Measuring the Cosmic Microwave Background with the South Pole Telescope and Future Instruments

CaJAGWR Seminar — April 24th, 2018
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Objective:

detect signatures from inflationary gravitational waves in the cosmic microwave background (CMB)

probe physics of the universe fractions of a second after the big bang
The Cosmic Microwave Background

Image Credit: Planck
Observing the Early Universe:

(what makes it challenging)

1. The signals we are trying to measure are very tiny.

2. The wavelength of the light is different than what we measure with our eyes and every day cameras.

   (typical wavelengths = 1 - 3 mm)

(and what makes it worthwhile)

1. We can probe physics when the universe was less complicated.

2. We can probe high energy physics that is hard to create in the modern universe.
CMB Instruments

The South Pole Telescope:
- SPT-SZ
- SPTpol
- SPT-3G

Quadrant
- QUAD
- Boomerang
- SPIDER

ACT
- ACT
- ACTpol
- AdvACT

POLARBEAR
- Simons Array
- Simons Observatory

COBE
- WMAP
- PLANCK

BICEP
- BICEP
- BICEP 2
- Keck
- Keck Array
- BICEP 3
- BICEP Array

NOT A COMPLETE LIST
What do you need for a successful CMB instrument?

Observing Site — the atmosphere is one of the biggest sources of noise

Sensitivity — how faint are the signals you can measure

Resolution — what scale objects you can measure
What do you need for a successful CMB instrument?

CMB Bands:
1 mm - 3 mm
300 GHz - 100 GHz

Image Credit: IRAM, France
What do you need for a successful CMB instrument?

Sensitivity — lots of detectors with very low noise that work at these frequencies

Key Technology:
Superconducting Transition Edge Sensor (TES) Bolometer
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Superconducting Transition Edge Sensor (TES) Bolometer

Photons

Absorber

Very Sensitive Thermometer

Weak Thermal Link

Thermal Bath
Key Technology: Superconducting Transition Edge Sensor (TES) Bolometer

- Photons
- Al and Ti TESs (Sensitive Thermometer)
- Absorber
- Very Sensitive Thermometer
- Weak Thermal Link
- Silicon Nitride Support Legs
- Thermal Bath

8 mm

Image Credit: TIME Collab.
Key Technology:
Superconducting Transition Edge Sensor (TES)
Bolometer

Ohm’s Law
\[ V = I \times R \]
voltage = current \times resistance

normal resistor

superconductor

Temperature (Kelvin)

Resistance (ohms)
Key Technology:
Superconducting Transition Edge Sensor (TES) Bolometer

Ohm's Law:
\[ V = I \times R \]

Voltage = Current \times Resistance

Electro-Thermal Feedback:

Superconducting Transition

Normal Resistor

Temperature (Kelvin)

Resistance (ohms)
Key Technology: Superconducting Transition Edge Sensor (TES) Bolometer

Image and figure Credit: TIME Collab., George et al 2014
“Lots of Detectors”

<table>
<thead>
<tr>
<th>CMB Experiment Stage</th>
<th>2010-2015</th>
<th>2015-2019</th>
<th>2020 — 2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of TES Detectors</td>
<td>~1000’s</td>
<td>~ 10,000</td>
<td>~500,000</td>
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</tbody>
</table>
Cryogenics

3He Sorption Refrigerator

Image Credit: Bhatia et al. 2000
1000 pixels

pixel size = 4 mm
What do you need for a successful CMB instrument?

Resolution — what scale objects you can measure

10 m primary mirror

Image Credit: SPT

1.5 m primary mirror

Image Credit: ESA
Planck
143 GHz
50 deg²
South Pole Telescope

150 GHz

50 deg²

13x resolution

50x deeper
0. Constrain the Cosmological Parameters
Describing our Universe
“Lambda CDM Cosmology”

- Will the universe expand forever, or will it collapse?
- Is the universe dominated by exotic dark matter?
- What is the shape of the universe?
- How and when did the first galaxies form?
- Is the expansion of the universe accelerating rather than decelerating?
Science Objectives

0. Constrain the Cosmological Parameters Describing our Universe “Lambda CDM Cosmology”

What are the parameters the CMB constrains?

Atoms (Baryons)  
Dark Matter  
Dark Energy  

Hubble Constant  
Reionization Redshift  
Spectral Tilt

Credit: NASA WMAP
Hubble Constant: The current expansion rate of your universe, in km/sec per megaparsec. It is a measure of how fast an object is moving away from us based upon its distance from the Earth today.

Age: 6.9 billion years
Flatness: 1.7

https://wmap.gsfc.nasa.gov/resources/camb_tool/index.html
Atoms: The amount of ordinary matter (atoms) in your universe, as a percentage of the critical density.

Age: 0.2 billion years
Flatness: 0.2

https://wmap.gsfc.nasa.gov/resources/camb_tool/index.html
Cold Dark Matter: The amount of cold dark matter in your universe, as a percentage of the critical density. Cold dark matter cannot be seen or felt, and has not been detected in the laboratory, but it does exert a gravitational pull.

Age: 11.7 billion years

Flatness: 1.00

https://wmap.gsfc.nasa.gov/resources/camb_tool/index.html
CMB Analyzer

Answer Button:
I Give Up!

No! Don’t give up yet! Play some more...
or... if you must:
Set the model components to the WMAP values.

Age: 13.7 billion years
Flatness: 1.00

Universe Content
Atoms: 4%
Cold Dark Matter: 22%
Dark Energy: 74%

Additional Properties
Hubble Constant: 73
Reionization redshift: 11
Spectral Index: 0.95

https://wmap.gsfc.nasa.gov/resources/camb_tool/index.html
Connection to LIGO measurements!

https://wmap.gsfc.nasa.gov/resources/camb_tool/index.html
LIGO vs. CMB Measurements of the Hubble Constant, $H_0$

Figure Credit:
Science Objectives

1. detect signatures from inflationary gravitational waves in the cosmic microwave background (CMB)

probe physics of the universe fractions of a second after the big bang
Science Objectives

1. Why is the universe homogeneous? Why is the universe flat?

Inflation?!

Inflation is an exponential expansion of the universe in the first fractions of a second after the big bang.
Science Objectives

2. measure gravitational lensing of the CMB by matter in our universe

Properties of neutrinos affect the structure in our universe!

Image Credit: Stompor et al 2015  Image Credit: Planck
Understanding the Power Spectrum of the CMB

If the sky looks like this  The power spectrum looks like this:

Power spectrum slides courtesy of Phil Korngut
Understanding the Power Spectrum of the CMB

If the sky looks like this

The power spectrum looks like this:

Power spectrum slides courtesy of Phil Korngut
Understanding the Power Spectrum of the CMB

If the sky looks like this

The power spectrum looks like this:

Power spectrum slides courtesy of Phil Korngut
Understanding the Power Spectrum of the CMB

If the sky looks like this:

The power spectrum looks like this:

Power spectrum slides courtesy of Phil Korngut
The sky looks like this

And the power spectrum looks like this!

Credit: Planck, wikipedia
What do you need for a successful CMB instrument?

ability to detect the polarization of the CMB signal
CMB Polarization

Thomson scattering generates linear polarization.

Image Credit: Hu and Dodelson, 2001
The CMB polarization can be decomposed into E-modes and B-modes.

Image Credit: Seljak and Zaldarriaga
The TT and EE spectra probe acoustic oscillations in the early Universe.
The BB spectrum probes gravitational waves from inflation!

BB auto- and cross-frequency spectra between BICEP2/Keck Array (150 GHz) and Planck (217 and 353 GHz), BKP find a 95% upper limit of $r < 0.12$. (A Joint Analysis of BICEP2/Keck Array and Planck Data)
Upper Limits on the Stochastic Gravitational-Wave Background from Advanced LIGO’s First Observing Run

Figure Credit: LIGO Scientific and Virgo Collaborations, 2017
The amplitude of the gravity wave signal depends on the energy scale of inflation.

BB auto- and cross-frequency spectra between BICEP2/Keck Array (150 GHz) and Planck (217 and 353 GHz), BKP find a 95 % upper limit of $r < 0.12$. (A Joint Analysis of BICEP2/Keck Array and Planck Data)
Gravitational lensing of the CMB creates a BB signal at small angular scales
Neutrino mass affects lensing – CMB can measure $\Sigma m_\nu$
CMB Polarization B-Mode Lensing Power Spectrum and Neutrino Mass

- direct implication of massive neutrinos is a non-zero hot dark matter (HDM)
- this suppresses the power spectrum due to neutrinos free streaming below the matter-radiation equality scale

Image Credit: Abazajian et al, 2014
How do we make this measurement in practice?
South Pole Telescope
150 GHz
50 deg$^2$
Outline of a CMB map making pipeline

1. Read in raw data

2. Interpolate over short pointing glitches and timestream dropouts

3. cut on elnod response, both pixels partners being live, pointing and flagged bolometers (squid off, zero bias, etc).

4. Process data: relative calibration, polynomial subtraction

5. Time stream rms cut (removes very noisy timestreams), other cuts (glitchy timestreams.

6. Make left and right going scan maps

7. Make sum and difference maps for each observation

6. Make cuts of noisy maps

8. Coadd maps in to bundles of ~20 maps
Maps to Power Spectra

Set of South Pole Telescope Polarization maps

Cross-correlate pairs of maps

Mask bright point sources

Apodize the map edges

Described in Lueker et. al. 2009 arXiv:0912.4317

\[ \hat{D}_b^{AB} \equiv \left\langle \frac{\ell(\ell + 1)}{2\pi} \text{Re}[\hat{m}_\ell^A \hat{m}_\ell^{B*}] \right\rangle_{\ell \in b} \]
Maps to Power Spectra

Outline of a CMB power spectrum pipeline

1. Cross-correlate pairs of maps
2. Correct resulting spectra for telescope beam
3. Correct for filtering effects and mode mixing from the cut sky
4. Calculate errors
5. Check for Systematic Errors

\[ < \tilde{C}_{\ell}^{ii} > = \sum_{\ell'} M_{\ell \ell'} [W] F_{\ell'} B_{\ell'}^{2} < C_{\ell'} > \]
The Angular Power Spectrum of the Cosmic Microwave Background

Crites et al. 2015

Keisler et al. 2015
SPTpol Survey Fields

Deep Field
First year, 100 deg$^2$

Survey Field
Three years, 500 deg$^2$

Entire survey, 2500 deg$^2$

SPT-SZ

Also SPT-3G Field

Also BICEP/Keck Field

IRAS from Schlegel et al. 1998
4+ years of SPTpol data
4+ years of SPTpol data

Image Credit: Henning et al, 2017
Science from SPTpol

Hanson et al. 2013 — Detection of lensing with Hershel
Crites et al. 2015 — 100 sq deg EE
Keisler et al. 2015 — 100 sq deg lensing BB

Story et al. 2015 — 100 sq deg Lensing
Manzotti et al. 2017 —
100 sq deg delensing with SPTpol and Hershel

Henning et al. 2017— 500 sq deg EE
Sayre et al. in prep — 500 sq deg BB
What’s Next For CMB?

Variance

E-mode polarization patterns

lensing of EE to BB

$\sum m_\nu = 1.5 \text{ eV}$

Inflationary Gravitational wave oscillations

B-mode polarization patterns
What’s Next For CMB?

One big challenge: Foregrounds

we need to measure the signal at many frequencies!
What's Next For CMB?

We need to measure the signal at many frequencies!

Image Credit: Dickinson et al 2016
What's Next for CMB

Image Credit: Watts et al 2015
What’s Next For CMB?

CMB-S4 will have a profound impact on our understanding of fundamental physics!

... and more!
CMB-based Cosmological Constraints With CMB Stage 4

Credit: CMB Technology Book arxiv:1706.02464
Conclusions: Measurements of the Cosmic Microwave Background

Polarization sensitivity to probe new physics
Many, many detectors to make measurements of faint signals
Many frequencies to remove foregrounds

Science: Inflation, neutrinos, Ho, dark energy!
My Science Interests

Science

- Inflation
- Neutrinos
- Epoch of Reionization
- Star Formation
- Dark Energy

Probe

- CMB Polarization
- Ionized Carbon ([CII])
- CO lines
- Galaxy Clusters with Kinetic Sunyaev-Zeldovich Effect

Instruments

- SPTpol (polarization sensitive mm-wavelength photometers)
- CMB S4 (polarization sensitive mm-wavelength photometers)
- TIME (begin operation in ~1 yr)
- Super TIME (mm-wavelength spectrometers)

Data

- data in hand
- 5+ years
- 3-5 years
- begin operation in ~1 yr
- begin operation in ~1 yr
Thank You!

GEOGRAPHIC
SOUTH Pole

ROALD AMUNDSEN  ROBERT F. SCOTT

DECEMBER 14, 1911  JANUARY 17, 1912

“So we arrived and were able to plant our flag at the geographical South Pole.”

“The Pole. Yes, but under very different circumstances from those expected.”

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