Application of machine learning method
with cosmic photons

Bo-Qiang Ma（马伯强）

Peking University（北京大学)

28th LHC Mini-Workshop
(吉林-通化, July 8, 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

洛伦兹破缺

唯象分析

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

理论研究

包含洛伦兹破缺的理论和模型：

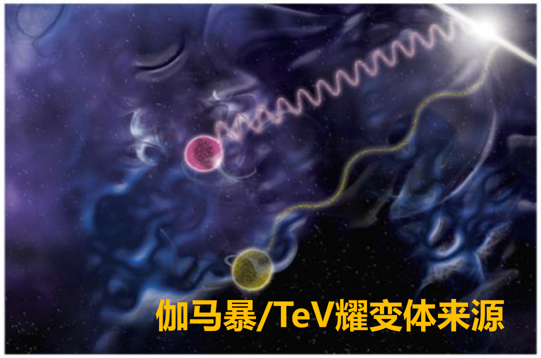
- 量子引力的理论与模型
- 时空结构模型
- 低能有效场论拓展

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

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

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
……

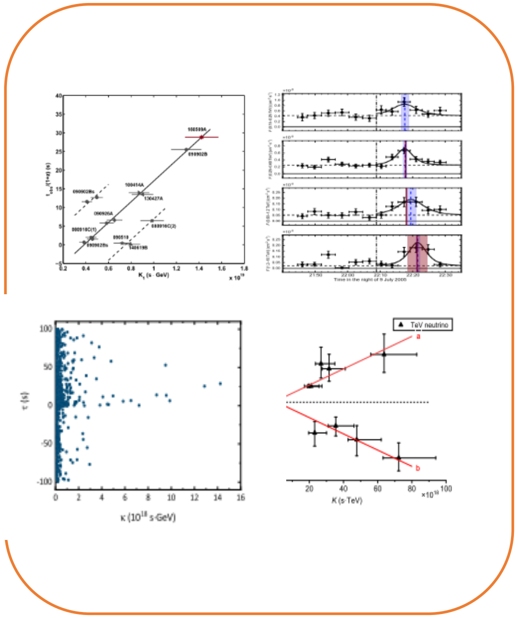
光子
洛伦兹破缺

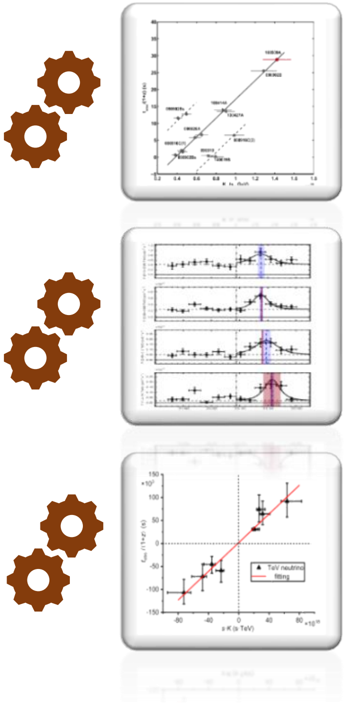
对中微子也可以开展类似研究

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**

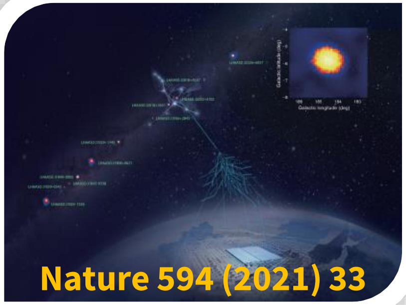
H. Li, B.-Q. Ma, Sci. Bull. 65 (2020) 262
J. Zhu, B.-Q. Ma, PLB 820 (2021) 136546……

- **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


Nature 594 (2021) 33

- **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

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

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

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

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


Science 373 (2021) 425

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

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

Modified photon dispersion relation from LV

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

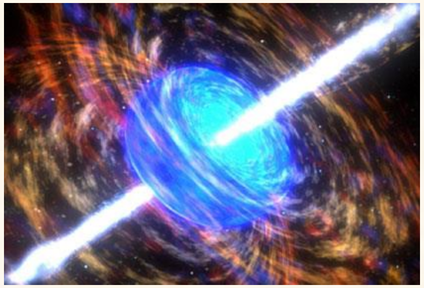
$$\sqrt{\hbar c/G} \simeq 1.22 \times 10^{19} \ \mathrm{GeV/c^2}$$

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)

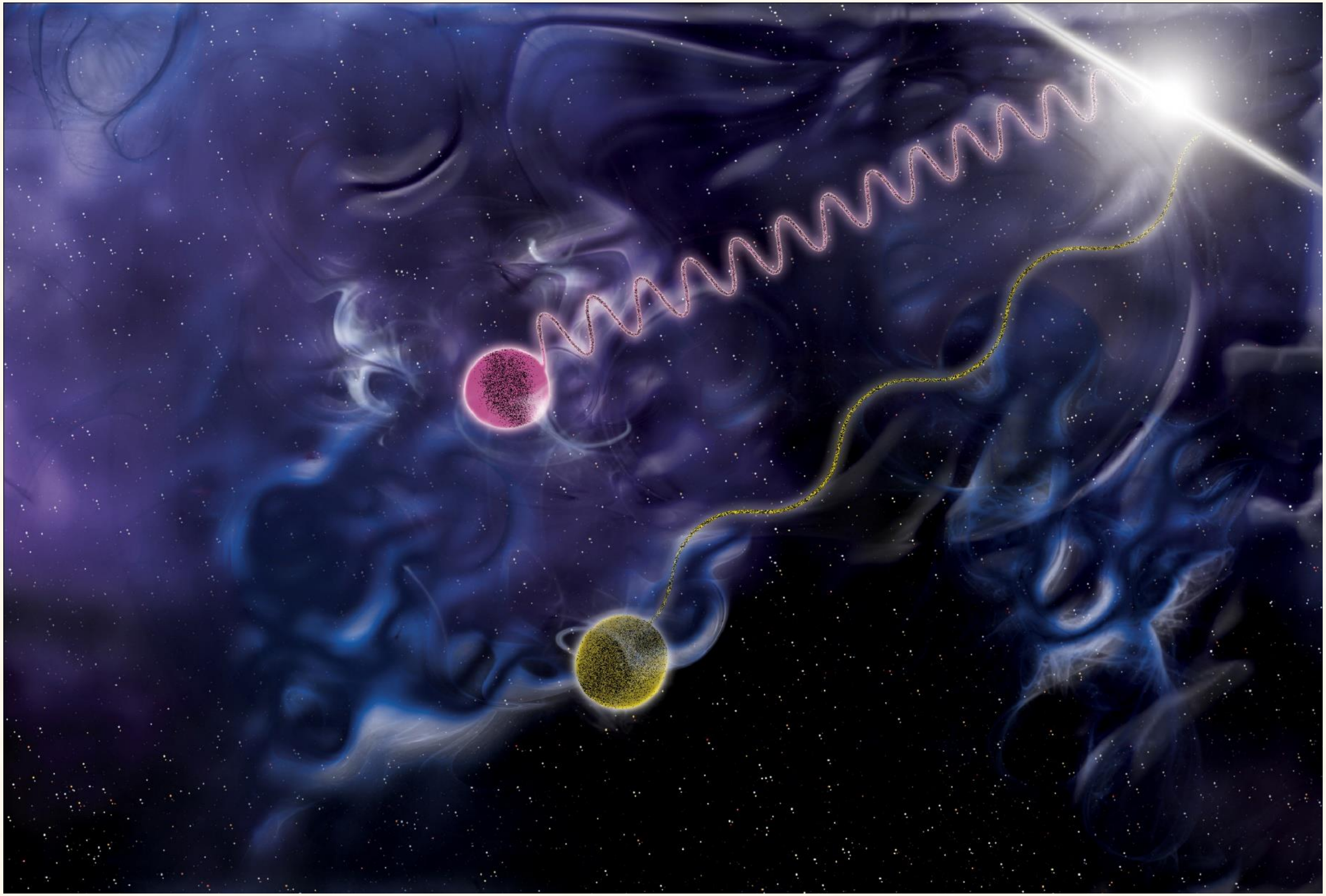


- The most energetic astrophysical process except the Big Bang
- 2 types [Piran'05, Rev. Mod. Phys.]
  - long GRBs: duration > 2 s; collapses of massive rapidly rotating stars
  - short GRBs: duration < 2 s; coalescence of two neutron stars or a neutron star and a black hole
- Long distance from detector:

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

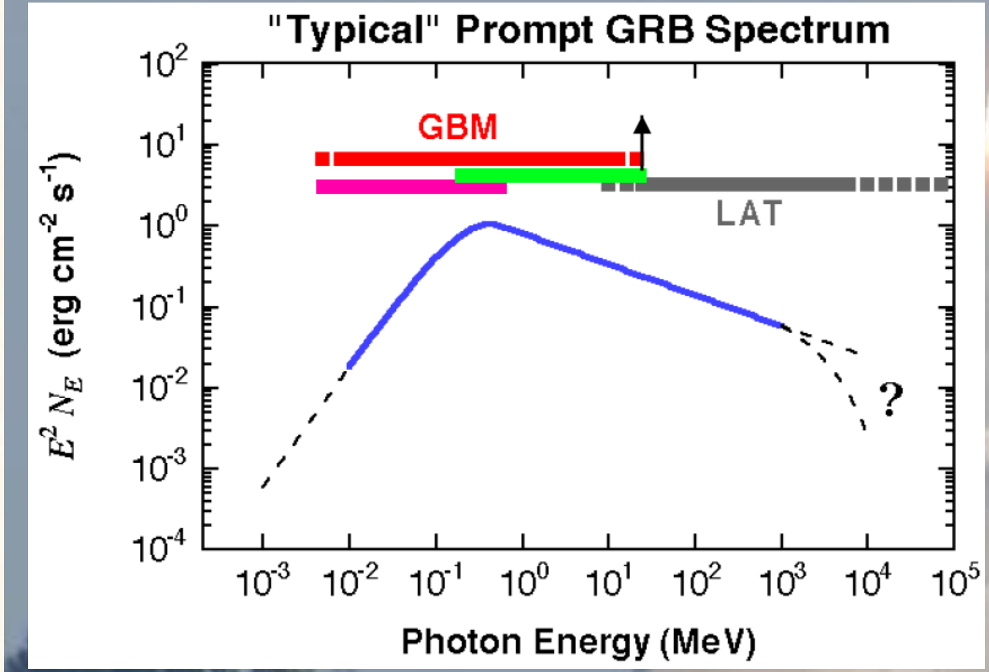
  $z \approx 0.5$ for short GRBs
- Use GRBs to test LV [Amelino-Camelia et al.'98, Nature]

Time-lag by GRB

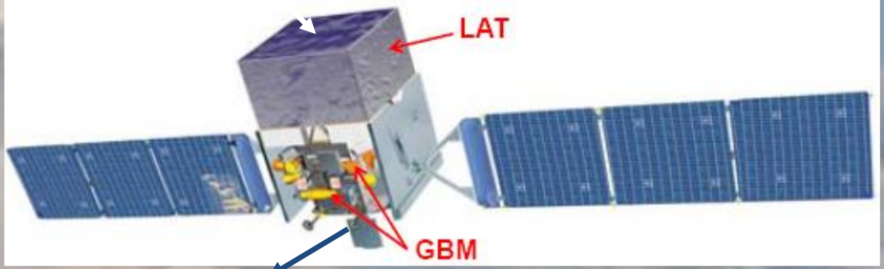


June 11, 2008

Fermi instruments



~ 300 GeV



trigger photons ~ 0.1 MeV

Model independent LV photon dispersion relation

$$\mathcal{E}^2 = \mathbf{p}^2 \left[1 - s_n \left(\frac{|\mathbf{p}|}{E_{\mathrm{LV},n}} \right)^n \right]$$

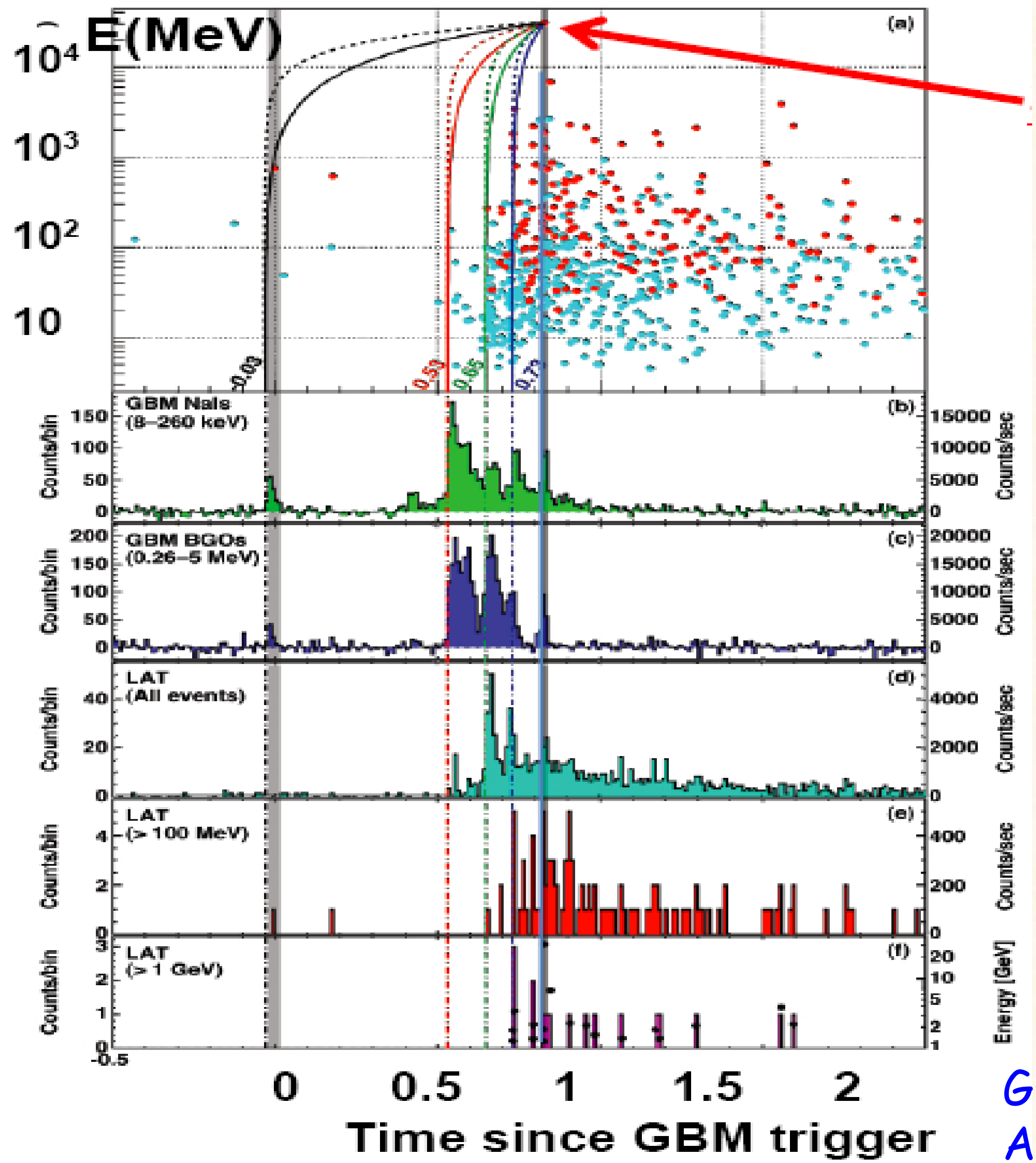
$$v = 1 - s_n \frac{n+1}{2} \left(\frac{\mathcal{E}}{E_{\mathrm{LV},n}} \right)^n$$

$n = 1$ 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



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

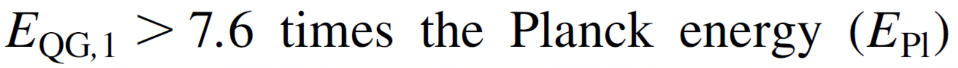
a lower limit of $1.2E_{\text{Planck}}$

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

$M \sim 7.72 \times 10^{19}$ GeV

$6.32 M_{\text{Pl}}$

Vasileiou et al., PRD 87 (2013) 122001



$E_{\text{QG},1} > 7.6$ times the Planck energy (E_{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

……

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

……

Formulas in our analysis of LV parameter

linear and quadratic energy dependence

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

N=1

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

N=2

$M_{\rm QG}c^2 = E_{\rm LV}$ **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 LV effect

- Expansion universe [Jacob & Piran'08, JCAP]

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

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

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

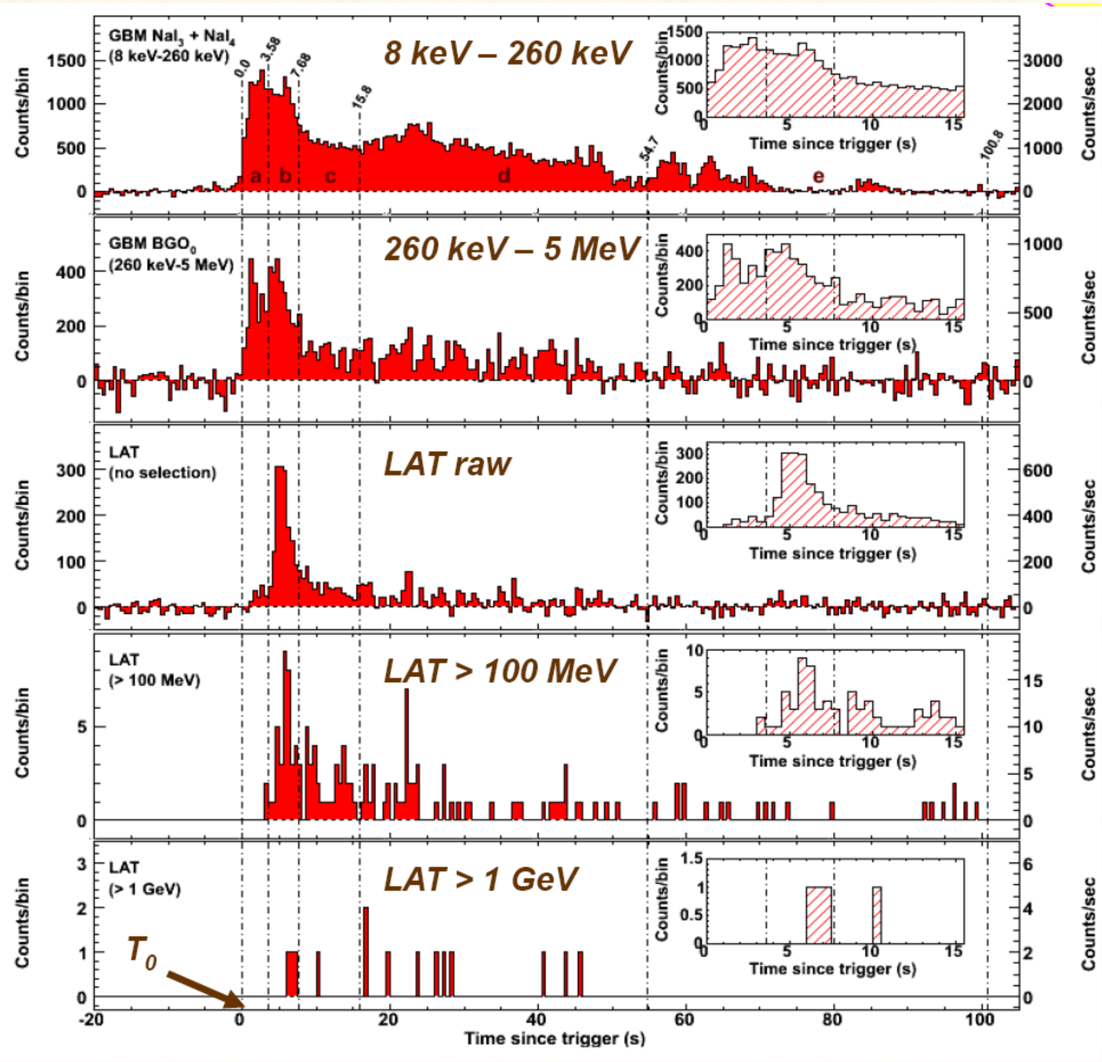
$$H_0 \simeq 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

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

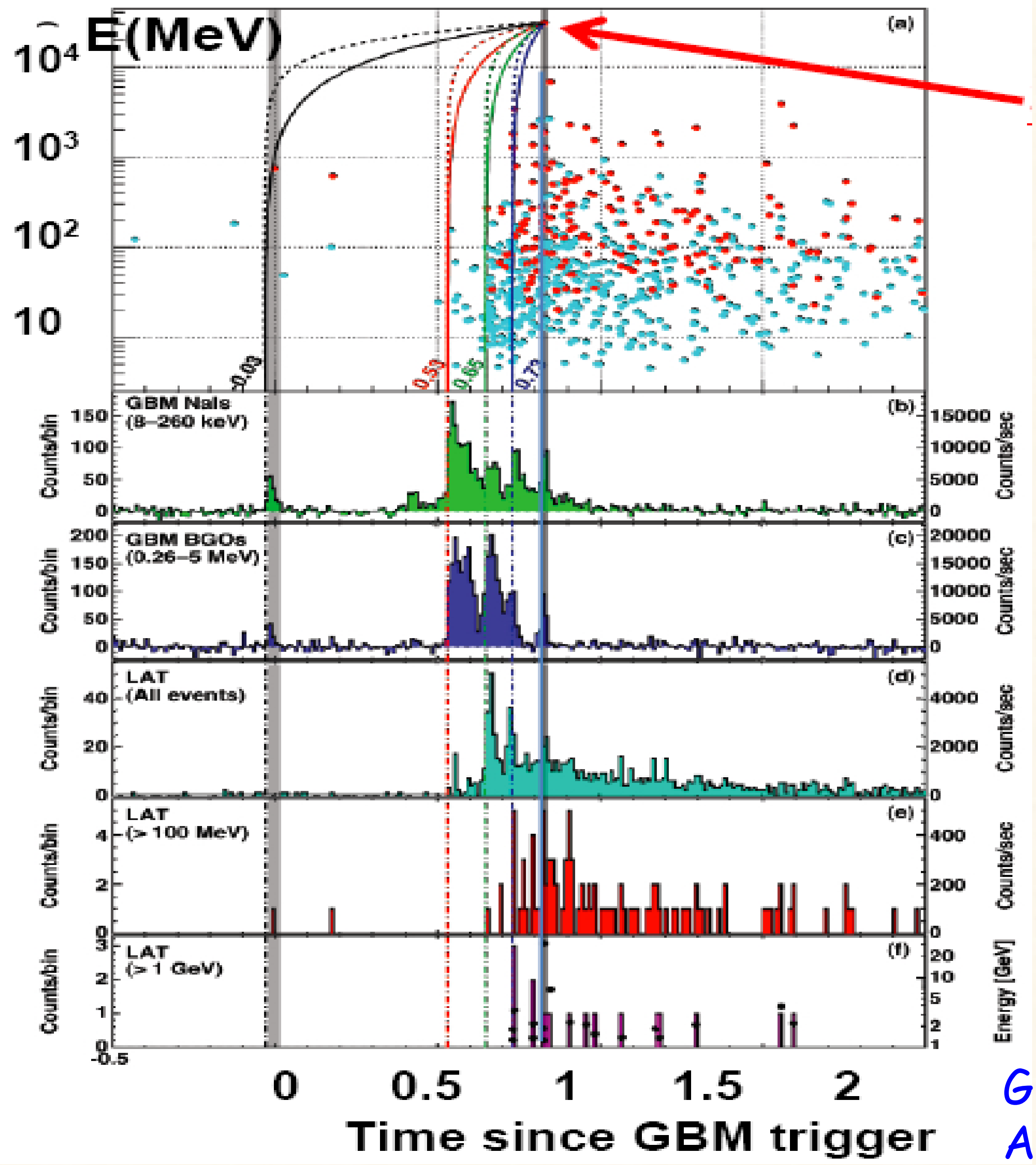
New derivation from Finsler geometry:

J. Zhu, B.-Q. Ma, PRD 12 (2022) 124069.

Lag determinations



GRB080916C -- Abdo et al.'09, Science



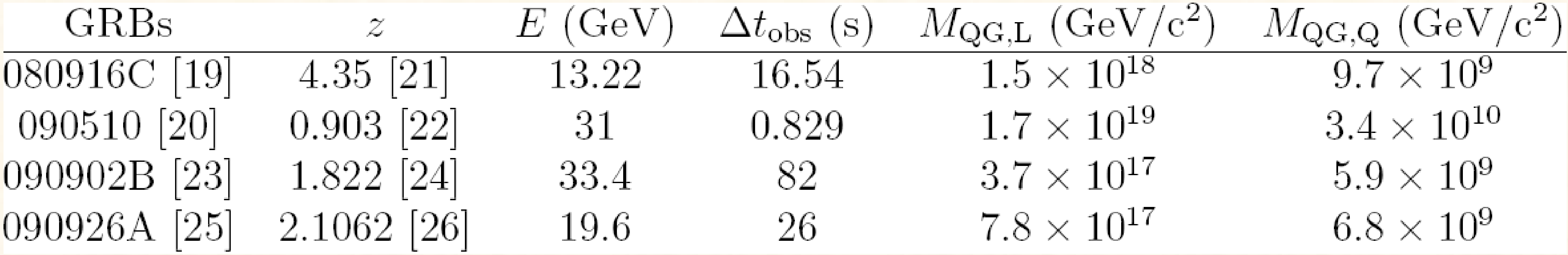
31 GeV

Time lags are affected both artificially and instrumentally

GRB090510
Abdo et al.'09, Nature

Four Fermi observations around 2010

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}

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

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

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

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.]

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

An intuitive way to perform analysis

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

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

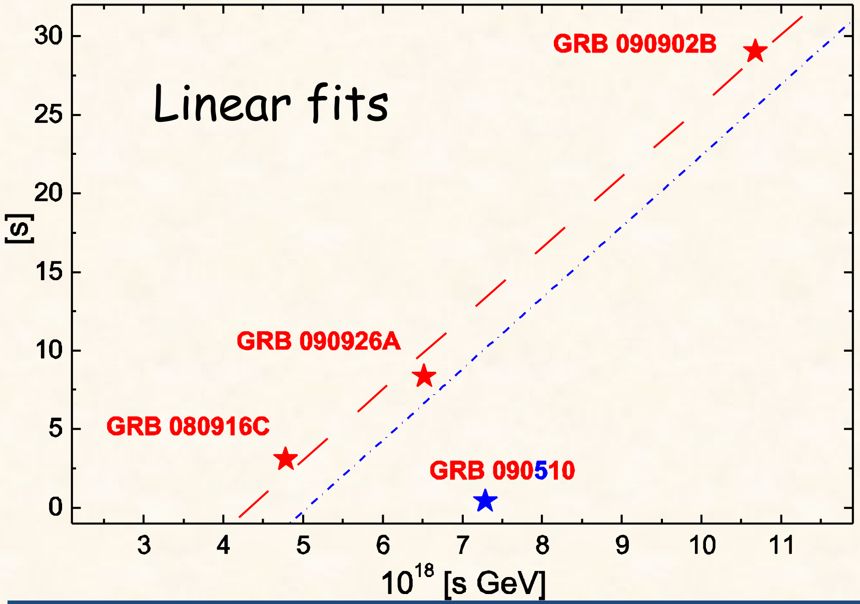
$$K_n = \frac{1+n}{2H_0} \frac{E^n_{\mathrm{high}} - E^n_{\mathrm{low}}}{1+z} \int_0^z \frac{(1+z')^n \mathrm{d}z'}{\sqrt{\Omega_{\mathrm{m}}(1+z')^3 + \Omega_\Lambda}}$$

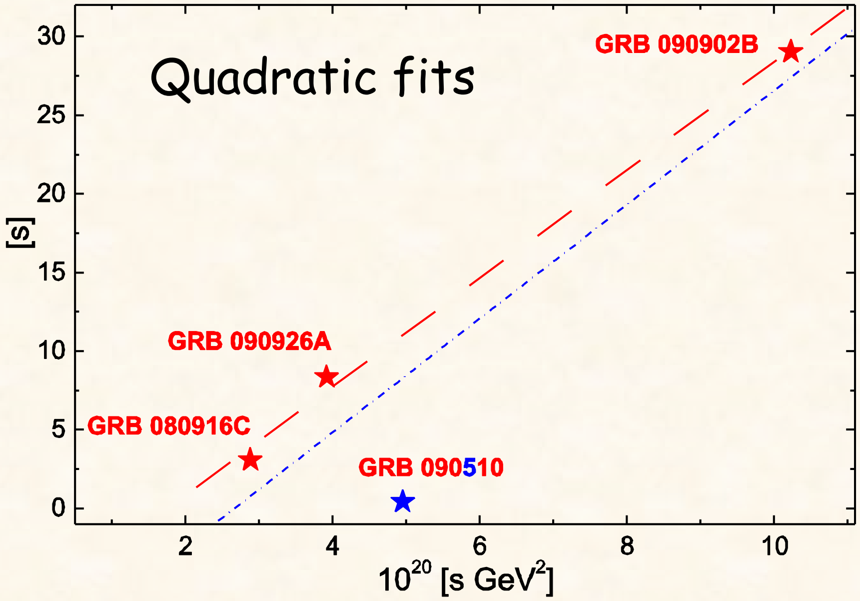
L.Shao, Z.Xiao and B.-Q.Ma, APP 33 (2010) 312

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

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

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



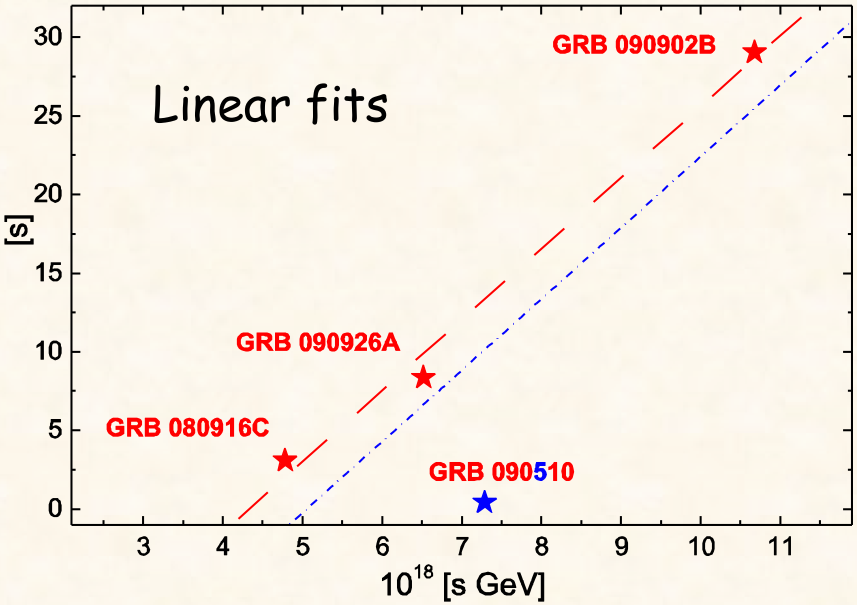


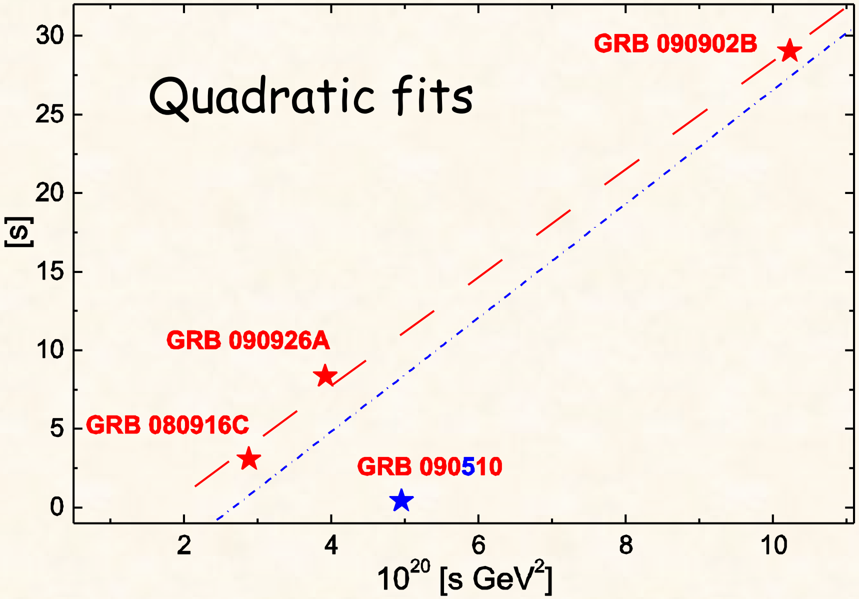
$$M_{\mathrm{QG,L}} = (2.2 \pm 0.2) \times 10^{17}\ \mathrm{GeV/c^2}\ \text{and}\ M_{\mathrm{QG,Q}} = (5.4 \pm 0.2) \times 10^{9}\ \mathrm{GeV/c^2}$$

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

Discussions

- negative intercepts

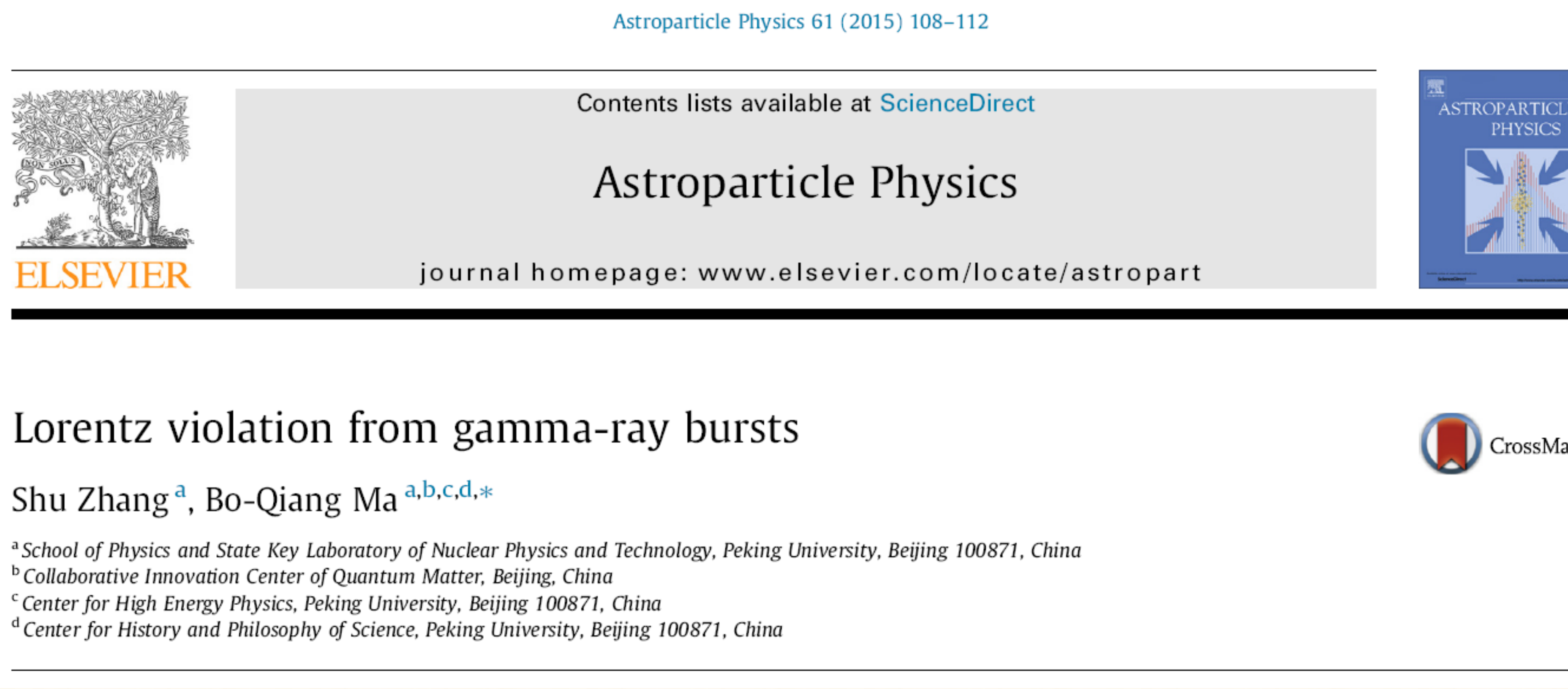




~ -20 s for linear dependence
-6 s ~ -10 s for quadratic dependence

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

further development around 2015



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

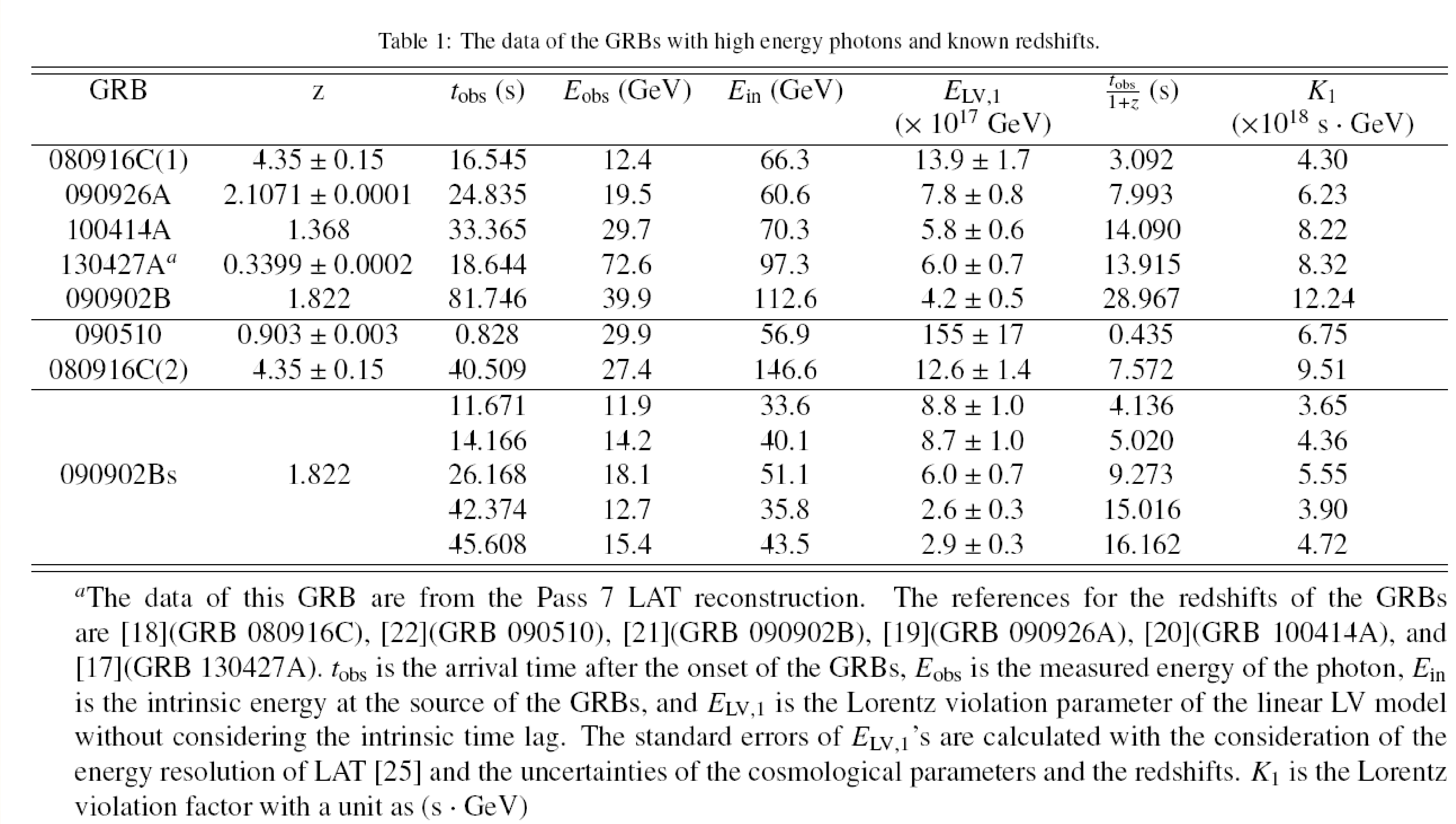


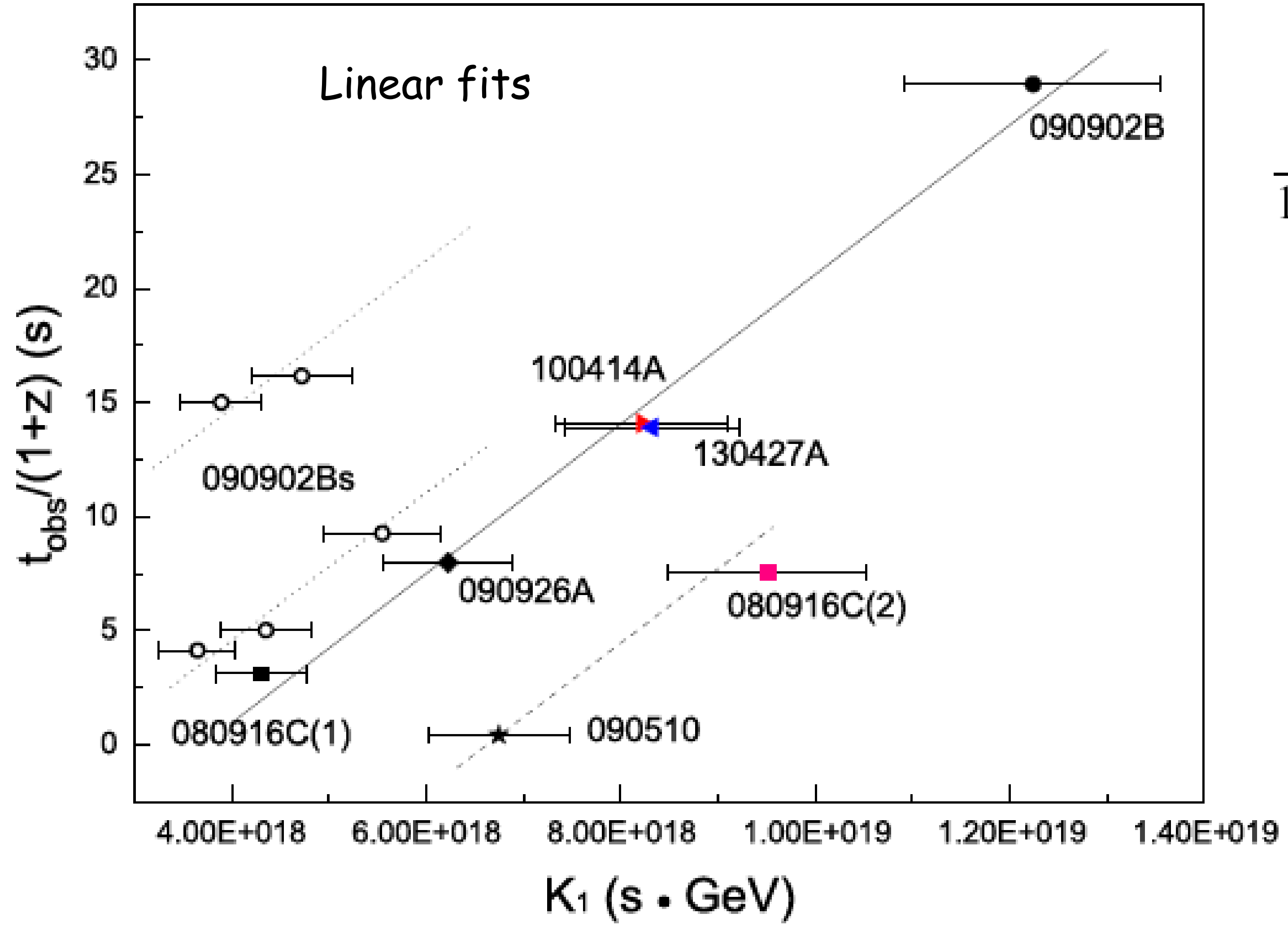
Table 1: The data of the GRBs with high energy photons and known redshifts.

GRB	z	$t_{\rm obs}$ (s)	$E_{\rm obs}$ (GeV)	$E_{\rm in}$ (GeV)	$E_{{\rm LV},1}$ ($\times 10^{17}$ GeV)	$\frac{t_{\rm obs}}{1+z}$ (s)	K_1 ($\times 10^{18}$ s $\cdot$ 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). $t_{\rm obs}$ is the arrival time after the onset of the GRBs, $E_{\rm obs}$ is the measured energy of the photon, $E_{\rm in}$ is the intrinsic energy at the source of the GRBs, and $E_{{\rm LV},1}$ is the Lorentz violation parameter of the linear LV model without considering the intrinsic time lag. The standard errors of $E_{{\rm LV},1}$'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 $\cdot$ 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?

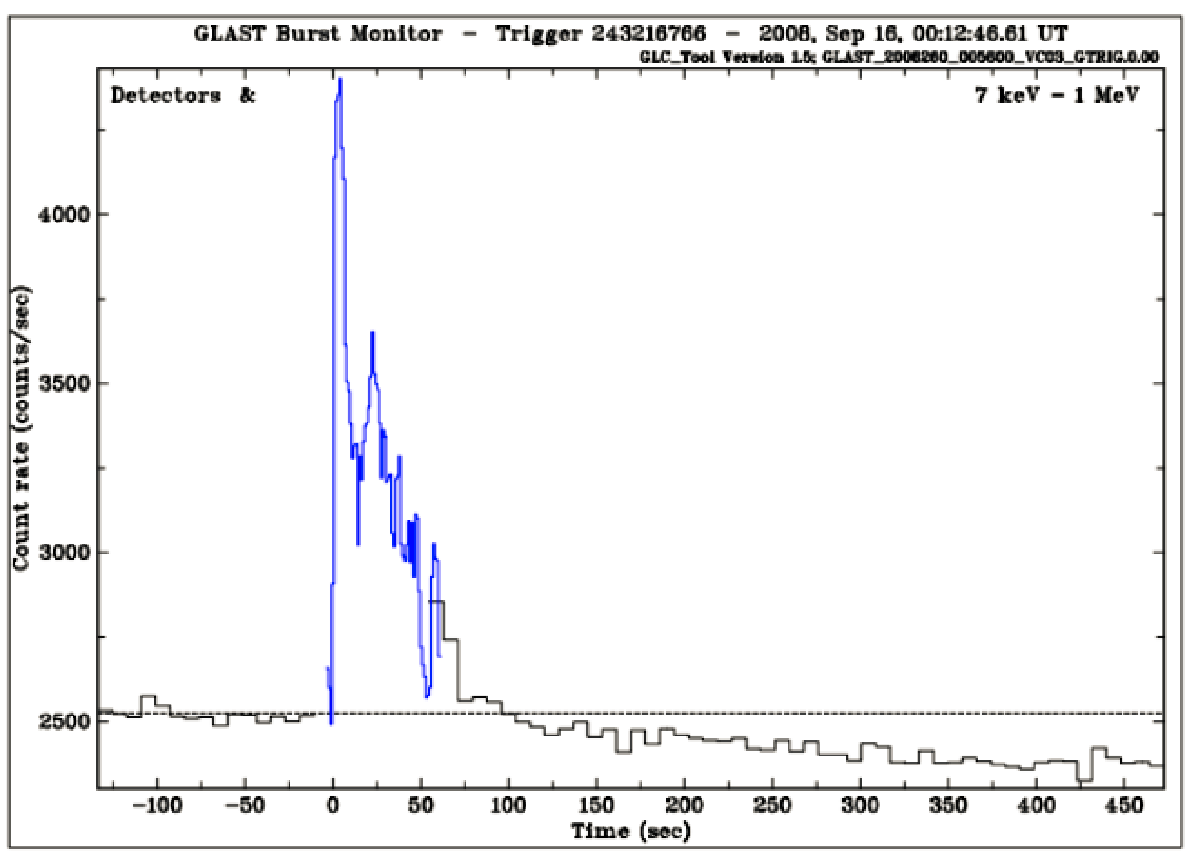
Trigger:

- 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 78 (2018) 825, 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

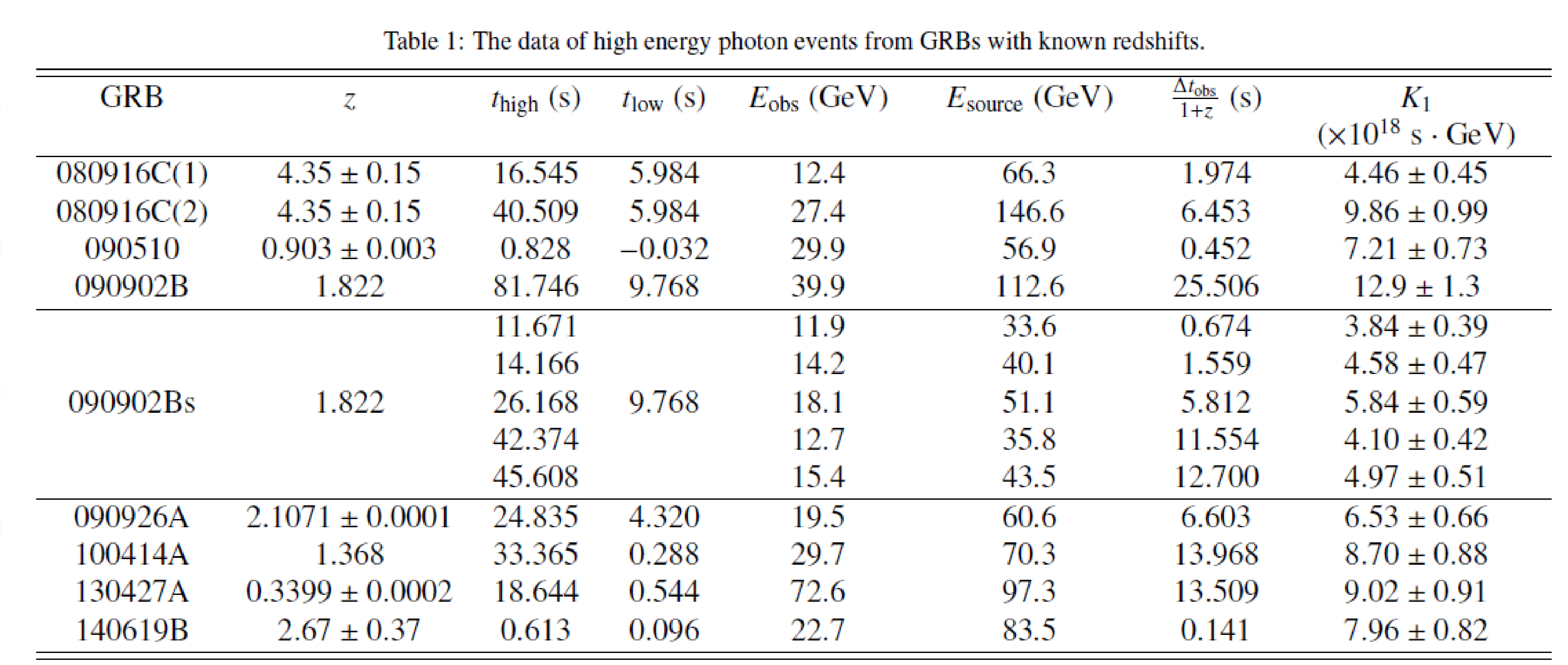
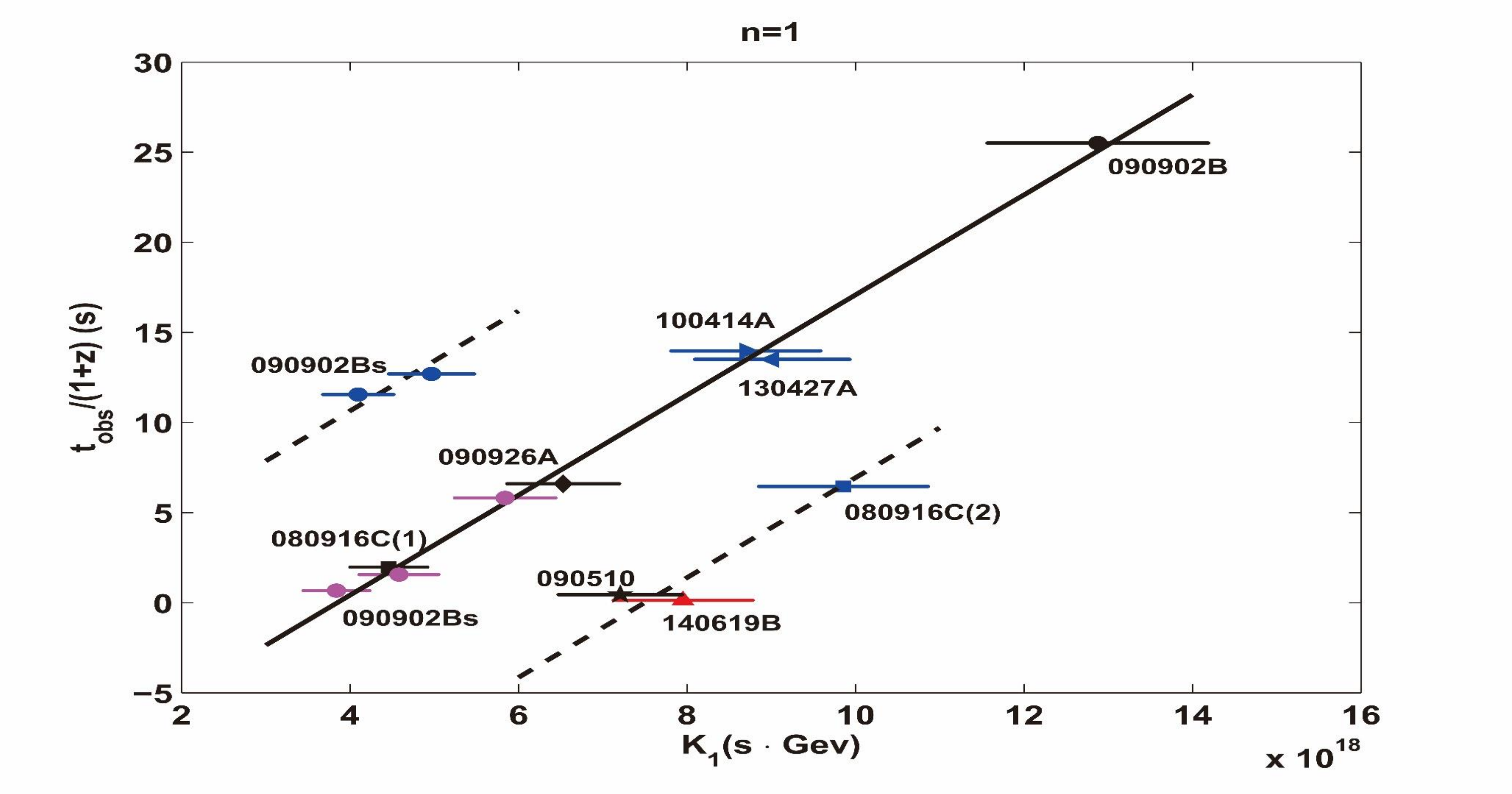


Table 1: The data of high energy photon events from GRBs with known redshifts.

GRB	z	t_{high} (s)	t_{low} (s)	E_{obs} (GeV)	E_{source} (GeV)	$\frac{\Delta t_{\mathrm{obs}}}{1+z}$ (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

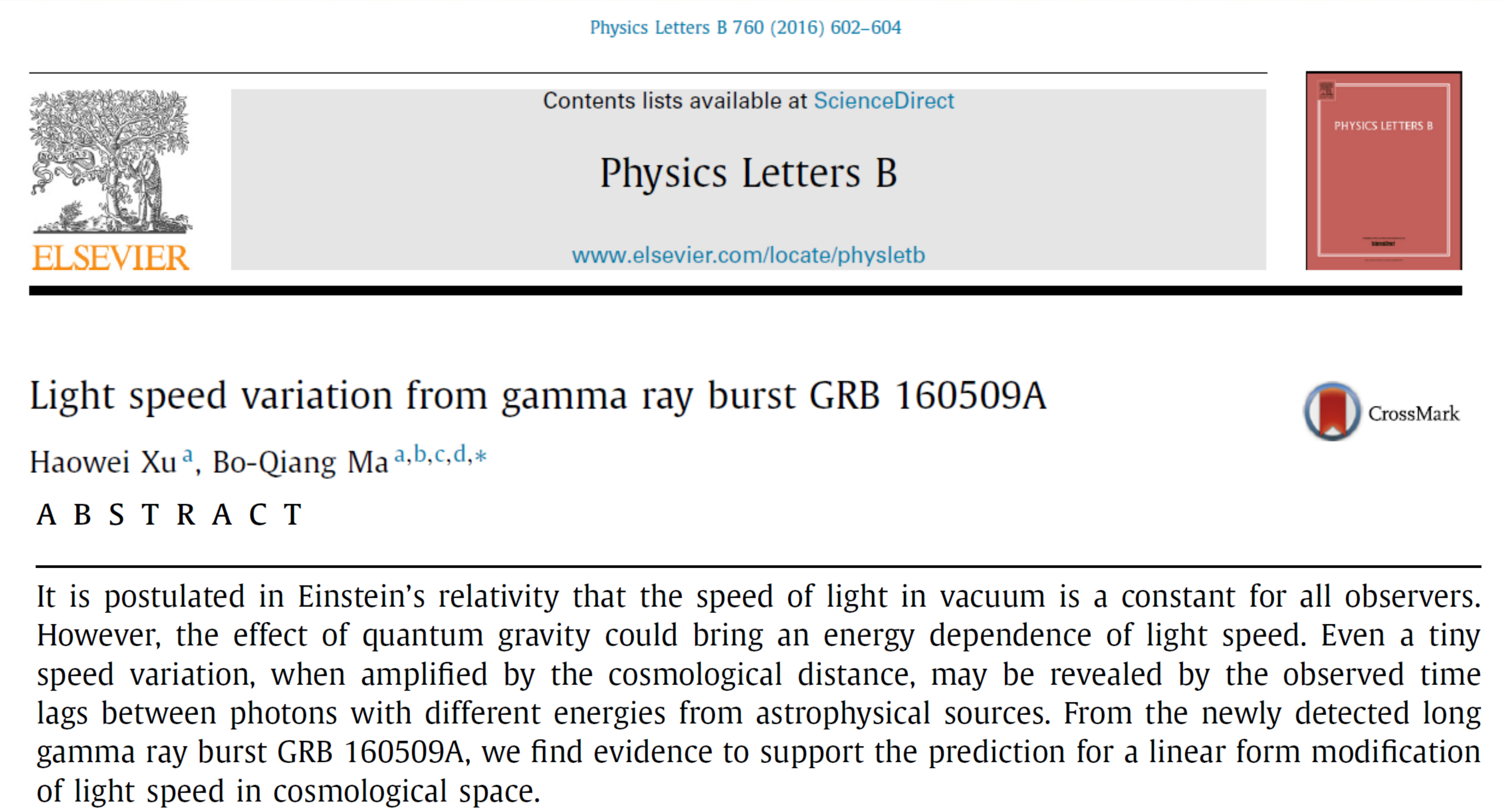
- H.Xu, B.-Q.Ma, APP 82 (2016) 72, arXiv: 1607.03203

New Results



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

New GRB: 160509A



Physics Letters B 760 (2016) 602–604

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Light speed variation from gamma ray burst GRB 160509A

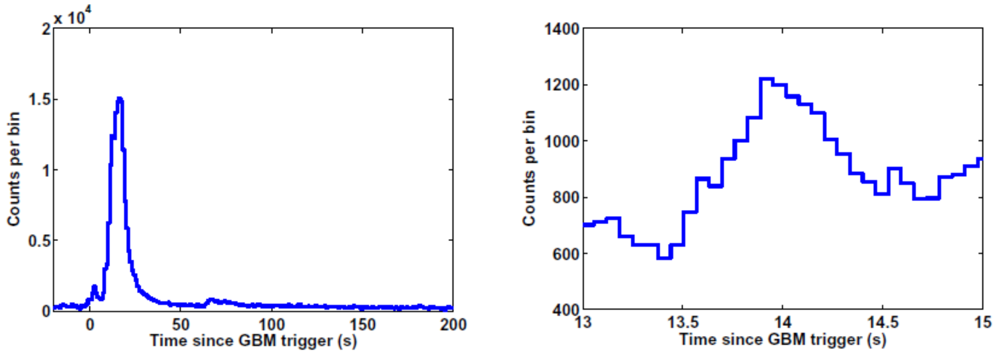
Haowei Xu[a], Bo-Qiang Ma[a,b,c,d,*]

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



(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 $T_{\mathrm{peak}} = 13.920$ s.

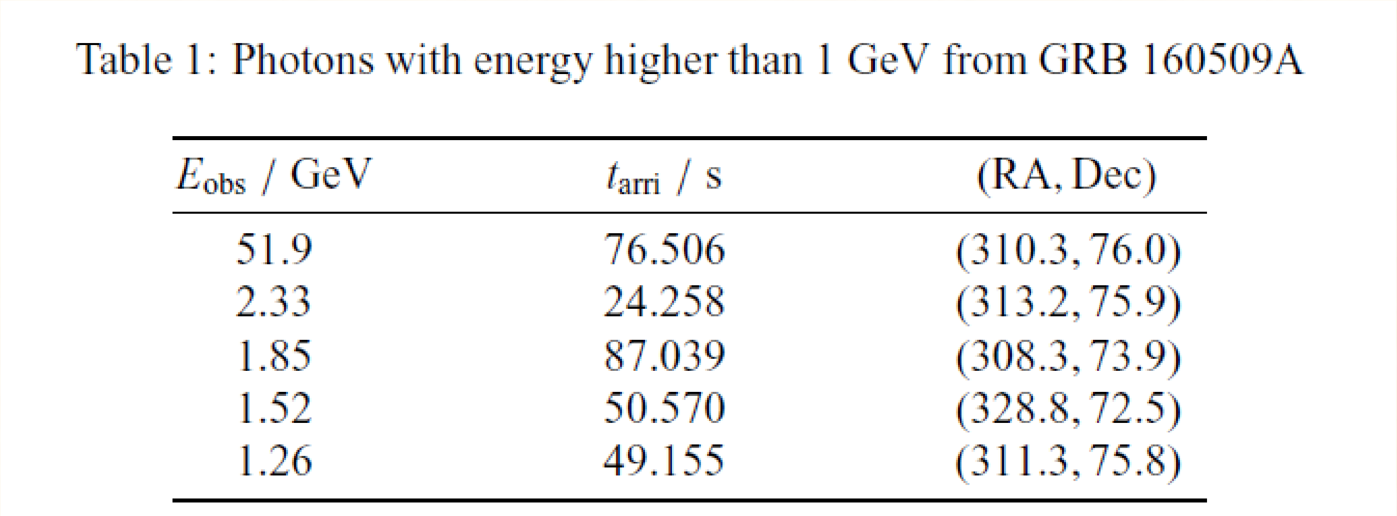


Table 1: Photons with energy higher than 1 GeV from GRB 160509A

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

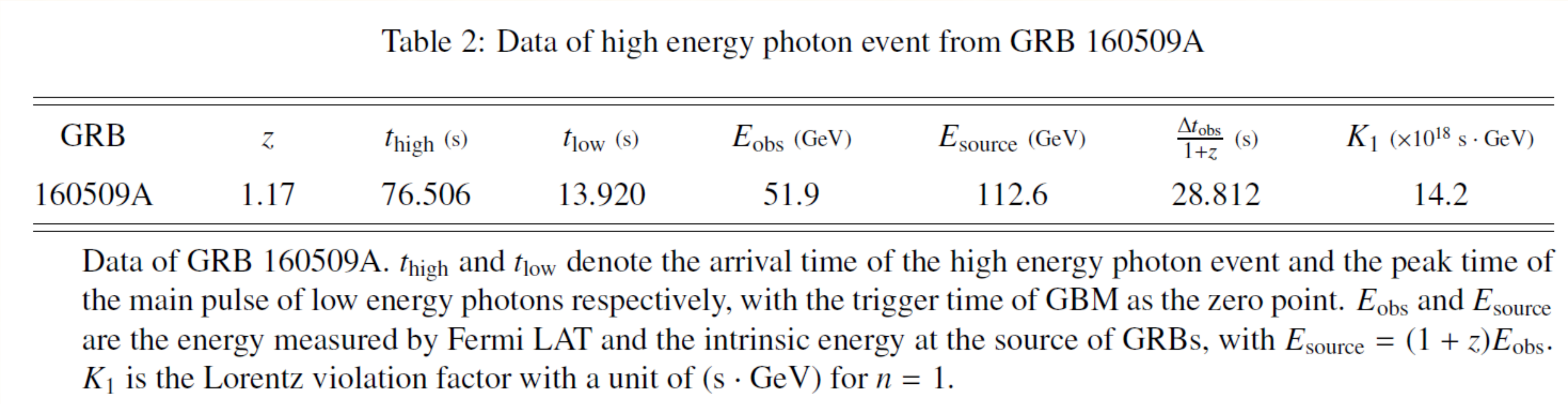


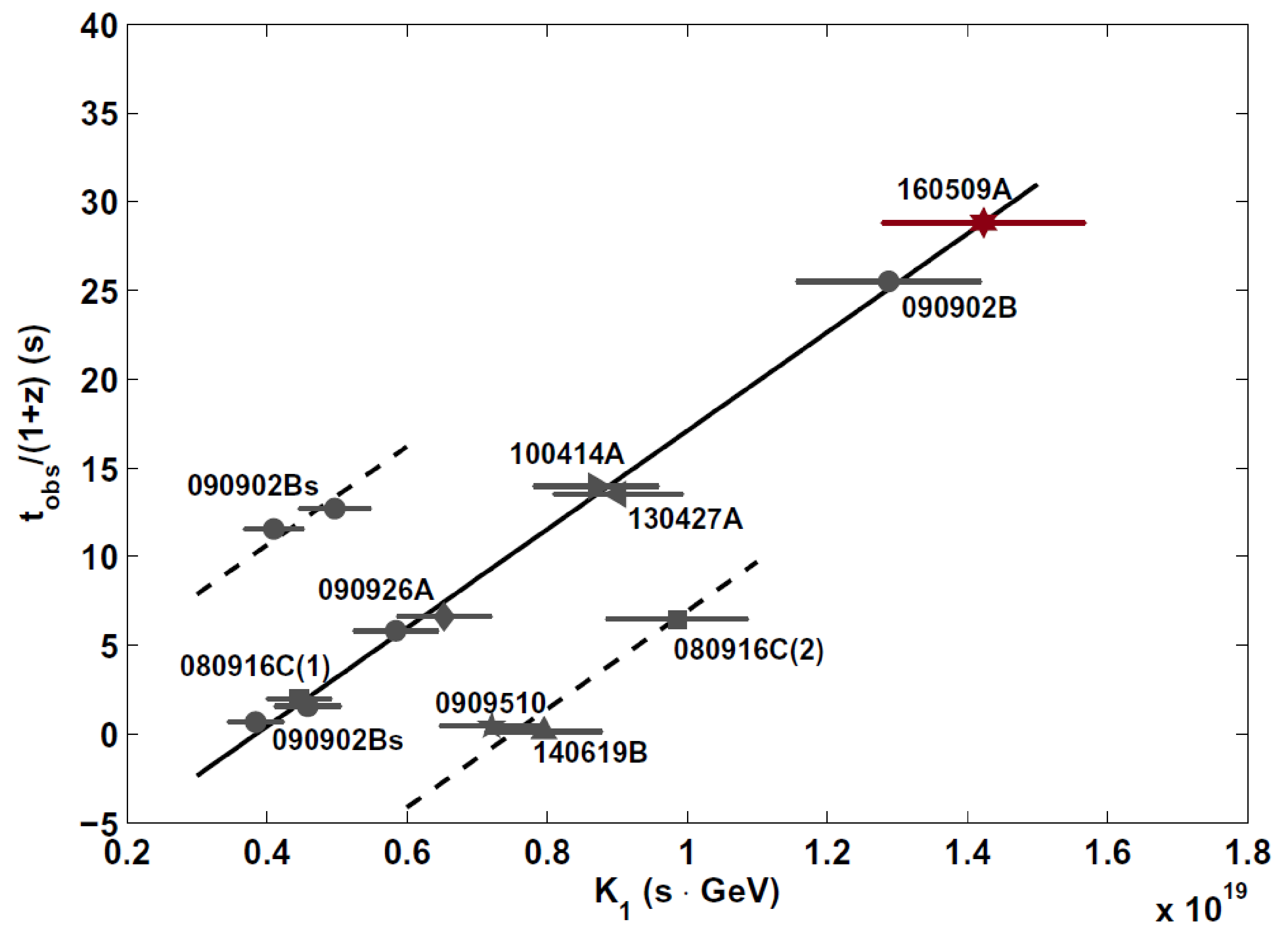
Table 2: Data of high energy photon event from GRB 160509A

GRB	z	t_{high} (s)	t_{low} (s)	E_{obs} (GeV)	E_{source} (GeV)	$\frac{\Delta t_{\mathrm{obs}}}{1+z}$ (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_{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 $E_{\mathrm{source}} = (1+z)E_{\mathrm{obs}}$. 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

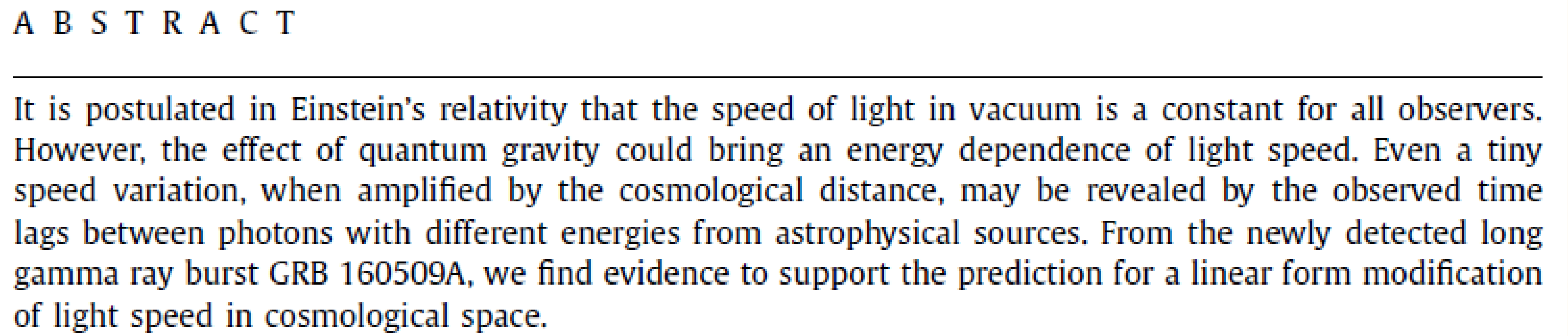
New GRB: 160509A

we find evidence

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

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

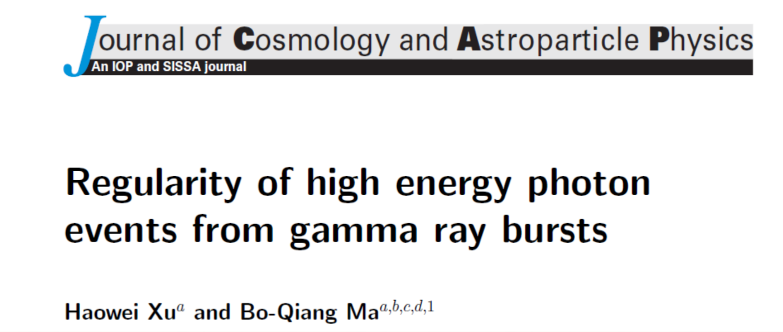
$$E_{\rm LV} = 3.60 \times 10^{17}\ {\rm GeV}$$



ABSTRACT

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]

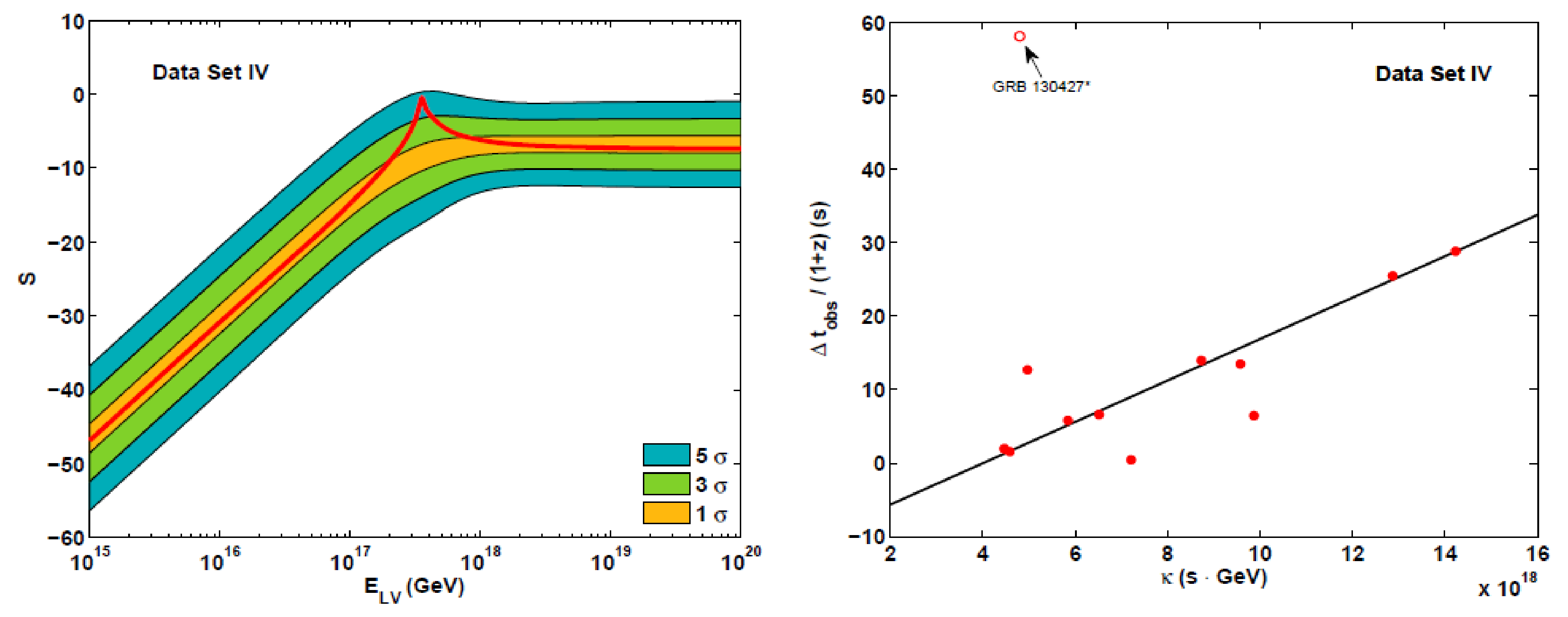
H.Xu, B.-Q.Ma, JCAP 1801 (2018) 050

- 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

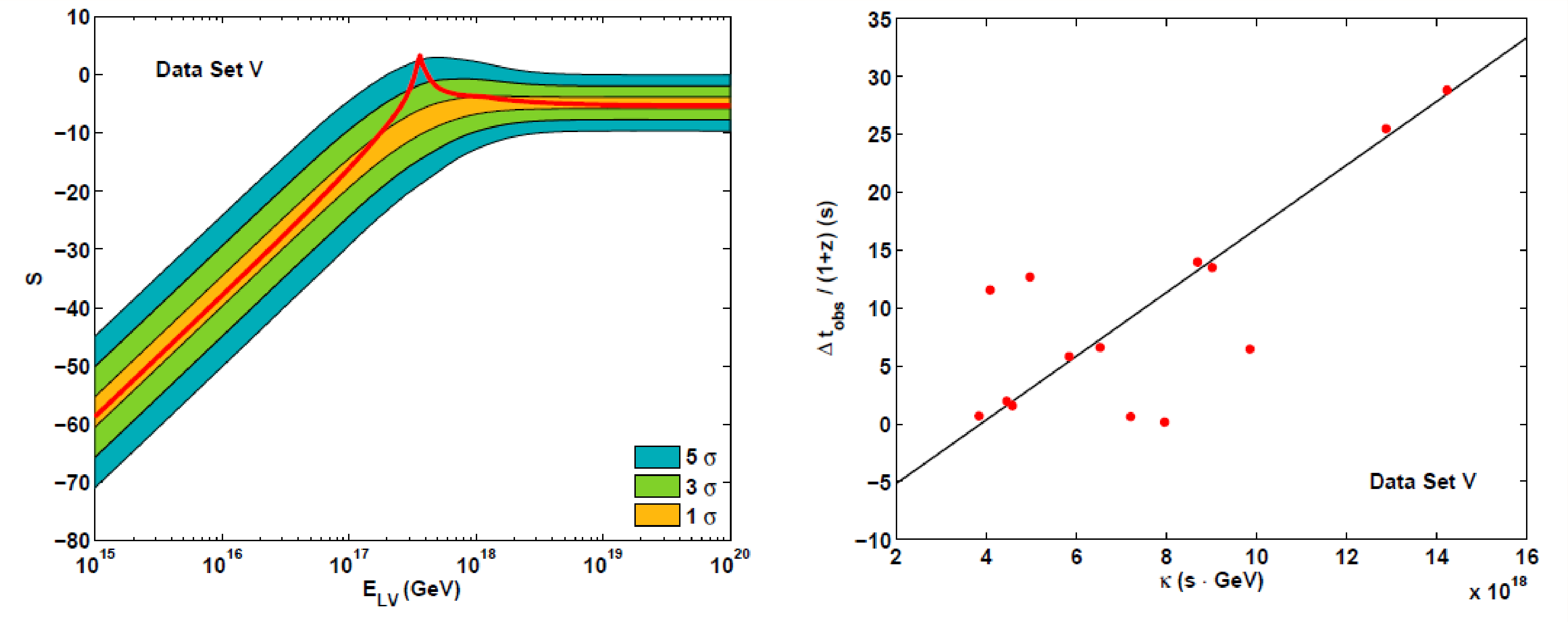
H.Xu, B.-Q.Ma, JCAP 1801 (2018) 050

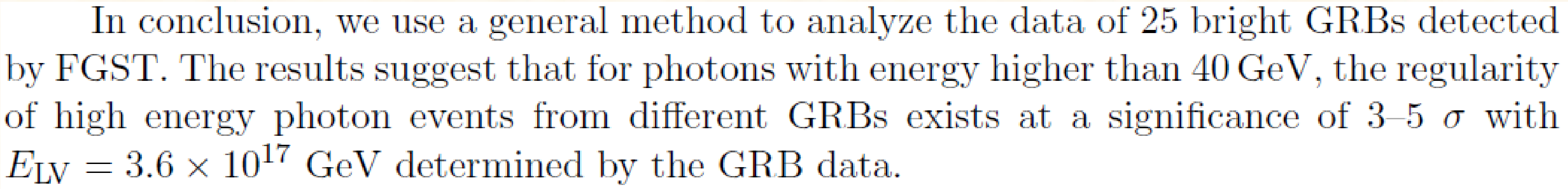
$$S(E_{\rm LV}) = \sum_{i=1}^{N-\rho} \log\left(\frac{\rho}{t_{i+\rho} - t_i}\right)$$



new development

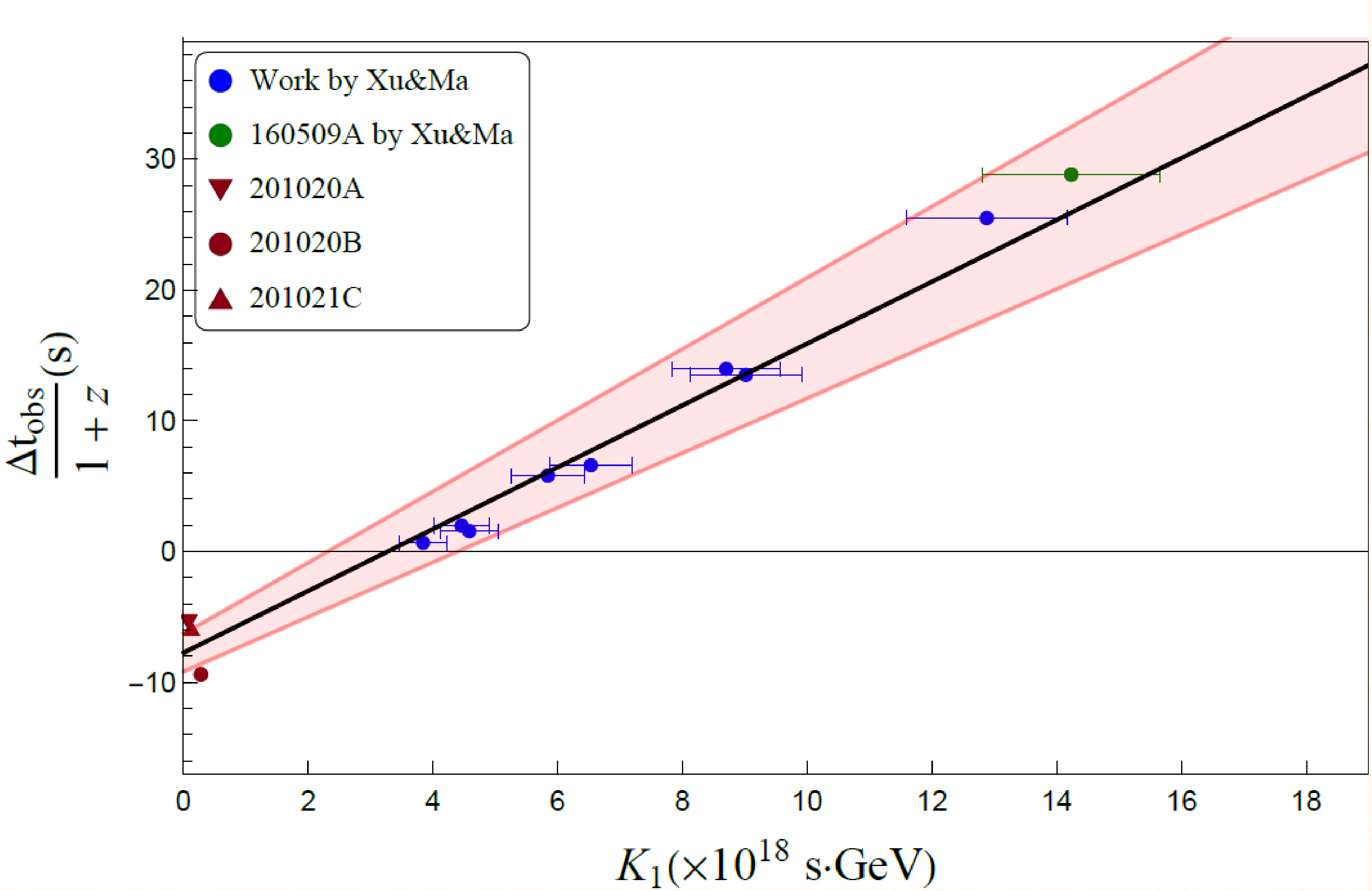
H.Xu, B.-Q.Ma, JCAP 1801 (2018) 050




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

- J.Zhu, B.-Q.Ma, Phys.Lett.B 820 (2021) 136518

New GRBs: 201020A, 201020B, 201021C



- J.Zhu, B.-Q.Ma, Phys.Lett.B 820 (2021) 136518

New GRBs: 201020A, 201020B, 201021C

Physics Letters B 820 (2021) 136518

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

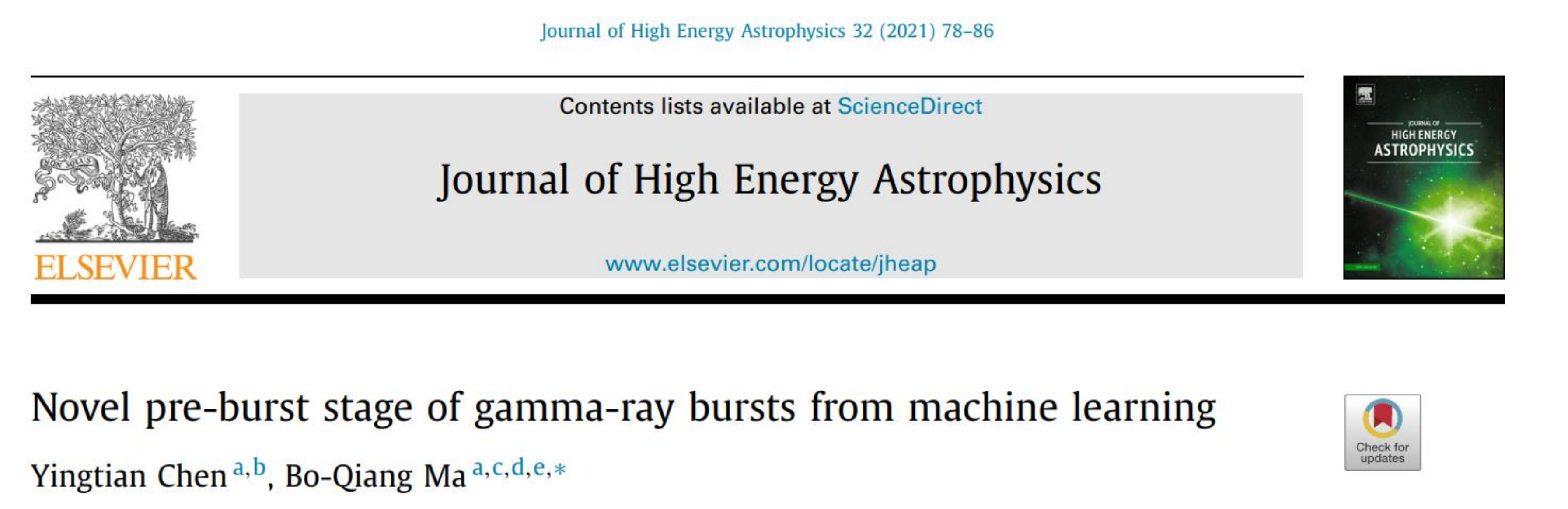
Pre-burst events of gamma-ray bursts with light speed variation

Jie Zhu [a], Bo-Qiang Ma [a,b,c,*]

- **Direct evidence for pre-burst stage of GRBs**
- **Support of light speed variation at** $E_{\rm LV} = 3.60 \times 10^{17}\ \mathrm{GeV}$

- Y.Chen, B.-Q.Ma, JHEAp 32 (2021) 78-86

Pre-burst of GRBs from machine learning



Journal of High Energy Astrophysics 32 (2021) 78–86

Contents lists available at ScienceDirect

Journal of High Energy Astrophysics

www.elsevier.com/locate/jheap

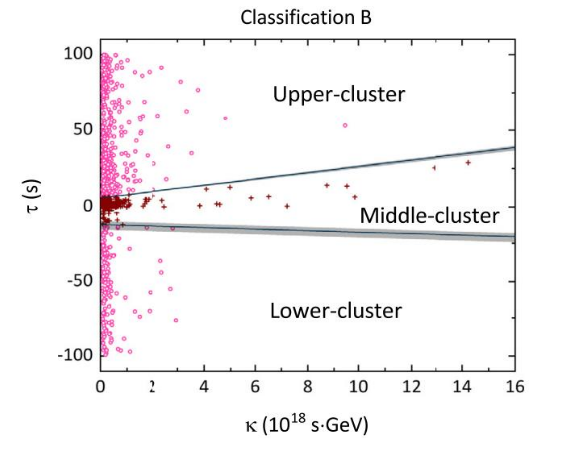
Novel pre-burst stage of gamma-ray bursts from machine learning

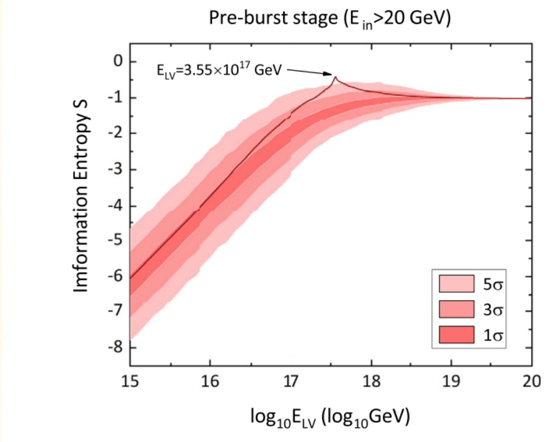
Yingtian Chen [a,b], Bo-Qiang Ma [a,c,d,e,*]

- **Strong support for pre-burst stage of GRBs**
- **Support of light speed variation at** $E_{\mathrm{LV}} = 3.60 \times 10^{17}\ \mathrm{GeV}$

- Y.Chen, B.-Q.Ma, JHEAp 32 (2021) 78-86

Pre-burst of GRBs from machine learning

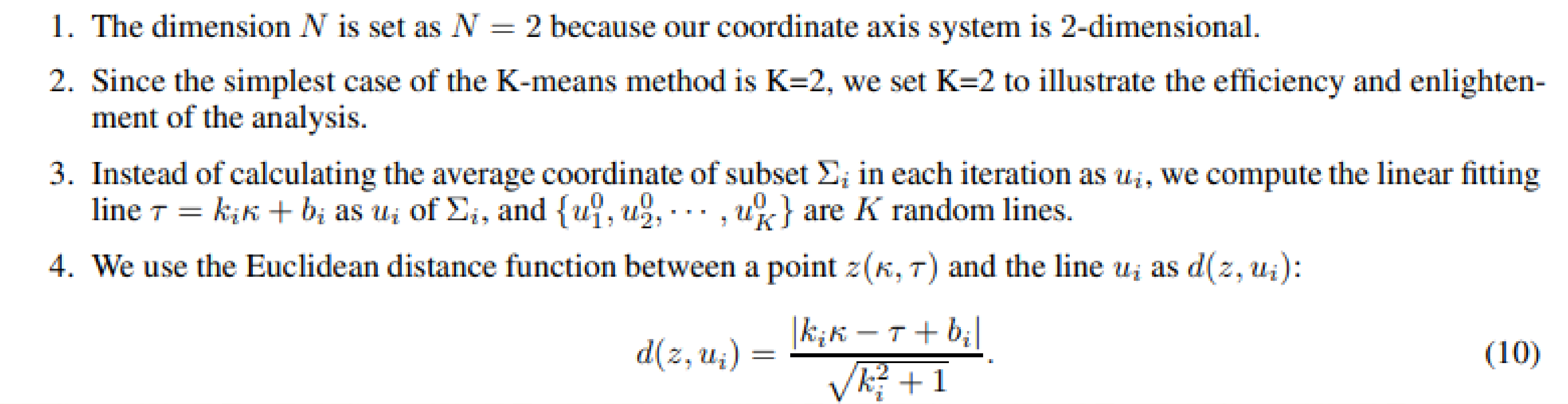




- **Strong support for pre-burst stage of GRBs**
- **Support of light speed variation at** $E_{\mathrm{LV}} = 3.60 \times 10^{17}\ \mathrm{GeV}$

- Y.Chen, B.-Q.Ma, JHEAp 32 (2021) 78-86

K-means classification method

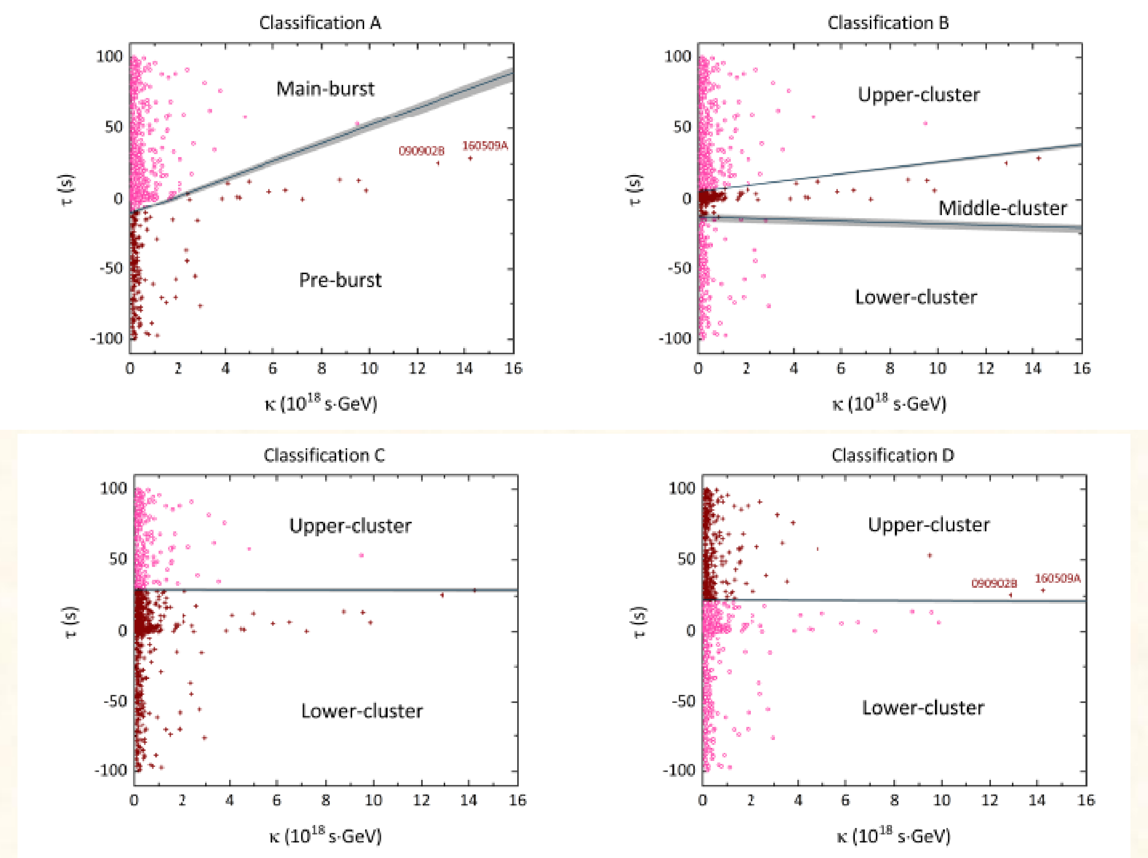


1. The dimension N is set as $N = 2$ because our coordinate axis system is 2-dimensional.
2. Since the simplest case of the K-means method is K=2, we set K=2 to illustrate the efficiency and enlightenment of the analysis.
3. Instead of calculating the average coordinate of subset Σ_i in each iteration as u_i, we compute the linear fitting line $\tau = k_i \kappa + b_i$ as u_i of Σ_i, and $\{u_1^0, u_2^0, \cdots, u_K^0\}$ are K random lines.
4. We use the Euclidean distance function between a point $z(\kappa, \tau)$ and the line u_i as $d(z, u_i)$:

$$d(z, u_i) = \frac{|k_i \kappa - \tau + b_i|}{\sqrt{k_i^2 + 1}}. \tag{10}$$

- Y.Chen, B.-Q.Ma, JHEAp 32 (2021) 78-86

4-cases of classification



- Y.Chen, B.-Q.Ma, JHEAp 32 (2021) 78-86

Results corresponding to classifications A&B

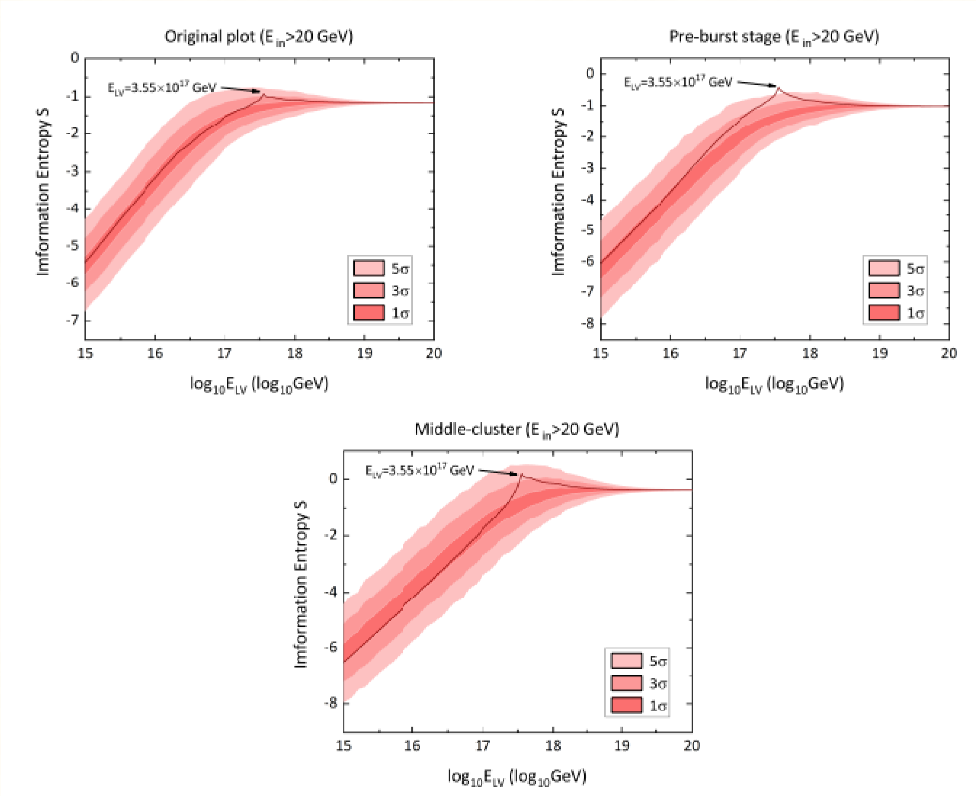


Figure 10: The $S(E_{\mathrm{LV}})$ plots of 3 situations. (a) is the original plot of the unclassified situation; (b) is the plot of the pre-burst stage in classification A; (c) is the plot of the middle-cluster in classification B.

- Y.Chen, B.-Q.Ma, JHEAp 32 (2021) 78-86

Results corresponding to classifications C&D

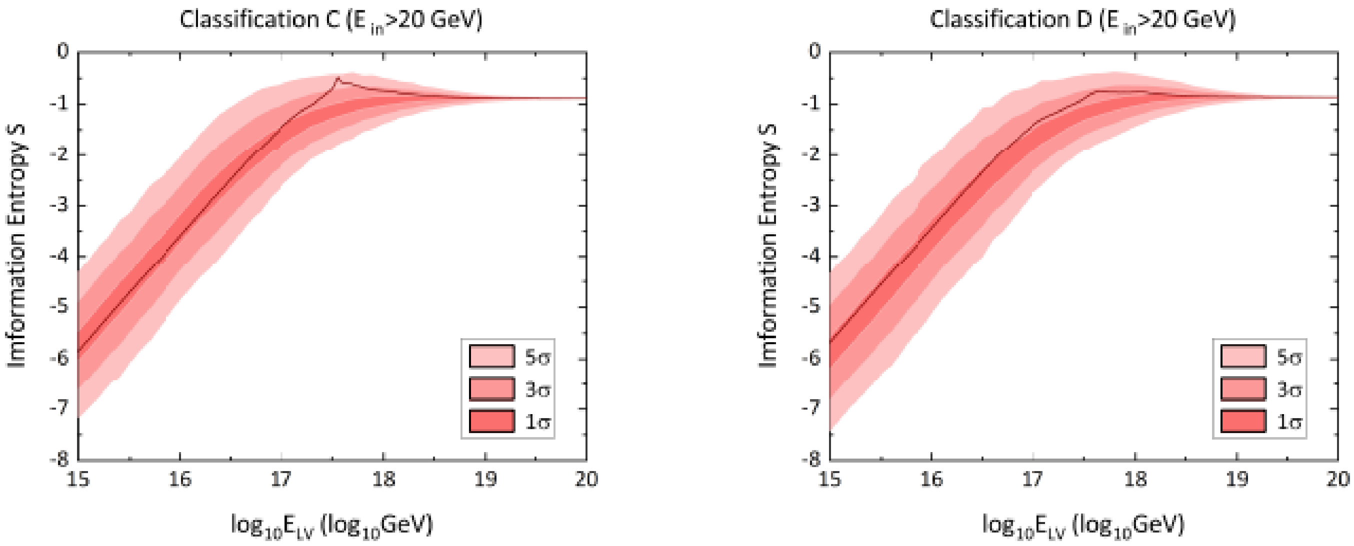
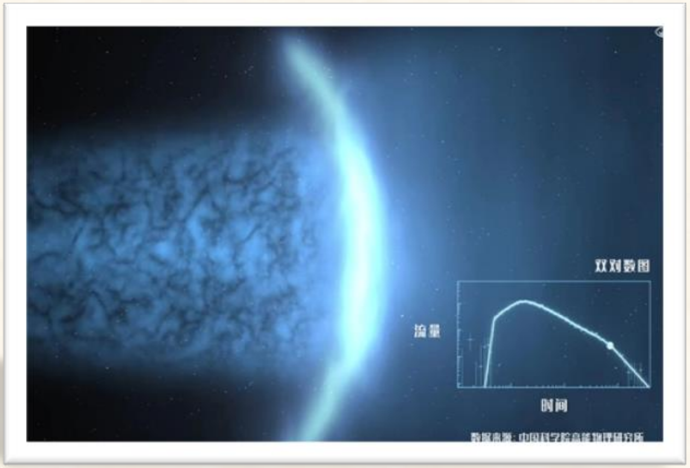
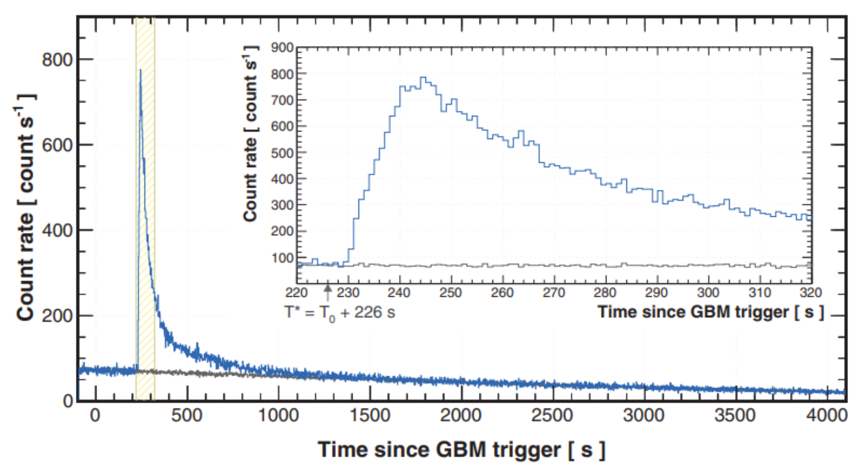


Figure 12: The $S(E_{\rm LV})$ plots of the lower-clusters of classifications C and D.

Newly observed GRB221009A



数据来源：中国科学院高能物理研究所



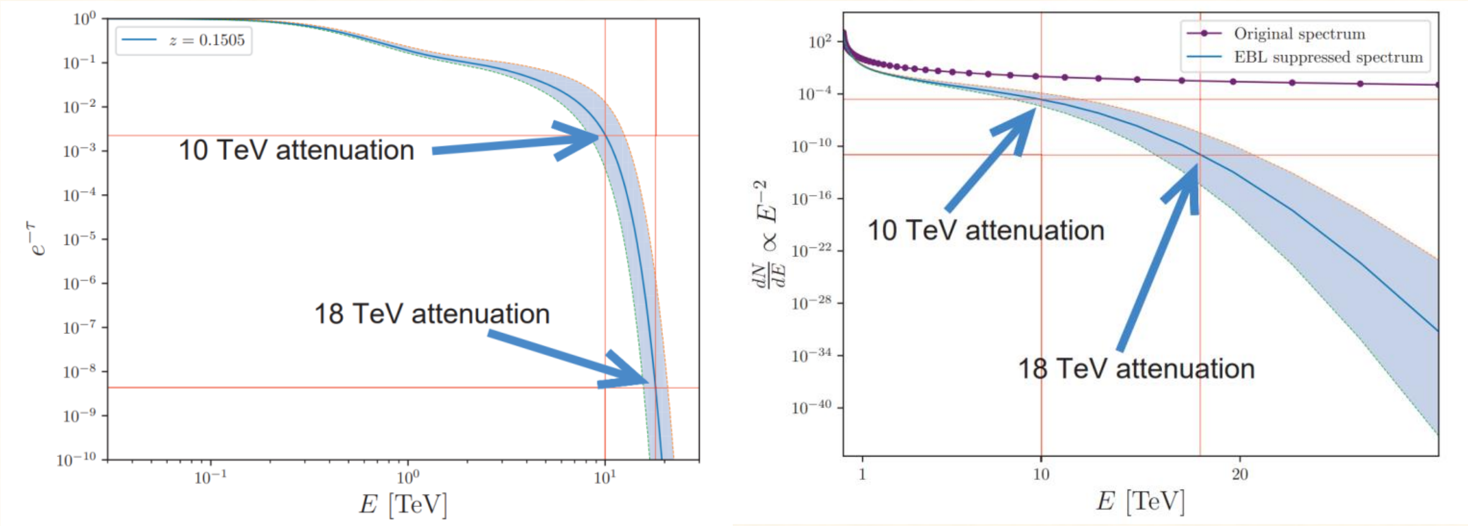
- Triggered by Fermi and Swift
- Very bright GRB with very short distance

  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

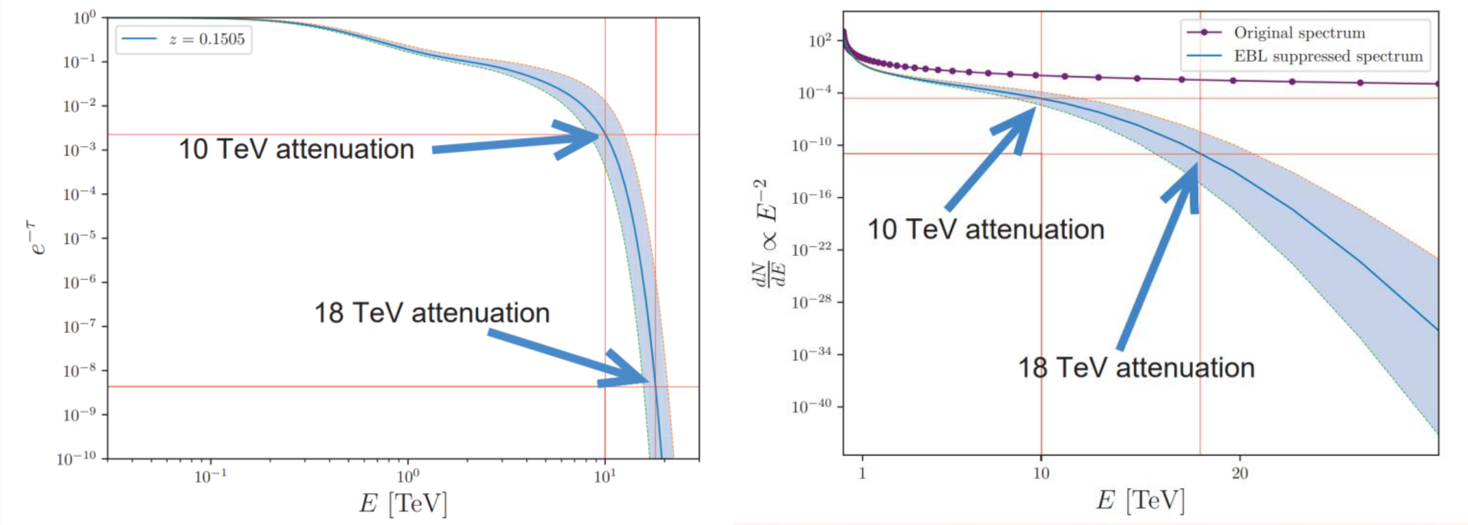
Newly observed GRB221009A



- 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，我们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。

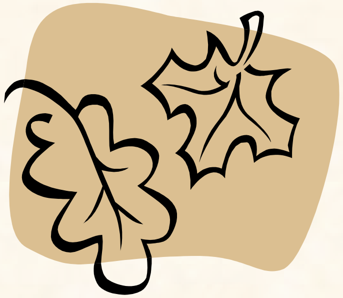
H. Li and B.-Q. Ma, arXiv:2210.06338, APP 148 (2023) 102831

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



Summary: cosmic 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 scenario is supported by new GRB 160509A and also previous AGNs.**
- **A machine learning method also supports the above conclusion.**

Thanks 谢谢！