BICEP2 and quantum fluctuations

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South Africa Gravity Society meeting SAGS 2014 & George Ellis 75
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GEORGE ELLIS 75

Congratulations!
WASHINGTON, Nov. 22. -- Confirmation of the view that the spiral nebulae, which appear in the heavens as whirling clouds, are in reality distant stellar systems, or "island universes," has been obtained by Dr. Edwin Hubbell of the Carnegie Institution's Mount Wilson observatory, through investigations carried out with its powerful telescopes.

In 1929 Hubble formulated the Redshift Distance Law, Hubble's law

Big Bang

"Oerknal (Engels: big bang) beskryf hoe die heelal 13,8 miljard jaar gelede ontstaan het uit 'n superdigte, dimensielose en ontsettend warm (sowat $10^{28}$ K) singulariteit." [Wikipedia Afrikaans]

“At some moment all matter in the universe was contained in a single point” [Wikipedia]

Georges Lemaître (1894-1966)

Theory, 1927: Solution (Friedmann’s) of Einstein’s Eqs
Annales Société Scientifique Bruxelles 47, 49 (1927), Eddington MNRAS (1930)

Observational evid.: V. Slipher redshifts + E. Hubble distancies

"hypothèse de l’atome primitif“ Nature 127, 706 (1931)

primeval atom, cosmic egg
Big Bang: Evidences

- Expansion according to Hubble’s law
- CMB Radiation 1964 A. Penzias R. Wilson
- Abundancy of primordial elements: helium-4, helium-3, deuterium, lithium-7
- Evolution & distribution of galaxies
- Primordial gas clouds
- Distant quasars
- Detection of primordial gravitational waves?

17 March 2014
Alternatives:

**Steady State theory:** James Jeans, 1920s, conjectured a steady state cosmology based on a hypothesized continuous creation of matter in the universe. The idea was revised in 1948 by Fred Hoyle, Thomas Gold, Hermann Bondi and others.

Hoyle, on 28 March 1949, on the BBC Third Programme: “Big Bang”. Published in The Listener in 1950.

**Cyclic model (or oscillating universe):** A universe that expanded and contracted in a cyclic manner was put forward in a 1791 poem by Erasmus Darwin. Edgar Allan Poe presented a similar cyclic system in his 1848 essay *Eureka: A Prose Poem*

Albert Einstein, 1930s, theorized a universe following an eternal series of oscillations, each beginning with a big bang and ending with a big crunch.

Richard C. Tolman, 1934, showed cyclic model failed because universe would undergo inevitable thermodynamic heat death.

One new cyclic model is a brane cosmology model of the creation of the universe, derived from the earlier ekpyrotic model. It was proposed in 2001 by Paul Steinhardt of Princeton U and Neil Turok of Cambridge U. It evades the entropy problem by having a net expansion each cycle, preventing entropy from building up.

**On the very origin**

A mathematical singularity?

Extrapolation of the expansion of the universe backwards in time using general relativity yields an infinite density and temperature at a finite time in the past [Hawking and Ellis, The Large-Scale Structure of Space-Time (Cambridge U.P., 1973)]

\[
\ell_P = \sqrt{\frac{\hbar G}{c^3}} \approx 1.616\, 199(97) \times 10^{-35} \text{ m}
\]

\[
t_P \equiv \sqrt{\frac{\hbar G}{c^5}} \approx 5.39106(32) \times 10^{-44} \text{ s}
\]

\[
\hbar = 1.054571726(47) \times 10^{-34} \text{ J s} = 6.58211928(15) \times 10^{-16} \text{ eV s}
\]

Planck region?
History of the Universe

Inflation Generates Two Types of Waves

Gravitational Waves

Density Waves

Waves Imprint Characteristic Polarization Signals

Baryon Acoustic Oscillations (BAO)

Free Electrons Scatter Light

Earliest Time Visible with Light

Radius of the Visible Universe

Big Bang

Gut Epoch

Quark-Gluon Plasma

E-Weak Epoch

Hadron Epoch

Lepton Epoch

Photon Epoch

Nuclear Fusion Begins

Nuclear Fusion Ends

Cosmic Microwave Background

Neutral Hydrogen Forms

Matter Dominance

Recombination

Reionization

Solar System

Modern Universe

Age of the Universe

0

10^{-32} s

1 μs

0.01 s

3 min

380,000 yrs

13.8 Billion yrs

Matter Dominance

Recombination

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Matter Dominance

Recombination

Reionization

Solar System

Modern Universe
Zero point energy

QFT vacuum to vacuum transition: \( \langle 0 | H | 0 \rangle \)

Spectrum, normal ordering (harm oscill):

\[
H = \left( n + \frac{1}{2} \right) \lambda_n \ a_n \ a_n^\dagger
\]

\[
\langle 0 | H | 0 \rangle = \frac{\hbar c}{2} \sum_n \lambda_n = \frac{1}{2} \text{tr} \ H
\]

gives \( \infty \) physical meaning?

Regularization + Renormalization (cut-off, dim, \( \zeta \))

Even then: Has the final value real sense?
Some Books

2nd Ed June 2012

Cosmology, the Quantum Vacuum, and Zeta Functions

A Choice of Papers

Emilio Elizalde
CSIC, UB
IEEC, UAB

Emilio Elizalde in Moscow. May 20, 2009, during the Fourth International Sakharov Conference on Physics.

Zeta Regularization Techniques with Applications

Analytic Aspects of Quantum Fields

Cosmology, Quantum Vacuum, and Zeta Functions

Papers in honor of Emilio Elizalde on the occasion of his 60th Birthday

Diego Sáez-Gómez • Sergei Odintsov • Sebastià Xambó
Editors

Springer
Inflation

App. $10^{-36}$ seconds after the origin, a phase transition caused a cosmic inflation, during which the universe grew very quickly. The inflationary epoch lasted from $10^{-36}$ to $10^{-35}$ seconds after the origin to some $10^{-33}$ to $10^{-32}$ s.

De Sitter space (1917) is the analog in Minkowski space (spacetime) of a sphere in ordinary, Euclidean space. It is the maximally symmetric, vacuum solution of Einstein’s eqs, corresponding to a positive vacuum energy density and negative pressure. De Sitter space can be defined as a submanifold of a Minkowski space of one higher dimension. Take Minkowski space $\mathbb{R}^{1,n}$ with the standard metric:

$$ds^2 = -dx_0^2 + \sum_{i=1}^{n} dx_i^2.$$ 

De Sitter space is the submanifold described by the hyperboloid of one sheet:

$$-x_0^2 + \sum_{i=1}^{n} x_i^2 = \alpha^2$$

where $\alpha$ is some positive constant with dimensions of length.

In the early 1970s, Zeldovich: flatness and horizon problems of BB cosmology. In the late 1970s, Sidney Coleman applied the instanton techniques of A. Polyakov et al to study the fate of the false vacuum in quantum field theory. Like a metastable phase in statistical mechanics — water below the freezing temperature or above the boiling point — a quantum field needs to nucleate a large enough bubble of the new vacuum (new phase), to make a transition.

(In QFT, a false vacuum is a metastable sector of space that appears to be a perturbative vacuum, but is unstable due to instanton effects that may tunnel to a lower energy state. This tunneling can be caused by quantum fluctuations or the creation of high-energy particles. This is analogous to metastability for first-order phase transitions.)
baryonic (Plausibly it is made up of the hypothetical elementary particles postulated in the 1980s, for example axions or the lowest mass supersymmetric partner of the known particles.) incompatible with the flat geometry predicted by inflation unless the Universe contains an additional unclustered and dominant contribution to its energy density, for example a cosmological constant $\Lambda$ such that $\Omega_m + \Omega_\Lambda \approx 1$. Two largescale structure surveys carried out in the late 1980s, the APM (automated photographic measuring) photographic survey and the QDOT redshift survey of infrared galaxies, showed that the power spectrum of the galaxy distribution, if it traces that of the mass on large scales, can be fitted by a simple CDM model only if the matter density is low, $\Omega_m \approx 0.3$. This independent confirmation of the dynamical arguments led many to adopt the now standard model of cosmology, $\Lambda$CDM. The supernova evidence is consistent with $\Omega_\Lambda \approx 0.7$, just the value required for the flat universe predicted by inflation. [The large-scale structure of the Universe, Volker Springel, Carlos S. Frenk & Simon D. M. White, NATURE, 440, 27 April 2006]

**Gravitational waves**

$$\bar{h}^{\alpha\beta} \equiv g^{\alpha\beta} - \sqrt{|\det g|} g^{\alpha\beta}$$

$$\square \bar{h}^{\alpha\beta} = -16\pi \tau^{\alpha\beta}, \quad \tau^{\alpha\beta} \text{ stress–energy tensor plus quadratic terms involving } \bar{h}^{\alpha\beta}$$

Linear approximation, space is nearly flat

$$\bar{h}^{\alpha\beta} = \frac{1}{r} \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & A_+ (t - r, \theta, \phi) & A_\times (t - r, \theta, \phi) \\ 0 & 0 & A_\times (t - r, \theta, \phi) & -A_+ (t - r, \theta, \phi) \end{bmatrix}$$

The pattern of polarization in the cosmic microwave background can be broken into two components. One, a curl-free, gradient-only component, the **E-mode** (named in analogy to electrostatic fields), was first seen in 2002 by the Degree Angular Scale Interferometer (DASI). The second component is divergence-free, curl only, and is known as the **B-mode** (named in analogy to magnetic fields). The electric (E) and magnetic (B) modes are distinguished by their behavior under a parity transformation $n \rightarrow -n$. E modes have $(-1)^l$ parity and B modes have $(-1)^{l+1}$. The local distinction between the two is that the polarization direction is aligned with the principal axes of the polarization amplitude for E and crossed $45^\circ$ for B.

**E-mode**

**B-mode**
On 17 Mar 2014, John Kovac announced that, by looking at the CMB signal, BICEP2 had found the imprint of gravitational waves from the Big Bang:
- polarization of the CMB
- curly patterns known as B modes
- generated by gravitational waves during inflation
BICEP2 I: DETECTION OF B-mode POLARIZATION AT DEGREE ANGULAR SCALES


to be submitted to a journal TBD

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

1. INTRODUCTION

The discovery of the Cosmic Microwave Background (CMB) by Penzias & Wilson (1965) confirmed the hot big bang paradigm and established the CMB as a central tool for the study of cosmology. In recent years, observations of its temperature anisotropies have helped establish and refine the “standard” cosmological model now known as $\Lambda$CDM, under which our universe is understood to be spatially flat, dominated by cold dark matter, and with a cosmological constant ($\Lambda$) driving accelerated expansion at late times. CMB temperature measurements have now reached remarkable precision over angular scales ranging from the whole sky to arcminute resolution, producing results in striking concordance with predictions of $\Lambda$CDM and constraining its key parameters to sub-percent precision (e.g. Bennett et al. 2013; Hin...
Detection of B-Mode Polarization at Degree Angular Scales by BICEP2


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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 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 low-foreground region of sky with an effective area of 380 square deg was observed to a depth of 87 nK deg 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. Cross correlating against WMAP 23 GHz maps we find that Galactic synchrotron makes a negligible contribution to the observed signal. We also examine a number of available models of polarized dust emission and find that at their default parameter values they predict power $\sim (5-10) \times$ smaller than the observed excess signal (with no significant cross-correlation with our maps). However, these models are not sufficiently constrained by external public data to exclude the possibility of dust emission bright enough to explain the entire excess signal. 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 dust at $1.7\sigma$. The observed $B$-mode power spectrum is well fit by a lensed-$\Lambda$CDM + tensor theoretical model with
In the preprint version of this paper an additional DDM2 model was included based on information taken from *Planck* conference talks. We noted the large uncertainties on this and the other dust models presented. In the *Planck* dust polarization paper [96] which has since appeared the maps have been masked to include only regions “where the systematic uncertainties are small, and where the dust signal dominates total emission.” This mask excludes our field. We have concluded the information used for the DDM2 model has unquantifiable uncertainty. We look forward to performing a cross-correlation analysis against the *Planck* 353 GHz polarized maps in a future publication.

Could Quantum Gravity ever be detected?

Freeman Dyson at Singapore conference Aug 2013, celebrating his 90th Birthday:

*physically impossible

*to detect individual graviton, mirrors need be so heavy they would collapse to form a Black Hole


- gravitational waves stretch spacetime along one direction while contracting it along the other
- would affect how electromagnetic radiation travels through space, causing it to be polarized
- “…measurement of polarization of CMB due to gravitational waves from Inflation would firmly establish the quantization of gravity”
- gravitational waves can be traced back to individual gravitons, “…what we finally hope to detect is the signal from a single graviton amplified by the Universe expansion”

And Alan Guth “…the expected gravitational waves arise from the quantum properties of the gravitational field itself, and are not merely a by-product of the gravitational field interacting with the quantum fluctuations of other fields”
Using cosmology to establish the quantization of gravity

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While many aspects of general relativity have been tested, and general principles of quantum dynamics demand its quantization, there is no direct evidence for that. It has been argued that development of detectors sensitive to individual gravitons is unlikely, and perhaps impossible. We argue here, however, that measurement of polarization of the cosmic microwave background due to a long wavelength stochastic background of gravitational waves from inflation in the early Universe would firmly establish the quantization of gravity.

Direct detection of gravitational waves is an exciting frontier of experimental physics, with positive results anticipated soon (e.g., Ref. [1]). The anticipated signals are classical disturbances, comprised of coherent superpositions of many individual quanta. The possibility of detecting individual gravitons is far more daunting. Indeed, recently Freeman, Dyson, and colleagues [2] have cogently estimated that it may in fact be infinitely more daunting, namely, that it is likely to be impossible, to physically realize a detector sensitive to individual gravitons without having the detector collapse into a black hole in the process.

If that is the case, one might wonder whether we can ever detect a stochastic gravitational wave background, even if it is there. This question is important because it is through gravitational wave detection that we may eventually learn about the forces that drive the expansion of the universe, and the magnitude, even within the inflationary scenario, depends on the rate of expansion during inflation. If the background is not observed, it could simply indicate a relatively small rate of expansion. But detection is a plausible possibility, as we describe, and major efforts are underway to achieve it. We should also emphasize that no essentially new predictions or calculations are presented here; we are merely bringing to the foreground an implication of existing results that seems particularly noteworthy.

The fact that quantization associated with gravity appears to be an essential feature of a gravitational wave background generated by inflation is suggested by existing calculations, including the following. A period
“Good Morning, Inflation! Hello, Multiverse!” (Max Tegmark)

Hawking tells Turok: “You owe me!” But Turok's sticking with his cyclic universe.

“I believe that if both Planck and the new results agree, then together they would give substantial evidence against inflation!” (Neil Turok)

“There's a significant possibility of some of the polarization signal in E and B modes not being cosmological. If genuine, then the spectrum is a bit strange and may indicate something added to the normal inflationary recipe” (Peter Coles)

“What is strange is that all the blue dots lie so close to zero. Statistically speaking this is extremely unlikely and it may suggest that the noise levels have been over-estimated” (Hans Kristian Eriksen)

Reserve judgement until this is confirmed by other experiments: STP, POLARBEAR, ABS, ACTPOL, CLASS, EBEX, SPIDER, PIPER, and PLANCK
Quasi-matter domination parameters in bouncing cosmologies

E. Elizalde, J. Haro, S.D. Odintsov  
arXiv:1411.3475

For bouncing cosmologies, a fine set of parameters is introduced in order to describe the nearly matter dominated phase, and which play the same role that the usual slow-roll parameters play in inflationary cosmology.

It is shown that, as in the inflation case, the spectral index and the running parameter for scalar perturbations in bouncing cosmologies can be best expressed in terms of them.

Further, they explicitly exhibit the duality which exists between a nearly matter dominated Universe in its contracting phase and the quasi de Sitter regime in the expanding one. In particular, the spectral index for a matter dominated Universe in the contracting phase is, in fact, the same as the spectral index for an exact Sitter regime in the expanding phase.

In both the inflationary and the matter bounce scenarios, the theoretical values of the spectral index and of the running parameter are compared with their experimental counterparts, obtained from the most recent PLANCK data: the bouncing models here discussed do fit well accurate astronomical observations.

Slow-roll inflationary models are generically less favored by observational data, due to the rather small value of the running parameter predicted, as compared with bounce theories.
GEORGE ELLIS 75

Congratulations!