BICEP/Keck: Constraining primordial gravitational waves with CMB polarization observations from the South Pole

Marion Dierickx for the BICEP/Keck Collaboration
APS DPF, July 31st 2019

Photo credit: R. Schwarz
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 20,000,001 oriented the other.)"
The CMB is our messenger from inflation
In standard $\Lambda$CDM only E-modes are present at last scattering.

Inflationary gravitational waves are the unique source of B-modes → peaking at $l \approx 100$ : degree scales.
E-mode
Primordial B-mode

In standard $\Lambda$CDM only E-modes are present at last scattering.

During propagation some of the E-modes are transformed into B-modes by lensing.

Inflationary gravitational waves are the unique source of B-modes → peaking at $l \approx 100$ : degree scales.
Galactic Foregrounds

Mitigation strategy for additional “foreground” E- and B-mode signals:
- Observe at high galactic latitudes
- Expand frequency range in order to perform component separation
South Pole Dark Sector

Why there?
• High altitude (9,300 ft = 2,800 m, most of it ice)
• Lack of day/night cycles makes for a very stable atmosphere
• Consistently dry
• Southern sky observable for 6 months of continuous darkness
• Minimal radio frequency interference
South Pole Dark Sector

BICEP1
BICEP2
BICEP3

DASI
QUAD
Keck Array
BICEP Array

South Pole Telescope (SPT-3G)

IceCube Lab
South Pole Dark Sector

BICEP1
BICEP2
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BICEP Array

South Pole Telescope (SPT-3G)

IceCube Lab

Talks by Zhaodi Pan, Lindsey Bleem
South Pole Dark Sector

BICEP/Keck Experimental Strategy:
• Target 2-degree peak of B-mode power spectrum
• Target the same 1% patch of sky since 2006
• Small-aperture refractive optics (cheap, low systematics)
• Initial effort at 150 GHz, now multi-frequency observations

BICEP1
BICEP2
BICEP3

DASI
QUAD
Keck Array
BICEP Array

South Pole Telescope
(SPT-3G)

IceCube Lab
Telescope as compact as possible while allowing angular resolution to observe degree-scale features.

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

A pulse tube cryogenic cooler cools the optical elements to 4.2K.

A 3-stage helium sorption refrigerator further cools the TES detectors to 0.27K.
$\times 5 =$

$\times 4 =$
Currently in the field

BICEP2

x 5 =

Keck Array

BICEP3

x 4 =

BICEP Array
Latest published analysis: BK15

BICEP2 $\times 5 =$ Keck Array

BICEP3 $\times 4 =$ BICEP Array
Currently building
Keck 2015 season-only E-mode Maps

95 GHz E signal

150 GHz E signal

220 GHz E signal
In one year of observations, the 220 GHz map is already 3x deeper than Planck’s 217 GHz.
BK15 Auto- and cross- spectra between BICEP/Keck, WMAP, and Planck bands

For BK15 we included our new 220 GHz channel, yielding 78 spectra.
Take the joint likelihood of all the spectra simultaneously, compare to a model for BB:
• Expectation for \( \Lambda \)CDM and lensing
• 7-parameter foreground model
• \( r \)
Multicomponent Likelihood Analysis

Take the joint likelihood of all the spectra simultaneously, compare to a model for BB:
• Expectation for $\Lambda$CDM and lensing
• 7-parameter foreground model
• $r$

Foreground model = dust + synchrotron

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

- Amplitudes @ $l=80$
- Frequency spectral indices
- Spatial spectral indices
- Dust/sync spatial correlation
BK15 Results

Priors on the frequency spectral indices of dust & sync

Marginalize over generous ranges in spatial spectral indices

Allow dust/sync correlation
BK15 Results

$r < 0.07$ (95% CL)

Plus many alternate analyses presented:
- Foreground priors
- Including EE
- WMAP/Planck data
- Dust decorrelation

Priors on the frequency spectral indices of dust & sync

Marginalize over generous ranges in spatial spectral indices

Allow dust/sync correlation
2019 onwards: BICEP Array

- 4 receivers
- Zotefoam IR filters
- Nylon IR filter
- Niobium mag shield
- Focal plane
- Sorption fridge
- Lenses
- Pulse tube
- ~60 cm

<table>
<thead>
<tr>
<th>Frequency</th>
<th>30/40 GHz</th>
<th>95 GHz</th>
<th>150 GHz</th>
<th>220/270 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tiles</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td># Detectors</td>
<td>192/300</td>
<td>3456</td>
<td>7776</td>
<td>13824/16224</td>
</tr>
<tr>
<td># Det/ Tile</td>
<td>32/50</td>
<td>288</td>
<td>648</td>
<td>1152/1352</td>
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<tr>
<td>Beam FWHM (arcmin)</td>
<td>76/57</td>
<td>24</td>
<td>15</td>
<td>10/8.5</td>
</tr>
<tr>
<td>NET per det (uK-rts)</td>
<td>268/334</td>
<td>267</td>
<td>315</td>
<td>900/1800</td>
</tr>
<tr>
<td>Instr. NET (uK-rts)</td>
<td>21/21</td>
<td>4.93</td>
<td>3.87</td>
<td>8.3/15</td>
</tr>
<tr>
<td>3-yr map depth (uK-arcmin)</td>
<td>7.5/7.5</td>
<td>1.9</td>
<td>1.4</td>
<td>3.0/5.5</td>
</tr>
</tbody>
</table>
BICEP Array mount at U. Minnesota
BA1 (30, 40 GHz) integration

Receiver performance

Optics

HDPE lenses

Alumina IR filter
Summary
Conclusions

• BICEP/Keck lead the field in the quest to detect or set limits on inflationary gravitational waves:
  • Best published sensitivity to date
  • Best proven systematic control at degree angular scales

• BK15: Adding 2015 data including, for the first time, at 220 GHz:
  • Incremental improvement wrt BK14: from $r_{0.05} < 0.09$ to $r_{0.05} < 0.07$
  • Plank 15 + BK15 $r_{0.05} < 0.06$ [$r_{0.002} < 0.055$] (arXiv 1810.05216)

• Currently analyzing 3 years (2016-18) of 95 GHz from BICEP3 and 2 years of 270GHz from Keck: BK18 data analysis
  • Pushing multiband observations & component separation

• And we can go much further:
  • BICEP Array begins observing in 2020 - expect $\sigma(r) \sim 0.003$
  • Delensing using SPT/SPT-3G data
  • Next Generation CMB Experiment: CMB Stage-4
Extra slides
BK15: Current Band Sensitivity (at $l=80$)
BK17 errors on $r$ will be dominated by synchrotron sensitivity.
Redirecting the beam with a mirror
Optical 100 GHz Demodulated

Photo credit: E. Yang