# Cosmic photons and neutrinos

**Bo-Qiang Ma（马伯强）**

**Peking University（北京大学）**

**第十七届粒子物理、核物理和宇宙学交叉科学前沿问题探讨会**

**(贵州, 贵阳, July 12-16, 2024)**

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**

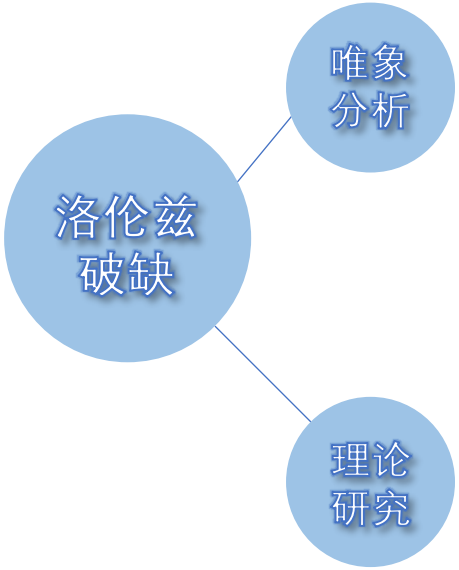
- **New physics from cosmic photons and neutrinos:**

  **Lorentz violation**

  **CPT violation**

  **Axion**

# New Physics Beyond Relativity: Lorentz Invariance Violation




**高能光子的洛伦兹破缺：**

- 光子的真空色散（光速变化）
- 光子的真空双折射
- 光子的超光速衰变
- 双光子湮灭反应“阈反常”

**其他粒子的洛伦兹破缺：**

- 极高能中微子的速度变化
- 中微子的超光速衰变
- 中微子味转变与退相干
- 电子的真空切伦科夫效应

**包含洛伦兹破缺的理论和模型：**

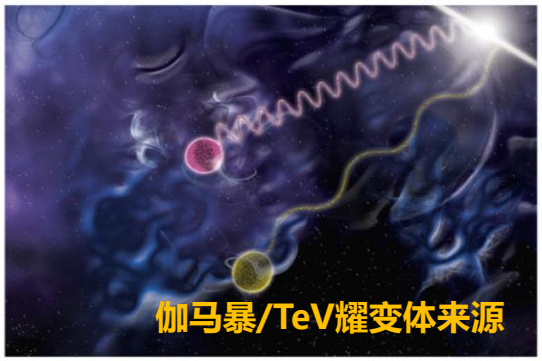
- 量子引力的理论与模型
- 时空结构模型
- 低能有效场论拓展

P. He, B.-Q. Ma, Universe 8 (2022) 323

# Searching for Lorentz Violation from Light-Speed Variation

- 以光速改变为例：

  **搜寻高能宇宙光子的飞行时间差**




需要进一步开拓和深入

**既往唯象分析建议光速可能改变的迹象**

$$v(E) = c(1 - E/E_{\mathrm{LV}}) \quad E_{\mathrm{LV}}^{(\gamma)} \gtrsim 3.6 \times 10^{17}\ \mathrm{GeV}$$

L. Shao, Z. Xiao, B.-Q. Ma, APP 33 (2010) 312
S. Zhang, B.-Q. Ma, APP 61 (2015) 108
H. Xu, B.-Q. Ma, APP 82 (2016) 72
H. Xu, B.-Q. Ma, PLB 760 (2016) 602
H. Xu, B.-Q. Ma, JCAP 1801 (2018) 050
Y. Liu, B.-Q. Ma, EPJC 78 (2018) 825
J. Zhu, B.-Q. Ma, PLB 820 (2021) 136518
H. Li, B.-Q. Ma, Sci. Bull. 65 (2020) 262
……

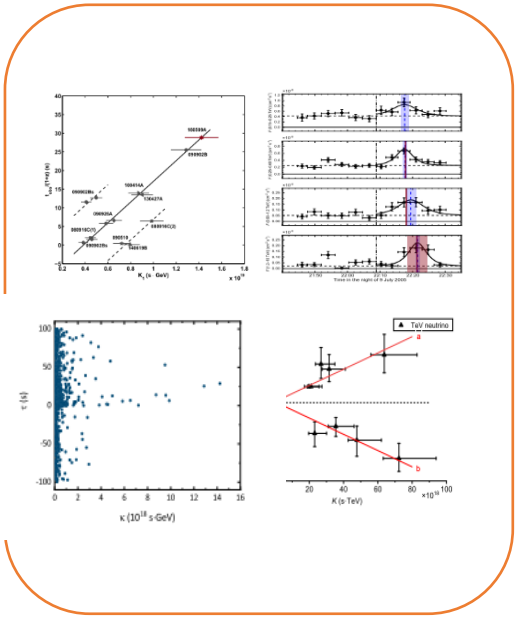
**光子**
**洛伦兹破缺**

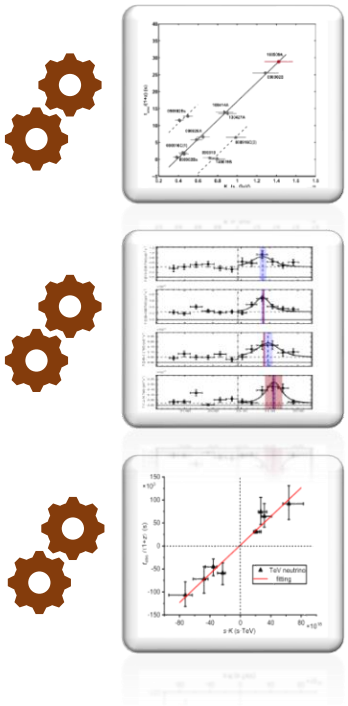
**对中微子也可以开展类似研究**

Y. Huang, B.-Q. Ma, Commun. Phys. 1 (2018) 62
Y. Huang, H. Li, B.-Q. Ma, PRD 99 (2019) 123018
Y. Huang, B.-Q. Ma, Fund. Res. 4 (2024) 51

最早建议：G. Amelino-Camelia+, Nature 393 (1998) 763, 我组最早工作：Z. Xiao, B.-Q. Ma, PRD 80 (2009) 116005

# Phenomenological Studies on Light-Speed Variation





- **对Fermi伽马暴数据的分析提示光速可能有线性能量相关性，暗示光子传播可能受量子引力效应的影响**

H. Xu, B.-Q. Ma, PLB 760 (2016) 602; JCAP 01 (2018) 050
J. Zhu, B.-Q. Ma, PLB 820 (2021) 136518 ……

- **对TeV耀变体及其他新近观测的分析也建议类似规律**

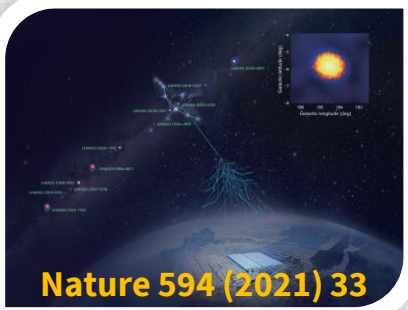
H. Li, B.-Q. Ma, Sci. Bull. 65 (2020) 262
J. Zhu, B.-Q. Ma, PLB 820 (2021) 136546……

- **IceCube极高能中微子与伽马暴的关联分析建议中微子传播速度的能量相关性，暗示中微子洛伦兹/CPT破缺**

Y. Huang, B.-Q. Ma, Commun. Phys. 1 (2018) 62
Y. Huang, H. Li, B.-Q. Ma, PRD 99 (2019) 123018
Y. Huang, B.-Q. Ma, Fund. Res. 4 (2024) 51

# LHAASO discoveries set strong constraints on superluminal Lorentz violation

## 对粒子物理标准模型的精确检验




- **LHAASO的最高能量 1.4 PeV 光子的突破性观测**
  **对光子超光速洛伦兹破缺给出极强约束**

$$E_{\mathrm{LV}}^{\gamma(\mathrm{sup})} \gtrsim 2.7 \times 10^{24}\ \mathrm{GeV} \gg E_P$$

C. Li, B.-Q. Ma, PRD 104 (2021) 063012
C. Li, B.-Q. Ma, Sci. Bull. 66 (2021) 2254

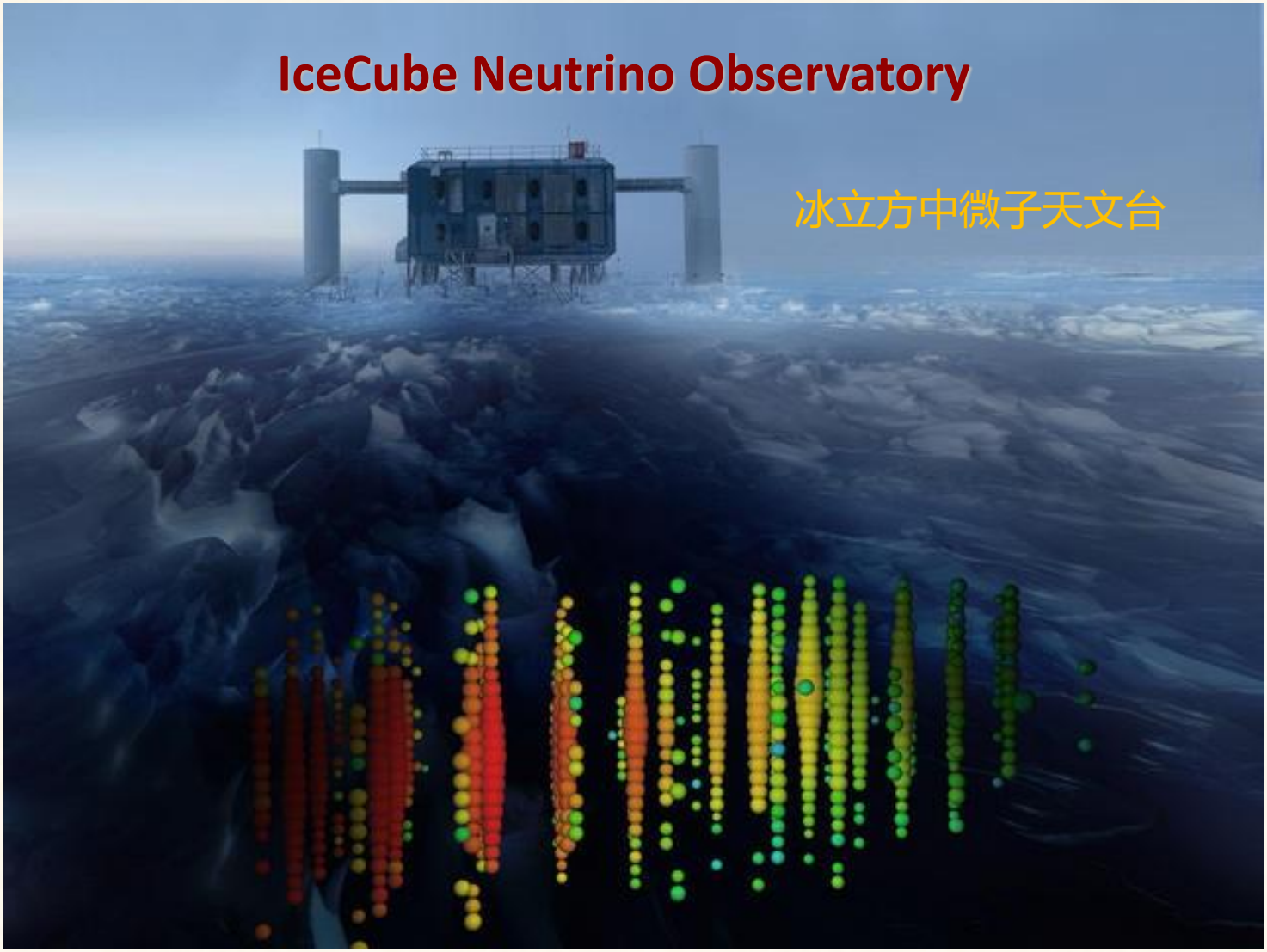
**光子/电子洛伦兹破缺参数的联合限制**

P. He, B.-Q. Ma, PLB 829 (2022) 137034
P. He, B.-Q. Ma, PRD 108 (2023) 063006

**LHAASO对 1.1 PeV 蟹状星云辐射的首次测量**
**对电子超光速洛伦兹破缺的强限制**

$$E_{\mathrm{LV}}^{e(\mathrm{sup})} \gtrsim \mathcal{O}(10^{26})\ \mathrm{GeV} \gg E_P$$

C. Li, B.-Q. Ma, PLB 829 (2022) 137034


IceCube Neutrino Observatory
冰立方中微子天文台

# IceCube Neutrinos
# —results reported by IceCube

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

- **More than ten 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.**

# 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.**

# From photons to neutrinos

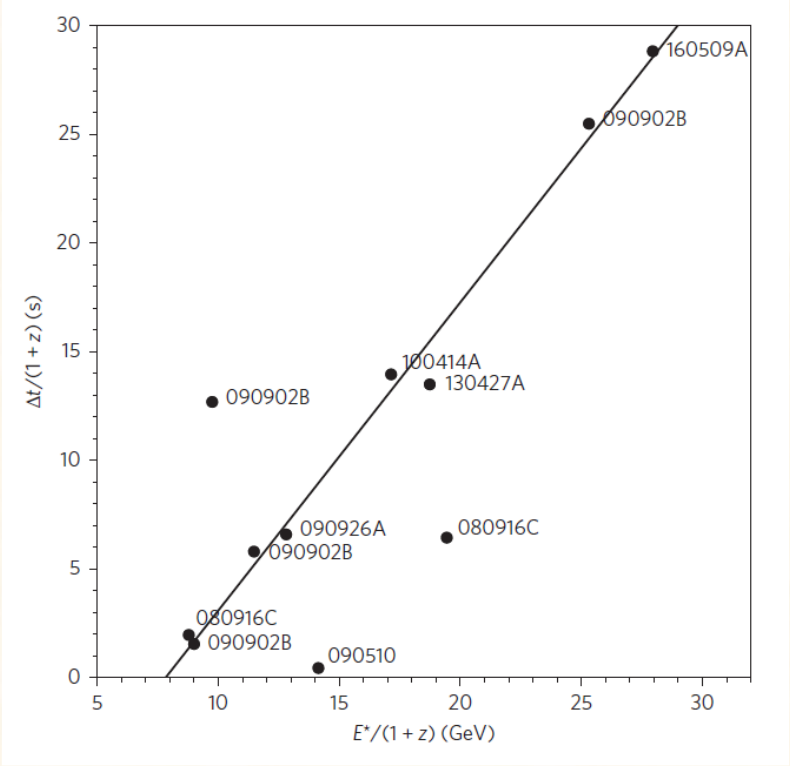
nature astronomy

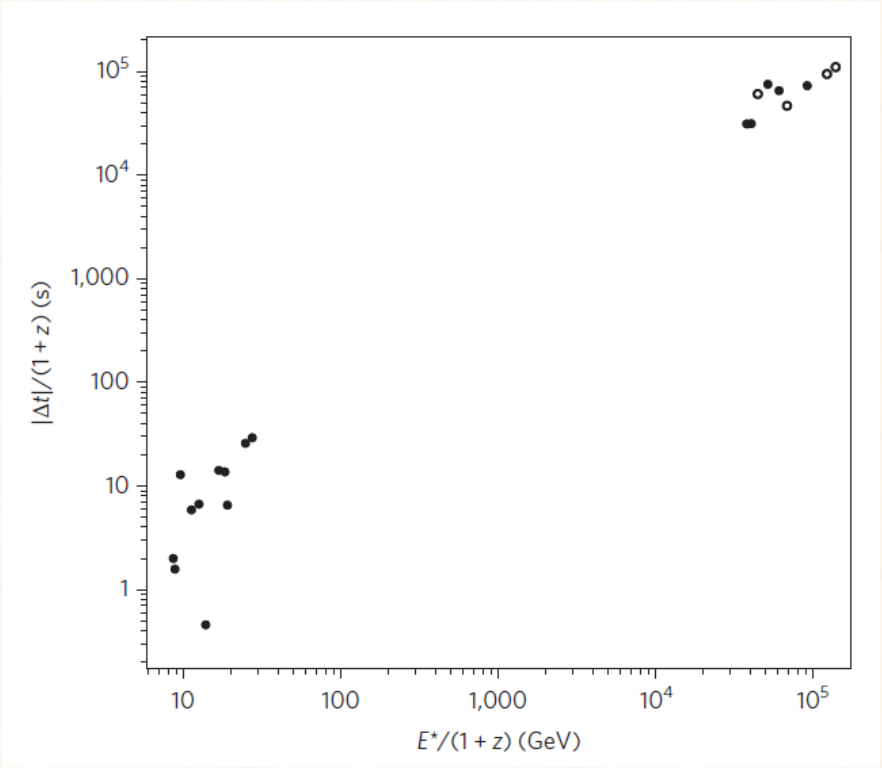
ARTICLES

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]



# Extension of Time Window to Days

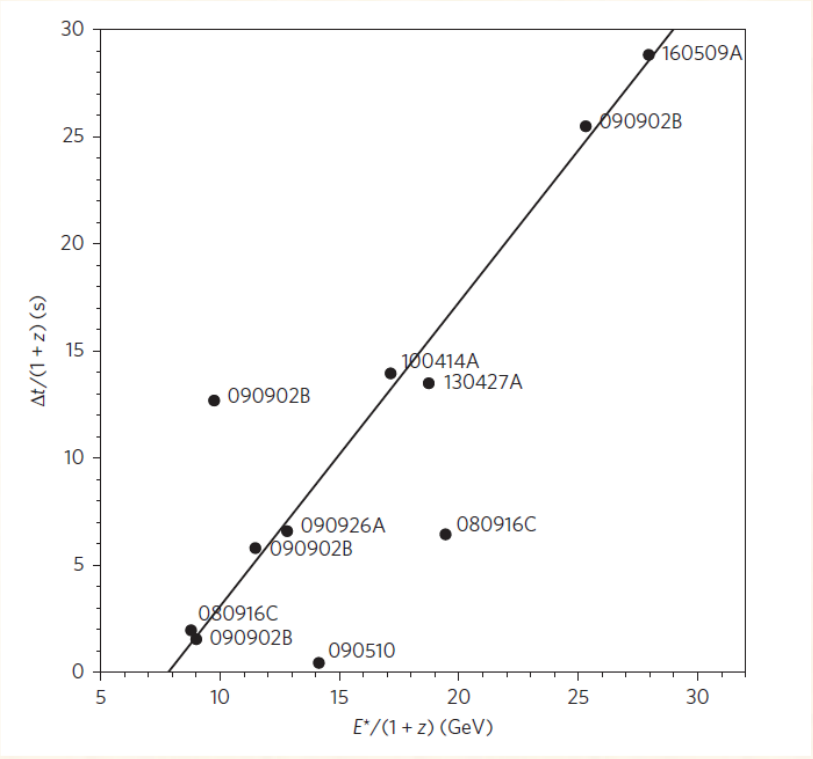
nature astronomy

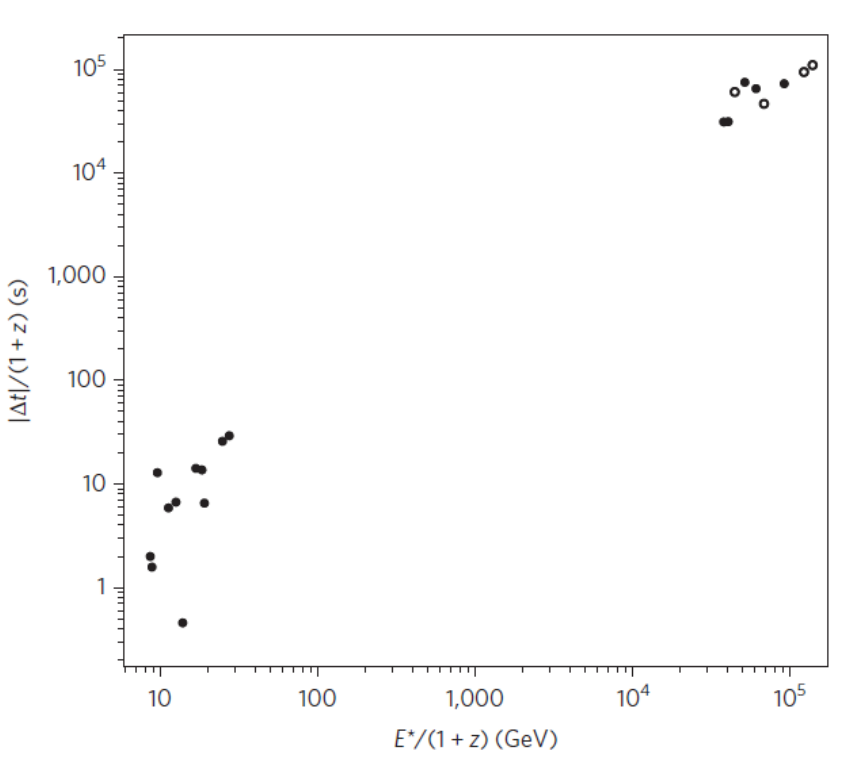
ARTICLES

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

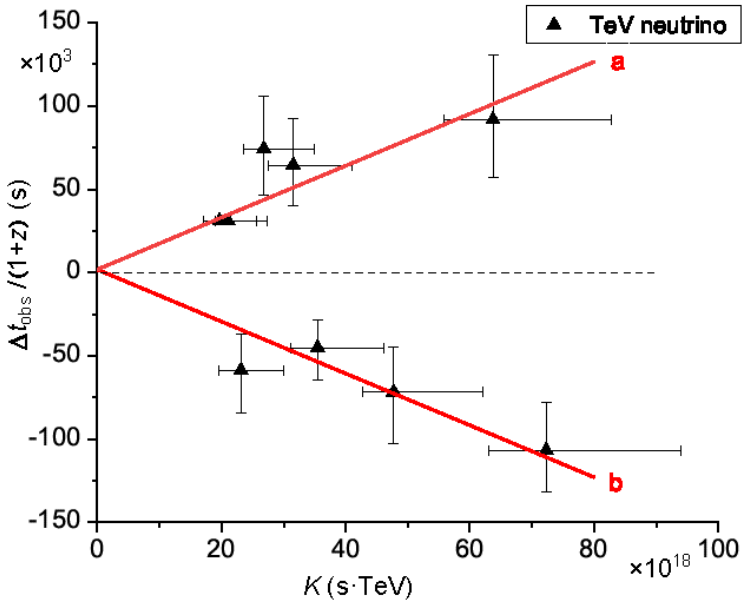
COMMUNICATIONS PHYSICS

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]




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

$$E_{\rm LV}=(6.5\pm0.4)\times10^{17}\ {\rm GeV}$$

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

# Reanalysis of TeV Events

COMMUNICATIONS PHYSICS

ARTICLE

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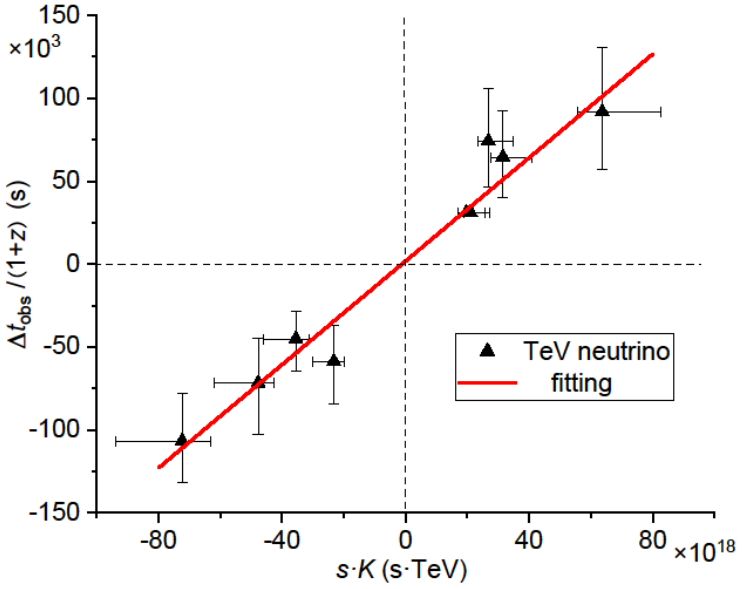


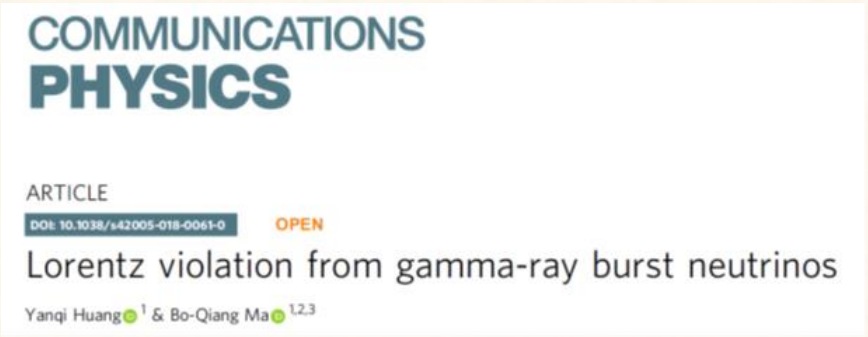

$$\frac{\Delta t_{\rm obs}}{1+z} = \Delta t_{\rm in} + s\frac{K}{E_{\rm LV}}$$

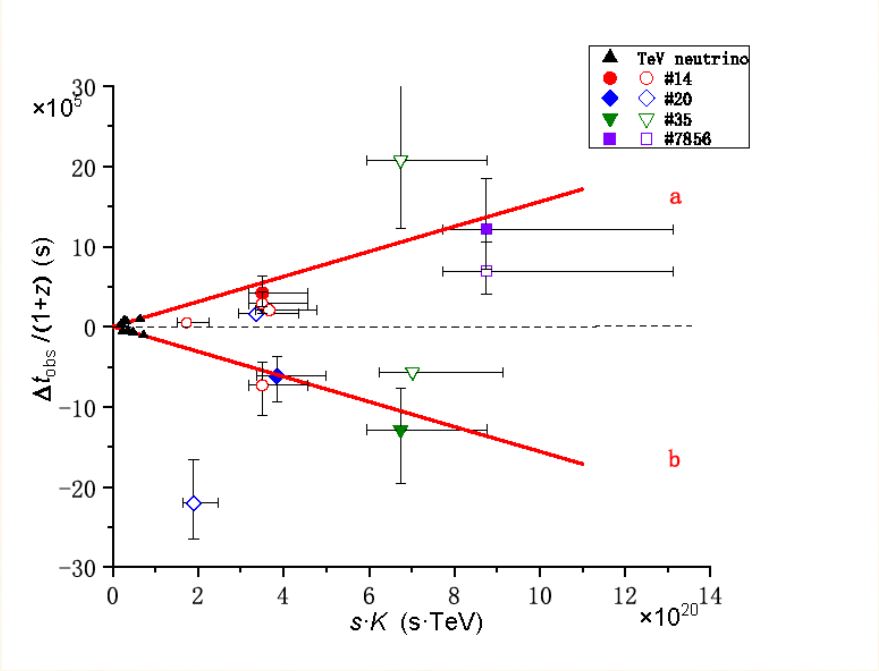
$$s = \pm 1$$

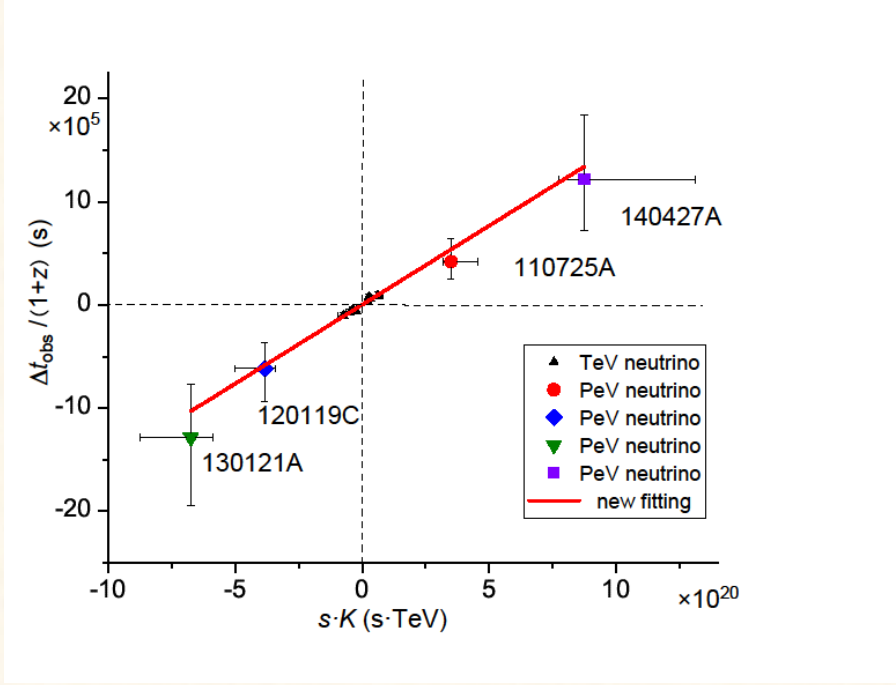
Y. Huang, B.-Q. Ma, Comms.Phys.1 (2018) 62

# First Analysis of PeV Events

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



# Association of IceCube Neutrinos with GRBs

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

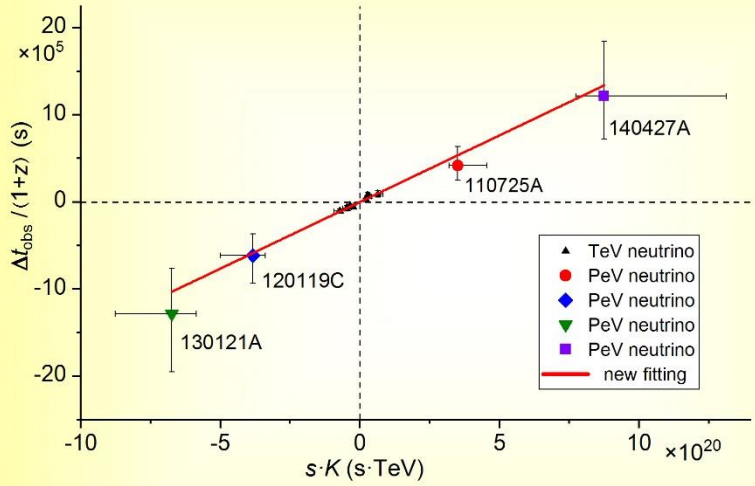
**Table 3 The properties of PeV neutrino events with associated GRB candidates**

| | $E$ (PeV) | $\sigma$ | $\Delta\Psi$ | $z$ | $\Delta t_{obs}$ ($10^3$s) | $\frac{\Delta t_{obs}}{1+z}$ ($10^3 s$) | $K$ ($10^{18}$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 $\sigma$ 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

PHYSICAL REVIEW D **99,** 043013 (2019)

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

Xinyi Zhang[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 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.**

PHYSICAL REVIEW D **99,** 123018 (2019)

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*

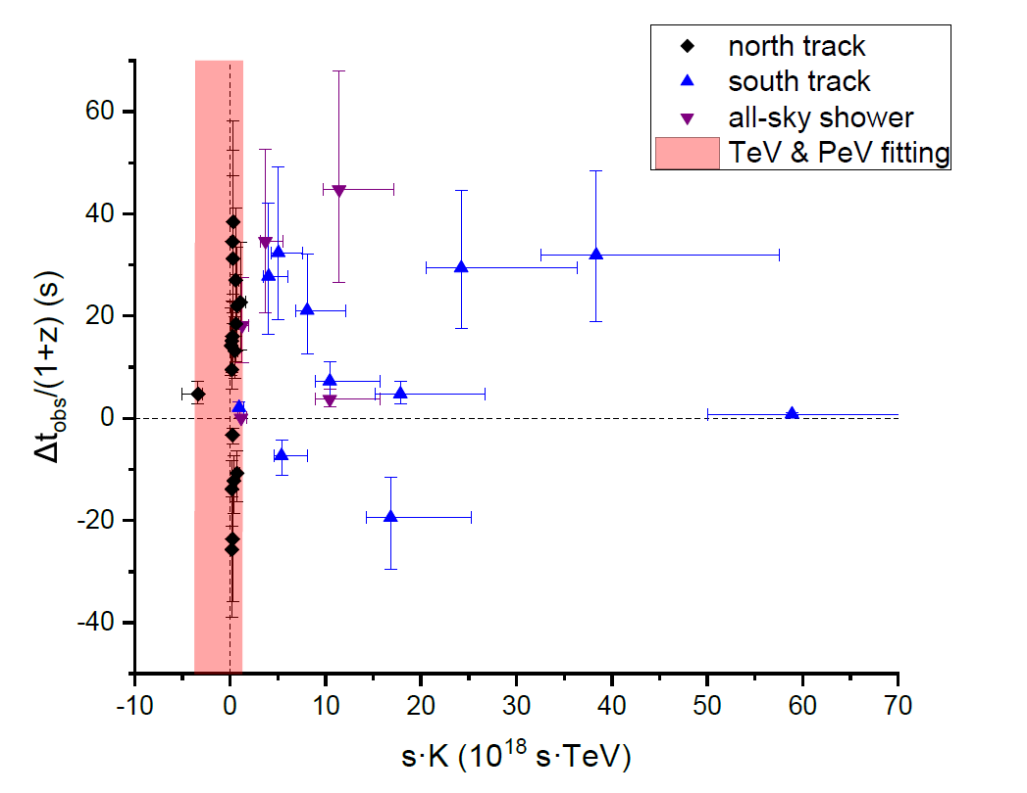
[3]*Center for High Energy Physics, Peking University, Beijing 100871, China*

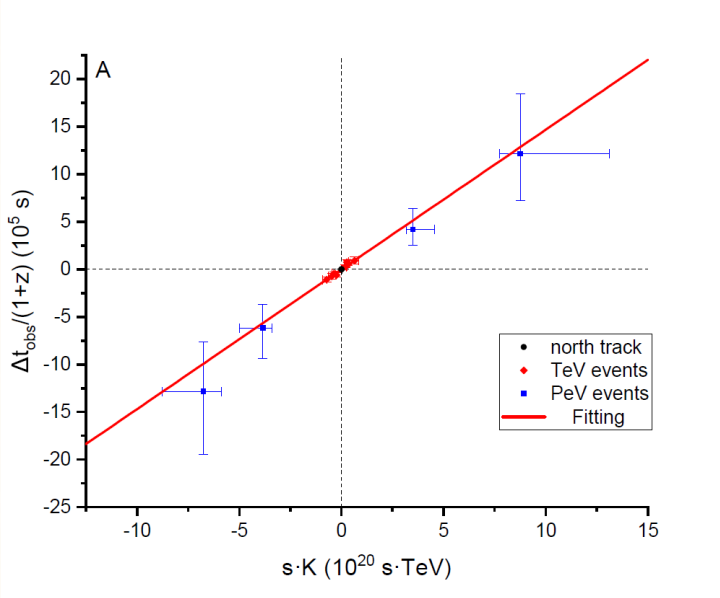
(Received 31 January 2019; published 21 June 2019)

- **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

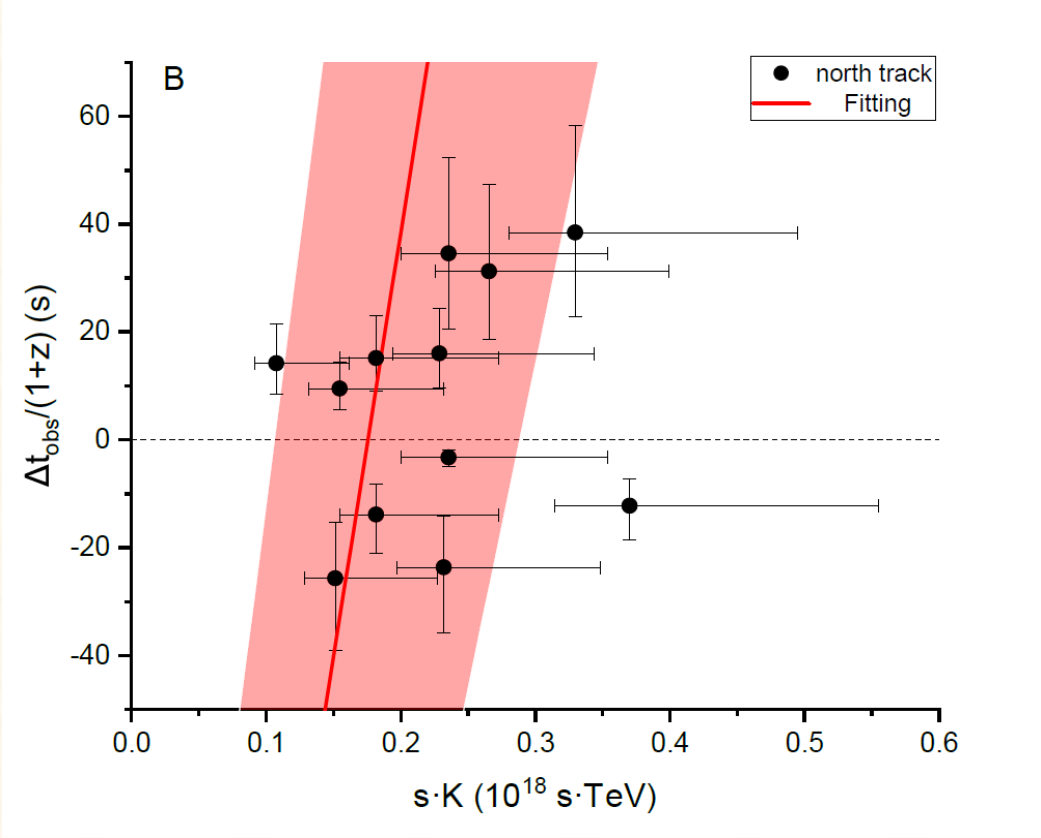
Y. Huang, H.Li, B.-Q. Ma, PRD 99 (2019) 123018

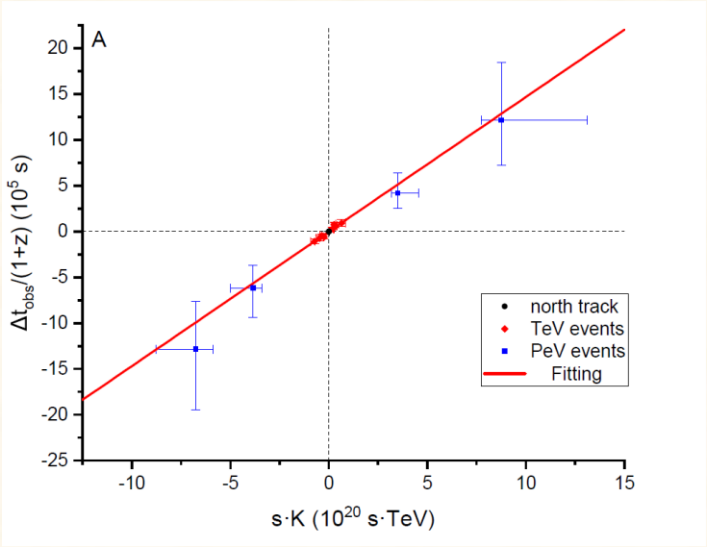


# 12 IceCube neutrinos near 1 TeV as new support to the TeV+PeV regularity

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

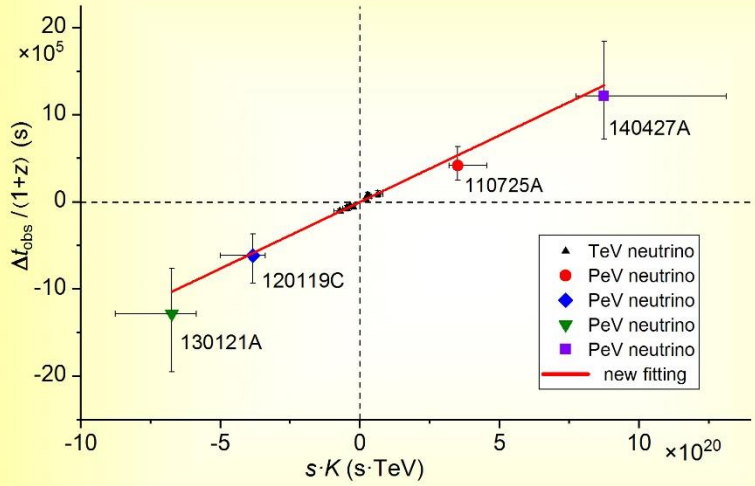



**TeV + PeV + near-TeV neutrinos (r=0.99)**

# CPT Violation from Cosmic Neutrinos:

## Difference properties between neutrinos and antineutrinos.



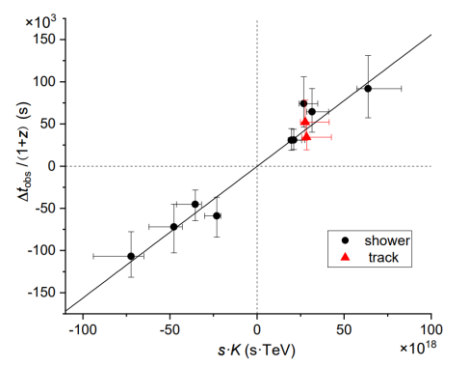

Y. Huang, B.-Q. Ma, Comms.Phys.1 (2018) 62

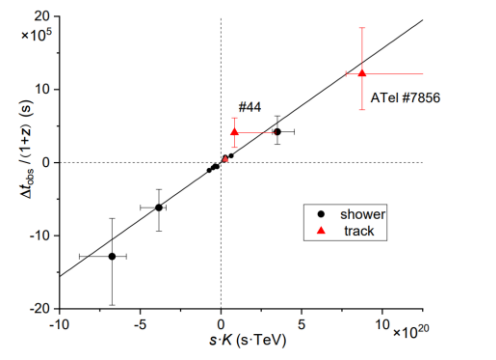
https://astronomycommunity.nature.com/users/179714-bo-qiang-ma/posts/39327-cpt-violation-from-cosmic-neutrinos

Y. Huang, B.-Q. Ma, Fundamental Research 4 (2024) 51 , arXiv:2211.00231

# Lorentz Violation of Cosmic Neutrinos:

## Association of IceCube Neutrino Events with GRBs




- We associate IceCube TeV and PeV neutrino events with gamma-ray bursts (GRBs).
- Among these 24 neutrino ``shower'' events above 60 TeV, 12 events are associated with GRBs.
- Track events are also associated with GRBs under the same Lorentz violation of neutrinos.
- The results support the Lorentz violation of neutrinos, indicating new physics beyond relativity.


Fundamental Research xxx (xxxx) xxx

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Article

Ultra-high energy cosmic neutrinos from gamma-ray bursts


Yanqi Huang, Ph.D. [a], Bo-Qiang Ma, Ph.D. [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 B S T R A C T

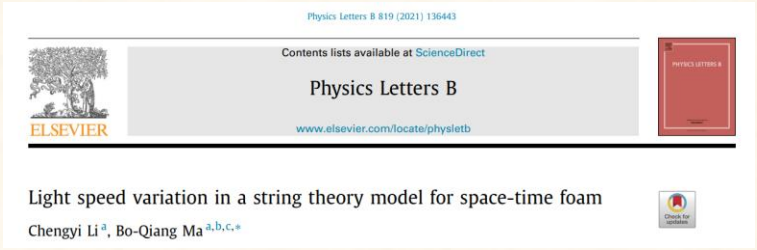
Based on the recent association of IceCube TeV and PeV neutrino events with gamma-ray bursts (GRBs) by considering the Lorentz violation of neutrinos, we provide a new estimate on the GRB neutrino flux with a more significant result compared to the previous constraint by the IceCube Collaboration. Among these 24 neutrino "shower" events above 60 TeV, 12 events are associated with GRBs. Such a result is compatible with the prediction from GRB fireball models. Analysis of track events provides a consistent result with the shower events to associate high energy cosmic neutrinos with GRBs under the same Lorentz violation features of neutrinos. We also make a background estimation and reveal GRBs as a significant source for the ultra-high energy IceCube neutrino events. Our work supports the Lorentz violation and *CPT*-violation of neutrinos, indicating new physics beyond relativity.

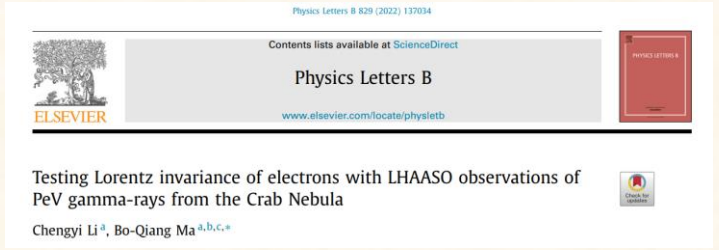
C.Li and B.-Q.Ma, PLB 835 (2022) 137543, JHEP 03 (2023) 230

# The string theory model of space-time foam:

## Lorentz- and CPT-violating neutrinos from string/D-brane model

**We show that the space-time foam model from string/D-brane theory predicts a scenario in which neutrinos can possess linearly energy dependent speed variation, together with an asymmetry between neutrinos and antineutrinos, indicating the possibility of Lorentz and CPT symmetry violation for neutrinos.**

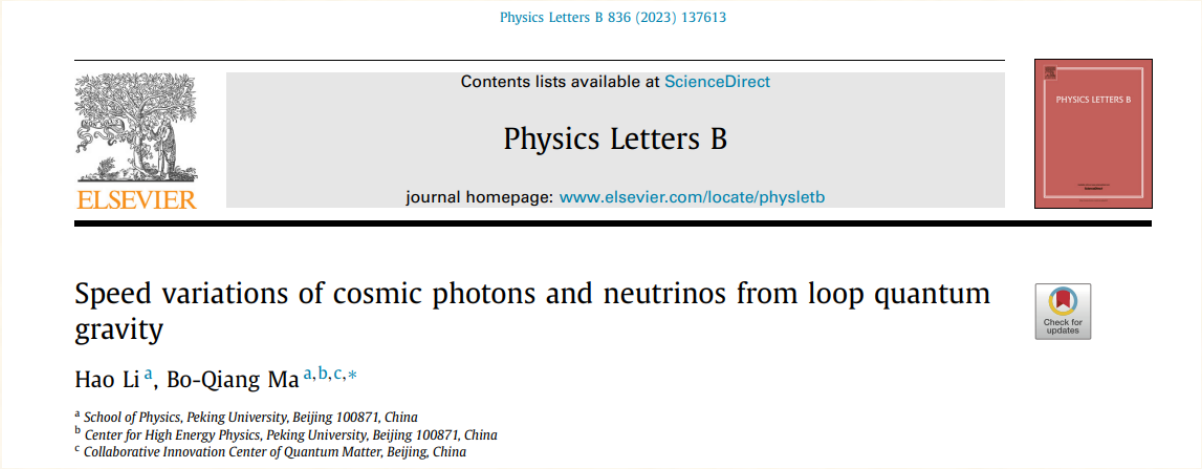



C.Li, B.-Q.Ma, PLB 819 (2021) 136443, PLB 829 (2022) 137034,
PLB 835 (2022) 137543, JHEP 03 (2023) 230

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

# Theoretical Studies on Lorentz Violation of Photons and Neutrinos

## 探索洛伦兹破缺与时空的新理论

**[弦理论]**
C. Li, B.-Q. Ma, JHEP 03 (2023) 230
C. Li, B.-Q. Ma, PLB 835 (2022) 137543
C. Li, B.-Q. Ma, PLB 819 (2021) 136443

**[圈量子引力]**
H. Li, B.-Q. Ma, PLB 836 (2023) 137613

**[Finsler几何]**
J. Zhu, B.-Q. Ma, EPJC 83 (2023) 349
J. Zhu, B.-Q. Ma, PRD 105 (2022) 12

**[标准模型拓展]**
X. Zhang, B.-Q. Ma, PRD 99 (2019) 043013
Z. Xiao, B.-Q. Ma, PRD 80 (2009) 116005
L. Zhou, B.-Q. Ma, CPC 35 (2011) 987 ……

**- 基于弦理论的时空泡沫模型**

对弦/D膜理论的时空泡沫（D泡沫）图景下粒子传播与反应行为的理论和唯象研究

**- 圈量子引力的半经典近似**

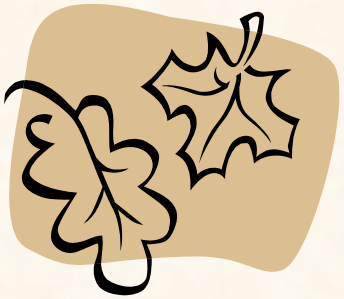
对圈引力半经典（WBSC）近似下光子/中微子速度色散特征的研究，及其唯象学应用

**- Finsler几何与宇宙学**

考虑量子引力的有效描述，在Finsler背景下对粒子测地轨迹及其传播时间差的理论计算

**- 类标准模型拓展的有效描述（洛伦兹破缺矩阵）**

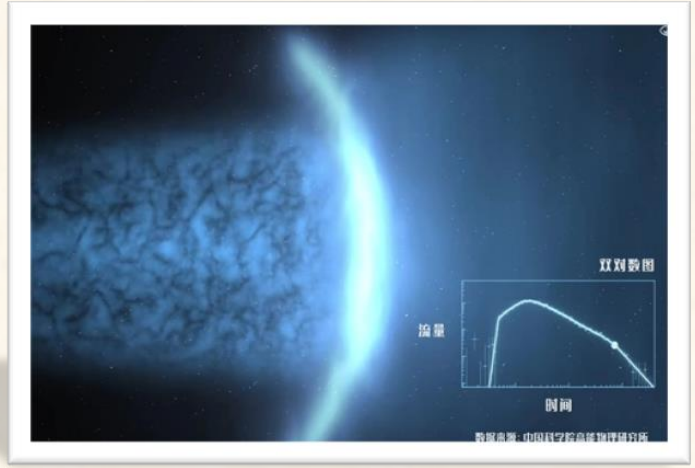
标准模型拓展（SME）的理论和唯象讨论；对标准模型补充（SMS）框架的原创性理论研究

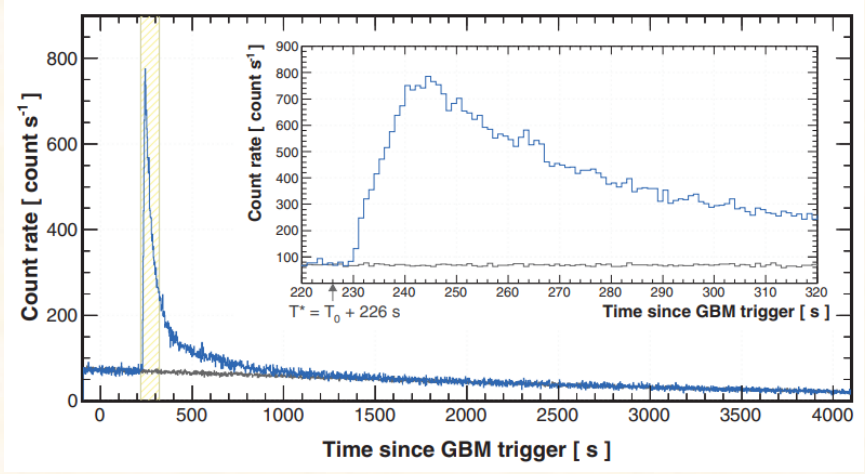


# Remarks: neutrinos

- 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 anti-neutrinos.

# Newly observed GRB221009A



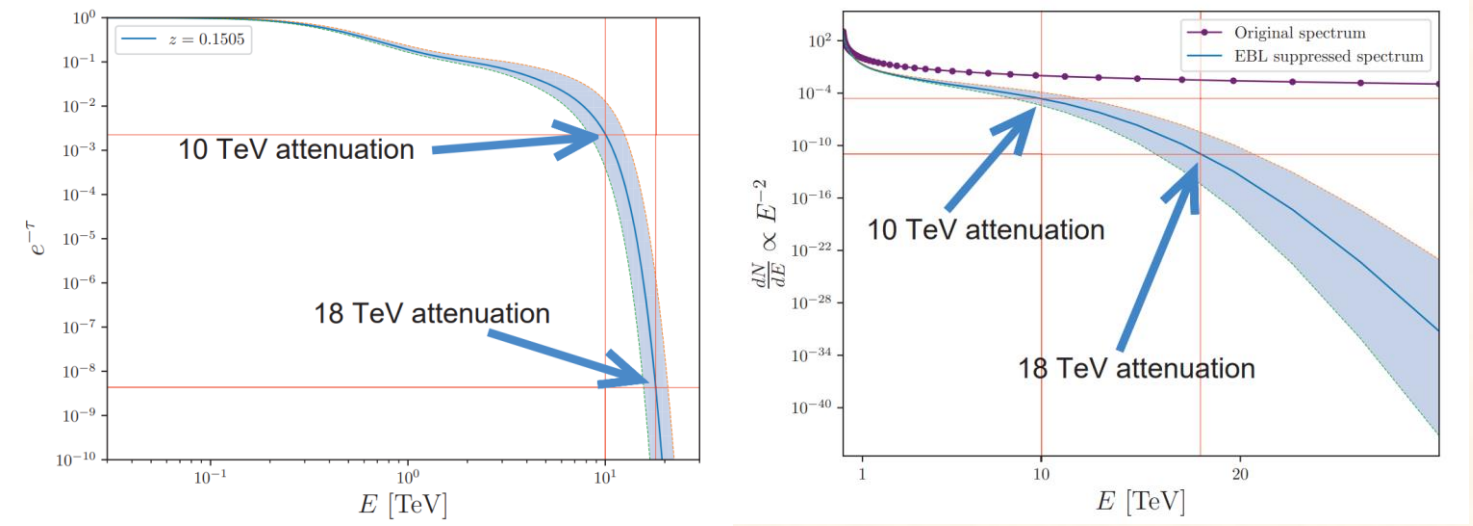




- Triggered by Fermi and Swift
- Very bright GRB with very short distance
  z=0.1505 (2.4 billion light years)
- LHAASO observation: 64000 high energy events with energies larger than 200 GeV including photons with energy larger than 10 TeV.

**2022年10月9日，LHAASO首先发现伽玛暴超出10TeV的光子事例。**

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

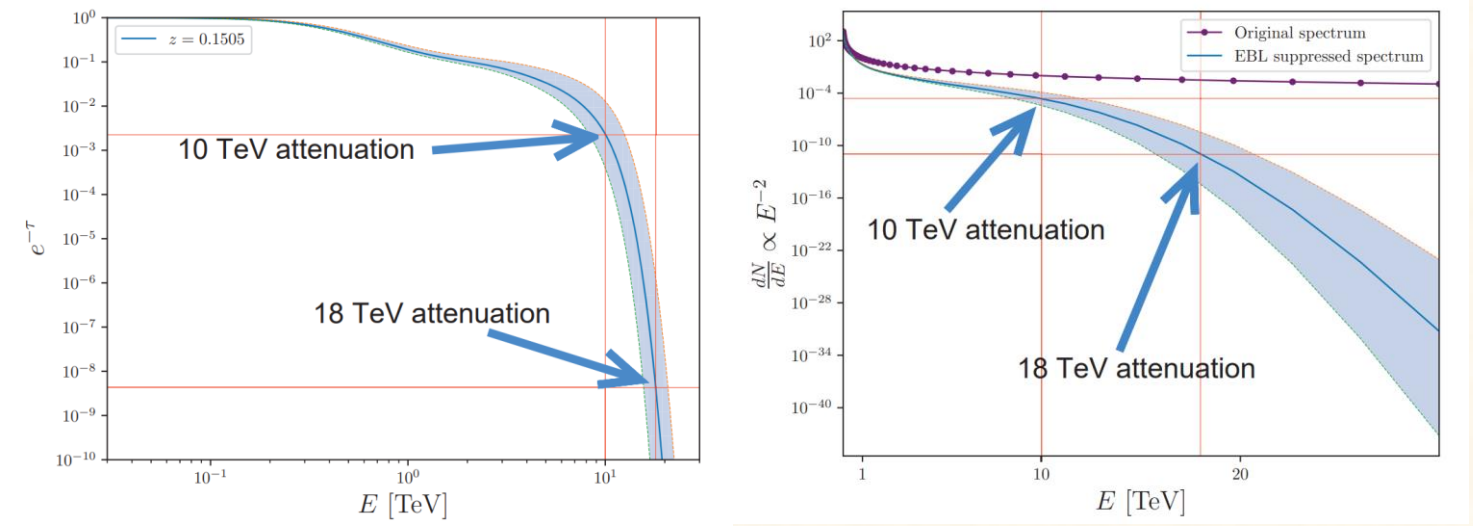
# Newly observed GRB221009A




- 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

# Newly observed GRB221009A




- 在GRB221009A消息的第二天，马伯强组就在国际上首先指出，从正常方式难以理解超出10TeV来自GRBs的事例，并建议LHAASO数据可以开展对洛伦兹对称性破缺的研究。这些理论建议推动同行们关注LHAASO的结果，并开展对洛伦兹破缺参数的细致约束。

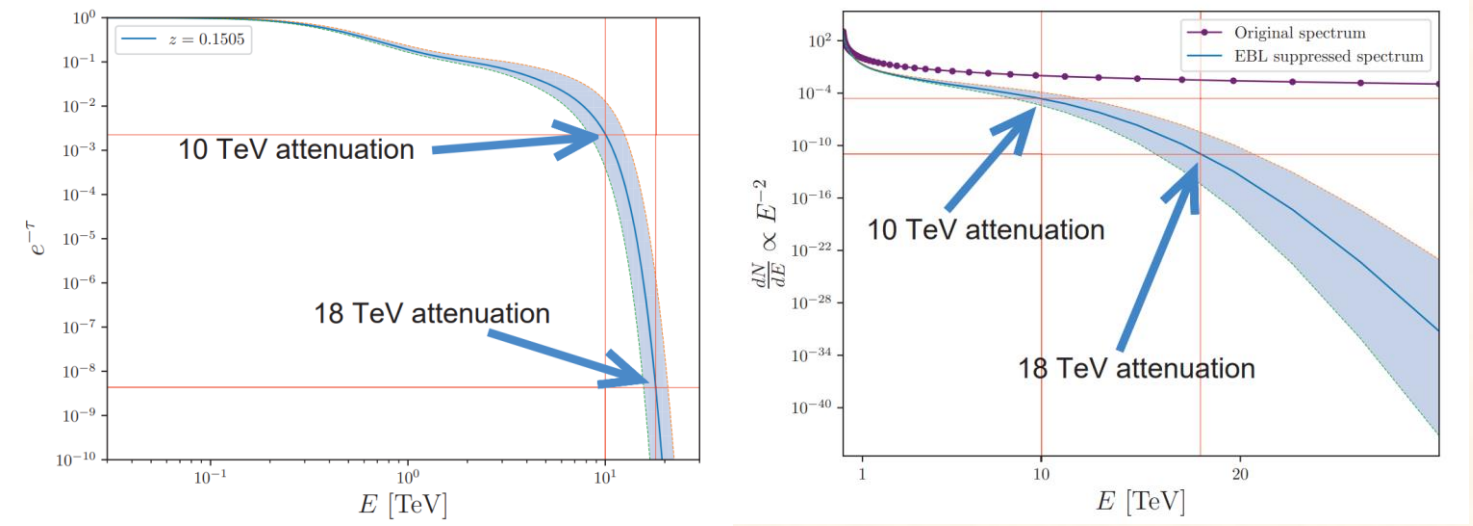
H. Li and B.-Q. Ma, arXiv:2210.06338, APP 148 (2023) 102831

See also：

H. Li and B.-Q. Ma, arXiv:2210.05563, EPJC 83 (2023) 192

H. Li and B.-Q. Ma, arXiv:2306.02962 , JCAP 10 (2023) 061

H. Li and B.-Q. Ma, arXiv:2307.14256, Mod.Phys.Lett.A 39 (2024) 04

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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, B.-Q. Ma, arXiv: 2210.13120 , CPL 40 (2023) 011401

在国际上较早指出，**LHAASO关于GRB221009A的数据也可以开展对轴子新物理物理的研究。**

Chinese Physics Letters **40**, 011401 (2023)

**Axion-Photon Conversion of LHAASO Multi-TeV and PeV Photons**

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G. Zhang, B.-Q. Ma, arXiv: 2210.13120 , CPL 40 (2023) 011401

L. Wang and B.-Q. Ma, arXiv:2304.01819, PRD (2023) in press

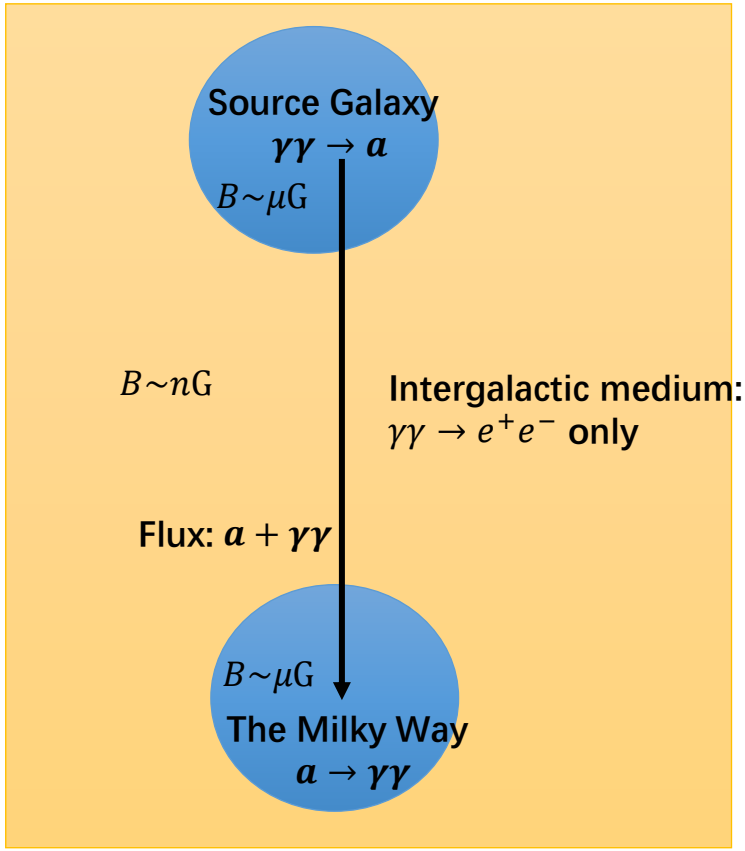
# The picture of photon-axion conversion

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.

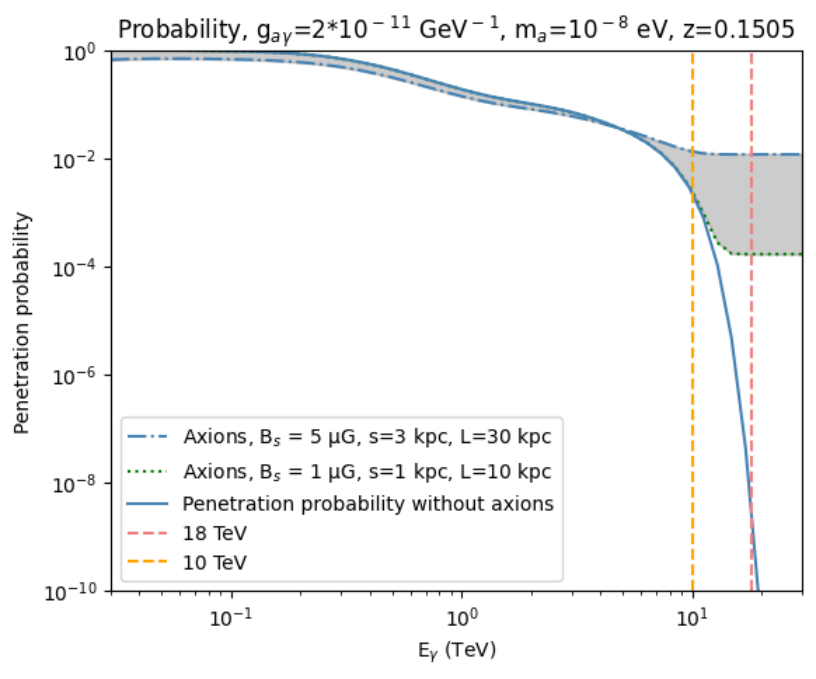
3. **Back conversion (逆转化)**: ALPs-Photon 在穿过银河系磁场时, 部分高能 ALPs 再度转化为光子, 使得地球上的观测者可以探测到本应消失的高能光子.



并通过细致分析对有关轴子新物理的参数给出约束。

L. Wang, B.-Q. Ma, arXiv: 2304.01819,  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 (12.2) 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.