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Parameters of axion-like particles required to explain high-energy photons from GRB 221009A

Dedicated to the memory of my teacher Valery Rubakov

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An unusual energetic astrophysical transient Swift J1913.1 + 1946 has been detected on October 9, 2022 [1] and soon associated with a gamma-ray burst GRB 221009A detected by Fermi GBM [2]. The redshift of the GRB is $z \approx 0.151$ [3–5]. The main peculiarity of the transient is the presence of extremely energetic gamma rays, never detected from a GRB. LHAASO reported the detection of thousands of photons with energies up to 18 TeV in the first 2000 s [6], and Carpet-2 reported the detection of a 251-TeV photon-like air shower 4536 s after the trigger [7]. Both observations challenge conventional understanding because gamma rays of that high energies cannot reach us from distant sources [8]. They should instead produce e^+e^- pairs on the cosmic background radiation. The optical depth for a source at $z = 0.151$ is estimated as $\sim 15 \pm 5$ for 18 TeV and > 3000 for 251 TeV. Non-standard physics is required to overcome this problem.

One possibility is mixing of photons with hypothetical axion-like particles (ALPs) in the external magnetic field [9], see [10, 11]; for reviews and more references, e.g. [12–14]. ALPs do not produce pairs and so they propagate unattenuated through the Universe. In sufficiently strong magnetic fields, photons convert to ALPs and back, and the mixed particle beam can travel longer than pure photons. It is important to distinguish two cases [15]. (1) ALP parameters allow for conversion in the extragalactic magnetic field, so the photon-ALP oscillations happen along the entire path from the source to the observer [10, 11]. (2) Stronger fields are required for non-negligible mixing, so that the conversion happens near the source, in the host galaxy, cluster or filament, and again in the Local Supercluster or in the Milky Way [16, 17]. In the case of intergalactic mixing, the gamma-ray part of the mixed beam is constantly fed by the ALP part and attenuates, so, in the limit of large distance, all energy finally goes to e^+e^- pairs. If the intergalactic mixing is suppressed, then some part of photons may convert to ALPs near the source and reconvert back to gamma rays near the observer; the remaining gamma-ray part of the beam attenuates as usual. For large distances, larger photon fluxes are expected to be observed in the latter case [15]. In the context of GRB 221009A, ALP/photon mixing was partly addressed in [18] and [19].

We assume the maximal mixing in the source and neglect the mixing in the intergalactic space. The state arriving to the Milky Way is thus pure ALP and the flux is $1/3$ of the emitted photon flux. In the Milky Way, we solve numerically the evolution equation in the density-matrix formalism, as described e.g. in [20]. We use the Galactic magnetic field model of [21] for the line of sight to GRB 221009A.

In Figure 1, above the full blue and dashed red lines, the surviving probability for photons of 18 and 251 TeV, respectively, exceeds 1 %, so that the ALP-gamma conversion could in principle help to observe gamma rays from the distant source. We need to guarantee that the mixing in intergalactic magnetic field is suppressed, which results in the shaded excluded regions to the left of Fig. 1. The used value of 1 nG is close to the observational upper bound on the intergalactic magnetic field [25], the lines would shift to smaller m if the field is weaker. The white central part of the plot corresponds to the values of m and g for which the observations by LHAASO and Carpet-2 may be explained by photon-ALP mixing. These parameters are motivated in some ALP models, e.g., [26, 27]. Some constraints from astrophysical photon observations probe this part of the ALP parameter space but depend on the assumptions about poorly known magnetic fields in astrophysical sources [20, 13]. The strongest of these constraints [24] is shown in Fig. 1 as a gray dash-dotted line. There remains an allowed part of the parameter space for the explanation of the observed energetic photons.

Only a small fraction of events detected by LHAASO and Carpet-2 are photons. For LHAASO, [19] estimated the expected number of background cosmic-ray events with ~ 18 TeV energies during 2000 s observation time as 2.8, using published results of a different LHAASO

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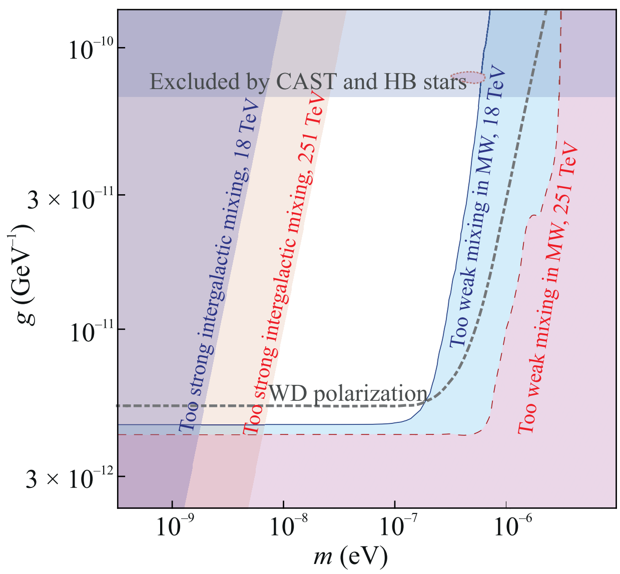

Fig. 1. (Color online) ALP mass m and photon coupling g. ALPs with parameters in the white central part of the plot can explain both 18 TeV and 251 TeV photons. The top band is disfavoured by the CAST search for solar axions [22] and by constraints from the evolution of horizontal-branch (HB) stars [23]. In the shaded area to the left, strong mixing in the intergalactic space (for the magnetic field of 1 nG) results in strong suppression of the photon flux. The upper limit from magnetic white dwarf polarization [24] is shown by the gray dash-dotted line. See the text for details and discussion

analysis as the input, so the real value may differ significantly from this estimate. Carpet-2 events similar to the 251-TeV photon-like shower are certainly rare [28], and the probability of the background coincidence is 1.2×10^{-4} [7].

There remains a possibility that the highest-energy events came from a Galactic source, especially given the low Galactic latitude, $b \approx 4°$, of the event [7]. In this case, the photons would not have time to produce pairs [7, 29]. It remains to be understood if any Galactic source can be responsible for the observed events. It can even be possible that a superposition of a GRB and a Galactic flare was observed (note the unusual light curve of the transient [30, 31]).

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