Birefringence in CMB anisotropies due to cosmological pseudoscalar fields

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We review the data on isotropic cosmic birefringence coming from Cosmic Microwave Background (CMB) linear polarization observations. We show the different constraints on the coupling constant $g_\phi$ between photons and axion-like particles acting as dark matter.
1. Introduction - Cosmological pseudoscalar field acting as dark matter

The usual coupling between the electromagnetic tensor $F_{\mu\nu}$ and a pseudoscalar field $\phi$ 
$-1/4 g_\phi \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$ induces a rotation of the linear polarization plane during propagation. For a single photon this rotation angle is proportional to the coupling constant $g_\phi$ and to the variation of the field during propagation [1, 2]:

$$\frac{g_\phi}{2} \left[ \phi(x) - \phi(x_{\text{em}}) \right].$$  \hspace{1cm} (1)

In presence of a cosmological pseudoscalar field acting as dark matter - e.g. assuming for the pseudoscalar field a potential of the form $V(\phi) = m^2 f^2 (1 - \cos \phi / f)$ - it is possible to study the effects of this coupling over cosmological distances.

In Section 2 we summarize the results for isotropic CMB polarization data. In Section 3 we show how these observations induce constraints in the $(m, g_\phi)$-plane for axion-like particles acting as dark matter.

2. CMB constraints on isotropic cosmic birefringence

Many experiments and satellites [3–10] provide data on the birefringence angle $\alpha$ describing the rotation of CMB linear polarization during propagation from last scattering surface to today (cosmic birefringence). We summarize the main results on the isotropic effect in Fig. 1.

In the approximation of a redshift/time independent isotropic rotation angle $\bar{\alpha}$, cosmic birefringence is degenerate with an angular miscalibration of the detector [11, 12]:

$$C_{\ell}^{T,\text{const}} = C_{\ell}^{T,\text{rec}} \cos(2\bar{\alpha}), \quad C_{\ell}^{E,\text{const}} = C_{\ell}^{E,\text{rec}} \cos^2(2\bar{\alpha}), \quad C_{\ell}^{B,\text{const}} = C_{\ell}^{E,\text{rec}} \sin^2(2\bar{\alpha}),$$

$$C_{\ell}^{T,\text{const}} = C_{\ell}^{T,\text{rec}} \sin(2\bar{\alpha}), \quad C_{\ell}^{E,\text{const}} = \frac{1}{2} C_{\ell}^{E,\text{rec}} \sin(4\bar{\alpha}).$$ \hspace{1cm} (2)

Recently the detection of a nonzero isotropic cosmic birefringence was claimed using polarized galactic foreground emission to disentangle cosmic birefringence from miscalibration of the detector, see [13–15] (e.g. $\bar{\alpha} = 0.342^{+0.094}_{-0.091}$ deg in [15]). These hints of a non-zero isotropic cosmic birefringence - see the last three data points in Fig. 1 - are still quite controversial since it is very difficult to model foreground emissions, in particular interstellar dust polarization.

These observations can be used to constrain $g_\phi$, the coupling constant between axion-like particles and photons. In [19] we modified the Boltzmann equation for linear polarization considering a redshift/time dependent isotropic birefringence angle, overcoming the wildly used approximation of a redshift/time independent rotation angle, see Eqs. (2). We showed that the impact of the birefringence angle on the CMB power spectra depends on the evolution profile of the pseudoscalar field and not only on the total variation of the field. We later extended and updated our considerations in [20, 21].

We plot CMB birefringence constraints in the $(m, g_\phi)$-plane in Fig. 2 assuming that the pseudoscalar field is contributing to the dark matter content of the universe. We also show the values the coupling constant $g_\phi$ should have in order to induce an isotropic cosmic birefringence of 0.34 deg [15, 21].
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3. Conclusions

We summarized CMB isotropic birefringence observations and corresponding constraints for axion-like particles acting as dark matter in Fig. 2. CMB observations put interesting constraints on pseudoscalar-photon coupling constant $g_\phi$ for small values of the mass $m$. For higher values of the mass the pseudoscalar field oscillates very quickly and the effect rapidly decreases.

Other interesting constraints, in this area of the axion-like particle parameter space $(m, g_\phi)$, are obtained looking at ultraviolet polarization of distant radio galaxies [22]. In this low mass region there are also data coming from periodic oscillations of the polarization coming from the Crab supernova remnant (observed by the QUIJOTE MFI instrument) and pulsars from the Parkers Pulsar Timing Array (PPTA) [23].

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References

**Figure 2:** Coupling constant $g\phi$ as a function of the mass $m$ of the pseudoscalar field. Plot created with the AxionLimits code [24], see online documentation for references on different constraints. We added the constraints coming from CMB birefringence in blue [20] (light blue [21]); we plotted the values the coupling constant $g\phi$ should have in order to induce an isotropic cosmic birefringence of 0.34 deg [15, 21] (blue continuous line). The constraint coming from ultraviolet polarization of distant radio galaxies is plotted in pink [22].


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