Planck, BICEP, and the Early Universe

Raphael Flauger

KICP Colloquium, Chicago, December 2, 2015
measurement of excess antenna temperature and
interpretation in terms of CMB published in July 1965
Rocket Measurement of the Cosmic-Background-Radiation mm-Wave Spectrum

H. P. Gush, M. Halpern, and E. H. Wishnow
Department of Physics, University of British Columbia, Vancouver, Canada V6T 2A6
(Received 10 May 1990)

A PRELIMINARY MEASUREMENT OF THE COSMIC MICROWAVE BACKGROUND SPECTRUM BY THE COSMIC BACKGROUND EXPLORER (COBE) SATELLITE


Received 1990 January 16; accepted 1990 February 19
CMB@50

Dipole

Velocity of the Earth with Respect to the Cosmic Background Radiation

E. K. Conklin

Radio Astronomy Institute,
Stanford University,
Stanford, California.

Received March 17, 1969.

Isotropy of the 3 K Background

\[ 3.2 \pm 0.8 \text{ mK} \]

Joseph Henry Laboratories,
Department of Physics,
Princeton University,
Princeton, New Jersey 08540

Received May 17, 1971.

(Planck 2015: 3.3645 \pm 0.0020 \text{ mK})
Planck & WMAP

- Planck and WMAP temperature data agree very well at WMAP resolution.

(N_{side}=512)
Planck & WMAP

Planck 100 GHz
- WMAP 94 GHz =
Planck & WMAP

The small but visible difference is due to a CO emission line

Planck 100 GHz
- WMAP 94 GHz =

vs Planck CO(1 − 0) map
Planck & WMAP

• Planck and WMAP temperature data agrees very well at WMAP resolution

• Planck is much more powerful

WMAP 94 GHz

Planck 100 GHz

(N_{\text{side}}=1024)
Planck & WMAP

- Planck and WMAP temperature data agrees very well at WMAP resolution
- Planck is much more powerful
The early universe is remarkably simple and the CMB temperature data is in good agreement with the six-parameter LCDM model.

\[ \begin{array}{ll}
\hline
\text{Parameter} & \text{Planck TT+lowP} \\
\hline
\Omega_b h^2 & 0.02222 \pm 0.00023 \\
\Omega_c h^2 & 0.1197 \pm 0.0022 \\
100\theta_{MC} & 1.04085 \pm 0.00047 \\
\tau & 0.078 \pm 0.019 \\
\ln(10^{10} A_s) & 3.089 \pm 0.036 \\
n_s & 0.9655 \pm 0.0062 \\
H_0 & 67.31 \pm 0.96 \\
\Omega_m & 0.315 \pm 0.013 \\
\sigma_8 & 0.829 \pm 0.014 \\
10^9 A_s e^{-2\tau} & 1.880 \pm 0.014 \\
\hline
\end{array} \]

* the sum of the neutrino masses is kept fixed at 0.06 eV

(Ade et al. 2015)
LCDM+X

(Ade et al. 2015)
In the context of LCDM, we can predict the TE and EE angular power spectra and compare with the Planck measurements (systematics remain to be understood) (Ade et al. 2015)
In addition, LCDM is consistent with all low redshift large-scale structure* and supernova data

(Anderson et al. 2013)  
(Betoule et al. 2014)

* on small scales baryonic feedback should be understood better to assess whether there are departures from LCDM
Parameter Constraints

Parameter constraints from TT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2013N(DS)</th>
<th>2015F(CHM)</th>
<th>2015F(CHM) (Pl_k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$100\theta_{MC}$</td>
<td>1.04131 ± 0.00063</td>
<td>1.04094 ± 0.00048</td>
<td>1.04086 ± 0.00048</td>
</tr>
<tr>
<td>$\Omega_b h^2$</td>
<td>0.02205 ± 0.00028</td>
<td>0.02225 ± 0.00023</td>
<td>0.02222 ± 0.00023</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>0.1199 ± 0.0027</td>
<td>0.1194 ± 0.0022</td>
<td>0.1199 ± 0.0022</td>
</tr>
<tr>
<td>$H_0$</td>
<td>67.3 ± 1.2</td>
<td>67.48 ± 0.98</td>
<td>67.26 ± 0.98</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.9603 ± 0.0073</td>
<td>0.9682 ± 0.0062</td>
<td>0.9652 ± 0.0062</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>0.315 ± 0.017</td>
<td>0.313 ± 0.013</td>
<td>0.316 ± 0.014</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>0.829 ± 0.012</td>
<td>0.829 ± 0.015</td>
<td>0.830 ± 0.015</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.089 ± 0.013</td>
<td>0.079 ± 0.019</td>
<td>0.078 ± 0.019</td>
</tr>
<tr>
<td>$10^9A_s e^{-2\tau}$</td>
<td>1.836 ± 0.013</td>
<td>1.875 ± 0.014</td>
<td>1.881 ± 0.014</td>
</tr>
</tbody>
</table>

- Good consistency between 2013 and 2015 parameters
Parameter Constraints

Parameter constraints from TT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2013N(DS)</th>
<th>2015F(CHM)</th>
<th>2015F(CHM) (Plik)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$100\theta_{MC}$</td>
<td>$1.04131 \pm 0.00063$</td>
<td>$1.04094 \pm 0.00048$</td>
<td>$1.04086 \pm 0.00048$</td>
</tr>
<tr>
<td>$\Omega_b h^2$</td>
<td>$0.02205 \pm 0.00028$</td>
<td>$0.02225 \pm 0.00023$</td>
<td>$0.02222 \pm 0.00023$</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>$0.1199 \pm 0.0027$</td>
<td>$0.1194 \pm 0.0022$</td>
<td>$0.1199 \pm 0.0022$</td>
</tr>
<tr>
<td>$H_0$</td>
<td>$67.3 \pm 1.2$</td>
<td>$67.48 \pm 0.98$</td>
<td>$67.26 \pm 0.98$</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.9603 \pm 0.0073$</td>
<td>$0.9682 \pm 0.0062$</td>
<td>$0.9652 \pm 0.0062$</td>
</tr>
<tr>
<td>$\Omega_{m}$</td>
<td>$0.315 \pm 0.017$</td>
<td>$0.313 \pm 0.013$</td>
<td>$0.316 \pm 0.014$</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>$0.829 \pm 0.012$</td>
<td>$0.829 \pm 0.015$</td>
<td>$0.830 \pm 0.015$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$0.089 \pm 0.013$</td>
<td>$0.079 \pm 0.019$</td>
<td>$0.078 \pm 0.019$</td>
</tr>
<tr>
<td>$10^9A_{s} e^{-2\tau}$</td>
<td>$1.836 \pm 0.013$</td>
<td>$1.875 \pm 0.014$</td>
<td>$1.881 \pm 0.014$</td>
</tr>
</tbody>
</table>

- The optical depth is one exception. It has shifted due to dust polarization data at 353 GHz.
Parameter Constraints

Shift in optical depth for WMAP due to 353 GHz data

- Low-\(\ell\) polarization data
  - Ka, Q, V cleaned with K-band and WMAP dust model, then coadded

- High-\(\ell\) temperature data
  - hybrid-cleaned cross-halfmission spectra

• Most parameters are degenerate with \(\tau\).
  The old measurement of optical depth would have led to \(\sim 0.5 \sigma\) shifts in parameters.
LFI and WMAP polarization currently do not agree on large scales.
Parameter Constraints

Parameter constraints from TT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2013N(DS)</th>
<th>2015F(CHM)</th>
<th>2015F(CHM) (Plik)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$100\theta_{MC}$</td>
<td>1.04131 ± 0.00063</td>
<td>1.04094 ± 0.00048</td>
<td>1.04086 ± 0.00048</td>
</tr>
<tr>
<td>$\Omega_b h^2$</td>
<td>0.02205 ± 0.00028</td>
<td>0.02225 ± 0.00023</td>
<td>0.02222 ± 0.00023</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>0.1199 ± 0.0027</td>
<td>0.1194 ± 0.0022</td>
<td>0.1199 ± 0.0022</td>
</tr>
<tr>
<td>$H_0$</td>
<td>67.3 ± 1.2</td>
<td>67.48 ± 0.98</td>
<td>67.26 ± 0.98</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.9603 ± 0.0073</td>
<td>0.9682 ± 0.0062</td>
<td>0.9652 ± 0.0062</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>0.315 ± 0.017</td>
<td>0.313 ± 0.013</td>
<td>0.316 ± 0.014</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>0.829 ± 0.012</td>
<td>0.829 ± 0.015</td>
<td>0.830 ± 0.015</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.089 ± 0.013</td>
<td>0.079 ± 0.019</td>
<td>0.078 ± 0.019</td>
</tr>
<tr>
<td>$10^9 A_s e^{-2\tau}$</td>
<td>1.836 ± 0.013</td>
<td>1.875 ± 0.014</td>
<td>1.881 ± 0.014</td>
</tr>
</tbody>
</table>

- The scalar spectral index has shifted between 2013 and 2015
- much of the shift in the spectral index between 2013 and 2015 can be traced to systematics in 2013 217 GHz detector set spectra.
Parameter Constraints

Parameter constraints from TT

217x217 predicted from 100x100, 143x143, and 143x217

\[ \ell^2 (\ell+1)^2 C_{\ell}/2\pi [\mu K^2] \]
Analysis

Fig. 7.— Constraints on key parameters in the $\Lambda$CDM model and extensions in the presence of high-frequency foreground cleanings.

- Left panel: The top middle and bottom panels show the marginalized one-dimensional likelihoods for the scalar spectral index $n_s$, the matter density $\Omega_m$, and the Hubble constant $H_0$ in the $\Lambda$CDM models. The solid blue line is the standard Planck result for the CAMSpec likelihood including the $vuu \times vyx$, $vyx \times wv7$, and $vyx \times wv7$ spectra. The dashed blue line shows the results when the $wv7 \times wv7$ spectra are not used; these correspond to results presented in Figure B of mPlanck Collaboration mXVIn wuvxns. The solid and dashed black lines show the same for the cleaned spectra presented here.

- Right panel: Constraints on the tensor-to-scalar ratio ($r$) and the mass of the neutrino ($\nu$) are weakened with cleaning of the spectra. The cleaned spectra do not show a preference for running of the scalar spectral index $\dot{n}_s$ computed from the cleaned season crosses, the power spectrum amplitude is higher for $\dot{n}_s > 1500$. This increased amplitude leads to a shift in cosmological parameters. The most notable shifts are along a modest degeneracy line between $n_s$, $H_0$, and $\Omega_m$:

  \[
  \begin{align*}
  &n_s: 0.285, 0.295, 0.305, 0.315 \\
  &\Omega_m: 0.957, 0.960, 0.963, 0.966, 0.969, 0.972, 0.975 \\
  &H_0: 65, 66, 67, 68, 69, 70
  \end{align*}
  \]

Fig. 8.— Constraints in the $\Omega_m - n_s$ plane (left) and $H_0 - \Omega_m$ plane (right) for various cleaning strategies and datasets compared to the Planck results. The circles show results obtained with the nominal Planck data, the squares show results from the hybrid cleaning procedure, the diamond are obtained when only cleaning with the $xyx$ GHz data, and the triangle when using the $zzy$ GHz data to clean the lower frequencies. For comparison, the results are shown for the season spectra without additional cleaning (upside down triangle). The cosmological results are robust to a change in the cleaning procedures.
Fig. 7.— Constraints on key parameters in the $\Lambda$CDM model and extensions in the presence of high-frequency foreground cleanings.

Left panel: The top, middle, and bottom panels show the marginalized one-dimensional likelihoods for the scalar spectral index $n_s$, the matter density $\Omega_m$, and the Hubble constant $H_0$ in the $\Lambda$CDM models. The solid blue line is the standard Planck result for the CAMSpec likelihood including the $v_{uu} \times v_{uu}$$v_{yx} \times v_{yx}$$w_{v7} \times w_{v7}$ spectra. The dashed blue line shows the results when the $w_{v7} \times w_{v7}$ spectra are not used; these correspond to results presented in Figure B3 of Planck Collaboration XVIII. The solid and dashed black lines show the same for the cleaned spectra presented here.

Right panel: Constraints on the tensor-to-scalar ratio in the top left panel and mass of the neutrino in the top right panel are weakened with cleaning of the spectra. The bottom right panel shows the mass of the neutrino. The cleaned spectra do not show a preference for running of the scalar spectral index.

The power spectrum amplitude is higher for $\Omega_m > 1500$. This increased amplitude leads to a shift in cosmological parameters. The most notable shifts are along a modest degeneracy line between $n_s$, $H_0$, and $\Omega_m$:

- $n_s$: 0.285 to 0.295
- $\Omega_m$: 0.957 to 0.975
- $H_0$: 65 to 70

Fig. 8.— Constraints in the $\Omega_m - n_s$ plane (left) and $H_0 - \Omega_m$ plane (right) for various cleaning strategies and datasets compared to the Planck results. The circles show results obtained with the nominal Planck data, the squares show results from the hybrid cleaning procedure, the diamonds are obtained when only cleaning with the $<\omegaGHz$ data, and the triangle when using the $>\omegaGHz$ data to clean the lower frequencies. For comparison, the results are shown for the season spectra without additional cleaning (upside-down triangle). The cosmological results are robust to a change in the cleaning procedures.
Parameter Constraints

Parameter constraints from TT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2015F(CHM)</th>
<th>2015F(CHM) (Plk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$100\theta_{MC}$</td>
<td>$1.04094 \pm 0.00048$</td>
<td>$1.04086 \pm 0.00048$</td>
</tr>
<tr>
<td>$\Omega_b h^2$</td>
<td>$0.02225 \pm 0.00023$</td>
<td>$0.02222 \pm 0.00023$</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>$0.1194 \pm 0.0022$</td>
<td>$0.1199 \pm 0.0022$</td>
</tr>
<tr>
<td>$H_0$</td>
<td>$67.48 \pm 0.98$</td>
<td>$67.26 \pm 0.98$</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.9682 \pm 0.0062$</td>
<td>$0.9652 \pm 0.0062$</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>$0.313 \pm 0.013$</td>
<td>$0.316 \pm 0.014$</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>$0.829 \pm 0.015$</td>
<td>$0.830 \pm 0.015$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$0.079 \pm 0.019$</td>
<td>$0.078 \pm 0.019$</td>
</tr>
<tr>
<td>$10^9A_s e^{-2\tau}$</td>
<td>$1.875 \pm 0.014$</td>
<td>$1.881 \pm 0.014$</td>
</tr>
</tbody>
</table>

- CAMspec and Plik disagree on spectral index by $\sim 0.5 \sigma$. 
Parameter Constraints

Parameter constraints from TT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2015F(CHM) (P1ik)</th>
<th>2015F(CHM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{143}^{tSZ}$</td>
<td>$5.2 \pm 1.9$</td>
<td>$3.2^{+1.4}_{-2.6}$ ($-1.0\sigma$)</td>
</tr>
<tr>
<td>$A_{217}^{CIB}$</td>
<td>$63.9 \pm 6.6$</td>
<td>$46 \pm 7$ ($-2.7\sigma$)</td>
</tr>
<tr>
<td>$A_{kSZ}$</td>
<td>$&lt; 4.46$</td>
<td>$5.2^{+3.6}_{-2.5}$ ($+0.7\sigma$)</td>
</tr>
<tr>
<td>$c_{100}$</td>
<td>$0.99788 \pm 0.00078$</td>
<td>$0.99678 \pm 0.00097$ ($-1.4\sigma$)</td>
</tr>
<tr>
<td>$c_{217}$</td>
<td>$0.9959 \pm 0.0015$</td>
<td>$0.9972 \pm 0.0018$ ($+0.9\sigma$)</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.9655 \pm 0.0062$</td>
<td>$0.9682 \pm 0.0062$ ($+0.4\sigma$)</td>
</tr>
<tr>
<td>$Y_P$</td>
<td>$0.24532 \pm 0.00010$</td>
<td>$0.244922 \pm 0.000099$ ($-3.9\sigma$)</td>
</tr>
</tbody>
</table>

- also disagreement on calibration and foreground parameters
- CAMspec tSZ and CIB(+PS) amplitude in good agreement with ACT/SPT
Parameter Constraints

Parameter constraints from TE, EE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Planck TT+lowP</th>
<th>Planck TE+lowP</th>
<th>Planck EE+lowP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>0.02222 ± 0.00023</td>
<td>0.02228 ± 0.00025</td>
<td>0.0240 ± 0.0013</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>0.1197 ± 0.0022</td>
<td>0.1187 ± 0.0021</td>
<td>0.1150±^{0.0048}_{-0.0055}</td>
</tr>
<tr>
<td>100$\theta_{MC}$</td>
<td>1.04085 ± 0.00047</td>
<td>1.04094 ± 0.00051</td>
<td>1.03988 ± 0.00094</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.078 ± 0.019</td>
<td>0.053 ± 0.019</td>
<td>0.059±^{0.022}_{-0.019}</td>
</tr>
<tr>
<td>$\ln(10^{10}A_s)$</td>
<td>3.089 ± 0.036</td>
<td>3.031 ± 0.041</td>
<td>3.066±^{0.046}_{-0.041}</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.9655 ± 0.0062</td>
<td>0.965 ± 0.012</td>
<td>0.973 ± 0.016</td>
</tr>
<tr>
<td>$H_0$</td>
<td>67.31 ± 0.96</td>
<td>67.73 ± 0.92</td>
<td>70.2 ± 3.0</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>0.315 ± 0.013</td>
<td>0.300 ± 0.012</td>
<td>0.286±^{0.027}_{-0.038}</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>0.829 ± 0.014</td>
<td>0.802 ± 0.018</td>
<td>0.796 ± 0.024</td>
</tr>
<tr>
<td>$10^9A_s e^{-2\tau}$</td>
<td>1.880 ± 0.014</td>
<td>1.865 ± 0.019</td>
<td>1.907 ± 0.027</td>
</tr>
</tbody>
</table>

- The polarization data is still preliminary but leads to cosmological parameters consistent with those from TT
Parameter Constraints

Parameter constraints from TE, EE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Planck TT+lowP</th>
<th>Planck TE+lowP</th>
<th>Planck EE+lowP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>$0.02222 \pm 0.00023$</td>
<td>$0.02228 \pm 0.00025$</td>
<td>$0.0240 \pm 0.0013$</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>$0.1197 \pm 0.0022$</td>
<td>$0.1187 \pm 0.0021$</td>
<td>$0.1150^{+0.0048}_{-0.0055}$</td>
</tr>
<tr>
<td>$100 \theta_{MC}$</td>
<td>$1.04085 \pm 0.00047$</td>
<td>$1.04094 \pm 0.00051$</td>
<td>$1.03988 \pm 0.00094$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$0.078 \pm 0.019$</td>
<td>$0.053 \pm 0.019$</td>
<td>$0.059^{+0.022}_{-0.019}$</td>
</tr>
<tr>
<td>$\ln(10^{10} A_s)$</td>
<td>$3.089 \pm 0.036$</td>
<td>$3.031 \pm 0.041$</td>
<td>$3.066^{+0.046}_{-0.041}$</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.9655 \pm 0.0062$</td>
<td>$0.965 \pm 0.012$</td>
<td>$0.973 \pm 0.016$</td>
</tr>
<tr>
<td>$H_0$</td>
<td>$67.31 \pm 0.96$</td>
<td>$67.73 \pm 0.92$</td>
<td>$70.2 \pm 3.0$</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>$0.315 \pm 0.013$</td>
<td>$0.300 \pm 0.012$</td>
<td>$0.286^{+0.027}_{-0.038}$</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>$0.829 \pm 0.014$</td>
<td>$0.802 \pm 0.018$</td>
<td>$0.796 \pm 0.024$</td>
</tr>
<tr>
<td>$10^9 A_s e^{-2\tau}$</td>
<td>$1.880 \pm 0.014$</td>
<td>$1.865 \pm 0.019$</td>
<td>$1.907 \pm 0.027$</td>
</tr>
</tbody>
</table>

- Although consistent with TT, the polarization data favors lower matter density $\Omega_m$ and $\sigma_8$. 
Clustering

\[ \frac{P}{P_{\text{max}}} \]

(tSZ power spectrum (Hill, Spergel 2013)

Planck 2015 TT+lowP
Paper XIII

\[ \sigma_8 \left( \frac{\Omega_m}{0.282} \right)^{0.26} \]

• similar tensions exist between the Planck TT data and a number of other low redshift observations
Clustering

- A milder tension also exists between Planck lensing and cosmology predicted by Planck TT.
Clustering

Planck 2015 TT+lowP
Planck 2015 lensing
Planck 2015 TE+lowEB
Planck 2015 EE+lowEB

\[ \sigma_8 \left( \frac{\Omega_m}{0.3} \right)^{0.25} \]

\[ \frac{P}{P_{\text{max}}} \]

• however, both Planck TE and Planck EE cosmologies in excellent agreement with Planck lensing
Parameter Constraints

Parameter constraints from TT marginalized over $A_L$ and TE

- The TT power spectrum data favors $\sim 2\sigma$ higher $A_L$ than expected theoretically or observed in lensing power spectrum.
Parameter Constraints

Parameter constraints from TT marginalized over $A_L$ and TE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Planck TT + lowP − $A_L$</th>
<th>Planck TE + lowEB</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>0.02262 ± 0.00029</td>
<td>0.02233 ± 0.00025</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>0.1166 ± 0.0025</td>
<td>0.1169 ± 0.0021</td>
</tr>
<tr>
<td>$100\theta_{MC}$</td>
<td>1.04137 ± 0.00053</td>
<td>1.04126 ± 0.00050</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.059 ± 0.021</td>
<td>0.055 ± 0.020</td>
</tr>
<tr>
<td>$\ln(10^{10}A_s)$</td>
<td>3.046 ± 0.041</td>
<td>3.026 ± 0.044</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.9740 ± 0.0073</td>
<td>0.975 ± 0.011</td>
</tr>
<tr>
<td>$H_0$</td>
<td>68.9 ± 1.2</td>
<td>68.55 ± 0.93</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>0.295 ± 0.015</td>
<td>0.298 ± 0.012</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>0.802 ± 0.018</td>
<td>0.797 ± 0.019</td>
</tr>
<tr>
<td>$10^9 A_s e^{-2\tau}$</td>
<td>1.868 ± 0.015</td>
<td>1.849 ± 0.027</td>
</tr>
<tr>
<td>$A_L$</td>
<td>1.224 ± 0.096</td>
<td>1.111 ± 0.011</td>
</tr>
</tbody>
</table>

- Marginalization over $A_L$ leads to higher value of Hubble parameter, lower value of matter density $\Omega_m$ and $\sigma_8$, and better agreement with polarization.
The Hubble Constant

Reid et al. 2013

Riess et al. 2011

Efstathiou 2013

Hinshaw et al. 2013

Ade et al. 2015

Spergel, Flauger, Hlozek 2013

\[ H_0/(\text{km/s/Mpc}) \]

- UGC 3789
- NGC 4258
- LMC
- MW
- NGC 4258
- LMC
- MW
- WMAP+ACT
  - Planck TT
  - Planck TE
  - Planck TT - \( A_L \)
  - Planck
Measurements of the CMB have taught us that the primordial perturbations

- existed before the hot big bang
- are nearly scale invariant
- are very close to Gaussian
- are adiabatic

What generated them?
Assuming inflation took place, what can we learn about it beyond $n_s$ and $\Delta R^2$?

- What is the energy scale of inflation?
- How far did the field travel?
- Are there additional light degrees of freedom?
- What is the propagation speed of the inflaton quanta?
Energy Scale of Inflation

In addition to the scalar modes, inflation also predicts a nearly scale invariant spectrum of gravitational waves

$$\Delta_{h}^{2}(k) = \frac{2H^{2}(t_{k})}{\pi^{2}}$$

A measurement of the tensor contribution would provide a direct measurement of the expansion rate of the universe during inflation, as well as the energy scale

$$V_{\text{inf}}^{1/4} = 1.06 \times 10^{16} \text{ GeV} \left( \frac{r}{0.01} \right)^{1/4}$$

with

$$r = \frac{\Delta_{h}^{2}}{\Delta_{R}^{2}}$$
• For $r > 0.01$ the inflaton must have moved over a super-Planckian distance in field space. (Lyth 1996)

• Motion of the scalar field over super-Planckian distances is hard to control in an effective field theory

$$V(\phi) = V_0 + \frac{1}{2} m^2 \phi^2 + \frac{1}{3} \mu \phi^3 +$$

$$+ \frac{1}{4} \lambda \phi^4 + \phi^4 \sum_{n=1}^{\infty} c_n (\phi / \Lambda)^n$$

$$\Lambda < M_p$$
Field Range

Possible Solution:

Use a field with a shift symmetry and break the shift symmetry in a controlled way.

e.g. Linde’s chaotic inflation with

\[ V(\phi) = \frac{1}{2} m^2 \phi^2 \quad \text{with} \quad m \ll M_p \]

natural inflation

Freese, Frieman, Olinto, PRL 65 (1990)

\[ V(\phi) = \Lambda^4 \left[ 1 + \cos \left( \frac{\phi}{f} \right) \right] \quad \text{with} \quad f \gtrsim M_p \]
Field Range

In field theory we may simply postulate such a symmetry, but it is far from obvious that such shift symmetries exist in a theory of quantum gravity.

In fact, the most naive implementation of an axion with $f \gtrsim M_p$ seems hard to realize string theory.

Banks, Dine, Fox, Gorbatov hep-th/0303252
Arkani-Hamed, Motl, Nicolis, Vafa hep-th/0601001

more recently
Rudelius 1503.00795
Brown, Cotrell, Shiu, Soler 1503.04783, 1504.00659
Heidenreich, Reece, Rudelius 1506.03447, 1509.06374
Bachlechner, Long, McAllister 1412.1093, 1503.07853

This motivates a systematic study of large field models of inflation in quantum gravity/string theory
Axion Monodromy Inflation

So far there is no systematic study, but a number of lamp posts

One mechanism that allows super-Planckian excursions with sub-Planckian $f$ is monodromy
Axion Monodromy Inflation

Monodromy occurs in various contexts

• in non-Abelian gauge theories
• in string theory
  • in the presence of branes
  • in the presence of fluxes
Axion Monodromy Inflation

Comic version of axion monodromy inflation
The original axion monodromy model is just one example of a larger class of models with potentials

\[ V(\phi) = \mu^{4-p} \phi^p \]

so far with \( p = \frac{2}{3}, 1, \frac{4}{3}, 2, 3 \)
Axion Monodromy Inflation

These models often make additional predictions

![Diagram showing NS5 and anti-NS5 branes](image)

Instanton corrections may lead to oscillatory contributions to the potential.

\[ V(\phi) = \mu^3 \phi + \Lambda^4 \cos \left( \frac{\phi}{f} \right) \]

These lead to oscillations in the power spectrum that can be searched for.
Axion Monodromy Inflation

In the larger class of models they are of the form

\[ V(\phi) = \mu^{4-p} \phi^p + \Lambda(\phi)^4 \cos \left( \frac{\phi_0}{f_0} \left( \frac{\phi}{\phi_0} \right)^{1+p_f} + \Delta \phi \right) \]

This can be shown to lead to a power spectrum of the form

\[ \Delta^2_R(k) = \Delta^2_R \left( \frac{k}{k_*} \right)^{n_s-1} \left( 1 + \delta n_s \cos \left[ \frac{\phi_0}{f} \left( \frac{\phi}{\phi_0} \right)^{p_f+1} + \Delta \phi \right] \right) \]

\[ \delta n_s = 3b \left( \frac{2\pi}{\alpha} \right)^{1/2} \quad \text{with} \quad \alpha = (1+p_f) \frac{\phi_0}{2fN_0} \left( \frac{\sqrt{2pN_0}}{\phi_0} \right)^{1+p_f} \]
Axion Monodromy Inflation

Search for oscillations with drifting period in Planck nominal mission data and full mission data
Axion Monodromy Inflation

Improvement of the fit over $\Lambda$CDM: $\Delta \chi^2 = 18$

Expectation based on simulations in the absence of a signal: $\Delta \chi^2 = 16.5 \pm 3.5$

One should keep in mind that not the entire parameter space was searched and more work is required, but as of now there is no evidence for oscillations in the primordial power spectrum.

The amplitude is very model dependent, and a non-detection does not rule out these models, but it means for now* we are stuck with $n_s$ and $r$.

(*) LSS may some day dramatically improve the constraints
Experimental Constraints on $r$

BICEP2 polarization data

Noise level: 87 nK deg - the deepest map at 150 GHz of this patch of sky
(Planck noise level: few $\mu$K deg)
Experimental Constraints on $r$

Foreground models made in collaboration with David Spergel, Colin Hill, and Aurelien Fraisse
Experimental Constraints on $r$

- measurement of BB in the BICEP2 region at 353 GHz rescaled to 150 GHz

$$D_{\ell}^{BB} = 1.32 \times 10^{-2} \mu K_{\text{CMB}}^2$$
Experimental Constraints on $r$

$$V_{\inf}^{1/4} < 1.7 \times 10^{16} \, GeV$$
Experimental Progress on $r$

With the current data, we can constrain $r$ with

- the tensor contribution to the temperature anisotropies on large angular scales
- the B-mode polarization generated by tensors.

The two likelihood are essentially independent

$$L(r_{TT}, r_{BB}) = L_{TT}(r_{TT}) L_{BB}(r_{BB})$$

Typically we talk about $L(r, r)$
Experimental Progress on $r$

$L(r_{TT}, r_{BB})$ before March

Constraint dominated by temperature data
Experimental Progress on $r$

$L(r_{TT}, r_{BB})$ after BICEP2

![Graph showing experimental progress on $r$ for Planck+BICEP1 and Planck+BICEP2]
Experimental Progress on $r$

$L(r_{TT}, r_{BB})$ after BICEP2

Constraint from polarization data comparable to constraint from temperature and will soon be significantly stronger.
Experimental Progress on ongoing and upcoming:

Ground: BICEP2, Keck Array, BICEP3, SPTPol/SPT3G, ACTPol/AdvACT, ABS, CLASS, POLARBEAR/Simons Array, C-BASS, QUIJOTE, B-Machine,...

Balloon: EBEX, SPIDER, PIPER

future (>5 years)

Ground: CMB Stage IV

Satellite: LiteBIRD, PIXIE,...
Experimental Progress on $r$

- Preliminary
- E-modes
- Lensing B-modes
- Residual lensing B-modes

- Cleanest 30% at 150 GHz
- Cleanest 1% at 150 GHz
- $r=0.01$
- $r=0.001$
Forecasting exactly how well it can do is difficult given our current level of understanding of foregrounds.

Models for polarized foreground need three ingredients, typically

- Intensity map
- Polarization fraction
- Polarization angles

Planck helps on large scales at frequencies 150 GHz and up.
\[ N_{\text{eff}} \]

\[
\sigma_{\text{CMBS4}}(N_{\text{eff}}) \approx 0.02
\]

Brust, Kaplan, Walters 1303.5079
Conclusions

- The LCDM model with inflationary spectrum of perturbations is consistent with all current cosmological data.
- The CMB will continue to provide valuable information about primordial gravitational waves, neutrino masses, the number of effective relativistic degrees of freedom, dark matter, ...
- Large scale structure surveys will provide a useful counter part
- The next decade should be very interesting in cosmology
Thank you