Cosmology from CMB Polarization with POLARBEAR and the Simons Array

Darcy Barron for the POLARBEAR Collaboration

NSF Astronomy and Astrophysics Postdoctoral Fellow
Townes Fellow - UC Berkeley Space Science Lab
Chamberlain Fellow - Lawrence Berkeley National Lab
Outline

• This talk
  • POLARBEAR instrument and observations
  • Expansion to POLARBEAR-2 and Simons Array
• Next talk (Giulio Fabbian)
  • Data analysis and current results
Cosmology from B-mode Polarization

- Two sources of B-mode polarization in cosmic microwave background
  - Inflationary signature in primordial CMB
  - Energy scale of inflation
- Gravitational lensing
  - Neutrinos, dark energy
Cosmology from B-mode Polarization

- Two sources of B-mode polarization in cosmic microwave background
  - Inflationary signature in primordial CMB
    - Energy scale of inflation
  - Gravitational lensing
  - Neutrinos, dark energy
Cosmology from B-mode Polarization

- Two sources of B-mode polarization in cosmic microwave background
  - Inflationary signature in primordial CMB
    - Energy scale of inflation
  - Gravitational lensing
  - Neutrinos, dark energy

Darcy Barron - UC Berkeley - Cosmology from CMB polarization with POLARBEAR
CMB B-mode Measurements

\[ C_{\ell}^{BB} = \frac{\ell(\ell + 1)C_{\ell}^{BB}}{(2\pi)^2} (\mu K^2) \]

Multipole Moment, \( \ell \)

DASI, CBI, MAXIPOL, BOOMERanG, CAPMAP, WMAP-9yr, QUaD, BICEP1-3yr, ACTPol, BKP, SPTpol, POLARBEAR

Darcy Barron - UC Berkeley - Cosmology from CMB polarization with POLARBEAR
CMB B-mode Measurements

\[ C_{\ell}^{BB} \]

Multipole Moment, \( \ell \)

DASI, CBI, MAXIPOL, BOOMERanG, CAPMAP, WMAP-9yr, QUaD, QUIET-Q, QUIET-W, BICEP1-3yr, ACTPol, BKP, SPTpol, POLARBEAR

\[ \ell(\ell + 1)C_{\ell}^{BB} / (2\pi) (\mu K^2) \]

Galactic Foregrounds

Darcy Barron - UC Berkeley - Cosmology from CMB polarization with POLARBEAR
And many more in years past...
The POLARBEAR Experiment

- Dedicated CMB polarization experiment
- Located on Cerro Toco at 5200 meters in Atacama desert
- First light January 2012
- Now in fourth season of observations with POLARBEAR-1
- Two additional telescopes under construction now
POLARBEAR Observations

Intensity (FDS Dust Map)

POLARBEAR Site
Observable Sky Area

Latitude 23° S
Min. elevation 30°

Darcy Barron - UC Berkeley - Cosmology from CMB polarization with POLARBEAR
Polarbear Observations

Atmospheric transmission at Chajnantor Plateau

- Blue line: PWV = 0.5 mm
- Green line: PWV = 2 mm

Frequency (GHz)

Transmission (%)
**POLARBEAR Observations**

**Huan Tran Telescope**

- Guard ring
- 2.5 meter precision primary
- Shielding
- Secondary mirror
- Receiver enclosure

- Off-axis Gregorian-Dragone design
  - Low cross-polarization
  - Large field-of-view
- 3.5’ FWHM beams @ 150 GHz

Darcy Barron - UC Berkeley - Cosmology from CMB polarization with POLARBEAR
Polarbear Observations

• Scan in azimuth at fixed elevation
• Remove “ground template,” fixed in Az-El coordinates
• Modulate CMB Polarization
  • Apparent sky rotation
  • Half-wave plate
Polarbear-1

Focal Plane

- 637 dual polarization pixels
- Beam-forming lenslet coupled to each pixel
- 1274 superconducting transition-edge sensor bolometers
POLARBEAR-1
Focal Plane

- 637 dual polarization pixels
- Beam-forming lenslet coupled to each pixel
- 1274 superconducting transition-edge sensor bolometers
POLARBEAR-1
Cryogenic Receiver

- Pulse tube cooler
- $^3\text{He} / ^4\text{He}$ sorption cooler
- Reimaging lenses
- DfMUX SQUID output
- Focal plane
- Rotating HWP/IR blocking filters
- Vacuum window

2 meters

Darcy Barron - UC Berkeley - Cosmology from CMB polarization with POLARBEAR
POLARBEAR Observations

POLARBEAR-1 Initial survey:
Deep integration on 3x3 degree patches
Observations at 150 GHz

Intensity
(FDS Dust Map)

Darcy Barron - UC Berkeley - Cosmology from CMB polarization with POLARBEAR
POLARBEAR-2
Overview

- Next-generation receiver design
- Multi-chroic pixels, broadband optics
- Larger focal plane, field-of-view
- $\sigma(\Sigma m_v) < 100$ meV
**POLARBEAR-2**

Overview

- Next-generation receiver design
- **Multi-chroic pixels**, broadband optics
- Larger focal plane, field-of-view
- $\sigma(\sum m_v) < 100$ meV

![Broadband sinuous antenna](image1)

- 4 detectors per pixel
- TES bolometers
- 271 pixels / wafer

Darcy Barron - UC Berkeley - Cosmology from CMB polarization with POLARBEAR
**POLARBEAR-2**

**Overview**

- Next-generation receiver design
- Broadband optics, multi-chroic pixels
- **Larger focal plane**, field-of-view
- $\sigma(\Sigma m_\nu) < 100 \text{ meV}$

---

**Detector Module**

**Focal Plane**

- **NET bolometer**: $360 \, \mu\text{K}\sqrt{s}$
- **NET array**: $4.1 \, \mu\text{K}\sqrt{s}$
  - (95 GHz + 150 GHz)

---

Darcy Barron - UC Berkeley - Cosmology from CMB polarization with POLARBEAR
**POLARBEAR-2**

**Overview**

- Next-generation receiver design
- Multi-chroic pixels, broadband optics
- Larger focal plane, field-of-view
- \( \sigma(\Sigma m_v) < 100 \text{ meV} \)

<table>
<thead>
<tr>
<th></th>
<th>POLARBEAR-1</th>
<th>POLARBEAR-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>150 GHz</td>
<td>95 GHz + 150 GHz</td>
</tr>
<tr>
<td>Pixels</td>
<td>637</td>
<td>1897</td>
</tr>
<tr>
<td>Detectors</td>
<td>1274</td>
<td>7588</td>
</tr>
<tr>
<td>Field-of-view</td>
<td>2.3°</td>
<td>4.8°</td>
</tr>
</tbody>
</table>

Darcy Barron - UC Berkeley - Cosmology from CMB polarization with POLARBEAR
Simons Array

Leverage POLARBEAR experience to rapidly increase sensitivity

- Two telescopes under construction now
- Install at Chilean site end of 2015

3 receivers (22,764 bolometers) observing at 95, 150, 220 GHz

Three-year survey of 65% of sky

Funded by the Simons Foundation, NSF, MEXT
Simons Array
Projected sensitivity

Foreground rejection with multi-frequency Simons Array data

\[ \sigma(\Sigma m_\nu) = 40 \text{ meV} \]

w/ DESI BAO, including foreground contamination

\[ \sigma(r = 0.1) = 0.006 \]

Residual computation method:
Errard et al. 2011, Phys. Rev. D 84, 063005

Darcy Barron - UC Berkeley - Cosmology from CMB polarization with POLARBEAR
Thank you

- **Polarbear-1** in fourth season of observations
- First-season results with **Polarbear-1**:
  - Deflection power spectrum:
    POLARBEAR Collab. PRL 113, 021301 (2014)
  - Galaxy cross-correlation:
    POLARBEAR Collab. PRL 112, 131302 (2014)
  - Angular power spectrum:
- **Polarbear-2** designed for increased sensitivity, foreground mitigation (deploying soon!)
  - Dichroic pixel:
    A. Suzuki et al. JLTP Jan. 2014
  - Readout: Barron et al. SPIE 2014, Bender et al SPIE 2014
  - Optics: Inoue et al. SPIE 2014
- **Simons Array** initial survey:
  65% of sky at 3 freqs. (22,764 bolometers)
  - Arnold et al. SPIE 2014
Back-up slides
POLARBEAR-1
Focal Plane

- 637 dual polarization pixels
- Beam-forming lenslet coupled to each pixel
- 1274 superconducting transition-edge sensor bolometers
- Frequency-domain multiplexing readout (8x)
Polarbear-1
Instrument performance

• 1015 detectors (80% yield)
• Median NET: 550 $\mu$K$\sqrt{\text{s}}$
• First season average instrument NET: 23 $\mu$K$\sqrt{\text{s}}$
• ~3.5˚ FWHM, ~5% ellipticity
• ~40% optical efficiency
POLARBEAR-2
Cryogenic Receiver

Pulse-tube cooler & sorption fridge (hidden)
Alumina reimaging lenses
Alumina Filter
Vacuum Window
Dedicated pulse-tube cooler for optics (hidden)
2 meters

Darcy Barron - UC Berkeley - Cosmology from CMB polarization with POLARBEAR
Polarbear-2
Focal Plane

Broadband sinuous antenna

TES bolometers
4 detectors per pixel

Beam-forming silicon lenslet w/ 2-layer AR coating

AR-coated lenslets on seating wafer

271 pixels / wafer

NET bolometer: 360 μK/√s

NET array: 4.1 μK/√s (95 GHz + 150 GHz)

1897 pixels
7588 detectors

365 mm

Darcy Barron - UC Berkeley - Cosmology from CMB polarization with POLARBEAR
POLARBEAR-2
Detector Pixel

Broadband sinuous antenna

TES bolometers
4 detectors per pixel

Freq. band measurement

271 pixels / wafer
Polarbear-2
Readout

- PB-2 focal plane has 6x as many detectors as PB-1
  - Increase multiplexing from 8x to 40x
  - Achieved with closer frequency spacing, increased SQUID readout bandwidth
• PB-2 focal plane has 6x as many detectors as PB-1
  • Increase from 8x to 40x
  • Achieved with closer frequency spacing, increased SQUID readout bandwidth

• Requirements
  • Low-loss interdigitated capacitors
  • Low-inductance cold wiring
POLARBEAR-2

Readout

Frequency domain multiplexing

Measured while observing

- 1.9 ms time constant (85 Hz 3dB freq)
- Detectors fast enough to resolve all CMB signals
Lenslet-coupled dual-slot dipole antennas
The Next Generation of CMB Instruments

• Higher sensitivity
  – Reduce noise variance

• Spectral information
  – Characterize and remove polarized foregrounds

• Large sky coverage
  – Reduce sample variance

• Beamsize < 4’
  – Characterize lensing and de-lens