Inflationary cosmology with BICEPs

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Stanford University
SLAC National Accelerator Lab
Density perturbations and gravitational waves

Sub-atomic vacuum fluctuations of “inflaton”

Inflation

Sub-atomic vacuum fluctuations of graviton (quanta of gravity)

Density perturbations studied by Planck, WMAP, SPT, etc.

Gravitational waves
Generation of **scalar/tensor** perturbations

Quantum fluctuations in the vacuum state of the *inflaton*/*graviton* fixes the r.m.s of the linear solutions

\[ \delta G_{\mu\nu} = 8\pi G \delta T_{\mu\nu} \]

→ two linear wave equations for scalar /tensor

Mukhanov & Chibisov ‘81
Guth & Pi; Hawking; ‘82; Bardeen et al., ’83, Sasaki ‘83

Grishchuk 74; Starobinsky 79
Rubakov et al, 82; Frabri & Pollock , 82

Quantum fluctuations in the vacuum state of the *inflaton*/*graviton* fixes the r.m.s of the linear solutions
Inflationary B-modes, known as the “Holy Grail” of cosmology

- Started out as graviton vacuum fluctuations
- Energy scale of inflation $\sim$ expansion rate $\sim$ GW amplitude
- Alternative models generate no GW
- *Field range and “UV” completeness*
Only gravitational waves can generate B-modes

Seljak & Zaldarriaga ‘97
Kamionkowski, Kosowsky, Stebbins ‘97
Polarization pattern caused by Rayleigh scattering is E-mode.
Polarization pattern caused by Rayleigh scattering is NOT B-mode
Gravitational waves generate \( E \)-mode polarization
Gravitational waves generate \emph{B}-mode polarization
The polarization pattern is unique, but small.

Vertical / Horizontal differ by 1 part in 30,000,000.
South Pole is the Mecca of CMB research (BICEP1, BICEP2, Keck Array, BICEP3)

• High, dry, cold, low water vapor in the atmosphere
• Stable climate for continuous 6 months
• Great logistical support (NSF-Office of Polar Program+ Lockheed)
BICEP/Keck series
BICEP1/2/3
Keck Array

microwave (95/150 GHz)
Superconducting sensors
Low temperature physics (0.25K)

Lithographic detectors
High packing density
Mass production
On going program + R&D for the future


BICEP3: 2015…
CLK notebook

a design was found after 3 years

9/21/2006
Detecting the CMB radiation

BICEP2 Detector: Transition-Edge Superconductor

Superconducting thermometer

CMB light from antenna

Radiation Converted to heat

0.1 mm
>100 tiles
(>12,000 detectors)
have been produced
over the past 8 yrs
3 BICEP2 year = 30 BICEP1 years!

BICEP1

48
150 GHz detectors

JPL : antenna-coupled TES arrays

BICEP2

512
150 GHz detectors
BICEP2 Postdocs

Colin Bischoff  
Jeff Filippini  
Martin Lueker  
Walt Ogburn  
Abigail Vieregg  
Immanuel Buder  
Stefan Fliescher  
Roger O'Brient  
Angiola Orlando  
Zak Staniszewski  

BICEP2 Winterovers

Steffen Richter 2010
Steffen Richter 2011
Steffen Richter 2012

BICEP2 Graduate Students

Randol Aikin  
Justus Brevik  
Chris Sheehy  
Grant Teply  
Chin Lin Wong  
Kirit Karkare  
Jon Kaufman  
Sarah Kernasovskiy  
Jamie Tolan
Total polarization

BICEP2 total polarization signal

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

BICEP2 B–mode signal

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

BICEP2 B-mode signal

Scale: $1.7 \mu K$

Declination [deg.]

Right ascension [deg.]
B-mode contribution

BICEP2 B–mode signal

Scale: $0.3 \mu K$
B-mode contribution

BICEP2 B-mode signal

Scale: $0.3 \mu K$
Temperature and Polarization Spectra

The Bicep2 Collaboration

- Power spectra
- Lensed-ΛCDM
- Temporal split jackknife

$r = 0.2$
Bandpower deviations from mean of lensed-$\Lambda$CDM+noise simulations and normalized by the std of those sims.

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

- **real data**
- **lensed-$\Lambda$CDM + noise sims**
  - $\pm 1\sigma$
  - $\pm 2\sigma$

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Check Systematics: Jackknifes

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 ("Tag 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.

<table>
<thead>
<tr>
<th>Jackknife</th>
<th>Bandpowers</th>
<th>Bandpowers</th>
<th>Bandpowers</th>
<th>Bandpowers</th>
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<td>1–9 $\chi^2$</td>
<td>1–5 $\chi$</td>
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<td>AB/CBB best/worst</td>
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<td>0.709</td>
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<td>0.114</td>
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<td>0.307</td>
<td>0.094</td>
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<td>0.589</td>
<td>0.872</td>
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<td>0.750</td>
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</table>
The Bicep2 Collaboration

Additional Cross Spectra

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
Calibration Measurements

For instance...

Far field beam mapping

Hi-Fi beam maps of individual detectors

Detailed description in companion Instrument Paper
Systematics beyond Beam imperfections

All systematic effects that we could imagine were investigated!

We find with high confidence that the apparent signal cannot be explained by instrumental systematics!
The Bicep2 Collaboration

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:

$\rightarrow$ lensed-$\Lambda$CDM + noise simulations
$\rightarrow$ weighted version of the 5 bandpowers
$\rightarrow$ 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$\sigma$

$r = 0.20^{+0.07}_{-0.05}$

The Bicep2 Collaboration
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.
Polarization fraction from *Planck XIX* (May 6)
Fig. 7. Histograms of the observed polarization fraction at 1° resolution for the whole sky shown in Fig. 1 (red), the Galactic plane within $|b_{\parallel}| < 5°$ (green) and the inner Galactic plane within $|b_{\parallel}| < 5°$ and $|\ell_{\parallel}| < 90°$ (blue).
Lensing deflects CMB photons, slightly mixing the dominant E-modes into B-modes -- dominant at high multipoles.

Planck data constrain the amplitude of the lensing effect to $A_L = 0.99 \pm 0.05$.

BICEP2 data is perfectly compatible with a lensing amplitude of $A = 1$.

Marginalizing over $r$, we detect lensing B-modes at $2.7\sigma$.
Compatibility with Indirect Limits on $r$

Using temperature data over a wide range of angular scales limits on $r$ have been set:

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

$r = 0.2$ makes a small change to the temperature spectrum.

(In this plot $r=0.2$ simply added to Planck best fit model with no re-optimization of other parameters)
BICEP2 and upper limits from other experiments:
Future

• We really want to confirm the signal (Keck-100, BICEP3, SPTpol, Planck, …)
• Increase the frequency and sky coverage
• Test the scale invariance of B-modes ($n_T$)
  • All sky survey
  • delensing with large aperture telescopes
• Test the Gaussianity of B-modes
• Search for the (tensor) reionization bump
• Can we fit tensor into TT spectrum?
Prospects

**BICEP1:** 2006, 2007, 2008

**BICEP2:** 2010, 2011, 2012

**Keck Array:** 2011, 2012, 2013, 2014 (576 100GHz detectors)…

**BICEP3:** 2015…
Prospects


BICEP3: 2015 –

(another 2560 100GHz detectors)
IR filter
(alumina coated with epoxy)
For large BICEP3 cold optics
Epoxy-based AR-coating On curved lens
Advanced materials (99.6% Al₂O₃)
For large BICEP3 cold optics
Large aperture
Metal mesh IR blocking filters
CMB after Planck, ACT, SPT, POLARBEAR, BICEP3?
Three fundamental *maps* of our Universe

Map # 1
(scalar perturbations)

Planck
Three fundamental maps of our Universe

Map # 2
(tensor perturbations)
Three fundamental *maps* of our Universe

Map # 3
(lensing deflection field)
CMB B-mode polarization
Snowmass Process (HEP community summer study)

• P5 = US Particle Physics Projects Prioritization Panel

May 23, 2014:

“Recommendation 18: Support CMB experiments as part of the core particle physics program. The multidisciplinary nature of the science warrants continued multiagency support.”

Budget for CMB-S4 project is included under all three budget scenarios considered.
Lensing reconstruction

$T$

$E$-polarization

$B$

$B$-polarization

$\Phi$

$\Phi(L)$

$B(l_2)$

$E(l_1)$
CMB as a probe of neutrinos

Arcminute-measurements of CMB polarization is a probe of cosmic neutrinos

- Number of relativistic species $N_{\text{eff}}$ (CMB “damping tail” in polarization)
- Sum of neutrino masses ($\sum m_\nu$) suppresses structures (lensing $B$-modes)
A Guide to Designing Future Ground-based CMB Experiments

W. L. K. Wu,1,2, J. Errard,3,4 C. Dvorkin,5 C. L. Kuo,1,2 A. T. Lee,4,6 P. McDonald,6 A. Slosar,7 and O. Zahn8

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(Dated: February 18, 2014)

In this follow-up work to the High Energy Physics Community Summer Study 2013 (HEP CSS 2013, a.k.a. SNOWMASS), we explore the scientific capabilities of a future Stage-IV Cosmic Microwave Background polarization experiment (CMB-S4) under various assumptions on detector count, resolution, and sky coverage. We use the Fisher matrix technique to calculate the expected uncertainties in cosmological parameters in $\nu$CDM that are especially relevant to the physics of fundamental interactions, including neutrino masses, effective number of relativistic species, dark-energy equation of state, dark-matter annihilation, and inflationary parameters. To further chart the landscape of future cosmology probes, we include forecasted results from the Baryon Acoustic Oscillation (BAO) signal as measured by DESI to constrain parameters that would benefit from low redshift information. We find the following best 1-$\sigma$ constraints: $\sigma(M_\nu) = 15$ meV, $\sigma(N_{\text{eff}}) = 0.0156$, Dark energy Figure of Merit = 303, $\sigma(p_{\text{ann}}) = 0.00558 \times 3 \times 10^{-26} \text{ cm}^3/\text{s}/\text{GeV}$, $\sigma(\Omega_K) = 0.00074$, $\sigma(n_s) = 0.00110$, $\sigma(\alpha_s) = 0.00145$, and $\sigma(r) = 0.00009$. We also detail the dependences of the parameter constraints on detector count, resolution, and sky coverage.
### Inflation: spectral index

<table>
<thead>
<tr>
<th></th>
<th>CMB</th>
<th>CMB+BAO</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>1' 2' 3' 4'</td>
<td>1' 2' 3' 4'</td>
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<tr>
<td>$10^4$ detectors</td>
<td></td>
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<tr>
<td>$f_{\text{sky}} = 0.25$</td>
<td>2.91 2.94 2.98 3.04</td>
<td>2.19 2.23 2.29 2.36</td>
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<td>$f_{\text{sky}} = 0.50$</td>
<td>2.11 2.13 2.16 2.21</td>
<td>1.64 1.67 1.71 1.75</td>
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<td>1.45 1.51 1.57 1.61</td>
<td>1.10 1.12 1.16 1.20</td>
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Table V: $n_s$ $1-\sigma$ constraints in units of $10^{-3}$ from CMB and from CMB+BAO. “CMB” includes lensing.
Inflation: spectral index

![Graph showing inflation spectral index with various models and data points.](image)
Inflation: Mean spatial curvature

\[ 1\sigma \sim \text{few } 10^{-3} \]
Thank you!
Spectral Index of the B-mode Signal

Comparison of $B_2 \times B_2$ with $B_2 \times B_1^{150} \times B_1^{100}$ 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 $2.2/2.3\sigma$.

Comparison of $B_2$ auto with $B_2^{150} \times B_1^{100}$ 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 $2.2/2.3\sigma$.
Comparison of B2 auto with $B_{2_{150}} \times B_{1_{100}}$ 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 $11/30\sigma$. 

Spectral index of the E-mode Signal