Constraints on Lorentz invariance violation from H.E.S.S. observations of PKS 2155-304 flaring period of July 2006

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& γLIV working group

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Outline

Lorentz invariance violation

- Lorentz invariance is central in modern theories (QFT & GR)
- However, for $E \sim E_{Pl} = \sqrt{\hbar c^5/G} \approx 1.22 \times 10^{19}$ GeV, some quantum gravity models (QG) predict that spacetime fluctuations modify photon propagation in vacuum according to their energy
  $\Longrightarrow$ **Lorentz invariance violation (LIV)**
- Study this phenomenon
  - → determine characteristic QG energy E_{QG}
  - → fix constraints on different models predicting LIV

Experimentally detectable effects

LIV expected effects:

Use of a **generic** modified dispersion relation based on a series expansion:

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

Subluminal or superluminal LIV $\rightarrow \pm$
Experiments are only sensitive to $n = 1, 2$

Note that E_{QG} is often compared to E_{Pl}, but could be very different from it

⇒ Photon speed depends on their energy

⇒ **Time delay** between photons with different energies

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

with κ_n the source distance parameter (κ_n increases with z and depends on the considered model), for $n = 1, 2$.

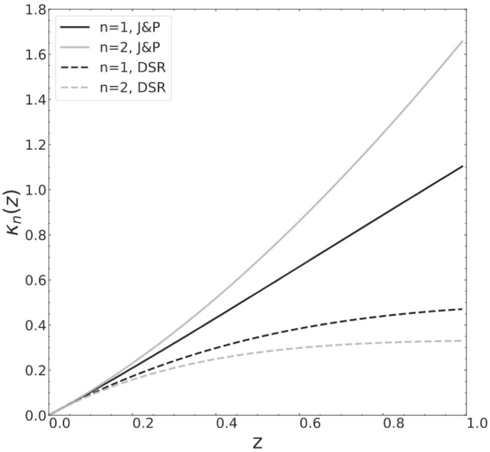


Fig. 1. Different models for κ [Bolmont *et al.* 2022 ApJ]. Other relevant models will be added in the future analysis paper.

Time delays

In practice we want to constrain or measure the **lag parameter**

$$\lambda_n = \frac{\Delta t_n}{\Delta E_n \, \kappa_n(z)} \simeq \pm \frac{n+1}{2 H_0 E_{QG}^n} \quad (3)$$

so we need sources

- up to **very high energies** and large energy range to maximise $\Delta E_n = E_h^n - E_l^n$
- **far away**, so that the speed difference is observed as a large enough time delay between photons to be measured: $d > 1\text{kpc}$ up to $z \sim 0.1$ and more (interaction with the EBL is limiting for higher $z \Rightarrow$ high luminosity sources)
- and **variable**

Current status

- For now, the lower limits obtained on E_{QG} are of the order of $10E_{Pl}$ for individual GRBs, and of the order of 10^{17} GeV when using several GRBs [Ellis *et al.* 2019 Phys.Rev.D]. The best limit obtained by H.E.S.S. is currently 2.1×10^{18} GeV with the PKS 2155-304 flare on the night of July 28, 2006 [Abramowski *et al.* 2011 Astrop.Phys.] (limits obtained for $n = 1$, 95% CL)

- No population study available at TeV energies yet $\rightsquigarrow$ creation of the γ-LIV working group, which is also preparing CTAO LIV analyses

The γLIV working group (H.E.S.S., MAGIC, VERITAS and LST-1)

Goal

Get a combined limit using all available sources (GRBs, flaring AGNs, pulsars) detected by all IACT experiments, plus some Fermi-LAT GRBs $\rightarrow$ first population study at TeV energies

Already achieved

- Development of an analysis framework, to simulate, analyse and combine results from different experiments: **LIVelihood**
- Code tested on simulated data $\rightsquigarrow$ first paper [Bolmont *et al.* 2022 ApJ]

On-going

Combination of real datasets from the 4 collaborations

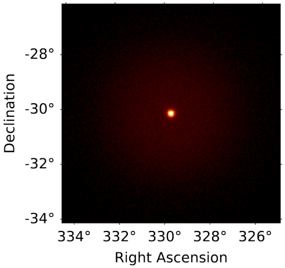
The High Energy Stereoscopic System telescope

- Located in Khomas highlands of Namibia, 1800m a.s.l.
- Array of 5 Cherenkov telescopes (IACT)
- Four 12m mirror telescopes + one 28m mirror telescope
- 100 GeV to 10 TeV

About PKS 2155-304

General information

- BL-Lac object, at z=0.116
- one of the brightest BL-Lac
- enter regular flaring phases
- long term monitoring by H.E.S.S.



In July 2006, H.E.S.S. observed two very bright flares from this source:

- the first night's flare was short and bright and is called the "Big flare"
- the second night's flare benefited from multiwavelength observations and is called "Chandra flare"

$\Longrightarrow$ **Focus on the LIV analysis of the second flare**

PKS 2155-304 July 2006 second flare data

Why this flare?

- Huge data set, not yet analysed for a LIV search
  - Full night of observation, 15 runs, 32612 excess events, 254σ
  - Zenith angle varied from 53° to 8° to 50°
  - Variability timescale down to $\sim$2 minutes
- Possibility for a good limit on E_{QG} & important addition to the combined multi-instrument analysis

The MW analysis of this night was published in [Aharonian *et al.* 2009 A&A]

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- The plan is to use H.E.S.S. public data release on PKS2155-304 29/07/2006 flare as a benchmark and provide a reproducible analysis
- Also, first test of the full analysis using both Gammapy and LIVelihood

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Likelihood technique

Likelihood formula [Martinez & Errando, 2008 Astrop.Phys.]

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

A is the effective area, M the energy migration matrix, Γ_s the spectrum of the source and C_s is the lightcurve
λ is the likelihood parameter to be measured or constrained

$$L(\lambda) = -\sum_i \log \left(\frac{dP}{dE_m dt}(E_{m,i}, t_i; \lambda) \right) \quad (5)$$

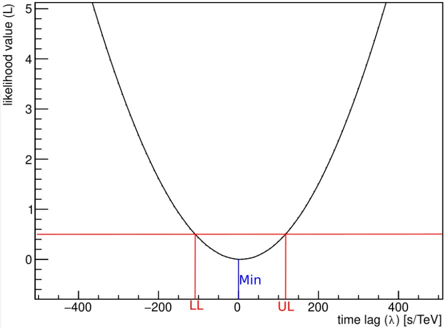


Fig. 2. Likelihood computed from a list of simulated photons following the template time distribution. Minimum and confidence interval at 1σ ($L = 0.5$) are indicated.

PKS2155-304 July 2006 second flare spectrum

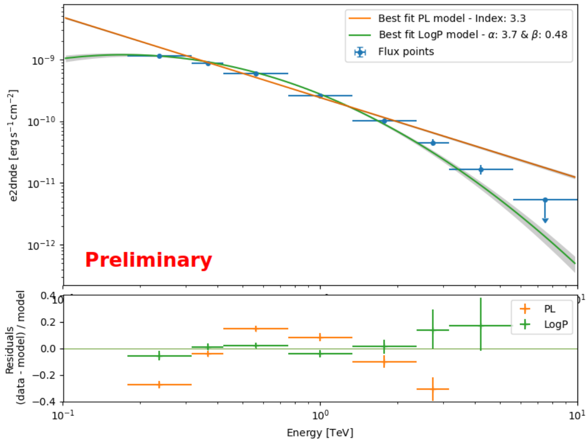


Fig. 3. Spectrum from the PKS2155-304 29/06/2006 flare (H.E.S.S. DR1 with Gammapy)

PKS 2155-304 July 2006 second flare lightcurves

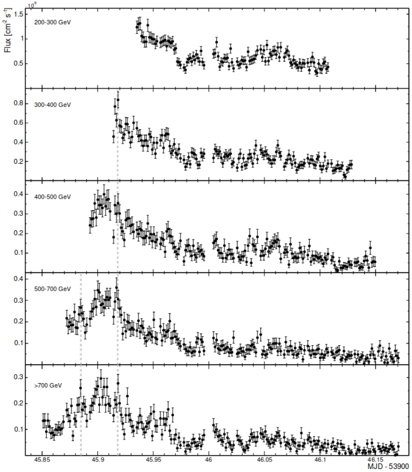


Fig. 4. Lightcurves taken from the original paper [Aharonian *et al.* 2009]

To compute the time lag, we need a **template** lightcurve (from low energy photons) to compare to high energy photons.

In order to not be biased by the absence of low energy photons at higher zenith angles, we apply a cut **E>400 GeV**.

$\Longrightarrow$ split the photons into low and high energy parts, using the median energy (for the full flare $E_{med} = 0.61$TeV)

PKS2155-304 July 2006 second flare lightcurve

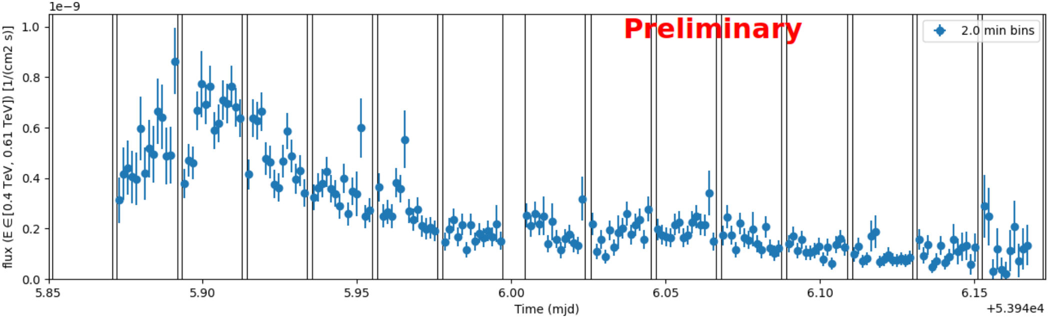
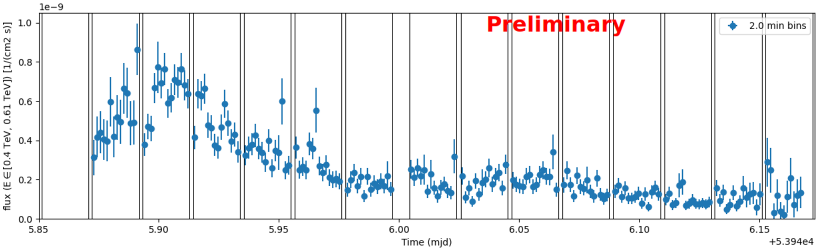


Fig. 5. Lightcurve from H.E.S.S. DR1 at low energies (400-610 GeV). Vertical lines separate runs.

PKS2155-304 July 2006 second flare template lightcurve

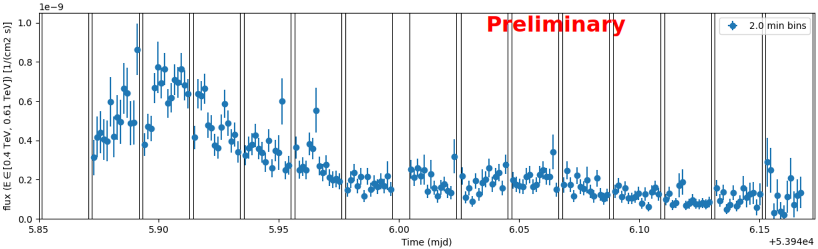
Hard to fit the whole lightcurve because of the many free parameters in the usual fitting method (sum of asymmetric Gaussians)



PKS2155-304 July 2006 second flare template lightcurve

Hard to fit the whole lightcurve because of the many free parameters in the usual fitting method (sum of asymmetric Gaussians)

$\longrightarrow$ introduce new method to get rid of the fit $\Longrightarrow$ **Spline interpolation**



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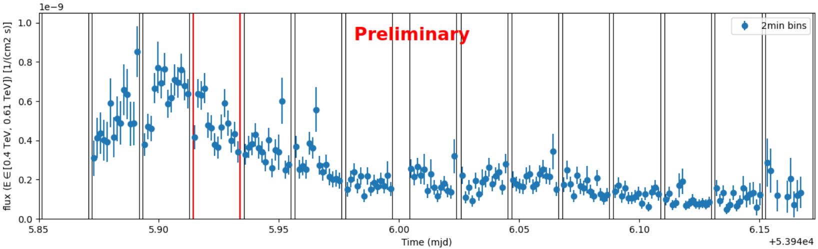
⟶ to validate it, reduce the analysis to the **4th run**, where the fitting method is usable



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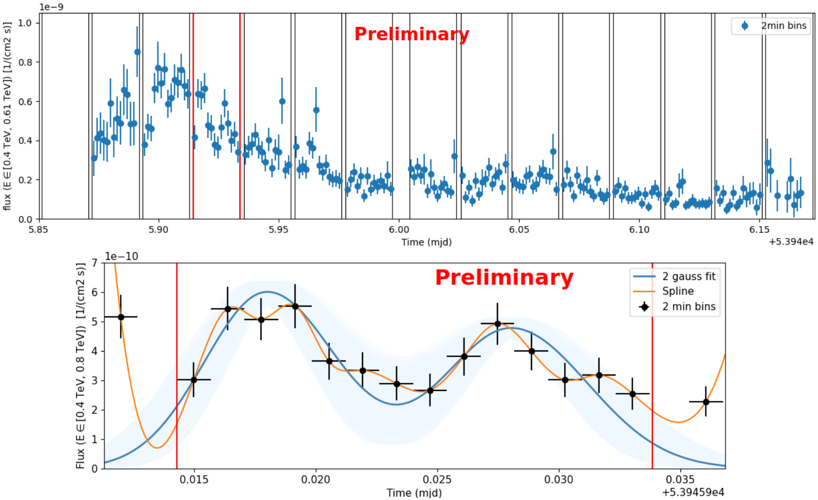


Fig. 6. Two templates for the lightcurve on low energies (in this run [0.4,0.79] TeV)

Reconstruction of the lag from simulations - Sanity check

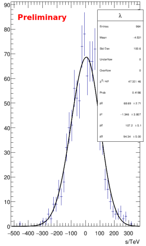
Process

- **Simulate** high and low energy photons from this 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

$\rightarrow$ then repeat the process for 1000 simulations

$\rightarrow$ get the distributions of minimum values and lower and upper limits

$\rightarrow$ extract the mean values of each distribution



$\rightarrow$ reconstructed at -1$\pm$100s/TeV

Fit - Reconstruction of the lag

Repeat with injected lag in the simulated dataset and fill the calibration plot below:

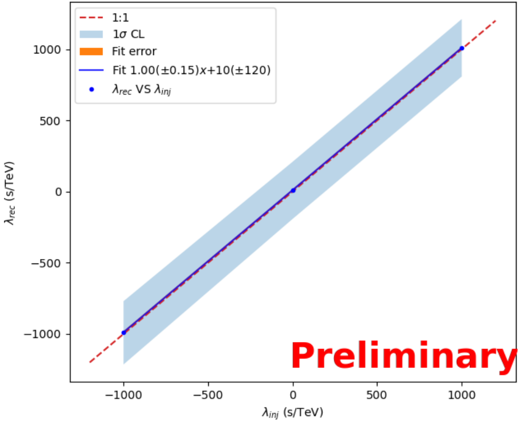


Fig. 7. Plot of the mean reconstructed lag VS injected lag, the blue contour is obtained from the mean lower and upper limits at 1σ

Everything works nicely!

Now let's try on real data

Fit - Likelihood from real data

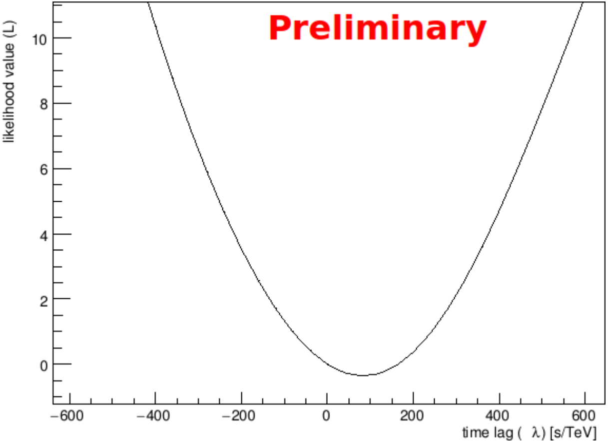


Fig. 8. Likelihood computed from real data

Minimum: 87s/TeV
LL (1σ): -57 s/TeV
UL (1σ): 220 s/TeV

Fit - Systematic errors

Systematic error evaluation process

- Instead of fixing the value of nuisance parameters (such as spectral index, redshift, etc.), let them free in their error bars
- The minimization process finds the best set of nuisance parameters for each given photon list
- Compute the likelihood for one randomly generated list of photons using the formula below

New likelihood formula for systematic error evaluation

$$L(\lambda, \vec{\theta}) = L_S(\lambda) + L_{template}(\vec{\theta_{LC}}) + L_\gamma(\theta_\gamma) + L_B(\vec{\theta}_B) + L_{ES}(\theta_{ES}) + L_z(\theta_z) \tag{6}$$

with

$$L_x(\vec{\theta}_x) = \sum_i \frac{(\theta_{x,i} - \bar{\theta}_{x,i})^2}{2\sigma_{x,i}^2}, \tag{7}$$

assuming a normal distribution.

Fit - Systematic errors

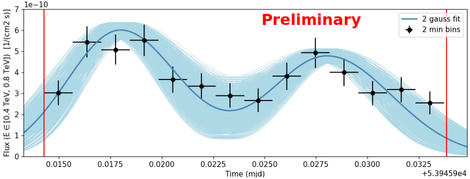


Fig. 9. Errors on lightcurve parameters

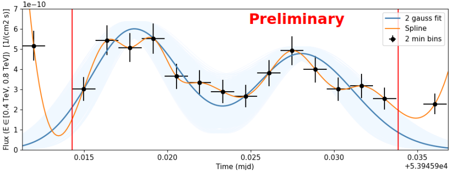
	Template	Spectral index	Redshift	Background proportion	Energy scale
Values	$\pm 1\sigma$	± 0.02	$\pm 10^{-3}$	$\pm 1\%$	$\pm 10\%$
Contribution (s/TeV)	204	23	11	~ 1	18

Finally, compute the energy limit from the mean value and systematic error (see at the end for the result)

J&P $\lambda_1 = 87 \pm \binom{110}{113}_{stat} \pm \binom{208}{202}_{syst}$ s/TeV

Spline - Template, calibration and application to real data

Follow the same procedure: define lightcurve template, check the calibration, apply to real data and study systematics



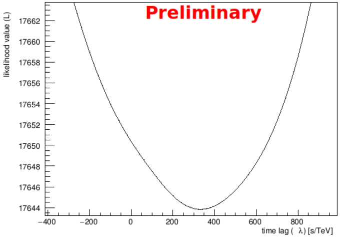


Fig. 10. Likelihood curve from real data.

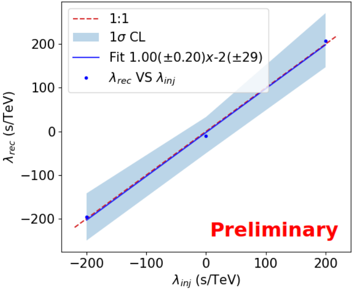


Fig. 11. Calibration plot for the spline template.

Real data likelihood

Minimum: 333 s/TeV
1σLL: 236 s/TeV
1σUL: 428 s/TeV

Spline - Difference between the fitting method and the spline interpolation to evaluate the systematic errors

For fitted templates

- We choose a certain basic shape (Gaussian, asymmetric Gaussian, sum of these, etc.) and fit it to the real data, giving best values and error bars on the fitting parameters
- We define a TF1 following this basic shape with those best parameter values
- The minimization process finds the best values within the error bars for each parameter and for each photon list

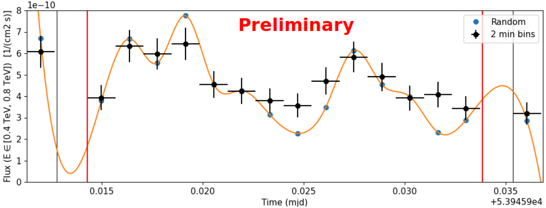
For spline templates

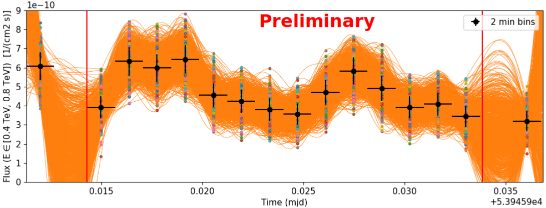
- We choose which kind of spline to use (cubic splines) and interpolate the flux lightcurve
- Problem here: **we don't have errors on parameters** of the spline, it's an interpolation!

Systematic error from the spline template

Method

Interpolate splines (1000) from the fluctuations of the flux points within their error bars





Generate photon lists (1000) as before

Associate randomly each spline to one photon list to calculate the likelihood

Spline - All systematic errors

Using this method, but taking all the nuisance parameters into account, the distribution of the minima becomes:

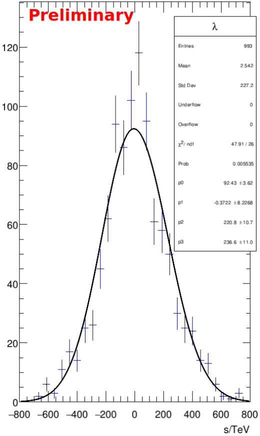


Fig. 12. Distribution of $\lambda_{\rm rec}$ from 1000 simulations following the real photon list time and energy distribution.

Values

Minimum = 0s/TeV
1σLL = -221s/TeV
1σUL = 237s/TeV

$\downarrow$

Systematic error

$\pm \binom{210}{195}$ **s/TeV**

All errors

J&P

$$\lambda_1 = 333 \pm \binom{111}{103}_{stat} \pm \binom{210}{195}_{syst} \text{ s/TeV}$$

Note: compatible with the fit method λ

Spline - All systematic errors

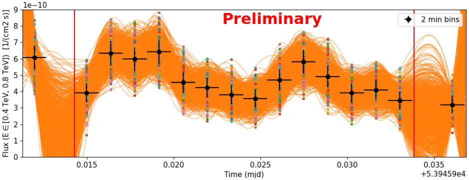


Fig. 13. Error from lightcurve template

	Template	Spectral index	Redshift	Background proportion	Energy scale
Values	/	± 0.02	$\pm 10^{-3}$	$\pm 1\%$	$\pm 10\%$
Contribution (s/TeV)	198	23	11	~ 1	18

Finally, compute the energy limit from the mean value and systematic error (see at the end for the result)

Results (Preliminary) - Jacob&Piran n=1

Limits on E_{QG} at 95% CL

Chandra flare Run 4 (Fit)	8.4e17 GeV
Chandra flare Run 4 (Spline)	5.6e17 GeV
Big flare	2.1e18 GeV

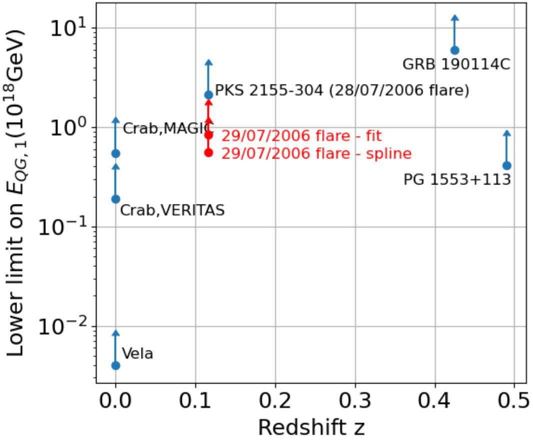


Fig. 14. Current limits on $E_{QG,1}$

Conclusions and next steps

Spline interpolation method

- Spline interpolation **doesn't assume** a lightcurve shape and is easier to implement
- However systematic error from the template is trickier to obtain

PKS 2155-304 29/07/2006 flare

- Analysis on run 4 is final and provide a **good limit** with one run
- **Allowed to compare** the spline interpolation and fitting methods

Now:

- Apply this method to the **whole flare** and extract the E_{QG} limit
- Combine the data from the two nights
- The MAGIC collaboration published a paper on another method using non-parametric template [MAGIC Collaboration *et al.* 2024], which could be compared to this method