Probing Physics with CMB polarization

(Focusing on primordial gravity waves, new light particle species, and neutrino mass)

<p>| | | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$r$</td>
<td>$N_{\text{eff}}$</td>
<td>$\text{Sum}(m_\nu)$</td>
</tr>
<tr>
<td>LCDM value</td>
<td>0</td>
<td>3.046</td>
</tr>
</tbody>
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John Ruhl
Case Western Reserve University
(For the CMB-S4 and SPT Collaborations)
The South Pole Telescope Collaboration

- 2007: SPT-SZ
  - 960 detectors
  - 95,150,220 GHz

- 2012: SPTpol
  - 1600 detectors
  - 95,150 GHz
  + Polarization

- 2017: SPT-3G
  - 16,000 detectors
  - 95,150, 220 GHz
  + Polarization

funding:
~150 CMB scientists, from all current US (and some non-US) CMB experiments.

Meeting twice yearly for the past ~3 years; more info in a science book, a technology book, and a “Concept Definition Team” report all available at

http://cmb-s4.org
Planck Satellite - all sky CMB temperature anisotropy map
Planck
143 GHz
50 deg²
SPTpol
150 GHz
50 deg$^2$
at 7x finer angular resolution and
7x deeper
Constraints on cosmological parameters

Enormous precision and accuracy:
- Flat universe ($\Omega_k < 0.005$)
- $\Omega_b h^2 = 0.02222 \pm 0.00023$
- $\Omega_c h^2 = 0.1197 \pm 0.0022$
- (>50σ detection of non-baryonic dark matter)

Peaks => curvature, baryon and DM densities, and more.

TT-only parameters:
- Damping tail =>
- \(\sum(m_\nu) < 0.7\text{eV}\), \(N_{\text{eff}} \approx 3.6 \pm 0.5\),
- Low ell => \(r < 0.1\)

The future: polarization and lensing
“CMB lensing” : CMB photon paths diverted by large scale structure

Average ~2 arcminute deflections, coherent over ~degree scales on the sky, dominated by structure at z~2-3.

Carries information about structure growth.
Lensing of the CMB

17°x17°

from Alex van Engelen
Lensing of the CMB

17° x 17°

from Alex van Engelen
Planck Collaboration: Gravitational lensing by large-scale structures with Planck Collaboration XI

small portion of the sky. The lensing convergence example to cross-correlate with an additional mass tracer over a very red power spectrum, with most of its power on large angular scales. The construction has considerable additional power due to noise. As can be seen in Fig. 3, the reconstruction and input are clearly correlated, although the reconstruction has considerable additional power due to noise. As we shall discuss in Sect. 3.4, the temperature-lensing cross-correlation shows that this is correlated with the lensing potential power spectrum in our fiducial model, given by 1.0134. We have not applied any scaling to the fiducial model power spectra and simulations.

In this section, we provide a summary of the first science results from the Planck mission. We refer the reader to the Planck Collaboration XI for a review. We apply, discussed in Appendix A, a model and fiducial model power spectra and simulations. We use the associated likelihood alone, and present in Sect. 3.5 a set. In addition to rescaling the FFP8 maps as already discussed, we have also adjusted the power spectra of the fiducial model by 1.0134. We have not applied any scaling to the fiducial model power spectra and simulations.

Finally, the power spectrum of the lensing potential is presented in Sect. 3.6. We estimate it using a map constructed from the Planck Collaboration XI, to constrain cosmological parameters in Sect. 4.5. As a visual illustration of the signal-to-noise level in the lensing estimate, given by 1.0134, we plot the Wiener-filtered minimum-variance lensing reconstruction. The raw lensing potential estimate has a factor of 1.0134. We have not applied any scaling to the fiducial model power spectra and simulations.

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The odd-parity modes measured by Planck are used as a basis for a Monte Carlo simulation through reionization. The raw lensing potential estimate has a factor of 1.0134. We have not applied any scaling to the fiducial model power spectra and simulations.
CMB lensing with SPT

SPT-SZ + Planck lensing map in SPT 2500 deg$^2$

More sensitive lensing in SPTpol 100d and 500d regions (Story et al, 2015; Mocanu et al. 2017)

SPT-3G will be deeper still

No great impact on parameters yet... but CMB-S4 -> 40% of the sky, very deep => strong limits joint with LSS/BAO (DESI), on neutrino mass from effects on structure growth.
CMB Polarization Signals

Curl-free -> caused by density perturbations
CMB Polarization Signals

Curl-free -> caused by density perturbations

Lensing

Curl pattern (still only from density)
CMB Polarization Signals

Curl-free \(\rightarrow\) caused by density perturbations

Primordial Curl (Gravitational waves)

Lensing

Curl pattern (still only from density)

Primordial GW signals

\[ D_\ell \propto (\text{uK}^2) \]

\[ r = 0.1, r = 0.01, r = 0.001 \]
Current state of CMB anisotropy measurements

Angular scale $\theta$ [degrees]

Temperature

E modes

Lensing B modes

CMB-S4 science book

CMB-S4 Forecast
Planck 2015
ACTPol
Polarbear
SPT(TT) / SPTpol
Current state of CMB anisotropy measurements

CMB only:
- $\text{Sum}(m_\nu) < 0.5\text{eV}$
- $N_{\text{eff}} \approx 3.0 \pm 0.3$
- $r < 0.09$

Add BAO:
- $\text{Sum}(m_\nu) < 0.2\text{eV}$

Planck 2015
Planck 2015 + BKP
CMB-S4 Goal #1 - Search for primordial gravitational waves via their “B-mode” polarization signature

Challenges:
- Sensitivity,
- Galactic foregrounds,
- Lensing B-modes

CMB-S4 Survey:
- ~3-8% of sky
- 0.5m telescopes +
- 5m telescope for delensing
- ~1uK-arcmin depth

Figure from J. Carlstrom/T. Crawford.
Sensitivity =>

Increase detector count by a factor of \( \approx 10 \) over current instruments.

<table>
<thead>
<tr>
<th>Source: CDT Report (2017)</th>
<th>Band center in GHz</th>
<th>N_det total</th>
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<tbody>
<tr>
<td></td>
<td>20  30  40  85  95  145  155  220  270</td>
<td></td>
</tr>
<tr>
<td><strong>5m telescopes (2-3)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam fwhm</td>
<td>arcmin</td>
<td>11   7  5.2  -  2.2  1.4  -  1  0.8</td>
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<tr>
<td>Number of detectors</td>
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<td>420  890 1,600 75,000 75,000 25,700 25,700</td>
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<tr>
<td><strong>0.5m telescopes (~14)</strong></td>
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<td></td>
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<tr>
<td>Beam fwhm</td>
<td>arcmin</td>
<td>-  77  58  27  24  16  15  11  8.5</td>
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<tr>
<td>Number of detectors</td>
<td></td>
<td>260  470 17,000 21,000 18,000 21,000 34,000 54,000</td>
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\( \approx 370,000 \) detectors
Observing bands from 20GHz to 270GHz, to subtract out Galactic Dust and Synchrotron emission by a factor of ~10.

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<td>-</td>
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<td>1.4</td>
<td>-</td>
<td>1</td>
<td>0.8</td>
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<td>890</td>
<td>1,600</td>
<td>75,000</td>
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<td>25,700</td>
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<td>54,000</td>
<td>165,730</td>
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<td>11</td>
<td>8.5</td>
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The B-mode foreground problem

The challenge is to use maps with auto-spectra below to tell the difference between...

\[ r = 0.000 \]
The B-mode foreground problem

and...

\[ r = 0.001 \]
$N_{\text{eff}}$ and light thermal relics

Sets natural, and exceedingly challenging, target of $\Delta N_{\text{eff}} = 0.027$ for a relic scalar, 0.054 for a vector.

Green, Meyers in CMB-S4 Science Book (http://CMB-S4.org)  
also see Baumann, Green, Wallisch “A New Target for Cosmic Axion Searches” arXiv:1604.08614
Goal #2 - Search for new “light” particle species

(via effect on early expansion rate)

\[
\rho_r = T_\gamma^4 (1 + z)^4 \left[ 1 + N_{\text{eff}} \left( \frac{7}{8} \right) \left( \frac{4}{11} \right)^{4/3} \right] \left( \frac{\pi^2}{15} \right)
\]
$N_{\text{eff}}$ and CMB damping

fixing $\Omega_b h^2$, $z_{\text{EQ}}$, $\theta_s$

$\ell^2 D_\ell \left[ 10^8 \mu K^2 \right]$

Planck 2015

SPT-SZ
Helium fraction & $N_{\text{eff}}$ degeneracy

Also keep $\theta_d$ constant with $N_{\text{eff}}$ by varying the helium fraction, $Y_P$

$N_{\text{eff}} = 3.15 \pm 0.23$ (along BBN consistency curve)

$N_{\text{eff}} = 3.14 \pm 0.44$ (marginalizing over $Y_P$)

$\Rightarrow$ Highly significant detection of neutrino background!
CMB-S4 promises much tighter bounds on Neff, whether marginalizing over Yp or not.

Survey: ~40% of sky with small beams (~5m telescopes), to ~1uK-arcmin depth
Great prospects for probing physics...

### From CMB-S4 Science Book Figure 3

<table>
<thead>
<tr>
<th>Year</th>
<th>Stage</th>
<th>Detectors</th>
<th>$r$</th>
<th>$N_{\text{eff}}$</th>
<th>$\Sigma m_\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>Stage 2</td>
<td>~1000</td>
<td>0.035</td>
<td>3.046</td>
<td>$&gt; 59$ meV</td>
</tr>
<tr>
<td>2016</td>
<td>Stage 3</td>
<td>~10,000</td>
<td>0.006</td>
<td>0.14</td>
<td>$0.15$ eV</td>
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<tr>
<td>2017</td>
<td>Stage 4</td>
<td>CMB-S4</td>
<td>~500,000</td>
<td>0.0005</td>
<td>0.027</td>
</tr>
</tbody>
</table>

- $\sigma(r)$
- $\sigma(N_{\text{eff}})$
- $\sigma(\Sigma m_\nu)$

Boss BAO prior

- DESI BAO + $\tau_e$ prior

LCDM value: $0.3046 > 59$ meV

- $\Sigma m_\nu$: sum of neutrino masses.
Thank you!