PROCEEDINGS OF SCIENCE

Cosmology and particle physics with POLARBEAR

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Cosmic inflation predicts that primordial gravitational waves were created during the inflationary era. Measurements of polarization of the Cosmic Microwave Background (CMB) radiation are known as the best probe to detect the primordial gravitational waves. POLARBEAR is a telescope designed to detect the CMB B-mode with very sensitive polarimeters based on superconductive transition edge sensor (TES) detector technology. Its large primary mirror with a diameter of 3.5m also allows us to constrain or measure the sum of neutrino masses beyond the limit obtained so far. POLARBEAR is located on the Chajnantor plateau in the Atacama desert in northern Chile at an altitude of 5,200m. We received the first light in January 2012 and are taking CMB data at 150 GHz. In this paper we will describe the current status and prospect of POLARBEAR.

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1. Introduction

Measurements of the Cosmic Microwave Background (CMB) have provided us rich information on the universe. The first detection by Penzias and Wilson was a landmark test of the Big-Bang model of the universe, and the discovery of the temperature anisotropies by the COBE satellite showed the existence of seeds of the complex structures that characterize the universe today. Finally, through the precise measurement of the temperature fluctuations by WMAP, the standard model on the origin, evolution and composition of the universe is firmly established. Now the frontier of the CMB studies have moved to characterizing the polarization anisotropies, which promises to bring new insight into the epoch of the inflationary universe.

The anisotropy of the CMB polarization has yet to be fully explored. Maps of the polarized CMB can be decomposed into a curl-free component (E-modes) and curl component (B-modes). The E-modes, since their first detection [1], have been measured and characterized by various experiments and are consistent with the predictions of the standard ΛCDM model. On the other hand, the B-modes remain entirely elusive. While E-modes are sensitive to the scalar density fluctuations in the early universe, the B-modes would be evidence for primordial gravitational waves, which are sourced only by the inflation. The detection of B-modes is not only the smoking gun of inflation, but also a unique opportunity to measure the energy scale of the inflationary potential [2, 3].

The other significant source of B-modes is generated from the gravitational lensing by large-scale structure, which converts some of the initial E-modes signal to B-modes. This leads to a B-mode signal that peaks on small angular scales ($l \sim 1000$). The shape and amplitude of the lensed B-mode power spectrum depends on the sum of neutrino masses, Σm_ν, because the energy density of massive neutrinos decreases more slowly with expansion than is the case for massless neutrinos. This leads to slower growth of structure - and, hence suppression of lensed B-mode power - on scales smaller than the neutrino free-streaming length.

POLARBEAR is a ground-based experiment in the Atacama desert in Chile, designed to measure the CMB polarization on angular scales ranging from a few degrees to a few arc minutes ($40 \leq l \leq 2500$), with unprecedented levels of sensitivity. The projected sensitivity on the E and B-mode polarization signal is shown in Figure 1(a). POLARBEAR's designed sensitivity and 3.5' resolution will enable a greater than 10σ detection of the lensing B-mode. When combined with the Planck temperature data, POLARBEAR will yield a 1σ error of 75 meV on the sum of the neutrino masses, and we can possibly detect the indication of the effect from finite neutrino masses if the mass hierarchy is inverted. On large angular scales, POLARBEAR will enable a 2σ detection of r = 0.025. With this sensitivity, a significant majority of large field slow-roll models of inflation can be either detected or ruled out. Here we describe the instrumentation, the site and observation strategy, as well as the current status.

2. Instrument

The Huan Tran Telescope (HTT) is a 3.5 m off axis Gregorian Dragone telescope located at the James Ax Observatory in the Atacama desert in Chile (Figure 1(b)). The current telescope optics produce a 3.5' FWHM beam at 150 GHz with a conservative illumination of the inner 2.5 meters

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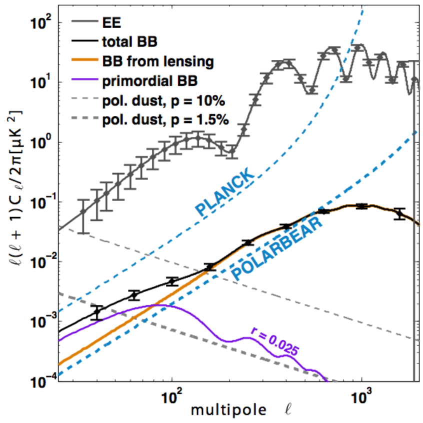
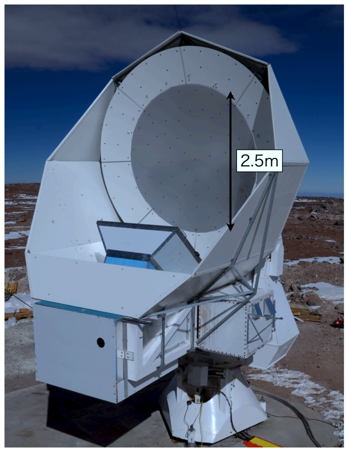


(a)



(b)

Figure 1: (a) Expected POLARBEAR sensitivity (blue thick dashed line) shown with theoretical B-mode spectra from primordial gravitational wave (r = 0.025) (magenta) and gravitational lensing (orange) (b) Huan Tran Telescope deployed at the Atacama desert in Chile.

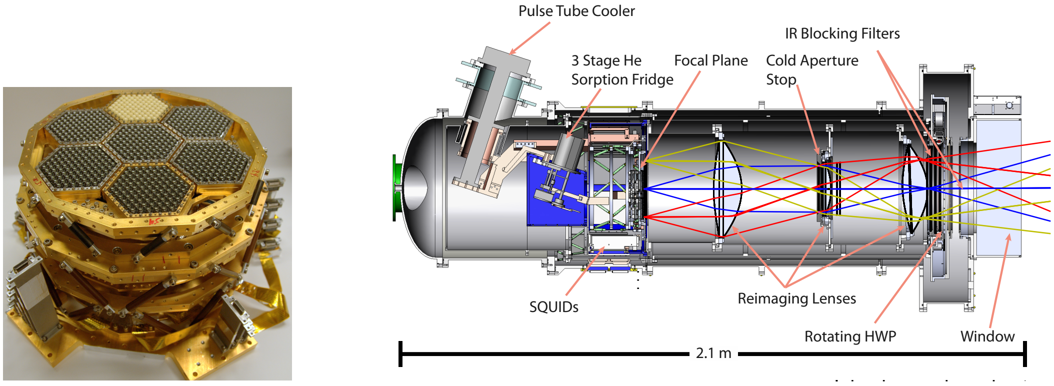
of the telescope, allowing the experiment to prove out to $l \sim 2500$ and characterize the peak of the lensing B-modes. The telescope also has a co-moving ground-shield to suppress sidelobe response. A rotating half-wave plate (HWP) is installed inside the receiver cryostat. By regularly rotating the HWP, we modulated the instrumental-polarization axis, suppressing instrumental-polarization systematic errors.

Figure 2(a) shows the POLARBEAR focal plane, which consists of 1,274 element antenna-coupled superconductive Transition Edge Sensor (TES) bolometers [4]. The focal plane is cooled down to 260 mK with a pulse tube cooler and a helium multi stage sorption refrigerator chain.

Figure 2(b) shows the cross-sectional view of the receiver cryostat with rays entering the vacuum window from the secondary mirror. The telescope focus lies just in front of the first re-imaging lens of the receiver. The field, aperture, and collimating lenses serve to reimage the curved focus of the telescope to a flat, telecentric focal plane that can be coupled to a detector array on the focal plane. The POLARBEAR optics was designed to give the telescope a 2.3° diffraction-limited field of view for a 19 cm focal plane. The fractional throughput is evaluated to be 37% [5]. Here the fractional throughput is a ratio between the power seen by a detector from a source at the input of the receiver and what would be seen if the detector had perfect efficiency to that same source

All detectors are biased and read out with cryogenic SQUID amplifiers developed by the NIST group [6] and a digital frequency-domain multiplexer system (DfMUX) developed by McGrill group [7]. We multiplex 8 resonant channels on each SQUID, with frequency separation between channels of ~ 120 kHz or larger to minimize crosstalk. A total of 168 SQUIDs are used to readout the 1,274 optical TES channels in addition to various dark TES bolometers and other calibration channels.

Details of the POLARBEAR instruments are found in [5, 8].



(a) (b)

Figure 2: (a) Focal plane of POLARBEAR. (b) Cross-sectional drawing of the POLARBEAR receiver system.

3. Site and Observation

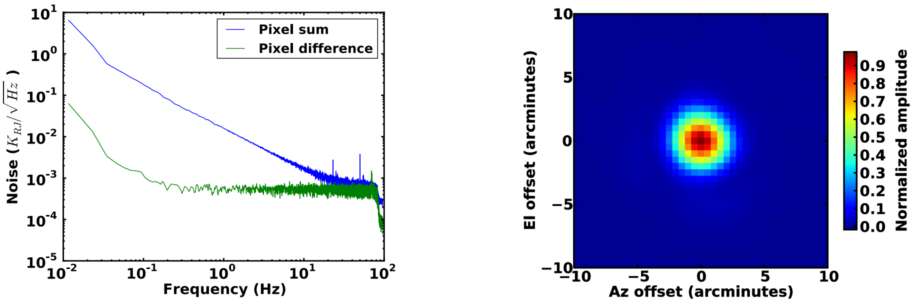
POLARBEAR is located at 5200 m altitude near Cerro Toco. The site offers exceptional conditions for radio astronomy because of its high altitude and low water vapor. Under median conditions, the zenith sky brightness at 150 GHz is ~ 12 K.

We scan three patches on the sky, each covering $15^\circ \times 15^\circ$ sky region. We selected the patches for their low dust emission evaluated with the theoretical intensity, and because the patches are separated from the Sun and Moon throughout the year, which allows uninterrupted observations throughout the season. Each patch is scanned with a periodical azimuth motion at fixed elevation until it drifts out of the line of the sight. The elevation and azimuth are then changed to recenter the patch, and this process continues until the patch sets and another patch is selected. By scanning at constant elevation for each patch scan, we observe through a constant column density of atmosphere and ensure a stable atmospheric contribution.

4. Current status

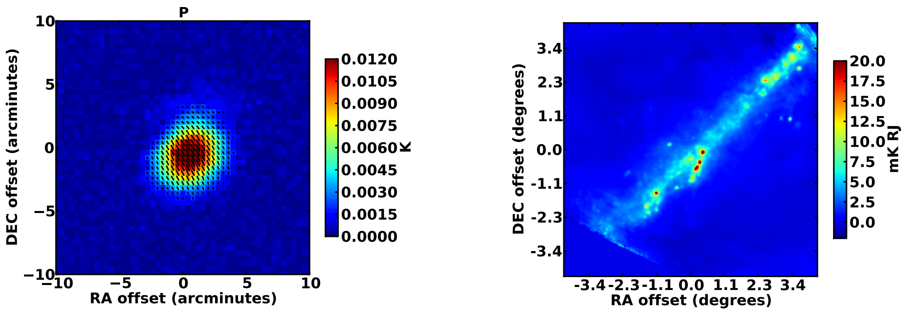
In late September of 2011, concrete was poured for the James Ax Observatory at the site. In the four months that followed, the HTT was assembled at the site and the receiver was integrated. We received the "first light" with the fully integrated experiment on January 10, 2012 with a scan of Jupiter. After a short commissioning phase which included calibration measurements, POLARBEAR started its science observation in April 2012. In the following, we present some preliminary results on the instrument performance in Chile.

Figure 3(a) shows the sum and difference timestream noise spectral densities during an observation of one CMB patch. Pixel differencing effectively suppresses the atmospheric fluctuation over a large bandwidth. The knee frequency (~ 0.1 Hz) is lower than the typical scan frequency, such that we scan in the white-noise regime of the pixel on polarization.



(a) (b)

Figure 3: (a) Pixel sum (power) and difference (polarization) timestream noise spectral densities. (b) Beam map from the Saturn observation.



(a) (b)

Figure 4: (a) The polarization and polarization angle of the TauA. (b) A map of a bright region of the galaxy.

Figure 3(b) shows the beam map from the Saturn observation. The measured beam size (3.5') and shape are consistent with optics simulation.

Figure 4(a) shows a polarization and polarization angle map of the TauA observation. TauA is a supernova remnant at the heart of the Crab nebula, which is the brightest polarized source the in mm-wave region, and we use it as an astrophysical calibrator for the detector absolute angle. Regular observations of TauA will be made at several HWP rotation angles to both characterize the systematic errors and verify the detector polarization angles on the sky. The resultant maps agree well with the result published by Armont *et al* [9], and demonstrate that our receiver system works as expected.

A preliminary temperature map of a patch of the galaxy with bright compact sources from our observation is shown in Figure 4(b). This map, made as the $7^\circ \times 7^\circ$ patch moved across the sky, demonstrates the first order functionality of the instrument and the part of our analysis chain.

POLARBEAR has successfully fielded a large superconductive TES bolometer array as described. Currently, routine observations are underway at the site, and the data will give us exciting scientific results in the near future.

5. Future Prospects: POLARBEAR-2

POLARBEAR-2 is an upgraded experiment of the POLARBEAR. The POLARBEAR-2 receiver system has a total of 1897 pixels, each with dual-frequency of 95GHz and 150GHz and dual polarization for each frequency. The total number of TES bolometers is thus 7588, which allows us to achieve unprecedented sensitivity with an expected array sensitivity of 5.7 $\mu K\sqrt{s}$. Having two frequencies is also important for mitigating contamination of foreground emission.

The sensitivity, assuming three years of observation, allows us to possibly detect B-modes from primordial gravitational waves, or to put a stringent limit on the tensor-to-scalar ratio r of $\sim$ 0.01. POLARBEAR-2 will also measure lensing B-mode, and would give an 1σ error of 40 meV on the sum of neutrino masses when combined with the Planck data.

Acknowledgement

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