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 astro-
physical 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 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 pseudo-scalar particles which arise as the
Nambu-Goldstone Bosons of the broken Peccei-Quinn
symmetry [1]. They obtain a mass when the CP viol-
ating 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 ($m M \sim m_\pi f_\pi$ where $m$ is
the axion mass and $M$ is the inverse axion coupling, see
section 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 La-
grangian 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
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 luminos-
ity 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 ap-
pear difficult to reconcile with baryon acoustic oscillation
observations [5-7].

In Ref. [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 Ref. [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 ob-
jects at cosmological distances has led to a reconsidera-
tion 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 back-
ground 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 Ref. [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 effi-
ciently, 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 analyse 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 section II we shall go over the mathematics of the mixing phenomenon and discuss the mixing of photons and axions in astrophysical sources. Then in section 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 section 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),

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

where $F_{\mu \nu}$ is the electromagnetic stress tensor and $\tilde{F}_{\mu \nu} = (1/2) \epsilon_{\mu \rho \nu \lambda} F_{\rho \lambda}$ is its dual, $a$ denotes the pseudo-scalar axion, $m$ is the axion mass and $M$ is the inverse axion-photon coupling. Because of the $F_{\mu \nu} F^{\mu \nu}$ 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 [13] [15]. We will be interested in light, $m \lesssim 10^{-5}$ eV, axions with inverse coupling mass scale $M \sim$ 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) $\omega^2 + \partial_z^2 \rightarrow 2 \omega (\omega - i \partial_z)$, so that the field equations become Schrödinger-like,

$$i \partial_z \Psi = - (\omega + \mathcal{M}) \Psi; \quad \Psi = \left( \begin{array}{c} A_x \\ A_y \end{array} \right), \quad (1)$$

where

$$\mathcal{M} \equiv \left( \begin{array}{ccc} \Delta_p + \Delta_{Q,\parallel} & 0 & \Delta_{Mx} \\ 0 & \Delta_p + \Delta_{Q,\perp} & \Delta_{My} \\ \Delta_{Mx} & \Delta_{My} & \Delta_m \end{array} \right).$$

The mixing is determined by the refraction parameter $\Delta_p$, the axion-mass parameter $\Delta_m$, the mixing parameter $\Delta_M$ and the QED dispersion parameter $\Delta_{Q,\perp}$. The first three parameters are equal to

$$\Delta_M = \frac{B_i}{2M} = 153 \left( \frac{B_i}{1 \text{ G}} \right) \left( \frac{10^{10} \text{ GeV}}{M} \right) \text{pc}^{-1},$$

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

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

respectively. Here $\omega^2 = 4 \pi \alpha n_e / m_e$ 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, $M$ is the electron mass, $\alpha$ is the fine-structure constant and $\omega$ is the photon (axion) energy.

The QED dispersion parameter is

$$\Delta_{Q,\parallel} = \frac{m^2}{2 \omega},$$

where $m^2_{\parallel}$ 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 Ref. [17] (see also Ref. [18] for a similar but less explicit result),

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

where

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

and

$$\kappa = \frac{1}{m^3} \sqrt{\left( e F_{\mu \nu} l_{\nu} \right)^2} = \frac{\omega}{m_e} \frac{B_i}{B_{cr}} \approx 0.44 \left( \frac{\omega}{10^{19} \text{ eV}} \right) \left( \frac{B_i}{1 \text{ G}} \right) \quad (3)$$

$F_{\mu \nu}$ is the electromagnetic stress tensor, $l_{\nu}$ is the photon 4-momentum, $B_i$ is the component of the magnetic field perpendicular to the photon propagation and $B_{cr} = m^2_e / e \approx 4.4 \times 10^{13}$ G;

$$f(z) = i \int_0^\infty dt e^{-i (zt + t^3/3)}$$
Ref. [17] does not work.

Mass are of the same order and the approximation of

Note that at \( \alpha \kappa \), the opposite asymptotics is

which is often quoted, Eq. (2) may be approximated as

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 Ref. [17]. In the region \( \kappa \ll 1 \), which is often quoted, Eq. (2) may be approximated as follows,

\[
m_{\gamma,\parallel}^2 \approx \alpha m_e^2 \left( -\frac{11}{90\pi} \kappa^2 - i \sqrt{\frac{3}{2}} \frac{1}{16} \kappa e^{-8/3} \right), \tag{4}\]

\( \kappa \ll 1 \).

The opposite asymptotics is

\[
m_{\gamma,\perp}^2 \approx \alpha m_e^2 \frac{5}{28\pi^2} \sqrt{3} \Gamma^4(2/3)(1-i\sqrt{3})(3\kappa)^{2/3}, \tag{5}\]

\[ 1 \ll \kappa \ll \alpha^{-3/2}. \]

Note that at \( \alpha \kappa^{2/3} \gtrsim 1 \), the photon mass and electron mass are of the same order and the approximation of Ref. [17] does not work.

We arrive to the expression

\[
\Delta Q_{\parallel,\perp} = 1.49 \times 10^{13} \text{ pc}^{-1} \left( \frac{\omega}{10^{19} \text{ eV}} \right)^{-1} F_{\parallel,\perp}(\kappa),
\]

where

\[
F_{\parallel,\perp}(\kappa) = \frac{m_{\gamma,\parallel,\perp}(\kappa)}{\alpha m_e^2}.
\]

is a function of \( \kappa \) plotted in Fig. 1.

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

\[
P = \frac{4\Delta^2_{\parallel}}{(\Delta_p + \Delta_{Q,\perp} - \Delta_m)^2 + 4\Delta^2_M} \sin^2 \left( \frac{1}{2} L \Delta_{\text{osc}} \right),
\]

where

\[
\Delta^2_{\text{osc}} = (\Delta_p + \Delta_{Q,\perp} - \Delta_m)^2 + 4\Delta^2_M
\]

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

\[
4\Delta^2_M \gg (\Delta_p + \Delta_{Q,\perp} - \Delta_m)^2.
\tag{6}\]

In an earlier version of this paper, we neglected the contribution of \( \Delta_Q \) 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 Ref. [19], using Eq. 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

\[
F_{\perp}(\kappa) \ll 2.33 \times 10^{-11} \kappa \left( \frac{M}{10^{10} \text{ GeV}} \right)^{-1}.
\tag{7}\]

In Ref. [19], the small-\( \kappa \) expansion, Eq. (4), was used, which results in the condition

\[
\kappa \ll 3.31 \times 10^{-9} \left( \frac{M}{10^{10} \text{ GeV}} \right)^{-1},
\tag{8}\]

or equivalently

\[
\left( \frac{B}{G} \right) \left( \frac{\omega}{10^{19} \text{ eV}} \right) \ll 1.07 \times 10^{-9} \left( \frac{M}{10^{10} \text{ GeV}} \right)^{-1}.
\]

An alternative approach is to make use of the change of sign of \( F_{\perp}(\kappa) \) which was suggested in Ref. [20]. Neglecting the possibility of precise cancellations (to many decimal points) between \( \Delta_m \) and \( \Delta_Q \), 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 \( \Delta_M \) 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 \( \omega = 10^{19} \text{ eV} \), this regime corresponds to fields of 10^{14} 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).
FIG. 2. Typical values of the magnetic field \( B \) and electron density \( n_e \) in various astrophysical objects (IG: intergalactic space, MW: the Milky Way, NLR and BLR: narrow- and broad-line 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).

Other maximal-mixing conditions, which also must be met, are
\[
\Delta_m \ll 2\Delta_M ,
\]
and
\[
\Delta_p \ll 2\Delta_M ,
\]
which are equivalent to
\[
\omega \gg 255 \text{ eV} \left( \frac{m}{10^{-9} \text{ eV}} \right)^2 \left( \frac{B}{\text{G}} \right)^{-1} \left( \frac{M}{10^{10} \text{ GeV}} \right), \quad (9)
\]
\[
n_e \ll 2.8 \times 10^{19} \text{ cm}^{-3} \left( \frac{\omega}{10^{19} \text{ eV}} \right) \left( \frac{B}{\text{G}} \right) \left( \frac{M}{10^{10} \text{ GeV}} \right)^{-1} . \quad (10)
\]
In addition, to have large mixing one should require that the size \( L \) of the region in which conditions (8), (9), (10) are fulfilled should exceed the oscillation length,
\[
L \gtrsim \frac{\pi}{\Delta_{osc}} ,
\]
that is
\[
L \gtrsim 0.01 \text{ pc} \left( \frac{B}{\text{G}} \right)^{-1} \left( \frac{M}{10^{10} \text{ GeV}} \right) . \quad (11)
\]

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 \( \sim 10 \) 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 can be superimposed on the Hillas plot for various astrophysical sources (Fig. 4). We see that if an axion like 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 \( F_\gamma \) independently of the gamma-ray emission mechanism (for the maximal mixing, fluxes of axions and of photons of each polarisation 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 esti-
mated 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°. 

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° [25].

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 [26].

An independent test of the cosmic ray – BL Lac correlation is underway [31] 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 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 [28].

Even beyond the Standard model it is difficult to find a non-contradictory explanation of the observed correla-
From Fig. 3, it
cles (neutron or
\[ \pi \]
Lorentz-invariance violation \[37\] decaying neutral parti-
plain the shower development. Only in the models with
fer the same problem.
gamma radiation.
ning radiation in conflict with constraints on diffuse cosmic
particles that there should be huge fluxes of accompany-
low and therefore one would expect for each one of these
should be heavy enough not to be detected in accelera-
tions. New stable strongly interacting particles \[33, 34\]
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 accompan-
ying radiation in conflict with constraints on diffuse cosmic
gamma radiation.

Models which suggest the existence of a relatively
heavy (\sim\text{MeV}) axion like particle (sgoldstino) \[32\]
suffer the same problem.

In the models where there is an enhanced neutrino-
air cross section (see e.g. \[35\]), besides some theoretical
difficulties, the cross section rise is not sufficient to ex-
plain the shower development. Only in the models with
Lorentz-invariance violation \[37\] decaying neutral parti-
cles (neutron or \(\pi^0\) 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 \[6, 9, 10, 11\] are satisfied (cf. Figs. \[2, 3, 4\]) 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 inter-
galactic magnetic field (IGMF) at scales \(\sim\text{Mpc}\) which at
present is poorly known.

Case 1: \(m \sim 10^{-7}\) eV, weak IGMF. From Fig. \[3\], it
is clear that conditions \[9, 10\] leave a window of \(\sim\)
\(10^{-13}\) 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 satis-
fied. 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 Ref. \[38\],
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 \((E \gtrsim 10^{20}\text{ eV})\) energies in
the sources (according to Ref. \[21\], acceleration of pro-
tons 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 located
in, or near, a “filament”, then intensive mixing there con-
verts 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 ax-
ion part propagates unattenuated. Then, upon arrival at

![FIG. 5. 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 neu-
trons and red (shown for comparison) to protons. The lines for protons and photons are taken from the review \[32\].](image-url)
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 \( \omega \sim 10^{12} \text{ eV} \) either; nor mixing is possible in the “filaments” for these energies. However, the scenario of Ref. [11] (mixing in the source and in the Milky Way) works for TeV photons.

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

Case 3: \( m \sim 10^{-5} \text{ eV}, \) In this case, the conditions [8] and [9] leave a very narrow stripe on the \( \omega - B \) parameter plane, Fig. 3. For UHE photons, this strip allows for the conversion at \( B \sim 10^{-9} \text{ G}, \) 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: \( m \lesssim 10^{-9} \text{ eV, strong IGMF.} \) This is a realization of the scenario of Refs. [3, 10] of conversion at IGMF, working for both \( \omega \sim 10^{12} \text{ eV} \) and \( \omega \sim 10^{19} \text{ eV}. \) 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. Ref. [39] for a review) constrain the magnetic fields at \( \gtrsim \text{Mpc} \) scale to be in the range \( (10^{-16} \ldots 10^{-9}) \text{ G}, \) the lower bound [42] coming from non-observation of GeV emission from certain TeV sources [30] while the upper one coming from the CMB polarization [41] and Faraday rotation measurements [12]. The simulations of Ref. [38] favour very low \( (\sim 10^{-15} \text{ G}) \) 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, \( \sim 10^{-9} \text{ G} \) 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 [43] but these are model-dependent. The CMB measurements by the Planck satellite, currently in flight, will test the IGMF in the range \( (\sim 10^{-11} \ldots 10^{-9}) \text{ G}, \) crucial for the choice of the axion conversion scenario.

In the case of conversion in voids, that is of strong \((\sim 10^{-9} \text{ G}) \) IGMF, one cannot use directly the oscillation formalism outlined above for UHE gamma rays and axions because the attenuation length of \( \omega \sim 10^{19} \text{ eV} \) photons on the radio background radiation is \( l \sim 3 \text{ Mpc,} \) cf. Fig. 5 (the precise value of \( l \) is sensitive to the poorly known intergalactic radio background). Within our pre-

The condition of the scenario of Refs. [9, 10] of conversion at IGMF is not possible for \( \omega \sim 10^{-9} \text{ G}, \) crucial for the choice of the axion IGMF-conversion scenario reads as

\[
J_{\text{IG}} E_0 \sim \left( \frac{D}{l} \right)^2 0.03 J_{\text{CR}} \frac{E^2}{E_0} \sim 10^{-6} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}.
\]

(12)

This is of the same order as the diffuse GeV flux observed by Fermi [46]. Given all uncertainties in our estimate, as well as in the observational value [46,48] 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 \( 4\pi \text{ sr} \). The number of sources \( N_s \) may be estimated from the statistics of clustering [49] as \( N_s \sim 60 \). In this case, the value of the single-source flux,

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

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 \(2/9\) of the emitted one. The flux of a single source is then

\[
J_{\text{IG}} \sim \frac{4\pi \text{ sr}}{N_s} \frac{2}{9} 0.03 J_{\text{CR}} \frac{E^2}{E_0} \sim 10^{-9} \text{cm}^{-2} \text{s}^{-1},
\]

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
For each BL Lac with coordinates (we use the method recently becoming popular in tests of distribution was isotropic). To quantify these suspicions, to turn up in the most densely shaded region if the dis-expected random distribution (they would be more likely One sees that they do not appear to follow exactly the events are plotted, together with the exposure, in Fig. 6. The correlated sample of 156 BL Lacs studied in [12, 13]. The 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 [56–58]. 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? 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 non-uniformity 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).

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 [27]: the photon energies are underestimated [29] by this detector by a factor of four on average [30], 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 axion-like particle with mass \(m \lesssim 10^{-5}\) eV and the inverse coupling to photon close to the current experimental limits, \(M \sim (1/10) \times 10^{10}\) 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 [50–58].

To summarize, the existence of an axion-like 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 par-
ticles 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 is 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 axion-like particle would also help explain some other astrophysical conundrums such as the white dwarf luminosity function [59].

Finally it is appropriate to re-iterate 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 [10] 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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