Predicting the limits on Lorentz invariance violation effects from flaring blazars using the Cherenkov Telescope Array

A. Rosales de León[1,2], J. Bolmont[1], H. Sol[2]

[1] Sorbonne Université, CNRS, IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), 4 place Jussieu, F-75252 Paris, France

[2] Laboratoire Univers et Théorie (LUTh), Observatoire de Paris-Meudon, 5 Place Jules Janssen, 92190 Meudon, France

MOTIVATION AND SUMMARY

Lorentz Invariance Violation (LIV) effects could be spotted by Imaging Atmospheric Cherenkov Telescopes (IACTs) by searching for energy-dependent time delays in the gamma-ray photons coming from distant and highly variable astrophysical sources. As part of its scientific program, The Cherenkov Telescope Array Observatory (CTAO) will explore problems in fundamental physics, including studying and constraining the Extragalactic Background Light (EBL), searching for LIV effects and setting constraints on the characteristic LIV energy scale. This work presents the results from a feasibility study performed by simulating realistic observations with the CTA-AGN-VAR pipeline, a Python package based on Gammapy. Using an AGN Evolution Simulator Code (AGNES), the broadband spectra of a TeV blazar flare were modelled using a time-dependent one-zone Synchrotron-Self-Compton (SSC) scenario, and the presupposed LIV delays were introduced as linearly energy-dependent time-lags. Observations with the CTAO Alpha and Omega configuration arrays were assumed for our simulations, taking into account observational constraints. The response and limits on a significant detection of intrinsic and LIV time delays are predicted for CTAO under the assumed scenario.

INTRODUCTION

A searching strategy proposed to identify LIV signatures from Very High Energy (VHE) remote cosmic sources, such as blazars, is to look for energy-dependent time delays on the arrival-time of photons at different energies [1]. Particularly, flaring episodes from blazars have been analysed to check for LIV signatures in the VHE gamma-ray data from the current generation of Imaging Atmospheric Cherenkov Telescopes (IACT) [2,3].

AGN Modelling: AGNES [4]

- Based on Mrk 421 bright TeV flare of Feb, 2010 [5].
- One-zone SSC model parameterization [6].
- Intrinsic cooling-driven regime [7]: fast acceleration, slow decay, and **decreasing trend** of time delay with energy at VHE.
- ~5.5 h evolution of the flare.
- Output: SED snapshots with different values of injected LIV delays.

LIV injection:

- 1st order correction to the dispersion relation [1]:

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

- Linear dependency of time lags with energy.
- Test subluminal (+) and superluminal (-) LIV effect.
- Injected LIV time delays: ±400, ±200 s/TeV.

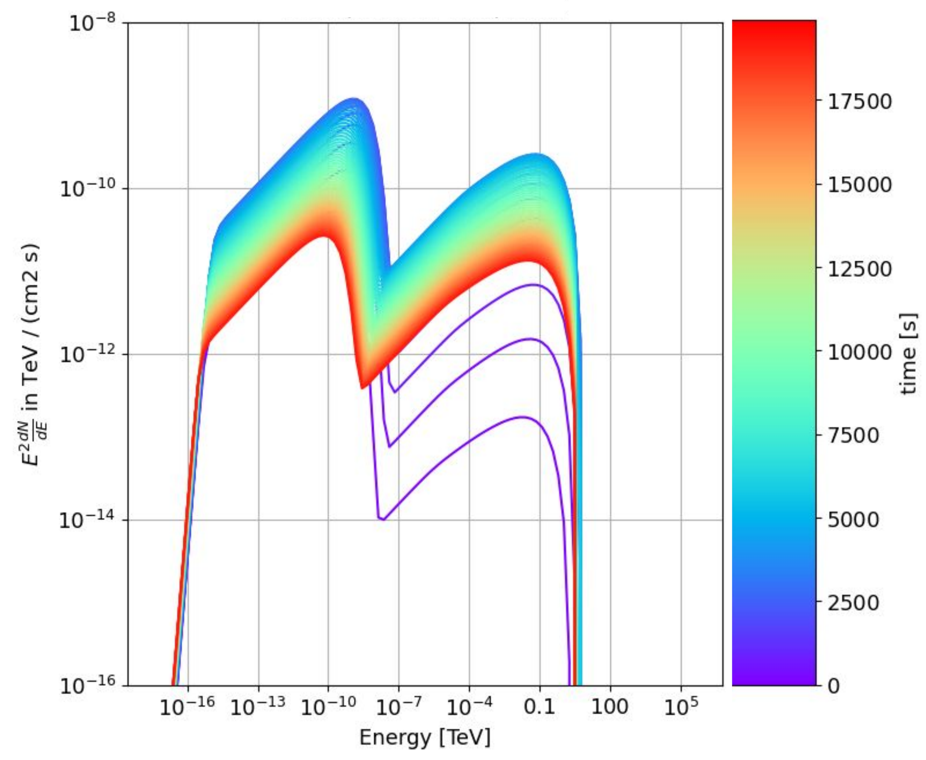

Fig. 1. Temporal evolution of the SED during the flaring state computed with AGNES.

CTA-AGN-VAR PIPELINE [8]

- Alpha array configuration:
  CTA-N: 4 LSTs and 9 MSTs
  CTA-S: 14 MSTs and 37 SSTs
- Omega array configuration:
  CTA-N: 4 LSTs and 15 MSTs
  CTA-S: 4 LSTs, 25 MSTs, 70 SSTs
- Prod5 v0.1 IRFs [10]
- Follow-up of Mrk421 by CTA-N and of a virtual twin flare by CTA-S.
- Fit an analytical spectral model: Power Law + Exp Cut-Off
- Extragalactic Background Light (EBL) attenuation effect [11].
- Input: Temporal evolution of the SED during flare with and without an injected LIV delay.

OUTPUT

- Output: Reconstructed light curves from simulations on different energy bands.
- Light curves are fitted using a Fast Rise Exponential Decay (FRED) function:

$$F(t) = A\lambda e^{\left(-\frac{\tau_1}{t-t_s} - \frac{t-t_s}{\tau_2}\right)}$$

where $\lambda = e^{(2\tau_1/\tau_2)^{1/2}}$

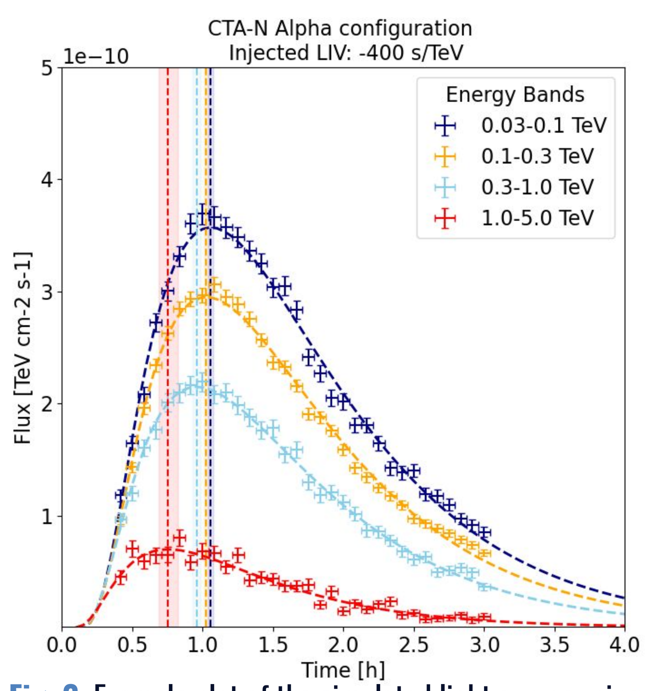

Fig. 2. Example plot of the light curves using CTA-AGN-VAR.

THE FUTURE OF LIV SEARCHES:

- Use LIVelihood [12]: a code for Lorentz Invariance Violation searches in gamma-ray astronomy, to: Asses the LIV limits, including the systematic errors by analysing photon lists of simulated gamma-ray events with CTA-AGN-VAR.
- Improvements: Modify the code to include the effects of intrinsic time delays.
- Produce a common platform for analysing simulated and real data from IACTs (CTA-AGN-VAR + LIVelihood).
- Being able to perform joint analysis of all available IACTs data and get ready for the CTAO era: combine analysis of sources and both observatories (CTAO-North and CTAO-South)

INTRINSIC AND LIV TIME DELAYS

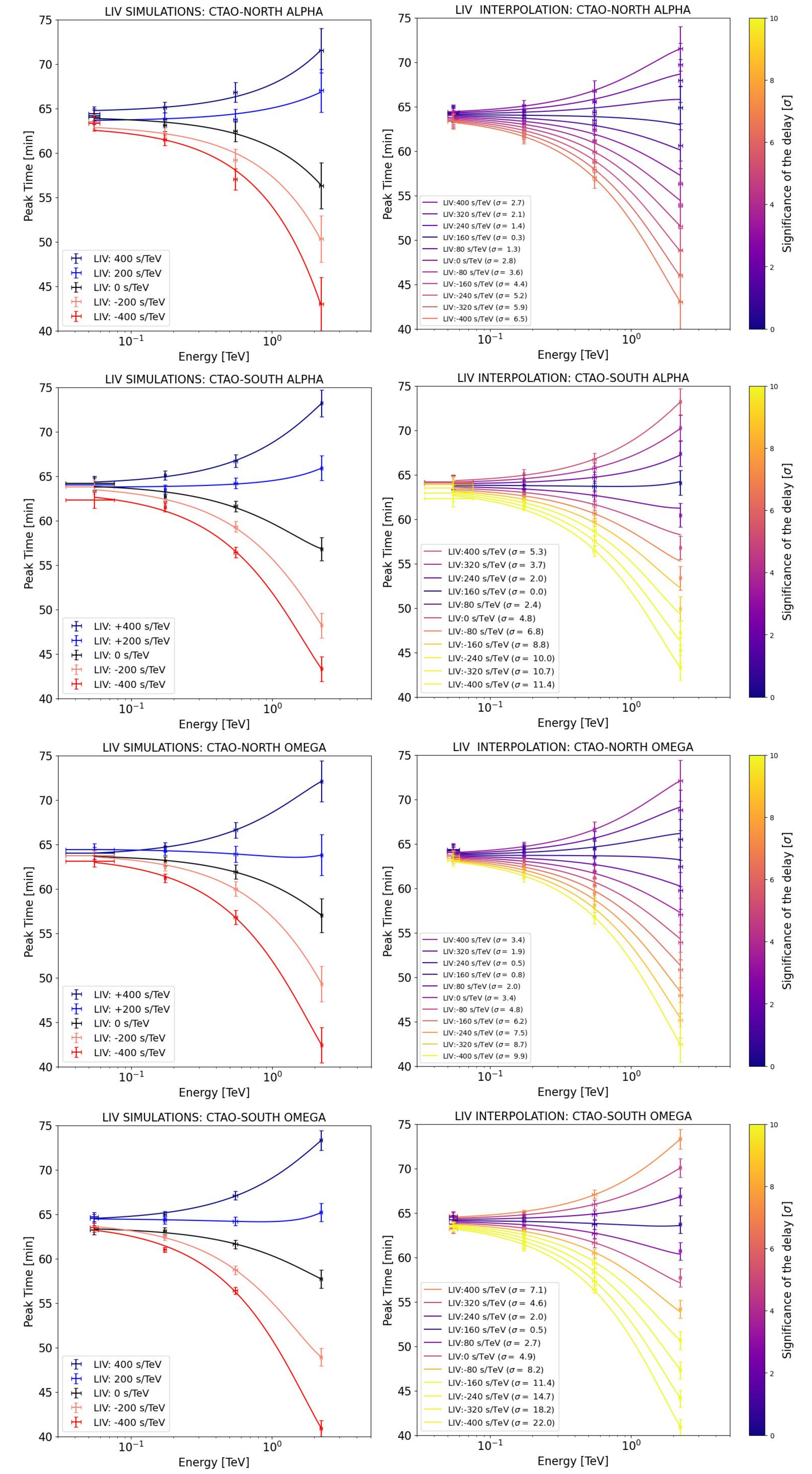

Fig 2. Peak time of light curves as a function of energy for the different CTAO configurations: the simulated observations (left panel) were used to predict the significance of the time delay in a range of LIV injected values using a 2nd degree polynomial interpolation (right panel).

CONCLUSIONS

- An injected LIV of ~160 s/TeV compensates the effect of the intrinsic time delay.
- For the intrinsic case (LIV=0 s/TeV), the significance of the time delay is ~3σ level for the CTAO-N Alpha array and ~5σ level for CTAO-S Omega array.
- CTA-S Omega array has a better performance overall. The uncertainty on the measured time delay can be reduced up to 30% in comparison to the Alpha array (See Fig. 2).
- Assuming Markarian 421 might have a flaring episode like this in the future, the predicted limits for the subluminal/superluminal scenario:
  CTAO-N Alpha: 400 s/TeV (~2.7σ) / -240 s/TeV (~5.2σ) CTAO-N Omega: 400 s/TeV (~3.4σ) / -100 s/TeV (~5.2σ)
  CTAO-S Alpha: 400 s/TeV (~5σ) / -20 s/TeV (~5.4σ) CTAO-S Omega: 320 s/TeV (~5σ) / -20 s/TeV (~5.7σ)
- For an injected LIV of 400 s/TeV, the approximated energy scale would be E_{QG} ~1.9×10^{19} GeV

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