Lorentz Violation from High Energy Cosmic Photons with LHAASO new results

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In collaboration with Zhi Xiao, Lijing Shao, Shimin Yang, Lingli Zhou, Haowei Xu, Yunqi Xu, Nan Qin, Shu Zhang, Yue Liu, Yanqi Huang, Xinyi Zhang, Hao Li, Yingtian Chen, Chengyi Li, Jie Zhu, ……

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

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

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

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

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

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

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Formulas in our analysis of LV parameter

linear and quadratic energy dependence

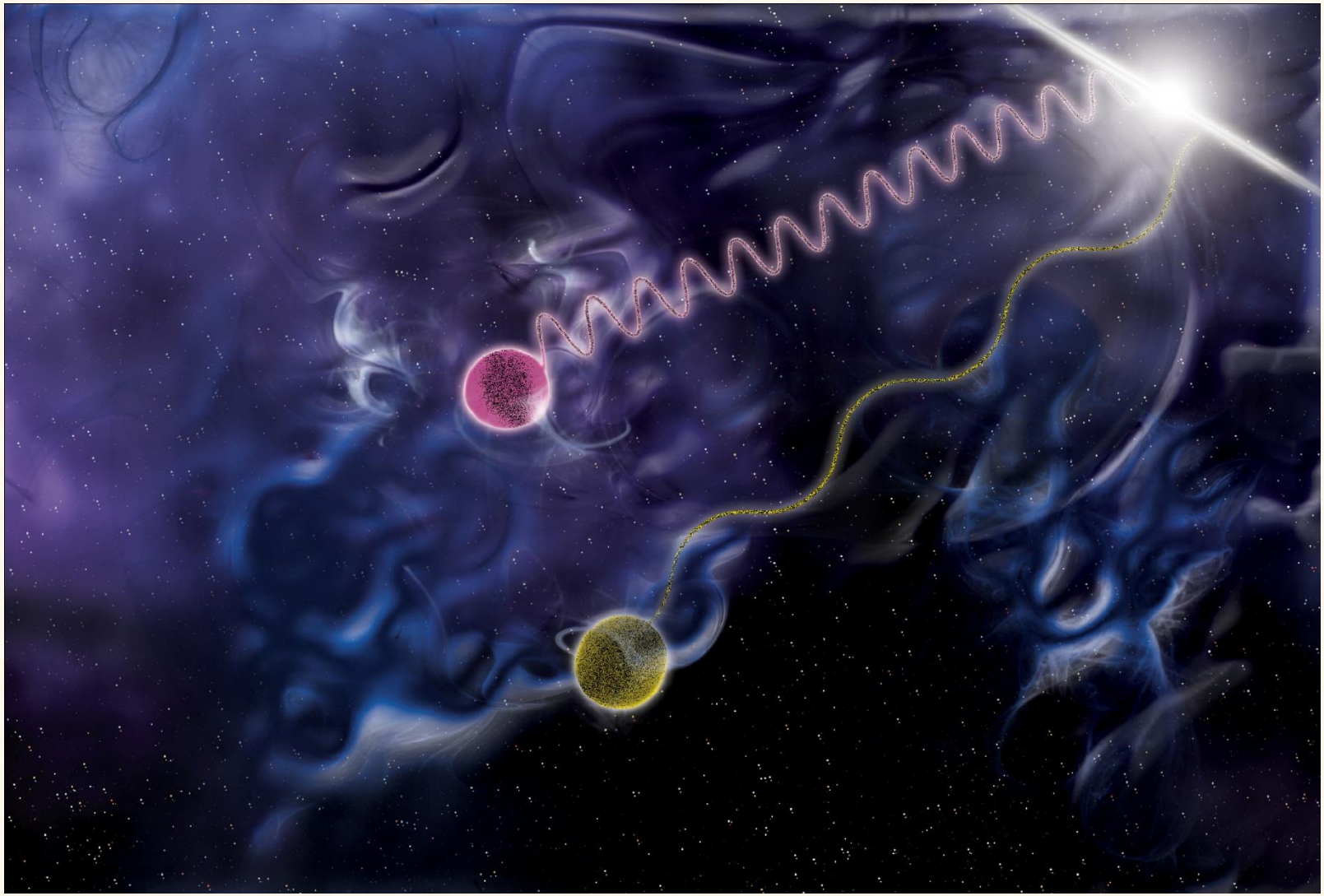
$$v(E) = c_0\left(1 - \frac{E}{M_{\mathrm{QG}}c^2}\right)$$ N=1

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

$$M_{\mathrm{QG}}c^2 = E_{\mathrm{LV}}$$ **Lorentz Violation or Light-speed Variation**

- 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 GRB



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

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

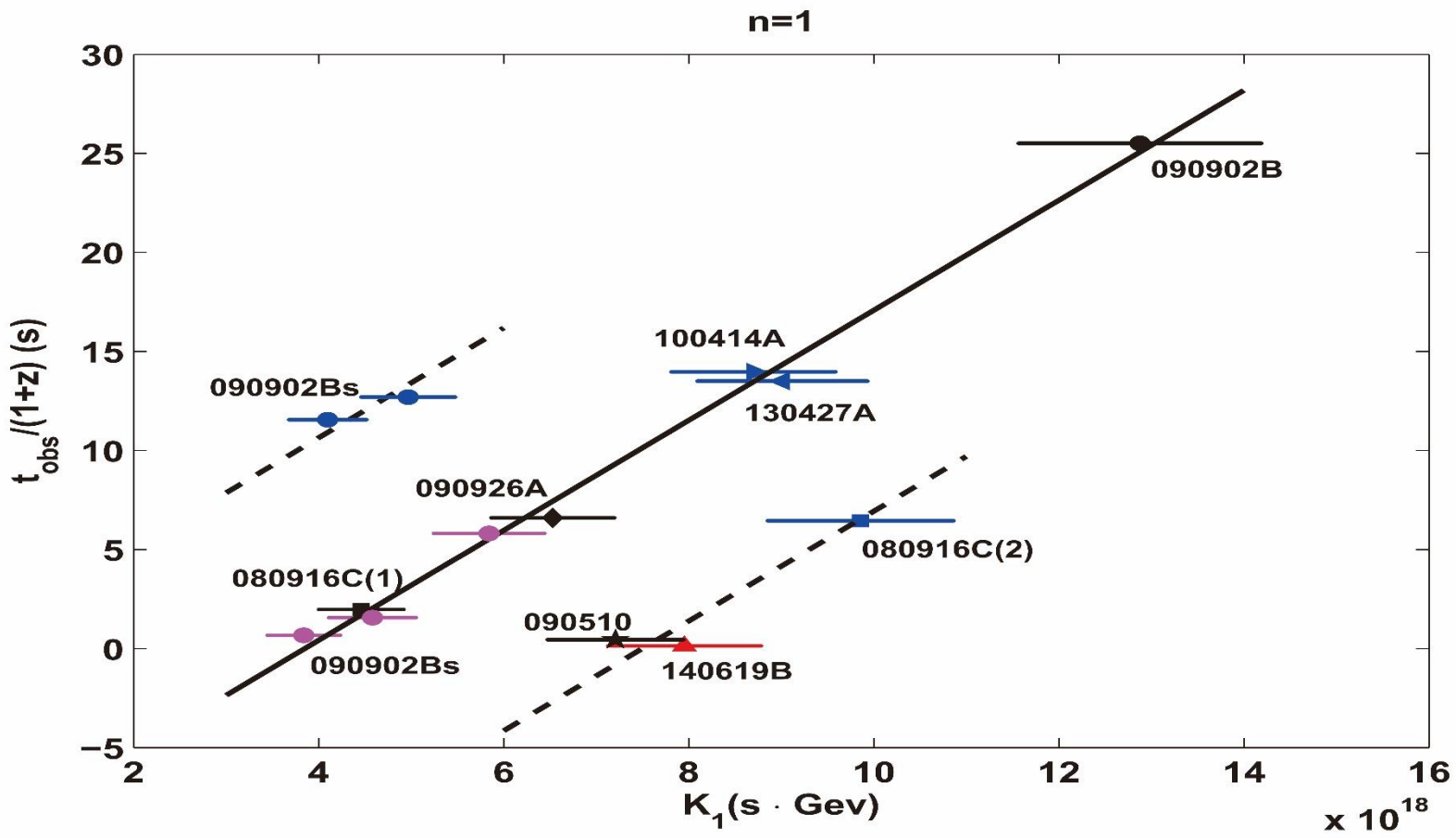
New Analysis of Data

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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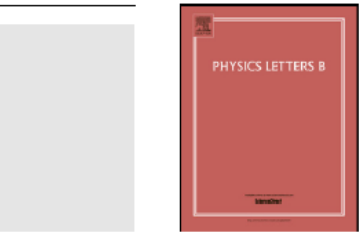


Light speed variation from gamma ray burst GRB 160509A

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

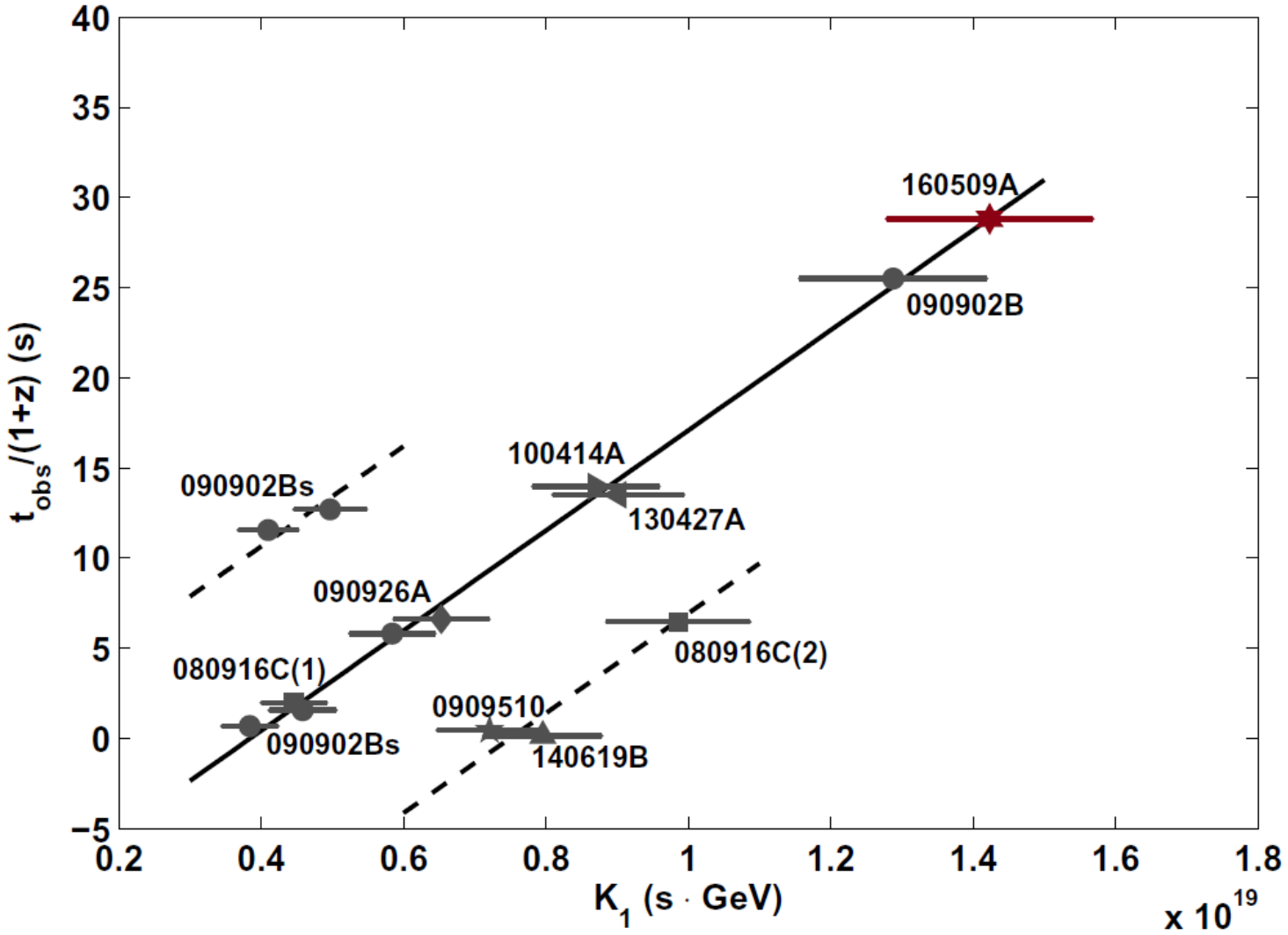
Table 2: Data of high energy photon event from GRB 160509A

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 $\cdot$ GeV)
160509A	1.17	76.506	13.920	51.9	112.6	28.812	14.2

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

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

New GRB: 160509A



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

New GRB: 160509A

we find evidence

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

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

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

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.

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**
- **Require subluminal Lorentz violation**
- **Leading towards a string theory model for space-time foam**

Cosmic microwave background (CMB)

Discovered in 1965 by Penzias and Wilson

as evidence of relic photons from the big bang

temperature $T = 2.73\,\mathrm{K}$

photon number density $n_\gamma = 413\ \mathrm{photon/cm}^3$

mean energy per photon $\varepsilon_\gamma = 6.35 \times 10^{-4}\ \mathrm{eV}$

Energy limitation of cosmic photons

cosmic photon annihilation with CMB

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

$$4E\varepsilon_{\gamma} \approx (2m_e)^2 \qquad E \sim 4\times 10^{14}\ \text{eV}$$

Attenuation of above threshold E=370 TeV photons

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.**

- **Any observation of above threshold E=370 TeV photons from extragalactic sources can be considered as signals for new physics beyond special relativity.**

Summary

- High energy cosmic photons provide opportunity to study the Lorentz violation properties of photons.
- We reveal a light speed variation from analysis of GRB data.
- The LHAASO observation of 1.4 PeV photon puts strong constraint on superluminal Lorentz violation.
- Subluminal Lorentz violation is required to explain the above threshold (E=370 TeV) photon events:

  LHAASO event of E=1.4 PeV=1400 TeV

- Our prediction of optical transparency of cosmic photons can be tested by LHAASO observation of any above threshold photons from extragalactic sources.