The March toward $r=0.001$
The March toward $r=0.001$

Foregrounds

Speed
(sensitivity)

Chao-Lin Kuo
Stanford/SLAC
New Horizons in Inflationary Cosmology, SITP, March 3, 2017
The March toward $r=0.001$

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Speed (sensitivity)

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Stanford/SLAC
New Horizons in Inflationary Cosmology, SITP, March 3, 2017
Outline

• Removal of Foregrounds
• Control of Systematics
• Achieving the Required Sensitivity
• When? $\sigma(r)[\text{year}]$
Outline

• Removal of Foregrounds
• Control of Systematics
• Achieving the Required Sensitivity
• When \( \sigma(r)[\text{year}] \) \( $(\text{year})$\
  
  – BICEP/Keck +SPT, Ali-CMB, LiteBIRD, CMB-S4
Outline

• Removal of Foregrounds
First and foremost:
Gravitational waves & CMB
Foregrounds

Galactic magnetic field and polarized mm emission seen by Planck
BICEP2 + Keck BB auto and cross-spectra
BICEP2 + Keck BB auto and cross-spectra
BICEP2 + Keck BB auto and cross-spectra

cross-spectrum only traces spatially correlated component of maps
Variations from Baseline Analysis

![Graphs showing variations from Baseline Analysis. The graphs represent different parameters such as $r$, $A_{\text{dust}}$, and $A_{\text{synch}}$. Each graph includes different scenarios represented by distinct lines and colors, indicating changes in parameters under various conditions.](image)
Polarized galactic synchrotron dominates at low frequencies.

Planck provides polarized maps at 7 frequencies.

Polarized thermal emission (~20K) from galactic dust aligned in magnetic fields dominates at high frequencies.

Fortunately for the future.. Although modeling of foregrounds can be complicated, their frequency dependences are distinctly different.
$T_1, \Sigma_1$

$T_2, \Sigma_2$

Tassis & Pavlidou 2015
Large-Scale Structure Lenses the CMB

- RMS deflection of ~2.5’
- Lensing efficiency peaks at $z \sim 2$
- Coherent on ~degree (~300 Mpc) scales
$Q, U$ (unlensed)

$\varphi$ (lens)

$Q, U$ (observed)
$Q, U, E$
(unlensed)

$\varphi$
(lens)

$Q, U$
(observed)

graphic from ESA website
CMB lensing

SPTpol 500d lensing potential reconstruction of BICEP field, $L < 250$ imaged with s/n $> 1$.

CMB-S4 will measure modes with s/n $> 1$ to $L \sim 1100$ over most of the sky.

*From John Carlstrom’s talk*
Outline

• Removal of Foregrounds
• Control of Systematics
Temperature & E-modes leak into B-modes

Angular scale $\theta$ [degrees]

$\ell(\ell+1)/2\pi C_\ell [\mu K^2]$

$S4$ science book
Advantages of small aperture program

- Active boresight rotation of the entire instrument
- Co-moving forebaffle, improving sidelobe rejection
- Cold, on-axis, refracting optics, providing low and stable system offsets
- Full characterization pre-deployment with modest antenna range
- Reduced experiment cost, a sharp function of the size and weight of the instrument

These are now fully recognized in the CMB-S4 community
A lesson from Planck is that preflight requirements are often too tight; knowledge requirements not enough (temporal responses, spectra, beams, ..). Eventually these parameters are obtained from the data:

- Information on far side-lobes from the Galaxy
- Main beams from planets
- Band centers & CO sensitivity from template fitting
- Time constants from planets & cosmic ray hits/modeling

If there is enough redundancy, unbiased measurements of the sky can still be made. If not, untrustworthy modes will be deprojected. We will comprehensively explore limitations of these mitigation techniques by searching for degeneracy in cosmological, foregrounds, and instrumental parameters in the data cube $TQU(\vec{r},\nu)$.

### Table 3: Deprojection Templates and Fit Coefficients

<table>
<thead>
<tr>
<th>Differential Mode</th>
<th>Symbol</th>
<th>Definition</th>
<th>Fit Coefficient</th>
<th>Template</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>$\delta g$</td>
<td>$g_A - g_B$</td>
<td>$\delta g$</td>
<td>$\tilde{T}$</td>
</tr>
<tr>
<td>Pointing, x</td>
<td>$\delta x$</td>
<td>$x_A - x_B$</td>
<td>$\delta x$</td>
<td>$\nabla_x \tilde{T}$</td>
</tr>
<tr>
<td>Pointing, y</td>
<td>$\delta y$</td>
<td>$y_A - y_B$</td>
<td>$\delta y$</td>
<td>$\nabla_y \tilde{T}$</td>
</tr>
<tr>
<td>Beamwidth</td>
<td>$\delta \sigma$</td>
<td>$\sigma_A - \sigma_B$</td>
<td>$\sigma \delta \sigma$</td>
<td>$(\nabla_x^2 + \nabla_y^2) \tilde{T}$</td>
</tr>
<tr>
<td>Ellipticity, +</td>
<td>$\delta p$</td>
<td>$p_A - p_B$</td>
<td>$(\sigma^2/2) \delta p$</td>
<td>$(\nabla_x^2 - \nabla_y^2) \tilde{T}$</td>
</tr>
<tr>
<td>Ellipticity, x</td>
<td>$\delta c$</td>
<td>$c_A - c_B$</td>
<td>$(\sigma^2/2) \delta c$</td>
<td>$2\nabla_x \nabla_y \tilde{T}$</td>
</tr>
</tbody>
</table>

BICEP/Keck instrument systematics, 2015
Planck Example:

Blue: pre-flight
Red: component separation
What does a modulator fix?
(mostly, $T\rightarrow P$ leakage)

<table>
<thead>
<tr>
<th></th>
<th>Continuously rotating HWP</th>
<th>Stepped HWP</th>
<th>No HWP</th>
</tr>
</thead>
<tbody>
<tr>
<td>True 1/f</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Main beam</td>
<td>yes</td>
<td>yes</td>
<td>deproj</td>
</tr>
<tr>
<td>Relative gain variations</td>
<td>yes</td>
<td>deproj</td>
<td>deproj</td>
</tr>
<tr>
<td>Bandpass mis.</td>
<td>yes</td>
<td>yes</td>
<td>deproj</td>
</tr>
<tr>
<td>Focal plane temp. (common mode)</td>
<td>yes</td>
<td>deproj</td>
<td>deproj</td>
</tr>
<tr>
<td>Focal plane temp. (spatial modes)</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Unpolarized atmosphere</td>
<td>yes</td>
<td>gain corr.</td>
<td>gain corr.</td>
</tr>
<tr>
<td>Polarized atmosphere</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Implementation Complexity</td>
<td>high (optical and mechanical)</td>
<td>medium (optical)</td>
<td>low</td>
</tr>
</tbody>
</table>
Outline

• Removal of Foregrounds
• Control of Systematics
• Achieving the Required Sensitivity
Sensitivity

The graph shows the approximate raw experimental sensitivity (μK) over time from 2000 to 2020. The sensitivity is measured on a logarithmic scale. Key milestones and projects include:

- **WMAP**
- **Planck**
- **CMB-S4**

The graph compares different stages:

- **Space based experiments**
- **Stage-I** = 100 detectors
- **Stage-II** = 1,000 detectors
- **Stage-III** = 10,000 detectors
- **Stage-IV** = 100,000 detectors
Transition-edge sensor bolometers

Planar antenna array

- Orthogonal slot sub-antennas
- Difference measures scalar Q or U Stokes parameter
- Sum measures intensity

Lithographic → scalable!

one pixel

8 mm fab at Caltech/JPL

- Absorbs power from one polarization
- Bolometer temperature T(P,G)
- 250 mK bath (focal plane)

TES on bolometer island

- Superconducting thermometer
- Radiation converted to heat
- Thermal isolation

- Natural Stokes polarization parametrization
- Rotate pixel to measure both Q and U

- TES transition has sharp R(T)

Titanium 500 mK transition
Dec. 2015

BICEP3
Dec. 2015

Next gen. focal Plane from ~2,500 To 40,000 sensors (each one tile ~ entire BICEP3)
Microwave SQUID readout

33-channel uMUX
20mm x 4 mm

Stanchfield et al Proc of SPIE (2016)
SLAC CMB-S4 Meeting

Slide from NIST
Outline

• Removal of Foregrounds
• Control of Systematics
• Achieving the Required Sensitivity
• When ? $\sigma(r)[\text{year}]$
Where we are

\[ r_{0.05} < 0.07 \]
<table>
<thead>
<tr>
<th>Year</th>
<th>Stage</th>
<th>Detectors</th>
<th>Sensitivity ($\mu K^2$)</th>
<th>$\sigma(r)$</th>
<th>$\sigma(\text{Neff})$</th>
<th>$\sigma(\Sigma m_\nu)$</th>
<th>Dark Energy F.O.M</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>Stage 2</td>
<td>1000 detectors</td>
<td>$\approx 10^{-5}$</td>
<td>0.035</td>
<td>0.14</td>
<td>0.15 eV</td>
<td>Boss BAO prior</td>
</tr>
<tr>
<td>2016</td>
<td>Stage 3</td>
<td>10,000 detectors</td>
<td>$10^{-6}$</td>
<td>0.006</td>
<td>0.06</td>
<td>0.06 eV</td>
<td>DES + BOSS SPT clusters</td>
</tr>
<tr>
<td>2017</td>
<td>Stage 3</td>
<td>10,000 detectors</td>
<td>$10^{-6}$</td>
<td>0.006</td>
<td>0.06</td>
<td>0.06 eV</td>
<td>DES + DESI SZ Clusters</td>
</tr>
<tr>
<td>2018</td>
<td>Stage 4</td>
<td>CMB-S4</td>
<td>$10^{-8}$</td>
<td>0.0005</td>
<td>0.027</td>
<td>0.015 eV</td>
<td>DESI BAO +T_e prior</td>
</tr>
<tr>
<td>2019</td>
<td>Stage 4</td>
<td>CMB-S4</td>
<td>$10^{-8}$</td>
<td>0.0005</td>
<td>0.027</td>
<td>0.015 eV</td>
<td>DESI + LSST S4 Clusters</td>
</tr>
<tr>
<td>2020</td>
<td>Stage 4</td>
<td>CMB-S4</td>
<td>$10^{-8}$</td>
<td>0.0005</td>
<td>0.027</td>
<td>0.015 eV</td>
<td>DESI + LSST S4 Clusters</td>
</tr>
<tr>
<td>2021</td>
<td>Stage 4</td>
<td>CMB-S4</td>
<td>$10^{-8}$</td>
<td>0.0005</td>
<td>0.027</td>
<td>0.015 eV</td>
<td>DESI + LSST S4 Clusters</td>
</tr>
<tr>
<td>2022</td>
<td>Stage 4</td>
<td>CMB-S4</td>
<td>$10^{-8}$</td>
<td>0.0005</td>
<td>0.027</td>
<td>0.015 eV</td>
<td>DESI + LSST S4 Clusters</td>
</tr>
<tr>
<td>2023</td>
<td>Stage 4</td>
<td>CMB-S4</td>
<td>$10^{-8}$</td>
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<td>0.015 eV</td>
<td>DESI + LSST S4 Clusters</td>
</tr>
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Target: 
- $10^{-8}$
- 0.0005
- 0.027
- 0.015 eV
- 1250 Clusters
BICEP program on its way to $\sigma(r) = 0.004$ (before S4 starts)
Hunting for primordial $B$-modes from the South Pole

- Ground-based telescopes at the South Pole
  - Good atmospheric conditions for microwave frequencies (dry!)
  - Continuously observe small sky patch to detect faint primordial $B$-mode
  - Focused on the 2 deg anisotropy peak of the primordial $B$-mode pattern
    - only needed small aperture telescopes! Until now.. Lensing is becoming a factor
Why go to the South Pole or High Plateaus?

- Good microwave transmittance!
  - A cold desert: lowest precipitable water vapor
- Ground based program can observe in 30-300 GHz window

- NOAA weather balloon data for 2010-12 winters at 57 deg obs elevation
Complementary strengths of ground and space

- Ground: Resolution required for CMB lensing (+de-lensing!), damping tail, clusters....
- Space: All sky for reionization peak; high frequencies for dust.
- Combined data will provide best constraints.
LiteBIRD is a proposed JAXA/NASA mission dedicated to search/measure inflationary B-modes.

Top level science requirement:
\[ \delta r = 0.001 \] including systematic & foreground uncertainties

US selection: March 2017
Japan selection: mid 2018
Launch date is 2025
High Frequency Camera
will be developed at Stanford
Challenges that have already been overcome
THANK YOU

We have already come very far
We’re deeply in there