Searching for Primordial Gravitational Waves with the BICEP/Keck Telescopes
BK15 Results On arxiv Today

BICEP2 / Keck Array: Constraints on Primordial Gravitational Waves using Planck, WMAP, and New BICEP2/Keck Observations through the 2015 Season


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We present results from an analysis of all data taken by the BICEP2/Keck CMB polarization experiments up to and including the 2015 observing season. This includes the first Keck Array observations at 220 GHz and additional observations at 95 & 150 GHz. The QHB map reaches depths of 5.2, 2.9 and 26 μJy beam−1 arcmin at 95, 150 and 220 GHz respectively over an effective area of ≈ 400 square degrees. The 220 GHz maps achieve a signal-to-noise on polarized dust emission approximately equal to that of Planck at 353 GHz. We take autos and cross-spectra between these maps and publicly available WMAP and Planck maps at frequencies from 23 to 353 GHz. We evaluate the joint likelihood of the spectra versus a multicomponent model of lensed-CDM + dust + synchrotron + noise. The foreground model has seven parameters, and we impose priors on some of these using external information from Planck and WMAP derived from larger regions of sky. The model is shown to be an adequate description of the data at the current noise levels. The likelihood analysis yields the constraint $r_{\text{obs}} = 0.07$ at 95% confidence, which tightens to $r_{\text{obs}} < 0.09$ in conjunction with Planck temperature measurements and other data. The lensing signal is detected at 8.8σ significance. Running maximum likelihood searches on simulations we obtain unbiased results and find that $e(\nu) = 0.23$. These are the strongest constraints to date on primordial gravitational waves.

arxiv/1810.05216

BK15 = includes all data taken up to, and including, 2015 season

Three years since BK14 – Sorry for the delay!
Experimental Strategy

→ Small aperture telescopes (cheap, fast, low systematics)
→ Target the 2 degree peak of the B-mode
→ Integrate continuously from South Pole
→ Observe 1% patch of sky
→ Scan and pair difference modulation
The BICEP2/Keck Telescopes

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/pulse tube cools the optical elements to 4 K.

3-stage helium sorption refrigerator further cools the detectors to 0.27 K.
Planar superconducting detector arrays

...designed to scale in frequency

Up to 2013 – all 150GHz
2014 – 2x95 3x150GHz
2015 – 2x95 1x150 2x220GHz
2016 – B3 1x150 4x220GHz
2017 – B3 4x220 1x270GHz
2018 – B3 4x220 1x270GHz
BK15 95GHz Maps

95 GHz T signal

95 GHz T noise

95 GHz Q signal

95 GHz Q noise

95 GHz U signal

95 GHz U noise

BK15 95GHz – 5 μK arcmin
BK15 220GHz Maps

220 GHz T signal

220 GHz T noise

220 GHz Q signal

220 GHz Q noise

220 GHz U signal

220 GHz U noise

Declination [deg.]

Right ascension [deg.]

BK15 220GHz – 25 µK arcmin
Just for fun: Keck 2015 single season E-mode maps

This plot shows LCDM E-modes with high s/n at three frequencies from data taken in a single season!

Already deeper than Planck 217 GHz
Add to the mix: Planck at 7 frequencies and WMAP at 2 frequencies

Polarized galactic synchrotron dominates at low frequencies

Polarized thermal emission (~20K) from galactic dust aligned in magnetic fields dominates at high frequencies

From arxiv 1502.01582

From arxiv 1212.5225
Take all possible auto- and cross spectra between the BICEP/Keck, WMAP, and Planck bands (78 of them)
Upper/right plots are EE (black points)

Lower/left plots are BB (blue points)

220GHz auto/cross spectra are all new

Red solid line is best fit multicomponent model from previous (BK14) analysis - It fits all the spectra

Chi-squared is OK – no evidence yet for non-Gaussianity of the dust pattern
Multicomponent parametric likelihood analysis

Take the joint likelihood of all the spectra simultaneously vs. model for BB that is the $\Lambda$CDM lensing expectation + 7 parameter foreground model + r

foreground model = dust + synchrotron

\[
\begin{align*}
A_{dust} & \quad \downarrow \\
\beta_{dust} & \quad \downarrow \\
\alpha_{dust} & \quad \downarrow \\
\varepsilon & \\
A_{synch} & \quad \downarrow \\
\beta_{synch} & \quad \downarrow \\
\alpha_{synch} & \\
\end{align*}
\]

- $A_{dust}$, $A_{synch}$: amplitudes @ l=80
- $\beta_{dust}$, $\beta_{synch}$: frequency spectral indices
- $\alpha_{dust}$, $\alpha_{synch}$: spatial spectral indices
- $\varepsilon$: dust/synch spatial correlation
Put priors on the frequency spectral indices of dust & sync

Allow dust/sync correlation

Marginalize over generous ranges in spatial spectral indices

BK14

arxiv/1510.09217
Put priors on the frequency spectral indices of dust & sync

Marginalize over generous ranges in spatial spectral indices

Allow dust/sync correlation

BK15
arxiv/1810.05216
Put priors on the frequency spectral indices of dust & sync

Allow dust/sync correlation

Marginalize over generous ranges in spatial spectral indices

$r < 0.07$ (95% CL)

BKP baseline
BK14 baseline
BK15 baseline

$A_{dust}$

$A_{synch}$

$r$

$A_{dust}$

$A_{synch}$

BK15

arxiv/1810.05216
Put priors on the frequency spectral indices of dust & sync

Allow dust/sync correlation

Marginalize over generous ranges in spatial spectral indices

$A_{\text{dust}}$

$A_{\text{synch}}$

$r < 0.07 \ (95\% \ CL)$

Weak sync detection?

BK15

arxiv/1810.05216
Adding in temperature

$r < 0.09$

BKP

arxiv/1502.00612
Adding in temperature

$B$-modes with $r_{0.05} < 0.07$

Planck TT+lowP+lensing+ext + BK14

Convex
Concave

with $B$-modes

no $B$-modes

$r_{0.05} < 0.07$

BK14
arxiv/1510.09217
Adding in temperature

\[ r_{0.05} < 0.06 \]

BK15
arxiv/1810.05216
Why BK15 comes 3 years after BK14...

Planck 2016

Planck intermediate results. L. Evidence for spatial variation of the polarized thermal dust spectral energy distribution and implications for CMB E-mode analysis


(Affiliations can be found at the references)

Preprint version: June 24, 2016

ABSTRACT

The characterization of the Galactic foregrounds has been shown to be the main obstacle in the challenging quest to detect primordial E-modes in the polarized microwave sky. We make use of the Planck-HFI 2015 data release at high frequencies to place new constraints on the properties of the polarized thermal dust emission at high Galactic latitudes. Here, we specifically study the spatial variability of the dust emission on angular scales of 60 degrees and its implications for the determination of the primordial E-mode polarization. As a way to quantify the spatial variation of the dust emission on angular scales of 60 degrees, we define the correlation ratio from unity that cannot be attributed to a spurious decorrelation due to the cosmic microwave background, instrumental noise, or instrumental systematics... detected at more than 99% confidence

We find no evidence for a loss of correlation. ... might not be a problem for CMB experiments aiming at a primordial B-mode detection limit on the tensor-to-scalar ratio $r \sim 0.01$...
Latest Planck Dust Analysis

Paper says: “We find no evidence for a loss of correlation”

arxiv/1606.07335 Fig3

arxiv/1801.04945 table 3

BK patch a few times cleaner than extrapolation

arxiv/1801.04945 Fig3
Upper/right plots are EE (black points)

Lower/left plots are BB (blue points)

220GHz auto/cross spectra are all new

Red solid line is best fit multicomponent model from previous (BK14) analysis - It fits all the spectra

Red dashed line is same model but with strong decorrelation – better for 95x353, worse for 150x353

Need better data to say for sure
Include dust correlation parameter?

➢ The standard BK15 marginalized likelihood analysis (COSMOMC style) is unbiased for $r$ – i.e. when run on lensed-LCDM+dust+noise sims 50% of the $r$ curves peak at zero.

➢ However, if add a dust correlation parameter and restrict to physical range ($<1$) then $r$ becomes biased – i.e. 72% of curves peak at zero

➢ This is because $r$ and dust correlation parameter are partially degenerate

➢ Can run alternate maximum likelihood searches where parameters are allowed to take unphysical values ($r<0$ and dust correlation $>1$)

➢ These really should be unbiased...
BK15 ML Search Results for Sims

Upper = standard lensed-LCDM+dust+noise sims

Lower = lensed-LCDM+dust+noise sims with dust decorrelation

\[ \Delta_d = \frac{D_{80}(217 \times 353)}{\sqrt{D_{80}(217 \times 217)D_{80}(353 \times 353)}} \]
Also run ML search on sims containing 3rd party foreground models which do not necessarily conform to the foreground parameterization we are using in the re-fit. For the models considered so far bias is small compared to \( \sigma(r) \) – additional models are welcome.

<table>
<thead>
<tr>
<th>Model</th>
<th>( \overline{A_d} )</th>
<th>( \overline{A_s} )</th>
<th>( \beta_d ) prior</th>
<th>( \beta_d ) free</th>
<th>( \sigma(r), \overline{r}/\sigma(r) ) with decorr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian</td>
<td>3.8</td>
<td>0.1</td>
<td>0.020, +0.1( \sigma )</td>
<td>0.023, 0.0( \sigma )</td>
<td>0.021, +0.0( \sigma )</td>
</tr>
<tr>
<td>PySM 1</td>
<td>10.9</td>
<td>1.1</td>
<td>0.026, +0.2( \sigma )</td>
<td>0.028, +0.2( \sigma )</td>
<td>0.028, +0.1( \sigma )</td>
</tr>
<tr>
<td>PySM 2</td>
<td>24.2</td>
<td>0.9</td>
<td>0.028, +0.1( \sigma )</td>
<td>0.029, +0.1( \sigma )</td>
<td>0.032, +0.1( \sigma )</td>
</tr>
<tr>
<td>PySM 3</td>
<td>12.1</td>
<td>1.1</td>
<td>(0.030, +0.4( \sigma ))</td>
<td>0.031, +0.1( \sigma )</td>
<td>(0.032, +0.2( \sigma ))</td>
</tr>
<tr>
<td>MHDv2</td>
<td>2.9</td>
<td>5.6</td>
<td>0.020, +0.2( \sigma )</td>
<td>0.027, −0.2( \sigma )</td>
<td>0.021, −0.1( \sigma )</td>
</tr>
<tr>
<td>G. Decorr.</td>
<td>4.6</td>
<td>0.1</td>
<td>(0.023, +1.5( \sigma ))</td>
<td>(0.026, +1.3( \sigma ))</td>
<td>0.022, +0.0( \sigma )</td>
</tr>
</tbody>
</table>
2016 onwards: BICEP3 “Super receiver”

All 95 GHz

2560 detectors in modular focal plane

Larger-aperture optics

> 10x optical throughput of single BICEP2/Keck receiver

Means larger field of view and lower noise faster
Larger receiver = more sky area

Keck 95 GHz Q map after 4 receiver years

BICEP3 95 GHz Q map after 1 receiver year (2017) (Increased area, angular-resolution and sensitivity)
Next Gen Experiment BICEP Array Under Construction

4 wide-field receivers
- 30/40 GHz
- 95 GHz
- 150 GHz
- 220/270 GHz

Focal plane layout
BICEP Array Is Under Construction
Conclusions

➢ BICEP/Keck lead the field in the quest to detect or set limits on inflationary gravitational waves:

➢ New BK15 result sets $r_{0.05} < 0.07$ and $\sigma(r) = 0.020$

➢ BICEP3 is running since 2016 with high sensitivity at 95GHz, and Keck Array continues to run at 220GHz, plus new 270GHz band

➢ We intend to go straight to BK17 (or BK18) analysis which will approach $\sigma(r) = 0.010$

➢ BICEP Array is under construction and will go much further

➢ Next gen. receivers in five bands

➢ Delensing in conjunction with SPT3G is under development

➢ Project BK23 $\sigma(r) < 0.003$

➢ And beyond that is mega experiment CMB-S4…

➢ Foreground complexity will remain a serious issue – the hope is that we can measure it and constrain $r$ simultaneously without a large loss of sensitivity. Additional ground/balloon measurements at low/high frequencies may be able to help.