News from the BICEP/Keck CMB program

Zeeshan Ahmed
KIPAC, SLAC National Accelerator Laboratory
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In standard $\Lambda$CDM only E-modes are present at last scattering.

Lensing by intervening structure converts some to B-modes.

Inflationary gravity waves produce B-modes peaking at $l \approx 100$: degree scales. Measure tensor-to-scalar ratio, $r$.

Foregrounds also generate polarized emission. Can be teased apart from different spectral dependence of CMB.
**Zotefoam Window**

**HDPE Lenses**

**PT-410 Pulse Tube**

**He4-He3 Sorption Fridge**

**26.4 cm Aperture**

**HDPE Window**

**55 cm Aperture**

**Alumina Lenses**

**PT-415 Pulse Tube**

**Reflective Metal-Mesh Filters**

**BK Program Cameras**

**He4-He3 Sorption Fridge**
Antenna-coupled TES detectors at multiple frequencies

95 GHz

150 GHz

220 GHz

Transition edge sensor
Situated at a high, dry desert

South Pole Research Station, Antarctica
~10,000ft, ~0.25mm PWV
6 months of cold, stable winter sky with uninterrupted integration
**BICEP2+Keck through 2014 (150 + 95 GHz)**

**B2 + Keck thru 2014 (150 GHz) → Final map depth: 3.0 μK’**

**Keck 2014 (95 GHz) → Final map depth: 7.6 μK’**

Observations focused on ~400 deg² patch = 1% of the sky

BK14: PRL 116.031302

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BK14 BB Spectra (150x150, 95x95 and 95x150 GHz)

\[ \ell (\ell+1) C_\ell / 2\pi [\mu K^2] \]

Multipole, \( \ell \)

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DPF 2017
Add data from Planck and WMAP

Polarized galactic **synchrotron** dominates at low frequencies

Planck provides polarization measurements in 7 other bands at lower S/N, but can be included in analysis. Two WMAP bands as well.

Polarized thermal emission (~20K) from galactic **dust** dominates at high frequencies
r_{0.05} < 0.09 at 95% confidence

Now beats the best constraints from temperature data

Keck 95 GHz maps help break CMB–dust degeneracy

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Constraints on inflation from B modes and T

Combined 95% upper limit: $r_{0.05} < 0.07$
Direct measurement of Gravitational Lensing

Despite modest resolution (0.5°), BK map depth (3μK’) makes it possible to directly reconstruct lensing potential φ using information at large angular scales only (ell ≤ 700)
Physics from anisotropic cosmic birefringence

- **Axion-like particles**
  
  String theory generally predicts presence of axion-like particles coupled with electromagnetic fields (e.g. Pospelov+’09, Caldwell+’11)
  
  \[
  \text{Lagrangian} \supset \frac{\phi}{2f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}
  \]
  
  Coupling constant

  This coupling leads to spatial variation of polarization angle rotation

  \[
  \alpha(n) = \frac{\Delta \phi(n)}{f_a}
  \]
  
  Changes in phi during photon propagation

- **Primordial magnetic fields**
  
  Lead to the polarization rotation by Faraday rotation (e.g. Kosowsky&Loeb’96, Harari+’97)

  \[
  \alpha(n) = \frac{3c^2}{16\pi e^2} v^{-2} \int \mathbf{i} \cdot \mathbf{B} \cdot d\mathbf{l}
  \]
  
  Magnetic field

Measurement of the anisotropic polarization rotation is a unique probe of the early universe and provides important implications for high energy physics!
Constraints from rotation anisotropy power

Scale-invariant cosmic birefringence amplitude (95%CL)

\[ A_{\text{CB}} \leq 0.33 \]

Chern-Simons coupling of Nambu-Goldstone boson to photons

\[ f_\alpha \geq 1.7 \times 10^2 \frac{H_I}{2\pi} \]

Primordial Magnetic Fields

\[ B_{1\text{Mpc}} \leq 30\text{nG} \]
• Include our own 220 GHz data

• Dust decorrelation will be included in likelihood model

• Marginalize over instrumental systematic nuisance parameters
  • T to P leakage from undeprojected beam systematics
  • Uncertainties in band centers

Keck 220 GHz now 3x deeper than Planck 217 GHz!
BICEP Array (30k sensors over 30, 40, 95, 150, 220, 270 GHz)
BICEP Array mount fabrication to start imminently
Thanks for your attention!
Summary of sensitivity