Probing the Cosmic Frontier with the Cosmic Microwave Background: Current Status and Future Challenges

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It is an exciting time for cosmology

We now have a model that describes the evolution of our Universe from a hot and dense state.

We are able to make precise predictions and test them with powerful new experiments.

The model has some unusual features - new physics - Dark Matter, Dark Energy, and starts with a period of Inflation.
Much of the model has been determined from measurements of the Cosmic Microwave Background (CMB) radiation.

Measurements of the CMB provide a snapshot of the universe as it was 14 billion years ago.
Discovery of the Cosmic Microwave Background

“smoking gun” evidence for a Hot Big Bang

Arno Penzias & Robert Wilson in front of the 20ft Bell Labs antenna used to discover the microwave background in 1965

Received 1978 Nobel Prize

Enormous impact on Cosmology
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Uniform to a part in $10^5$
the smoothness problem -
led to Inflation theory
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Structure in the background discovered in 1992 by the COBE Satellite.

Uniform to a part in $10^5$
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Structure in background discovered in 1992

COBE Satellite

Wavelength [mm]

Intensity [MJy/sr]

FIRAS data with 400σ error bars

2.725 K Blackbody

Uniform to a part in $10^5$

do not hallucinate.

the smoothness problem -
led to Inflation theory

COBE team leaders
John Mather & George Smoot
received 2006 Nobel Prize
Early universe as an HEP lab

HyperPhysics (©C.R. Nave, 2010)
Early universe as an HEP lab

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Inflation generates
- Density (scalar) fluctuations:

\[ P_s(k) = A_s k^{(n_s - 1 + \frac{1}{2} \alpha_s \ln k)} \]

- Gravitational wave (tensor) fluctuations:

\[ P_t(k) = A_t k^{n_t} \]

\( A_s, n_s, \alpha_s, A_t, n_t \) are measurable and related to the shape of the inflaton potential

\( r = \frac{A_t}{A_s} \) determines the energy scale
Superhorizon features
Connecting the smallest and largest scales in the universe
Experiments w/ tens of detectors circa 1995-2005
Incredible progress with CMB


Line is fit to a flat $\Lambda$CDM cosmology model with just six parameters:

- Inflation (flat, $n_s$)
- Non-baryonic dark matter (3rd peak)
- Dark Energy

$\Omega_b h^2$, $\Omega_m h^2$, $A_s$, $\tau$, $n_s$, $\Omega_\Lambda$
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Push to higher resolution
ACT and SPT

6m Atacama Cosmology Telescope
http://www.physics.princeton.edu/act/

10m South Pole Telescope
http://spt.uchicago.edu

• High, dry sites for dedicated CMB observations.
• Exploiting ongoing revolution in low-noise bolometer cameras
The 10 meter South Pole Telescope

Some Key Features:
• 1 arcmin resolution at 150 GHz
• 1 deg FOV, unblocked optics
• 960 feedhorn coupled detectors
• Observe in 3+ bands 90, 150 & 220 GHz simultaneously with a modular focal plane
• Site: fantastic atmospheric transparency and stability, 24/7/52 observing
South Pole Telescope Camera developed and built at U.C. Berkeley

Brad Benson

Erik Shirokoff

Ongoing revolution of mm & submm arrays. Soon it will be possible to field tens to hundreds of thousands of detector focal plane arrays.
Sample SPT map of CMB anisotropy

1/10 of SPT survey; 150 GHz only

Keisler et al., arXiv:1105.3182
**CMB anisotropy damping tail measurements**

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\[ n_s = 0.966 \pm 0.011 \]

rejects $n_s = 1$ at $3.1\sigma$
(at $3.6 \sigma$ with Ho and BAO included)

SPT: Keisler et al., arXiv:1105.3182; for ACT results see Dunkley et al arXiv:1009.0866
Going beyond the 6 $Λ$CDM parameters: fitting an additional parameter
Improved limit to tensor perturbations

$r < 0.21$ at 95% CL
($r < 0.17$ with $H_0$ and BAO included)
Running of the spectral index?

\[ \frac{dn_s}{d\ln k} = -0.024 \pm 0.013 \]
Number of relativistic species, $N_{\text{eff}}$

$N_{\text{eff}} = 3.87 \pm 0.61$

rejects $N_{\text{eff}} = 0$ at $7.5\sigma$

($N_{\text{eff}} = 3.85 \pm 0.44$ with $H_0$ and BAO)

To understand CMB sensitivity to $N_{\text{eff}}$, see Hou et al., arXiv: 1104.2333
Additional neutrinos?

Adding cluster abundance constraint on $\sigma_8$ pushes $N_{\text{eff}}$ closer to 3

Using $\sigma_8$ constraints from local abundance of galaxy clusters (Vikhlinin et al., 2009).
Stay tuned for more results from SPT, ACT & Planck
Zoom in on an SPT map
Zoom in on an SPT map

All these “large-scale” fluctuations are primary CMB.
Zoom in on an SPT map

All these “large-scale” fluctuations are primary CMB.

Lots of bright sources: SPT discovery of a new population of distant stars forming galaxies.
Zoom in on an SPT map

All these “large-scale” fluctuations are primary CMB.

~15-sigma SZ detection of massive cluster of galaxies
(Note SZ effect independent of distance, i.e., redshift)

Lots of bright sources:
SPT discovery of a new population of distant star forming galaxies
Polarization of the CMB

The CMB must be polarized due to Thomson scattering

from W. Hu’s web page
Polarization of the CMB

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Quadrupole Anisotropy

Thomson Scattering

Linear Polarization

from W. Hu’s web page
Generating CMB polarization

Before decoupling:
- electron ‘sees’ only a local monopole

During decoupling:
- mean free path increases and electron ‘sees’ quadrupole
- scattered light is polarized

hotter due to Doppler shift
E-mode Polarization (even parity)

Polarization parallel & perpendicular to wave vector

Even parity, curl-free

Density (scalar) fluctuations generate only E-Polarization
Gravitational wave induced CMB polarization

'+' mode, \( \bar{k} \) parallel

E-mode

Figure from John Kovac’s thesis
Gravitational wave induced CMB polarization

'E-mode, $\vec{k}$ parallel

'B-mode, $\vec{k}$ not parallel

E-mode

B-mode (Inflationary GW B-modes)

Figure from John Kovac's thesis
**B-mode Polarization (odd parity)**

Polarization oriented ±45 degrees to wave vector

Odd parity, div free

Can NOT be generated by the density fluctuations, but can be generated by gravitational waves sourced by Inflation in the first instants of the universe, $10^{-35}$ seconds, at GUT energies.

“Smoking gun” test of Inflation and direct measure of its energy scale
CMB polarization

Spectra generated with WMAP7 parameters using CAMB, Lewis and Challinor

TT

density oscillations

EE
CMB polarization

- **TT**
- **EE**
- **$\text{BB}_{\text{IGW}}$**

- Density oscillations
- Inflationary Gravitational wave oscillations
CMB polarization

\[ r = 0.24, \ 3 \times 10^{16} \text{GeV} \]

\[ r = 0.01, \ 0.6 \times 10^{16} \text{GeV} \]

\[ r \] is the tensor to scalar ratio of the primordial fluctuations

\[ C_{\ell}(\ell+1)/(2\pi) \]
CMB polarization

\[ r = 0.01, 0.6 \times 10^16 \text{GeV} \]
CMB polarization

\[ \sum m_\nu = 0 \]

\[ \sum m_\nu = 1.5 \text{ eV} \]
CMB polarization

CMB measurements should be able to achieve $\sigma(\sum m_\nu) = 0.05\text{eV}$, comparable to $\Delta m$ measured by neutrino oscillations.
CMB polarization

Expected polarized foregrounds over best 75% of sky at 90 GHz
Dunkley et al., arXiv:0811.3915
CMB polarization

Expected polarized foregrounds over best 3% of southern sky. SPTpol to survey 24/7/52

\[ \sum m_\nu = 0 \]

\[ \sum m_\nu = 1.5 \text{ eV} \]
Closing in on inflation

BICEP’s upper limit on B-mode level sets \( r < 0.7 \)

From 2 years w/ 50 pixels

100 nK

\( r = 0.2 \)

Need more sensitivity!

Achieved with more throughput with large focal planes of background limited detectors.
Two general approaches for detectors:
- coherent, i.e., direct amplification
- incoherent, i.e., bolometers (IR)

Radiation

Absorber

Weak thermal link

cold bath

e.g., BOOMERANG, Maxima, ACBAR, QUaD, SPT, ACT, BICEP, Planck HFI, ...
Background limited performance (BLIP) from the ground, balloon and space.

e.g., COBE, WMAP, CBI, DASI, CapMap, QUIET, Planck LFI, ...
Several times quantum noise limit performance. Competitive sensitivity at low frequencies from the ground.
Coherent detectors - cooled HEMT amplifiers

State of the art MMICs (35nm gate)

NRAO (Bryerton et. al., 2009)
JPL (L. Samoska)

Once amplified and quantum noise penalty taken, signal is easily manipulated, cryogenics simple

Several times quantum limited performance achieved, competitive at $\nu \leq 90$ GHz on ground.

Technology of choice at lower frequencies.

Future CMB requires improvement in noise and scalability
Coherent detectors
- cooled HEMT amplifiers

1st step in scalability: polarimeter on a chip...

See talk on QUIET by Hogan Nguyen
Bolometers - TES sensors

Voltage biased transition edge sensor (TES).

Measure incident power (pW) by change in bias current using SQUIDS.

Multiplexed in frequency or time.
Bolometers - MKID sensors

- MKID - Microwave Kinetic Inductance Detector

Measure incident power (pW) by change resonator frequency and quality factor (Q)

Potentially simple multiplexing.
Rapid Progress in Superconducting Bolometer Detectors

State of the Art Bolometer Arrays

Slide adapted from Jamie Bock
Dual Polarization, Single Band

Advantages

- Photon-limited sensitivity
- Multiplexed readout for arrays
- Planar architecture for arrays
- No coupling optics
- Easily scaled in frequency
JPL: Planar Antenna-Coupled Polarimeters

Slide adapted from Jamie Bock
BICEP2, Keck Array, Spider focal plane: 256 planar feed pixels, 512 TES bolometers
on degree scale
CMB experiments
at the South Pole

Keck Array (soon to be 5 telescopes)
And soon on a balloon ...

“Spider”

The 1284 liter, 6-telescope flight cryostat
Berkeley: “Polarbear” Lensed coupled arrays

Slide adapted from Adrian Lee
Multichroic pixel focal planes - UC Berkeley sinuous planar antenna

Receiver *end-to-end* efficiency

4:1 Bandwidth, Symmetric beams, low cross-pol
NIST Polarimeter Arrays

- Superconducting transition-edge-sensor polarimeters (TES)
- Monolithic corrugated silicon feedhorn arrays
- For ABS (Atacama B-mode Search), ACTpol, SPTpol

See talk by Michael Niemack and more info at http://casa.colorado.edu/~henninjw/TRUCE/TRUCE.html
First Argonne Labs TES pixels (90 GHz)

See talk on Argonne efforts and SPTpol by Clarence Chang
South Pole Telescope
initial polarimeter “SPTpol”

588 pixels at 150GHz from NIST
192 pixels at 95GHz from Argonne
**last words**

Driven by advances in detectors, we expect the next ten years of CMB research to be as exciting as the last ten.

- Put $\Lambda$CDM to the test & constrain extensions
  *More surprises?*
- Tests of dark energy. Is it just $\Lambda$ or...
- Neutrino masses from CMB polarization
- Test inflation with CMB polarization