Milky Way as a kiloparsec-scale axionscope

Melanie Simet

Department of Astronomy and Astrophysics, The University of Chicago, Chicago, Illinois 60637-1433, USA

Dan Hooper and Pasquale D. Serpico

Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500, USA

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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. Recent observations of cosmologically distant gamma-ray emitters by ground based gamma-ray telescopes have, however, revealed a surprising degree of transparency of the universe to very high energy photons. One possible mechanism to explain this observation is the oscillation between photons and axionlike particles (ALPs). Here we explore this possibility further, 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 examples, we consider the spectrum observed from two HESS sources: 1ES1101-232 at redshift $z = 0.186$ and H 2356-309 at $z = 0.165$. We also discuss features of this scenario which could be used to distinguish it from standard or other exotic models.

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I. INTRODUCTION

Very high energy (VHE, $E_\gamma \gtrsim 0.1$ TeV) gamma rays 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 ($\gamma_{\rm VHE} + \gamma_{\rm EBL} \to e^+e^-$). This mechanism is expected to strongly suppress the VHE spectra from distant sources and opens the possibility of measuring the spectrum and density of the EBL via gamma-ray observations [1]. Recent findings by imaging atmospheric Cherenkov telescopes, however, indicate a relatively large degree of transparency of the universe to gamma rays [2,3]. 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 [4,5]. On the other hand, it is also possible that some exotic mechanism is responsible for the observed lack of attenuation.

In Ref. [6], it was argued that the oscillations of photons into axionlike particles (ALPs) in extragalactic magnetic fields could provide a way of avoiding the exponential suppression of the gamma-ray spectrum resulting from pair production. This mechanism is especially effective for extremely distant sources and in the presence of relatively strong (nanogauss scale) extragalactic magnetic fields. While consistent with present bounds, there is no observational evidence for such strong fields, which appear hard to generate dynamically. For example, recent simulations based on magneto-hydrodynamic amplification of seed magnetic fields driven by structure formation predict fractions of extragalactic space containing nanogauss or stronger fields ranging from less than 0.1% [7] to 10% [8]. Also, recent results from the Pierre Auger Observatory appear to favor magnetic fields which are closer to the weaker estimates, with upper limits for Mpc coherence lengths in the 0.1–1 nG range in most of the sky [9,10]. In this respect, although photon-ALP oscillations in extragalactic magnetic fields may in principle be possible, it would require unsupported assumptions on the fields in order to act as an effective mechanism for avoiding the attenuation of VHE gamma-ray sources.

A somewhat different approach was taken in Refs. [11,12] where it was argued that the magnetic fields present in astrophysical accelerators themselves would lead to significant photon-ALP conversion over a large range of ALP parameter space, including a small region of the very interesting parameter space in which Peccei-Quinn axions provide a solution to the strong *CP* problem. This effect is expected to become significant at gamma-ray energies, including the range being explored by the ground based gamma-ray telescopes HESS [13], MAGIC [14], VERITAS [15], and CANGAROO-III [16], as well as of the forthcoming satellite mission, GLAST [17]. In this article, we explore the possibility of reducing the cosmological attenuation of VHE gamma-rays through a photon-ALP mixing mechanism, but invoking only known magnetic fields: those needed to confine and accelerate cosmic rays at the gamma-ray sources, where a significant ALP flux is produced via oscillations. To reconvert a fraction of the ALP flux back into photons, well after the primary photon flux has disappeared due to the absorption on the EBL, we rely only on the magnetic field of the Milky Way. This mechanism can lead to the appearance of a substantial flux of gamma rays (up to ~30% of the low-energy extrapolation) at energies where none are expected to be seen. It has also some other very peculiar observational predictions, which we will also discuss.

The remainder of this paper is structured as follows. In Sec. II we describe the mechanism proposed. In particular, we devote Sec. II A to the details of the reconversion of ALPs in the galactic magnetic field. In Sec. II B we describe how we treat the absorption of photons by the EBL during the propagation from their sources to the Milky Way. In Sec. II C, in order to illustrate the impact of such mechanism in a realistic scenario, we present the reconstructed spectrum for two HESS sources: 1ES1101-232 at redshift $z = 0.186$ and H2356-309 at $z = 0.165$. In Sec. III we discuss and summarize our results, focusing on the distinctive observational features of the scenario outlined here.

II. THE MECHANISM

As discussed in Refs. [11,12], 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. That is, for $E \gg \mathcal{E}$ there could potentially be an ALP flux from VHE gamma-ray sources as large as $\sim$50% of the residual gamma-ray flux exiting the source. The energy $\mathcal{E}$ naturally falls in the gamma-ray band. Although it is not crucial for the viability of the mechanism being discussed, we shall assume that $\mathcal{E} \ll 0.1$ TeV, thus insuring that the spectrum observed by ground based gamma-ray telescopes will not demonstrate peculiar spectral features resulting from the onset of photon-ALP oscillations. As we shall see below, this condition is naturally fulfilled over the most viable range of parameters for which the mechanism is efficient (see [11] for details). Thus, over the whole range of energy observed by atmospheric Cherenkov telescopes, the ALP flux generated at the source via oscillation follows exactly the same spectrum of the photons at the source.

This photon-ALP mix then propagates towards the Milky Way without further oscillations, since in absence of an external field the ALPs and the photons effectively decouple. During propagation over cosmological distances, the spectrum of photons is depleted via pair production. As a result, upon reaching the Milky Way, the flux will be dominated by ALPs, some of which can be converted back into photons by the galactic magnetic field. Since this step is crucial and it constitutes the more original part of the mechanism we propose, in Sec. II A we describe it in detail.

A. 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 [18]

$$P_{a\to\gamma}(s) = \frac{g_{a\gamma}^2}{4}\left(\left|\int_0^s ds' e^{i(\Delta_a - \Delta_{pl})s'} B_a(s')\right|^2 + \left|\int_0^s ds' e^{i(\Delta_a - \Delta_{pl})s'} B_b(s')\right|^2\right). \quad (1)$$

This probability is a factor of 2 larger than $P_{\gamma\to a}(s)$ given in Ref. [18] 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 $\Delta_{pl} = \omega_{pl}^2/2E$, where $\omega_{pl} = \sqrt{4\pi\alpha n_e/m_e}$ is the plasma frequency, E the photon energy, m_e the electron mass, n_e the electron density, and α the fine structure constant. For the following considerations, it is useful to introduce the following dimensionless quantities: $g_{11} = g_{a\gamma}/10^{-11}$ GeV^{-1}, $s_{kpc} \equiv s/\text{kpc}$, $m_{neV} \equiv m/\text{neV}$ and $E_{TeV} \equiv E/\text{TeV}$. Results from the CAST experiment [19] provide a direct bound on the ALP-photon coupling of $g_{11} \lesssim 8.8$ for $m_a \lesssim 0.02$ eV, nominally below the long-standing globular cluster limit [20]. For ultralight ALPs ($m_a \lesssim 10^{-11}$ eV), the absence of gamma rays from SN 1987A yields a stringent limit of $g_{11} \lesssim 1$ [21] or even $g_{11} \lesssim 0.3$ [22]. In the range 10^{-11} eV $\ll m_a \ll 10^{-2}$ eV, the CAST bound is the most general and stringent. For a range of μeV-scale masses, bounds from ADMX [23] are stronger, but rely on the assumption that axions constitute the galactic dark matter. In these illustrative units, the phases can be rewritten as

$$\Delta_a s_{kpc} = -0.77 \times 10^{-4} m_{neV}^2 s_{kpc} E_{TeV}^{-1},$$
$$\Delta_{pl} s_{kpc} = -1.11 \times 10^{-7}\left(\frac{n_e}{\text{cm}^{-3}}\right) s_{kpc} E_{TeV}^{-1}. \quad (2)$$

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

$$m_{neV} \ll \sqrt{1.3 \times 10^3 E_{TeV}},$$
$$n_e \ll 0.90 \times 10^6\ \text{cm}^{-3} E_{TeV}. \quad (3)$$

For the energies of interests for atmospheric Cherenkov telescopes, 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, which is not very well known, especially in the directions toward the galactic center and away from the galactic plane. In Fig. 1, we show isocontours in ALP-photon conversion probability for three different models of the galactic magnetic field (see Ref. [24]). Following the authors' initials, we label the models as PS (M. Prouza and R. Smida, Ref. [25]), TT (P. G. Tinyakov and I. I. Tkachev, Ref. [26]), and HMR (D. Harari, S. Mollerach, and E. Roulet, Ref. [27]). Physically, the PS model includes a dipolar field which produces a small component perpendicular to the galactic plane in the Solar neighborhood but is responsible for a strong field in the galactic bulge. The PS model also includes a toroidal halo field at kpc distances above and below the galactic plane. The HMR model does not include a dipolar field, but has a more prominent field in the halo characterized by the same symmetry pattern of the field in the disk. Finally, the TT model is the most conservative of the three, with a weaker intensity for the local coherent field and no prominent regular field in the galactic center or in the halo. Each of the models implement a thin disk field following the spiral pattern of the Galaxy, but the symmetry with respect to the galactic plane in the TT model is opposite to the one assumed in HMR and PS. Further details can be found in Ref. [24].

The isocontours of ALP-photon conversion probability shown in Fig. 1 were calculated using Eq. (1), for $g_{11} = 5$ and assuming that the conditions of Eq. (3) are satisfied. This means that the probability can be rescaled according to g_{11}^2, as long as $P_{a\to\gamma} \ll 1$ [Eq. (1) 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. 1 the positions of all currently known VHE gamma-ray sources at a redshift of 0.1 or greater, symbol-coded according to Table I. It is clear 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 HMR model, 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 galactic magnetic field. In the remaining of this paper, we shall assume reconversion probabilities of $\sim$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, consistently with the assumption put forth in Sec. II.

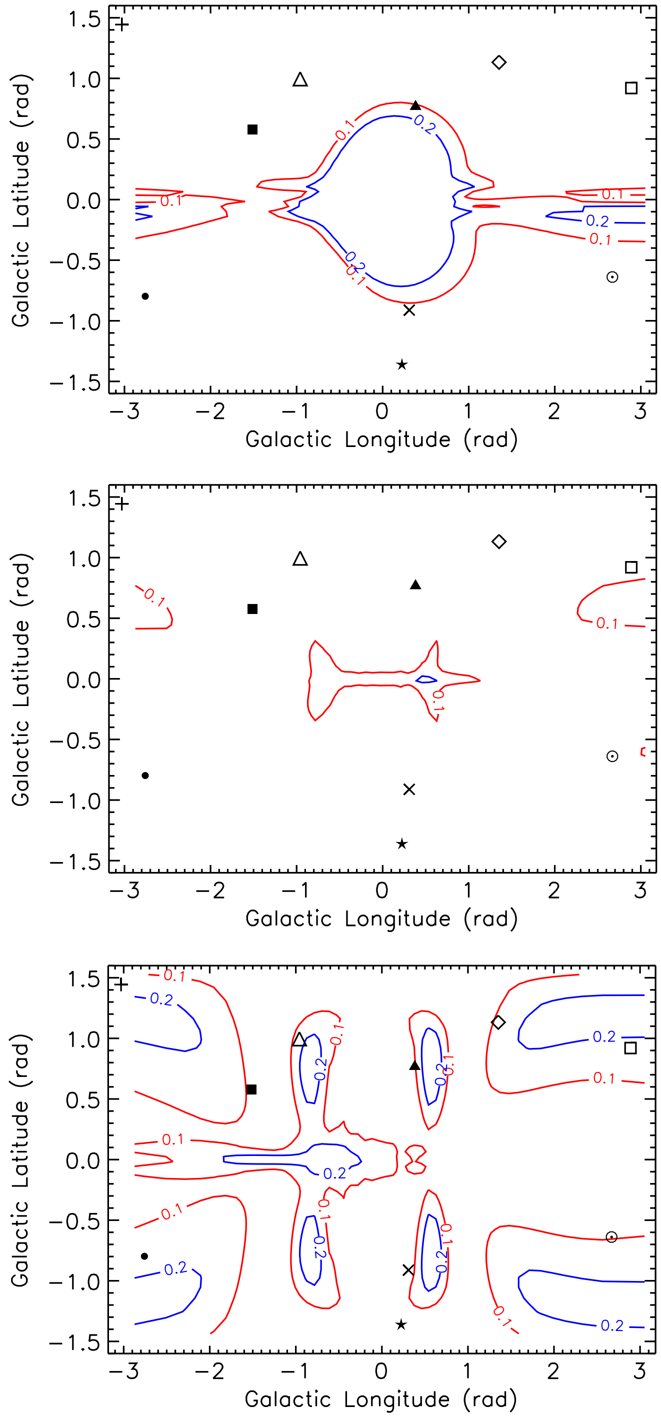

FIG. 1 (color online). The probability of ALP-photon conversion in three different models of the galactic magnetic field (PS, TT, HMR from top to bottom), for $g_{11} = 5$ and assuming that the conditions of Eq. (3) are satisfied. Also shown are the locations of the known very high energy gamma-ray sources at redshift greater than 0.1, labeled according to the symbols found in Table I.

TABLE I. The current catalog of known very high energy gamma-ray sources at redshift greater than 0.1. The locations of these objects are also shown in Fig. 1.

Object	z	l	b	Ref.	Symbol
3C279	0.536	305.10	57.06	[28]	△
PG 1553 + 113	>0.25	21.91	43.96	[29]	▲
1ES1011 + 496	0.212	165.53	52.71	[30]	□
1ES0347 − 121	0.188	201.93	−45.71	[31]	•
1ES1101-232	0.186	273.19	33.08	[32]	■
1ES1218 + 304	0.182	186.36	82.73	[33]	+
H 2356-309	0.165	12.84	−78.04	[34]	⋆
1ES0229 + 200	0.140	152.94	−36.61	[35]	⊙
H1426 + 428	0.129	77.49	64.90	[36]	◇
PKS2155-304	0.117	17.73	−52.25	[37]	×

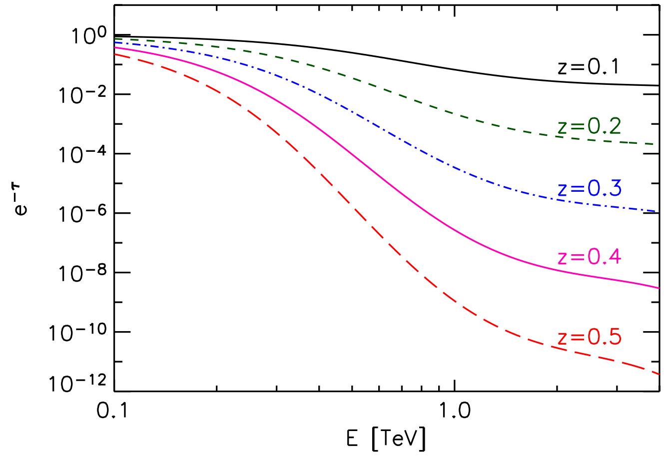

FIG. 2 (color online). Suppression of the gamma-ray spectrum due to pair production for sources at redshifts of $z = 0.1$, 0.2, 0.3, 0.4, and 0.5, from top to bottom.

B. 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:

$$\tau = \int_0^{z_0} \frac{dz}{(1+z)H(z)} \int d\omega \frac{dn}{d\omega}(\omega, z)\bar{\sigma}(E, \omega, z), \quad (4)$$

where

$$\bar{\sigma}(E, \omega, z) \equiv \int_{-1}^{1-2/E\omega} \frac{1}{2}(1-\mu)\sigma_{\gamma\gamma}(E, \omega, \mu)d\mu. \quad (5)$$

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 [38].

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. [39] and the data of Ref. [40]. 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. [41] 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.

C. Results

At this point, we have all of the ingredients needed to compute the spectra of VHE gamma-ray sources, including ALP reconversion. In Fig. 3, we show the results for a source spectrum of $dN/dE \propto E^{-\Gamma}$ with $\Gamma = 2$ after propagating from $z = 0.2$ (top) and $z = 0.5$ (bottom). For comparison, we also include the results for a standard scenario with no ALPs. Clearly, in the presence of ALP-photon mixing, the quasiexponential cutoff is interrupted, and a plateau in the spectrum appears at high energies.

We next use this model to compute the source spectra of two HESS sources, 1ES1101-232 at $z = 0.186$ and H 2356-309 at $z = 0.165$, using the data given in Ref. [2]. 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 extremely hard injection spectra are required ($\Gamma \approx 0.6$ and -0.2 for the two objects, respectively) to match the observed spectrum after propagation if one restricts oneself to the fiducial astrophysical models for the EBL. If the effects of ALP-photon oscillations are included, however, the required slope of the source spectrum is softened to a reasonable value for each source ($\Gamma \approx 2.0$ and 1.8, respectively, in this example, assuming $P_{a\gamma} = 0.1$ in our Galaxy). In each frame, 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 the 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.

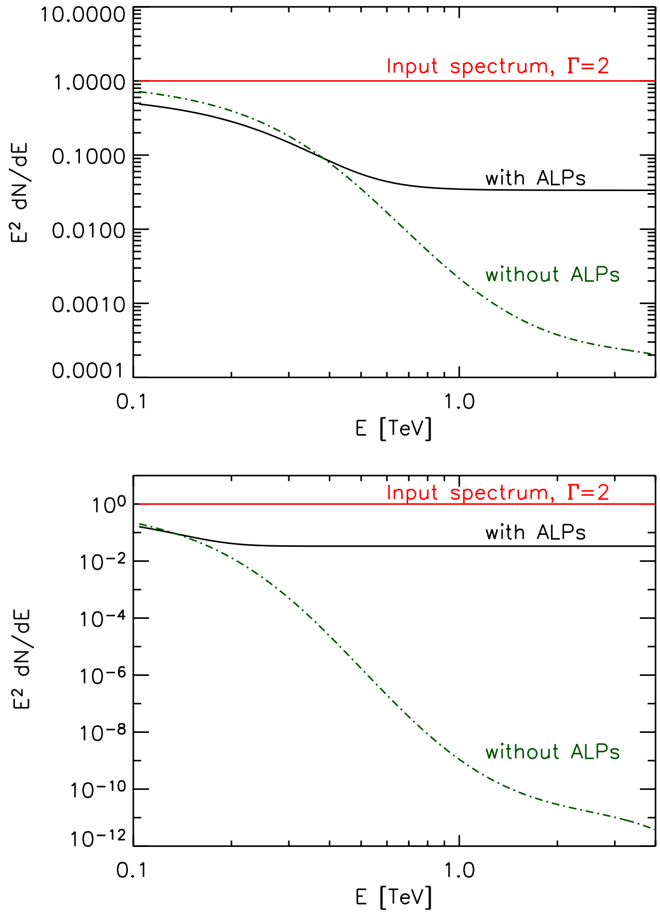

FIG. 3 (color online). The gamma-ray spectrum from a source with an injected spectrum of $dN/dE \propto E^{-2}$, after propagation over a distance of $z = 0.2$ (top) and $z = 0.5$ (bottom). Results are shown with and without the effect of photon-ALP oscillations. The ALP-photon mixing mitigates the impact of absorption via pair production and leads to a plateau in the spectrum at high energies. We have calculated the effects of ALP-photon mixing assuming a source conversion probability of 0.3 and a Milky Way reconversion probability of 0.1. The vertical axis is in arbitrary units.

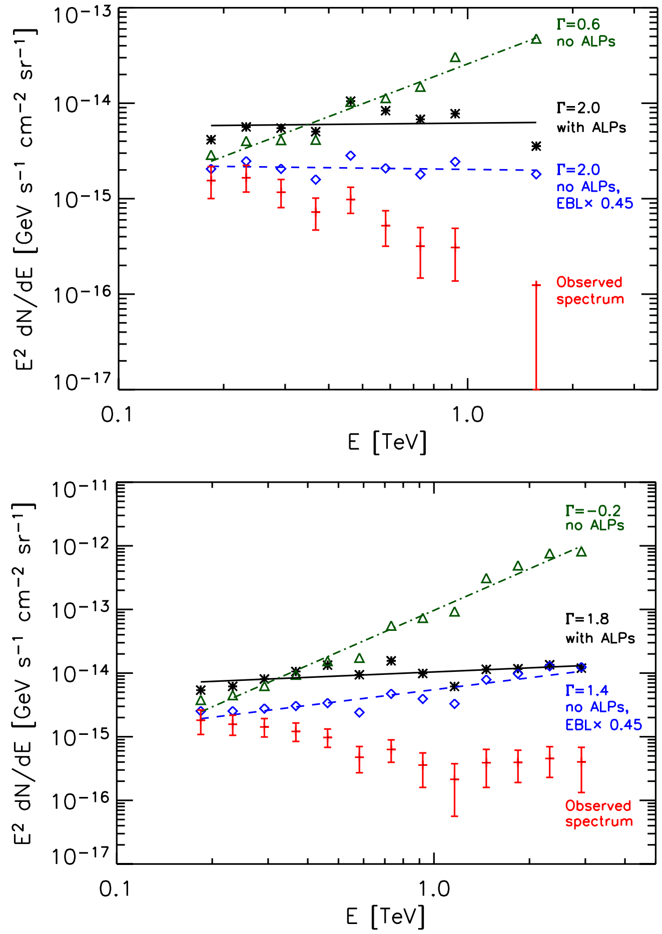

FIG. 4 (color online). The points shown with error bars represent the observed gamma-ray spectrum of H 2356-309 (top) and 1ES1101-232 (bottom), from the data of Ref. [2]. The other points shown denote the spectra required to be injected at the source in order to generate the observations after accounting for the absorption by the EBL. Using a conventional EBL spectrum and density, the reconstructed source spectra are required to be extremely hard ($dN/dE \propto E^{-0.6}$ and $dN/dE \propto E^{0.2}$). The mechanism of photon-ALP mixing, however, can soften the required spectral slope at injection to acceptable values. See text for more details.

III. 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 the infrared to ultraviolet range. 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 [2,3]. While astrophysical explanations of these observations have been discussed [4,5], it has also been proposed that this lack of suppression could be the result of photon mixing with axionlike particles (ALPs), with oscillations occurring in the presence of the magnetized intergalactic medium [6].

In this article, we have discussed an alternative mechanism involving photon-ALP mixing, but requiring 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} eV $\lesssim m_a \lesssim 10^{-8}$ 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. [6]) 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.

The absorption of gamma rays via pair production does not affect only pointlike source emission, but also the diffuse (or unresolved) spectrum (see e.g. Ref. [42]). 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 radiation offers an independent test of the crucial ingredient of this model, namely, the role of the galactic magnetic field.

Through the conversion of photons into ALPs in the galactic magnetic field, a peculiar, direction-dependent depletion of photons should arise in the Galaxy (at up to the 30% level). This idea was considered previously for a different range of the ALP parameter space, impacting the diffuse X-ray background [43]. The anisotropies in the diffuse emission should anticorrelate 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 atmospheric Cherenkov telescopes 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 discovered by GLAST. Ultimately, next generation gamma-ray observatories, such as CTA [44] or AGIS [45], will enable considerably more detailed studies.

The mechanism described here provides yet another example of the new opportunities for discovery made possible as a result of the recent progress in the field of high energy gamma-ray astrophysics.

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