Searching for Inflation with CMB Polarimetry at the South Pole: the BICEP and Keck Array Program

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Direct Evidence for Inflation?

- Generic prediction of Inflation: primordial gravitational waves
- CMB Polarization:
  - “E-modes” from density fluctuations (first seen by DASI 2002)
  - “B-modes” a signature of gravitational waves
  \[ \rightarrow \text{Strength scales with energy scale of Inflation} \]
Temperature spectrum traces density evolution of acoustic oscillations in early universe.

E-polarization spectrum:
- $10^2$ lower
- correlated with $T$ but out of phase

B-polarization spectrum:
- $10^2 - 10^3$ lower still!
- gravitational waves: large angular scale
- lensing: small angular scale

B-modes are a teeny signal! Hard to detect!
Why Bother with B-modes?

We need CMB polarization measurements to push deeper on the tensor-to-scalar ratio $r$!

- SPT + WMAP7 + BAO + $H_0$: $r < 0.11$
  (Story et al., 2012)
- Planck + WMAP (pol.): $r < 0.12$
  (Planck Collab. XXII, 2013)
- Theoretical limit from sample variance for CMB temperature measurements: $r < 0.1$
  (Knox & Turner, 1994)

$\rightarrow$ Can’t do better with temperature alone
Published CMB Polarization Results to Date

Best limit on $r$ (tensor-to-scalar ratio) is from BICEP1!

$\ell = 100$ peak, $r=0.1$

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Purpose-built machines targeted to look for the inflationary B-mode polarization signature in the CMB

→ With BICEP/Keck Array program, we have the sensitivity and systematics control to get to $r=0.01$
The BICEP/Keck Array Collaboration

- British Columbia
- Caltech
- CEA Grenoble
- Chicago
- Harvard
- JPL
- Minnesota
- NIST
- Stanford
- Toronto
- Wales Cardiff
The BICEP/Keck Array Strategy

• Small Aperture
• Compact, single-frequency, refractive telescopes
• Stare deep into clean patch of sky
• Start with 150 GHz until you see B-modes
• Observe from the best high, dry, stable site
• Lots of detectors & tight control of systematics
12” aperture defines half degree beams → target peak of inflationary B-mode spectrum
• On-axis, refractive telescope
• Large field of view
• High throughput
  – Compact, co-mount five telescopes

• Good control of systematics
  – All cold optics (4K)
  – Multiple stages of baffling
  – Rotation about boresight
Observe Where Foregrounds are the Smallest

**“Southern Hole”**

- WMAP K-band $P @ 150$ GHz (assuming index $-3.0$)
- Color range 0 to 4 $\mu$K

**Synchrotron**

- Color range 0 to 4 $\mu$K

**Dust**

- Color range 0 to 4 $\mu$K

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**Full SPUD Sensitivity**

- $l(l+1)C_l/2\pi$ at $l=85$

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**Full Keck Sensitivity**

- $r=0.3$
- $r=0.02$

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**@ 150 GHz (until you see B-modes)**

- Pryke & Kovac

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Observe from the South Pole

- Extremely stable, dry atmosphere
- Pressure altitude: 10,500 ft
- One night and one day per year
- High Observing Efficiency
  - “Southern Hole” visible 24/7
The Quest for More Sensitivity

BICEP1
2006-2008

50 @ 100 GHz
48 @ 150 GHz

Current best limits on Inflationary polarization
The Quest for More Sensitivity

BICEP1
2006-2008

BICEP2
2010-2012

50 @ 100 GHz
48 @ 150 GHz

512 @ 150 GHz

Current best limits on Inflationary polarization

x10 mapping speed

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The Quest for More Sensitivity

BICEP1
2006-2008
50 @ 100 GHz
48 @ 150 GHz

BICEP2
2010-2012
512 @ 150 GHz
x10 mapping speed

Keck Array
3 x deployed Jan 2011
2 x deployed Jan 2012
4 Years of Observation
5 x 512 @ 150 GHz
(plans for 100 GHz and 220 GHz)
x50 mapping speed

Current best limits on Inflationary polarization
The Quest for More Sensitivity

BICEP1
2006-2008

50 @ 100 GHz
48 @ 150 GHz

Current best limits on Inflationary polarization

BICEP2
2010-2012

512 @ 150 GHz
x10 mapping speed

BICEP3
Will Deploy in 2014

2056 @ 100 GHz

Keck Array
3 x deployed Jan 2011
2 x deployed Jan 2012
4 Years of Observation

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BICEP1 (2006-2008)

- 49 pairs of feed horn-coupled polarization sensitive NTD bolometers
- 100 & 150 GHz
- 2 year results: $r < 0.72$ (Chiang et al. 2009)
BICEP1 did not find B modes.

New world’s best limit from polarization measurements:
tensor-to-scalar ratio $r < 0.70$
@ 95% CL

3-year map depth: 500 nK-deg
BICEP2 (2010-2012)

- 512 dual-polarization slot antenna coupled Transition Edge Sensor (TES) Bolometers at 150 GHz
- 10x BICEP1 mapping speed
The Keck Array (2011-

- 5x BICEP2
- New: pulse tube coolers
- Currently 5 @ 150 GHz
- This year: 100, 220 GHz
Verifying Keck and BICEP2 Optical Performance

Big Mirror

Rotating Polarized Microwave Source

Detector Response, Normalized

Source Angle (Degrees)

Measured Beam

Gaussian Fit

Far Field Beam Profile

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Beam Mismatch and Mitigation

- Beam pointing mismatch observed between orthogonally-polarized detectors in a pair
- Much improved in recent focal planes (now observing at Pole)
- $T \rightarrow P$ leakage can be mitigated in analysis (Aikin et al., in prep)
- Sufficient control of beam systematics to achieve sensitivity goal

A - B

(Fractional Amplitude)

2011 Keck Example

2013 Keck Example
BICEP2 and Keck Array: The Deepest Maps at Degree Angular Scales

**BICEP2** 3-year: 128 nK-deg

**Keck** 2012 only: 170 nK-deg
### Achieved Program Sensitivity

<table>
<thead>
<tr>
<th></th>
<th>Sensitivity (uK $\sqrt{\text{s}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BICEP 1</td>
<td>54</td>
</tr>
<tr>
<td>BICEP 2</td>
<td>16</td>
</tr>
<tr>
<td>Keck Array 2011</td>
<td>20</td>
</tr>
<tr>
<td>Keck Array 2012</td>
<td>11</td>
</tr>
<tr>
<td>Keck Array 2013</td>
<td>9.5</td>
</tr>
</tbody>
</table>

- **BICEP 1**: 3 receivers only in 2011
- **BICEP 2**: All 5 receivers deployed, 1 focal plane with improved sensitivity
- **Keck Array 2011**: 5 receivers, 2 more focal planes with improved sensitivity
BICEP3 (2015- )

- 2560 detectors at 100 GHz
- Larger aperture, faster optics → 10x BICEP2’s optical throughput
- Doubles the program’s survey speed
- Important for foreground separation

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Summary

- BICEP1: final results in preparation, still the best constraint on B modes from inflation
- BICEP2/Keck Array: first results soon
- BICEP3: double our mapping speed
- We can reach $r=0.01$, and we are improving every year!
- Careful analysis is critical and new techniques have been developed (deprojection of beam systematics)
- With our achieved sensitivity, we fully expect that foreground separation and delensing will become critical soon