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Photon-ALP conversion and celestial gamma-ray sources

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Propagating gamma-ray photons from Galactic and extragalactic sources can mix in the presence of magnetic fields with light pseudo-scalar particles that are predicted in many extension of standard model physics. Even though the magnetic fields in astrophysical environments are small compared to values achievable in the laboratory, the large distances compensate this to saturate the conversion probabilities even for couplings which are below the value probed in laboratory experiments. There are in principle, two different observational tests for the presence of new and light (typically with masses of neV or below) pseudo scalar particles possible: either the disappearance of propagating photons due to conversion of photons to pseudo-scalars or the appearance of photons converting and re-converting after propagating through an optically thick medium (e.g., gamma-ray sources at cosmological distance). In this contribution, the two observational tests are described and available observations summarized.

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1. Introduction

A well-studied high-energy extension of the standard model to solve the strong CP-problem is the introduction of the shift symmetric axion field a. The (suppressed) coupling of axions to the electromagnetic field is described by the Langrangian term

$$\mathscr{L}_{a\gamma\gamma} = -\frac{1}{4} g a F_{\mu\nu}\tilde{F}^{\mu\nu} = g a \vec{E}\cdot\vec{B}, \tag{1.1}$$

with a (suppressed but guaranteed) coupling to photons from the Primakoff process

$$g = \frac{\alpha}{2\pi f_a}\left(\frac{2}{3}\frac{m_u+4m_d}{m_u+m_d}\right) \approx 10^{-13}\ \mathrm{GeV}^{-1}\left(\frac{10^{10}\mathrm{GeV}}{f_a}\right). \tag{1.2}$$

A similar type of coupling as described by Eqn. 1.1 may arise in a generalization of the axion-type field, often referred to as axion-like particles (ALPs: see, e.g., the extensive and recent review [1]). Even though ALPs do not necessarily solve the strong CP-problem, they are often predicted in theories beyond the standard model and may even contribute to the dark matter budget present throughout a large fraction of the universe's life time [2]. In specific models, a mass hierarchy (one per decade of mass) of ALPs with similar coupling g may exist [3].

The coupling of ALPs to photons give naturally rise to a rich phenomenology that may be probed in laboratory experiments as well as in astrophysical observations. In this contribution, we focus on the opportunities to search for ALPs in gamma-ray spectra of Galactic and extra-galactic objects.

2. Propagation of gamma-rays in the presence of ALPs and magnetic fields

The theoretical description of gamma-rays propagating in the presence of ALPs and magnetic fields has been considered by a number of authors [4], a recent description of the problem and the solution with emphasis on propagating gamma-rays can be found in [5].
Since we are concerned with gamma-rays, we consider an unpolarized photon beam. The photons propagate along the line-of-sight $\vec{l}$ in the intervening medium which is characterized by a magnetic field $\vec{B}(\vec{l})$, a thermal background plasma with electron density $n_e(\vec{l})$, as well as an approximately isotropic (in the observer's frame) photon field with a number density $n_\gamma(\vec{l},\varepsilon)$ in the narrow energy interval from $\varepsilon \ldots \varepsilon + d\varepsilon$. For simplicity, we neglect now cosmological effects, a generalization is straight-forward.
The beam of unpolarized photons is described as a density matrix

$$\rho(\vec{l}) = \begin{pmatrix} A_1 \\ A_2 \\ a \end{pmatrix} \otimes (A_1 \;\; A_2 \;\; a), \tag{2.1}$$

with A_1, A_2 the polarization amplitudes perpendicular to the line-of-sight, and a the strength of the ALP field. An unpolarized beam is described by $A_1 = A_2$ and $a = 0$.

If we choose a coordinate system (x_1, x_2, x_3) with x_3 parallel to $\vec{l}$, the evolution of the density matrix is described by

$$i\frac{d\rho}{dx_3} = [\rho, \mathscr{M}_0], \tag{2.2}$$

with the mixing matrix $\mathcal{M}_0$:

$$\mathcal{M}_0 = \begin{pmatrix} \Delta_\perp & 0 & 0 \\ 0 & \Delta_{\shortparallel} & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_a \end{pmatrix}. \tag{2.3}$$

The matrix elements $\Delta_{\shortparallel} = \Delta_{\rm pl} + 7/2\ \Delta_{\rm QED}$ and $\Delta_\perp = \Delta_{\rm pl} + 2\ \Delta_{\rm QED}$ describe the effects of the background plasma $\Delta_{\rm pl} = -\omega_{\rm pl}/(2E)$ with $\omega_{\rm pl} = 3.69 \times 10^{-11} \sqrt{n_e/\mathrm{cm}^{-3}}$ eV and vacuum birefringence $\Delta_{\rm QED} \propto B_\perp^2$. Finally, the propagation of the ALPs and its mixing with the photon modes follows from $\Delta_a = -m_a^2/(2E)$ and $\Delta_{a\gamma} = 0.5\ g_{a\gamma} B_\perp$. Numerical values suitable for calculations are listed in [6].

The solution of Eqn. 2.2 at propagation distance x_3 is obtained for a homogeneous medium ($n_e(x_3) = const.$, $B_\perp(x_3) = const.$ by a transfer matrix $\mathcal{T}(x_3;E)$:

$$\rho(x_3) = \mathcal{T}(x_3)\rho(0)\mathcal{T}^\dagger(x_3). \tag{2.4}$$

When neglecting birefringence ($\Delta_{\rm QED} \to 0$), it can be shown that the mixing becomes energy independent and maximal above a critical energy:

$$E_{\rm crit} = E\frac{|\Delta_a - \Delta_{\rm pl}|}{2\Delta_{a\gamma}} \approx 2.5 \frac{|m_a^2 - \omega_{\rm pl}^2|}{1\ \mathrm{neV}} \left(\frac{g_{a\gamma}}{10^{-11}\ \mathrm{GeV}}\right)^{-1} \left(\frac{B_\perp}{1\ \mu\mathrm{G}}\right)^{-1}\ \mathrm{GeV}. \tag{2.5}$$

In the more typical case of an inhomogeneous medium, the solution is obtained for a sufficiently small distance over which the parameters are assumed to be constant. The transfer matrix for the beam propagating through multiple domains is the product of the respective transfer matrices. More elaborate solutions for turbulent magnetic field are given in [7].

The absorption of photons is treated by adding a complex component to $\Delta_\perp$ and $\Delta_{\shortparallel}$: $\Delta_{\perp,\shortparallel} \to \Delta_{\perp,\shortparallel} + i/(2\lambda_\gamma)$ with λ_γ the mean free path for photon pairproduction

$$\lambda_\gamma^{-1}(E) = \int d\varepsilon \int d\mu \frac{1-\mu}{2} n_\gamma \sigma_{pp}(\varepsilon, E, \mu), \tag{2.6}$$

with σ_{pp} the cross-section for pair-production. The photon density $n_\gamma(\varepsilon)$ is dominated by the primordial contribution of the cosmic-microwave background. However, the attenuation of gamma-rays in the energy range of 100 GeV to 10 TeV is the result of scattering on photons of shorter wavelength in the ultra-violet to mid infra-red. The origin of background light in this wave length range is closely related to the star-formation history of the universe (see, e.g., the review [8] for details). In turn, observations of attenuation-like features in gamma-ray spectra are sensitive to the level of the extra-galactic background light (EBL). Observations of the Fermi-LAT satellite have been searched to find the tell-tale attenuation in gamma-ray spectra, leading to a significant detection of absorption [9]. A similar type of analysis has been carried out with a different set of sources at higher energies [10].

3. Appearance channel: extra-galactic gamma-ray sources

The expected attenuation of gamma-ray sources is of relevance for almost all extra-galactic objects that have been detected at very-high energies (VHE: $E > 100$ GeV). In Fig. 1, a set of spectral measurements are indicated in the plane of energy and red shift. Isocontours of optical depth ($\tau = d/\lambda_\gamma$) are indicated for a specific model of n_γ, which represents a lower-limit on the expected EBL [11], tuned to match the lower-limits from galaxy counts.

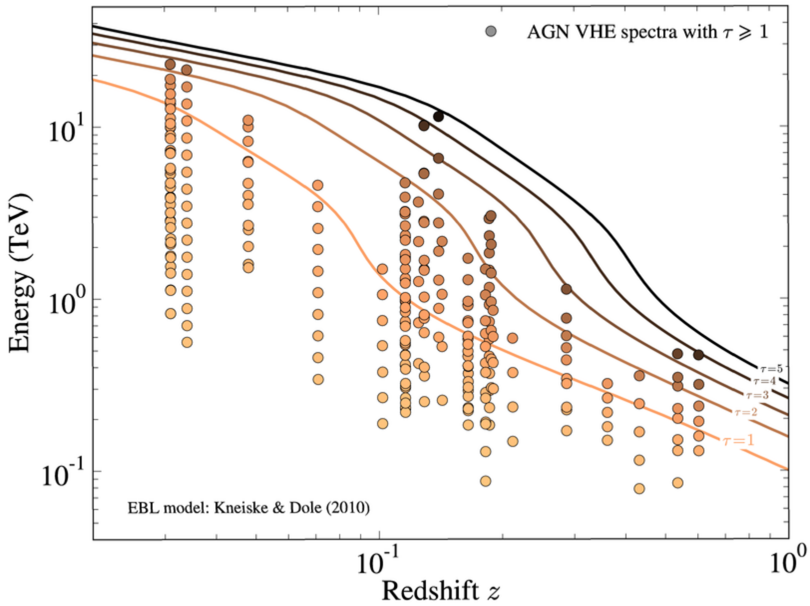

Figure 1: Individual differential flux measurements of a sample of VHE sources in the energy vs. red shift plane - the overlaid isocontours indicate the optical depths $\tau = 1, 2, 3, 4, 5$ for the minimal EBL model [11]. The figure is adapted from [19].

Once the probability for converting an initial photon state to an ALPs state and back to a photon state is competitive or even larger than the survival probability $= \exp(-\tau)$, *photon appearance* may be detected. In this case, the spectrum follows the predicted attenuation until at a sufficiently high energy the back-conversion of ALPs states may be detected and dominates over the absorption process. An example of the expected attenuation in the case of absorption only compared with the modification of the exponential attenuation in the presence of mixing with ALPs is shown in Fig. 2.

First indications for a deviations from the expected behaviour in the context of mixing with ALPs were discussed in [12, 13] where in the so-called DARMA scenario, the observed logarithmic slope of VHE spectra were compared with the expected effect of pair-production absorption. A similar comparison is shown in Fig. 3.

The pink shaded region of Fig. 3 indicates the expected softening of VHE spectra at increasing red shift (increasing absorption). The measurements (from a data sample collected in [8]) seem to indicate a systematic deviation from the expectation.

In the first quantitative study, it was shown that the spectral measurements at large optical depth (note, the optical depth is a monotonic function of both energy and red shift, see also Fig. 1) deviate by 4.2 σ from the measurements in the optically thin regime [14]. Systematic effects (energy calibration, measurement bias of flux measurements at the detection limits) were discussed to

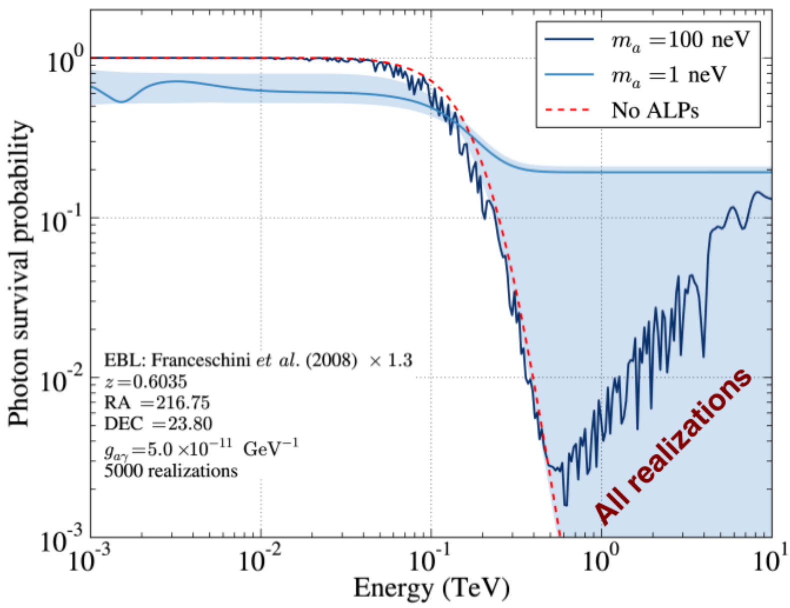

Figure 2: For one specific object, the modification of the apparent energy spectrum is shown with absorption only (*No ALPs*) and in the presence of two different ALPs scenarios with different masses (1 neV vs. 100 neV). In the case of a more massive ALP, one realization of the randomly oriented cells is shown to underline the additional fluctuations present in the spectrum. The blue shaded region indicates the range of modifications found in 5000 randomly chosen realizations. The figure is adapted from [19].

be insufficient to explain the entire effect. Individual newly discovered AGN at large red-shift have strenghtened the claim for anomalous transparency (e.g., the observation of PKS 1424+240 [15]). In a recent study of a similar data-set and in combination with Fermi-LAT data, the significance of a deviation (here in the form of a break in the energy spectrum with a hardening of the power-law beyond the break) from the absorption-only scenario was estimated to be > 10 sigma [16]. It remains to be clarified how the difference of the significance can be explained. A number of differences in the analysis exist (combination of Fermi-LAT and ground based measurements, shifting of energy bins, different statistical tests).
The interpretation of this *pair production anomaly* in the context of the appearance channel from photon-ALPs mixing is consistent with a mass of $m_a < \mu$eV and coupling $g_{a\gamma\gamma} > 10^{-11}$ GeV^{-1}, not violating any existing bounds [17]. The uncertainty on coupling and mass is a direct result of our ignorance on the morphology and strength of the intervening magnetic field.
Finally, Fermi-LAT data have been analysed to search for the appearance of photons from BL Lac type objects at high red shift [18]. The findings are consistent with a similar mass and coupling as derived from the higher energy, smaller red shift sample [19].

Photon-ALPs conversion can take place at various places along the line of sight and can lead to subsequently different spectral signatures. In the recent years, conversion in the jet of AGN [20], in the magnetic field of the host galaxy cluster [21] in the inter-galactic magnetic field [6], in the Galactic magnetic field [22], and the combination of these assumptions [23]. have been considered. In addition, the methods for dealing with turbulent magnetic field structure have been considered

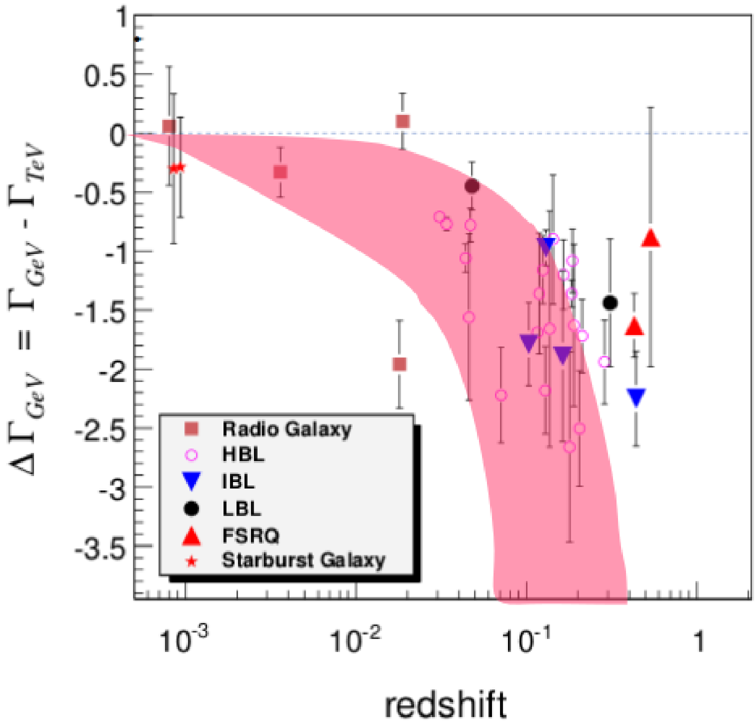

Figure 3: The prediction of the spectral break between Fermi-LAT and ground based measurements [13] is confronted with a larger data-set [8]. The shaded region indicates the degree of uncertainty related to the level of the extra-galactic background light. The data indicate that the observed softening remains invariant at $z > 0.1$, not consistent with the expectations. The figure has been adapted from [8].

[7] and can be used to replace the previously used approach to model the propagation in an inhomogeneous medium by a series of cells with a coherent magnetic field with random alignment with respect to the line of sight.

The appearance channel is quite sensitive as the photon-ALPs mixing is effective, leading to a maximum ALPs content of the beam of $1/3$. The back-conversion in the Galactic B-field is probably the most effective way to re-generate the photon beam. Furthermore, the back-conversion depends on the direction and is predictable, once the magnetic field structure of the Galaxy is fixed. In Fig. 4, we show the back-conversion probability in one particular model of the Galactic B-field and electron density as it has been constructed to re-produce the polarization radio-observations of background AGN and dispersion of radio pulsar data [24]. Furthermore, the positions of VHE emitting blazars is indicated in the diagram. The typical angular scale of changes in the conversion probability can in fact be used to search for auto-correlations in the spectral behaviour that would be predicted in a scenario with dominating back-conversion in the Galactic magnetic field. Even though the sensitivity of the available data is not sufficient to detect such an auto-correlation, it may be possible in the future [25].

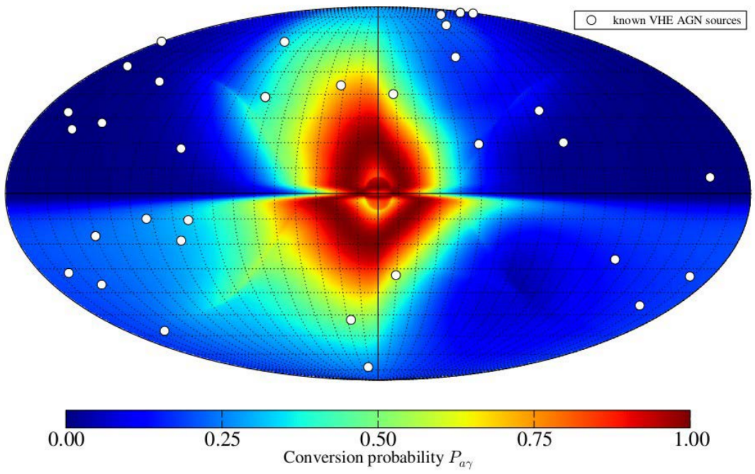

Figure 4: The conversion probability for an incoming ALP to convert into a photon in the Galactic magnetic field. The figure has been adapted from [19]. The position of BL Lac type objects at known red shift are indicated.

4. Disappearance channel

With the re-conversion probability $P_{a\to\gamma}$ given in Fig.4, the probability for a photon to convert into an ALP in the Galactic magnetic field and be undetectable (to disappear) is easily calculated. This will lead to a suppression of the gamma-ray spectra above the critical energy which marks the transition from weak to strong mixing (Eqn. 2.5). For $m_a = \mathscr{O}(\mathrm{neV})$, for typical magnetic fields of $B = \mathscr{O}(\mu\mathrm{G})$, and couplings favored by the estimates from the appearance channel, the resulting critical energy is within reach of energy spectra obtained with Fermi-LAT.

The large scale magnetic field follows closely the shape of the spirals, with the local $\vec{B}$ tangentially aligned to the spiral arms. Additional components extending out of the plane are present as well (as can also be seen from the conversion probability plotted in Fig.4), leading to a conversion probability even for line-of-sights oblique to the disc.
A first look into the conversion probabilities for individual pulsars is shown in Fig. 5. These are examples for two pulsars with known distance and with a line-of-sight favoring efficient disappearance of the gamma-ray spectra. The expected suppression is sufficient to be detected for bright objects with small statistical uncertainties on the measured spectra.

5. Discussion and conclusion

Here, we have summarized the current situation of observational indications and evidence for an anomalous transparency for gamma-ray photons from extra-galactic sources. Currently, two alternative explanations for the anomalous transparency are considered. The radiation transport of gamma-rays in a soft-photon background is simplified by treating the pair-production processes by an absorption of the primary beam. However, the pairs could lead to further cascading and subsequently modification of this simple scheme. The anomalous transparency has been also used as an argument in favour of a scenario, where BL Lac type objects are powerful ultra-high energy

cosmic-ray accelerators and the apparent gamma-ray emission from these sources is a result of cascading of the UHECR accelerated in BL Lacs [26].
An important observation to clarify the origin of the anomalous transparency could be the observation of auto-correlation in the gamma-ray spectra which may be accessible with future observations with CTA [25]. However, the time required to collect sufficient data with CTA after its potential completion > 2020 may leave us without an answer for another decade.
Here, we consider the possibility to use Fermi-LAT observations of pulsars at various locations

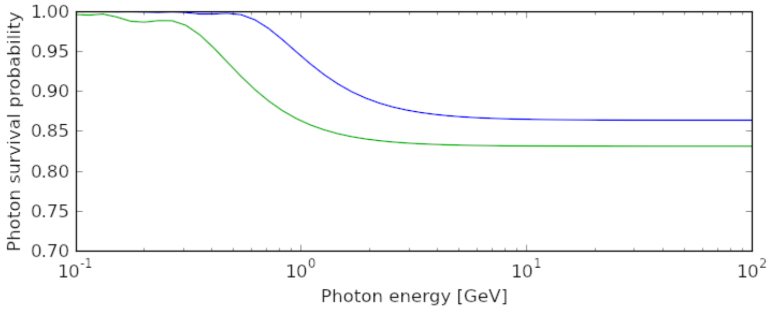

Figure 5: The modification for the energy spectrum for two pulsars along two different lines of sight, traversing different spiral arms and at different distances ($g_{a\gamma} = 5 \times 10^{-11}$ and $m = 1$ neV). The suppression of the primary flux is sufficiently large to be detected even with one individual spectrum. Additional spectra can be used to cross-check the result.

and widely different line-of-sight dependent conversion of photons to ALPs. The reasonably well known structure of the large-scale magnetic field of the Galaxy allows to predict the photon-ALPs conversion and its effect on the observed gamma-ray spectra.
The *disappearance* channel is sensitive in a rather narrow mass-range (roughly one octave for each source), but by combining many pulsars and other bright Galactic and extra-galactic gamma-ray sources, the mass-range is extended to one decade and the sensitivity to couplings down to $g_{a\gamma} < 10^{-11}$ GeV^{-1} is feasible.

The reconstruction of the underlying parameters of the ALPs (favored mass and coupling) is generally not possible in the appearance channel as the stochastic conversion in the turbulent magnetic field is not predictable. The estimates derived [17] are therefore very uncertain. In the disappearance channel on the other hand, it is possible to reconstruct the parameters by fitting the spectral modification factors to the observed spectra, only a degeneracy with the assumed magnetic field remains.

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