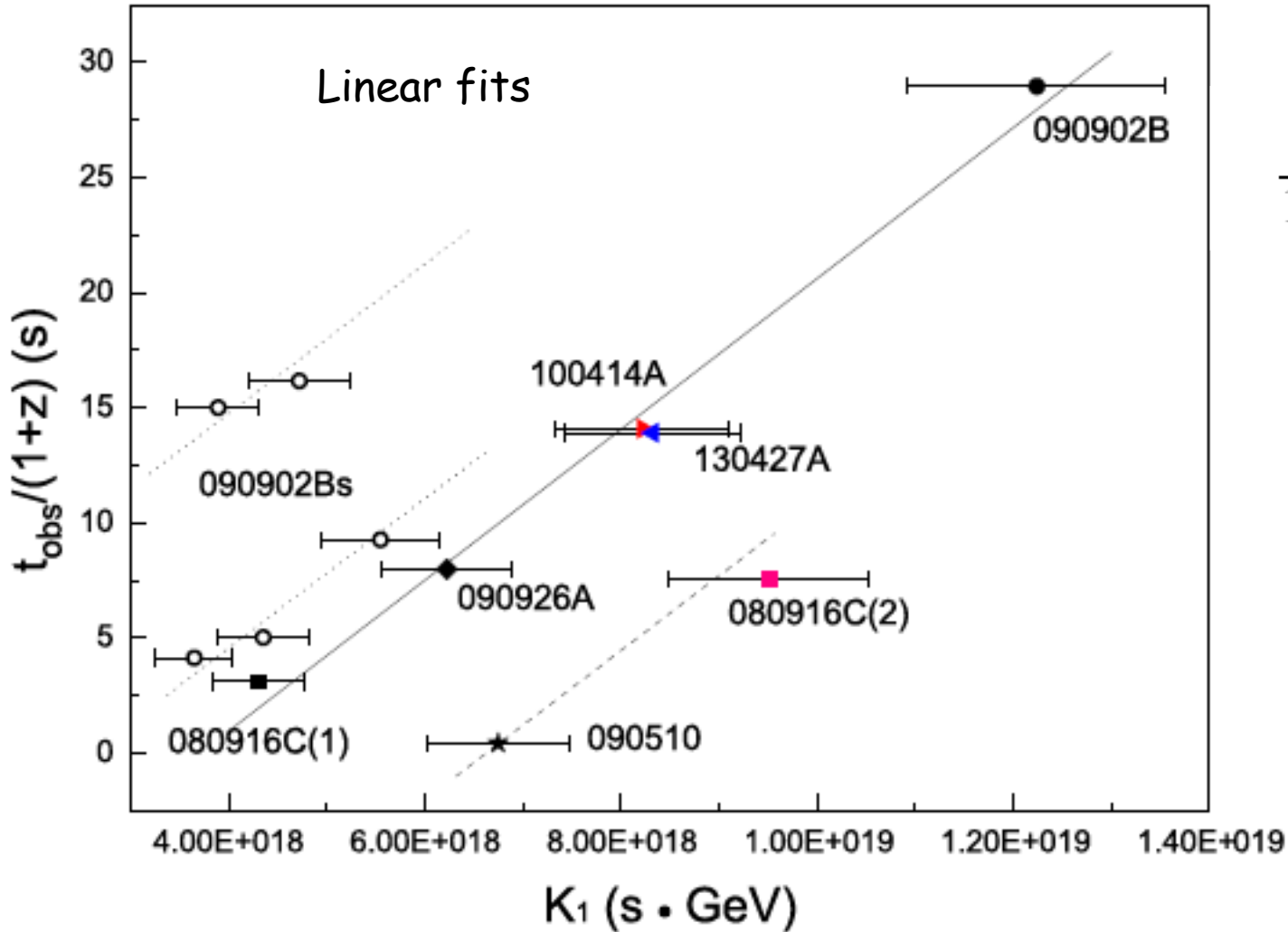
Added data

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

GRB	z	t_{obs} (s)	E_{obs} (GeV)	E_{in} (GeV)	$E_{\text{LV},1}$ ($\times 10^{17}$ GeV)	$\frac{t_{\text{obs}}}{1+z}$ (s)	K_1 ($\times 10^{18}$ s · 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
		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
090902Bs	1.822	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

^aThe 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 $E_{\text{LV},1}$ 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 · 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?

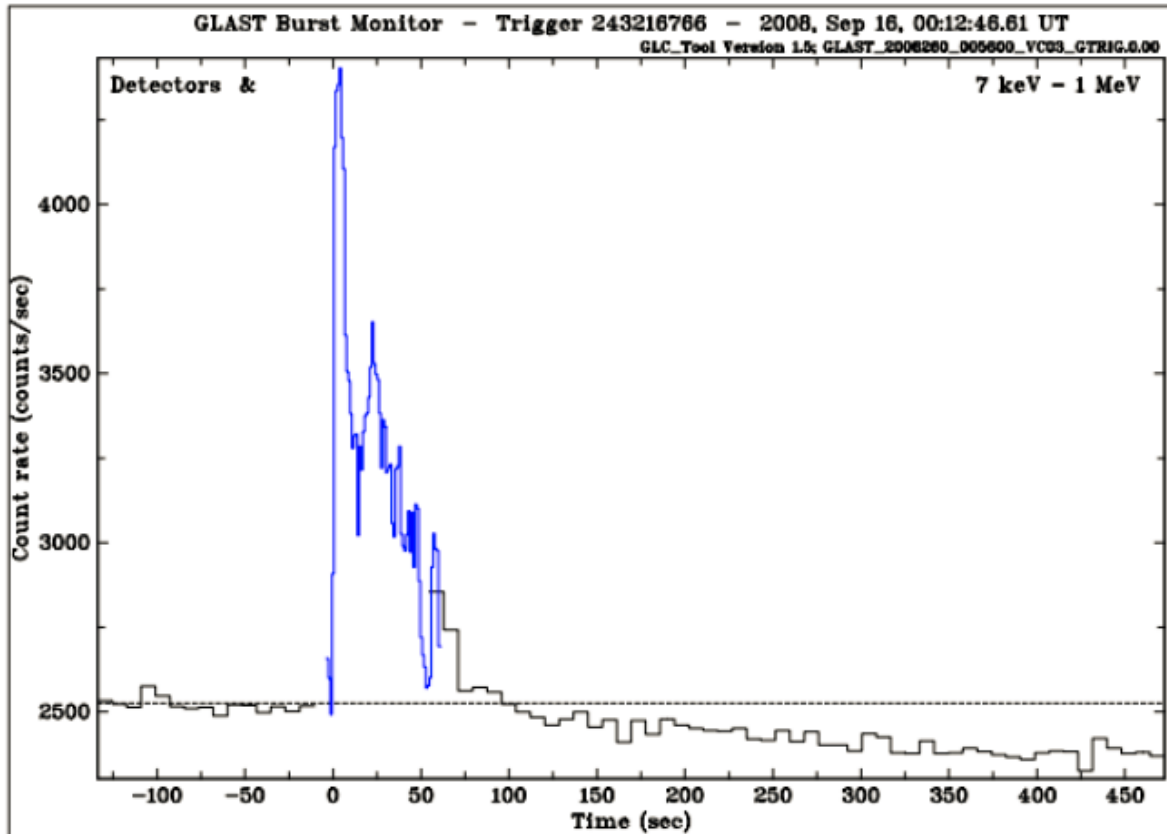
Trigger:

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

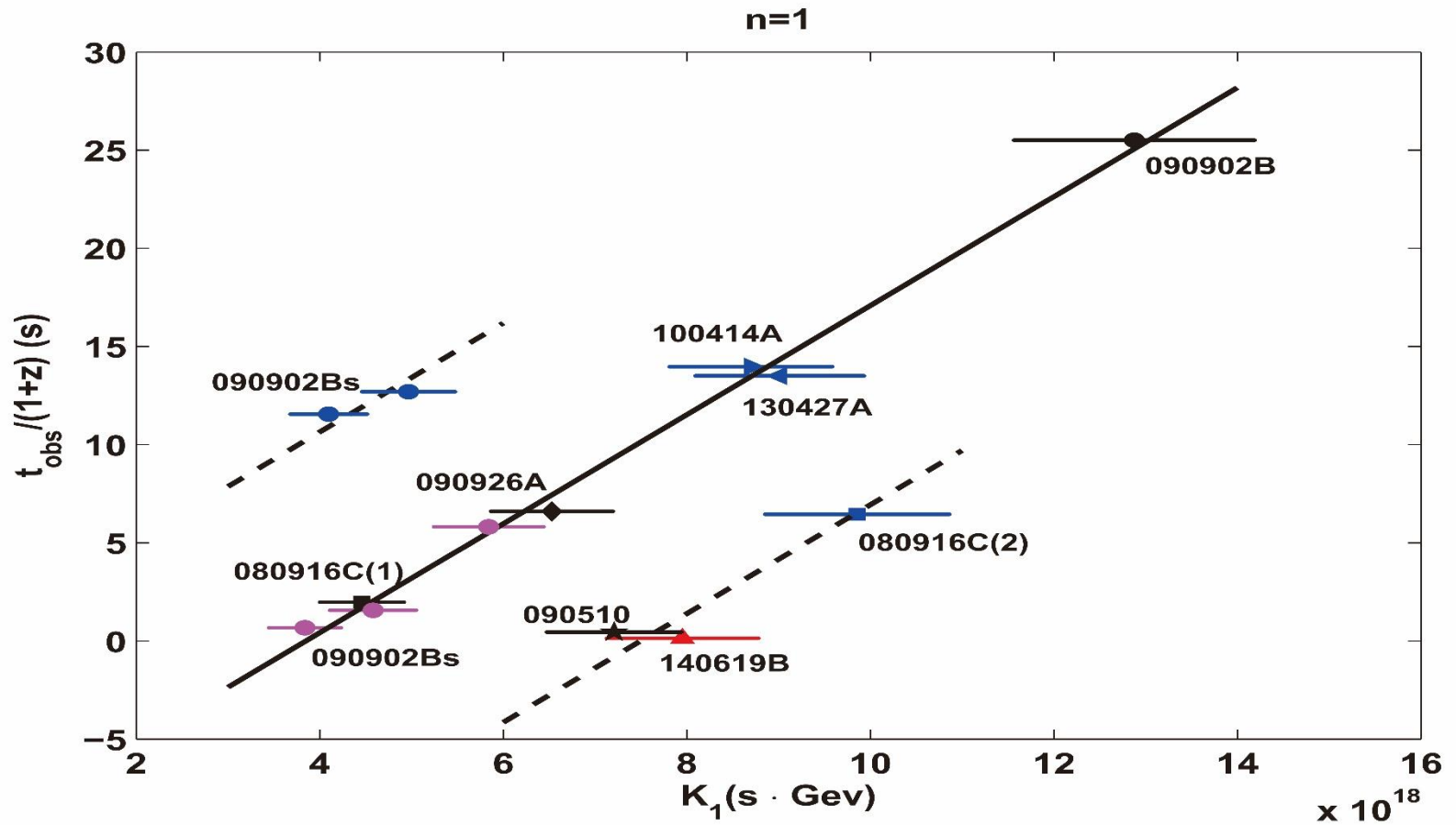
New Analysis of Data

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

GRB	z	t_{high} (s)	t_{low} (s)	E_{obs} (GeV)	E_{source} (GeV)	$\frac{\Delta t_{\text{obs}}}{1+z}$ (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
		11.671		11.9	33.6	0.674	3.84 ± 0.39
		14.166		14.2	40.1	1.559	4.58 ± 0.47
090902Bs	1.822	26.168	9.768	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

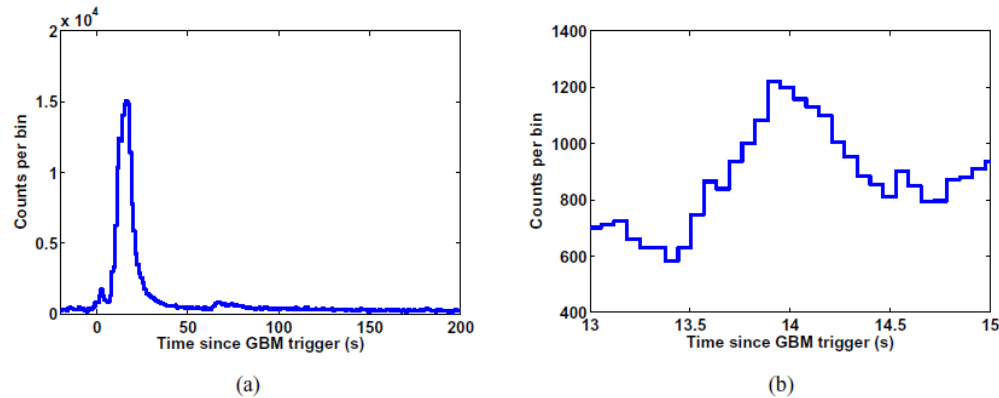


Figure 1: Light curves of the two brightest trigger detectors combined (GBM NaI-n0 and NaI-n3, 8 ~ 260 keV) for GRB 160509A. In the left panel (a), photon events are binned in 1 second intervals. In the right panel (b), photon events are binned in 0.064 seconds intervals to determine the peak of the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

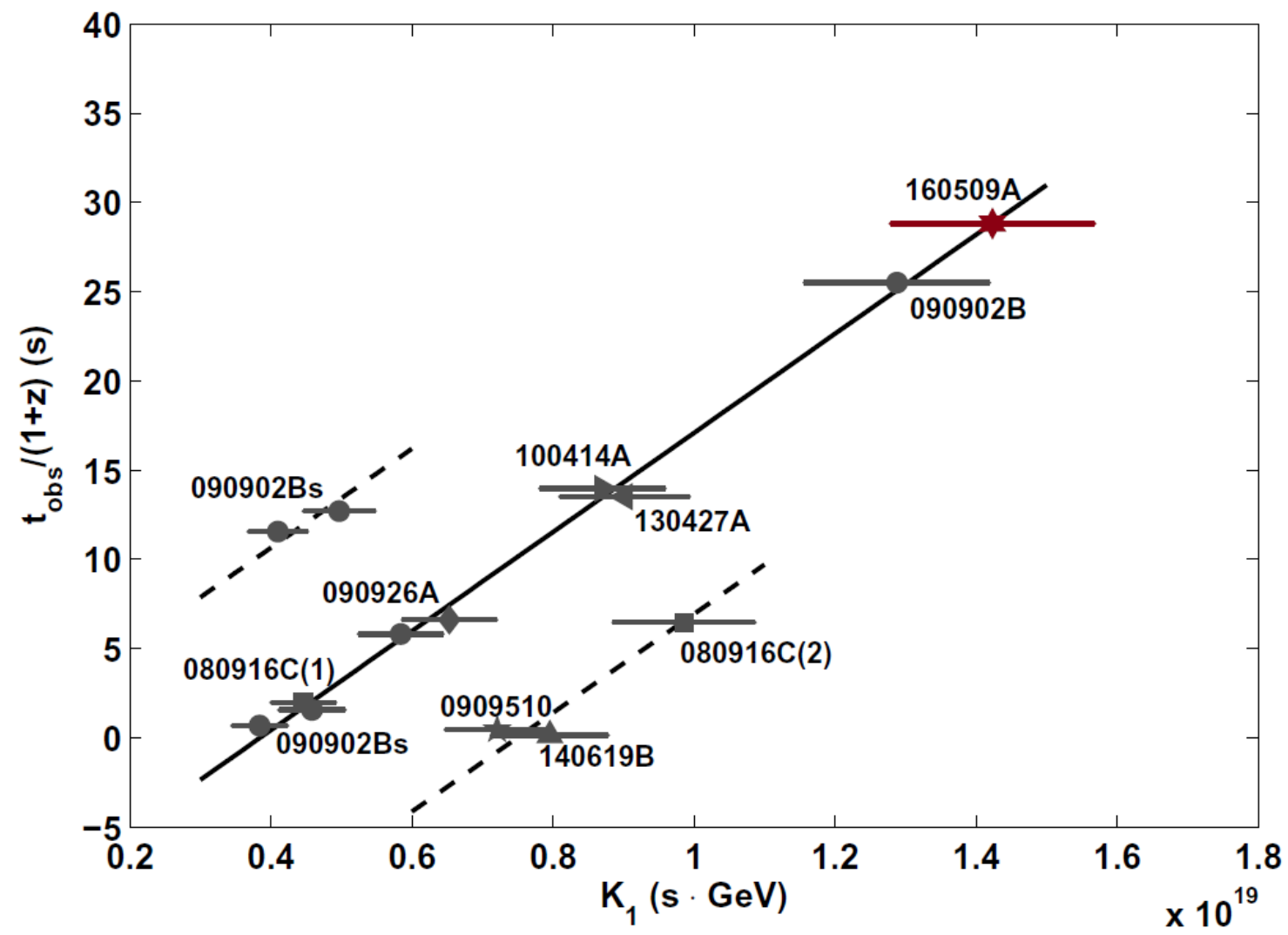
Table 2: Data of high energy photon event from GRB 160509A

GRB	z	t_{high} (s)	t_{low} (s)	E_{obs} (GeV)	E_{source} (GeV)	$\frac{\Delta t_{\text{obs}}}{1+z}$ (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 $E_{\text{source}} = (1 + z)E_{\text{obs}}$. 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

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

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

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.

new development

Journal of **C**osmology and **A**stroparticle **P**hysics
An IOP and SISSA journal

Regularity of high energy photon
events from gamma ray bursts

Haowei Xu^a and Bo-Qiang Ma^{a,b,c,d,1}

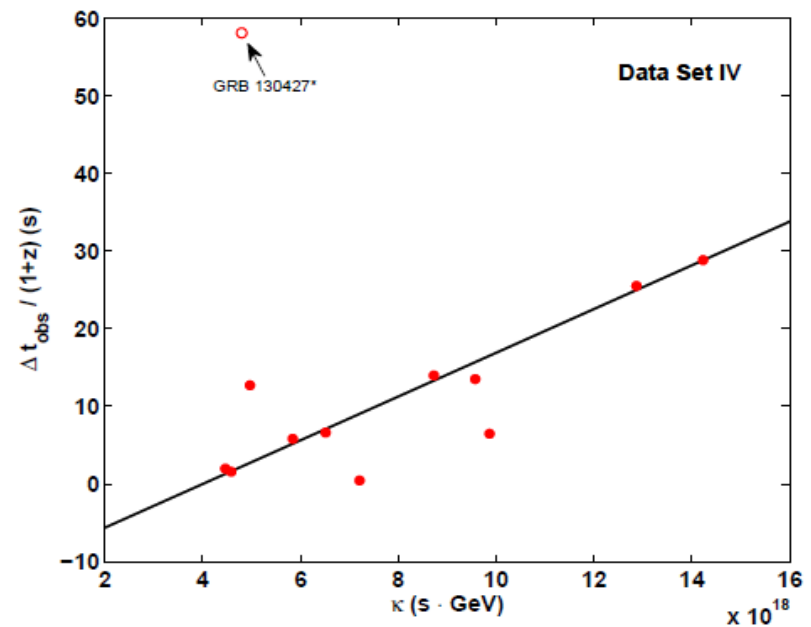
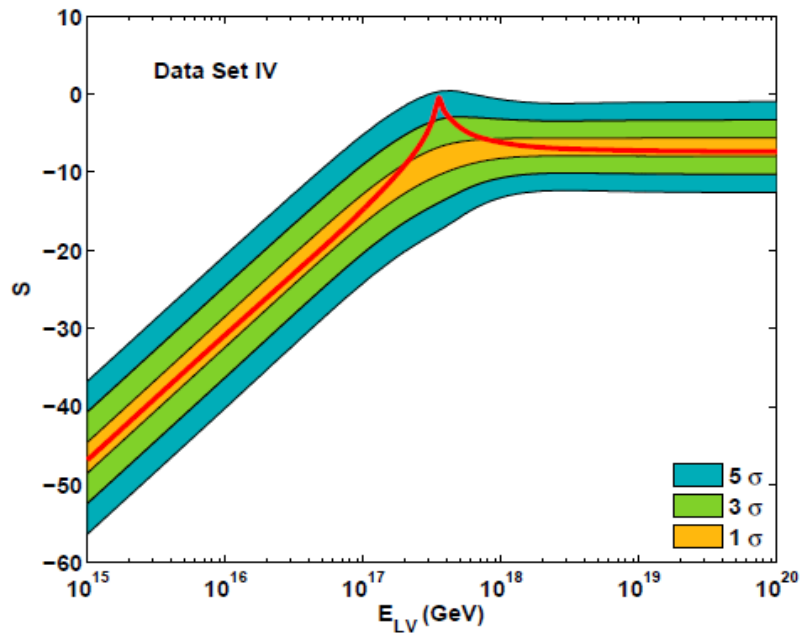
H.Xu, B.-Q.Ma, JCAP 1801 (2018) 050

- A general analysis on the data of 25 bright GRBs
- Allow a completed scan over all possibilities without bias
- **The regularity exists at a significance of 3-5 σ**

new development

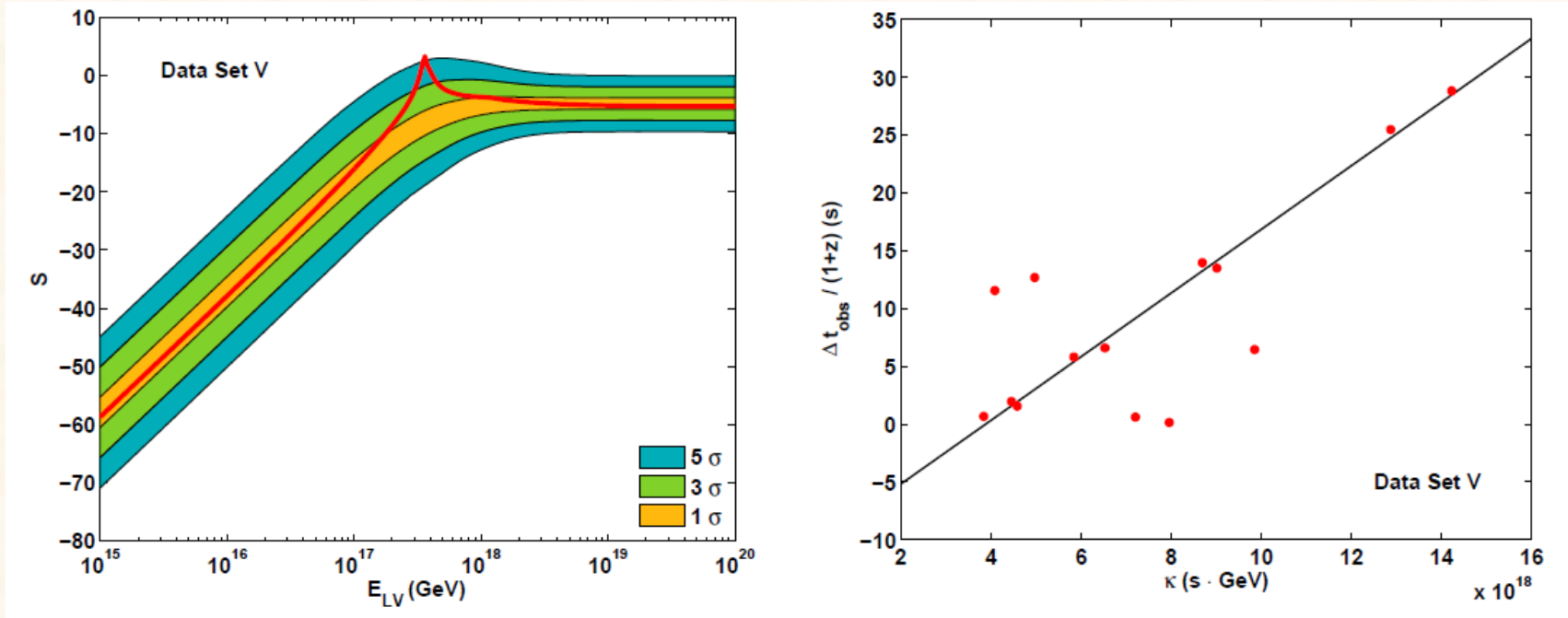
H.Xu, B.-Q.Ma, JCAP 1801 (2018) 050

$$\mathcal{S}(E_{LV}) = \sum_{i=1}^{N-\rho} \log \left(\frac{\rho}{t_{i+\rho} - t_i} \right)$$



new development

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



In conclusion, we use a general method to analyze the data of 25 bright GRBs detected by FGST. The results suggest that for photons with energy higher than 40 GeV, the regularity of high energy photon events from different GRBs exists at a significance of 3–5 σ with $E_{LV} = 3.6 \times 10^{17}$ GeV determined by the GRB data.

Two options for light speed variation

- A consequence of the matter effect in space: cosmic medium.
- An observation of the Lorentz violation effect at

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

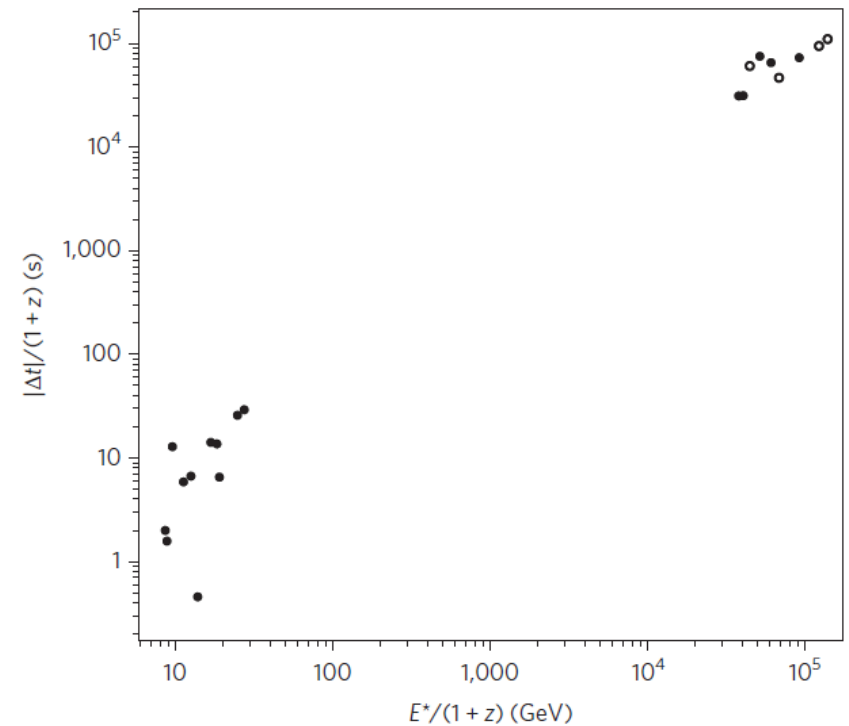
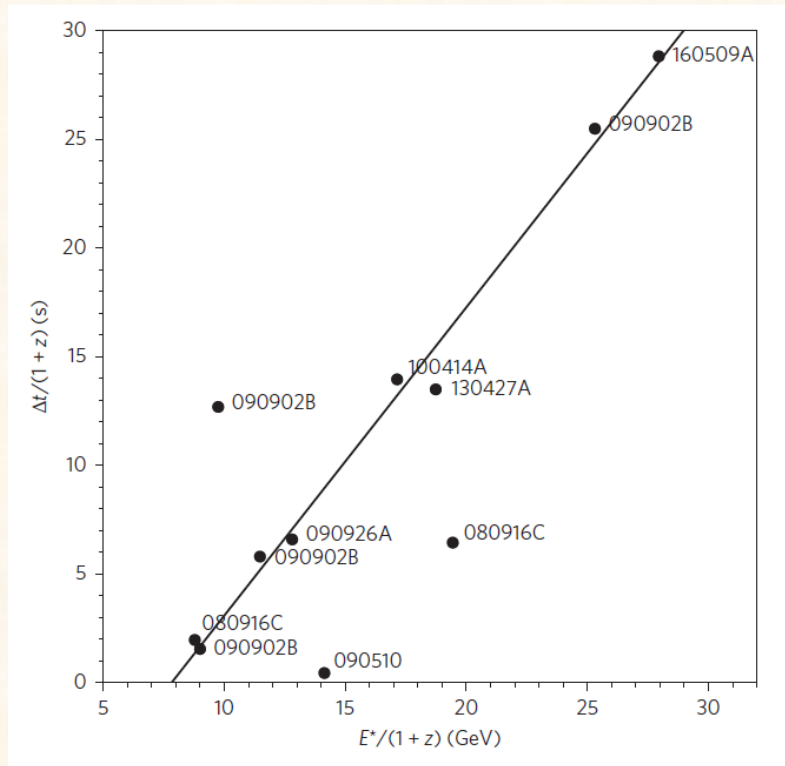
$$\text{Planck scale } (E \sim E_{Pl} = \sqrt{\hbar c^5 / G} \simeq 1.22 \times 10^{19} \text{ GeV})$$

The exact parameter for quantum gravity or Lorentz violation should be determined from experimental evidence rather than a priori assumption.

From photons to neutrinos

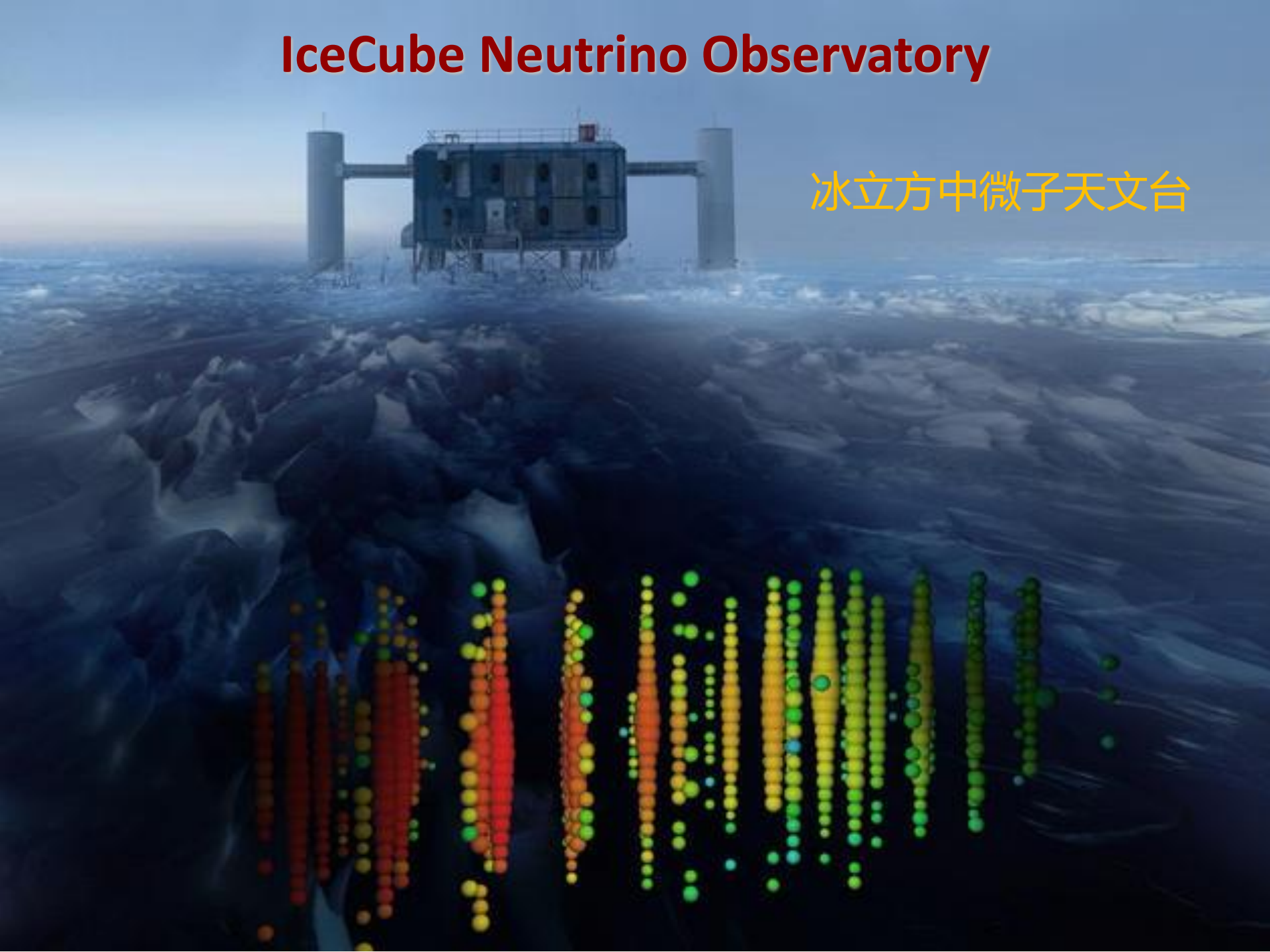
In vacuo dispersion features for gamma-ray-burst neutrinos and photons

Giovanni Amelino-Camelia^{1,2*}, Giacomo D'Amico^{1,2}, Giacomo Rosati³ and Niccoló Loreti⁴



IceCube Neutrino Observatory

冰立方中微子天文台



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 < 100 GeV, neutrino = TeV -> PeV**
- **Time difference: photon = a few seconds**
neutrino = a few hundred seconds -> months
- **Intrinsic time difference: can be safely neglected.**

IceCube Neutrinos

—results reported by IceCube

- IceCube, *Astrophys.J.* 843 (2017) 2292
 - Y. Huang, B.-Q. Ma, *Comms.Phys.*1 (2018) 62
-
- **9 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.**

Extension of Time Window to Days

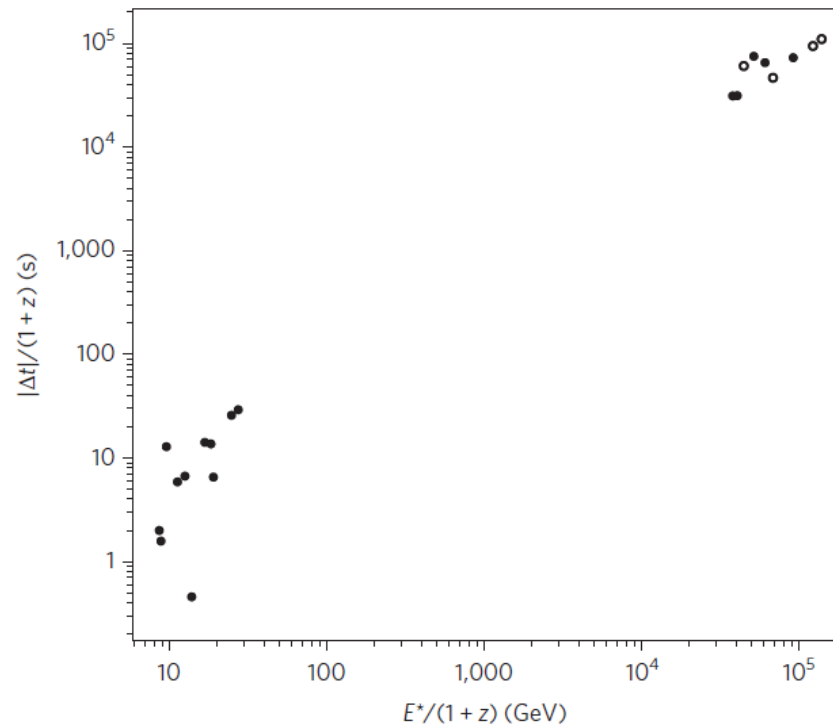
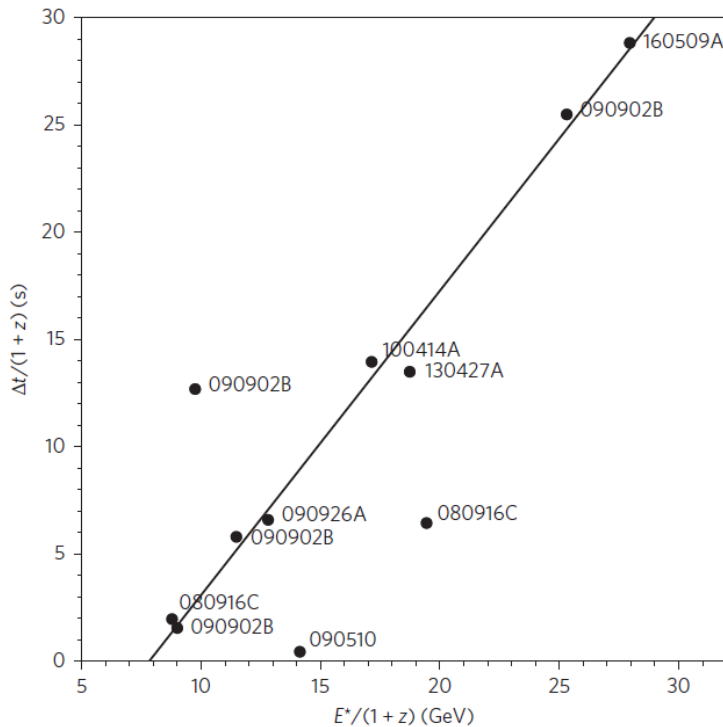
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ARTICLES

PUBLISHED: 5 JUNE 2017 | VOLUME: 1 | ARTICLE NUMBER: 0139

In vacuo dispersion features for gamma-ray-burst neutrinos and photons

Giovanni Amelino-Camelia^{1,2*}, Giacomo D'Amico^{1,2}, Giacomo Rosati³ and Niccoló Loret⁴



Reanalysis of TeV Events

COMMUNICATIONS PHYSICS

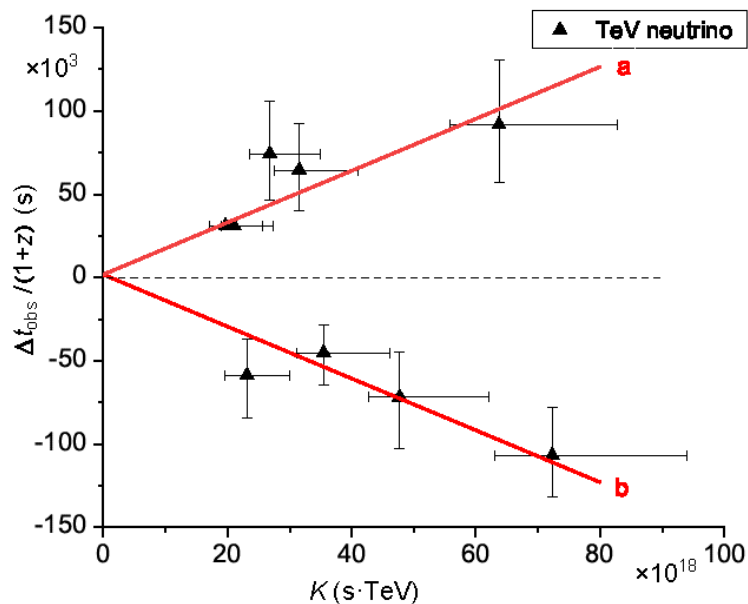
ARTICLE

DOI: 10.1038/s42005-018-0061-0

OPEN

Lorentz violation from gamma-ray burst neutrinos

Yanqi Huang¹ & Bo-Qiang Ma^{1,2,3}



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

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

Reanalysis of TeV Events

COMMUNICATIONS PHYSICS

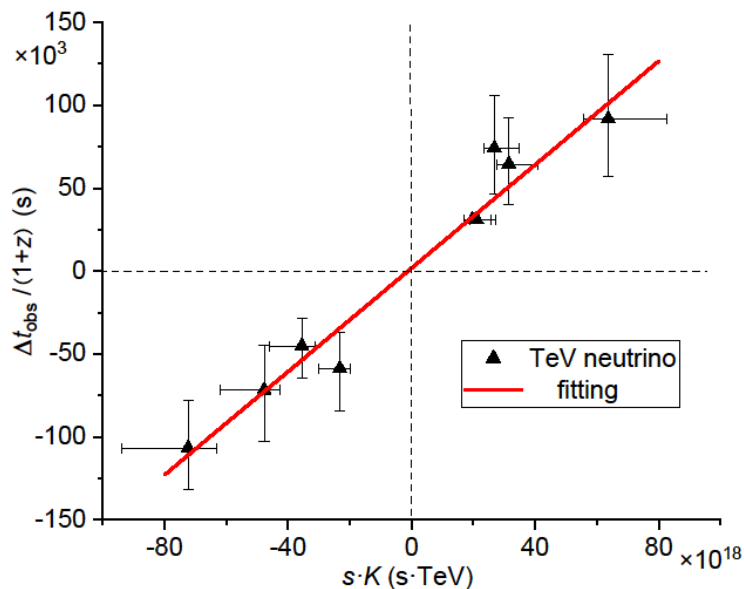
ARTICLE

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OPEN

Lorentz violation from gamma-ray burst neutrinos

Yanqi Huang¹ & Bo-Qiang Ma^{1,2,3}



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

$$s = \pm 1$$

First Analysis of PeV Events

COMMUNICATIONS PHYSICS

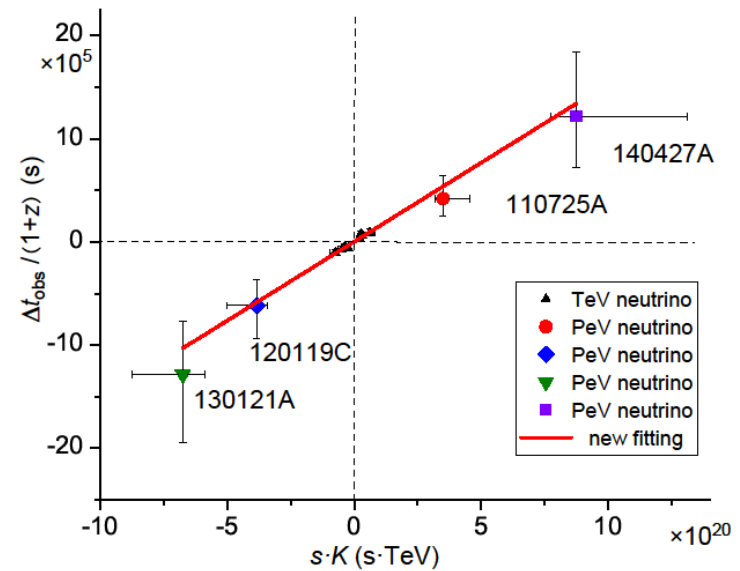
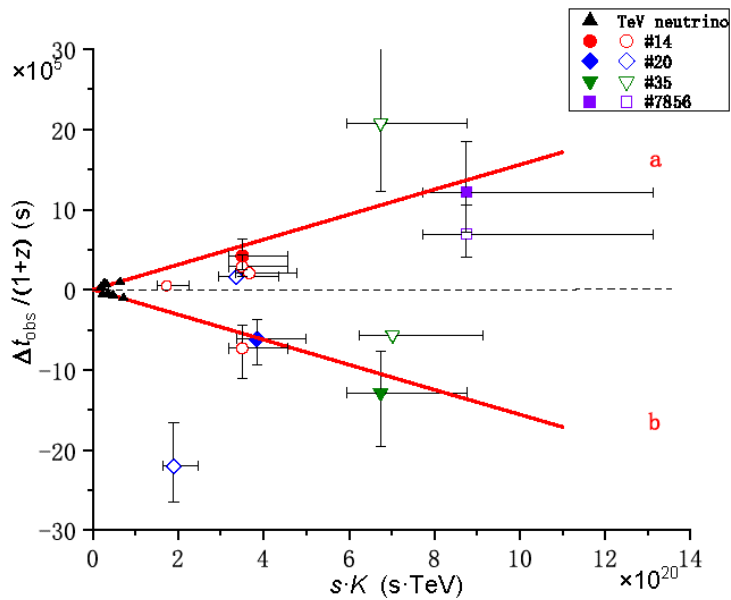
ARTICLE

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OPEN

Lorentz violation from gamma-ray burst neutrinos

Yanqi Huang¹ & Bo-Qiang Ma^{1,2,3}



Association of IceCube Neutrinos with GRBs

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

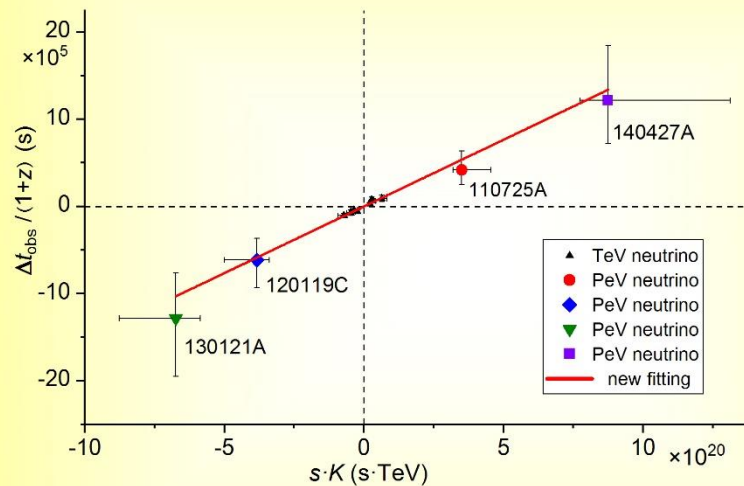
Table 3 The properties of PeV neutrino events with associated GRB candidates

	E (PeV)	σ	$\Delta\Psi$	z	Δt_{obs} (10^3s)	$\frac{\Delta t_{\text{obs}}}{1+z}$ (10^3s)	K ($10^{18}\text{s} \cdot \text{TeV}$)
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>

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

Xinyi Zhang¹ 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.**

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*

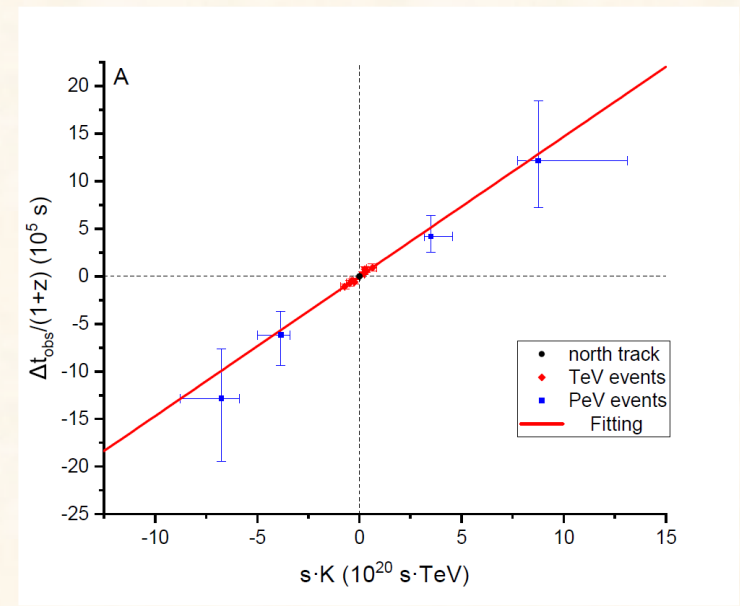
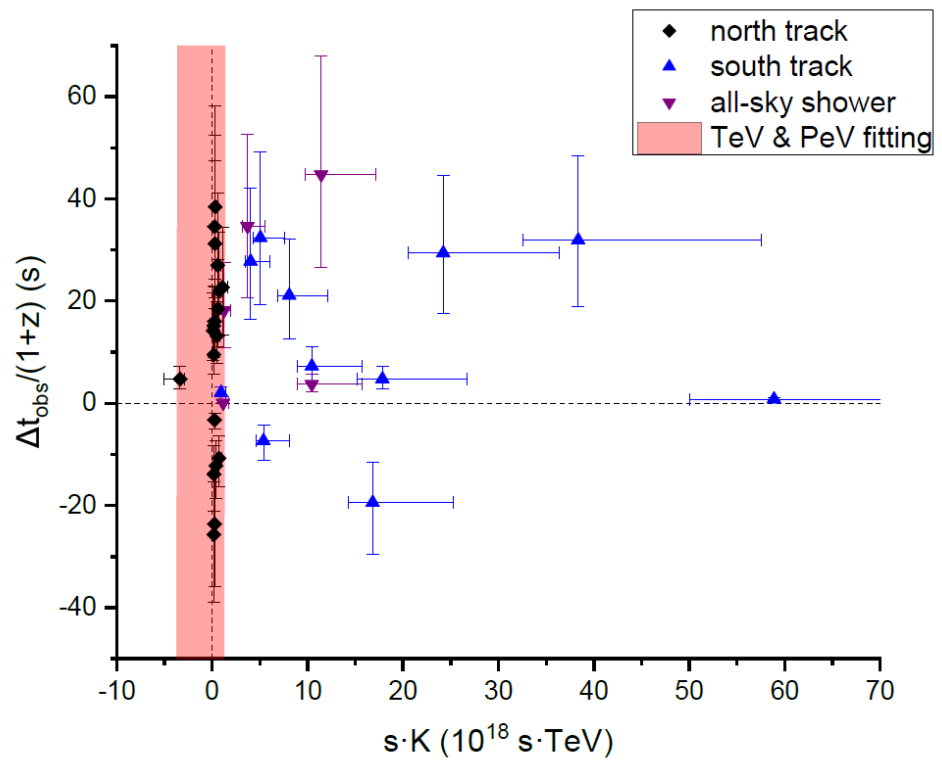


(Received 31 January 2019; published 21 June 2019)

- **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.**

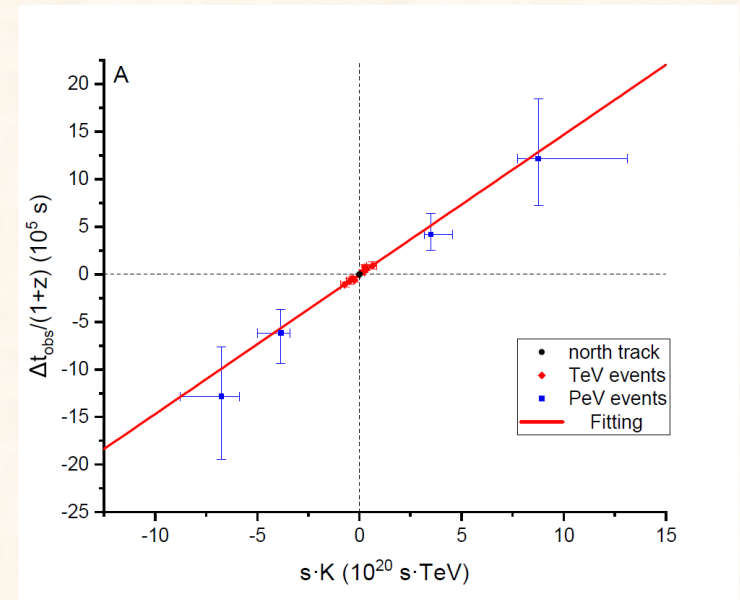
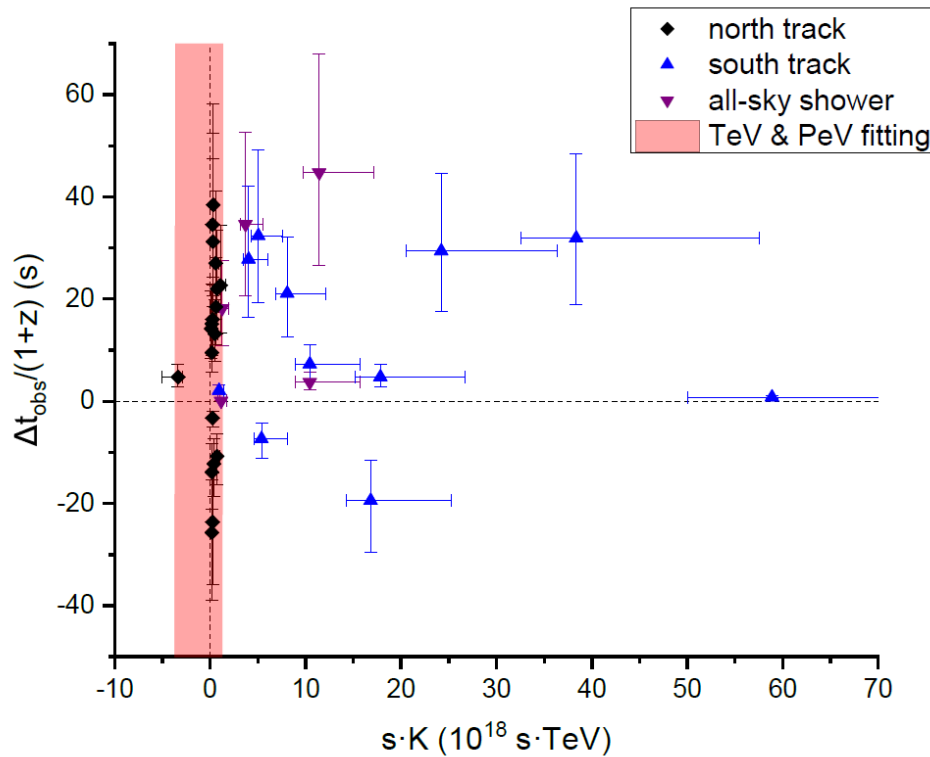
IceCube Neutrinos near 1 TeV & GRBs

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



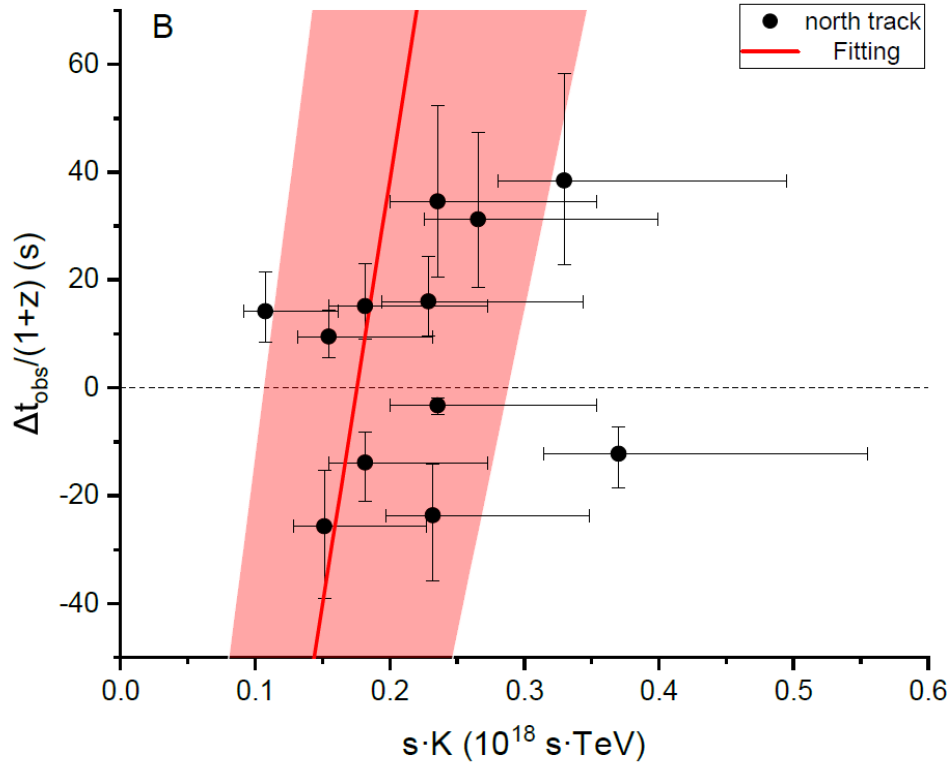
IceCube Neutrinos near 1 TeV & GRBs

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

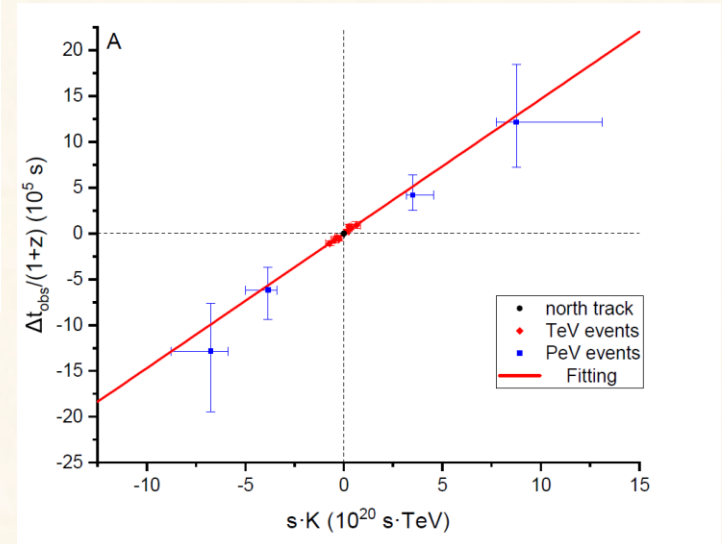


12 IceCube neutrinos near 1 TeV as new support to the TeV+PeV regularity

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



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

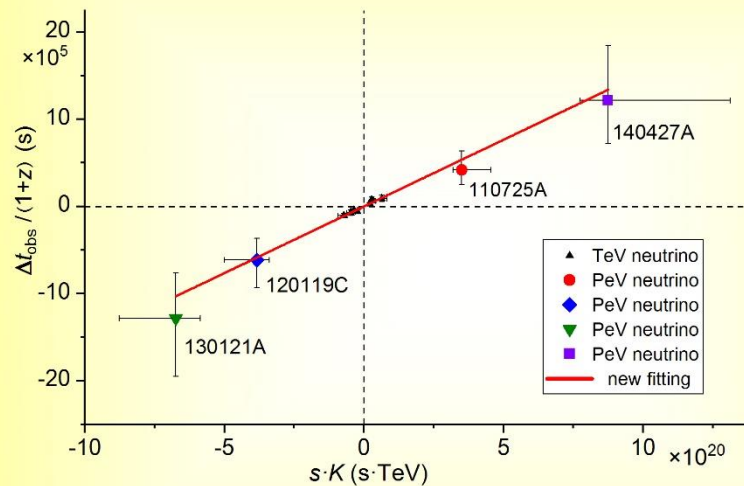


Summary: ultrahigh energy cosmic neutrinos

- **We first associate all 4 IceCube events of PeV neutrinos with gamma-ray bursts (GRBs).**
- **We unveil a regularity of these energetic neutrinos indicting Lorentz violation.**
- **We find different propagation properties between neutrinos and antineutrinos.**
- **The result indicates the CPT violation between neutrinos and antineutrinos.**


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>

A scenic view of a pond with a pavilion and modern buildings in the background. The pavilion has a red roof and is surrounded by lush greenery. The pond is filled with large green lily pads. In the background, there are several modern buildings under a clear blue sky. The text "Thanks 谢谢!" is overlaid in red on the image.

Thanks 谢谢!