Lorentz Invariance Violation：

Theory & Phenomenology

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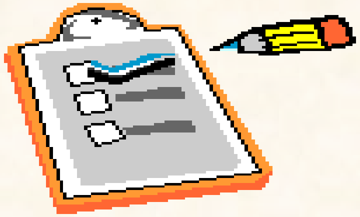
In collaboration with Zhi Xiao, Lijing Shao, Shimin Yang, Lingli Zhou, Haowei Xu, Yunqi Xu, Nan Qin, Shu Zhang, Yue Liu, Yanqi Huang, Xinyi Zhang, Hao Li, Yingtian Chen, Chengyi Li, Jie Zhu, ……



Outline

- Motivation: Quantum Gravity & New Physics
- LIV Theories
- Phenomena:

  ultra-high energy cosmic rays (UHECRs)

  light speed variation of cosmic photons (GRB, AGN)

  LHAASO PeV photons

  speed variation of neutrinos (IceCube neutrinos)
- Remarks

The highest energy particles

can be observed by human being are from SKY

- Frontiers of human knowledge:

  Cosmology, Astronomy, and Physics

- The combination of cosmology, astrophysics, and particle physics → cosmology & particle astrophysics
- Better understanding of the universe:

  from most small to most big → connecting quarks to the cosmos

- New physics from cosmic photons and neutrinos:

  Lorentz violation & CPT violation

Einstein's Special Relativity

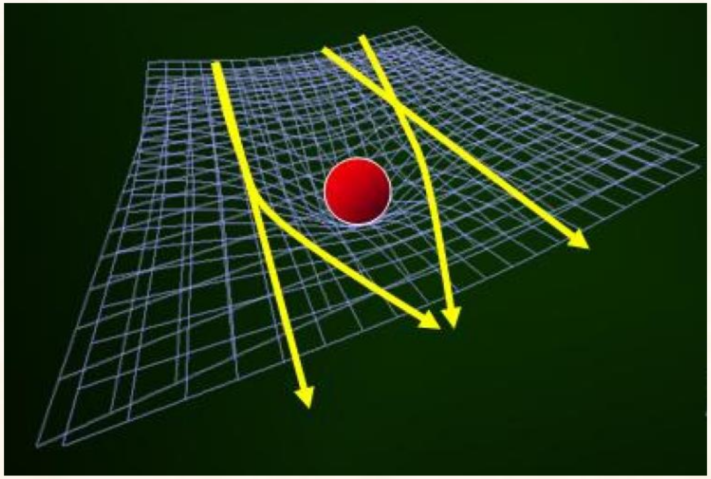
In 1905, Einstein published his famous paper "On the Electrodynamics of Moving Bodies".

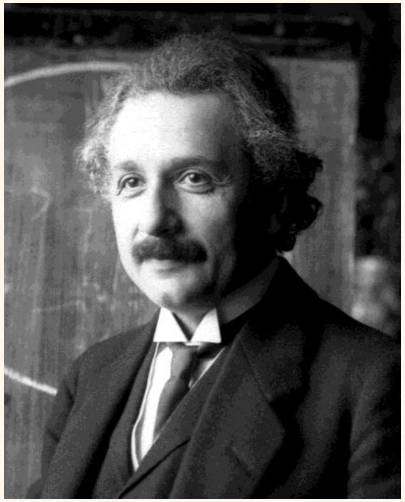
Principles of Special Relativity

- Principle of Relativity: the equations describing the laws of physics have the same form in all admissible frames of reference.
- Principle of constant light speed: the speed of light is the same in all directions in vacuum in all reference frames, regardless whether the source of the light is moving or not.

Einstein's theory of general relativity

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$





The curvature of space and time are determined by matter and energy.

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

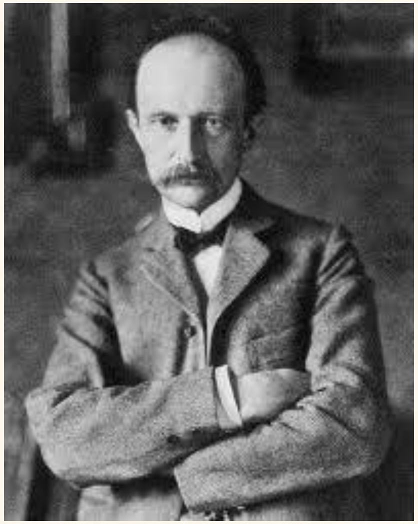
the equations describing the laws of physics have the same form in all admissible reference frames.

So is there any reason that we seek for

Lorentz Violation ?

Planck's *God-Given Unit System*

(Planck, 1899)



Planck, 1900

$c,\ G,\ \hbar,\ k_B,$ and $1/4\pi\epsilon_0$

units of length, mass, time, and temperature that would, independently of special bodies and substances, necessarily retain their significance for all times and all cultures, even extraterrestrial and extrahuman ones, and which may therefore be designated as natural units of measure. (Planck 1899, pp. 479–480)

Planck, M.: Über irreversible Strahlungsvorgänge. Sitzungsberichte der Königlich Preuischen Akademie der Wissenschaften zu Berlin **5**, 440 (1899)

Basic units of the universe: Planck Units

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

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

$$M_P = \sqrt{\frac{\hbar c}{G}} = 1.22089(6)\times 10^{19}\,\frac{\mathrm{GeV}}{\mathrm{c}^2} = 2.17644(11)\times 10^{-8}\,\mathrm{kg}$$

$$E_{\mathrm{P}} \equiv \sqrt{\hbar c^5/G} \simeq 2.0 \times 10^9\ \mathrm{J}$$

$$T_{\mathrm{P}} \equiv \sqrt{\hbar c^5/G k_B^2} \simeq 1.4 \times 10^{32}\ \mathrm{K}$$

A physical argument of discrete space-time

Y.Xu & B.-Q.Ma, MPLA 26 (2011) 2101, arXiv: 1106.1778

- From two known entropy constraints:

$$S_{\text{matter}} \le 2\pi E R, \qquad S_{\text{matter}} \le \frac{A}{4},$$

- Combined with black-body entropy

$$S = \frac{4}{45}\pi^2 T^3 V = \frac{16}{135}\pi^3 R^3 T^3.$$

- We arrive at a minimum value of space

$$R \ge \left(\frac{128}{3645\pi}\right)^{\frac{1}{2}} l_{\text{P}} \simeq 0.1 l_{\text{P}},$$

We reveal from physical arguments that space-time is discrete rather than continuous.

Proposal of a new fundamental length scale instead of the Newtonian constant

L.Shao & B.-Q.Ma, Sci.China Phys. Mech. Astro. 54 (2011) 1771, arXiv: 1006.3031

- If gravity is emergent, a new fundamental constant should be introduced to replace G.
- It is natural to suggest a fundamental length scale.
- Such constant can be explained as the smallest length scale of quantum space-time.
- Its value can be measured through searches of Lorentz violation.

LV as Window on the Nature of Space-Time

- The typical scale of quantum gravity is Planck scale

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

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

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

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

Pioneers' study of Lorentz symmetry violation

The early discussion on the effects of Lorentz violation

- Dirac's æther and nonlinear electrodynamics
  P.A.M. Dirac, Nature **168**, 906 (1951).
- Goldstone boson associated to Spontaneous Lorentz symmetry breaking(SLSB)
  ▷Bjorken's earlier attempts: Photon as Goldstone boson associated to SLSB. J.D. Bjorken, Ann.Phys. **24**, 174 (1963).
  ▷Is Graviton also a Goldstone boson?
  P.R. Phillips, Phys. Rev. **146**, 966 (1966)....
- An universal length scale
  T.G. Pavlopoulos, Phys. Rev. **159**, 1106 (1967)
- Nielsen's renomalization group calculation of the beta-function for a non-covariant pure Yang-Mills theory
  H.B. Nielsen and M. Ninomiya, Nucl. Phys. B **141**, 153 (1978). ...

Many possible ways for Lorentz violation

- spacetime foam [Ellis et al.'08, PLB]
- loop gravity [Alfaro et al.'00, PRL]
- backgrounds in general gravity [Ni'75, PRL; Yan'83, TP,]
- vacuum condensate of antisymmetric tensor fields in string theory [Kostelecky & Samuel'89 & '91, PRL]
- Doubly special relativity [Amelino-Camelia'02, Nature & '02 IJMPD]
- Finsler Geometry (Zhe Chang)

… …

Lagrangians in three SME frameworks: fermions

$$\mathcal{L} \rightarrow \mathcal{L} + \partial_i \Psi \epsilon \partial^i \Psi$$

S.R.Coleman and S.L.Glashow, PRD 59 (1999) 116008

$$\mathcal{L} = \frac{1}{2} i \overline{\nu}_A \gamma^\mu \overleftrightarrow{D_\mu} \nu_B \delta_{AB} + \frac{1}{2} i c^{\mu\nu}_{AB} \overline{\nu}_A \gamma^\mu \overleftrightarrow{D^\nu} \nu_B - a^\mu_{AB} \overline{\nu}_A \gamma^\mu \nu_B + \cdots$$

D.Colladay and V.A.Kostelecky, PRD 58, 116002 (1998)

$$\mathcal{L}_{\mathrm{F}} = \bar{\psi}_A (i\gamma^\alpha \partial_\alpha - m_A) \psi_A + i \Delta^{\alpha\beta}_{AA} \bar{\psi}_A \gamma_\alpha \partial_\beta \psi_A$$

Zhou L., B.-Q. Ma, MPLA 25, 2489 (2010); Chin.Phys.C 35, 987 (2011)

Lorentz-violation as background fields

- It is useful to discuss various LV effects based on traditional techniques of effective field theory in particle physics.
- One can collect all possible background fields coupled with standard model particles, in a way such as standard model extension (SME).
- But such kind of works cannot be ranked as theory, but

  a platform for phenomenological applications to confront with data.

Human being needs fundamental theory for or against Lorentz-invariance violation.

An example of SME

- Effective Field Theory
  - Standard Model Extension
    an explicitly introduction of condensation of background tensor field
    $\mathcal{L}_{LV} \sim \frac{\lambda}{M^k_{\rm Planck}} < T > \overline{\psi}\Gamma(i\partial)^k\chi$
    D. Colladay and V.A. Kostelecký, Phys. Rev. D **58**, 116002 (1998).

Effective Field Theory
SME

- The total Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \delta\mathcal{L}, \tag{4}$$

where $\delta\mathcal{L}$ denotes tiny LV parts.

- take QED as example

$$\delta\mathcal{L}_{\rm QED} = \delta\mathcal{L}_{\rm photon} + \delta\mathcal{L}_{\rm electron}, \tag{5}$$

where

$$\delta\mathcal{L}_{\rm photon} \supset -\frac{1}{4}(k_F)_{\kappa\lambda\mu\nu}F^{\kappa\lambda}F^{\mu\nu} + \frac{1}{2}(k_{AF})_\kappa \epsilon^{\kappa\lambda\mu\nu}A_\lambda F_{\mu\nu}, \tag{6}$$

$$\begin{aligned}\delta\mathcal{L}_{\rm electron} \supset & \frac{1}{2}i\overline{\psi}(\widetilde{c}^{(\nu\mu)}\gamma_\nu + \widetilde{d}^{\nu\mu}\gamma_5\gamma_\nu + \frac{1}{2}\widetilde{g}^{\lambda\nu\mu}\sigma_{\lambda\nu})\overleftrightarrow{D}_\mu\,\psi \\ & -\overline{\psi}(\widetilde{b}_\mu\gamma_5\gamma^\mu + \frac{1}{2}\widetilde{H}_{\mu\nu}\sigma^{\mu\nu})\psi. \end{aligned} \tag{7}$$

Some remarks on SME

- **The coefficients of background fields with standard model particles serve as LV parameters.**
- **The Lorentz-violation in SME is due to the existance of background fields, or in a sense of "new aether" as backgrounds.**
- **There is no Lorentz-violation for the whole system of standard-model-particles+backgrounds**

Lagrangians in three SME frameworks: fermions

$$\mathcal{L} \to \mathcal{L} + \partial_i \Psi \epsilon \partial^i \Psi$$

S.R.Coleman and S.L.Glashow, PRD 59 (1999) 116008

$$\mathcal{L} = \frac{1}{2} i \overline{\nu}_A \gamma^\mu \overleftrightarrow{D_\mu} \nu_B \delta_{AB} + \frac{1}{2} i c^{\mu\nu}_{AB} \overline{\nu}_A \gamma^\mu \overleftrightarrow{D^\nu} \nu_B - a^\mu_{AB} \overline{\nu}_A \gamma^\mu \nu_B + \cdots$$

D.Colladay and V.A.Kostelecky, PRD 58, 116002 (1998)

$$\mathcal{L}_\mathrm{F} = \bar{\psi}_A (i\gamma^\alpha \partial_\alpha - m_A)\psi_A + i\Delta^{\alpha\beta}_{AA} \bar{\psi}_A \gamma_\alpha \partial_\beta \psi_A$$

Zhou L., B.-Q. Ma, MPLA 25, 2489 (2010); Chin.Phys.C 35, 987 (2011)

A New Theory: the replacement of basic principle in Special Relativity

- Principle of Relativity: the equations describing the laws of physics have the same form in all admissible frames of reference.

- Principle of physical invariance :

the equations describing the laws of physics have the same form in all admissible mathematical manifolds.

Zhou Lingli and B.-Q. Ma, MPLA 25 (2010) 2489, arXiv:1009.1331;
CPC 35 (2011) 987, arXiV: 1109.6387

A new theory of Lorentz violation

- a replacement of the common derivative operators by covariant co-derivative ones

$$\partial^\alpha \to M^{\alpha\beta}\partial_\beta, \quad D^\alpha \to M^{\alpha\beta}D_\beta,$$

- The effective minimal Standard Model

$$\mathcal{L}_{SM} = \mathcal{L}_G + \mathcal{L}_F + \mathcal{L}_{HG} + \mathcal{L}_{HF},$$
$$\mathcal{L}_G = -\frac{1}{4}F^{a\alpha\beta}F^a_{\alpha\beta},$$
$$\mathcal{L}_F = i\bar{\psi}\gamma^\alpha D_\alpha \psi,$$
$$\mathcal{L}_{HG} = (D^\alpha\phi)^\dagger D_\alpha\phi + V(\phi),$$

- A new standard model with supplementary terms

$$\mathcal{L}_{SMS} = \mathcal{L}_{SM} + \mathcal{L}_{LV},$$
$$\mathcal{L}_{LV} = \mathcal{L}_{GV} + \mathcal{L}_{FV} + \mathcal{L}_{HFV}$$

Zhou Lingli and B.-Q. Ma, MPLA 25 (2010) 2489, arXiv:1009.1331 ;   CPC 35 (2011) 987, arXiv: 1109.6387

physical independence of mathematical background manifolds

The Lorentz invariance violation matrix

$$M^{\alpha\beta} = g^{\alpha\beta} + \Delta^{\alpha\beta},$$

$$\Delta^{\alpha\beta} = \begin{cases} 0 & \text{LI exact} \\ \to 0 & \text{LV small} \\ \text{otherwise} & \text{LV big} \end{cases} .$$

Zhou Lingli and B.-Q. Ma, MPLA 25 (2010) 2489

The Lorentz violation for protons from GZK cut-off

A special case is

$$\Delta^{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \xi & 0 & 0 \\ 0 & 0 & \xi & 0 \\ 0 & 0 & 0 & \xi \end{pmatrix},$$

$$E^2 = (1-\delta)\vec{p}^2 + m^2,$$
$$\delta = -\xi^2 + 2\xi.$$

$$\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 10^{-23} & 0 & 0 \\ 0 & 0 & 10^{-23} & 0 \\ 0 & 0 & 0 & 10^{-23} \end{pmatrix},$$

Zhou Lingli and B.-Q. Ma, MPLA 25 (2010) 2489

Three scenarios
on how to understand and handle the backgrounds

- **Scenario I: fixed background scenario**

- **The backgrounds are taken as fixed parameters in any inertial frame of reference one decides to work. It means that there is an absolute background which is the same for any working reference frames such as earth-rest frame, sun-rest frame, or CMB frame.**
- **It can be adopted when one does not care about relations between different frames, or the situation could become very complicated with different formalisms in different frames.**
- **This scenario can apply as a practical tool for all of the three versions of SME: the simple Coleman-Glashow model, the minimal SME, and the SMS.**

S.R.Coleman and S.L.Glashow, PRD 59 (1999) 116008

Three scenarios
on how to understand and handle the backgrounds

- Scenario II: "new aether" scenario

- It means that there exists a privileged inertial frame of reference in which the the background can be considered as the ``new aether", i.e., the ``vacuum" at rest, which changes from one frame to another frame by Lorentz transformation.

- This scenario cannot apply directly to the Coleman-Glashow model, as the LV parameter is a scaler which should keep invariant in any working reference frame, but it can apply to the minimal SME and also to the SMS.

V. A. Kostelecky, N. Russell, Rev. Mod. Phys. 83 (2011) 11

Three scenarios on how to understand and handle the backgrounds

- **Scenario III: covariant scenario**

- **The background fields transform as tensors adhered with the corresponding standard model particles.**

- **The background fields are emergent and covariant with their standard model particles.**

- **This scenario cannot apply to the Coleman-Glashow model, but can apply to the minimal SME and also to the SMS.**

B.-Q.Ma, Mod.Phys.Lett. A 28 (2013) 1340012

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

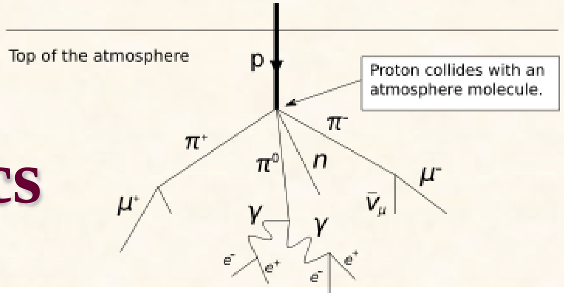
- Looking up at the Sky again:

  Ultra-high energy comic rays (UHECRs) : 10^20 eV or higher

  Cosmic photons from gamma ray bursts: 10~100 GeV or higher

  Cosmic neutrinos with much higher energy: ~TeV-PeV

Cosmic Rays & Particle Physics



- The cosmic rays were discovered by Victor Hess in 1912.
  The term "cosmic rays" was named by Robert A. Millikan.
  a proper name should be "cosmic particles" .

- The early 1930s: phenomenological studies of cosmic rays.

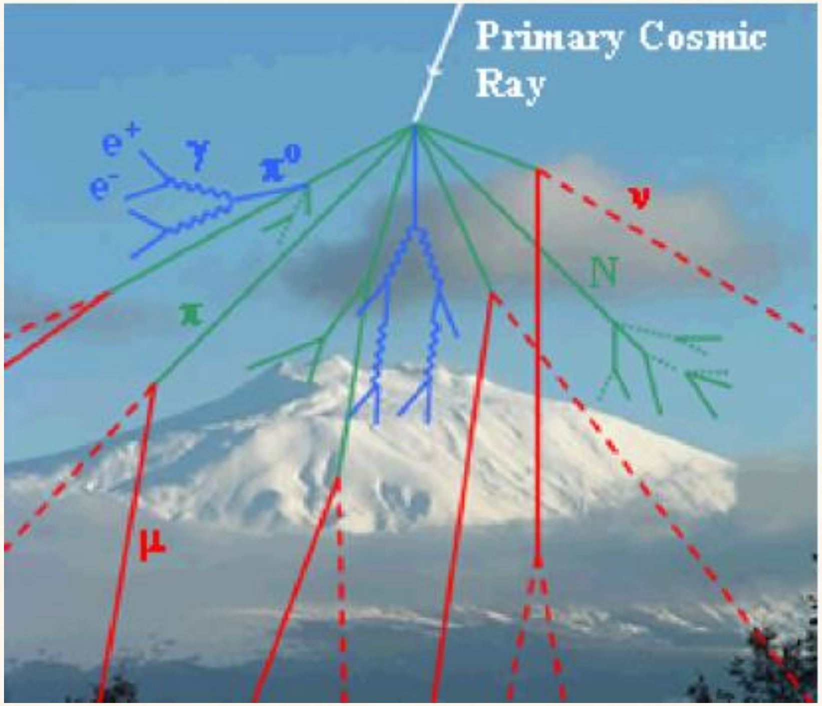
- Particles discovered in cosmic rays: positron e^+ , μ , π , K etc.

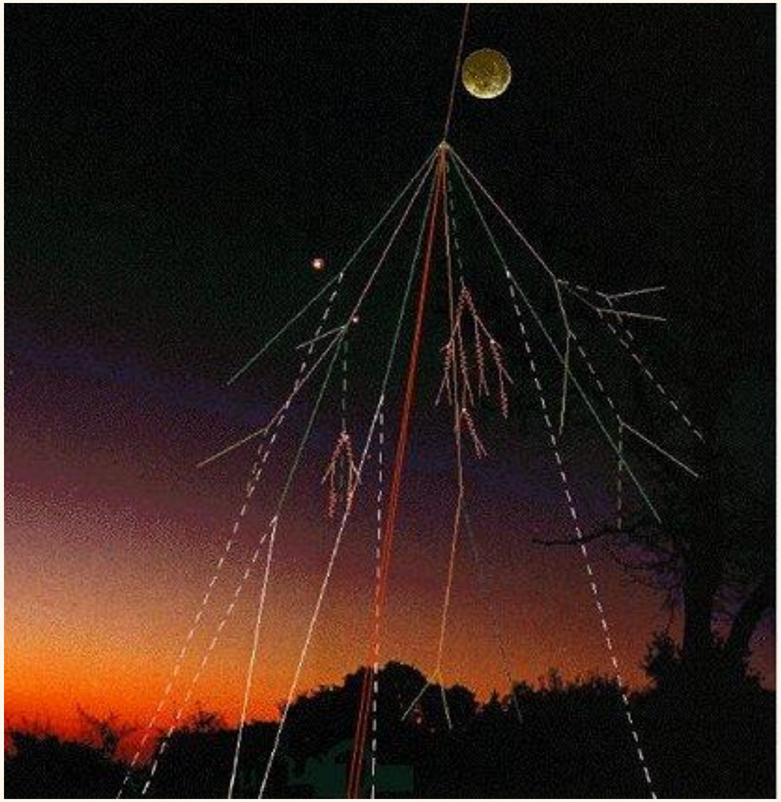
- Until early 1950s, the study of cosmic rays was characterized by:
  discoveries of new particles,
  understanding of electromagnetic interaction,
  understanding of weak interaction,
  primary understanding of strong interaction

- Nobel Prizes related to Cosmic Rays: Victor Hess, Carl D. Anderson, Paul Dirac, Hideki Yakawa, …

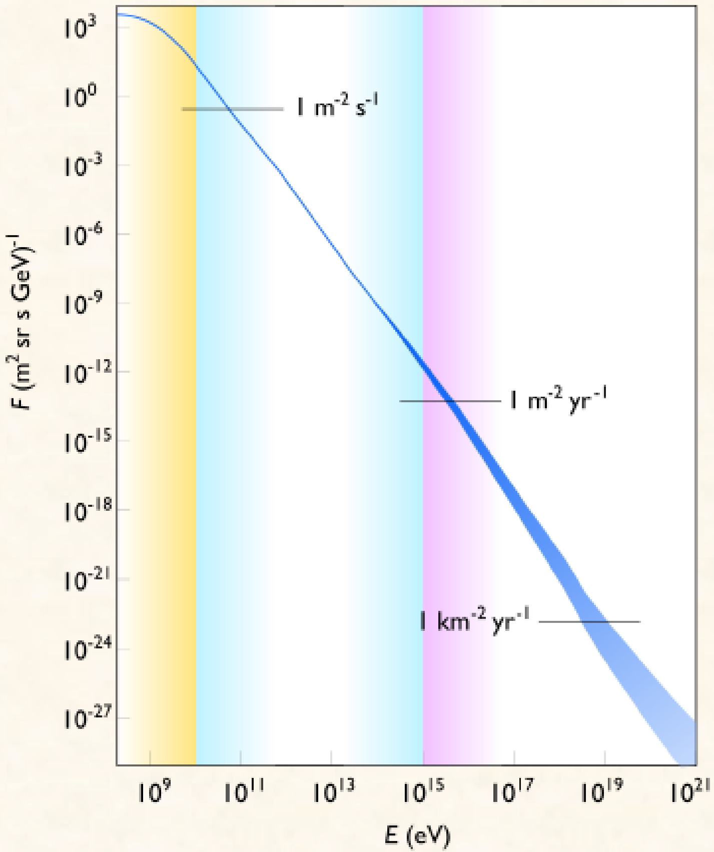
Extended Air Showers

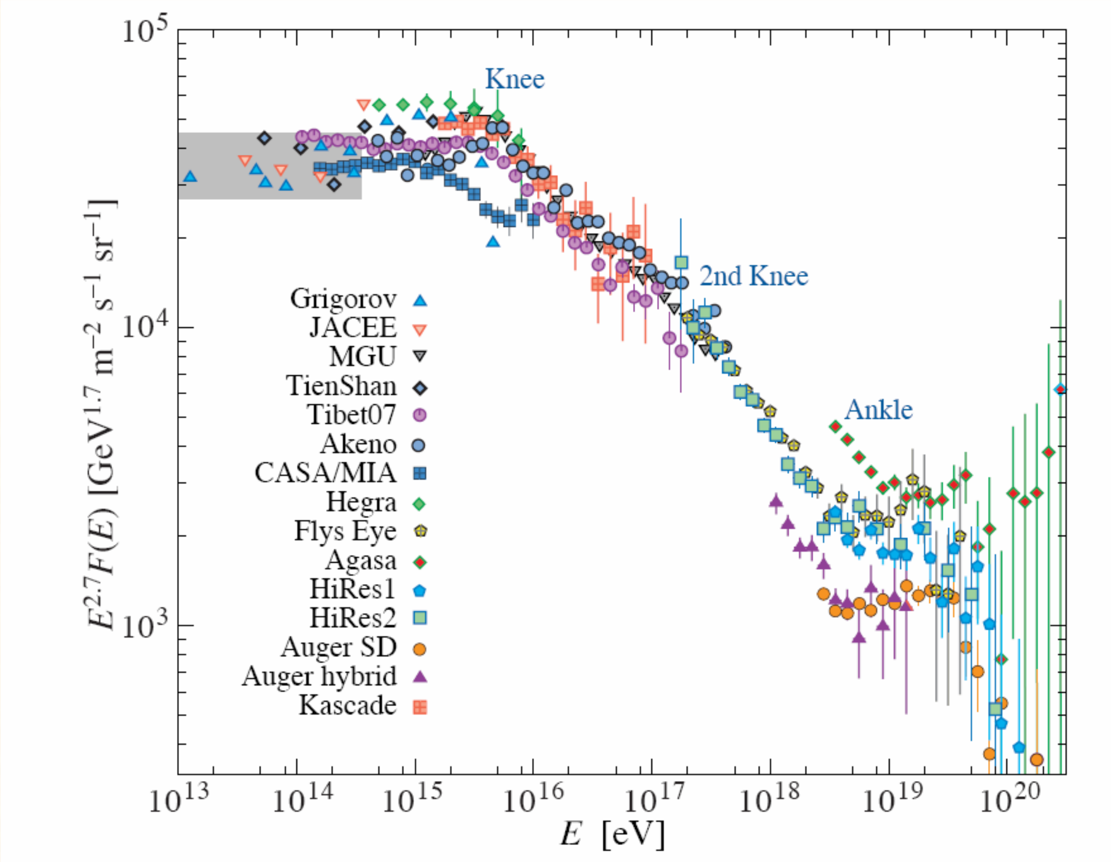
- **1937-1939 observed by accident Pierre Auger the apparent coincidence between Cosmic Ray telescopes set up several hundred meters apart.**



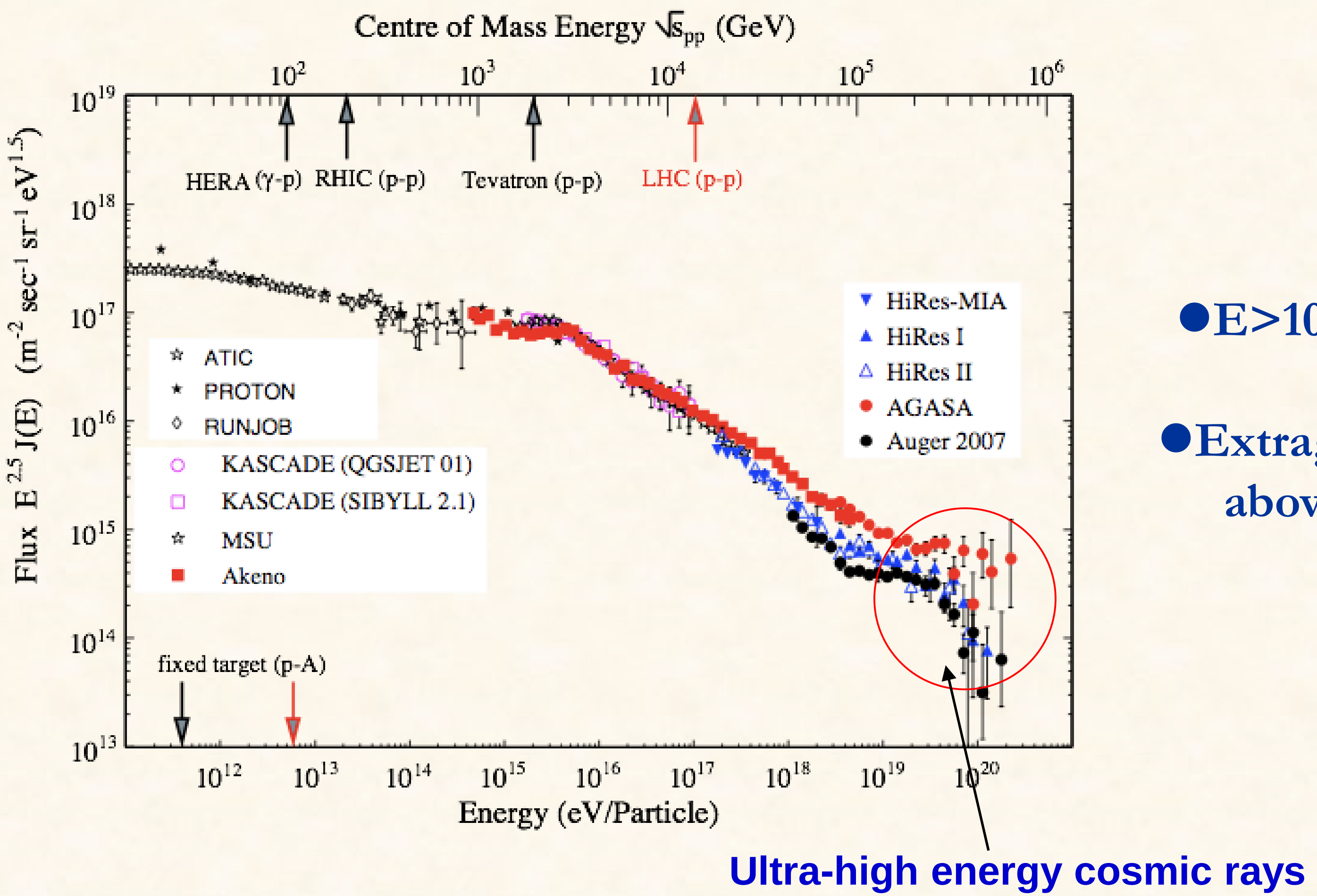


The energy spectrum of cosmic rays





Ultra-high energy cosmic rays (UHECRS)



- E>10^18-10^19 eV
- Extragalactic origin above the ankle

Energy=50J, the same as a well-hit tennis ball at 42 m/s.

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 $\varepsilon_\gamma = 6.35 \times 10^{-4}\ \mathrm{eV}$

Greisen-Zatsepin-Kuzmin (GZK) cutoff energy of nucleon cosmic rays

predicted in 1966

pion production $N + \gamma_{CMB} \rightarrow \pi + N$

$$E = \frac{S - m_\pi^2}{2\varepsilon_\gamma (1 - \cos\theta)}$$

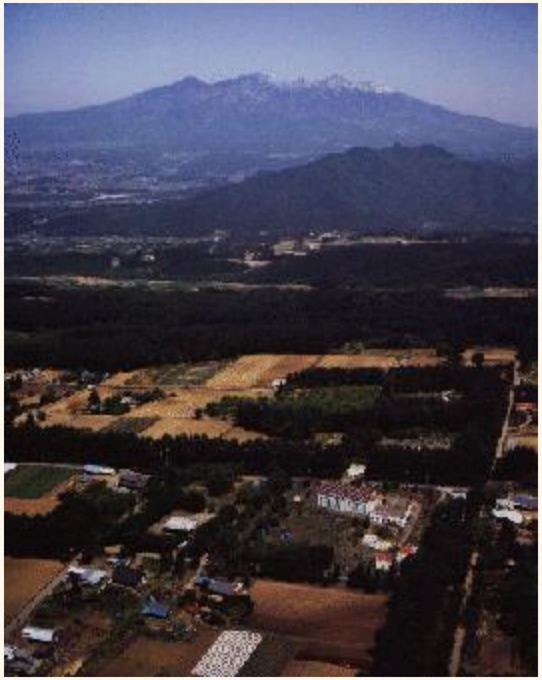
threshold energy $E \approx \dfrac{2m_N m_\pi + m_\pi^2}{4\varepsilon_\gamma} = 1.10 \times 10^{20}\ \mathrm{eV}$

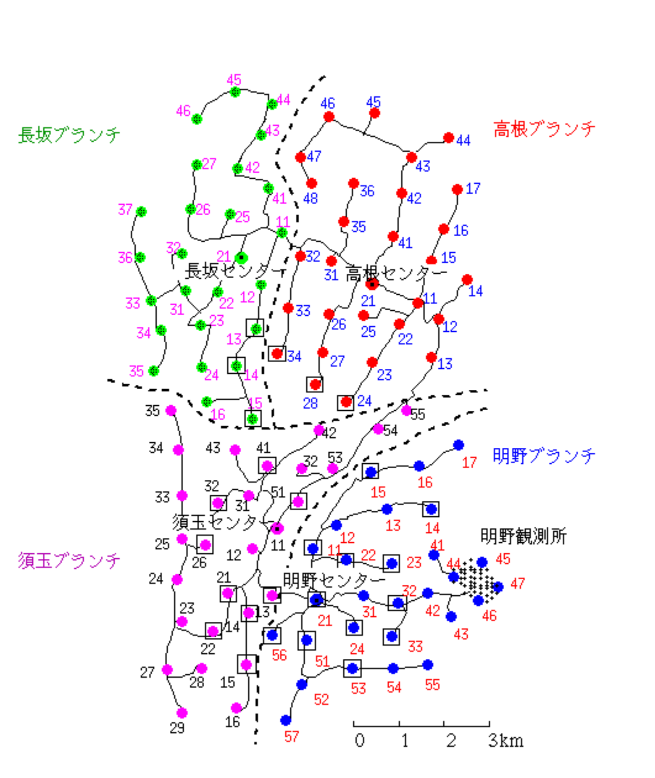
mean free path $\lambda_N \sim 3\,\mathrm{Mpc}$ GZK zone $\sim 50\ \mathrm{Mpc}$

W-Y.P. Hwang, B.-Q. Ma, Eur.Phys.J. A25 (2005) 467

Experimental facility: AGASA

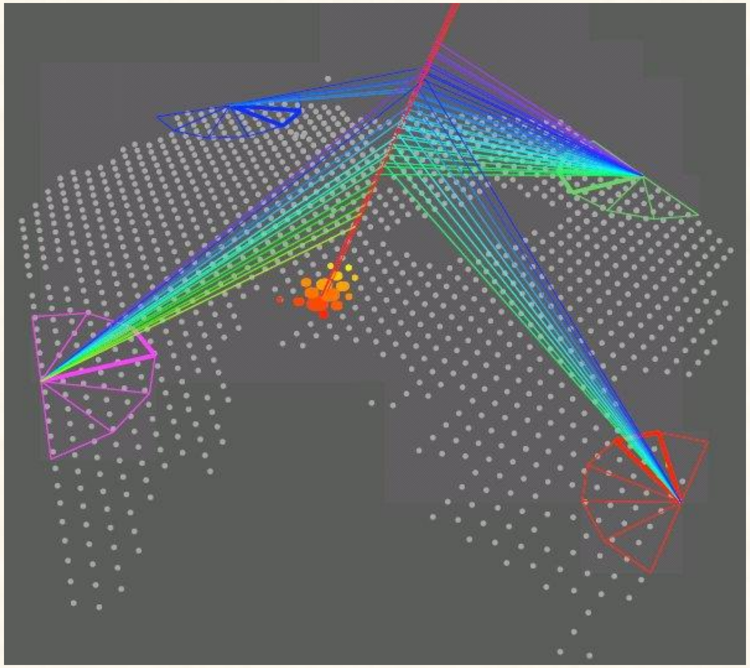
AGASA: **Akeno Giant Air Shower Array@the Akeno Observatory Institute for Cosmic Ray Research, University of Tokyo, JAPAN**





Experimental facility: HiRes

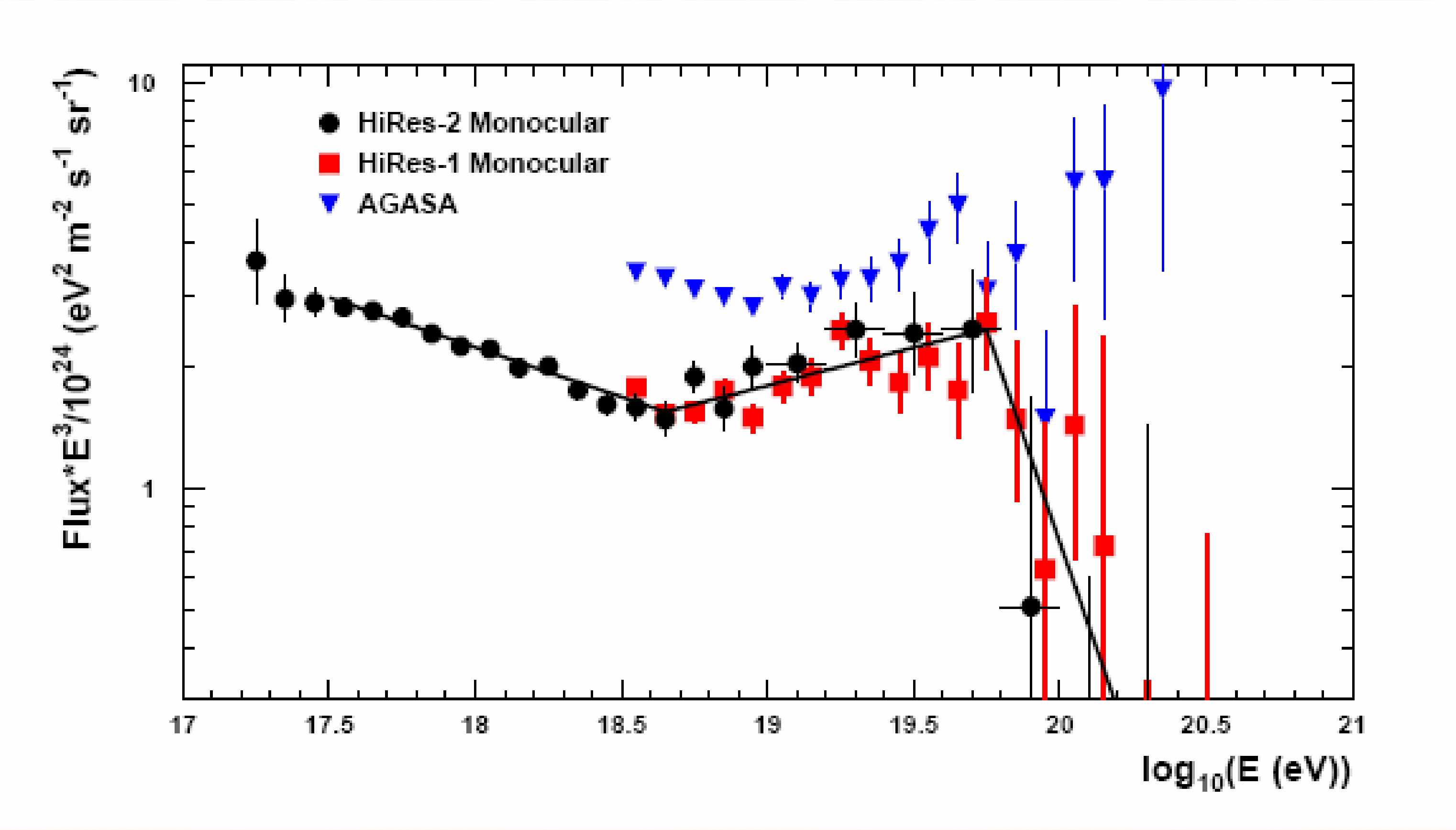
HiRes: High Resolution Fly's Eye@University of Utah



Experimental facility: Pierre Auger Observatory

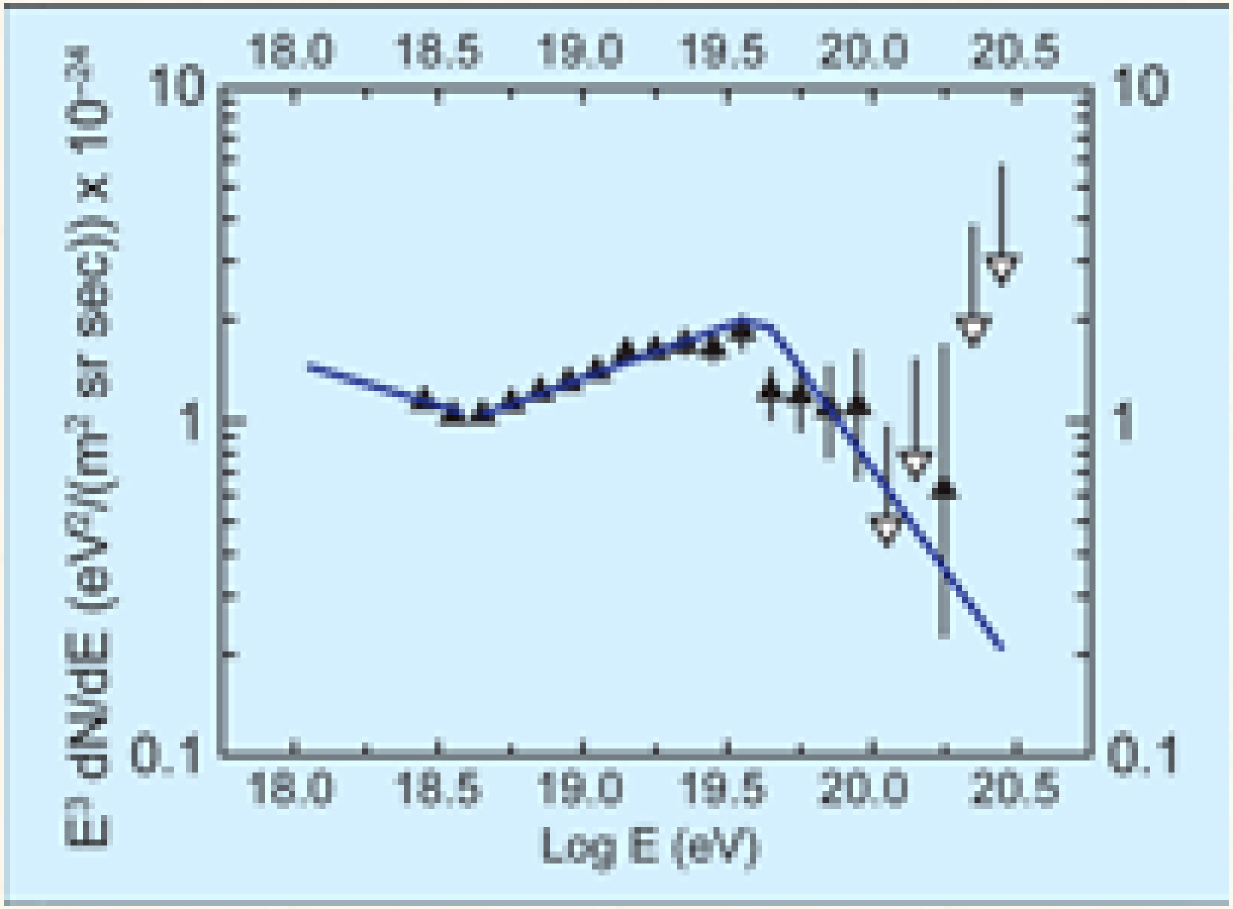
Auger: Pierre Auger Observatory@Argentina

However, new experimental results appeared: HiRes 2007



HiRes, Phys.Rev.Lett.100:101101,2008.

However, new experimental results appeared: Auger 2007



Pierre Auger Collaboration, *Phys. Rev. Lett.* **101**, 061101 (2008)

Lorentz Violation as a mechanism for Super-GZK events *Coleman&Glashow*

- Starting from a free field Lagrangian,

$$\mathcal{L} = \partial_\mu \Psi^* Z \partial^\mu \Psi - \Psi^* M^2 \Psi,$$

and adding a LV term $\mathcal{L} \to \mathcal{L} + \partial_i \Psi \epsilon \partial^i \Psi,$

- Modified dispersion relation with LV effect

$$p^2 = E^2 - \vec{p}^{\,2} = m^2 + \epsilon \vec{p}^{\,2} .$$

$$c_a = \sqrt{1+\epsilon} c$$

$$E_a^2 = \vec{p}_a^{\,2} c_a^2 + m_a^2 c_a^4.$$

$$m_a = m/(1+\epsilon)$$

where c_a is the maximal attainable velocity for the ath particle

Lorentz violation & enhancement of threshold energy

- Take the nucleon-photon to Delta process as example

$$P + \gamma(\mathrm{CMB}) \rightarrow \triangle(1232)$$

$$\omega + E_p \geq E_\triangle$$

- With LV effect

$$\omega + E_p \geq \sqrt{(|\vec{P}_p| - \omega)^2 c_\triangle^2 + m_\triangle^2 c_\triangle^4}\,.$$

$$E_p = \frac{\omega\sqrt{1 - 1/2\frac{K}{\omega^2}\left(1 - \frac{c_\triangle}{c_p}\right)} - \omega}{1 - \frac{c_\triangle}{c_p}} \simeq -\frac{K}{4\omega} - \frac{K^2}{32\omega^3}\left(1 - \frac{c_\triangle}{c_p}\right) + \cdots$$

$$1 - \frac{c_\triangle}{c_p} = -\frac{2w(E_p - E_{\mathrm{thre}})}{E_{\mathrm{thre}}^2}.$$

simply assume $c_\triangle = 1$

Z.Xiao, B.-Q. Ma, IJMPA 24 (2009) 1539.

Lorentz Violation & Super-GZK events

- The earlier reports on super-GZK events triggered attention on Lorentz-Violation (LV or LIV).

S.R.Coleman and S.L.Glashow, PRD 59 (1999) 116008

- The new results of observation of GZK cut-off put strong constraints on Lorentz-Violation parameters, see, e.g.,

Z.Xiao, B.-Q. Ma, IJMPA 24 (2009) 1539.

X.J.Bi, Z.Cao, Y.Li, Q.Yuan , PRD 79 (2009) 083015.

F.W.Stecker, S.T.Scully, New J.Phys.11(2009) 085003.

Constraints on LV parameters

- *Z.Xiao, B.-Q. Ma, IJMPA 24 (2009) 1539.*

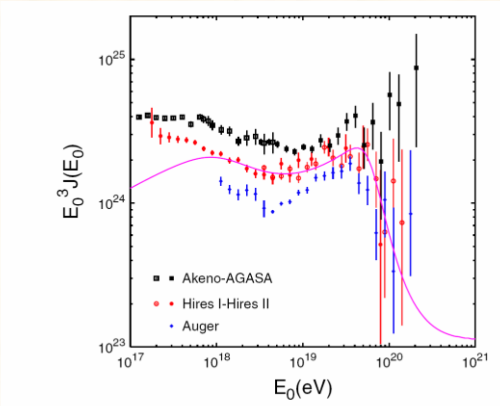
A rough estimate

$$\epsilon_p \sim 10^{-24}$$

- *X.J.Bi, Z.Cao, Y.Li, Q.Yuan , PRD 79 (2009) 083015.*

An analysis with shape

$$\epsilon_p \sim 10^{-23}$$



- *F.W.Stecker, S.T.Scully, New J.Phys.11(2009) 085003.*

$$\epsilon_p \sim 10^{-23}$$

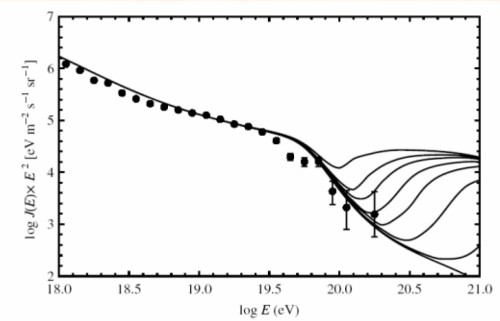


Figure 4. Comparison of the latest Auger data with calculated spectra for various values of $\delta_{\pi p}$, taking $\delta_p = 0$ (see text). From top to bottom, the curves give the predicted spectra for $\delta_{\pi p} = 1 \times 10^{-22}, 6 \times 10^{-23}, 4.5 \times 10^{-23}, 3 \times 10^{-23}, 2 \times 10^{-23}, 1 \times 10^{-23}, 3 \times 10^{-24}$ and 0 (no Lorentz violation) [44].

The Lorentz violation for protons from GZK cut-off

A special case is

$$\Delta^{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \xi & 0 & 0 \\ 0 & 0 & \xi & 0 \\ 0 & 0 & 0 & \xi \end{pmatrix},$$

$$E^2 = (1-\delta)\vec{p}^2 + m^2,$$
$$\delta = -\xi^2 + 2\xi.$$

$$\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 10^{-23} & 0 & 0 \\ 0 & 0 & 10^{-23} & 0 \\ 0 & 0 & 0 & 10^{-23} \end{pmatrix},$$

Zhou Lingli and B.-Q. Ma, MPLA 25 (2010) 2489

Lessons from new results

- The observation of GZK cut-off by HiRes and Auger put strong constraints on previous models for the super-GZK events.
- There are still uncertainties on the re-construction of the energy, so final conclusion still may change
- Detailed features are important: how large of the GZK events, shape, and direction.

Open Questions related with UHECRs

- The composition of UHECRs: nucleons or heavy nuclei, neutrons and antiproton, or other exotic objects
- Origin of UHECRs: what is the source, extra-galactic, gamma-ray bursts or supernovae, correlation of arrival direction with source
- The acceleration mechanism: why the energies of these particles could be so high?
- Detection of neutrinos from GZK mechanism
- UHECRs as laboratory to study physics under extreme conditions.

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?

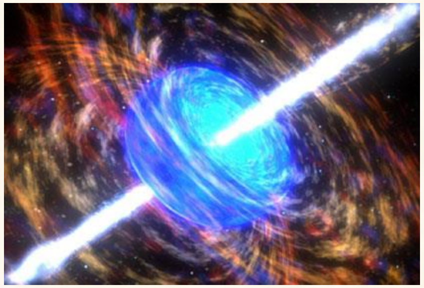
  the effect is too tiny to be detected on Earth

- 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

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]

Modified photon dispersion relation from LV

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

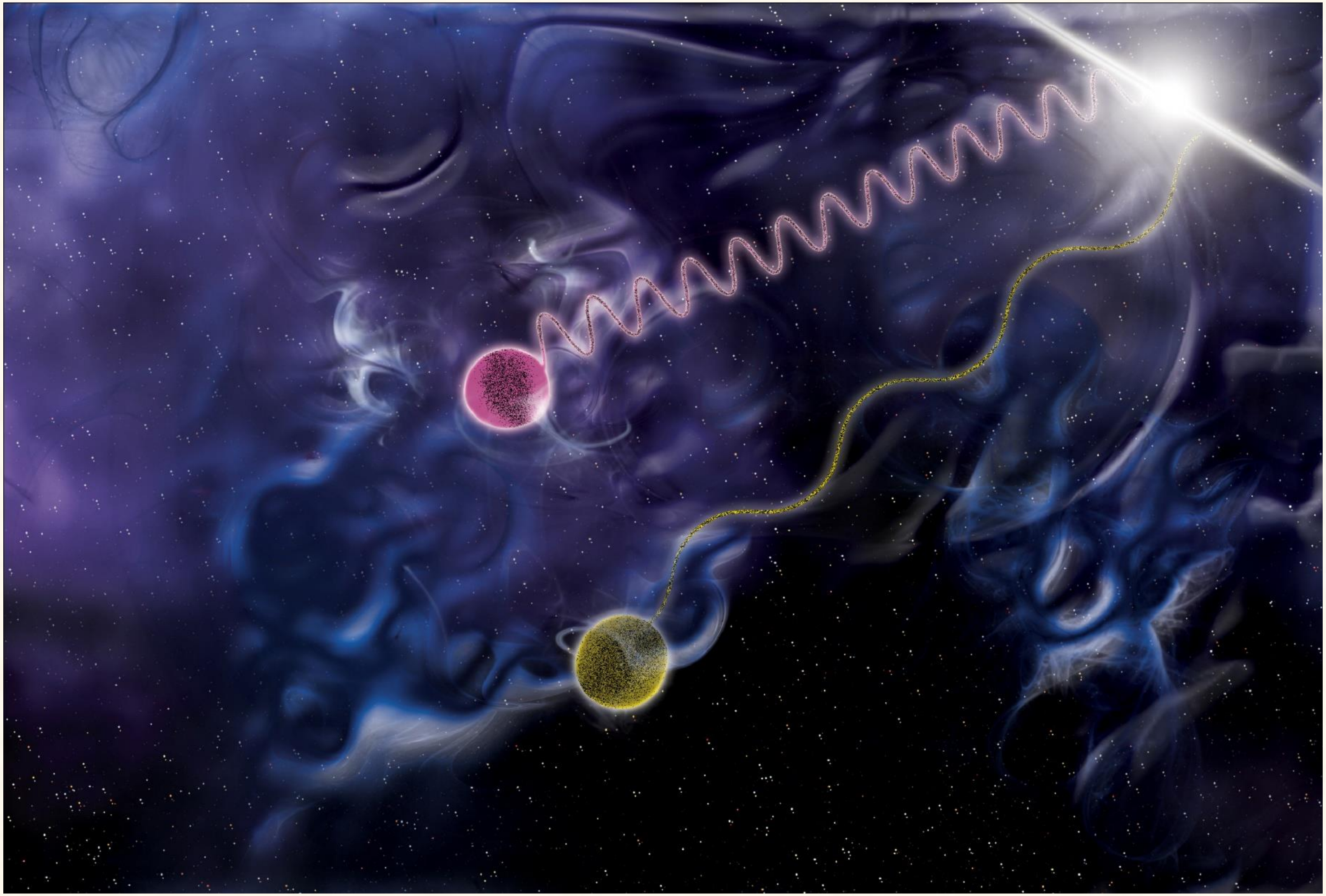
$$\sqrt{\hbar c / G} \simeq 1.22 \times 10^{19} \ \mathrm{GeV/c^2}$$

Z.Xiao and B.-Q.Ma, PRD 80 (09) 116005, arXiv:0909.4927

See also, e.g.,

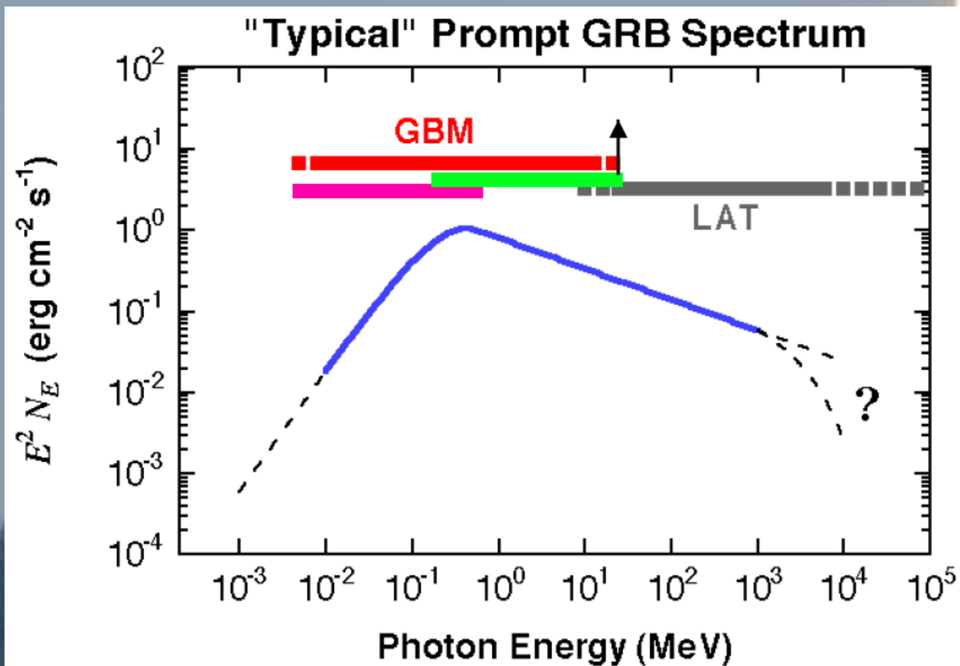
Jacobson et al.'06, Ann. Phys.
Kostelecky & Mewes'09, PRD
Mattingly'05, Living Rev. Rel.
Amelino-Camelia & Smonlin'09, PRD

Time-lag by GRB



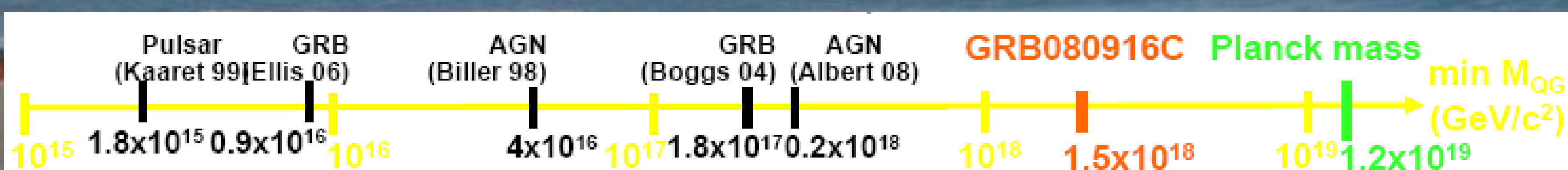
June 11, 2008

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 dependenc

s=1 subluminal case; s=-1 superluminal case

L.Shao and B.-Q.Ma, MPLA 25 (2010) 3251

See also, e.g.,
H.Xu, B.-Q.Ma, APP 82 (2016) 72, arXiv: 1607.03203
H.Xu, B.-Q.Ma, PLB 760 (2016) 602, arXiv: :1607.08043
H.Xu, B.-Q.Ma, JCAP 1801 (2018) 050, arXiv: 1801.08084

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].

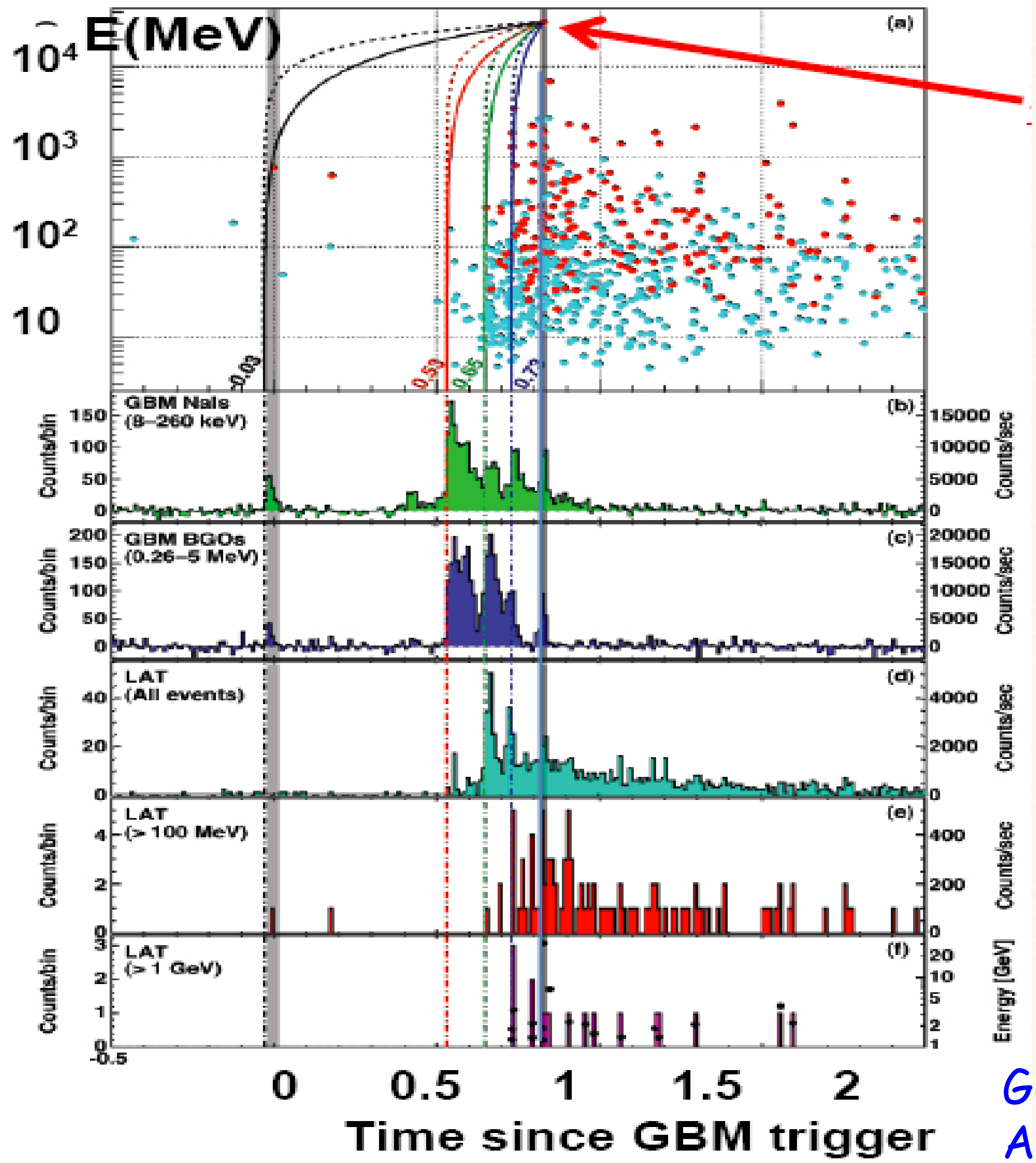
$$M \geq 1.4 \times 10^{16} \text{ GeV}$$

… …

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 $1.2E_{\text{Planck}}$

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

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

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.

LV 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

... ...

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

......

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

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

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]

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

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

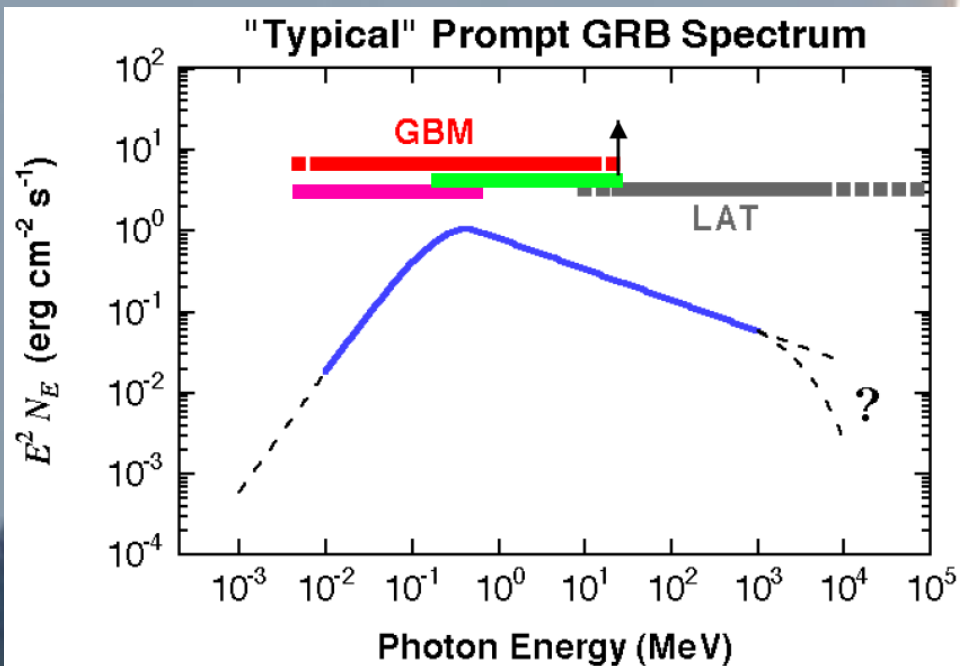
$$h(z) = \sqrt{\Omega_\Lambda + \Omega_{\rm M}(1+z)^3}$$

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

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

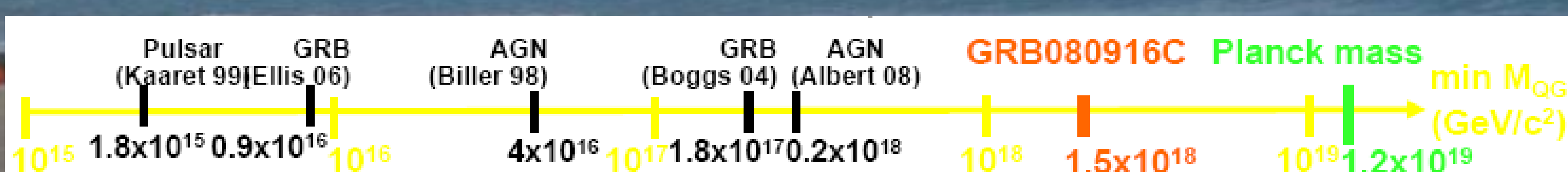
June 11, 2008

Fermi instruments

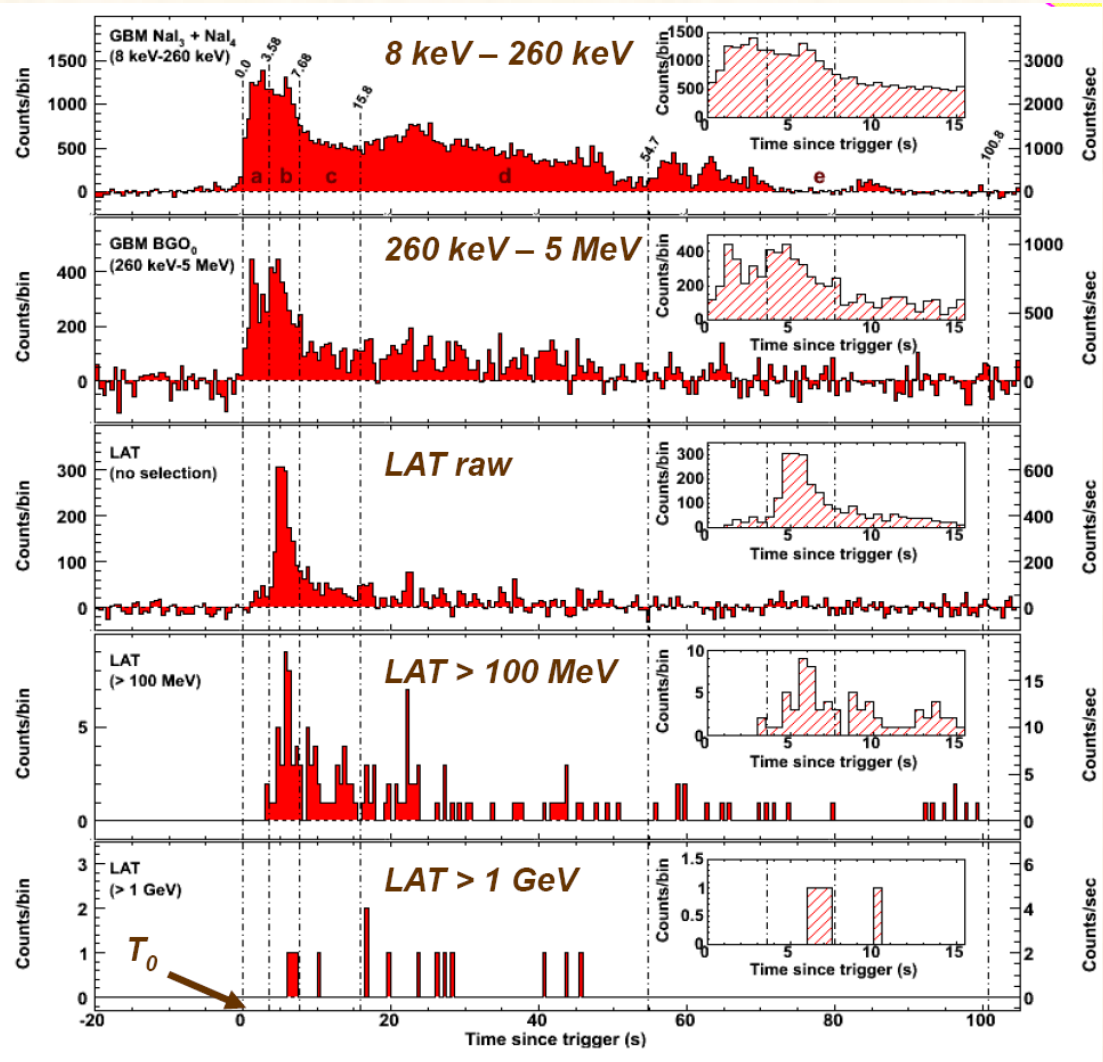


~ 300 GeV

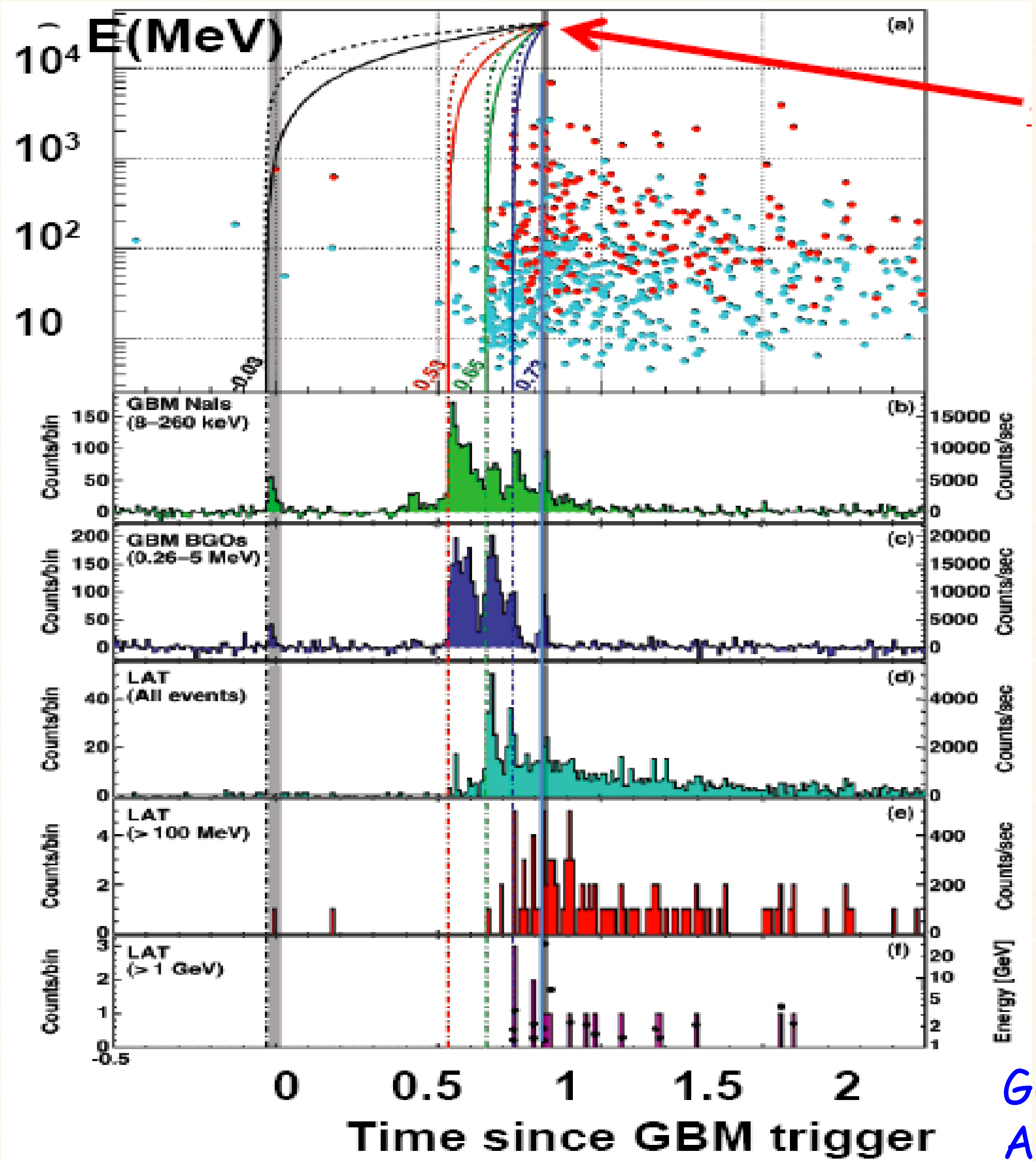
trigger photons ~ 0.1 MeV



Lag determinations



GRB080916C -- Abdo et al.'09, Science



Time lags are affected both artificially and instrumentally

GRB090510
Abdo et al.'09, Nature

Four Fermi observations

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}

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

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

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

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

An intuitive way to perform analysis

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

$$\frac{\Delta t_{\rm obs}}{1+z} = s_n \frac{K_n}{E_{{\rm LV},n}^n} + \Delta t_{\rm in}$$

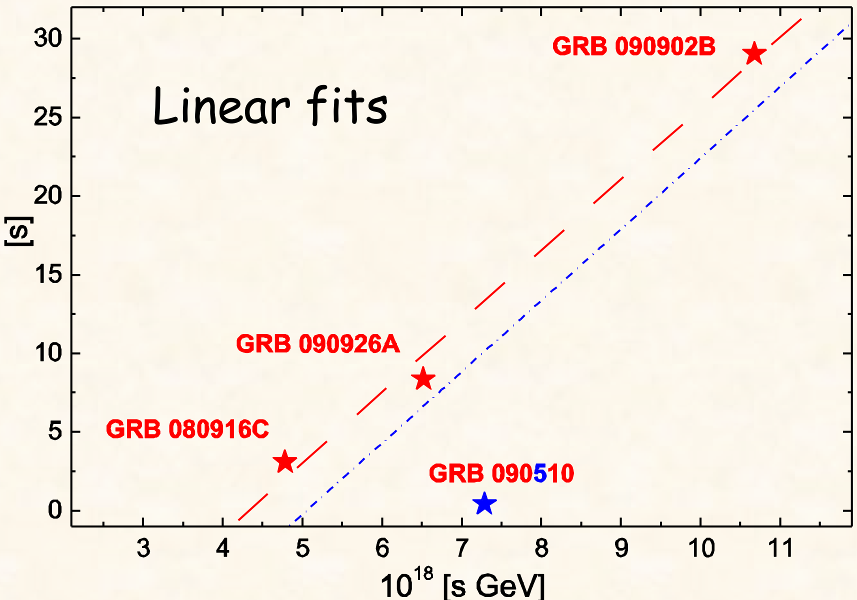
$$K_n = \frac{1+n}{2H_0}\frac{E_{\rm high}^n - E_{\rm low}^n}{1+z}\int_0^z \frac{(1+z')^n {\rm d}z'}{\sqrt{\Omega_{\rm m}(1+z')^3+\Omega_\Lambda}}$$

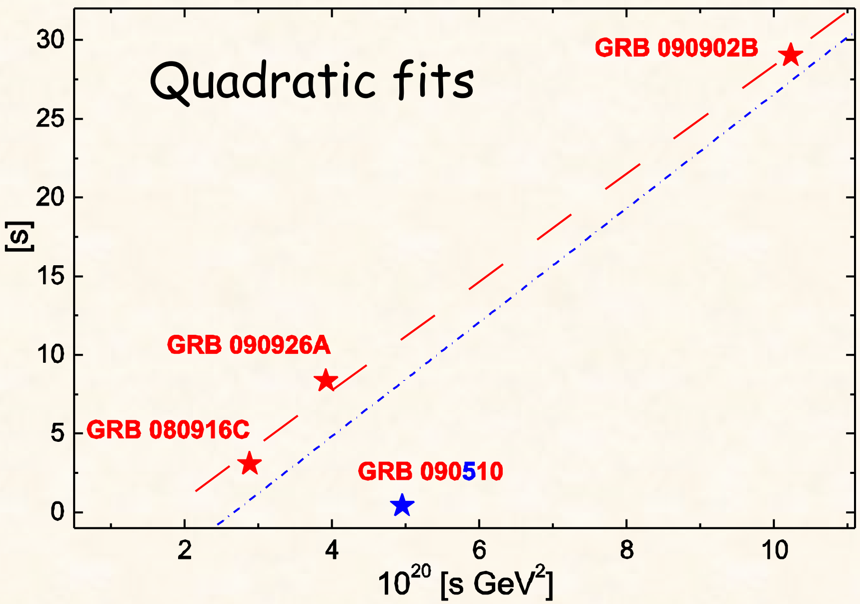
L.Shao, Z.Xiao and B.-Q.Ma, APP 33 (2010) 312

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

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

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





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

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

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

further development

Astroparticle Physics 61 (2015) 108–112

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Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropart

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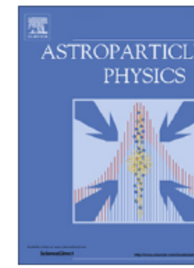


Lorentz violation from gamma-ray bursts

CrossMa

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

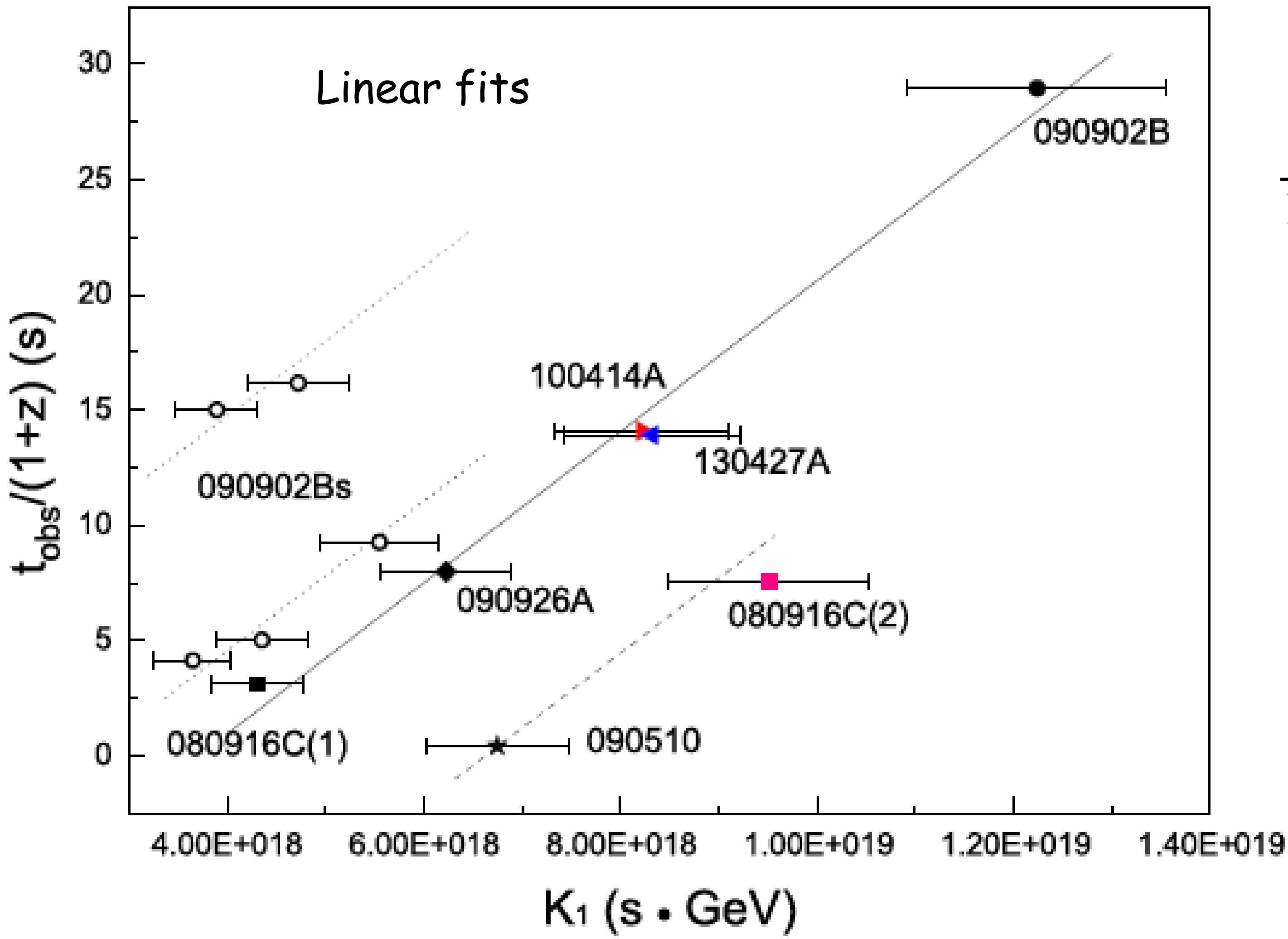
Table 1: The data of the GRBs with high energy photons and known redshifts.

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

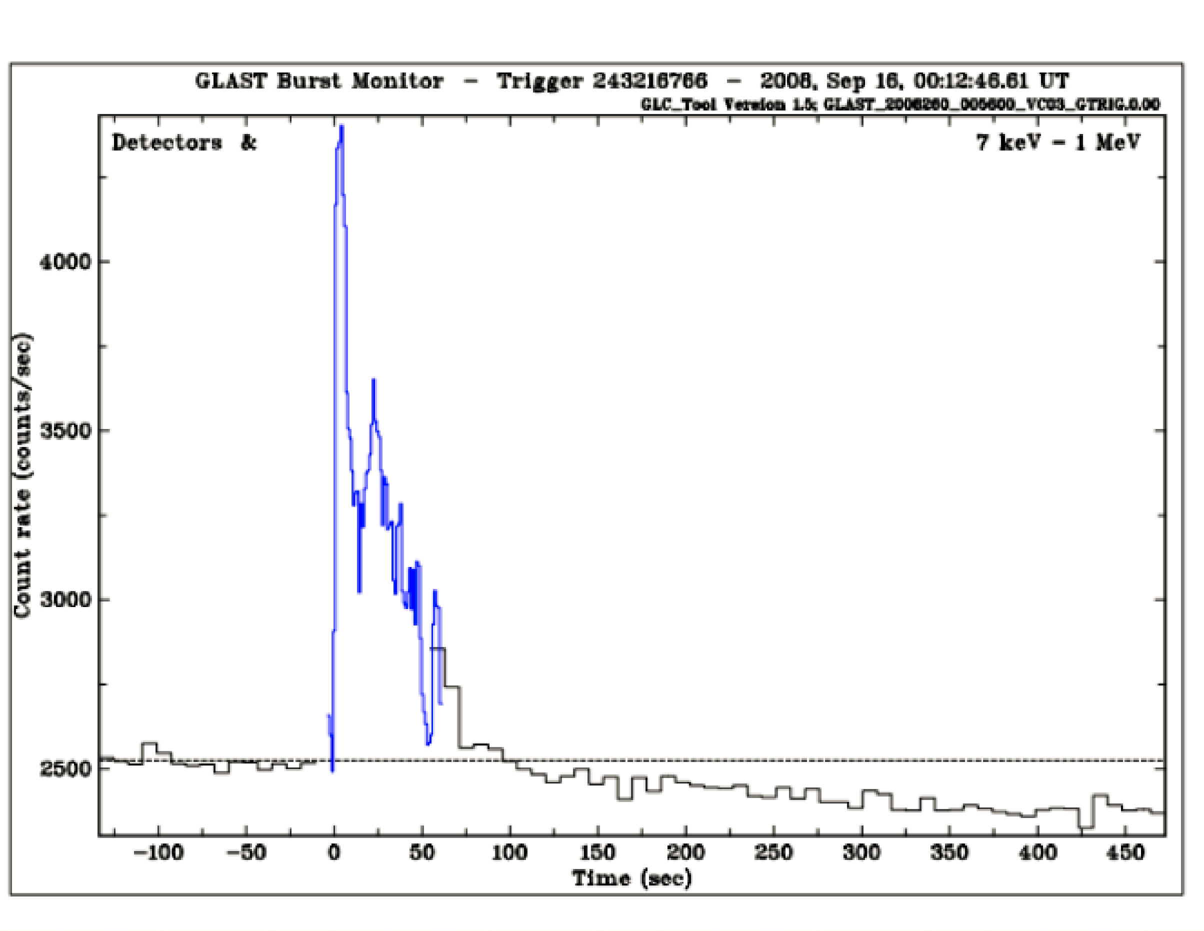
Trigger:

- 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

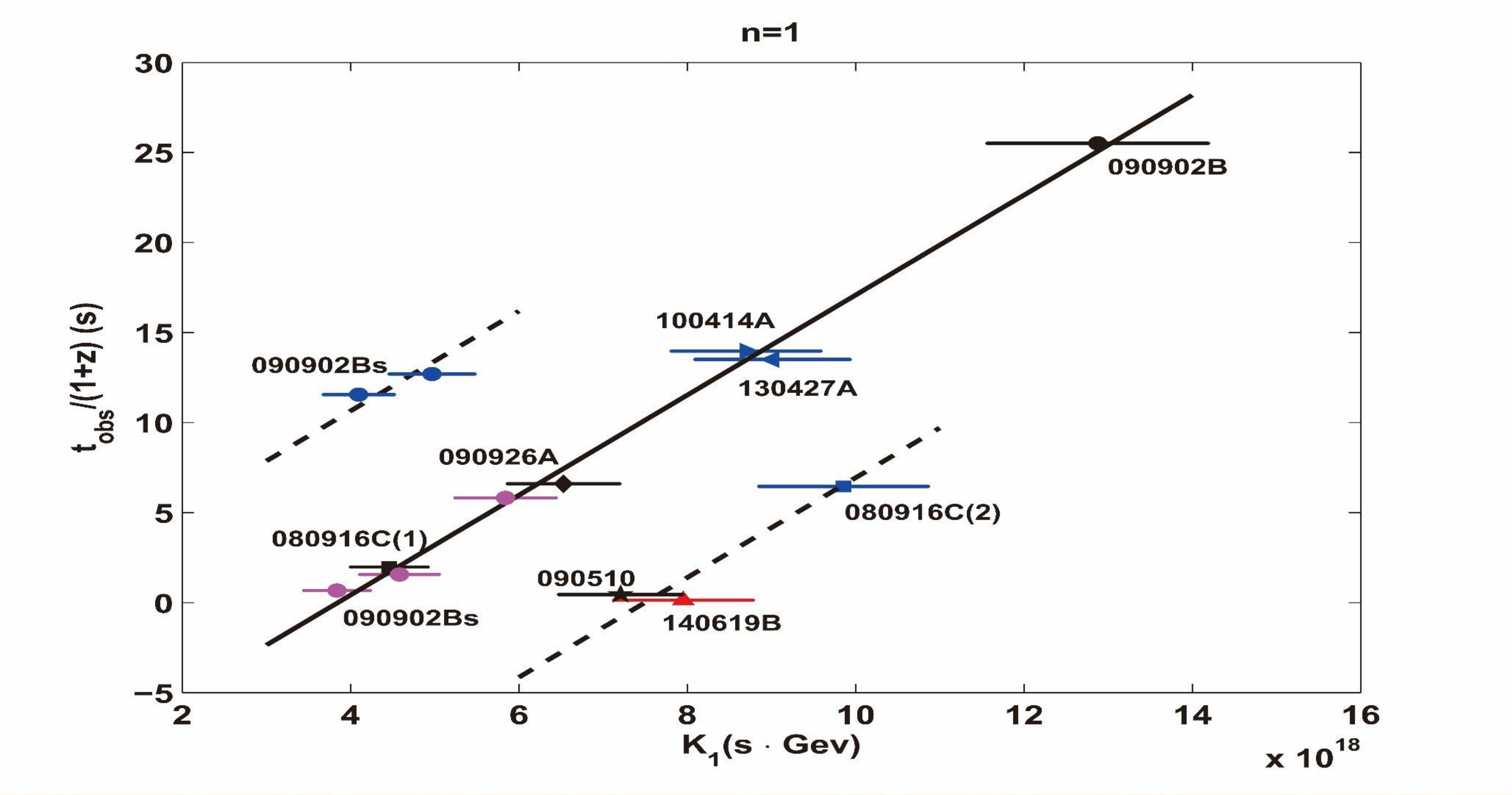
New Analysis of Data

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)	$\frac{\Delta t_{\text{obs}}}{1+z}$ (s)	K_1 ($\times 10^{18}$ s $\cdot$ 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
		11.671		11.9	33.6	0.674	3.84 ± 0.39
		14.166		14.2	40.1	1.559	4.58 ± 0.47
090902Bs	1.822	26.168	9.768	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

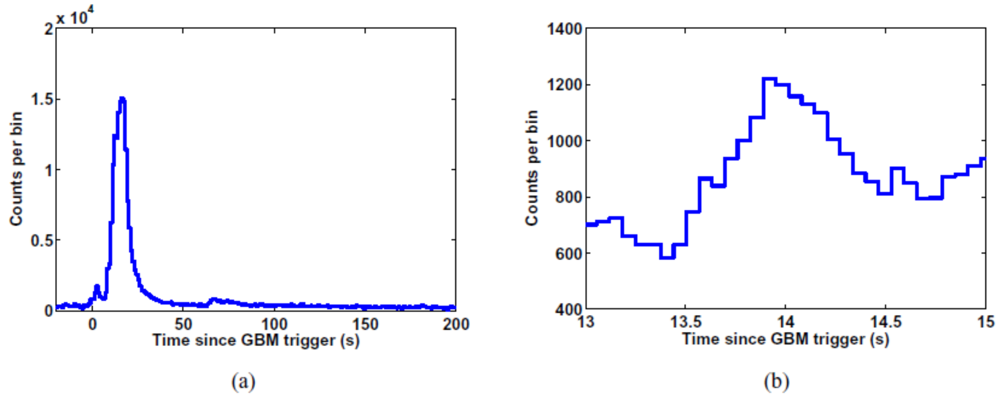


Figure 1: Light curves of the two brightest trigger detectors combined (GBM NaI-n0 and NaI-n3, 8 ~ 260 keV) for GRB 160509A. In the left panel (a), photon events are binned in 1 second intervals. In the right panel (b), photon events are binned in 0.064 seconds intervals to determine the peak of the main pulse as T_{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

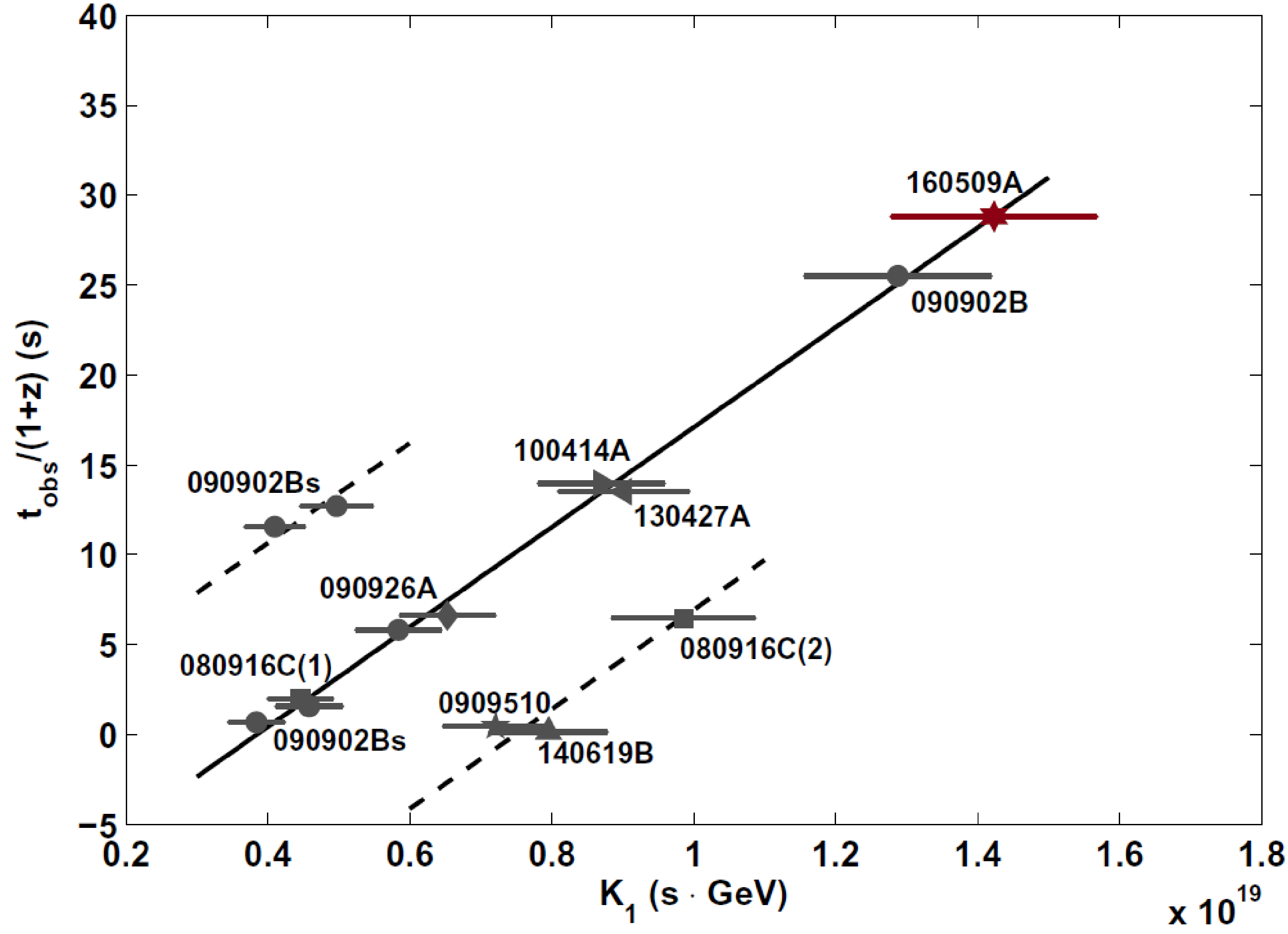
Table 2: Data of high energy photon event from GRB 160509A

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 · 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 · 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

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

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

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.

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]

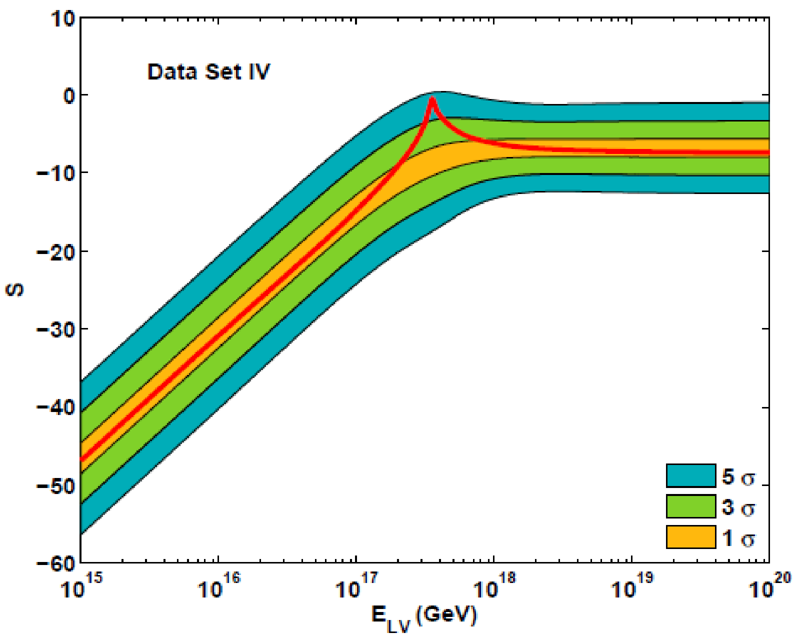
H.Xu, B.-Q.Ma, JCAP 1801 (2018) 050

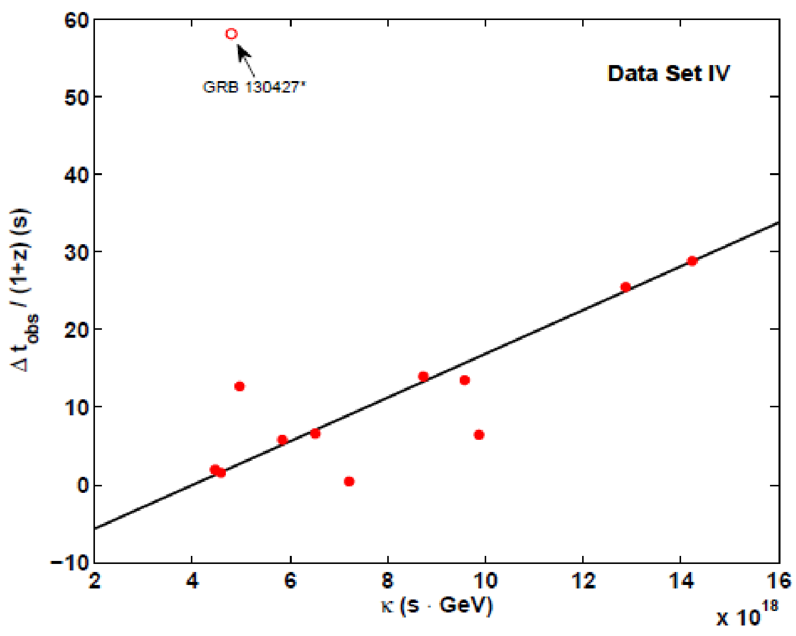
- **A general analysis on the data of 25 bright GRBs**
- **Allow a completed scan over all possibilities without bias**
- **The regularity exists at a significance of 3-5 σ**

new development

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

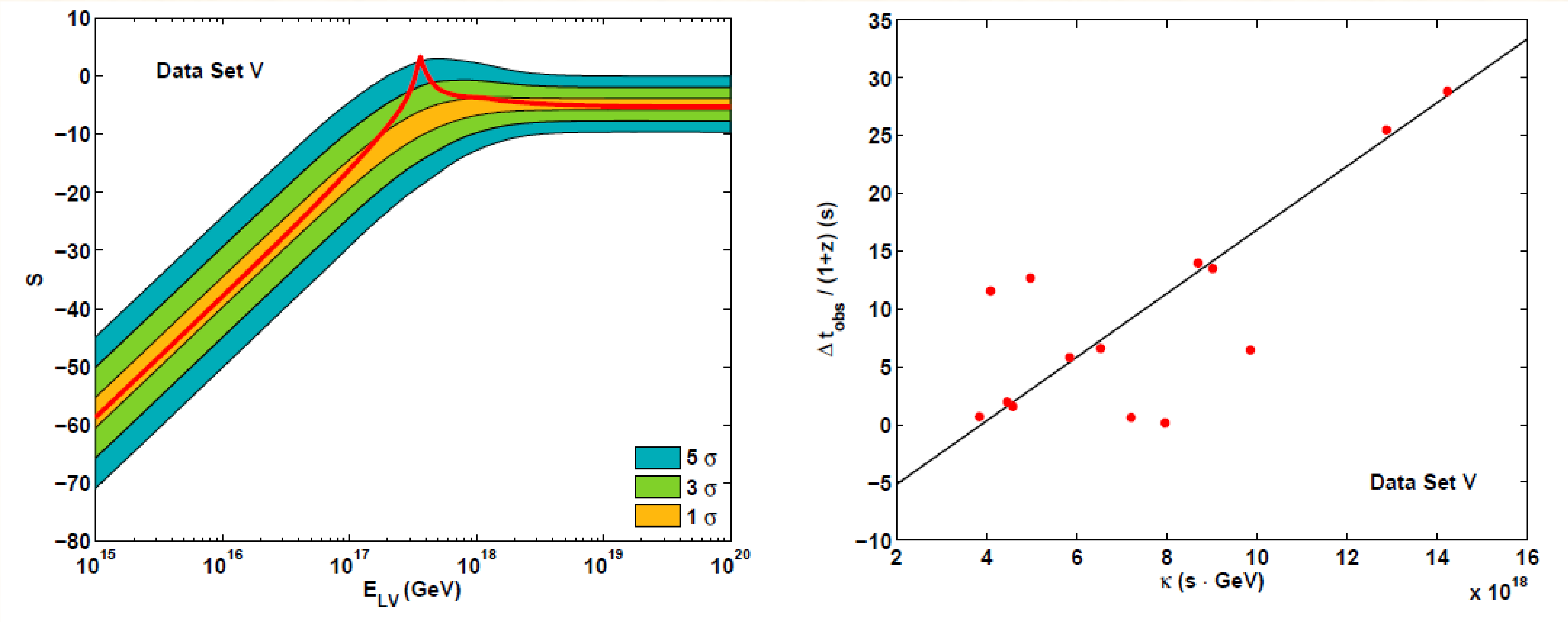
$$S(E_{\mathrm{LV}}) = \sum_{i=1}^{N-\rho} \log\left(\frac{\rho}{t_{i+\rho} - t_i}\right)$$





new development

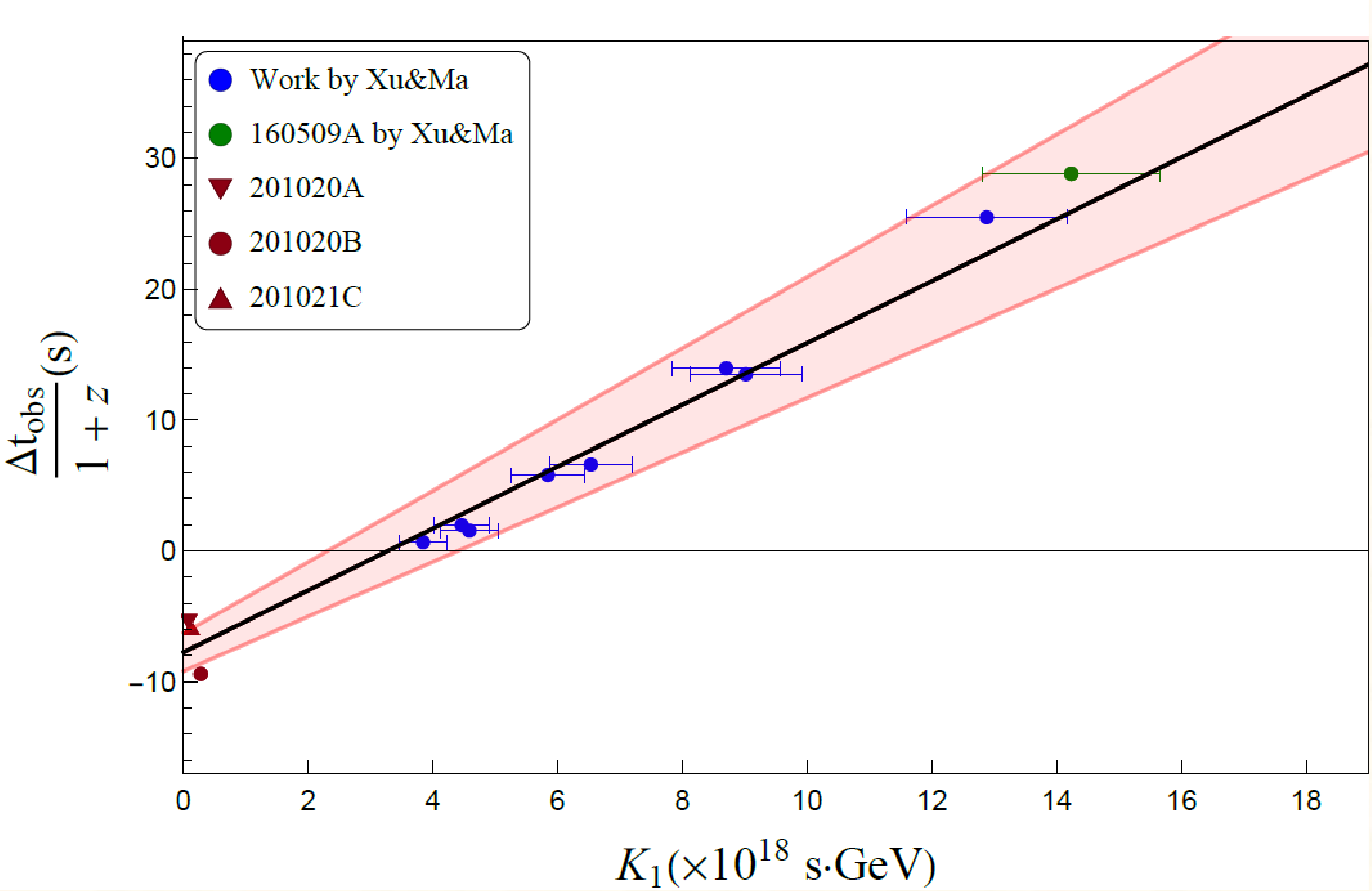
H.Xu, B.-Q.Ma, JCAP 1801 (2018) 050



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

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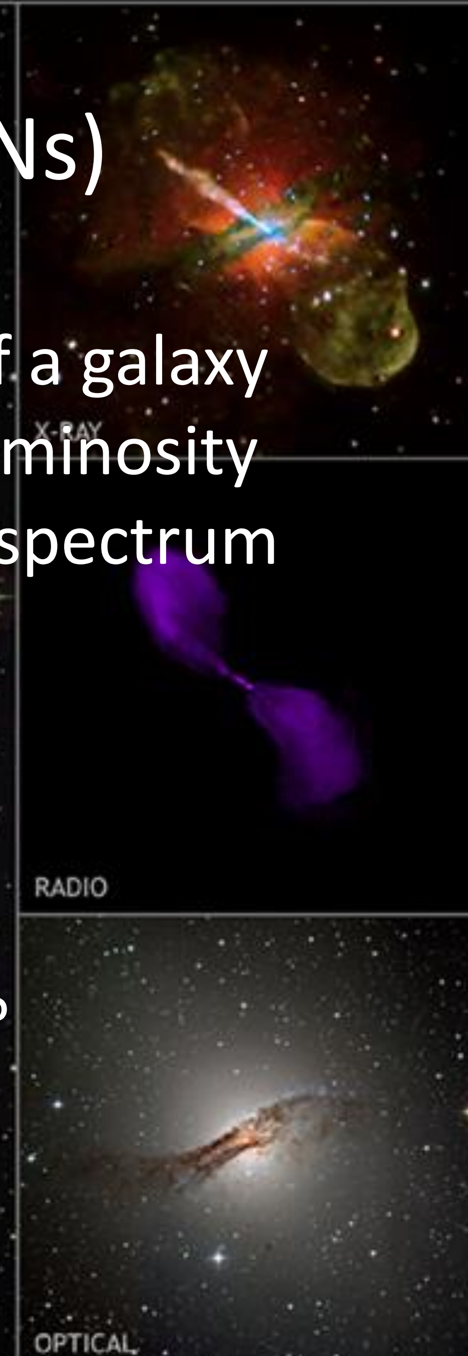
Pre-burst events of gamma-ray bursts with light speed variation

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

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

Active galactic nuclei (AGNs)

- AGN is a compact region at the centre of a galaxy which has a much higher than normal luminosity over some or all of the electromagnetic spectrum [wikipedia]
- AGNs vs GRBs [Ellis et al.'09, PLB]
  - distance & time structure
  - energy of flares; rare & unpredictable
  - different types & distinct intrinsic time lags?



GRBs vs AGNs

- AGNs data solely are inadequate to carry out a robust analysis
- a complementary probe: different observational methods and distinct origins
- Fermi GRBs: the regularity of several high energy photons fall on a same line -> light-speed variation
- Conversely, the AGN results can be considered as a support for the light-speed variation from GRBs

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

H. Li and B.-Q. Ma, Science Bulletin 65 (2020) 262

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

A brief review on LV from AGNs

- **Markarian 421** – no time lag > 280 s between energy bands < 1 TeV and > 2 TeV [Biller et al.'99, PRL]

$$M_{\mathrm{QG,L}} > 4.9 \times 10^{16}\ \mathrm{GeV/c^2}\ \text{and}\ M_{\mathrm{QG,Q}} > 1.5 \times 10^{10}\ \mathrm{GeV/c^2}$$

- **Markarian 501** – 4 min lag for ΔE ~ 2 TeV [Albert et al.'08, PLB]

$$M_{\mathrm{QG,L}} \sim 1.2 \times 10^{17}\ \mathrm{GeV/c^2}$$

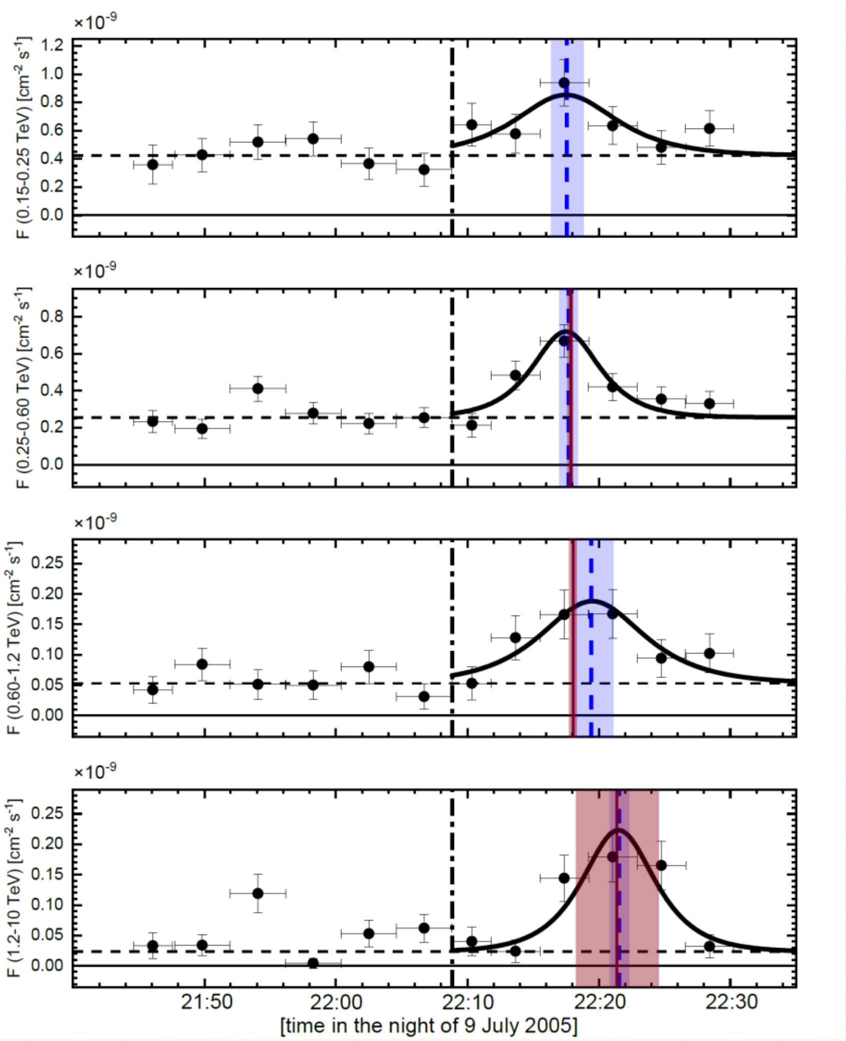
- **PKS 2155-304** – ~20 s lag for ΔE ~ 1.0 TeV & ΔE^2 ~ 2.0 TeV^2 [Aharonian et al.'08, PRL]

$$M_{\mathrm{QG,L}} \sim 2.6 \times 10^{18}\ \mathrm{GeV/c^2} \quad M_{\mathrm{QG,Q}} \sim 9.1 \times 10^{10}\ \mathrm{GeV/c^2}$$

$$\boxed{\Delta t_{\mathrm{in}} = 0}$$

H. Li and B.-Q. Ma, Science Bulletin 65 (2020) 262

Light Speed Variation from AGN: Mrk501



Light curves (LC) binned in 4 minutes for the flare of Mrk 501 in the night on 9 July 2005 by MAGIC

A shift of peak by 4±1 minutes between bands 0.15-0.25 TeV and 1.2-10 TeV

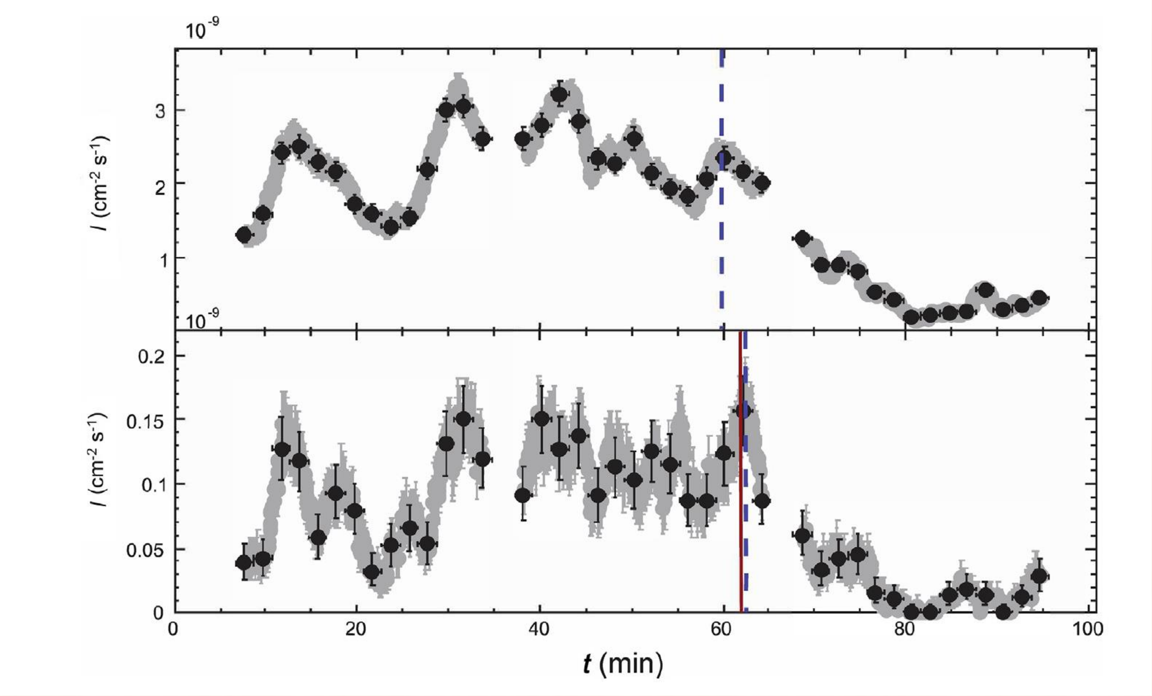
$$E_{\rm LV}^{\rm agn} = 3.68^{+0.46}_{-0.37} \times 10^{17}\ {\rm GeV}$$

$$E_{\rm LV}^{\rm grb} = (3.60 \pm 0.26) \times 10^{17}\ {\rm GeV}$$

A support for the subluminal light speed variation from GRBs

H. Li and B.-Q. Ma, Science Bulletin 65 (2020) 262

Light Speed Variation from AGN: PKS 2155-304



Light curves (LC) for the flare of PKS 2155-304 on 28 July 2006 by H.E.S.S.

No clear one to one correspondence between peaks: a shift of peak by 2 minutes between the last peaks of the two bands 200-800 GeV and over 800 GeV

Supplementary support for the light speed variation from GRBs (red line=predicted 136 s）

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

Prediction of Light speed variation from space-time foam

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.

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

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

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Light speed variation in a string theory model for space-time foam

Chengyi Li[a], Bo-Qiang Ma[a,b,c,*]

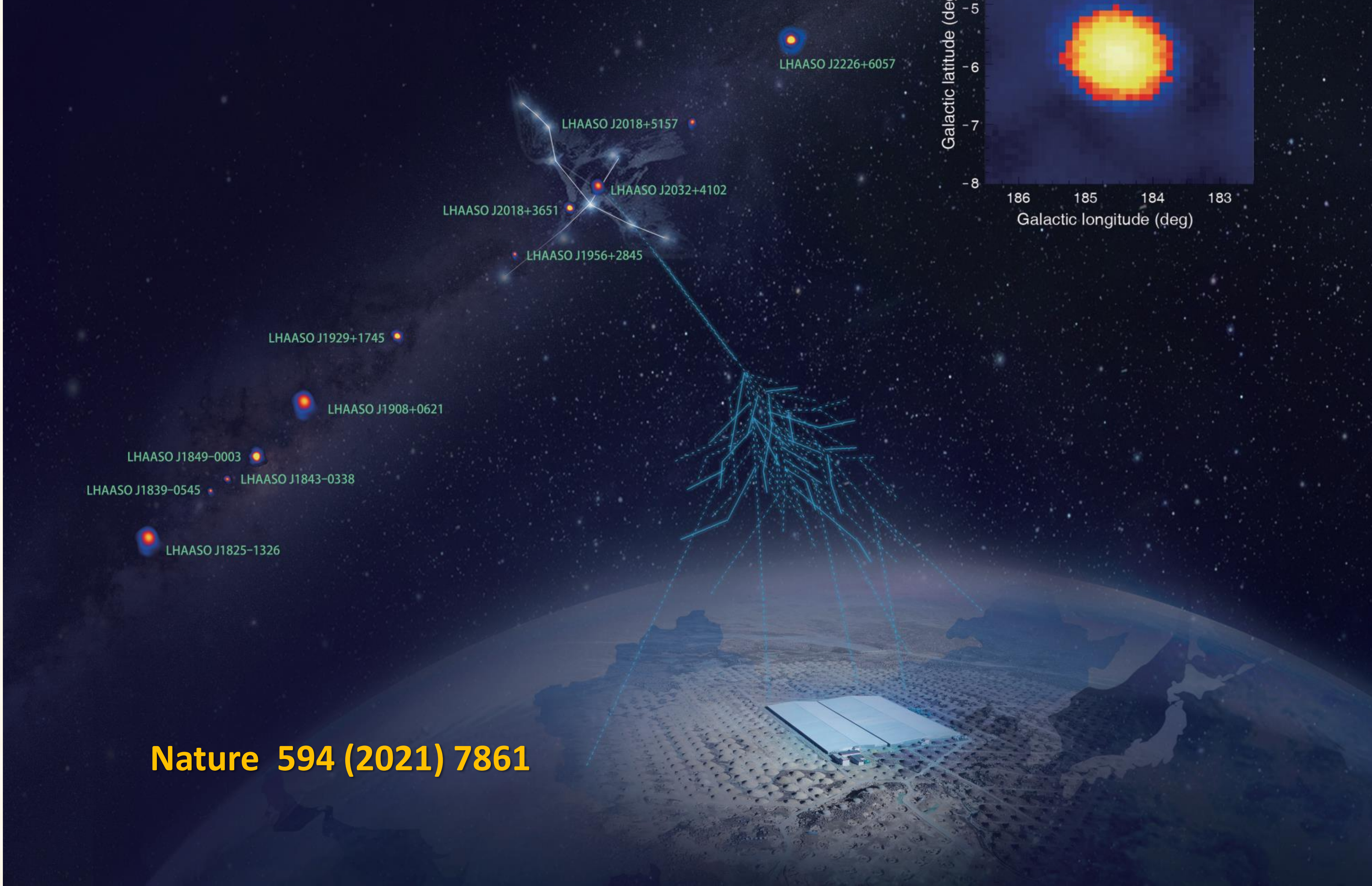
C.Li, B.-Q.Ma, PLB 819 (2021) 136443, arXiv:2105.06515

Predictions of LV features from space-time foam

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

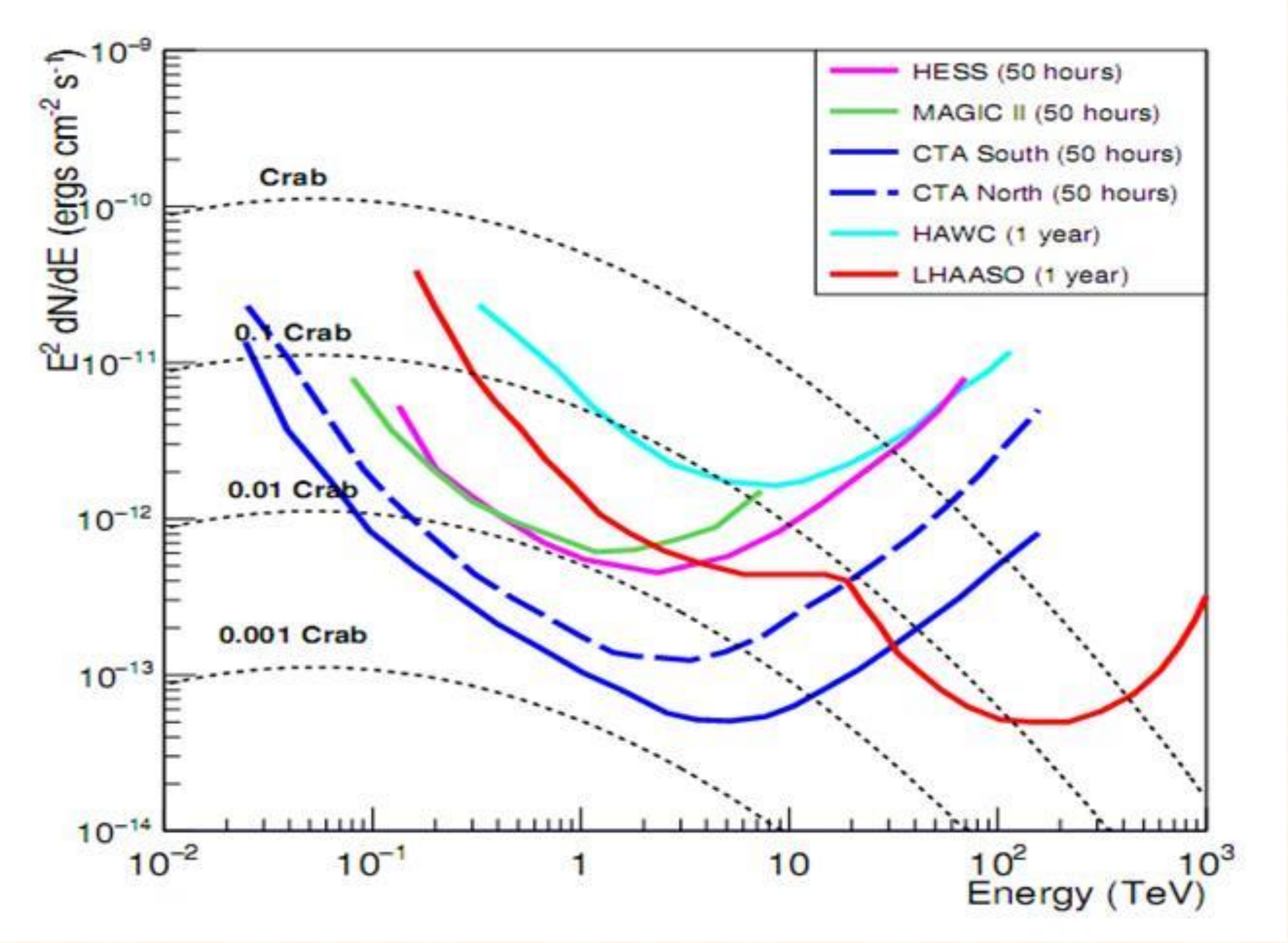
Predictions are consistent with all current observations including a subluminal light speed variation

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 (in press), 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**
- **Hint for subluminal Lorentz violation**
- **Towards a string theory model for space-time foam**

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

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

$$\Downarrow$$

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

- **Stringent constraints on certain LV theories**

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

C.Li and B.-Q.Ma, arXiv:2105.07967 (PRD) & Science Bulletin

Strong Constraint on Superluminal Lorentz Violation

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

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

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

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

  LHAASO, arXiv:2106.12350

- **Similar analysis on LHAASO data by**

  Chen et al., arXiv: 2105:07927

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**
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- **Hint 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 $\varepsilon_\gamma = 6.35 \times 10^{-4}\ \mathrm{eV}$

Greisen-Zatsepin-Kuzmin (GZK) cutoff energy of nucleon cosmic rays

predicted in 1966

pion production $N + \gamma_{CMB} \rightarrow \pi + N$

$$E = \frac{S - m_\pi^2}{2\varepsilon_\gamma (1 - \cos\theta)}$$

threshold energy $E \approx \dfrac{2m_N m_\pi + m_\pi^2}{4\varepsilon_\gamma} = 1.10 \times 10^{20}\ \mathrm{eV}$

mean free path $\lambda_N \sim 3\,\mathrm{Mpc}$ GZK zone $\sim 50\ \mathrm{Mpc}$

W-Y.P. Hwang, B.-Q. Ma, Eur.Phys.J. A25 (2005) 467

Energy limitation of other particles

- photon

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

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

- electron

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

- neutrino

$$\nu + \bar{\nu} \rightarrow Z \rightarrow q + \bar{q} \rightarrow N + \bar{N} + \gamma + X$$

$$E = \frac{M_Z^2}{2m_\nu} \sim 4 \times 10^{21} (\frac{1\,\text{eV}}{m_\nu}) \text{ eV}$$

Z-burst

Energy limitation of cosmic photons

from standard special relativity

cosmic photon annihilation with CMB

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

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

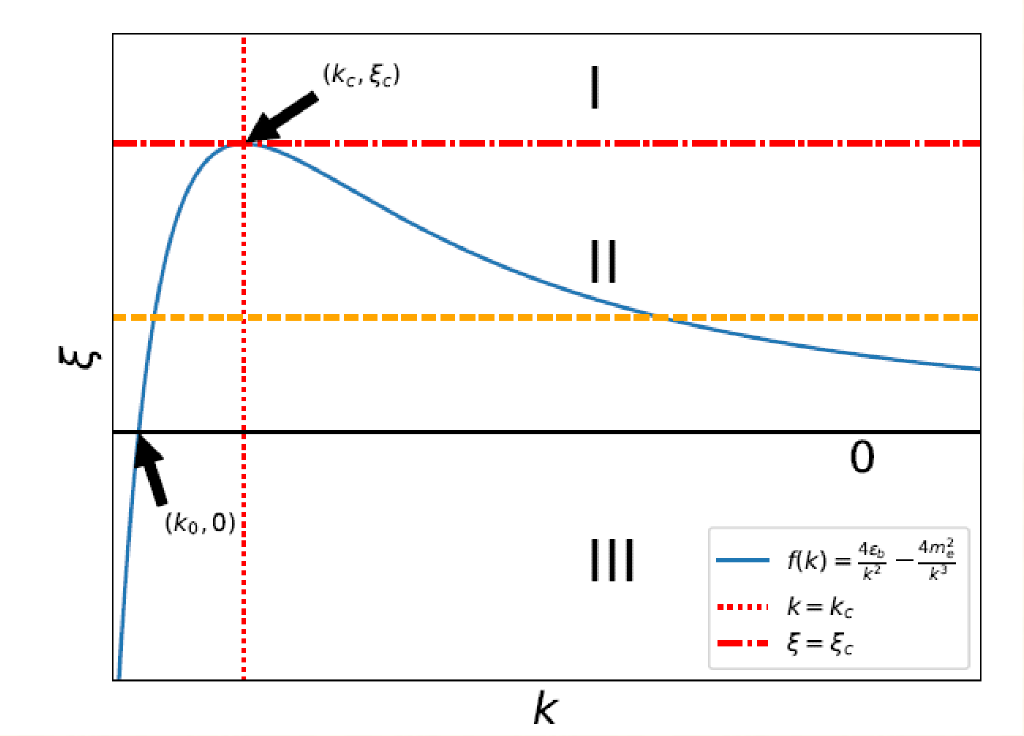
Attenuation of above threshold E=411 TeV photons

H.Li and B.-Q.Ma, JHEAP (in press), arXiv:2105.06647

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

H.Li and B.-Q.Ma, JHEAP, arXiv:2105.06647

Threshold Anomalies of Cosmic Photons due to Lorentz Violation



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

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

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

H.Li and B.-Q.Ma, JHEAP, 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, arXiv:2105.07967 & Science Bulletin (in press)

Breakthrough: LHAASO discovery of PeV photons

- **Observation of photons with energies above the threshold of photon annihilation process**
- **Hint for the subluminal Lorentz violation: an upper bound with $E_{\rm LV}^{\rm (sub)} < \xi_c^{-1} \simeq 4.5 \times 10^{23}$ GeV can explain 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**

Remarks: photons

- High energy cosmic photons provide opportunity to study the Lorentz violation of photons.
- We suggest a subluminal light speed variation from analyses of GRB data, with also supports from AGNs.
- The LHAASO observation of 1.4 PeV photon puts strong constraint on superluminal Lorentz violation.
- Subluminal Lorentz violation can explain the above threshold (E=410 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.

C.Li, B.-Q.Ma, arXiv:2105.07967 (PRD)

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.

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Light speed variation in a string theory model for space-time foam

Chengyi Li [a], Bo-Qiang Ma [a,b,c,*]

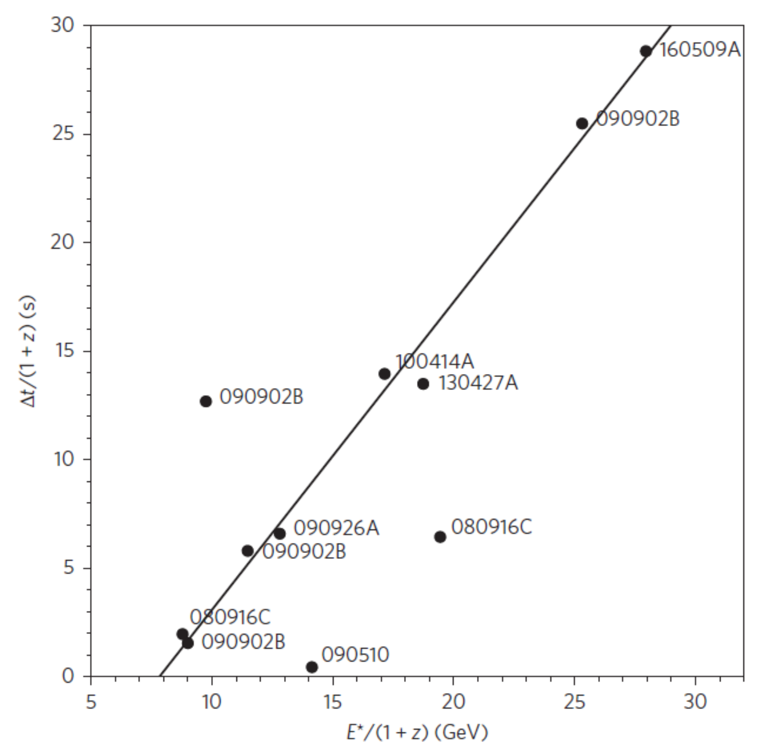
C.Li, B.-Q.Ma, PLB (2021) 136443, arXiv:2105.06151

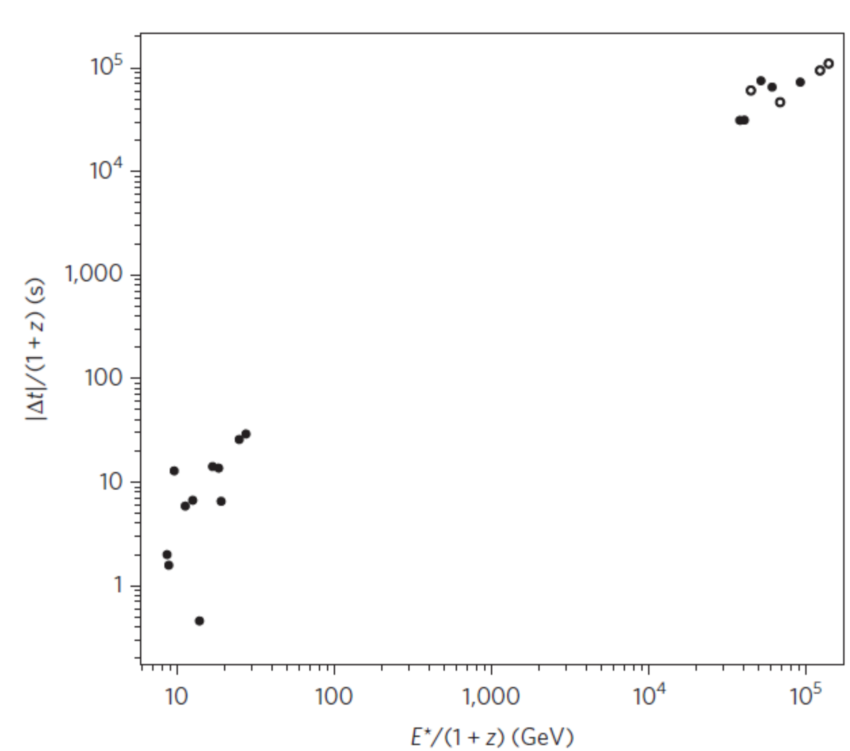
From photons to neutrinos

nature astronomy
ARTICLES
PUBLISHED: 5 JUNE 2017 | VOLUME: 1 | ARTICLE NUMBER: 0139

In vacuo dispersion features for gamma-ray-burst neutrinos and photons

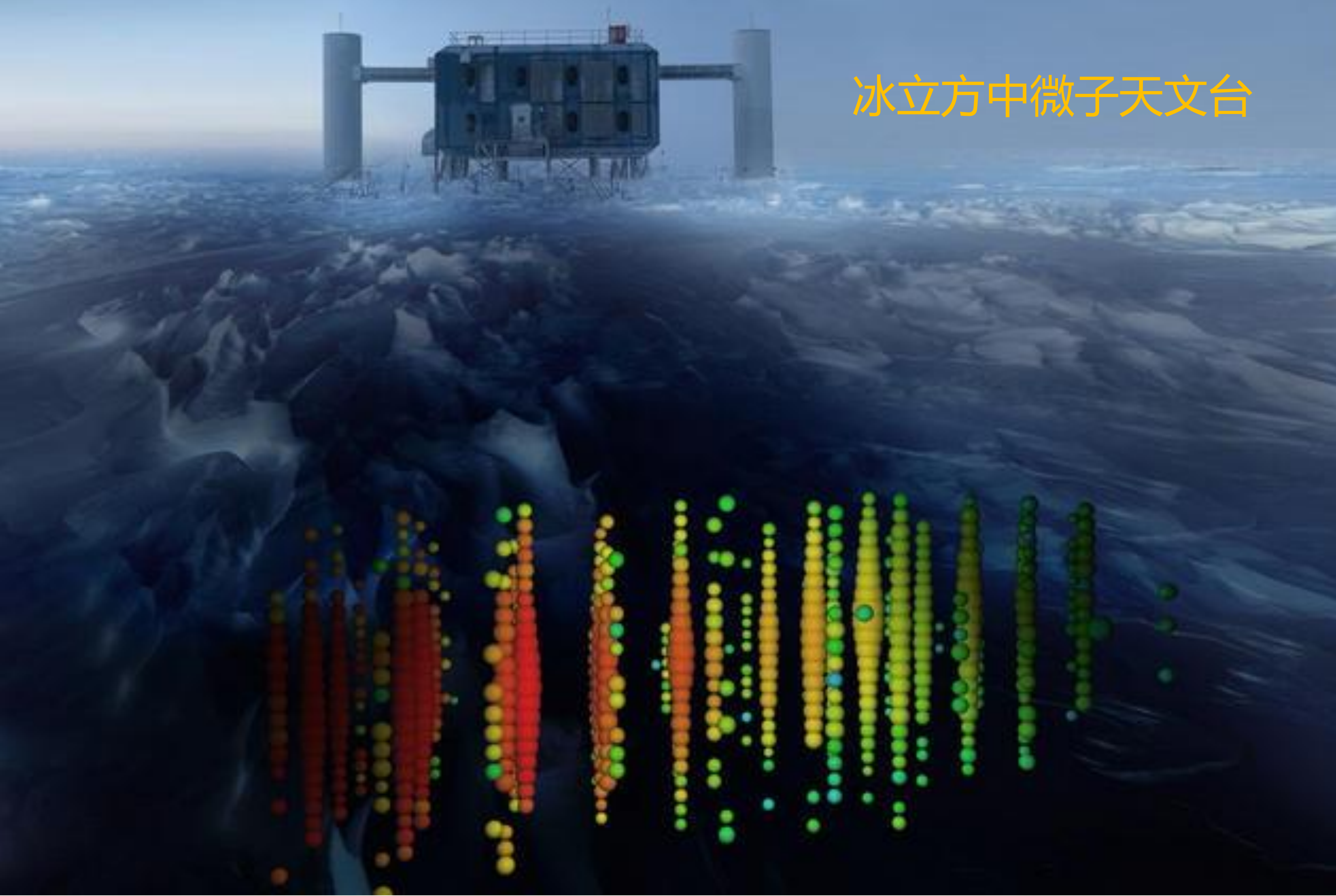
Giovanni Amelino-Camelia[1,2*], Giacomo D'Amico[1,2], Giacomo Rosati[3] and Niccoló Loret[4]





IceCube Neutrino Observatory

冰立方中微子天文台



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.**

IceCube Neutrinos
—results reported by IceCube

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

- **9 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.**

Extension of Time Window to Days

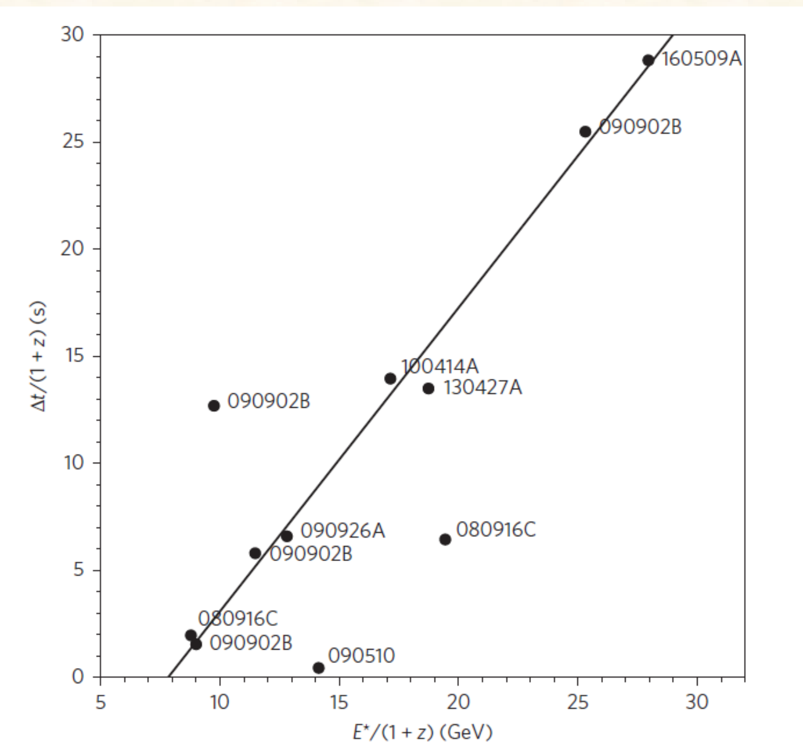
nature astronomy

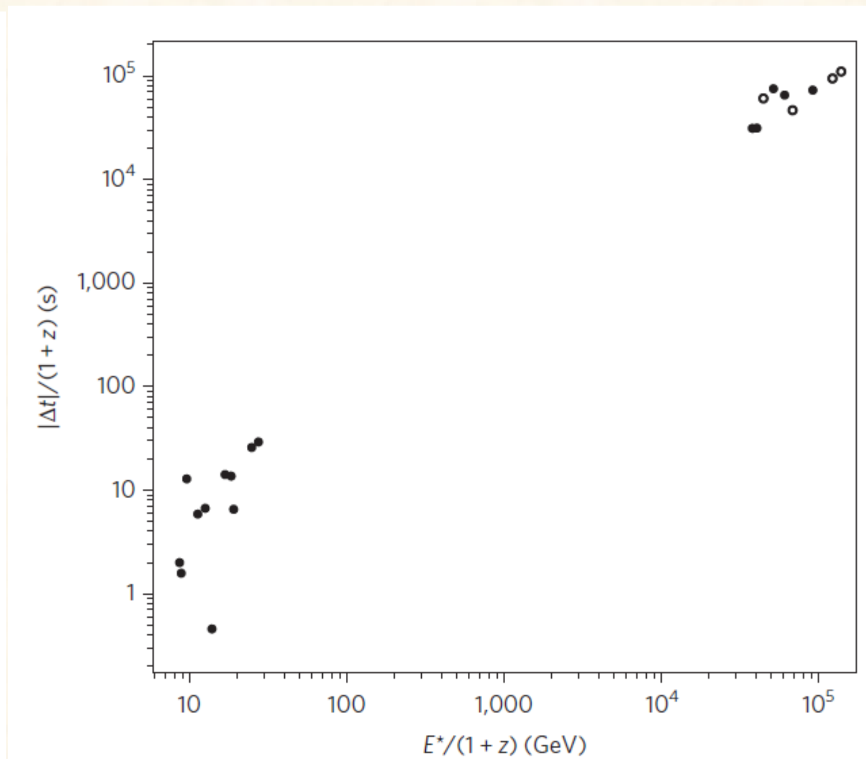
ARTICLES

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

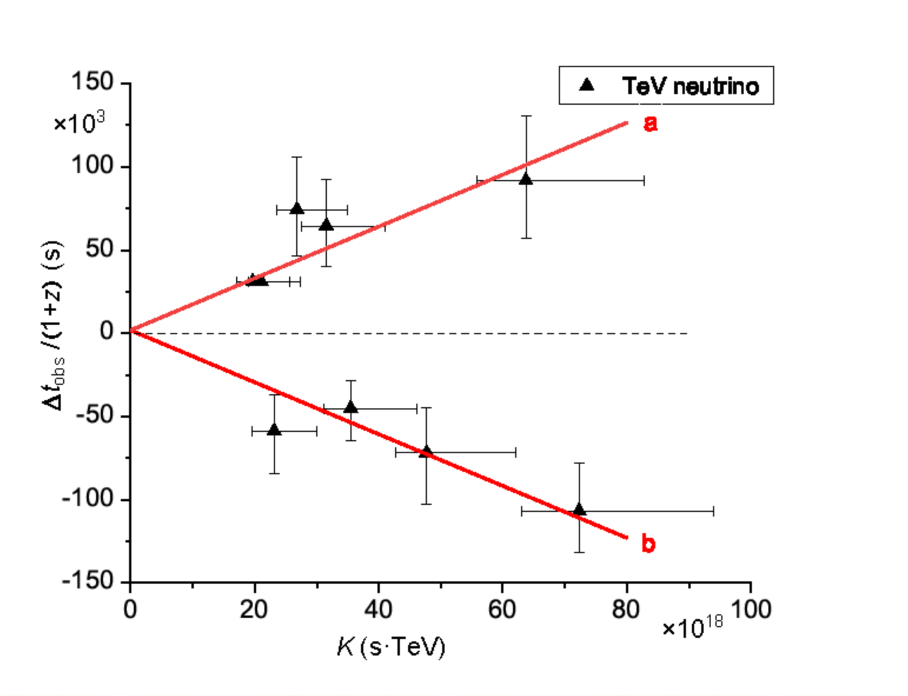
COMMUNICATIONS
PHYSICS

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]



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

$$E_{\mathrm{LV}} = (6.5 \pm 0.4) \times 10^{17}\ \mathrm{GeV}$$

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

Reanalysis of TeV Events

COMMUNICATIONS
PHYSICS

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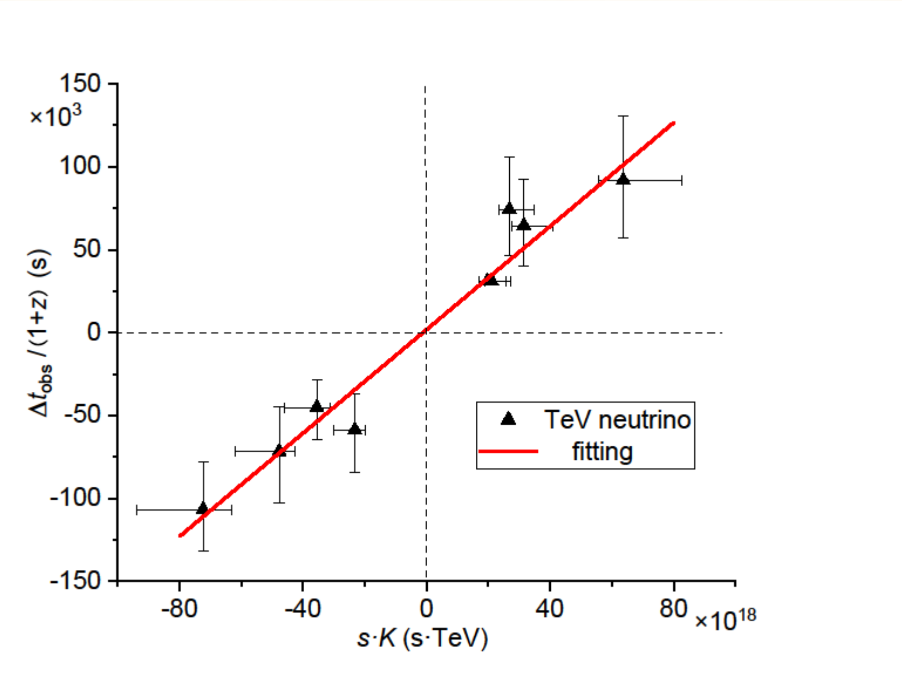


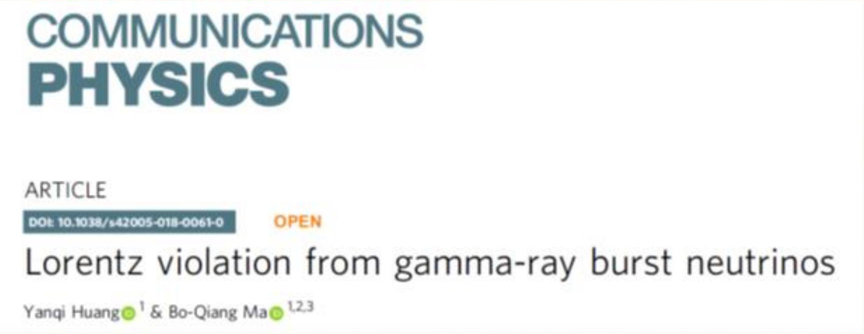
$$\frac{\Delta t_{\rm obs}}{1+z} = \Delta t_{\rm in} + s\frac{K}{E_{\rm LV}}$$

$$s = \pm 1$$

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


COMMUNICATIONS PHYSICS

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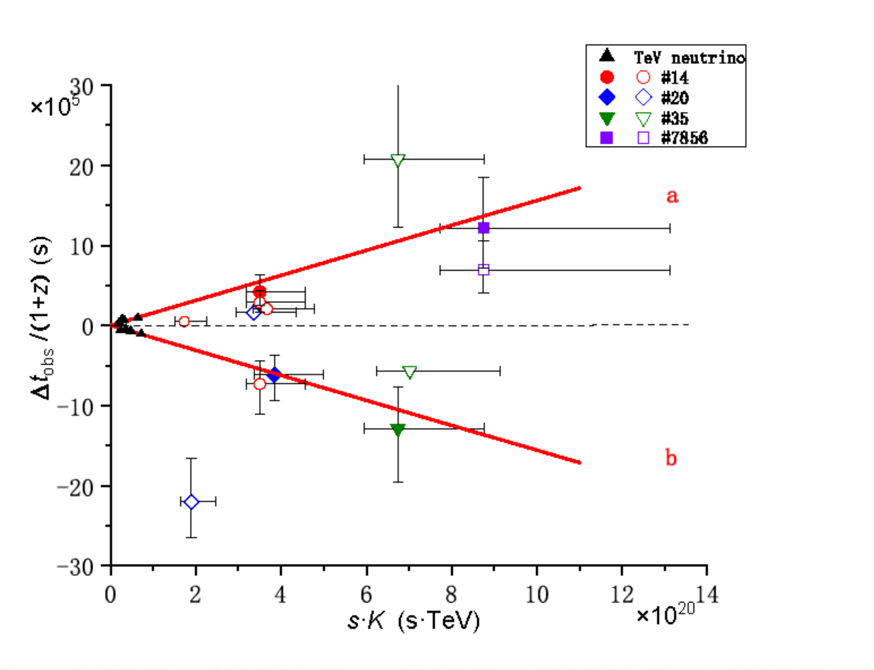
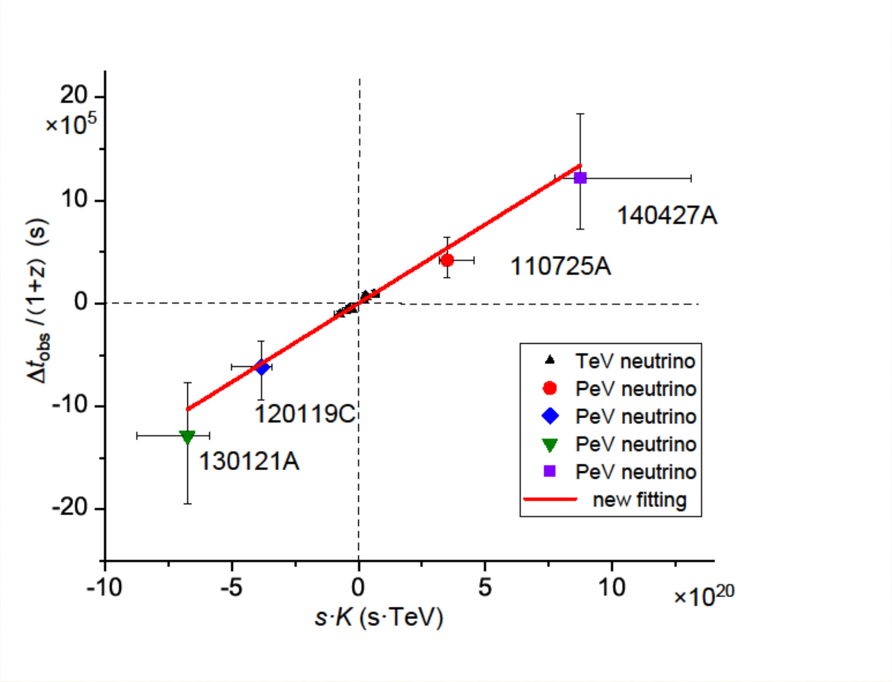




Association of IceCube Neutrinos with GRBs

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

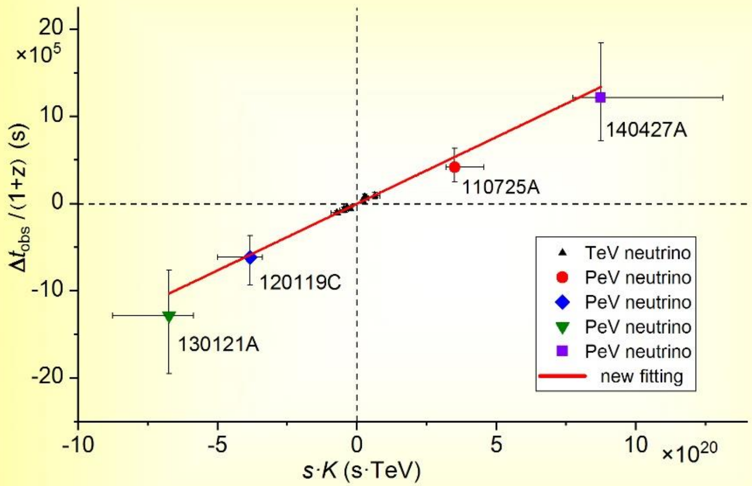
Table 3 The properties of PeV neutrino events with associated GRB candidates

	E (PeV)	σ	$\Delta\Psi$	z	Δt_{obs} (10^3s)	$\frac{\Delta t_{obs}}{1+z}$ (10^3s)	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 σ 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

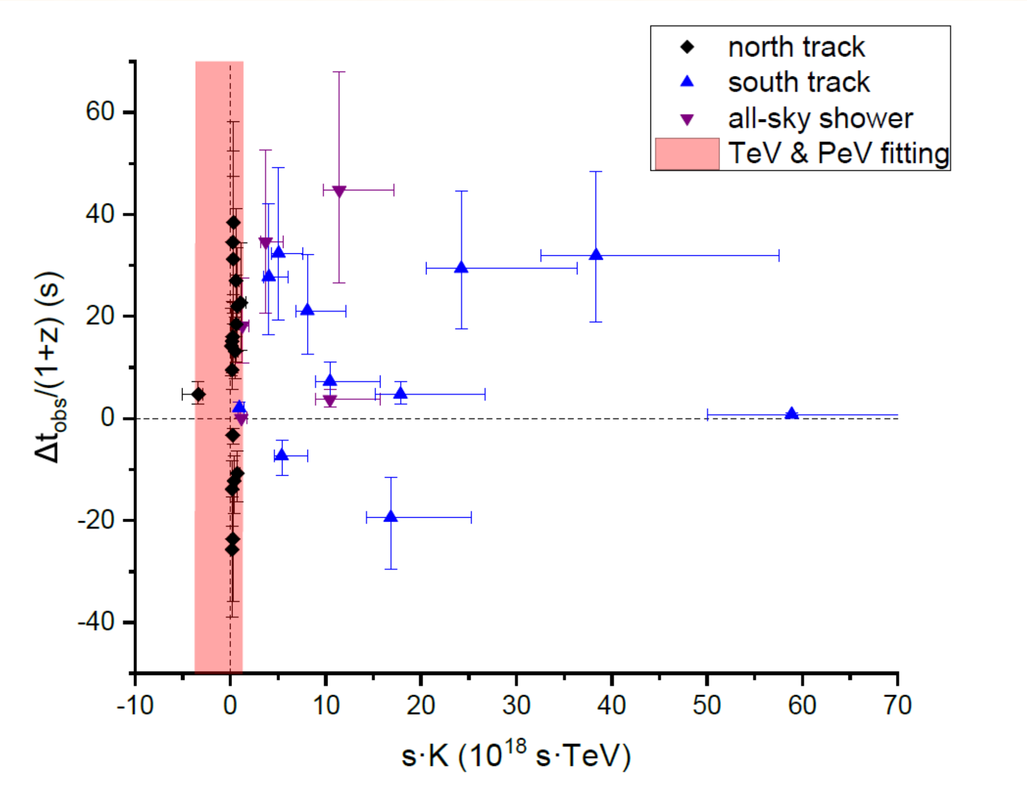
Yanqi Huang,[1] Hao Li,[1] and Bo-Qiang Ma[1,2,3,*]
[1]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
[2]*Collaborative Innovation Center of Quantum Matter, Beijing, China*
[3]*Center for High Energy Physics, Peking University, Beijing 100871, China*

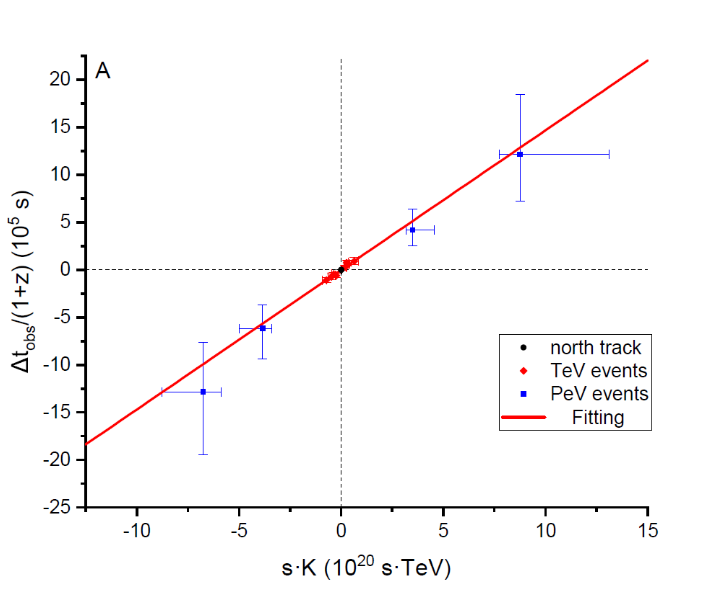
(Received 31 January 2019; published 21 June 2019)

- **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

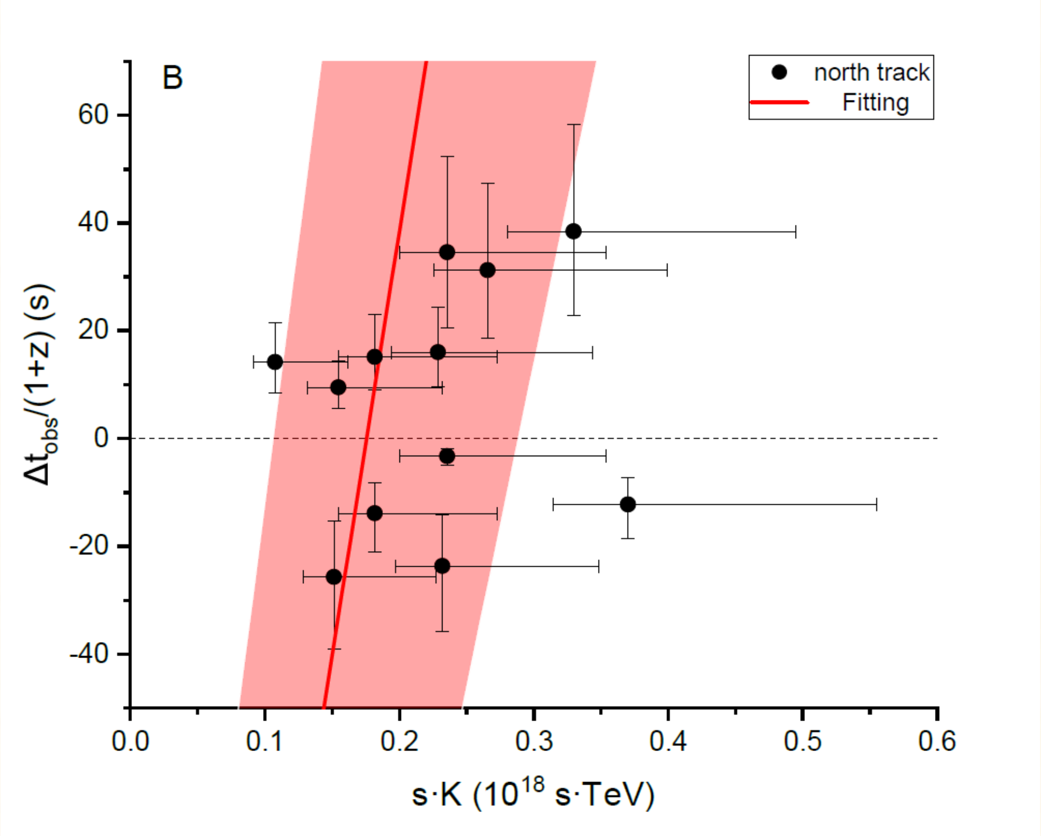
Y. Huang, H.Li, B.-Q. Ma, PRD 99 (2019) 123018



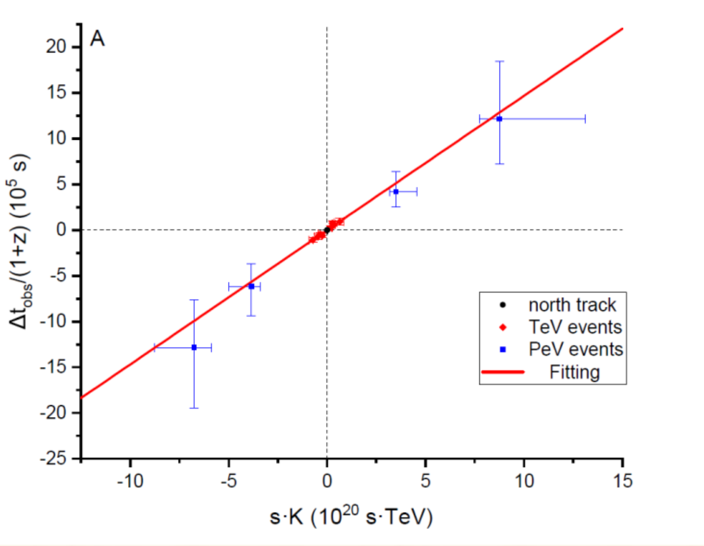


12 IceCube neutrinos near 1 TeV as new support to the TeV+PeV regularity

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



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



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.

Final Remarks

- Researches on Lorentz violation have been active for many years with various theories.
- There might be signals for Lorentz violation yet, but still need to be confirmed.
- The Lorentz violation study can bring conceptual revolution on the understanding of space-time or finding of new physics.
- Lorentz violation is being an active frontier both theoretically and experimentally.