Searching for Lorentz invariance violation with PKS2155-304

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Abstract:

Some models of quantum gravity predict Lorentz invariance violation from the modification of the photon dispersion relation in vacuum. The measure of time delays between photons of different energies in transient astrophysical events allows to set constraints on the energy scale of such models. The observation of the July 29–30 2006 flare of PKS2155-304 by HESS is analysed with LIVelihood, developed by the γ-LIV working group including researchers from HESS, MAGIC, VERITAS and LST collaborations.

Lorentz invariance violation

Lorentz invariance violation (LIV) is one of the rare observable features we could expect in a QG theory [1]. through the modification of the photon dispersion relation:

$$E^2 = p^2c^2 \times \left[1 \pm \sum_{n=1}^{\infty}\left(\frac{E}{E_{QG,n}}\right)^n\right], \qquad (1)$$

where $E_{QG,n}$ is the characteristic energy of the model.
⇒ Modification of the speed of photons which then depends on their energy in vacuum
⇒ Time delay at arrival between photons with different energies:

$$\Delta t_n \simeq \pm\frac{n+1}{2}\frac{E_h^n - E_l^n}{H_0 E_{QG}^n}\kappa_n(z), \qquad (2)$$

where κ_n is the source distance parameter and depends on the spacetime model. To maximise the delay, the source needs to be far, emitting in a large range of high energies, and transient: pulsars, blazar flares or gamma-ray bursts are the candidates. Then this delay is measured and represented by the lag parameter λ:

$$\lambda_n = \frac{\Delta t_n}{\Delta E_n\,\kappa_n(z)} \simeq \pm\frac{n+1}{2H_0E_{QG}^n}. \qquad (3)$$

The observation of such sources is done by gamma telescope such as HESS in Namibia. HESS is an atmospheric imaging Cherenkov telescope, observing photons in the range 30 GeV - 100 TeV.

Likelihood technique

In order to find λ_n for a given model, we compare high and low energy photons time distributions by calculating the likelihood that the time distribution of high energy photons matches a certain lag with respect to low energies. The contributing probability density function for one photon is

$$\frac{dP}{dE_m dt} = \frac{w_s}{N_s}\int A(E_t,\epsilon)M(E_t,E_m)F_s(E_t,t;\lambda)dE_t + \text{bkg. contrib.}, \qquad (4)$$

where A is the effective area, M the energy migration matrix, and F_s is the low energy flux parametrized from low energies. λ is the likelihood parameter that is varied. The likelihood is then defined as the sum of these contributions:

$$L(\lambda) = -\sum_i \log\left(\frac{dP}{dE_m dt}(E_m,i,t_i;\lambda)\right). \qquad (5)$$

Calibration and analysis

The application of the likelihood technique to LIV search was implemented by the γ-LIV working group [3] and follow the procedure below.

- **Simulate** high and low energy photons from the template lightcurve at low energies and the energy spectrum
- Compute the likelihood curve for the **time lag parameter** λ
- Find the **minimum** and the lower and upper limits at 1σ
- Then **repeat** 1000 times $\longrightarrow$ gives the statistical error
- Then **inject lag** in simulations and **repeat** for calibration check
- **Add** nuisance parameters and **repeat**
- Apply to the real list of photons

Lightcurve - Template

First, the lightcurve at low energy (photons below the median energy of the analysed dataset) needs to be modelled analytically to define a template F_s. But the whole flare here shows many fluctuations so we restrict the analysis to the 4th run.

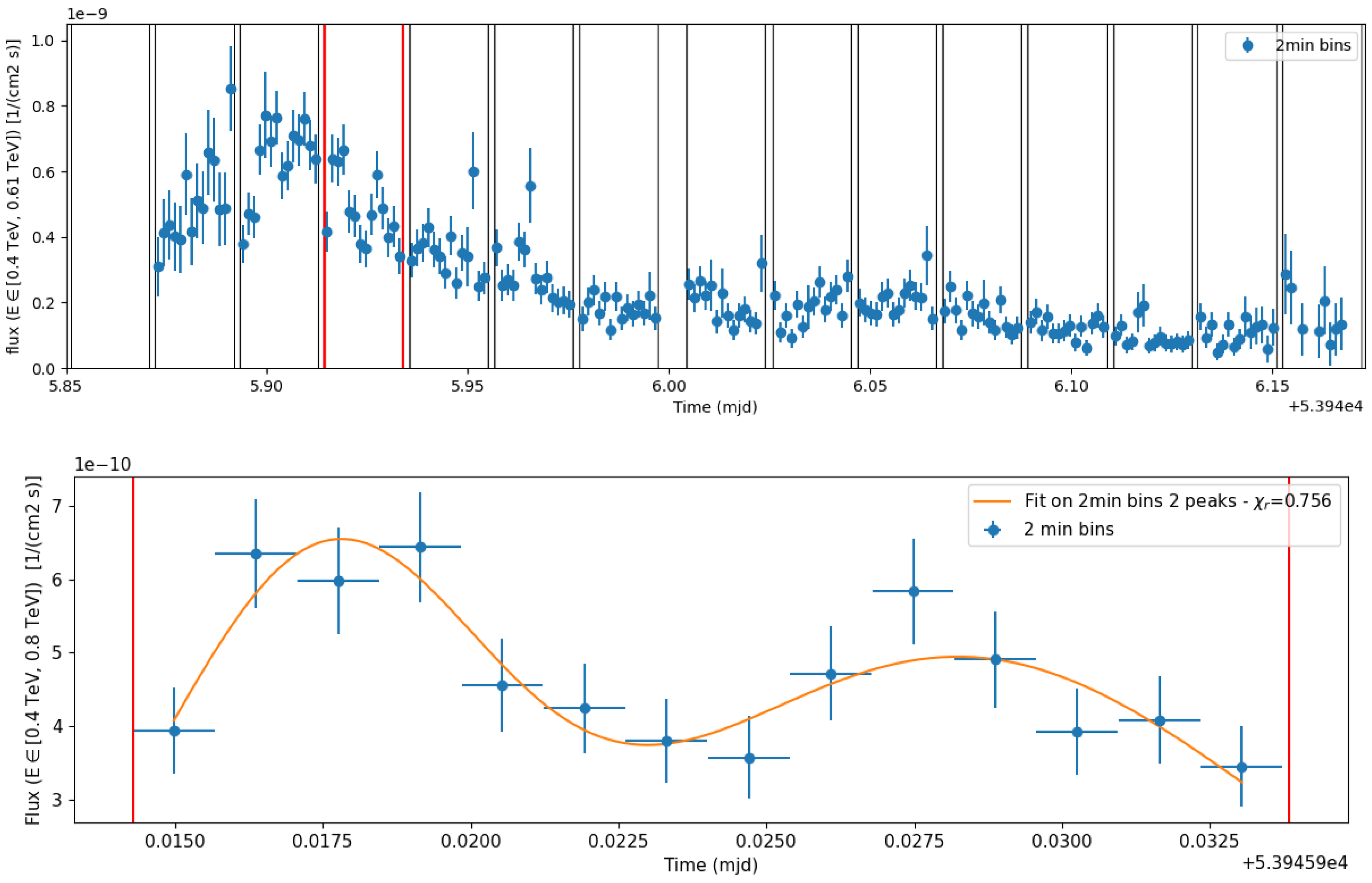
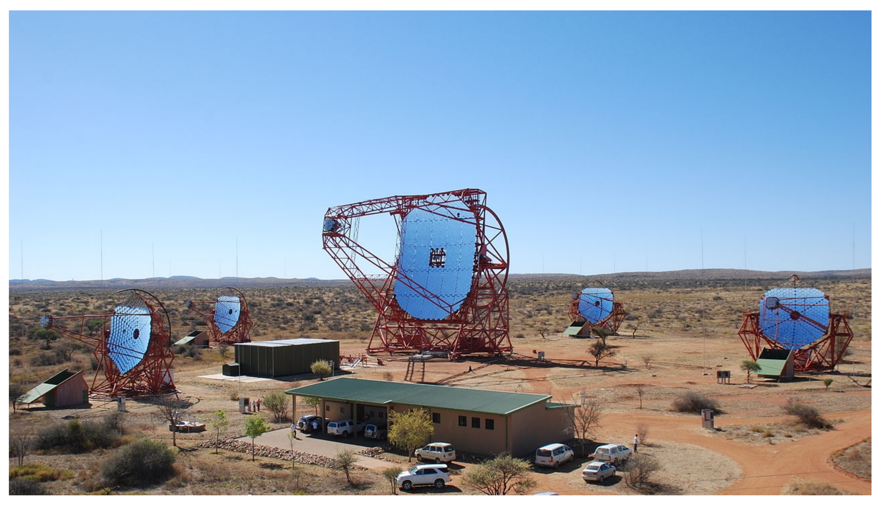


Fig. 1. Lightcurves at low energies: (top) is the whole night - (bottom) is a zoom on the 4th run with a fit of two gaussians



PKS2155 - Chandra flare

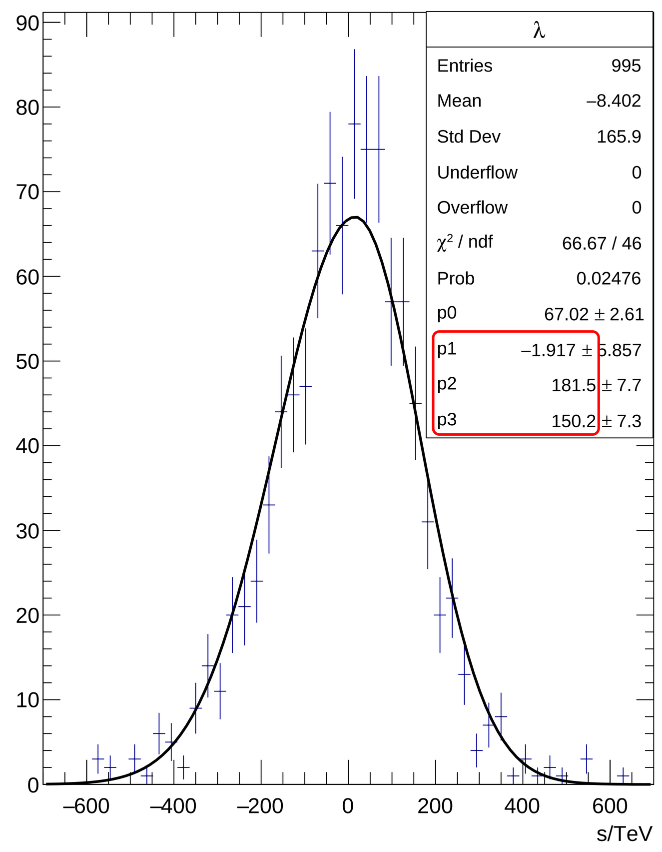


Fig. 2. Distribution of the minima from simulated lists of photons with no injected lag

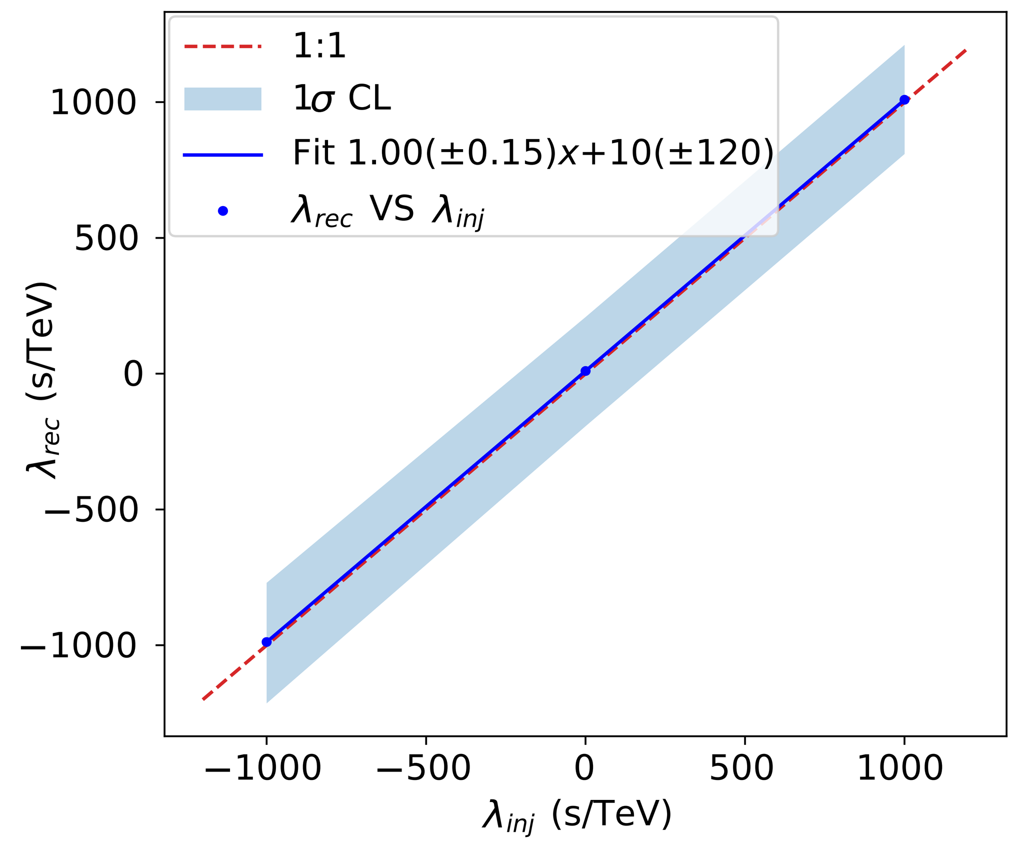
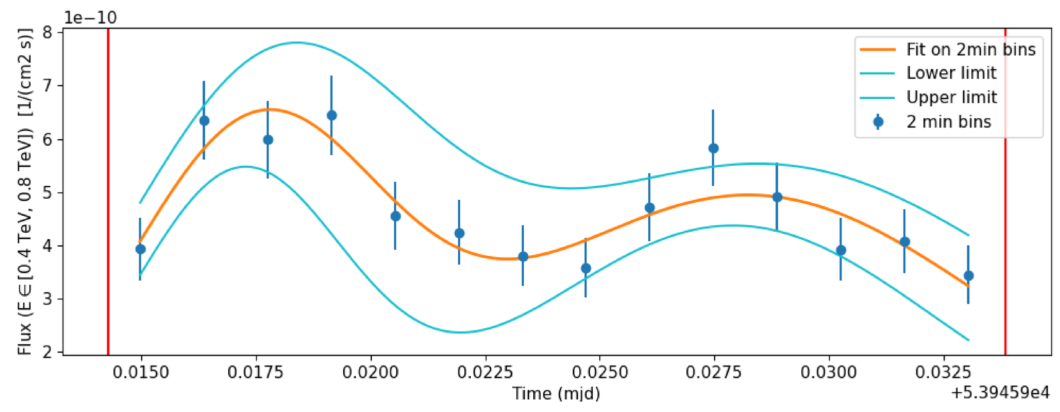


Fig. 3. Plot of the reconstructed VS injected lag

The agreement between reconstructed and injected lag confirm the proper calibration of the reconstruction method. So then the likelihood method is applied to the real list of photons and the lag is extracted.



Spectral index	± 0.02
Redshift	$\pm 10^{-3}$
Background	$\pm 20\%$
Energy scale	$\pm 10\%$

Fig. 4. Errors on lightcurve parameters

Then, re-do the whole process with these nuisances to assess systematic errors in order to get a final limit on E_{QG}.

Result

J&P $\lambda_1 = -146 \pm \left(^{182}_{198}\right)_{stat} \pm \left(^{412}_{405}\right)_{syst}$

$E_{QG,1} > 0.31 \times 10^{18}$ GeV (95% CL)

Conclusion

This result can be compared to other limits obtained from other sources.

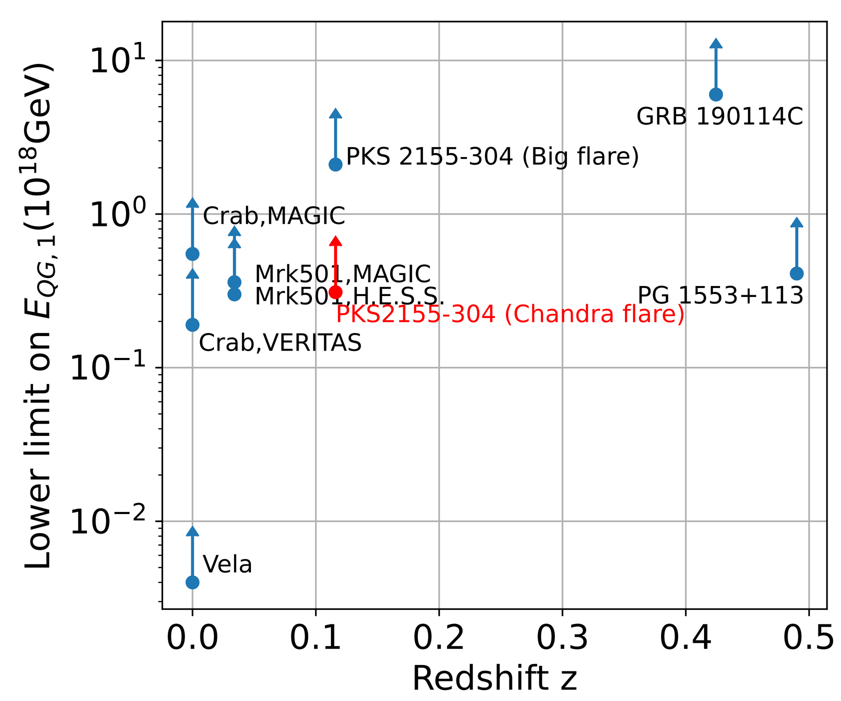


Fig. 5. Limits obtained from different sources, with the linear J&P model

The result is competitive, taking into account the fact that only one run is used. Further improvements are expected using the whole flare. This work is a part of the γ-LIV working group, and combinations of sources from the different IACTs is ongoing.

Bibliographie

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- [2] Martinez & Errando, 2008 Astrop.Phys.
- [3] Bolmont *et al.* 2022 ApJ