Explanation of the very-high-energy emission from GRB221009A

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Introduction – On 22/10/11 the LHAASO experiment has reported the observation of the Gamma Ray Burst GRB221009A with more than 5000 very-high-energy (VHE) photons up to around 18 TeV. Specifically, GRB 221009A is detected by LHAASO-WCDA at energy above 500 GeV, centered at RA = 288.3°, Dec = 19.8° within 2000 seconds after T0, with the significance above 100 s.d., and is observed as well by LHAASO-KM2A with the significance about 10 s.d., where the energy of the highest photon reaches 18 TeV, and its redshift has been estimated to be \( z = 0.151 \) [1].

Moreover, on 22/10/12 the Carpet-2 at Baksan Neutrino Observatory has detected – still from the gamma ray burst GRB221009A – an air shower consistent with being caused by a photon of energy 251 TeV from the same GRB. These findings provide a strong hint both at the existence of axion-like-particles (ALPs) with mass \( m_a \simeq 10^{-10} \) eV and two-photon coupling \( g_{a\gamma\gamma} \simeq 5 \times 10^{-12} \) GeV\(^{-1}\) and at a Lorentz Invariance Violation at 251 TeV. Our ALP parameters are consistent with all available constraints, and these ALPs are good candidates for cold dark matter.

On 22/10/11 we provided a sketcy description of GRB221009A based on Axion-Like Particles (ALPs). Our aim is to offer a much more detailed account of the same matter, including in addition Lorentz Invariance Violation (LIV).

Cosmic photon extinction – As a preliminary step, we briefly discuss the above mentioned electron-positron pair-production process giving rise to a strong dimming of the beam. Very-high-energy (VHE, \( \mathcal{E} > 100 \) GeV) emitted photons enroute to us scatter off the infrared-optical-ultraviolet photons of the extragalactic background light (EBL), namely the background emitted by the whole population of stars during the cosmic evolution (for a review of the EBL, see [5]). Over the years, several methods to estimate the effect of the EBL have been developed (for a short summary, see Section III, Part B of [6] and references therein, while for some subsequent references, see [7–11]). In order to be definite, here we take the rather conservative model of Franceschini and Rodighiero in order to derive the corresponding optical depth \( \tau_{EBL}^{CP} \) according to conventional physics (CP) [10]. Specifically, it reads \( \tau_{EBL}^{CP} \simeq 14 \) at \( \mathcal{E} = 18 \) TeV and \( \tau_{EBL}^{CP} \simeq 15000 \) at \( \mathcal{E} = 251 \) TeV. As a consequence, the photon survival probabilities are

\[
P_{CP}^{FR}(\mathcal{E} = 18 \text{ TeV}; \gamma \rightarrow \gamma) = e^{-\tau_{EBL}^{CP}(\mathcal{E})} \simeq 8.5 \times 10^{-7} \, , \quad (1)
\]

and

\[
P_{CP}^{FR}(\mathcal{E} = 251 \text{ TeV}; \gamma \rightarrow \gamma) = e^{-\tau_{EBL}^{CP}(\mathcal{E})} \simeq e^{-15000} \, . \quad (2)
\]

Just for comparison, the model of Gilmore et al. [8] gives \( \tau_{CP}^{GB} \simeq 14 \) at \( \mathcal{E} = 18 \) TeV – identical to the previous case – while \( \tau_{CP}^{GB} \simeq 9500 \) at \( \mathcal{E} = 251 \) TeV, so that Eq. [1] remains unchanged whereas Eq. [2] becomes

\[
P_{CP}^{FR}(\mathcal{E} = 251 \text{ TeV}; \gamma \rightarrow \gamma) = e^{-\tau_{EBL}^{CP}(\mathcal{E})} \simeq e^{-9500} \, . \quad (3)
\]

Manifestly – within conventional physics alone – photons with these survival probabilities are impossible to detect.
Axion-like particles (ALPs) – Many extensions of the Standard Model of particle physics – especially superstring and superbrane theories – predict the existence of ALPs (for an incomplete list of references, see e.g. [12][22] and references therein), and for ALP reviews, see [3][23][25]. ALPs – as denoted by $a$ – are very light pseudo-scalar bosons of mass $m_a$ with a characteristic coupling to two-photons $g_{\gamma\gamma}$ described by the Lagrangian

$$L_{\gamma\gamma} = - \frac{1}{4} g_{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} a = g_{\gamma\gamma} E \cdot B a , \quad (4)$$

where $F_{\mu\nu}$ is the Faraday tensor with electric and magnetic components $E$ and $B$, respectively and $F^{\mu\nu}$ is its dual. Other couplings to conventional particles can exists but will be discarded here. We stress that within this assumption ALPs do not interact either with single photons or with matter (for a proof, see e.g. [26]). Moreover – at variance with the axion [27] – ALPs do not interact either with single photons or with matter. The only laboratory upper bound on $g_{\gamma\gamma}$ is provided by the CAST experiment at CERN, which is $g_{\gamma\gamma} < 0.66 \times 10^{-10}$ GeV$^{-1}$ for $m_a < 0.02$ eV at the 2σ level [28].

Owing to Eq. (4), in the presence of an external magnetic field $B$, $\gamma \rightarrow a$ and $a \rightarrow \gamma$ conversions take place (in Eq. (4) $E$ is the photon electric field). As a consequence, as a photon beam propagates these conversions produce $\gamma \leftrightarrow a$ oscillations, quite similar to flavor oscillations of massive neutrinos apart from the need of $\gamma$-beams to compensate for the spin mismatch [29][30]. The photon-ALP interaction produces many consequences both on the observed spectra with possible hints at the ALP existence (see e.g. [31][39]) and on the final photon polarization (see e.g. [40][48]).

ALP scenario for GRB221009A – Below, we independently show that the guess of Carpet-2 about the need of ALPs is indeed correct by an explicit calculation.

We are now in a position to compute the photon survival probability $P_{\text{ALP}}(E;\gamma \rightarrow a)$ from the source to us taking ALP effects into account. As benchmark values we assume $m_a \simeq 10^{-10}$ eV and $g_{\gamma\gamma} \simeq 0.5 \times 10^{-11}$ GeV$^{-1}$, as in our previous papers (see [3]). Note that also a possible different mass range $10^{-10}$ eV $< m_a \lesssim 10^{-7}$ eV is compatible with our model (more about this, later). Because of lack of space it would be impossible to report the whole formalism necessary to get the results reported in this Letter, we refer the reader to the appropriate Sections of various quoted papers. We merely state that for $m_a \ll E$ – which is obviously the present case – the beam propagation equation becomes a Schrödinger-like equation with the time replaced with the propagation direction $y$, and so the photon survival probability can be computed just like in quantum mechanics [30]. Actually, the photon/ALP beam is treated exactly like a three-level $(A_x(y), A_y(y), a(y))$ decaying non-relativistic quantum system, where $A_x(y)$ and $A_y(y)$ are the photon amplitudes with polarization along $x$ and $z$, respectively, while $a(y)$ is the ALP amplitude [49]. We denote by $U(\mathcal{E};y_0)$ the corresponding transfer matrix, namely the solution of the Schrödinger-like equation such that $U(\mathcal{E};y_0, y_0) = 1$. Finally, the plasma frequency is $\omega_p = 3.69 \times 10^{-11} (n_e/cm^{-3})^{1/2}$ eV, where $n_e$ is the electron number density.

1) Conversion inside the source: Because GRB221009A is observed in the afterglow, we assume a model with external shock and we suppose that the detected photons are emitted in the jet at distance $L_{\text{GRB}} \simeq 2 \times 10^{16}$ cm, assuming the corresponding magnetic field strength to be $B_{\text{GRB}} \simeq 1$ G and that the electron number density is $n_{\text{GRB},e} < 10^3$ cm$^{-3}$ [50]. Moreover, we take the Lorentz factor $\Gamma = 1000$ since this GRB is very much brighter than GRB 190114C (see e.g. [51][52] and references therein). We are well aware that these benchmark values are uncertain, but with the available information about GRB221009A – and with the present knowledge of GRBs in general – no one could do any better. The calculations can be done by following Sect. III of [53], and yield $U_{\text{GRB}}(\mathcal{E};y_B, y_P)$ where $y_B$ and $y_P$ denote the position of the border of the GRB and of the production region, respectively.

2) Conversion inside the host galaxy: In the lack of any knowledge of the nature of the galaxy hosting the GRB, we are very cautious about photon-ALP conversion therein. In particular, the magnetic field of normal spiral galaxies has a regular component with coherence length $L_{\text{host,reg}} \simeq 10$ kpc plus a turbulent one with coherence length $L_{\text{host,turb}} \simeq (10 - 100)$ pc – both with roughly the same strength $B_{\text{host,spir}} = (1 - 10) \mu$G. Elliptical galaxies possess only a turbulent magnetic field with strength $B_{\text{host,ell}} \simeq 5 \mu$G and coherence length $L_{\text{host,turb}} \simeq 150$ pc [54][55]. Let us consider first the case of a hosting elliptical galaxy. By following Sect. 3.2 of [55], we can compute the transfer matrix in the host $U_{\text{host}}(\mathcal{E};y_{\text{host}}, y_B)$ where $y_{\text{host}} \simeq 15$ kpc is the position of the luminous border of the host galaxy. Anyway, its inclusion leads to an effect which is much smaller than all the other ones considered in this Letter. Next, we address an extreme hosting spiral galaxy with $B_{\text{host,spir}} = 10 \mu$G and $L_{\text{host,reg}} = 10$ kpc. Correspondingly, ALP effects become sizable but one has to make four assumptions: i) extreme spiral galaxy, ii) $B_{\text{host,spir}} = 10 \mu$G in the whole galaxy (with coherence $L_{\text{host,reg}} = 10$ kpc), iii) the line of sight to GRB221009A must lie inside the disk, iv) the GRB is in the innermost galactic region. Because satisfying all these hypotheses looks very unlikely, we discard the case of a host spiral. After all – since GRB221009A is such an extreme GRB – presumably also the host galaxy should be exceptional, and not an ordinary one, something like e.g. a merging of two galaxies.
3) Conversion in extragalactic space: According to the current wisdom, the extragalactic magnetic field $B_{\text{ext}}$ can be modeled as a domain-like network, wherein $B_{\text{ext}}$ is assumed to be homogeneous over a whole domain of size $L_{\text{dom}}$ equal to its coherence length, with $B_{\text{ext}}$ changing randomly its direction from one domain to the next, keeping approximately the same strength. Accordingly, the beam propagation becomes a random process, and only a single realization at once can be observed. Moreover, it is generally assumed that such a change of direction is abrupt, because then the beam propagation equation is easy to solve [56, 57]. This scenario – called domain-like sharp-edges (DLSHE) – relies upon outflows from primeval galaxies, further amplified by turbulence [58–61]. Common benchmark values are $B_{\text{ext}} = O(1) \text{nG}$ on a coherence length $O(1) \text{Mpc}$, whence $L_{\text{dom}} = O(1) \text{Mpc}$ (for more details, see [54]). In order to be definite, we choose $B_{\text{ext}} = 1 \text{nG}$ and $L_{\text{dom}}$ in the range $(0.2-10) \text{Mpc}$ and with $(L_{\text{dom}}) = 2 \text{Mpc}$.

However, the abrupt change in direction at the interface of two adjacent domains leads to a failure of the DLSHE model at the energies considered here, owing to photon dispersion on the CMB [62]. A way out of this difficulty is to smooth out the sharp edges of the domains, in such a way that the components of $B_{\text{ext}}$ change continuously across the interface, thereby leading to the domain-like smooth-edges (DLSME) model, built up in [55, 63].

Coming back to the propagation of a photon/ALP beam in extragalactic space within the DLSME model, $\gamma \leftrightarrow a$ oscillations imply that the photons behave in two-fold fashion. When they are true photon, they undergo EBL absorption, but when they are ALPs they do not. So, the effective optical depth $\tau_{\text{ALP}}(\mathcal{E})$ gets reduced. The crux of the argument is that the photon survival probability now becomes

$$P_{\text{ALP}}(\mathcal{E}; \gamma \rightarrow \gamma) = e^{-\tau_{\text{ALP}}(\mathcal{E})},$$

and so even a small decrease of $\tau_{\text{ALP}}(\mathcal{E})$ gives rise to a large increases of $P_{\text{ALP}}(\mathcal{E}; \gamma \rightarrow \gamma)$. Moreover, photon dispersion on the CMB induces small energy oscillations in the beam. This analysis has been done in [20], and gives $U_{\text{EGS}}(\mathcal{E}; y_{\text{MW}}, y_{\text{host}})$ where $y_{\text{MW}}$ denotes the outer luminous radius of the Milky Way.

Beautiful as it is, there is no observational evidence that such a scenario is realized in Nature, since $B_{\text{ext}}$ must lie in the range $10^{-7} \text{nG} \lesssim B_{\text{ext}} \lesssim 1.7 \text{nG}$ on the scale of $O(1) \text{Mpc}$ [64–66]. Therefore, we shall consider also the extremely conservative case of $B_{\text{ext}} < 10^{-15} \text{G}$ (more about this, later).

4) Conversion in the Milky Way: Clearly, the beam propagation – as triggered by $\gamma \leftrightarrow a$ oscillations – in the Milky Way depends both on the morphology of the magnetic field $B_{\text{MW}}$ and on the electron number density $n_{\text{MW},e}$, which fixes in turn the plasma frequency $\omega_{\text{MW,pl}}$.

We believe that the best model for $B_{\text{MW}}$ is the one developed by Jansson and Farrar [67–69]. It includes a disc and a halo – which are both parallel to the Galactic plane – and a poloidal ‘X-shaped’ component at the Galactic centre. Even if this model contains a regular and a turbulent components, only the former one is relevant for the present needs [70]. Anyway, we have tested the robustness of our results by considering also the alternative model of Pshirkov et al. [71]. Even with some little modifications our findings are basically unchanged.

As far as $n_{\text{MW},e}$ is concerned, its overall best estimate is $n_{\text{MW},e} \simeq 1.1 \times 10^{-2} \text{cm}^{-3}$ [72], which results in $\omega_{\text{MW,pl}} \simeq 3.9 \times 10^{-12} \text{eV}$.

Correspondingly, $\mathcal{A}_{\text{MW}}(\mathcal{E}, y_{\Theta}, y_{\text{MW}})$ where $y_{\Theta}$ is the position of the Earth – can be evaluated as in Section 3.4 of [38].

Results – Once all the above transfer matrices are known, the total transfer matrix from the photon production region in GRB221009A up to the Earth is given by

$$U(\mathcal{E}, y_{\Theta}, y_{\text{pl}}) = U_{\text{MW}}(\mathcal{E}, y_{\Theta}, y_{\text{MW}}) \times U_{\text{EGS}}(\mathcal{E}, y_{\text{MW}}, y_{\text{host}}) \times U_{\text{host}}(\mathcal{E}, y_{\text{host}}, y_{\text{B}}) \times U_{\text{GRB}}(\mathcal{E}, y_{\text{B}}, y_{\text{pl}}).$$

![FIG. 1. Photon survival probability $P(\mathcal{E}; \gamma \rightarrow \gamma)$ versus energy $\mathcal{E}$ in conventional physics and when ALPs (for $B_{\text{ext}} = 1 \text{nG}$ and $B_{\text{ext}} < 10^{-15} \text{G}$) are taken into account.](image-url)

Assuming that the emitted photons are unpolarized, we have to employ the generalized polarization density matrix $\rho(y) \equiv (A_x(y), A_y(y), a(y))^T \otimes (A_x(y), A_y(y), a(y))$. Therefore the overall photon survival probability is

$$P_{\text{ALP}}(\mathcal{E}; \gamma \rightarrow \gamma) = \sum_{i=x,y} \text{Tr}[\rho_i U(\mathcal{E}, y_{\Theta}, y_{\text{pl}}) \times \rho_{\text{amp}} U_i^d(\mathcal{E}, y_{\Theta}, y_{\text{pl}})],$$

where $\rho_{\text{amp}}$ is the amplification matrix, and $U_i^d$ is the total transfer matrix from the photon production region in GRB221009A up to the Earth.
where \( \rho_x \equiv \text{diag}(1, 0, 0) \), \( \rho_z \equiv \text{diag}(0, 1, 0) \) and \( \rho_{\text{unp}} \equiv (\frac{1}{2}, 0) \).

The photon survival probability \( P_{\text{ALP}}(E; \gamma \to \gamma) \) and the optical depth \( \tau_{\text{ALP}}(E) \) calculated both within conventional physics and in the ALP scenario are reported in Fig. 1 and Fig. 2, respectively. As discussed in [26], above \( \mathcal{O}(5) \) TeV, photon-ALP conversion in the extragalactic space becomes inefficient because of the photon dispersion on the CMB [62]: thus, we do not find significant lower bounds on \( m_a \) as instead in [73]. In Figs. 1 and 2, we consider both the case of an efficient (\( B_{\text{ext}} = 1 \) nG) and negligible (\( B_{\text{ext}} < 10^{-15} \) G) photon-ALP conversion in the extragalactic space. Remarkably, even if the effect is reduced for \( B_{\text{ext}} < 10^{-15} \) G, we can still consistently explain the observation of photons at both \( E = 18 \) TeV and \( E = 251 \) TeV with no substantial difference. Note that for larger values of \( m_a \) than those considered here – with \( m_a \) approaching \( m_a = \mathcal{O}(10^{-7}) \) eV – conversion in the extragalactic space becomes inefficient and we recover the analogous case \( B_{\text{ext}} < 10^{-15} \) G, which produces similar results (see Figs. 1 and 2).

**Lorentz Invariance Violation (LIV) –** Extensions of the standard model of particle physics encompassing quantum gravity predict a violation of Lorentz invariance (for a review, see [74]). As far as the present work is concerned, its main implication is the following modification of the photon dispersion relation

\[
E^2 - p^2 = -\frac{\mathcal{E}_n + 2}{\mathcal{E}_{\text{LIV}}},
\]

where \( E \) and \( p \) are the photon energy and momentum, respectively, while \( \mathcal{E}_{\text{LIV}} \) is the high-energy scale above which LIV is observed. As already demonstrated in [75] and [76] for a redshift very close to that of GRB221009A, we see that LIV cannot account for a reduced opacity at 18 TeV for the current LIV limits [77] (see also Fig. 3 and a very recent paper [78]). But the possible detection at 251 TeV is a totally different story. As shown by \( \tau_{\text{LIV}}(E) \) in Fig. 3 for both the cases of \( n = 1 \) with \( \mathcal{E}_{\text{LIV}, n=1} = 3 \times 10^{29} \) eV and \( n = 2 \) with \( \mathcal{E}_{\text{LIV}, n=2} = 5 \times 10^{23} \) eV the detection at such a VHE can be explained within the current LIV bounds [77].

**Discussion and Conclusions –** We have shown that ALPs with mass \( m_a \approx 10^{-10} \) eV and two-photon coupling \( g_{a\gamma\gamma} \approx 5 \times 10^{-12} \) GeV\(^{-1} \) are indeed very good candidates to explain the results observed by LHAASO-KM2A [1] and Carpet-2 [2]. We stress that the considered values of both \( m_a \) and \( g_{a\gamma\gamma} \) are in agreement with the strongest bound coming from the very recent analysis of magnetic white dwarfs (which contains also a summary of previous bounds) [79]. Moreover, these ALPs are good candidates for cold dark matter [80].

The alternative LIV scenario is instead unable to explain the GRB221009A detection at 18 TeV within current limits, but can explain the detection at 251 TeV.

Manifestly, our scenario for the photon into ALP conversion in the source should be placed in the more general context of the GRB221009A formation envisioning an external shock, but to date not enough information is available. A possibility is [81], but many other options are possible.

We plan to come back to the matters presented in this Letter in more detail elsewhere, when more information about GRB221009A will be provided.
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