Listening for the Echoes of Inflation with BICEP2

BICEP2 I: Ade et al., PRL 112, 241101 (2014)

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A History of Creation

- Modern Universe
- Quantum Fluctuations
- Radius of the Visible Universe
- Inflation
- Protons Formed
- Nuclear Fusion Begins
- Nuclear Fusion Ends
- Neutral Hydrogen Forms
- Free Electrons Scatter Light
- Earliest Time Visible with Light
- Cosmic Microwave Background
- Universe becomes transparent
- Modern Universe

Universe becomes transparent at 380,000 years after the Big Bang, marking the end of the period when the universe was opaque and unable to emit or absorb light.

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Inflation

Quantum fluctuations…

“inflaton”

… imprinted onto cosmic scales

Homogeneity
Isotropy
Nearly-flat geometry ($\Omega \sim 1$)
Super-horizon fluctuations
Nearly-scale invariant density perturbations ($n_s \sim 1$)

Density perturbations

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Primordial Perturbations

Quantum fluctuations…

“inflaton”

metric tensor

… imprinted onto cosmic scales

Primordial gravitational waves

\[ r \approx \frac{V[\phi]}{(4 \times 10^{16}\text{GeV})^4} \]

GUT-scale physics!?

Density perturbations

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History of the Universe

Inflation Generates Two Types of Waves

Gravitational Waves

Density Waves

Waves Imprint Characteristic Polarization Signals

Free Electrons Scatter Light

Earliest Time Visible with Light

Radius of the Visible Universe

Big Bang

Quantum Fluctuations

Inflation

Protons Formed

Nuclear Fusion Begins

Nuclear Fusion Ends

Cosmic Microwave Background

Neutral Hydrogen Forms

Modern Universe

Modern Universe

0

$10^{-32}$ s

1 $\mu$s

0.01 s

3 min

380,000 yrs

13.8 Billion yrs

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CMB Polarization

From Thomson scattering wherever there is ionized gas and quadrupole anisotropy.

Quadrupole Anisotropy

Thomson Scattering

Linear Polarization

Wayne Hu

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Patterns of Polarization

E-mode Polarization

B-mode Polarization
Patterns of Polarization

Density Wave:
- Hot
- Cold (seen by electrons)
- Temperature pattern

Gravitational Wave:
- Squeezes space
- Stretches space
- Cold
- Hot

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The Lay of the Land

\[ \Lambda CDM, r=0.1, \tau=0.1 \]

Reionization (>30°)

Last-scattering (~1°)

Lensing

~ Known amplitude

~2°

Uncertain amplitude

Lensing “limit” at r~0.01

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The Challenge

Extremely faint signal demands a map that is...

- **Precise**
  Detectors approach photon noise limit
  Many detectors (*multiplexing*)

- **Accurate**
  Rigid control of polarized *systematics*

- **Uncontaminated**
  Avoidance (or subtraction) of polarized *foregrounds*

- **Not necessarily high angular resolution!**

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Inflation Investigators
A Targeted Strategy

• Minimum aperture (~26 cm) to resolve degree scales

• Systematic control
  • Cold (4.2K), on-axis optics
  • Bore sight rotation

• Foreground avoidance
  • Clean sky: ~400 sq. deg.
  • 150 GHz: low atmospheric and foreground emission

• Deep mapping
  • 3 years: 87 nK-deg!
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Caltech/JPL Detectors

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The View from the Bottom of the World
BICEP2 T and Stokes Q/U Maps

Sum maps

Difference maps
Total Polarization

BICEP2 total polarization signal

Declination [deg.]

Right ascension [deg.]

1.7 µK
B-mode Signal

BICEP2 B-mode signal

Declination [deg.]

Right ascension [deg.]

1.7 μK
B-mode Signal

BICEP2 B-mode signal

Declination [deg.]

Right ascension [deg.]

0.3μK
BICEP2 B-mode Power Spectrum

- Clear excess of B-modes at low $l$ above lensed-$\Lambda$CDM
  - PTE: $1.3 \times 10^{-7}$
  - Significance: $5.3\sigma$
- Good fit to expected inflationary signal spectrum

$C_l = \frac{l(l+1)C}{2\pi}[\mu K^2]$
What could this be?

• **Instrumental systematics?**
• Galactic foregrounds?
• Cosmology?
Jackknife tests

**Splits by boresight rotation**
Amplifies differential pointing in comparison to fully added data. Check of deprojection.

**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.
Systematic Errors

Simulate effect of measured beam and instrument imperfections.

We find with high confidence that the apparent signal cannot be explained by instrumental systematics.
Cross Spectra

- **3.5σ** detection of BB in cross with color-combined BICEP1 ($r_{\text{max}}=0.19$)

- Excess power also evident in cross with 2 years of Keck Array data (150 GHz, *preliminary*)!
What could this be?

- Instrumental systematics?
- Galactic foregrounds?
- Cosmology?
Polarized Foregrounds

Planck 2014 magnetic field

- Galactic emission can be polarized by galactic magnetic fields!
- BICEP2 observes where galactic emission is dim
- BICEP2 observes at one “color”: 150 GHz

Planck 2014

Minimum varies across sky

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Any polarized astrophysical emission between last scattering and us!

- **Synchrotron** “Red”: $\sim \nu^{-3}$
  *No correlation with WMAP-K*
  $$\beta = -3.3 : r_{\text{sync}}=0.0008 \pm 0.0041$$

- **Dust** “Blue”: $\sim \nu^{+1.75}$
  *Brighter than existing models*
  *Lack of cross-correlation*
  *Angular spectrum consistent with GW signal*

- **Point sources**
  *No cross-correlation with source catalogs*  
  *(Planck, ATCA)*

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Polarized Foregrounds

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Spectral Index Constraint

- Constrain BB signal color with $B_{2150\times B_{1100}}$
  - If dust, expect little correlation
  - If synchrotron, expect bright correlation

Antenna temperature frequency power law

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What could this be?

- Instrumental systematics?
- Galactic foregrounds?
- **Cosmology**
Constraint on Tensor/Scalar Ratio

- Best-fit $r = 0.20$ (PTE of fit 0.9)
  
  *Consistent with large-field, GUT-scale inflation*

- $r = 0$ disfavored at $7.0\sigma$ (PTE $3.3 \times 10^{-12}$) (no FG)

- Sample variance dominated -> *Need more sky!*

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Effect of Foregrounds

- Foregrounds could contribute small amount of observed BB
- Total power spectrum does not look like foreground expectations
- Dust contributes most in the first band power. Deweighting this bin would give less deviation from our base result
Dust-up

• Planck maps polarized dust up to 353 GHz

• Data for BICEP2 region has not been released (*challenging!*)

• More data in coming months: Planck, Keck 100 GHz, others …

• **Planck-BICEP2 joint analysis is in progress!**

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What next?

**Keck Array**
- South Pole, 2011 - 2016
- 2011: 1536 TESs @ 150 GHz
- 2012-13: 2560 @ 150 GHz
- 2014 upgrade:
  - 1536 @ 150 GHz
  - 576 @ 100 GHz

**Bicep3**
- South Pole, 2015-16
- 2560 TESs @ 100 GHz

**Spider**
- Long-duration balloon 2014
- Large (~10%) sky coverage
- Half-wave plate
- 2400 TESs
  - 1536 @ 150 GHz
  - 864 @ 100 GHz
Conclusions

- BICEP2 observes $5.3\sigma$ excess above lensed-$\Lambda$CDM; $r=0$ disfavored at $7\sigma$ before foreground subtraction
- Consistent with expectations for primordial gravitational waves from GUT-scale inflation
- Extensive studies disfavor systematic error or synchrotron radiation as origin
- Data from Planck will update dust models; Planck-BICEP2 joint analysis in progress to understand signal origin
- The era of B-mode cosmology has begun!

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