Observability of the Very-High-Energy Emission from GRB 221009A

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The LHAASO Collaboration detected the gamma ray burst GRB 221009A at energies above 500 GeV with a tail extending up to 18 TeV, whose spectral analysis has presently been performed up to 7 TeV for the lower energy instrument LHAASO-WCDA only, with no indication of a cutoff. Soon thereafter, Carpet-2 at Baksan Neutrino Observatory reported the observation of an air shower consistent with being caused by a photon of energy 251 TeV from the same GRB. Given the source redshift $z = 0.151$, the expected attenuation due to the extragalactic background light is very severe so that these detections have proven very hard to explain. In this Letter, we show that the existence of axionlike particles 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} strongly reduce the optical depth of TeV photons, thus explaining the observations. Our ALPs meet all available constraints, are consistent with two previous hints at their existence, and are good candidates for cold dark matter. Moreover, we show that Lorentz invariance violation can explain the Carpet-2 result but *not* the LHAASO observations.

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Introduction.—On 2022/10/11, the LHAASO Collaboration reported the detection of more than 5000 very-high-energy [(VHE), $\mathcal{E} > 100$ GeV] photons from the gamma ray burst GRB 221009A. Specifically, GRB 221009A was detected by LHAASO-WCDA above 500 GeV within 2000 sec after the initial burst with significance over 100σ, and by LHAASO-KM2A with significance about 10σ with the highest photon energy reaching 18 TeV [1]. Absorption features in the optical spectrum allowed us to measure the redshift, which is $z = 0.151$ [2]. Before this discovery, the largest photon energy ever detected from a GRB was about 3 TeV observed by H.E.S.S. from GRB 190829A at $z = 0.079$ [3].

On 2022/10/12, the Carpet-2 Collaboration at Baksan Neutrino Observatory announced the detection of an air shower consistent with being caused by a photon of energy 251 TeV from a position encompassing GRB 221009A and observed 4536 sec after the Fermi-GBM trigger [4].

The detection of photons with energies $\mathcal{E} > 10$ TeV is a very important discovery, as the flux of VHE photons from extragalactic sources is strongly attenuated through e^+e^- pair production on the extragalactic background light (EBL). As we shall see, at $z = 0.151$ the attenuation of a photon flux with $\mathcal{E} = 18$ TeV is at least $\mathcal{O}(10^6–10^8)$, making it extremely difficult to explain the LHAASO and even more the Carpet-2 detection (below we shall pay more attention to the LHAASO events because of their higher reliability). One possibility to solve the problem is to invoke unconventional particle physics, such as axionlike particles (ALPs), a scenario which we have been deeply investigating over the last several years [5].

In this Letter, we propose—for the first time—that ALPs explain the detection of multi-TeV photons from any GRB, and specifically from GRB 221009A [6]. As we shall show, the gist of our strategy is that beam photons can convert into ALPs whose propagation is unaffected by the EBL, so that the effective optical depth $\tau_{\mathrm{ALP}}(\mathcal{E})$ is strongly reduced. Furthermore, we analyze the implications at $\mathcal{E} > 10$ TeV of the spectral data of GRB 221009A released so far by the LHAASO Collaboration, which are limited to the low energy instrument [LHAASO-WCDA, (0.2–7) TeV] and show consistency with a power-law spectrum up to ~7 TeV with no indication of a cutoff [12] (see also Appendix). We also show that Lorentz invariance violation (LIV) can explain the Carpet-2 result but *not* the LHAASO observations.

Cosmic photon extinction.—On their way to us from extragalactic sources, VHE photons scatter off the EBL, namely, the infrared-optical-ultraviolet photon background emitted by the whole stellar population and possibly reprocessed by dust during the cosmic evolution (for a review, see Ref. [13]). Several EBL models have been proposed so far and they are discussed in the Supplemental Material [14]. Given an EBL model, the resulting optical depth $\tau_{\mathrm{CP}}(\mathcal{E})$ can be computed, in terms of which the photon survival probability reads $P_{\mathrm{CP}}(\mathcal{E};\gamma \to \gamma) = e^{-\tau_{\mathrm{CP}}(\mathcal{E})}$. Here we employ the Saldana-Lopez *et al.* EBL model [59]—to be referred to as SL EBL—because of four different reasons: (i) it is the most recent one; (ii) it is based on the deepest galaxy datasets ever obtained; (iii) it is derived by a satellite borne detector, which minimizes foreground effects (like zodiacal light); (iv) it is the one used by the LHAASO Collaboration to infer their spectral results [12]. The corresponding values of the photon survival probability for the nominal photon energies reported by LHAASO and Carpet-2—and also at lower energies to allow for an uncertainty of (15%–20%) [60] and 50%, respectively—are $P_{\rm CP}(15~{\rm TeV}; \gamma \to \gamma) = 3 \times 10^{-6}$, $P_{\rm CP}(18~{\rm TeV}; \gamma \to \gamma) = 1 \times 10^{-8}$, $P_{\rm CP}(100~{\rm TeV}; \gamma \to \gamma) = 3 \times 10^{-96}$, and $P_{\rm CP}(251~{\rm TeV}; \gamma \to \gamma) \sim 0$ (see also [7]). Thus, within conventional physics alone, $\mathcal{E} > 10$ TeV photons are extremely unlikely to detect since their observation would require a huge TeV luminosity which is in tension with model predictions (see last section).

Axionlike particles (ALPs).—Many extensions of the Standard Model of particle physics—especially superstring and superbrane theories—predict the existence of ALPs (see, e.g., [61–71] and references therein, and [5,72–74] for reviews). Here, we provide only the minimal information about ALPs needed to understand the proposed scenario (details are reported in Supplemental Material [14]).

ALPs are very light pseudoscalar bosons of mass m_a and with two-photon coupling $g_{a\gamma\gamma}$ described by the Lagrangian

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

where a is the ALP field and $F_{\mu\nu}$ is the electromagnetic tensor with electric and magnetic components $\mathbf{E}$ and $\mathbf{B}$, respectively, and $\tilde{F}^{\mu\nu}$ is its dual [in Eq. (1) $\mathbf{E}$ is the photon electric field]. In this context two additional effects should be considered, namely, the QED vacuum polarization [75–78] and the photon dispersion on the CMB [79] (see Supplemental Material [14]). Other couplings to conventional particles can exist but are irrelevant here, hence they are discarded. Actually, Eq. (1) entails that in the presence of an external magnetic field $\mathbf{B}$ $\gamma \to a$ and $a \to \gamma$ *conversions* take place, thereby implying that as a photon beam propagates these conversions produce $\gamma \leftrightarrow a$ *oscillations* [75,80]. Still, within this scenario ALPs do not effectively interact either with single photons or with matter [81]. As a consequence $\tau_{\rm ALP}(\mathcal{E})$ gets reduced, but—since the photon survival probability is presently $P_{\rm ALP}(\mathcal{E}; \gamma \to \gamma) = e^{-\tau_{\rm ALP}(\mathcal{E})}$—even a small decrease of $\tau_{\rm ALP}(\mathcal{E})$ with respect to $\tau_{\rm CP}(\mathcal{E})$ gives rise to a large increase of $P_{\rm ALP}(\mathcal{E}; \gamma \to \gamma)$ [82] (see Supplemental Material [14]).

The photon-ALP interaction gives rise to several effects both on the observed spectra (with possible hints at the ALP existence, see, e.g., [82–91]) and on the final photon polarization (see, e.g., [92–101]). Under the assumption $\mathcal{E} \gg m_a$—which is presently satisfied—the beam propagation equation obeys a Schrödinger-like equation with time replaced with the beam propagation direction y, so that a photon-ALP beam can be treated as a nonrelativistic quantum system [75]. This fact entails that the pure states of the beam are described by the wave function $\psi(y) = (A_x(y), A_z(y), a(y))$ with $A_x(y)$, $A_z(y)$, $a(y)$ denoting the photon and ALP amplitudes, respectively (see Supplemental Material [14]). Moreover, the *transfer matrix* of the beam over the distance interval $[y_i, y_{i+1}]$ is denoted by $\mathcal{U}_i(\mathcal{E}; y_{i+1}, y_i)$, and the total transfer matrix over a number N of intervals is

$$\mathcal{U}(\mathcal{E}; y_{N+1}, y_1) = \prod_{i=1}^{N} \mathcal{U}_i(\mathcal{E}; y_{i+1}, y_i). \tag{2}$$

Assuming unpolarized emitted photons, we must employ the polarization density matrix $\rho(y) \equiv |\psi(y)\rangle\langle\psi(y)|$. Therefore, the overall photon survival probability is

$$P_{\rm ALP}(\mathcal{E}; \gamma \to \gamma) = \sum_{i=x,z} {\rm Tr}[\rho_i \mathcal{U}(\mathcal{E}; y_{N+1}, y_1) \times \rho_{\rm unp} \mathcal{U}^\dagger(\mathcal{E}; y_{N+1}, y_1)], \tag{3}$$

where $\rho_x \equiv {\rm diag}(1, 0, 0)$, $\rho_z \equiv {\rm diag}(0, 1, 0)$ and $\rho_{\rm unp} \equiv {\rm diag}(0.5, 0.5, 0)$ [85]. The quantities m_a and $g_{a\gamma\gamma}$ are totally unrelated, and we take $10^{-12}~{\rm eV} \le m_a \le 10^{-6}~{\rm eV}$ and $10^{-13}~{\rm GeV}^{-1} \le g_{a\gamma\gamma} \le 10^{-10}~{\rm GeV}^{-1}$ as starting ALP parameter space.

ALP scenario applied to GRB 221009A.—In order to enhance the clarity of our investigation, we consider at once the individual media crossed by the photon-ALP beam as it travels from the source to us. Below, we outline the logic of our calculations, which are reported in great detail in the Supplemental Material [14].

(i) *Conversion inside the source:* The exact time when photons above 10 TeV have been recorded is currently unknown, but the timescale (within 2000 sec) suggests that this detection is related to the afterglow emission, similarly to all previous detections of TeV GRBs [3,102,103]. In this scenario, photons are produced in the downstream region of the forward shock. The path traveled by the photons in the shocked region is of order R/Γ (comoving frame), where R is the distance from the central engine and Γ the bulk Lorentz factor. We take $R \sim 2 \times 10^{17}$ cm, $\Gamma = 45$, comoving electron density $n' = 450~{\rm cm}^{-3}$ and comoving magnetic field strength $B' = 2$ G (see Supplemental Material for justification [14]). Given these values and by following a similar procedure as in [90], we compute the transfer matrix $\mathcal{U}_1(\mathcal{E}; y_2, y_1)$ in the GRB jet, where y_2 and y_1 denote the position of the border of the GRB and of the production region, respectively. We find that photon-ALP conversions in the source are negligible, whence $\mathcal{U}_1(\mathcal{E}; y_2, y_1) \simeq 1$.

(ii) *Conversion inside the host galaxy:* In [104] evidence that the host galaxy of GRB 221009A is a disclike one is presented. In the lack of any firm knowledge of its nature, we consider the two most likely possibilities: a typical spiral (see, e.g., [105,106]) and a starburst with intermediate properties similar to M82 [107,108].

According to [104], the host galaxy has an edge-on orientation—hence causing the photon-ALP beam to propagate inside the disk—with the GRB located close to the nuclear region. So, we place our GRB in the neighborhood of the galactic center (see also [109,110]). We take into account all components of the host magnetic field $\mathbf{B}_{\rm host}$ with their stochastic properties [105,111,112] and their radial profiles [113], which are relevant for the photon-ALP conversion. The magnetic field strength assumed for the spiral is $B_{\rm host,spiral} = \mathcal{O}(5\text{–}10)$ μG, while for the starburst is $B_{\rm host,starburst} = \mathcal{O}(20\text{–}50)$ μG. Knowing the behavior of $\mathbf{B}_{\rm host}$ and of the other relevant parameters for either a spiral or a starburst hosting galaxy, we compute the transfer matrix in the host $\mathcal{U}_2(\mathcal{E}; y_3, y_2)$, where y_3 denotes the position of the external luminous galaxy edge.

(iii) *Conversion in extragalactic space:* Unfortunately, our knowledge of the extragalactic magnetic field $\mathbf{B}_{\rm ext}$ is still very poor. All we know is that $B_{\rm ext}$ lies in the range 10^{-7} nG $\lesssim B_{\rm ext} \lesssim 1.7$ nG on the scale of $\mathcal{O}(1)$ Mpc [114–116]. Nevertheless, it has become customary to model $B_{\rm ext}$ as a domainlike network, wherein $\mathbf{B}_{\rm ext}$ is assumed to be homogeneous over a whole domain of size $L_{\rm dom}^{\rm ext}$ equal to its coherence length, with $\mathbf{B}_{\rm ext}$ changing randomly its direction from one domain to the next, keeping approximately the same strength [117,118]. Accordingly, the beam propagation becomes a *random process*, and only a single realization at once can be observed. We employ a recent and physically accurate model to describe $\mathbf{B}_{\rm ext}$ with $B_{\rm ext} = \mathcal{O}(1)$ nG and $L_{\rm dom}^{\rm ext} = \mathcal{O}(1)$ Mpc [119,120]. The latter possibility—our option 1—is suggested by several scenarios [121–124]. Given the above uncertainty, we also consider the very conservative value $B_{\rm ext} < 10^{-15}$ G (option 2). In either case, we take the photon dispersion on the CMB into account. Having fixed the properties of $\mathbf{B}_{\rm ext}$ and following [81] we evaluate the transfer matrix $\mathcal{U}_3(\mathcal{E}; y_4, y_3)$ in the extragalactic space for both options, where y_4 denotes the position of the outer luminous edge of the Milky Way.

(iv) *Conversion in the Milky Way:* The morphology of the magnetic field $\mathbf{B}_{\rm MW}$ and of the electron number density $n_{{\rm MW},e}$ in the Galaxy are nowadays rather well known. Concerning $\mathbf{B}_{\rm MW}$, we adopt the model by Jansson and Farrar [125–127], which is more complete with respect to the one of Pshirkov *et al.* [128], even though we do not find substantial differences by employing the latter. Regarding $n_{{\rm MW},e}$, we use the model developed in [129]. The transfer matrix in the Milky Way $\mathcal{U}_4(\mathcal{E}; y_5, y_4)$—where y_5 is the position of the Earth—is evaluated as in Sec. 3.4 of [90].

Results within the ALP model.—Once all individual transfer matrices are known, the total one from the photon production region in GRB 221009A to the Earth is given by Eq. (2) and the photon survival probability in the presence of photon-ALP interaction $P_{\rm ALP}(\mathcal{E}; \gamma \to \gamma)$ follows from Eq. (3). Figure 1 shows $P_{\rm ALP}(\mathcal{E}; \gamma \to \gamma)$ at $\mathcal{E} = 15$ TeV for values of m_a and $g_{a\gamma\gamma}$ in the range $10^{-12}\ {\rm eV} \leq m_a \leq 10^{-6}$ eV and $10^{-13}\ {\rm GeV}^{-1} \leq g_{a\gamma\gamma} \leq 10^{-10}\ {\rm GeV}^{-1}$ (see Supplemental Material [14] for similar plots at different energies). We assume $B_{\rm ext} = 1$ nG and a starburst hosting galaxy.

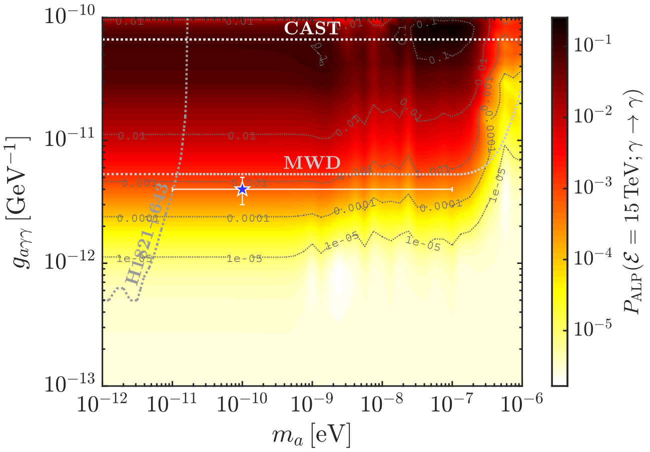

FIG. 1. Photon survival probability $P_{\rm ALP}(\mathcal{E}; \gamma \to \gamma)$ at energy $\mathcal{E} = 15$ TeV as a function of the ALP mass m_a and of the photon-ALP coupling $g_{a\gamma\gamma}$ assuming the SL EBL model, $B_{\rm ext} = 1$ nG and a starburst hosting galaxy. The blue star with error bar represents our choice for the ALP parameters: $m_a = 10^{-10}$ eV and $g_{a\gamma\gamma} = 4 \times 10^{-12}$ GeV^{-1}. The three bounds mentioned in the text are also plotted.

Our next step concerns the ALP parameter space. To date the most reliable bounds are as follows: $g_{a\gamma\gamma} < 0.66 \times 10^{-10}$ GeV^{-1} for $m_a < 0.02$ eV from the CAST experiment [130], $g_{a\gamma\gamma} < 6.3 \times 10^{-13}$ GeV^{-1} for $m_a < 10^{-12}$ eV from observations of H1821 + 643 in the x-ray band [131] and $g_{a\gamma\gamma} < 5.4 \times 10^{-12}$ GeV^{-1} for $m_a < 3 \times 10^{-7}$ eV from the polarimetric analysis of magnetic white dwarfs (MWD) [132]. Within these bounds, the values of m_a and $g_{a\gamma\gamma}$ which maximize $P_{\rm ALP}(\mathcal{E} = 15\ {\rm TeV}; \gamma \to \gamma)$ are $m_a \simeq (10^{-11}\text{–}10^{-7})$ eV and $g_{a\gamma\gamma} \simeq (3-5) \times 10^{-12}$ GeV^{-1}. We choose $m_a = 10^{-10}$ eV and $g_{a\gamma\gamma} = 4 \times 10^{-12}$ GeV^{-1} as benchmark values based on two previous hints at the ALP existence [86,91]. We report both $P_{\rm CP}(\mathcal{E}; \gamma \to \gamma)$ and $P_{\rm ALP}(\mathcal{E}; \gamma \to \gamma)$ in Fig. 2 for the case of a starburst galaxy hosting the GRB. As discussed in [81], above $\mathcal{O}(5)$ TeV the photon-ALP conversion in the extragalactic space becomes inefficient because of the photon dispersion on the CMB. In Fig. 2 we consider both the case of an efficient ($B_{\rm ext} = 1$ nG) and negligible ($B_{\rm ext} < 10^{-15}$ G) photon-ALP conversion in the extragalactic space. Remarkably, even though the effect is reduced for $B_{\rm ext} < 10^{-15}$ G, we can still consistently explain the photon observations of *both* LHAASO *and* Carpet-2 with no substantial difference. Note that as m_a approaches $m_a = \mathcal{O}(10^{-7})$ eV the conversion in extragalactic space becomes inefficient and we recover the case $B_{\rm ext} < 10^{-15}$ G, which produces similar results (see Figs. 1 and 2).

The recent LHAASO spectral data analysis up to 7 TeV shows the spectrum of GRB 221009A in different time slices during the 2000 sec observational time [12]. In order

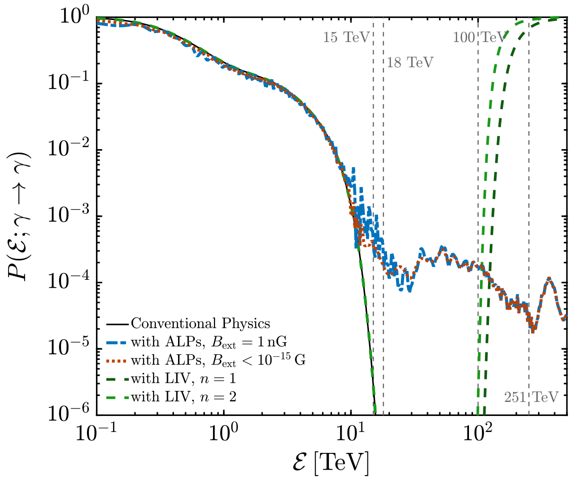

FIG. 2. Photon survival probability $P(\mathcal{E};\gamma\to\gamma)$ versus energy $\mathcal{E}$ in conventional physics, taking into account LIV and ALP effects in the case of a starburst hosting galaxy. We assume $m_a=10^{-10}$ eV and $g_{a\gamma\gamma}=4\times10^{-12}\ {\rm GeV}^{-1}$.

to evaluate its detectability at higher energies, we compute its time averaged spectrum extended up to 18 TeV as discussed in the Appendix. Hence, we exhibit in Fig. 3 the intrinsic averaged spectrum and the observed one both in conventional physics and when photon-ALP effects are at work, along with the LHAASO sensitivity (see Appendix). Figure 3 shows that conventional physics *cannot* account for the detection of photons with $\mathcal{E}>10$ TeV even in the best scenario wherein the spectrum continues as a power law, and in particular with energies even below the lower limit of the uncertainty about the LHAASO event at 18 TeV, while our ALP scenario with $m_a\simeq(10^{-11}\text{–}10^{-7})$ eV and $g_{a\gamma\gamma}\simeq(3-5)\times10^{-12}\ {\rm GeV}^{-1}$ explains the LHAASO observations (see Appendix).

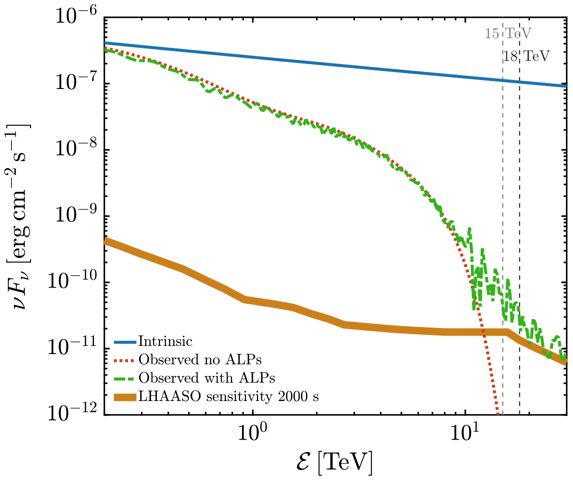

FIG. 3. Intrinsic average spectrum of GRB 221009A as measured by LHAASO [12] extended up to ~20 TeV and the corresponding observed one versus energy $\mathcal{E}$ within conventional physics and when ALP effects are taken into account. The LHAASO sensitivity at 2000 sec is also shown (see Appendix).

The case of a spiral galaxy hosting the GRB is reported in the Supplemental Material [14], and leads to results in the same ballpark of those derived for a starburst galaxy even if slightly smaller.

Lorentz invariance violation.—Extensions of the standard model of particle physics encompassing quantum gravity predict a violation of Lorentz invariance (for a review, see Ref. [133]). As far as the present analysis is concerned, its main implication is the following modification of the photon dispersion relation

$$\mathcal{E}^2-p^2=-\frac{\mathcal{E}^{n+2}}{\mathcal{E}^n_{\rm LIV}}, \tag{4}$$

where $\mathcal{E}$ and p are the photon energy and momentum, respectively, while $\mathcal{E}_{\rm LIV}$ is the high-energy scale above which LIV becomes important. As already demonstrated in [134,135] for a redshift very close to that of GRB 221009A, within the current LIV limits [136] LIV *cannot* explain a reduced opacity at LHAASO energies [1] (see also [7] and Fig. 2). On the contrary, at energies around the detection by Carpet-2 [4], the photon survival probability $P_{\rm LIV}(\mathcal{E})$ in the presence of LIV effects approaches the value $P_{\rm LIV}(\mathcal{E})=1$ (see Fig. 2), for both the cases of $n=1$ with $\mathcal{E}_{{\rm LIV},n=1}=3\times10^{29}$ eV and $n=2$ with $\mathcal{E}_{{\rm LIV},n=2}=5\times10^{21}$ eV within the current LIV bounds [136].

Discussion and conclusions.—We restate that within conventional physics alone $\mathcal{E}>10$ TeV photons are extremely unlikely to detect since their observation would require a huge TeV luminosity which is in tension with model predictions. Specifically, among the theoretical models proposed to explain the origin of $\mathcal{E}>10$ TeV photons in GRB 221009A there are synchrotron self-Compton (SSC) radiation and secondary emission from ultrahigh energy protons [137–141]. In all these studies, the predicted emission—once EBL attenuation and instrument efficiency are considered—is found to have a low chance to be detected, and only for contrived choices of the model parameters [138], and/or peculiar choices on the location of the GRB [137,139]. Thus, observations appear to be in tension with the possibility to produce a $\mathcal{E}>10$ TeV emission luminous enough to be detected by LHAASO within conventional physics.

A most effective way to achieve the same goal is to invoke photon-ALP oscillations, a mechanism which strongly reduces the opacity of the Universe to VHE photons. This possibility has been investigated in this Letter for the first time concerning TeV GRBs in general and for GRB 221009A in particular. Taking uncertainties into account, we have shown that ALPs with mass $m_a\simeq(10^{-11}\text{–}10^{-7})$ eV and two-photon coupling $g_{a\gamma\gamma}\simeq(3-5)\times10^{-12}\ {\rm GeV}^{-1}$ significantly increase the photon survival probability of multi-TeV photons and explain the LHAASO detection above 10 TeV in conjunction with the SL EBL model, which is the best one available to date. We stress that the considered values of both m_a and $g_{a\gamma\gamma}$ are in agreement with the strongest bounds. Moreover, these values are consistent with two previous hints at the ALP existence [86,91] and make them good candidates for cold dark matter [142].

We also investigated the alternative LIV scenario, finding that it is *unable* to explain photon detection at LHAASO energies within current limits, but *can* explain that by Carpet-2.

The ALP parameter space employed here will be probed with astrophysical data collected by several observatories such as ASTRI [143], CTA [144], GAMMA-400 [145], HAWC [146], HERD [147], LHAASO [148], and TAIGA-HiSCORE [149], by laboratory experiments like ALPS II [150], IAXO [151,152], and STAX [153], with the techniques developed by Avignone and collaborators [154–156], and possibly by the ABRACADABRA experiment [157].

Note added.—After the acceptance of this Letter, the LHAASO Collaboration released a preprint on a first analysis of the GRB 221009A spectrum above 10 TeV [158]. Therein, the highest energy bin can be at $\mathcal{E} \sim 13$ TeV or at $\mathcal{E} \sim 18$ TeV, depending on the adopted fitting procedure. According to the LHAASO Collaboration “Observations of photons up to 13 TeV from a source with a measured redshift of $z = 0.151$ requires more transparency in intergalactic space than previously expected, in order to avoid an unusual pile-up at the end of the spectrum. Alternatively, one may invoke new physics such as Lorentz Invariance Violation (LIV) or assume an axion origin of very high energy (VHE) signals”. This LHAASO conclusion makes our results about ALPs solving the problem even more robust, while we stress that, as shown in detail in our paper, LIV actually provides no benefit in explaining this experimental evidence.

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Appendix.—GRB 221009A spectrum: The spectrum of GRB 221009A has recently been released by LHAASO for energies $0.2\ \text{TeV} \lesssim \mathcal{E} \lesssim 7\ \text{TeV}$ [12]. The LHAASO Collaboration fits the intrinsic spectrum $\mathcal{F}_i$ in the ith time interval once data are EBL deabsorbed by means of the “standard,” “high,” and “low” SL EBL models with the power law

$$\mathcal{F}_i(\mathcal{E}) \equiv \frac{dN}{d\mathcal{E}} = A\left(\frac{\mathcal{E}}{\text{TeV}}\right)^{-\gamma}, \tag{A1}$$

where A is a normalization constant expressed in units of $10^{-8}\ \text{TeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}$ and γ is the spectral slope. Different values of A and γ are reported in Table S2 of [12] for 5 time intervals covering the full time range (231–2000) sec of LHAASO detection after the Fermi-GBM trigger. The LHAASO Collaboration does not find any curvature in the intrinsic spectrum up to 7 TeV. Therefore, an extrapolation of Eq. (A1) up to about 20 TeV looks justified.

In order to compare the observed spectrum of GRB 221009A with the LHAASO sensitivity (see below) we compute the time averaged intrinsic spectrum $\mathcal{F}_{\text{int}}$ defined as

$$\mathcal{F}_{\text{int}} \equiv \langle \mathcal{F}_i \rangle = \frac{1}{T}\sum_{i=1}^{5} \Delta t_i \mathcal{F}_i, \tag{A2}$$

where $T = 1769$ sec is the total duration of the LHAASO detection, while Δt_i is the duration of the ith time interval, as reported in Table S2 of [12].

The observed spectrum $\mathcal{F}_{\text{obs}}$ can be evaluated by means of

$$\mathcal{F}_{\text{obs}}(\mathcal{E}) = P(\mathcal{E};\gamma \to \gamma)\mathcal{F}_{\text{int}}(\mathcal{E}), \tag{A3}$$

where $P(\mathcal{E};\gamma \to \gamma) = P_{\text{CP}}(\mathcal{E};\gamma \to \gamma)$ in the case of conventional physics and $P(\mathcal{E};\gamma \to \gamma) = P_{\text{ALP}}(\mathcal{E};\gamma \to \gamma)$ when ALP effects are considered (see the main text and Supplemental Material [14] for its derivation). We recall that the spectral energy distribution (SED) reported in Fig. 3 is related to $\mathcal{F}_{\text{obs}}$ by $\nu F_\nu = \mathcal{E}^2 \mathcal{F}_{\text{obs}}$.

The observed time-averaged spectrum integrated over the energy error range of the instrument around the event at $\mathcal{E} = 18$ TeV with an exposure time of 3600 sec and a KM2A effective area of $\sim 10^9\ \text{cm}^2$ [159] shows that conventional physics is unable to justify such a detection, while the ALP scenario considered in this Letter accomplishes the task.

We have checked the robustness of our results by considering the standard, high, and low SL EBL models, an efficient or negligible photon-ALP conversion in the extragalactic space, and the cases of both a spiral and a starburst galaxy hosting the GRB. Passing from a high to a low SL EBL model and/or from an efficient to a negligible photon-ALP conversion in the extragalactic space and/or from a starburst to a spiral host galaxy, we progressively need higher values of $g_{a\gamma\gamma}$ inside the range $(3\text{–}5) \times 10^{-12}\ \text{GeV}^{-1}$ to explain the LHAASO detection above 10 TeV. The value of m_a is less constrained: the upper limit $m_a < 10^{-7}$ eV is necessary in order to have an efficient photon-ALP conversion, while the lower limit $m_a > 10^{-11}$ eV is imposed by the ALP bound concerning observations of $\text{H}1821 + 643$ in the x-ray band [131].

LHAASO sensitivity: The LHAASO observatory is composed of two instruments: LHAASO-WCDA more sensitive for $\mathcal{E} < \mathcal{O}(15)$ TeV and LHAASO-KM2A more sensitive at higher energies. The sensitivity curve of the entire LHAASO observatory for an exposure time of 1 yr is reported in [148].

We rescale such a curve for our purposes at an exposure time of 2000 sec taking into consideration that the yearly sensitivity includes periods when the source is below the horizon or the effective area drops significantly enough to neglect the contribution. For the declination of the GRB, LHAASO observes the position within 40° of zenith distance for ~6 h per day, and we consider this daily time effect for rescaling the sensitivity. This is motivated from the published observation of Crab Nebula with the partial KM2A Array, where especially below few tens of TeV the effective area is negligible above 40° [159].

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[1] LHAASO Collaboration, GCN Circular no. 32677, 2022, https://gcn.gsfc.nasa.gov/gcn3/32677.gcn3.
[2] Stargate Collaboration, GCN Circular no. 32648, 2022, https://gcn.gsfc.nasa.gov/gcn3/32648.gcn3.
[3] H.E.S.S. Collaboration, Science **372**, 1081 (2021).
[4] Carpet-2 Collaboration, ATel #15669 (2022), https://astronomerstelegram.org/?read=15669.
[5] G. Galanti and M. Roncadelli, Universe **8**, 253 (2022).
[6] Subsequently, a few attempts along similar lines have been put forward. See Refs. [7–11].
[7] A. Baktash, D. Horns, and M. Meyer, arXiv:2210.07172.
[8] S. V. Troitsky, Pis'ma Zh. Eksp. Teor. Fiz. **116**, 745 (2022).
[9] M. M. Gonzales, D. Avila Rojas, A. Pratts, S. Hernández-Cadena, N. Fraija, R. Alfaro, Y. Pérez Araujo, and J. A. Montes, Astrophys. J. **944**, 178 (2023).
[10] P. Carenza and M. C. D. Marsh, arXiv:2211.02010.
[11] L. Wang and Bo-Q. Ma, Phys. Rev. D **108**, 023002 (2023).
[12] LHAASO Collaboration, Science **380**, 1390 (2023).
[13] E. Dwek and F. Krennrich, Astropart. Phys. **43**, 112 (2013).
[14] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.131.251001 for discussion about existing EBL models, which includes Refs. [15–41], for details about ALPs, their astrophysical effects and existing bounds, which includes Refs. [42–54], and for details about photon-ALP propagation in GRBs, which includes Refs. [55–58].
[15] A. Nikishov, Sov. Phys. JETP **14**, 393 (1962), http://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] G. G. Fazio and F. W. Stecker, Nature (London) **226**, 135 (1970).
[18] G. Breit and J. A. Wheeler, Phys. Rev. **46**, 1087 (1934).
[19] W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, Oxford, 1960).
[20] M. G. Hauser and E. Dwek, Annu. Rev. Astron. Astrophys. **39**, 249 (2001).
[21] J. R. Primack, R. S. Sommerville, J. S. Bullock, and J. E. G. Devriedent, AIP Conf. Proc. **558**, 463 (2001).
[22] J. R. Primack, J. S. Bullock, and R. S. Sommerville, AIP Conf. Proc. **745**, 23 (2005).
[23] R. C. Gilmore, P. Madau, J. R. Primack, R. S. Somerville, and F. Haardt, Mon. Not. R. Astron. Soc. **399**, 1694 (2009).
[24] R. C. Gilmore, R. S. Sommerville, J. R. Primack, and A. Dominguez, Mon. Not. R. Astron. Soc. **422**, 3189 (2012).
[25] Y. Inoue, S. Inoue, M. A. R. Kobayashi, R. Makiya, Y. Niino, and T. Totani, Astrophys. J. **768**, 197 (2013).
[26] A. Franceschini, G. Rodighiero, and M. Vaccari, Astron. Astrophys. **487**, 837 (2008).
[27] A. Franceschini and G. Rodighiero, Astron. Astrophys. **603**, A34 (2017).
[28] S. Matsuura *et al.* (CIBER Collaboration), Astrophys. J. **839**, 7 (2017).
[29] T. M. Kneiske, K. Mannheim, and D. H. Hartmann, Astron. Astrophys. **386**, 1 (2002).
[30] T. M. Kneiske, T. Bretz, K. Mannheim, and D. H. Hartmann, Astron. Astrophys. **413**, 807 (2004).
[31] J. D. Finke, S. Razzaque, and C. D. Dermer, Astrophys. J. **712**, 238 (2010).
[32] T. M. Kneiske and H. Dole, Astron. Astrophys. **515**, A19 (2010).
[33] P. Madau and L. Pozzetti, Mon. Not. R. Astron. Soc. **312**, L9 (2000).
[34] A. Dominguez *et al.*, Mon. Not. R. Astron. Soc. **410**, 2556 (2011).
[35] M. Schroedter, Astrophys. J. **628**, 617 (2005).
[36] F. Aharonian *et al.*, Astron. Astrophys. **448**, L19 (2006).
[37] D. Mazin and M. Raue, Astron. Astrophys. **471**, 439 (2007).
[38] D. Mazin and F. Goebel, Astrophys. J. **655**, L13 (2007).
[39] J. D. Finke and S. Razzaque, Astrophys. J. **698**, 1761 (2009).
[40] M. R. Orr, F. Krennrich, and E. Dwek, Astrophys. J. **733**, 77 (2011).
[41] G. Galanti, F. Piccinini, M. Roncadelli, and F. Tavecchio, Phys. Rev. D **102**, 123004 (2020).
[42] S. L. Cheng, C. Q. Geng, and W. T. Ni, Phys. Rev. D **52**, 3132 (1995).
[43] A. Ayala, I. Domínguez, M. Giannotti, A. Mirizzi, and O. Straniero, Phys. Rev. Lett. **113**, 191302 (2014).
[44] M. Ajello *et al.* (Fermi-LAT Collaboration), Phys. Rev. Lett. **116**, 161101 (2016).
[45] M. Berg, J. P. Conlon, F. Day, N. Jennings, S. Krippendorf, A. J. Powell, and M. Rummel, Astrophys. J. **847**, 101 (2017).
[46] J. P. Conlon, F. Day, N. Jennings, S. Krippendorf, and M. Rummel, J. Cosmol. Astropart. Phys. 07 (2017) 005.
[47] 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).
[48] S. Schallmoser, S. Krippendorf, F. Chadha-Day, and J. Weller, Mon. Not. R. Astron. Soc. **514**, 329 (2022).
[49] J. H. Matthews *et al.*, arXiv:2202.08875.
[50] A. Payez, C. Evoli, T. Fischer, M. Giannotti, A. Mirizzi, and A. Ringwald, J. Cosmol. Astropart. Phys. 02 (2015) 006.

[51] N. Bar, K. Blum, and G. D'Amico, Phys. Rev. D **101**, 123025 (2020).

[52] M. Meyer, T. Petrushevska (Fermi Collaboration), Phys. Rev. Lett. **124**, 231101 (2020); **125**, 119901(E) (2020).

[53] M. Meyer, D. Montanino, and J. Conrad, J. Cosmol. Astropart. Phys. 09 (2014) 003.

[54] P. Carenza, C. Evoli, M. Giannotti, A. Mirizzi, and D. Montanino, Phys. Rev. D **104**, 023003 (2021).

[55] R. D. Blandford and C. F. McKee, Phys. Fluids **19**, 1130 (1976).

[56] L. Nava, L. Sironi, G. Ghisellini, A. Celotti, and G. Ghirlanda, Mon. Not. R. Astron. Soc. **433**, 2107 (2013).

[57] E. Derishev and T. Piran, Astrophys. J. **923**, 135 (2021).

[58] E. Derishev, Mon. Not. R. Astron. Soc. **519**, 377 (2023).

[59] A. Saldana-Lopez, A. Domínguez, P. G. Pérez-González, J. Finke, M. Ajello, J. R. Primack, V. S. Paliya, and A. Desai, Mon. Not. R. Astron. Soc. **507**, 5144 (2021).

[60] ASTRI and LHAASO Workshop, Milan, 2023, https://indico.ict.inaf.it/event/2288/.

[61] N. Turok, Phys. Rev. Lett. **76**, 1015 (1996).

[62] E. Witten, Phys. Lett. **149B**, 351 (1984).

[63] J. P. Conlon, J. High Energy Phys. 05 (2006) 078.

[64] P. Svrcek and E. Witten, J. High Energy Phys. 06 (2006) 051.

[65] J. P. Conlon, Phys. Rev. Lett. **97**, 261802 (2006).

[66] K.-S. Choi, I.-W. Kim, and J. E. Kim, J. High Energy Phys. 03 (2007) 116.

[67] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell, Phys. Rev. D **81**, 123530 (2010).

[68] B. S. Acharya, K. Bobkov, and P. Kumar, J. High Energy Phys. 11 (2010) 105.

[69] M. Cicoli, M. Goodsell, and A. Ringwald, J. High Energy Phys. 10 (2012) 146.

[70] A. G. Dias, A. C. B. Machado, C. C. Nishi, A. Ringwald, and P. Vaudrevange, J. High Energy Phys. 06 (2014) 037.

[71] M. J. Scott, D. J. E. Marsh, C. Pongkitivanichkul, L. C. Price, and B. S. Acharya, Phys. Rev. D **96**, 083510 (2017).

[72] J. Jaeckel and A. Ringwald, Annu. Rev. Nucl. Part. Sci. **60**, 405 (2010).

[73] A. Ringwald, Phys. Dark Universe **1**, 116 (2012).

[74] I. G. Irastorza and J. Redondo, Prog. Part. Nucl. Phys. **102**, 89 (2018).

[75] G. G. Raffelt and L. Stodolsky, Phys. Rev. D **37**, 1237 (1988).

[76] W. Heisenberg and H. Euler, Z. Phys. **98**, 714 (1936).

[77] V. S. Weisskopf, K. Dan. Vidensk. Selsk. Mat. Fys. Medd. **14**, 6 (1936).

[78] J. Schwinger, Phys. Rev. **82**, 664 (1951).

[79] A. Dobrynina, A. Kartavtsev, and G. Raffelt, Phys. Rev. D **91**, 083003 (2015); **91**, 109902(E) (2015).

[80] L. Maiani, R. Petronzio, and E. Zavattini, Phys. Lett. B **175**, 359 (1986).

[81] G. Galanti and M. Roncadelli, J. High Energy Astrophys. **20**, 1 (2018).

[82] A. De Angelis, M. Roncadelli, and O. Mansutti, Phys. Rev. D **76**, 121301(R) (2007).

[83] M. Simet, D. Hooper, and P. D. Serpico, Phys. Rev. D **77**, 063001 (2008).

[84] M. A. Sánchez-Conde, D. Paneque, E. Bloom, F. Prada, and A. Domínguez, Phys. Rev. D **79**, 123511 (2009).

[85] A. De Angelis, G. Galanti, and M. Roncadelli, Phys. Rev. D **84**, 105030 (2011); **87**, 109903(E) (2013).

[86] F. Tavecchio, M. Roncadelli, G. Galanti, and G. Bonnoli, Phys. Rev. D **86**, 085036 (2012).

[87] D. Wouters and P. Brun, Phys. Rev. D **86**, 043005 (2012).

[88] F. Tavecchio, M. Roncadelli, and G. Galanti, Phys. Lett. B **744**, 375 (2015).

[89] K. Kohri and H. Kodama, Phys. Rev. D **96**, 051701(R) (2017).

[90] G. Galanti, F. Tavecchio, M. Rooncadelli, and C. Evoli, Mon. Not. R. Astron. Soc. **487**, 123 (2019).

[91] G. Galanti, M. Roncadelli, A. De Angelis, and G. F. Bignami, Mon. Not. R. Astron. Soc. **493**, 1553 (2020).

[92] P. Jain, S. Panda, and S. Sarala, Phys. Rev. D **66**, 085007 (2002).

[93] N. Bassan, A. Mirizzi, and M. Roncadelli, J. Cosmol. Astropart. Phys. 05 (2010) 010.

[94] N. Agarwal, A. Kamal, and P. Jain, Phys. Rev. D **83**, 065014 (2011).

[95] A. Payez, J. R. Cudell, and D. Hutsemékers, Phys. Rev. D **84**, 085029 (2011).

[96] R. Perna, W. C. G. Ho, L. Verde, M. van Adelsberg, and R. Jimenez, Astrophys. J. **748**, 116 (2012).

[97] F. Day and S. Krippendorf, Galaxies **6**, 45 (2018).

[98] G. Galanti, Phys. Rev. D **105**, 083022 (2022).

[99] G. Galanti, Phys. Rev. D **107**, 043006 (2023).

[100] G. Galanti, M. Roncadelli, F. Tavecchio, and E. Costa, Phys. Rev. D **107**, 103007 (2023).

[101] G. Galanti, M. Roncadelli, and F. Tavecchio, arXiv:2301.08204.

[102] V. A. Acciari *et al.* (MAGIC Collaboration), Nature (London) **575**, 455 (2019).

[103] V. A. Acciari *et al.* (MAGIC Collaboration), Nature (London) **575**, 459 (2019).

[104] A. J. Levan *et al.*, Astrophys. J. Lett. **946**, L28 (2023).

[105] R. Beck, Astron. Astrophys. Rev. **24**, 4 (2016).

[106] A. Fletcher, Astron. Soc. Pac. Conf. Ser. **438**, 197 (2010), https://aspbooks.org/custom/publications/paper/438-0197.html.

[107] T. A. Thompson, E. Quataert, E. Waxman, N. Murray, and C. L. Martin, Astrophys. J. **645**, 186 (2006).

[108] E. Lopez-Rodriguez, J. A. Guerra, M. Asgari-Targhi, and J. T. Schmelz, Astrophys. J. **914**, 24 (2021).

[109] P. K. Blanchard, E. Berger, and W. Fong, Astrophys. J. **817**, 144 (2016).

[110] J. D. Lyman *et al.*, Mon. Not. R. Astron. Soc. **467**, 1795 (2017).

[111] B. G. Elmegreen and J. Scalo, Annu. Rev. Astron. Astrophys. **42**, 211 (2004).

[112] M. Haverkorn, J. C. Brown, B. M. Gaensler, and N. M. McClure-Griffiths, Astrophys. J. **680**, 362 (2008).

[113] V. Heesen *et al.*, Astron. Astrophys. **669**, A8 (2023).

[114] A. Neronov and I. Vovk, Science **328**, 73 (2010).

[115] R. Durrer and A. Neronov, Astron. Astrophys. Rev. **21**, 62 (2013).

[116] M. S. Pshirkov, P. G. Tinyakov, and F. R. Urban, Phys. Rev. Lett. **116**, 191302 (2016).

[117] P. P. Kronberg, Rep. Prog. Phys. **57**, 325 (1994).

[118] D. Grasso and H. R. Rubinstein, Phys. Rep. **348**, 163 (2001).

[119] G. Galanti and M. Roncadelli, Phys. Rev. D **98**, 043018 (2018).

[120] A different model has been proposed in A. Kartavtsev, G. Raffelt, and H. Vogel, J. Cosmol. Astropart. Phys. 01 (2017) 024.

[121] M. J. Rees and G. Setti, Nature (London) **219**, 127 (1968).

[122] F. Hoyle, Nature (London) **223**, 936 (1969).

[123] P. P. Kronberg, H. Lesch, and U. Hopp, Astrophys. J. **511**, 56 (1999).

[124] S. Furlanetto and A. Loeb, Astrophys. J. **556**, 619 (2001).

[125] R. Jansson and G. R. Farrar, Astrophys. J. **757**, 14 (2012).

[126] R. Jansson and G. R. Farrar, Astrophys. J. **761**, L11 (2012).

[127] M. C. Beck, A. M. Beck, R. Beck, K. Dolag, A. W. Strong, and P. Nielaba, J. Cosmol. Astropart. Phys. 05 (2016) 056.

[128] M. S. Pshirkov, P. G. Tinyakov, P. P. Kronberg, and K. J. Newton-McGee, Astrophys. J. **738**, 192 (2011).

[129] J. M. Yao, R. N. Manchester, and N. Wang, Astrophys. J. **835**, 29 (2017).

[130] V. Anastassopoulos *et al.* (CAST Collaboration), Nat. Phys. **13**, 584 (2017).

[131] J. Sisk-Reynés *et al.*, Mon. Not. R. Astron. Soc. **510**, 1264 (2022).

[132] C. Dessert, D. Dunsky, and B. R. Safdi, Phys. Rev. D **105**, 103034 (2022).

[133] A. Addazi *et al.*, Prog. Part. Nucl. Phys. **125**, 103948 (2022).

[134] G. Galanti, F. Tavecchio, and M. Landoni, Mon. Not. R. Astron. Soc. **491**, 5268 (2020).

[135] F. Tavecchio and G. Bonnoli, Astron. Astrophys. **585**, A25 (2016).

[136] R. G. Lang, H. Martínez-Huerta, and V. de Souza, Phys. Rev. D **99**, 043015 (2019).

[137] N. Mirabal, Mon. Not. R. Astron. Soc. **519**, 85 (2023).

[138] M. M. Gonzalez, D. Avila Rojas, A. Pratts, S. Hernández-Cadena, N. Fraija, R. Alfaro, Y. Pérez Araujo, and J. A. Montes, Astrophys. J. **944**, 178 (2023).

[139] S. Das and S. Razzaque, Astron. Astrophys. **670**, L12 (2023), https://www.aanda.org/articles/aa/full_html/2023/02/aa45377-22/aa45377-22.html.

[140] Z.-C. Zhao, Y. Zhou, and S. Wang, Eur. Phys. J. C **83**, 92 (2023).

[141] S. Sahu, B. Medina-Carrillo, G. Sánchez-Colón, and S. Rajpoot, Astrophys. J. **942**, 30 (2023).

[142] P. Arias, D. Cadamuro, M. Goodsell, J. Jaeckel, J. Redondo, and A. Ringwald, J. Cosmol. Astropart. Phys. 06(2012) 013.

[143] S. Vercellone *et al.*, J. High Energy Astrophys. **35**, 1 (2022).

[144] https://www.cta-observatory.org/.

[145] A. E. Egorov, N. P. Topchiev, A. M. Galper, O. D. Dalkarov, A. A. Leonov, S. I. Suchkov, and Y. T. Yurkin, J. Cosmol. Astropart. Phys. 11 (2020) 049.

[146] https://www.hawc-observatory.org/.

[147] X. Huang *et al.*, Astropart. Phys. **78**, 35 (2016).

[148] Z. Cao *et al.*, Chin. Phys. C **46**, 035001 (2022).

[149] https://taiga-experiment.info/taiga-hiscore/.

[150] R. Bähre *et al.*, J. Instrum. **8**, T09001 (2013).

[151] I. G. Irastorza *et al.* (IAXO Collaboration), J. Cosmol. Astropart. Phys. 06 (2011) 013.

[152] E. Armengaud *et al.*, J. Cosmol. Astropart. Phys. 06 (2019) 047.

[153] L. M. Capparelli, G. Cavoto, J. Ferretti, F. Giazotto, A. D. Polosa, and P. Spagnolo, Phys. Dark Universe **12**, 37 (2016).

[154] F. T. Avignone III, Phys. Rev. D **79**, 035015 (2009).

[155] F. T. Avignone III, R. J. Crewick, and S. Nussinov, Phys. Lett. B **681**, 122 (2009).

[156] F. T. Avignone III, R. J. Crewick, and S. Nussinov, Astropart. Phys. **34**, 640 (2011).

[157] Y. Kahn, B. R. Safdi, and J. Thaler, Phys. Rev. Lett. **117**, 141801 (2016).

[158] Z. Cao *et al.*, arXiv:2310.08845.

[159] F. Aharonian *et al.*, Chin. Phys. C **45**, 025002 (2021).