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Axion field tomography: cosmic birefringence from the epochs of recombination and reionization

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When coupled to electromagnetism through a Chern-Simons interaction, axion-like particles (ALP) produce a rotation of the plane of linear polarization known as cosmic birefringence (CB). As CB depends on the evolution of the ALP field during the flight of photons, the cosmic microwave background (CMB) photons emitted during reionization might experience a different rotation than those emitted during recombination. Recent measurements from small angular scale CMB polarization anisotropies hint at a $\beta_{\rm rec} \approx 0.3^\circ$ CB angle from the recombination epoch. Here, we combine large and small angular scale CMB polarization data to simultaneously measure instrumental miscalibration angles and the CB rotation from both epochs, deriving preliminary $|\beta_{\rm reio}| < 4.55^\circ$ (68% CL) constraints on the CB angle from the reionization epoch through the use of EE and BB information.

1st General Meeting and 1st Training School of the COST Action COSMIC WSIPers (COSMICWISPers)
5-14 September, 2023
Bari and Lecce, Italy

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1. Introduction

Axion-like particles (ALP) englobe a variety of light bosons predicted in supersymmetry and string theories as well-motivated dark matter candidates [1]. If coupled to the electromagnetic tensor and its dual via a Chern-Simons term in the Lagrangian density, $\mathcal{L} \subset \frac{1}{4} g_{\phi\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$, ALP would rotate the photons' plane of linear polarization clockwise in the sky by $\beta = -\frac{1}{2} g_{\phi\gamma} \int \partial\phi/\partial t dt$. This rotation is known as cosmic birefringence (CB) [2] and, in the case of cosmic microwave background (CMB) polarization measurements, is degenerate with any potential α miscalibration of the detectors' polarization angle.

For ALP masses around 10^{-32} eV $\leq m_\phi \leq 10^{-29}$ eV, the CMB photons emitted during the recombination and reionization epochs would have seen different values of $\phi(t)$, leading to distinct $\beta_{\rm reio}$ and $\beta_{\rm rec}$ angles. In particular, the large angular scales of the CMB polarization angular power spectra (APS) allow us to distinguish between $\beta_{\rm reio}$ and $\beta_{\rm rec}$ [3, 4], offering a tomographic view into the ALP field between $z \approx 10$ and $z \approx 1100$. Here, we combine the large and small angular scales of *Planck* `SRoll2` data [5] to isolate the contribution of each rotation and obtain the first simultaneous measurement of α miscalibrations and both $\beta_{\rm reio}$ and $\beta_{\rm rec}$ CB angles. All the preliminary results quoted correspond to 68% CL.

2. $\beta_{\rm rec}$ from high-ℓ analysis

Small angular scale ($\ell \gtrsim 30$) CMB polarization data is sensitive to instrumental miscalibrations and $\beta_{\rm rec}$ rotations. At these scales, we can use Galactic foreground emission to break the degeneracy between CB and small α_i miscalibrations of the detectors' polarization angle [6, 7]. We measure both rotations by closely following the methodology presented in Refs. [8, 9]. To summarize, within the small-angle approximation, the EB correlation that CMB experiments observe at different ν_i frequency bands takes the form

$$C_\ell^{E_iB_j,\rm ob} \approx 2\alpha_j C_\ell^{E_iE_j,\rm ob} - 2\alpha_i C_\ell^{B_iB_j,\rm ob} + \mathcal{A} C_\ell^{E_iB_j,\rm dust} + 2\beta_{\rm rec}\left(C_\ell^{E_iE_j,\Lambda\rm CDM} - C_\ell^{B_iB_j,\Lambda\rm CDM}\right), \quad (1)$$

where $C_\ell^{XY,\Lambda\rm CDM}$ denotes the theoretical CMB spectra in the absence of ALP, and $C_\ell^{XY,\rm dust}$, the spectra of polarized Galactic dust emission, both convolved by beam and pixel window functions. Hence, we can simultaneously self-calibrate α_i angles and measure CB from the EB cross-correlations observed across multiple frequency bands by providing dust and CMB models.

Following Refs. [8, 9], we use the `Commander` sky model [10] as our dust model and leave $\mathcal{A}$ as a free amplitude parameter. We take $\mathcal{A}$ as a single overall amplitude and use `Commander`'s spectral energy distribution to scale the dust template to the target frequencies. Unlike Refs. [8, 9], we work with half-mission (HM) splits. Assuming that miscalibrations do not change over time, we assign the same α_i angle to both HM splits, with $i = 100, 143, 217, 353$ GHz. Although we are only interested in α_{100} and α_{143} for the subsequent low-ℓ analysis, the inclusion of the dust-dominated 217 and 353 GHz channels improves our ability to constrain dust emission, reducing the overall statistical uncertainty. We build a common analysis mask by joining the $f_{\rm sky} = 0.85$ mask used in Refs. [8, 9] with the unobserved pixels of each HM split [5]. After applying a 2.5° cosine apodization, we are left with a $f_{\rm sky} = 0.56$ sky fraction. We calculate the pseudo-C_ℓ of the observed signal and foreground model for $50 \leq \ell \leq 1500$ multipoles using `NaMaster`[1] [11].

Our analysis of `SRoll2` small angular scale data yields $\beta_{\rm rec} = 0.38^\circ \pm 0.15^\circ$, $\alpha_{100} = -0.38^\circ \pm 0.16^\circ$, $\alpha_{143} = 0.06^\circ \pm 0.15^\circ$, $\alpha_{217} = 0.01^\circ \pm 0.14^\circ$, and $\alpha_{353} = -0.15^\circ \pm 0.13^\circ$.

3. $\beta_{\rm reio}$ from low-ℓ analysis

Large angular scale ($\ell \lesssim 30$) CMB polarization data is sensitive to α_i miscalibrations and both CB rotations. In particular, we can use the height of the reionization bump to distinguish between $\beta_{\rm reio}$ and $\beta_{\rm rec}$ [3, 4]. At these scales, polarized foreground emission vastly overpowers CMB anisotropies, and Eq. (1) can no longer be used to estimate β and α simultaneously. Therefore, we remove Galactic foregrounds from our observations and instead use Bayesian inference to estimate α_i and both β rotations from the CMB EE and BB signal. Our results are derived using `momento` [12, 13], a semi-analytical likelihood approximation based on the principle of maximum entropy. To summarize, `momento` uses near-optimal quadratic cross-spectra to compress the CMB data into a set of APS, sampling over cosmological parameters to find the fiducial APS that most likely describes the data.

We obtain our CMB APS ($C_\ell^{XY,\rm CMB}$) by using the foreground cleaning, noise covariance matrices, and data compression procedure presented in Ref. [13]. As in Ref. [13], we cross-correlate `SRoll2` 100 and 143 GHz full-mission maps to reduce the impact of correlated noise and systematics. We approximate the effect that α_i miscalibrations and CB have on the CMB APS with

$$\begin{aligned} C_\ell^{E_{100}E_{143},\rm CMB} \approx\ & \cos(2\alpha_{100}+2\beta_{\rm reio})\cos(2\alpha_{143}+2\beta_{\rm reio})\, C_\ell^{EE,\rm reio} \\ & + \cos(2\alpha_{100}+2\beta_{\rm rec})\cos(2\alpha_{143}+2\beta_{\rm rec})\, C_\ell^{EE,\rm rec}, \end{aligned} \tag{2}$$

$$\begin{aligned} C_\ell^{B_{100}B_{143},\rm CMB} \approx\ & \sin(2\alpha_{100}+2\beta_{\rm reio})\sin(2\alpha_{143}+2\beta_{\rm reio})\, C_\ell^{EE,\rm reio} \\ & + \sin(2\alpha_{100}+2\beta_{\rm rec})\sin(2\alpha_{143}+2\beta_{\rm rec})\, C_\ell^{EE,\rm rec} + C_\ell^{BB,\Lambda\rm CDM}, \end{aligned} \tag{3}$$

where $C_\ell^{XY,\rm CMB}$ have been deconvolved by the beam and pixel window functions. We calculate $C_\ell^{EE,\rm rec}$ by running the Boltzmann solver `CAMB`[2] [14] with $\tau = 0$. Following Ref. [4], we estimate the reionization contribution to the EE power spectrum as $C_\ell^{EE,\rm reio} = C_\ell^{EE}(\tau = 0.06) - e^{-2\times 0.06} C_\ell^{EE}(\tau = 0)$.

We perform five-dimensional scans in a $\{\tau, \beta_{\rm reio}, \beta_{\rm rec}, \alpha_{100}, \alpha_{143}\}$ parameter grid, allowing A_s to change according to a fixed value of $10^9 A_s e^{-2\tau} = 1.870$. The remaining cosmological parameters are fixed to *Planck*'s ΛCDM best-fit cosmology ($H_0 = 67.04, \Omega_b h^2 = 0.0221, \Omega_c h^2 = 0.12, \Omega_\nu h^2 = 0.00064, \theta_* = 1.0411, n_s = 0.96$) [15] with $r = 0$. We include the results from the high-ℓ analysis (after marginalizing over α_{217} and α_{353}) as a three-dimensional Gaussian prior on $\{\beta_{\rm rec}, \alpha_{100}, \alpha_{143}\}$. We find $\tau = 0.054 \pm 0.006$ and $|\beta_{\rm reio}| < 4.55^\circ$ best-fit values from the analysis of EE and BB multipoles in the range $2 \leq \ell \leq 10$. The low-ℓ estimates of $\{\beta_{\rm rec}, \alpha_{100}, \alpha_{143}\}$ are prior-dominated due to the low constraining power that large-scale CMB multipoles have over such parameters.

[1] https://github.com/LSSTDESC/NaMaster
[2] https://camb.info/

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4. Discussion and future work

We have presented preliminary results on the first analysis combining high- and low-ℓ CMB polarization data to simultaneously measure α_i miscalibrations and both $\beta_{\rm reio}$ and $\beta_{\rm rec}$ CB rotations. First, we used $50 \leq \ell \leq 1500$ multipoles to measure $\beta_{\rm rec} = 0.38^\circ \pm 0.15^\circ$ and self-calibrate α_i angles. Then, we derived $\tau = 0.054 \pm 0.006$ and $|\beta_{\rm reio}| < 4.55^\circ$ constraints from the $\ell \leq 10$ multipoles of the EE and BB APS. Our next steps include the addition of EB information to the analysis and the assessment of the impact that foreground residuals and the uncertainty in the calibration of the instrument's polarization efficiency have on our measurements.

No robust constraints on the nature of ALP can be drawn from our results at this stage. A more detailed study and, especially, high-precision full-sky CMB polarization measurements like those LiteBIRD [16] will provide are needed to confirm the values currently favored for both CB angles.

Acknowledgments

This publication is based upon work from COST Action COSMIC WISPers CA21106, supported by COST (European Cooperation in Science and Technology). PDP acknowledges financial support from the grant PID2019-110610RB-C21 funded by MCIN/AEI/10.13039/501100011033. We acknowledge the use of `CAMB` [14], `HEALPix` [17], `NaMaster` [11], and `Numpy` [18].

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