Cosmic Photons from LHAASO as Probes of Lorentz Invariance Violation

Bo-Qiang Ma（马伯强）

Peking University（北京大学）

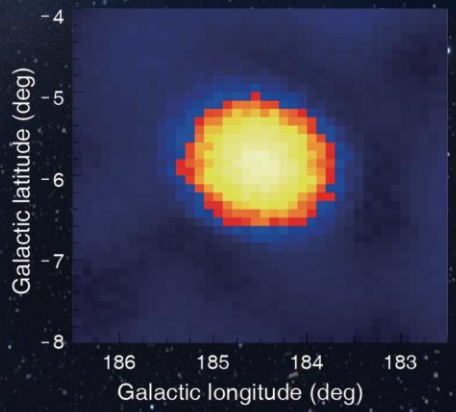
October 29, 2021

TeV Particle Astrophysics 2021 (TeVPA2021)

Chengdu, China

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, ……

LHAASO discovery of PeV photons



LHAASO J2226+6057

LHAASO J2018+5157

LHAASO J2032+4102

LHAASO J2018+3651

LHAASO J1956+2845

LHAASO J1929+1745

LHAASO J1908+0621

LHAASO J1849−0003

LHAASO J1843−0338

LHAASO J1839−0545

LHAASO J1825−1326

Nature 594 (2021) 7861

C.Li and B.-Q.Ma, PRD 104 (2021) 063012, arXiv:2105.07967

LHAASO Observation of Cosmic Photons

versus

Lorentz Violation

- **Highest energy photon (E=1.4 PeV) observed by human being**
- **Strong constraint on superluminal Lorentz violation**
- **Permission for subluminal Lorentz violation**
- **Towards a string theory model for space-time foam**

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 dependenc

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

C.Li and B.-Q.Ma, PRD 104 (2021) 063012, arXiv:2105.07967

Strong Constraint on Superluminal Lorentz Violation

- **Photon decay due to superluminal LV**

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

- **Constraint from LHAASO discovery of E=1.42 PeV photon**

$$E_{\rm LV}^{(\rm sup)} \gtrsim 9.57 \times 10^{32}\ {\rm eV} \left(\frac{E_\gamma}{\rm PeV}\right)^3$$

$$E_{\rm LV}^{(\rm sup)} \gtrsim 2.74 \times 10^{24}\ {\rm GeV}$$

- **Stringent constraints on certain LV theories**

- **Support for the space-time foam prediction: no photon decay**

C.Li and B.-Q.Ma, PRD 104 (2021) 063012, arXiv:2105.07967

Strong Constraint on Superluminal Lorentz Violation

- **Constraint from LHAASO discovery of E=1.42 PeV photon**

$$E_{\rm LV}^{(\rm sup)} \gtrsim 9.57 \times 10^{32}\ {\rm eV} \left(\frac{E_\gamma}{\rm PeV}\right)^3$$

$$E_{\rm LV}^{(\rm sup)} \gtrsim 2.74 \times 10^{24}\ {\rm GeV}$$

- **More detailed analysis of data by LHAASO Collaboration**

  LHAASO, arXiv:2106.12350

- **Similar analysis on LHAASO data by**

  Chen et al., arXiv: 2105:07927, CPC published

Energy limitation of cosmic photons

from standard special relativity

cosmic photon annihilation with CMB

$$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$$

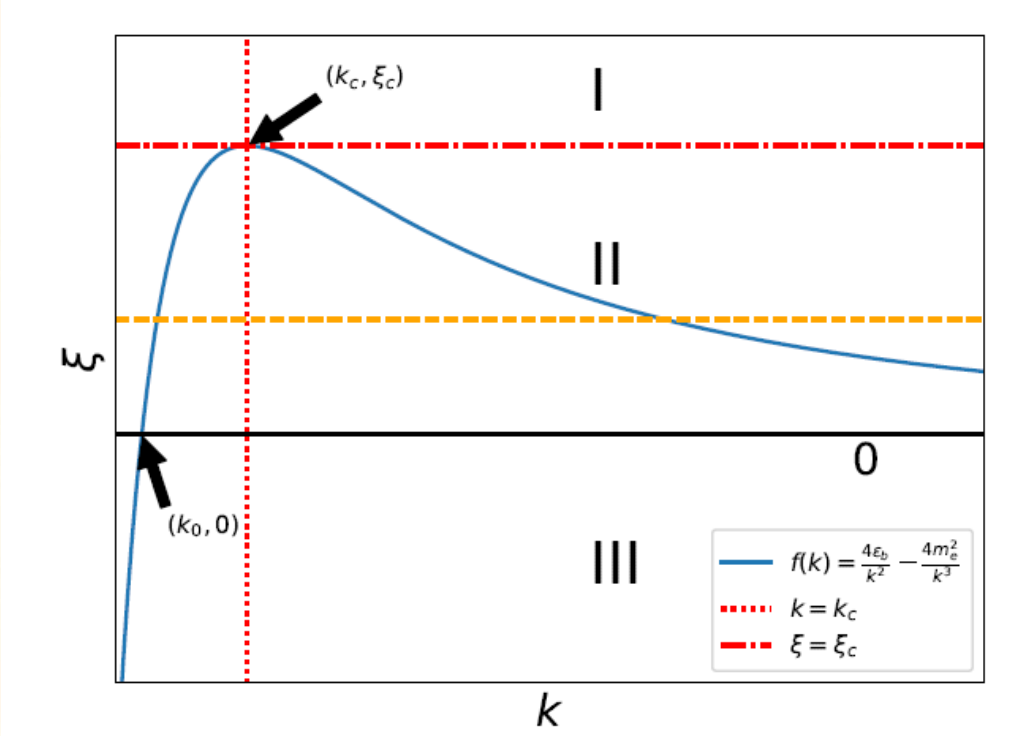
$$4E\varepsilon_{\gamma} \approx (2m_e)^2 \qquad E \sim 4\times10^{14}\ \text{eV}$$

Attenuation of above threshold E=411 TeV photons

H.Li and B.-Q.Ma, JHEAP 32(2021)1, arXiv:2105.06647

$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$ H.Li and B.-Q.Ma, JHEAP32 (2021)1, arXiv:2105.06647

Threshold Anomalies of Cosmic Photons due to Lorentz Violation



Case I Optical Transparency, $0 < \xi_c^{-1} = E_{LV} < 4.5 \times 10^{23}$ GeV

Case II Reappearance of UHE Photons, $\xi_c^{-1} = E_{LV} > 4.5 \times 10^{23}$ GeV

Case III Threshold Reduction, $\xi_c^{-1} = E_{LV} < 0$

H.Li and B.-Q.Ma, JHEAP32(2021)1, arXiv:2105.06647

Threshold Anomalies of Cosmic Photons due to Lorentz Violation

- **Photon annihilation is forbidden due to subluminal Lorentz violation.**

$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

- **We predict optical transparency of cosmic photons for subluminal LV scale less than** $\xi_c^{-1} \simeq 4.5 \times 10^{23}\ \mathrm{GeV}$

- **Any observation of above threshold E=411 TeV photons from extragalactic sources can be considered as signals for new physics beyond special relativity.**

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

Breakthrough: LHAASO discovery of PeV photons

- **Observation of photons with energies above the threshold of photon annihilation process**
- **Permission for the subluminal Lorentz violation:**

  an upper bound with $E_{\rm LV}^{(\rm sub)} < \xi_c^{-1} \simeq 4.5 \times 10^{23}\ \rm GeV$

  are compatible with the observation of PeV photons
- **The sources for the above threshold photons:**

  galactic or extragalactic?
- **Further studies are necessary to identify sources for PeV photons**

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

Energy limitation of cosmic photons

from standard special relativity

cosmic photon annihilation with EBL (extragalactic background light)

$$\gamma\gamma_{\mathrm{b}} \rightarrow e^{+}e^{-}$$

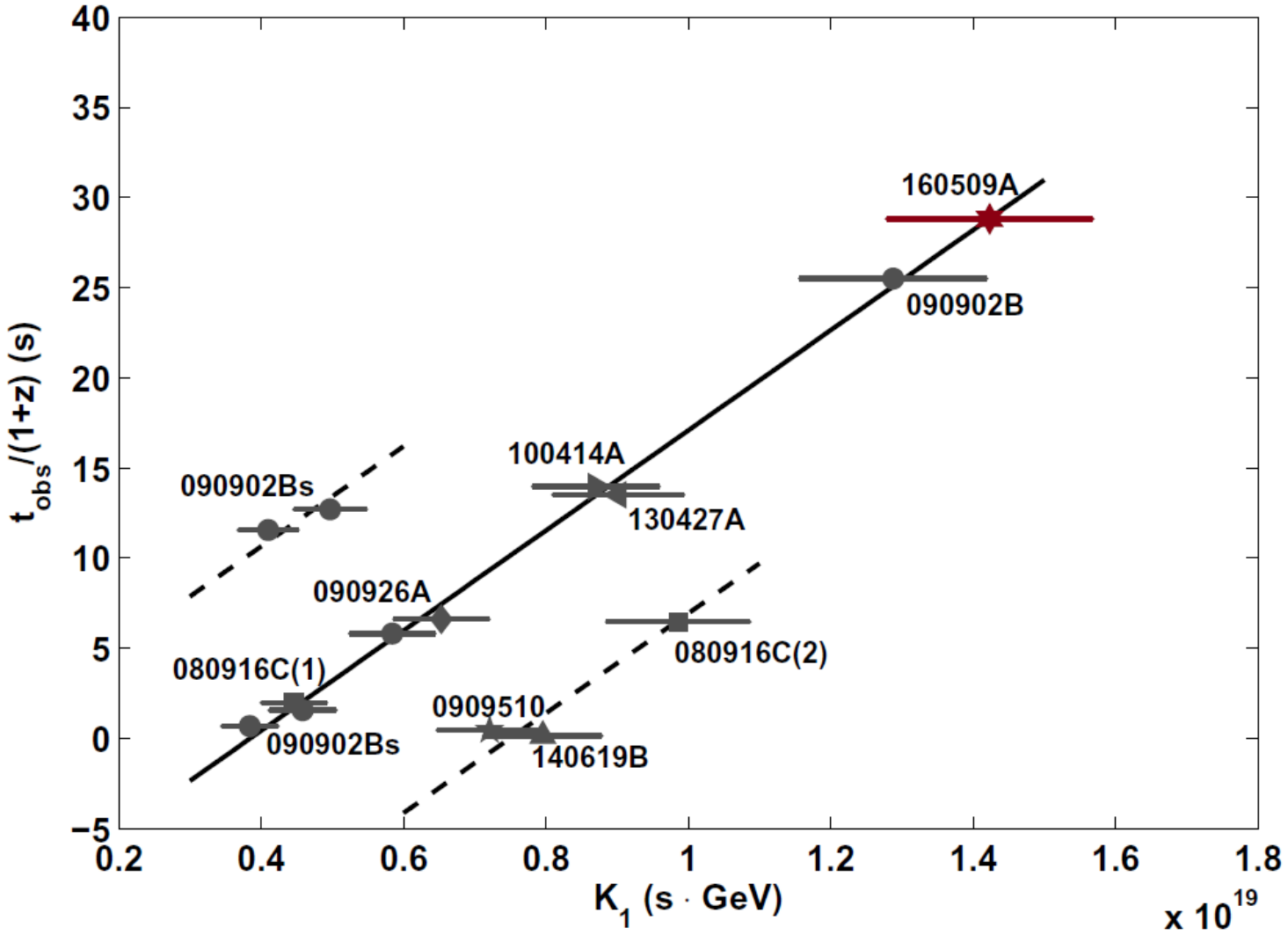
$4E\varepsilon_{\gamma} \approx (2m_e)^2$ $\quad E \sim 4\times10^{14}$ eV ⟸ CMB

EBL: Attenuation of above threshold E=260 GeV photons

H.Li and B.-Q.Ma, JHEAP 32(2021)1, arXiv:2105.06647

- 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

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

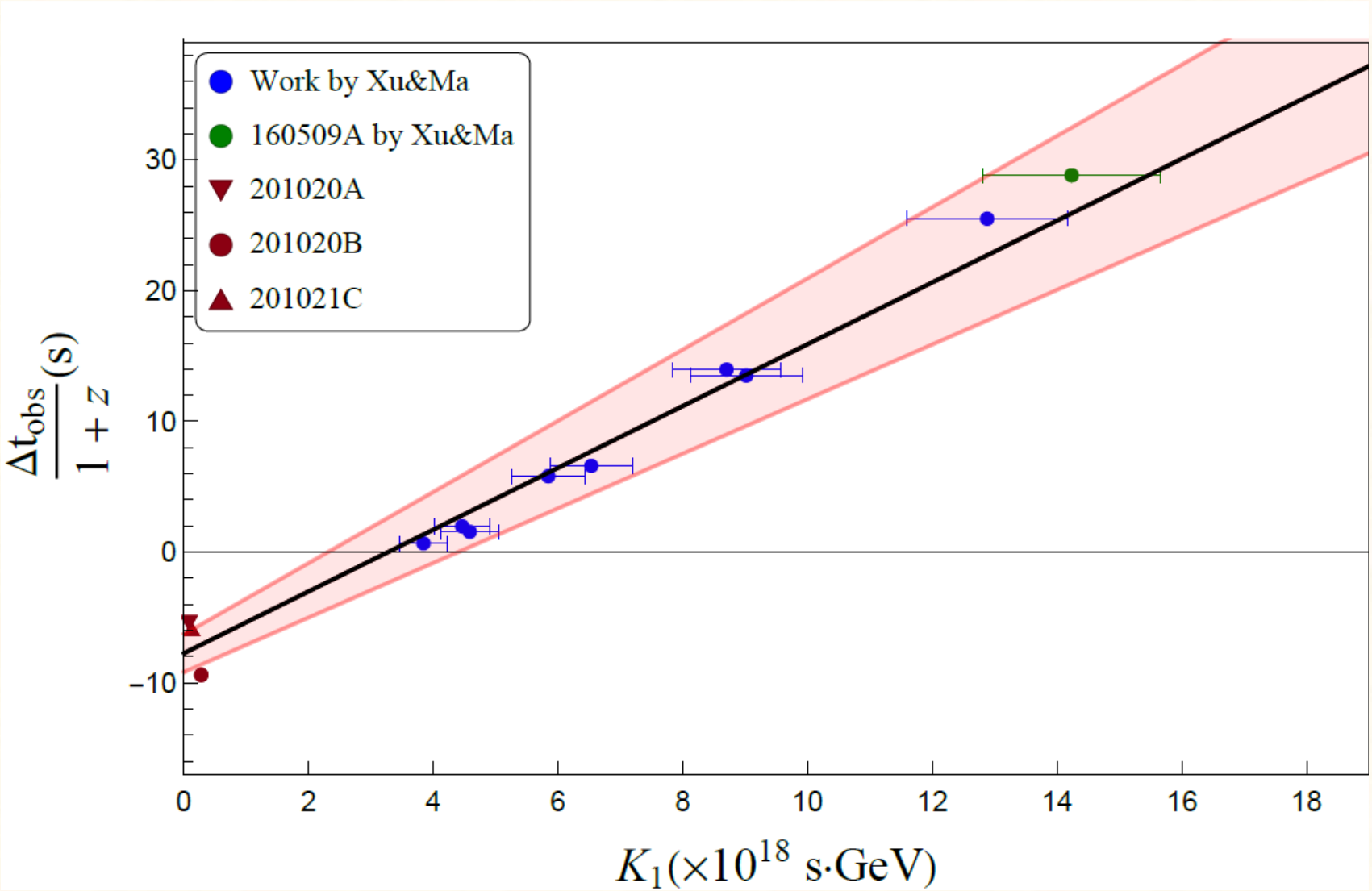
$$E_{\mathrm{LV}} = 3.60 \times 10^{17}\ \mathrm{GeV}$$

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



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

Predictions of LV features from space-time foam

- Linear energy dependence of light speed variation
- Subluminal Lorentz violation
- Photons are stable, no photon decay
- No birefringence for photon propagation in vacuum

Predictions are consistent with all current observations including a subluminal light speed variation

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

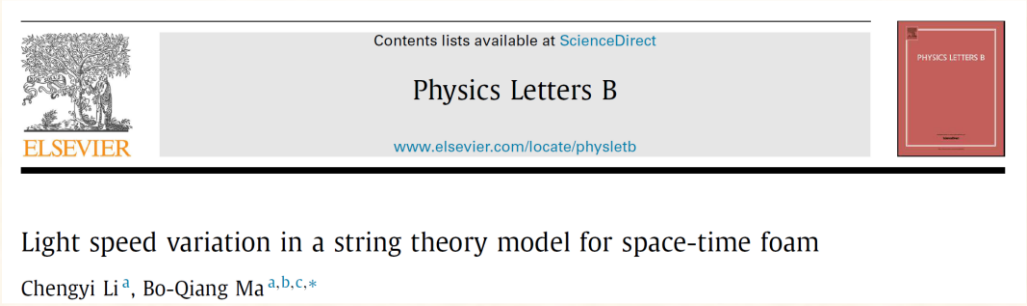
The string theory model of space-time foam

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.



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

Summary

- High energy cosmic photons provide opportunity to study the Lorentz violation of photons.
- The LHAASO observation of 1.4 PeV photon puts strong constraint on superluminal Lorentz violation.
- Subluminal Lorentz violation permits the above threshold (E=410 TeV) photon events:

  LHAASO event of E=1.4 PeV=1400 TeV

- Combined with the suggestion for a subluminal light speed variation from analyses of GRB data, we predict the optical transparency of cosmic photons .
- Our prediction of optical transparency of cosmic photons can be tested by LHAASO observation of any above threshold photons from extragalactic sources.