BICEP/Keck: Constraining primordial gravitational waves with CMB polarization observations from the South Pole

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COSMO19, September 4 2019

Photo credit: R. Schwarz
Primordial Gravitational Waves and the CMB
Inflationary gravitational waves are the unique source of B-modes → peaking at $l \approx 100$ : degree scales
In standard ΛCDM only E-modes are present at last scattering. During propagation some of the E-modes are transformed into B-modes by lensing. Inflationary gravitational waves are the unique source of B-modes → peaking at $l \approx 100$ : degree scales.
Galactic Foregrounds

Mitigation strategy for additional “foreground” E- and B-mode signals:
- Observe at high galactic latitudes
- Expand frequency range in order to perform component separation

![Graph showing Synchrotron and Dust brightness temperature vs frequency.](https://via.placeholder.com/150)
South Pole Dark Sector

Why there?

- High altitude (9,300 ft = 2,800 m, most of it ice)
- Lack of day/night cycles makes for a very stable atmosphere
- Consistently dry
- Southern sky observable for 6 months of continuous darkness
- Minimal radio frequency interference
South Pole Dark Sector

BICEP1
BICEP2
BICEP3

DASI
QUAD
Keck Array
BICEP Array

South Pole Telescope (SPT-3G)

IceCube Lab
South Pole Dark Sector

BICEP1
BICEP2
BICEP3

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BICEP Array

South Pole Telescope (SPT-3G)

IceCube Lab

Talk by Kimmy Wu
South Pole Dark Sector

BICEP/Keck Experimental Strategy:
• Target 2-degree peak of B-mode power spectrum
• Target the same 1% patch of sky since 2006
• Small-aperture refractive optics (cheap, low systematics)
• Initial effort at 150 GHz, now multi-frequency observations
Telescope as compact as possible while allowing angular resolution to observe degree-scale features.

On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation.

A pulse tube cryogenic cooler cools the optical elements to 4.2K.

A 3-stage helium sorption refrigerator further cools the TES detectors to 0.27K.
Currently in the field

BICEP2

BICEP3

x 5 =

Keck Array

x 4 =

BICEP Array
Latest published analysis: BK15
BICEP2

BICEP3

Keck Array

x 5 =

x 4 =

Currently building
Keck Array
2012-13

150 150 150 150
Keck 2015 season-only E-mode Maps

95 GHz E signal

150 GHz E signal

220 GHz E signal

Right ascension [deg.]

Declination [deg.]

µK

µK

µK
In one year of observations, the 220 GHz map is already 3x deeper than Planck’s 217 GHz.
BK15 Auto- and cross- spectra between BICEP/Keck, WMAP, and Planck bands

For the BK15 release we included our new 220 GHz channel, yielding 78 spectra.
Multicomponent Likelihood Analysis

Take the joint likelihood of all the spectra simultaneously, compare to a model for BB:
• Expectation for ΛCDM and lensing
• 7-parameter foreground model
• $r$
Multicomponent Likelihood Analysis

Take the joint likelihood of all the spectra simultaneously, compare to a model for BB:
• Expectation for $\Lambda$CDM and lensing
• 7-parameter foreground model
• $r$

Foreground model = dust + synchrotron

\[
\begin{align*}
A_{\text{dust}} & \quad \Rightarrow \quad A_{\text{sync}} \\
\beta_{\text{dust}} & \quad \Rightarrow \quad \beta_{\text{sync}} \\
\alpha_{\text{dust}} & \quad \Rightarrow \quad \alpha_{\text{sync}} \\
\varepsilon & \\
\end{align*}
\]

- Amplitudes @ $l=80$
- Frequency spectral indices
- Spatial spectral indices
- Dust/sync spatial correlation
BK15 Results

Priors on the frequency spectral indices of dust & sync

Marginalize over generous ranges in spatial spectral indices

Allow dust/sync correlation

A_{dust}

A_{sync}

L/L_{peak
BK15 Results

$r < 0.07$ (95% CL)

Plus many alternate analyses presented:
- Foreground priors
- Including EE
- WMAP/Planck data
- Dust decorrelation

Allow dust/sync correlation

Priors on the frequency spectral indices of dust & sync

Marginalize over generous ranges in spatial spectral indices
Keck Array
2015

220 220
150
95 95
95
2019 onwards: BICEP Array

<table>
<thead>
<tr>
<th>Frequency</th>
<th>30/40 GHz</th>
<th>95 GHz</th>
<th>150 GHz</th>
<th>220/270 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tiles</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td># Detectors</td>
<td>192/300</td>
<td>3456</td>
<td>7776</td>
<td>13824/16224</td>
</tr>
<tr>
<td># Det/ Tile</td>
<td>32/50</td>
<td>288</td>
<td>648</td>
<td>1152/1352</td>
</tr>
<tr>
<td>Beam FWHM (arcmin)</td>
<td>76/57</td>
<td>24</td>
<td>15</td>
<td>10/8.5</td>
</tr>
<tr>
<td>NET per det (uK-rts)</td>
<td>268/334</td>
<td>267</td>
<td>315</td>
<td>900/1800</td>
</tr>
<tr>
<td>Instr. NET (uK-rts)</td>
<td>21/21</td>
<td>4.93</td>
<td>3.87</td>
<td>8.3/15</td>
</tr>
<tr>
<td>3-yr map depth (uK-arcmin)</td>
<td>7.5/7.5</td>
<td>1.9</td>
<td>1.4</td>
<td>3.0/5.5</td>
</tr>
</tbody>
</table>
BICEP Array mount at U. Minnesota
BA1 (30/40 GHz) integration

Receiver performance

Optics

HDPE lenses

Alumina IR filter
**CMB-S4 Measurement of $r$**

Goal: $r < 0.001$ at 95%, or detect $r = 0.003$ at high confidence

This means $< 10$ nK uncertainties at degree scales. Requires:
- Raw sensitivity
- Systematics control
- Foreground separation

Figures from CMB-S4 DSR
The S4 reference design for the SAT mounts, optics and shielding is modeled after Stage-3 BICEP3 and BICEP Array.

3 optics tubes inside a single cryostat

<table>
<thead>
<tr>
<th>bands</th>
<th>lenses</th>
<th>field of view</th>
<th>min edge taper</th>
<th>modulation</th>
<th>detectors/tube</th>
<th>tubes</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 / 40</td>
<td>2x 55cm Al</td>
<td>29°</td>
<td>-9.3 dB</td>
<td>scan</td>
<td>576</td>
<td>1</td>
</tr>
<tr>
<td>85 / 145</td>
<td>2x 55cm Al</td>
<td>29°</td>
<td>-6.2 dB</td>
<td>scan</td>
<td>7056</td>
<td>4</td>
</tr>
<tr>
<td>95 / 155</td>
<td>2x 55cm Al</td>
<td>29°</td>
<td>-8.4 dB</td>
<td>scan</td>
<td>7056</td>
<td>4</td>
</tr>
<tr>
<td>220 / 270</td>
<td>2x 44cm Si</td>
<td>29°</td>
<td>-12.5 dB</td>
<td>scan</td>
<td>16884</td>
<td>3</td>
</tr>
</tbody>
</table>

Subtotals: 107,676 detectors

<table>
<thead>
<tr>
<th>bands</th>
<th>lenses</th>
<th>field of view</th>
<th>min edge taper</th>
<th>modulation</th>
<th>detectors/tube</th>
<th>tubes</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 / 40</td>
<td>3x 55cm Al</td>
<td>35°</td>
<td>-6.8 dB</td>
<td>scan</td>
<td>684</td>
<td>1</td>
</tr>
<tr>
<td>85 / 145</td>
<td>3x 44cm Si</td>
<td>35°</td>
<td>-5.7 dB</td>
<td>HWP</td>
<td>6084</td>
<td>2</td>
</tr>
<tr>
<td>95 / 155</td>
<td>3x 44cm Si</td>
<td>35°</td>
<td>-8.0 dB</td>
<td>HWP</td>
<td>6084</td>
<td>2</td>
</tr>
<tr>
<td>220 / 270</td>
<td>3x 44cm Si</td>
<td>35°</td>
<td>-13.4 dB</td>
<td>HWP</td>
<td>16884</td>
<td>1</td>
</tr>
</tbody>
</table>

Subtotals: 41,904 detectors

Figures from CMB-S4 DSR
Conclusions

• BICEP/Keck lead the field in the quest to detect or set limits on inflationary gravitational waves:
  • Best published sensitivity to date
  • Best proven systematic control at degree angular scales

• BK15: Adding 2015 data including, for the first time, at 220 GHz:
  • Incremental improvement wrt BK14: from $r_{0.05} < 0.09$ to $r_{0.05} < 0.07$
  • Plank 15 + BK15 $r_{0.05} < 0.06$ $[r_{0.002} < 0.055]$ (arXiv 1810.05216)
  • Beam systematics constrained to 0.1 $\sigma(r)$ (arXiv 1904.01640)

• Currently analyzing 3 years (2016-18) of 95 GHz data from BICEP3 and 2 years of 270 GHz data from Keck: BK18 data analysis
  • Pushing multiband observations & component separation

• And we can go much further:
  • BICEP Array begins observing in 2020 - expect $\sigma(r) \sim 0.003$
  • Delensing using SPT/SPT-3G data
  • Next Generation CMB Experiment: CMB Stage-4
Thank you!
Extra slides
BK15: Current Band Sensitivity (at l=80)
BK17 errors on $r$ will be dominated by synchrotron sensitivity.
Adding in temperature

\( r_{0.05} < 0.07 \)
Adding in temperature

$\phi^2$

no B-modes

with B-modes

Convex

Concave

$r_{0.05} < 0.06$
Far-Field Beam Mapping
Optical 100 GHz Demodulated

Photo credit: E. Yang