

A MEASUREMENT OF THE COSMIC MICROWAVE BACKGROUND *B*-MODE POLARIZATION WITH POLARBEAR

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ABSTRACT

POLARBEAR is a ground-based experiment located in the Atacama desert of northern Chile. The experiment is designed to measure the Cosmic Microwave Background *B*-mode polarization at several arcminute resolution. The CMB *B*-mode polarization on degree angular scales is a unique signature of primordial gravitational waves from cosmic inflation and *B*-mode signal on sub-degree scales is induced by the gravitational lensing from large-scale structure. Science observations began in early 2012 with an array of 1,274 polarization sensitive antenna-couple Transition Edge Sensor (TES) bolometers at 150 GHz. We published the first CMB-only measurement of the *B*-mode polarization on sub-degree scales induced by gravitational lensing in December 2013 followed by the first measurement of the *B*-mode power spectrum on those scales in March 2014. In this proceedings, we review the physics of CMB *B*-modes and then describe the POLARBEAR experiment, observations, and recent results.

Key words: cosmic background radiation – cosmology: observations – large-scale structure of the universe

1. INTRODUCTION

Precise measurements of the Cosmic Microwave Background radiation (CMB) have revolutionized cosmology in recent decades. The excellent success on the CMB temperature anisotropy measurement and many other cosmological observations, e.g. Type Ia supernovae measurements, puts the Big Bang theory on a firm basis and elevates cosmology to precision science. But we haven't understood the initial conditions for the universe

Theory suggests that the initial conditions were those of an exponential expansion (“inflation”) of a microscopic volume. Inflationary models with the *single-large-field slow roll* condition are the simplest and are favored phenomenologically (Pagano et al. (2008)). These are regarded as representative inflationary model that should be tested. Inflation predicts to produce primordial gravitational waves (PGW, as known as tensor fluctuation) with an amplitude depending on the inflationary energy scale of $V^{1/4} = 1.06 \times 10^{16} \times (r/0.01)^{1/4}$ GeV. Here r is the ratio of the amplitude of tensor fluctuations to the amplitude of scalar fluctuations. If we can detect the PGW at the level of $r \sim 0.01$, we can access extremely high energy scale, which is compatible to that of the Grand Unified Theory (GUT) scale. Furthermore, the representative inflationary models mentioned above have a lower bound on $r > 0.002$ from the “Lyth relation”, $r \simeq 2 \times 10^{-3} (\Delta\phi/m_{\text{pl}})$ (Lyth & Riotto (1999)). Here m_{pl} is the Planck mass and $\Delta\phi$ is the field variation that satisfies $\Delta\phi > m_{\text{pl}}$ for the large-field models during inflation.

The PGW produces a direct and unique, but very faint CMB polarization pattern called “primordial B -mode signal” on large angular scales at last scattering and reionization. That means we can directly determine r by measuring the primordial CMB B -mode signal. Tighter limits on r or an actual detection of the PGW would constrain most of the theoretical models of inflation. Therefore, a high precision measurement of r will provide a unique opportunity to probe the early universe and a regime of high energy physics that is inaccessible by any other measurements.

CMB polarization measurements can also measure or limit neutrino masses. The CMB E -mode polarization, which is mainly produced by scalar fluctuations, is lensed by large-scale structure (LSS) generating “lensing B -mode signal” on smaller angular scales. Massive neutrinos suppress the formation of LSS because they are relativistic and do not fall into potential wells though they contribute to the mass density. Then measurements of the lensing B -mode signal have the potential to measure the sum of neutrino masses or set sufficiently strong constraints that they can rule out some high-energy physics models for neutrinos.

2. INSTRUMENT & OBSERVATION

We designed the POLARBEAR instrument to measure both primordial and gravitational lensing B -mode signals. It is composed of a two-mirror reflective telescope named as the Huan Tran Telescope (HTT). The tele-



Figure 1. Photograph of the 3.5-m Huan Tran Telescope (HTT) at the James Ax Observatory in the Atacama Desert in Northern Chile.

scope is installed at the James Ax Observatory in the Atacama desert in northern Chile. The HTT is an off-axis Gregorian telescope satisfying the Mizuguchi-Dragone condition (Mizuguchi et al. (1976); Dragone (1978); Tran et al. (2008)), which can provide low cross-polarization and astigmatism over the diffraction-limited field of view. The telescope optics, cryogenic receiver, and electronics are installed on a mount. Projected along boresight, the aperture is an ellipse with a 3.5 m minor axis, which gives a beam size of 3.5 arcmin full-width at half-maximum (FWHM). Figure 1 shows a photograph of the HTT at the site. The cryogenic receiver coupled to the HTT houses a cold half-wave plate, re-imaging optics, aperture stop, and a focal plane consisting of 1,274 superconducting transition-edge sensor (TES) bolometers with a 2.4 degrees diameter field of view. The design band of the TES bolometers is centered at 148 GHz with 26% fractional integrated bandwidth.

We began regular scientific observations of the CMB for three small patches of the sky in June 2012. We collected 2,400 hours of calibrated CMB observations and 400 hours of calibration data until June 2013. Averaged over these observations, the array sensitivity is $23 \mu\text{K}\sqrt{\text{s}}$.

3. RESULTS

We estimate the C_ℓ^{BB} power spectrum from the measurements (Figure 2). We fit the power spectrum to a Λ CDM model with a single A_{BB} amplitude parameter. We find $A_{BB} = 1.12 \pm 0.61(\text{stat})_{-0.12}^{+0.04}(\text{sys}) \pm 0.07(\text{multi})$, where $A_{BB} = 1$ is defined by power spectrum evaluated from the WMAP-9 Λ CDM model. To calculate the lower

bound on the additive systematic uncertainties on this number, we linearly subtract all the possible bias effects in each band from the measured band powers and calculate A_{BB} . The measurement rejects the hypothesis of no C_ℓ^{BB} from lensing with a confidence of 2.2σ .

With the same data, we also estimate gravitational lensing power spectra from the CMB using the non-Gaussianity imprinted in the CMB by LSS (The POLARBEAR Collaboration et al. (2014a,b)). Those results are also consistent with the Λ CDM model. We calculate the combined significance with the non-Gaussian *B*-modes and the C_ℓ^{BB} measurements. This calculation results in a rejection of the hypothesis that there are no lensing *B*-modes with 4.7σ confidence.

4. CONCLUSION

We have reported a measurement of the lensing *B*-mode signal with the POLARBEAR experiment, which is enabled by the combination of high angular resolution (3.5 arcmin), small statistical noise ($23 \mu\text{K}\sqrt{\text{s}}$) and excellent control of systematic errors. By combined with the non-Gaussian *B*-modes and the C_ℓ^{BB} signals measured by POLARBEAR, we achieve a rejection of the hypothesis that there are no lensing *B*-modes with 4.7σ confidence. We are now observing a larger sky focusing on measurements of the primordial *B*-mode signal. Analysis done for the lensing *B*-mode measurement will enable precision characterization of this measurement.

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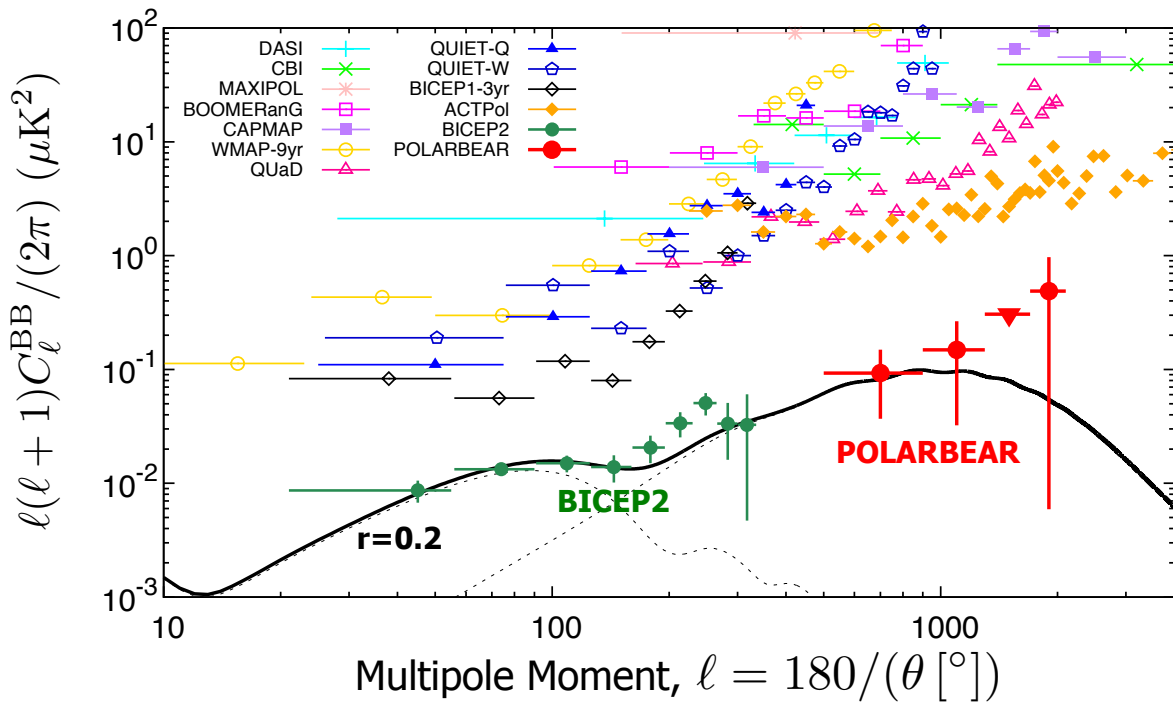


Figure 2. The first season POLARBEAR B -mode power spectrum (The POLARBEAR Collaboration: P. A. R. Ade et al. (2014)) complement existing data from other CMB polarization experiments (Montroy et al. (2006), Leitch et al. (2005), Sievers et al. (2007), Wu et al. (2007), Bischoff et al. (2008), Brown et al. (2009), QUIET Collaboration et al. (2011), QUIET Collaboration et al. (2012), Bennett et al. (2013), Barkats et al. (2014), Ade et al. (2014), Naess et al. (2014)). The experiments except POLARBEAR and BICEP2 show 95 % confidence upper limits. The third bin of the POLARBEAR spectrum (inverted triangle mark) also corresponds to a 95 % confidence upper limit because the central value is negative. Theoretical spectrum from a Λ CDM model with $r = 0.2$ is shown for comparison.