Constraints on Lorentz Invariance Violation from MAGIC observation of GRB 190114C

D. Kerszberg, G. D'Amico, M. Martinez, C. Perennes, J. Rico, T. Terzić for the MAGIC collaboration

INTRODUCTION

- Some candidate quantum-gravity (QG) theories predict a violation or deformation of the Lorentz symmetry, also known as Lorentz invariance violation (LIV). One of the manifestations of LIV can be parametrized as an energy-dependent corrections to the in vacuo photon dispersion relation ($s_\pm$ can be plus or minus one)

$$E^2 \simeq p^2 \cdot \left[1 - \sum_{n=1}^{\infty} s_\pm \left(\frac{E}{E_{QG,n}}\right)^n\right]$$

which results in an energy-dependent time delay between photons.

- For a source at z=0.424, taking into account only the leading LIV-correction of order n, the time delay of a photon of energy E (relative to a low-energy one) is

$$\Delta t(E,\eta_1) = \eta_1 \cdot 17\ \mathrm{s/TeV} \cdot E\ , \quad \Delta t(E,\eta_2) = \eta_2 \cdot 25\ \mathrm{s/TeV}^2 \cdot E^2$$

for linear (n=1) and quadratic (n=2) scenarios respectively.

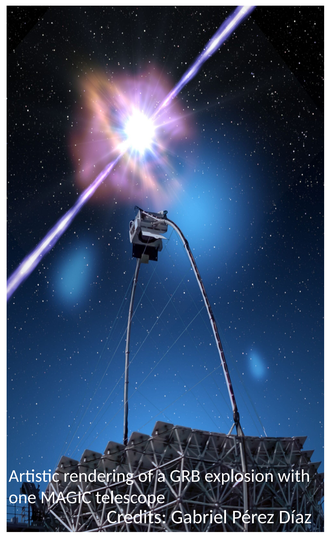
- In the last expressions we have introduced the parameter η defined as the ration between the Planck energy and the QG energy scale

$$\eta_1 = s_\pm \cdot E_{\mathrm{Pl}}/E_{\mathrm{QG},1}\ , \quad \eta_2 = 10^{-16} \cdot s_\pm \cdot E^2_{\mathrm{Pl}}/E^2_{\mathrm{QG},2}$$

We aim to present the results of a LIV study based on the VHE γ-ray signal from GRB 190114C

MAGIC OBSERVATION OF GRB 190114C

- MAGIC is a system of two 17 meter diameter Imaging Atmospheric Cherenkov telescopes, located in the Roque de los Muchachos observatory on the Canary Island of La Palma.
- The MAGIC telescopes detected a strong VHE γ-ray signal from GRB 190114C at redshift z = 0.424, after the initial trigger on 14 January 2019 at 20:57:03 Universal Time (UT) (hereafter T_0).
- This resulted in a total of N_{ON} = 726 and N_{OFF} =119 events with estimated energies from E_{min} = 300 GeV to E_{max}=1955 GeV and arrival times from t_{min} = 62 s to t_{max} = 1212 s after T_0



Artistic rendering of a GRB explosion with one MAGIC telescope
Credits: Gabriel Pérez Díaz

MAXIMUM LIKELIHOOD ANALYSIS

In order to get the value of η (the ratio between the Planck energy and the QG energy scale) that better describes the observation we perform a likelihood analysis:

- We first define the following statistic:

$$L = -2\ln\left(\frac{\max(\mathcal{L})_I}{\max(\mathcal{L})_{\eta_n,I}}\right)$$

which according to the Wilks' theorem should asymptotically follow under the null hypothesis a Chi-Squared distribution with one degree of freedom.

- The likelihood is defined as follows:

$$\mathcal{L}(\eta_n, I) = \prod_i^{N_{on}} \left(\frac{N_{on} - N_{off}}{N_{on}} \cdot f_s(t_i, E_i \,|\, \eta_n, I) + \frac{N_{off}}{N_{on}} \cdot f_b(t_i, E_i)\right) \cdot P(I)$$

PDF of detecting a signal event with a given estimated energy E and arrival time t

PDF of detecting a background event with a given estimated E energy and arrival time t

PDF of the nuisance parameters

- The probability distribution function (PDF) of detecting a signal event is given by:

Extragalactic background light attenuation — Collection area

$$f_s(t, E_{est} \,|\, \eta_n, I) \propto \int_0^\infty dE\ \Phi_1(E) \cdot \Phi_2(t - \Delta t(E;\eta_n,z)) \cdot F(E) \cdot A_{eff}(E) \cdot G(E_{est}, E)$$

Intrinsic spectrum — Intrinsic Light Curve — LIV delay — Energy resolution

Intrinsic spectrum described by a time independent power law distribution

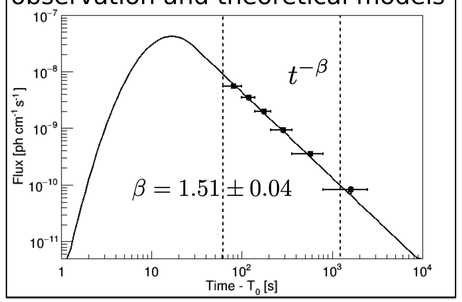
$$\Phi_1(E) \propto E^{-\alpha}$$

$$\alpha = 2.5 \pm 0.2$$

Nuisance parameter distribution:

$$P(I) = \mathcal{N}(\beta|1.51, 0.04) \cdot \mathcal{N}(\alpha|2.5, 0.2)$$

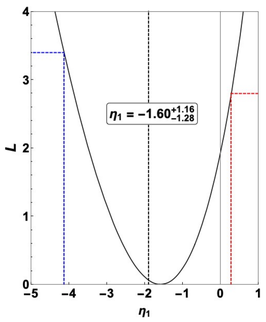
Intrinsic Light Curve obtained from observation and theoretical models



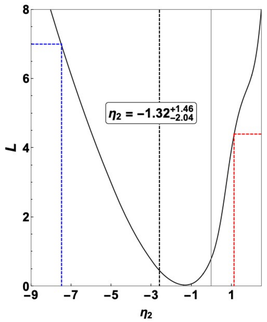
RESULTS

- The likelihood profile obtained from the data is compatible with the null hypothesis at a p-value of 0.78 and 0.59 for linear and quadratic scenarios respectively

Linear scenario



Quadratic scenario



- From the likelihood profile we were able to obtain the following 95% lower limits for the QG energy scale

	η^{LL}	η^{BF}	η^{UL}
η_1	-2.2	0.3	2.1
η_2	-4.8	1.3	3.7
	superl.		subl.
$E_{QG,1}$ [10^{19} GeV]	0.55		0.58
$E_{QG,2}$ [10^{10} GeV]	5.6		6.3

DISCUSSION

- MAGIC discovered a γ-ray signal above 0.2 TeV from GRB 190114C, detecting the highest energy photons from a GRB. Using conservative assumptions, we searched for an energy-dependent delay in the arrival time of the most energetic photons.
- Our results are compatible with the null hypothesis of no time delay. For the linear case limits are one order of magnitude lower than those obtained by Fermi, while they are compatible for the quadratic case.
- It is worth noting that MAGIC observed a featureless afterglow phase of the GRB 190114C, limiting the sensitivity of our LIV analysis. We are looking forward to VHE observations of an expectedly feature-rich GRB prompt phase, which would enhance the analysis sensitivity of LIV effects.

SELECTED REFERENCES

1. Acciari, V.A., Ansoldi, S., Antonelli, L.A. *et al.* Teraelectronvolt emission from the γ-ray burst GRB 190114C. *Nature* 575, 455–458 (2019)
2. Acciari, V.A., Ansoldi, S., Antonelli, L.A. *et al.* Observation of inverse Compton emission from a long γ-ray burst. *Nature* 575, 459–463 (2019)
3. Acciari, V.A., Ansoldi, S., Antonelli, L.A. *et al.* Bounds on Lorentz Invariance Violation from MAGIC Observation of GRB 190114C. Phys. Rev. Lett. 125, 021301 (2020)