New physics from the gamma-ray burst GRB 221009A?

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Abstract

Astronomical objects offer unique opportunities to probe physics beyond the Standard Model (SM) since they reach energies exceeding those attainable in laboratories. A striking example is the gamma-ray burst GRB 221009A at redshift z = 0.151, detected up to ~15 TeV by LHAASO and even up to ~300 TeV by Carpet. Within the SM, photons above ~10 TeV are mainly absorbed by the extragalactic background light, making the LHAASO detections extremely challenging and the Carpet event impossible. We show that photon–Axion-Like Particle (ALP) oscillations increase the cosmic transparency, thereby naturally accounting for the LHAASO photons but not the Carpet event. Instead, Lorentz-Invariance Violation (LIV) alters photon dispersion relation explaining the Carpet observation but not the LHAASO photons. Therefore, GRB 221009A provides two distinct hints at new physics. We offer a new self-consistent scenario where photon-ALP oscillations occur in a LIV framework, providing a full explanation of GRB 221009A.

Introduction

The gamma-ray burst GRB 221009A – detected on October 9, 2022 at redshift z = 0.151 – is the **brightest** of all times (BOAT). GRB 221009A is also the GRB observed at the **maximal** very-high-energy (VHE).

VHE detections:
- LHAASO [1]:
  - 5000 photons at energy E > 500 GeV.
  - 8 photons at E > 10 TeV.
- **Carpet** [2]:
  - single photon-like event at $E \simeq$ 300 TeV (chance probability ~9×10^{-3}).

Such energies are strongly **incompatible** with standard photon propagation.

Extragalactic background light (EBL), cosmic microwave background (CMB) and radio background (RB) should fully **absorb** photons above ~10 TeV due to the process $\gamma_{VHE} + \gamma_{EBL, CMB, RB} \rightarrow e^+ + e^-$ [3].

LHAASO and especially Carpet observations challenge standard propagation models and provides **clues of new physics**.

Previous result: LHAASO photons with energy E > 10 TeV yield a **hint** at the existence of an Axion-Like Particle (ALP) with mass $m_a \simeq (10^{-11} - 10^{-7})$ eV and two-photon coupling $g_{a\gamma\gamma} \simeq (3 - 5) \times 10^{-12}$ GeV^{-1}. In addition, Lorentz Invariance Violation (LIV) **cannot explain** the LHAASO detection [4].

Goal: how to explain the ~300 TeV Carpet photon.

Findings: the observability of the ~300 TeV photon **cannot** be explained by ALPs but **can** by LIV in specific settings. We obtain the **first self-consistent model** of photon-ALP interaction in a LIV framework, in order to explain both LHAASO and Carpet detections [5].

General Strategy

Assume emitted photon flux extrapolated from LHAASO observations.

Observed flux:
- $F_{obs}(E) = P(E; \gamma \rightarrow \gamma) F_{em}(E)$.

Photon survival probability $P(E; \gamma \rightarrow \gamma)$ includes:
- EBL/CMB/radio absorption.
- Possible new-physics (ALPs, LIV) effects.

We compute the **expected number of Carpet photons** for four scenarios – standard physics, ALPs only, LIV only, and ALP + LIV – by:
- Integrating over the energy range (262 – 343) TeV.
- Using Carpet effective area (~60 m^2).
- Considering the exposure time of 1 day.

Conventional Physics

Photon survival probability at ~300 TeV is extremely **suppressed**.

Expected number of photons:
- N_γ ~10^{-96}.

→ **Complete failure to explain the Carpet event.**

Axion-Like Particles (ALPs)

ALPs are predicted by **String Theory** [6], and are among the best **dark matter** candidates [7]. Specifically, ALPs, denoted by a, are a generalization of the axion and are neutral, very light, spin-0 pseudoscalar bosons of mass m_a primarily interacting with two photons through the coupling $g_{a\gamma\gamma}$, as described by the Lagrangian
- $\mathcal{L}_{ALP} = \frac{1}{2} \partial^\mu a\, \partial_\mu a - \frac{1}{2} m_a^2\, a^2 + g_{a\gamma\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$,

where $\mathbf{E}$ represents the electric field associated with a propagating photon and $\mathbf{B}$ is an external magnetic field.

In the presence of $\mathbf{B}$, **photon-ALP oscillations** can take place **reducing** the effective photon absorption due to EBL, CMB, RB [8].

So, can ALPs explain the detection of GRB 221009A above ~10 TeV?
- **YES**, regarding LHAASO events up to ~15 TeV with parameters [4]:
  - $m_a \simeq (10^{-11} - 10^{-7})$ eV and $g_{a\gamma\gamma} \simeq (3 - 5) \times 10^{-12}$ GeV^{-1}.
- **NO**, concerning the Carpet event at ~300 TeV [5]:
  - Expected photons: N_γ ~10^{-5}.

→ **ALPs alone cannot explain the Carpet photon.**

Lorentz Invariance Violation (LIV)

Several extensions of the Standard Model of particle physics towards a quantum theory of gravity predict a **violation of Lorentz invariance** at extremely high energies, close to the Planck mass [9].

However, LIV also produces effects at much lower energies with a rich phenomenology by modifying standard physics interactions and allowing for otherwise forbidden processes, such as photon decay, photon splitting, the **modification of photon dispersion relation** [10].

In particular, the photon dispersion relation modified by LIV reads
- $p^2 = E^2 [1 \pm (E/E_{LIV, n})^n]$,

where p and E represent the photon momentum and energy, respectively, while $E_{LIV, n}$ is the LIV energy scale at order n. The + sign refers to the subluminal case, while the – sign to the superluminal one.

In particular, the last effect provokes the shifting of the threshold of the $\gamma_{VHE} + \gamma_{EBL, CMB, RB} \rightarrow e^+ + e^-$ process, which produces a consequent **increase** of the transparency of VHE photons above ~100 TeV for **subluminal** LIV models (the + in the modified dispersion relation) [11].

We consider the **two subluminal LIV models**: (i) n = 1; (ii) n = 2.

So, can LIV explain the detection of GRB 221009A above ~10 TeV?
- **NO**, regarding LHAASO events up to ~15 TeV within LIV bounds [4].
- **YES**, concerning the Carpet event at ~300 TeV [5]:
  - Expected photons: N_γ ~1.

→ **LIV alone cannot explain the LHAASO photons.**

Results

To explain the full set of VHE observations of GRB 221009A up to ~300 TeV, including both LHAASO and Carpet detections, we consider an **ALP + LIV model**, in which photon-ALP oscillations occur within a LIV framework. Our results are reported in Figs. 1 and 2.
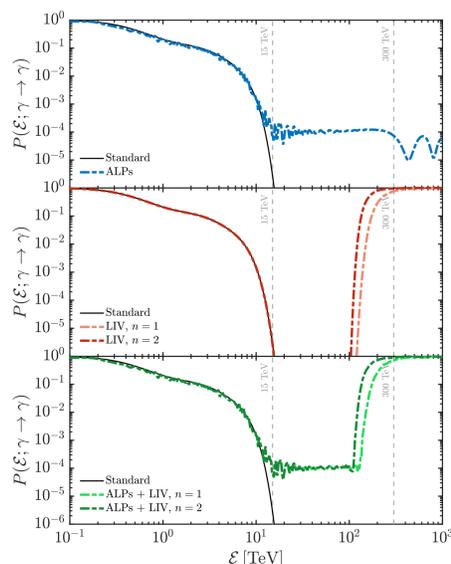

Figure 1: $P(E; \gamma \rightarrow \gamma)$ versus E within different models (Credit [5]).
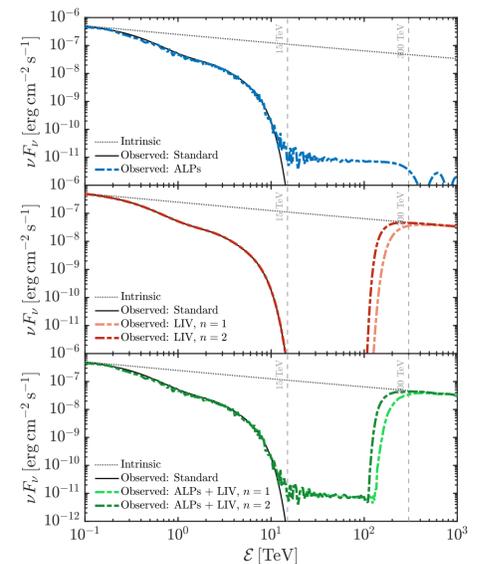
Results

Figure 2: GRB 221009A spectral energy distribution (SED) versus E within different models (Credit [5]).

Within the ALP + LIV model we obtain the following **constraints** at 95% confidence level on $E_{LIV, n}$, which can explain the Carpet event [5]:
- $E_{LIV, 1}$ < 1.22×10^{21} GeV for n = 1.
- $E_{LIV, 2}$ < 2.03×10^{13} GeV for n = 2.

We obtain a **new self-consistent scenario** [5]:
- If photons and ALPs share the same LIV-modified dispersion relation, photon-ALP oscillations remain unaffected by LIV.
- ALPs dominate at lower VHE explaining LHAASO photons.
- LIV dominates at higher VHE explaining the Carpet photon.

This scenario naturally emerges in D-brane models.

Conclusions

GRB 221009A provides **two** independent **hints of new physics**:
- **ALPs** at LHAASO energies.
- **LIV** at Carpet energies.

Conventional astrophysical models fail by ~100 orders of magnitude.

The **combined ALP + LIV model**:
- Explains both LHAASO and Carpet observations.
- Accounts for the observed time delay [12].
- Is currently the only natural, non ad hoc scenario.
- Is compatible with the existing ALP and LIV bounds.

If confirmed, this would represent the **first observational hint of LIV**.

Acknowledgments

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