CPT Violation from Cosmic Neutrinos

Bo-Qiang Ma（马伯强）

Peking University (北京大学)

October 5, 2018, USTC

Seminar at Modern Physics Department, USTC

In collaboration with Zhi Xiao, Lijing Shao, Shimin Yang, Zhou Lingli, Haowei Xu, Yunqi Xu, Nan Qin, Shu Zhang, Yue Liu, Yanqi Huang, ……

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

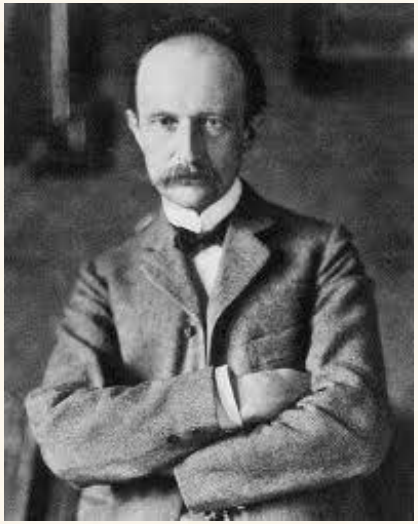
the equations describing the laws of physics have the same form in all admissible reference frames.

So is there any reason that we seek for

Lorentz Violation ?

Planck's *God-Given Unit System*

(Planck, 1899)



Planck, 1900

$c, \; G, \; \hbar, \; k_B, \;$ 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:

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

- Combined with black-body entropy

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

- We arrive at a minimum value of space

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

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

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

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

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

LV as Window on the Nature of Space-Time

- The typical scale of quantum gravity is Planck scale

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

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

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

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]

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

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

- Principle of physical invariance :

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

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

A new theory of Lorentz violation

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

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

- The effective minimal Standard Model

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

- A new standard model with supplementary terms

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

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

physical independence of mathematical background manifolds

The Lorentz invariance violation matrix

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

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

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

The Lorentz violation for protons from GZK cut-off

A special case is

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

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

$$\delta = -\xi^2 + 2\xi.$$

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

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

LV from energetic photon emissions from 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 (2018) in press, arXiv: 1810.00636

……

Modified photon dispersion relation from LV

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

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

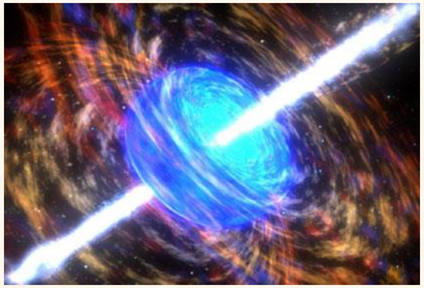
Z.Xiao and B.-Q.Ma, PRD 80 (09) 116005, arXiv:0909.4927

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 [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

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

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

- 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]

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

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

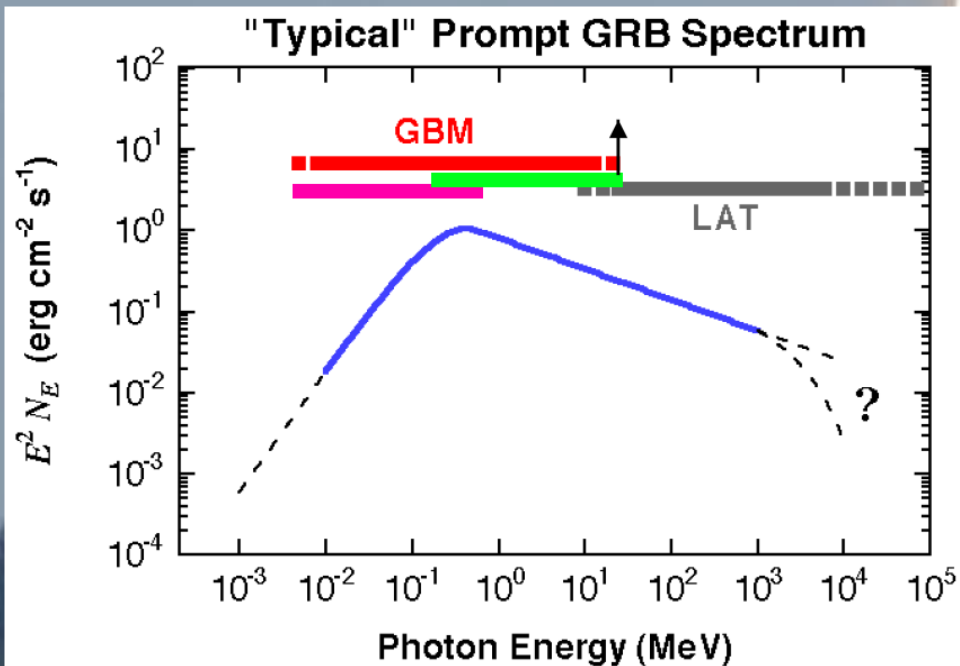
$$h(z) = \sqrt{\Omega_\Lambda + \Omega_{\mathrm{M}}(1+z)^3}$$

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

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

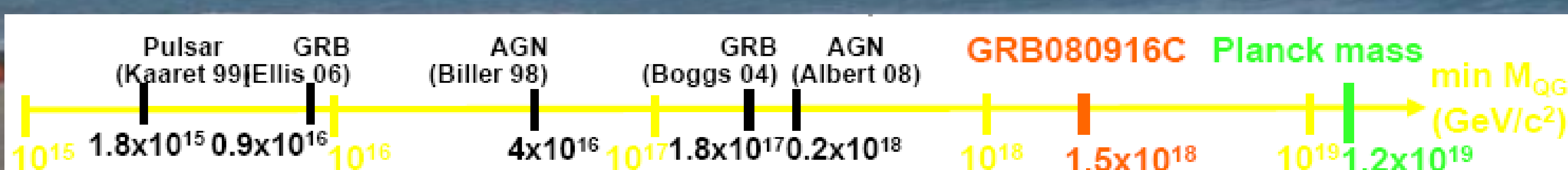
June 11, 2008

Fermi instruments

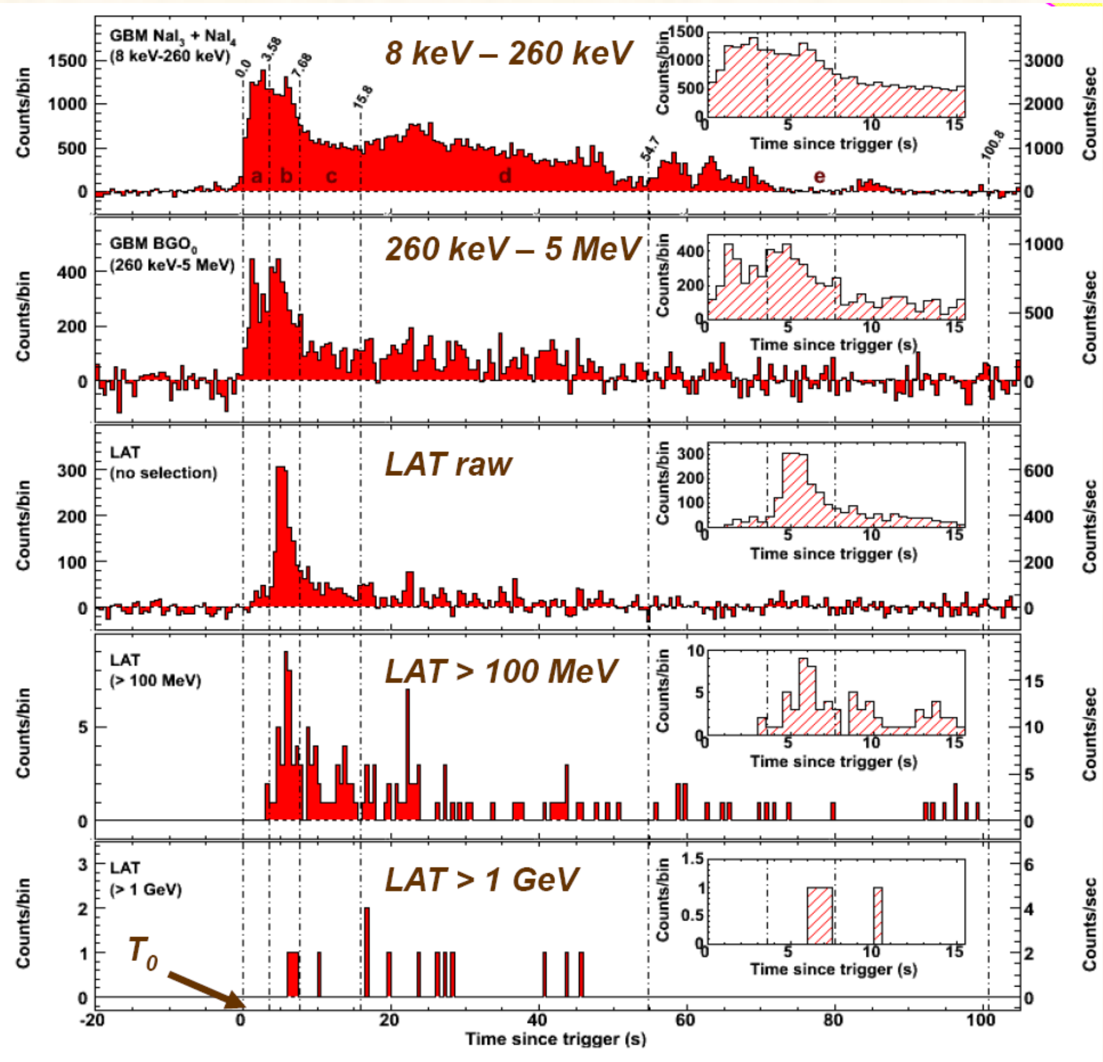


~ 300 GeV

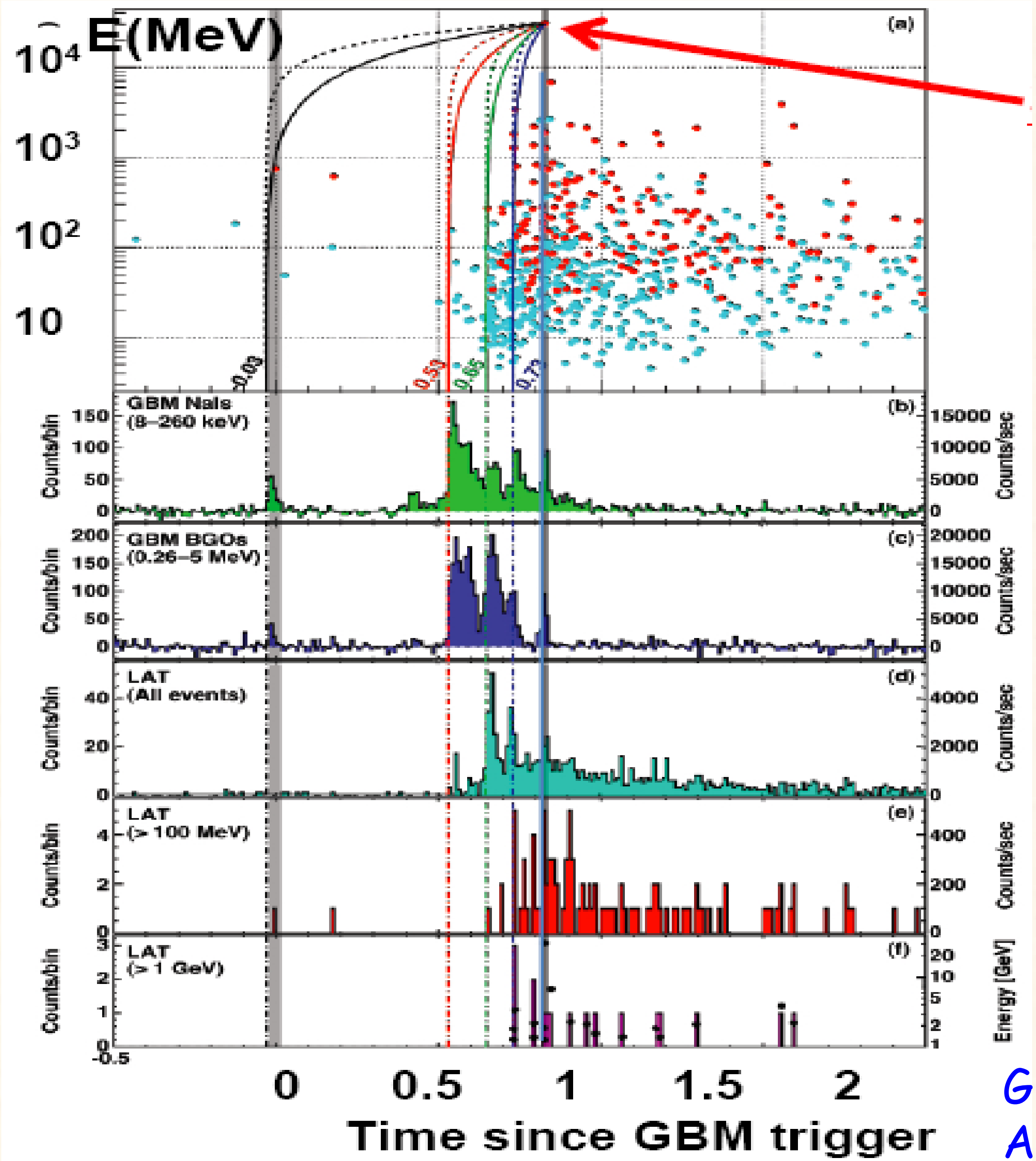
trigger photons ~ 0.1 MeV



Lag determinations



GRB080916C -- Abdo et al.'09, Science

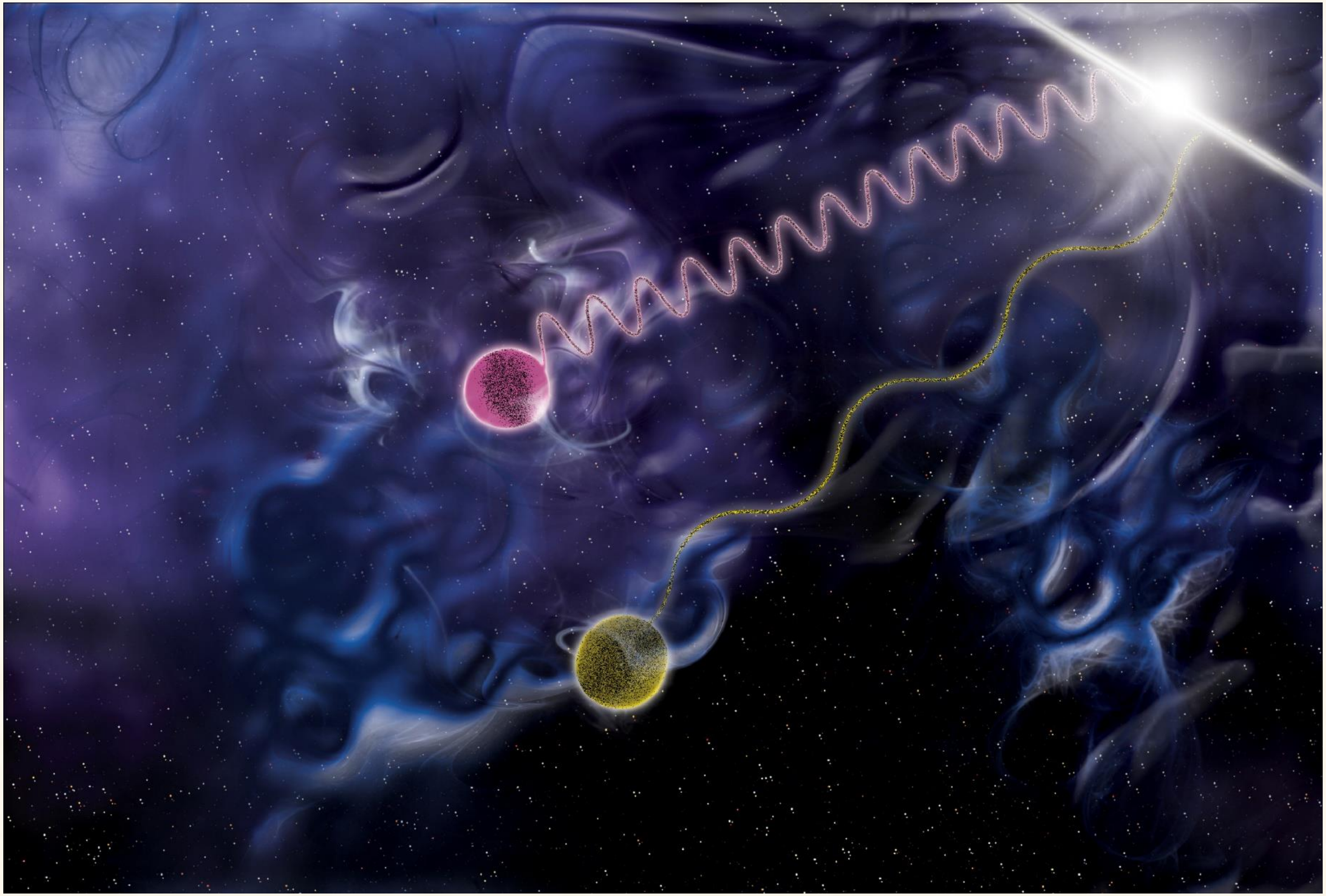


31 GeV

Time lags are affected both artificially and instrumentally

GRB090510
Abdo et al.'09, Nature

Time-lag by GRB



Four Fermi observations

the arrival of the highest energy photon to GBM trigger

GRBs	z	E (GeV)	$\Delta t_{\rm obs}$ (s)	$M_{\rm QG,L}$ (GeV/c^2)	$M_{\rm QG,Q}$ (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}

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

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

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

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

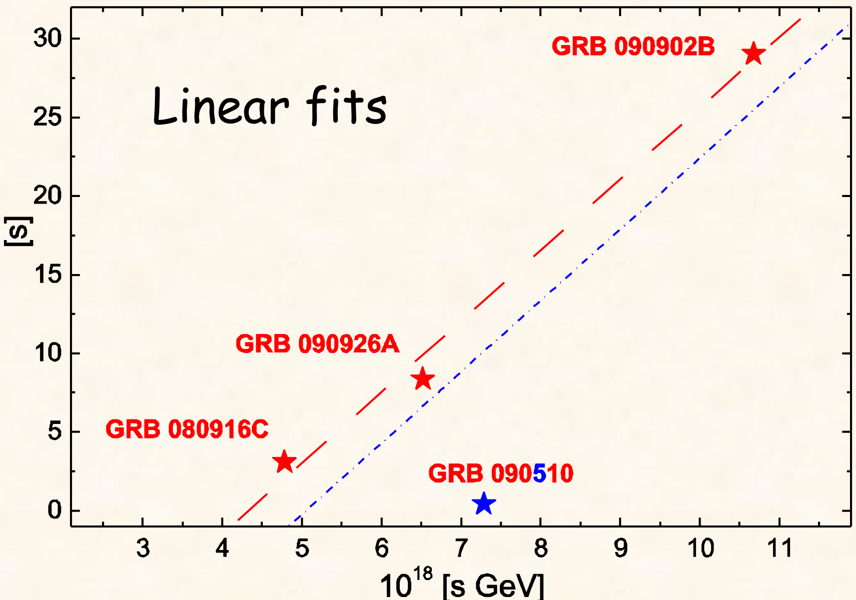
Separation of astrophysical time lags from LV delay

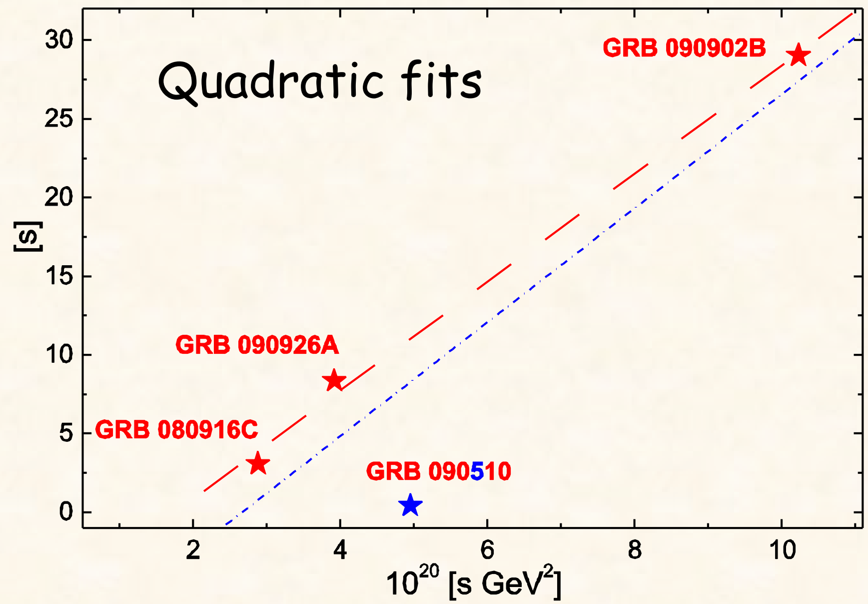
- imperfect knowledge of radiation mechanism of GRBs
- a survey of GRBs at different redshifts
  - the time lag induced by LV accumulates with propagation distance
  - the **intrinsic source** induced time lag is likely to be a distance independent quantity
- A robust survey [Ellis et al.'06 & 08, Astropart.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

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

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

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





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

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

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

An intuitive way to perform analysis

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

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

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

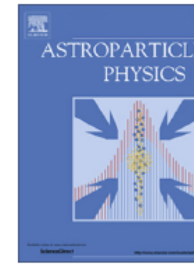
further development

Astroparticle Physics 61 (2015) 108–112

Contents lists available at ScienceDirect

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,*]

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

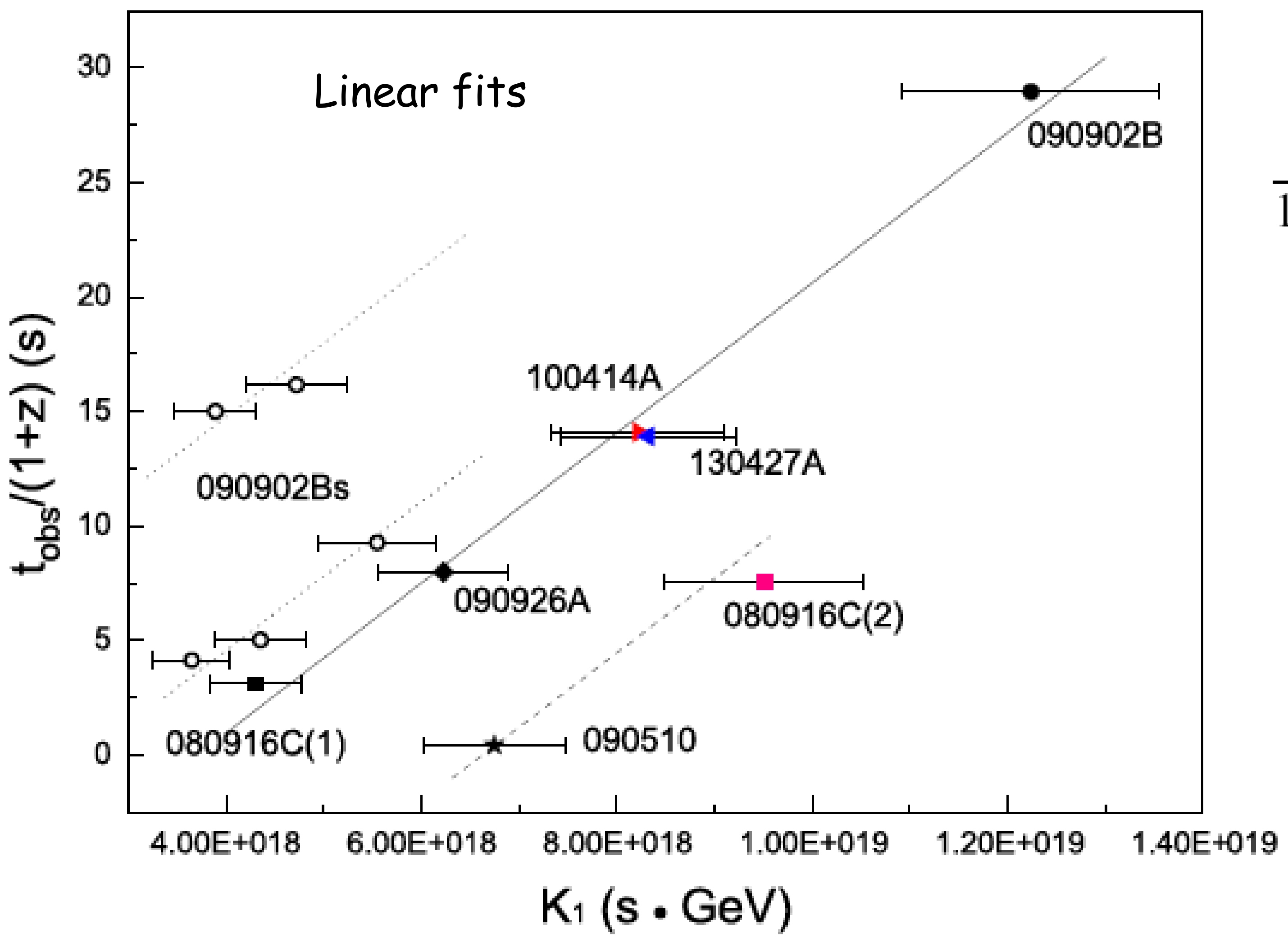
Table 1: The data of the GRBs with high energy photons and known redshifts.

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 · 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 · 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?

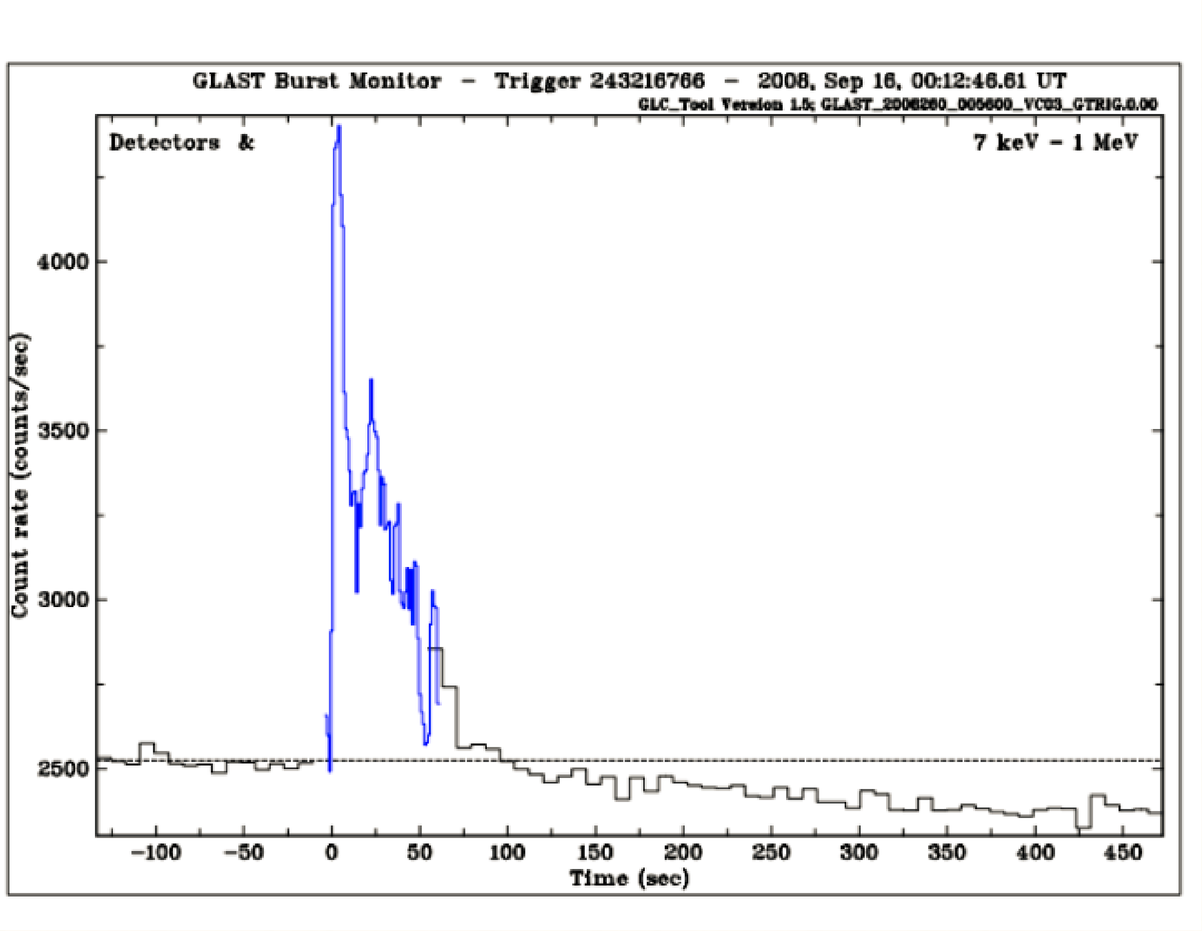
Trigger:

- 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 (2018) in press, 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

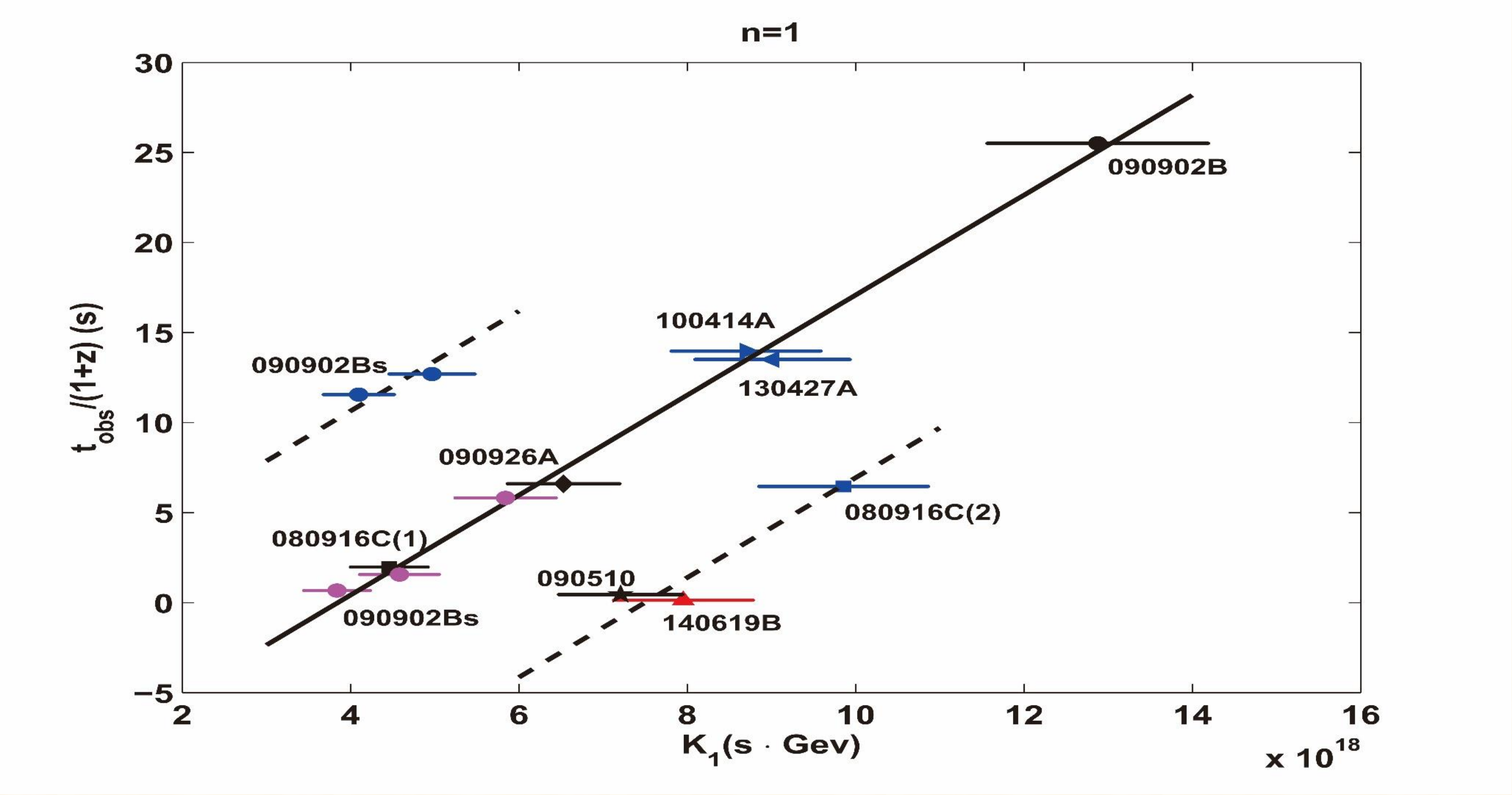
New Analysis of Data

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

GRB	z	t_{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 $\cdot$ 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

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Light speed variation from gamma ray burst GRB 160509A

CrossMark

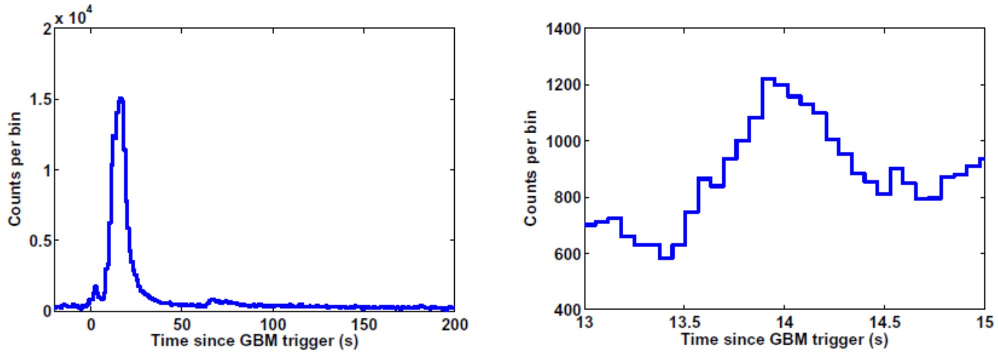
Haowei Xu [a], Bo-Qiang Ma [a,b,c,d,*]

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



(a) (b)

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_{peak} = 13.920 s.

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

E_{obs} / GeV	t_{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

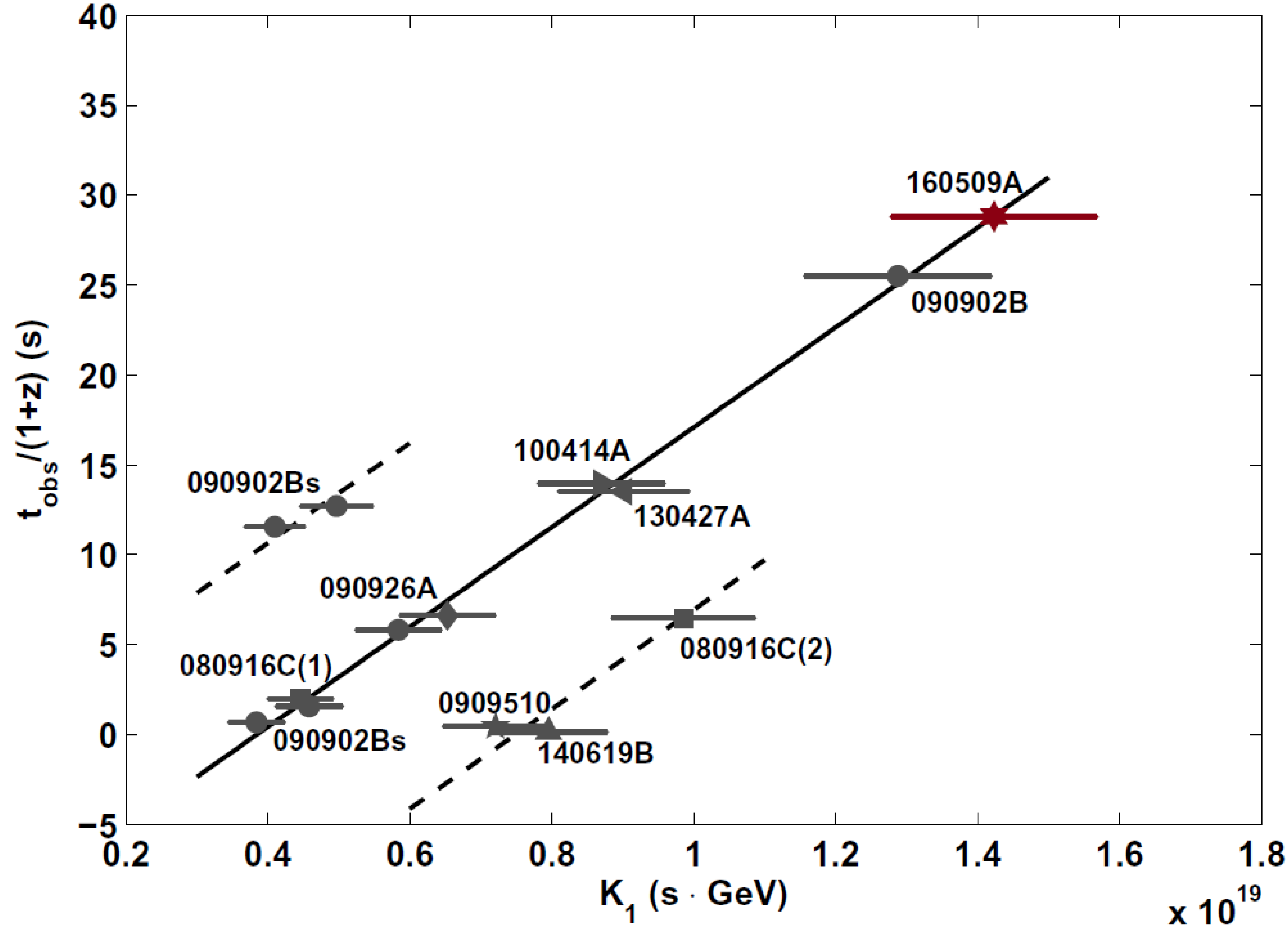
Table 2: Data of high energy photon event from GRB 160509A

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

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

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

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 Cosmology and Astroparticle Physics
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]

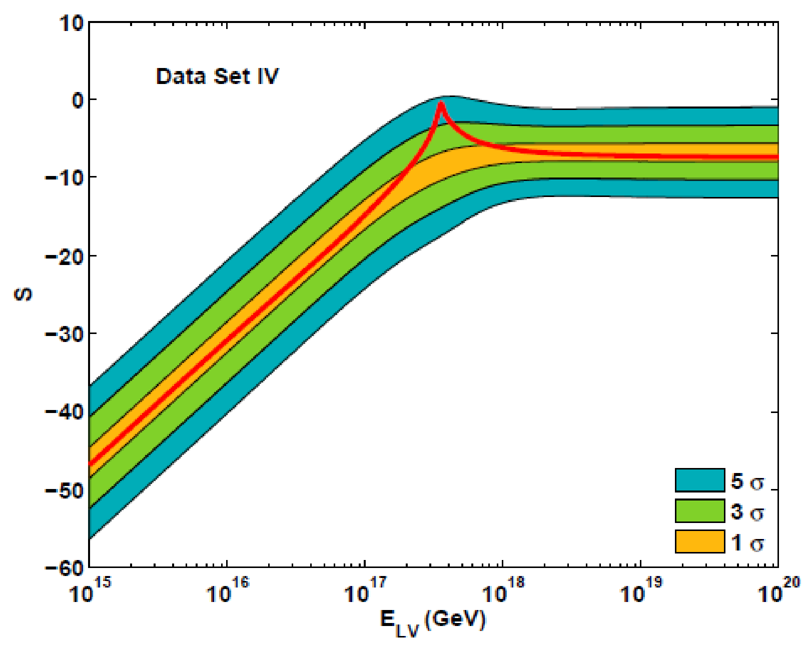
H.Xu, B.-Q.Ma, JCAP 1801 (2018) 050

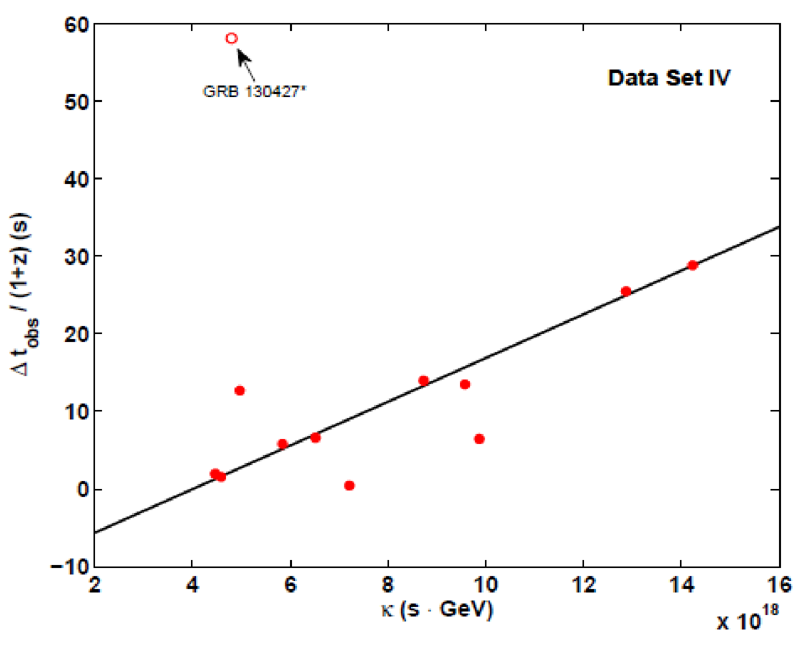
- **A general analysis on the data of 25 bright GRBs**
- **Allow a completed scan over all possibilities without bias**
- **The regularity exists at a significance of 3-5 σ**

new development

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

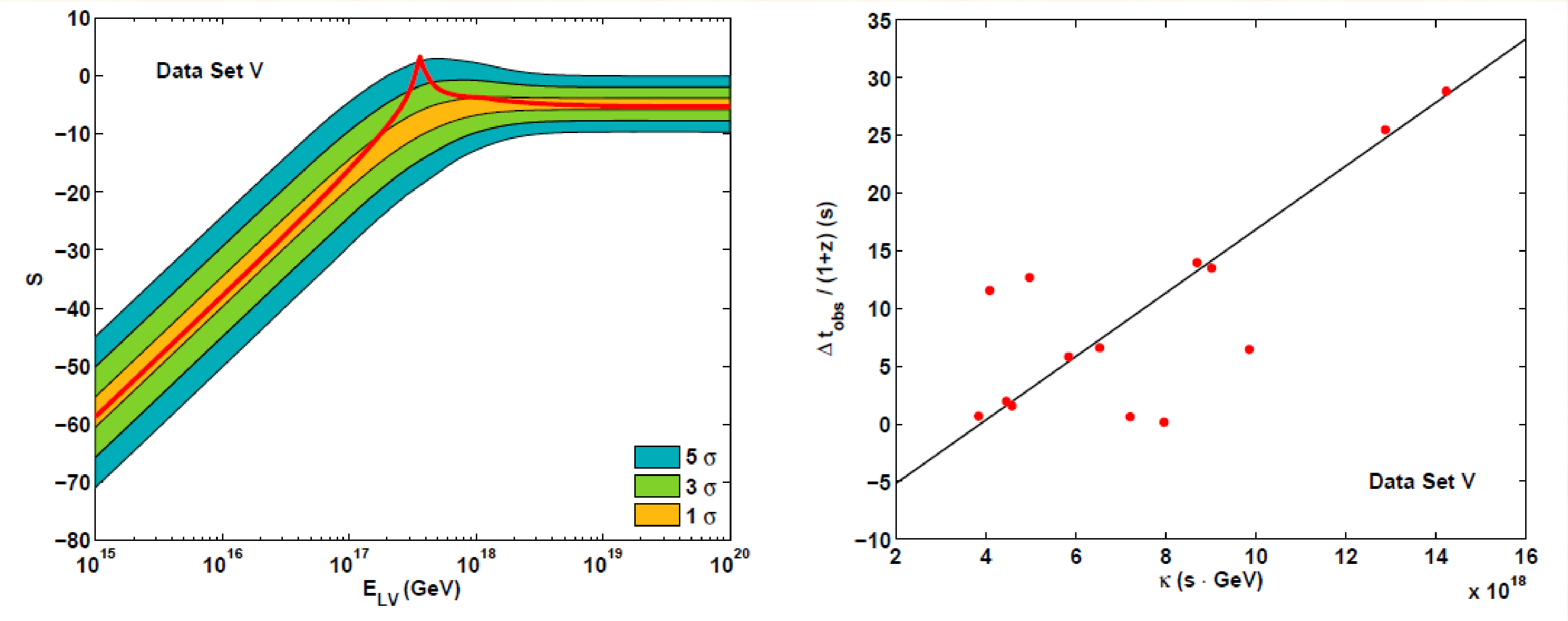
$$S(E_{\rm LV}) = \sum_{i=1}^{N-\rho} \log\left(\frac{\rho}{t_{i+\rho} - t_i}\right)$$





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 $E_{\mathrm{LV}} = 3.6 \times 10^{17}$ GeV determined by the GRB data.

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

Two options for light speed variation

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

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

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

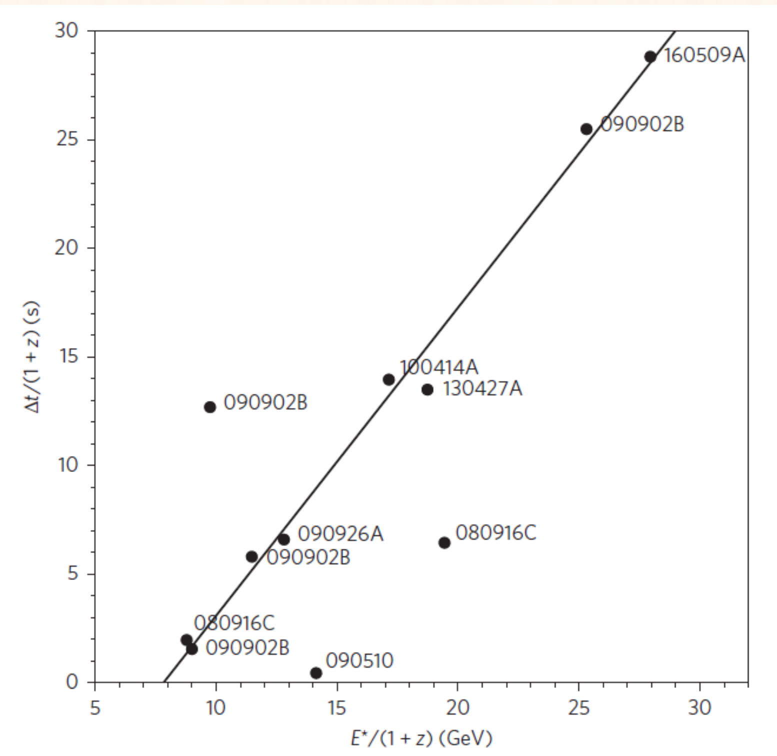
nature astronomy

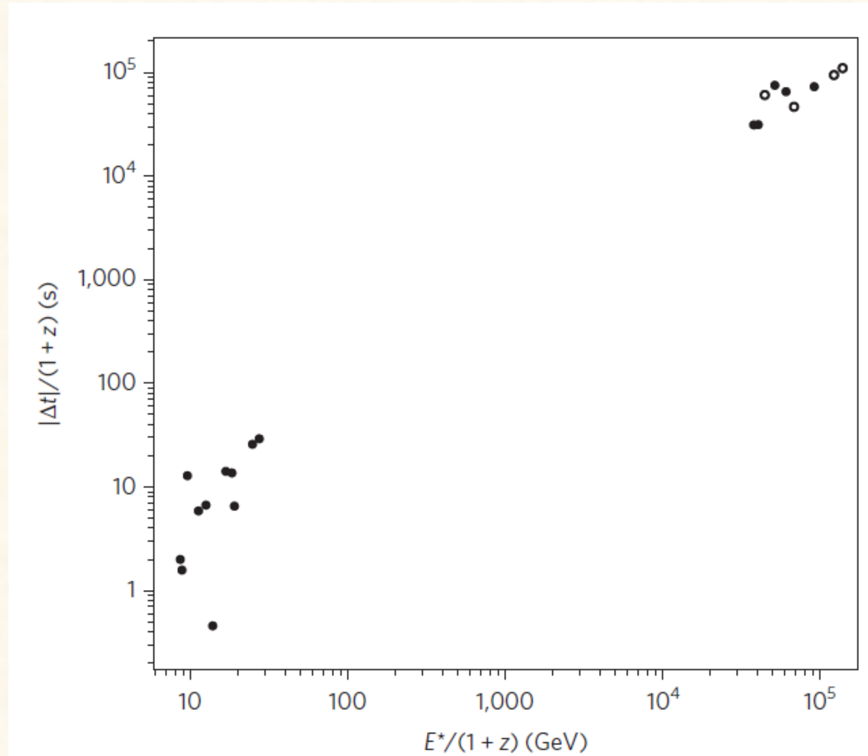
ARTICLES

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

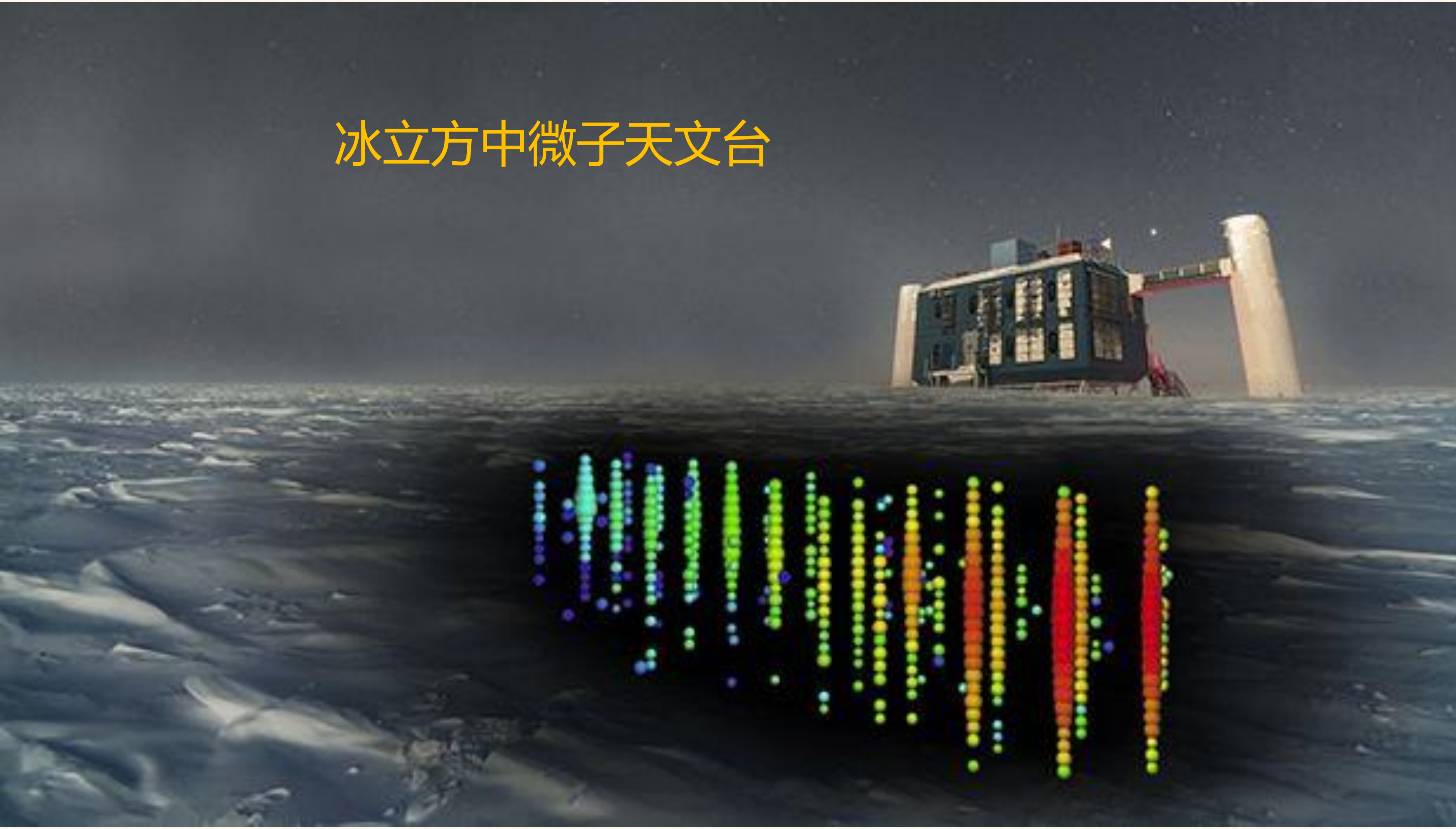
In vacuo dispersion features for gamma-ray-burst neutrinos and photons

Giovanni Amelino-Camelia[1,2]*, Giacomo D'Amico[1,2], Giacomo Rosati[3] and Niccoló Loret[4]





IceCube Neutrino Observatory



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.**

IceCube Neutrinos

- 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

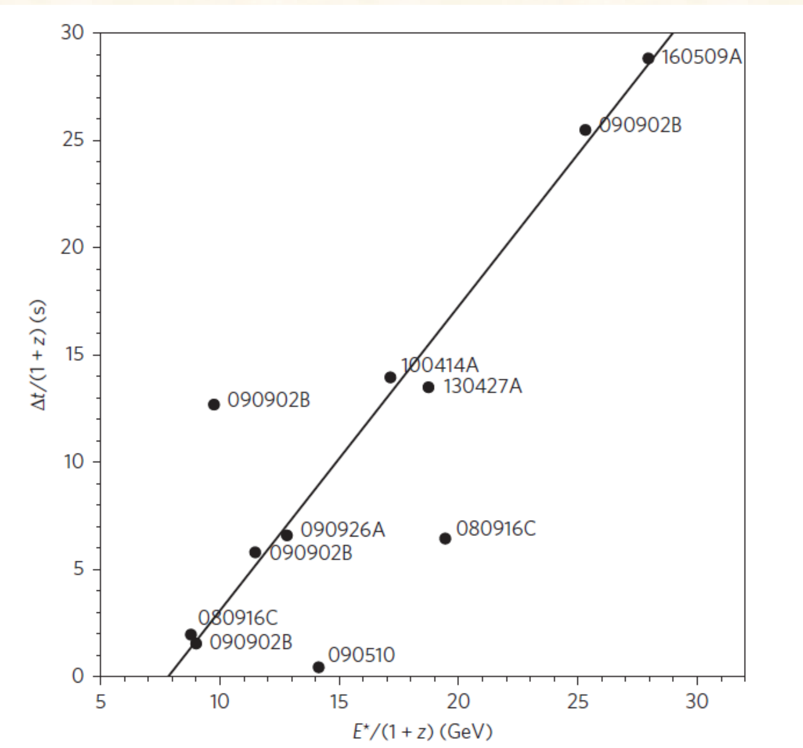
nature astronomy

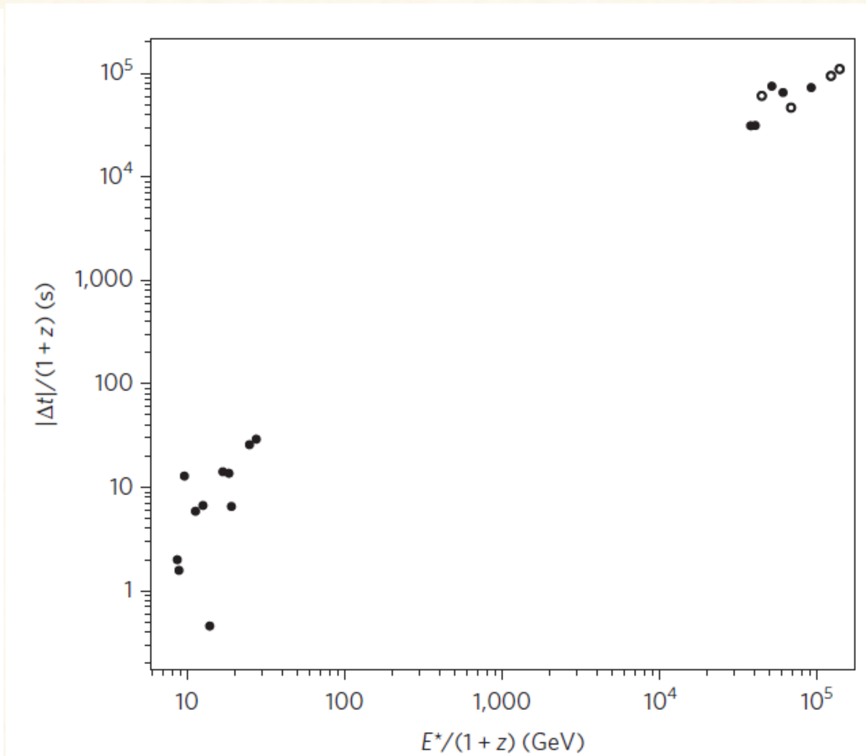
ARTICLES

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 Rosati[3] and Niccoló Loret[4]





Reanalysis of TeV Events

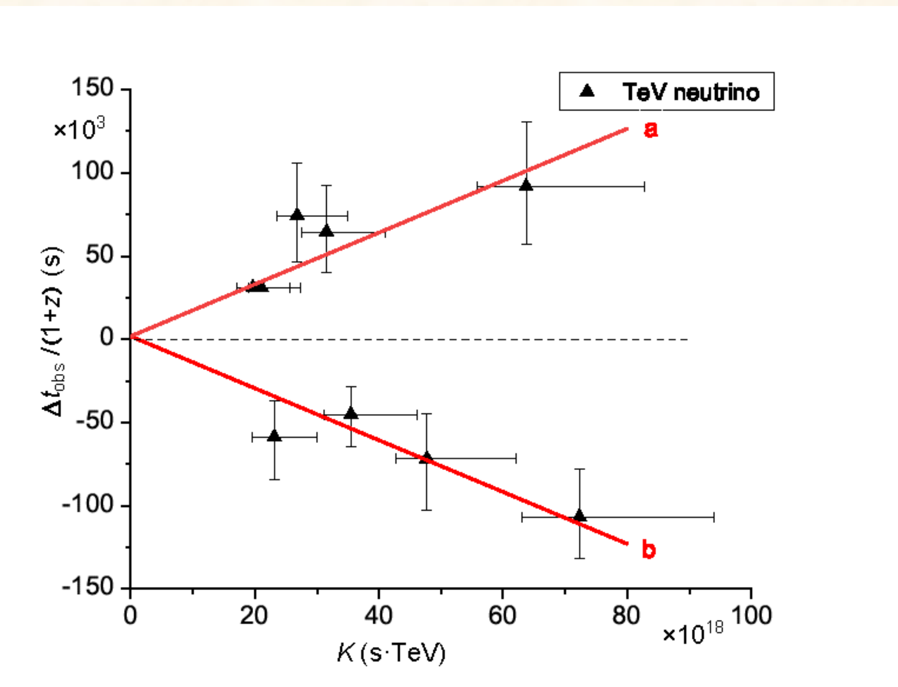
COMMUNICATIONS
PHYSICS

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]



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

Reanalysis of TeV Events

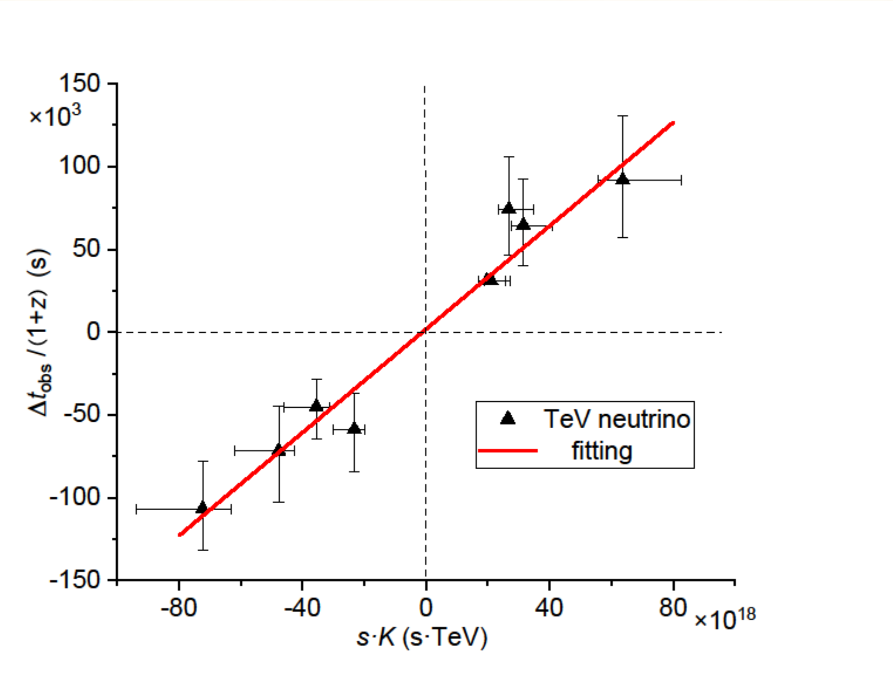
COMMUNICATIONS PHYSICS

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]



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

$$s = \pm 1$$

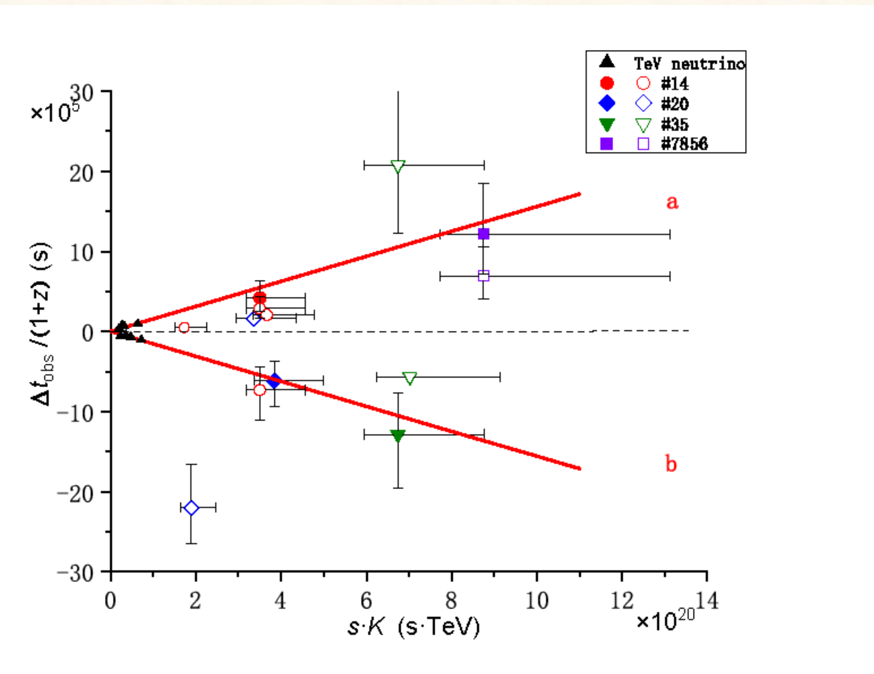
First Analysis of PeV Events

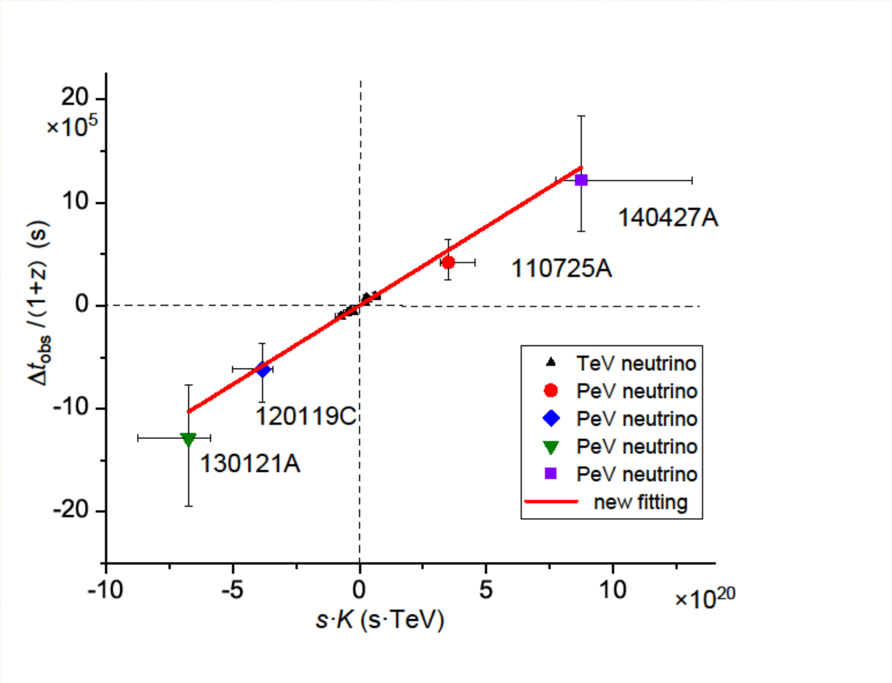
COMMUNICATIONS
PHYSICS

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]





Association of IceCube Neutrinos with GRBs

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

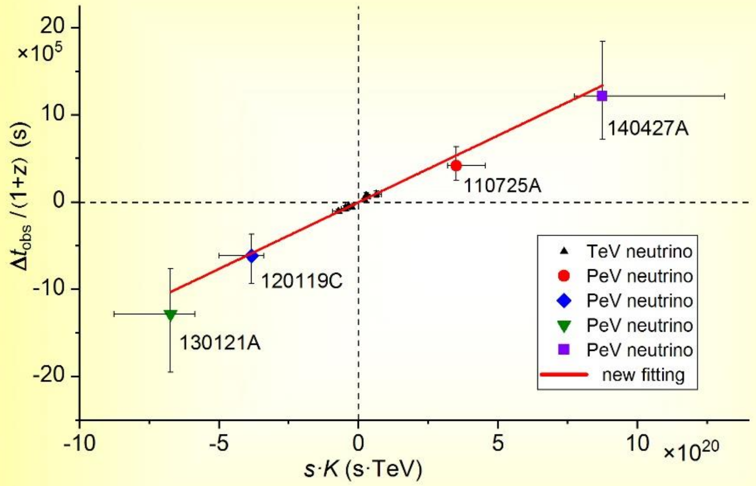
Table 3 The properties of PeV neutrino events with associated GRB candidates

	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

Summary 1: photons

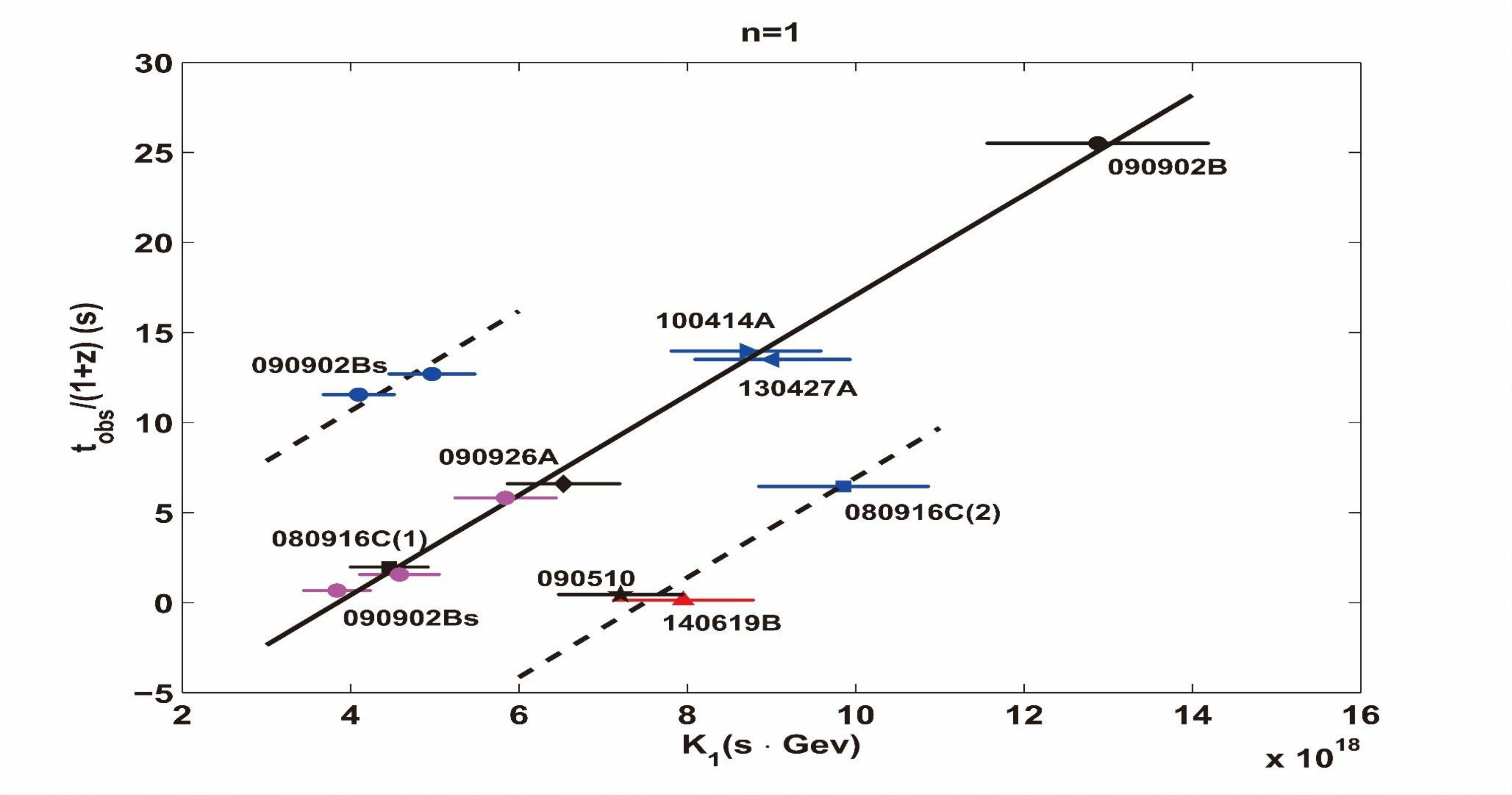
- We analyse the data of the energetic photons from the gamma-ray bursts (GRBs).
- We unveil a surprising regularity behind the data of these energetic photons.
- We find events to support the energy dependence of the light speed.
- The predictions from such scenarios are strongly supported by new GRB 160509A.
- A general analysis suggests a significance of 3-5 σ.

Summary 2: neutrinos

- We first associate all 4 IceCube events of PeV neutrinos with gamma-ray bursts (GRBs).
- We unveil a surprising regularity of these energetic neutrinos indicting Lorentz violation.
- We find different propagation properties between neutrinos and antineutrinos.
- We thus reveal the Charge, Parity, and Time violation.

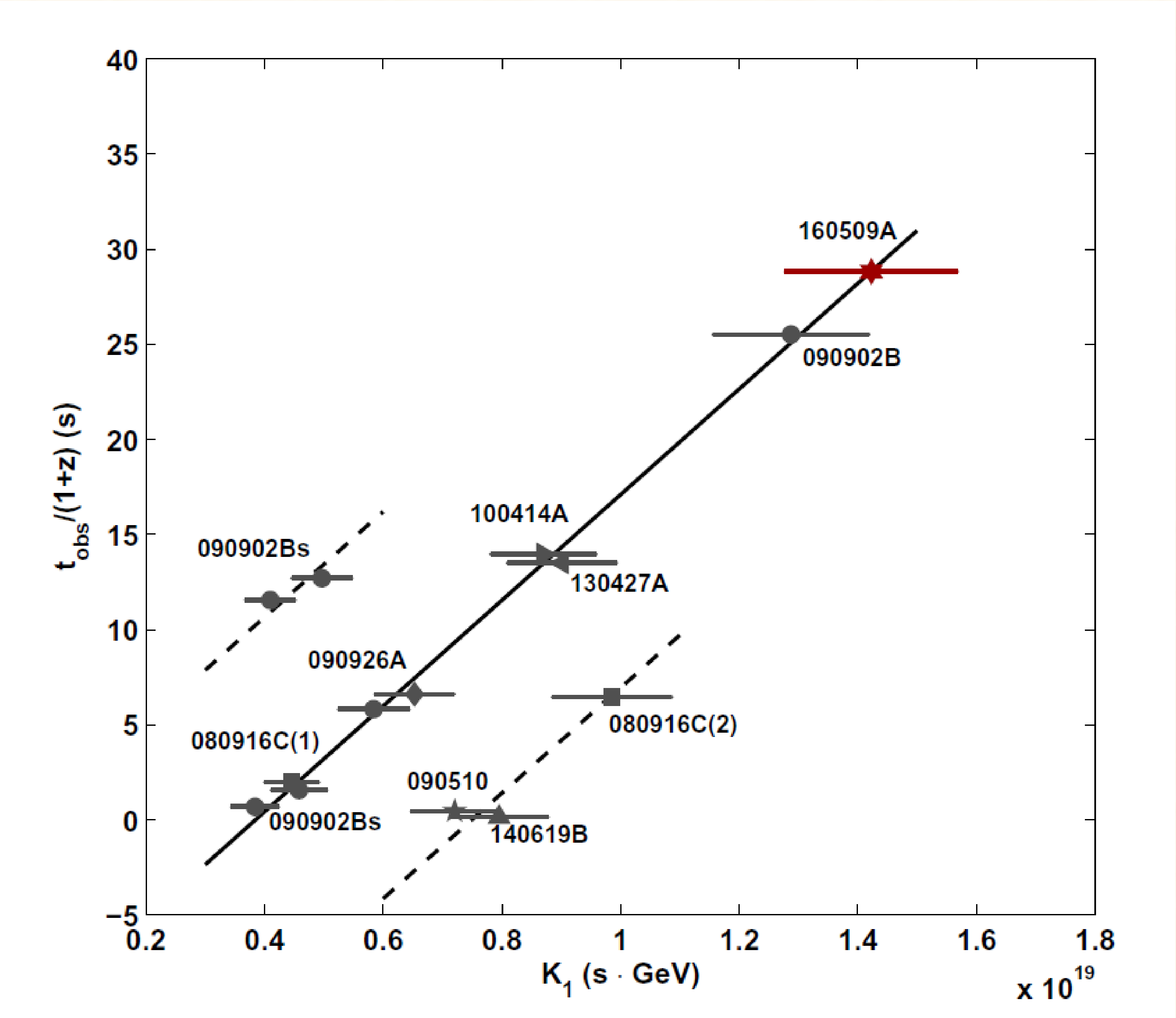
- H.Xu, B.-Q.Ma, APP 82 (2016) 72, arXiv: 1607.03203

Results from previous GRBs



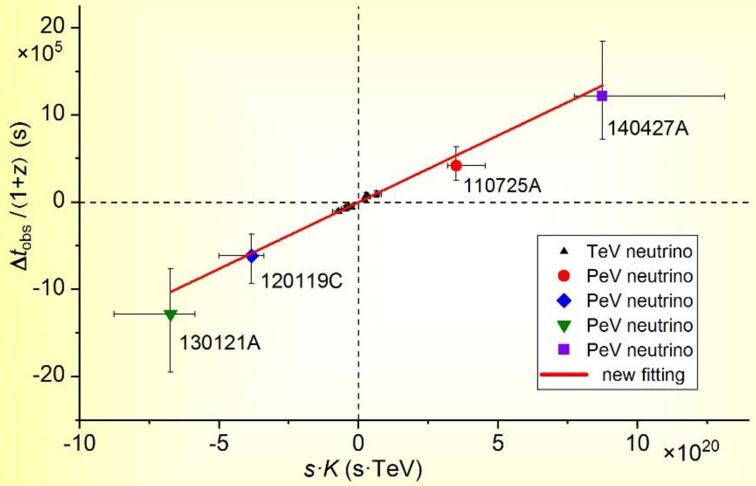
- H.Xu, B.-Q.Ma, Phys.Lett.B 760 (2016) 602, arXiv:1607.08043

New GRB: 160509A



CPT Violation from Cosmic Neutrinos:

Difference properties between neutrinos and antineutrinos.



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


Thanks 谢谢！