Constraint on Lorentz invariance violation: First combined limit from a cooperation of Imaging Atmospheric Cherenkov Telescopes

Ugo Pensec for the γLIV WG

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H.E.S.S. CTAO LST COLLABORATION MAGIC VERITAS Enigmass HrZZ Hrvatska zaklada za znanost

Outline

Lorentz invariance violation

- Lorentz invariance is fundamental 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) allow for the interaction of spacetime fluctuations with photons, modifying their 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

- Phenomenology: use of a **generic** modified dispersion relation (MDR) based on a series expansion:

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

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

Time delays

MDR $\Rightarrow$ Photon speed depends on its energy

$\Rightarrow$ **Time delay** between photons with different energies (emitted from the same source at the same time):

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

with κ_n the source distance parameter (κ_n increases with z and **encodes the space-time model**), for $n = 1, 2$.

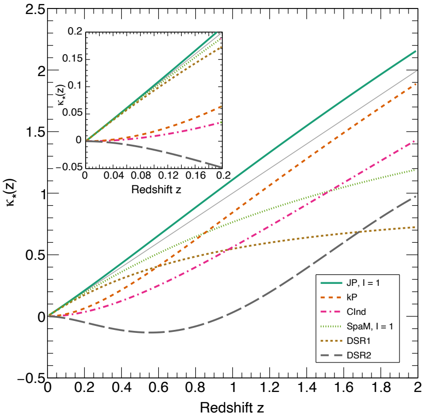


Fig. 1. Different models for κ [Caroff *et al.*, 2025, Phys. Rev. D]. Other relevant models will be added in the future analysis paper.

Time-of-flight studies

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

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

so we need sources

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

Candidates = **Blazar flares, GRBs, and pulsars**

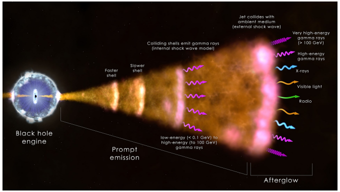
Source types

Active galactic nuclei (AGN)

Blasar flare : VHE (up to $\approx 10\,\text{TeV}$), $z \sim 0.1$, active phases happen regularly (up to several times a year) and can last several days

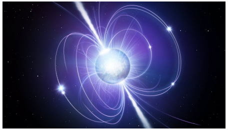
Gamma Ray Bursts (GRB)

VHE (up to $\approx 10\,\text{TeV}$), up to $z \approx 1$, but brief (few seconds to few minutes) and unpredictable



Pulsars

HE (up to $\approx 1\,\text{TeV}$), galactic sources, strong variability $\rightarrow$ accumulate data to improve sensitivity



Current status

- For now: best lower limits obtained on E_{QG} are $\sim 10 E_{Pl}$ for individual, bright GRBs
- Best limit obtained from the combination of several GRBs observed by *Fermi*-LAT is $\sim 10^{17}$ GeV [Ellis *et al.* 2019 Phys.Rev.D]
- Different sources have different advantages $\rightarrow$ interesting to combine their strength and use sources at different distances $\Longrightarrow$ **population study**
- 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

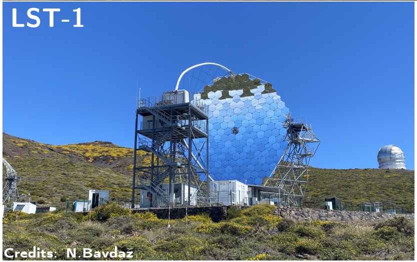
Already achieved

- **LIVelihood**: analysis framework (unbinned maximum likelihood approach), to simulate, analyse and combine results from different experiments
- Code tested on simulated data $\rightsquigarrow$ first paper [Bolmont *et al.* 2022 ApJ]

On-going

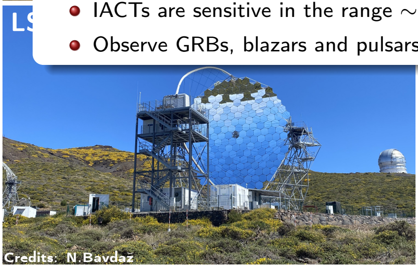
- Combination of real datasets: 3 BL-Lac flares observed by LST-1, GRB190114C observed by MAGIC, one 1ES 1959+650 flare observed by VERITAS and one PKS2155-304 flare observed by H.E.S.S. (presented here)
- Combination of all the available datasets from the 4 collaborations

Imaging Atmospheric Cherenkov Telescopes



Imaging Atmospheric Cherenkov Telescopes

- H.E.S.S. is located in Namibia, MAGIC and LST-1 in the Canary Islands, and VERITAS in the USA
- IACTs are sensitive in the range $\sim 100\,\mathrm{GeV}$ to $\sim 10\,\mathrm{TeV}$
- Observe GRBs, blazars and pulsars


Credits: N.Bavdaz


Credits: VERITAS collaboration

Likelihood technique

Idea:

Define a *template lightcurve* from LE photons.
Compare arrival time of HE photons to this template.

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

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

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

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

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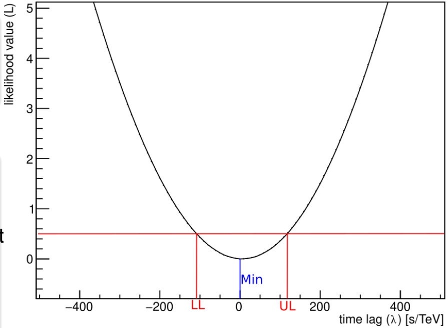
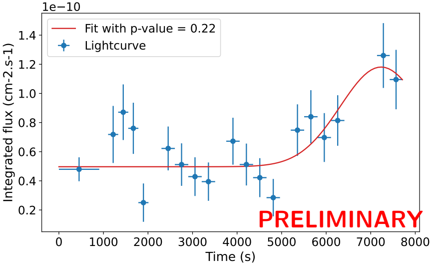


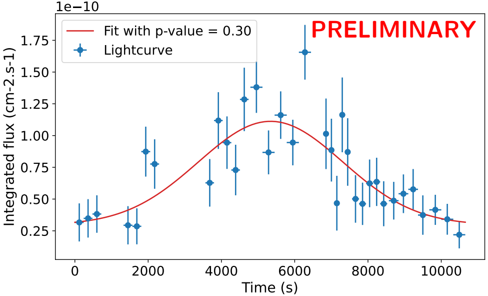
Fig. 4. Likelihood computed from a list of simulated photons following the template time distribution. Minimum and confidence interval at 1σ ($L = 0.5$) are indicated.

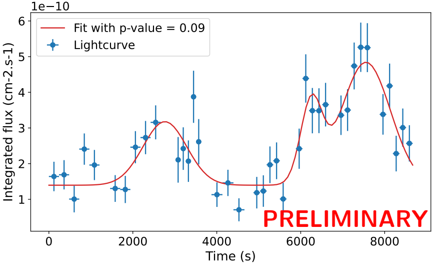
BL-Lac lightcurves (preliminary)

BL Lacertae

Bright flaring blazar ($z = 0.069$)
3 flaring nights selected after a scan of all AGN data from 2021 to May 2025 (34 sources, 505 nights)
Analysis by Cyann Plard and Sami Caroff from LST observations



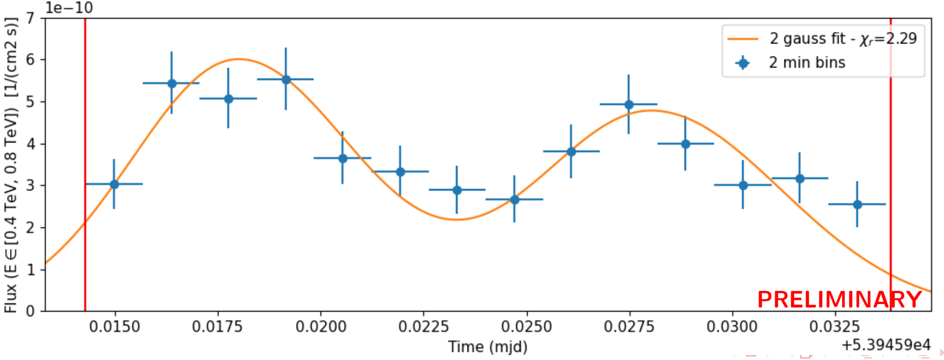




PKS 2155-304 lightcurve (preliminary)

PKS 2155-304

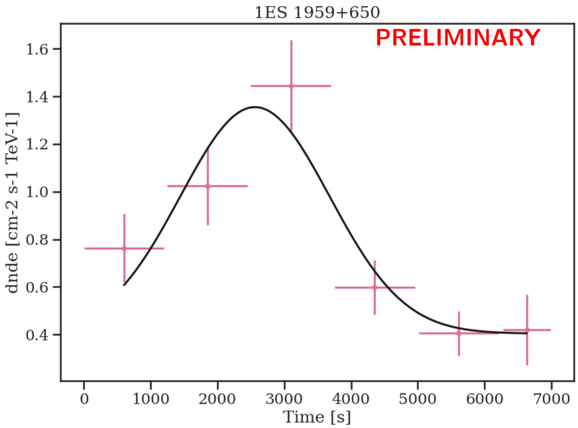
Bright and regularly flaring blazar ($z = 0.116$)
Long term monitored by H.E.S.S.
Flare of July 29, 2006 [Aharonian *et al*, 2009, A&A]
Analysis by me (Ugo Pensec) and Julien Bolmont from H.E.S.S.



1ES 1959+650 lightcurve (preliminary)

1ES 1959+650

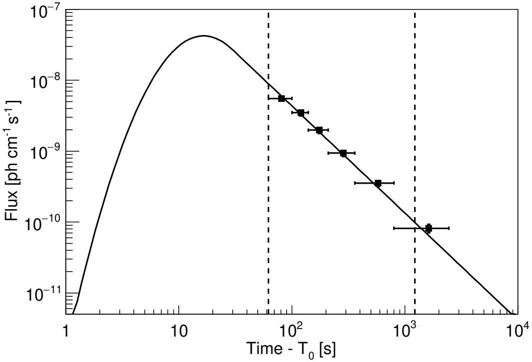
Bright flaring blazar ($z = 0.047$)
Flare of May 20, 2012 [Aliu *et al.*, 2014, ApJ].
Analysis by Samantha Wong from VERITAS



GRB 190114C lightcurve

GRB 190114C

Bright GRB ($z = 0.425$)
On January 14, 2019 [Acciari *et al.*, 2019, Nature]
Analysis by Tomislav Terzic from MAGIC



[Acciari *et al.*, 2020, Phys. Rev. Lett.]

Reconstruction of the lag with the combined sources

Using an **unbinned maximum likelihood** approach, contributions add up: [Bolmont *et al.* 2022 ApJ]

$$L_{\mathrm{comb}}(\lambda_n) = \sum_{\text{all sources}} L_S(\lambda_n).$$

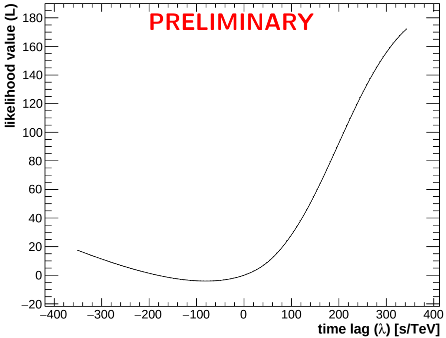


Fig. 5. Likelihood computed on the **real data** from the 4 flares.
Minimisation gives: $\lambda_{\mathrm{rec}} = -80^{+78}_{-98}$ s/TeV at 95% CL.

Sources of bias:

- Computational parameters (discretisation of the IRFs)
- IRFs are assumed constant over each observation run

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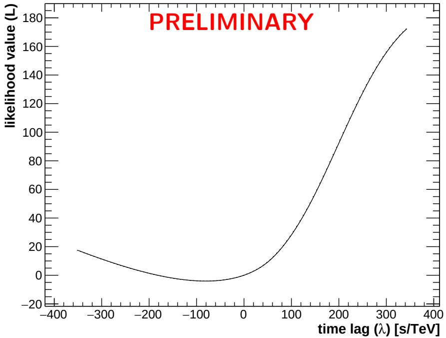

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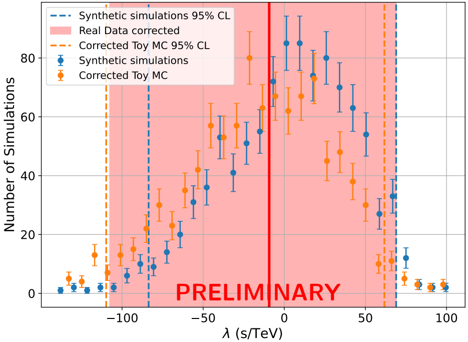

Fig. 6. Correction of the bias computed with bootstrap simulations
λ_{rec} becomes $\lambda_{\text{rec}} = -9.3^{+78}_{-98}$ s/TeV at 95% CL.

Results from the combination

2 models: ·J&P, a common model in LIV searches
·DSR model designed to cancel the contribution of GRB 190114C

Limits (n=1) (Preliminary result)

	J&P	DSR
superluminal	4.44×10^{18} GeV	0.448×10^{18} GeV
subluminal	5.58×10^{18} GeV	0.615×10^{18} GeV

/!\ Analysis doesn't take into account all the systematics
$\Longrightarrow$ combined limit will be reduced

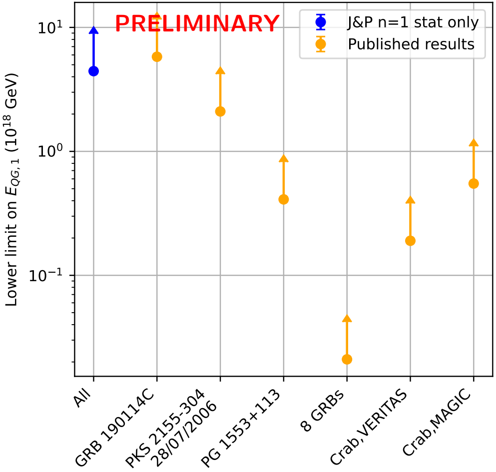

Fig. 7. Current limits on $E_{J\&P,1}$ (subluminal)

Conclusion

- First constraint on LIV derived from a collaborative analysis combining real data from all major IACTs: H.E.S.S., MAGIC, VERITAS, and the LST-1 of CTAO
- Result obtained using different source types, spread over a wide range of redshifts
- Competitive limit obtained, which enhances the robustness and sensitivity of LIV searches
- Demonstrate the scientific value of cooperation in LIV studies in the IACT community
- Current goal: combine all other available sources (other observation of blazar flares are available, as well as pulsars and GRBs from the four experiments)
- Work currently ongoing on studying different lag-redshift models

Thank you!

Source intrinsic effects

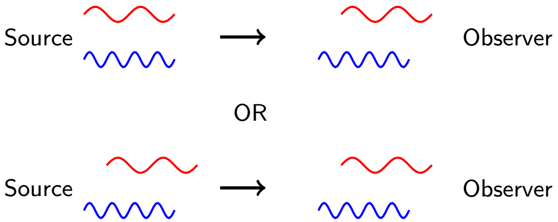

Fig. 8. LIV or intrinsic effect?

Examples

Acceleration mechanism, source extension...

Solution

- **population study**: mitigate the intrinsic effects influence by looking at sources of the same type but at different distances
- **modelisation**: constrain intrinsic effects with modelisation of acceleration mechanisms

J&P

$$\kappa_n^{J\&P}(z) = \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}} dz' \tag{6}$$

Doubly Special Relativity

$$\kappa_n^{DSR}(z) = \int_0^z \frac{h^{2n}(z')}{(1+z')^n\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}} dz' \tag{7}$$

with

$$h(z') = 1 + z' - \sqrt{\Omega_m(1+z')^3+\Omega_\Lambda} \times \int_0^{z'} \frac{dz''}{\sqrt{\Omega_m(1+z'')^3+\Omega_\Lambda}} \tag{8}$$