Assessment of ALP scenarios for GRB 221009A

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About one month after the revolutionary discovery of the Gamma Ray Burst (GRB) GRB 221009A and intense theoretical efforts to explain its detection, time seems to us ripe to make an assessment of the axion-like particle (ALP) based scenarios, since it is a common belief that conventional physics would have prevented such a detection. We overcome the almost complete lack of information – so far only astronomical telegrams have been released – by relying as much as possible upon the analogy with the emission from the GRB 190114C detected by the MAGIC collaboration in 2019, since it was the highest energy GRB detected before and for a time lapse similar to that over which GRB 221009A has been observed.

I. INTRODUCTION

The revolutionary discovery of GRB 221009A at redshift $z = 0.151$ [1] at energy up to $\mathcal{E} = 18$ TeV made by the LHAASO collaboration lasting 2000 s after the trigger $t_0$ [2] and at $\mathcal{E} = 251$ TeV by the Carpet-2 collaboration at 4536 s after $t_0$ [3] strongly challenges conventional physics. The trigger $t_0$ has been set by Fermi/GBM on October 10, 2022 at 13:16:60 UT [4]. Throughout this paper we suppose that both observations indeed concern GRB 221009A.

Basically, at such very-high-energies (VHE, $\mathcal{E} > 100$ GeV) photons from GRB 221009A scatter off photons of the Extragalactic Background Light (EBL) – the diffuse light emitted by all stars during the cosmic evolution – thereby producing $e^+e^-$ pairs, and so largely depleting the photon beam (for a review, see [5]). Because axion-like particles (ALPs) reduce such a dimming through photon-ALP conversions and reconversions in the presence of a magnetic field – as first recognized in [6] – several papers have considered ALP scenarios with different properties [7–11].

Very recently, Carenza and Marsh made an overview of them (thereafter CM) [11]. Our goal is very similar in nature to that of such an overview, but it greatly differs in its content. Given the almost complete lack of information – only astronomical telegrams have been released so far – we try to use as much as possible what has been learnt from GRB 190114C, the previous highest energy GRB detected by the MAGIC collaboration in 2019, which has been observed up to an energy $\mathcal{E} \simeq 1$ TeV [12, 13]. We prefer to consider GRB 190114C since it has been observed during the time interval $62 \text{s} \lesssim t \lesssim 2454 \text{s}$ after the trigger – which is of the same order of magnitude of the time interval over which GRB 221009A has been detected – while GRB 190929A reaching an energy $\mathcal{E} \simeq 3.3$ TeV has been monitored by the H.E.S.S. collaboration during the time lapse $1.5 \cdot 10^4 \text{s} \lesssim t \lesssim 2 \cdot 10^5 \text{s}$ after the trigger [14] – much larger than that of GRB 221009A – hence less similar to GRB 221009A (see also [15]). So, throughout this paper GRB 190114C will be considered as a sort of ‘smaller twin’ of GRB 221009A as far as the emission is concerned.

II. SOME PRELIMINARIES

Let us first recall a few basic properties of the GRBs which will be useful later. First of all, short GRBs (with the prompt emission lasting less than 2 seconds) originate from the merging of two neutron stars (or a neutron star with a black hole), whereas long GRBs (with the prompt emission lasting more than 2 seconds) arise from ultrarelativistic jets launched from the collapsing cores of dying massive stars. Moreover, GRBs are characterized by two phases: an initial prompt and a subsequent afterglow. The prompt emission comes from the jet, is highly variable and has its maximum in the keV-MeV band. Its duration lasts from milliseconds to minutes. Thereafter, the afterglow emission takes over – also rapidly varying – which is due to the shock waves produced by the interaction of the jet with the external medium and can last up to months. The highest frequencies are generated at the beginning of the afterglow, and as time goes by progressively lower and lower frequencies are emitted, spanning the whole
electromagnetic spectrum from the gamma band down to the radio band. According to this view, GRB 221009A has been observed at the beginning of the afterglow, and not in the prompt emission as stated in [8]. While it is generally believed that the prompt emission is explained as synchrotron radiation by electrons accelerated in the jet, the spectral energy distribution (SED) of the afterglow is not so simple and will be discussed later. We emphasize that this is the conventional view based on the fireball model. Nevertheless, alternative models have been proposed, which are however unimportant for our needs. An authoritative review of GRBs up to 2005 is contained in [16], while an up-to-date account can be found in [15].

III. MOTIVATION FOR ALP SCENARIOS

As we said, the EBL strongly suppresses the flux emitted by GRB 221009A. In order to address this point in a quantitative fashion, we start by recalling that the photon survival probability within conventional physics (CP) is given by

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

where $\tau_{\text{CP}}(\mathcal{E})$ is the optical depth. In the literature several estimates of $\tau_{\text{CP}}(\mathcal{E})$ can be found, and a fairly complete list has been reported in [8]. Since we have to make a choice, here we adopt the rather conservative estimate of Franceschini and Rodighiero [17], which gives $\tau^{\text{FR}}_{\text{CP}} \simeq 14$ at $\mathcal{E} = 18$ TeV and $\tau^{\text{FR}}_{\text{CP}} \simeq 15000$ at $\mathcal{E} = 251$ TeV. Therefore, the corresponding photon survival probabilities read

$$P^{\text{FR}}_{\text{CP}}(\mathcal{E} = 18 \text{ TeV}; \gamma \to \gamma) \simeq 8.5 \times 10^{-7},$$

and

$$P^{\text{FR}}_{\text{CP}}(\mathcal{E} = 251 \text{ TeV}; \gamma \to \gamma) \simeq e^{-15000}.$$  

This can be compared with the model of Gilmore et al. [18], which yields $\tau^{\text{G}}_{\text{CP}} \simeq 14$ at $\mathcal{E} = 18$ TeV – identical to the previous case – while $\tau^{\text{G}}_{\text{CP}} \simeq 9500$ at $\mathcal{E} = 251$ TeV. Accordingly, Eq. (2) remains unchanged but Eq. (3) becomes

$$P^{\text{G}}_{\text{CP}}(\mathcal{E} = 251 \text{ TeV}; \gamma \to \gamma) \simeq e^{-9500}.$$  

According to the common wisdom, within conventional physics it is impossible to detect photons with these survival probabilities (more about this, in the last Section). This is also emphasized in [3].

We refrain from discussing the formalism of photon-ALP conversions and reconversions both because we do not use it here and because it is described in so many papers (for the motivation of ALPs see [19, 20], and for a review see [21] and references therein). The photon-ALP Lagrangian is

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

where $a$ is the ALP field and – in the present context – $\mathbf{E}$ represents the electric field of a propagating photon whereas $\mathbf{B}$ stands for the external magnetic field. The last term in Eq. (5) is represented by the Feynman diagram in Fig. 1.

![Fig. 1: ALP-two photons vertex with coupling constant $g_{a\gamma\gamma}$](image)

where the horizontal photon leg corresponds to $\mathbf{E}$ while the vertical one to $\mathbf{B}$. This diagram represents a photon-to-ALP or an ALP-to-photon conversion, which takes place in principle within any magnetized astronomical object. We stress that – according to Eq. (5) – ALPs do not couple either to single photons or to matter, as explicitly shown in [22].

Thus, a way to reduce the EBL absorption is to have photon-to-ALP conversions in the source or close to it, and ALP-to-photon conversions in the Milky Way since the EBL is fully transparent to the ALPs.
Another strategy to reduce the EBL absorption is based on photon-ALP oscillations occurring as the photon-ALP beam propagates in extragalactic space, provided that the extragalactic magnetic field is sufficiently strong. Pictorially, this process arises by joining two vertices in Fig. 1 by one E or one ALP horizontal leg, while the other vertical photon legs represent B. This is shown in Fig. 2.

As a consequence, photons acquire a ‘split personality’: when they behave as true photons they interact with the EBL but when they behave as ALPs they do not. This fact reduces the effective optical depth $\tau_{\text{ALP}}(E)$ (accounting for both CP and ALPs). So, Eq. (1) gets now replaced by

$$P_{\text{ALP}}(E; \gamma \rightarrow \gamma) = e^{-\tau_{\text{ALP}}(E)}.$$  \hspace{1cm} (6)

The crux of the argument is the negative exponential dependence of $P_{\text{ALP}}(E; \gamma \rightarrow \gamma)$ on $\tau_{\text{ALP}}(E)$, since a small reduction of $\tau_{\text{ALP}}(E)$ with respect to $\tau_{\text{CP}}(E)$ gives rise to a large enhancement of $P_{\text{ALP}}(E; \gamma \rightarrow \gamma)$ as compared with $P_{\text{CP}}(E; \gamma \rightarrow \gamma)$.

Manifestly, both possibilities can occur at the same time.

IV. PHOTON-ALP INTERCONVERSIONS

Different authors have chosen different places for the initial photon-to-ALP conversion. Below, we review the various possibilities, adding some remarks. All ALP scenarios for GRB 221009A considered in this paper involve the ALP reconversion to photons in the Milky Way, basically employing the magnetic field model developed by Jansson and Farrar [25–27].

**Photon-to-ALP conversion in the jet** – Recalling that GRB 221009A is observed in the early phase of the afterglow, a possibility for such a conversion is inside the jet in such a situation. This scenario has been put forward in the first attempt to understand the GRB 221009A emission [7]. The job is to fix the free parameters. The ALP mass $m_{\text{ALP}}$ is taken to be $m_{\text{ALP}} \approx 10^{-10}$ eV, in line with the previous work of the authors, and the two-photon coupling is chosen as $g_{a\gamma\gamma} \approx 5 \cdot 10^{-12}$ GeV$^{-1}$ so as to meet the strongest upper bound coming from the magnetized white dwarfs, which reads $g_{a\gamma\gamma} \lesssim 5.4 \cdot 10^{-12}$ GeV$^{-1}$ at the 2$\sigma$ level [28]. Three free parameters are the magnetic field strength in the jet $B_{\text{jet}}$, the electron number density in the jet $n_{e,\text{jet}}$, both when it is at the beginning of the afterglow (which means outside the source but close to it) and the bulk Lorentz factor $\Gamma$. Only an ‘educated guess’ allows to fix them. And such an ‘educated guess’ comes from the analogy with the ‘smaller twin’ GRB 190114C [12, 13]. In this way the author’s choice is $B_{\text{jet}} \approx 1$ G, $n_{e,\text{jet}} \approx 10^3$ cm$^{-3}$ and $\Gamma \approx 1000$. It goes without saying that fixing the astrophysical parameters is very uncertain business, but nowadays no more reliable estimate is possible. A similar option is chosen also in [10], where it is instead assumed that $B_{\text{jet}} \approx 10^6$ G. It is easy to see that such a strong magnetic field makes the photon-to-ALP conversions totally negligible, owing to the one-loop vacuum polarization effect [24].

**Photon-to-ALP conversion in the host galaxy** – Other authors prefer to assume that the initial photon-to-ALP conversion occurs only in the host galaxy of GRB 221009A [8–11], while [7] considers also this option. Unfortunately, at the time of writing no information about the host galaxy is available. What is clear is that GRBs are hosted by star forming galaxies, but no agreement among the experts exists as to whether these are normal spiral galaxies or starburst galaxies [16]. As far as normal spiral galaxies are concerned, the most likely possibility is that a GRB forms in the spiral arms, where star formation is highest. Note that GRB 190114C is hosted by a normal spiral in its centre, but this is an exception and not the rule. Moreover, even if we rely as much as possible on the analogy with GRB 190114C for its emission, this does not imply that the analogy should be true for the host galaxy and for the location of the GRB inside it. Specifically, [8] implicitly considers a spiral galaxy with $B = 0.5 \mu$G with coherence length $L_{\text{coh}} = 10$ Mpc, [9] supposes that the host galaxy is similar to the Milky Way and assumes that the maximal mixing
occurs in the host, namely that the photon-to-ALP conversion probability is 1/3. [10] take the host just equal to the Milky Way, and the same assumption is made in [11] but supposing that GRB 221009A is located in its centre.

Photon-to-ALP conversion in extragalactic space – Our knowledge of the extragalactic magnetic $B_{\text{ext}}$ field is still very poor. Observations only tell that its strength is constrained inside the range $10^{-7} \text{nG} \lesssim B_{\text{ext}} \lesssim 1.7 \text{nG}$ on the scale $O(1)\text{Mpc}$ [23–32]. Nonetheless, since about twenty years it has become customary to described $B_{\text{ext}}$ by means of a very specific model. It consists of a domain-like network, in which $B_{\text{ext}}$ is supposed 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. As a consequence, the photon-ALP beam propagation becomes a random process, and only a single realization at once can be observed. In addition, it is assumed that such a change of direction is abrupt, because then the beam propagation equation is easy to solve [33–34]. Such a scenario – called domain-like sharp-edges (DLSHE) – rests on outflows from primeval galaxies, further amplified by turbulence [35–38]. 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 [39]). In order to be definite, the authors of [7] choose $B_{\text{ext}} = 1\text{nG}$ and $L_{\text{dom}}$ in the range $(0.2 – 10)\text{Mpc}$ and with $\langle L_{\text{dom}} \rangle = 2\text{Mpc}$. But the abrupt change in direction at the interface between two adjacent domains leads to a failure of the DLSHE model at the energies considered here, owing to photon dispersion on the CMB [10]. A way out of this difficulty is to smooth out the sharp edges of the domains, so 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 [39–41]. Only the ALP scenario described in [7] contemplates photon-ALP oscillations in extragalactic space within the DLSME model. As discussed in detail in [22], above a few TeV photon dispersion on the CMB makes the probability for photon-ALP oscillations vanishingly small. Surprisingly, this point has been misunderstood in [11], which states: ‘the extragalactic scenario may explain the LHAASO observation of an 18 TeV photon, but is incapable of explaining the Carpet-2 event. At very high energies, the extragalactic conversion is efficient across the full range of coupling constants that we consider. As explained in [9], ALPs are then continuously reconverted to photons and absorbed over relatively short distances, thereby depleting the photon flux’. Such a statement is obviously incorrect, since at the energy of Carpet-2 – namely $E = 251 \text{TeV}$ – no photon-ALP oscillation is possible in extragalactic space, as explained above.

V. SPECTRAL ENERGY DISTRIBUTION (SED)

This is a crucial issue. Until the LHAASO and Carpet-2 collaborations will release their results the observed SED is unknown. Nevertheless some totally unjustified statements have been made, as we are going to discuss below.

We recall that the flux $F(E, t) \equiv dN(t)/(dtdAdE)$ is related to the SED $\nu F_{\nu}(E, t)$ as

$$\nu F_{\nu}(E, t) = E^2 F(E, t). \quad (7)$$

Now, Fermi/LAT has observed a photon flux in the energy range $1\text{MeV} \lesssim E \lesssim 1\text{GeV}$ equal to $(6.2 \pm 0.4) \cdot 10^{-3}\gamma \text{cm}^{-2}\text{s}^{-1}$ in the time interval $200\text{s} \lesssim t \lesssim 800\text{s}$ after $t_0$, with a spectral index $\Gamma = -1.87 \pm 0.04$, and in addition a single photon of energy $E = 99.3\text{GeV}$ at $240\text{s}$ after $t_0$ [4]. Explicitly, the Fermi/LAT flux can be restated as

$$\int^{1\text{GeV}}_{100\text{MeV}} dE \ F(E, t) = (6.2 \pm 0.4) \cdot 10^{-3}\gamma \text{cm}^{-2}\text{s}^{-1}, \quad 200\text{s} + t_0 < t < 800\text{s} + t_0, \quad (8)$$

which indeed shows that the Fermi/LAT flux is time-independent over the range $200\text{s} + t_0 < t < 800\text{s} + t_0$. The further statement that the spectral index is $\Gamma = -1.87 \pm 0.04$ implies that $F(E)$ is a power law. Using this information and inserting $F(E) \propto E^{-1.87 \pm 0.04}$ into Eq. (8) the normalization constant gets fixed. This has been done in [8], finding

$$F(E) = 2.1 \cdot 10^{-6} \left(\frac{E}{\text{TeV}}\right)^{-1.87} \text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}, \quad 200\text{s} + t_0 < t < 800\text{s} + t_0. \quad (9)$$

Both [8] and [11] have extrapolated the flux in Eq. (9) to arbitrarily large energies. We stress that such an extrapolation up to LHAASO photons implies that the LHAASO flux is time-independent over its full observation time, namely over $2000\text{s}$ after $t_0$. We fully disagree for two reasons. First, it looks unreasonable to us that the LHAASO emission remains constant over such a long time as $2000\text{s}$, since all GRBs observed so far exhibit a very fast variability at any observed frequency. Second, because such extrapolation has no physical motivation. In order to clarify the last point, we still rely upon GRB 190114C, whose observed SED has been re-evaluated by us using the parameters reported in [42] and is exhibited in Fig. 3. The reader should keep in mind that the emission varies rapidly in time – hence the same is true for the observed SED – as it is evident from the figures in [42]. Therefore, Fig. 3 is true at a single observation time only.
Because GRB 221009A extends to considerably higher energies with respect to GRB 190114C we do expect that also the inverse Compton peak has been observed and that it is partially responsible for the emission detected by LHAASO and responsible for the photon observed by Carpet-2. This is the main message we want to convey. Of course, the analogy between the observed SED of GRB 221009A and of GRB 190114C is only qualitative, since the former extends up to 251 TeV while the latter extends only up to about 1 TeV. So, for GRB 221009A the inverse Compton peak should be shifted to considerably higher energies, at least during the observation times of LHAASO and Carpet-2. Moreover, it is plausible to have a hardening of the flux in Eq. (9) before the peak.

VI. DISCUSSION AND CONCLUSIONS

We have critically reviewed a few scenarios involving axion-like particles devised to explain the observation of the GRB 221009A. Our conclusions differ in some cases from the similar review paper by Carenza and Marsh [11]. The novelty of the present paper is that we make up for the lack of information by regarding GRB 190114C as a sort of ‘smaller twin’ of GRB 221009A as far as the emission is concerned. Below, we cursorily discuss the key-features of the various ALP scenarios from our point of view.

All authors assume that the ALP-to-photon conversion occurs in the Milky Way. The difference among the various scenarios is threefold.

- The site where the photon-to-ALP conversion takes place.
- Whether photon-ALP oscillations in extragalactic space are considered.
- Whether or not a SED (or flux) is assumed.

Schematically, the situation is as follows.

[7] contemplates the photon-to-ALP conversion both inside the GRB jet at the beginning of the afterglow and in the host galaxy. Also photon-ALP oscillations in extragalactic space are included, but they disappear for energies above a few TeV. Only the photon survival probability is considered – fluxes are not taken into account – and so it can explain both the LHAASO and the Carpet-2 results depending on the rapidly time-varying SED of GRB 221009A. Finally, the assumed value of $g_{a\gamma\gamma}$ is in agreement with the upper bound from the magnetized white dwarfs [28]. Thus, this model is viable.
uses the host galaxy to perform the photon-to-ALP conversion for GRB 221009A considered in the prop phase. The power-law flux observed by Fermi/LAT for $100 \text{ MeV} \lesssim E \lesssim 1 \text{ GeV}$ in Eq. [8] is extrapolated to the highest considered energies, contrary to the expectation from GRB 190114C. The assumed value of $\alpha_{\gamma\gamma}$ depends on the assumed extrapolation and is in disagreement with the upper bound from the magnetized white dwarfs [28], thereby implying that such a model is not viable.

Also this paper supposes that the photo-to-ALP conversion occurs in the host galaxy. It is assumed that the maximal mixing occurs in the host – namely that the photon-to-ALP conversion probability is $1/3$ – and a close to maximal mixing takes place in the Milky Way. However, this is merely a wishful thinking since one should demonstrate that a realistic magnetic field in the host and in the Milky Way indeed produces the maximal mixing. And the magnetic field model of Jansson and Farrar [25–27] fails to do the job, so this model is at this stage not viable.

Consider several topics – including the leptonic inverse Compton scattering – and among them also an ALP scenario. The photon-to-ALP conversion is supposed to take place both in the jet and in the host galaxy, assumed to have both a morphology and a magnetic field similar to those of the Milky Way. But we already pointed out that no photon-to-ALP conversion can actually occur in the jet with their assumed parameters. Three $(m_{\text{ALP}}, \alpha_{\gamma\gamma})$ pairs of values are chosen, but the value of $\alpha_{\gamma\gamma}$ always exceeds the upper bound from the magnetized white dwarfs [28], hence this model is not viable.

Reconsiders the ALP scenarios discussed in the present paper. In particular, it focuses the attention on the case in which the photon-to-ALP conversion takes place in the host galaxy, supposed to be identical to the Milky Way. It assumes again that the power-law flux observed by Fermi/LAT for $100 \text{ MeV} \lesssim E \lesssim 1 \text{ GeV}$ is extrapolated to the highest considered energies, contrary to the expectation from GRB 190114C. It emphasizes that both LHAASO and Carpet-2 results cannot be explained with the flux in Eq. [9], which we however consider unrealistic. Moreover, in order to explain the LHAASO events a value of $\alpha_{\gamma\gamma}$ in disagreement with the upper bound from the magnetized white dwarfs [28] is needed. Therefore, also this model is not viable.

We stress that among the above models the one with the smallest ALP mass $m_{\text{ALP}} \approx 10^{-10} \text{ eV}$ is [7], hence this ALP is a good candidate for the dark matter [43].

Some remarks are now in order. Our main assumptions are as follows.

1. Both the LHAASO and the Carpet-2 collaborations have really observed the GRB 221009A. We note that the latter result has been called into question by some authors: for instance [8] states that: ‘more simple explanation would be a misidentification of a charged cosmic-ray air shower’. Another question is: why has the Carpet-2 event not been detected also by LHAASO? A possible answer might be that such an event was not anymore in the field of view of LHAASO at 4536 s after $t_0$ because of the rotation of the Earth. Another possibility is that some selection cut prevented such a detection. The LHAASO collaboration should clarify these points.

2. The EBL prevents the observability of both the LHAASO and the Carpet-2 observations. This reflects a widespread belief, which is also reported in [3]: ‘high-energy photons attenuate through production of electron-positron pairs on cosmic background radiation, and 250 TeV photons (as well as 18 TeV photons detected by LHAASO) cannot reach us from the assumed GRB redshift $z = 0.151$ unless unconventional particle physics is involved. Examples are axion-like particles’. Obviously, this depends on the unknown emitted flux, and some authors have questioned the need of new physics (see e.g. [44, 45]). We believe that this issue will be settled when the LHAASO and Carpet-2 collaborations will release their spectra. Another source of uncertainty is the level of the EBL, which varies depending on the considered paper: some values of $\tau_{\text{CP}}(18 \text{ TeV})$ are reported in Table 1 of [8] but the EBL model considered in this paper [17] is not included, which is the most recent reference apart from [46] (note that [46] has $\tau_{\text{CP}}(18 \text{ TeV}) \approx 19.1$ while we take more conservatively $\tau_{\text{CP}}(18 \text{ TeV}) \approx 14.7$).

Moreover, we have stressed that the extrapolation of Eq. [9] to arbitrarily high energies has no physical motivation, and – in analogy with the case of GRB 190114C – we expect that the inverse Compton peak should be present in the observed SED of GRB 221009A. This is our main message, which remains true even if the ALP scenarios will turn out to be unwarranted. Anyway, only the knowledge of the spectra observed by the LHAASO and Carpet-2 collaborations will shed light on the nature of GRB 221009A in general, and on the need of ALP scenarios in particular.
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[1] GCN Circular n. 32648 [A. de Ugarte Postigo et al.] (2022).
[2] GCN Circular n. 32677 [LHAASO collaboration] (2022).
[3] ATEL #15669 [Carpet-2 collaboration] (2022).
[4] GCN Circular n. 32658 [Fermi/LAT collaboration] (2022).
[5] E. Dwek and F. Krennrich, Astropart. Phys. 43, 112 (2013).
[6] A. De Angelis, M. Roncadelli and O. Mansutti, Phys. Rev. D 76, 121301 (2007).
[7] G. Galanti, M. Roncadelli and F. Tavecchio, arXiv:2210.05659 (2022).
[8] A. Baktash, D. Horns and M. Meyer, arXiv:2210.07172 (2022).
[9] S. V. Troitsky, arXiv:2210.09250 (2022).
[10] M. M. Gonzales et al., arXiv:2210.15857 (2022).
[11] P. Carenza and M. C. D. Marsh, arXiv:2211.02010 (2022).
[12] V. A. Acciari et al. [MAGIC collaboration], Nature 575, 455 (2019).
[13] V. A. Acciari et al. [MAGIC collaboration], Nature 575, 459 (2019).
[14] H. Abdalla et al., [H.E.S.S. collaboration], Nature, 575, 464 (2019).
[15] L. Nava, Universe 7, 503 (2021).
[16] T. Piran, Rev. Mod. Phys. 76, 1143 (2004).
[17] A. Franceschini and G. Rodighiero, Astron. Astrophys. 603, 34 (2017).
[18] R. C. Gilmore, R. S. Somerville, J. R. Primack, and A. Dominguez, Mon. Not. R. Astron. Soc. 422, 3189 (2012).
[19] J. Jaeckel and A. Ringwald, Ann. Rev. Nucl. Part. Sci. 60, 405 (2010).
[20] A. Ringwald, Phys. Dark Univ. 1, 116 (2012).
[21] G. Galanti and M. Roncadelli, Universe 8, 253 (2022).
[22] G. Galanti and M. Roncadelli, J. High Energy Astrophys. 20, 1 (2018).
[23] L. Maiani, R. Petronzio and E. Zavattini, Phys. Lett. B 175, 359 (1986).
[24] G. G. Raffelt and L. Stodolsky, Phys. Rev. D 37, 1237 (1988).
[25] R. Jansson and G. R. Farrar, Astrophys. J. 757, 14 (2012).
[26] R. Jansson and G. R. Farrar, Astrophys. J. 761, L11 (2012).
[27] M. C. Beck et al., JCAP 05, 056 (2016).
[28] C. Dessert, D. Dunsky and B. R. Safdi, Phys. Rev. D 105, 103034 (2022).
[29] A. Neronov and I. Vovk, Science 328, 73 (2010).
[30] A. Ringwald, Phys. Rev. D 87, 103003 (2013).
[31] M. S. Pshirkov, P. G. Tinyakov, and F. R. Urban, Phys. Rev. Lett. 116, 191302 (2016).
[32] E. I. Podlesnyi, T. A. Dzhatdoev and V. I. Galkin, Mon. Not. R. Astron. Soc. 516, 4 (2022).
[33] P. P. Kronberg, Rep. Prog. Phys. 57, 325 (1994).
[34] D. Grasso and H. R. Rubinstein, Phys. Rev. D 48, 163 (2001).
[35] M. J. Rees and G. Setti, Nature 219, 127 (1968).
[36] F. Hoyle, Nature 219, 936 (1969).
[37] P. P. Kronberg, H. Lesch, and U. Hopp, Astrophys. J. 511, 56 (1999).
[38] S. Furlanetto and A. Loeb, Astrophys. J. 556, 619 (2001).
[39] G. Galanti and M. Roncadelli, Phys. Rev D 98, 043018 (2018).
[40] A. Dobrynina, A. Kartavtsev, and G. Raffelt, Phys. Rev. D 91, 083003 (2015); erratum D 91, 109902(E) (2015).
[41] A. Kartavtsev, G. Raffelt and H. Vogel, JCAP 01, 024 (2017).
[42] S. Yamasaki and T. Piran, Mon. Not. R. Astron. Soc. 512, 2142 (2022).
[43] P. Arias et al., JCAP 06, 013 (2012).
[44] Z.-C. Zhao, Y. Zhou and S. Wang, arXiv:2210.10778 (2022).
[45] B. T. Zhang et al., arXiv:2211.05754 (2022).
[46] A. Saldana-Lopez et al., Mon. Not. R. Astron. Soc. 507, 5144 (2021).