Cosmology with the Cosmic Microwave Background

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Planck Project Scientist
European Space Agency
1. The Cosmic Microwave Background
2. Current state of CMB cosmology
3. Future directions

Most of this talk is based on the Planck Legacy paper (Planck Coll I 2018) downloadable from

http://www.cosmos.esa.int/web/planck/publications
Physics at the time of recombination

At the largest angular scales, the spectrum of primordial fluctuations is preserved.

Reionisation increases the optical depth.

Acoustic oscillations in the last scattering layer.

Photon diffusion damps the signal amplitudes at small angular scales.
The angular power spectrum of the temperature and polarisation anisotropies can be used to extract the value of fundamental cosmological parameters.
The shape of the power spectrum depends sensitively on the value of cosmological parameters.

Hu 2002

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Theoretical angular power spectrum of the polarised CMB

\[
\frac{\Delta T}{T} = \sum_{l,m} a_l^m Y_l^m(\theta, \varphi)
\]

\[
C_l = \langle |a_l^m|^2 \rangle
\]

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Penzias & Wilson

COBE

WMAP

Planck

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The temperature fluctuations of the CMB

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-300 300 µK
1. General assumptions: GR, homogeneity, isotropy, ...
2. Close-to-zero curvature and simple topology
3. Contents of the Universe
   a. photons
   b. Baryons
   c. Dark matter
   d. Dark energy that behaves like a cosmological constant
   e. Sub-dominant levels of relativistic particles (low-mass neutrinos)
4. Initial density variations are gaussian, adiabatic, nearly-scale-invariant (inflation)
Variations in density were laid down everywhere at early times. The curvature of space is very small.

More details can be found in limits for some 1-parameter extensions to the CDM model. The third set below the double line gives 95% confidence limits on a number of derived parameters (as obtained from standard BBN); the amplitude, $n_s$, of a power-law spectrum of adiabatic perturbations; the optical depth to Thomson scattering from reionization, $\tau$; and the geometric mean of the Hubble scale and the mean free path, so $\Omega_b h^2 \lesssim 10^{3}$, as required by the calculation, are slight changes to the primordial signal due to the anisotropy spectra, without the low-$\ell$ plateaux and with sharper peaks.

The neutrinos are extremely light: 0.00063 eV. Other parameters can be read out. For example, since $\Omega_b h^2 = 0.02237 \pm 0.00015$, $\Omega_m h^2 = 0.1200 \pm 0.0012$, and $100\theta = 1.0492 \pm 0.0003$, the Hubble parameter becomes $H_0 = 67.36 \pm 0.54$ km s$^{-1}$ Mpc$^{-1}$.

For textbook treatments, and for historical discussions, the base parameters can be found in the aforementioned textbooks or in Tables 6 and 7. Further details can be found in the Planck Collaboration: The cosmological legacy of Planck.
Age of the Universe: 13.8 Gyr
Hubble constant: 67.4 km s\(^{-1}\)/Mpc
Reionization redshift: \(z_{\text{re}} \sim 7.7\)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Planck alone</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Omega_b h^2)</td>
<td>0.02237 ± 0.00015</td>
</tr>
<tr>
<td>(\Omega_c h^2)</td>
<td>0.1200 ± 0.0012</td>
</tr>
<tr>
<td>100(\theta_{MC})</td>
<td>1.04092 ± 0.00031</td>
</tr>
<tr>
<td>(\tau)</td>
<td>0.0544 ± 0.0073</td>
</tr>
<tr>
<td>(\ln(10^{10}A_s))</td>
<td>3.044 ± 0.014</td>
</tr>
<tr>
<td>(n_s)</td>
<td>0.9649 ± 0.0042</td>
</tr>
</tbody>
</table>

- Percent accuracies except for \(\tau\)
- Consistency between temperature and polarization
- Consistency with other tracers of cosmology
Extensions to $\Lambda$CDM allow to

- Test assumptions
- Constrain theoretical parameters, e.g. set upper limits

<table>
<thead>
<tr>
<th>Parameter</th>
<th>95% CL for Planck</th>
<th>95% CL for CMB</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_K$</td>
<td>$-0.0096 \pm 0.0061$</td>
<td>$0.0007 \pm 0.0019$</td>
</tr>
<tr>
<td>$\Sigma m_\nu$ [eV]</td>
<td>$&lt; 0.241$</td>
<td>$&lt; 0.120$</td>
</tr>
<tr>
<td>$N_{\text{eff}}$</td>
<td>$2.89^{+0.36}_{-0.38}$</td>
<td>$2.99^{+0.34}_{-0.33}$</td>
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<tr>
<td>$r_{0.002}$</td>
<td>$&lt; 0.101$</td>
<td>$&lt; 0.106$</td>
</tr>
</tbody>
</table>

$$f_{\text{NL}} = 2.5 \pm 5.7$$

Extensions to $\Lambda$CDM allow to

- Departures from flatness
- Neutrino masses
- Number of relativistic species
- Spatial non-gaussianity
- Tensor modes (primordial gravitational waves)
- Deviations from scalar invariance
- Dark energy equation of state
- Deviations from isotropy
- Strange topologies
- Non-adiabaticity
- ...

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<table>
<thead>
<tr>
<th>Prediction</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>A spatially flat universe with a <em>nearly</em> scale-invariant (red) spectrum</td>
<td>$\Omega_K = 0.0007 \pm 0.0019$</td>
</tr>
<tr>
<td>of density perturbations, which is almost a power law, dominated by scalar</td>
<td>$n_s = 0.967 \pm 0.004$</td>
</tr>
<tr>
<td>perturbations, which are Gaussian and adiabatic, with negligible topological</td>
<td>$dn/d \ln k = -0.0042 \pm 0.0067$</td>
</tr>
<tr>
<td>defects</td>
<td>$r_{0.002} &lt; 0.07$</td>
</tr>
<tr>
<td></td>
<td>$f_{\text{NL}} = 2.5 \pm 5.7$</td>
</tr>
<tr>
<td></td>
<td>$\alpha_{-1} = 0.00013 \pm 0.00037$</td>
</tr>
<tr>
<td></td>
<td>$f &lt; 0.01$</td>
</tr>
</tbody>
</table>
The linear matter power spectrum ($z \approx 0$) from different probes spanning 14Gyr in time and >3 decades in scale.
Concordance cosmology

**Lower Left Panel:**
- BBN (Big Bang Nucleosynthesis)
- Standard BBN
- Aver et al. (2015)
- (Adelberger et al. 2011)
- Cooke et al. (2018)

**Upper Right Panel:**
- BAO (Baryon Acoustic Oscillations)
- SDSS MGS
- WiggleZ
- DES ($D_M$)
- BOSS DR12
- SDSS quasars
- DR14 LRG
- BOSS Ly-α ($D_M$)

**Lower Right Panel:**
- RSD (Redshift Space Distortions)
- SDSS MGS
- SDSS LRG
- FastSound
- GAMA
- VIPERS
- DR14 quasars

**Upper Panel:**
- Lensing
- DES lensing
- Planck lensing
- (DES+Planck) lensing
- Planck TT, TE, EE+lowE

**Lower Panel:**
- $\Omega_m$
- $\sigma_8$

**Footnote:**
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The Hubble constant

$H_0 [\text{km s}^{-1} \text{Mpc}^{-1}]$

Riess et al. (2018)

$\Omega_m$

$\text{BAO+Pantheon+D/H BBN}$
$\text{BAO+Pantheon+D/H BBN+lensing}$
$\text{BAO+Pantheon+D/H BBN+}\theta_{MC}$
$\text{Planck TT,TE,EE+lowE}$
CMB measurements state of the art
Cosmological parameters over time

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"Moore’s Law" of CMB sensitivity

Year

Approximate raw experimental noise (µK)

from 2013 Snowmass documents

10^{-4}

10^{-3}

10^{-2}

10^{-1}

Space based experiments
Stage-I – ≈ 100 detectors
Stage-II – ≈ 1,000 detectors
Stage-III – ≈ 10,000 detectors
Stage-IV – ≈ 100,000 detectors

But need more than detectors…

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What next?

- CMB anisotropies + lensing
  - Primordial grav waves
  - Neutrino parameters
  - Cluster science
  - ...

- CMB spectrum
  - Distortion signals
  - Recombination- and reionization-era lines
  - ...

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Potential future satellites

Litebird

CORE

Pixie

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Sub-orbital

2.5m POLARBEAR
Huan Tran Telescope
bolo.berkeley.edu/polarbear

6m Atacama Cosmology Telescope
physics.princeton.edu/act/

10m South Pole Telescope
pole.uchicago.edu

BICEP3 and KECK at South pole
bicepkeck.org

CLASS telescope #1
http://sites.krieger.jhu.edu/class/

Exceptional high and dry sites for dedicated CMB observations.
Exploiting and driving ongoing revolution in low-noise bolometer cameras

Small aperture (big beam) CMB telescopes
BICEP3 and KECK at South pole
bicepkeck.org

CLASS telescope #1
http://sites.krieger.jhu.edu/class/

The OLIMPO experiment is a first attempt at spectroscopic measurements of CMB anisotropy.
A large balloon-borne telescope (2.6m aperture) with a 4-bands photometric array and a plug-in room temperature spectrometer
PI Silvia Masi (Sapienza). See http://olimpo.roma1.infn.it for a collaborators list and full details on the mission

Main scientific targets:
– SZ effect in clusters
– Unbiased estimates of cluster parameters
– Spectrum of CMB anisotropy
– Anisotropic spectral distortions

Disadvantages:
• Stringent limits on mass, power
• Complexity of automation
• Insane integration schedule
• Narrow, and scarce, flight windows
• Risky recovery

NASA/JPL detector modules
Ground-based forecasts

<table>
<thead>
<tr>
<th>Year</th>
<th>Stage</th>
<th>Detectors</th>
<th>Sensitivity ($\mu$K$^2$)</th>
<th>$\sigma(r)$</th>
<th>$\sigma(\text{N}_{\text{eff}})$</th>
<th>$\sigma(\Sigma \nu_m)$</th>
<th>Dark Energy F.O.M</th>
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<tbody>
<tr>
<td>2015</td>
<td>Stage 2</td>
<td>1000</td>
<td>$\approx 10^{-5}$</td>
<td>0.035</td>
<td>0.14</td>
<td>0.15eV</td>
<td>DES+BOSS prior</td>
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<tr>
<td>2016</td>
<td>Stage 2</td>
<td>1000</td>
<td>$10^{-5}$</td>
<td>0.035</td>
<td>0.14</td>
<td>0.15eV</td>
<td>DES+BOSS prior</td>
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<tr>
<td>2017</td>
<td>Stage 3</td>
<td>10,000</td>
<td>$10^{-6}$</td>
<td>0.003</td>
<td>0.06</td>
<td>$\sim 0.06$eV</td>
<td>DES + DESI BAO prior</td>
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<tr>
<td>2018</td>
<td>Stage 3</td>
<td>10,000</td>
<td>$10^{-6}$</td>
<td>0.003</td>
<td>0.06</td>
<td>$\sim 0.06$eV</td>
<td>DES + DESI BAO prior</td>
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<tr>
<td>2027/34</td>
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<td></td>
<td>$10^{-8}$</td>
<td>0.0005</td>
<td>0.03</td>
<td>0.015eV</td>
<td>DES + LSST S4 Clusters</td>
</tr>
</tbody>
</table>

SPT clusters
DES + BOSS

DESI BAO + Te prior

DES + LSST S4 Clusters

Stage 2
Stage 3
The Cosmic Microwave Background is at the origin of the Hot Big Bang scenario.

It remains one of the major contributors to the development of a standard concordance cosmology.

It tests fundamental assumptions and provides precision measures of model parameters.
  - The challenge now is to achieve coherence between early and late Universe probes.

The CMB’s impact has grown according to the instrumental capabilities.
  - We can expect that it will continue to provide priceless cosmological information.

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Thank you