BICEP2 Results, Implications, and the Future of Tensor Cosmology

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Amazing combination of

Theoretical ideas:
• Inflation
• Inflation generates gravitational waves
• Gravitational waves generate B-modes

Technology:
• Refractor in a cryostat
• Polarimeters on a chip
• TES and SQUIDs
• and focus, hard work, faith, etc.
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.)"
Inflation

Need something to move the blue lines below the red line

below the red line
How does Inflation work?

- Solved the horizon and flatness problems
- How is it achieved? Exponential expansion.

\[ G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu} \]

\[ T_{\mu\nu} = \partial_\mu \varphi \partial_\nu \varphi - \frac{1}{2} g_{\mu\nu} \partial^\sigma \varphi \partial_\sigma \varphi - g_{\mu\nu} V(\varphi) \]

\[ H^2 = \frac{8\pi G}{3} V(\varphi) \]

Slow roll, \( \sim \) const. Hubble
\( \sim \) exponential expansion (inflation)
Generation of perturbations

• *This is the part that connects* quantum *w/ cosmos*
• Prior to BICEP2, the properties of the scalar perturbations have become the strongest evidence for inflation
  – Adiabatic (1 D.o.F., related to inflaton field $\varphi$)
  – Gaussian (vacuum state of $\varphi$)
  – Spectral index $n_s \lesssim 1$
Density perturbations and gravitational waves

Sub-atomic vacuum fluctuations of "inflaton"

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

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

Gravitational waves detected by BICEP2
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
Inflationary B-modes, known as the “Holy Grail” of cosmology

- Started out as graviton vacuum fluctuations
- Energy scale of inflation ~ expansion rate ~ 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
Gravitational waves generate \textit{E}-mode polarization
Gravitational waves generate $B$-mode polarization
The polarization pattern is unique, but small

Vertical / Horizontal differ by 1 part in 30,000,000
Amazing combination of

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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 (US NSF-Office of Polar Program)
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
A very focused program on B-modes

Keck Array: 2011, 2012, 2013, ...

BICEP3: 2015...
A very focused program on B-modes

Keck Array: 2011, 2012, 2013, ...

BICEP3: 2015...

More and more detectors ..
A very focused program on B-modes
A very focused program on B-modes

BICEP1: 2006, 2007, 2008 \( (r<0.70; \ 95\%) \)


BICEP3: 2015…
3 BICEP2 year = 30 BICEP1 years!

BICEP1
48
150 GHz detectors

JPL: antenna-coupled TES arrays

BICEP2
512
150 GHz detectors
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
Total polarization (3 yrs of data)
B-mode contribution

BICEP2 B-mode signal

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

BICEP2 B-mode signal

Scale: $0.3 \mu K$

Declination [deg.]

Right ascension [deg.]
B-mode contribution

BICEP2 B-mode signal

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

The Bicep2 Collaboration

- **TT** - $l(l+1)C_l/2\pi [\mu K^2]$
- **TE** - $\chi^2$ PTE = 0.30
- **EE** - $\chi^2$ PTE = 0.04
- **BB** - $\chi^2$ PTE = $1.3 \times 10^{-7}$
- **TB** - $\chi^2$ PTE = 0.67
- **EB** - $\chi^2$ PTE = 0.06

**Notes:**
- **power spectra**
- **temporal split jackknife**
- **lensed-$\Lambda$CDM**
- **$r=0.2$**
Bandpower Deviations

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

- real data
- lensed-$\Lambda$CDM + noise sims
  - $\pm 1\sigma$
  - $\pm 2\sigma$
Check Systematics: Jackknifes

**TABLE 1**

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<tr>
<th>Jackknife</th>
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<td>All/split best/worst</td>
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<td>0.589</td>
<td>0.872</td>
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</table>

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.
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
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:
- lensed-$\Lambda$CDM + noise simulations
- weighted version of the 5 bandpowers
- B-mode sims scaled to various levels of $r$ ($n_T=0$)

Within this simplistic model we find:

$\hat{r} = 0.2$ with uncertainties dominated by sample variance.

PTE of fit to data: 0.9
- model is perfectly acceptable fit to the data.

$r=0$ ruled out at $7.0\sigma$.
Polarized Dust Foreground Projections

The BICEP2 Collaboration

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.
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:

\[ \frac{1}{2\pi} C_{l}^{BB} \] vs Multipole
(Standard) implications

• Inflation happened
• Gravity is quantized
• Inflation happened at the GUT scale
• Chaotic Inflation models are favored
• Many string-motivated models have been ruled out
• Inflation field moves over Super Planckian range → needs shift symmetry in Q.G.
• Half of axion parameter space is ruled out
• Low ell anomaly becomes worse
• .....
Prospects

BICEP1: 2006, 2007, 2008 \( (r<0.70; \ 95\%) \)

BICEP2: 2010, 2011, 2012 \( (r=0.2 \ +0.07-0.05) \)


BICEP3: 2015…
Prospects


BICEP3: 2015 –

(another 2560 100GHz detectors)
Advanced materials (99.6% Al₂O₃) For large BICEP3 cold optics
Epoxy-based AR-coating on curved lens
Strain-relieving AR layer using high power UV laser
Large aperture
Metal mesh IR blocking filters
After B2? Increasing the sky coverage
After B2? Increasing the sky coverage

BICEP3/Keck

Declination limit at the South Pole
After B3? Increasing the sky coverage
T-REX (TensoR EXperiment): Straight duplication of BICEP3

A project that is “shovel-ready”
Where will T-REX land?

![Diagram showing the primordial tilt (n_s) vs. tensor-to-scalar ratio (r_{0.002}) with various model predictions and data points, including BICEP2 and Planck results.](image-url)
Where will T-REX land?
Thank you!
Spectral Index of the B-mode Signal

Comparison of B2 auto with B2\textsubscript{150} x B1\textsubscript{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 2.2/2.3σ.

\[ \beta = -1.55^{+1.25}_{-0.86} \]
Spectral Index of the E-mode Signal

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 $11/30\sigma$. 

$$\beta = -0.69^{+0.14}_{-0.13}$$
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!
Constraint on $r$ under Foreground Projections

Probability that each of these models reflect reality hard to assess

DDM2 uses all publicly available information from Planck - modifies constraint to: $r = 0.16^{+0.06}_{-0.05}$

Dust contribution is largest in the first bandpower. Deweighting this bin would lead to less deviation from our base result.

Adjust likelihood curve by subtracting the dust projection auto and cross spectra from our bandpowers: