WHISPERS FROM INFLATION

+ 

AFTER INFLATION

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2014.03.19
BICEP2 I: DETECTION OF B-mode POLARIZATION AT DEGREE ANGULAR SCALES


ABSTRACT

We report results from the BICEP2 experiment, a Cosmic Microwave Background (CMB) polarimeter specifically designed to search for the signal of inflationary gravitational waves in the B-mode power spectrum around $\ell \sim 80$. The telescope comprised a 26 cm aperture all-cold refracting optical system equipped with a focal plane of 512 antenna coupled transition edge sensor (TES) 150 GHz bolometers each with temperature sensitivity of $\approx 300 \, \mu K_{\text{CMB}}/\sqrt{s}$. BICEP2 observed from the South Pole for three seasons from 2010 to 2012. A lowforeground region of sky with an effective area of 380 square degrees was observed to a depth of 87 nK-degrees in Stokes Q and U. In this paper we describe the observations, data reduction, maps, simulations and results. We find an excess of B-mode power over the base lensed-$\Lambda$CDM expectation in the range $30 < \ell < 150$, inconsistent with the null hypothesis at a significance of $> 5\sigma$. Through jackknife tests and simulations based on detailed calibration measurements we show that systematic contamination is much smaller than the observed excess. We also estimate potential foreground signals and find that available models predict these to be considerably smaller than the observed signal. These foreground models possess no significant cross-correlation with our maps. Additionally, cross-correlating BICEP2 against 100 GHz maps from the BICEP1 experiment, the excess signal is confirmed with $3\sigma$ significance and its spectral index is found to be consistent with that of the CMB, disfavoring synchrotron or dust at $2.3\sigma$ and $2.2\sigma$, respectively. The observed B-mode power spectrum is well-fit by a lensed-$\Lambda$CDM + tensor theoretical model with tensor/scalar ratio $r = 0.20^{+0.07}_{-0.05}$, with $r = 0$ disfavored at 7.0$\sigma$. Subtracting the best available estimate for foreground dust modifies the likelihood slightly so that $r = 0$ is disfavored at 5.9$\sigma$.

Subject headings: cosmic background radiation — cosmology: observations — gravitational waves — inflation — polarization
Stephen Hawking claims victory in gravitational wave bet
Cosmologist says he has won the wager with a Canadian physicist about what happened in first moments after big bang

Ian Sample, science correspondent
theguardian.com, Tuesday 18 March 2014 12.25 GMT

Gravitational waves are 'another confirmation of inflation', Stephen Hawking told BBC Radio 4's Today programme. Photograph: Damir Dzelilovic/Alamy

In the news ...

Space Ripples Reveal Big Bang's Smoking Gun  New York Times
Disclaimer

• context and importance of result, not details
• I am not an observer/ experimentalist
• I have not digested the latest result yet …

• IT IS EARLY
  - independent confirmation needed
  - for confirmed inflationary origin — rule out arguments against alternative explanations
Live Peer Review!

ongoing discussions

https://www.facebook.com/groups/574544055974988/
Where did the fluctuations in the CMB come from? How did we populate the universe get populated (with particles)?
inflation!

- inflation
  - what is it
  - why do we need it
  - recent status!

- ending inflation/populating our universe
  - why it is important
  - different scenarios
  - observational signatures
what is inflation?

$10^{27}$

$\ddot{a} > 0$

$10^{-35}$ seconds!

flu virus

galaxy!
how to get accelerated expansion

\[ \ddot{a} > 0 \]
\[ \frac{\ddot{a}(t)}{a(t)} = -\frac{1}{2m_{pl}^2} (\rho + 3P) \]
\[ P < -\frac{1}{3} \rho \]
\[ P_\varphi = \frac{1}{2} \dot{\varphi}^2 - V(\varphi) \approx -V(\varphi) \]
\[ \rho_\varphi = \frac{1}{2} \dot{\varphi}^2 + V(\varphi) \approx V(\varphi) \]
\[ P_\varphi \approx -\rho_\varphi \]
\[ H^2 = \frac{1}{3m_{pl}^2} \rho_\varphi \approx \frac{1}{3m_{pl}^2} V(\varphi) \approx \text{constant} \]

- inflation
- Einstein
- need
- scalar field
- slow roll!
slow roll inflation

$\varphi$ inflation

$V(\varphi)$

increase in size

$10^{-35}$ seconds!

$10^{27}$
The angular power spectrum is indicated by the green shaded area around the best fit model. The low-

Table 8.

The 2013 Planck angular power spectrum. The error bars include cosmic variance, whose magnitude

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best fit</th>
<th>68% limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu K$</td>
<td>1000</td>
<td>2000</td>
</tr>
<tr>
<td>Angular scale</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multipole moment, $\ell$</td>
<td>2</td>
<td>10</td>
</tr>
</tbody>
</table>

Constraints on the basic six-parameter CMB temperature angular power spectrum. The error bars include cosmic variance, whose magnitude...
underlying initial conditions

\[ \Delta^2 R(k) = A_*(k/k_*)^{n_s - 1} \]

\[ n_s = 0.9616 \pm 0.0094 \]

- almost scale invariant
- correlations on super Hubble scales

known physics

initial conditions
inflation: cause of fluctuations

- zero point fluctuations of
  - inflaton, gravitational potential, gravitational waves
    \[ \delta \varphi \quad \text{dominant source} \quad \Psi \quad h_{\mu \nu} \]

- wavelength stretched to enormous scales

\[ d_{H_i} = c/H_i \sim \text{const.} \]
causal

\[ \lambda \propto a \]

\[ d_H \equiv 1/H \]

expansion stretches perturbations

Hubble horizon

increasing, modes can leave the horizon

quantum fluctuation
scale invariant (almost)

- causal
- gaussian
- scale invariant

\[ \ddot{\delta \varphi}_k + 3H \dot{\delta \varphi}_k + \omega_k^2 \delta \varphi_k \approx 0 \]

\[ k^{3/2} \delta \varphi_k \sim H_{ex} \]

\[ t \rightarrow \]
initial conditions from inflation

\[ d_H = H^{-1} \]

\[ \lambda \propto a \]

\[ \Delta^2_{\Psi}(k) \sim \frac{H_{inf}^2}{\epsilon m_{pl}^2} \]

\[ \epsilon = 2m_{pl}^2 \left( \frac{V' (\varphi)}{V (\varphi)} \right)^2 \]
peaks & troughs — re-entry in phase
quantum fluctuations + inflation ------- structure
inflation: causal fluctuations

- zero point fluctuations of
  - inflaton, gravitational potential, **gravitational waves**

\[ \delta \varphi \quad \text{dominant source} \quad \Psi \]

- wavelength stretched to enormous scales

\[ d_{H_i} = c/H_i \sim \text{const.} \]
gravitational waves

The contributions to CMB anisotropies from scalar and tensor (gravitational wave) perturbations generated during inflation. The concordance $\Lambda$CDM model has been assumed with exactly scale-invariant initial fluctuations. The amplitudes of the tensor and scalar power spectra have been chosen arbitrarily to be equal at $\ell = 10$. Observed CMB anisotropies at low multipoles constrain this energy scale in simple inflationary models to be $V_{\text{inf}} < \sim (3.5 \times 10^{16} \text{ GeV})^4$. The energy scale of inflation must be more than three orders of magnitude lower than the Planck scale. Generally, the ratio of amplitudes of the scalar and tensor CMB power spectra at low multipoles is given by

$$r \equiv \frac{C_T}{C_S} \sim 10^\epsilon,$$

where the exact numerical factor on the right-hand side of this equation depends on the multipole at which the ratio is evaluated and on the values of certain cosmological parameters, in particular the cosmological constant $\Lambda$. The spectral indices for the scalar and tensor power spectra, $n_S$ and $n_T$, can be expressed to first order in terms of the two slow-roll parameters $\epsilon$ and $\eta$ as

$$n_S - 1 \simeq -6\epsilon + 2\eta,$$

and

$$n_T \simeq -2\epsilon.$$

Furthermore, these spectra will not necessarily be pure power laws. The deviation from a pure power law can be expressed in terms of the following derivative, sometimes called the run in the spectral index:

$$\frac{dn_S}{d\ln k} \simeq -16\epsilon\eta + 24\epsilon^2 + 2\xi^2,$$

where the parameter $\xi$ is

$$\xi^2 = \frac{m^4}{8\pi^2} \left( \frac{V'}{V''} \right)^2.$$
there is more! polarization

why?
Thomson scattering

probes:
nature and type perturbations
polarization

Density Wave

E-Mode Polarization Pattern

Temperature Pattern Seen by Electrons

Gravitational Wave

B-Mode Polarization Pattern

http://bicepkeck.org/visuals.html
decompose signal

- specific \((B \text{ mode})\) polarization signal in the CMB
- **B-mode**: generated by g-waves from inflation (2-4 deg)
- **B-mode**: generated by lensing (\(~\text{arcmin}\))
comparison of signals

![Graph showing comparison of signals with labels for polarization and primordial signals.](image)
so far ...
But what about the primordial ones?
Drum roll ...
BICEP2 : March 17

BICEP2 B-mode signal

Right ascension [deg.]

Declination [deg.]
But what about the primordial ones?
previous experiments ...
The exciting new result? from lensing Bicep2 (2014)
why is this **important**!
quantum aspects of gravity?

- If true and from inflation, this is a confirmation that quantizing linearized gravity around classical backgrounds is ok!

cautionsary note later
primordial B-modes = g-waves =
direct probe of energy scale of inflation

\[ \Delta_{\Psi}^2(k) \sim \frac{H_{\text{inf}}^2}{\epsilon m_{\text{pl}}^2} \]

\[ \epsilon = 2m_{\text{pl}}^2 \left( \frac{V'(\phi)}{V(\phi)} \right)^2 \]

\[ \Delta_h^2(k) \sim \frac{H_{\text{inf}}^2}{m_{\text{pl}}^2} \]
the tensor to scalar ratio

\[ r = \frac{\Delta^2_h(k_0)}{\Delta^2_\psi(k_0)} \]

spectral index \( n_s \)

\[ \Delta^2_\psi(k_0) \sim A_S \left( \frac{k}{k_0} \right)^{n_s-1} \]
inflationary constraints
(before Monday: Planck)

without running of spectral index
inflationary constraints
(before Monday)
with running of spectral index

**Fig. 4.** Marginalized joint 68% and 95% CL regions for \((r, n_s)\), using *Planck*+WP+BAO with and without a running spectral index.

inflationary constraints with Bicep2!

$r = 0.2^{+0.05}_{-0.07}$

$r = 0$ disfavored at 7 sigma
inconsistent with Planck? (maybe...)
inflationary constraints
(with running of spectral index)

This is just “one” way

important! included running of spectral index
caution

• theorists’ paradise but …

• wait till things settle … systematics-foregrounds—could bring value of r down

• wait for confirmation/hints from other experiments (Planck, Keck Array, SPTPol, ActPIPol, Class, Ebex, SPIDER, PIPER, BICEP3 etc soon!)

• beyond the minimal model:
  • post inflationary contribution : phase transitions?
  • classical generation during inflation ?
Stepping back ...

**Modern Universe**

- **Quantum Fluctuations**
- **Radius of the Visible Universe**
- **Inflation**
  - Protons Formed
  - Nuclear Fusion Begins
  - Nuclear Fusion Ends
  - Neutral Hydrogen Forms

**Gravitational Waves**

- **Density Waves**
- **Waves Imprint Characteristic Polarization Signals**

**History of the Universe**

- **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**

- **Age of the Universe**
  - 0
  - $10^{-32}$ s
  - 1 µs
  - 0.01 s
  - 3 min
  - 380,000 yrs
  - 13.8 Billion yrs

[http://bicepkeck.org/visuals.html](http://bicepkeck.org/visuals.html)
“The long search for tensor $B$-modes is apparently over, and a new era of $B$-mode cosmology has begun.” - Bicep2 I
summary so far

• inflation - successful paradigm
• quantum origin gravitational waves “detected”
  - many models might be ruled out!
  - guidance from observations: forthcoming!

how does this fit into the rest of (particle) physics?
WHAT HAPPENED AT THE END OF INFLATION?
Dark Matter, Structure Formation

(5 billion yrs) (8.7 billion yrs)

$10^{27}$

$10^{35}$ sec
• What does the universe look like at the end of inflation?

• Energy transfer: how did the universe get populated?
slow roll inflation

\[ V(\varphi) \]

relative separation

10^{-35} seconds!
ending inflation

$V(\varphi)$

end: oscillatory regime
dynamics at the end of inflation

- shape of the potential
- how does it couple to other fields
I : perturbative decay

\[ V \sim \frac{1}{2} m_{\varphi}^2 \varphi^2 + h \varphi \bar{\psi} \psi + \ldots \]

\[ \Gamma(\varphi \to \psi \psi) \sim \frac{h^2 m_{\varphi}}{8\pi} \ll H \]
is this it?
2 : explosive decay

\[ V \sim \frac{1}{2} m_\phi^2 \phi^2 + g^2 \phi^2 \chi^2 + h \phi \bar{\psi} \psi + \ldots \]

\[ \Box \chi = V, \chi = g^2 \phi^2 \chi \]

Movie courtesy R Easther

Trachen & Brandenberger (1990), Kofman, Linde, Starobinsky et. al (1994) ...
parametric resonance

inflaton  
daughter fields

Felder and Kofman 2006
parametric resonance

inflaton
daughter fields

Felder and Kofman 2006
3 : explosive decay + coherent structures

\[ V \sim \frac{1}{2}m^2\varphi^2 - \frac{\lambda}{4}\varphi^4 + \ldots + \hbar\varphi\bar{\psi}\psi \]

Also see: McDonald & Broadhead, Rajantie & Copeland, Gleiser et. al. and the Q-ball literature
lumps?

(1) oscillatory (2) spatially localized (3) very long lived

the all important sign

\[
V \sim \frac{1}{2} m^2 \phi^2 - \frac{\lambda}{4} \phi^4 + \frac{g^2}{6m^2} \phi^6 + \ldots + \hbar \phi \bar{\psi}
\]
the all important sign

\[ V \sim \frac{1}{2} m^2 \varphi^2 - \frac{\lambda}{4} \varphi^4 + \frac{g^2}{6m^2} \varphi^6 + \ldots + \hbar \varphi \bar{\psi} \]

Movie: courtesy of A Speranza, undergrad@MIT
stability, lifetimes, social life ...

- MA & Shirokoff 2010 (stability in 3d)
- MA 2013 (K-oscillons, stability)
- Segur and Kruskal 1987
- MA, Yang, Nagreanu (in progress)
generic emergence

> 80% energy density in oscillons!

Farhi et. al 2008
generic emergence

> 80% energy density in oscillons!

Farhi et. al 2008
“anharmonic” oscillations of the homogeneous inflaton are unstable, causing a resonant growth of fluctuations
“anharmonic” oscillations of the homogeneous inflaton are unstable, causing a resonant growth of fluctuations.
need large fluctuations

• start with tiny ‘quantum’ fluctuations

• amplify them via resonance
requires efficient growth

- growth rate $\mu_k$
- expansion rate $H$

$\mu_k \gg H$

$\mu_k$ depends on the parameters, and can be calculated easily
emergence condition

\[
\left[ \frac{|\mathcal{R}(\mu_k)|}{H} \right]_{\text{max}} \approx f(\alpha) \frac{m_{\text{pl}}}{M} \gg 1
\]
aside: number density

\[ n_{osc} a^3 \sim \left( \frac{k_{nl}}{2\pi} \right)^3 \]
energy fraction: $\gg 50\%$

\[
f = \frac{E_{osc}}{E_{tot}}
\]

(inverse)scale where potential changes shape

asymptotic slope

\[
m_{pl}/M \gg 1
\]

\[
\alpha \lesssim 1
\]

MA, Easther, Finkel, Flauger, Hertzberg 2011
inflation fragmentation

resonant growth

>>50%!
what does the universe look like at the end of inflation?

caveat: details of how we get to a “thermal” universe is still incomplete
observational signatures?

• difficult
  - extremely small length scales
  - thermalization

• possibilities
  - indirect: expansion history
  - gravitational waves?
  - non-gaussianities?
violent motion: gravitational waves!

Movie: R. Easther

Khlebnikov & Tkachev 1998, Easther & Lim 2006, Dufaux et. al 2007 ...
gravitational waves

\[ \frac{\Omega_{gw}(f)}{\Delta \log f} \]

fraction of energy density in g-waves (per logarithmic frequency interval)

\[ 10^{16} \quad 10^{14} \quad 10^{10} \quad 10^{6} \quad 10^{2} \quad 10^{6} \quad 10^{10} \]

\[ f \text{ [Hz]} \]

Adapted from Abott et. al. 2007
• **theory**
  - inflation + couplings!!

• **phenomenology**
  - complex (numerical) analysis
  - observational signatures

• **observations**
  - high frequency gravitational waves
  - non-gaussianity, expansion history?
summary

• inflation
  - successful paradigm
  - B-modes from Bicep2!
    - which model, theoretical work, confirmation?
• end of inflation
  - dynamics is rich and complex
  - need to consider realistic models
  - observational signatures
    - g-waves, relics, expansion history?