利用伽玛暴限制洛伦兹不变性破坏

报告者：魏俊杰、吴雪峰

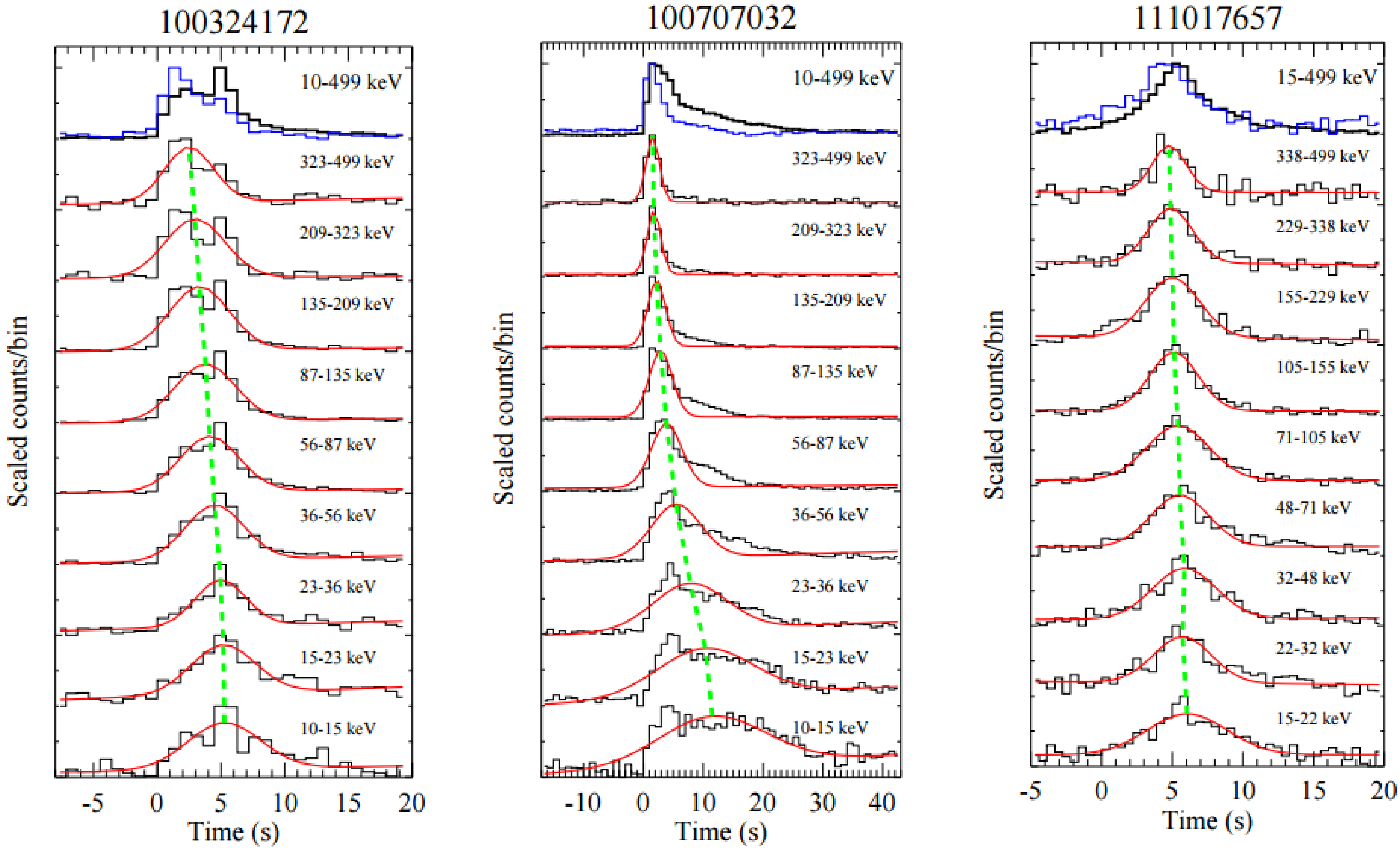
合作者：**张**彬彬、邵琅、Peter Mészáros

Purple Mountain Observatory, Chinese Academy of Sciences

The spectral lags of GRBs

Most GRBs show *positive* lags at low energy scales

i.e, light curves at higher energies peak earlier than those at lower energies



Shao et al. 2016, arXiv:1610.07191

The spectral lags of GRBs

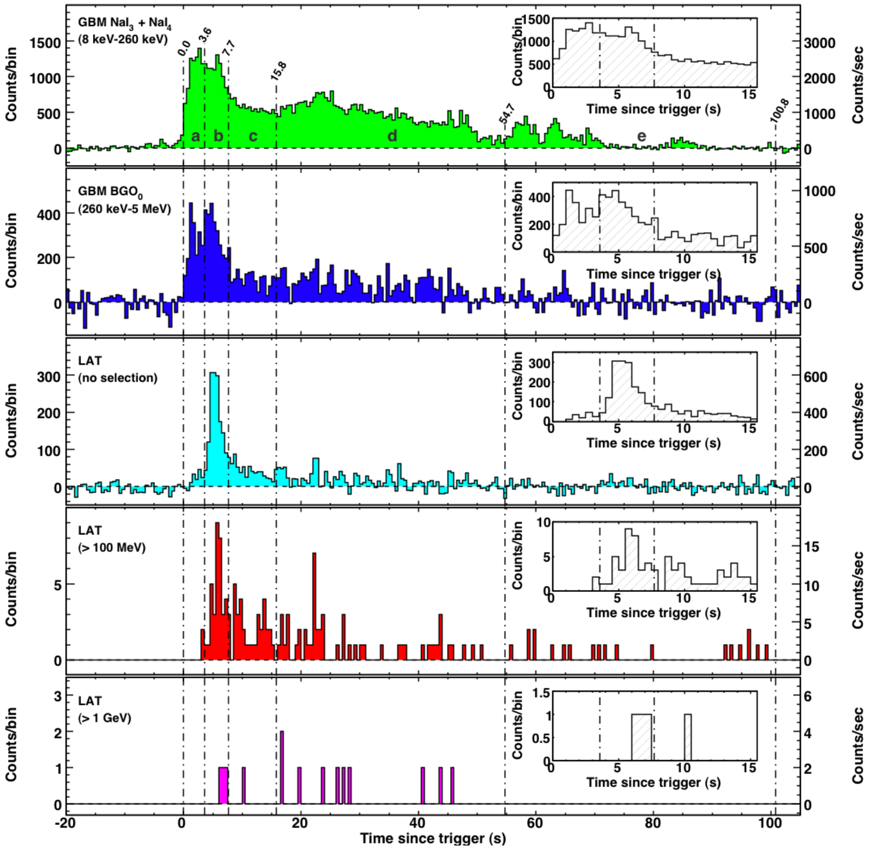
In contrast to the *positive* lags of low energy emission,
GeV photons are found delayed with respect to MeV photons (i.e, *negative* lags)

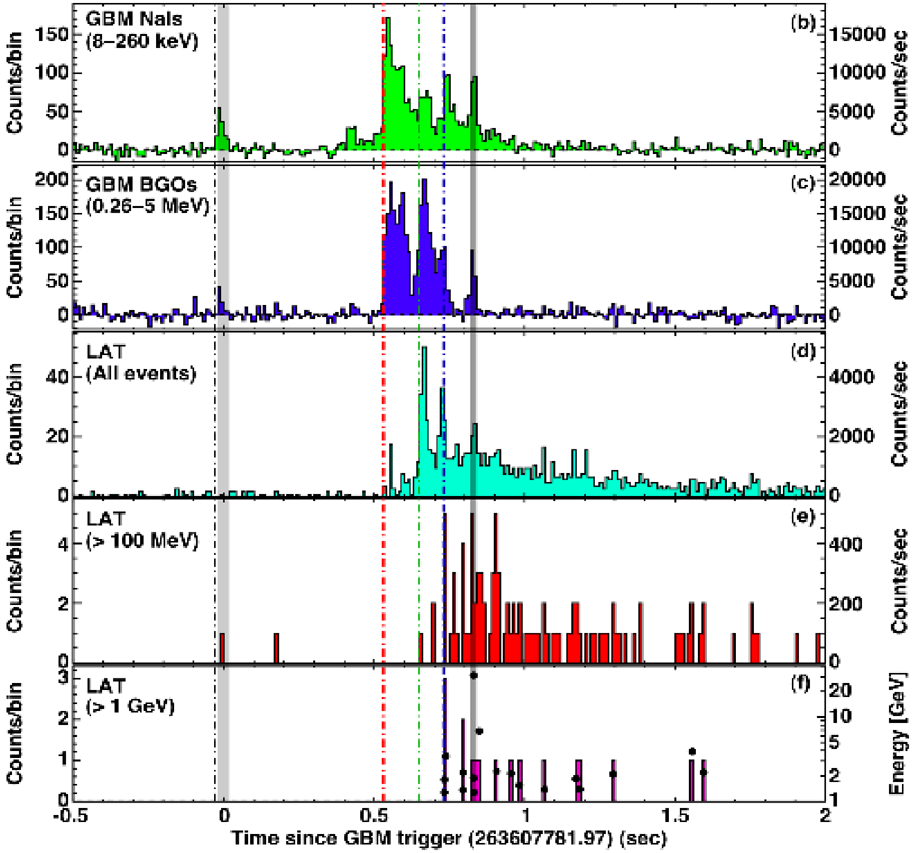
Long GRB 080916C

Abdo et al. 2009, Science 323, 1688

Short GRB 090510

Abdo et al. 2009, Nature 462, 331





- **第一个LAT脉冲跟第二个GBM脉冲关联**
- **高能辐射滞后时间: ~4-5秒**

- **早期几个GBM脉冲阶段无LAT辐射**
- **高能辐射滞后时间: ~0.1-0.2 秒**

Thanks to their short spectral lags, cosmological distances, and very high energetic photons, GRBs have been viewed as the most promising sources for studying the LIV effects.

(Amelino-Camelia et al. 1998; Coleman & Glashow 1999; Schaefer 1999; Ellis et al. 2003, 2006; Boggs et al.2004; Kahniashvili et al. 2006; Jacob & Piran 2008; Abdo et al. 2009a,b; Biesiada & Pi´ orkowska 2009; Xiao & Ma 2009; Shao et al. 2010; Chang et al. 2012, 2016; Nemiroff et al. 2012; Ellis & Mavromatos 2013; Kosteleck´ y & Mewes 2013; Vasileiou et al. 2013, 2015; Pan et al. 2015; Zhang & Ma 2015; Xu & Ma 2016; Wei et al. 2016……).

洛伦兹不变性是爱因斯坦狭义相对论的基本假定：

一个非加速物理系统在做洛伦兹坐标变换时，
其中的相关物理规律不会改变

一些量子引力模型 (e.g., Amelino-Camelia et al. 1998, Nature)

→ **预言“洛伦兹不变性”破缺**

普朗克单位

- 普朗克长度：

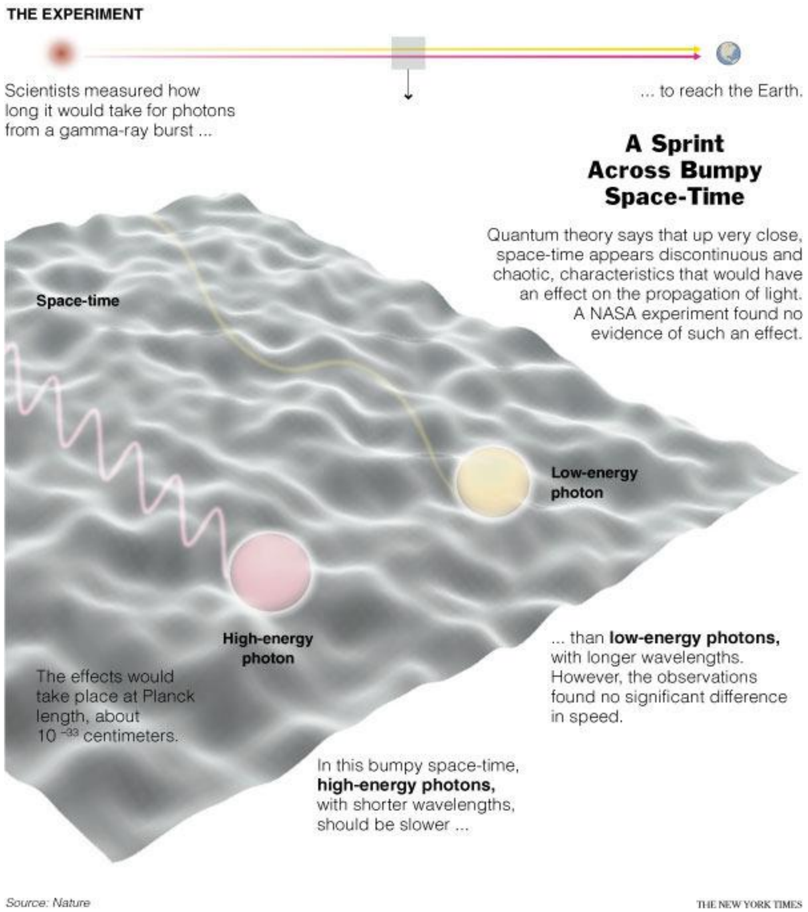
$$l_P = \sqrt{\frac{G\hbar}{c^3}} = 1.61624(8) \times 10^{-35}\, m$$

- 普朗克时标：

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

- 普朗克质量/能量：

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



THE EXPERIMENT

Scientists measured how long it would take for photons from a gamma-ray burst ...

... to reach the Earth.

A Sprint Across Bumpy Space-Time

Quantum theory says that up very close, space-time appears discontinuous and chaotic, characteristics that would have an effect on the propagation of light. A NASA experiment found no evidence of such an effect.

The effects would take place at Planck length, about 10^{-33} centimeters.

In this bumpy space-time, **high-energy photons,** with shorter wavelengths, should be slower ...

... than **low-energy photons,** with longer wavelengths. However, the observations found no significant difference in speed.

Source: Nature

THE NEW YORK TIMES

普朗克尺度下时空呈“泡沫”化

洛伦兹不变性破缺（LIV）后果是光子在真空中的传播速度不再是光速，而是跟光子能量有关：$v(E) \neq c$

$E \ll E_{QG}$

$$E^2 \simeq p^2c^2 + m^2c^4 \pm E^2\left(\frac{E}{E_{QG}}\right)^n$$

洛伦兹不变性破缺造成的时间延迟

$$\boxed{\Delta t = \frac{1+n}{2H_0}\frac{E^n}{E^n_{QG}}\int_0^z \frac{(1+z')^n}{\sqrt{\Omega_\Lambda+\Omega_M(1+z')^3}}dz'}$$

Ellis et al. (2003);
Jacob and Piran (2008)

发生在红移z处的一个暂现源

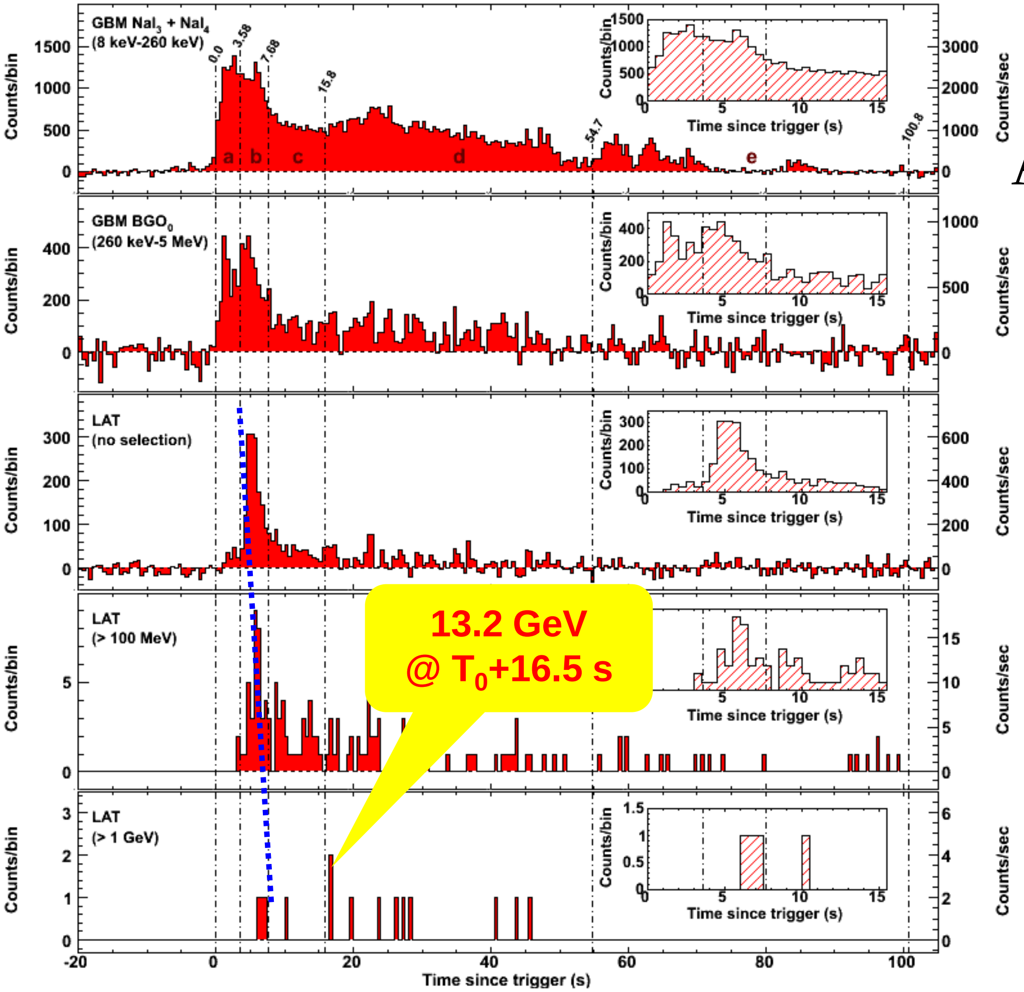
高能光子 (E_h)

低能光子 (E_l)

观测者
z=0

n=1 线性LIV
n=2 二阶LIV

利用单个GeV光子检验洛伦兹不变性



长暴 GRB 080916C对LIV的限制

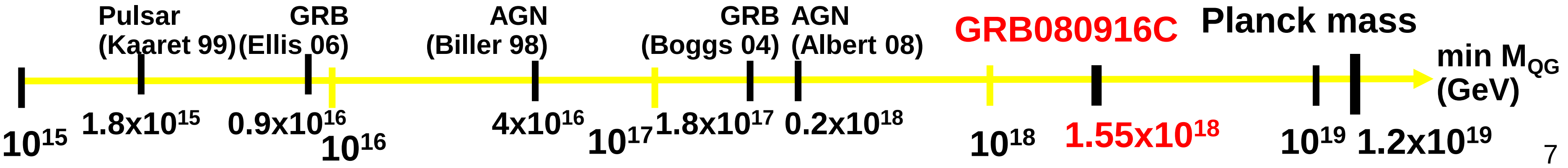
Abdo et al., 2009, Science, 323, 1688

- □ **GBM触发16.5秒后探测到能量达13.2GeV的最高能光子**

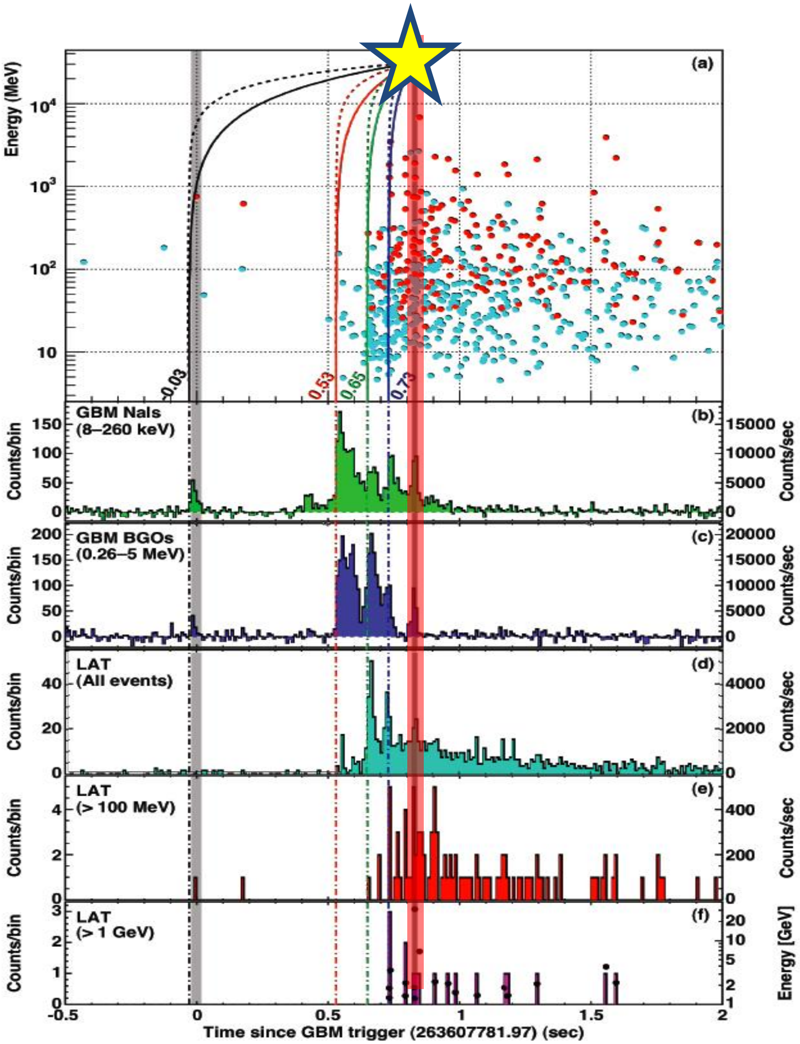
- □ **线性LIV的保守下限**

M_{QG}> (1.55 +/- 0.04)×10^{18} GeV/c^2

比以前用同类方法的最佳值还要高1个量级，比普朗克能量低1个量级



利用单个GeV光子检验洛伦兹不变性



短暴 GRB 090510对LIV的限制

Abdo et al., 2009, Nature, 462, 331

◆**最保守估计：**

能量为31GeV光子与触发的MeV光子在暴源是同时发出的

$\Delta t < 859$ ms,

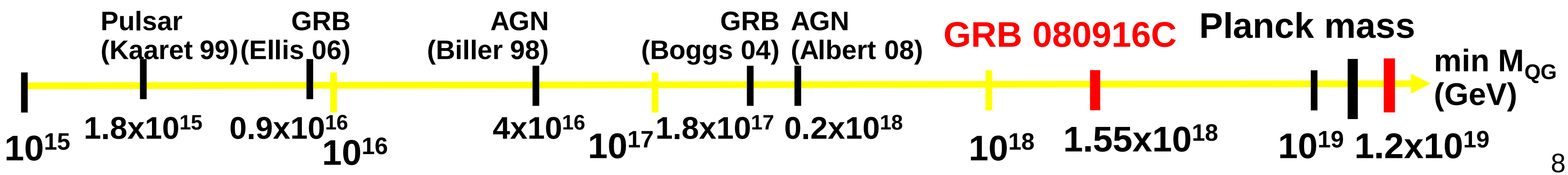
$\mathbf{M_{QG,1}/M_{plank} > 1.19}$

◆**最激进估计:**

能量为31 GeV光子与几乎同时的<1 MeV光子脉冲在暴源是同时发出的

$\Delta t < 10$ms,

$\mathbf{M_{QG,1}/M_{plank} > 102}$

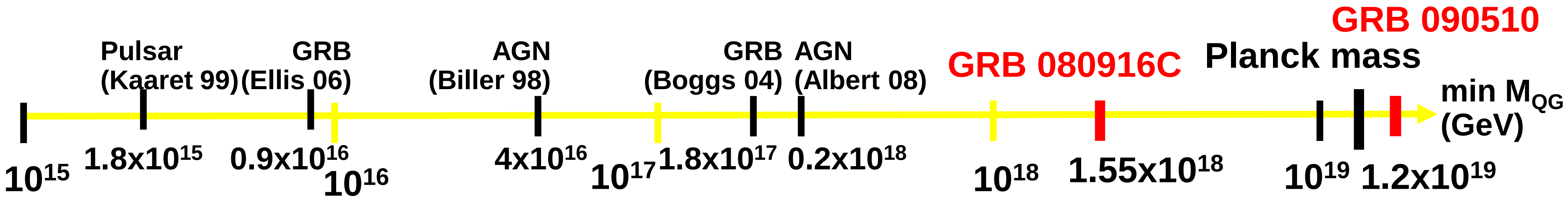


利用单个GeV光子检验洛伦兹不变性

利用伽玛暴GeV光子得到的E_{QG}保守下限

	GRB 080916C	**GRB 090510**
E_h	13.2 GeV	31 GeV
Δt	16.5 s	0.86 s
$E_{QG,1}$ (n=1)	$> 0.1\ E_{Planck}$	$>1.2\ E_{Planck}$
$E_{QG,2}$ (n=2)	$> 7.9\text{x}10^{-10}\ E_{Planck}$	$> 2.7\text{x}10^{-9}\ E_{Planck}$

GRB 090510基本上排除了一阶（线性）LIV



Pulsar (Kaaret 99)

GRB (Ellis 06)

AGN (Biller 98)

GRB (Boggs 04)

AGN (Albert 08)

GRB 080916C

GRB 090510

Planck mass

min M_{QG} (GeV)

10^{15} $1.8\text{x}10^{15}$ $0.9\text{x}10^{16}$ 10^{16} $4\text{x}10^{16}$ 10^{17} $1.8\text{x}10^{17}$ $0.2\text{x}10^{18}$ 10^{18} $1.55\text{x}10^{18}$ 10^{19} $1.2\text{x}10^{19}$

The intrinsic time delay problem

The first attempt to disentangle the intrinsic time delay problem was presented in Ellis et al. (2006).

- The observed time lag:

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

- The time delay induced by LIV:

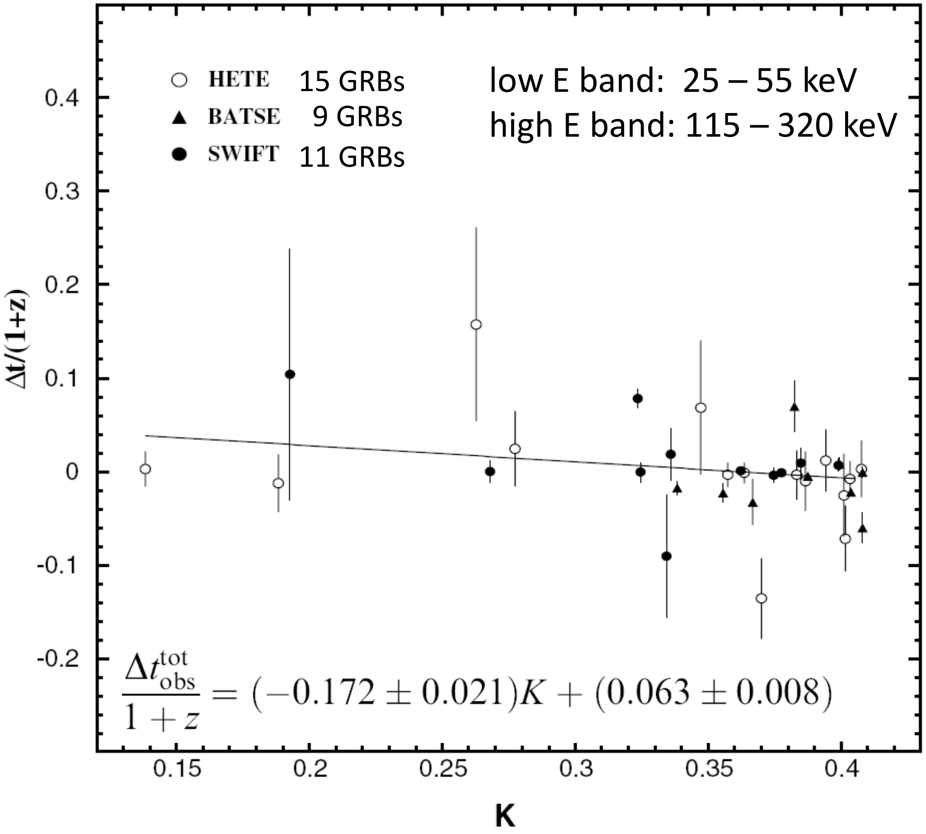
$$\Delta t_{\rm LV} = H_0^{-1} \frac{\Delta E}{M} \int_0^z \frac{{\rm d}z}{h(z)}$$

- The intrinsic time delay: $b_{\rm sf}$

$$\boxed{\frac{\Delta t_{\rm obs}}{1+z} = a_{\rm LV} K + b_{\rm sf}}$$

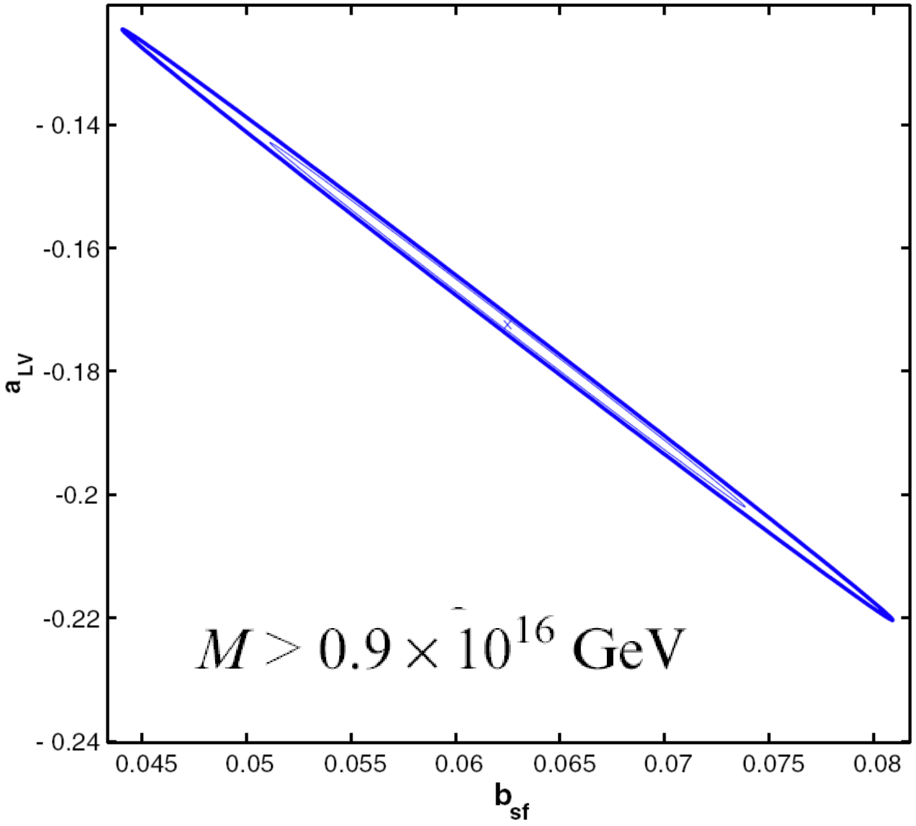
where $a_{\rm LV} = H_0^{-1} \frac{\Delta E}{M}$, $K \equiv \frac{1}{1+z} \int_0^z \frac{{\rm d}z}{h(z)}$

The intrinsic time delay problem



low E band: 25 – 55 keV
high E band: 115 – 320 keV

$$\frac{\Delta t_{\rm obs}^{\rm tot}}{1+z} = (-0.172 \pm 0.021)K + (0.063 \pm 0.008)$$



$$M > 0.9 \times 10^{16}\ \mathrm{GeV}$$

Ellis et al. 2006, Astroparticle Physics, 25, 402

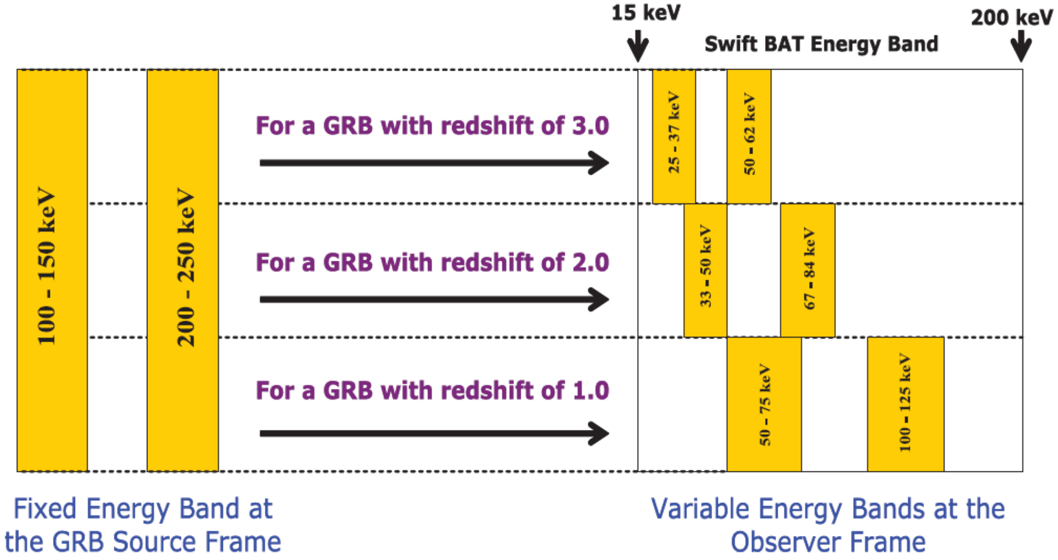
Disadvantages for the treatment of Ellis et al. (2006)

$$\boxed{\frac{\Delta t_{\rm obs}}{1+z} = a_{\rm LV} K + b_{\rm sf}}$$

1. They looked for spectral lags in the light curves between the selected observer-frame energy bands 25-55 and 115-320 keV.

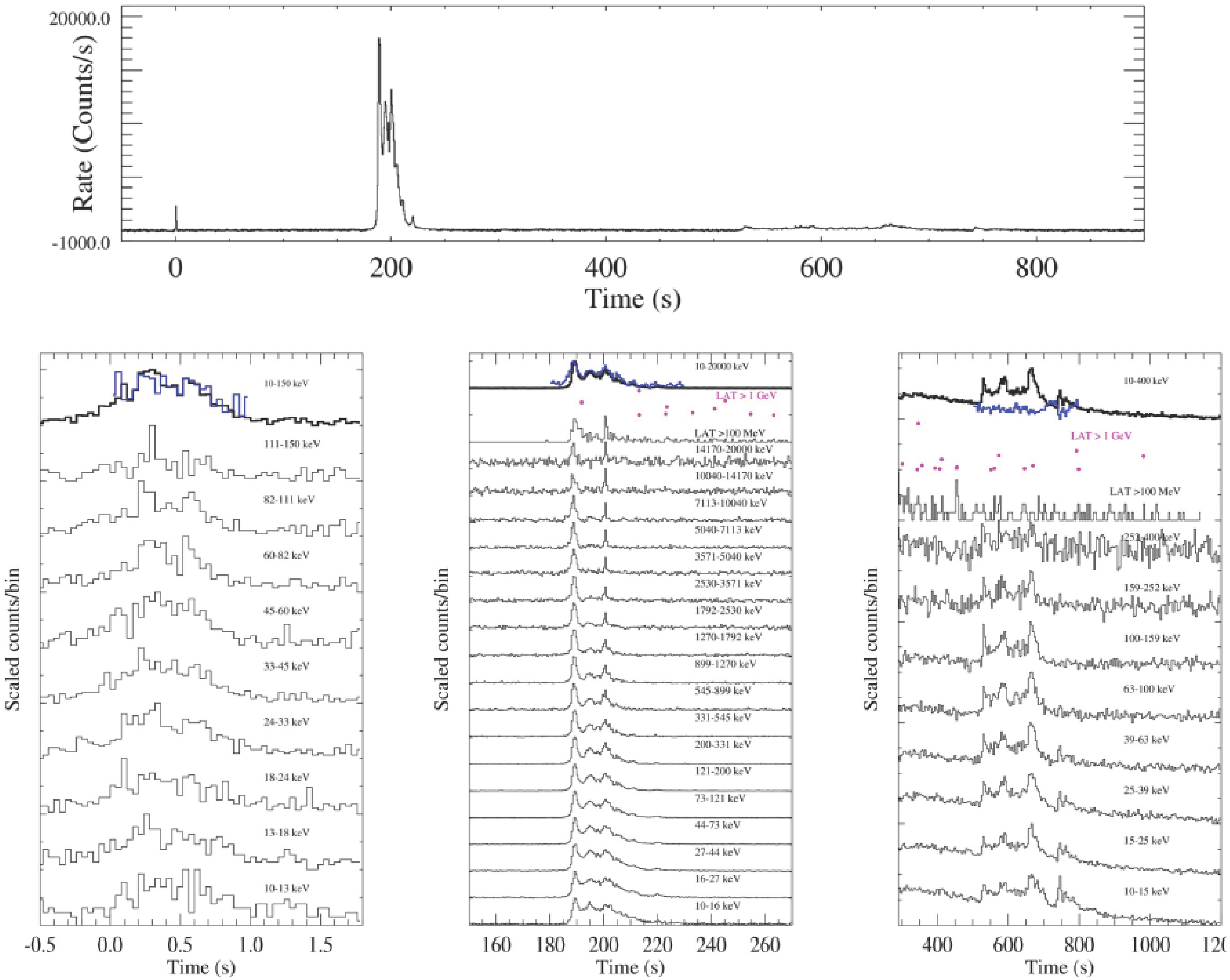
   Note that the observer-frame lag does not directly represent the source-frame lag.

2. It is not likely that different GRBs have the same intrinsic time lag.



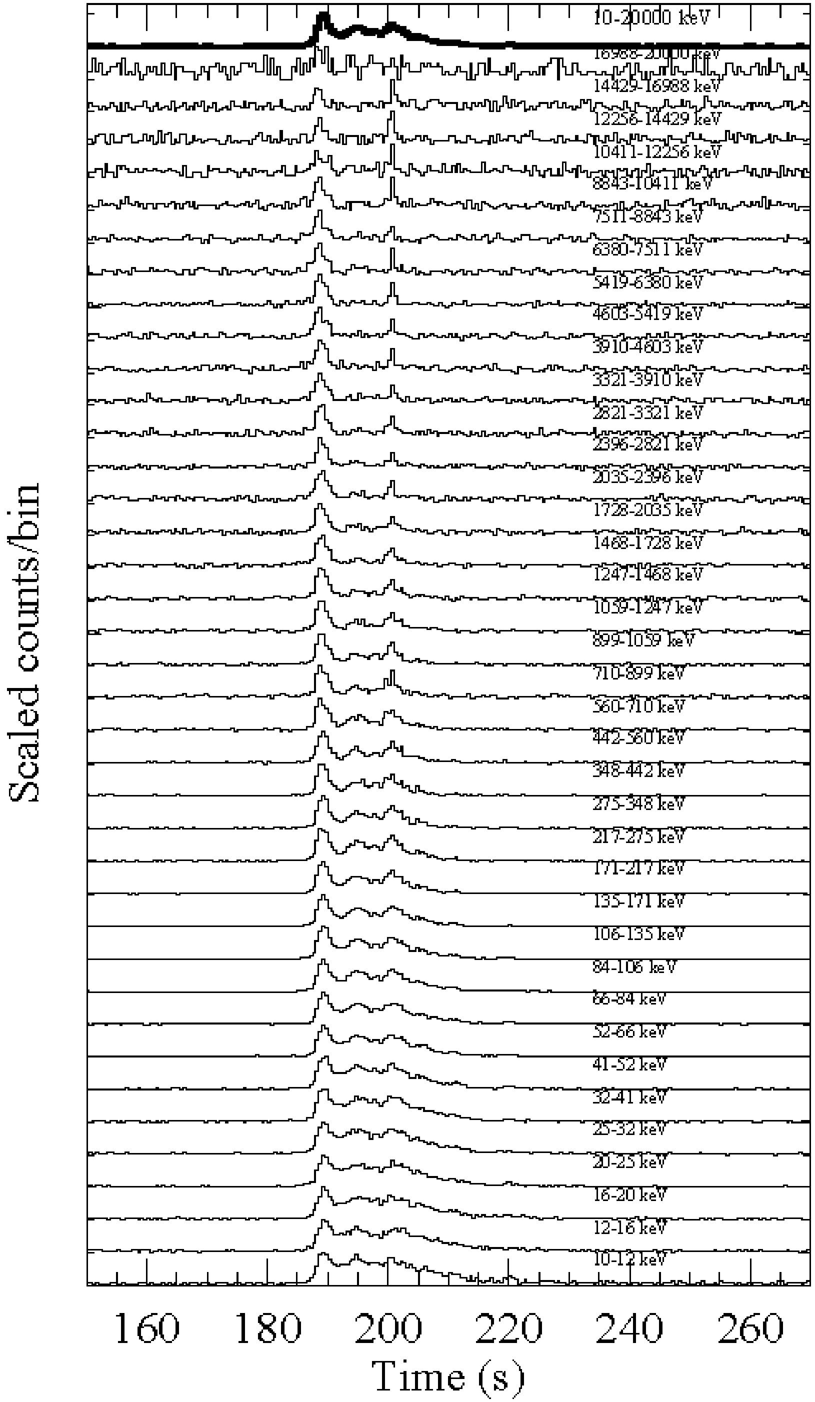
Ukwatta et al. 2012

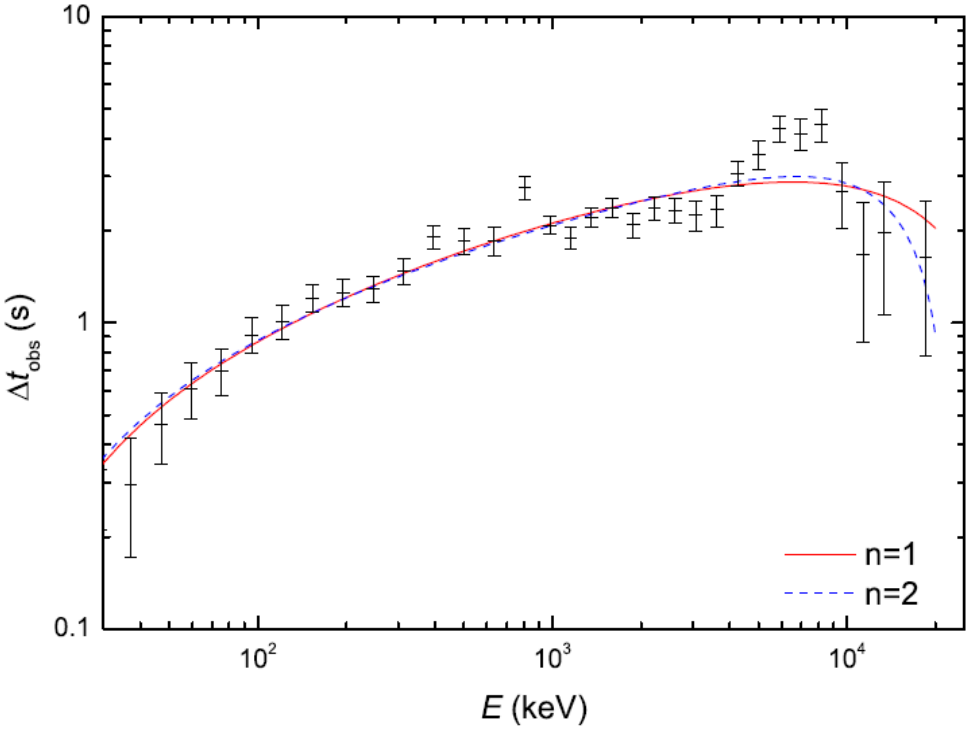
GRB 160625B As a New Probe of LIV



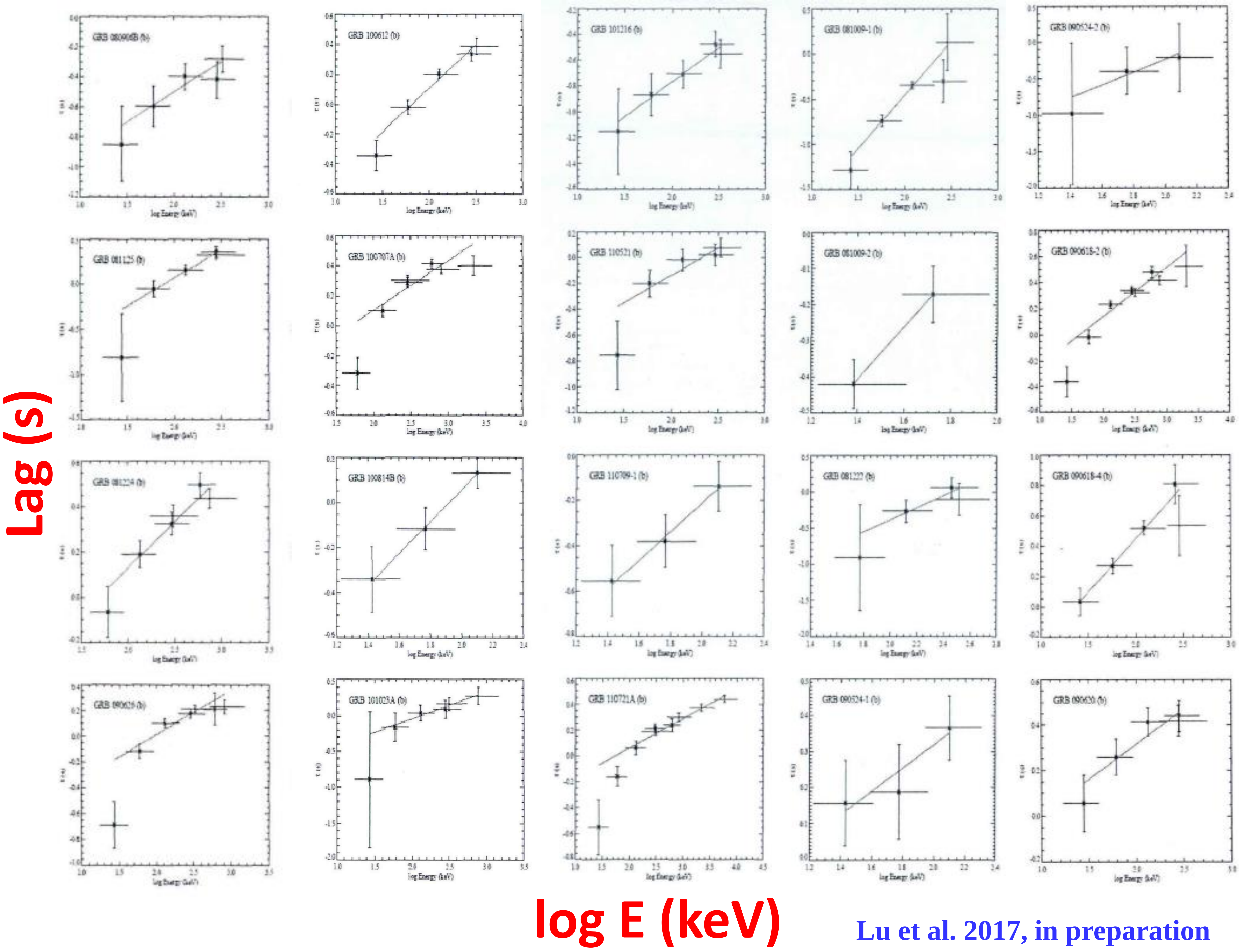
Zhang et al. 2016, arXiv:1612.03089; Wang et al. 2016, arXiv:1611.04879

GRB 160625B As a New Probe of LIV





Wei, Zhang, Shao, Wu, Meszaros 2017, ApJL, 834, L13



Lu et al. 2017, in preparation

GRB 160625B As a New Probe of LIV

- **The observed time lag:**

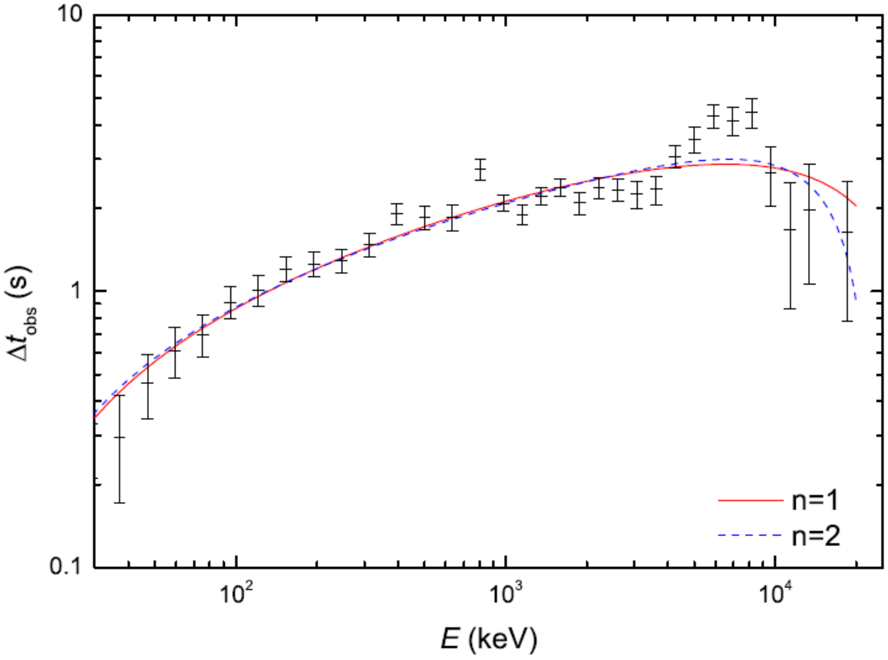
$$\Delta t_{\rm obs} = \Delta t_{\rm int} + \Delta t_{\rm LIV}$$

- **The time delay induced by LIV:**

$$\begin{aligned}\Delta t_{\rm LIV} &= t_{\rm l} - t_{\rm h} \\ &= -\frac{1+n}{2H_0}\frac{E^n - E_0^n}{E^n_{{\rm QG},n}}\int_0^z \frac{(1+z')^n dz'}{\sqrt{\Omega_{\rm m}(1+z')^3 + \Omega_\Lambda}}\end{aligned}$$

- **The intrinsic time delay:**

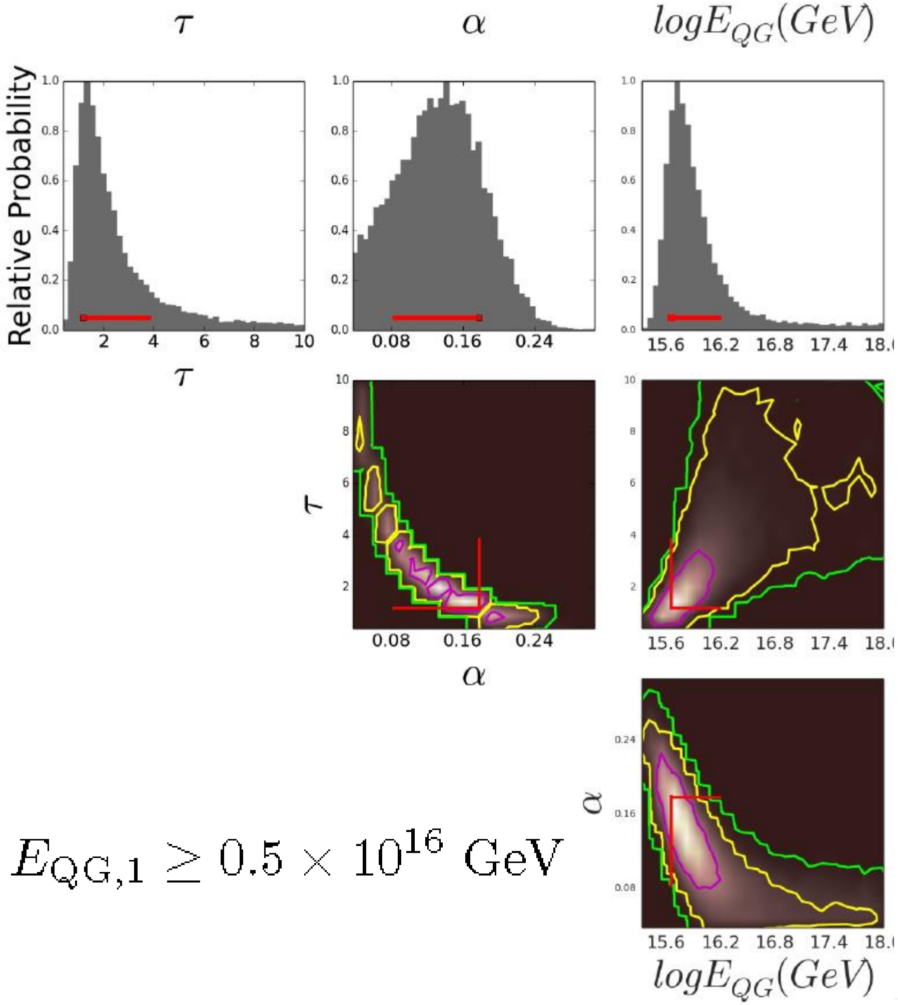
$$\Delta t_{\rm int}(E) = \tau\left[\left(\frac{E}{\rm keV}\right)^{\alpha} - \left(\frac{E_0}{\rm keV}\right)^{\alpha}\right]\ {\rm s}$$



Wei, Zhang, Shao, Wu, Meszaros 2017, ApJL, 834, L13

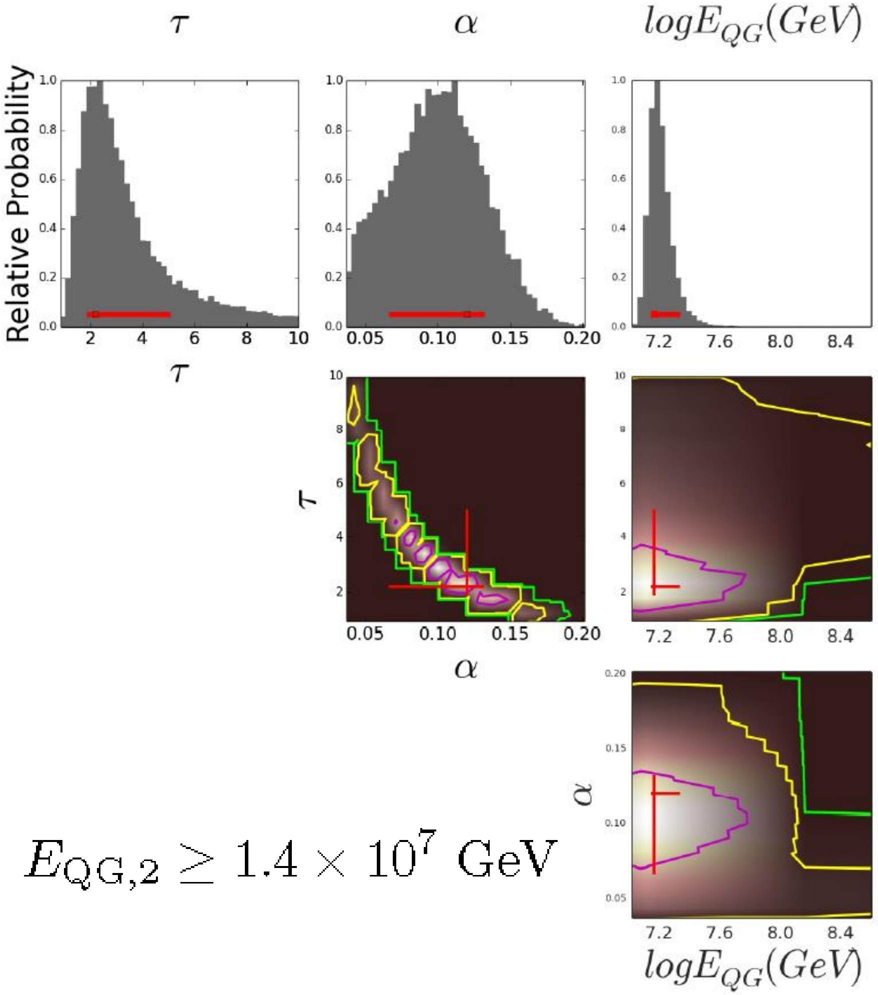
GRB 160625B As a New Probe of LIV

the linear ($n = 1$) LIV term



$$E_{\rm QG,1} \geq 0.5 \times 10^{16}\ {\rm GeV}$$

the quadratic ($n = 2$) LIV term



$$E_{\rm QG,2} \geq 1.4 \times 10^{7}\ {\rm GeV}$$

Wei, Zhang, Shao, Wu, Meszaros 2017, ApJL, 834, L13

Prospects on testing LIV with LHAASO/WCDA

- WCDA: Water Cherenkov Detector Array with detection area of 10^4 m^2 (at ~100 GeV), ~ 10^5 LAT!
- Suppose:
  - ✓ GRB spectrum $\mathrm{d}N\left(E\right)/\mathrm{d}N \propto E^{-\beta}$, β~2.3
  - ✓ ~10 photons with energies higher than 1 GeV detected by LAT
- The number of > 100 GeV photons detected by WCDA should be

$$10^5 \times 10 \times 100^{1-\beta} \sim 6 \times 10^3$$

- \> 100 GeV light curves can be produced for bright HE GRBs.
- LHAASO/WCDA could set much more (1-2 orders of magnitude) competitive limits on LIV.

Summary

- **GRB 160625B, the only burst so far with a well-defined transition from *positive* lags to *negative* lags provides a unique opportunity to put new constraints on LIV.**
- **We consider the contributions to $\Delta t_{\rm obs}$ from both $\Delta t_{\rm int}$ and $\Delta t_{\rm LIV}$, and assuming $\Delta t_{\rm int}$ has a positive dependence on the photon energy, we obtain robust limits on LIV by directly fitting the spectral lag data of GRB 160625B.**
- **In addition, we give for the first time a reasonable formulation of the intrinsic energy-dependent time lag.**
- **Future observations of GRBs with LHAASO/WCDA could improve the limits on LIV.**

Thanks for your attention!