Searching for a Cosmological Background of Gravitational Waves

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Using Gravitation to Explain the Universe -- and Conversely
Evolution of a Homogenous & Isotropic Universe

Mass*acceleration = Force

\[ m \frac{d^2R}{dt^2} = -GmM(<R)/R^2 \]

\[ M(<R) = \rho \frac{4}{3} \pi R^3 = \text{constant} \]

\[ \frac{d^2R}{R dt^2} = -4\pi G \rho \]

\[ \frac{d\rho}{dt} = -3 \frac{dR}{R dt} \rho \]

Equations of Motion for a Homogenous Universe
Evolution of a Homogenous & Isotropic Universe

Albert Einstein

Equations of Motion for a Homogenous Universe

\[ \frac{d^2 R}{dt^2} = -4\pi G \left( \rho + 3p \right) + \Lambda/3 \]

\[ \frac{d\rho}{dt} = -3 \frac{dR}{R dt} (\rho + p) \]

Bonus constant! Should it be 0?

Pressure is a kind of energy

Matter-Energy Bends Space-Time
Whoops…

The Universe is Expanding!

It Always Pays to Look

Albert Einstein

Edwin Hubble
The CMB is the Furthest Back We Can See*

The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

*with photons
Modern cosmology c. 1980

1) The universe is expanding.
   (Hubble, 1920s)

2) It was once hot and dense, like the inside of the Sun.
   (Alpher, Gamow, Herman, 1940s)

3) You can still see the glow!
   The *Cosmic Microwave Background*
   (Penzias & Wilson, 1964)

⇒ acceptance of the “HOT BIG BANG”
The Sky at ~Optical Wavelengths
Every Direction is the SAME Temperature to ~10 ppm!
How Can This BE? A Deeply Troubling Question for Cosmologists in 1980…
Evolution of a Homogenous & Isotropic Universe

Albert Einstein

Equations of Motion for a Homogenous Universe

\[ \frac{d^2R}{Rdt^2} = -4\pi G \left( \rho + 3p \right) + \Lambda/3 \]

\[ \frac{d\rho}{dt} = -3 \frac{dR}{Rdt} \left( \rho + p \right) \]

\[ \Lambda \neq 0? \]

\[ R = R_0 \exp \left[ \left( \frac{\Lambda}{3} \right)^{1/2} t \right] \]

Exponential Expansion!!

Negative pressure? \( p = -\rho \)

\[ \frac{d\rho}{dt} = 0, \ \rho = \text{constant} \]

\[ R = R_0 \exp \left[ \left( 8\pi G \rho \right)^{1/2} t \right] \]

Exponential Expansion!!

OK, so you need a strange form of matter-energy to get negative pressure…

Matter-Energy Bends Space-Time
The Remarkable Theory of Inflation

A. Guth

Late-time acceleration!

Dark energy?

Λ?
Kitchen Cosmology

resistor  amplifier  speaker  jello

quantum fluctuations  inflation  density waves  primordial plasma
Cosmic Microwave Background

The Planck Satellite
CMB Temperature Power Spectrum

Angular Size [°]: 10° 1° 0.1°

Signal [μK²]:

Low Tones

High Tones

Angular Frequency [ℓ]:

Large Structures

Small Structures

Flat Universe...

... to < 1 %

Structures larger than causal horizon

Peaks phased coherently

Flat spectrum

... but slightly tipped

Gaussian statistics
How Can We Test Inflation Further?

Sub-atomic vacuum fluctuations of “inflaton”

- **Inflationary gravitational waves:** CMB “B-mode” polarization
- **Spectral index of fluctuations:** CMB and large-scale structure of galaxies
- **Non-Gaussianity:** Sensitive to Inflaton field, large-scale structure (SPHEREx)

Gravitational waves? → telltale polarization pattern

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

13.8 Billion yrs

0

10^{-32} s

1 \mu s

0.01 s

3 min

380,000 yrs

Age of the Universe
CMB polarization: scattering from sound waves

what about gravitational waves?
The Signature of Gravitational Waves

Density fluctuations cannot make B-mode patterns
CMB Polarization

Density Wave

E-Mode Polarization Pattern

Gravitational Wave

B-Mode Polarization Pattern
CMB Polarization

Density Wave

Gravitational Wave

Temperature Pattern Seen by Electrons

E-Mode Polarization Pattern

B-Mode Polarization Pattern
CMB Power Spectra

Angular Size [$^\circ$]

Temperature

Signal [$\mu K^2$]

Low Tones

Angular Frequency [$\ell$]

High Tones

E-Mode Polarization

Planck
ACTPol
SPTPol
BICEP2/Keck
PBear

Large Structures

Small Structures

10° 1° 0.1°
CMB Power Spectra

Angular Frequency $[\ell]$  
Angular Size [$^\circ$] 0.1$^\circ$

Signal $[\mu K^2]$  
Temperature
Gravitational Lensing
E-Mode Polarization
B-Mode Polarization

Low Tones

High Tones

Large Structures

Small Structures

Planck
ACTPol
SPTPol
BICEP2/Keck
PBEar
Gravitational Lensing of the CMB

Background undeflected CMB

Lumpy matter bends light

Observer today

400 kyr
1 Gyr
5 Gyr
14 Gyr

CMB without lensing

Observed CMB: slightly deflected by gravitational lensing
Gravitational Lensing of the CMB

Background undeflected CMB

Observer today

Lumpy matter bends light

CMB with lensing

Observed CMB: slightly deflected by gravitational lensing
CMB Power Spectra

Angular Size [°] 10° 1° 0.1°

Temperature

Large Structures

Small Structures

Low Tones

High Tones

Angular Frequency [\ell]

[\mu K^2]

Gravitational Lensing

Gravitational Waves at \( r=0.1 \)

E-Mode Polarization

B-Mode Polarization

Planck

ACTPol

SPTPol

BICEP2/Keck

PBear

Inset image: Goose
BICEP Concept: Unique Optics

Small-Telescope Design
Invented in 2001
- 26 cm aperture
- Wide 20° FOV
- Optics cooled to 4 K
- Low sidelobe response
- Boresight rotation
BICEP/Keck: A Staged Program

BICEP2 (2010-2012)

Keck Array (2012-2017)

BICEP3 (2015-)

BICEP Array (2018-)

Telescope and Mount

Focal Plane

Beams on Sky
The South Pole: The Best Place on Earth
Relentless Observing
B-modes constitute about 15% of the total polarization signal.
Total Polarization Map

95 GHz

Keck14 95 GHz total polarization signal

\[1.7 \mu K\]
**Synchrotron**
- Spiraling electrons
- Emission $\alpha \propto (\text{Frequency})^{-3}$

**Dust**
- Galactic dust grains
- Emission $\alpha \propto (\text{Frequency})^{1.75}$
Planck Visualization of Polarized Dust Emission

With apologies to Vincent van Gogh
All-Sky Maps from the Planck Satellite

- 30 GHz
- 44 GHz
- 70 GHz
- 100 GHz
- 143 GHz
- 217 GHz
- 353 GHz
- 545 GHz
- 857 GHz
Latest Constraints on the Inflationary Gravitational Wave Background

BICEP/Keck 2014 data + Planck

\[ r = 0.028^{+0.026}_{-0.025} \]

\[ r < 0.09 \text{ (95 \% CF)} \]

Best constraints on GWs now come from B-mode polarization (as predicted in the 1990s)

New Data Coming - Keck220 and BICEP3

2015 season
95 GHz depth doubles
First observations at 220 GHz
BICEP3 commissioned

2016 upgrades
220 GHz receivers: 2 → 4
BICEP3 reaches full power
= 10 Keck Array receivers
Next Step: the BICEP-Array

Stage 2
- funded operations

Stage 3
- proposed operations

Keck Array
BICEP Array
BICEP3

Map Sensitivity [mK·arcmin]

Tests slow-roll inflation

σ(t)

A_1 = 1.0
A_1 = 0.5
A_1 = 0.2

Knox raw sensitivity

Gravitational waves can tell us what powered inflation
- Inflation requires new physics at high energies
- Connects Einstein’s gravity to quantum mechanics
- Only \textit{some} inflation models make copious waves

New analysis from 2015 Keck Array data
- Gravitational wave amplitude \( r < 0.09 \)
- Polarization data have now overtaken temperature data
- Limited by errors in foreground removal

Program will push down to \( \delta r = 1\% (3\sigma) \) in several years
- \textit{Stay tuned!}
Spectral Constraints from Auto- and Cross-Spectra

Dominant error comes from dust subtraction

- CMB: 150x150 sensitivity $\Delta r < 1\%$
- Dust: best information from 150xP353
- Sync: not yet detected
- New: Keck data provides dust measurement in 95x150