Study of time lags in HETE-2 Gamma-Ray Bursts with redshift: search for astrophysical effects and Quantum Gravity signature

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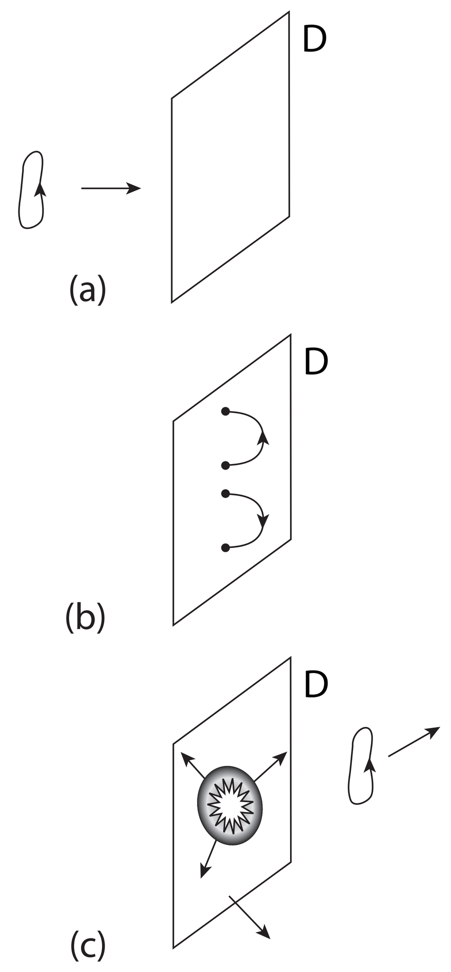
1 - Motivations and Model

This study (see [1] for details) is based on a model developped in the frame of String Theory [2]. Gravitation is considered as a gauge interaction and Quantum Gravity effects result from graviton-like exchange in a background classical space-time.

The situation is represented in the figure on the right. (a) A graviton (closed string) propagates in an extra-dimension. (b) It interacts with a D-brane representing our Universe. (c) After the interaction, the graviton continues on its way. The D-brane is left in an excited state and gets a recoil movement.



This model leads to the fact that velocity of light depends on the energy of the photons:

$$v(E) = \frac{c}{n(E)}$$

Then, it is possible to write a dispersion relation for the velocity of photons. At the first order, this relation gives:

$$v \approx c\left(1 - \frac{E}{E_{QG}}\right)$$

This leads to the fact that two photons emitted at the same time with an energy difference ΔE will be detected with a time lag Δt.

In this work, we measure time lags for several Gamma-Ray Bursts (GRBs) observed by the satellite HETE-2 with different redshifts. Our goal is to detect a possible QG effect on light propagation.

As GRBs are at cosmological distances, the expression of Δt as a function of the redshift and energy gap ΔE depends on the cosmological model. Following [3], the first-order time lag is given by

$$\Delta t = H_0^{-1}\frac{\Delta E}{E_{QG}} K_l \quad \text{where} \quad K_l = \int_0^z \frac{dz}{\sqrt{\Omega_\Lambda + \Omega_M (1+z)^3}} \quad \text{with } \Omega_\Lambda = 0.7 \text{ and } \Omega_M = 0.3.$$

2 - HETE-2 Fact Sheet

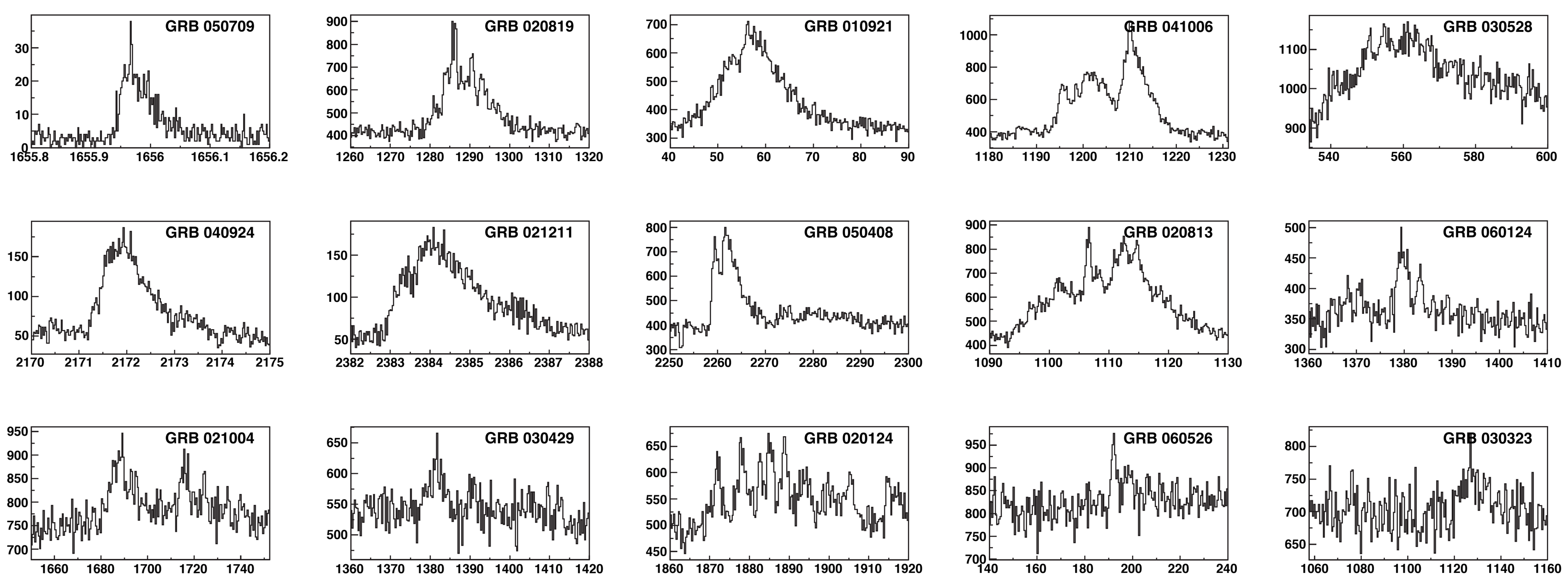
Operations: october 2000 - november 2006
Mass: 125 kg
Observed GRBs: >250
Number of localised GRBs: 120
Number of measured redshifts: 24
Instruments:

- **FREGATE** (*French Gamma-ray Telescope*)
  NaI (Tl)
  6 keV < E < 400 keV
  Energy resolution = 25% at 20 keV
  Time resolution = 6.4 μs
  Deadtime = 10 μs
  F.o.v. = 4 sr
- **WXM** (*Wide field X-ray Monitor*)
  Coded mask + proportional counter
  2 keV < E < 25 keV
  Localisation < 10′
- **SXC** (*Soft X-ray Camera*)
  Coded mask + CCD camera
  500 eV < E < 14 keV
  Localisation < 1′

HETE-2 was dedicated to fast localisation of GRBs. It was primarily developed and fabricated in-house at the MIT by a small scientific and engineering team, with major hardware and software contributions from international partners in France and Japan [4].

3 - The data

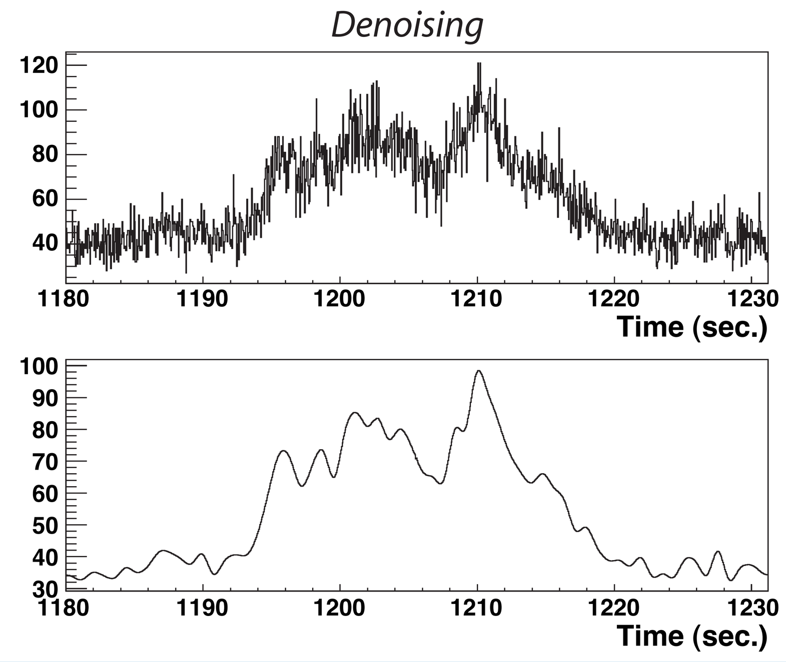
- 15 GRBs with 0.16 < z < 3.37.
- Use of FREGATE photon tagged data ➡ several energy bands scenarios are studied.



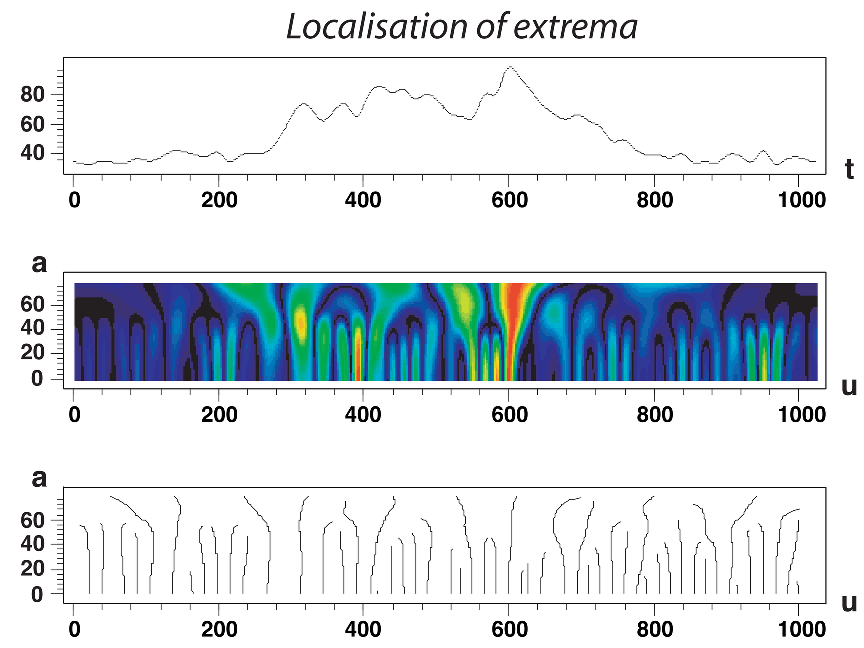
4 - Denoising and extrema localisation

- Wavelet transform is a multi-scale analysis method.
- Discrete Wavelet Transform (DWT) is used to remove the noise ➡ Use of WaveLab [5].
- Continuous Wavelet Transform (CWT) is used to localise extrema ➡ Use of LastWave [6].

Denoising

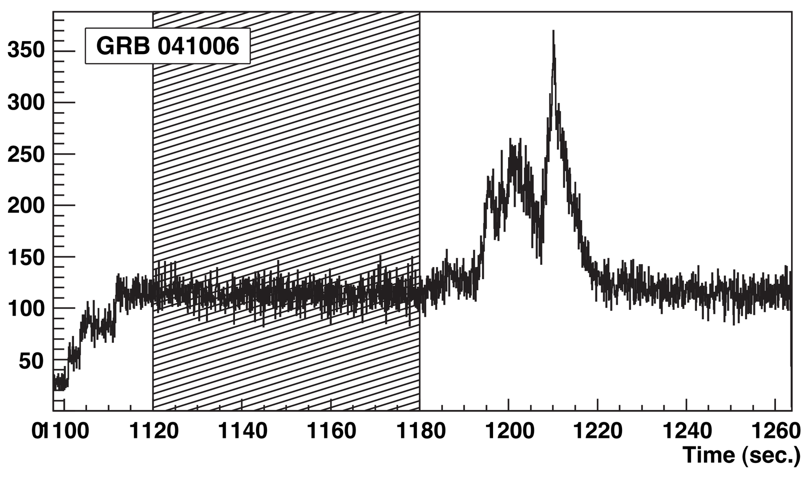


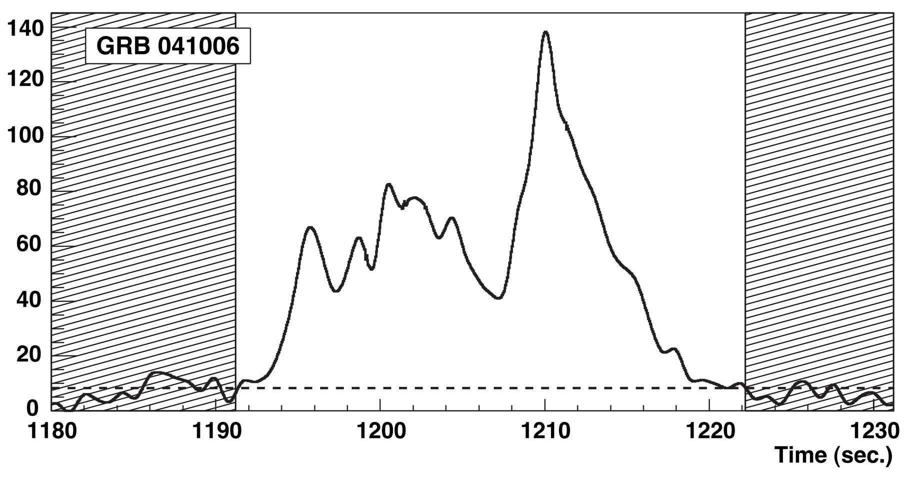
Localisation of extrema



5 - Noise

- Variance and mean of the background noise are obtained before the burst.
- Signal is studied only in the range where it is above $1\sigma_{bkg}$. For GRB 030323, GRB 030429 and GRB 060526, a level of $0.5\sigma_{bkg}$ is used.





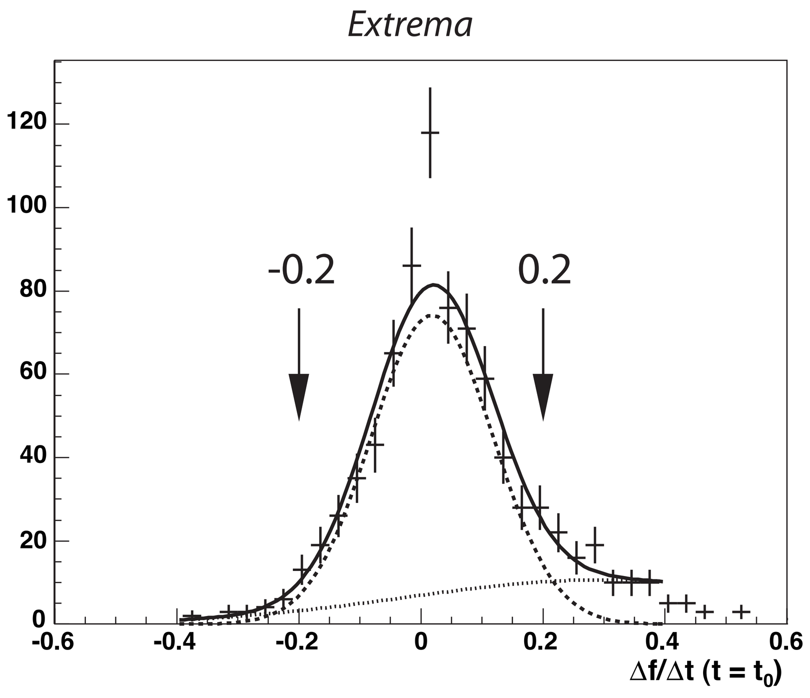
6 - Selections

For each extremum, the derivative, the Lipschitz coefficient α and its error $\delta\alpha$ are computed. α and $\delta\alpha$ are obtained with the CWT.

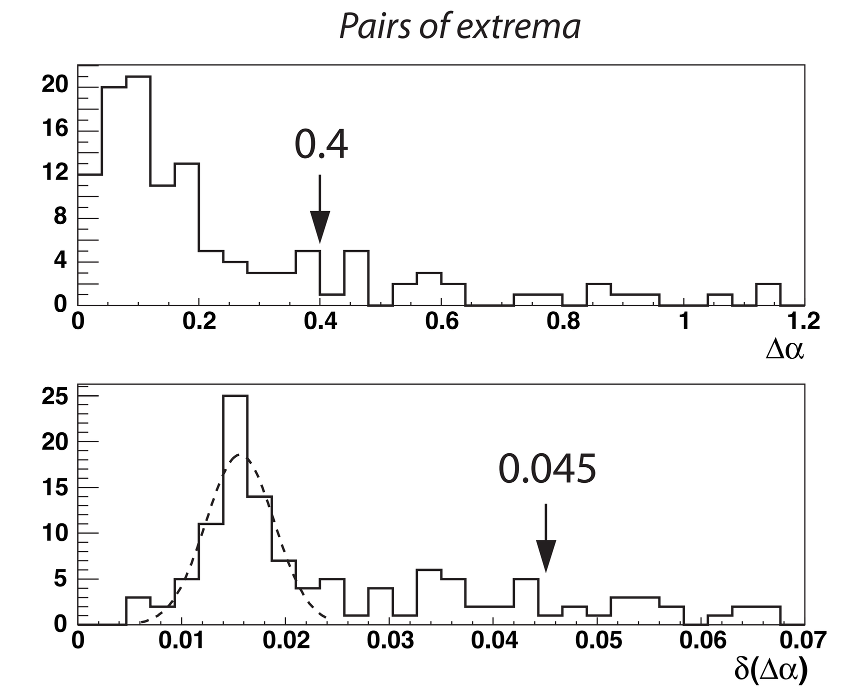
The Lipschitz coefficient is a measurement of the regularity of the signal.

$$\begin{cases} \Delta t = t_2 - t_1 \\ \Delta\alpha = |\alpha_2 - \alpha_1| \\ \delta(\Delta\alpha) = \sqrt{\delta\alpha_1^2 + \delta\alpha_2^2} \end{cases}$$

Extrema



Pairs of extrema



7 - Results

- Time lags are first studied as a function of K_l:

$$\Delta t = a\,K_l + b\,(1+z).$$

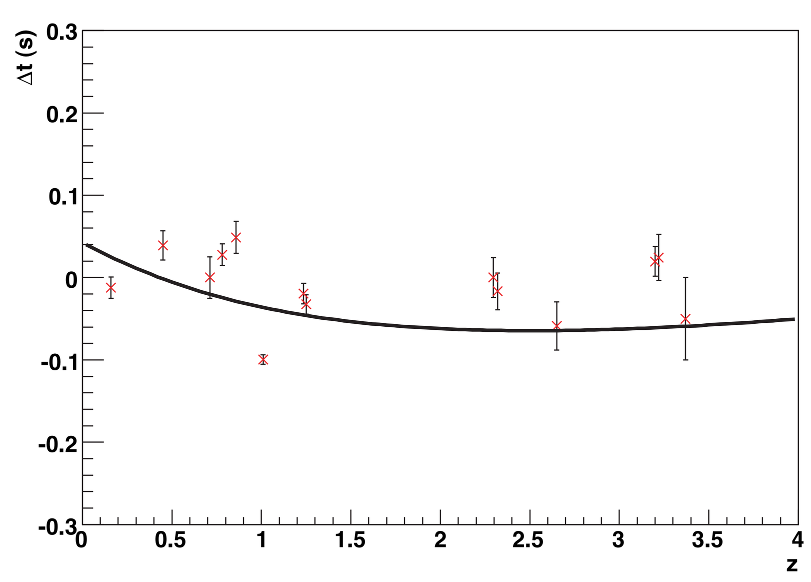
This yields an estimate $\tilde{b}$ of the intrisic parameter b.

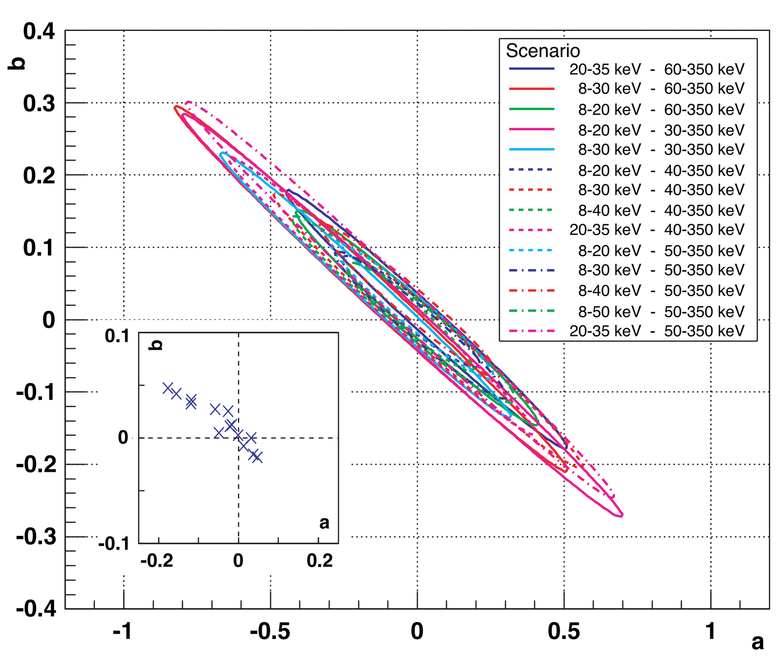
- For each energy gap scenario, we define a χ^2 function as a function of the energy scale M:

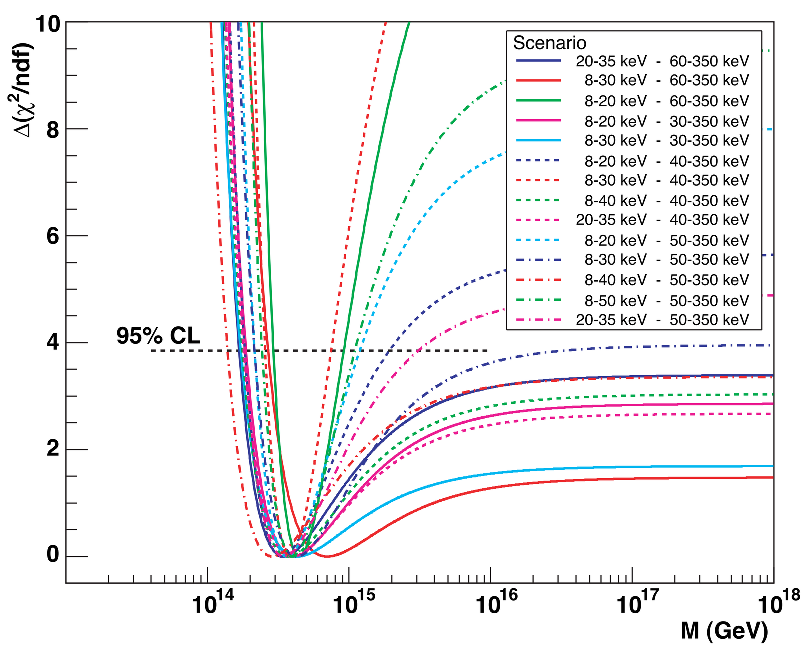
$$\chi^2(M) = \sum_{\text{all GRBs}} \frac{\left(\Delta t_i - \tilde{b}\,(1+z) - a_l(M)\,K_{li}\right)^2}{\sigma_i^2 + (1+z_i)\,\sigma_b^2} \quad \text{with}$$

$$a_l(M) = \frac{1}{H_0}\frac{\Delta\langle E\rangle_i}{M}$$

The best limit (95% CL) : $E_{QG} > 3 \times 10^{14}$ GeV







9 - Conclusion and outlook

Light curves of 15 GRBs with known redshifts observed by the satellite HETE-2 have been studied using wavelet analysis in order to look for a Quantum Gravity effect on light propagation. No effect is detected above ±3σ and a lower limit on E_{QG} is set to 2.9×10^{14} GeV.

This work will be extended to a larger sample of GRBs using an estimator for the redshift [7].

Notes and References

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