Constraining Lorentz Invariance Violation with Fermi

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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) → $u_\gamma(E_\gamma) \neq c$.

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 $=\{0, \pm 1\}$

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

$$M_{QG} \lesssim M_{Planck} \equiv \sqrt{\hbar c/G} \approx 1.22 \times 10^{19} GeV/c^2$$
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:

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

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

- 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 → 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 $\Delta t$:

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

- Short GRB, duration <2s

- Spectroscopically-measured redshift $z=0.903\pm0.003$

- 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 $\Delta t$ 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 $E_l$).

\[ \Delta t = \frac{(1+n)}{2H_0} \frac{E_{h}^{n} - E_{l}^{n}}{(M_{QG},c^2)^n} \int_{0}^{z} \frac{(1+z')^{n}}{\sqrt{\Omega_m (1+z')^3 + \Omega_{\Lambda}}} \, dz' \]

- Method only constrains positive time delays $\rightarrow$ subluminal propagation
- Used conservative values for $E_h$ and $z$
Method #1

1. **Most conservative case:** A 31 GeV 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 >100 MeV 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 >1 GeV 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:

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

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

  $$|\Delta t| < 19\text{ms} \Leftrightarrow M_{QG,1} > 1.33M_{Pl}$$
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 \( s_n = \pm 1 \).

*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 \( \frac{E_Y}{M_{QG}} \).

- 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 → renders constrained models highly implausible.

- Results can be used to guide future development of QG and Planck-scale models.
Backup Slides
Figure 2. Shannon Information versus trial values of $\theta$ for the interval $T - T_{0,*} = 0.50 - 1.45\ s$. The best value of $\theta$ is annotated, and shown as a vertical solid line. The two dashed vertical lines left and right of the best value represent the $\theta$ values which are $0.01 \times$ less probable than the best $\theta$ 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.
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. $\theta_{\text{min}}$ for these 100 realizations is within the range $\pm 0.03$ s/GeV.
Finding the onset time of the >100MeV Emission
| #  | $t_{\text{start}}$ (ms) | Limit on $|\Delta t|$ (ms) | Reasoning for choice of $t_{\text{start}}$ or limit on $\Delta t$ or $|\Delta t/\Delta E|$ | $E_i$ (MeV) | Valid for $s_n$ * | Degree of confidence * | Limit on $M_{0.65}/M_{\text{planck}}$ |
|----|------------------------|-----------------------------|--------------------------------------------------------------------------------|-----------|-----------------|-------------------------|-------------------------------|
| (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 $\gamma$-ray from $1^{st}$ spike                                   | 0.1       | -1              | low                    | > 1.33                        |