Improved Constraints on Cosmic Birefringence from the WMAP and Planck Cosmic Microwave Background Polarization Data

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The observed pattern of linear polarization of the cosmic microwave background (CMB) photons is a sensitive probe of physics violating parity symmetry under inversion of spatial coordinates. A new parity-violating interaction might have rotated the plane of linear polarization by an angle \( \beta \) as the CMB photons have been traveling for more than 13 billion years. This effect is known as “cosmic birefringence.” In this paper, we present new measurements of cosmic birefringence from a joint analysis of polarization data from two space missions, Planck and WMAP. This dataset covers a wide range of frequencies from 23 to 353 GHz. We measure \( \beta = 0.342^{+0.094}_{-0.091} \) (68\% C.L.) for nearly full-sky data, which excludes \( \beta = 0 \) at 99.987\% C.L. This corresponds to the statistical significance of 3.6\sigma. There is no evidence for frequency dependence of \( \beta \). We find a similar result, albeit with a larger uncertainty, when removing the Galactic plane from the analysis.

I. INTRODUCTION

Photons of the cosmic microwave background (CMB), the afterglow of the primordial fireball Universe \[1\], are linearly polarized \[2\]. One can decompose the observed pattern of linear polarization into eigenstates of parity called \( E \) and \( B \) modes, which transform differently under inversion of spatial coordinates \[3, 4\]. This property can be used to probe new physics beyond the standard model of elementary particles and fields that violates parity symmetry \[5\].

A pseudoscalar “axionlike” field, \( \phi \), that couples to electromagnetism is an example of such new physics. Consider a Lagrangian density given by \[6, 7\]

\[
\mathcal{L} = -\frac{1}{2}(\partial \phi)^2 - V(\phi) - \frac{\alpha}{4f} \phi F \tilde{F},
\]

(1)

where \((\partial \phi)^2 \equiv g^{\mu \nu} \partial_\mu \phi \partial_\nu \phi \) with the metric tensor \( g^{\mu \nu} \), \( V(\phi) \) is \( \phi \)’s potential, \( F^{\mu \nu} \equiv g^{\mu \rho} g^{\nu \sigma} F_{\rho \sigma} \), \( \tilde{F} \equiv F_{\mu \nu} \epsilon^{\mu \nu \rho \sigma} F_{\rho \sigma} / (2\sqrt{-g}) \), and \( \alpha \) and \( f \) are a dimensionless coupling constant and the so-called axion decay constant, respectively. Here, \( F_{\mu \nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu \) is the antisymmetric electromagnetic tensor with the vector potential \( A_\mu \), \( \epsilon^{\mu \nu \rho \sigma} \) is a totally antisymmetric symbol with \( \epsilon^{0123} = 1 \), and \( g \) is the determinant of the metric tensor.

The last term in Eq. (1) is familiar in particle physics, as it appears in the low-energy effective action of quantum chromodynamics \[8\]. A pion is a pseudoscalar \[9\] and a neutral pion decays into two photons via this term with \( \alpha \) and \( f \) determined precisely by experiments. In cosmology, \( \phi \) is a new pseudoscalar and a candidate for dark matter and dark energy \[10, 11\] with \( \alpha / f \) being a free parameter.

The observed pattern of linear polarization of the cosmic microwave background (CMB) photons is a sensitive probe of physics violating parity symmetry under inversion of spatial coordinates. A new parity-violating interaction might have rotated the plane of linear polarization by an angle \( \beta \) as the CMB photons have been traveling for more than 13 billion years. This effect is known as “cosmic birefringence.” In this paper, we present new measurements of cosmic birefringence from a joint analysis of polarization data from two space missions, Planck and WMAP. This dataset covers a wide range of frequencies from 23 to 353 GHz. We measure \( \beta = 0.342^{+0.094}_{-0.091} \) (68\% C.L.) for nearly full-sky data, which excludes \( \beta = 0 \) at 99.987\% C.L. This corresponds to the statistical significance of 3.6\sigma. There is no evidence for frequency dependence of \( \beta \). We find a similar result, albeit with a larger uncertainty, when removing the Galactic plane from the analysis.

When \( \phi \) depends on spacetime, the plane of linear polarization of photons rotates \[12–14\] by an angle \( \beta(\mathbf{n}) = \frac{\pi}{2} \phi(\eta_0, \mathbf{n}) \), where \( \mathbf{n} \) is the direction of an observer’s line of sight, \( \eta_0 \) and \( \eta_0 \) are the conformal times of observation and emission of photons, respectively, and \( r \equiv \eta_0 - \eta_0 \) is the conformal distance to the emitter. We take the speed of light to be unity throughout this paper.

This effect is often called “cosmic birefringence,” and is best probed by analyzing the oldest polarized light in the Universe, that is, the CMB (see Ref. \[15\] for a review).

Discovery of a non-zero value of \( \beta \) would have profound implications for the fundamental physics behind dark energy \[16, 17\], dark matter \[18, 19\], and quantum gravity \[20, 21\].

When analyzing CMB data, one decomposes the Stokes parameters for linear polarization as \[3, 4\]

\[
Q(\mathbf{n}) \pm iU(\mathbf{n}) = -\sum_{\ell=2}^{\ell_{\text{max}}} \sum_{m=-\ell}^{\ell} (E_{\ell m} \pm iB_{\ell m}) \pm \varepsilon Y^m_{\ell}(\mathbf{n}),
\]

(2)

where \( E_{\ell m} \) and \( B_{\ell m} \) are the spherical harmonics coefficients of the \( E \) and \( B \) modes, respectively, \( \varepsilon Y^m_{\ell}(\mathbf{n}) \) are the spin-2 spherical harmonics, and \( \ell_{\text{max}} \) is the maximum multipole used for the analysis.

The coefficients transform under inversion of spatial coordinates, \( \mathbf{n} \rightarrow -\mathbf{n} \), as \( E_{\ell m} \rightarrow (-1)^\ell E_{\ell m} \) and \( B_{\ell m} \rightarrow (-1)^{\ell+1} B_{\ell m} \). The cross-power spectrum of \( E \) and \( B \) modes, \( C_{\ell}^{EB} \equiv (2\ell+1)^{-1} \sum_m \text{Re}(E_{\ell m}^{*} B_{\ell m}) \), has odd parity and is sensitive to \( \beta \) \[3\]. When the plane of linear polarization rotates uniformly on the sky by an angle \( \beta \), the observed \( E \) and \( B \) modes become \( E_{\ell m}^{\beta} = E_{\ell m} \cos(2\beta) - B_{\ell m} \sin(2\beta) \) and \( B_{\ell m}^{\beta} = E_{\ell m} \sin(2\beta) + B_{\ell m} \cos(2\beta) \), re-
respectively. One thus finds that \[22–26\]

\[
C_{\ell}^{EB,o} = \frac{\tan(4\beta)}{2} \left( C_{\ell}^{EE,o} - C_{\ell}^{BB,o} \right) + \frac{C_{\ell}^{EB}}{\cos(4\beta)}, \quad (3)
\]

where the last term is the intrinsic EB correlation at the time of emission, and \(C_{\ell}^{EE}\) and \(C_{\ell}^{BB}\) are the auto-power spectra of \(E\) and \(B\) modes, respectively. One finds that \[26\] for a single channel. Here, “fg” and “CMB” denote the polarized emission of interstellar gas, called the Galactic plane. These angles will be degenerate with the cosmic birefringence angle \(\beta\). We will from now on denote misalignment angles by \(\alpha\), which should not be confused with the coupling constant in Eq. (1).

Hence, the observed EB power spectrum measured by an instrument gets an extra rotation contribution from its misalignment angle \(\alpha\), inducing a total rotation of \(\alpha + \beta\). Without knowledge of \(\alpha\), one can only determine the sum of the two angles, \(\alpha + \beta\).

The sky contains not only the CMB, but also the polarized emission of interstellar gas, called the Galactic foreground. Photons of the foreground emission do not travel for a long distance, receiving only a negligible amount of \(\beta\) when \(\phi\) varies slowly in spacetime; thus, the foreground polarization is rotated only by the misalignment angle \(\alpha\). \[26\] The foreground emission might possess a non-vanishing intrinsic EB correlation, which needs to be taken into account.

These considerations lead to

\[
\begin{bmatrix}
E_{\ell m}^o \\
B_{\ell m}^o
\end{bmatrix} = \begin{bmatrix}
\cos(2\alpha) & -\sin(2\alpha) \\
\sin(2\alpha) & \cos(2\alpha)
\end{bmatrix} \begin{bmatrix}
E_{\ell m}^{fg} \\
B_{\ell m}^{fg}
\end{bmatrix} + \begin{bmatrix}
\cos(2\alpha + 2\beta) & -\sin(2\alpha + 2\beta) \\
\sin(2\alpha + 2\beta) & \cos(2\alpha + 2\beta)
\end{bmatrix} \begin{bmatrix}
E_{\ell m}^{CMB}^{fg} \\
B_{\ell m}^{CMB}
\end{bmatrix},
\]

for a single channel. Here, “fg” and “CMB” denote the foreground and CMB, respectively. One finds that \[26\]

\[
C_{\ell}^{EB,o} = \frac{\tan(4\beta)}{2} \left( C_{\ell}^{EE,o} - C_{\ell}^{BB,o} \right) + \frac{C_{\ell}^{EB,fg}}{\cos(4\beta)} + \frac{\sin(4\beta)}{2\cos(4\alpha)} \left( C_{\ell}^{EE,CMB} - C_{\ell}^{BB,CMB} \right) + \frac{\cos(4\beta)}{\cos(4\alpha)} C_{\ell}^{EB,CMB}. \quad (4)
\]

for a single channel. Here, “fg” and “CMB” denote the foreground and CMB, respectively. One finds that \[26\]

\[
C_{\ell}^{EB,o} = \frac{\tan(4\beta)}{2} \left( C_{\ell}^{EE,o} - C_{\ell}^{BB,o} \right) + \frac{C_{\ell}^{EB,fg}}{\cos(4\beta)} + \frac{\sin(4\beta)}{2\cos(4\alpha)} \left( C_{\ell}^{EE,CMB} - C_{\ell}^{BB,CMB} \right) + \frac{\cos(4\beta)}{\cos(4\alpha)} C_{\ell}^{EB,CMB}. \quad (5)
\]

This equation allows us to determine \(\alpha\) and \(\beta\) simultaneously, independent of the \(E\) and \(B\)-mode auto-power spectra of the foreground, \(C_{\ell}^{EE,fg}\) and \(C_{\ell}^{BB,fg}\).

Eq. (5) still requires knowledge of \(C_{\ell}^{EB,fg}\) and \(C_{\ell}^{EB,CMB}\). Discovery of the latter would be similarly revolutionary in cosmology; however, we ignore this term in this paper because the current data are not yet sensitive enough to detect it.

We take into account the effect of \(C_{\ell}^{EB,fg}\). As the foreground helps us constrain \(\alpha\), neglecting any non-zero \(C_{\ell}^{EB,fg}\) in the analysis can bias the measurement of \(\alpha\). A biased \(\alpha\) will necessarily bias \(\beta\) since the CMB highly constrains the sum, \(\alpha + \beta\).

After being verified on simulations with multiple frequency channels \[31\], the method was applied to the high frequency instrument (HFI \[32\]) maps of the Planck Public Release 3 (PR3) in Ref. \[33\]. The authors measured \(\beta = 0.35^\circ \pm 0.14^\circ\) for nearly full-sky data. We quote the 68\% confidence level (C.L.) intervals throughout this paper. The method was then applied to the Planck PR4 HFI data \[34\], yielding \(\beta = 0.30^\circ \pm 0.11^\circ\). The low frequency instrument (LFI \[36\]) maps of the Planck PR4 were included in the analysis of Ref. \[37\], which found \(\beta = 0.33^\circ \pm 0.10^\circ\). The statistical significance exceeds 3\(\sigma\).

Ref. \[37\] also measured the frequency dependence of the signal by fitting a power-law model, \(\beta(\nu) \propto \nu^\alpha\), finding \(n = -0.35 \pm 0.48\). This is consistent with a frequency-independent signal predicted by the anisotropic field, Eq. (1).

These authors \[33, 35, 37\] initially ignored \(C_{\ell}^{EB,fg}\) in the analysis. As the foreground is dominated by polarized dust emission at the HFI frequencies \[35\], they noted that the positive dust signal is ignored, the inferred value of \(\beta\) is the cause of the decline of \(\beta\) for lower sky fractions. Although one finds similar values of \(\beta\) from the Planck data regardless of the sky fraction used for the analysis when \(\alpha = 0\), that is, the EB signal \(\alpha + \beta \simeq 0.3^\circ\) is isotropic in the sky, the inferred value of \(\alpha\) depends on the sky fraction via \(C_{\ell}^{EB,fg}\). This was foreseen in the work by Ref. \[39\], which argued that there should be a mostly positive \(C_{\ell}^{EB,fg}\) for smaller sky fractions (larger Galactic masks). This would bias a measurement of \(\beta\) towards a lower value whenever \(C_{\ell}^{EB,fg}\) is ignored.

The authors of Ref. \[35\] suggested an ansatz to model \(C_{\ell}^{EB,fg}\) based on the results of Ref. \[39\]. Including their ansatz to the equations confirmed that \(C_{\ell}^{EB,fg}\) was the cause of the decline of \(\beta\) for lower sky fractions. Including \(C_{\ell}^{EB,fg}\) in the inference gave robust positive measurements of \(\beta\) at all sky fractions.

Therefore, the results so far indicate the presence of an isotropic and frequency-independent signal of cosmic birefringence in the Planck data with a statistical sig-
nificance of 3σ. The detailed study [35, 41] using the simulations of PR4 [34] shows that the impact of the known systematics of the Planck HFI on β is negligible compared with the statistical uncertainty.

In this paper, we continue to search for the isotropic β by including the polarization data of the Wilkinson Microwave Anisotropy Probe (WMAP) 9-year observations [42] in a joint analysis with the polarized Planck channels. The polarization data of WMAP have a lower signal-to-noise ratio than those of the Planck HFI, but the inclusion of the WMAP channels gives rise to many cross-power spectra with both itself and the Planck LFI and HFI channels. This allows us to increase the precision of β. As there is no evidence [43–46] for fluctuations in β(ν), we focus on the isotropic β.

The rest of the paper is organized as follows. We describe the data and the analysis method in Sec. II. We present the results in Sec. III and conclude in Sec. IV.

II. DATA AND ANALYSIS METHOD

We use the WMAP 9-year maps for each differenting assembly, which contain 1, 1, 2, 2, and 4 maps at ν = 23, 33, 41, 61, and 94 GHz, respectively [42]. As in Refs. [33, 35, 37], we also use the Planck PR4 (often called NPIPE-reprocessed data [31]) maps at ν = 30, 44, 70, 100, 143, 217, and 353 GHz. The NPIPE pipeline divided detectors of a given frequency band into two groups, hence creating 2 detector split maps for each band. However, as there were not enough detectors to make 2 maps for each of 30 and 44 GHz bands, we use the so-called half-mission maps for these bands. This means that the 30 and 44 GHz bands have 1 miscalibration angle each, whereas the others have 1 miscalibration angle per detector split map.

The analysis method we use in this paper is similar to those presented in Refs. [33, 35, 37], which we summarize here. The multi-channel generalization of Eq. (5) is

\[
C_{EiBj,\nu} = R^T(\alpha_i, \alpha_j)R^{-1}(\alpha_i, \alpha_j)[C_{EiEj,\nu}^{\text{CAMB}}, C_{EiBj,\nu}^{\text{CAMB}}] + R^T(\alpha_i + \beta_i, \alpha_j + \beta_j) - R^T(\alpha_i, \alpha_j)R^{-1}(\alpha_i, \alpha_j)
\]

\[
\cdot R(\alpha_i + \beta_i, \alpha_j + \beta_j)[C_{EiEj,\nu}^{\text{CAMB}}, C_{EiBj,\nu}^{\text{CAMB}}],
\]

where

\[
R(\theta, \phi) = \begin{bmatrix}
\cos(2\theta)\cos(2\phi) & \sin(2\theta)\sin(2\phi) \\
\sin(2\theta)\sin(2\phi) & \cos(2\theta)\cos(2\phi)
\end{bmatrix},
\]

\[
R(\theta, \phi) = \begin{bmatrix}
\cos(2\theta)\sin(2\phi) \\
-\sin(2\theta)\cos(2\phi)
\end{bmatrix}.
\]

Here, α_i is the miscalibration angle for a given frequency band and data split, i. As we also allow β to depend on frequency, β_i denotes the value of β(ν) at ν = ν_i. We group the cross-power spectra of different combinations of maps into the observed power spectra vector \( \tilde{C}_\nu = [C_{EiEj,\nu}, C_{EiBj,\nu}, C_{EiBj,\nu}^{\text{CAMB}}]^T \). The CMB power spectra, \( C_{EE,\nu}^{\text{CAMB}} \), and \( C_{EB,\nu}^{\text{CAMB}} \), are computed from the Boltzmann solver CAMB [17] with the best-fitting cosmological parameters given in Ref. [48]. We beam-smooth them using the beam transfer functions, \( b_\nu^q \), and pixel window functions, \( w_\nu^q \).

\[
\tilde{C}_{\alpha \beta} = \begin{bmatrix}
C_{EE,\nu}^{\text{CAMB}} b_\nu^E b_\nu^E w_\nu^E w_\nu^E \\
C_{EB,\nu}^{\text{CAMB}} b_\nu^E b_\nu^B w_\nu^E w_\nu^B
\end{bmatrix},
\]

where \( C_{EE,\nu}^{\text{CAMB}} \) and \( C_{EB,\nu}^{\text{CAMB}} \) are the power spectra from CAMB. As not all the official transfer functions of WMAP reach up to \( \ell = 1490 \) used in our analysis, we set \( b_\nu^\ell = 0 \) for \( \ell \) in which transfer functions are not available.

Following Refs. [33, 39, 40], we model \( C_{EB,\nu}^{E,\text{dust}} \) by assuming that the dust EB is proportional to the observed dust TB, that is, \( C_{EB,\nu}^{E,\text{dust}} / C_{E,\nu}^{E,\text{dust}} \propto C_{EB,\nu}^{E,\text{dust}} / C_{E,\nu}^{E,\text{dust}} \). Specifically, we use

\[
C_{EB,\nu}^{E,\text{dust}} = A_\nu C_{E,\nu}^{E,\text{dust}} \sin(4\psi_\nu),
\]

where \( A_\nu \leq 0 \) is a free amplitude parameter and

\[
\psi_\nu = \frac{1}{2} \arctan \left( \frac{C_{EB,\nu}^{E,\text{dust}}}{C_{E,\nu}^{E,\text{dust}}} \right).
\]

We calculate \( \psi_\nu \) from smoothing each of the symmetrized TB and TE spectra of the 353 GHz A and B split maps using a one-dimensional Gaussian filter. The parameter \( A_\nu \) is expected to depend on \( \ell \) weakly. Following Refs. [33, 37], we sample \( A_\nu \) for 4 ranges in 51 ≤ \( \ell \) ≤ 130, 131 ≤ \( \ell \) ≤ 210, 211 ≤ \( \ell \) ≤ 510, and 511 ≤ \( \ell \) ≤ 1490 with flat positive priors.

Unlike Refs. [33, 37], we do not relate Eq. (10) to the effective angle of the foreground EB, \( \gamma \) (cf. Eq. (2) of Ref. [35]). We instead use Eq. (10) directly in our analysis. This procedure is more reliable because it does not require a small-angle approximation or multiplying a noisy factor \( C_{E,\nu}^{E,\text{dust}} / (C_{E,\nu}^{E,\text{dust}} - C_{B,\nu}^{B,\text{dust}}) \) taken from the 353 GHz channels.

We define matrices

\[
A_{i,j} = [-A_{i}^T(\alpha_i, \alpha_j)A_{i}^{-1}(\alpha_i, \alpha_j), 1],
\]

\[
B_{i,j} = [R^T(\alpha_i + \beta_i, \alpha_j + \beta_j) - A_{i}^T(\alpha_i, \alpha_j)A_{i}^{-1}(\alpha_i, \alpha_j)
\]

\[
\cdot R(\alpha_i + \beta_i, \alpha_j + \beta_j),
\]

[1] \url{https://github.com/cmbant/CAMB}
where
\[
\mathbf{A}_\ell(\alpha_i, \alpha_j) = \mathbf{R}(\alpha_i, \alpha_j) + \mathbf{D}(\alpha_i, \alpha_j) \mathbf{F}_\ell, \\
\mathbf{A}_\ell^T(\alpha_i, \alpha_j) = \mathbf{R}^T(\alpha_i, \alpha_j) + \mathbf{D}^T(\alpha_i, \alpha_j) \mathbf{F}_\ell, \\
\mathbf{D}(\theta_i, \theta_j) = \begin{bmatrix}
\cos(2\theta_i) \cos(2\theta_j) \\
\sin(2\theta_i) \cos(2\theta_j) \\
\sin(2\theta_i) \sin(2\theta_j)
\end{bmatrix}, \\
\mathbf{D}(\theta_i, \theta_j) = \begin{bmatrix}
-\cos(2\theta_i) \sin(2\theta_j) \\
\sin(2\theta_i) \cos(2\theta_j) \\
\cos(2\theta_i) \sin(2\theta_j)
\end{bmatrix}, \\
\mathbf{F}_\ell = A_\ell \sin(4\psi_i) \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}.
\]

Here, the matrix \( \mathbf{F} \) is defined differently from that given in Refs. \[35, 37\] to simplify the expression.

We bin the observed power spectra with a bin size \( \Delta \ell = 20 \), and limit the range of multipoles to \( \ell_{\text{min}} \leq \ell \leq \ell_{\text{max}} \) with \( \ell_{\text{min}} = 51 \) and \( \ell_{\text{max}} = 1490 \). We thus use \( N_{\text{bin}} = 72 \) bins. The bin size and multipole range are the same as in the previous work \[33, 35, 37, 49\]. The results are robust against changes in \( \ell_{\text{min}} \) and \( \ell_{\text{max}} \).

To find the posterior distributions of the sampled parameters \( (\alpha_i, \beta_i, A_i) \), we use a Metropolis Markov Chain Monte Carlo sampler to evaluate
\[
\ln L = -\frac{1}{2} \sum_{b=1}^{N_{\text{bin}}} \left( \mathbf{v}_b^T \mathbf{M}_b^{-1} \mathbf{v}_b + \ln |\mathbf{M}_b| \right),
\]
where \( b \) is the bin number, \( \mathbf{M}_b \) is the binned covariance matrix, and \( \mathbf{v}_b^T \equiv \mathbf{A C}^0 - \mathbf{B C}^\text{ACDM} \). The unbinned covariance matrix is given by \( \mathbf{M}_\ell = \mathbf{A C}(\mathbf{C}^0, \mathbf{C}^0) \mathbf{A}^T \). We bin \( \text{Cov}(\mathbf{C}^0, \mathbf{C}^0) \) as \[31\]
\[
\text{Cov}(\mathbf{C}^0, \mathbf{C}^0) = \frac{1}{\Delta \ell^2} \sum_{\ell \in b} \text{Cov}(\mathbf{C}^{XY}, \mathbf{C}^{ZW}),
\]
where we use an approximate covariance for each \( \ell \),
\[
\text{Cov}(\mathbf{C}^{XY}, \mathbf{C}^{ZW}) = \frac{C_{\ell}^{XY, a} C_{\ell}^{YW, a} + C_{\ell}^{XY, a} C_{\ell}^{YZ, a}}{(2\ell + 1)f_{\text{sky}}},
\]
with \( f_{\text{sky}} \) being the fraction of sky used for the analysis.

We avoid using \( EB \) terms in the right-hand side of Eq. \[21\] due to the statistical fluctuations of \( C^{EB, \ell} \). We thus set \( \text{Cov}(\mathbf{C}^{EB, j}, \mathbf{C}^{EB, k}) = C^{EB, j} C^{EB, k} / (2\ell + 1)f_{\text{sky}} \) where \( i, j, p, q \) denote different maps. We also do not use off-diagonal elements in the covariance matrix of Eq. \[21\].

We use PolSpice\[60\] to get the observed power spectra in \( \mathbf{C}^\ell \). We use 14 Planck and 10 WMAP maps, which give 24 \cdot 23 = 552 cross-power spectra, whereas auto-power spectra are excluded.

\[\text{http://www2.iap.fr/users/hivon/software/PolSpice/}\]

**TABLE I.** Measurements of the cosmic birefringence angle, \( \beta \). The baseline result is shown in bold face. For \( \alpha_i = 0 \) we jointly sample \( \beta \), the misalignment angles, \( \alpha_i \), and the dust \( EB \) amplitude, \( A_i \) [Eq. \[10\]], whereas for \( \alpha_i = 0 \) we only sample \( \beta \). The numbers in the third and seventh row (Planck HFI, \( \alpha_i = 0 \)) are taken from Ref. \[35\].

| \( \alpha_i \) | \( \beta \) | \( \text{Planck HFI} \) | \( \text{Planck HFI+LFI} \) + WMAP |
|---|---|---|---|
| 0 | 0.36 ± 0.11 | 0.29 ± 0.28 |
| 0 | 0.30 ± 0.11 | 0.25 ± 0.23 |
| 0 | 0.33 ± 0.035 | 0.18 ± 0.14 |
| 0 | 0.308 ± 0.032 | 0.330 ± 0.035 |
| 0 | 0.288 ± 0.032 | 0.288 ± 0.091 |

Our baseline result is based on the largest, nearly full-sky coverage mask used in Ref. \[37\]. This mask excludes pixels in which the intensity of a carbon-monoxide (CO) line is stronger than 45 K \( \text{Km s}^{-1} \). The CO emission is not polarized, but it could induce intensity-to-polarization leakage. Although the CO line exists only in some of the HFI maps, we apply the same CO mask to all the maps to simplify the analysis. The mask also excludes the locations of known polarized point sources. Specifically we use the union of the point-source masks of all the polarized Planck maps.

We calculate the sky fraction using \[51, 52\]
\[
f_{\text{sky}} = \frac{1}{N_{\text{pix}}} \left( \sum_{i=1}^{N_{\text{pix}}} w_i^4 \right)^2, 
\]
where \( N_{\text{pix}} \) is the number of pixels and \( w_i \) is the weight of the apodized mask at the \( i \)th pixel. We find \( f_{\text{sky}} = 0.92 \) for the baseline CO and point-source mask.

To explore the dependence of \( \alpha_i \) and \( C^{EB, \text{dust}}_\ell \) on the mask, we also use a 30% Galactic mask in union with the CO and point-source masks. The sky fraction is \( f_{\text{sky}} = 0.62 \). These two masks correspond to the largest and smallest \( f_{\text{sky}} \) used in Ref. \[37\].

The code to reproduce the results of this paper is publicly available\[3\].

**III. RESULTS**

First, we assume \( \alpha_i = 0 \) and measure \( \beta = 0.288^\circ \pm 0.032^\circ \) and \( 0.330^\circ \pm 0.035^\circ \) from the Planck HFI data for \( f_{\text{sky}} = 0.92 \) and 0.62, respectively (see the 6th row in Table I). We find similar results for other \( f_{\text{sky}} \). As the

\[\text{https://github.com/LilleJohs/Cosmic_Birefringence}\]
CMB can only determine the sum of $\beta$ and miscalibration angles, this result shows that the $EB$ signal is isotropic in the sky, and we robustly measure $\bar{\alpha} + \beta \simeq 0.3^\circ$ regardless of $f_{\text{sky}}$, where $\bar{\alpha}$ is some suitable average value of $\alpha_i$ for the HFI. This result is not affected by $C_{\ell}^{EB,fg}$ and is consistent with the Planck team’s result performed on foreground-cleaned maps \cite{39}. The foreground emission is not responsible for this signal.

Using all the WMAP and Planck polarization data and still assuming $\alpha_i = 0$, we measure $\beta = 0.298^\circ \pm 0.032^\circ$ and $0.343^\circ \pm 0.035^\circ$ for $f_{\text{sky}} = 0.92$ and 0.62, respectively (second-last row). The statistical power of the data is sufficient to make a significant detection of $\beta$, provided that we know $\alpha_i$.

As both the WMAP and Planck have flown and ended the missions already, we cannot precisely measure the miscalibration angles of their detectors anymore. We thus rely on the foreground to measure $\alpha_i$ as done in Refs. \cite{33,35,37}. When $C_{\ell}^{EB,fg}$ is ignored in the analysis, the WMAP and Planck data yield $\beta = 0.288^\circ \pm 0.091^\circ$ for $f_{\text{sky}} = 0.92$. This is more precise than the Planck HFI result, $\beta = 0.30^\circ \pm 0.11^\circ$ \cite{59}, showing the additional information gained from the LFI and WMAP data.

Still ignoring $C_{\ell}^{EB,fg}$, we find that the Galactic mask reduces the value of $\beta$ to $0.18^\circ \pm 0.14^\circ$ for $f_{\text{sky}} = 0.62$, but not as much as to $-0.25^\circ \pm 0.23^\circ$ found for the Planck HFI-only result \cite{59}. The inclusion of the cross-power spectra with low frequency bands, in which the intensity of polarized dust emission is much weaker, reduces the impact of $C_{\ell}^{EB,dust}$ and significantly increases the measured value of $\beta$. The Planck LFI+HFI analysis reported in Ref. \cite{57} gave $\beta = 0.14^\circ \pm 0.17^\circ$ for $f_{\text{sky}} = 0.62$. The inclusion of the WMAP channels further increases the mean value and tightens the uncertainty of $\beta$.

We now account for $C_{\ell}^{EB,fg}$. The foreground emission in the Planck LFI bands and similar frequency bands of WMAP is dominated by synchrotron rather than by dust. Unlike for dust, there is no evidence for the intrinsic $EB$ correlation of synchrotron emission \cite{33}. We thus ignore $C_{\ell}^{EB,synch}$ but use $C_{\ell}^{EB,dust}$ presented in Eq. (10) to model the dust $EB$ correlation and apply it only to the HFI maps of Planck and the 94 GHz maps of WMAP.

Jointly sampling a frequency-independent $\beta$, 22 miscalibration angles $\alpha_i$, and the dust $EB$ amplitudes $A_\ell$ in 4 ranges of $\ell$, we measure $\beta = 0.342^\circ \pm 0.094^\circ$ and $0.37^\circ \pm 0.14^\circ$ for $f_{\text{sky}} = 0.92$ and 0.62, respectively (the 4th row in Table 1). The former is our baseline result, which excludes $\beta = 0$ at 99.987% C.L. The latter agrees with the former within 1$\sigma$ and excludes $\beta = 0$ at 99.5% C.L.

In Figs. 1 and 2 we show the posterior distributions of $\beta$ and $A_\ell$ in 4 bins for $f_{\text{sky}} = 0.92$ and 0.62, respectively. The dust $EB$ amplitudes are consistent with zero except for the first multipole bin ($51 \leq \ell \leq 130$) for $f_{\text{sky}} = 0.62$.

In Fig. 3 we show the 1-dimensional marginalized posterior distributions of 22 miscalibration angles, $\alpha_i$, for the baseline result. The distributions for the WMAP and Planck LFI are broader than those of the Planck HFI, as expected from the signal-to-noise ratio. The measured $\alpha_i$ are in agreement with the reported calibration uncertainties, 1.5$^\circ$ for WMAP \cite{29} and 1$^\circ$ for Planck \cite{54}.

We now introduce a frequency-dependent cosmic birefringence signal as $\beta(\nu) = \beta_0(\nu/150 ~ \text{GHz})^n$ \cite{37}. Using the WMAP and Planck data and accounting for $C_{\ell}^{EB,dust}$, we find $\beta_0 = 0.30^\circ \pm 0.10^\circ$ and $n = -0.20_{-0.39}^{+0.41}$. Our measurements are thus consistent with a frequency-independent cosmic birefringence signal predicted by the axionlike field.

These results support the following hypothesis. Synchrotron emission has little to no intrinsic $EB$ correlations that could bias the measurement of $\beta$, whereas dust contains $EB$ correlations which bias the measurement when not accounted for, especially for smaller $f_{\text{sky}}$. Although no synchrotron $EB$ has been found so far \cite{58}, more evidence is needed to rule out synchrotron $EB$ as one of the culprits. The C-BASS and QUIJOTE experiments will give us a better understanding of synchrotron in the near future \cite{33,56}.

Finally, we show the average of the observed $EB$ power spectra (“stacked observed $EB$ power spectrum”) with the uncertainty in Fig. 4 and Fig. 5 for $f_{\text{sky}} = 0.92$ and 0.62, respectively. We calculate the inverse-variance
FIG. 2. Same as Fig. 1 but for $f_{\text{sky}} = 0.62$.

FIG. 3. Marginalized posterior distributions of 22 miscalibration angles, $\alpha_i$, for the baseline result. The distribution of $\beta$ (thick black line) is the same as in the top-left corner of Fig. 1.

The weighted average of the observed EB power spectra from

$$\mathbb{E} \left( C_b^{EB,o} \right) = \frac{1}{\mathbf{1} \cdot \mathbf{M}_b^{-1} \cdot \mathbf{1}^T} \cdot \bar{v}_b,$$  \hspace{1cm} (23)

and the variance from

$$\text{Var} \left( C_b^{EB,o} \right) = \frac{1}{\mathbf{1} \cdot \mathbf{M}_b^{-1} \cdot \mathbf{1}^T}.$$

(24)

We use $\alpha_i = 0$ and $\beta = 0$ in $\bar{v}_b$ to get the stacked EB power spectrum shown in the black points with error bars in the upper panels of Fig. 4 and Fig. 5. We find similar stacked EB power spectra for both sky fractions, which are expected because similar values of $\beta$ are found when assuming $\alpha_i = 0$ (see the 4th row of Table I).

The blue 1$\sigma$ bands show the EB power spectra as predicted by the baseline cosmic birefringence angle, $\beta = 0.342^\circ \pm 0.094^\circ$ for $f_{\text{sky}} = 0.92$, and $\beta = 0.37^\circ \pm 0.14^\circ$ for $f_{\text{sky}} = 0.62$. We fix $\alpha_i = 0$ in the covariance matrix, $\mathbf{M}_b$, for this case. The red 1$\sigma$ bands show the contributions from $\alpha_i$ where $\alpha_i$ is included in $\mathbf{M}_b$. The smaller sky fraction increases the uncertainty on the contribution...
from $\alpha_i$, but still yields consistent results.

In the lower panels we show the residual with respect to the best-fitting $A$, $\alpha$, $\beta$, and $\gamma$ model. The $\chi^2$ for the degree of freedom of 72 is 65.3 and 65.8 for $f_{\text{sky}} = 0.92$ and 0.62, respectively. We thus conclude that the residuals are consistent with null.

\section{Conclusions}

We have presented new constraints on the cosmic birefringence angle, $\beta$, from a joint analysis of the $EB$ power spectra of the WMAP 9-year maps \[32\] and the Planck PR4 LFI and HFI maps \[34\], which cover a wide range of frequencies from $\nu = 23$ to 353 GHz. We used the method based on Refs. \[35\] \[39\] \[40\] to account for the potential impact of the intrinsic $EB$ correlation of polarized dust emission on the determination of instrumental miscalibration angles, $\alpha_i$, for $\nu \geq 94$ GHz. Marginalizing over $\alpha_i$ and the dust $EB$ amplitudes, we measure $\beta = 0.342^{+0.094}_{-0.091}$ (68\% C.L.) for nearly full-sky data, excluding zero at 99.987\% C.L. This is consistent with, and more precise than, the previous results from the Planck data \[33\] \[35\] \[37\], and corresponds to the statistical significance of 3.6$\sigma$.

The consistent results of the joint analysis reinforce the conclusion of the Planck HFI analysis \[33\] \[41\] that errors due to instrumental systematics are smaller than statistical errors. In Table I we show previous measurements of cosmic birefringence where there is a clear trend of increased statistical significance when new datasets are added or a filamentary dust model for $EB$ is included.

If we remove the Galactic plane from the analysis, we find $\beta = 0.37^{+0.14}_{-0.15}$ for $f_{\text{sky}} = 0.62$, excluding zero at 99.5\% C.L. We thus find consistent signals of cosmic birefringence for both sky fractions. We also find that adding the cross-power spectra with lower frequency data from WMAP and Planck LFI reduces the impact of polarized dust emission on $\alpha_i$ compared to the HFI-only analysis \[37\]. We have not accounted for the intrinsic $EB$ correlation of synchrotron emission which dominates at low frequencies because there is no evidence for frequency dependence of $\beta$. For $\beta(\nu) \propto \nu^n$, we measure $n = -0.20^{+0.45}_{-0.35}$ when accounting for $C^{EB,\text{dust}}_\ell$. This is consistent with $n = 0$ predicted by the axionlike field [Eq. (1)] but disfavors, for example, $n = -2$ predicted by the Faraday rotation effect from the intergalactic (including primordial) or interstellar magnetic field.

A better understanding of the foreground emission is needed to completely rule out the foreground $EB$ as the culprit. However, the best way forward is to improve upon the calibration work rather than relying on the foreground emission to determine $\alpha_i$. If the calibration accuracy reaches $\pm 0.06^\circ$, $\beta$ can be reliably detected with a statistical significance of $> 5\sigma$. We also need confirmation from more independent datasets to completely rule out the (unknown) systematics of WMAP and Planck.

To this end, both on-going and future ground-based \[58\] \[62\] \[64\] \[65\], balloon-borne \[67\] \[68\], and space-borne \[69\] \[70\] experiments are expected to lead to a convincing discovery (or otherwise) of cosmic birefringence. If proven to be a cosmological signal, isotropic cosmic birefringence would have a profound impact on cosmology, particle physics, and quantum gravity \[71\] \[81\].

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\begin{table}
\centering
\begin{tabular}{|c|c|c|}
\hline
Datasets & $\beta$ & Dust $EB$ model \\
\hline
Planck PR3 HFI & $0.34^{+0.14}_{-0.14}$ & No \\
Planck PR4 HFI & $0.30^{+0.11}_{-0.11}$ & No \\
Planck PR4 HFI & $0.36^{+0.11}_{-0.11}$ & Yes \\
Planck PR4 HFI + LFI & $0.33^{+0.10}_{-0.10}$ & No \\
Planck PR4 + WMAP & $0.34^{+0.094}_{-0.091}$ & Yes \\
\hline
\end{tabular}
\end{table}

TABLE II. Previous measurements of cosmic birefringence at nearly full-sky that adopts the method of Refs. \[26\] \[31\]. The right column indicates if the filamentary dust model of $C^{EB,\text{dust}}_\ell$ [Eq. (10)] was applied to the high-frequency data where dust is the dominating foreground contribution. The last row displays this work.
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