CMB Polarization Power Spectra from Two Years of BICEP Data

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Path to CMBPol Workshop
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Searching for B-mode polarization in the CMB

E-mode polarization: mainly sourced by density fluctuations

B-mode polarization: generated by inflationary gravitational waves and lensing

Inflationary B-mode amplitude is parameterized by tensor-to-scalar ratio, current upper limit is $r < 0.22$ (WMAP TT + BAO + SN)

Target inflationary B-mode at angular scales of $30 < \ell < 300$
Background Imaging of Cosmic Extragalactic Polarization

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Overview of the BICEP telescope

Minimize polarization systematics
  Azimuthal symmetry
  Simple refractor, no mirrors

Optimize to $30 < \ell < 300$
  Beam sizes $\sim 0.9$ deg, 0.6 deg
  Field of view $\sim 18$ deg
  Observed sky fraction $\sim 2\%$

Frequency coverage
  100 GHz: 25 pixels
  150 GHz: 22 pixels
  220 GHz: 2 pixels

Signal-to-noise considerations
  PSB differencing
  South Pole: long integration over contiguous patch of sky, reduced atmospheric loading

(Yoon et al., astro-ph/0606278)
Primary CMB field: “Southern Hole”
- Dust emission 100x lower than median
- Total emission minimized at 150 GHz

48-hour observing cycles
- 4 x 9-hour CMB observations
- Az / el raster scans
- Fixed boresight angle \{-45°, 0°, 135°, 180°\}

Three years of data: 2006 to 2008
- Initial analysis: first two years
- Conservative data cuts

150 GHz FDS dust model
**Instrument characterization**

**Bolometer transfer functions**

Method: Gunn or noise diode source, analyze response to transitions

Result: relative gain uncertainty < 0.3% over 0.1 – 1 Hz after deconvolution

**Relative gains**

Method: atmospheric signal from “elevation nods”

Result: common mode rejection > 98.9%

**Absolute gains and detector pointing**

Method: cross-correlate BICEP and WMAP temperature maps

Result: gain uncertainty ~2%, centroid uncertainty 0.03° rms
Instrument characterization

Cross-polar leakage and polarization orientation angle

Method: rotating polarized sources (dielectric sheet, wire grid, etc.)

Result: cross-polar leakage uncertainty ±0.01, orientation angle uncertainty ±0.7°

Main beam shapes

Method: map far-field sources (thermal source and noise diode)

Result: average FWHM 0.93°, 0.60° at 100, 150 GHz; differential pointing 1.3 ± 0.4%

More details: Takahashi et al., arXiv:0906:4069
Timestreams to maps

- Form gain-adjusted sum/diff PSB timestreams, polynomial filter + azimuth template subtraction
- Noise in two-year polarization maps: $0.81 \, \mu K$ and $0.64 \, \mu K$ per sq. deg. at 100 and 150 GHz
From maps to power spectra

\[
\hat{C}_\ell = \sum_{\ell'} \kappa_{\ell\ell'} F_{\ell'} B_{\ell'}^2 C_{\ell'} + \hat{N}_\ell
\]

Output of Spice estimator

Spice kernel

Ell space filter function

Beam / pixel factor

The answer: underlying $C_\ell$
BICEP detects EE peak at \( \ell \sim 140 \) with high S/N

BB spectrum is consistent with zero, other spectra consistent with LCDM

Polarization data pass jackknife consistency tests
Potential systematics

- Uncertainties in calibration quantities can leak T, E into B
- Define $r = 0.1$ benchmark for systematics: false BB $< 0.007 \mu K^2$ at ell $\sim 100$
- Use signal simulations to calculate false BB from systematic errors

<table>
<thead>
<tr>
<th>Instrument property</th>
<th>Benchmark ($r = 0.1$)</th>
<th>Measured</th>
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</thead>
<tbody>
<tr>
<td>Relative gain uncertainty</td>
<td>0.9%</td>
<td>&lt;1.1%</td>
</tr>
<tr>
<td>Differential beam size</td>
<td>3.6%</td>
<td>&lt; 0.3%</td>
</tr>
<tr>
<td>Differential pointing</td>
<td>1.9%</td>
<td>1.3 $\pm$ 0.4%</td>
</tr>
<tr>
<td>Differential ellipticity</td>
<td>1.5%</td>
<td>&lt; 0.2%</td>
</tr>
<tr>
<td>Polarization orientation uncertainty</td>
<td>2.3°</td>
<td>&lt; 0.7°</td>
</tr>
<tr>
<td>Telescope pointing uncertainty</td>
<td>5 arcmin</td>
<td>0.2 arcmin</td>
</tr>
<tr>
<td>Polarized sidelobes (100, 150 GHz)</td>
<td>-9, -4 dBi</td>
<td>-26, -17 dBi</td>
</tr>
<tr>
<td>Focal plane temperature stability</td>
<td>3 nK</td>
<td>1 nK</td>
</tr>
<tr>
<td>Optics temperature stability</td>
<td>4 $\mu$K</td>
<td>0.7 $\mu$K</td>
</tr>
</tbody>
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More details: Takahashi et al., arXiv:0906:4069
Assume fixed LCDM parameters, calculate template BB, vary $r$

Calculate chi-squared and likelihood as function of $r$

**BICEP BB:** $r = 0.03$, $+0.31$, $-0.27$, upper limit is $r < 0.73$ at 95% confidence
The state of the field

BICEP contributes highest S/N polarization measurements at $\ell \sim 100$

BB upper limits are the most powerful to date

Upcoming analysis will use full data set, relaxed data cuts... plenty of room for improvement!

BICEP two-year results:
arXiv:0906.1181

BICEP data:
http://bicep.caltech.edu