A New Test of Lorentz Invariance Violation: The Spectral Lag Transition of GRB 160625B

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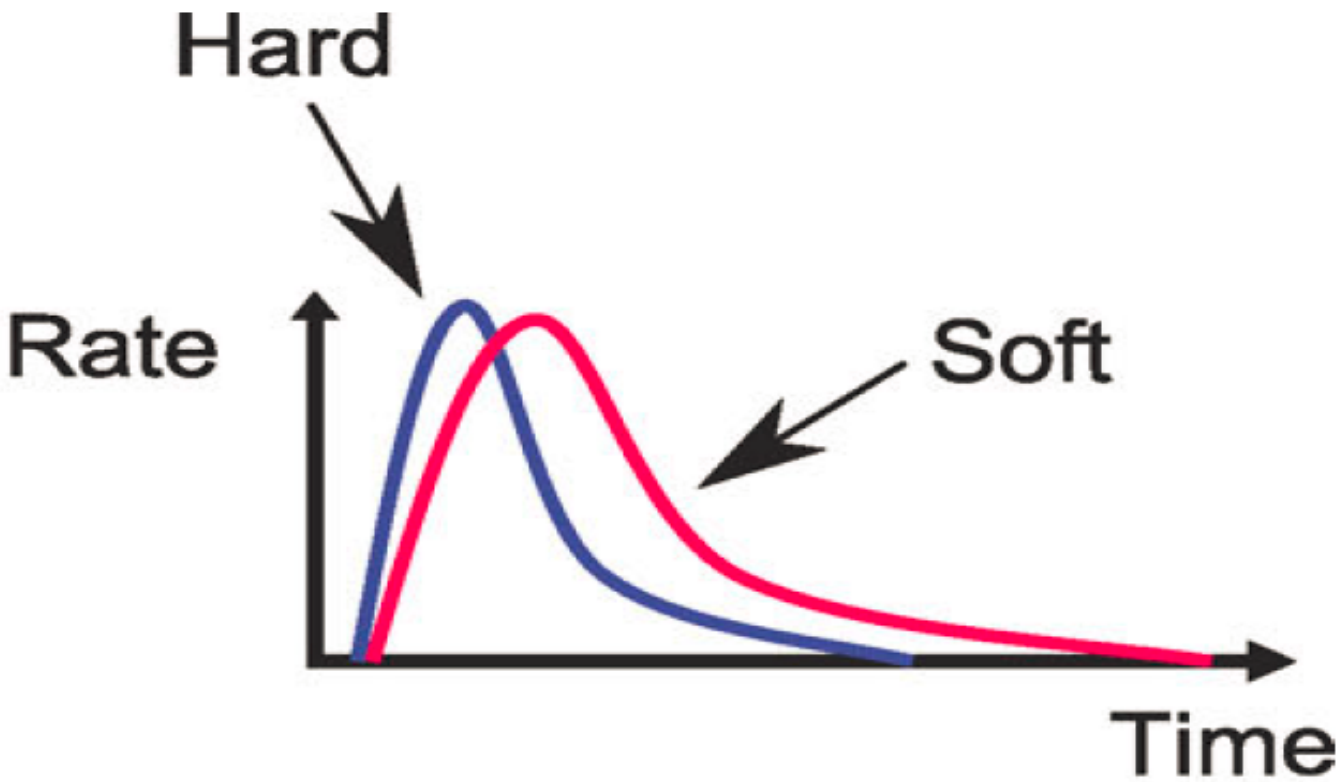
The spectral lags of GRBs

Spectral lag is defined as the arrival time delay between light curves in different energy bands (or between correlated photons with different energies).

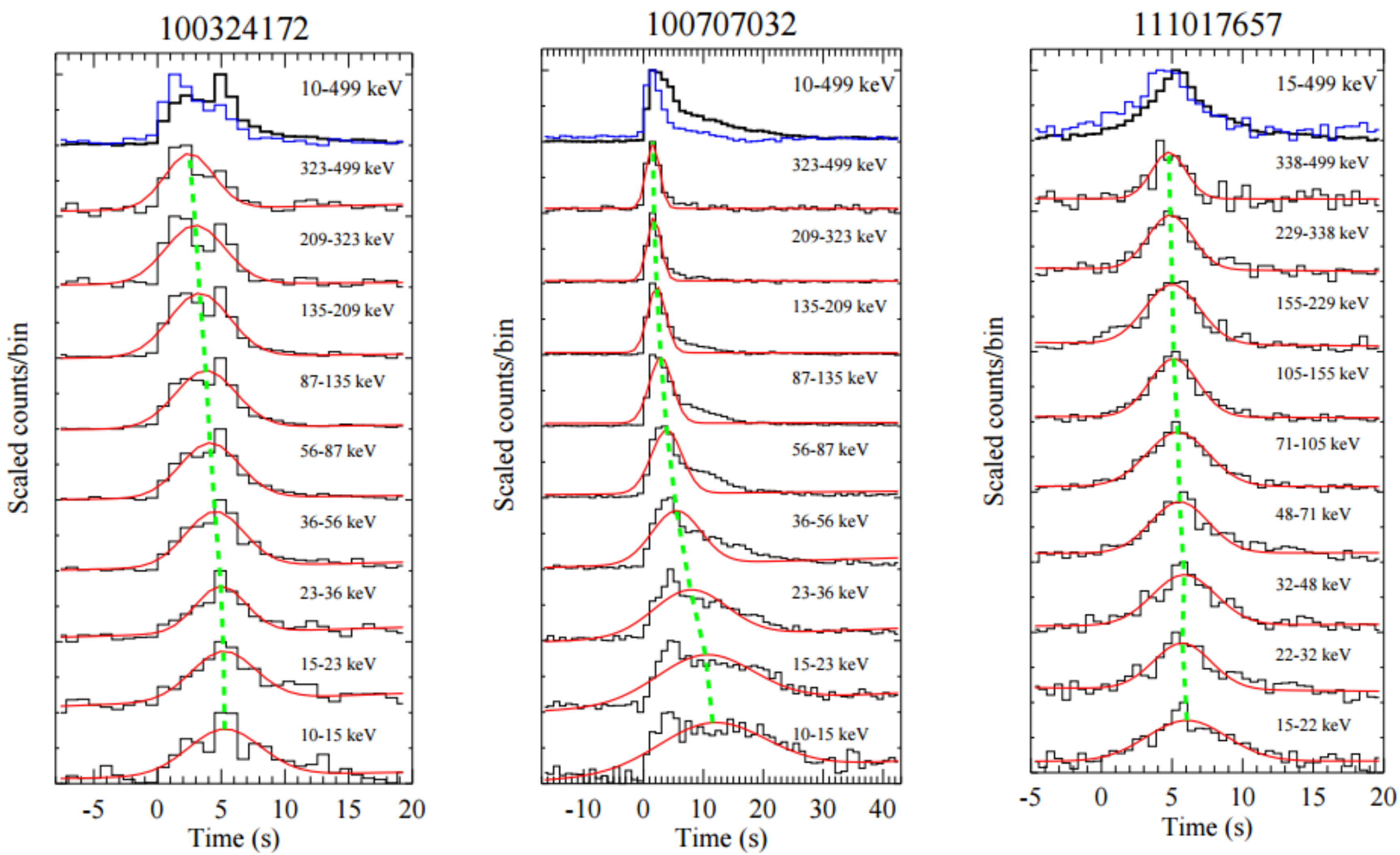


Cheng, L. X., Ma, Y. Q., Cheng, K. S., Lu, T., & Zhou, Y. Y., 1995, A&A;
Norris et al. 1996; Band 1997; Shen et al. 2005; Lu et al. 2006; Ukwatta et al. 2010

The *positive* lags of low energy emission

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, ApJ, 844, 126

Some models for *positive* lags

(1) Hard-to soft evolution of the spectrum

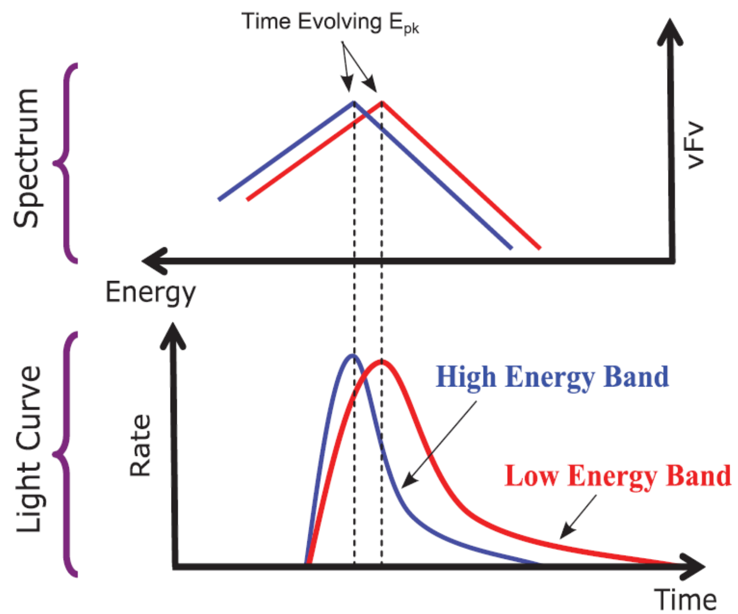


Figure 5. The time evolution of the $E_{\rm pk}$ across energy bands may cause the observed spectral lags in GRBs.

(2) The curvature effect

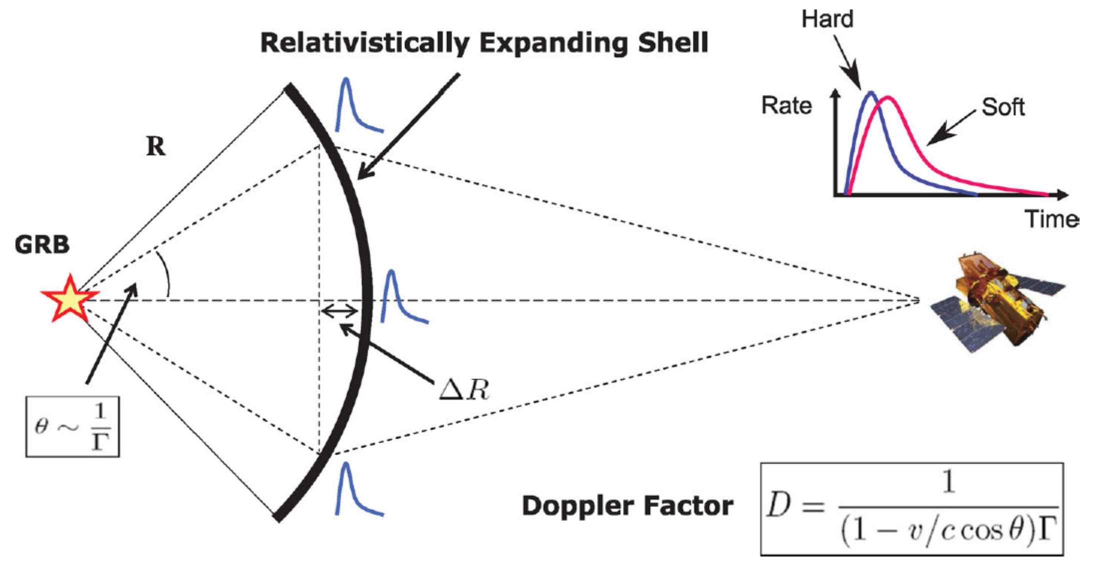


Figure 6. Spectral lags could arise due to the curvature effect of the shocked shell. At the source, the relativistically expanding shell emits identical pulses from all latitudes. However, when the photons reach the detector, on-axis photons get boosted to higher energy (hard). Meanwhile, off-axis photons get relatively smaller boost and travel longer to reach the detector. Thus, these photons are softer and arrive later than the on-axis photons.

However, the calculated cooling times based on simple synchrotron models are relatively small compared to the observed lags.

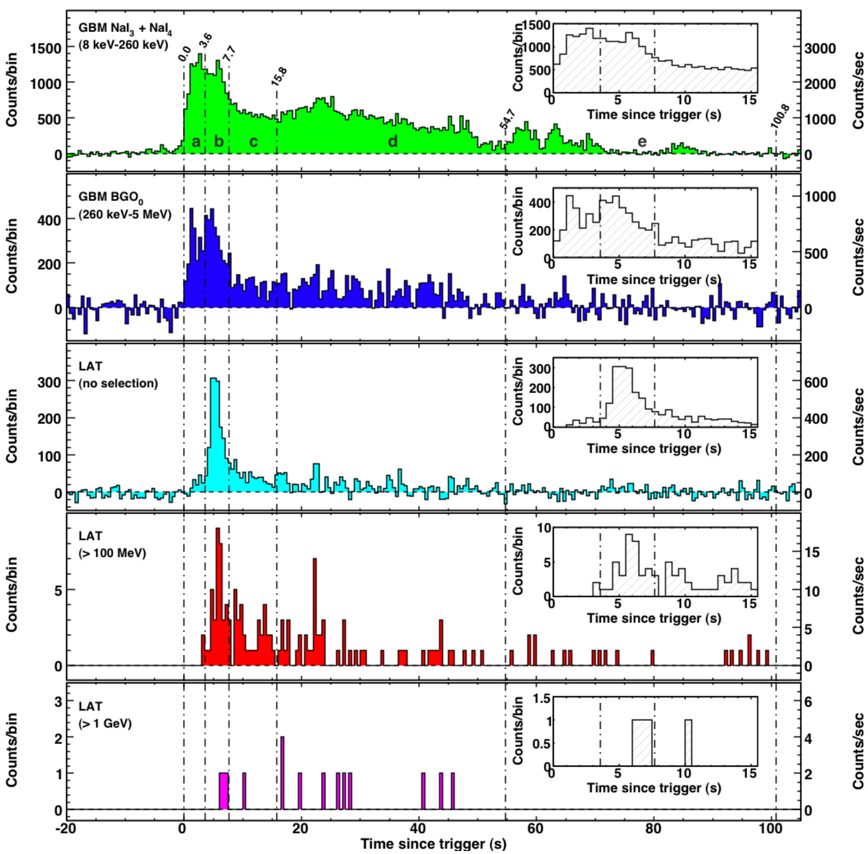
However, some of the observed lags are negative, and therefore these lags present a real challenge for the simple curvature models.

Ukwatta et al. 2012

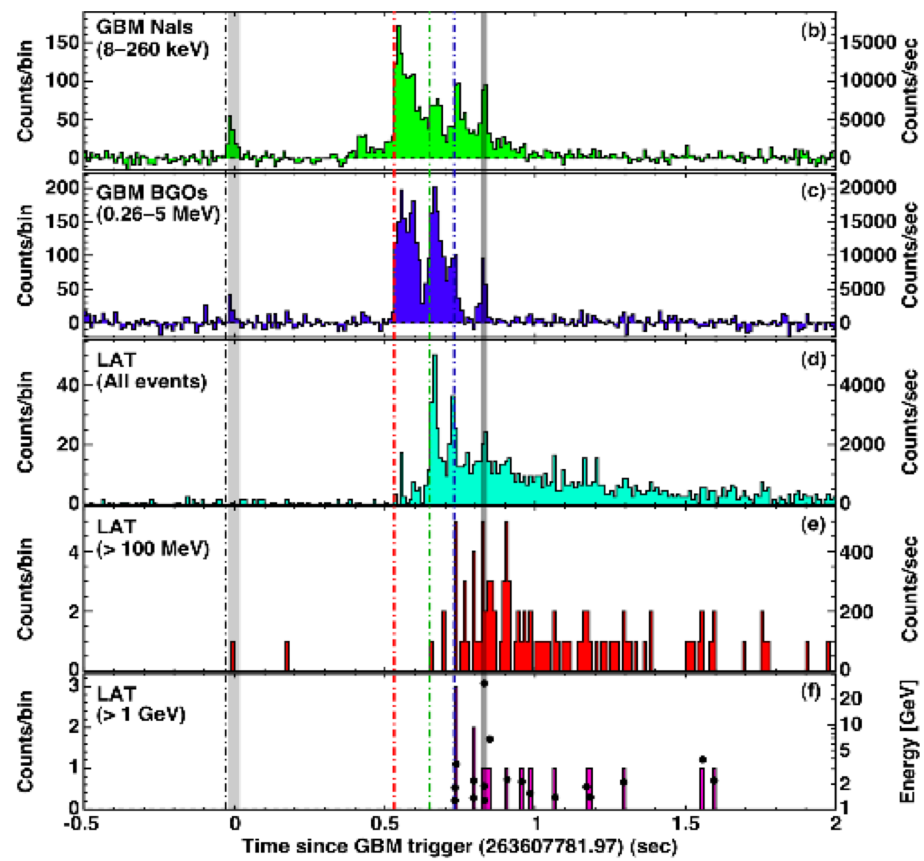
The *negative* lags of GeV photons

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



On the other hand, one possible explanation for the *negative* lags is provided by quantum gravity effects.

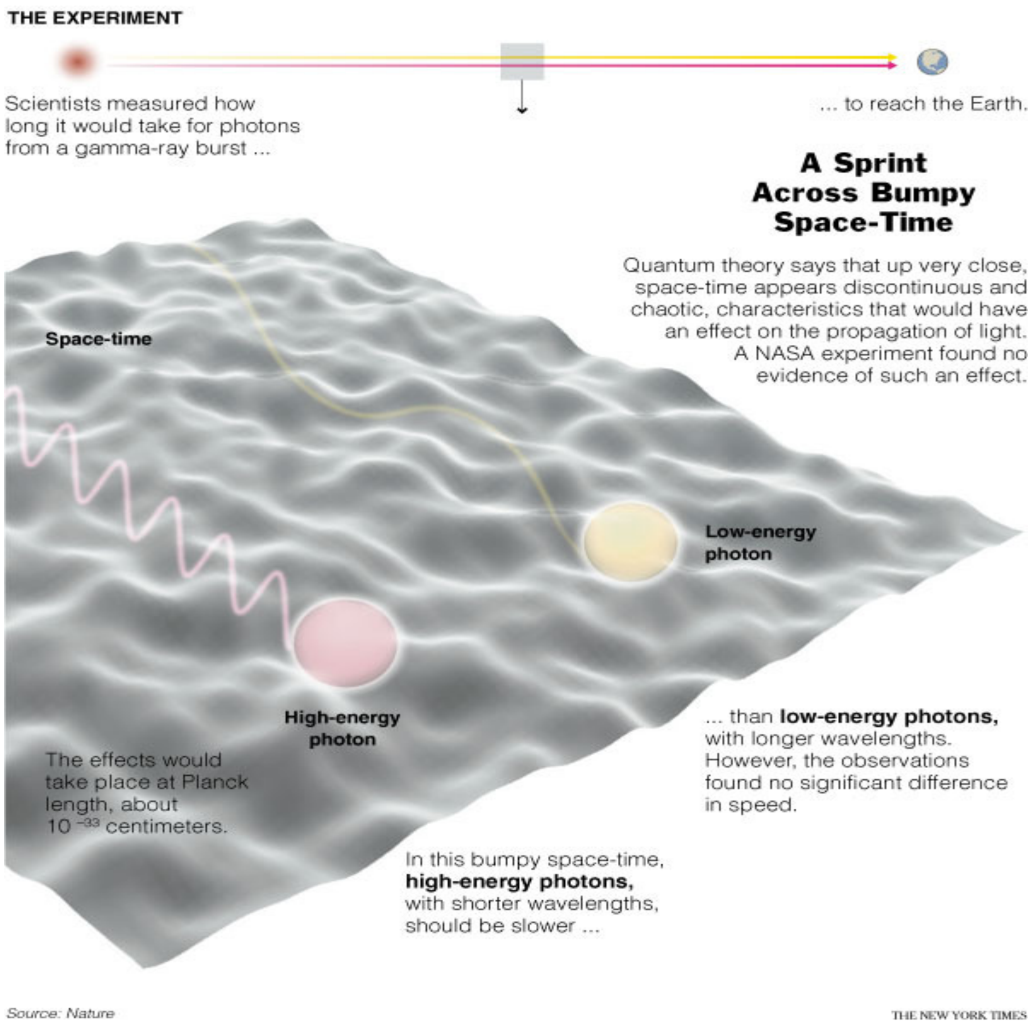
Thanks to their short spectral lags, cosmological distances, and very high energetic photons, GRBs have been viewed as the most promising sources for studying the LIV effects.

(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……).

Lorentz invariance is a fundamental symmetry of Einstein's relativity.

However, many Quantum Gravity models :
(e.g., Amelino-Camelia et al. 1998, Nature)

➡ **Predict the existence of deviations from Lorentz symmetry at the Planck energy scale** $E_{\rm Pl} = \sqrt{\hbar c^5/G} \simeq 1.22 \times 10^{19}$ GeV



The foamy structure of space-time at small spatial scales

(e.g., Kostelecky & Samuel 1989; Amelino-Camelia et al. 1997; Ellis et al. 1999; Gambini & Pullin 1999; Amelino-Camelia 2002; Myers & Pospelov 2003......)

Vacuum dispersion from Lorentz invariance violation

As a consequence of LIV, the speed of light in a vacuum would have an energy dependence,

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

n=1	linear LIV
n=2	quadratic LIV

The time delay induced by LIV:

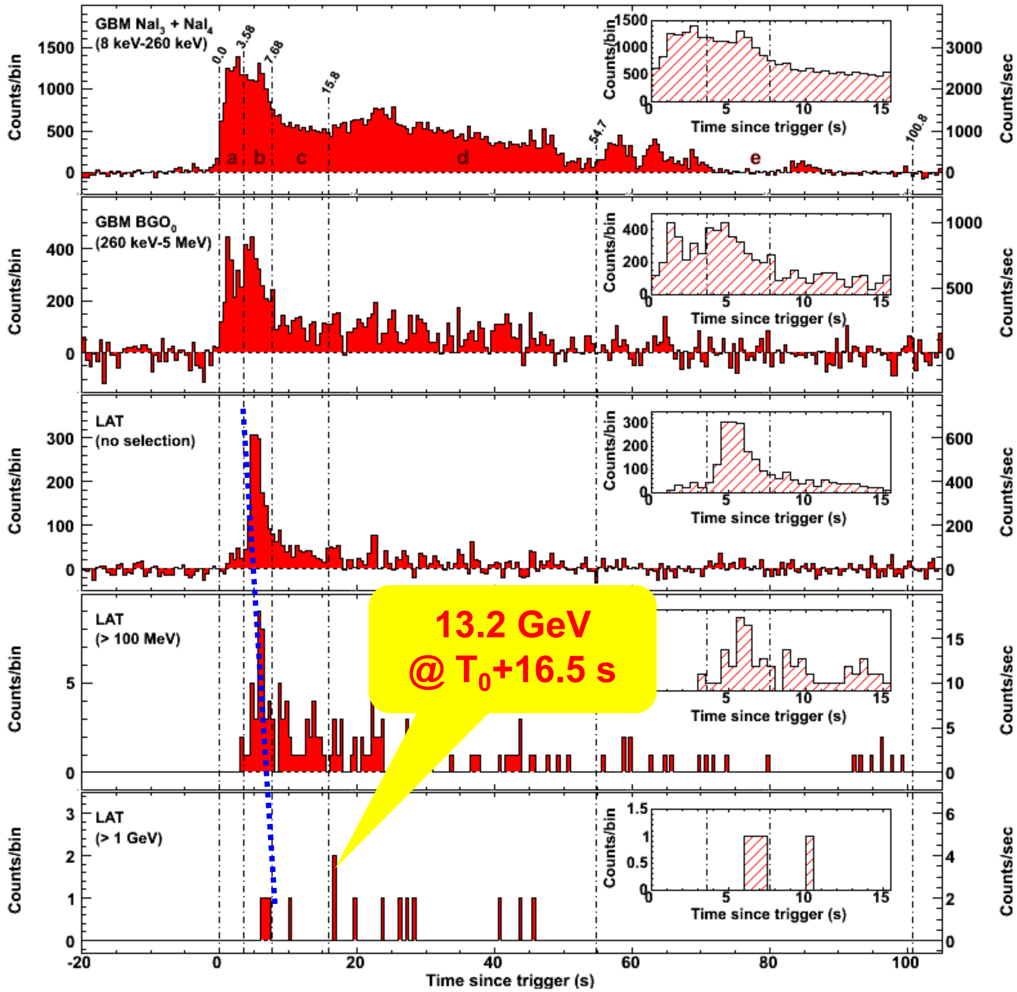
$$\boxed{\Delta t = \frac{1+n}{2H_0}\frac{E^n}{E^n_{\mathrm{QG}}}\int_0^z \frac{(1+z')^n}{\sqrt{\Omega_\Lambda + \Omega_M(1+z')^3}}dz'}$$

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

higher frequency,
longer distance,
shorter arrival time

bigger E_QG
more stringent constraint

Testing LIV with a single GeV photon



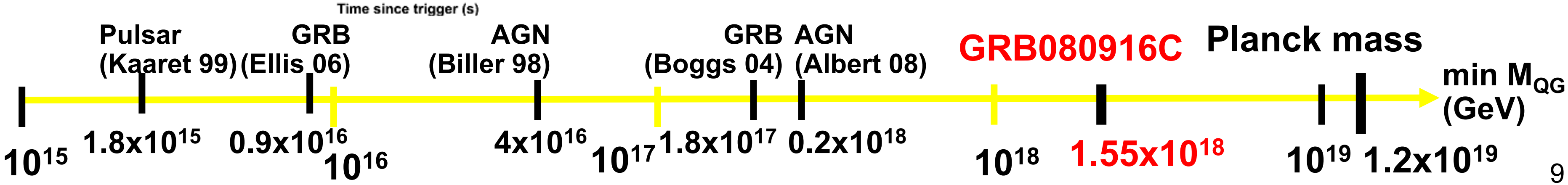
Long GRB 080916C

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

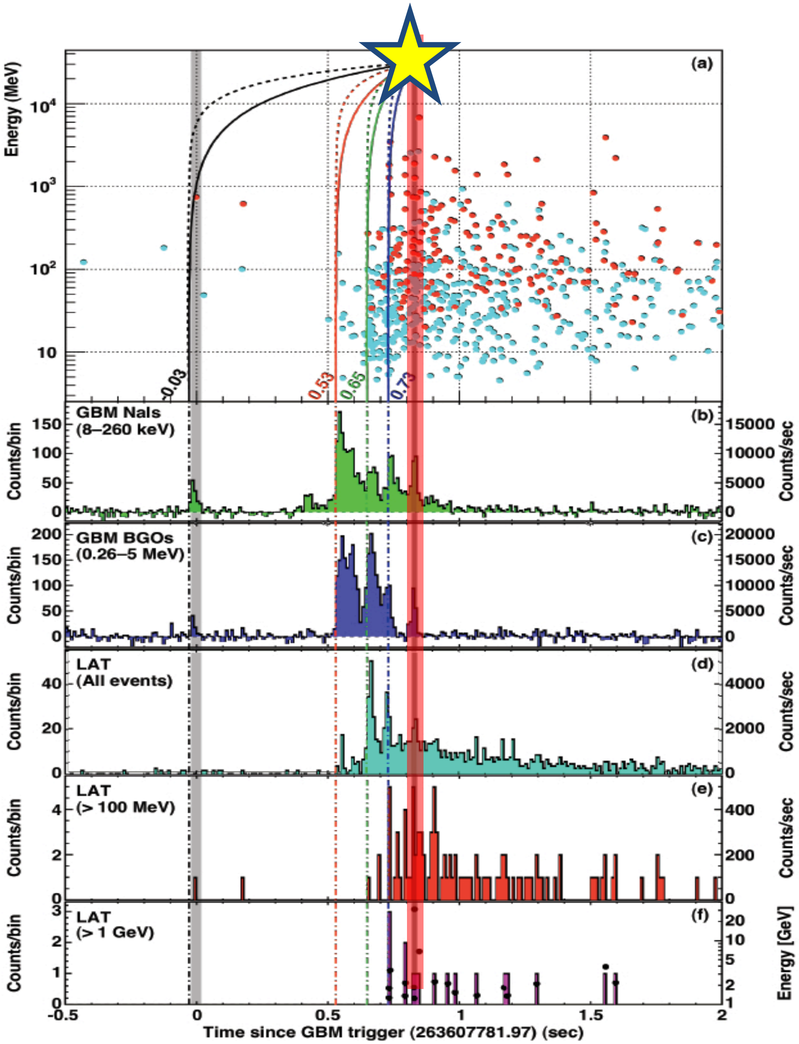
- A single 13.2 GeV photon was detected at 16.5 s after the GBM trigger time.
- The conservative constraint on the linear LIV energy scale:

$$M_{QG} > 1.3 \times 10^{18}\ \mathrm{GeV/c^2}$$

improving the previous limits by one order of magnitude.



Testing LIV with a single GeV photon



Short GRB 090510

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

◆The most conservative limit:

Assuming the highest energy (31 GeV)
Photon is emitted at the GBM trigger time

$\Delta t < 859$ ms,

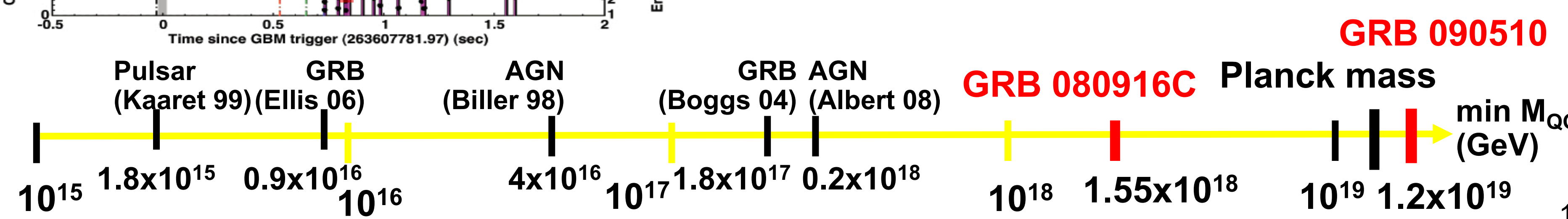
$M_{QG,1}/M_{plank} > 1.19$

◆The most radical limit:

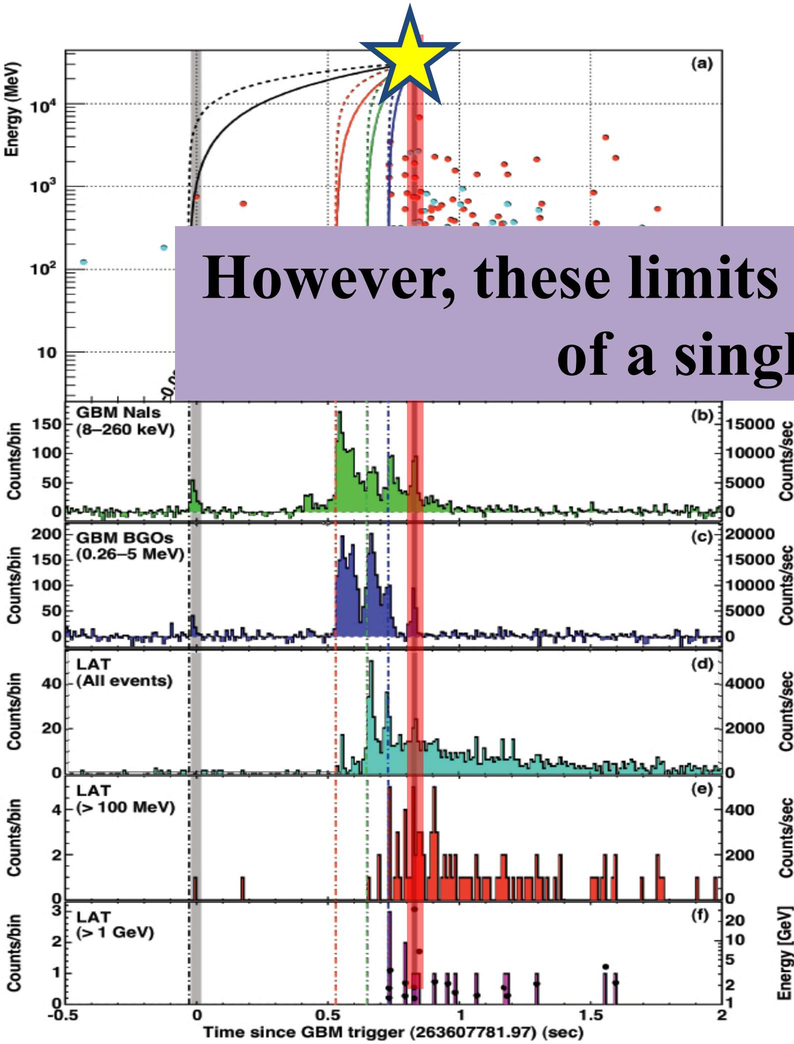
Assuming the 31 GeV photon is emitted at the same time of <100 MeV pulse emission

$\Delta t < 10$ms,

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



Testing LIV with a single GeV photon



Short GRB 090510

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

However, these limits were based on the rough time lag of a single GeV-scale photon.

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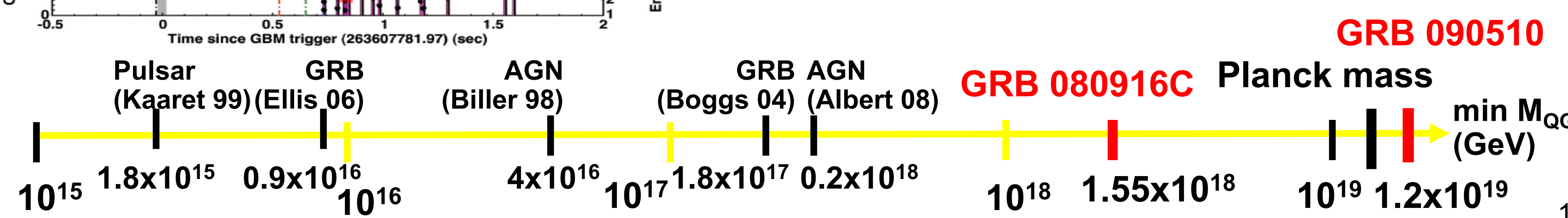
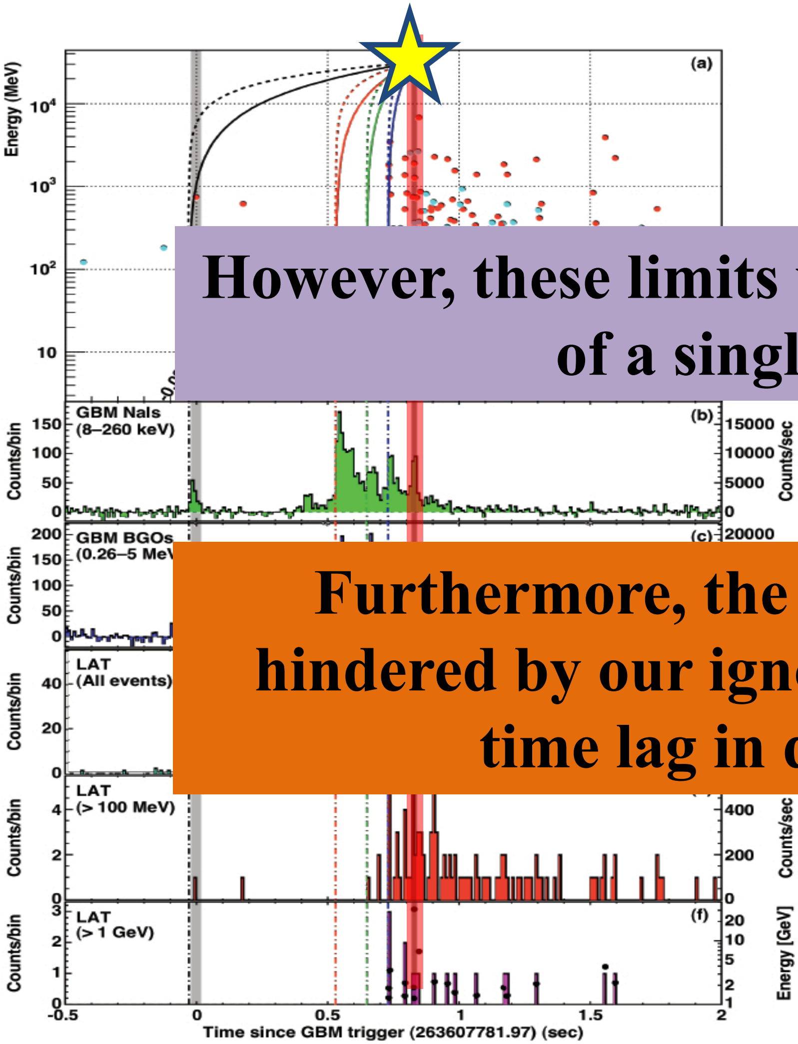


Testing LIV with a single GeV photon



Short GRB 090510

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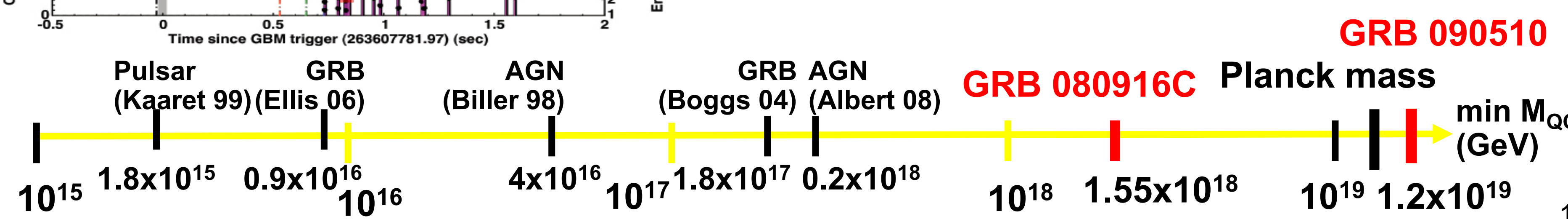
However, these limits were based on the rough time lag of a single GeV-scale photon.

Furthermore, the search for LIV lags has been hindered by our ignorance concerning the intrinsic time lag in different energy bands.



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:**

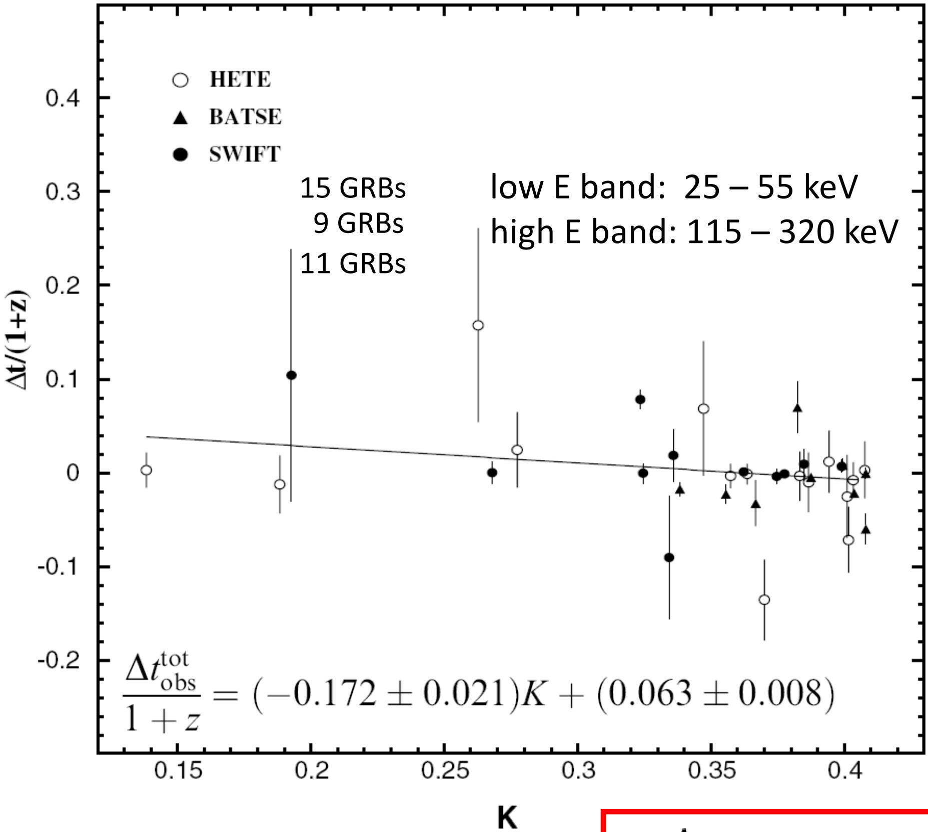
$$\Delta t_{\rm LV} = H_0^{-1}\frac{\Delta E}{M}\int_0^z \frac{{\rm d}z}{h(z)}$$

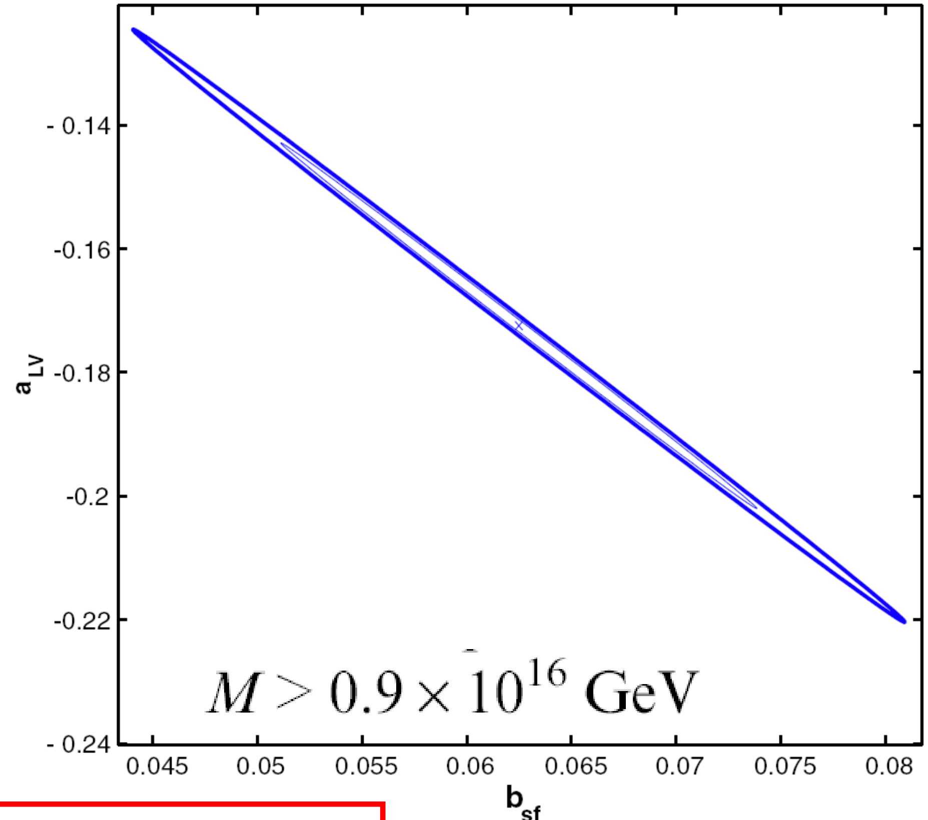
- **The intrinsic time delay:** $b_{\rm sf}$

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

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





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

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

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

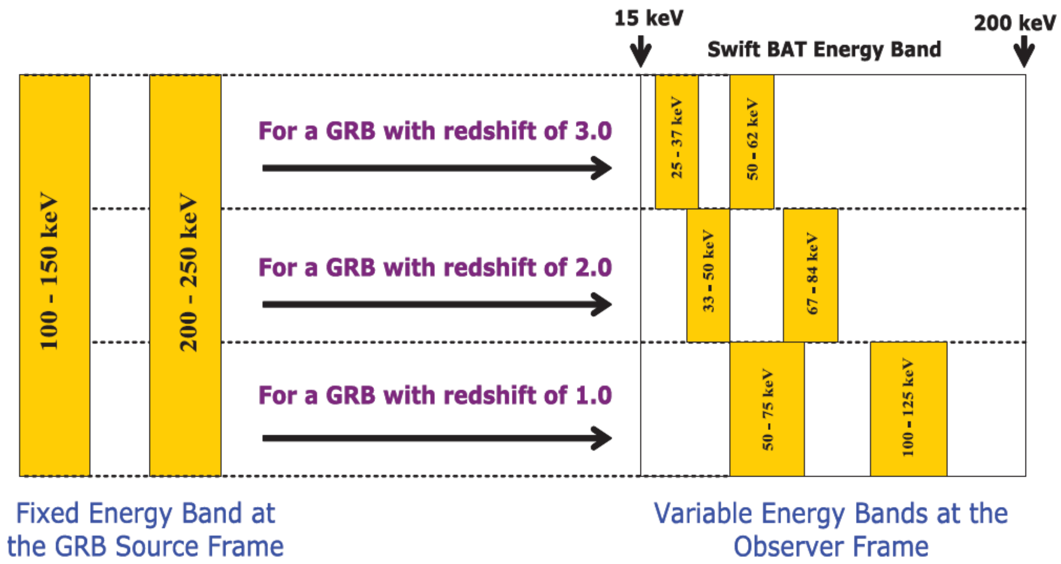
Disadvantages for the treatment of Ellis et al. (2006)

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

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

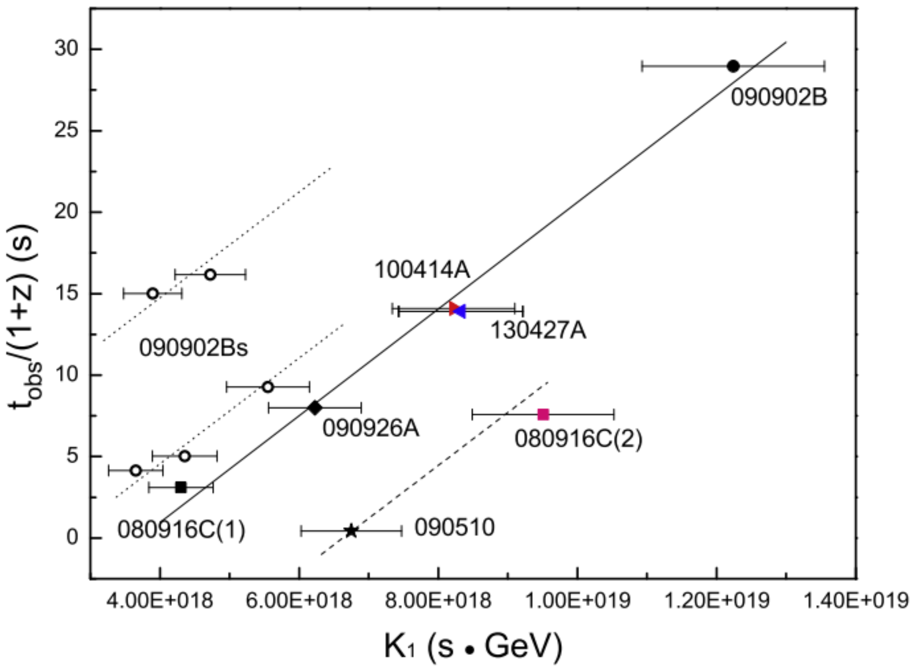
   Note that the observer-frame lag does not directly represent the source-frame lag.

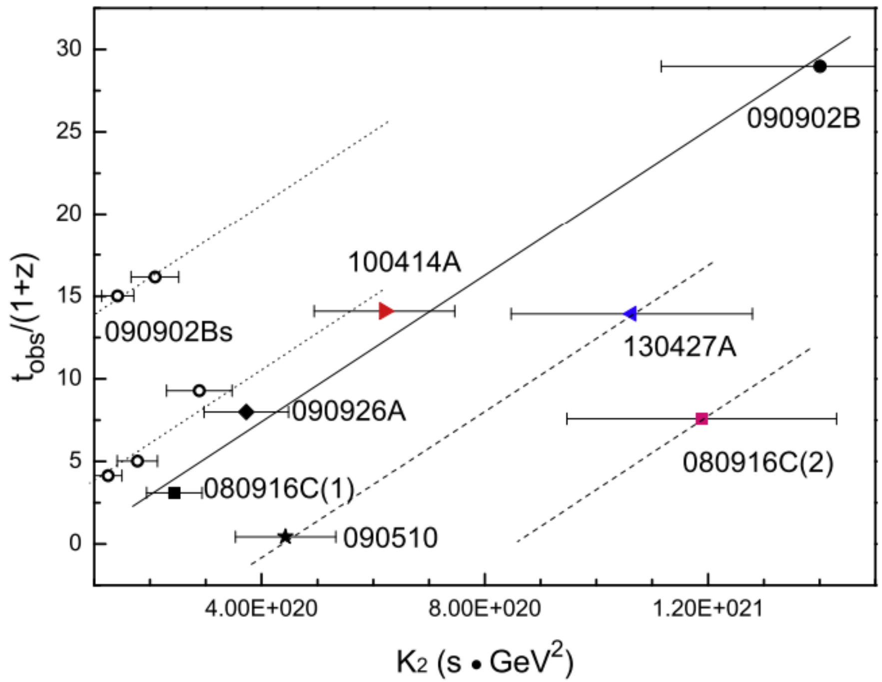
2. It is not likely that different GRBs have the same intrinsic time lag.



Ukwatta et al. 2012

The intrinsic time delay problem





$$t_{\rm obs} = t_{\rm LV} + (1+z)t_{\rm in} \qquad \frac{t_{\rm obs}}{1+z} = \frac{K_{\rm n}}{E^n_{\rm LV,n}} + t_{\rm in}$$

$$K_{\rm n} = \frac{1+n}{2H_0}\frac{E^n}{1+z}\int_0^z \frac{(1+z')^n dz'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}$$

Zhang & Ma 2015, Astroparticle Physics, 61, 108;
Xu & Ma 2016, Astroparticle Physics, 82, 72

The intrinsic time delay problem

Estimating the intrinsic time lag of GRBs with the magnetic jet model:

$$\Delta t = \frac{3r_0(1+z)}{2c}\left[\left(\frac{r_{\gamma\gamma}(E_0)}{r_0}\right)^{1/3} - \left(\frac{r_p}{r_0}\right)^{1/3}\right]$$

$$\Delta t_{\rm int} = \Delta t(E_{\rm high}) - \Delta t(E_{\rm low})$$

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

Table 2

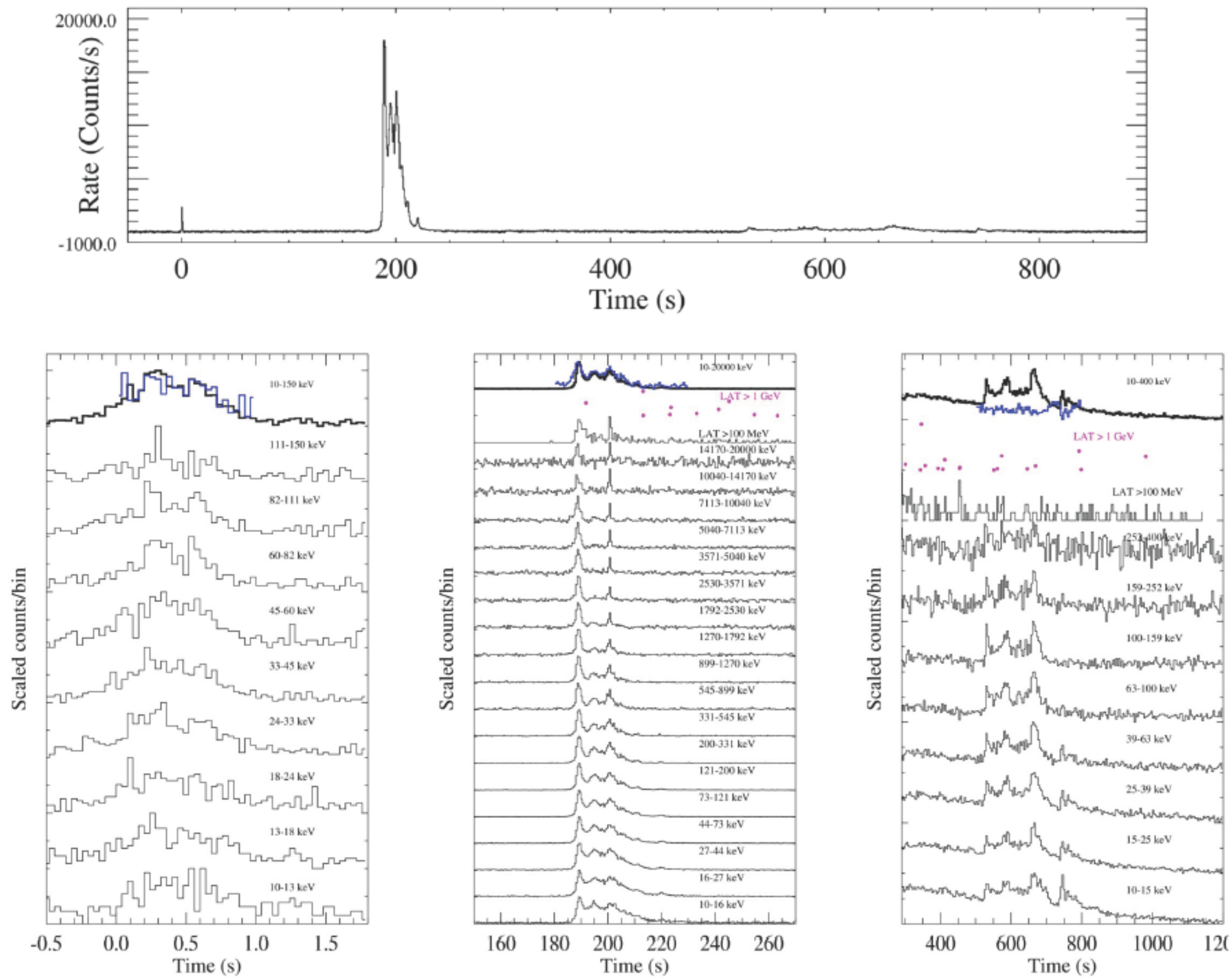
The LIV induced time delay $\Delta t_{\rm LIV}$ and quantum gravity energy scale M_1c^2 derived from four *Fermi*-detected GRBs. $\Delta t_{\rm obs}$ is collected from Refs. [2–5]. $\Delta t_{\rm LIV} = \Delta t_{\rm obs} - \Delta t_{\rm int}$, where $\Delta t_{\rm int}$ is calculated by Eqs. 4, 6 and 7. The value of $\sigma_{0,3}$ in each GRB is approximately the bulk Lorentz factor of the jet in unit of 10^3 and is taken as $\sigma_{0,3} \sim 1$ [22]. $r_{0,7}$ is chosen as 16.7, 0.1, 28.7 and 55.0 for GRB 080916c, GRB 090510, GRB 090902b and GRB 090926, respectively.

GRB	$E_{\rm low}$ (MeV)	$E_{\rm high}$ (GeV)	$\Delta t_{\rm obs}$ (s)	$\Delta t_{\rm LIV}$ (s)	$K(z)$ s · GeV	M_1c^2 (GeV)
080916c	100	13.22	12.94	0.24	4.50×10^{18}	10.02×10^{19}
090510	100	31	0.20	0.14	7.02×10^{18}	9.73×10^{19}
090902b	100	11.16	9.5	0.10	3.38×10^{18}	9.94×10^{19}
090926	100	19.6	21.5	0.20	6.20×10^{18}	9.59×10^{19}

However, the magnetic jet model relies on some particular theoretical parameters, and this leads to uncertainties on the LIV results.

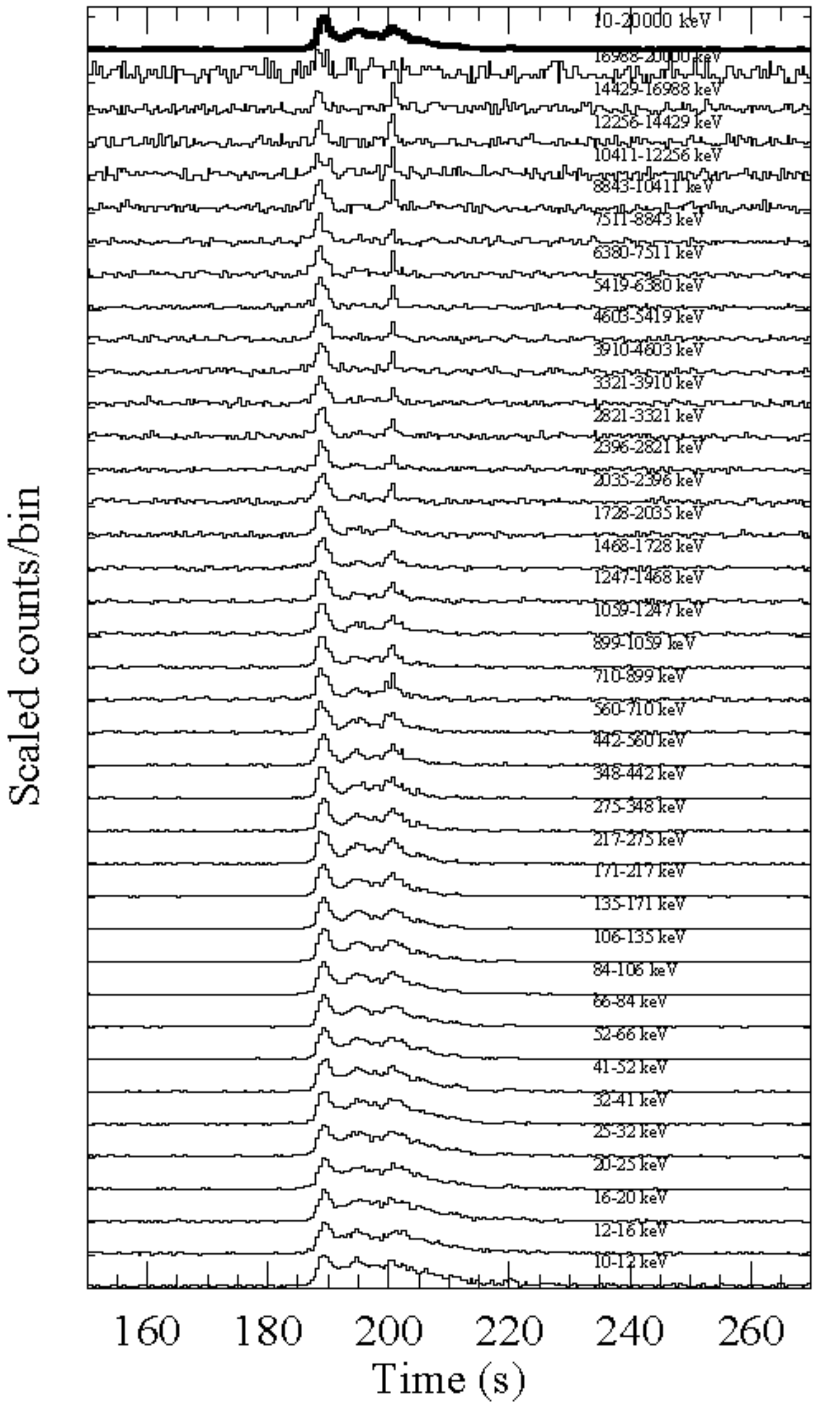
Chang, Jiang, & Lin 2012, Astroparticle Physics, 36, 47

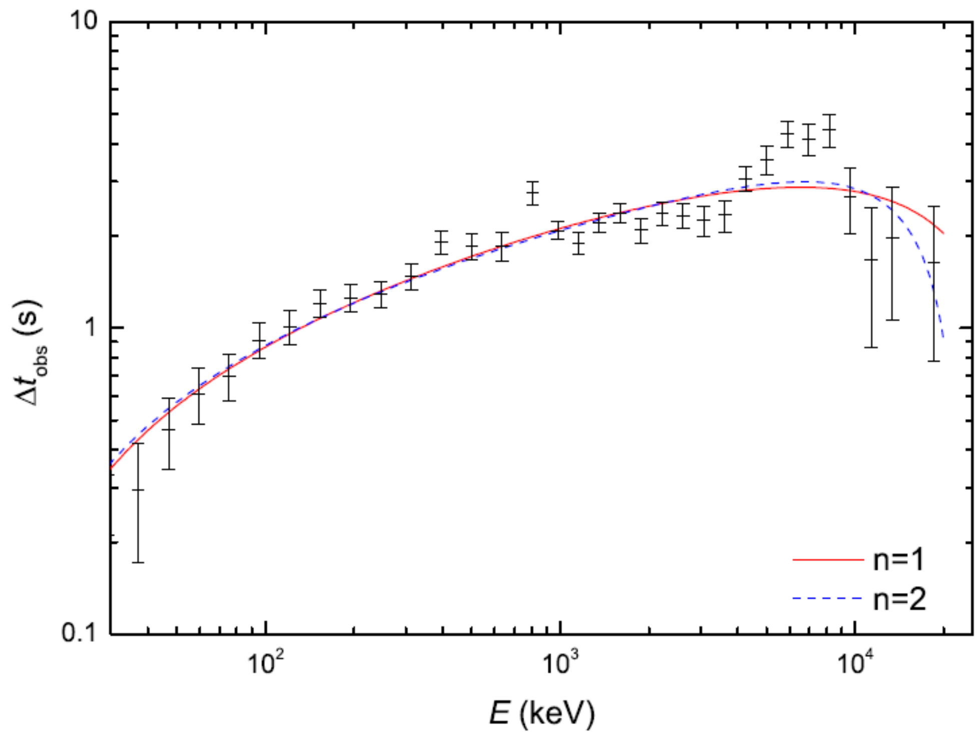
GRB 160625B As a New Probe of LIV



Zhang et al. 2018, Nature Astronomy, 2, 69

GRB 160625B As a New Probe of LIV





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

GRB 160625B As a New Probe of LIV

- **The observed time lag:**

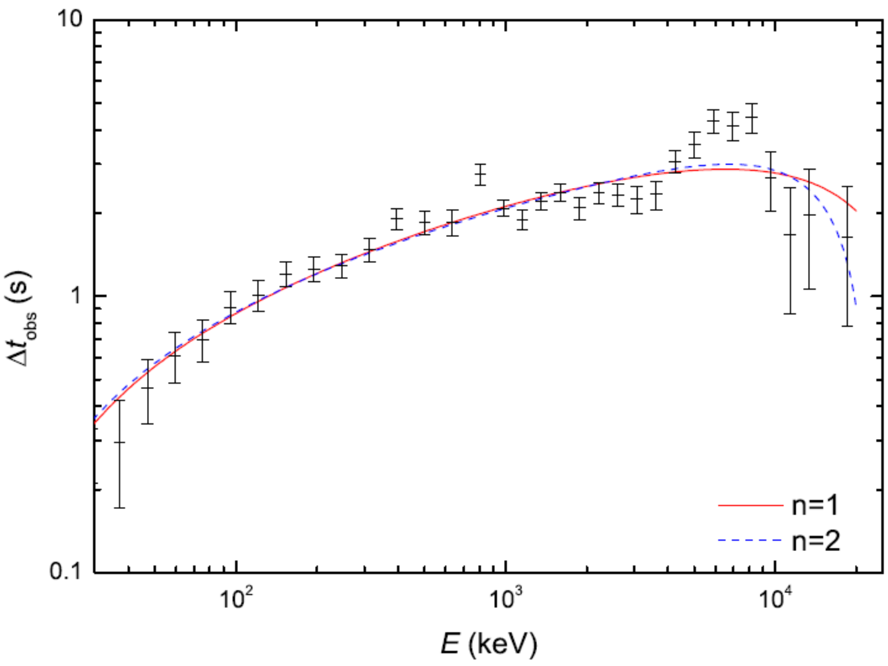
$$\Delta t_{\rm obs} = \Delta t_{\rm int} + \Delta t_{\rm LIV}$$

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

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

- **The intrinsic time delay:**

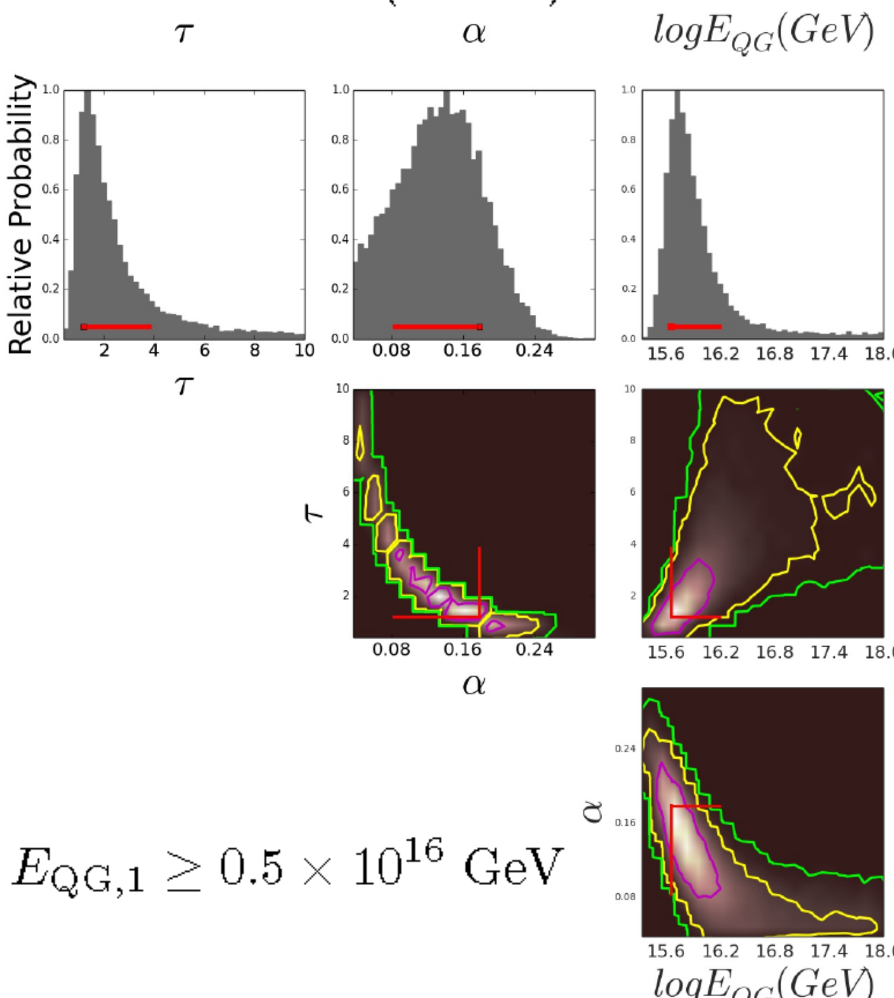
$$\Delta t_{\rm int}(E) = \tau\left[\left(\frac{E}{\rm keV}\right)^\alpha - \left(\frac{E_0}{\rm keV}\right)^\alpha\right]\ {\rm s}$$



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

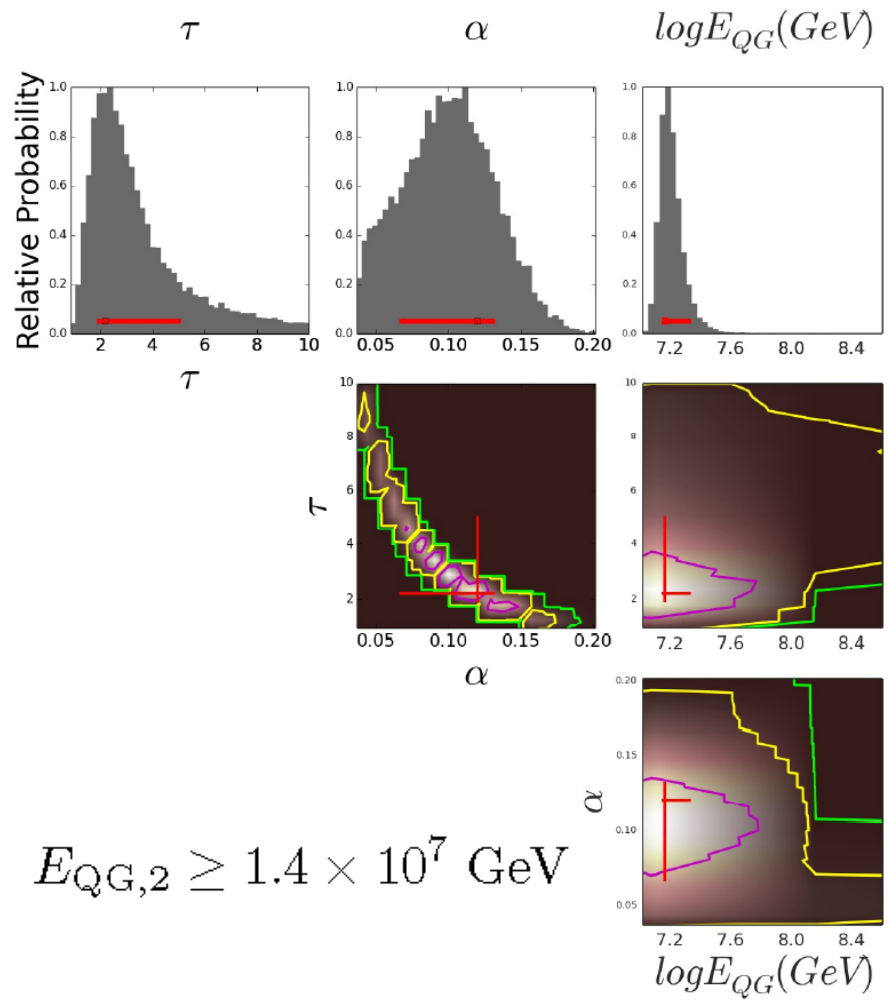
GRB 160625B As a New Probe of LIV

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 $\sim 10^5 m^2$ (at ~100 GeV), ~ 10^5 LAT!
- Suppose:
  - ✓ GRB spectrum $\mathrm{d}N(E)/\mathrm{d}N \propto E^{-\beta}$, 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!