Searching New Physics from LHAASO Observations of High Energy Cosmic Photons

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(Xian Technological Univ. , July 24-28, 2023)

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, ……

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: 10~100 GeV or higher to multi-TeV

  Cosmic neutrinos with much higher energy: ~TeV to PeV

- **New physics from cosmic photons and neutrinos:**

  Lorentz violation

  CPT violation

  Axion

Modified photon dispersion relation from LV

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

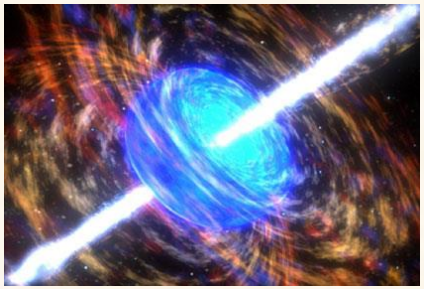
$$\sqrt{\hbar c / G} \simeq 1.22 \times 10^{19}\ \mathrm{GeV/c^2}$$

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)

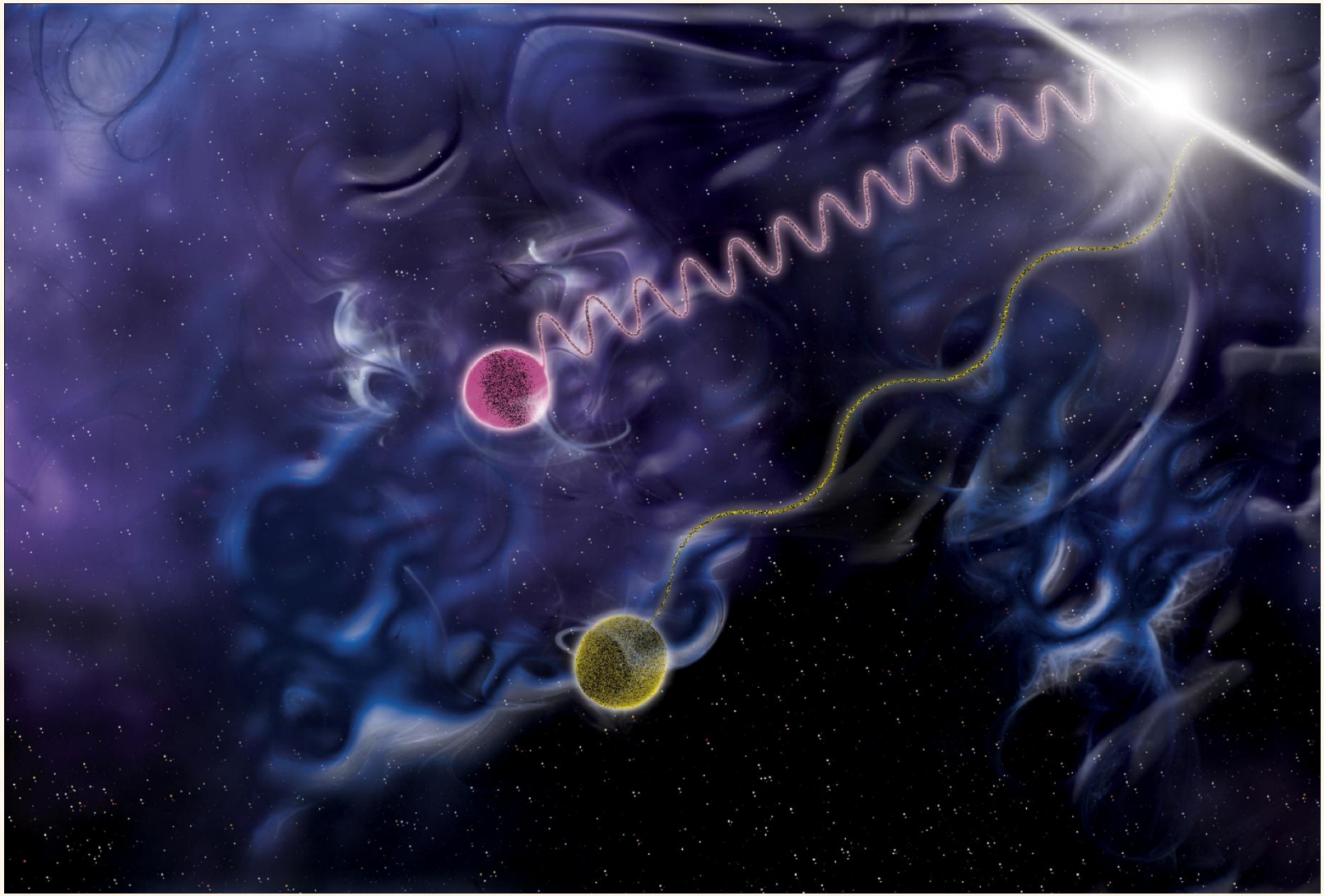


- The most energetic astrophysical process except the Big Bang
- 2 types [Piran'05, Rev. Mod. Phys.]
  - long GRBs: duration > 2 s; collapses of massive rapidly rotating stars
  - short GRBs: duration < 2 s; coalescence of two neutron stars or a neutron star and a black hole
- Long distance from detector:

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

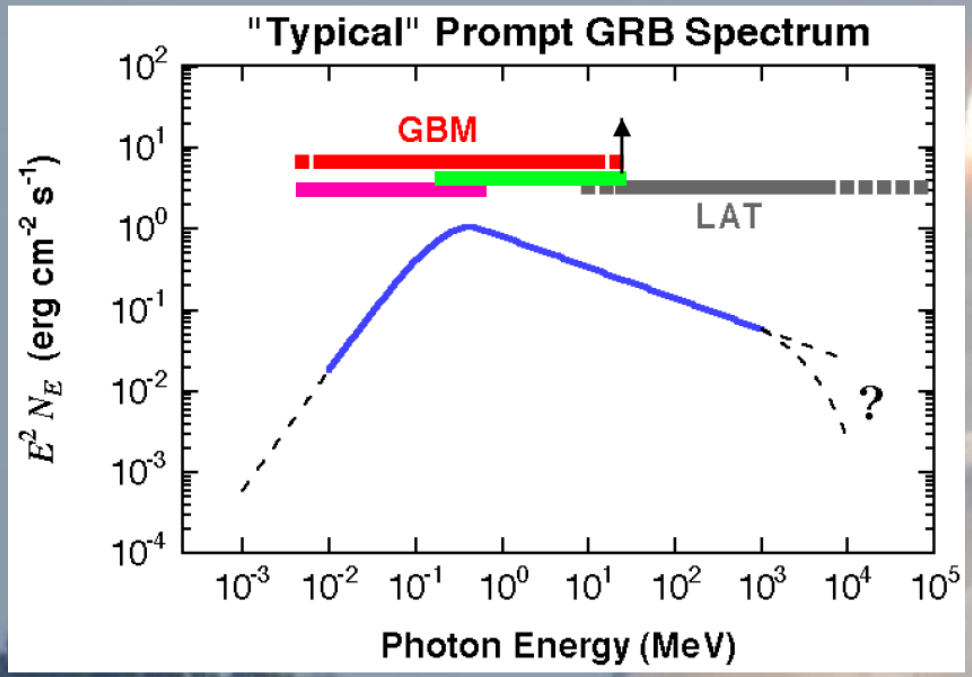
  $z \approx 0.5$ for short GRBs
- Use GRBs to test LV [Amelino-Camelia et al.'98, Nature]

Time-lag by GRB

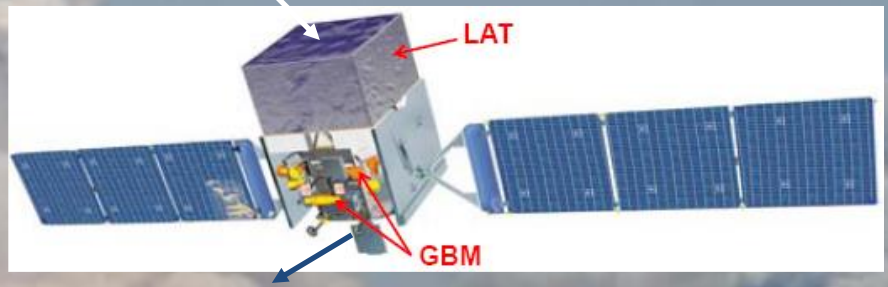


June 11, 2008

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

Pioneering analyses of real GRB data with robust constraint on LV scale

Ellis, Farakos, Mavromatos, Mitsou, Nanopoulos, APJ 535(2000) 139

$$M \gtrsim 10^{15}\ \text{GeV}$$

Ellis, Mavromatos, Nanopoulos, Sakharov, Sarkisyan, APP 25 (2006) 402 [Corrigendum 29 (2008)158].

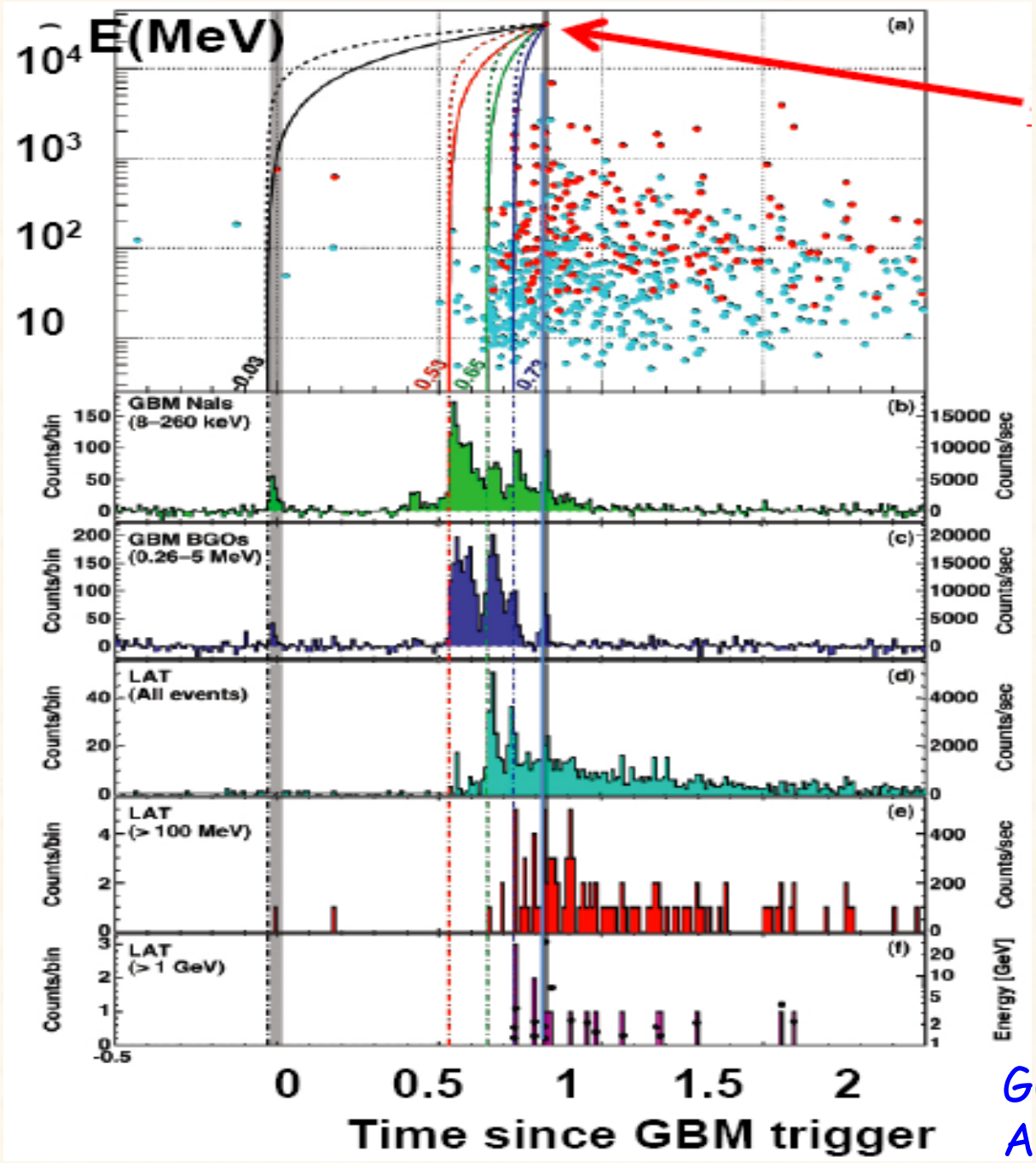
$$M \geq 1.4 \times 10^{16}\ \text{GeV}$$

… …

Ellis, Konoplich, Mavromatos, Nguyen, Sakharov, Sarkisyan,PRD 99 (2019) 083009

$$8.4 \times 10^{17}\ \text{GeV or}\ 2.4 \times 10^{17}\ \text{GeV}$$

……



31 GeV

Time lags are affected both artificially and instrumentally

GRB090510
Abdo et al.'09, Nature

Strong constraint from short GRB090510 & Fermi-LAT data

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

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

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

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

Vasileiou et al., PRD 87 (2013) 122001

$E_{\rm QG,1} > 7.6$ times the Planck energy $(E_{\rm Pl})$

… …

From Fermi Nature paper: we simply assume that it (high-energy photon) was emitted sometime during the relevant lower-energy emission episode.

Lorentz Violation

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, arXiv: 2108.05804
Y.Chen, B.-Q.Ma, JHEAP 32 (2021) 78–86, arXiv: 1910.08043
J.Zhu, B.-Q.Ma, JPG 50 (2023) 06LT01, arXiv: 2210.11376

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H.Li, B.-Q. Ma, Science Bulletin 65 (2020) 262 arXiv: 2012.06967 LV on AGN
H.Li, B.-Q.Ma, APP 148 (2023) 102831 arXiv: 2310.06338

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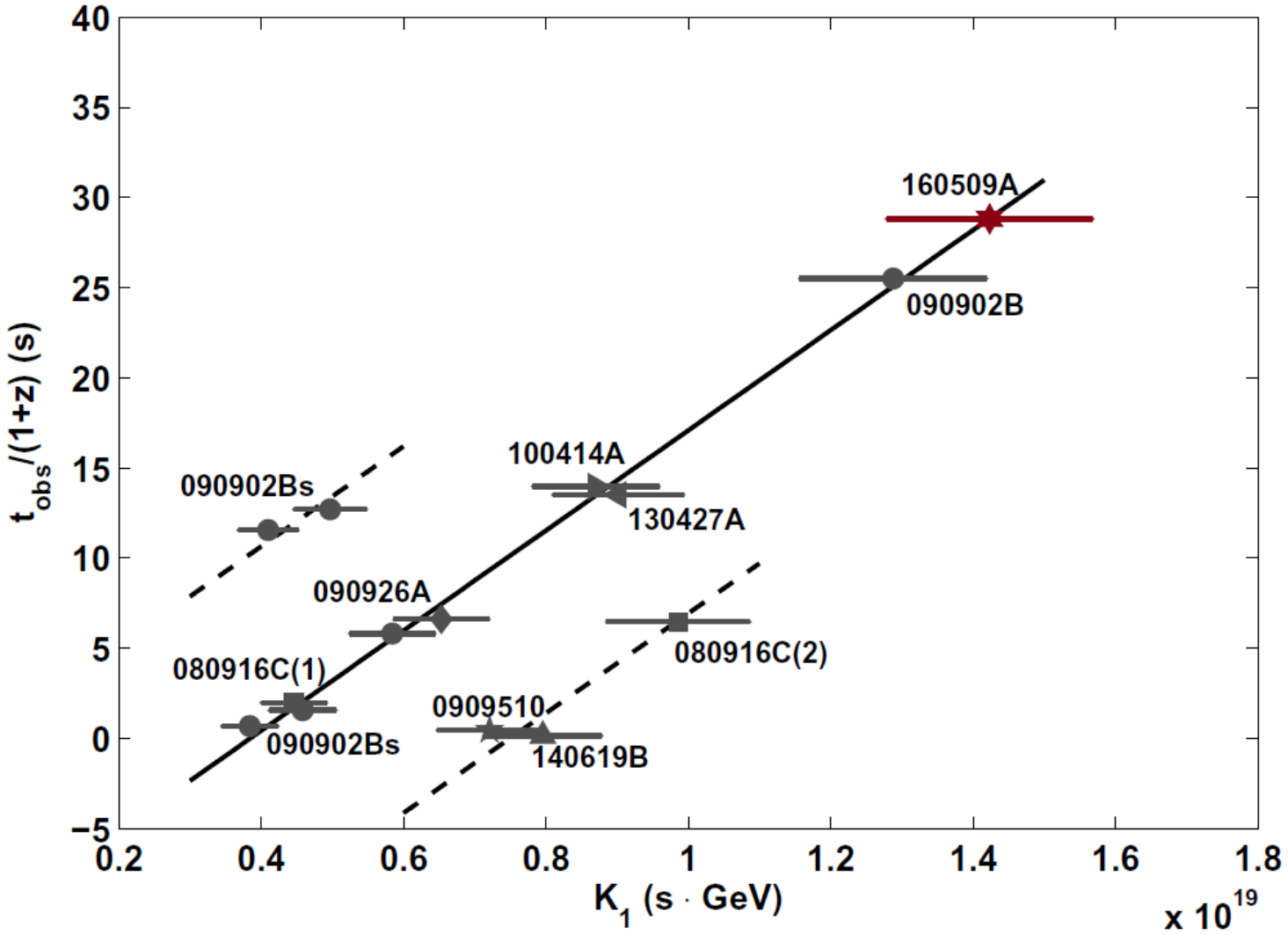
- H.Xu, B.-Q.Ma, Phys.Lett.B 760 (2016) 602

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

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

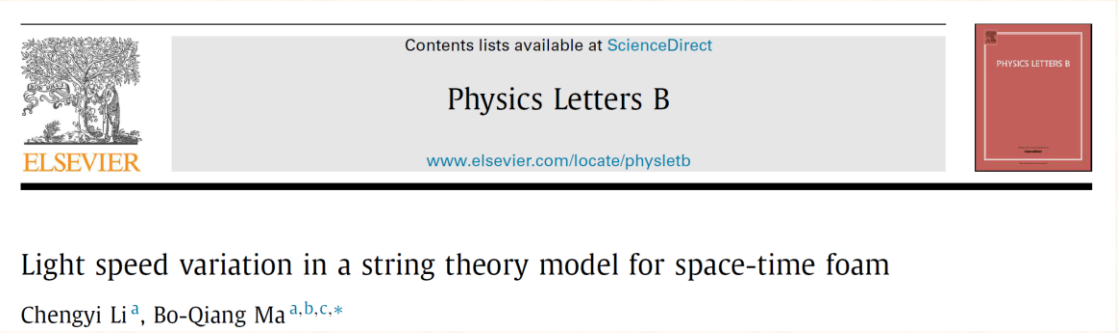
$$E_{\mathrm{LV}}^{(\mathrm{sub})} \gtrsim 3.60 \times 10^{17}\ \mathrm{GeV}$$

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.

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

Prediction of Light speed variation from space-time foam



$$c_g = 1 - 2g_s \frac{\zeta_D |\mathbf{p}|}{M_s} \simeq 1 - \mathcal{O}\left(g_s \frac{n_D \mathcal{E}}{M_s}\right), \quad \langle\langle \lambda \rangle\rangle_D = \zeta_D > 0$$

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.

$$M_s \gtrsim 7.20 \times 10^{17} \zeta_D g_s \text{ GeV}$$

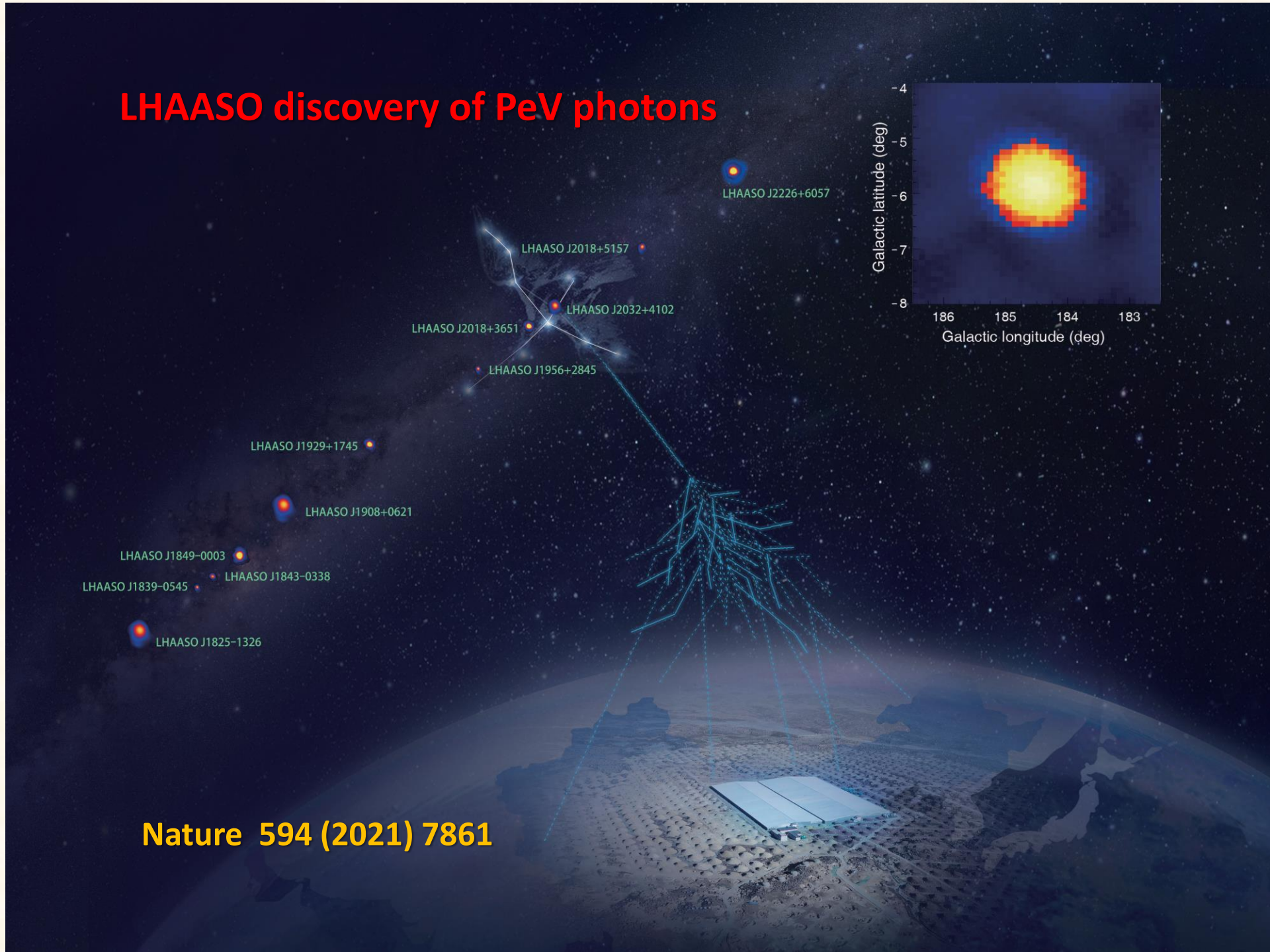
C.Li, B.-Q.Ma, PLB 819 (2021) 136443, arXiv:2105.06515

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

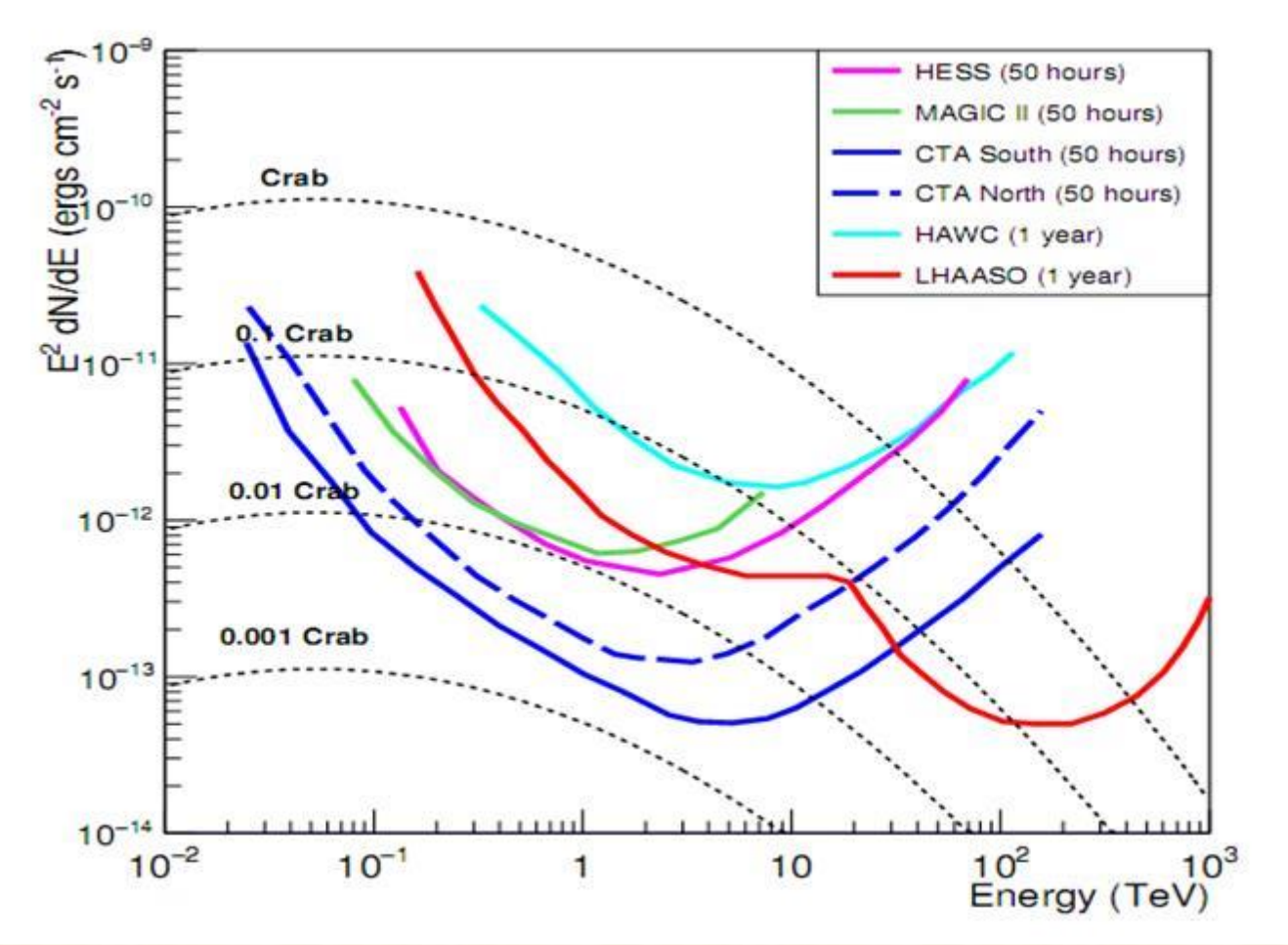
Predictions are consistent with all current observations permitting a subluminal light speed variation

LHAASO discovery of PeV photons



Nature 594 (2021) 7861

LHAASO: the ideal platform to detect TeV and PeV Cosmic Photons



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**

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**

No $\gamma \to e^+ + e^-$

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

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

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

  LHAASO, arXiv:2106.12350, PRL 128 (2022) 051102

- **Similar analysis on LHAASO data by**

  Chen et al., arXiv: 2105:07927, CPC 45 (2021) 105105

LHAASO discovery of PeV photons from 2.3 PeV electrons

Science

RESEARCH ARTICLES

Cite as: The LHAASO Collaboration, *Science* 10.1126/science.abg5137 (2021).

PeV gamma-ray emission from the Crab Nebula

The LHAASO Collaboration*†

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†The LHAASO Collaboration authors and affiliations are listed in the supplementary materials.

The Crab Nebula is a bright source of gamma-rays powered by the Crab Pulsar's rotational energy, through the formation and termination of a relativistic electron-positron wind. We report the detection of γ-rays from this source with energies from 5×10^{-4} to 1.1 petaelectronvolts (PeV), with a spectrum showing gradual steepening over three energy decades. The ultra-high-energy photons imply the presence of a PeV electron accelerator (a pevatron) in the nebula, with an acceleration rate exceeding 15% of the theoretical limit. We constrain the pevatron's size between 0.025 and 0.1 pc, and magnetic field ≈110 μG. The production rate of PeV electrons, 2.5×10^{36} erg s^{-1}, constitutes 0.5% of the pulsar spin-down luminosity, although we cannot exclude a contribution of PeV protons to the production of the highest energy γ-rays.

Science 373 (2021) 6553, 425-430

C.Li and B.-Q.Ma, PLB 835 (2022) 137034

Physics Letters B 829 (2022) 137034

Contents lists available at ScienceDirect

Physics Letters B

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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,*]

- **LHAASO discovery of 1.12 PeV photon suggested 2.3 PeV electron**
- **The existence of 2.3 PeV electron puts strong constraints on LV parameter of electrons:** $E_{\mathrm{LV}e}^{(\mathrm{sup})} \gtrsim 9.4 \times 10^{25}\ \mathrm{GeV}$

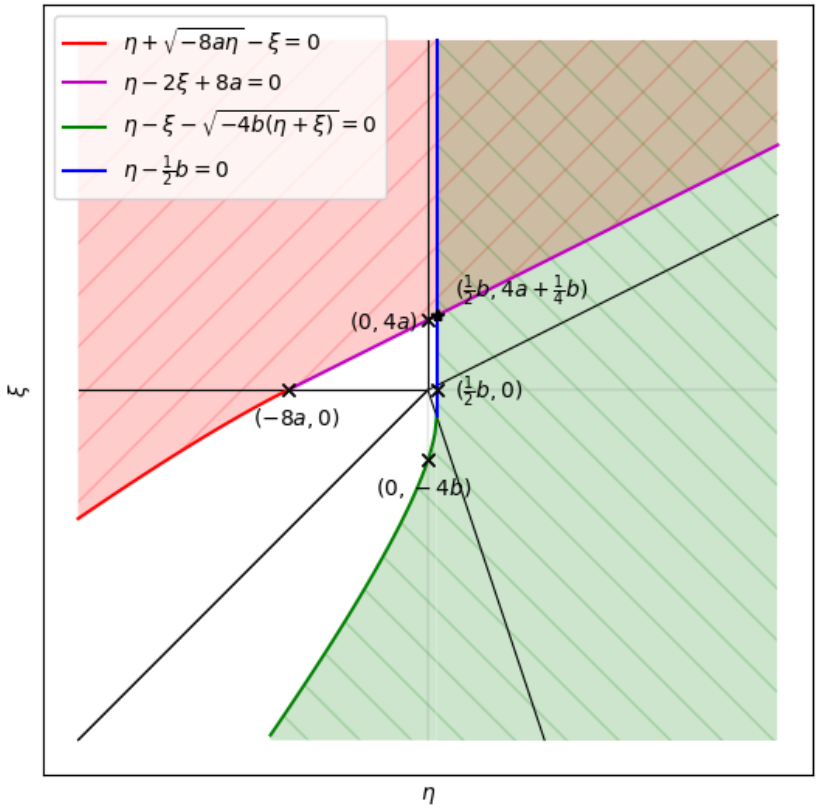
As Cherenkov radiation of lepton may occur with LV of electrons

$e \to e\gamma$ $\qquad E^2 = m^2 + p^2[1 + \eta_{\mathrm{n}}(\frac{p}{E_{\mathrm{Pl}}})^n]$

H.He and B.-Q.Ma, PLB 835 (2022) 137536, arXiv:2210.14817

Joint Constraint on Photon-Electron LV Parameter Plane

- **LHAASO discovery of 1.42 PeV photon and suggested 2.3 PeV electron**



$$\omega^2 = k^2[1+\xi_n(\frac{k}{E_{Pl}})^n]$$

$$E^2 = m^2 + p^2[1+\eta_n(\frac{p}{E_{Pl}})^n]$$

Our result permits the parameter space for new physics beyond relativity

C.Li and B.-Q.Ma, 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**

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

from standard special relativity

cosmic photon annihilation with CMB

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

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

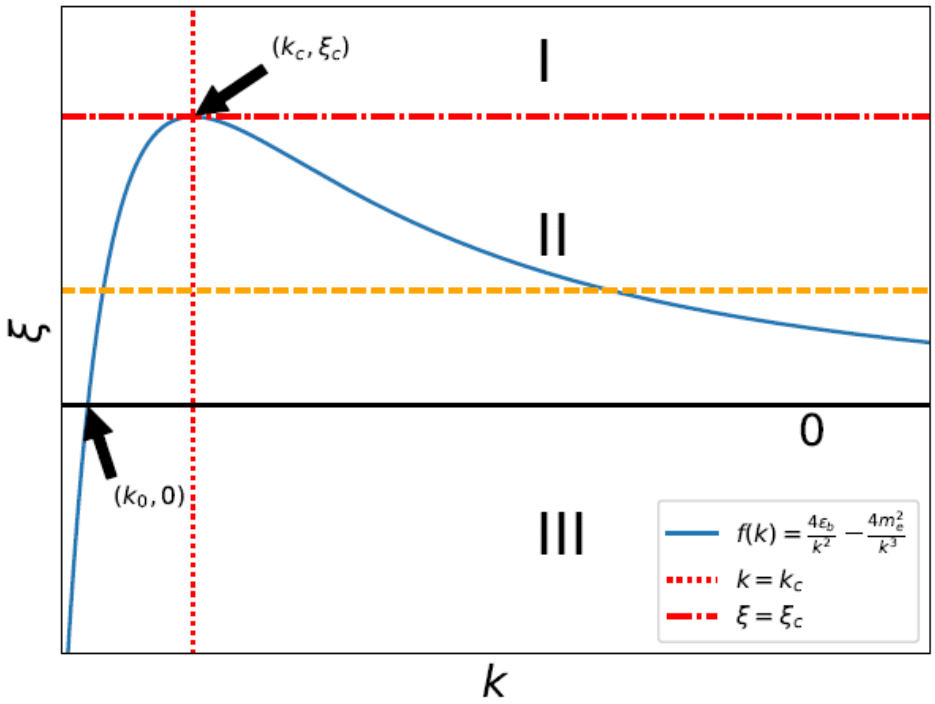
Attenuation of above threshold E=411 TeV photons

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

$$\omega(k) \simeq k^2 - \xi k^3$$



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

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

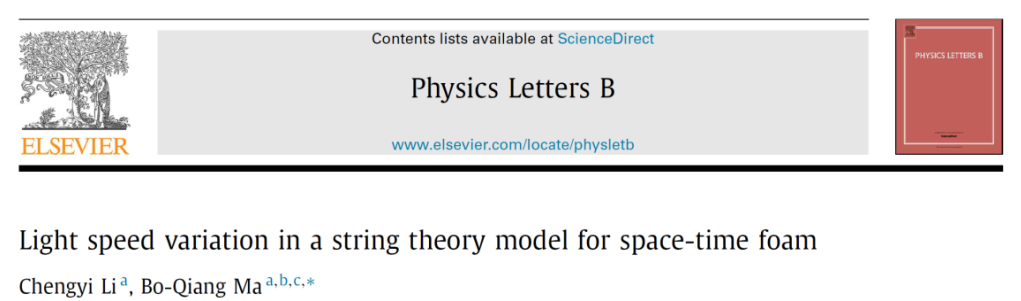
The string theory model of space-time foam

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.

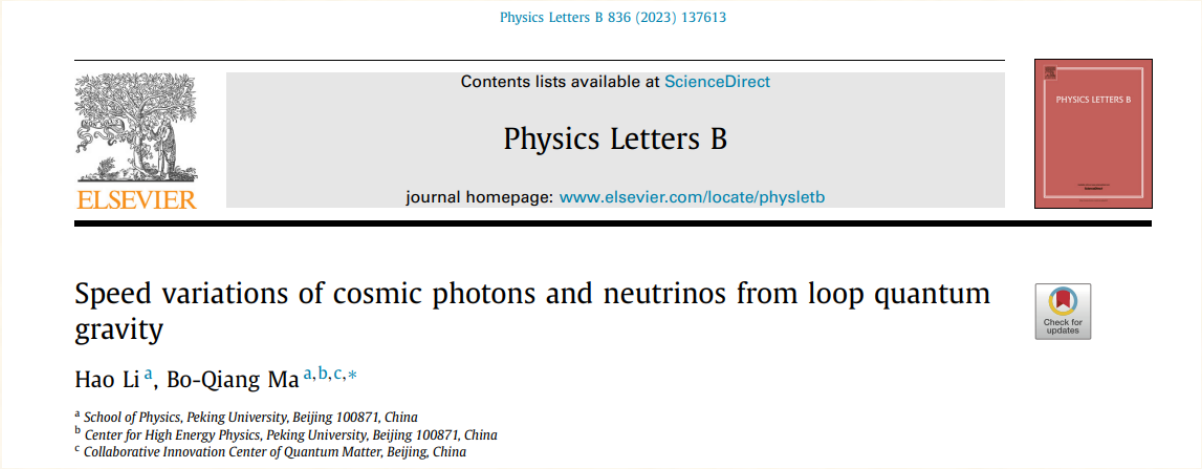
T. Li, N.E. Mavromatos, D.V. Nanopoulos, D. Xie, Time delays of strings in D-particle backgrounds and vacuum refractive indices, Phys. Lett. B 679 (2009) 407, https://doi.org/10.1016/j.physletb.2009.07.062, arXiv:0903.1303.



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

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

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

Remarks: photons

- 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.
- The subluminal light speed variation is still permissible.
- Subluminal Lorentz violation permits the above threshold (E=410 TeV for CMB and E=260 GeV for EBL) photon events:

  LHAASO event of E=1.4 PeV=1400 TeV

  LHAASO event from GRB221009A of E=18 TeV
- Our prediction of optical transparency of cosmic photons can be tested by LHAASO observation of any above threshold photons from extragalactic sources.

Energy limitation of cosmic photons

from standard special relativity

cosmic photon annihilation with EBL (extragalactic background light)

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

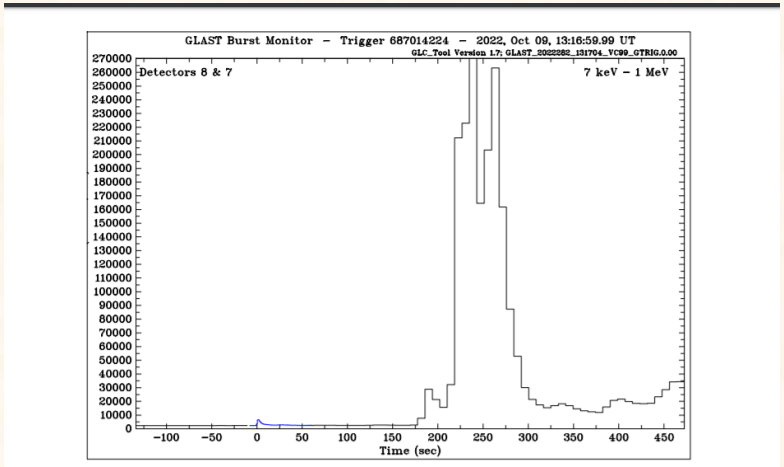
$$4E\varepsilon_{\gamma} \approx (2m_e)^2 \qquad E \sim 4\times10^{14}\ \mathrm{eV} \Leftarrow \text{CMB}$$

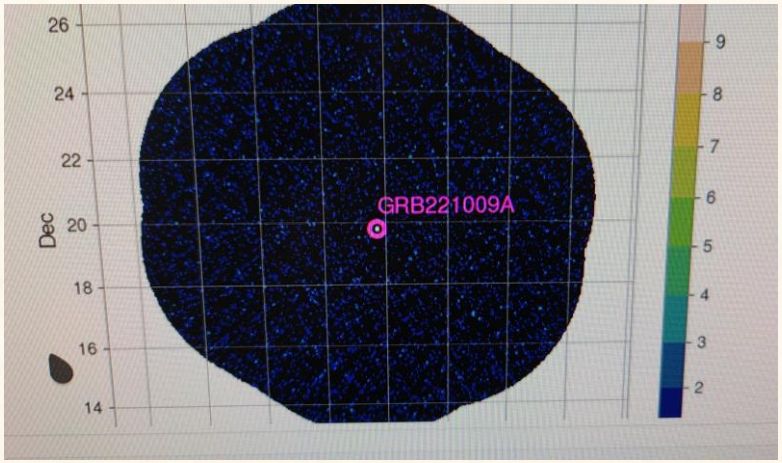
EBL: Attenuation of above threshold E=260 GeV photons

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

H.LI and B.-Q.Ma, arXiv:2210.05563, EPJC, arXiv:2210.06338, APP

Newly observed GRB221009A





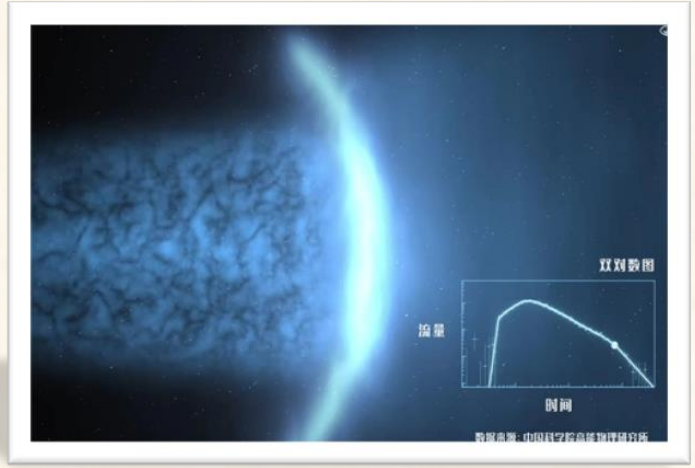
- Triggered by Fermi and Swift
- Very bright GRB with very short distance

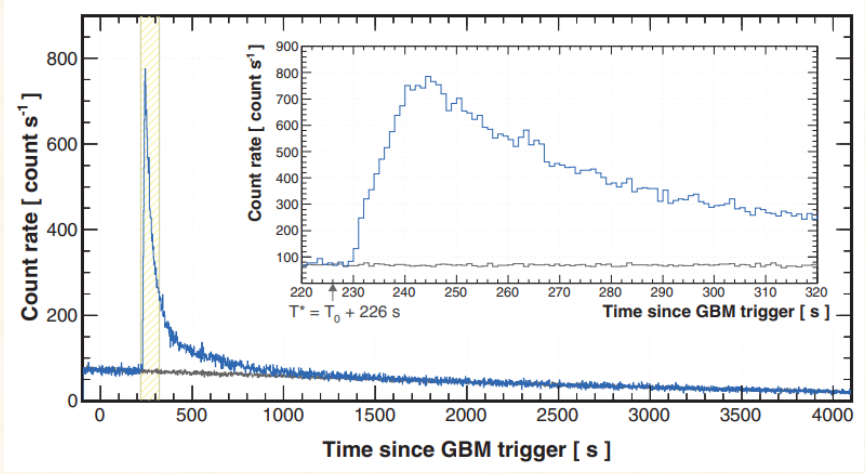
  z=0.1505 (2.4 billion light years)
- LHAASO observation: 5000 high energy events with energies larger than 500 GeV including photons with energy up to 18 TeV

LHAASO, Y.Huang et al., GCN Circ.32677 (2022) (Oct.11,2022)

H. Li and B.-Q. Ma, Astropart. Phys. 148 (2023) 102831, arXiv:2210.06338 (Oct.12,2022)

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.

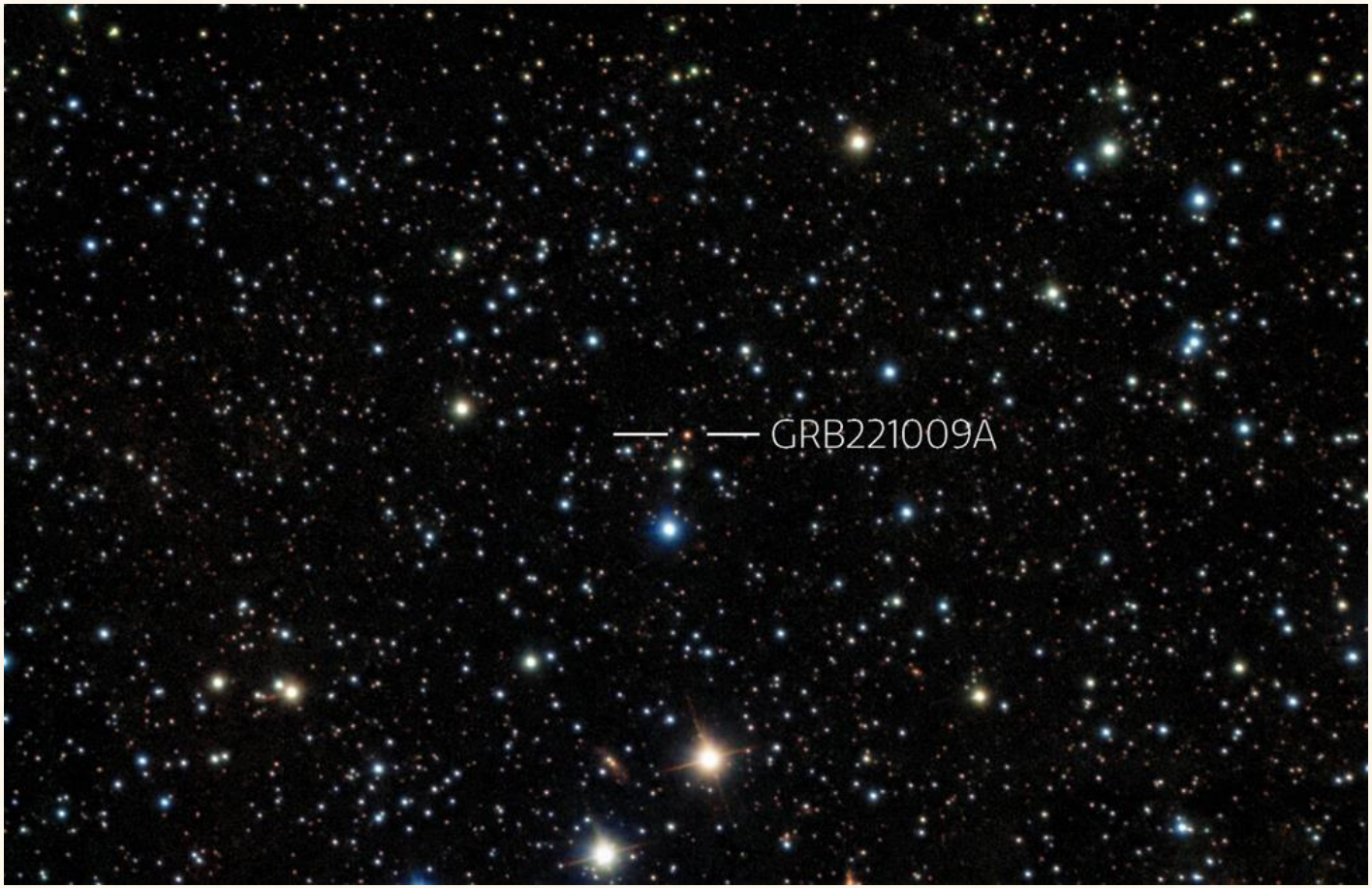
LHAASO, Science 380 (2023) 1390, June 8, 2023, arXiv:2306.06372

Rare GRB: GRB221009A

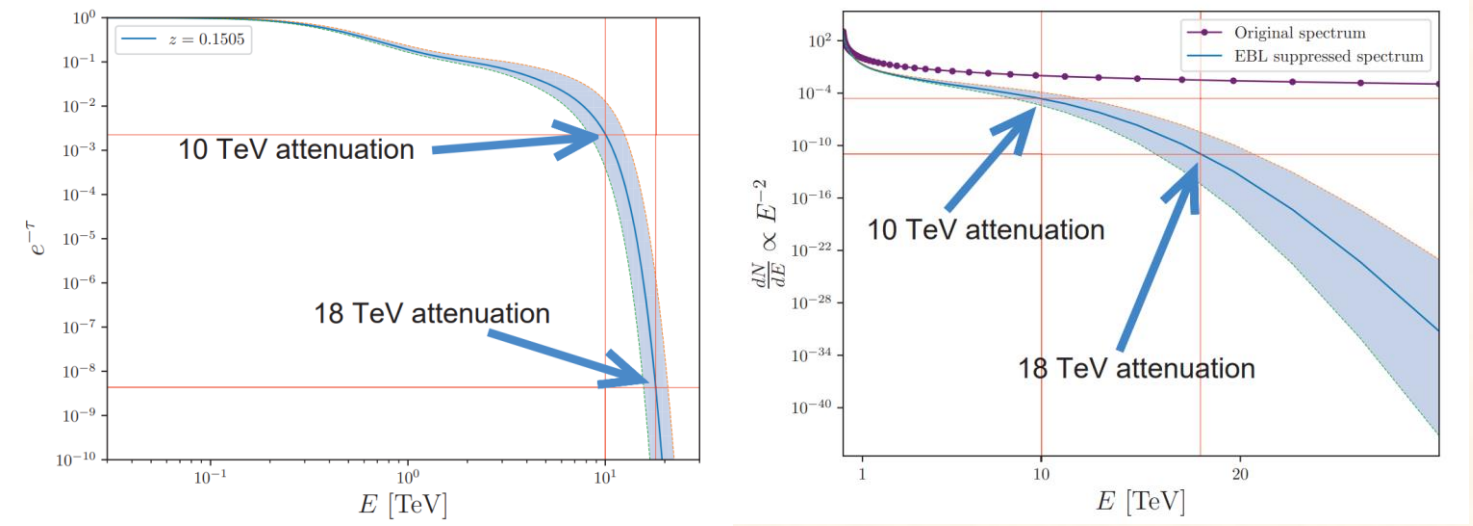
- Assuming a constant GRB formation rate, we obtain 1 extremely energetic GRB per 130 yr.
- Assuming the GRB formation rate of Palmerio & Daigne (2021), we obtain 1 extremely energetic GRB per 520 yr.
- We conclude that there is a 10% probability to observe an event like GRB 221009A about 50 years after the discovery of the first GRB.

Jean-Luc Atteia, GCN Circ. 32793 (2022)

Rare GRB221009A: Thousand years once



Newly observed GRB221009A

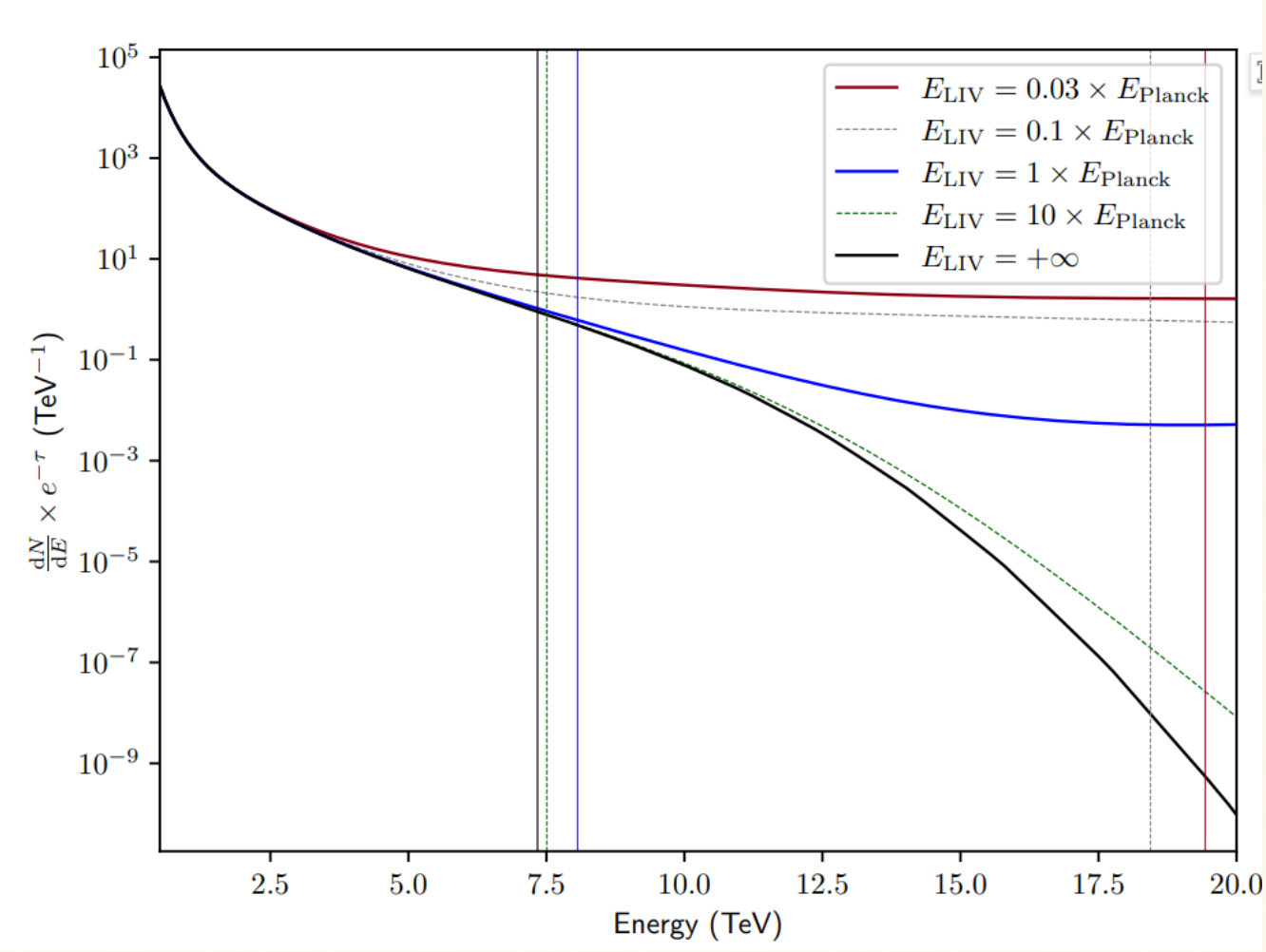


- Within standard model, extragalactic background light (EBL) could absorb cosmic photons severely and the flux is too weak to be observed.
- We suggest that Lorentz invariance violation induced threshold anomaly of $\gamma\gamma \to e^- e^+$ process provides a candidate to explain the LHAASO observation 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

H.Li and B.-Q. Ma, arXiv:2306.02926

Revisit of LIV from GRB221009A



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.

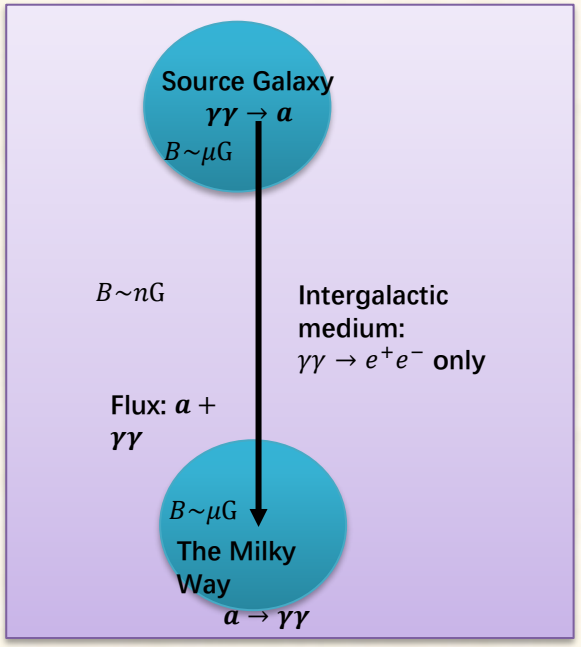
G. Zhang and B.-Q. Ma, arXiv:2210.13120

L. Wang, B.-Q. Ma, PRD 108 (2023) 023002

The picture of photon-axion conversion

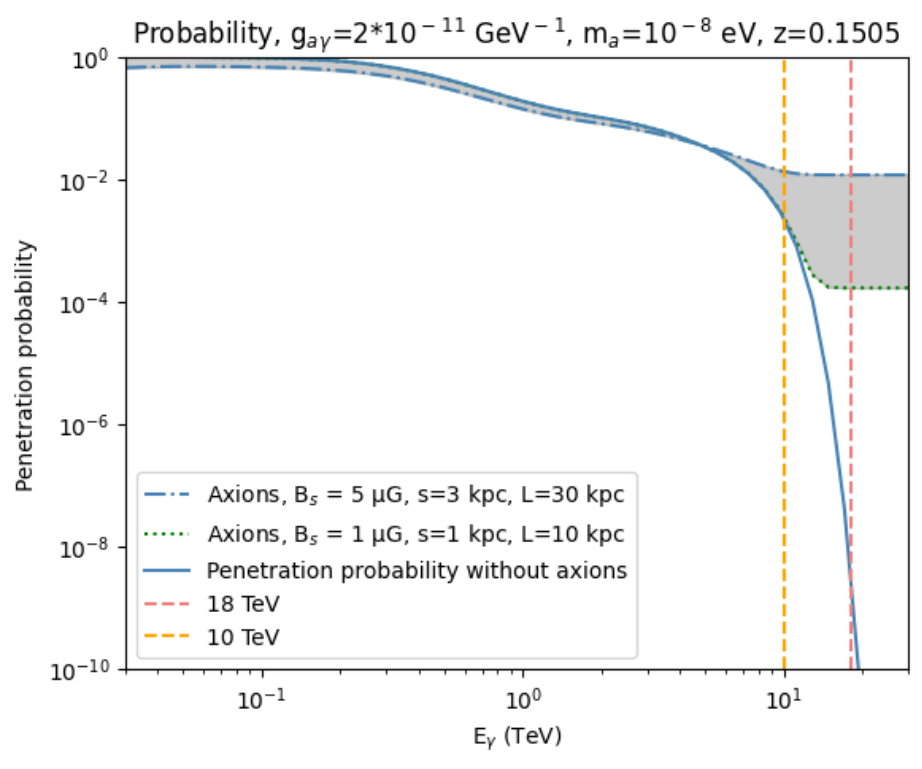
应用ALP-Photon转化机制来解释 GRB221009A 探测到大量VHE光子的现象, 并给出对ALP粒子质量 m_a, 耦合常量 $g_{a\gamma}$.

1. **GRB源星系处磁场的特点**: 方向? 强度? 尺度? 源星系内的转化概率? => Cellular model.
2. **星系间传播**: ALPs-Photon混合束在穿越星系间区域时不发生 $\gamma\gamma a$ 的转化, 仅存在 $\gamma\gamma \to e^+e^-$, 这对m_a, $g_{a\gamma}$有一定约束.
3. **Back conversion (逆转化)**: ALPs-Photon 在穿过银河系磁场时, 部分高能 ALPs 再度转化为光子, 使得地球上的观测者可以探测到本应消失的高能光子.



L. Wang, B.-Q. Ma, 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

Summary

- High energy cosmic photons provide opportunity to study new physics: Lorentz violation or axions
- Subluminal Lorentz violation permits the above threshold photon events:

  LHAASO event of E=1.4 PeV=1400 TeV

  LHAASO event from GRB 221009A of E=18 TeV

- Photon-axion conversion serves as an alternative mechanism for the observation of above threshold photon events
- Our prediction of optical transparency of cosmic photons due to Lorentz violation or axions can be tested by LHAASO observation of any above threshold photons from extragalactic sources.