launching Cosmology’s greatest wild goose chase

The Search for Inflationary B-Modes

Andrew Lange
Caltech Marvin L. Goldberger Professor of Physics
1957 - 2010
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Resolution</th>
<th>FOV</th>
<th>Angular Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>BICEP (2006–2008)</td>
<td>98 NTDs (95/150 GHz)</td>
<td>0.93°/0.60° FWHM</td>
<td>18°</td>
</tr>
<tr>
<td>BICEP2 (2010–2012)</td>
<td>512 TESs (150 GHz)</td>
<td>0.52° FWHM</td>
<td>17°</td>
</tr>
<tr>
<td>KeckArray (2011–)</td>
<td>2560 TESs (150 GHz)</td>
<td>0.37° FWHM</td>
<td></td>
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<tr>
<td>BICEP3 (2015–)</td>
<td>2560 TESs (95 GHz)</td>
<td>0.37° FWHM</td>
<td></td>
</tr>
</tbody>
</table>

**Note:** The table compares the resolution, field of view (FOV), and angular throughput of different instruments. The angular throughputs are calculated based on the instrument's specifications.
Telescope as compact as possible while still having the angular resolution to observe degree-scale features.

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

Liquid helium (or PT cooler) cools the optical elements to 4.2 K.

A 3-stage helium sorption refrigerator further cools the detectors to 0.27 K.
Mass-produced superconducting detectors from JPL

- Focal plane
- Planar antenna array
- Slot antennas
- Transition edge sensor
- Microstrip filters
Detecting the CMB radiation

BICEP2 Detector: Transition-Edge Superconductor

Superconducting thermometer

CMB light from antenna

Radiation Converted to heat
>100 tiles (>12,000 detectors) have been produced over the past 8 yrs.
March 16 - 18, 2015
Cambridge, Massachusetts, U.S.A.

The Harvard-Smithsonian Center for Astrophysics will be hosting the 26th International Symposium on Space Terahertz Technology, which will take place from March 16th through March 18th 2015 at the Knafel Center in the Radcliffe Yard on the Harvard University campus in Cambridge Massachusetts.

Scope

The meeting will focus on millimeter, submillimeter, and Terahertz technology and applications, including:

- Ultra-sensitive detectors
- Sources and instrumentation
- Optical design and measurement techniques
- Back end signal processors
- Applications of receivers and detector systems

CMB technology will be a focus!

REGISTRATION NOW OPEN!!!

Scientific Organizing Committee Members

- Andrey Baryshev (Space Research Organization of Netherlands, The Netherlands)
- Victor Belitsky (Chalmers University, Sweden)
- Raymond Blundell (Smithsonian Astrophysical Observatory, USA)
- Gregory Gol’tsman (Moscow State Pedagogical University, Russia)
NSF’s South Pole Station:
A popular place with CMB Experimentalists!

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

Atacama offers a proven & developed excellent alternative site. Greenland, Tibet may offer viable sites for northern coverage.
South Pole: “Relentless Observing”
BICEP2 3-year Data Set

Live Time

Instantaneous Sensitivity

Cumulative Map Depth

Final map depth:

87 nK-deg
Cosmic Microwave Background

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

Bicep2's CMB polarization map

Power \( l(l+1) C_l/2\pi [\mu K^2] \)

Intensity

Polarization

The Bicep2 Collaboration
CMB Polarization

Need 2D basis to describe polarization map...

...familiar choice: Stokes Parameters Q&U
The Bicep2 Collaboration

CMB Polarization

Bicep2's CMB polarization map

...map eigenmode-based B separation for highest fidelity

The Bicep2 Collaboration
CMB Polarization

The Bicep2 Collaboration

- E-mode
- B-mode

Bicep2's CMB polarization map

Eigenmode-based B separation for highest fidelity

Multipole $l$

Power $(l+1) C_l / 2\pi \, [\mu K^2]$
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 only from lensed-ΛCDM we find:

\( \chi^2 \text{ PTE} = 1.3 \times 10^{-7} \)

significance \( 5.3 \sigma \)
Temperature and Polarization Spectra

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

John Kovac for The Bicep2 Collaboration

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

14 jackknife tests applied to 3 spectra, 4 statistics

<table>
<thead>
<tr>
<th>Jackknife</th>
<th>Bandpowers</th>
<th>Bandpowers</th>
<th>Bandpowers</th>
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<tr>
<td></td>
<td>1-5 (\chi^2)</td>
<td>1-9 (\chi^2)</td>
<td>1-5 (\chi)</td>
<td>1-9 (\chi)</td>
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<td>0.004</td>
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<td>0.529</td>
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<td>0.024</td>
<td>0.048</td>
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<tr>
<td>Tile/Deck jackknife</td>
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<tr>
<td>EE</td>
<td>0.048</td>
<td>0.088</td>
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<td>0.840</td>
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<td>0.591</td>
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<td>Focal Plane inner/outer jackknife</td>
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<td>0.597</td>
<td>0.022</td>
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<td>0.042</td>
<td>0.850</td>
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<tr>
<td>Tile top/bottom jackknife</td>
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<tr>
<td>EE</td>
<td>0.209</td>
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<td>BB</td>
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<td>EB</td>
<td>0.545</td>
<td>0.683</td>
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<td>0.932</td>
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<tr>
<td>Tile inner/outer jackknife</td>
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<tr>
<td>EE</td>
<td>0.772</td>
<td>0.533</td>
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<td>EB</td>
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<td>0.737</td>
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<td>Moon jackknife</td>
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<tr>
<td>EE</td>
<td>0.409</td>
<td>0.089</td>
<td>0.481</td>
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<tr>
<td>BB</td>
<td>0.144</td>
<td>0.287</td>
<td>0.898</td>
<td>0.858</td>
</tr>
<tr>
<td>EB</td>
<td>0.269</td>
<td>0.339</td>
<td>0.531</td>
<td>0.307</td>
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<tr>
<td>All offset best/worst</td>
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<tr>
<td>EE</td>
<td>0.317</td>
<td>0.311</td>
<td>0.868</td>
<td>0.709</td>
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<tr>
<td>BB</td>
<td>0.114</td>
<td>0.064</td>
<td>0.307</td>
<td>0.094</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>

Splits the 4 boresight rotations
Amplifies differential pointing in comparison to fully added data. Important check of deprojection. See later slides.

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

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

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

Splits 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.
Calibration Measurements

For instance...

Far field beam mapping

Hi-Fi beam maps of individual detectors

Detailed description in companion Instrument Paper

John Kovac for The Bicep2 Collaboration
We know our Beam Shapes

Because contamination from beam shape mismatch is entirely deterministic, we can both *filter it out (deprojection)* and *predict it in simulation* using calibration data and Planck T map as input.

Calibration data for each channel

Simulation (explicit convolution with Planck T map)

Predictions of contamination

analysis by Chris Sheehy, Chin Lin Wong
All systematic effects that we could imagine were investigated.

We find with high confidence that the apparent signal cannot be explained by instrumental systematics!
~3σ evidence of excess power in the B2 x BICEP1 (100+150 GHz) cross spectrum

Excess power is also evident in the B2 x Keck 2012/13 (150 GHz) cross spectrum

Cross spectra:
Powerful additional evidence against a systematic origin of the apparent signal
**March 2014: Spectral Index of the B-mode Excess**

Comparison of B2 auto with B2_{150} \times B1_{100} constrains signal frequency dependence, independent of foreground projections, but only with very modest significance.

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

\[ \beta_{\text{excess}} = -1.65^{+1.85}_{-1.08} \]
\[ \beta_{\text{total}} = -1.55^{+1.25}_{-0.86} \]
March 2014: Constraint on $r$ under Foreground Projections

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

$r = 0.15$ to $0.19$, based on these models at default values.
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 $\approx 300 \, \mu \text{K}_{\text{CMB}} \sqrt{\ell}$. 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-ΛCDM 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-ΛCDM + 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.

arXiv:1403.3985 / published PRL June 19
Timeline Since March 2014...

• Many early instrumental / stat queries… mostly seem to have faded

• Major outstanding issue:
  Polarized dust foreground may be stronger than previously projected…
  March 18: J. L. Puget: “For certainty, dust maps must be subtracted; wait for Planck”

• May: 4 new papers on dust polarization appeared from Planck
  – mid-latitude only; faintest regions excluded where systematics and noise dominated.
  – Trend to higher polarization in low dust regions. 4% avg (i.e. consistent w/ models), but > 10% in some regions – spatial variation of polarized power not yet understood!

• June: PRL final version of paper published:
  Uncertainty on interpretation has increased: “Is it all dust?”
  BICEP2(+1) internal constraints are weak. Dust models appear not to be reliable.
  B-mode detection + analysis are secure – the measurements work!
  Getting new data remains more important than ever.

• July: Joint Analysis begun with Planck, combining maps to cross spectra

• September: PIP-XXX released, including high-latitude dust study
September 2014: Planck XXX

➢ The 353x353 spectrum scaled to 150 GHz (Bicep2’s frequency)

➢ SED and uncertainty is derived from average over large sky fraction – Planck XXX finds no evidence of departures of polarized dust from this scaling.

➢ In a single broad bin roughly matches the power seen by BICEP2

➢ Planck XXX paper states: “The present uncertainties are large and will be reduced through an ongoing, joint analysis of the Planck and BICEP2 data sets.”

“Good news for component separation” – F. Boulanger
Coming next (1): BICEP2 + Planck Joint analysis

• SOON. Unfortunately can’t discuss results today!
• The combination of B2 and Planck is far more powerful than either alone
• Collaborative effort has been extremely fruitful (+ enjoyable)
• Exchange of maps, full filtering matrices, signal and noise simulations, cross-checks of power spectrum estimators – good template for future joint analyses
• Analysis invokes all spectra and cross spectra
• Multi-component, parametric CMB+foreground analysis for likelihood
  – full data release, spectra and likelihood code
• Timeline has allowed inclusion of full Keck 2012+13 150 GHz datasets
Consistency of dust amplitude in Planck 353 and 217 GHz BB auto spectra with dust amplitude in the cross spectrum limits possible spatial decorrelation of dust signal between frequencies (e.g. from a spatially varying color spectral index).

- Averaging over the 400 deg$^2$ patches yields a mean decorrelation ratio $d = 1.01 \pm 0.07$.
- Averaging over the six $0.3 < f_{\text{sky}} < 0.8$ patches yields $d = 1.01 \pm 0.03$. 
Limits on systematic decorrelation

- Consistency of B2K and Planck 143 GHz year-split TT auto spectra with the cross spectrum limits possible decorrelation from pointing error, pipeline errors, etc. Weighted mean over multipole yields decorrelation ratio $d = 0.9996 \pm 0.0001$.
- Consistency of the EE spectra will be an important test.

![Graph showing consistency of B2K and Planck 143 GHz spectra with decorrelation limits.](image)

(error bars include no sample variance)
Coming next (1): **BICEP2 + Planck Joint analysis**

Coming next (2): **Keck Array 2014 at 95 GHz**

Keck 2014 has a full season with 2 receivers at 95 GHz
BICEP2 + Keck12+13 E-mode signal

\[ \text{1.7} \mu \text{K} \]
Coming next (2): Keck Array 2014 at 95 GHz
Coming next (2): **Keck Array 2014 at 95 GHz**

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<td>Bicep2</td>
<td>87 (5.2)</td>
<td>3.15</td>
<td>101,000</td>
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<tr>
<td>Bicep2 + Keck12+13</td>
<td>57 (3.4)</td>
<td>2.01</td>
<td>248,000</td>
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<tr>
<td>Keck14 95 GHz</td>
<td>126 (7.6)</td>
<td>4.60</td>
<td>61,000</td>
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</table>

Dust BB expected ~5x fainter at 95 GHz vs 150 GHz
What’s Next?

• We are actively working with the Planck collaboration on a joint analysis of the two data sets
  – The combination of the two is more powerful than either alone
  – Goal is a joint paper in late Nov (meeting here at UMN in a couple of weeks to discuss)

• We also ran two of the Keck Array receivers this season at 100 GHz
  – Data in the can probably offers a stronger constraint on the value of $r$ than BICEP2+Planck
  – Guys here are gearing up to analyze as fast as possible when the data taking finishes on Nov 1 (Stefan, Eric, Justin)

• We are right now preparing to deploy BICEP3 which is an all 100GHz super receiver…
Coming next (3):
BICEP3 in 2015

BICEP2/Keck

Receiver from C.L. Kuo’s group at Stanford

BICEP3
BICEP3 large optics

Advanced materials (99.6% Al₂O₃)
For large BICEP3 cold optics
~60 cm aperture
BICEP3 in lab: October 2014
Modular focal plane
New type of SQUID MUX
~ SPT-3G in size & $\Delta \Omega$

BICEP3 in 2015
~ Four 95GHz Keck receivers

BICEP3 at South Pole: December 2014
BICEP3 receiver is going onto BICEP mount at Pole as we speak today.
Coming next (4): **Keck Array 220 GHz**

Keck receivers in 2015:
- 2 x 220 GHz
- 2 x 95 GHz
- 1 x 150 GHz

Keck first light @ 220 reported today (Jan 15)
Coming next:

Results from current data:

- **Planck X BK150 GHz** ~ by end of Jan 2015
  - will be limited by noise on dust template over BK field
- **Keck 95 GHz** ~ by spring 2015
  - Maps are already nearly as deep as B2, 5x lower dust
- **BICEP3 + Keck 220 GHz** ~ by end of 2015
  - We’ve already added a 3rd frequency. Ultra-deep maps at 220 GHz coming, while 95 GHz will soon surpass 150 GHz. At this ultra-deep level, we can expect to learn a lot quickly about FG discrimination.
- **More joint analyses to come**: SPTpol, others soon?
Coming next:

Results from current data:

• Planck X BK150 GHz ~ by end of Jan 2015
  • will be limited by noise on dust template over BK field
• Keck 95 GHz ~ by spring 2015
  • Maps are already nearly as deep as B2, 5x lower dust
• BICEP3 + Keck 220 GHz ~ by end of 2015
  • We’ve already added a 3rd frequency. Ultra-deep maps at
    220 GHz coming, while 95 GHz will soon surpass 150 GHz.
    At this ultra-deep level, we can expect to learn a lot quickly
    about FG discrimination.

• More joint analyses to come: SPTpol, others soon?

Prospects:

• More sky? Note that map at upper right is S/N < 1 everywhere
  cyan or bluer, with high correlations—so lots still to learn about
  the faintest regions. Looks promising for 95 GHz and larger f_sky.

• Small aperture measurements work very well, so expect another round of upgrade!
Stay tuned!