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Photon-axion mixing and ultra-high energy cosmic rays from BL Lac type objects: Shining light through the Universe

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Photons may convert into axion-like particles and back in the magnetic field of various astrophysical objects, including active galaxies, clusters of galaxies, intergalactic space and the Milky Way. This is a potential explanation for the candidate neutral ultra-high energy ($E > 10^{18}$ eV) particles from distant BL Lac type objects which probably have been observed by the High Resolution Fly's Eye experiment. Axions of the same mass and coupling may explain also TeV photons detected from distant blazars.

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I. INTRODUCTION

Axions are pseudoscalar particles which arise as the Nambu-Goldstone Bosons of the broken Peccei-Quinn symmetry [1]. They obtain a mass when the CP violating QCD theta term is driven to zero in agreement with observations [2,3]. When motivated in this way, the relationship between the axion mass and coupling is related to the pion mass and decay constant such that for a given axion mass, the coupling to photons is determined up to factors of order a few ($mM \sim m_\pi f_\pi$ where m is the axion mass and M is the inverse axion coupling, see Sec. II). While considerable experimental and theoretical work has eliminated much of the parameter space of such models, axions are still a viable candidate for both the solution of the strong-CP problem and for cold dark matter.

The term Axion-Like Particle refers to a particle with a similar Lagrangian structure to the Peccei-Quinn axion but where the constraints on the parameters of the Lagrangian have been relaxed. In other words there may be particles like the axion weakly coupled to the Standard Model even if they do not solve the strong-CP problem. For simplicity, in the rest of this paper, we shall refer to all such particles as axions, while the particular kind of particle associated with the solution of the strong-CP problem we shall refer to as the Peccei-Quinn axion.

Axions have been invoked to solve a variety of different problems in physics and astrophysics. For example, it has been suggested that they might be responsible for the dimming of supernovae. Photons from distant type Ia supernovae might convert into axions as they cross the Universe to reach us which may explain the apparent low luminosity of high redshift supernovae normally subscribed to the presence of a cosmological constant [4]. Such models are interesting, although there may be problems with the frequency dependence of the dimming effect and they appear difficult to reconcile with baryon acoustic oscillation observations [5–7].

In [8], photon-axion oscillations in intergalactic space have been suggested as an explanation of super-GZK cosmic rays detected by the AGASA experiment although mixing in the source was not considered. Since such mixing means that photons spend some of their time as axions while on route to earth, the attenuation length of photons is effectively increased. Unfortunately it seems that for the parameters of [8], the original flux of photons in the source should exceed the flux observed at the Earth by several orders of magnitude. All these additional photons have to lose their energy in cascades on the background radiation which would be in conflict with EGRET and FERMI limits on the diffuse gamma-ray background.

More recently, the detection of TeV photons from objects at cosmological distances has led to a reconsideration of axions. It is difficult to explain how such photons could reach the Earth given the opacity of the Universe at those wavelengths due to pair production on the background infrared radiation. It has been suggested that the mixing of photons with axions in the intergalactic magnetic field may explain this, although the required intergalactic magnetic field has to be on the high side [9] (for a more recent work and review, see [10]). Another suggestion is that photons are converted into axions in the magnetic field of the active galaxy itself, which is a rather reasonable assumption for axions with low masses. If such a mixing were to take place efficiently, up to one third of the initial high-energy photon flux may cross the Universe in the form of axions before being converted back into photons in the magnetic field of the Milky Way, avoiding the attenuation that photons would experience as they travel across the Universe. The authors of [11] identified the axion parameters and galactic magnetic field which can explain the arrival of TeV photons from cosmological sources. In this note, we shall analyze these axion scenarios to see if they might also explain the origin of apparently neutrally charged ultra-high energy cosmic rays which may come from distant extragalactic sources—BL Lac type objects [12,13].

One of the most fascinating predictions of theories which contain axions is the idea that one may ‘‘shine light through walls’’ by converting photons to and from axions on either side of a wall using strategically placed magnetic fields. In this work we are doing the same experiment but we are using the Universe as our wall and galaxies and their environment for our magnetic fields.

In Sec. II we shall go over the mathematics of the mixing phenomenon and discuss the mixing of photons and axions in astrophysical sources. Then in Sec. III we will discuss the evidence for the arrival of ultra-high energy cosmic rays from directions coincident with BL Lac objects before discussing photon-axion mixing as a possible explanation for these events in Sec. IV. Finally we will list some of the consequences of this model and other ways to test it before moving to our conclusions.

II. PHOTON-AXION MIXING IN ASTROPHYSICAL OBJECTS

The Lagrangian describing the photon and axion takes the following form (similar results hold for a scalar),

$$\mathcal{L} = \frac{1}{2}(\partial^\mu a \partial_\mu a - m^2 a^2) - \frac{1}{4}\frac{a}{M}F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu},$$

where $F_{\mu\nu}$ is the electromagnetic field-strength tensor and $\tilde{F}_{\mu\nu} = \epsilon_{\mu\nu\rho\lambda}F_{\rho\lambda}$ is its dual, a denotes the pseudoscalar axion, m is the axion mass and M is the inverse axion-photon coupling. Because of the $F_{\mu\nu}\tilde{F}^{\mu\nu}$ term, there is a finite probability for the photon to mix with the axion in the presence of a magnetic field. Mixing also occurs between photon components with different polarizations [14,15]. We will be interested in light, $m \lesssim 10^{-5}$ eV, axions with inverse coupling mass scale $M \sim \text{few} \times 10^{10}$ GeV. For axions of these masses the most stringent bound on the coupling, $M > 1.1 \times 10^{10}$ GeV at the 95% CL, has been placed by the CAST experiment [16].

Technically, the mixing may be described as follows. We represent the photon field $A(t, x)$ as a superposition of fixed-energy components $A(x)e^{-i\omega t}$. If the magnetic field does not change significantly on the photon wavelength scale and the index of refraction of the medium $|n - 1| \ll 1$, one can decompose [15] the operators in the field equations as (for a photon moving in the z direction) $\omega^2 + \partial_z^2 \to 2\omega(\omega - i\partial_z)$, so that the field equations become Schrodinger-like,

$$i\partial_z\Psi = -(\omega + \mathcal{M})\Psi; \qquad \Psi = \begin{pmatrix} A_x \\ A_y \\ a \end{pmatrix}, \tag{1}$$

where

$$\mathcal{M} \equiv \begin{pmatrix} \Delta_p + \Delta_{Q,\parallel} & 0 & \Delta_{Mx} \\ 0 & \Delta_p + \Delta_{,\perp} & \Delta_{My} \\ \Delta_{Mx} & \Delta_{My} & \Delta_m \end{pmatrix}.$$

The mixing is determined by the refraction parameter Δ_p, the axion mass parameter Δ_m, the mixing parameter Δ_M and the QED dispersion parameter $\Delta_{,\perp}$. The first three parameters are equal to

$$\Delta_{Mi} = \frac{B_i}{2M} = 540\left(\frac{B_i}{1\text{ G}}\right)\left(\frac{10^{10}\text{ GeV}}{M}\right)\text{ pc}^{-1},$$

$$\Delta_m = \frac{m^2}{2\omega} = 7.8 \times 10^{-11}\left(\frac{m}{10^{-7}\text{ eV}}\right)^2\left(\frac{10^{19}\text{ eV}}{\omega}\right)\text{ pc}^{-1},$$

$$\Delta_p = \frac{\omega_p^2}{2\omega} = 1.1 \times 10^{-6}\left(\frac{n_e}{10^{11}\text{ cm}^{-3}}\right)\left(\frac{10^{19}\text{ eV}}{\omega}\right)\text{ pc}^{-1},$$

respectively. Here $\omega_p^2 = 4\pi\alpha n_e/m_e$ is the plasma frequency squared (effective photon mass squared), n_e is the electron density, B_i, $i = x, y$ are the components of the magnetic field B, m_e is the electron mass, α is the fine-structure constant and ω is the photon (axion) energy.

The QED dispersion parameter is

$$\Delta_{Q,\parallel(\perp)} = \frac{m^2_{\gamma,\parallel(\perp)}}{2\omega},$$

where $m^2_{\gamma,\parallel(\perp)}$ is the effective mass square of the longitudinal (transverse) photon which arises due to interaction with the external magnetic field. This quantity has been calculated in [17] (see also [18] for a similar but less explicit result),

$$m^2_{\gamma,\parallel(\perp)} = \frac{\alpha m_e^2}{6\pi}\int_1^\infty du\,\frac{8u + 1 \mp 3}{zu\sqrt{u(u-1)}}f'(z), \tag{2}$$

where

$$z = \left(\frac{4u}{\kappa}\right)^{2/3}$$

and

$$\kappa = \frac{1}{m_e^3}\sqrt{(eF_{\mu\nu}l_\nu)^2} = \frac{\omega}{m_e}\frac{B_\perp}{B_{\text{cr}}} \approx 0.44\left(\frac{\omega}{10^{19}\text{ eV}}\right)\left(\frac{B}{1\text{ G}}\right) \tag{3}$$

$F_{\mu\nu}$ is the electromagnetic field-strength tensor, l_ν is the photon 4-momentum, $B_\perp$ is the component of the magnetic field perpendicular to the photon propagation and $B_{\text{cr}} = m_e^2/e \approx 4.4 \times 10^{13}$ G;

$$f(z) = i\int_0^\infty dt e^{-i(zt+t^3/3)}$$

and the real and imaginary parts of the function $f(z)$ may be expressed explicitly through the Airy functions. We plot the real and imaginary parts of the squared mass of the longitudinal and transverse photons in Fig. 1 which is similar to Fig. 1 of [17]. In the region $\kappa \ll 1$, which is often quoted, Eq. (2) may be approximated as follows,

$$m^2_{\gamma,\|(\perp)} \approx \alpha m_e^2 \left(-\frac{11 \mp 3}{90\pi}\kappa^2 - i\sqrt{\frac{3}{2}}\frac{3 \mp 1}{16}\kappa e^{-8/3\kappa}\right), \quad \kappa \ll 1. \tag{4}$$

(see also [19] and Eq. 9 of [20]). The opposite asymptotics is

$$m^2_{\gamma,\|(\perp)} \approx \alpha m_e^2 \frac{5 \mp 1}{28\pi^2}\sqrt{3}\Gamma^4(2/3)(1 - i\sqrt{3})(3\kappa)^{2/3}, \quad 1 \ll \kappa \ll \alpha^{-3/2}. \tag{5}$$

This expression is equivalent to Eq. 10 of Tsai and Erber [20]. Note that at $\alpha\kappa^{2/3} \gtrsim 1$, the photon mass and electron mass are of the same order and the approximation of [17,20] does not work.

We arrive to the expression

$$\Delta_{Q,\|(\perp)} = 1.49 \times 10^{13}\ \mathrm{pc}^{-1}\left(\frac{\omega}{10^{19}\ \mathrm{eV}}\right)^{-1} F_{\|(\perp)}(\kappa),$$

where

$$F_{\|(\perp)}(\kappa) = \frac{m^2_{\gamma,\|(\perp)}(\kappa)}{\alpha m_e^2}$$

is a function of κ plotted in Fig. 1.

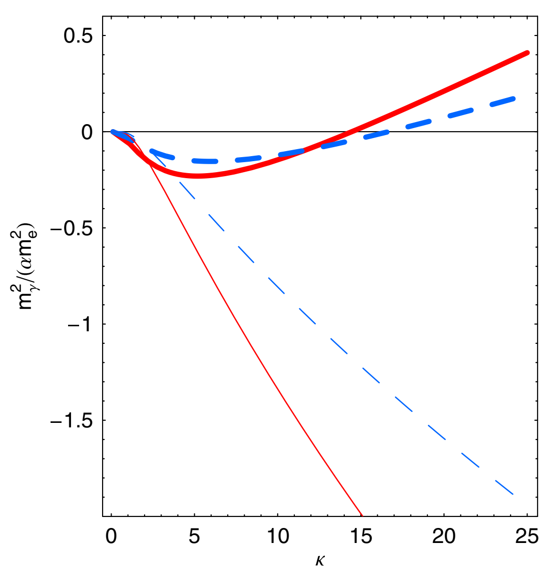

FIG. 1 (color online). Effective mass squared [17] of the transverse (red full lines) and longuitudinal (blue dashed lines) photon in the external magnetic field, expressed in terms of αm_e^2, as a function of $\kappa = (\omega/(m_e))(B/B_{\mathrm{cr}})$. Thick lines represent the real part and thin lines represent the imaginary part.

For constant magnetic field and electron density, the conversion probability is

$$P = \frac{4\Delta_M^2}{(\Delta_p + \Delta_{Q,\perp} - \Delta_m)^2 + 4\Delta_M^2}\sin^2\left(\frac{1}{2}L\Delta_{\mathrm{osc}}\right),$$

where

$$\Delta^2_{\mathrm{osc}} = (\Delta_p + \Delta_{Q,\perp} - \Delta_m)^2 + 4\Delta_M^2$$

and we assumed that imaginary parts of all Δ's can be neglected. If B and n_e change spatially, the probability can be found by a numerical solution of Eq. (1). The condition for the strong mixing is

$$4\Delta_M^2 \gg (\Delta_p + \Delta_{Q,\perp} - \Delta_m)^2. \tag{6}$$

In an earlier version of this paper, we neglected the contribution of Δ_Q and arrived at the conclusion that for certain values of the parameters, conditions for strong photon-axion mixing are satisfied in the blazar and in the Milky Way, but not in the intergalactic space, both for very-high energy (TeV) and ultra-high energy (10^{19} eV) gamma rays. However, as it has been pointed out (e.g., in [21]), using equations for the real part of the QED-induced photon mass and given its negative sign, the condition (6) can be satisfied only in the case

$$\Delta_{Q,\perp} \ll \Delta_M$$

which reads as

$$F_\perp(\kappa) \ll 1.64 \times 10^{-10}\kappa\left(\frac{M}{10^{10}\ \mathrm{GeV}}\right)^{-1}. \tag{7}$$

In [21], the small-κ expansion, Eq. (4), was used, which results in the condition

$$\kappa \ll 3.31 \times 10^{-9}\left(\frac{M}{10^{10}\ \mathrm{GeV}}\right)^{-1} \tag{8}$$

or equivalently

$$\left(\frac{B}{\mathrm{G}}\right)\left(\frac{\omega}{10^{19}\ \mathrm{eV}}\right) \ll 7.52 \times 10^{-9}.$$

An alternative approach is to make use of the change of sign of $F_\perp(\kappa)$ which was suggested in [22]. Neglecting the possibility of precise cancellations (to many decimal points) between Δ_m and Δ_Q, this means that one should have $\kappa = \kappa_0 \approx 15$. However, in this case, the imaginary part of the photon mass is much larger than Δ_M and a photon produces an electron-positron pair much quickly than it is converted to an axion. It would be interesting to understand what happens in the strong quantum regime $\kappa > \alpha^{-3/2}$ since for $\omega = 10^{19}$ eV, this regime corresponds to fields of 10^4 G which are not extremely large. We see that the only possible way to obtain strong mixing in the weak-coupling regime is to satisfy Eq. (8).

Other maximal-mixing conditions, which also must be met, are

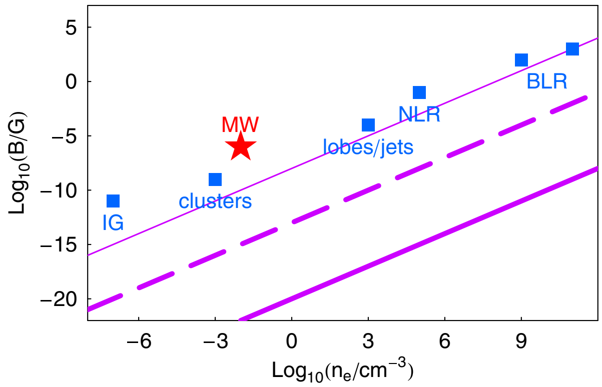

FIG. 2 (color online). Typical values of the magnetic field [37] and electron density [61,62] in various astrophysical objects (IG: intergalactic space, MW: the Milky Way, NLR and BLR: narrow- and broadline regions in active galactic nuclei). The condition (10) is satisfied above the thick line for energies $\omega > 10^{19}$ eV, above the dashed line for $\omega > 1$ TeV and above the thin line for $\omega > 10$ MeV (for $M = 10^{10}$ GeV).

$$\Delta_m \ll 2\Delta_M,$$

and

$$\Delta_p \ll 2\Delta_M,$$

which are equivalent to

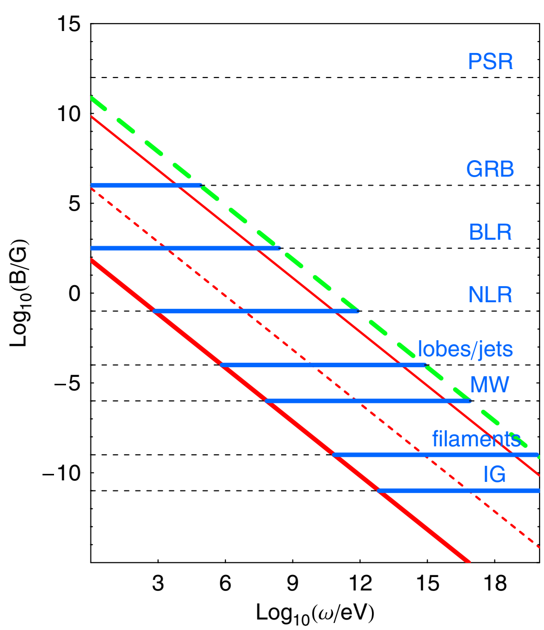

FIG. 3 (color online). The conditions (8) and (9) on the parameter plane "photon energy"—"magnetic field". The condition (9) is satisfied above red lines (thin for $m = 10^{-5}$ eV, dotted for $m = 10^{-7}$ eV, thick for $m = 10^{-9}$ eV). Horizontal lines indicate typical B values for various astrophysical sources, the condition (8) is satisfied below a thick dashed green line: the mixing is possible below the green line but above the red lines as indicated, for $m = 10^{-9}$ eV, by the thick blue parts of the horizontal lines (for $M = 10^{10}$ GeV).

$$\omega \gg 70\ \text{eV}\left(\frac{m}{10^{-9}\ \text{eV}}\right)^2\left(\frac{B}{\text{G}}\right)^{-1}\left(\frac{M}{10^{10}\ \text{GeV}}\right), \tag{9}$$

$$n_e \ll 10^{20}\ \text{cm}^{-3}\left(\frac{\omega}{10^{19}\ \text{eV}}\right)\left(\frac{B}{\text{G}}\right). \tag{10}$$

In addition, to have large mixing one should require that the size L of the region in which conditions (8)–(10) are fulfilled should exceed the oscillation length,

$$L \gtrsim \frac{\pi}{\Delta_{\text{osc}}},$$

that is

$$L \gtrsim 5.8 \times 10^{-3}\ \text{pc}\left(\frac{B}{\text{G}}\right)^{-1}\left(\frac{M}{10^{10}\ \text{GeV}}\right). \tag{11}$$

From Fig. 2, one sees that Eq. (10) is certainly fulfilled for ultra-high energy particles in all astrophysical gamma-ray sources. For axion-photon coupling close to its experimental limit, the condition (10) is met down to energies as low as ~10 MeV. The conditions (8) and (9) are illustrated in Fig. 3.

The condition (11), also very restrictive, depends on both the size and the magnitude of the magnetic field and

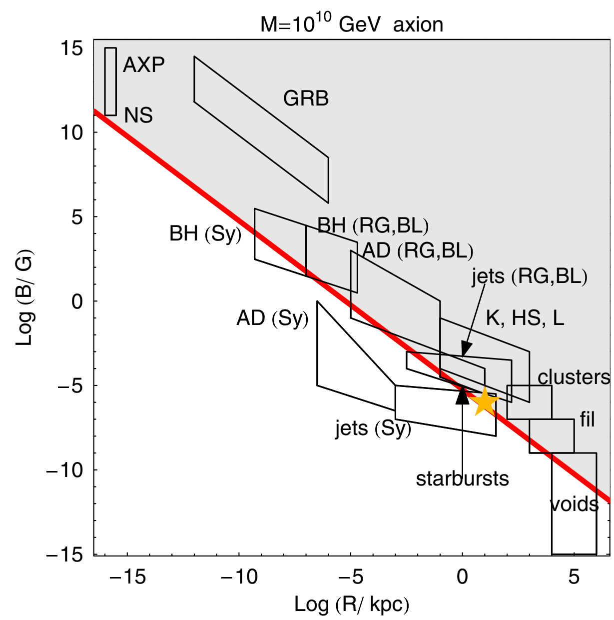

FIG. 4 (color online). The condition (11) for $M = 10^{10}$ GeV on the updated Hillas plot [37]. The condition is satisfied in the shadowed region. The Milky Way parameters are denoted by a star. Also shown are parameters for anomalous X-ray pulsars and magnetars (AXP), neutron stars (NS), central black holes (BH) and for the central few parsecs (AD) of active galaxies (low-power Seyfert galaxies (Sy), powerful radio galaxies (RG) and blazars (BL)), relativistic jets, knots (K), hot spots (HS) and lobes (L) of powerful active galaxies (RG and BL); nonrelativistic jets of low-power galaxies (Sy); starburst galaxies; gamma-ray bursts (GRB); galaxy clusters and intercluster voids.

can be superimposed [23] on the Hillas plot for various astrophysical sources (Fig. 4). We see that if an axionlike particle exists with the mass and coupling outlined above, high-energy photons readily mix with it in many astrophysical objects and environments. As a result, the axion flux $F_a = F_\gamma/2$ accompanies the gamma-ray flux F_γ independently of the gamma-ray emission mechanism (for the maximal mixing, fluxes of axions and of photons of each polarization are equal).

III. NEUTRAL PARTICLES FROM DISTANT SOURCES

A number of studies suggest that a correlation may exist between the arrival directions of cosmic rays and catalogues of BL Lac objects. This correlation exists without taking into account the magnetic field of the galaxy, suggesting that the cosmic rays experience zero deflection as they traverse this field and are therefore neutral particles, challenging conventional models of cosmic-ray physics.

These claims are based upon two samples of cosmic rays, the first sample combines events from the Akeno Giant Air Shower Array (AGASA) of cosmic rays with estimated primary energies $E > 4.8 \times 10^{19}$ eV) and a sample from the Yakutsk Extensive Air Shower Array (Yakutsk) of events with estimate primary energy $E > 2.4 \times 10^{19}$ eV. An excess of correlations between the position of BL Lacs and the arrival direction of cosmic rays in this combined data set was seen at separations less than 2.5° [24].

Similarly, a sample of events with $E > 10^{19}$ eV observed by the High Resolution Fly's Eye detector (HiRes) tested positive for correlations between source and BL Lac objects at angular separations less than 0.8° [12].

In both cases the separation was consistent with the detector's angular resolution (which was much better in HiRes than in AGASA and Yakutsk). The correlation with the HiRes sample was confirmed in an unbinned study and was found to extend to lower energies [13]. The probability to observe the correlation with three independent experiments by chance was estimated by [25] as 3×10^{-5} by a Monte Carlo study.

The correlation between BL Lacs and UHECRs seen in HiRes data [12,13] has been tested by the Pierre Auger Collaboration [26] and no positive signal has yet been found. However, it turns out that this is unsurprising for the following three reasons:

Firstly, Pierre Auger is located in the Southern hemisphere and sees different BL Lacs to other experiments and due to incompleteness of the astronomical catalogs, fewer potential UHECR emitters are known in the South.

Secondly, the angular resolution of the Pierre Auger array is also inferior to that of the HiRes stereoscopic telescope which means that the sensitivity to such correlations can only be achieved with much more data.

Finally, as has been pointed out in [12,13] and further discussed in [27], the correlation observed by HiRes implies neutral cosmic particles traveling for cosmological distances, a fact which requires unconventional physics. Most probably the primary particles of the resulting air showers are neither protons nor nuclei. However, the energy determination of the PA surface detector is extremely sensitive to the type of the primary cosmic particle because of very strong sensitivity of water tanks to muons in the air shower. For instance, energies of gamma rays are always underestimated by a factor of a few (see e.g. [28,29]). Because of the steeply falling spectrum of UHECRs, this may dilute the observed signal. It would therefore be interesting if the Pierre Auger collaboration were able search for the correlation using their Fluorescence detectors rather than the water tanks.

An independent test of the cosmic-ray—BL Lac correlation is underway [30] with the Telescope Array experiment located in the Northern hemisphere and equipped with the array of scintillator detectors and fluorescent telescopes capable of stereo imaging.

Having discussed the evidence for the correlation between the arrival direction of ultra-high energy cosmic rays and BL Lac objects, we will move on to look at the use of axions to explain how neutral particles could traverse the Universe without complete attenuation.

IV. AXIONS AS ULTRA-HIGH ENERGY COSMIC RAYS

In the framework of the standard model of particle physics and assuming standard astrophysics, neutral particles with energies $\sim 10^{18}$ eV cannot propagate for $\gtrsim 100$ Mpc, the distance to the nearest BL Lacs. The only exception is the neutrino which can be excluded as an explanation for these events by considering the height of development of the atmospheric showers and noting that they are not close enough to the ground to be consistent with the weak interaction cross sections.

Photons interact with the background radiation which results in pair production and the development of electromagnetic cascades. Known unstable particles decay at much shorter distances (Fig. 5). In the framework of more involved descriptions which do not require new physics, the neutral particles may be created in interactions of protons inside or not far from the Milky Way; however, in this case the observed effect also cannot be explained [27].

Even beyond the standard model it is difficult to find a noncontradictory explanation of the observed correlations. New stable strongly interacting particles [31,32] should be heavy enough not to be detected in accelerators, but the probability to create such a heavy particle is low and therefore one would expect for each one of these particles that there should be huge fluxes of accompanying radiation in conflict with constraints on diffuse cosmic gamma radiation.

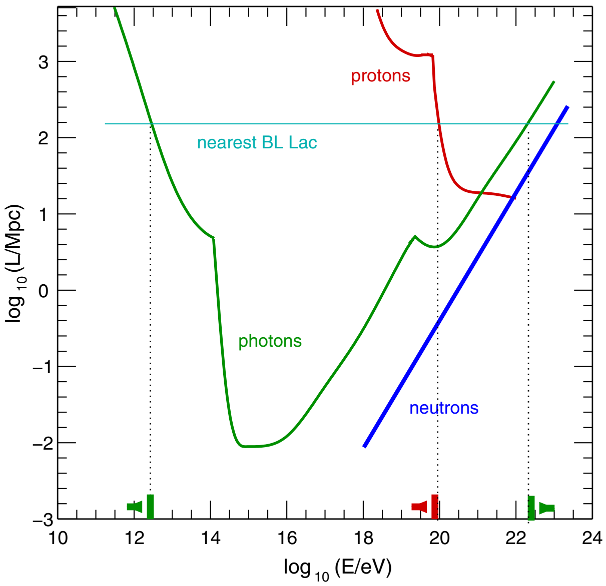

FIG. 5 (color online). Attenuation length of different kinds of particles as compared to the distance to the nearest BL Lac (blue horizontal line) and the size of the Universe (upper bound of the plot). The green line corresponds to photons, blue to neutrons and red (shown for comparison) to protons. The lines for protons and photons are taken from the review [63].

Models which suggest the existence of a relatively heavy (∼ MeV) axionlike particle (sgoldstino) [33] suffer the same problem.

In the models where there is an enhanced neutrino-air cross section (see, e.g., [34]), besides some theoretical difficulties, the cross section rise is not sufficient to explain the shower development. Only in the models with Lorentz-invariance violation [35] decaying neutral particles (neutron or π^0 meson) might be stable in a certain energy region and propagate to cosmological distances. It can be argued however that postulating the existence of a new particle is less drastic than altering the framework of relativity.

The scenario which we investigate here is based on the mixing of photon with light axions. The parameters of the model which work in explaining the conundrum of the neutral primaries outlined above do not contradict any experimental limits and may allow one to explain some other astrophysical puzzles as well.

The maximal-mixing conditions (8)–(11) are satisfied (cf. Figures 2–4) for various astrophysical objects, allowing for different scenarios of axion-photon transitions which might be relevant for the BL Lac correlation. We summarize them in Table I and describe in more detail below. For convenience, we include also the information about TeV photon mixing relevant for the gamma-ray observations. As we will see, the choice of a particular scenario depends on the value of the intergalactic magnetic field (IGMF) at scales $\gtrsim$ Mpc which at present is poorly known.

Case 1: $m \sim 10^{-7}$ eV, *weak-IGMF*. From Fig. 3, it is clear that conditions (8) and (9) leave a window of $\sim(10^{-13} \dots 10^{-9})$ G for conversion of $\sim 10^{19}$ eV photons. If IGMF in voids is $\sim 10^{-11}$ G or weaker, conversion on it is suppressed since the condition (9) is not satisfied. Intense photon-axion conversion may happen in the regions of a few megaparsec size with the magnetic field $\sim 10^{-9}$ G. According to simulations of [36], these conditions are satisfied in certain elements of the large-scale structure of the Universe which we somewhat loosely call "filaments" for brevity. In this case, protons are accelerated to ultra-high ($E \gtrsim 10^{20}$ eV) energies in the sources (according to [37], acceleration of protons in BL Lacs up to these energies contradicts neither the Hillas criterion nor the radiation losses). Interaction of these protons with the intense blazar emission results in the pion photo-production similar to the GZK effect which for a fraction of the accelerated particles takes place directly in the source. If the source is

TABLE I. Different scenarios for mixing of high-energy cosmic photons with axions. Columns give: the number of the scenario (as referred to in the main text); the axion mass m; the assumed value of IGMF in large-scale voids; the energy of photons ω (two cases are presented, ω ∼ 1012 eV relevant for TeV gamma rays from distant blazars and ω ∼ 1019 eV relevant for the cosmic-ray—BL Lac correlations); potential sites where the strong mixing is possible (+) or not (−); and the principal sites of the $\gamma \to$ a and a $\to \gamma$ conversion (BL = BL Lacs, fil = filaments, IG = intergalactic voids, MW = Milky Way). More details are discussed in the text.

					strong mixing in			
No.	m eV	IGMF G	ω eV	BL	fil	IG	MW	dominant conversion
1	~10-7	≲ 10 − 11	1012	+	−	−	+	source + MW
			1019	−	+	−	−	fil + fil
2	~10-7	~10-9	1012	+	−	−	+	source + MW
			1019	−	+	+	−	IGMF + IGMF
3	∼10 − 5	any	1012	+	−	−	−	no explanation
			1019	−	+	−	−	fil + fil (IGMF if strong)
4	≲ 10 − 9	$\sim 10^{-9}$	1012	+	+	+	+	IGMF + IGMF
			1019	−	−	+	−	IGMF + IGMF

located in, or near, a "filament", then intensive mixing there converts $1/3$ of photons into the axions of the same energy so the axion-photon beam propagates into space towards earth. Further mixing in intergalactic space before the photon-axion beam arrives at the local "filament" where the observer sits is suppressed due to small magnetic fields in voids. The photon part of the beam interacts with background photons and loses energy while the axion part propagates unattenuated. Then, upon arrival at the local "filament" where the magnetic field is several orders of magnitude higher than in voids, intensive mixing again takes place and a significant fraction ($2/3$ for maximal mixing) of the axions are converted back into photons which are then detected as neutral particles from BL Lacs. The maximum fraction of photons detected in cosmic-ray detectors on earth can be $2/9$ of the total flux of photons of same energy emitted in the source. We note that for the parameters of this case, the mixing in IGMF is not possible for $\omega \sim 10^{12}$ eV either; nor mixing is possible in the "filaments" for these energies. However, the scenario of [11] (mixing in the source and in the Milky Way) works for TeV photons.

Case 2: $m \sim 10^{-7}$ eV, *strong IGMF*. The condition (11) is satisfied for IGMF $\sim 10^{-9}$ G, so the dominant place of conversion of UHE photons is IGMF in this case. At the same time, for $\omega \sim 10^{12}$ eV, the condition (9) forbids strong mixing at IGMF and the "source—Milky Way" mechanism is again operational for TeV photons.

Case 3: $m \sim 10^{-5}$ eV. In this case, the conditions (8) and (9) leave a very narrow strip on the "$\omega - B$" parameter plane, Fig. 3. For UHE photons, this strip allows for the conversion at $B \sim 10^{-9}$ G, that is in "filaments" for weak IGMF and in voids for the strong one. No viable conversion scenario exists for TeV photons in this case.

Case 4: $m \lesssim 10^{-9}$ eV, *strong IGMF*. This is a realization of the scenario of [9,10] of conversion at IGMF, working for both $\omega \sim 10^{12}$ eV and $\omega \sim 10^{19}$ eV. For TeV photons, other conversion sites are possible but their effect is negligible compared to that of long-distance IGMF.

We see that the applicability of various scenarios is strongly dependent of the assumed values of IGMF. Current observational limits (see, e.g., [38] for a review) constrain the magnetic fields at $\gtrsim$ Mpc scale to be in the range $(10^{-16} \dots 10^{-9})$ G, the lower bound [64] coming from nonobservation of GeV emission from certain TeV sources [40] while the upper one coming from the CMB polarization [39] and Faraday rotation measurements [41]. The simulations of [36] favor very low ($\sim 10^{-15}$ G) magnetic fields in the large-scale voids (otherwise far too high fields in the galaxy clusters are produced, incompatible with observations). At the same time, $\sim 10^{-9}$ G fields are obtained in this simulations for certain few-megaparsec scale parts of the "filaments." There are also other indications to very weak magnetic fields in the voids [42] but these are model-dependent. The CMB measurements by the Planck satellite, currently in flight, will test the IGMF in the range $(\sim 10^{-11} \dots 10^{-9})$ G, crucial for the choice of the axion conversion scenario.

In the case of conversion in voids, that is of strong ($\sim 10^{-9}$ G) IGMF, one cannot use directly the oscillation formalism outlined above for UHE gamma rays and axions because the attenuation length of $\omega \sim 10^{19}$ eV photons on the radio background radiation is $l \sim 3$ Mpc, cf. Fig. 5 (the precise value of l is sensitive to the poorly known intergalactic radio background). Within our precision and given lack of knowledge of the field, we may estimate the flux of the photons arriving to the Earth as a $P(l)^2 \sim (l/D)^2 \sim (10^{-3} \dots 10^{-4})$ fraction of the initial photon number flux, where D is the distance to the source. This estimate does not contradict the observed UHE cosmic-ray flux within the photoproduction scenario for UHE gamma rays. The remaining part of the flux interacts with the cosmic background radiation and experiences electromagnetic cascades down to photons of $\sim$GeV energies for whom the Universe is transparent. Depending on the radiation and magnetic field strengths in the source, in its close environment and along the trajectory to the Earth, these secondary GeV photons contribute either to the (extended) image of the source or to the diffuse gamma-ray background. The corresponding flux may be estimated as follows. The flux of events correlated with BL Lacs is [43] roughly 0.03 of the total cosmic-ray flux at 10^{19} eV. The latter flux as detected by HiRes [44] is $J_{\rm CR} E^3 \approx 2 \times 10^{24}$ eV^2 m^{-2} s^{-1} sr^{-1}. The estimate of the corresponding flux of $E_0 \sim$ GeV photons may be obtained from the energy conservation and in the IGMF-conversion scenraio reads as

$$J_{\rm IG} E_0 \sim \left(\frac{D}{l}\right)^2 0.03 J_{\rm CR} \frac{E^2}{E_0} \sim 10^{-6}\ {\rm cm}^{-2}\,{\rm s}^{-1}\,{\rm sr}^{-1}. \qquad (12)$$

This is of the same order as the diffuse GeV flux observed by Fermi [45]. Given all uncertainties in our estimate, as well as in the observational value [45–47] of the GeV flux, we do not use this number to constrain the scenario; with the present precision it may, depending on the assumptions, either explain the part of the GeV background unaccounted for by known contributors, or overshoot the observed value thus indicating that the scenario is not viable. If the magnetic fields and radiation backgrounds allow for formation of an extended image of the source, then the flux in Eq. (12) should be distributed among the observed sources rather than spread uniformly over 4π sr. The number of sources N_s may be estimated from the statistics of clustering [48] as $N_s \sim 60$. In this case, the value of the single-source flux,

$$J_{1,\rm IG} \sim \frac{4\pi\ {\rm sr}}{N_s} J_{\rm IG} E_0 \sim 10^{-7}\ {\rm cm}^{-2}\,{\rm s}^{-1},$$

is too high to be realistic for 60 sources.

On the other hand, for weak-IGMF scenarios roughly $1/3$ of original UHE photons are converted to axions within a few Mpc from the source and $2/3$ of them convert back to photons within a few Mpc from the Earth. Therefore, instead of $(l/D)^2$, the observed flux constitutes $\sim 2/9$ of the emitted one. The flux of a single source is then

$$J_{1,\mathrm{F}} \sim \frac{4\pi\ \mathrm{sr}}{N_s}\frac{2}{9}0.03 J_{\mathrm{CR}}\frac{E^2}{E_0} \sim 10^{-9}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1},$$

well within the Fermi sensitivity. The angular size of the halo is then $\theta \approx \frac{l}{D}$, which is a fraction of a degree, well below the width of the point spread function of either EGRET or Fermi. This means that the correlated BL Lacs should be gamma-ray sources in agreement with the results of [49,50]. A method of detection of the size of extended images of this kind is discussed in [51].

Because the cosmic magnetic fields, in particular, in "filaments", are nonuniform, we expect the probability for axions which arrive from far away to convert back into photons to depend upon the direction they move before they arrive at Earth. This should reflect itself in the distribution of the arrival directions of the correlated events. To look for the possible anisotropy, we use the list of correlated BL Lacs from [12] and compare their distribution with respect to the experimental exposure with the full sample of 156 BL Lacs studied in [12,13]. The correlated events are plotted, together with the exposure, in Fig. 6. One sees that they do not appear to follow exactly the expected random distribution (they would be more likely to turn up in the most densely shaded region if the distribution was isotropic). To quantify these suspicions, we use the method recently becoming popular in tests of global anisotropy of UHECR arrival directions [52–54]. For each BL Lac with coordinates (l_i, b_i) we calculate the value of the experimental exposure towards this point of the sky, $A_i = A(l_i, b_i)$. Then we compare, by means of the Kolmogorov-Smirnov test, the distributions of these A_i for BL Lacs which are correlated with cosmic rays and for all BL Lacs, correlated or not [55]. The test gives a probability of 0.024 that the two distributions of A_i are realizations of the same distribution, thus disfavoring the idea that correlated events come from random/isotropic regions on the sky. Though it is not possible to judge, without a quantitative model of magnetic fields outside the Galaxy, whether the nonuniformity is related to the field structure at the megaparsec scale, it is tempting to note that a similar deviation from isotropy would be expected in our weak-IGMF scenarios (cases 1 and 3).

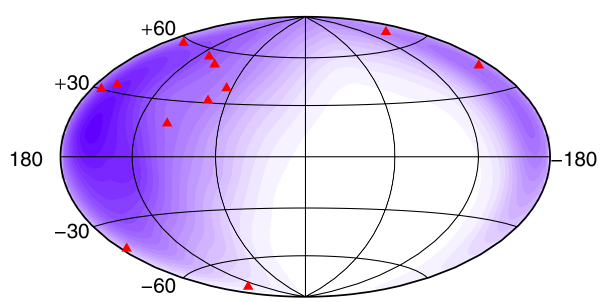

FIG. 6 (color online). The exposure of the HiRes cosmic-ray detector—darker shaded regions have had more exposure. The red triangle data points correspond to cosmic rays correlated with the position of BL Lacs.

V. DISCUSSION AND CONCLUSIONS

We have shown in the previous section that there is some motivation for a possible interpretation of the neutral events correlated with the position of BL Lac objects in the sky being due to photons that have been able to traverse the Universe because of their conversion into axions and then back into photons. More data with regards to the intergalactic magnetic field, especially at the megaparsec scale, and more cosmic-ray events will be able to add or subtract confidence in this interpretation but the scenario leads to several other consequences which may be tested in future studies.

Primary particle type of the correlated events. Clearly, if axions are the explanation, then the primary particles of the correlated events should be photons. Currently studies of the primary particle type for the HiRes events are not published. The photon-primary hypothesis agrees perfectly with the absence of correlations in the Auger surface detector data [26]: the photon energies are underestimated [28] by this detector by a factor of four on average [29], so that the correlated events would be lost among a large number of hadronic events of lower energy. Such a situation should also be the case in the future data, although as alluded to earlier, the correlations should be seen in the data of fluorescent detectors of Pierre Auger and Telescope Array and in the surface detector of Telescope Array.

Secondary photons and the extended image. As discussed above in Sec. IV, in certain scenarios the extended image of the source in GeV photons is formed and may be detected. Other scenarios result in a contribution to the GeV diffuse background. Both possibilities may be constrained with the Fermi data.

Axion parameters. The model requires the axionlike particle with mass $m \lesssim 10^{-5}$ eV and the inverse coupling to photon close to the current experimental limits, $M \sim (1 \div 10) \times 10^{10}$ GeV. The most direct confirmation of the scenario would come from the discovery of that particle. This region of the parameter space is available for exploration with CAST at sufficiently large exposure. The axion with these parameters may also affect the polarization of extragalactic radio sources [56–58].

To summarize, the existence of an axionlike particle with an inverse coupling $M \sim 10^{10}$ GeV and a low mass $m \lesssim 10^{-5}$ eV has been invoked by other authors to explain the detection on earth of TeV photons from cosmological sources—flux which is difficult to explain given that such photons should produce electron-positron pairs on the cosmic infrared background [9,11]. The presence of such a particle would enable some photons to convert into axions and to travel over the intervening space without interacting with the background radiation before turning back into photons.

In this work we have tried to use the same method to explain a set of ultra-high energy cosmic-ray events which seem to come from BL Lac objects. Since such events seem to lead straight back to the source, the particles should be neutral because charged particles would be deflected by the magnetic field of the galaxy. However, no neutral particles in the standard model seem capable of traversing the Universe at such a high energy. The same idea of photons turning into axions and then back into photons is immediately applicable to this cosmic-ray situation.

Clearly, more data are needed to show whether or not this correlation has occurred by chance, both cosmic-ray data and data on the arrival of TeV photons from cosmological sources will help to add support to or rule out this hypothesis.

It has been suggested that the existence of a light axionlike particle would also help explain some other astrophysical conundrums such as the white dwarf luminosity function [59].

Finally it is appropriate to reiterate that the parameters of interest for this effect suggest a weak coupling for the axion, but not so weak that it cannot be probed by experiments such as CAST [16] or the new generation axion helioscope [60]. The low mass required to ensure that one is in the region of maximal mixing means that such an axion should be able to be ruled out or confirmed by one of these experiments.

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