The oldest light
Planck

J.L. Puget
Institut d’Astrophysique Spatiale
ESTEC Feb 2018
large scale structure, CMB anisotropies and acoustic peaks

- Zeldovich, Kurt and Sunyaev 1968 ZhETF
- Sunyaev and Zeldovich, 1970 ApSS 7,20
  1987, MNRAS 226,655

COBE background radiation and LSS in the universe
• M3 call (1993)
• 2 proposals to detect the acoustic peaks
  – Reno Mandolesi COBRAS: HEMT based not cooled
  – JLP SAMBA: Dilution cooler (A Benoit) Bolometers cooled at 100 mk Caltech
  – H Sorption cooler (JPL) + 4K cooler (UK)
  – merged into CBRAS-SAMBA → Planck mission
Planck cryogenic system

Dilution cooler in space (Alain Benoit)
Sorption Cooler
Bolometers 0.1K (A. Lange, N.Coron)
HEMT at 100 GHz
HFI cut-away

filters @ 1.6K

Bolometers @ 100mK

F. R. Bouchet: "The Planck High Frequency Instrument Sky"

PLANCK conference 2011, January 10th, Paris
The 2018 HFI maps

- freq
- 100
- 143
- 217
- 353
- 545
- 857
- POLARBEAR & ACTPol are direct BB
- SPT & “preliminary” ACTPol are indirect lensing BB

Planck (2013)
ACTPol (2014, ~650 hours)
SPTPol (2013/14)
BICEP2 (2014)
PBear (2014)

$l(\ell+1)C_{\ell}/2\pi$ vs. Multipole $\ell$
The 2013 data had strong noise/syste excesses at low $\ell$ in Polarization

- noise limited sensitivity of Planck channels maps limited at 100, 143 and 217 GHz
- Gaussian 1/f noise mostly associated with glitches tails not removed
- strong low $\ell$ excess due to leakages T into E and B
- the problem was more severe in relative terms for HFI than for LFI
Synchrotron polarization map

- Derived from the LFI data
Magnetic field lines derived from interstellar dust polarization

J.L. Puget, IAS, Orsay
ESTEC 8/02/2018
• CMB alone cannot measure accurately the parameters without the assumption of flat space
• having enough sensitivity to measure CMB lensing gives a constraint on the late evolution
• adding BAO removes completely the need for the flat space prior
stacking of Planck polarization on T peaks and troughs
Polarization

- use of TT or add TE gives models differing by $< 0.5 \sigma$
- need either WMAP or Planck low ell EE or prior

- use of EE and their low ell part only is an almost independent model
- differences associated
  - with $\tau$
  - with recalibration of spectra
$T(\hat{n}) \ (\pm 350 \mu K)$

$E(\hat{n}) \ (\pm 25 \mu K)$

$B(\hat{n}) \ (\pm 2.5 \mu K)$
Stacking the Planck mass maps at the positions of peaks and troughs of Cosmic Infrared Background leads to a strong detection of the mass associated with these distant star forming galaxies. This is mostly Dark Matter,
### Temperature vs Polarization

- **Temperature vs Polarization**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>[1] Planck TT+lowP</th>
<th>[4] Planck TT,TE,EE+lowP</th>
<th>([1] − [4])/σ_{[1]}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ω_bh^2</td>
<td>0.02222 ± 0.00023</td>
<td>0.02225 ± 0.00016</td>
<td>−0.1</td>
</tr>
<tr>
<td>Ω_c h^2</td>
<td>0.1197 ± 0.0022</td>
<td>0.1198 ± 0.0015</td>
<td>0.0</td>
</tr>
<tr>
<td>100θ_{MC}</td>
<td>1.04085 ± 0.00047</td>
<td>1.04077 ± 0.00032</td>
<td>0.2</td>
</tr>
<tr>
<td>τ</td>
<td>0.078 ± 0.019</td>
<td>0.079 ± 0.017</td>
<td>−0.1</td>
</tr>
<tr>
<td>ln(10^{10}A_s)</td>
<td>3.089 ± 0.036</td>
<td>3.094 ± 0.034</td>
<td>−0.1</td>
</tr>
<tr>
<td>n_s</td>
<td>0.9655 ± 0.0062</td>
<td>0.9645 ± 0.0049</td>
<td>0.2</td>
</tr>
<tr>
<td>H_0</td>
<td>67.31 ± 0.96</td>
<td>67.27 ± 0.66</td>
<td>0.0</td>
</tr>
<tr>
<td>Ω_m</td>
<td>0.315 ± 0.013</td>
<td>0.3156 ± 0.0091</td>
<td>0.0</td>
</tr>
<tr>
<td>σ_8</td>
<td>0.829 ± 0.014</td>
<td>0.831 ± 0.013</td>
<td>0.0</td>
</tr>
<tr>
<td>10^9 A_s e^{-2τ}</td>
<td>1.880 ± 0.014</td>
<td>1.882 ± 0.012</td>
<td>−0.1</td>
</tr>
</tbody>
</table>

- note the degeneracy $A_s$ – ♦: $10^9 A_s e^{-2τ}$ is very well measured
- lensing can break the degeneracy
- best way is to use large angular scales E modes
lensing power spectrum

$[L(L+1)^2C_{L}^{\phi\phi}]/2\pi \times 10^7$

amplitude constrained to 2.5%

40 detection of lensing
Wiener filtered lensing potential
Astrophysical cosmology measurements vs Planck best model

- **BAO**
  - Baryonic acoustic oscillations are geometric measurements in the line-of-sight and in the transverse direction.

\[
H_0 = (67.3 \pm 1.0) \text{ km s}^{-1}\text{Mpc}^{-1} \quad \text{Planck TT+lowP.}
\]

\[
\Omega_m = 0.315 \pm 0.013
\]

\[
H_0 = (67.6 \pm 0.6) \text{ km s}^{-1}\text{Mpc}^{-1} \quad \text{Planck TT+lowP+BAO.}
\]

\[
\Omega_m = 0.310 \pm 0.008
\]

- from Planck TT: 67.3 ±1 Km/s/Mpc
- adding BAO: 67.6 ±0.6
- revision by Efstathiou 2014 of Reiss 2011 with revised maser for NGC4258: 73.8 → 70.6
- the tension with Freedman 2012(74.3) and Bennet 2014 (73.0) remains and even increases with the full mission data
Primordial universe

- testing the predictions of the quantum origin of fluctuations
- $\Omega_k = -0.052 \pm 0.05$ TT Planck alone,
- $\Omega_k = -0.0008 \pm 0.004$ (combining Planck and external data) space is flat
- $n_s = 0.9645 \pm 0.0049$ deviation from scale invariance 7.2
Inflation related parameters

• Planck alone $r_{0.002} < 0.11$
• Bicep2-Keck-Planck (95%)
• illustration of sensitivity to extension $\nabla\text{N}_{\text{eff}} = 0.39$
Reionization parameter $\tau$ from CMB (historical)

- **WMAP**
  - Spergel et al., 2006: $\tau = 0.099 \pm 0.030$
  - Hinshaw et al., 2013: $\tau = 0.089 \pm 0.014$

- **Planck 2015**
  - Planck Coll. XVI, 2014: $\tau = 0.089 \pm 0.012$
  - Planck Coll. XIII, 2015: $\tau = 0.067 \pm 0.022$

- **Planck pre-2018**
  - Planck Coll., pre-2016: $\tau = 0.053 \pm 0.012$
  - Planck lowEH (EE HFI 100x143) PCL: $\tau = 0.055 \pm 0.008$
  - Planck lowEH (EE HFI 100x143) QML: $\tau = 0.055 \pm 0.010$
models of reionization

- CMB polarised EE
- high redshift sources
- HI 21cm
- other lines...

combined to constrain the first sources history
models of reionisation based on the high redshift sources observations with the new Planck constraints

Robertson et al 2015
BB power spectrum level

BICEP2 field

galactic magnetic field traced by the polarized dust emission

galactic coordinates

North
galactic poles

South
BICEP2 field: estimate of the dust contribution

\[
\frac{D_{BB}}{\mu K^2} \quad \text{vs. Multipole } t
\]

\[
\sigma_{\text{stat}} \quad \sigma_{\text{stat+extr}} \quad \Lambda CDM \text{ tensor } r = 0.2
\]
Improving Planck HFI 353 GHz

- The Planck 353 GHz is the best all sky dust foreground tracer today
- we improve it by correcting systematic effects at very low ell
- for B-modes detection: limitation introduced the dust correction using 353 GHz assumed to be white noise limited