Lorentz Invariance Violation: The latest Fermi results and the GRB/AGN complementarity

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Introduction
The formalism in use

- QG related effects should appear at $E \sim O(E_P = 1.2 \times 10^{19} \text{GeV})$
- These effects include deformation or violation of Lorentz Invariance
- For $E \ll E_P$, a series expansion is expected to be possible, giving:
  \[ c' = c \left( 1 \pm \xi \frac{E}{E_P} \pm \zeta^2 \frac{E^2}{E_P^2} \right) \text{ at the 2}^{\text{nd}} \text{ order} \]
- Depending on their energies, photons travel at different speeds
- Tiny modifications can add-up over very large propagation distances and lead to measurable delays
  $\rightarrow$ use of variable and distant sources (GRBs, AGN flares)
- We consider two photons with energy $E_1$ and $E_2$ emitted at the same time and detected at times $t_1$ and $t_2$.
  - At the first order:
    \[ \frac{\Delta t}{\Delta E} \approx \frac{\xi}{E_P H_0} \int_0^z dz' \frac{(1 + z')}{\sqrt{\Omega_m (1 + z')^3 + \Omega_\Lambda}} \]
  - At the second order:
    \[ \frac{\Delta t}{\Delta E^2} \approx \frac{3 \zeta}{2 E_P^2 H_0} \int_0^z dz' \frac{(1 + z')^2}{\sqrt{\Omega_m (1 + z')^3 + \Omega_\Lambda}} \]

\[ \Delta t = t_1 - t_2 \quad \Delta E = E_1 - E_2 \quad \Delta E^2 = E_1^2 - E_2^2 \quad \Omega_\Lambda = 0.7 \quad \Omega_m = 0.3 \]
The formalism in use

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QG Effects vs. Source Effects

- **BUT**: Emission processes or the structure of the source can introduce a time lag too!
- It is necessary to separate the two effects $\rightarrow$ population studies

### Quantum Gravity effect

- **Emission** $\rightarrow$ **Source Effect**

### Possible source effect

- **Emission** $\rightarrow$ **Source Effect**

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**Propagation $\rightarrow$ LIV Effect**

**Emission $\rightarrow$ Source Effect**
The latest Fermi results

«Constraints on Lorentz Invariance Violation with Fermi-LAT observations of GRBs»

V. Vasileiou, F. Piron, J. Cohen-Tanugi (LUPM Montpellier)
A. Jacholkowska, JB, C. Couturier (LPNHE Paris)
J. Granot (Open Univ. of Israel)
F. Stecker (NASA GSFC)
F. Longo (INFN Trieste)

Accepted for publication by PRD
arXiv:1305.1553
Overview

- Use of LAT data
  - 20 MeV - 300 GeV
  - High effective area
  - Low background
  - Good energy reconstruction accuracy
    (~10 % at 10 GeV)

- 4 GRBs are analyzed
  - 090510, 090902B, 090926A, 080916C
  - Known redshifts (from 0.9 up to 4.3)
  - Variability time scale down to tens of ms
  - Maximum energy detected: 31 GeV
  - ~100 events/GRB above 100 MeV

- 3 analysis methods ➔ «PairView», «Sharpness Maximization Technique», «Maximum Likelihood»
  - Complementarity in sensitivity
  - Reliability of the results
Method #1: PairView

- Calculate the spectral lags $l_{i,j}$ between all pairs of photons $i$ and $j$ in a dataset.
- The distribution of $l_{i,j}$ values peaks approximately at the true value of $\tau$.
  - Histogram
- The peak position is determined using a Kernel Density Estimate of the distribution.
  - Smooth curve
- The KDE peak gives the estimate for $\tau$.
  - Dashed line

$$l_{i,j} \equiv \frac{t_i - t_j}{E_{i}^{n} - E_{j}^{n}}$$
Method #2: Sharpness Maximization Technique

- LIV spectral dispersion smears light-curve structure and decreases sharpness.
- Apply an inverse dispersion to the data to maximize the sharpness.
  - Smooth curve
- The sharpness peak gives the estimate for $\tau$.
  - Dashed line
- The sharpness $S$ is defined by the formula on the right, where $t'_i$ is the modified detection time of the $i^{th}$ photon and $\rho$ is a parameter selected using simulations.

$$S(\tau_n) = \sum_{i=1}^{N-\rho} \log \left( \frac{\rho}{t'_i + \rho - t'_i} \right)$$
Method #3: likelihood fit

- Study of the correlation between the arrival time and the energy of the photons
- Method used by Lamon et al. for INTEGRAL, by Martinez and Errando for MAGIC and by Abramowski et al. for H.E.S.S.
- We use the following form for the probability density function:

\[ P(t, E) = N \int_0^\infty A(E_S) \Gamma(E_S) G(E - E_S, \sigma(E_S)) F_S(t - \tau E_S) \, dE_S \]

where \( \Gamma(E_S) \) is the emitted spectrum, \( G(E-E_S, \sigma(E_S)) \) is the smearing function in energy, \( A(E_S) \) is the acceptance of the detector and \( F_S \) is the emission time distribution at the source
- Here we assume linear and quadratic effects with a time-lag parameter \( \tau \) expressed in s/GeV (s/GeV^2)
- The likelihood function is then given by the product

\[ L = \prod_i P_i(t, E) \]

over all photons in the studied sample
- The maximum of the likelihood gives the time-lag \( \tau_1 \) (\( \tau_q \)) in s/GeV (s/GeV^2)
Method #3: Example

- The minimum of the curve gives the best estimate of $\tau$: on the right plot, 080916C (full line), 090902B (dotted line) and 090926A (dashed double-dotted line)
Results

- Three methods → three points for each GRB
- Markers → best estimate of $\tau$
- 90% (99%) CL intervals

All confidence intervals are compatible with 0 dispersion

Constraints with the 3 methods are in good agreement
Accounting for Source-Intrinsic Effects

- It is probable the measured lag has two components:
  \[ \tau = \tau_{\text{INT}} + \tau_{\text{LIV}} \]
  where \( \tau_{\text{INT}} \) is the intrinsic dispersion (due to the source) and \( \tau_{\text{LIV}} \) is the LIV-induced dispersion.

- There is no good model available to predict the value of \( \tau_{\text{INT}} \).
  ➔ A conservative modelization of \( \tau_{\text{INT}} \) is used.

- We assume the observations are dominated by source effects:
  - The PDF of \( \tau_{\text{INT}} \) is chosen to match \( \tau \) allowed by the data:
    - Average of 0
    - Width matching the width of \( \tau \)
  - \( \tau_{\text{INT}} \) is modelled to reproduce the allowed range of possibilities for \( \tau \):
    ➔ Worst case scenario
    ➔ Less stringent limits on \( \tau_{\text{LIV}} \)

Most conservative limits on \( \tau_{\text{LIV}} \)
95% CL lower limits on $E_{\text{QG}}$

- Subluminal case, Left: linear LIV, Right: quadratic LIV
- Bars: average constraint accounting for GRB-intrinsic effects
- Current limits improved by a factor 2-4

$E_{\text{QG}} \gtrsim 8 \ E_{\text{Pl}}$ for $n=1$

$E_{\text{QG}} \gtrsim 1.3 \times 10^{11}$ GeV for $n=2$
95% CL lower limits on $E_{QG}$

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Over the Planck scale for 090510, even accounting for intrinsic effects
Conclusions and prospects
Summary of the last Fermi results

- Paper available: arXiv/1305.3463
  - 30 pages
  - Detailed description of procedures, systematics, verification tests
  - Accepted by PRD

- 4 bright GRBs analysed
- 3 different methods used

\[ E_{QG,1} > 7.6 \ E_{Pl} \]
\[ E_{QG,2} > 1.3 \times 10^{11} \ \text{GeV} \]

- The most stringent and robust constraints for linear and quadratic LIV so far
- Linear LIV has reached the Planck scale boundary
- Quadratic LIV still need to be improved
GRB/AGN Complementarity

- Comparison between Vasileiou et al. results (ML) and previous results obtained with AGNs
- AGNs $\rightarrow$ high statistics with ground-based instruments BUT low redshift (EBL) and low statistics with satellites
- GRBs $\rightarrow$ high statistics with space instruments BUT lower energies and no detection from the ground

![Graph showing GRB/AGN Complementarity](image)

- High energies, low distance
- Low energies, large distance

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<th>Event</th>
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Lower Limit on $E_{\gamma}/E_{\rho}$ ($n = 1$, 95% CL, $s_\gamma = +1$)
What’s next ?

- CTA
  - Start around 2018
  - Large energy range coverage (~10 GeV - 100 TeV) with different sizes of telescopes
    - Overlap with satellites
  - Sensitivity increased by a factor 10
    - More sources discovered
  - Dedicated pointing strategy for transient source discoveries
    - More sources discovered that can be used for LIV searches

- Linear LIV has reached the physically meaningful bound of the Planck scale

- In the future, the effort should be put on constraining the quadratic LIV!
  - Ground-based detectors and satellites will need to work together to make the energy range as large as possible (GeV - TeV)
  - Necessary work on source effects
Grazie mille !