

Lorentz-Violating Scenarios for the Highest-Energy Photons from GRB 221009A

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A photon at $\mathcal{E} \simeq 251$ TeV from GRB 221009A was detected by the Carpet Collaboration in 2022 using a partial dataset. Very recently, Carpet has completed its full data analysis reporting further support for its previous photon now at $\mathcal{E} = 300_{-38}^{+43}$ TeV. Within standard propagation models, this observation is in strong tension with conventional expectations since such a photon is absorbed by the CMB. Further, we show that this detection is strongly disfavored within the explored scenarios involving axionlike particles (ALPs) alone. Instead, we find that the considered photon is compatible with specific Lorentz invariant violation (LIV) frameworks with the LIV scale obeying in the linear case $\mathcal{E}_{\text{LIV},1} < 1.22_{-0.22}^{+0.19} \times 10^{21}$ GeV at 95% CL and in the quadratic case $\mathcal{E}_{\text{LIV},2} < 2.03_{-0.22}^{+0.17} \times 10^{13}$ GeV at 95% CL. Finally, we outline scenarios where standard photon-ALP oscillations are combined with LIV-induced modifications of photon propagation, which provide a consistent interpretation of the observations of GRB 221009A concerning the highest-energy photons detected by the LHAASO and the Carpet Collaborations.

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Introduction—The exceptionally bright gamma-ray burst GRB 221009A—named the brightest of all times (BOAT) [1]—was detected on October 9, 2022, by the Swift observatory [2] and by the Fermi Gamma-ray Burst Monitor (Fermi-GBM) [3]. It lies at redshift $z = 0.151$ [4–6]. Concerning its highest-energy photons, the observational situation is as follows. More than 5000 photons have been recorded by the Water Cherenkov Detector Array (WCDA) of the LHAASO Collaboration at $\mathcal{E} > 500$ GeV during the first 2000 s after the Fermi-GBM trigger time (henceforth, the *trigger*) [7]. Moreover, 142 photonlike events have been registered by the KM2A detector—also of the LHAASO Collaboration—in the energy range $3 \text{ TeV} \leq \mathcal{E} \leq 20 \text{ TeV}$ over the time lapse $230 \text{ s} \leq t \leq 900 \text{ s}$ after the trigger, 8 of which with $\mathcal{E} > 10 \text{ TeV}$ [8]. In addition, preliminary evidence for a single photonlike event of energy $\mathcal{E} \simeq 251$ TeV at $t = 4536$ s after the trigger has been reported by the Carpet Collaboration [9]. The Carpet observatory consists of photon detectors, an inner small-area muon (ISAM) detector, and four outer large-area muon

(OLAM) detectors—all of which were operative at the time of GRB 221009A—but the first reported result was based only on the data collected by the ISAM detector over 4536 s [9,10].

Very recently, the Carpet Collaboration completed the analysis of the data collected by the whole detector over one day instead of 4536 s. The updated result is a single photonlike event of energy $\mathcal{E} = 300_{-38}^{+43}$ TeV coincident—with chance probability of about 9×10^{-3} —with GRB 221009A in its arrival direction and time. The probability that this event is a misidentified hadron is about 3×10^{-4} [11]. Furthermore, the Carpet Collaboration has shown that the same *emitted* power law photon flux, which ultimately fits the photons observed by both the WCDA and KM2A detectors, is in order-of-magnitude agreement with the Carpet event when extrapolated to much higher energies [11]. Finally, why has the Carpet event not been observed by LHAASO and HAWC? According to the Carpet Collaboration [11], its photonlike event was close to the limit of the field of view of the LHAASO experiment, whereas the line of sight to GRB 221009A of the HAWC detector was beneath the horizon [12]. Below, we take this result at face value.

We stress that the observation of photons of $\mathcal{E} > 10 \text{ TeV}$ from GRB 221009A at redshift $z = 0.151$ is in tension with conventional physics for standard emission models. In fact, they tend to be fully absorbed through the $\gamma\gamma \rightarrow e^+e^-$ process by the *extragalactic background light*

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(EBL)—namely the infrared, optical, and/or ultraviolet photons emitted by all galaxies during their whole evolution—as well as by the CMB and the radio background [13–45], with the CMB becoming the dominant absorption process at the Carpet energies [17,18]. As a consequence, the observation of the highest-energy photons from GRB 221009A challenges standard propagation models—as also stressed in [8] and [46] for LHAASO photons—and provides clues of new physics. Such a situation is further exacerbated for the Carpet event.

Elsewhere, we have shown that the 8 photon-like events of $\mathcal{E} > 10$ TeV detected by LHAASO yield a hint at the existence of a viable axionlike particle (ALP). In addition, we have demonstrated that such a result *cannot* be obtained by Lorentz invariance violation (LIV) [47].

Here, relying upon the newly reported Carpet result, we demonstrate that for the $\mathcal{E} = 300^{+43}_{-38}$ TeV photonlike event its observability is very difficult to explain with ALPs but *can* with LIV in specific settings. We note that so far only lower bounds on the LIV scale have been derived by employing—among other methods—the very-high-energy (VHE, $100 \text{ GeV} < \mathcal{E} < 100 \text{ TeV}$) photon emission from astronomical sources in general, and since 1998 from *gamma-ray bursts* (GRBs) in particular [48–68].

The aim of this Letter is to show under what assumptions specific LIV models *do* explain the Carpet event. More generally, we offer scenarios in which photon-ALP oscillations occur in certain LIV frameworks so that a consistent interpretation of the observations of GRB 221009A emerges including the highest-energy photons detected by the LHAASO Collaboration. We emphasize that many more details and all unproven statements (for lack of space) made in this Letter are justified in Supplemental Material [69].

General strategy—In order to carry out a quantitative analysis of the Carpet event, we need to know the emitted photon flux $\mathcal{F}_{\text{em}}(\mathcal{E})$. As already stated, it has been shown by the Carpet Collaboration that a good fit to $\mathcal{F}_{\text{em}}(\mathcal{E})$ is given by a higher-energy extrapolation of the one reported by LHAASO [7,8] (see Fig. 7 of [11]). The expected photon flux $\mathcal{F}_{\text{exp}}(\mathcal{E})$ is obtained upon multiplication of $\mathcal{F}_{\text{em}}(\mathcal{E})$ by the photon survival probability $P(\mathcal{E}; \gamma \rightarrow \gamma)$, which quantifies the EBL, CMB, and radio absorption, as well as new physical effects [147]. Yet, by definition, the expected photon flux is $\mathcal{F}_{\text{exp}}(\mathcal{E}) \equiv dN_\gamma(\mathcal{E})/(d\mathcal{E} dA dt)$, where $dN_\gamma(\mathcal{E})$ is the number of expected photons in the energy range $d\mathcal{E}$ about $\mathcal{E}$ within the effective detector area dA during the exposure time dt . Hence, we get

$$\frac{dN_\gamma(\mathcal{E})}{d\mathcal{E} dA dt} = P(\mathcal{E}; \gamma \rightarrow \gamma) \mathcal{F}_{\text{em}}(\mathcal{E}). \quad (1)$$

So—when $P(\mathcal{E}; \gamma \rightarrow \gamma)$ is known—we obtain the number of expected Carpet photons N_γ by integrating Eq. (1) over the Carpet energy range $262 \text{ TeV} \leq \mathcal{E} \leq 343 \text{ TeV}$ and

multiplying it by both the Carpet effective area of $\sim 60 \text{ m}^2$ and the exposure time of one day [11].

Conventional physics— $P_{\text{CP}}(\mathcal{E}; \gamma \rightarrow \gamma)$ is computed in Supplemental Material [69], and the above procedure based on Eq. (1) gives $N_\gamma(\text{CP}) \sim 10^{-96}$. We restate that at this energy the leading photon absorption is due to the CMB, which makes our result robust since its uncertainty is much smaller than that affecting the EBL.

Axionlike particles (ALPs)—They are very light neutral pseudoscalar bosons (see Supplemental Material [69]) quite similar to the axion [148–150], but their mass m_a and two-photon coupling $g_{a\gamma\gamma}$ are *unrelated*. ALPs are attracting an ever growing interest since they are a generic prediction of superstring theory (for a detailed motivation see [151,152], and for a very incomplete list of references see Refs. [153–170]). Moreover, they explain some astrophysical anomalies [47,171,172] and are among the best dark matter candidates [173] (general reviews on ALP are [174–177]). Because we are interested in their interactions with photons alone, the corresponding Lagrangian is [178]

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B} a, \quad (2)$$

where a is the ALP field, while $\mathbf{E}$ and $\mathbf{B}$ are, respectively, the electric and magnetic components of the electromagnetic tensor $F_{\mu\nu}$ whose dual is $\tilde{F}^{\mu\nu}$. ALP-induced astrophysical effects arise in the presence of an *external* $\mathbf{B}$ field, and so $\mathbf{E}$ is the *electric* field of a *propagating* photon. Therefore, the last term in Eq. (2) yields an off-diagonal mass matrix in the photon-ALP sector so that the interaction eigenstates differ from the mass eigenstates. This fact gives rise to two effects [179,180]: (1) photon-ALP oscillations, and (2) change of the photon polarization state, which are potentially detectable in high-energy and VHE astrophysics both on astrophysical spectra [47,171,172,181–190] and on photon polarization [191–200]. The key point is that photon-ALP oscillations *largely reduce* the EBL, CMB, and radio absorption, thereby allowing a *considerably greater* number of VHE photons to be expected (see Supplemental Material [69]). Moreover, when $\mathcal{E} \gg m_a$ —which is presently the case—the photon-ALP beam propagation equation along the y axis becomes [180]

$$\left(i \frac{d}{dy} + \mathcal{E} + \mathcal{M}(\mathcal{E}, y) \right) \begin{pmatrix} A_x(y) \\ A_z(y) \\ a(y) \end{pmatrix} = 0. \quad (3)$$

Here, $A_x(y)$ and $A_z(y)$ denote the two photon polarization amplitudes along the x and z axes, respectively, and $a(y)$ the ALP amplitude. $\mathcal{M}(\mathcal{E}, y)$ is the photon-ALP mixing matrix (see Supplemental Material [69]), which fails to be self-adjoint when photon absorption occurs. Since Eq. (3) is a Schrödinger-like equation (with $t \rightarrow y$), it follows that the

beam is formally described as a *nonrelativistic three-level decaying quantum system*, a fact that greatly simplifies the calculations.

Now, we are in a position to investigate whether photon-ALP oscillations alone can explain the Carpet event. We evaluate $P_{\text{ALP}}(\mathcal{E}; \gamma \rightarrow \gamma)$ by accounting for the relevant astrophysical uncertainties (see the Appendix and Supplemental Material [69]). To maintain our previous explanation of the LHAASO photons [47], the ALP parameters are constrained to $m_a \simeq (10^{-11} - 10^{-7})$ eV and $g_{a\gamma\gamma} \simeq (3-5) \times 10^{-12}$ GeV $^{-1}$. Across this entire parameter space, the expected photon count for the Carpet event remains $N_\gamma(\text{ALP}) \lesssim \mathcal{O}(10^{-4})$. Since $N_\gamma(\text{ALP})$ is manifestly a very small number in the Carpet case, we have to use the Poisson statistics. Accordingly, at 95% CL, we should satisfy $N_\gamma(\text{ALP}) \geq 0.0513$ [201], and so ALPs fail to bridge the gap to the observation by about 2 orders of magnitude.

Lorentz invariance violation (LIV)—Manifestly, a new kind of physics has to be looked for in order to allow for the observability of the Carpet event, which must coexist with the previous ALPs in such a way to retain their explanation of the LHAASO VHE photons. To this end, we suppose that LIV is a good option. We first investigate whether LIV alone accomplishes the desired task, and next we address the merging of ALPs and LIV into consistent scenarios. Even though LIV theory is well known [202–209], for the reader’s convenience, we very briefly recall its implications that are relevant for us. The widespread belief is that gravity should be quantized, but this goal has not yet been achieved. Nonetheless, its basic features have clearly emerged. Quantum gravitational effects show up around the Planck scale $M_P \equiv (\hbar c/G)^{1/2} \simeq 1.22 \times 10^{19}$ GeV, where they give rise to an ever changing metric and topology, which impart a *foamlike structure* to spacetime [210–214]. A natural expectation is that the resulting particle propagation exhibits a violation of Lorentz invariance at a scale $\mathcal{E}_{\text{LIV}}$ —which can be smaller or larger than M_P by some orders of magnitude—so that the goal of LIV theories is to capture its low-energy relic effects in special regimes. One of them is the deformation of the photon dispersion relation $p^2 = \mathcal{E}^2$. A convenient parametrization is

$$p^2 = \mathcal{E}^2 \left[1 + f\left(\frac{\mathcal{E}}{\mathcal{E}_{\text{LIV}}}\right) \right], \quad (4)$$

where $f(\cdot)$ is a model-dependent smooth function such that $f(0) = 0$ since it must vanish in the limit $\mathcal{E}_{\text{LIV}} \rightarrow \infty$. At energies $\mathcal{E} \ll \mathcal{E}_{\text{LIV}}$, Eq. (4) can be expanded in a power series of $\mathcal{E}/\mathcal{E}_{\text{LIV}}$. A drawback of this approach is that some terms must be dropped when they give rise to unwanted physical effects since the coefficients of the expansion cannot be predicted. Denoting as $\mathcal{E}^n/\mathcal{E}_{\text{LIV},n}^n$ the first physically allowed term, Eq. (4) reduces to

$$p^2 = \mathcal{E}^2 \left(1 + \xi_n \frac{\mathcal{E}^n}{\mathcal{E}_{\text{LIV},n}^n} \right), \quad (5)$$

with $\xi_n = 1$ corresponding to subluminal propagation and $\xi_n = -1$ to superluminal propagation while $\mathcal{E}_{\text{LIV},n}$ denotes the LIV energy scale at order n . Observe that formally the LIV term looks like an effective photon mass square $m_{\text{eff}}^2 \equiv -\xi_n \mathcal{E}^{n+2}/\mathcal{E}_{\text{LIV},n}^n$. In the following, we shall restrict our attention to the *subluminal case* and to the two leading orders, $n = 1, 2$. LIV modifies the quantum mechanical propagators and the reaction thresholds. Our focus is on the implications of these effects for the $\gamma\gamma \rightarrow e^+e^-$ process [215–219]. At Carpet energies, it turns out that for subluminal propagation VHE photons from a cosmological source interact with background photons at *higher* energies where the photon density is *lower*, thereby increasing the transparency of the Universe, which is quantified by the resulting photon survival probability [220–222]. Thus, it looks natural to inquire whether such an effect allows the Carpet event to be expected (for superluminal propagation the cosmic transparency is lower than in conventional physics, and so we discard this possibility). Recall that at $\mathcal{E} \sim 300$ TeV the standard cosmic transparency is essentially determined by the CMB [17,18], hence making our subsequent LIV bounds remarkably robust against the uncertainties affecting EBL models, which instead dominate at lower energies. Another LIV effect that follows from Eq. (5) is that photons acquire an energy-dependent velocity [48,208,209]. Hence, for subluminal propagation, they are affected by a *time delay* [223] and are stable against photon decay ($\gamma \rightarrow e^+e^-$) and photon splitting ($\gamma \rightarrow N\gamma$) [208,209]. So far, we have considered LIV effects for photons, but LIV can affect any particle. Is the LIV modification of the dispersion relations of photons and massive particles the same? As classical gravity acts equally on any particle (equivalence principle), the answer seems to be yes. However, this is not true in general since LIV-induced quantum gravitational effects depend on the considered framework. For instance, a LIV acting differently on electrons and photons has been found in the Liouville string model of spacetime foam [224–227], where only photons have a LIV-deformed dispersion relation. More generally, a nonuniversal LIV emerges naturally in the D-brane physics since excitations carrying nonvanishing charges under the standard model gauge group are represented as open strings with their ends attached to a brane, while neutral excitations propagate as closed strings in the bulk space transverse to the brane [228]: only the latter excitations—like photons and ALPs—can possess LIV-deformed dispersion relations.

New consistent scenarios—Hitherto we have dealt with LIV alone. Now we have to identify the contexts in which the LIV-induced observation of the Carpet event is consistent with the ALP-induced detection of the $\mathcal{E} > 10$ TeV LHAASO photons. We assume that photon-ALP

oscillations are Lorentz invariant also in the presence of LIV. As a consequence, two conditions should be met: (1) the term $\mathbf{E} \cdot \mathbf{B}a$ in Eq. (2) is *not* affected by LIV, and (2) photons and ALPs violate Lorentz invariance by the *same* amount. We stress that the emerging frameworks arise from a LIV effective Lagrangian containing only two terms with equal coefficients: one for the photon and the other for the ALP (they are dimension 5 operators in the $n = 1$ case and dimension 6 operators in the $n = 2$ case) [206]. The resulting implications for the beam propagation Eq. (3) are discussed in Supplemental Material [69], along with the calculation of $P_{\text{ALP+LIV},n}(\mathcal{E}; \gamma \rightarrow \gamma)$, whose LIV contribution is evaluated as in [217,229,230] for the deformed dispersion relation (5) in the cases $n = 1, 2$. In Supplemental Material [69], it is also shown that consistent ALP + LIV scenarios emerge. An intriguing possibility is that the interaction term in Eq. (2) arises as an effect of quantum corrections within an underlying LIV background [231,232].

Results—Our main task is the determination of $\mathcal{E}_{\text{LIV},n}$ for $n = 1, 2$ in such a way that one photonlike event of $\mathcal{E} = 300^{+43}_{-38}$ TeV is observed from GRB 221009A. We follow the same strategy outlined just after Eq. (1) to evaluate the expected number of photons $N_\gamma(\mathcal{E}_{\text{LIV},n})$, which initiate the single air-shower event observed by Carpet. As in the ALP case, we have to employ the Poisson statistics since $N_\gamma(\mathcal{E}_{\text{LIV},n})$ is a very small number. Correspondingly, at 95% CL, we should satisfy $N_\gamma(\mathcal{E}_{\text{LIV},n}) \geq 0.0513$ [201]. We can now go back to Eq. (1), which can be rewritten as

$$\frac{dN_\gamma(\mathcal{E})}{d\mathcal{E}dAdt} = P_{\text{ALP+LIV},n}(\mathcal{E}; \gamma \rightarrow \gamma) \mathcal{F}_{\text{em}}(\mathcal{E}). \quad (6)$$

We solve this equation in the same fashion as for Eq. (1), by integrating over the Carpet energy range and multiplying by the effective area and exposure time. Hence, by imposing the condition $N_\gamma(\mathcal{E}_{\text{LIV},n}) \geq 0.0513$, we get the upper bounds on the LIV scales at 95% CL,

$$\mathcal{E}_{\text{LIV},1} < 1.22^{+0.19}_{-0.22} \times 10^{21} \text{ GeV}, \quad n = 1, \quad (7)$$

$$\mathcal{E}_{\text{LIV},2} < 2.03^{+0.17}_{-0.22} \times 10^{13} \text{ GeV}, \quad n = 2, \quad (8)$$

where the reported errors reflect the systematic uncertainties on the Carpet spectral normalization [11] (see the Appendix for details).

As carefully shown in Supplemental Material [69], the above limits are in agreement with all available bounds for $n = 1$ and $n = 2$ LIV. Nevertheless, one of them deserves to be mentioned here. In conventional physics, $n = 1$ LIV gives rise to birefringence (that is, a rotation of the polarization plane of photons); hence, astronomical sources at cosmological distances like GRBs should be unpolarized [233]. This is in sharp contradiction with astronomical evidence, and the most updated bounds are $\mathcal{E}_{\text{LIV},1} > 3.6 \times 10^{34}$ GeV and $\mathcal{E}_{\text{LIV},2} > 1.3 \times 10^{11}$ GeV [208,234,235]. While this

looks at odds with our result for $n = 1$, it becomes viable in the above-considered D-brane models since—in spite of the fact that the photon dispersion relation is generally LIV deformed—no birefringence arises because the two circular polarization states of the photon propagate at the same speed [203,236]. No similar limitation exists for the $n = 2$ case.

Moreover, Ofengeim and Piran [237] have very recently demonstrated that the time delay of more than 1 hour between the observation of VHE LHAASO photons and the Carpet event is explained by $n = 2$ LIV for $\mathcal{E}_{\text{LIV},2} = 1.59^{+0.56}_{-0.35} \times 10^{12}$ GeV. Observe that this value of $\mathcal{E}_{\text{LIV},2}$ is *consistent* with our upper bound.

A full account of our results is exhibited in Figs. 1 and 2, where we plot the photon survival probability and the expected spectral energy distribution [SED $\equiv \nu F_\nu(\mathcal{E}) = \mathcal{E}^2 \mathcal{F}_{\text{exp}}(\mathcal{E})$] in the various cases.

As benchmark values, we take $m_a = 10^{-10}$ eV, $g_{a\gamma\gamma} = 4 \times 10^{-12} \text{ GeV}^{-1}$, $\mathcal{E}_{\text{LIV},1} = 3 \times 10^{20}$ GeV, and $\mathcal{E}_{\text{LIV},2} = 5 \times 10^{12}$ GeV, all consistent with the above constraints. In Fig. 2, we include the uncertainty on the intrinsic Carpet spectrum. In Figs. 1 and 2, the colored regions

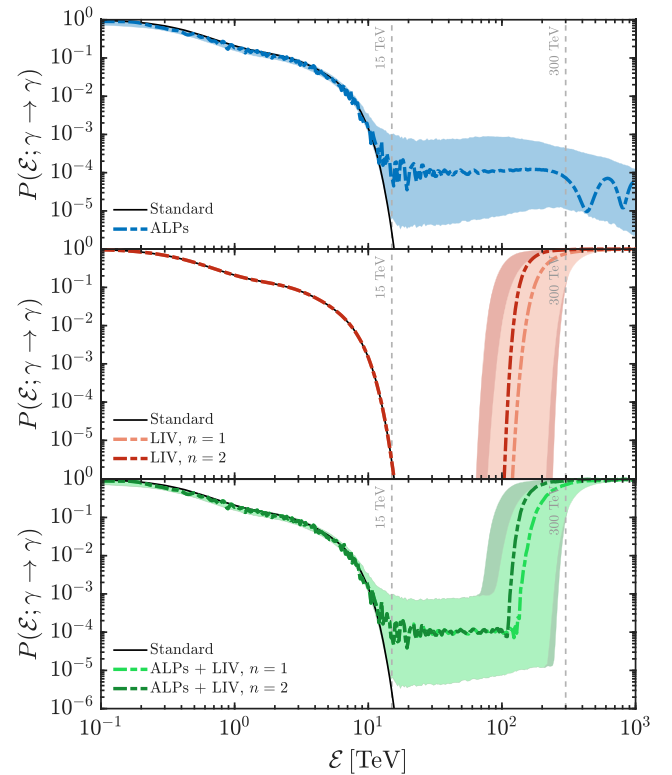


FIG. 1. Photon survival probability $P(\mathcal{E}; \gamma \rightarrow \gamma)$ versus energy $\mathcal{E}$, taking into account ALP and LIV effects separately (upper and central panels) and in combination (lower panel). Curves correspond to our benchmark values, while shaded bands illustrate the range of predicted values for the corresponding scenarios (lighter bands for LIV with $n = 1$, darker bands for $n = 2$) as obtained from the parameter variations described in the Appendix. Conventional physics is shown in all panels for comparison.

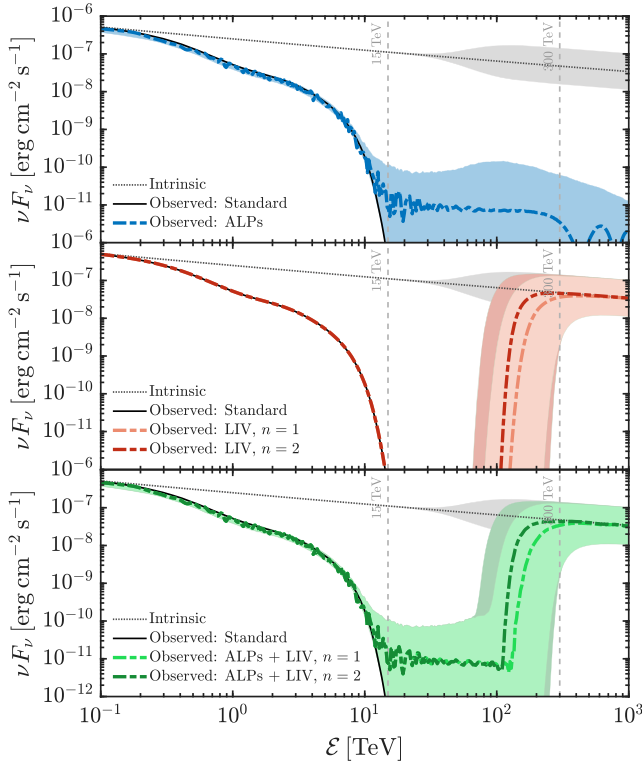


FIG. 2. Expected SED versus energy $\mathcal{E}$, taking into account ALP and LIV effects separately (upper and central panels) and in combination (lower panel). Curves correspond to our benchmark values, whereas shaded bands illustrate the range of predicted SED for the corresponding scenarios (lighter bands for LIV with $n = 1$, darker bands for $n = 2$), as obtained from the parameter variations described in the Appendix. The black dotted line denotes the intrinsic SED of GRB 221009A as estimated by LHAASO [7,8] and extrapolated to Carpet energies [11], with its associated uncertainty shown as a shaded region. Observed SED versus energy $\mathcal{E}$ in conventional physics is reported in all panels for comparison.

illustrate the range of predicted photon survival probability and, respectively, SED in the ALP-only, LIV-only, and ALP + LIV scenarios, as obtained by varying the relevant parameters within their allowed ranges (see the Appendix for details), indicating that the qualitative behavior is stable across the explored configurations.

Discussion and conclusions—The GRB 221009A is unique in several respects. Not only is it the brightest GRB of all times—to such an extent to ionize the upper ionosphere—but also the one whose emitted photons have reached the highest energies. As shown elsewhere [47], the photons of $\mathcal{E} > 10$ TeV detected by the LHAASO Collaboration [8] provide a hint at the existence of an 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 this Letter, we have interpreted the photonlike event of $\mathcal{E} = 300^{+43}_{-38}$ TeV observed by the Carpet Collaboration [11] as a LIV effect.

Within conventional physics an additional emission component—such as the proton synchrotron or hadronic origin—from GRB 221009A is insufficient to account for the Carpet result since it could mitigate the problem by a few orders of magnitude, but a correction of more than 90 orders of magnitude would be compelling. We have also shown that ALPs cannot account for the GRB 221009A observation at $\mathcal{E} = 300^{+43}_{-38}$ TeV within the considered parameter space. In addition, we find no qualitative change in the main conclusions across the full range of model parameters explored in this analysis when the uncertainties associated with the Carpet spectrum are included.

Besides, it looks tantalizing that the combination of our result with that of Ofengeim and Piran [237] shows that $n = 2$ LIV in four-dimensional space accounts for both the Carpet photonlike event and its time delay with respect to the VHE LHAASO ones.

Before closing this Letter, there is one more point worth mentioning. Our consistent scenarios are not *ad hoc*, in that ALPs explain not only the VHE photons detected by LHAASO but also two other astrophysical anomalies [171,172]. As systematically discussed in Supplemental Material [69], this represents a unique feature of our proposal as compared to others. In addition, the alternative explanations put forward so far face significant challenges. Indeed, unconventional attempts based on standard physics such as the *proton beam model* [46] and the *neutron beam model* [11,238] appear unable to account for the observations within a realistic physical setup (see Supplemental Material [69]).

In conclusion, the combined ALP + LIV frameworks presented in this Letter provide a consistent interpretation of the GRB 221009A VHE emission, suggesting a potential first indication of LIV in the considered contexts. Needless to say, our findings require further confirmations by future observations. Only time will tell whether the above two clues are real discoveries.

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Data availability—The data that support the findings of this study are available from the corresponding author upon request.

- [1] E. Burns *et al.*, *Astrophys. J. Lett.* **946**, L31 (2023).
- [2] M. A. Williams *et al.* (SWIFT Collaboration), *Astrophys. J. Lett.* **946**, L24 (2023).

- [3] S. Lesage *et al.* (Fermi Collaboration), *Astrophys. J. Lett.* **952**, L42 (2023).
- [4] A. de Ugarte Postigo *et al.*, GRB Coordinates Network **32648**, 1 (2022), <https://gcn.gsfc.nasa.gov/gcn3/32648.gcn3>.
- [5] A. J. Castro-Tirado *et al.*, GRB Coordinates Network **32686**, 1 (2022), <https://gcn.gsfc.nasa.gov/gcn3/32686.gcn3>.
- [6] D. B. Malesani *et al.*, *Astron. Astrophys.* **701**, A134 (2025).
- [7] LHAASO Collaboration, *Science* **380**, adg9328 (2023).
- [8] LHAASO Collaboration, *Sci. Adv.* **9**, eadj2778 (2023).
- [9] D. Dzhappuev *et al.* (Carpet Collaboration), *Astronomer's Telegram* **15669** (2022), <https://astronomerstelegam.org/?read=15669>.
- [10] Why muon detectors? They play a crucial role in discriminating between a primary photon emitted by the GRB 221009A and a secondary photon originating from proton-proton collisions in a cosmic ray shower since in the latter case also pions are produced. We recall that neutral pions decay into two photons while charged pions decay into neutrinos and muons, which can be recorded on Earth. So, the lack of muon detection by Carpet is a proof that their observed photon is not a misidentified hadron.
- [11] D. D. Dzhappuev *et al.* (Carpet-3 Collaboration), *Phys. Rev. D* **111**, 102005 (2025).
- [12] H. Ayala *et al.* (HAWC Collaboration), GRB Coordinate Network **32683**, 1 (2022), <https://gcn.gsfc.nasa.gov/gcn3/32683.gcn3>.
- [13] G. Breit and J. A. Wheeler, *Phys. Rev.* **46**, 1087 (1934).
- [14] W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, Oxford, 1960).
- [15] A. Nikishov, *Sov. Phys. JETP* **14**, 393 (1962), <https://www.jetp.ras.ru/cgi-bin/e/index/e/14/2/p393?a=list>.
- [16] R. J. Gould and G. P. Schreder, *Phys. Rev.* **155**, 1404 (1967).
- [17] F. W. Stecker, *Phys. Rev.* **180**, 1264 (1969).
- [18] G. G. Fazio and F. W. Stecker, *Nature (London)* **226**, 135 (1970).
- [19] F. W. Stecker, O. C. de Jager, and M. H. Salamon, *Astrophys. J. Lett.* **390**, L49 (1992).
- [20] P. Madau and L. Pozzetti, *Mon. Not. R. Astron. Soc.* **312**, L9 (2000).
- [21] M. G. Hauser and E. Dwek, *Annu. Rev. Astron. Astrophys.* **39**, 249 (2001).
- [22] J. R. Primack, R. S. Somerville, J. S. Bullock, and J. E. G. Devriendt, *AIP Conf. Proc.* **558**, 463 (2001).
- [23] T. M. Kneiske, K. Mannheim, and D. H. Hartmann, *Astron. Astrophys.* **386**, 1 (2002).
- [24] T. M. Kneiske, T. Bretz, K. Mannheim, and D. H. Hartmann, *Astron. Astrophys.* **413**, 807 (2004).
- [25] J. R. Primack, J. S. Bullock, and R. S. Somerville, *AIP Conf. Proc.* **745**, 23 (2005).
- [26] M. Schroedter, *Astrophys. J.* **628**, 617 (2005).
- [27] F. Aharonian *et al.*, *Astron. Astrophys.* **448**, L19 (2006).
- [28] D. Mazin and M. Raue, *Astron. Astrophys.* **471**, 439 (2007).
- [29] D. Mazin and F. Goebel, *Astrophys. J.* **655**, L13 (2007).
- [30] A. Franceschini, G. Rodighiero, and M. Vaccari, *Astron. Astrophys.* **487**, 837 (2008).
- [31] J. D. Finke and S. Razzaque, *Astrophys. J.* **698**, 1761 (2009).
- [32] R. C. Gilmore, P. Madau, J. R. Primack, R. S. Somerville, and F. Haardt, *Mon. Not. R. Astron. Soc.* **399**, 1694 (2009).
- [33] J. D. Finke, S. Razzaque, and C. D. Dermer, *Astrophys. J.* **712**, 238 (2010).
- [34] T. M. Kneiske and H. Dole, *Astron. Astrophys.* **515**, A19 (2010).
- [35] A. Dominguez *et al.*, *Mon. Not. R. Astron. Soc.* **410**, 2556 (2011).
- [36] M. R. Orr, F. Krennrich, and E. Dwek, *Astrophys. J.* **733**, 77 (2011).
- [37] R. C. Gilmore, R. S. Somerville, J. R. Primack, and A. Dominguez, *Mon. Not. R. Astron. Soc.* **422**, 3189 (2012).
- [38] E. Dwek and F. Krennrich, *Astropart. Phys.* **43**, 112 (2013).
- [39] Y. Inoue, S. Inoue, M. A. R. Kobayashi, R. Makiya, Y. Niino, and T. Totani, *Astrophys. J.* **768**, 197 (2013).
- [40] A. De Angelis, G. Galanti, and M. Roncadelli, *Mon. Not. R. Astron. Soc.* **432**, 3245 (2013).
- [41] F. W. Stecker, S. T. Scully, and M. A. Malkan, *Astrophys. J.* **827**, 6 (2016).
- [42] A. Franceschini and G. Rodighiero, *Astron. Astrophys.* **603**, A34 (2017).
- [43] S. Matsuura *et al.* (CIBER Collaboration), *Astrophys. J.* **839**, 7 (2017).
- [44] G. Galanti, F. Piccinini, M. Roncadelli, and F. Tavecchio, *Phys. Rev. D* **102**, 123004 (2020).
- [45] A. Saldana-Lopez, A. Domínguez, P. G. Pérez-González, J. Finke, M. Ajello, J. R. Primack, Vaidehi S Paliya, and Abhishek Desai, *Mon. Not. R. Astron. Soc.* **507**, 5144 (2021).
- [46] O. Kalashev, F. Aharonian, W. Essey, Y. Inoue, and A. Kusenko, *Phys. Rev. D* **112**, 023022 (2025).
- [47] G. Galanti, L. Nava, M. Roncadelli, F. Tavecchio, and G. Bonnoli, *Phys. Rev. Lett.* **131**, 251001 (2023).
- [48] G. Amelino-Camelia, J. Ellis, N. E. Mavromatos, D. V. Nanopoulos, and S. Sarkar, *Nature (London)* **393**, 763 (1998).
- [49] B. E. Schaefer, *Phys. Rev. Lett.* **82**, 4964 (1999).
- [50] F. W. Stecker and S. L. Glashow, *Astropart. Phys.* **16**, 97 (2001).
- [51] J. Ellis, N. E. Mavromatos, D. V. Nanopoulos, and A. S. Sakharov, *Astron. Astrophys.* **402**, 409 (2003).
- [52] K. S. Cheng and T. Harko, *Astropart. Phys.* **22**, 297 (2004).
- [53] S. E. Boggs, C. B. Wunderer, K. Hurley, and W. Coburn, *Astrophys. J.* **611**, L77 (2004).
- [54] J. Ellis, N. E. Mavromatos, D. V. Nanopoulos, A. S. Sakharov, and E. K. G. Sarkisyan, *Astropart. Phys.* **25**, 402 (2006).
- [55] M. Rodríguez Martínez and T. Piran, *J. Cosmol. Astropart. Phys.* **04** (2006) 006.
- [56] M. Gogberashvili, A. S. Sakharov, and E. K. G. Sarkisyan, *Phys. Lett. B* **644**, 179 (2007).
- [57] U. Jakob and T. Piran, *Nat. Phys.* **3**, 87 (2007).
- [58] M. Biesiada and A. Piórkowska, *J. Cosmol. Astropart. Phys.* **07** (2007) 011.
- [59] J. Bolmont, A. Jacholkowska, J.-L. Atteia, F. Piron, and G. Pizzichini, *Astrophys. J.* **673**, 972 (2008).

- [60] J. D. Scargle, J. P. Norris, and J. T. Bonnell, *Astrophys. J.* **673**, 972 (2008).
- [61] R. Lamon, N. Produit, and F. Steiner, *Gen. Relativ. Gravit.* **40**, 1731 (2008).
- [62] U. Jacob and T. Piran, *J. Cosmol. Astropart. Phys.* **01** (2008) 031.
- [63] R. G. Lang, H. Martínez-Huerta, and V. de Souza, *Phys. Rev. D* **99**, 043015 (2019).
- [64] Hao Li and Bo-Qiang Ma, *Phys. Rev. D* **104**, 063012 (2021).
- [65] Hao Li and Bo-Qiang Ma, *Astropart. Phys.* **148**, 102831 (2023).
- [66] T. Piran and D. D. Ofengeim, *Phys. Rev. D* **109**, L081501 (2024).
- [67] Yu-Ming Yang, Xiao-Jun Bi, and Peng-Fei Yin, *J. Cosmol. Astropart. Phys.* **04** (2024) 060.
- [68] Z. Cao *et al.* (LHAASO Collaboration), *Phys. Rev. Lett.* **133**, 071501 (2024).
- [69] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/zjh2-mc47>, which includes Refs. [70–146].
- [70] A. J. Levan *et al.*, *Astrophys. J. Lett.* **946**, L28 (2023).
- [71] P. K. Blanchard *et al.*, *Nat. Astron.* **8**, 774 (2024).
- [72] W. Heisenberg and H. Euler, *Z. Phys.* **98**, 714 (1936).
- [73] V. S. Weisskopf, K. Dan. Vidensk. Selsk. Mat. Fys. Medd. **14**, 6 (1936).
- [74] J. Schwinger, *Phys. Rev.* **82**, 664 (1951).
- [75] A. Dobrynina, A. Kartavtsev, and G. Raffelt, *Phys. Rev. D* **91**, 083003 (2015); **91**, 109902(E) (2015).
- [76] CAST Collaboration, *Nat. Phys.* **13**, 584 (2017).
- [77] A. Ayala, I. Domínguez, M. Giannotti, A. Mirizzi, and O. Straniero, *Phys. Rev. Lett.* **113**, 191302 (2014).
- [78] A. Payez, C. Evoli, T. Fischer, M. Giannotti, A. Mirizzi, and A. Ringwald, *J. Cosmol. Astropart. Phys.* **02** (2015) 006.
- [79] M. Ajello *et al.* (Fermi-LAT Collaboration), *Phys. Rev. Lett.* **116**, 161101 (2016).
- [80] M. Berg, J. P. Conlon, F. Day, N. Jennings, S. Krippendorf, A. J. Powell, and M. Rummel, *Astrophys. J.* **847**, 101 (2017).
- [81] J. P. Conlon, F. Day, N. Jennings, S. Krippendorf, and M. Rummel, *J. Cosmol. Astropart. Phys.* **07** (2017) 005.
- [82] C. S. Reynolds, M. C. David Marsh, H. R. Russell, A. C. Fabian, R. Smith, F. Tombesi, and S. Veilleux, *Astrophys. J.* **890**, 59 (2020).
- [83] J. Sisk-Reynés *et al.*, *Mon. Not. R. Astron. Soc.* **510**, 1264 (2022).
- [84] S. Schallmoser, S. Krippendorf, F. Chadha-Day, and J. Weller, *Mon. Not. R. Astron. Soc.* **514**, 329 (2022).
- [85] J. H. Matthews, C. S. Reynolds, M. C. David Marsh, J. Sisk-Reynés, and P. E. Rodman, *Astrophys. J.* **930**, 90 (2022).
- [86] C. Dessert, D. Dunskey, and B. R. Safdi, *Phys. Rev. D* **105**, 103034 (2022).
- [87] N. Bar, K. Blum, and G. D’Amico, *Phys. Rev. D* **101**, 123025 (2020).
- [88] R. D. Blandford and C. F. McKee, *Phys. Fluids* **19**, 1130 (1976).
- [89] L. Nava, L. Sironi, G. Ghisellini, A. Celotti, and G. Ghirlanda, *Mon. Not. R. Astron. Soc.* **433**, 2107 (2013).
- [90] E. Derishev and T. Piran, *Astrophys. J.* **923**, 135 (2021).
- [91] E. Derishev, *Mon. Not. R. Astron. Soc.* **519**, 377 (2023).
- [92] R. Beck, *Astron. Astrophys. Rev.* **24**, 4 (2016).
- [93] V. Heesen *et al.*, *Astron. Astrophys.* **669**, A8 (2023).
- [94] M. Meyer, D. Montanino, and J. Conrad, *J. Cosmol. Astropart. Phys.* **09** (2014) 003.
- [95] A. Fletcher, *Astron. Soc. Pac. Conf. Ser.* **438**, 197 (2010), <https://aspbooks.org/custom/publications/paper/438-0197.html>.
- [96] M. S. Pshirkov, P. G. Tinyakov, and F. R. Urban, *Phys. Rev. Lett.* **116**, 191302 (2016).
- [97] R. Alves Batista and A. Saveliev, *Universe* **7**, 223 (2021).
- [98] F. Aharonian *et al.* (H. E. S. S. and Fermi-LAT Collaborations), *Astrophys. J. Lett.* **950**, L16 (2023).
- [99] P. P. Kronberg, *Rep. Prog. Phys.* **57**, 325 (1994).
- [100] D. Grasso and H. R. Rubinstein, *Phys. Rep.* **348**, 163 (2001).
- [101] M. J. Rees and G. Setti, *Nature (London)* **219**, 127 (1968).
- [102] F. Hoyle, *Nature (London)* **223**, 936 (1969).
- [103] P. P. Kronberg, H. Lesch, and U. Hopp, *Astrophys. J.* **511**, 56 (1999).
- [104] S. Furlanetto and A. Loeb, *Astrophys. J.* **556**, 619 (2001).
- [105] A. Kartavtsev, G. Raffelt, and H. Vogel, *J. Cosmol. Astropart. Phys.* **01** (2017) 024.
- [106] R. Jansson and G. R. Farrar, *Astrophys. J.* **757**, 14 (2012).
- [107] R. Jansson and G. R. Farrar, *Astrophys. J.* **761**, L11 (2012).
- [108] M. C. Beck, A. M. Beck, R. Beck, K. Dolag, A. W. Strong, and P. Nielaba, *J. Cosmol. Astropart. Phys.* **05** (2016) 056.
- [109] P. Carenza, C. Evoli, M. Giannotti, A. Mirizzi, and D. Montanino, *Phys. Rev. D* **104**, 023003 (2021).
- [110] M. S. Pshirkov, P. G. Tinyakov, P. P. Kronberg, and K. J. Newton-McGee, *Astrophys. J.* **738**, 192 (2011).
- [111] J. M. Yao, R. N. Manchester, and N. Wang, *Astrophys. J.* **835**, 29 (2017).
- [112] K. Greisen, *Phys. Rev. Lett.* **16**, 748 (1966).
- [113] G. T. Zatsepin and V. A. Kuzmin, *JETP Lett.* **4**, 78 (1966), http://jetpletters.ru/ps/1624/article_24846.pdf.
- [114] F. W. Stecker, *Phys. Rev. Lett.* **21**, 1016 (1968).
- [115] M. Galaverni and G. Siegl, *Phys. Rev. Lett.* **100**, 021102 (2008).
- [116] R. G. Lang, H. Martínez-Huerta, and V. de Souza, *Astrophys. J.* **853**, 23 (2018).
- [117] H. Vankov and T. Stanev, *Phys. Lett. B* **538**, 251 (2002).
- [118] H. Bethe and W. Heitler, *Proc. R. Soc. A* **146**, 83 (1934).
- [119] G. Rubtsov, P. Satunin, and S. Sibiryakov, *J. Cosmol. Astropart. Phys.* **05** (2017) 049.
- [120] P. Satunin, *Eur. Phys. J. C* **79**, 1011 (2019).
- [121] M. Amenomori *et al.* (Tibet ASgamma Collaboration), *Phys. Rev. Lett.* **126**, 141101 (2021).
- [122] P. Satunin, *Eur. Phys. J. C* **81**, 750 (2021).
- [123] G. Galanti and M. Roncadelli, *arXiv:2504.01830*.
- [124] A. Baktash, D. Horns, and M. Meyer, *arXiv:2210.07172*.
- [125] P. Carenza and M. C. D. Marsh, *arXiv:2211.02010*.
- [126] S. V. Troitsky, *JETP Lett.* **116**, 767 (2022).
- [127] L. Wang and B.-Q. Ma, *Phys. Rev. D* **108**, 023002 (2023).
- [128] G. Zhang and B.-Q. Ma, *Chin. Phys. Lett.* **40**, 011401 (2023).
- [129] S. V. Troitsky, *J. Cosmol. Astropart. Phys.* **01** (2024) 013.
- [130] M. M. González, D. Avila Rojas, A. Pratts, S. Hernández-Cadena, N. Fraija, R. Alfaro, Y. Pérez Araujo, and J. A. Montes, *Astrophys. J.* **944**, 178 (2023).

- [131] S. Nakagawa, F. Takahashi, M. Yamada, and W. Yin, *Phys. Lett. B* **839**, 137824 (2023).
- [132] D. Avila Rojas, S. Hernández-Cadena, M. M. González, A. Pratts, R. Alfaro, and J. Serna-Franco, *Astrophys. J.* **966**, 114 (2024).
- [133] L.-Q. Gao, X.-J. Bi, J. Li, R.-M. Yao, and P.-F. Yin, *J. Cosmol. Astropart. Phys.* **01** (2024) 026.
- [134] S. Balaj, M. E. Ramirez-Quezada, J. Silk, and Y. Zhang, *Phys. Rev. D* **107**, 083038 (2023).
- [135] A. Y. Smirnov and A. Trautner, *Phys. Rev. Lett.* **131**, 021002 (2023).
- [136] L. Barnal, Y. Farzan, and A. Y. Smirnov, *J. Cosmol. Astropart. Phys.* **11** (2023) 098.
- [137] W. Essey and A. Kusenko, *Astropart. Phys.* **33**, 81 (2010).
- [138] W. Essey, O. Kalashev, and A. Kusenko, *Astrophys. J.* **731**, 51 (2011).
- [139] K. Murase, C. D. Dermer, H. Takami, and G. Migliori, *Astrophys. J.* **749**, 63 (2012).
- [140] M. J. Michalowski *et al.*, *Astron. Astrophys.* **582**, A78 (2015).
- [141] A. de Ugarte Postigo *et al.*, arXiv:2406.16726.
- [142] C. C. Thöne *et al.*, *Astron. Astrophys.* **690**, A66 (2024).
- [143] C. D. Dermer, S. Razzaque, J. D. Finke, and A. Atayan, *New J. Phys.* **11**, 065016 (2009).
- [144] J. P. Vallée, *New Astron. Rev.* **55**, 91 (2011).
- [145] R. Abbasi *et al.*, *Astrophys. J.* **946**, L26 (2023).
- [146] K. Kruiswijk *et al.*, *Proc. Sci. ICRC2023* (2023) 1511 [arXiv:2307.16354].
- [147] Since we are dealing only with GRB 221009A, the redshift dependence of the various quantities will not be exhibited.
- [148] J. H. Kim, *Phys. Rep.* **150**, 1 (1987).
- [149] H. Y. Cheng, *Phys. Rep.* **158**, 1 (1988).
- [150] J. E. Kim and G. Carosi, *Rev. Mod. Phys.* **82**, 557 (2010).
- [151] J. Jaeckel and A. Ringwald, *Annu. Rev. Nucl. Part. Sci.* **60**, 405 (2010).
- [152] A. Ringwald, *Phys. Dark Universe* **1**, 116 (2012).
- [153] N. Turok, *Phys. Rev. Lett.* **76**, 1015 (1996).
- [154] E. Witten, *Phys. Lett.* **149B**, 351 (1984).
- [155] J. P. Conlon, *J. High Energy Phys.* **05** (2006) 078.
- [156] P. Svrcek and E. Witten, *J. High Energy Phys.* **06** (2006) 051.
- [157] J. P. Conlon, *Phys. Rev. Lett.* **97**, 261802 (2006).
- [158] K.-S. Choi, I.-W. Kim, and J. E. Kim, *J. High Energy Phys.* **03** (2007) 116.
- [159] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell, *Phys. Rev. D* **81**, 123530 (2010).
- [160] B. S. Acharya, K. Bobkov, and P. Kumar, *J. High Energy Phys.* **11** (2010) 105.
- [161] M. Cicoli, M. Goodsell, and A. Ringwald, *J. High Energy Phys.* **10** (2012) 146.
- [162] A. G. Dias, A. C. B. Machado, C. C. Nishi, A. Ringwald, and P. Vaudrevange, *J. High Energy Phys.* **06** (2014) 037.
- [163] M. Cicoli, *J. Phys. Conf. Ser.* **485**, 012064 (2014).
- [164] J. C. Conlon and F. Day, *J. Cosmol. Astropart. Phys.* **11** (2014) 033.
- [165] M. Cicoli, J. C. Conlon, M. C. D. Marsh, and M. Rummel, *Phys. Rev. D* **90**, 023540 (2014).
- [166] D. Kraljic, M. Rummel, and J. C. Conlon, *J. Cosmol. Astropart. Phys.* **01** (2015) 011.
- [167] M. Cicoli, V. A. Diaz, V. Guidetti, and M. Rummel, *J. High Energy Phys.* **10** (2017) 192.
- [168] M. J. Scott, D. J. E. Marsh, C. Pongkitivanichkul, L. C. Price, and B. S. Acharya, *Phys. Rev. D* **96**, 083510 (2017).
- [169] A. Cisterna, M. Hassaine, J. Oliva, and M. Rinaldi, *Phys. Rev. D* **96**, 124033 (2017).
- [170] A. Cisterna, C. Erices, X.-M. Kuang, and M. Rinaldi, *Phys. Rev. D* **97**, 124052 (2018).
- [171] F. Tavecchio, M. Roncadelli, G. Galanti, and G. Bonnoli, *Phys. Rev. D* **86**, 085036 (2012).
- [172] G. Galanti, M. Roncadelli, A. De Angelis, and G. F. Bignami, *Mon. Not. R. Astron. Soc.* **493**, 1553 (2020).
- [173] P. Arias, D. Cadamuro, M. Goodsell, J. Jaeckel, J. Redondo, and A. Ringwald, *J. Cosmol. Astropart. Phys.* **06** (2012) 013.
- [174] I. G. Irastorza and J. Redondo, *Prog. Part. Nucl. Phys.* **102**, 89 (2018).
- [175] G. Galanti and M. Roncadelli, *Universe* **8**, 253 (2022).
- [176] G. Galanti, *Universe* **10**, 312 (2024).
- [177] G. Galanti, *Universe* **11**, 327 (2025).
- [178] Natural units ($c = 1$ and $\hbar = 1$) are employed throughout this Letter.
- [179] L. Maiani, R. Petronzio, and E. Zavattini, *Phys. Lett. B* **175**, 359 (1986).
- [180] G. G. Raffelt and L. Stodolsky, *Phys. Rev. D* **37**, 1237 (1988).
- [181] A. De Angelis, M. Roncadelli, and O. Mansutti, *Phys. Rev. D* **76**, 121301 (2007).
- [182] M. Simet, D. Hooper, and P. D. Serpico, *Phys. Rev. D* **77**, 063001 (2008).
- [183] M. A. Sánchez-Conde, D. Paneque, E. Bloom, F. Prada, and A. Domínguez, *Phys. Rev. D* **79**, 123511 (2009).
- [184] A. De Angelis, G. Galanti, and M. Roncadelli, *Phys. Rev. D* **84**, 105030 (2011); **87**, 109903(E) (2013).
- [185] D. Wouters and P. Brun, *Phys. Rev. D* **86**, 043005 (2012).
- [186] F. Tavecchio, M. Roncadelli, and G. Galanti, *Phys. Lett. B* **744**, 375 (2015).
- [187] K. Kohri and H. Kodama, *Phys. Rev. D* **96**, 051701 (2017).
- [188] G. Galanti and M. Roncadelli, *Phys. Rev. D* **98**, 043018 (2018).
- [189] G. Galanti and M. Roncadelli, *J. High Energy Astrophys.* **20**, 1 (2018).
- [190] G. Galanti, F. Tavecchio, M. Roncadelli, and C. Evoli, *Mon. Not. R. Astron. Soc.* **487**, 123 (2019).
- [191] P. Jain, S. Panda, and S. Sarala, *Phys. Rev. D* **66**, 085007 (2002).
- [192] N. Bassan, A. Mirizzi, and M. Roncadelli, *J. Cosmol. Astropart. Phys.* **05** (2010) 010.
- [193] N. Agarwal, A. Kamal, and P. Jain, *Phys. Rev. D* **83**, 065014 (2011).
- [194] A. Payez, J. R. Cudell, and D. Hutsemékers, *Phys. Rev. D* **84**, 085029 (2011).
- [195] R. Perna, W. C. G. Ho, L. Verde, M. van Adelsberg, and R. Jimenez, *Astrophys. J.* **748**, 116 (2012).
- [196] F. Day and S. Krippendorff, *Galaxies* **6**, 45 (2018).
- [197] G. Galanti, *Phys. Rev. D* **105**, 083022 (2022).
- [198] G. Galanti, *Phys. Rev. D* **107**, 043006 (2023).
- [199] G. Galanti, M. Roncadelli, F. Tavecchio, and E. Costa, *Phys. Rev. D* **107**, 103007 (2023).

- [200] G. Galanti, M. Roncadelli, and F. Tavecchio, *Phys. Rev. D* **108**, 083017 (2023).
- [201] N. Gehrels, *Astrophys. J.* **303**, 336 (1986).
- [202] G. Amelino-Camelia, *Mod. Phys. Lett. A* **17**, 899 (2002).
- [203] S. Liberati and L. Maccione, *Annu. Rev. Nucl. Part. Sci.* **59**, 245 (2009).
- [204] D. Mattingly, *Living Rev. Relativity* **8**, 5 (2005).
- [205] G. Amelino-Camelia, *Living Rev. Relativity* **16**, 5 (2013).
- [206] S. Liberati, *Classical Quantum Gravity* **30**, 133001 (2013).
- [207] G. Galanti, F. Tavecchio, and M. Landoni, *Mon. Not. R. Astron. Soc.* **491**, 5268 (2020).
- [208] A. Addazi *et al.*, *Prog. Part. Nucl. Phys.* **125**, 103948 (2022).
- [209] R. Alves Batista *et al.*, *Classical Quantum Gravity* **42**, 032001 (2025).
- [210] J. A. Wheeler, *Ann. Phys. (N.Y.)* **2**, 604 (1957).
- [211] J. A. Wheeler, *Geometrodynamics* (Academic Press, London, 1962).
- [212] J. A. Wheeler, in *Relativity, Groups and Topology*, edited by B. S. and C. M. De Witt (Gordon and Breach, New York, 1964).
- [213] S. W. Hawking, *Nucl. Phys.* **B144**, 349 (1978).
- [214] S. Carlip, *Phys. Rev. Lett.* **79**, 4071 (1997).
- [215] L. Gonzales-Mestres, in *Proceedings of the 25th International Conference on Cosmic Rays, Durban*, edited by M. S. Potgieter, C. Raubenheimer, and D. J. van der Walt (Potchefstroom University, Transvaal, 1997), Vol. 6, p. 109. <https://articles.adsabs.harvard.edu/pdf/1997ICRC..25f.109G>.
- [216] S. Coleman and S. L. Glashow, *Phys. Rev. D* **59**, 116008 (1999).
- [217] T. Kifune, *Astrophys. J.* **518**, L21 (1999).
- [218] R. Aloisio, P. Blasi, P. L. Ghia, and A. F. Grillo, *Phys. Rev. D* **62**, 053010 (2000).
- [219] G. Amelino-Camelia and T. Piran, *Phys. Rev. D* **64**, 036005 (2001).
- [220] F. W. Stecker and S. L. Glashow, *Astropart. Phys.* **16**, 97 (2001).
- [221] F. W. Stecker, *Astropart. Phys.* **20**, 85 (2003).
- [222] U. Jacob and T. Piran, *Phys. Rev. D* **78**, 124010 (2008).
- [223] The explicit equation for the time delay in the cosmological context has been derived in U. Jakob and T. Piran, *J. Cosmol. Astropart. Phys.* **01** (2008) 031.
- [224] J. R. Ellis, N. E. Mavromatos, and D. V. Nanopoulos, *Phys. Lett. B* **293**, 37 (1992).
- [225] J. R. Ellis, N. E. Mavromatos, and D. V. Nanopoulos, *Phys. Rev. D* **61**, 027503 (2000).
- [226] J. R. Ellis, N. E. Mavromatos, and A. S. Sakharov, *Astropart. Phys.* **20**, 669 (2004).
- [227] J. R. Ellis, N. E. Mavromatos, D. V. Nanopoulos, and A. S. Sakharov, *Int. J. Mod. Phys. A* **19**, 4413 (2004).
- [228] J. Polchinski, [arXiv:hep-th/9611050](https://arxiv.org/abs/hep-th/9611050).
- [229] M. Fairbairn, A. Nilsson, J. Ellis, J. Hinton, and R. White, *J. Cosmol. Astropart. Phys.* **06** (2014) 005.
- [230] F. Tavecchio and G. Bonnoli, *Astron. Astrophys.* **585**, A25 (2016).
- [231] L. H. C. Borges, A. G. Dias, A. F. Ferrari, J. R. Nascimento, and A. Yu. Petrov, *Phys. Rev. D* **89**, 045005 (2014).
- [232] A. J. G. Carvalho, A. G. Dias, A. F. Ferrari, T. Mariz, J. R. Nascimento, and A. Yu. Petrov, *Phys. Rev. D* **107**, 085021 (2023).
- [233] P. Laurent, D. Götz, P. Binétruy, S. Covino, and A. Fernandez-Soto, *Phys. Rev. D* **83**, 121301(R) (2011).
- [234] D. Götz, S. Covino, A. Fernandez-Soto, P. Laurent, and Z. Bosnjak, *Mon. Not. R. Astron. Soc.* **431**, 3550 (2013).
- [235] V. Vasileiou, A. Jacholkowska, F. Piron, J. Bolmont, C. Couturier, J. Granot, F. W. Stecker, J. Cohen-Tanugi, and F. Longo, *Phys. Rev. D* **87**, 122001 (2013).
- [236] Observe that a LIV-deformed dispersion relation for ALPs is consistent with D-brane physics.
- [237] D. D. Ofengeim and T. Piran, *Phys. Rev. D* **112**, 083055 (2025).
- [238] C. D. Dermer and A. Atoyan, *Astron. Astrophys.* **418**, L5 (2004).

End Matter

Appendix—We describe the procedure used to construct the bands shown in Figs. 1 and 2 for the ALP-alone, LIV-alone, and ALP + LIV scenarios. The three cases rely on different modeling assumptions: the ALP scenario is obtained from a systematic scan over the relevant parameter space, the LIV scenario is constrained by physically allowed intervals bounded by the independent upper bounds from Eqs. (7) and (8) and lower limits from observations, and the combined ALP + LIV case is derived from a single consistent propagation model in which both effects are simultaneously included within their respective allowed parameter ranges.

We emphasize that this 95% inclusion construction is distinct from the 95% confidence level used in the Poisson inference for the LIV bounds.

In all cases, we include the uncertainty associated with the intrinsic Carpet spectrum at $\mathcal{E} \sim 300$ TeV, allowing for a factor-of-three variation above and below the extrapolated LHAASO flux, in line with the systematic uncertainty reported by the Carpet analysis [11] (see also Fig. 2).

Robustness and limits of the ALP scenario: The range of ALP parameters m_a and $g_{a\gamma\gamma}$ adopted in the main text ensures $P_{\text{ALP}}(\mathcal{E}; \gamma \rightarrow \gamma) \gtrsim \mathcal{O}(10^{-5})$ at $\mathcal{E} \sim 15$ TeV, as required to account for the LHAASO data [47]. This choice incorporates the main astrophysical uncertainties, including host-galaxy morphology, magnetic-field configurations, and EBL models (see Supplemental Material [69]). In particular, a higher EBL density or weaker magnetic fields in the host galaxy require values of $g_{a\gamma\gamma}$ toward the upper end of the considered range. Conversely, m_a is

constrained to $m_a \lesssim 10^{-7}$ eV by the efficiency of photon-ALP conversion and to $m_a \gtrsim 10^{-11}$ eV by x-ray bounds [83]. We have also verified that including photon-ALP conversion in extragalactic space does not significantly affect the results (see Supplemental Material [69]).

The colored bands in Figs. 1 and 2 are obtained by scanning the relevant parameter space (including m_a , $g_{\gamma\gamma}$, and magnetic-field configurations), generating $\sim 10^3$ realizations. The bands correspond to the central 95% inclusion region, defined by excluding the lowest and highest 2.5% of the realizations at each energy.

We find that variations in the EBL model and in the magnetic field of the host galaxy do not qualitatively modify the results. In particular, for ALPs at $\mathcal{E} \sim 300$ TeV, the expected photon count remains around 2 orders of magnitude below the level required to account for the observation at 95% CL, even when considering the most favorable configurations within the explored parameter space (i.e., maximal coupling, magnetic-field strength, and coherence length). This demonstrates the robustness of the conclusion that ALPs alone cannot account for the Carpet event.

Robustness and constraints of the LIV scenario: For the LIV case, the bands correspond to the range of LIV scales consistent with both our derived upper limits, obtained from the requirement to explain the Carpet event at 95% CL (including the uncertainty on the observed flux), and the most stringent lower bounds available in the literature relevant to this scenario [63]. The resulting region, therefore, reflects the physically allowed interval for $\mathcal{E}_{\text{LIV},n}$ propagated to the corresponding observables, rather than a statistical confidence band.

In constructing the bands, we adopt the most restrictive upper limit on $\mathcal{E}_{\text{LIV},n}$ in Eqs. (7) and (8) including the uncertainty in the Carpet flux. This choice defines the most conservative case compatible with the observation;

alternative choices within the allowed range produce only marginal variations in the resulting bands.

Additional LIV constraints are discussed in Supplemental Material [69].

At the energies relevant for the Carpet event ($\mathcal{E} \sim 300$ TeV), the dominant attenuation mechanism in conventional physics is provided by interactions with the CMB, while the role of the EBL is subleading [17,18]. As a consequence, the determination of the LIV scale is largely insensitive to uncertainties in EBL modeling. Moreover, since LIV effects enter through modifications of the photon dispersion relation and of the pair-production threshold, they do not directly depend on astrophysical parameters such as magnetic-field configurations. This is in contrast with the ALP scenario, where magnetic-field properties play a central role in the conversion probability.

ALP + LIV scenario: For the combined ALP + LIV case, the bands are obtained from a fully consistent propagation model in which photon-ALP oscillations and LIV-modified dispersion relations are included simultaneously in the beam evolution. We perform the same scan over the ALP parameter space as described above, while for each realization the LIV scale $\mathcal{E}_{\text{LIV},n}$ is varied within the physically allowed range defined by our upper limits (from the requirement of explaining the Carpet event at 95% CL) and by the most stringent lower bounds available in the literature relevant to this case.

The resulting regions, therefore, represent the envelope of the predictions of the complete ALP + LIV framework, obtained from an independent variation of all parameters within their physically allowed domains. We emphasize that this construction does not correspond to a superposition of the separate ALP and LIV effects but arises from a single propagation calculation in which both mechanisms are simultaneously active.