Cosmology from CMB Polarization with POLARBEAR and the Simons Array

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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
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CMB B-mode Measurements

\[
\ell (\ell + 1) C^B_{\ell} / (2\pi) \quad (\mu K^2)
\]
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 fifth season of observations with POLARBEAR-1
- Expanding to POLARBEAR-2/Simons Array
POLARBEAR Observations

Atmospheric transmission at Chajnantor Plateau

Transmission (%)

Frequency (GHz)

- PWV = 0.5 mm
- PWV = 2 mm

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POLARBEAR Observations

Intensity (FDS Dust Map)

POLARBEAR Site Observable Sky Area

Latitude 23° S
Min. elevation 30°

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Polarbear Observations

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

Guard ring

2.5 meter precision primary

Shielding

Secondary mirror

Receiver enclosure

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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

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Polarbear
Cryogenic Receiver

2 meters

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Polarbear-1
Control of instrumental systematic effects

- Pixel-pair differencing to reject unpolarized atmosphere
- Modulate CMB Polarization with apparent sky rotation
- Scan strategy allows ground template removal
POLARBEAR-1

Control of instrumental systematic effects

End-to-end simulations using measured instrument characteristics

- Boresight & diff. pointing
- Pol. angle
- HWP-dependent gain
- HWP-independent gain
- Electrical crosstalk
- Differential beamsize
- Differential ellipticity
- Gain drift

Statistical uncertainty
B-mode theory
Sum of all systematic uncertainty

$\ell (\ell + 1) C_\ell^{BB} / (2\pi)$ (µK^2)


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POLARBEAR Observations

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

Deflection power spectrum: PRL 113, 021301 (2014)
Galaxy cross-correlation: PRL 112, 131302 (2014)

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Polarbear-2

Overview

- Next-generation receiver design
- Larger focal plane, field-of-view
- Broadband optics, multi-chroic pixels
- $\sigma(\Sigma m_v) < 100$ meV

Primary

Secondary

PB-2a deploying 2017

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POLARBEAR-2
Overview

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

<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>

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POLARBEAR-2
Focal Plane

POLARBEAR-1
Double-slot dipole

POLARBEAR-2
Broadband sinuous antenna

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POLARBEAR-2
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Polarbear

Focal Plane

**Polarbear-1**
Seven 4-inch wafers
1274 bolometers

19 cm

**Polarbear-2**
Detector module
Six-inch wafer with
1084 bolometers

15.4 cm

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Polarbear Focal Plane

**Polarbear-1**
Seven 4-inch wafers
1274 bolometers

**Polarbear-2**
Seven 6-inch wafers
7588 bolometers

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Simons Array

Leverage POLARBEAR experience to rapidly increase sensitivity

- Two new telescopes installed at Chilean site
- First new receiver will deploy in 2017

3 receivers (22,764 bolometers) observing at 95, 150, 220, 280 GHz

Hardware funded by the Simons Foundation, NSF, MEXT

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Simons Array
Projected sensitivity

Foreground rejection with multi-frequency Simons Array data

$$\sigma(\Sigma m_v) = 40 \text{ meV}$$
with DESI BAO, including foreground contamination

$$\sigma(r = 0.1) = 0.006$$

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

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What’s next?
Future CMB polarization experiments

- Want to extract the wealth of cosmological information in the presence of complex foregrounds
- Planning complementary measurements from ground and space

LiteBIRD

CMB-S4
What’s next?
Future CMB polarization experiments

- CMB-S4: “the ultimate ground-based CMB polarization experiment”
  - Proposed in Snowmass documents (2013) as input to Particle Physics Project Prioritization Panel (P5), recommended by P5 report
- **Goal**: Map CMB polarization across the sky to the sensitivity and resolution needed to reach lensing B-mode signal and beyond
  - Massive scaling up of current efforts
    - 50k detectors deploying by ~2018
    - S4 plans are ~ 500k detectors ~ 2025
  - Will require coordinated effort of entire CMB community
- Science Book published this summer (arXiv:1610.02743)
- Instrument white papers coming soon
The Simons Observatory

http://simonsobservatory.org

A five year, $45M+ program to pursue key Cosmic Microwave Background science targets, and advance technology and infrastructure in preparation for CMB-S4.

• Merger of the ACT and POLARBEAR/Simons Array teams.

Tentative plans include:
• Major site infrastructure
• Technology development (detectors, optics, cameras)
• Demonstration of new high throughput telescopes.
• CMB-S4 class receivers with partially filled focal planes.
• Data analysis

POLARBEAR/Simons Array

ACT
Thank you

- **Polarbear-1** in fifth 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!)
  - Readout: Barron et al. SPIE 2014, Bender et al SPIE 2016
  - Optics: Inoue et al. SPIE 2016
- **Simons Array**: expands POLARBEAR to 3 telescopes, 4 bands, 22,764 bolometers
  - Stebor et al. SPIE 2016
- **Simons Observatory**: funding and initial study phase started Sept. 2016

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