Results of gravitational lensing and primordial gravitational waves from the POLARBEAR experiment

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Abstract. POLARBEAR is a Cosmic Microwave Background radiation (CMB) polarization experiment that is located in the Atacama Desert in Chile. The scientific goals of the experiment are to characterize the B-mode signal from gravitational lensing, as well as to search for B-mode signals created by primordial gravitational waves (PGWs). POLARBEAR started observations in 2012 and has published a series of results. These include the first measurement of a non-zero B-mode angular auto-power spectrum at sub-degree scales where the dominant signal is gravitational lensing of the CMB. In addition, we have achieved the first measurement of cross-correlation between the lensing potential, which was reconstructed from the CMB polarization data alone by POLARBEAR, and the cosmic shear field from galaxy shapes by the Subaru Hyper Suprime-Cam (HSC) survey. In 2014, we installed a continuously rotating half-wave plate (CRHWP) at the focus of the primary mirror to search for PGWs and demonstrated the control of low-frequency noise. We have found that the low-frequency B-mode power in the combined dataset with the Planck high-frequency maps is consistent with Galactic dust foreground, thus placing an upper limit on the tensor-to-scalar ratio of $r < 0.90$ at the 95% confidence level after marginalizing over the foregrounds.

1. Introduction

The polarization of the Cosmic Microwave Background radiation (CMB) contains rich cosmological information that is a focus of ongoing and future CMB experiments. The pattern of linear polarization is divided into a gradient-like E-mode component and a curl-like B-mode component. E-mode polarization is mainly generated by the same scalar density fluctuations that generate CMB temperature anisotropies. In contrast, B-mode polarization could be generated by either the conversion of E-modes to B-modes due to gravitational lensing along the line of sight or tensor perturbations (primordial gravitational waves, PGWs) from inflation. Gravitational lensing induces a characteristic peak in the B-mode angular power spectrum at sub-degree scales (with an angular multipole of $\ell \sim 1000$). On degree scales, inflation models could predict B-mode polarization from PGWs that peak at degree scales from recombination ($\ell \sim 80$).

2. The Polarbear Experiment

We designed the Polarbear instrument to measure both primordial and gravitational lensing B-mode signals [1, 2]. It is composed of a two-mirror reflective telescope called the Huan Tran Telescope (HTT), which is located at the James Ax Observatory at an elevation of 5,190 m in the Atacama Desert in Chile. A 2.5-m primary mirror of the HTT produces a beam size of $3'.5$ full-width at half-maximum (FWHM). The Polarbear receiver consists of an array of 1,274 transition edge sensor (TES) bolometers, which are cooled to 0.3 K and observe the sky with the design band centered at 150 GHz through lenslet-coupled double-slot dipole antennas, which have a 2.4-deg diameter field of view. Regular scientific observations of the CMB began in June 2012 and continued until December 2016.

3. Selected Scientific Results

3.1. Gravitational Lensing

In the first two seasons between 2012 and 2014, we observed three small CMB fields. The total effective sky area of the three patched is $25\,\mathrm{deg}^2$, and the total observation time is 4,700 hours. We measured the B-mode angular auto-power spectrum, C_ℓ^{BB}, over the multipole range of $500 < \ell < 2100$. In 2014, we achieved the first measurement of non-zero B-mode power at sub-degree scales, where the dominant signal is gravitational lensing of the CMB [3]. In 2017, we doubled the sensitivity of the lensing amplitude in comparison to the first result and finally rejected the null hypothesis of non-B-mode polarization with 3.1σ confidence [4] (Figure 1). We also measured the cross-correlation between the lensing potential, which was reconstructed from the Polarbear data, and the cosmic shear field from galaxy shapes from the Subaru Hyper Suprime-Cam (HSC) survey, thus rejecting the null hypothesis at 3.5σ [5]. This is the first measurement of the cross-spectrum without relying on CMB temperature measurements, which is made possible by the deep Polarbear map and the deep HSC data.

3.2. Primordial Gravitational Waves

In 2014, a continuously rotating half wave plate (CRHWP) was installed to search for PGWs while demonstrating the control of low-frequency noise [6]. We observed one large CMB field with an effective sky area of $670\,\mathrm{deg}^2$, which overlaps with the area mapped by South Pole experiments, including the *BICEP2/Keck Array* and SPTpol. We continued to observe this large patch until the end of 2016, resulting in a total observation time for the CMB patch of 7,900 hours. We measured the CMB B-mode angular auto-power spectrum over a range of multipoles of $50 \leq \ell \leq 600$ with a knee in sensitivity of $\ell \sim 90$, where the inflationary gravitational wave signal is expected to peak. The measured B-mode power spectrum is made consistent with the Planck fiducial cosmology and single dust component model by taking the cross-correlation with the Planck high-frequency maps. Finally, we place an upper limit on the tensor-to-scalar ratio of $r < 0.90$ at a 95% confidence after marginalizing over the foregrounds [7] (Figure 1).

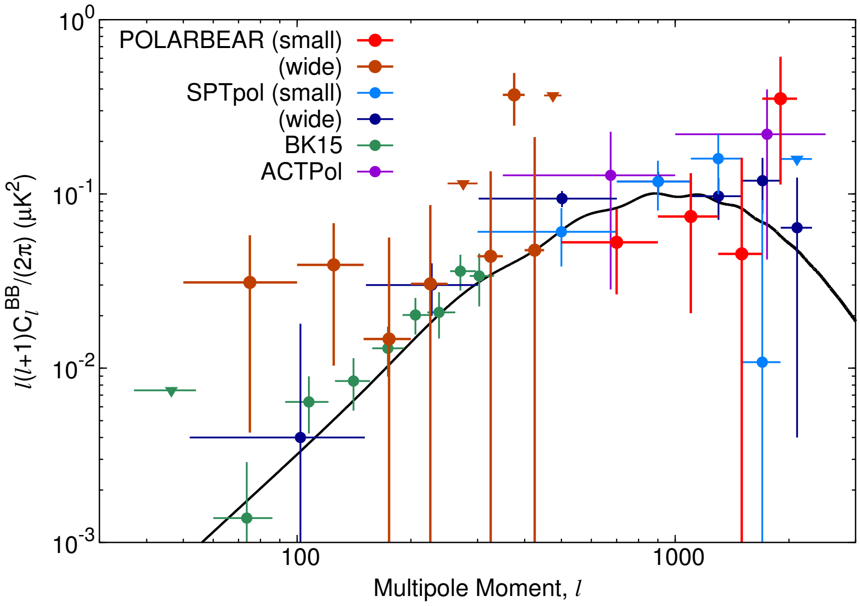

Figure 1. B-mode power spectra from POLARBEAR [3, 4, 7], SPTPOL [9, 10], ACTPOL [11], *BICEP2/Keck Array* [12]. Uncertainties correspond to a 68% confidence, while upper limits are quoted at a 95% confidence. The black curve is a theoretical ΛCDM spectrum. For display, the dust component is naively subtracted from POLARBEAR by using the model given by [7].

4. Conclusion

The POLARBEAR experiment is a successful experiment that has achieved the first measurement of a non-zero B-mode power spectrum, as well as the cross-correlation between the lensing potential reconstructed from the CMB polarization data alone and the cosmic shear field obtained by HSC. Furthermore, it has established an upper limit on the tensor-to-scalar ratio while demonstrating the control of low-frequency noise. Future experiments will have substantially better statistical power, including the Simons Array [8], which is upgraded from POLARBEAR.

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