Constraining Lorentz Invariance Violation with *Fermi*

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Lorentz-Invariance Violation

- There is a fundamental scale (Planck scale $\lambda_{Pl} \approx 10^{-35}$ m) at which quantum gravity (QG) effects are expected to strongly affect the nature of space-time.
- Lorentz symmetry implies a scale-free space-time
- QG effects might cause violations of Lorentz Invariance (LIV) $\rightarrow$ $u_\gamma(E_\gamma) \neq c$:
- LIV terms are typically described using a Taylor series:

$$c^2 p_\gamma^2 = E_\gamma^2 \left[1 + \sum_{k=1}^{\infty} s_k \left(\frac{E_\gamma}{M_{QG,k} c^2} \right)^k \right]$$

Model-dependent factor ={0,±1}

QG Mass – energy scale that QG effects are expected to be significant

$$\mathrm{M}_{QG} \lesssim M_{Planck} \equiv \sqrt{\hbar c/G} \simeq 1.22 \times 10^{19} GeV/c^2$$

Lorentz-Invariance Violation

- $E_\gamma \ll M_{QG}c^2 \rightarrow$ the sum is dominated by the lowest-order term (n) with $s_k \neq 0$.
- The now energy-dependent speed of light is:

Usually n=1 or 2 (linear and quadratic LIV respectively).

$$\upsilon_\gamma = \frac{\partial E_\gamma}{\partial p_\gamma} \simeq c\left[1 - s_n \frac{1+n}{2}\left(\frac{E_\gamma}{M_{QG,n}c^2}\right)^n\right]$$

LIV perturbation term we would like to constrain.

s_n=+1 or -1 for speed retardation or acceleration with an increasing photon energy.

- There are many models that *allow* such Lorentz-Invariance violations, and some others that *actually predict* them (e.g. stringy-foam model J. Ellis et al. 2008).

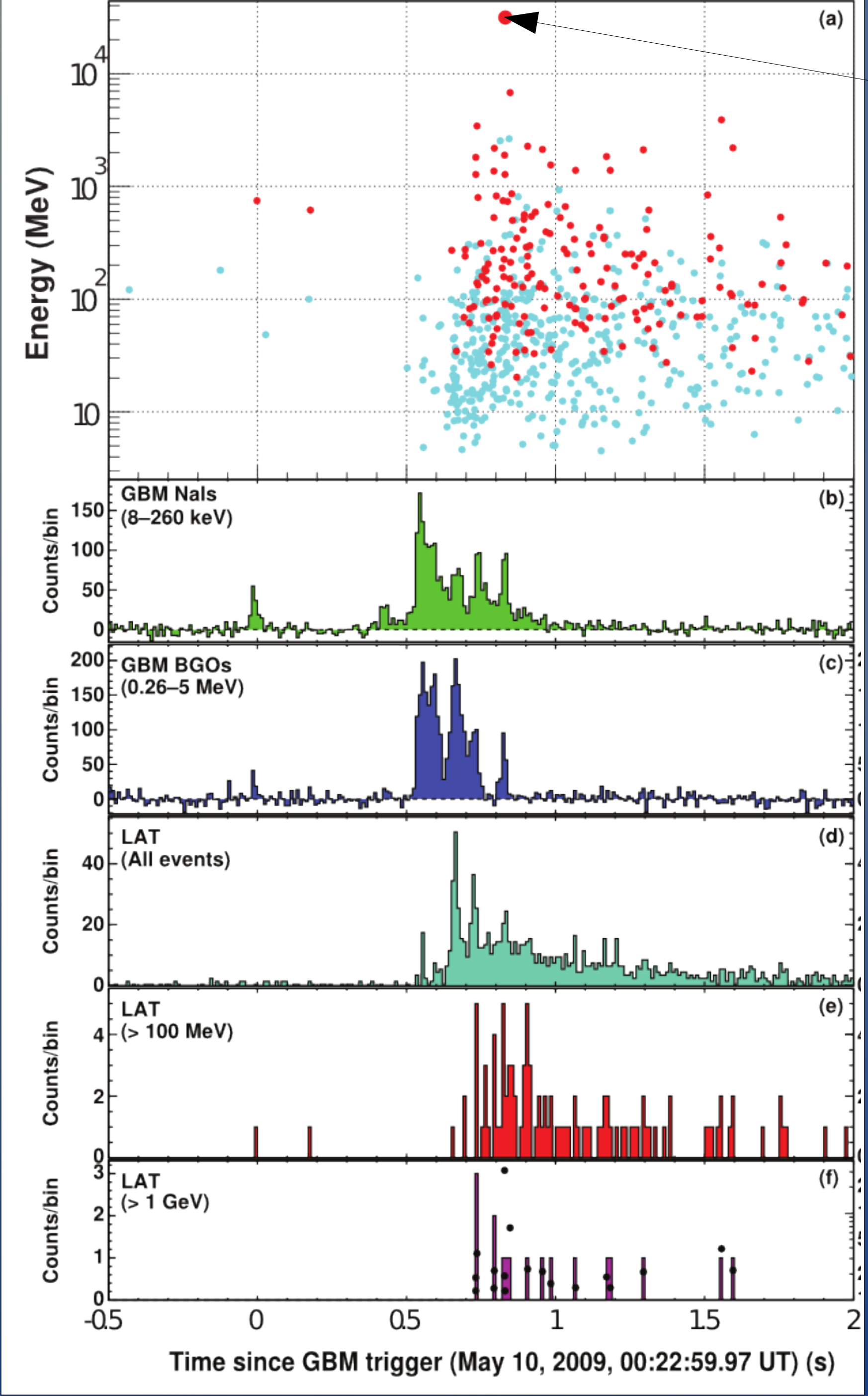
Lorentz-Invariance Violation

- If the speed of light depends on its energy $\rightarrow$ then two photons of different energies emitted together will arrive at different times.
  - Then, for example, in the case s_n=+1 (speed retardation), the higher-energy photon (E_h) will arrive after the lower-energy photon (E_l) after a time delay Δt:

$$\Delta t = \frac{(1+n)}{2H_0}\frac{E_h^n - E_l^n}{(M_{\mathrm{QG},n}c^2)^n}\int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}\,dz'$$

GRB090510

- We have used the joint *Fermi* LAT (20MeV – 300GeV) and GBM (8keV – 40MeV) observations of GRB090510 to place strong and meaningful constraints on LIV (on M_{QG}).
- Short GRB, duration <2s
- Spectroscopically-measured redshift z=0.903±0.003
- The detected emission extended up to 31GeV.
  - Highest-energy photon ever detected from a short GRB.

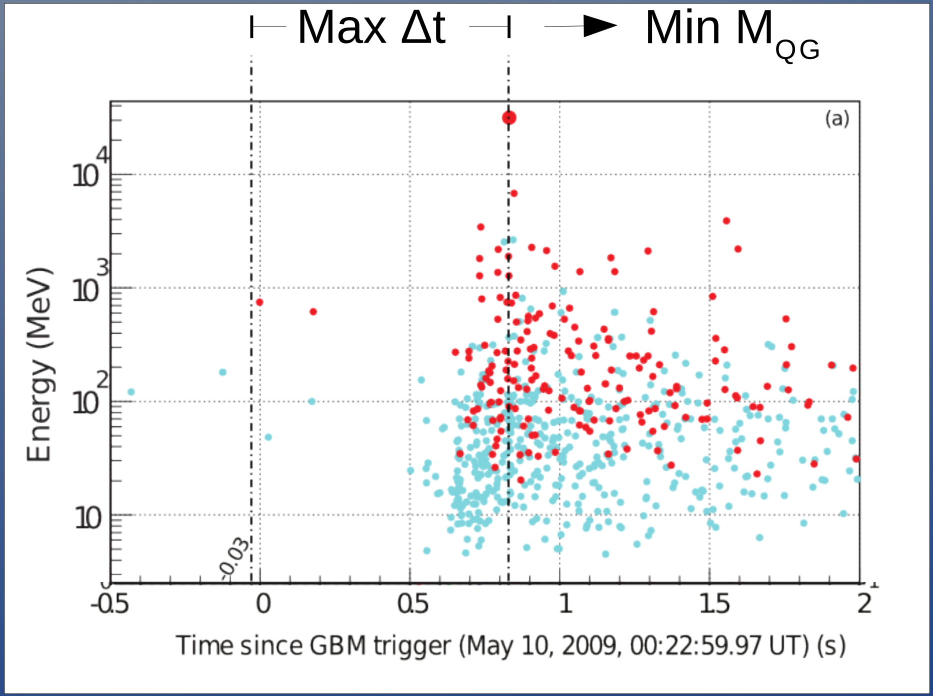


The 31GeV Photon

- Detected 0.829s after the GBM trigger.
- 1σ Confidence Interval for its energy is 27.97–36.32GeV
- Solid evidence of this event being a photon associated with this GRB
  - Did not trigger any ACD tiles. Signal at the tracker and the calorimeter consistent with an EM shower.
  - 5.8 arcmin from the Swift-UVOT localization (95% PSF at 30GeV is 16 arcmin for this type of event)
- Considerations based on the LAT background rate also support its association with the GRB

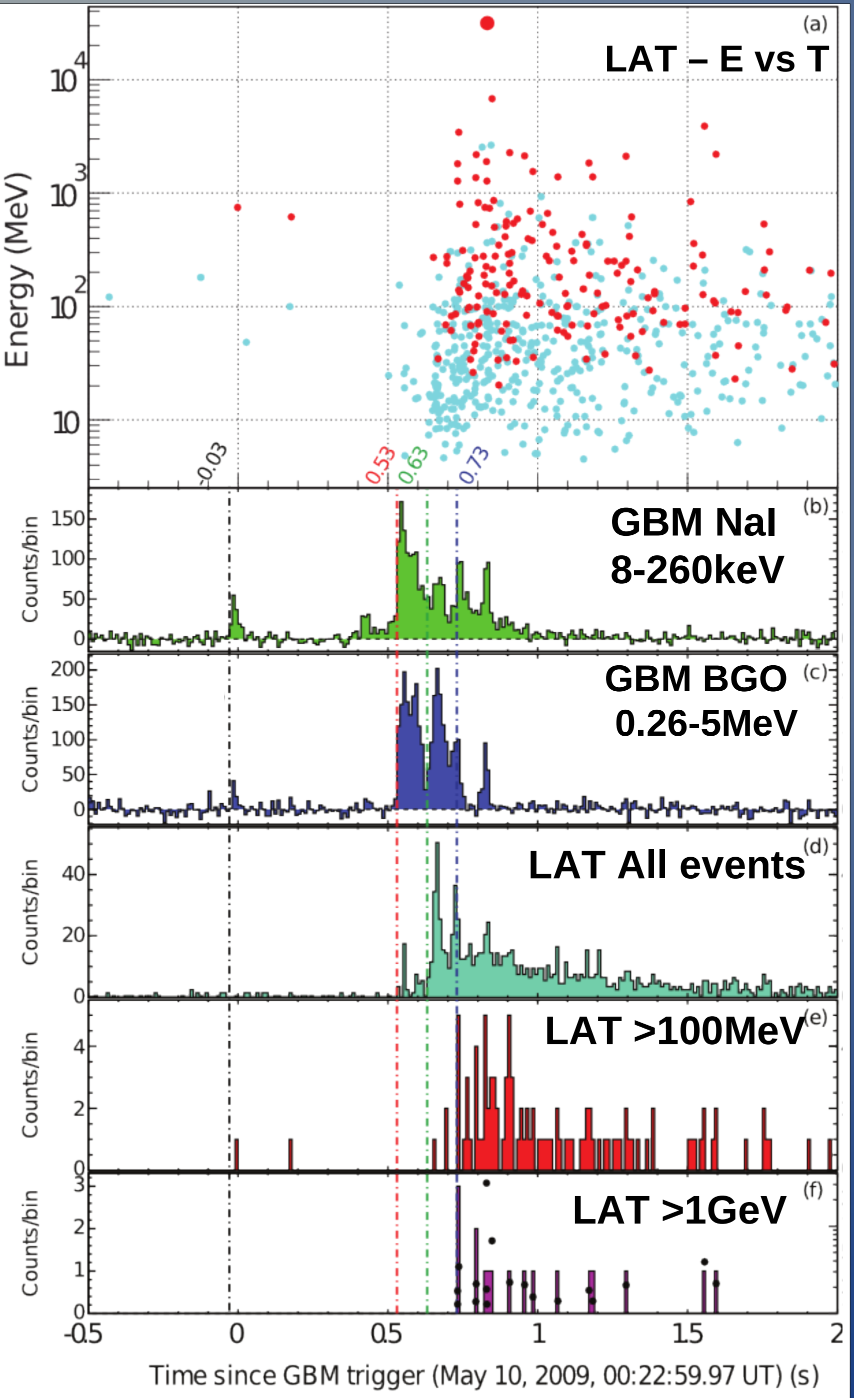
First method

- We set a lower limit on M_{QG} from an upper limit on the time delay Δt of the 31GeV photon.
- We don't try to assume the specific emission time of the 31GeV photon.
- We associate the 31GeV photon with a lower-energy emission episode (of energy E_l).



$$\Delta t = \frac{(1+n)}{2H_0} \frac{E_h^n - E_l^n}{(M_{\mathrm{QG},n}c^2)^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}} dz'$$

- Method only constrains positive time delays $\rightarrow$ subluminal propagation
- Used conservative values for E_h and z



Method #1

1. **<u>Most conservative case</u>: 31GeV** photon was emitted some time after the start of the GRB:

   $\Delta t \leq 859\text{ms} \leftrightarrow M_{QG,1} \geq 1.19 M_{Pl}$

2. Photon was emitted some time after the start of the main <MeV emission:

   $\Delta t \leq 299\text{ms} \leftrightarrow M_{QG,1} \geq 3.42 M_{Pl}$

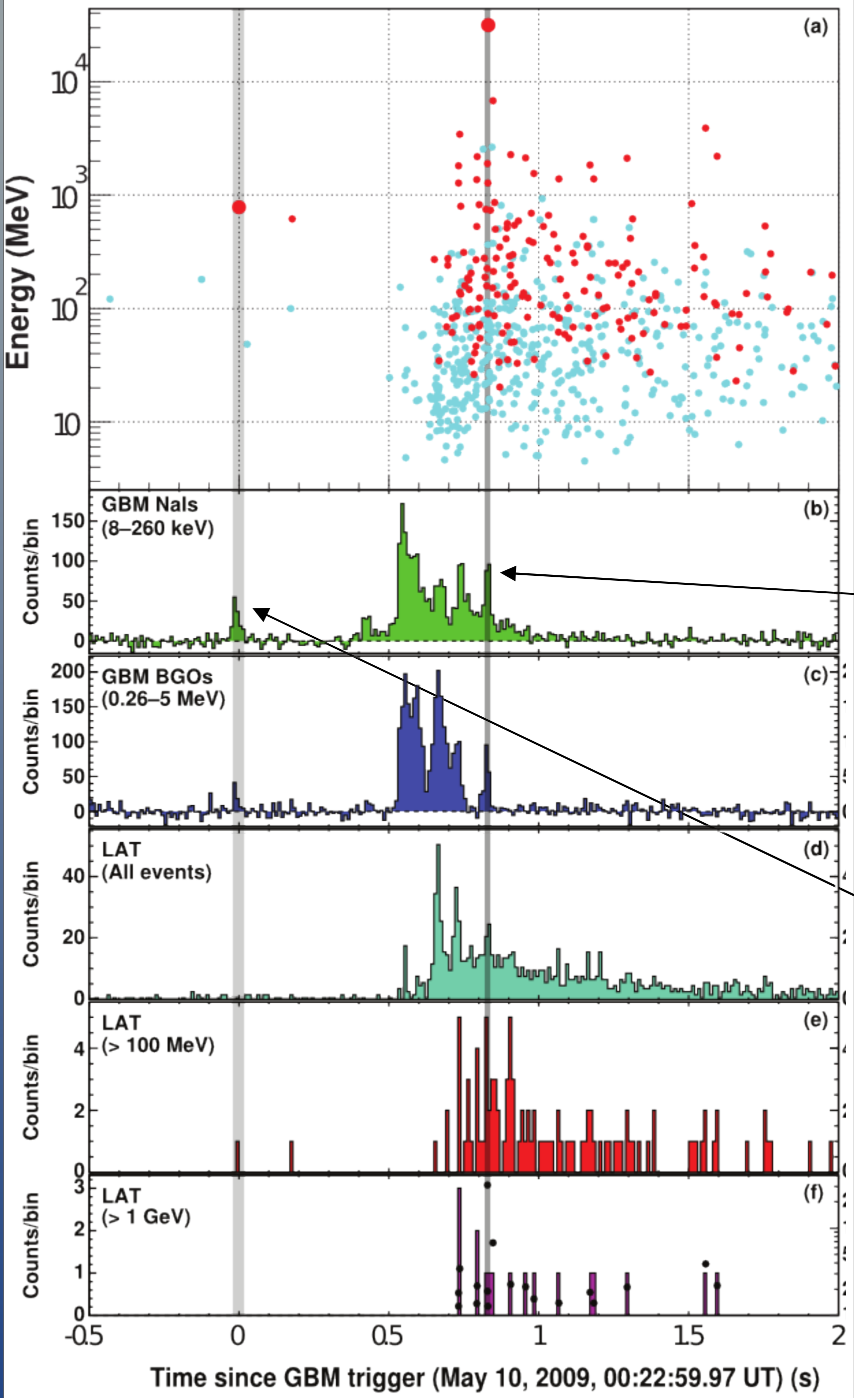
3. Photon was emitted some time after the start of the >100MeV emission:

   $\Delta t \leq 199\text{ms} \leftrightarrow M_{QG,1} \geq 5.12 M_{Pl}$

4. Photon was emitted some time after the start of the >1GeV emission:

   $\Delta t \leq 99\text{ms} \leftrightarrow M_{QG,1} \geq 10.0 M_{Pl}$

Method #1



- Associations with individual spikes constrain both positive and negative time delays ($s_n = \pm 1$)
- Such associations are not as secure → used as intuition builders (what we could do)
- 31GeV Photon lies at the center of a 20ms-wide pulse. We constrain both a positive and a negative time delay:

$$|\Delta t| < 10\text{ms} \leftrightarrow M_{QG,1} > 102 M_{Pl}$$

- 750MeV photon & precursor. We place one more limit on a negative time delay:

$$|\Delta t| < 19\text{ms} \leftrightarrow M_{QG,1} > 1.33 M_{Pl}$$

Method #2 – DisCan

- We also used an alternative and independent method (DisCan* – Dispersion Cancellation) to constrain LIV.
  - This method extracted dispersion information from all the detected LAT photons (detected energy range 35MeV – 31GeV).
  - Performed multiple trials, in which it moved each photon time according to a *trial spectral lag coefficient* (in ms/GeV).
  - The spectral lag coefficient *which maximized* the sharpness of the lightcurve was our measurement of the effective spectral lag.
  - The spectral lag coefficient *was found to be consistent with zero*.
- We also performed a bootstrap analysis to gauge the statistical errors of that measurement, which produced our final result:
  - a symmetric upper limit on the spectral lag coefficient

$$|\Delta t/\Delta E|<30\text{ms/GeV} \leftrightarrow M_{QG,1}>1.22M_{Pl}$$

(99% CL) on possible linear (n=1) dispersion of either sign (s_n=±1).

Scargle, J. D., Norris, J. P. & Bonnell J. T. 2008

Conclusion

- We constrained small changes in the speed of light caused by linear and quadratic perturbations in (E_γ/M_{QG}).
- Using two independent techniques, we have placed strong limits on linear perturbations for both super- and sub-luminal speeds that were all higher than the Planck Mass.
- Our results
  - support Lorentz invariance and disfavor models in which a quantum nature of space-time on a very small scale alters the speed of light, giving it a linear dependence on photon energy.
- This is the first time that direct measurements of the propagation speed of light set limits on $M_{QG,1}$ that are higher than the Planck Mass.
- Parameter space $M_{QG,1} > M_{Pl}$ unnatural $\rightarrow$ renders constrained models highly implausible.
- Results can be used to guide future development of QG and Planck-scale models.

Backup Slides

DisCan Method

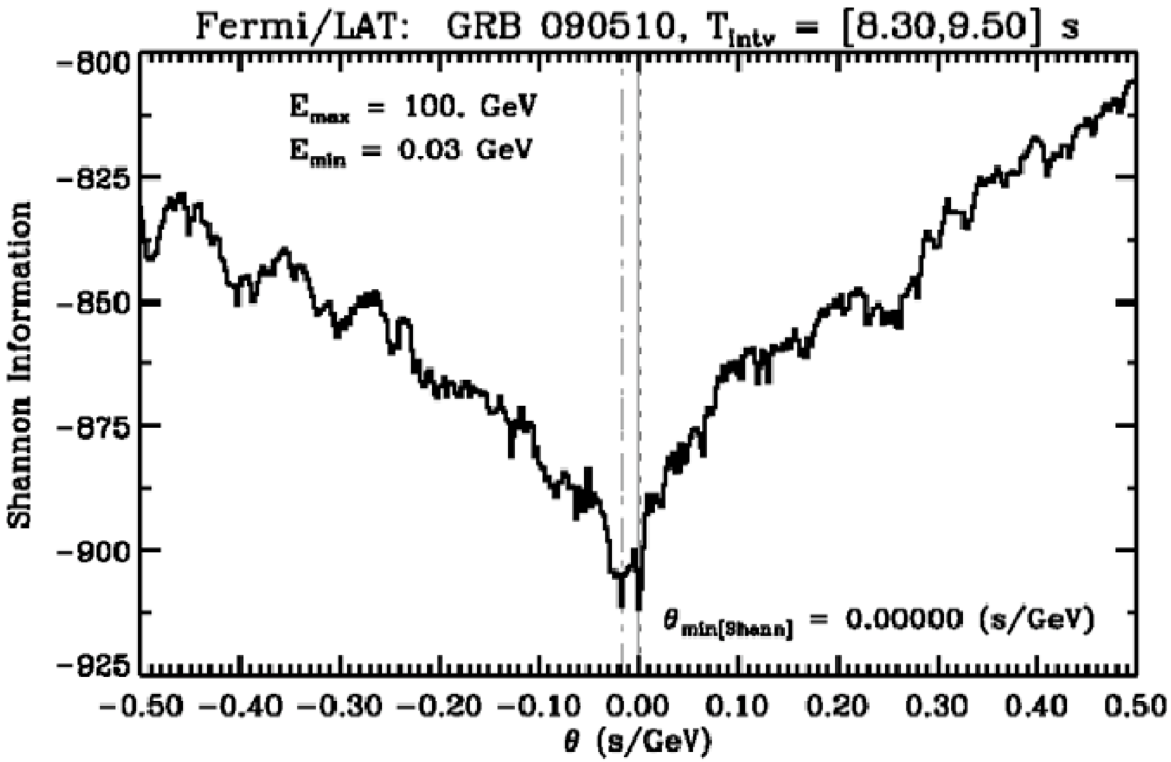


Figure 2. Shannon Information versus trial values of θ for the interval $T - T_{0,*} = 0.50 - 1.45$ s. The best value of θ is annotated, and shown as a vertical solid line. The two dashed vertical lines left and right of the best value represent the θ values which are $0.01 \times$ less probable than the best θ value, *for the given data set*. Thus the contained interval between the two dashed lines is an approximate error region, but *does not reflect statistical uncertainties.*

Bootstrap error analysis

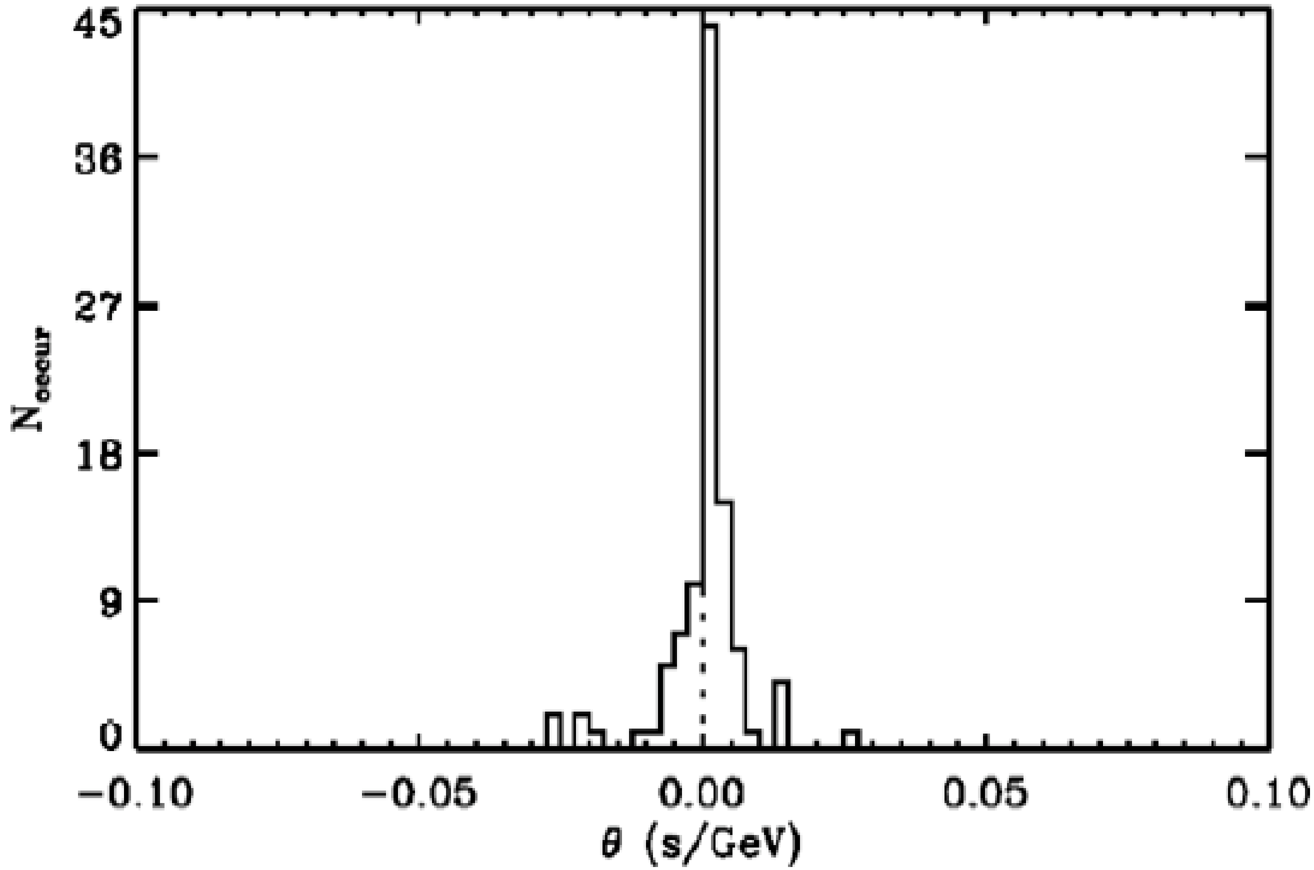
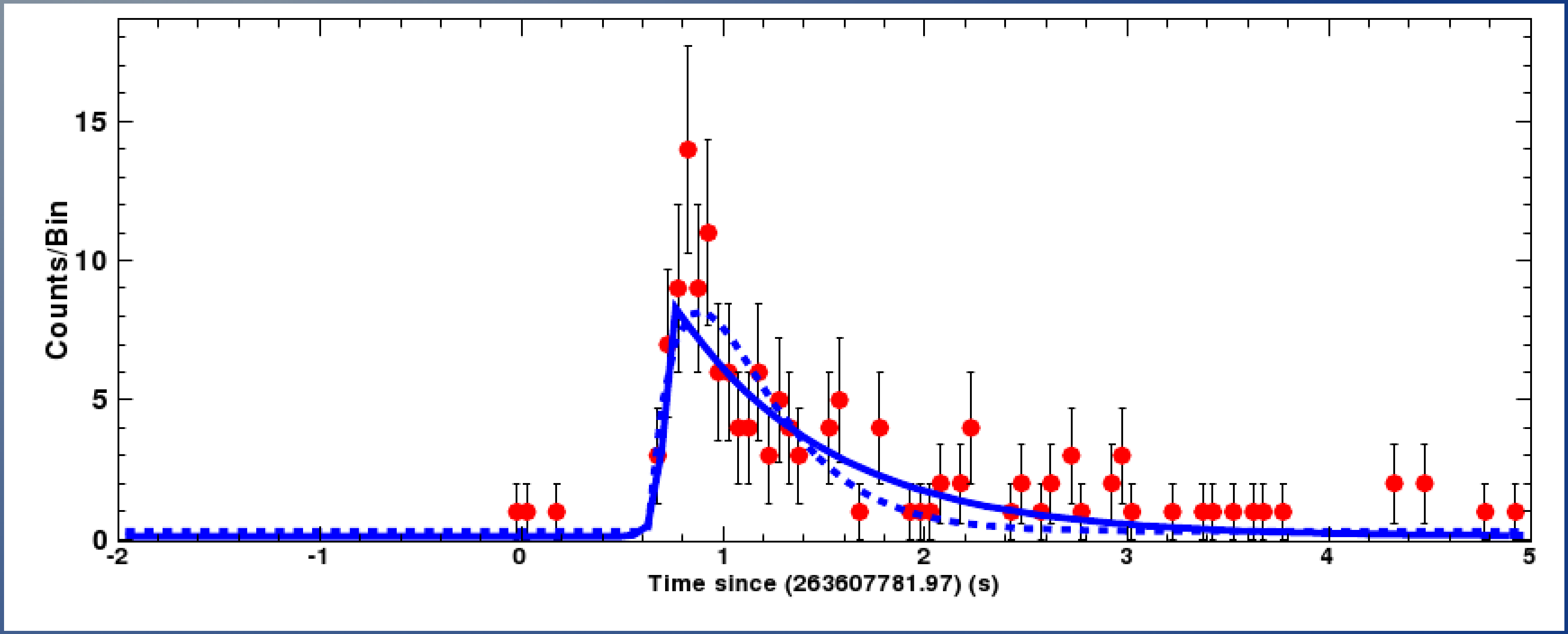


Figure 3. For the interval analyzed in Figure 2, to gauge uncertainty due to statistical variations we generated 100 realizations with the photon times randomized. $\theta_{\min}$ for these 100 realizations is within the range ± 0.03 s/GeV.

Finding the onset time of the >100MeV Emission



#	t_{start} (ms)	Limit on $\|\Delta t\|$ (ms)	Reasoning for choice of t_{start} or limit on Δt or $\|\Delta t/\Delta E\|$	E_l † (MeV)	Valid for s_n *	Degree of confidence *	Limit on $M_{QG,1}/M_{Planck}$
(a)*	−30	< 859	start of any < 1 MeV emission	0.1	1	very high	**> 1.19**
(b)*	530	< 299	start of main < 1 MeV emission	0.1	1	high	> 3.42
(c)*	630	< 199	start of main > 0.1 GeV emission	100	1	high	**> 5.12**
(d)*	730	< 99	start of > 1 GeV emission	1000	1	medium	> 10.0
(e)*	—	< 10	association with < 1 MeV spike	0.1	± 1	low	> 102
(f)*	—	< 19	If 0.75 GeV ‡ γ-ray from 1st spike	0.1	−1	low	> 1.33