The search for inflationary B-modes: latest results from BICEP/Keck
Motivation/Background

- Using the CMB and other data the LCDM cosmological paradigm has been developed – it works great and allows us to understand the development of the universe all the way back to a high energy state.
- However, LCDM leaves many unanswered questions such as the “horizon problem” and how the empirically simple conditions at the start of the plasma phase were set up.
- Theory of “Inflation” added on the beginning of LCDM to explain.
- If it happened Inflation will have made a background of gravitational waves which will have imprinted a B-mode (curl) into the polarization pattern of the CMB.
- We may be able to detect these if we can make a sensitive enough telescope – a wide range of inflation models exist – the simplest are already ruled out – more complex ones can produce $r$ which is undetectably small…
CMB power spectra

In standard $\Lambda$CDM, only E-modes are present at last scattering. During propagation, some of the E-modes are confused into B-modes by lensing. Inflationary gravitational waves are unique source of intrinsic B-modes → peaking at $l \approx 80$: few degree scales.
CMB power spectra

Contributions from PGW to T and E-spectra not shown here – However, ability to constrain $r$ from these already maxed out at cosmic variance – the main way to make further progress is using B-modes…

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

Inflationary gravitational waves are unique source of intrinsic B-modes → peaking at $l \approx 80$ : few degree scales
BICEP/Keck Basic Experimental Strategy

→ Small aperture telescopes (cheap, fast, low systematics)
→ Target the 2 degree peak of the PGW B-mode
→ Integrate continuously from South Pole
→ Observe 1% patch of sky (smaller is actually better!)
→ Scan and pair difference modulation
Forefront emission from our galaxy

The interstellar space within our galaxy contains cold dust grains which glow thermally in microwaves, and relativistic electrons which emit synchrotron radiation.
Overcoming Polarized Foreground Contamination

At low frequency synchrotron contamination
Mid frequencies minimum contamination
At high frequency dust contamination

Going to smaller/cleaner sky patch

The graph shows the E/B-mode RMS (μK) as a function of frequency [GHz]. The graph includes different contributions such as synchrotron, thermal dust, and various BB models (r = 10^-2, r = 10^-4). The sky coverage fraction (f_{sky}) is marked for different regions to indicate the area of interest.
Overcoming Polarized Foreground Contamination

At low frequency **synchrotron** contamination

Mid frequencies minimum contamination

At high frequency **dust** contamination

Since the different components of the sky pattern have different frequency dependencies one can separate them by making maps at multiple frequencies – and probe deeper for an inflation signal.
BICEP/Keck Experimental Concept

- Small aperture
- Wide field of view
- Cold refractor
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

Typical South Pole atmospheric transmission
Why do this at the Pole?

South Pole CMB telescopes

- High and *dry* – see out into space
- On Earth’s rotational axis - One day/night cycle per year
  - Long night makes for great quality data
- Good support infrastructure – power, cargo, data comm
- Food and accommodation provided
- Even Tuesday night bingo...
Add to the mix: Planck at 7 frequencies and WMAP at 2 frequencies

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<th>Frequency</th>
<th>Q</th>
<th>U</th>
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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
Analysis

Technique: Take all possible auto- and cross spectra between the BICEP/Keck, WMAP, and Planck bands (78 of them) and compare to model of CMB + foregrounds
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

$A_{\text{dust}}$ $A_{\text{synch}}$

$\beta_{\text{dust}}$ $\beta_{\text{synch}}$

$\alpha_{\text{dust}}$ $\alpha_{\text{synch}}$

$\varepsilon$

amplitudes @ $l=80$

frequency spectral indices

spatial spectral indices

dust/synch spatial correlation
Put priors on the frequency spectral and spatial indices.

BKP

arxiv/1502.00612
Put priors on the frequency spectral indices of dust & sync

Allow dust/sync correlation

Marginalize over generous ranges in spatial spectral indices

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)

BK15
arxiv/1810.05216
Combining with Planck
(Planck 2018 results include BK14 data)
BK15 Squeezes down a little more in on $r$

Steadily ruling out simpler inflationary models

BK15
arxiv/1810.05216
$r < 0.06$
BICEP3: Next Generation Receiver

All 95 GHz

2500 detectors in modular focal plane

Large-aperture optics and infrared filtering

> 10x optical throughput of BICEP2/Keck receivers
BK18 95GHz Map (Keck)
BK18 150GHz Map (BICEP2+Keck)
BK18 220GHz Map (Keck)
Stage 2

- **BICEP2** (2010-2012)
- **Keck Array** (2012-2019)

Stage 3

- **BICEP3** (2016-)
- **BICEP Array** (2020-)

Telescope and Mount

Focal Plane

Beams on Sky

- BICEP2
- Keck Array
- BICEP3
- BICEP Array
BICEP Array Under Construction

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

When complete >30,000 detectors
New mount about to ship from UMN to Pole
Lots of new hardware
As we increase the sensitivity, the sample variance on the lensing B-modes become the limiting factor.
We must delense to make further progress.
Delensing with SPT-3G data

High resolution maps

Can be used to reconstruct the lensing deflection map...

...which can then be used to calculate and remove the lensing signal enabling a deeper search for inflationary gravitational waves
Conclusions

➢ BICEP/Keck lead the field in the quest to detect or set limits on inflationary gravitational waves:
   ➢ BK15 result sets $r_{0.05} < 0.06$ 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 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 under development
   ➢ Projecting BK23 $\sigma(r) < 0.003$

➢ And beyond that is mega experiment CMB-S4...

➢ Foreground complexity is and will remain a serious issue – the hope is that we can measure it and constrain $r$ simultaneously without a large loss of sensitivity. Time will tell.