

Gamma ray astrophysics, the extragalactic background light, and new physics

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Very high energy gamma-rays are expected to be absorbed by the extragalactic background light over cosmological distances via the process of electron-positron pair production. However, recent observations of cosmologically distant emitters by ground based gamma-ray telescopes might be indicative of a higher-than-expected degree of transparency of the universe. One mechanism to explain this observation is the oscillation between photons and axion-like-particles (ALPs). Here we explore this possibility, focusing on photon-ALP conversion in the magnetic fields in and around gamma-ray sources and in the magnetic field of the Milky Way, where some fraction of the ALP flux is converted back into photons. We show that this mechanism can be efficient in allowed regions of the ALP parameter space, as well as in typical configurations of the Galactic Magnetic Field. As case example, we consider the spectrum observed from a HESS source. We also discuss features of this scenario which could be used to distinguish it from standard or other exotic models.

Keywords: gamma-ray sources; background radiations; axions.

I. INTRODUCTION

Every time a new “messenger” (different photon wavelengths or a different particle) has added to the list of observables accessible to astrophysicists, the Universe has appeared under a new light: it has revealed surprising features and triggered new questions, ultimately changing our understanding of fundamental physics and cosmology. Examples include the new elementary particles discovered in cosmic rays in the ‘30s and ‘40s, flavor oscillations from the solar and atmospheric neutrinos, or the revolutions brought by radio or X-ray astronomy. Recently, a new branch of astronomy is born: high energy (HE, $E \gtrsim 1$ GeV) and very high energy (VHE, $E \gtrsim 0.1$ TeV) gamma-ray astronomy. This field has undergone an impressive boost over the last two decades, both from space and from ground. The best example of the former has been the science delivered by the EGRET detector on board of the Compton Gamma Ray Observatory [1]. On the other hand, ground-based astronomy has mostly benefit from the maturation of Atmospheric Cherenkov telescopes (ACTs). This trend is continuing nowadays, with the GLAST [2] satellite in orbit and finally collecting data, and the existing generation of ACTs, HESS [3], MAGIC [4], VERITAS [5] and CANGAROO-III [6].

As an illustration of an unexpected feature recently realized, which may have implications for both astrophysics and particle physics, we discuss here the apparent “higher transparency” of the Universe to VHE photons. VHE are expected to be attenuated over cosmological distances by infrared, optical and ultraviolet photons of the extragalactic background light (EBL) via the process of pair production ($\gamma_{\text{VHE}} + \gamma_{\text{EBL}} \rightarrow e^+e^-$). This mechanism should strongly suppress the VHE spectra from distant sources and opens the possibility of measuring the spectrum and density of the EBL via gamma-ray ob-

servations [7]. Recent findings by imaging ACTs, however, raise the possibility that the universe might be more transparent to gamma-rays than previously thought [8–10]. Taken at face value, the data seem to require a lower density of the EBL than expected and/or considerably harder injection spectra than initially thought [11, 12]. On the other hand, it is also possible that some exotic mechanism is responsible for the observed lack of attenuation. To prove the viability of an exotic process, here we propose the following three-step mechanism [38]: i) Given the typical sizes and magnetic field strengths present in astrophysical accelerators, significant photon to ALP conversion can occur in or near the VHE gamma-ray sources over a large range of allowed ALP parameter space. In the limit of complete “depolarization” of the photon-ALP system, one expects 1/3 of the original photons to be converted into ALPs at the source above a critical energy $\mathcal{E} \equiv m_a^2/(2g_{a\gamma}B)$, where m_a is the ALP mass, $g_{a\gamma}$ is the ALP-photon coupling and B the field strength. The energy \mathcal{E} naturally falls in the gamma-ray band [15, 16]. ii) At relatively low-energies, the un-oscillated photons arrive to Earth and dominate the detected flux, consistently with standard observations. At high energies these un-oscillated photons are absorbed by the EBL, as in the standard picture. iii) The ALP flux, subdominant at low energies, produces observable VHE photons in ACTs via a back-conversion in the Galactic Magnetic Field. A “plateau” of up to $\sim 10\%$ of the original flux is potentially achievable this way. Since these photons only have to travel a few kpc, they do not get absorbed, thus potentially explaining the observed high-energy emission from cosmologically distant gamma-ray sources. As an illustration, the spectrum resulting from this process is represented in Fig.1 for a source with an injected spectrum of $dN/dE \propto E^{-2}$, after propagating from a redshift $z = 0.2$. The result without the effect of photon-ALP oscillations is also shown. The ALP-photon mixing mitigates the impact of absorption via pair production and leads to a plateau in the spectrum at high energies. We have calculated the effects of ALP-photon

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mixing assuming a source conversion probability of 0.3 and a Milky Way reconversion probability of 0.1.

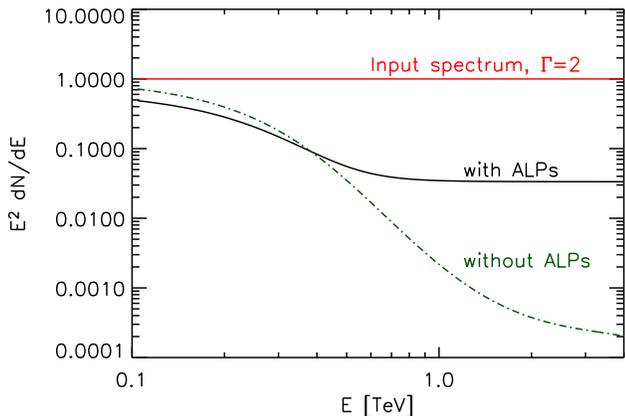


FIG. 1: The gamma-ray spectrum from a source with an injected spectral index $\Gamma = 2$, after propagation from a redshift of $z = 0.2$, assuming a source conversion probability of 0.3 and a Milky Way reconversion probability of 0.1. The result in absence of photon-ALP oscillations is also shown. The vertical axis is in arbitrary units.

In the following, we discuss this mechanism in further details, as well as explore its viability. The motivations for ALPs and the formalism relevant to the present model is discussed in Sec. II, together with phenomenological reasons to substantiate the relevance of astrophysical accelerators as potential sources of an ALP flux. In Sec. III we briefly describe the treatment of photon absorption onto the EBL during the propagation from their sources to the Milky Way. In Sec. IV the reconversion of ALPs in the Galactic Magnetic Field is analyzed. In Sec. V, in order to illustrate the impact of such mechanism in a realistic scenario, we present the reconstructed spectrum for a source detected by HESS, H 2356-309 at $z = 0.165$. In Sec. VI we discuss and summarize our results, focusing on the distinctive observational features of the scenario outlined here, including the synergies between terrestrial and space observations.

II. PHOTON-ALP CONVERSION IN GAMMA RAY SOURCES

The Peccei-Quinn (PQ) mechanism [17] remains perhaps the most compelling explanation of the CP problem of QCD. A new chiral $U_{\text{PQ}}(1)$ symmetry that is spontaneously broken at some large energy scale, f_a , would allow for the dynamical restoration of the CP symmetry in strong interactions. An inevitable consequence of this mechanism is the existence of axions, the Nambu-Goldstone bosons of $U(1)_{\text{PQ}}$ [18]. One of the most important phenomenological properties of the hypothetical axion is its two-photon vertex which allows for axion-

photon conversions in the presence of external electric or magnetic fields [19] through an interaction term

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

where a is the axion field, F is the electromagnetic field-strength tensor, \tilde{F} its dual, \mathbf{E} the electric field, and \mathbf{B} the magnetic field. The axion-photon coupling strength is quantified by

$$g_{a\gamma} = \xi \frac{\alpha}{2\pi} \frac{1}{f_a}, \quad (2)$$

where α is the fine-structure constant and ξ is a parameter of $\mathcal{O}(1)$ depending on the details of the electromagnetic and color anomalies of the axial current associated with the axion field. In particular, this coupling is used by the ADMX experiment to search for axion dark matter [20] and by the CAST experiment to search for solar axions [21, 22]. The Peccei-Quinn axion has the important feature that its mass m_a and interaction strength are inversely related to each other and are connected to the measured properties of pions. One may, however, conceive of a more general class of particles whose coupling and mass are unrelated to each other. Such states are known as axion-like particles (ALPs). ALPs may manifest themselves in the propagation of photons in magnetic fields, either in laboratory or astrophysical environments, and may have interesting astrophysical and cosmological consequences [23].

In particular, as a consequence of the interaction of Eq. (1), ALPs and photons oscillate into each other in the presence of an external magnetic field. For a photon of energy E , the probability of converting into an ALP can be written [24]

$$P_{\text{osc}} = \sin^2(2\theta) \sin^2 \left[\frac{g_{a\gamma} B s}{2} \sqrt{1 + \left(\frac{\mathcal{E}}{E} \right)^2} \right], \quad (3)$$

where s is the size of the domain and B is the magnetic field component along the polarization vector of the photon, which is assumed to be approximately constant within that domain. We have also defined an effective mixing angle θ and characteristic energy \mathcal{E} via

$$\sin^2(2\theta) = \frac{1}{1 + (\mathcal{E}/E)^2}, \quad \mathcal{E} \equiv \frac{m^2}{2g_{a\gamma} B}, \quad (4)$$

where the effective ALP mass squared is $m^2 \equiv |m_a^2 - \omega_{\text{pl}}^2|$, $\omega_{\text{pl}} = \sqrt{4\pi\alpha n_e/m_e}$ is the plasma frequency, m_e the electron mass, and n_e the electron density. For the following considerations, it is useful to introduce the dimensionless quantities: $g_{11} = g_{a\gamma}/10^{-11} \text{ GeV}^{-1}$, $B_G \equiv B/\text{Gauss}$, $s_{\text{pc}} \equiv s/\text{parsec}$, $m_{\mu\text{eV}} \equiv m/\mu\text{eV}$, $\mathcal{E}_{\text{GeV}} \equiv \mathcal{E}/\text{GeV}$. Recent results from the CAST experiment [22] provide a direct bound on the ALP-photon coupling of $g_{11} \lesssim 8.8$ for $m_a \lesssim 0.02 \text{ eV}$, nominally below the long-standing globular cluster limit [23]. Note that

$$\omega_{\text{pl}} = 0.37 \times 10^{-4} \mu\text{eV} \sqrt{n_e/\text{cm}^{-3}}, \quad (5)$$

which means that in the interstellar medium (ISM) of the Milky Way, where $n_e \sim 0.1 \text{ cm}^{-3}$, the effective mass of the ALP will not be smaller than $m_{\mu\text{eV}} \sim 10^{-5}$, independently of how small m_a is. For ultra-light ALPs ($m_a \lesssim 10^{-11} \text{ eV}$), the absence of gamma rays from SN 1987A yields a stringent limit of $g_{11} \lesssim 1$ [25] or even $g_{11} \lesssim 0.3$ [26]. But for $10^{-11} \text{ eV} \ll m_a \ll 10^{-2} \text{ eV}$, the CAST bound is the most general and stringent (bounds from ADMX, although stronger for some masses, assume that the axion is the Galactic dark matter).

From Eqs. (3,4) it follows that: (i) At energies below \mathcal{E} , the mixing is small and *a fortiori* the conversion probability is small. Above this critical energy, the mixing is large, and a significant conversion probability arises. In suitable units,

$$\mathcal{E}_{\text{GeV}} \equiv \frac{m_{\mu\text{eV}}^2}{0.4 g_{11} B_G}. \quad (6)$$

As we shall argue, when plugging in the previous formula typical astrophysical and ALP parameters, this critical energy naturally falls in the gamma ray energy range. Thus, the physics of light and weakly coupled ALPs naturally points to γ -rays as the most promising tool for discovery. (ii) A significant conversion into axions also requires that the argument of the oscillatory function in Eq. (3) is not too small, i.e.

$$g_{a\gamma} B s/2 \gtrsim 1, \quad \text{i.e. } 15 g_{11} B_G s_{\text{pc}} \gtrsim 1. \quad (7)$$

The condition in Eq. (7) depends on the product $B s$, which also determines the maximum energy E_{max} to which sources can confine and thus accelerate ultra-high energy cosmic rays (UHECRs). This is known as the Hillas criterion [27], and for protons it writes

$$E_{\text{max}} \simeq 9.3 \times 10^{20} \text{ eV } B_G s_{\text{pc}}. \quad (8)$$

This connection between cosmic ray acceleration and Eq. (7) is important. Since UHECRs with energies of a few times 10^{20} eV have been observed, environments where $B_G s_{\text{pc}} \gtrsim 0.3$ must exist in nature. This implies that couplings as small as $g_{11} \simeq 0.2$ might be probed, almost two orders of magnitude below present bounds.

III. PHOTON ABSORPTION ONTO THE EBL

To study the quantitative predictions of our model and make comparisons with the available data, we must also account for the standard dimming of the VHE photons from cosmologically distant sources. The spectra of distant VHE gamma-ray sources will be attenuated through electron-positron pair production. This attenuation takes the form $\exp(-\tau)$, where $\tau(E, z_0)$ is given by the equation:

$$\tau = \int_0^{z_0} \frac{dz}{(1+z)H(z)} \int d\omega \frac{dn}{d\omega}(\omega, z) \bar{\sigma}(E, \omega, z), \quad (9)$$

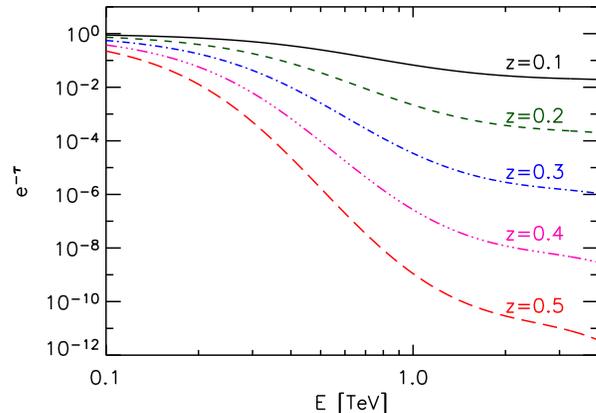


FIG. 2: Suppression of the gamma-ray spectrum due to pair production for sources at redshifts of $z = 0.1, 0.2, 0.3, 0.4,$ and 0.5 , from top to bottom.

where

$$\bar{\sigma}(E, \omega, z) \equiv \int_{-1}^{1-2/E\omega} \frac{1}{2} (1-\mu) \sigma_{\gamma\gamma}(E, \omega, \mu) d\mu. \quad (10)$$

Here, z_0 is the source redshift, $H(z)$ is the rate of Hubble expansion, E and ω are the (appropriately redshifted) source and background photon energies, respectively, μ is the cosine of the angle between the incoming and target photon, and $\sigma_{\gamma\gamma}$ is the cross section for electron-positron pair production [28].

The distribution of EBL photons in energy and redshift which we use, $dn/d\omega$, is based on the integrated galaxy light model of Ref. [29] and the data of Ref. [30]. We assume that the shape and normalization of the background radiation does not change except for redshifting between the source and the observer, which as suggested by the models of Ref. [31] is a reasonable assumption for $z < 0.4$. For the sources being considered here (see table I), we expect this to be a reasonable assumption. In Fig. 2, we plot the attenuation as a function of observed energy for sources at various redshifts. Note that it is not only the overall intensity of the source but the shape of the spectrum that is affected by this suppression.

IV. RECONVERSION IN THE MILKY WAY

In a given direction in Galactic coordinates, (b, l) , the unit vector, $\hat{\mathbf{s}}$, with components $\{\cos b \cos l, -\cos b \sin l, \sin b\}$ can be constructed. Through the usual orthogonalization procedure of Gram-Schmidt, $\hat{\mathbf{s}}$ can be completed into a \mathbb{R}^3 basis (along with, say, $\hat{\mathbf{a}}$ and $\hat{\mathbf{b}}$, two vectors orthogonal to $\hat{\mathbf{s}}$). One can thus decompose the magnetic field, $\mathbf{B}(\mathbf{x})$, into components $\{B_a, B_b, B_s\}$ in this basis and show that the probability of an ALP converting into a photon (of

any polarization) while traveling a distance s along $\hat{\mathbf{s}}$ is given by [32]:

$$P_{a \rightarrow \gamma}(s) = \frac{g_{a\gamma}^2}{4} \left(\left| \int_0^s ds' e^{i(\Delta_a - \Delta_{\text{pl}})s'} B_a(s') \right|^2 + \left| \int_0^s ds' e^{i(\Delta_a - \Delta_{\text{pl}})s'} B_b(s') \right|^2 \right) \quad (11)$$

This probability is a factor of 2 larger than $P_{\gamma \rightarrow a}(s)$ given in Ref. [32] due to the two photon states available for the ALP to convert into. In this expression, the quantities entering the phase factor are $\Delta_a = -m_a^2/2E$ and $\Delta_{\text{pl}} = \omega_{\text{pl}}^2/2E$. For the following considerations, it is useful to introduce $s_{\text{kpc}} \equiv s/\text{kpc}$, $m_{\text{neV}} \equiv m/\text{neV}$ and $E_{\text{TeV}} \equiv E/\text{TeV}$. In these illustrative units, the phases can be rewritten as:

$$\Delta_a s_{\text{kpc}} = -0.77 \times 10^{-4} m_{\text{neV}}^2 s_{\text{kpc}} E_{\text{TeV}}^{-1}, \quad (12)$$

$$\Delta_{\text{pl}} s_{\text{kpc}} = -1.11 \times 10^{-7} \left(\frac{n_e}{\text{cm}^{-3}} \right) s_{\text{kpc}} E_{\text{TeV}}^{-1}.$$

The integrals in Eq. (11) are very small unless the phases of the integrands vanish over typical Galactic sizes of ~ 10 kpc. Barring fine-tuning, we must require $|\Delta_i \times 10 \text{ kpc}| \ll 1$, leading to

$$m_{\text{neV}} \ll \sqrt{1.3 \times 10^3 E_{\text{TeV}}}, \quad (13)$$

$$n_e \ll 0.90 \times 10^6 \text{ cm}^{-3} E_{\text{TeV}}.$$

For the energies of interests for ACTs, the second condition is always satisfied in the Milky Way. The first condition only holds if $m_a \ll 10^{-7}$ eV. The optimal range of parameters for this mechanism is thus 10^{-10} eV $\lesssim m_a \lesssim 10^{-8}$ eV, over which couplings as large as $g_{11} \approx 8$ are consistent with present bounds.

The conversion probability also depends on the geometry of the Galactic Magnetic Field (GMF), which is not very well known, especially in the directions toward the Galactic Center and away from the Galactic Plane. In Fig. 3, we show isocontours in ALP-photon conversion probability in one particular model for the GMF, characterized by a regular disk field—following the spiral pattern of the Galaxy—which extends in the halo with the same symmetry pattern. Other models have been considered in [33], which we address for further details (see also [34]).

The isocontours of ALP-photon conversion probability shown in Fig. 3 were calculated using Eq. (11), for $g_{11} = 5$ and assuming that the conditions of Eq. (13) are satisfied. This means that the probability can be rescaled according to g_{11}^2 , as long as $P_{a \rightarrow \gamma} \ll 1$ (Eq. (11) indeed only holds at leading order in perturbation theory). In the limit of full mixing in the Galaxy, one would obtain a reconversion probability of 2/3.

For illustration, we also show in Fig. 3 the positions of known VHE gamma-ray sources at a redshift of 0.1 or greater, symbol-coded according to Table I. It is clear

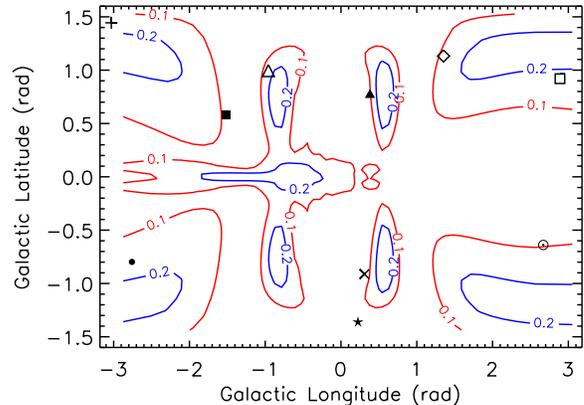


FIG. 3: The probability of ALP-photon conversion in one model of the Galactic Magnetic Field for $g_{11} = 5$ and assuming that the conditions of Eq. (13) are satisfied. Also shown are the locations of the known very high energy gamma-ray sources at redshift greater than 0.1, labeled according to the symbols found in table I.

that for $g_{11} = 5$ there are regions of the sky in which the reconversion probability can be 20% or even larger, and that a significant fraction of the sky corresponds to a probability larger than 10%. It is intriguing to notice that, in the simple GMF model considered, many of the VHE gamma-ray sources lie within or nearby these regions. We conclude that appreciable reconversion probabilities are possible, although difficult to predict given the scarcity of our knowledge regarding the structure of the GMF. In the remaining of this paper, we shall assume reconversion probabilities of ~ 0.1 and explore the resulting phenomenological consequences. Note that for $g_{11} \sim 5$, $m_a \sim 10^{-9}$ eV and microgauss-scale fields, the critical energy \mathcal{E} falls in the sub-GeV range, consistent with the implicit assumption that the mechanism is equally efficient over the whole range of energies accessible to ACTs ($E \gtrsim 100$ GeV).

V. RESULTS

At this point, we have all of the ingredients needed to compute the spectra of VHE gamma-ray sources, including ALP reconversion. We use this model to compute the source spectra of a HESS sources, H 2356-309 at $z = 0.165$, using the data given in Ref. [8]. Our results are shown as Fig. 4. The points shown with error bars represent the spectrum as measured by HESS, whereas the other points denote the source spectrum (before propagation) required in order to obtain the observed spectrum. From these figures, it is clear that an extremely hard injection spectrum is required, $\Gamma \approx 0.6$, to match the observed spectrum after propagation if one restricts oneself to the fiducial astrophysical models for the EBL. If the

Object	z	l	b	Symbol
3C279	0.536	305.10	57.06	\triangle
PG 1553+113	> 0.25	21.91	43.96	\blacktriangle
1ES1011+496	0.212	165.53	52.71	\square
1ES 0347-121	0.188	201.93	-45.71	\bullet
1ES1101-232	0.186	273.19	33.08	\blacksquare
1ES1218+304	0.182	186.36	82.73	$+$
H 2356-309	0.165	12.84	-78.04	\star
1ES 0229+200	0.140	152.94	-36.61	\odot
H 1426+428	0.129	77.49	64.90	\diamond
PKS 2155-304	0.117	17.73	-52.25	\times

TABLE I: A catalogue of known VHE gamma-ray sources at redshift greater than 0.1. The locations of these objects are also shown in Fig. 3. References can be found in [33].

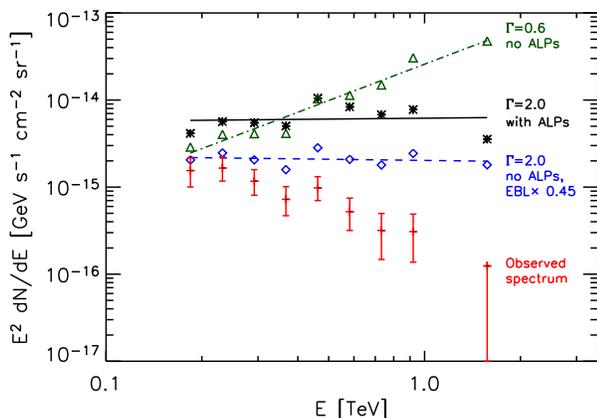


FIG. 4: The points shown with error bars represent the observed gamma-ray spectrum of H 2356-309, from the data of Ref. [8]. The other points shown denote the spectrum required to be injected at the source in order to generate the observations after accounting for the absorption by the EBL.

effects of ALP-photon oscillations are included, however, the required slope of the source spectrum is softened to a reasonable value: $\Gamma \approx 2.0$ in this example assuming $P_{a\gamma} = 0.1$ in our Galaxy. We also show the case in which the EBL is reduced to only 45% of its fiducial value. This is the scenario proposed by the HESS collaboration to explain the observed lack of attenuation.

With this exercise, we have shown that the effects of ALP-photon mixing in known magnetic fields enables one to fit the VHE data with a reasonable spectral index at the source ($\Gamma \approx 2$). This mechanism can accommodate the typical predictions for the EBL without need to modify the infrared to ultraviolet emission models from cosmic star formation, allowing spectra at the source that are certainly much easier to obtain in typical acceleration models. Also, this model has several distinctive phenomenological consequences, which we shall comment upon in the next section.

VI. DISCUSSION AND CONCLUSION

In recent years, imaging atmospheric Cherenkov telescopes have discovered many new TeV gamma-ray sources, some of which are cosmologically distant (see Table I). These sources provide us with a useful probe of the extragalactic background light. In particular, the spectra of very high energy gamma-ray sources at cosmological distances are expected to be attenuated by this background through the process of electron-positron pair production. Recent observations seem to indicate a far greater degree of transparency of the universe to very high energy gamma-rays than previously estimated [8–10].

In this article, we have discussed an exotic mechanism involving photon-ALP mixing to account for the observed phenomenology. Apart for the existence of the light ALP, it requires only known magnetic fields: namely the fields in or near the gamma-ray sources which are needed to confine and accelerate particles (which in turn are necessary to produce gamma-rays), and the Galactic Magnetic Field of the Milky Way. We have shown that this mechanism can be efficient for an ALP mass in the range $10^{-10} \text{ eV} \lesssim m_a \lesssim 10^{-8} \text{ eV}$ and couplings of $g_{11} \sim 4$. A precise prediction of the modification expected for a given source is precluded by our current ignorance regarding the detailed structure of the large scale magnetic field of the Milky Way. A very robust prediction of this model, however, (which is very different from both the standard expectation and the model proposed in Ref. [13]) is that the degree of dimming observed is expected to be dependent on the galactic coordinates $\{l, b\}$. Thus, the most striking signature would be a reconstructed EBL density which appears to vary over different directions of the sky: consistent with standard expectations in some regions, but inconsistent in others. Also, if e.g. an intrinsic power-law extends from GeV energies accessible to GLAST to VHE probed by ACTs, the same power law index should fit both ranges, but for a broken normalization (smaller for the VHE data, compared to low-energy extrapolations). The possibility that either GLAST or ACTs can detect the transition region which has a peculiar spectral shape also exists.

The absorption of gamma-rays via pair production does not affect only point-like source emission, but also the diffuse (or unresolved) spectrum (see e.g. Ref. [35]). Thus another signature of this mechanism might be an anomalous and direction-dependent spectral behavior of diffuse radiation. This will be challenging to detect with present atmospheric Cherenkov telescopes, however, as they are not well suited for the study of diffuse radiation over large fields-of-view. In contrast, the satellite-based experiment GLAST will observe the entire sky, although with much smaller exposures than are possible with ground based gamma-ray telescopes. Provided that the characteristic energy for the onset of the ALP-photon conversion mechanism naturally falls in the energy range to be explored by GLAST, the study of the diffuse radi-

ation offers an independent test of the crucial ingredient of this model, namely the role of the GMF. Through the conversion of photons into ALPs in the GMF, a peculiar, direction-dependent depletion of photons should arise in the Galaxy (at up to the 30% level). The anisotropies in the diffuse emission should anti-correlate with the regions of stronger fields as detected, for example, in Faraday rotation maps. Put another way, a peculiar dimming of the diffuse radiation in the 1-100 GeV range may be detected from the same regions where stronger than expected TeV sources are present.

A detailed test of such a scenario will become increasingly possible as a more complete picture of the high energy gamma-ray sky is developed. Since existing ACTs have a very small field of view, surveys of large fractions of the sky are unfeasible. A targeted survey may be possible, however, as new sources in the GeV range are discov-

ered by GLAST. Ultimately, next generation gamma-ray observatories, such as CTA [36] or AGIS [37], will enable considerably more detailed studies.

Should it be realized or not in Nature, we believe the mechanism described here provides yet another example of: a) the new opportunities for discovery made possible as a result of opening a new astronomical window; b) the synergic role played by ground-based observation and satellite based detectors of high energy gamma-ray.

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- [38] Another explanation invoking oscillations of photons into axion-like particles (ALPs) in extragalactic magnetic fields has been invoked in [13, 14].