On the impact of magnetic-field models in galaxy clusters on constraints on axion-like particles from the lack of irregularities in high-energy spectra of astrophysical sources

Maxim Libanov1,2 and Sergey Troitsky1

1 Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary Prospect 7a, Moscow 117312, Russia
2 Moscow Institute of Physics and Technology, Institutskii per., 9, 141700, Dolgoprudny, Moscow Region, Russia

Abstract

Photons may convert to axion-like particles (ALPs) in external magnetic fields. Under certain conditions, this effect should result in irregular features in observed spectra of astrophysical sources. Lack of such irregularities in particular spectra was used to constrain ALP parameters, with two most popular sources being the radio galaxy NGC 1275 and the blazar PKS 2155–304. The effect and, consequently, the constraints, depend on the magnetic fields through which the light from the source is propagated. Here, we revisit ALP constraints from gamma-ray observations of NGC 1275 taking into account the regular magnetic field of the X-ray cavity observed around this radio galaxy. This field was not accounted for in previous studies, which assumed a model of purely turbulent fields with coherence length much smaller than the cavity size. For the purely regular field, ALP constraints are relaxed considerably, compared to the purely turbulent one. Similar arguments hold also for PKS 2155–304. While the actual magnetic field around a source is an unknown sum of the turbulent and ordered components, the difference in results gives an estimate of the theoretical uncertainty of the study and calls for detailed measurements of magnetic fields around sources used to constrain ALP properties in this approach.

Keywords: axion-like particles, cluster magnetic fields, gamma-ray spectra

1. Introduction

Pseudoscalar axion-like particles (ALPs; for a review, see e.g. Ref. [1]) are common in various extensions of the Standard Model of particle physics. Their defining property is the interaction with the electromagnetic field, allowing in particular for photon/ALP mixing in the external magnetic field [2]. Experimentally allowed values of the photon-ALP coupling are however very low, which makes large-scale astrophysical environments a proper place to search for manifestations of this interaction. The astrophysical searches include studies of stellar energy losses, where indications to losses larger than predicted may be explained by interactions of ALPs, see Ref. [3] for a review. In particular, cooling of helium-burning stars [4] may suggest ALP-photon couplings just below the present limits from the solar ALP searches by the CERN Axion Solar Telescope, CAST [5]. The same range of couplings is favoured by ALP explanations of possible “anomalous transparency” effects [6, 7, 8, 9, 10] in the propagation of energetic gamma rays from distant sources [11, 12, 13, 14, 15, 16, 17] (for a short review, see Ref. [18]). These studies are however very sensitive to measurements of redshifts of the emitting sources, so the significance of the observed effects remains uncertain [19] and other ways to explore the relevant part of the ALP parameter space are welcome.

Under certain conditions, photon-ALP mixing may result in oscillatory features in the spectra of astrophysical photon sources seen through regions filled with magnetic fields [20]. While precise shape of these irregularities and the photon energies at which they appear depend on the ALP parameters and magnetic-field configurations, these features are not expected in (otherwise smooth) astrophysical spectra. Lack of these irregularities in observed spectra might in principle be used to constrain ALP parameters, see e.g. Refs. [21, 22, 23, 24, 25, 26].

Several attempts to follow this way have been made in recent years, exploiting the observed smoothness of X- and gamma-ray spectra of strong emitters presumably embedded in astrophysical magnetic fields. In particular, these included analyses of gamma-ray observations of PKS 2155–304 [27, 28, 29], NGC 1275 [30, 31] and several Galactic sources [32, 33, 34] relevant for ALP masses \(\sim (10^{-9} - 10^{-7}) \text{ eV}\) (overlapping with the range invoked for explanations of the “anomalous transparency” effects). For lower ALP masses, X-ray observations of 3C 218 [35], the same NGC 1275 [36, 37, 38], M 87 [39] and some other extragalactic sources [40] were used. Refs. [32, 33] found some favorable ranges in the ALP parameter space, though with ALP-photon couplings above the 95% CL CAST upper limit. Other works put limits on the ALP parameters which are often quoted on equal footing with other astrophysical and laboratory constraints [41]. The aim of the present work is to demonstrate how much these constraints de-
pend on the assumptions about magnetic fields involved and how much they could change if different astrophysically motivated field configurations are assumed.

As an example, we concentrate on the case of NGC 1275, the central radio galaxy of the Perseus cluster and the most popular target for the searches for spectral irregularities in the ALP context [30, 31, 36, 37]. We briefly review these studies in Sec. 2 and emphasize that they use a theoretical model of the magnetic field in the Perseus cluster, which is based on observations of other clusters, because of the lack of relevant observations in Perseus. This model assumes purely turbulent magnetic fields. In the present study, we revisit these constraints taking into account large-scale ordered magnetic fields which are expected to be present around giant radio galaxies from the interaction between lobes and environment in clusters [42, 43, 44, 45, 46]. Evidence for the regular magnetic fields ordered at scales ≳ 100 kpc have been found in several galaxy clusters [47, 48], see also reviews [49, 50]. Possible presence of the regular magnetic fields around radio galaxies is crucial for the present consideration.

In Sec. 3, we concentrate on the magnetic field in the Perseus cluster. Only two relevant observations of the Faraday rotation have been reported in the literature: Ref. [51] gives a measurement at the very center of the cluster, used in previous studies [30, 31, 36, 37] to normalize the field strength at this point; Ref. [52] presents a map of rotation measurements across the cluster (not used in previous studies). We recall numerous radio and X-ray observations indicating the presence of an X-ray cavity, or a radio mini-halo, around NGC 1275, consistent with the lobe-environment interaction [53, 54, 55, 56]. An analytical model of the regular magnetic field in such a cavity was presented (and supported by numerical simulations) in Ref. [57]; see also Refs. [58, 59] and especially [60] for more detailed simulations. We use this analytical model as a proxy to the regular field in the central X-ray cavity of the Perseus cluster, consistent with rotation measurements of Refs. [51, 52], as well as with X-ray observations of large-scale structures in Perseus [61, 62] and corresponding simulations [63].

Next, in Sec. 4, we turn to the effect of the ordered magnetic field on the observed photon spectrum, and consequently on constraints on the ALP parameters. As an example, we readdress the case of NGC 1275 and Fermi-LAT data [30]. In general, magnetic field in the cluster is the sum of regular and turbulent components, and their various combinations can fit scarce observational data. Since both components contribute to the observed Faraday rotation, stronger regular field implies weaker turbulent one. In particular, previous studies assumed purely turbulent models; here we consider the opposite case and assume a purely regular field, which is described in Sec. 3 and agrees with observations. Comparison of the results for these two limiting cases gives an estimate of the theoretical uncertainty of the constraints obtained in this way. We take the spectrum used in Ref. [30] and demonstrate that, for the assumed purely regular field configuration, the fits with and without ALPs are equally good for a large part of the parameter space, so that the resulting constraints on ALP parameters are much weaker than those obtained in Ref. [30] for the opposite case of purely turbulent field models. This is not surprising because spectral irregularities are enhanced when the field extends to the scales much larger than its coherence length, see e.g. Ref. [27]. Therefore, we expect a similar effect on other constraints obtained in the same way.

In Sec. 5, we briefly discuss another gamma-ray source, PKS 2155–304, which sits [64] in a small unnamed group of galaxies. Recent observations [65] suggest that this group is considerably smaller than it was assumed earlier, which might imply lower and more regular magnetic fields and correspondingly weaker constraints on ALP parameters.

In Sec. 6, we briefly reiterate our main conclusion: as it is illustrated by examples of the Perseus cluster hosting NGC 1275 and of an unnamed group hosting PKS 2155–304, constraints on the ALP parameters from the lack of irregularities in the spectra of astrophysical sources are very sensitive to the assumptions about magnetic fields surrounding the sources. In particular, regular fields, which are expected to be present close to these strong active galaxies, are very important. Detailed studies of the magnetic fields are required to reduce the uncertainties and to obtain firm limits on ALP parameters in this way.

2. Previous studies of NGC 1275 in the ALP context.

NGC 1275 is a radio galaxy located in the center of the Perseus cluster. It is a bright X-ray and gamma-ray source. Thanks to the intensity of the source, sufficient statistics could be collected to obtain detailed spectra suitable for the search for spectral features at high confidence level, which justified the choice of this source as a target for several attempts to constrain ALP parameters from the lack of irregularities in the spectrum. In Ref. [30], Fermi-LAT collaboration analyses their data in great detail, develops a statistical procedure and presents 95% CL exclusion limits for ALP parameters. Authors of Ref. [31] supplement Fermi-LAT data by published results of the MAGIC observations of the same target [66] to extend the energy range covered by the spectrum and, consequently, the excluded region in the ALP parameter space. Refs. [36, 37] used X-ray spectra of NGC 1275 obtained by Chandra to constrain ALPs with lower masses. In what follows, we will mainly refer to the Fermi-LAT study [30] as an example, though the same logic is fully applicable to other photon energy bands.

Measurements of astrophysical magnetic fields on galactic and larger scales often rely on the Faraday rotation of the polarization plane [49, 50]. The approach is not easy to implement directly since it requires sources of polarized emission behind the magnetic-field region, observed at different wavelengths λ so that the typical \( \lambda^2 \) dependence may be traced in the polarization angle. In addition, the outcome is the product of the longitudinal component of the magnetic field and the electron density, integrated over the line of sight, so some additional information and/or theoretical input are required to reconstruct the magnetic-field structure and values; note in particular that the other, transverse component of the field is relevant for the ALP-photon mixing. Still, Faraday rotation measurements remain the best available mean to reconstruct magnetic fields in galaxy clusters. Sadly, these measurements for the Perseus cluster are
very limited and do not allow to uniquely reconstruct the field from observations. That is why a theoretical model of the magnetic field in the cluster was used in Refs. [30, 31, 36, 37], and the real measurement in only one direction, towards the very center of the cluster [51], was used to construct the model.

Following general considerations of Ref. [24], Ref. [30] models the magnetic field in the Perseus cluster as purely turbulent, with the maximal coherence length of 35 kpc. The model used there is motivated by observations of clusters other than Perseus since, for Perseus, no detailed data are available. The model has 6 parameters, and reported ALP constraints correspond to their fiducial values. While the effect of variations of these parameters, one by one, on the resulting likelihood of the spectral fit was studied, see Fig. 7 of the Supplemental Material of Ref. [30], none of the considered variations included a regular component. However, if a regular field component exists, it contributes to the rotation measurement [51] so that the amplitude of the turbulent component, and consequently the strength of possible ALP-induced spectral irregularities, is smaller.

3. Regular magnetic fields in the Perseus cluster

In the center of the Perseus cluster, like in many other clusters containing a large active galaxy, an X-ray cavity was observed, spatially coinciding with the so-called radio mini-halo [53, 54, 55, 56]. This cavity most probably is a result of the interaction between outflows of NGC 1275 and the intracluster gas. The X-ray cavity size, according to Chandra observations [55], is 93 kpc, while the radio mini-halo extends slightly further [56]. Modelling [63] of the slashing cold front in the Perseus cluster, see e.g. Ref. [62], indicates that the X-ray cavity should be filled with relatively high magnetic field to support the required pressure. This magnetic-field region is seen on the rotation-measure map of the Perseus cluster [52] and explains high values of the rotation measure observed in Ref. [51] for the very center of the cluster.

For the X-ray cavities, blown by radio-galaxy jets in the intracluster plasma, magnetic fields are expected to be regular at large scales. Ref. [57] suggests the following consistent magnetic-field solution,

\[ B_r = 2 \cos \theta f(r_1)/r_1^2, \]
\[ B_\theta = -\sin \theta f'(r_1)/r_1, \]
\[ B_\phi = \alpha \sin \theta f(r_1)/r_1, \]

where

\[ f = C (\alpha \cos (\alpha r_1) - \sin (\alpha r_1)/r_1) - F_0 r_1^2/\alpha^2, \]
\[ F_0 = C \alpha^2 (\alpha \cos \alpha - \sin \alpha), \]

\[ \alpha \] is the lowest nonzero root of \( \tan \alpha = 3\alpha/(3 - \alpha^2) \), \( r_1 \equiv r/R \) for the cavity radius \( R \) and \( C \) is the normalization constant determined by the field value at \( r = 0 \). This analytical solution is supported also by numerical simulations in Ref. [57]. In the next section, we use this solution as a model of the regular field in the X-ray cavity around NGC 1275, assuming the viewing angle \( \theta = 45^\circ \) and the cavity radius of \( R = 93 \) kpc [55]. The normalization of the field is chosen in such a way that the Faraday Rotation Measurement of \( \sim 7300 \) rad/m \(^2\) [51] for the central direction is reproduced for the electron density derived from X-ray observations [61]. This normalization gives the total field in the center of 8.3 \( \mu \)G. The field components for the chosen line of sight are plotted in Fig. 1.

We should note that the central X-ray cavity may be not the only place in the Perseus cluster where fields ordered at large scales are present. Ref. [52] discusses also an organised structure in the rotation-measure map on the \( \sim \)Mpc scales, possibly associated [67] with a shock caused by the interaction of the intracluster matter with intergalactic matter in the large-scale structure filament, which may or may not be similar to the regular field structures observed in other galaxy clusters [47, 48] under similar conditions. In addition, X-ray observations reveal [61, 62] large-scale (\( > \) 100 kpc) spiral structure around NGC 1275, which also may host regular magnetic fields, like it happens in our own Galaxy. We stress therefore that the structure of regular magnetic fields in the Perseus cluster is rich and unknown, lacking explicit measurements. In the example in the next section, we concentrate on the best-studied X-ray cavity field only.

4. Example: ALP constraints from the Fermi-LAT spectrum of NGC 1275 for the X-ray cavity magnetic field

Consider now the interaction of the electromagnetic field \( A_\mu \) and the ALP field \( a \) described by the following Lagrangian,

\[ \mathcal{L} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} (\partial a)^2 - \frac{1}{2} m^2 a^2 - \frac{1}{4} g a F_{\mu\nu} F^{\mu\nu}, \]

where \( F_{\mu\nu} \) is the electromagnetic stress tensor, \( \tilde{F}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\lambda\rho} F^{\rho\lambda} \), \( m \) is the ALP mass and \( g \) is the ALP-photon coupling constant. The last term is responsible for axion-photon mixing in the external magnetic field [2], which in the adiabatic approximation is most conveniently described in terms of the density matrix \( \rho \).
obeying the equation

\[ i\frac{d\rho(y)}{dy} = [\rho(y), \mathcal{M}(E, y)], \quad \mathcal{M} = \frac{1}{2} \begin{pmatrix} 0 & 0 & -i\gamma B_{\phi} \\ 0 & 0 & -i\gamma B_{\phi} \\ i\gamma B_{\phi} & i\gamma B_{\phi} & \frac{m^2}{E} \end{pmatrix}. \tag{1} \]

For an initial unpolarized purely photon state,

\[ \rho(0) = \text{diag}(1/2, 1/2, 0). \tag{2} \]

The probability to observe an unpolarized photon at a distance \( y \) from the source is given by the sum \( \rho_{11}(y) + \rho_{22}(y) \) of the components of the solution \( \rho(y) \) to Eq. (1) with the boundary condition (2). Here, we assumed that the mixture of two transverse states of photons and one state of ALP is propagating along the direction \( y \) with the energy \( E \), and kept only terms relevant for the present study. The full expression for the matrix \( \mathcal{M} \) can be found e.g. in Ref. [14], but entries not shown in Eq. (1) can safely be neglected for energies, fields and distances studied here.

We use the magnetic-field model for the X-ray cavity around NGC 1275 described in Sec. 3. We assume that effects of the turbulent field in the outskirts of NGC 1275 are subleading, like it is normally assumed for our own Galaxy. For the Milky-Way magnetic field, we use the BSS model of Pshirkov et al. [68]. We assume the symmetry axis of the cavity field to be co-oriented with the observed jets, position angle \( \approx 147^\circ \) (from North to East) in Galactic coordinates. The redshift of NGC 1275 is only \( z = 0.018 \), so effects of pair production on the extragalactic background light are negligible at the Fermi-LAT energies. We assume a source of unpolarized photons in the center of the X-ray cavity and solve Eqs. (1), (2) numerically to obtain the probability to observe photons with a given energy at the Earth. Then, we concentrate on the Fermi-LAT data for the EDISP3 event type shown in Ref. [30]. We convolve the probability with the energy-dependent instrumental energy resolution presented in Supplemental Material of Ref. [30] to obtain the ratio of the observed photon spectrum to the emitted one, which we call the spectrum modification factor. For illustration, it is presented in Fig. 2 for benchmark values of ALP parameters, \( m = 10^{-9} \) eV and \( g = 10^{-11} \) GeV\(^{-1} \).

Next, we follow the logic of Ref. [30] and find best-fit spectra with and without ALPs and compare the quality of the fits. We use the EDISP3 event type spectrum of NGC 1275 from Fig. 1 of Ref. [30]. While the actual emitted spectrum is unknown, most of active-galaxy gamma-ray fluxes \( F(E) \) are perfectly fit by the so-called log-parabola function,

\[ F(E) = F_0 (E/E_0)^{-(\alpha+\beta\log(E/E_0))}, \tag{3} \]

where, following Ref. [30], we fix \( E_0 = 0.53 \) GeV and keep three parameters, \( F_0, \alpha \) and \( \beta \), free. We then perform two independent fits of the data, each with the free parameters: one by the log-parabola spectrum (3) and another by the same function multiplied by the spectrum modification factor for given values of the ALP parameters. The fits are performed by the usual chi-square minimization adopted to account for asymmetric statistical errors [69]. Upper limits are treated as zero values with the corresponding errors. This is a simplification compared to the procedure of Ref. [30], where the full likelihood function based on non-Gaussian distribution of errors was used; however, this is sufficient for our purposes since we are interested in the best fit only. For the same benchmark values of \( m = 10^{-9} \) eV and \( g = 10^{-11} \) GeV\(^{-1} \), the two best-fit spectra are shown in Fig. 3 together with the data. The fit quality is determined by \( \chi^2 \approx 115.9 \) for the fit without ALPs and \( \chi^2 \approx 110.6 \) for the fit with ALPs, for 114 degrees of freedom. We see that both fits are perfect, and the effects of ALPs with the benchmark parameters cannot be excluded for the regular field model used here, while they are excluded at the 95% CL for the purely turbulent field model in Ref. [30].

This fitting procedure was repeated for various pairs of ALP parameters \((m, g)\). The 95% exclusion contour in the \((m, g)\) plane was determined from the chi-squared distribution with 114 degrees of freedom. \( \chi^2_{05} \approx 139.9 \). This contour is shown in Fig. 4 together with the exclusion region obtained in Ref. [30] for purely turbulent fields. The difference between purely regular and purely turbulent cases is dramatic. Since the actual magnetic field around NGC 1275 is an unknown mixture of regular
Figure 4: Exclusion regions (95% CL) on the plane of ALP parameters \((m, g)\) for purely regular (this work, hatched) and purely turbulent (Ref. \[30\], shaded) magnetic fields around NGC 1275. The blue horizontal line represents the CAST \[5\] 95% CL upper limit on \(g\). Ref. \[30\] does not extend the exclusion above the CAST limit. For the regular field considered here, all exclusion regions are above the CAST limit. For a realistic combination of regular and turbulent fields, the exclusion is somewhere in between, but one needs to know magnetic fields around NGC 1275 in more detail to find where exactly.

and turbulent components, this difference gives an estimate of theoretical uncertainties of the constraints.

5. Notes on PKS 2155–304

Another popular target for searches for irregularities in the spectrum is PKS 2155–304, a bright blazar at the redshift of \(z \approx 0.116\). Here, the situation is even worse since no single measurement of Faraday rotation is available for lines of sight close to this source, and ALP properties are constrained on the basis of purely theoretical magnetic-field models. Indeed, for instance, in Ref. \[27\] it was noted that the source belongs to a small unnamed group of galaxies studied in Ref. \[64\]. Subsequent observations of this group have revealed \[65\] that the group is even smaller than it was assumed, having the virial radius of \(R_{\text{vir}} \approx 0.22\) Mpc, virial mass \(M_{\text{vir}} \approx 1.5 \times 10^{13}M_{\odot}\) and only 12 identified group members. Only in a few cases (not including this one), magnetic fields in such small groups have been determined observationally, and these fields were regular (see e.g. Ref. \[70\] and references therein), not turbulent. Ref. \[27\] and follow-up studies, contrary, assume purely turbulent magnetic fields with parameters inferred from observations of Coma (\(\sim 1000\) members, \(M_{\text{vir}} \sim 1.7 \times 10^{15}M_{\odot}\), \(R_{\text{vir}} \sim 2.9\) Mpc \[71\]) and Hydra (\(\sim 160\) members, \(M_{\text{vir}} \sim 2 \times 10^{13}M_{\odot}\), \(R_{\text{vir}} \sim 1.6\) Mpc \[72\]) clusters. While Ref. \[27\] allows for variations of the magnetic-field model parameters, it is unclear whether this purely turbulent field model can be used for the small group containing PKS 2155–304. In any case, constraints on ALP parameters obtained in this way depend crucially on the assumed model.

6. Conclusions

Magnetic fields regular on large scales are expected to be present around giant active galaxies, in particular around those which are used to constrain ALP parameters from the lack of irregularities in their spectra. Particular examples are NGC 1275 and PKS 2155–304, for which high-quality gamma-ray and X-ray spectra are available. In this paper, we revisit constraints from gamma-ray observations of NGC 1275 which assumed purely turbulent magnetic fields around this giant radio galaxy. We note that an X-ray cavity observed around the galaxy suggests the presence of ordered magnetic fields and use a model of the cavity field to study how the ALP constraints are changed in the presence of regular fields. Assuming that the observed Faraday rotation measurements are fully explained by the cavity field, we obtain constraints much weaker than those obtained in Ref. \[30\] for a purely turbulent field model, see Fig. 4. In reality, the field is expected to include both components, and actual constraints would lay somewhere in between, but unfortunately the lack of magnetic-field measurements in the Perseus cluster currently prevents one from disentangling the two contributions. Similar arguments are applied to other sources, in particular to PKS 2155–304, a blazar residing in a small group of galaxies, for which no Faraday rotation measurements are available.

While new observations of the same targets with sensitive instruments like CTA \[73\] or ATHENA+ \[74\] will reduce statistical uncertainties in the spectra and are certainly welcome for many reasons, uncertainties in the magnetic-field models should first be removed by complementary observations. In view of results of Ref. \[52\], Faraday rotation mapping of the Perseus cluster looks a promising way to obtain better constraints on the magnetic field in the region where the lobes of NGC 1275 interact with the intracluster matter. In addition, sources embedded in magnetic fields better studied observationally may be invoked for the search of irregularities, for instance M 87 \[39\] and Galactic sources \[32, 33, 34\]. For certain values of ALP parameters, the transition to the regime of strong mixing in the Galactic magnetic field may be observed or constrained also for extragalactic sources, cf. Ref. \[31\]. Note that the relevant part of the ALP parameter space will be explored by coming experiments, a purely laboratory instrument ALPS-IIC \[75\] and helioscopes TASTE \[76\] and IAXO \[77\].

Acknowledgements

The authors are indebted to Mikhail Kuznetsov, Maxim Pshirkov, Grigory Rubtsov and Dmitri Semikoz for interesting discussions and comments on the manuscript. ST acknowledges discussions with Igor Garcia-Irastorza and Manuel Meyer at the initial stage of this work. This work was supported by the Russian Science Foundation, grant 18-12-00258.
References

[1] J. Jaeckel and A. Ringwald, “The Low-Energy Frontier of Particle Physics,” Ann. Rev. Nucl. Part. Sci. 60 (2010) 405, doi:10.1146/annurev.nucl.012809.104433 [arXiv:1002.0329 [hep-ph]].

[2] G. Raffelt and L. Stodolsky, “Mixing of the Photon with Low Mass Particles,” Phys. Rev. D 37, 1237 (1988), doi:10.1103/PhysRevD.37.1237.

[3] M. Giannotti et al., “Cool WISPs for stellar cooling excesses,” JCAP 1605 (2016) 057, doi:10.1088/1475-7516/2016/05/057 [arXiv:1512.08108 [astro-ph.HE]].

[4] A. Ayala et al., “Revisiting the bound on axion-photon coupling from Globular Clusters,” Phys. Rev. Lett. 113 (2014) 191302, doi:10.1103/PhysRevLett.113.191302 [arXiv:1406.6053 [astro-ph.SR]].

[5] V. Anastassopoulos et al. [CAST Collaboration], “New CAST Limit on the Axion-Photon Interaction,” Nature Phys. 13 (2017) 584, doi:10.1038/nphys4109 [arXiv:1705.02290 [hep-ex]].

[6] A. Donato, G. Giudice and S. M. Khalil, “Bound on axion-photon coupling from a bump in the X-ray diffuse background,” JCAP 1202 (2012) 033, doi:10.1088/1475-7516/2012/02/033 [arXiv:1201.4711 [astro-ph.CO]].

[7] Y. T. Tanaka et al., “Fermi Large Area Telescope detection of two very-high-energy ($E > 100$ GeV) gamma-ray photons from the $z = 1.1$ blazar PKS 0426–320,” Astrophys. J. 777 (2013) L18, doi:10.1088/2041-8205/777/1/L18 [arXiv:1308.0959].

[8] G. Rubtsov and S. V. Troitsky, “Breaks in gamma-ray spectra of distant blazars and transparency of the Universe,” JETP Lett. 100 (2014) 355 [Physica Scripta T158/014606] [arXiv:1406.0239 [astro-ph.HE]].

[9] C. Sasaki et al., “Super GZK photons from photon axion mixing,” JCAP 0305 (2003) 005, doi:10.1088/1475-7516/2003/05/005 [hep-ph/0302030].

[10] A. De Angelis, M. Roncadelli and O. Mansutti, “Evidence for a new light spin-zero boson from cosmological gamma-ray propagation?,” Phys. Rev. D 76 (2007) 121301, doi:10.1103/PhysRevD.76.121301 [arXiv:0707.4312 [astro-ph]].

[11] M. Simet, D. Hooper and P. D. Serpico, “The Milky Way as a Kiloparsec-Scale Axionscope,” Phys. Rev. D 77 (2008) 063001, doi:10.1103/PhysRevD.77.063001 [arXiv:0712.2825 [astro-ph]].

[12] M. Ferreira, L. F. da Rocha and S. V. Troitsky, “Photon-axion mixing and ultra-high-energy cosmic rays from BL Lac type objects - Shining light through the Universe,” Phys. Rev. D 84 (2011) 125019, doi:10.1103/PhysRevD.84.125019 [arXiv:1101.4085 [astro-ph.HE]].

[13] M. Meyer, D. Hooper and M. Meyer, “Indications for a pair-production anomaly from the propagation of VHE gamma-rays,” JCAP 1202 (2012) 033, doi:10.1088/1475-7516/2012/02/033 [arXiv:1201.4711 [astro-ph.CO]].

[14] D. Horns and M. Meyer, “New bounds on axionlike particles from the Fermi Large Area Telescope observation of PKS 2155–304 energy spectrum,” Phys. Rev. D 92 (2015) 063009, doi:10.1103/PhysRevD.92.063009 [arXiv:1802.08420 [hep-ph]].

[15] D. Horns and M. Meyer, “New bounds on axionlike particles from the Fermi Large Area Telescope observation of PKS 2155–304 energy spectrum,” Phys. Rev. D 97 (2018) 063009, doi:10.1103/PhysRevD.97.063009 [arXiv:1802.08420 [hep-ph]].

[16] D. Horns and M. Meyer, “Indications for a pair-production anomaly from the propagation of VHE gamma-rays,” JCAP 1202 (2012) 033, doi:10.1088/1475-7516/2012/02/033 [arXiv:1201.4711 [astro-ph.CO]].

[17] G. Rubtsov and S. V. Troitsky, “Breaks in gamma-ray spectra of distant blazars and transparency of the Universe,” JETP Lett. 100 (2014) 355 [Physica Scripta T158/014606] [arXiv:1406.0239 [astro-ph.HE]].

[18] C. Sasaki et al., “Super GZK photons from photon axion mixing,” JCAP 0305 (2003) 005, doi:10.1088/1475-7516/2003/05/005 [hep-ph/0302030].

[19] A. De Angelis, M. Roncadelli and O. Mansutti, “Evidence for a new light spin-zero boson from cosmological gamma-ray propagation?,” Phys. Rev. D 76 (2007) 121301, doi:10.1103/PhysRevD.76.121301 [arXiv:0707.4312 [astro-ph]].

[20] M. Simet, D. Hooper and P. D. Serpico, “The Milky Way as a Kiloparsec-Scale Axionscope,” Phys. Rev. D 77 (2008) 063001, doi:10.1103/PhysRevD.77.063001 [arXiv:0712.2825 [astro-ph]].

[21] M. Ferreira, L. F. da Rocha and S. V. Troitsky, “Photon-axion mixing and ultra-high-energy cosmic rays from BL Lac type objects - Shining light through the Universe,” Phys. Rev. D 84 (2011) 125019, doi:10.1103/PhysRevD.84.125019 [arXiv:1101.4085 [astro-ph.HE]].

[22] D. Horns et al., “Hardening of TeV gamma spectrum of AGNs in galaxy clusters by conversions of photons into axion-like particles,” Phys. Rev. D 86 (2012) 075024, doi:10.1103/PhysRevD.86.075024 [arXiv:1207.0776 [astro-ph.HE]].

[23] M. Meyer, D. Hooper and M. Raue, “First lower limits on the photon-axion-photon coupling from very high energy gamma-ray observations,” Phys. Rev. D 87 (2013) 035027, doi:10.1103/PhysRevD.87.035027 [arXiv:1302.1208 [astro-ph.HE]].

[24] G. Galanti et al., “Axion-like particles explain the unphysical redshift-dependence of AGN gamma-ray spectra,” arXiv:1903.04436 [astro-ph.HE].

[25] S. V. Troitsky, “Axion-like particles and the propagation of gamma rays over astronomical distances,” JETP Lett. 105 (2017) 55, doi:10.1134/S0021364017010052 [arXiv:1612.01864 [astro-ph.HE]].

[26] A. Korockin, G. Rubtsov and S. Troitsky, “Distance-dependent hardenings in gamma-ray blazar spectra corrected for the absorption on the extragalactic background light,” arXiv:1810.03443 [astro-ph.HE].

[27] L. Ostman and E. Mortessle, “Limiting the dimming of distant Type Ia supernovae,” JCAP 0502 (2005) 005, doi:10.1088/1475-7516/2005/02/005 [astro-ph/0410501].

[28] D. Chelouche et al., “Spectral Signatures of Photon-Particle Oscillations from Celestial Objects,” Astrophys. J. Suppl. 180 (2009) 1, doi:10.1086/590047/180/1/1 [arXiv:0806.0411 [astro-ph]].
