Detection of B-mode Polarization at Degree Scales using BICEP2
BICEP2 I: Detection of $B$-mode Polarization at Degree Angular Scales


We report results from the BICEP2 experiment, a Cosmic Microwave Background (CMB) polarimeter specifically designed to search for the signal of inflationary gravitational waves in the $B$-mode power spectrum around $\ell \sim 80$. The telescope comprised a 26 cm aperture all-cold refracting optical system equipped with a focal plane of 512 antenna coupled transition edge sensor (TES) 150 GHz bolometers each with temperature sensitivity of $\approx 300 \mu$K/CMB$^{1/2}$. BICEP2 observed from the South Pole for three seasons from 2010 to 2012. A low-foreground region of sky with an effective area of 380 square degrees was observed to a depth of 87 nK-degrees in Stokes $Q$ and $U$. In this paper we describe the observations, data reduction, maps, simulations and results. We find an excess of $B$-mode power over the base lensed-$\Lambda$CDM expectation in the range $30 < \ell < 150$, inconsistent with the null hypothesis at a significance of $> 5\sigma$. Through jackknife tests and simulations based on detailed calibration measurements we show that systematic contamination is much smaller than the observed excess. Cross correlating against WMAP 23 GHz maps we find that Galactic synchrotron makes a negligible contribution to the observed signal. We also examine a number of available models of polarized dust emission and find that at their default parameter values they predict power $\sim 5 - 10 \times$ smaller than the observed excess signal (with no significant cross-correlation with our maps). However, these models are not sufficiently constrained by external public data to exclude the possibility of dust emission bright enough to explain the entire excess signal. Cross-correlating BICEP2 against 100 GHz maps from the BICEP1 experiment, the excess signal is confirmed with $3\sigma$ significance and its spectral index is found to be consistent with that of the CMB, disfavoring dust at $1.7\sigma$. The observed $B$-mode power spectrum is well-fit by a lensed-$\Lambda$CDM + tensor theoretical model with tensor/scalar ratio $r = 0.20^{+0.07}_{-0.05}$, with $r = 0$ disfavored at $7.0\sigma$. Accounting for the contribution of foreground dust will shift this value downward by an amount which will be better constrained with upcoming datasets.
The BICEP2 Postdocs

Colin Bischoff
Jeff Filippini
Martin Lueker
Walt Ogburn
Abigail Vieregg
Immanuel Buder
Stefan Fliescher
Roger O'Brient
Angiola Orlando
Zak Staniszewski

The BICEP2 Graduate Students

Randol Aikin
Justus Brevik
Chris Sheehy
Grant Teply
Chin Lin Wong
Kirit Karkare
Jon Kaufman
Sarah Kernasovskiy
Jamie Tolan

BICEP2 Winterovers

Steffen Richter 2010
Steffen Richter 2011
Steffen Richter 2012
launching Cosmology’s greatest wild goose chase

The Search for Inflationary B-Modes

Andrew Lange
Caltech Marvin L. Goldberger Professor of Physics
1957 - 2010
CMB Polarization

Density Wave

E-Mode Polarization Pattern

Gravitational Wave

B-Mode Polarization Pattern
CMB Polarization

Density Wave

Gravitational Wave

E-Mode Polarization Pattern

B-Mode Polarization Pattern
E-modes
COSMO 2002: DASI first detects polarization of CMB
E-modes from the ground

- Deep, Concentrated coverage (few modes)
- Foreground avoidance (limited frequencies)
- Systematic control with (repeated) in-situ calibration
- Large detector count, rapid technology cycle
- Relentless observing – large number of null tests

→ powerful recipe for high-confidence initial discovery
B-modes from the ground

• Deep, Concentrated coverage (few modes)
• Foreground avoidance (limited frequencies)
• Systematic control with (repeated) in-situ calibration
• Large detector count, rapid technology cycle
• Relentless observing – large number of null tests

→ powerful recipe for high-confidence initial discovery
The long search for Inflationary B-modes

Best previous limit on $r$ from BICEP1:

$r < 0.7$ (95% CL)

Note at high multipoles lensing B-mode dominant.

SPT x-corr: lower limits on lensing B-mode from cross correlation using the CIB
BICEP2 Experimental Concept

- Small aperture
- Wide field of view
- Cold refractor
Mass-produced superconducting detectors from JPL

Focal plane

Planar antenna array

Slot antennas

Transition edge sensor

Microstrip filters
South Pole CMB telescopes

10m South Pole Telescope
BICEP1
BICEP2
BICEP3
DASI
QUAD
Keck Array

NSF’s South Pole Station: A popular place with CMB Experimentalists!

Dry, stable atmosphere and 24h coverage of “Southern Hole”.

Atacama, Greenland(?) excellent alternatives offering different coverage.
South Pole: “Relentless Observing”
BICEP2 3-year Data Set

Live Time

Instantaneous Sensitivity

Cumulative Map Depth

Final map depth:
87 nK-deg

John Kovac for The Bicep2 Collaboration
Cosmic Microwave Background

Planck's all sky CMB temperature map scale ±500 µK

Bicep2's CMB polarization map

The Bicep2 Collaboration
CMB Polarization

Need 2D basis to describe polarization map...

Bicep2’s CMB polarization map

...familiar choice: Stokes Parameters Q&U

The Bicep2 Collaboration
CMB Polarization

Need 2D basis to describe polarization map...

...clever choice in this case: E&B-modes
The Bicep2 Collaboration

CMB Polarization

Need 2D basis to describe polarization map...

...clever choice in this case: E&B-modes

Bicep2's CMB polarization map

BICEP2 E–mode signal

BICEP2 B–mode signal
Analysis "calibrated" using lensed-ΛCDM+noise simulations.

The simulations repeat the full observation at the timestream level - including all filtering operations.

We perform various filtering operations: Use the sims to correct for these

Also use the sims to derive the final uncertainties (error bars)
BICEP2 B-mode Power Spectrum

B-mode power spectrum estimated from Q&U maps, including map based “purification” to avoid E→B mixing

Consistent with lensing expectation at higher l. (yes – a few points are high but not excessively…)

At low l excess over lensed-ΛCDM with high signal-to-noise.

For the hypothesis that the measured band powers come from lensed-ΛCDM we find:

\[ \chi^2 \text{ PTE} = 1.3 \times 10^{-7} \]

\[ \text{significance} \ 5.3 \sigma \]
Temperature and Polarization Spectra

Temperature and Polarization Spectra

$\ell(\ell+1)C_\ell / (2\pi) [\mu K^2]$

TT - $\chi^2$ PTE = 0.28

TE - $\chi^2$ PTE = 0.30

TE jack - $\chi^2$ PTE = 0.20

EE - $\chi^2$ PTE = 0.04

EE jack - $\chi^2$ PTE = 0.38

BB - $\chi^2$ PTE = 0.00

TB - $\chi^2$ PTE = 0.67

TB jack - $\chi^2$ PTE = 0.16

EB - $\chi^2$ PTE = 0.06

EB jack - $\chi^2$ PTE = 0.69

Multipole

- power spectra
- temporal split jackknife
- lensed-$\Lambda$CDM
- $r=0.2$
Check Systematics: Jackknifes

14 jackknife tests applied to 3 spectra, 4 statistics

### Split by boresight rotations
Amplifies differential pointing in comparison to fully added data. Important check of deprojection. See later slides.

### Split by time
Checks for contamination on long (“Temporal Split”) and short (“Scan Dir”) timescales. Short timescales probe detector transfer functions.

### Split by channel selection
Checks for contamination in channel subgroups, divided by focal plane location, tile location, and readout electronics grouping.

### Split by possible external contamination
Checks for contamination from ground-fixed signals, such as polarized sky or magnetic fields, or the moon.

### Split to check intrinsic detector properties
Checks for contamination from detectors with best/worst differential pointing. “Tile/dk” divides the data by the orientation of the detector on the sky.

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**Table 1: Jackknife PTE values from $\chi^2$ and $\chi$ (sub-of-deviation) Tests**

<table>
<thead>
<tr>
<th>Jackknife</th>
<th>1-5 $\chi^2$</th>
<th>1-9 $\chi^2$</th>
<th>1-5 $\chi$</th>
<th>1-9 $\chi$</th>
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<tr>
<td>EE</td>
<td>0.946</td>
<td>0.030</td>
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<td>BB</td>
<td>0.774</td>
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<td>0.529</td>
<td>0.577</td>
<td>0.840</td>
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<td>Max Col jackknife</td>
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<td>Tile/Deck jackknife</td>
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<td>Focal Plane inner/outer jackknife</td>
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<td>0.597</td>
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<td>0.060</td>
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<td>BB</td>
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<td>Tile inner/outer jackknife</td>
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<td>Moon jackknife</td>
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<td>0.689</td>
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<td>BB</td>
<td>0.144</td>
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<td>0.896</td>
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<td>EB</td>
<td>0.289</td>
<td>0.339</td>
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<td>All affect best/worst</td>
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<tr>
<td>EE</td>
<td>0.317</td>
<td>0.311</td>
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<td>0.709</td>
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<tr>
<td>EB</td>
<td>0.589</td>
<td>0.872</td>
<td>0.999</td>
<td>0.760</td>
</tr>
</tbody>
</table>

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See parallel session talk by Chris Sheehy
Calibration Measurements

For instance...

Far field beam mapping

Hi-Fi beam maps of individual detectors

Detailed description in companion Instrument Paper
We know our Beam Shapes

Because contamination from beam shape mismatch is entirely deterministic, we can both remove it (deprojection) and predict it in simulation using calibration data as input.

Calibration data for each channel

Simulation (explicit convolution with Planck T map)

Predictions of contamination

See parallel session talk by Chris Sheehy
All systematic effects that we could imagine were investigated!

We find with high confidence that the apparent signal cannot be explained by instrumental systematics!

See parallel session talk by Chris Sheehy
Cross Correlation with BICEP1

Though less sensitive, BICEP1 applied **different technology** (systematics control) and **multiple colors** (foreground control) to the **same sky**.

Cross-correlations with both colors are **consistent** with the B2 auto spectrum.

Cross with BICEP1$_{100}$ shows $\sim 3\sigma$ detection of BB power.
**Spectral Index of the B-mode Signal**

Comparison of B2 auto with B2_{150} × B1_{100} constrains signal frequency dependence, independent of foreground projections.

If dust, expect little cross-correlation

If synchrotron, expect cross higher than auto

Likelihood ratio test: consistent with CMB spectrum, disfavor pure dust for excess at 1.7σ

\[
\beta_{\text{total}} = -1.55^{+1.25}_{-0.86}
\]

\[
\beta_{\text{excess}} = -1.65^{+1.85}_{-1.08}
\]
Cross Spectra between 3 Experiments

Form cross spectrum between BICEP2 and BICEP1 combined (100 + 150 GHz):

- B2xB2
- B2xB1c
- B2xKeck (preliminary)

BICEP2 auto spectrum compatible with B2xB1c cross spectrum

~3σ evidence of excess power in the cross spectrum

Additionally form cross spectrum with 2 years of data from Keck Array, the successor to BICEP2

Excess power is also evident in the B2xKeck cross spectrum

Cross spectra:

Powerful additional evidence against a systematic origin of the apparent signal
Substantial excess power in the region where the inflationary gravitational wave signal is expected to peak

Find the most likely value of the tensor-to-scalar ratio $r$

Apply “direct likelihood” method, uses:

- lensed-$\Lambda$CDM + noise simulations
- weighted version of the 5 bandpowers
- $B$-mode sims scaled to various levels of $r$ ($n_T=0$)

Within this simplistic model we find:

- $r = 0.2$ with uncertainties dominated by sample variance
- PTE of fit to data: 0.9 → model is perfectly acceptable fit to the data
- $r = 0$ ruled out at 7.0σ

$r = 0.20^{+0.07}_{-0.05}$
Polarized Dust Foreground Projections

The BICEP2 region is chosen to have lowest foreground emission based on available pre-Planck models.

Use models of polarized dust emission to estimate foregrounds. (default parameter values)

Dust model auto spectra are well below observed signal level.

Cross spectra are lower, though this could indicate limitations of models.
Constraint on $r$ under Foreground Projections

"Probability that each of these models reflect reality hard to assess" – uncertainties could go in either direction, but large enough to equal entire signal.

$r = 0.15$ to $0.19$ based on models at default values.

Dust contribution is largest in the first bandpower. Deweighting this bin could lead to less deviation from our base result.
Conclusions circa March 17th

BICEP2 and limits from other experiments:

Deepest polarization maps yet made: 
87nK-deg / 3nK total

Power spectra perfectly consistent with lensed-ΛCDM except: 
5.2σ excess in the B-mode spectrum at low multipoles!

Extensive studies and jackknife test strongly argue against systematics as the origin

Foregrounds do not appear to be a large fraction of the signal:
→ foreground projections
→ lack of cross correlations
→ CMB-like spectral index
→ B-mode distribution / spectrum

With no foreground subtraction, constraint on tensor-to-scalar ratio r in simple inflationary gravitational wave model:

\[ r = 0.20^{+0.07}_{-0.05} \]

r = 0 is ruled out at 7.0σ. This shifts down depending on foreground level.
Developments Since March…

• Intense media and science community interest (!)
• Many early instrumental / stat queries… mostly seem to have faded
• Concerns seem to have boiled down to:
  - Polarized dust foreground may be stronger than previously projected…
• In May, 4 new papers on dust polarization appeared from Planck
  - These specifically mask out low foreground regions like ours (due to “non small systematics and not dust dominated”)
  - Trend to higher polarization in low dust regions. 4% mode, but > 10% in some regions
• PRL final version of paper published June:
  B-mode detection + analysis are secure.
  Uncertainty on interpretation has increased.
  “Is it all dust?”
  BICEP2(+1) internal constraints are weak. Dust models may not be reliable.
  Getting new data more important than ever.
• Joint Analysis underway with Planck, combining maps to cross spectra
  ➔ Most powerful way to overcome limitations of noise/systematics in Planck maps of polarized dust in our region.
Many other experiments are making rapid progress!

- **SPTpol** has data in the can over same sky patch at 100 and 150 GHz
  - Should be able to see signal alone and/or in cross correlation with BICEP2/Keck – analysis started
- **Polarbear**, **ACTpol** have exciting results
  - pushing toward degree-scales

- **ABS** running, **CLASS** soon…
- Balloons:
  
**EBEX** has data in the can (220?)

**Spider** will fly later this year.

**PIPER** will fly sometime soon.

See parallel session talks by Ryan Keisler and Blake Sherwin
Coming Next

Keck Array + BICEP3: new data @ 100 + 220

Keck 2014 is running right now with 2 receivers at 100GHz

BICEP3 to deploy this October!
Coming Next (summary)

• **Keck 2014** is running right now with 2 receivers at **100GHz**
  – Sensitivity of BICEP1 already surpassed, soon will **tighten foreground constraint**
  – **BICEP3** deploys in 3 months, doubles Keck’s power, all at 100 GHz

• **Planck** will weigh in soon
  – hints already of higher dust, but limited by noise/systematics
  – Joint **BICEP2 + Planck** map-based analysis should offer best constraints

• **Ground based efforts are moving VERY FAST:**
  – SPTpol, Polarbear, ACTpol, ABS, Spider, EBEX, CLASS, PIPER…

Most powerful way to advance the science is **more data, all used together**.