Parameters of Astrophysically Motivated Axion-like Particles

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Popular explanations of the anomalous transparency of the Universe for energetic gamma rays include conversion of photons into hypothetical axion-like particles (ALPs) and back in astrophysical magnetic fields. This could either happen in the gamma-ray source and in the Milky Way, or the photon-ALP oscillations could take place in the intergalactic magnetic fields all along the way between the source and the observer. Given recent astrophysical constraints on ALPs and on intergalactic magnetic fields, these two mechanisms imply very different ALP parameters: masses and couplings. Therefore, confirmation of the anomalies and identification of one of the scenarios would mean cornering of ALP parameters to a particular narrow region.

1 Anomalous transparency and ALPs

The modern evidence for the anomalous transparency of the Universe for energetic gamma rays is based on studies of ensembles of distant VHE sources. The observed spectra of these sources have been corrected for pair-production effects ("deabsorbed") within the lowest-absorption models to obtain the intrinsic spectra emitted at the sources. These intrinsic spectra exhibit unphysical redshift dependence which is readily interpreted as an overestimation of the absorption even in the minimal models [1–3].

An ALP mixes with photons in external magnetic fields [4], which may allow to suppress the attenuation due to pair production: gamma-ray photons convert to ALPs, then travel unattenuated and eventually convert back to photons. The photon beam is still attenuated, but the flux suppression becomes less severe. To reduce the opacity of the Universe for TeV gamma rays from blazars, two particular scenarios involving ALPs are important. The purpose of the present study is to emphasise and to explore the difference between the two approaches (see a more detailed discussion in Ref. [5]).

The first scenario implies that the intergalactic magnetic field is strong enough to provide for ALP/photon conversion all along the path between the source and the observer. Originally suggested in Ref. [6] in a different context, this mechanism, known also as the DARMA scenario, was invoked for the TeV blazar spectra in Ref. [7]. If it is at work, then the photon/ALP mixed beam propagates through the Universe and, since the photons are attenuated while ALPs are not, the effective suppression of the flux is smaller compared to the pure-photon case. A detailed recent study of this scenario is given in Ref [3], where the most recent constraints on the relevant ALP parameters are derived. In what follows, we will refer to this mechanism as the "intergalactic conversion" and use the parameter constraints [3] for this scenario.

The second approach assumes that there are quite strong magnetic fields inside or around the source, as well as around the observer, while for the most part of the distance the beam travels in weak magnetic fields, insufficient for ALP/photon mixing. The conversion may happen either in the blazar itself and in the Milky Way [8] or in the galaxy cluster or filament [9] (see also a more detailed subsequent study in Ref. [10]) containing the source and the observer, in various combinations. A detailed recent study of this mechanism is presented in Ref. [11], where it is called "the general-source" scenario. In the rest of the paper, we refer to this mechanism as the "galactic conversion" and use parameter constraints derived in Ref. [11] for this case.

Regions of parameters of the ALP, that is of its mass m and its inverse coupling to photons M, required for efficient operation of one or another mechanism, overlap in a large range. However, when the most recent experimental and astrophysical constraints are taken into account, the parameter regions allowed for the two scenarios become disconnected; this means that if we determine that one or another scenario works in Nature, we strongly constrain the ALP mass and coupling! We illustrate this fact in Fig. 1, where shaded blue areas, excluded by constraints from the CERN axion solar telescope (CAST, Ref. [13]), evolution of the horizontal-branch (HB) stars [14], reanalysis of the supernova (SN) 1987A data [15] and HESS constraints from the absence of irregularities in a blazar spectrum [16], indicate the most restrictive relevant limits. The key constraint contributing to the separation of the two regions is that of Ref. [15]. The separation of the two regions, which are often unified in a single large band referred to as the "transparency hint" in relevant plots, is remarkable.

2 Discrimination between galactic and intergalactic scenarios

Anisotropy.- The magnetic field of the Milky Way galaxy has a complicated structure, and the probability of the ALP/photon conversion there, which is required in the galactic scenario, depends strongly on the direction. Evidence for direction dependence in the anomalous transparency of the Universe may therefore be a strong argument in favour of the galactic scenario [8, 9, 17].

In Reference [8], it was pointed out that the positions of a few TeV blazars with redshifts $z > 0.1$ known by that time fit surprisingly well the regions in the sky where the conversion probability, calculated within the model of the Galactic magnetic field (GMF) of Ref. [12], is high. Here, we assume this as a hypothesis and attempt to test it with the new observational data. Clearly, more elaborated approaches should be used in further studies. We consider a sample of blazars with firm detection beyond $\tau = 1$ which consists of 15 objects observed by IACTs and 5 objects observed by FERMI LAT (the sample of Ref. [2]), supplemented by additional 6 blazars rejected in Ref. [2] because of the insufficient number of data points for fitting spectra with breaks. We drop 4 nearby objects with $z < 0.1$ from the sample, like it was done in Ref. [8]. Figure 2, represents the distribution of these objects in the sky together with the conversion probability for the same GMF model [12]. The objects indeed follow the regions of high conversion probability, qualitatively confirming the trend seen in Ref. [8].

It is not possible, however, to rigorously test the hypothesis quantitatively, because the blazars we discuss do not form a complete isotropic sample. Nevertheless, for illustration, we present here the results of a simple statistical test, keeping in mind its qualitative level. For each of the 22 sources in the sample, we calculate the ALP/photon conversion probability in the GMF of Ref. [12]. The same distributions were calculated and averaged for 100 sets of

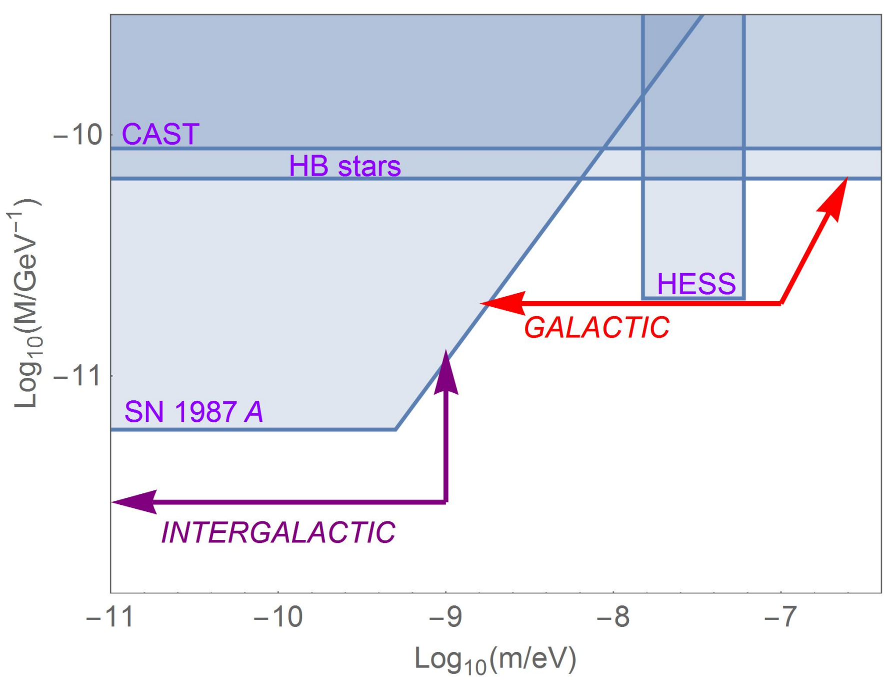

Figure 1: ALP parameter space (ALP-photon inverse coupling M versus ALP mass m) with current constraints (see text). The regions corresponding to the Galactic [3] and intergalactic [11] ALP/photon conversion explanations of the gamma-ray anomalies are indicated; they extend to the forbidden regions as shown by arrows. Given all constraints, the two regions are well separated.

22 objects distributed isotropically in the sky. The Kolmogorov-Smirnov probability that the distribution seen for the real data is a fluctuation of that for simulated directions is 0.02, that is, the entire picture does not contradict the galactic conversion scenario.

Distant objects.- In the ideal case and in the long-distance limit, the effective optical depth $\tau_{\rm ALP}$ behaves differently in the two scenarios: for intergalactic conversion, $\tau_{\rm ALP} \sim (2/3)\tau$ (and therefore grows approximately linearly with distance, like the standard optical depth τ), while for the galactic scenario, assuming maximal mixing, it reaches a constant, distance-independent value corresponding to the flux suppression by a factor of $\sim 2/9$, that is $\tau_{\rm ALP} \sim 1.5$. At a certain redshift $z_{\rm crit}$, the value of which depends on the details of the absorption model and of magnetic fields assumed, the two suppression factors are equal, while beyond $z_{\rm crit}$, the absorption becomes stronger and stronger in the intergalactic scenario, remaining constant in the galactic one. This means that for very high redshifts, the anomalous transparency effect would hardly be seen in observations for the intergalactic scenario, therefore any evidence for the effect for very distant sources [2] speaks in favour of the galactic conversion.

Intergalactic magnetic fields.- The intergalactic scenario requires rather high intergalactic magnetic fields (IGMF), $B \sim (10^{-10}$–$10^{-9})$ G, otherwise the conversion probability would be too low. The suppression of the intergalactic conversion is implied in the galactic scenario, so we refer to $B \lesssim 10^{-11}$ G in this case. Present-day knowledge does not allow for a firm conclusion about real values of B. A number of constraints are summarized in the review [18]. The most stringent observational limit, based on the redshift independence of the Faraday rotation from distant sources, is $B \leq 1.2 \times 10^{-9}$ G [19].

While all three methods to distinguish between the two scenarios favour weakly the galactic conversion mechanism, it is clear that future tests are required both to confirm the anomalous transparency of the Universe and to single out its explanation. To approach the tests on more solid grounds, future observations are necessary. Of particular importance are spectral and anisotropy studies, for which the following directions are especially important. First, to enlarge the overall statistics of TeV blazars, which is best achieved with the coming CTA. Second, to study absorption effects in the spectra of the most distant blazars, for which one needs high-sensitivity observations at energies $\sim$ (10-100) GeV. The sensitivities of both FERMI LAT and CTA [20] are insufficient in this energy range; the solution may be provided by high-altitude low-threshold Cerenkov detectors [21]. Presently, two projects of this kind are under consideration, the ALEGRO in Atacama, Chile, and EGO at the Mount Elbrus, Russia. Third, to move into the strong-absorption energy range for bright nearby blazars, which would require observations at $\sim$ 100 TeV. The proper instruments for that would be extensive-air-shower detectors, in particular, TAIGA [22] and the upgraded Carpet array in Baksan [23] in the nearest future, as well as LHAASO [24] and HiSCORE [25] several years later.

Additional important contributions to the discussion are expected from observational constraints on the IGMF values and, of course, from laboratory searches for the responsible ALP, with the most sensitive planned instruments being IAXO [26] and ALPS-II [27] .

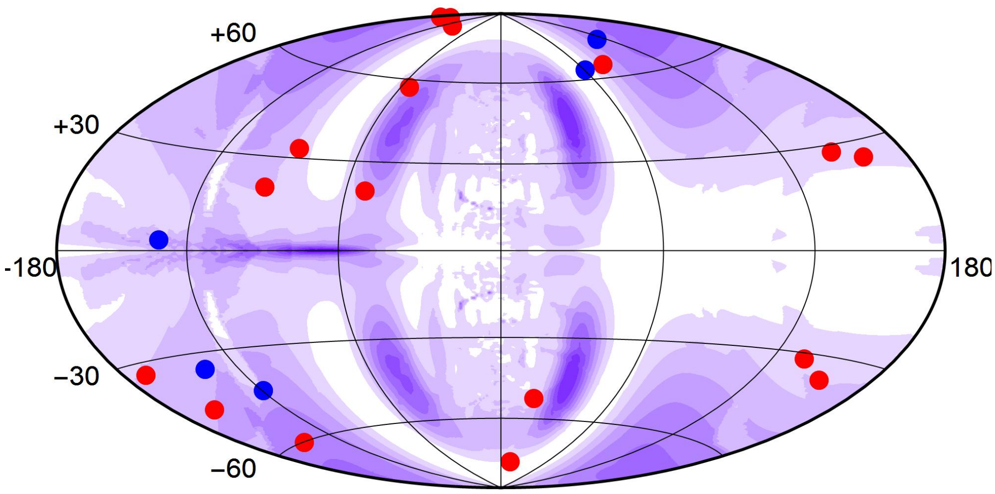

Figure 2: The skymap (Galactic coordinates, Hammer projection) with positions of blazars with detected gamma-ray flux at energies for which $\tau > 1$ (red, $0.1 < z < 1$; blue, $z > 1$), see text. Deeper shading corresponds to higher ALP-photon conversion probability in the Milky Way (the GMF of Ref. [12]).

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