Evidence for Inflationary Gravitational Waves from BICEP2
BICEP2 I: DETECTION OF $B$-MODE POLARIZATION AT DEGREE ANGULAR SCALES


ABSTRACT

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 $\approx 300 \, \mu K_{\text{CMB}} \sqrt{s}$. 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. We also estimate potential foreground signals and find that available models predict these to be considerably smaller than the observed signal. These foreground models possess no significant cross-correlation with our maps. Additionally, 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 synchrotron or dust at $2.3\sigma$ and $2.2\sigma$, respectively. 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$\sigma$. Subtracting the best available estimate for foreground dust modifies the likelihood slightly so that $r = 0$ is disfavored at 5.9$\sigma$.

Subject headings: cosmic background radiation — cosmology: observations — gravitational waves — inflation — polarization
BICEP2 Experimental Strategy

- small aperture telescope
- Target the 2 degree peak of the B-mode
- Integrate continuously from South Pole
The BICEP2 Postdocs

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Jon Kaufman
Sarah Kernasovsky
Jamie Tolan

BICEP2 Winterovers

Steffen Richter 2010
Steffen Richter 2011
Steffen Richter 2012
BICEP2 Experimental Strategy

- Observe the “Southern Hole” at 150 GHz
- a region of the sky exceptionally free of dust and radio emission from our galaxy
Next few slides are placeholders for Chao Lin's slides on "what is inflation, why do we believe it, GWs as smoking gun, how GW's make the B-mode pattern, it is very faint! (1/20,000,000, i.e. for every 20,000,000 photons oriented like this, on average you may get 20,000,001 oriented the other.)"
Next few slides are placeholders for Chao Lin's slides on:

- **What is inflation, why do we believe it, GWs as smoking gun,**
- **how GW's make the B-mode pattern, it is very faint! (1/20,000,000, i.e. for every 20,000,000 photons oriented like his, on average you may get 20,000,010 oriented the other.)**
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CMB Temperature Measurements / Inflation

CMB temperature anisotropy now measured over full range of angular scales.

Consistent with ΛCDM paradigm(?) and constrains its parameters to sub percent accuracy.

Inflation “invented” in 1980s to explain facts about the Universe which were known or suspected.

Makes additional prediction of a background of gravitational waves (aka tensor modes) – which will imprint a specific CMB polarization pattern… → so-called “smoking gun” → amplitude tells us the energy scale at which inflation occurred

Planck Collaboration & ESA
CMB polarization: arises at last scattering from local radiation quadrupole
The Long Search for B-modes

In simple inflationary gravitational wave models, the tensor-to-scalar ratio $r$ is the only parameter to the B-mode spectrum.

Until last week only upper limits

Best previous limit on $r$ from BICEP1: $r < 0.7$ (95% CL)

At high multipoles lensing B-mode dominant.
BICEP2 Experimental Concept

- Small aperture
- Wide field of view
- Cold refractor
BICEP2 on the Sky

Projection of the BICEP2 focal plane on the sky

The focal plane is 20 degrees across

Background is the CMB temperature map as measured with BICEP2

Clem Pryke for The Bicep2 Collaboration
BICEP2 T and Stokes Q/U Maps

Sum Maps

Difference Maps

Clem Pryke for The Bicep2 Collaboration
Total Polarization

BICEP2 total polarization signal

Scale: $1.7 \mu K$
B-mode Contribution

Apply purification operation to Q/U maps which leaves only pure B-modes (given all timestream filterings etc.)

Clem Pryke for The Bicep2 Collaboration
B-mode Contribution

Zoom in by factor 6 – see “swirly” B-mode

Clem Pryke for The Bicep2 Collaboration
B-mode Map vs. Simulation

Analysis “calibrated” using lensed-$\Lambda$CDM+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-\( \Lambda \)CDM with high signal-to-noise.

For the hypothesis that the measured band powers come from lensed-\( \Lambda \)CDM we find:

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

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

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

\[ \chi^2 \text{ PTE} = \text{value} \]

\[ \text{Multipole} \]

- **TT**
- **TE**
- **EE**
- **BB**
- **TB**
- **EB**

- **power spectra**
- **lensed-ΛCDM**
- **temporal split jackknife**
- **r=0.2**

Clem Pryke for The Bicep2 Collaboration
Polarized Dust Foreground Projections

The BICEP2 region is chosen to have extremely low foreground emission.

Use various models of polarized dust emission to estimate foregrounds.

All dust auto spectra well below observed signal level.

Cross spectra consistent with zero.
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} x 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/sync at $2.2/2.3\sigma$
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
Constraint on Tensor-to-scalar Ratio $r$

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

$\rightarrow$ model is perfectly acceptable fit to the data

$r = 0$ ruled out at 7.0$\sigma$

$r = 0.20^{+0.07}_{-0.05}$
Constraint on $r$ under Foreground Projections

Adjust likelihood curve by subtracting the dust projection auto and cross spectra from our bandpowers:

Probability that each of these models reflect reality hard to assess

DDM2 uses all publicly available information from Planck - modifies constraint to $r = 0.16^{+0.06}_{-0.05}$

$r = 0$ ruled out at 5.9$\sigma$

Dust contribution is largest in the first bandpower. Deweighting this bin would lead to less deviation from our base result.
Compatibility with Indirect Limits on $r$

Indirect limit on $r$ from combination of temperature data over a wide range of angular scales:

- \( \text{SPT+WMAP+BAO+}H_0 \) : $r < 0.11$
- \( \text{Planck+SPT+ACT+WMAP}_{\text{pol}} \) : $r < 0.11$

This apparent tension can be relieved with various extensions to lensed $\Lambda$CDM.

**Example:** running of the spectral index

Planck likelihood chains for lensed $\Lambda$CDM + tensors + running

Same chains, importance sampled with the BICEP2 $r$ likelihood

Other possibilities within $\Lambda$CDM?...
Conclusions

BICEP2 and upper limits from other experiments:

Most sensitive polarization maps ever made

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
→ shape of the B-mode spectrum

Constraint on tensor-to-scalar ratio r in simple inflationary gravitational wave model:
\[ r = 0.20^{+0.07}_{-0.05} \]

i.e. Energy scale of inflation is \(2 \times 10^{16}\) GeV!
What’s Next?

Confirm:

• Keck Array 2012/13 results coming soon (within few months)
• Planck may be able to confirm at either reionization (ell<10) or recombination (ell=80) bump.
• 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
• Keck 2014 running with two 100 GHz receivers – will rapidly surpass BICEP1 100 GHz sensitivity.
• Polarbear, ACTpol, ABS running…
• EBEX has data in the can… Spider will fly later this year… plus many others…

Refine:

• Need more sky/sensitivity to reduce uncertainty on r
• Need longer lever arm to measure tensor spectral index $n_T$
  – De-lense to push to higher ell
  – Big sky to push to lower ell
• Add small apertures to S4? Renewed interest in future space mission? Ground based spinners? (Cf. CLASS)