A Measurement of the CMB E-mode Angular Power Spectrum at Subdegree Scales from 670 Square Degrees of POLARBEAR Data

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Abstract

We report a measurement of the E-mode polarization power spectrum of the cosmic microwave background (CMB) using 150 GHz data taken from 2014 July to 2016 December with the POLARBEAR experiment. We reach an effective polarization map noise level of 32 μK-arcmin across an observation area of 670 square degrees. We measure the EE power spectrum over the angular multipole range 500 ≤ ℓ ≤ 3000, tracing the third to seventh acoustic peaks with high sensitivity. The statistical uncertainty on E-mode bandpowers is ~2.3 μK² at ℓ ~ 1000, with a systematic uncertainty of 0.5 μK². The data are consistent with the standard ΛCDM cosmological model with a probability-to-exceed of 0.38. We combine recent CMB E-mode measurements and make inferences about cosmological parameters in ΛCDM as well as in extensions to ΛCDM. Adding the ground-based CMB polarization measurements to the Planck data set reduces the uncertainty on the Hubble constant by a factor of 1.2 to H₀ = 67.20 ± 0.57 km s⁻¹ Mpc⁻¹. When allowing the number of relativistic species (N_{eff}) to vary, we find N_{eff} = 2.94 ± 0.16, which is in good agreement with the standard value of 3.046. Instead allowing the primordial helium abundance (Y_{He}) to vary, the data favor Y_{He} = 0.248 ± 0.012. This is very close to the expectation of 0.2467 from big bang nucleosynthesis. When varying both Y_{He} and N_{eff}, we find N_{eff} = 2.70 ± 0.26 and Y_{He} = 0.262 ± 0.015.

Unified Astronomy Thesaurus concepts: Cosmic microwave background radiation (322)
1. Introduction

Measurements of the cosmic microwave background (CMB) provide the foundation for our current understanding of cosmology. However, temperature measurements are now largely sample-variance-limited (Planck Collaboration et al. 2020a) out to small angular scales where extragalactic foregrounds become significant (Dunkley et al. 2013; Das et al. 2014; George et al. 2015). As a result, the focus of recent experiments has shifted to measuring the polarization of the CMB. CMB polarization anisotropies encode comparable amounts of information per angular multipole to the temperature anisotropy (Galli et al. 2014). Additionally, the relatively small polarization fraction of extragalactic sources (Seiffert et al. 2007; Battye et al. 2011; Gupta et al. 2019) means that measurements can be extended to smaller angular scales before becoming foreground-dominated.

The polarization patterns in the CMB are commonly separated into curl-free modes (E-modes) and gradient-free modes (B-modes). This division is made because density fluctuations will produce E-modes, but not B-modes, at first order. B-modes are instead produced by gravitational waves and gravitational lensing (Kamionkowski et al. 1997; Seljak & Zaldarriaga 1997).

E-mode anisotropy was first detected by DASI in 2002 (Kovac et al. 2002). Since then, the field has moved from detecting power to high signal-to-noise ratio measurements of the power spectrum by a number of experiments (Louis et al. 2017; BICEP2 Collaboration et al. 2018; Henning et al. 2018; Planck Collaboration et al. 2020a). To date, these E-mode measurements have supported the $\Lambda$CDM cosmological model. Due to the lower levels of polarized foregrounds, polarization measurements have the potential to surpass the amount of information that can be extracted from the CMB temperature anisotropy, and thus improve our ability to constrain cosmological models (Galli et al. 2014; Louis et al. 2017). Measuring CMB polarization can also help disentangle effects that are degenerate in the temperature data.

In this paper, we report a measurement of the $E$-mode auto-power spectrum (EE) in the angular multipole range, $500 \leq \ell < 3000$, using new data collected between July 2014 and December 2016 from the POLARBEAR experiment. The expanded POLARBEAR survey covers 670 deg$^2$ of sky at 150 GHz, a twenty-fivefold increase in area over the initial deep but small surveys by POLARBEAR (Polarbear Collaboration et al. 2017). The survey region overlaps the SPTpol and BICEP2/Keck Array surveys, and the new POLARBEAR bandpowers provide an independent measurement of the $E$-mode power spectrum on small angular scales. A measurement of the $B$-mode power spectrum on large angular scales on this field was presented by the Polarbear Collaboration et al. (2020, hereafter PB20), which overlaps this work in the narrow range of angular scales $500 \leq \ell \leq 600$. We combine the POLARBEAR bandpowers with other recent CMB power spectrum measurements (Story et al. 2013; Louis et al. 2017; Planck Collaboration et al. 2020a) as well as CMB lensing power spectrum measurements (Wu et al. 2019; Planck Collaboration et al. 2020a), baryon acoustic oscillation (BAO) results (Beutler et al. 2011; Ross et al. 2015; Alam et al. 2017) and Hubble constant measurements (Riess et al. 2019) to study the implications for cosmology. This is the first time the cosmological implications of this combined data set have been presented.

This paper is organized as follows. In Section 2, we give a brief overview of the POLARBEAR instrument and the 670 deg$^2$ survey. We continue to describe the low-level data processing and mapmaking in Section 3. The power spectrum analysis is outlined in Section 4. We test for systematic errors in Section 5. In Section 6, we present the measurements of the $E$-mode power spectra. Subsequently, we study the cosmological implications in Section 7. We conclude in Section 8.

2. The Polarbear 670 deg$^2$ Survey

POLARBEAR is a receiver with 1274 cryogenically cooled, transition-edge-sensor (TES) bolometers and a continuously rotating half-wave plate mounted on the 2.5 m aperture Huan Tran Telescope at the James Ax Observatory on the Atacama plateau in Chile. The elevation (5190m) and the low Precipitable Water Vapor (PWV) of the Atacama plateau make the site one of the best in the world for microwave observations. Information on the instrument and telescope can be found in Arnold et al. (2012), Kermish et al. (2012), and Takakura et al. (2017).

This work uses data taken with POLARBEAR on a 670 deg$^2$ field in three observing seasons from July 2014 to December 2016. The field is centered at (RA, Dec)=$(+0\degree12\min 0\sec , -59\degree18\arcmin )$, and largely overlaps the survey fields of BICEP2/Keck Array (BICEP2 Collaboration et al. 2018) and SPTpol (Henning et al. 2018). The data are taken in 1 hour blocks by scanning back and forth at a constant velocity (0.24 s$^{-1}$) and constant elevation as the sky rotates past. After every four hours, the telescope is adjusted to track the field and the bolometers are retuned. We only use the POLARBEAR polarization data in this work, as the temperature noise level is substantially higher due to atmospheric noise. More information on the scan strategy can be found in PB20.

3. Time-ordered Data to Maps

In this section, we review the data selection and filtering of the time-ordered data (TOD). We then briefly describe the mapmaking process, and the determination of the beam function and absolute calibration. These steps closely follow the treatment in PB20, and we refer the reader to that work for more details while highlighting any differences from that work below.

3.1. Data Selection and Filtering of the Time-ordered Data

The data selection and filtering of the TOD are described in detail by PB20, and we repeat only the main points and differences opted due to the multipole range ($\ell \leq 600$ for PB20 and $500 \leq \ell < 3000$ for this paper). Periods of bad data due to, e.g., weather or telescope turnarounds, are flagged and replaced by realizations of white noise before deconvolving the detector time constants and demodulating the effects of the continuously rotating HWP. The demodulated data are low-pass-filtered and downsampled to 8 Hz (approximately $\ell < 4000$) before being effectively high-pass-filtered to reduce the impact of low-frequency noise by projecting out a first-order polynomial from each subscan (which denotes one left-going or right-going motion of the telescope). The noise power spectral density for each TOD is fit to a model comprised of white noise and low-frequency noise like in PB20. Detectors with unusually high or low noise levels at this point are flagged. Unlike PB20, we did
A final cut is done based on the noise of produced $2'$ pixel maps (it was on degree-pixel maps for PB20). A total of 3391 constant elevation scans (CESes; each approximately 1 hour long) pass the cuts and are included in the analysis in this work.

After data selection and demodulation, the TOD are filtered as follows. First, any significant, narrow-band instrumental lines, for instance, due to electrical interference, are notch-filtered in Fourier space. Second, ground pickup is removed by subtracting a ground template separately from the $I$, $Q$, and $U$ TOD. Third, we estimate and subtract temperature-to-polarization leakage caused by detector nonlinearity and telescope design through a principal component analysis (PCA), as demonstrated by Takakura et al. (2017). Note that the temperature-to-polarization leakage removal is only applied to real data and not the simulations in Section 4.2. Fourth, we project out a ninth-order polynomial from each subscan (a first-order polynomial was used in PB20). Finally, to reduce the effects of atmosphere, a common mode signal is straightly removed from all detectors, while it is low-pass-filtered before subtraction in PB20.

### 3.2. Mapmaking

The cleaned TOD are binned into $2'$ pixels, using the oblique Lambert equal area projection from a sphere to flat-sky. In this binning, the data are weighted according to each detector’s power spectral density, which is consistent with white noise for individual detectors after filtering. To simplify the power spectrum analysis, we combine the data from the set of 3391 CESes into 12 “bundle” maps that have relatively similar noise properties and map coverage. The effective map polarization noise level for fully combined data is $32 \mu$K-arcmin, after we correct for the beam and transfer function of the filtering (see PB20).

### 3.3. Noise

Following PB20, we consider two noise models: sign-flip noise maps and simulated TOD noise realizations. The sign-flip noise maps are created by randomly multiplying half of the CESes that enter a bundle map by $-1$, instead of $+1$, and thus nulling the true sky signal while maintaining the noise power. The simulated TOD noise consists of white noise plus low-frequency noise. The TOD noise realizations are added to the simulated signal TOD to form simulated signal plus noise maps. The sign-flip noise maps provide the fiducial estimate of the noise covariance for this work, with the TOD noise realizations being used to cross-check the results. The TOD noise model is also used in the null test framework.

### 3.4. Beams and Calibration

The angular response of the instrument is determined using observations of Jupiter. As detailed by PB20, the beam is well-described by a Gaussian with an FWHM of $3/6$. The fractional uncertainty on the beam is determined by looking at the scatter in the recovered beam profile across the 50 Jupiter beam maps that pass quality cuts. Additionally, any errors in the pointing model will smear out the effective beam in the CMB survey maps. This pointing jitter is estimated by looking at bright sources in the survey region, and comparing the estimated FWHM on these sources to Jupiter. The beam uncertainties due to both the Jupiter measurements and jitter estimate are included in the likelihood as described in Section 4.4.

The absolute gain calibration of the data is done in two steps. First, we determine the relative calibration between detectors so that their data can be coadded together into maps. The relative calibration of detectors is determined using a combination of a chopped thermal source (located at the secondary mirror) and Jupiter observations. Second, we compare the measured E-mode power spectrum of these maps (see Section 6) to the predictions of the Planck best-fit ΛCDM model to set the absolute calibration. While the latter step implicitly assumes isotropy across the sky, isotropy has already been stringently tested to better than the 2% calibration uncertainty recovered in this work. One could get a much more precise calibration by comparing the actual temperature and polarization maps to Planck maps across this area (as was done by PB20), thus eliminating the significant sample variance. However, we choose not to implement such a scheme since the calibration uncertainty does not limit the cosmological inferences of these data.

### 4. Power Spectrum Analysis

The power spectrum is measured using a pseudo-$C_\ell$ cross-spectrum method (Hivon et al. 2002; Tristram et al. 2005). The POLARBEAR implementation of this method has been previously described by Polarbear Collaboration (2014), and as “Pipeline A” by Polarbear Collaboration et al. (2017) and PB20. In this section we outline the basic method while highlighting any changes from PB20. We express the bandpowers in terms of $D_\ell \equiv \ell (\ell + 1) C_\ell / (2\pi)$ unless otherwise noted.

Pseudo-$C_\ell$ methods are based on measuring the biased power spectrum, or pseudo-$C_\ell$, from the fast Fourier transform (FFT) of an apodized map (or a spherical harmonic transform in curved sky), and then correcting these pseudo-$C_\ell$’s for the finite sky coverage, beams and filtering to recover the true spectrum on the sky. Cross-spectrum methods iterate on this approach by replacing auto-spectra with cross-spectra between maps with independent noise properties to avoid any noise bias.

The binned pseudo-$C_\ell$’s can be written as

$$D^E_p = \sum_{\ell' \neq \ell} W_{E,p} W_{E,p} \frac{k(k+1)}{2\pi} \hat{m}_{E,j} \hat{m}_{E,j}. \quad (1)$$

Here $w$ is a weight factor, and the indices $i$ and $j$ specify different bundle maps. The $\ell$-bin is denoted by $b$, the angular wavevector by $k$, and the Fourier transform of an apodized bundle map by $\hat{m}_b$.

The true on-sky power spectrum is related to the binned pseudo-$C_\ell$’s by

$$D_b = K_{bb'} D_{b'} \quad (2)$$

where the matrix $K_{bb'}$ is known as the kernel matrix and defined by

$$K_{bb'} = \sum_{\ell\ell'} P_{\ell\ell'} M_{\ell\ell'} F_{\ell\ell'} B_{\ell\ell'}^2 Q_{\ell\ell'}. \quad (3)$$

Here, $P$ and $Q$ are binning and interpolation operators. The mode-coupling matrix $M_{\ell\ell'}$ accounts for the finite frequency resolution in the FFT of a finite area of sky. The beam function
of the instrument is represented by $B_1$ (see Section 3.4), while the transfer function $F_1$ accounts for the effects offiltering at the TOD and map levels.

We will discuss these factors in more detail in the following subsections.

### 4.1. Apodization Mask and Mode-coupling Matrix

We create an apodization mask in the following way. First we calculate the intersection of the nonzero weight regions of all 12 bundle maps. The edges of this region are smoothed by an 8° Hamming window. We also mask bright radio sources, setting the mask to zero within a 10′ disk around each source, surrounded by a 10′ cosine taper. The maps are multiplied by this apodization mask and zero-padded before being Fourier transformed.

We calculate the mode-coupling matrix, $M_{b'f}$, for this apodization mask following the analytic expressions in Appendix A of Hivon et al. (2002).

### 4.2. Simulations

We use end-to-end simulations to determine the filter transfer function in pseudo-$C_1$ methods as well as estimate the final bandpower uncertainties. We generate a suite of 192 simulated skies with an input signal drawn from the best-fit ΛCDM model for TT,TE,EE+lensing in Planck Collaboration et al. (2020c). The input skies are generated at a map pixel resolution of 1′ and have only $E$-modes. The simulated skies are re-observed using the real pointing information, and filtered exactly following the real data. One exception is the omission of the PCA filtering because temperature-to-polarization leakage is not added in simulated TODs. We also run a subset (48) of these simulated skies through the null test framework to estimate the expected level of residual signal and scatter in each null test (see Section 5).

### 4.3. Filter Transfer Function and Bandpower Window Functions

The transfer function, $F_1$, is calculated by comparing the $E$-mode power spectrum of these simulations to the original input power spectrum as described in Hivon et al. (2002). The transfer function is shown in Figure 1.

We also report the bandpower window functions necessary to compare the binned spectra to a theory curve. In the pseudo-$C_1$ formalism, these bandpower window functions, $w_{b'd}$, can be expressed as

$$w_{bf} = \sum_{b'f'} K_{b'}^{-1} P_{b'f'} M_{b'f} F_{f} B_{f'}.$$

The bandpower window functions are applied to an assumed theory spectrum, $C_1^\text{theory}$, to get the binned expectation bandpowers,

$$C_b^\text{theory} = w_{bf} C_1^\text{theory},$$

for comparison with the measured bandpowers.

We test the stability of the transfer function and bandpower window functions by running smaller numbers of simulations with different input cosmologies, and testing if the average resulting bandpowers for each simulated set match the expected bandpowers for the product of the bandpower window functions with the assumed cosmological model. We find agreement in all tests, validating the cosmological model. We also need to estimate the uncertainty on the measured bandpowers. The total uncertainties will include sample and noise variance as well as the beam and calibration uncertainties. To allow the simulations to be run before settling on the final absolute calibration, we calculate the sample and noise variance separately before combining the two estimates.

We use the 192 mock-observed noiseless CMB maps from Section 4.2 to estimate the covariance matrix due to sample variance. We use the calibrated, sign-flip noise maps from Section 3.2 to estimate the noise variance, while cross-checking the results with the simulated noise maps. For both the sample and noise variance, we estimate the covariance matrix at an initial binning of $\Delta \ell = 50$, and condition this matrix following Henning et al. (2018) to reduce the impact of uncertainties in the covariance estimate. Specifically, we require the correlation matrix to be a symmetric Toeplitz matrix. Given the expected correlation length, we also zero out the correlation for $\Delta \ell > 150$. The observed correlation at these $\Delta \ell$s is consistent with zero (although the uncertainty is large). We then rebin this estimate of the sample variance into the final bandpower binning.

Beam and calibration uncertainties are dealt with separately. We handle the calibration uncertainty by adding a calibration factor to the cosmological analysis with a prior set by the expected 2% calibration uncertainty. The beam uncertainty is propagated into a beam correlation matrix, $\rho_{bb'}$. At each step in the chain, this beam correlation matrix is combined with the binned theory spectrum $D_b$ and added to the sample and noise covariance matrix to yield the total covariance at that step:

$$C_{bb'}^{\text{tot}} = C_{bb'}^{\text{S+N}} + \rho_{bb'} D_b D_{b'}$$

### 5. Data Validation

We test the data for unknown systematics using null tests. Each null test splits the data set in approximately half, with the splits chosen to be sensitive to likely sources of systematic bias. The difference between the two halves removes nearly all true sky signal, thus suppressing the sample variance and allowing a more sensitive test for systematics. As will be described in more detail below, the null test suite shows no evidence for systematics in the data.

We have also run a suite of simulations for expected sources of systematic errors (information on the simulation procedure can be found in PB20). At $\ell > 1050$, the most significant systematics are related to detector cross-talk, pointing, and the half-wave plate; the estimated systematic uncertainty is less than 0.25 the statistical uncertainty in all bins (Polarbear Collaboration 2020, in preparation). Given that the systematic uncertainties are small compared to the statistical uncertainties on the $E$-mode bandpowers, we choose to neglect the systematic errors in this work.

We run a suite of 19 null tests to search for potential bias in our data set. Our framework has been previously used by the Polarbear Collaboration (2014, 2017, PB20), which is based on the formalism developed originally by the QUIET Collaboration (Bishoff 2010). The binned null spectrum, $C_b^{\text{null}}$, is constructed
as
\[ \hat{C}_b^{null} = \hat{C}_b^A + \hat{C}_b^B - 2\hat{C}_b^{AB}, \]

where \( \hat{C}_b^{A/B} \) are the spectra calculated following Section 4 for each half of the data split, and \( \hat{C}_b^{AB} \) is the cross-spectrum between the two halves (all after correcting for the appropriate filter transfer functions and mode-coupling matrices). For each null test, the data from each half is rebundled to maximize the overlapping area. The binning in \( \ell \) used in these null tests is the same one used in Table 1.

Most of these null tests have been previously described by PB20, but five are added to test specific potential concerns for the \( E \)-mode measurement. The new tests include: (1) a second test on Sun contamination, splitting the data by the distance to the Sun; (2) a test splitting the data based on the observed level of temperature-to-polarization leakage in each CES; (3 and 4) two tests of HWP contamination by splitting the data on the level of either the 2\( f \) or 4\( f \) line amplitude in each CES; and (5) a random split of the bolometers to test the quality of the noise model. A short description of all 19 tests can be found in Appendix A. We estimate the uncertainty on each null test bin, \( \sigma(\hat{C}_b^{null}) \), by looking at the standard deviation of a suite of 48 simulated null spectra. We then define the statistic
\[ (\chi^2_{null})^2 \equiv \left( \frac{\hat{C}_b^{null}}{\sigma(\hat{C}_b^{null})} \right)^2. \]

We compare the values of \( (\chi^2_{null})^2 \) from the real data to simulations to calculate the PTE for each test. Summing across all tests and all bins, we find the PTE for the total \( \chi^2 \) to be 67.9%. The data thus show no evidence for systematic biases.

We also test that the set of PTEs is consistent with a uniform distribution as expected. Specifically, we perform a Kolmogorov–Smirnov (KS) test on the three sets of PTEs of the \( \chi^2_{null} \) values by test, by bin, and overall. All three distributions are consistent with uniform distributions (PTE = 0.45, 0.30, 0.13), showing no evidence for a bias.

### 6. Bandpowers

The \( E \)-mode bandpowers measured by applying the analysis method of Section 4 to the POLARBEAR survey are shown in Figure 2 and tabulated in Table 1. \( E \)-mode power is detected at very high significance, with zero \( E \)-mode power excluded at 61\( \sigma \). The POLARBEAR bandpowers are consistent...
with the ΛCDM model; the POLARBEAR data have a PTE of 0.38 relative to the best-fit ΛCDM model for the POLARBEAR and Planck (Planck Collaboration et al. 2020a) data sets. The POLARBEAR bandpowers trace out the third through seventh acoustic peaks in the E-mode spectrum, and extend to ℓ = 3000 well into the Silk damping tail (Silk 1968).

We show the current state of E-mode power spectrum measurements in Figure 3. In this figure, we compile the bandpowers of this work with other recent E-mode measurements (Louis et al. 2017; BICEP2 Collaboration et al. 2018; Henning et al. 2018; Planck Collaboration et al. 2020a). The observed E-mode spectra agree well, enhancing our confidence in the E-mode measurements.

7. Cosmological Implications

We now turn to the cosmological implications of the POLARBEAR E-mode power spectrum along with other recent cosmological observations. We look at parameter constraints for the standard, six-parameter, ΛCDM cosmological model. We also look at two one-parameter extensions to ΛCDM, N_{eff}, or Y_{He}. These extensions are constrained primarily by the Silk damping scale in temperature data. Finally, we consider the two-parameter extension of Y_{He} + N_{eff}, of interest as a test of big bang nucleosynthesis (BBN).

7.1. Methodology

We derive parameter constraints using the 2019 version of the Markov Chain Monte Carlo (MCMC) package COSMOMC (Lewis & Bridle 2002). We have extended COSMOMC to include the POLARBEAR bandpowers in a manner similar to the public likelihood for Henning et al. (2018). The POLARBEAR likelihood code and associated data are available on the LAMBDA website.

In addition to the usual cosmological parameters in COSMOMC, we have added four nuisance parameters specific to the POLARBEAR data, most with an informative prior. The first parameter is the calibration factor (in power) for the POLARBEAR E-mode power spectrum. We set a prior on this factor based on the expected 2% uncertainty in the absolute calibration. The other three parameters relate to on-sky signals. First, we have one term to describe the polarized Poisson-distributed point source power in the field after masking. This power scales with ℓ as D_p ∝ ℓ^2, and we report the power at ℓ = 3000, D_p3000. We use a weakly informative prior on the point source power that is uniform for D_p [0, 10] mK^2. Second, we have one parameter to describe polarized Galactic dust, which we model as having a power spectrum

$$D^\text{dust}_\ell = D^\text{dust}_80 \left(\frac{\ell}{80}\right)^{a_\text{dust}}.$$  (9)

Given that the POLARBEAR bandpowers are at much higher angular multipoles, we apply strong priors from BICEP2 Collaboration et al. (2018). Specifically, we fix a_{dust} = −0.58 and apply a Gaussian prior that D^\text{dust}_80 is drawn from N(0.0188, 0.0042^2) μK^2. The results are insensitive to this term; we have run one chain for ΛCDM+N_{eff} with the dust power zeroed and have seen no shifts larger than 0.1σ. Finally, we allow for “super-sample lensing” variance (Manzotti et al. 2014).
This is parameterized by the mean lensing convergence across the field, \( \kappa \), to which we apply a Gaussian prior centered at zero with a 1\( \sigma \) width of 0.001.\(^{34}\)

### 7.2. Data Sets

We include the Planck 2018 TT, TE, and EE power spectra likelihoods in all results (Planck Collaboration et al. 2020a). Constraints from Planck alone are referred to by “Planck.” We also explore the effects of adding ground-based CMB measurements, specifically the SPT-SZ TT measurements (Story et al. 2013), ACTpol TT/TE/EE measurements (Louis et al. 2017), and the POLARBEAR EE spectrum in this work. While not the focus of this work, we also report the parameter constraints from Planck and POLARBEAR data only in Appendix B. We do not include BICEP2/Keck Array data at large angular scales, as we do not look at the tensor-to-scalar ratio. We include the ACTpol (but not SPTpol; Henning et al. 2018) TE/EE measurements because the ACTpol survey region does not overlap the POLARBEAR survey, while the SPTpol survey has nearly 100% overlap. Accounting for the common sample variance would be a nontrivial exercise and is not possible using only the publicly available likelihood. Given the agreement between the \( E \)-mode measurements in Figure 3, we are confident that it is appropriate to combine these different data sets. Constraints from the combination of Planck 2018 and the ground-based CMB measurements are referred to by “CMBselect.”

We also consider what impact data besides the primary CMB power spectra have on the cosmological constraints. Here we include the lensing power spectra from Planck and SPTpol (Wu et al. 2019; Planck Collaboration et al. 2020b). We also include the Riess et al. (2019) local measurement of the Hubble constant, \( H_0 = 74.03 \pm 1.42 \text{ km s}^{-1} \text{ Mpc}^{-1} \). Lastly, we include three baryon acoustic oscillation measurements: the SDSS-III BOSS DR12 Consensus sample ( Alam et al. 2017), the DR7 MGS sample ( Ross et al. 2015), and the 6dFGS survey (Beutler et al. 2011). We label constraints that include these data in addition to the CMB power spectrum data with “CMBExt.”

### 7.3. Constraints on the \( \Lambda \)CDM Model

As has been previously noted, the Planck 2018 CMB power spectrum data alone do an excellent job of constraining all six parameters in the standard \( \Lambda \)CDM model. We report the median parameter values and 68% confidence intervals in Table 2. While the optical depth is relatively uncertain with a 14% error bar, the other five parameters are measured with percent-level precision. Adding the ground-based CMB power spectrum measurements to Planck reduces the parameter uncertainties by \( \sim 7\% \) (except for the amplitude terms \( A_{\ell} \) and \( \tau \) which depend on the low-\( \ell \) polarization bump). Adding the BAO, \( H_0 \) and CMB lensing data further reduces uncertainties by an additional \( \sim 10\% \).

### 7.4. Constraints on the Primordial Helium Abundance

We also look at the inferred primordial helium fraction, which can be viewed as a test for new particles or physics during the epoch of big bang nucleosynthesis (BBN). The expected helium fraction under BBN consistency in the \( \Lambda \)CDM model for the CMBselect data set is extremely tightly constrained at \( Y_{\text{BBN}} = 0.246696 \pm 0.000062 \). Relaxing BBN consistency substantially weakens what we can infer about the helium fraction. However, the CMB anisotropies have some sensitivity to the helium fraction as it changes the number of free electrons at recombination. Higher helium fractions lead to fewer free electrons, a longer photon mean free path and thus more Silk damping. We show the posterior probability

| Parameter | Planck | CMBselect | CMBExt |
|-----------|--------|-----------|--------|
| \( \Omega_b h^2 \) | 0.02237 \( \pm 0.00015 \) | 0.02230 \( \pm 0.00014 \) | 0.02234 \( \pm 0.00015 \) |
| \( \Omega_c h^2 \) | 0.120 \( \pm 0.0014 \) | 0.1203 \( \pm 0.0013 \) | 0.1198 \( \pm 0.0011 \) |
| \( H_0/100 \) | 1.04089 \( \pm 0.00032 \) | 1.04102 \( \pm 0.00030 \) | 1.04104 \( \pm 0.00030 \) |
| \( \tau \) | 0.0548 \( \pm 0.0070 \) | 0.0527 \( \pm 0.0070 \) | 0.0518 \( \pm 0.0065 \) |
| \( \ln(10^{10} A_s) \) | 3.044 \( \pm 0.010 \) | 3.043 \( \pm 0.015 \) | 3.040 \( \pm 0.014 \) |
| \( n_s \) | 0.9650 \( \pm 0.0045 \) | 0.9656 \( \pm 0.0042 \) | 0.9647 \( \pm 0.0038 \) |
| \( H_0 \) (\( \text{km s}^{-1} \text{ Mpc}^{-1} \)) | 67.42 \( \pm 0.69 \) | 67.20 \( \pm 0.57 \) | 67.41 \( \pm 0.51 \) |

Note. The median values and 68% confidence intervals for the six \( \Lambda \)CDM parameters for the Planck, CMBselect, and CMBExt data sets. Adding the ground-based CMB power spectrum measurements to Planck reduces the parameter uncertainties by \( \sim 7\% \) (except for the amplitude terms \( A_{\ell} \) and \( \tau \) which depend on the low-\( \ell \) polarization bump). Adding the BAO, \( H_0 \) and CMB lensing data further reduces uncertainties by an additional \( \sim 10\% \).

34 We estimate the prior width of 0.001 for the POLARBEAR survey area from Figure 2 of Manzotti et al. (2014).
distribution function for the primordial helium fraction for three data sets in Figure 4. Using Planck alone, we find $Y_{He} = 0.239 \pm 0.013$. Adding the other CMB measurements improves this slightly to

$$Y_{He} = 0.248 \pm 0.012,$$

in excellent agreement with the expectation from BBN. There is no further improvement from adding the other cosmological data.

### 7.5. Constraints on the Number of Relativistic Species

The energy density of relativistic particles in the early universe is proportional to $N_{\text{eff}}$, the effective number of relativistic species. The standard model of particle physics predicts that $N_{\text{eff}} = 3.046$ for the three neutrino species plus a small correction from positron annihilation (Mangano et al. 2005). The preferred $N_{\text{eff}}$ from the CMBselect data set is within 0.4σ of this prediction

$$N_{\text{eff}} = 2.94 \pm 0.16.$$  

Adding the nonCMB data (i.e., the CMBext data set) slightly reduces the preferred value of $N_{\text{eff}}$, but it remains within 0.9σ of the expectation:

$$N_{\text{eff}} = 2.90 \pm 0.18.$$  

When $N_{\text{eff}}$ is allowed to vary, as shown in Figure 5 we see that it correlates strongly with $\Omega_c h^2$ and $n_s$. As discussed by Hou et al. (2013), increasing the matter density as $N_{\text{eff}}$ increases avoids shifting the redshift of matter-radiation equality. A side effect is that the CMB constraint on the Hubble constant significantly weakens: the uncertainty on the Hubble constant nearly triples from $\pm0.57$ to $\pm1.5$ km s$^{-1}$ Mpc$^{-1}$ (the central value changes by less than 0.4σ of the weakened constraint).

### 7.6. Constraints on the $\Lambda$CDM + $Y_{He}$ + $N_{\text{eff}}$ Model

We now consider the results when allowing both $N_{\text{eff}}$ and $Y_{He}$ to vary, as both parameters affect the damping tail. As with the other extensions to $\Lambda$CDM considered, freeing these two parameters does not significantly improve the quality of the fit ($\Delta \chi^2 \lesssim -1.2$ for two new parameters for the CMBext data set). The resulting parameter posteriors are shown in Figure 6. We find the following for the CMBselect data set:

$$N_{\text{eff}} = 2.70 \pm 0.26,$$

$$Y_{He} = 0.262 \pm 0.015.$$  

The CMBext data set prefers essentially the same values as well:

$$N_{\text{eff}} = 2.65 \pm 0.26,$$

$$Y_{He} = 0.263 \pm 0.014.$$  

Adding the ground-based CMB measurements of the damping tail to the Planck bandpowers pushes along the $N_{\text{eff}}/Y_{He}$ degeneracy toward higher values of $Y_{He}$, and lower values of $N_{\text{eff}}$. However, Figure 6 shows that the 2σ parameter ellipses still contain the $\Lambda$CDM values, and as mentioned above, the quality of the fit does not substantially improve. Table 3 summarizes the median and 68% confidence intervals for the parameters in the $\Lambda$CDM case and extensions, for the CMBext data set.

### 8. Conclusions

We have presented a measurement of the CMB E-mode power spectrum on angular multipoles $500 \leq \ell \leq 3000$ from 670 deg$^2$ surveyed with the POLARBEAR instrument. E-mode polarization is detected at high significance across the third through the seventh acoustic peaks of the E-mode power spectrum. We find no evidence for significant systematic biases in the null suite data. The POLARBEAR E-mode bandpowers provide an independent confirmation of the observed CMB E-mode power spectrum at intermediate-to-small angular scales.

We combine the POLARBEAR E-mode bandpowers with other recent CMB measurements (Louis et al. 2017; Henning et al. 2018; Planck Collaboration et al. 2020a) to explore the current state of CMB cosmological constraints. Adding the ground-based CMB bandpowers does not reduce the Hubble constant tension between the Planck-inferred value and direct local measurements ($4.3\sigma$ vs. $4.5\sigma$). We find no significant preference in the data for any of the extensions considered: $N_{\text{eff}}$, $Y_{He}$, $N_{\text{eff}}+Y_{He}$.

For the $\Lambda$CDM+$Y_{He}$ model extension, adding the ground-based CMB power spectrum measurements brings the helium abundance toward the BBN expectation of 0.2467. With Planck-only, the data favor $Y_{He} = 0.239 \pm 0.013$, shifting to $Y_{He} = 0.248 \pm 0.012$ when the other power spectrum measurements are added. As expected, the nonCMB-power-spectrum data does little for $Y_{He}$.

We also look at varying the effective number of relativistic species, $N_{\text{eff}}$. We find only minor improvements and shifts from adding data beyond the Planck bandpowers. For the combined CMBext data set, the data favor $N_{\text{eff}} = 2.90 \pm 0.18$, which is within 1σ of the expected value of 3.046.

Finally, we allow both $Y_{He}$ and $N_{\text{eff}}$ to vary to study the degeneracies between the two. Here, the full CMB data set slightly pulls $Y_{He}$ upward and $N_{\text{eff}}$ downward relative to the Planck constraints and expected values. We find for CMBext,
$N_{\text{eff}} = 2.65 \pm 0.26$ and $Y_{\text{He}} = 0.263 \pm 0.014$. However, the actual improvement in the quality of fit from adding these two parameters is small ($\Delta \chi^2 \approx -1.2$), suggesting that these shifts are not significant.

While the POLARBEAR survey has finished, its successor, the Simons Array, had first light in 2019. The complete Simons Array will have three telescopes with a total of about 20 times more detectors than POLARBEAR and will survey a large fraction of the Southern sky (Suzuki et al. 2016; Hasegawa et al. 2018). The Simons Array will also extend the survey area to the North at the equator, facilitating studies of cross-correlations with experiments at other wavelengths. The $E$-mode power spectrum measurement from the Simons Array survey will dramatically improve upon current $E$-mode constraints and enable new tests of cosmology.

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Figure 6. Parameter posteriors for the \( \Lambda \)CDM+\( Y_{\text{He}} \)+\( N_{\text{eff}} \) model. We have excluded the optical depth \( \tau \) and amplitude of scalar perturbations \( A_s \) to reduce the complexity of the figure as these two parameters change negligibly between the data sets.
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Appendix A

As mentioned in Section 5, we used 19 null tests to search for hidden systematics. Of these tests, 14 were previously used in PB20 and are listed here for the readers’ convenience. The PTEs for each multipole range and each null test are shown in Table 4.

1. “First half versus second half”: the data set is split into two equal-weight halves chronologically to probe for time-dependent changes in the instrument, such as drifting calibration.

2. “Middle versus rising and setting”: the three different CES types are split in middle range elevation scans versus rising plus setting scans to detect, for example, elevation-dependent miscalibration or residual ground synchronous signal.

Table 3
Parameter Constraints for the CMBext Data Set

| Parameter | ΩCDM | ΛCDM + N_{eff} | ΛCDM + ΛH_{0} | ΛCDM + ΛH_{0} + N_{eff} |
|-----------|------|----------------|----------------|--------------------------|
| Ω_{b}h^{2} | 0.02234 ± 0.00015 | 0.02220 ± 0.00022 | 0.02236 ± 0.00019 | 0.02221 ± 0.00020 |
| Ω_{c}h^{2} | 0.1198 ± 0.0011 | 0.1177 ± 0.0027 | 0.1197 ± 0.0011 | 0.1138 ± 0.0040 |
| 1000_{MC} | 1.04104 ± 0.00030 | 1.04125 ± 0.00040 | 1.04104 ± 0.00050 | 1.0424 ± 0.0011 |
| τ | 0.0518 ± 0.0065 | 0.0511 ± 0.0075 | 0.0511 ± 0.0074 | 0.0509 ± 0.0073 |
| ln(10^{10}A_{s}) | 3.040 ± 0.014 | 3.031 ± 0.016 | 3.039 ± 0.015 | 3.028 ± 0.016 |
| N_{eff} | 0.9647 ± 0.0038 | 0.9592 ± 0.0075 | 0.9648 ± 0.0066 | 0.9580 ± 0.0078 |
| ΛH_{0} | 2.90 ± 0.18 | 0.246 ± 0.011 | 0.263 ± 0.014 |
| H_{0} (km s^{-1} Mpc^{-1}) | 67.41 ± 0.51 | 66.5 ± 1.4 | 67.49 ± 0.59 | 65.1 ± 1.6 |

Note. The median parameter values and 68% confidence intervals with the CMBext data set for the ΛCDM model as well as the three extensions to the ΛCDM model considered in this work. In the last row, we also show the constraints on a derived parameter, the Hubble constant, ΛH_{0}, which has received attention recently due to tensions in the preferred value between different experiments.

Table 4
Null Test PTE Values

| ℓbin Summed Over Null Tests | Total EE χ^{2} PTE | Null Test Summed Over ℓbins | Total EE χ^{2} PTE |
|-----------------------------|--------------------|-----------------------------|--------------------|
| 500 ≤ ℓ < 550               | 34.7%              | First half vs. second half  | 90.1%              |
| 550 ≤ ℓ < 600               | 8.9%               | Middle vs. rising and setting | 88.0%              |
| 600 ≤ ℓ < 650               | 96.8%              | Left-going vs. right-going subscons | 39.5%              |
| 650 ≤ ℓ < 700               | 52.2%              | High gain vs. low gain CESs  | 58.0%              |
| 700 ≤ ℓ < 750               | 90.9%              | High PWV vs. low PWV         | 43.6%              |
| 750 ≤ ℓ < 800               | 47.1%              | Mean temperature leakage by bolometer | 11.4%              |
| 800 ≤ ℓ < 850               | 82.3%              | Mean temperature leakage by CES | 84.5%              |
| 850 ≤ ℓ < 900               | 96.8%              | 2f amplitude by bolometer    | 71.7%              |
| 900 ≤ ℓ < 950               | 39.2%              | 4f amplitude by bolometer    | 9.2%               |
| 950 ≤ ℓ < 1000              | 25.8%              | 2f amplitude by CES          | 47.5%              |
| 1000 ≤ ℓ < 1050             | 90.1%              | 4f amplitude by CES          | 24.4%              |
| 1050 ≤ ℓ < 1100             | 44.8%              | Q vs. U pixels                | 89.4%              |
| 1100 ≤ ℓ < 1150             | 79.6%              | Low or high distance from Sun | 96.7%              |
| 1150 ≤ ℓ < 1200             | 52.5%              | Sun above or below the horizon | 65.8%              |
| 1200 ≤ ℓ < 1250             | 69.3%              | Moon above or below the horizon | 82.1%              |
| 1250 ≤ ℓ < 1300             | 72.0%              | Top half vs. bottom half      | 69.9%              |
| 1300 ≤ ℓ < 1400             | 95.4%              | Left half vs. right half      | 88.8%              |
| 1400 ≤ ℓ < 1500             | 2.3%               | Top vs. bottom bolometers     | 96.9%              |
| 1500 ≤ ℓ < 1600             | 96.5%              | Random splits of bolometers  | 24.8%              |
| 1600 ≤ ℓ < 1700             | 18.8%              |                             |                    |
| 1700 ≤ ℓ < 1800             | 48.5%              |                             |                    |
| 1800 ≤ ℓ < 2000             | 47.6%              |                             |                    |
| 2000 ≤ ℓ < 2200             | 87.0%              |                             |                    |
| 2200 ≤ ℓ < 2500             | 66.9%              |                             |                    |
| 2500 ≤ ℓ < 3000             | 80.2%              |                             |                    |

Note. The PTE values for the total χ^{2} of the null tests when summed over all tests for a single ℓbin, and and when summed over all bins for a single null test. We see no evidence for a statistically significant excess in the null tests.
3. “Left-going versus right-going subsans”: the data set is split in half according to the direction of motion of the telescope to test for, for example, microphonic or magnetic pickup in the data.
4. “High gain versus low gain observations”: the data set is split into observations with above and below average mean detector gain coefficients to search for problems with the gain calibration.
5. “High PWV versus low PWV”: the data set is split by PWV as measured by the nearby APEX radiometer to check for loading- or weather-dependent effects.
6. “Mean temperature to polarization leakage by channel”: split the data set into detectors that see small and large temperature leakage coefficients to test the subtraction and search for residual contamination.
7. “2f amplitude by channel”, “4f amplitude by channel”: split the data by HWP signal amplitude to check for problems removing the HWP structure or systematic contamination coupling into the data through these terms.
8. “Q versus U pixels”: each detector wafer is fabricated with two sets of polarization angles. We split the data into the two pixel types to check for problems in the device fabrication.
9. “Sun above or below the horizon”, “Moon above or below the horizon”: we split observations based on whether or not the Sun or moon is up to check for residual sidelobe contamination.
10. “Top half versus bottom half”, “left half versus right half”: we split detectors by the boresight axis of the telescope to check for optical distortion and problems due to far sidelobes.
11. “Top versus bottom bolometers”: with a continuous HWP each bolometer TOD independently measures Q and U. We explicitly separate detector pairs to check for temperature aliasing or device mismatch.

The other five splits are:
1. “Mean temperature to polarization leakage by CES”: split the data set into CESs that see small and large temperature leakage coefficients to test the subtraction and search for residual contamination.
2. “2f amplitude by CES”, “4f amplitude by CES”: split the data by HWP signal amplitude for CES to check for problems removing the HWP structure or systematic contamination coupling into the data through these terms.
3. “Low distance or high distance from Sun”: we split observations based on the distance to the Sun to check for residual sidelobe contamination.
4. “Random splits of bolometers”: we randomly split bolometers into two halves to check the noise model.

Appendix B

We show parameter constraints for the Planck + POLARBEAR data alone in Table 5. For the ΛCDM, adding POLARBEAR data alone reduces the uncertainty of $H_0$ by 13%, which is substantial compared to the overall reduction by the CMBselect data set. POLARBEAR slightly improves the constraint of other parameters. For ΛCDM+$\Omega_{\text{CDM}}$, the Planck+POLARBEAR data set, and CMBext have comparable central values and uncertainties for $N_{\text{eff}}$ and $H_0$. POLARBEAR does not alter the constraint for the ΛCDM +$Y_{\text{He}}$ and ΛCDM+$Y_{\text{He}}$+$N_{\text{eff}}$ models.

| Parameter Constraints for the Planck + POLARBEAR |
|-----------------------------------------------|
| $\Omega_{\text{m}}h^2$ | $\Omega_{\text{CDM}}$ | $\Omega_{\text{CDM}}$+Y_{\text{He}} | $\Omega_{\text{CDM}}$+Y_{\text{He}}+N_{\text{eff}} |
| 0.02236 ± 0.00015 | 0.02224 ± 0.00022 | 0.02226 ± 0.00021 | 0.0222 ± 0.00022 |
| $\Omega_{\text{DE}}h^2$ | 0.1201 ± 0.0014 | 0.1183 ± 0.0030 | 0.1203 ± 0.0014 | 0.1175 ± 0.0041 |
| 100$\mu_\text{C}$ | 1.0408 ± 0.00031 | 1.04110 ± 0.00044 | 1.04057 ± 0.00057 | 1.0413 ± 0.0012 |
| $\tau$ | 0.0547±0.0070 | 0.0532 ± 0.0078 | 0.0539 ± 0.0077 | 0.0525 ± 0.0078 |
| ln(10$\%A_{\text{S}}$) | 3.045±0.015 | 3.038 ± 0.019 | 3.042 ± 0.016 | 3.034 ± 0.019 |
| $n_s$ | 0.9648 ± 0.0043 | 0.9595 ± 0.0087 | 0.9609 ± 0.0074 | 0.9583 ± 0.0089 |
| $N_{\text{eff}}$ | ... | 2.91 ± 0.19 | ... | 2.86±0.24 ±0.33 |
| $Y_{\text{He}}$ | ... | 0.237 ± 0.013 | ... | 0.246 ± 0.018 |
| $H_0$ (km s$^{-1}$Mpc$^{-1}$) | 67.30 ± 0.60 | 66.4 ± 1.4 | 67.05 ± 0.71 | 66.0±1.7 ±1.9 |

Note. The median parameter values and 68% confidence intervals with the Planck+POLARBEAR data set for the ΛCDM model as well as the three extensions to the ΛCDM model considered in this work. In the last row, we also show the constraints on a derived parameter, the Hubble constant, $H_0$. For the ΛCDM, adding POLARBEAR data alone reduces the uncertainty of $H_0$ by 13% and improves the constraint of other parameters slightly. For ΛCDM+$\Omega_{\text{CDM}}$, POLARBEAR improves the constraint of $N_{\text{eff}}$ and $H_0$ in similar orders as with CMBext. Adding POLARBEAR alone does not alter the constraint for the ΛCDM +$Y_{\text{He}}$ and ΛCDM+$Y_{\text{He}}$+$N_{\text{eff}}$ models.
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