Lorentz invariance violation searches and intrinsic effects with the Cherenkov Telescope Array: A feasibility study for flaring blazars

cherenkov telescope array

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MOTIVATION AND SUMMARY

Lorentz Invariance Violation (LIV) effects arise in some Quantum Gravity (QG) models due to quantum space time fluctuations that may exist at the Planck scale (~10^{-35} m, ~ 10^{19} GeV). A possible LIV signature could be spotted by searching for energy-dependent time delays in the gamma-ray photons coming from distant and highly variable astrophysical sources. Blazars and Gamma-ray bursts (GRBs) have been identified as the most promising sources for the search of these effects. As part of its scientific program, CTA will explore problems in fundamental physics, including searching for LIV effects and setting constraints on the characteristic LIV energy scale. CTA observations of flaring blazars would enable to look for spectral lags in the GeV–TeV range with high precision, in order to discriminate between possible LIV effects and time delays produced by emission and acceleration mechanisms at the source. In this work, the results from a feasibility study of the expected CTA potential to detect LIV and intrinsic time delays from blazars' flares are presented alongside the methodology, modeling, and simulation tools used for this purpose.

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 Modeling: 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.

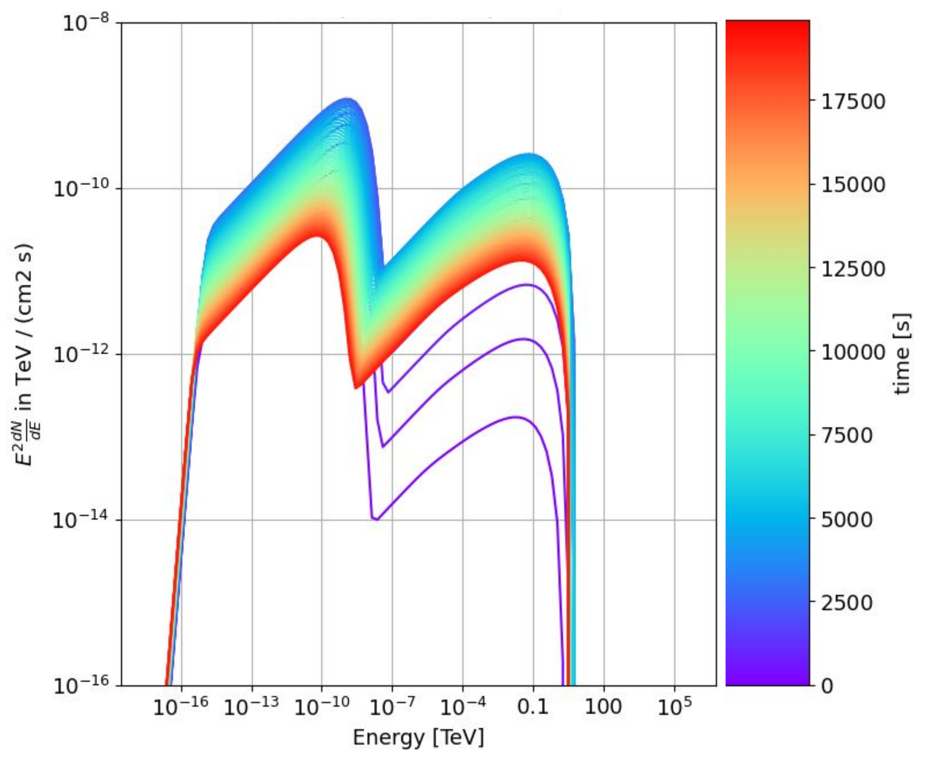

Fig. 1. Temporal evolution of the SED during the flaring state computed with AGNES.

CTA-AGN-VAR Pipeline [8]

- Input: AGN time-dependent spectral model.
- Dynamical selection of CTA Instrument Response Functions (IRFs).
- Takes into account observational constraints.
- Simulation of gamma-like events [9].
- Light curve reconstruction from input model.

Output and Open Questions

- Light curve comparison with and without LIV induced time delay in different energy bands.
- Would CTA detect intrinsic time delays?
- Is there an observable LIV signature?
- How can we discriminate LIV from intrinsic time delays?

SIMULATIONS: THE CTA-AGN-VAR PIPELINE

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

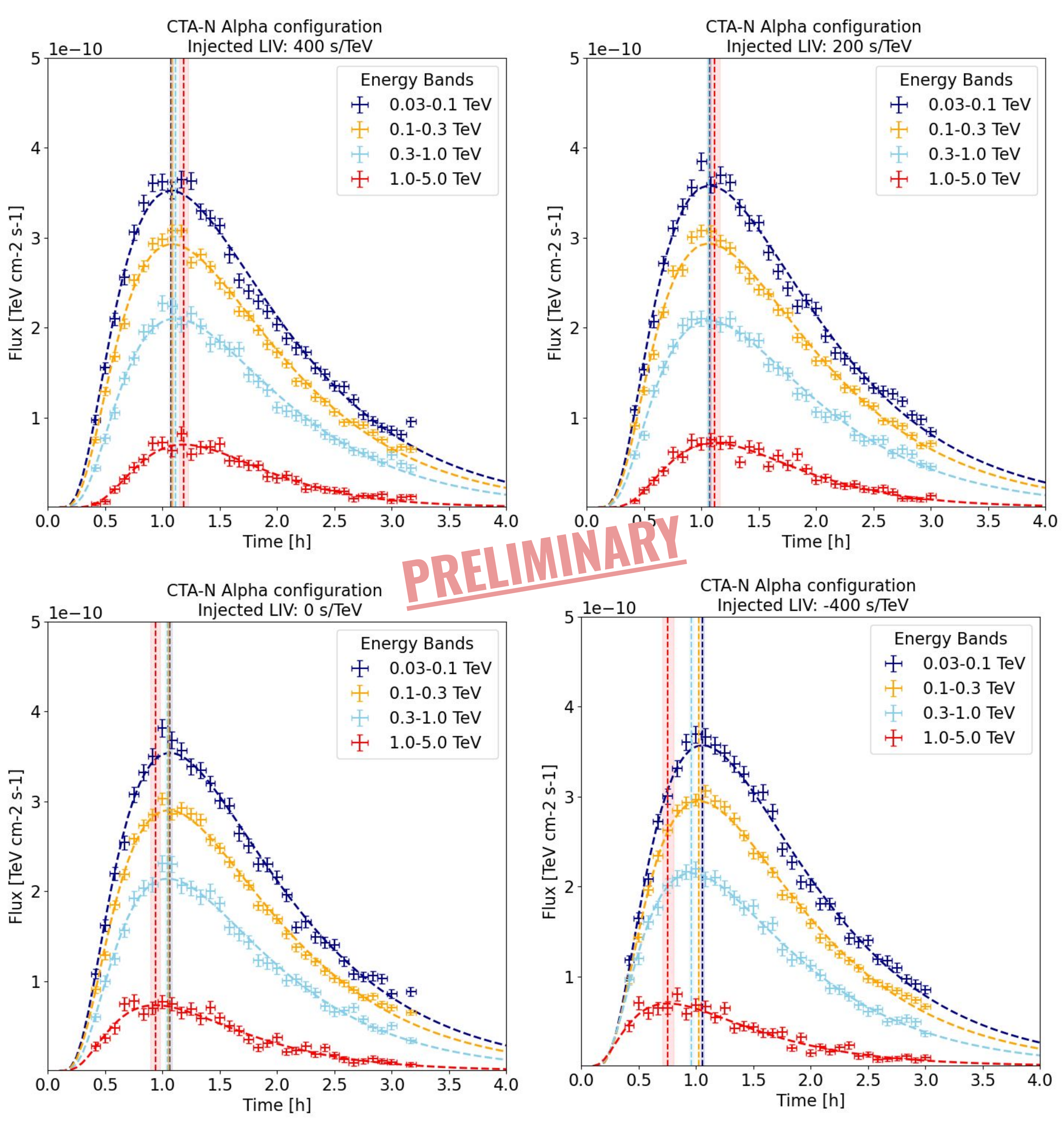

Fig 2. Simulated light curves in energy bands as possibly observed by CTA-N Alpha configuration using 5 min time bins and different values of injected LIV delays. Only time bins with significant flux detection (>5σ) are shown.

❖ CTA-N Alpha configuration array seems to be sensitive at TeV energies to the effect of the injected LIV time delays.

INTRINSIC AND LIV TIME DELAYS

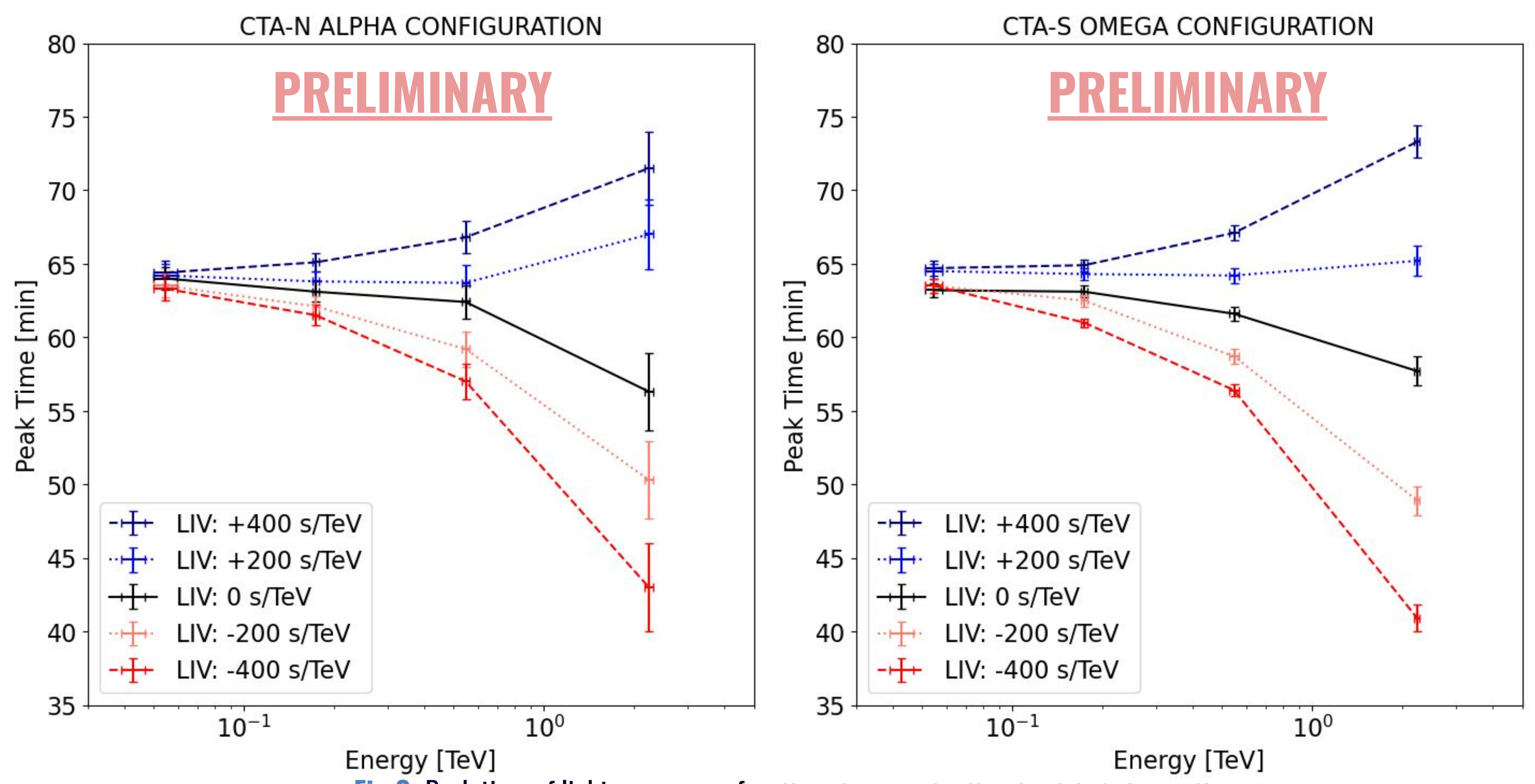

Fig 3. Peak time of light curves as a function of energy for the simulated observations.

$\Delta t_{LIV} = t_{HE} - t_{LE}$	$\Delta t \pm \sigma t$ [min] LIV= 400 s/TeV	$\Delta t \pm \sigma t$ [min] LIV= 200 s/TeV	$\Delta t \pm \sigma t$ [min] LIV= 0 s/TeV	$\Delta t \pm \sigma t$ [min] LIV= -200 s/TeV	$\Delta t \pm \sigma t$ [min] LIV= -400 s/TeV
CTA-N Alpha	6.6 ± 2.6	2.7 ± 2.6	-7.7 ± 2.7	-12.4 ± 2.7	-18.1 ± 3.1
CTA-N Omega	8.0 ± 2.4	-0.6 ± 2.4	-6.6 ± 2.0	-14.3 ± 2.1	-19.7 ± 2.1
CTA-S Alpha	9.0 ± 1.8	2.0 ± 1.6	-7.4 ± 1.5	-15.6 ± 1.6	-19.1 ± 1.7
CTA-S Omega	8.6 ± 1.2	0.7 ± 1.1	-5.6 ± 1.1	-14.6 ± 1.1	-22.6 ± 1.0

Table 1. Predicted peak time difference for the CTA configuration arrays between HE (1-5 TeV) and LE (0.03-0.1 TeV) band light curves. The color scale indicates the significance of the delay: <2σt, ≥2σt, ≥3σt, ≥5σt; where σt considers only statistical errors.

- ❖ An injected LIV of 200 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 ~2.9σ level for the CTA-N Alpha array and ~5.1σ level for CTA-S Omega array.
- ❖ CTA-S Omega array has the best performance overall. The uncertainty on the measured time delay can be reduced by ≥30% in comparison to the Alpha array.
- ❖ Subtracting the intrinsic effect, the CTA-S array (Alpha and Omega) with an injected LIV of +400 s/TeV would perceive a significant time delay.

HYSTERESIS PATTERNS

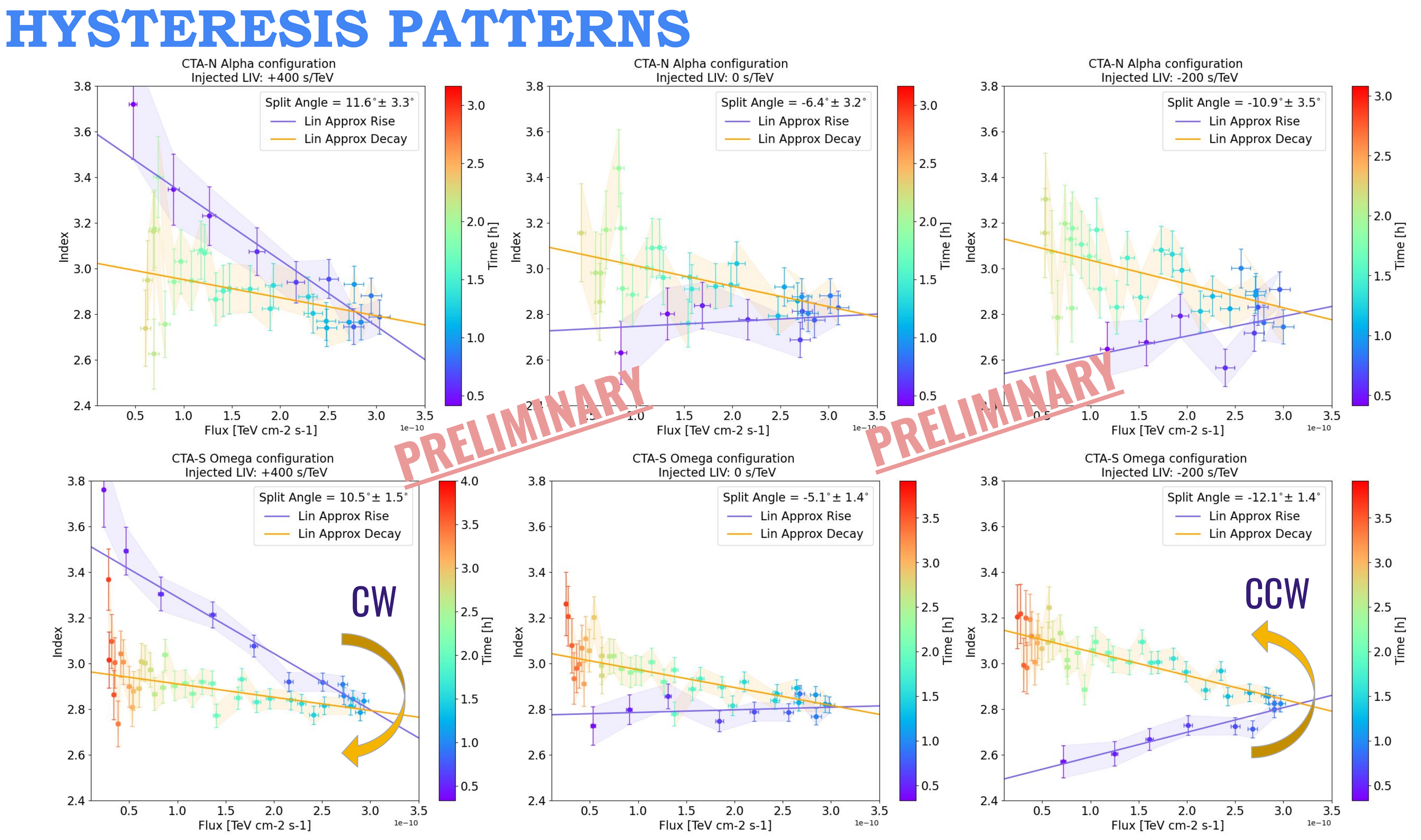

Fig 4. Hysteresis patterns in Hardness-Intensity Diagrams (HID) obtained from the simulated flare observations in an energy range of 0.3-3.0 TeV with CTA-N Alpha (upper panels) and CTA-S Omega (lower panels) configuration arrays.

- ❖ The orientation (CW/CCW) of the hysteresis patterns (and split angle between the linear approximations) characterize the regime of the delays (increasing or decreasing trend with energy at VHE).
- ❖ Comparing hysteresis between X-rays and γ-rays could allow discriminating LIV from intrinsic delays: opposite orientation in VHE would indicate the presence of non-intrinsic effects, possibly due to LIV.

CONCLUSION

From this analysis of a bright SSC flare, the CTA-N (CTA-S) Alpha configuration array seems sensitive to intrinsic time delays at ~2σ (>3σ) significance level. The Omega configuration will improve the significance of the measurements and seems to be required to open the possibility to search for LIV time delays. Furthermore, simultaneous X-ray data would be needed to discriminate LIV from intrinsic time delays.

Next steps:

- Perform a full analysis to assess the systematic errors.
- Check LIV time delays with quadratic dependency in energy.
- Apply the corresponding LIV delay to a simulated photon list and use LIVelihood [12] to obtain a statistical estimation on the limits of the possibly observed LIV delay.

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