Towards fundamental physics from the cosmic microwave background

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The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.
(Part of) the Planck team
Temperature quadrupole at surface of last scattering creates polarisation...
Radial (tangential) pattern around hot (cold) spots.

Planck Collaboration (2013)
Compress the CMB map to study cosmology

Express sky as: \[ \delta T(\theta, \phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta, \phi) \]

Angular power spectrum \[ C_l = \frac{1}{2l + 1} \sum_{m} |a_{lm}|^2 \]
WMAP “first light” spectrum

power

larger scales

smaller scales
Planck 2015 Temperature
Planck 2015 EE Polarization

Credit: Planck Collaboration
Radical data compression!

50 million pixels...

2500 multipoles...

six cosmological parameters!
Planck TT + lowP cosmological parameters

~directly measured

\[ \Omega_b h^2 = 0.02222 \pm 0.00023 \]
\[ \Omega_c h^2 = 0.1197 \pm 0.0022 \]
\[ n_s = 0.9655 \pm 0.0062 \]
\[ \tau = 0.078 \pm 0.019 \]
\[ \ln(10^{10}A_s) = 3.089 \pm 0.036 \]

derived

\[ H_0 = 67.31 \pm 0.96 \text{ km/s/Mpc} \]
\[ \Omega_{\Lambda} = 0.685 \pm 0.013 \]
\[ \sigma_8 = 0.829 \pm 0.014 \]

Cosmological parameters not “directly measured”; details depend on models [“priors”]
Deflections are ~ 2 arcmin
Detected at ~40σ (nearly doubled 2013 sensitivity):
breaks parameter degeneracies from primary CMB alone; new window on growth of cosmic structure

Credit: Planck Collaboration
CMB lensing potential reconstruction

2500 sq. deg. map of gravitational lensing potential projected along the line of sight

(South Pole Telescope 150 GHz + Planck 143 GHz)

Cross-correlations with large-scale structure probes

• **Secondary CMB contributions**
  *Integrated Sachs-Wolfe effect, thermal / kinetic Sunyaev-Zel’dovich effect, lensing, cosmic infrared background….*

• **Cross-correlations** with non-CMB “tracers”
  *Galaxy surveys, clusters, weak lensing mass maps, velocity reconstructions…*

• Reveals **interplay of dark and light matter** in evolved universe
  *Intracluster gas, “missing” baryons, star formation history, halo masses…*
Cross-correlations with large-scale structure probes

Original detection of kSZ
ACT x BOSS cluster positions
(Hand et al 2012)

kSZ (4.2σ)
DES clusters x SPT-SZ
(Soergel et al 2016)

WL x CMB lensing
DESxSPT, DESxPlanck
(Kirk et al 2015)

Geometry & Topology of the Universe

- Einstein’s General Relativity explains local curvature of spacetime but doesn’t tell us global geometry and topology of Universe.

- No evidence for non-trivial geometry or topology, tight constraints on models.

Simulated Bianchi CMB contributions

Best fit Bianchi component to Planck

Planck Collaboration (2015)
How isotropic is the Universe?

- Tested full Bianchi freedom to conduct general test of isotropy.
- Highly constraining polarisation data used for the first time.
- Vectors: \( (\sigma_V/H)_0 < 4.7 \times 10^{-11} \) (95% CL)
- Tensors: Collins and Hawking (1973) \( (\sigma_T/H)_0 < 1.0 \times 10^{-6} \) (95% CL)
- Anisotropic expansion of the Universe disfavoured by 120,000:1.
Inhomogeneous nonlinear (ultra)-large scale cosmology

- Dawn of **numerical relativity in cosmology**. CMB-related examples:
  - Constraining ultra-large scale inhomogeneities with CMB quadrupole
  - Testing eternal inflation with cosmic bubble collisions imprint on the CMB

\[
\frac{\alpha}{300} = 2
\]

\[
P\left(\log_{10}(A_\phi) \mid \hat{C}_{00}^{\text{obs}}\right)
\]

**ultra large scale structure amplitude**

$H_0$: Cosmological vs distance ladder measurements

Figure: Science Magazine
Cosmic (in)consistency: real or “tension in a teapot”?

Systematics? astrophysics? (new) physics?

“No one trusts a model except the person who wrote it; everyone trusts an observation, except the person who made it”.

paraphrasing H. Shapley
**Raw data:** ~quadrillion samples over 29 months (HFI), 50 months (LFI)

**Maps:** ~50 million pixels over 9 frequencies
Emission at frequency = CMB + astrophysical sources along line of sight.

Planck observes in 9 bands over 30–850 GHz to disentangle cosmology from astrophysics.
Just beginning to characterise polarised foregrounds

Fig. 21. Synchrotron polarization amplitude map, $P = pQ^2 + U^2$, at 30 GHz, smoothed to an angular resolution of $60^0$, produced by a weighted sum of Planck and WMAP data as described in (Planck Collaboration XXV 2015). The traditional loci of radio loops I–IV are marked in black, a selection of the spurs identified by Vidal et al. (2014) in blue, the outline of the Fermi bubbles in magenta, and features discussed for the first time in (Planck Collaboration XXV 2015) in red. Our measured outline for Loop I departs substantially from the traditional small circle.

Fig. 22. All-sky view of the angle of polarization at 30 GHz, rotated by 90° to indicate the direction of the Galactic magnetic field projected on the plane of the sky. The colours represent intensity, dominated at this frequency by synchrotron emission. The "drapery" pattern was obtained by applying the line integral convolution (LIC; Cabral & Leedom 1993) using an IDL implementation provided by Diego Falceta-Goncalves (http://each.uspnet.usp.br/fgoncalves/pros/lic.pro). Where the field varies significantly along the line of sight, the orientation pattern is irregular and difficult to interpret.

Fig. 23. Dust polarization amplitude map, $P = pQ^2 + U^2$, at 353 GHz, smoothed to an angular resolution of $10^0$, produced by the di↵use component separation process described in (Planck Collaboration X 2015) using Planck and WMAP data.

Fig. 24. All-sky view of the angle of polarization at 353 GHz, rotated by 90° to indicate the direction of the Galactic magnetic field projected on the plane of the sky. The colours represent intensity, dominated at this frequency by thermal dust emission. The "drapery" pattern was obtained by applying the line integral convolution (LIC; Cabral & Leedom 1993) using an IDL implementation provided by Diego Falceta-Goncalves (http://each.uspnet.usp.br/fgoncalves/pros/lic.pro). Where the field varies significantly along the line of sight, the orientation pattern is irregular and difficult to interpret.

Polarised FG complex & filamentary

Planck Collaboration (2015), Planck intermediate results. XLIV. (2016)
Frequency dependence of Galactic foregrounds

CMB obscured by astrophysical foregrounds at all frequencies

Orders of magnitude worse for polarisation
What do we know about cosmic initial conditions?

- **Background:**
  - Spatial flatness (tested at <1% level!)

- **Perturbations:**
  - Scalar fluctuations in the CMB temperature
    - nearly but not exactly scale-invariant (>5σ!)
    - approximately Gaussian (at the 10^{-4} level!)
  - Adiabatic fluctuations
  - Superhorizon perturbations
  - Primordial tensor fluctuations (stochastic gravitational waves)
Gravitational waves also create polarisation.... lensing creates $B$-mode polarisation from $E$-mode polarisation even if no tensors.

Credit: BICEP / Keck Collaborations
Measurements of Sub-degree B-mode Polarization in the Cosmic Microwave Background from 100 Square Degrees of SPTpol Data
R. Keisler et al.

Joint Analysis of BICEP 2 / Keck Array and Planck Data
P. Ade et al.

BICEP/Keck Array 95 GHz (2015)
r<0.09 (95%)

Yuji Chinone / Josquin Errard
CMB polarisation status

PolarBear Collaboration (2017)
The challenge

Typical degree-scale brightness fluctuations (150GHz)

Ground, Telescope mount etc  3-300 K
Atmosphere  30 mK - 3 K
Galaxy  0.3-30 mK
CMB T anisotropies  30 μK
Lensing B modes (at arcmin)  300 nK
r=0.01 B-modes  30 nK
noise you want to reach  <10 nK

Adapted from C. Pryke
Polarisation is not going to be easy.

- Planck/BICEP2/Keck: polarised dust and/or synchrotron important at all Galactic latitudes (1502.00612, 1502.01588)

- Lensing additional “foreground” for tensors

Errard, Feeney (joint first authors), Peiris, Jaffe (JCAP, 2016)
Designing next generation polarisation experiments

• Degree-scale B-modes: inflation

• Arc-minute scale B-modes: gravitational lensing
  – late-time physics: sum of neutrino masses
  – geometry: break geometric degeneracy, measure curvature

• EE and TE more constraining than TT (Galli+ 1403.5271)

• Huge investment!
  AdvACTPol, BICEP3, CLASS, Simons Array, SPT-3G, EBEX10K, PIPER, SPIDER, Simons Observatory, CORe+, LiteBIRD, PIXIE, Stage IV, …
Measurements of Sub-degree B-mode Polarization in the Cosmic Microwave Background from 100 Square Degrees of SPTpol Data

R. Keisler et al.

Joint Analysis of BICEP 2 / Keck Array and Planck Data
P. Ade et al.

A Measurement of the Cosmic Microwave Background B-Mode Polarization Power Spectrum at Sub-degree Scales with POLARBEAR
The POLARBEAR Collaboration

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BICEP/Keck Array 95 GHz (2015)
r<0.09 (95%)

foregrounds cleaning
[Stompor et al (2009),
Stivoli et al (2010)
Errard et al (2011+2012)]

delensing
[Seljak & Hirata (2004),
Smith et al (2012),
Sherwin & Schmittfull (2015)]
Polarisation is not going to be easy.

- Half-sky minimum for tensors: $\ell \sim 80, 75$ GHz

Errard, Feeney (joint first authors), Peiris, Jaffe (JCAP, 2016)
Experiments

- Frequency bands, polarisation noise, beams and fsky
- Pre-2020 all crossed with Planck

Errard, Feeney (joint first authors), Peiris, Jaffe (JCAP, 2016)
Experiments (post-2020 examples)

- Frequency bands, polarisation noise, beams and fsky
- Pre-2020 all crossed with Planck

Errard, Feeney (joint first authors), Peiris, Jaffe (JCAP, 2016)
**Foregrounds: selected real experiments**

- **Pre-2020:** ground x balloon
  - cleaned B-modes noise-dominated
  - residuals important
- **Post-2020:** ground x satellite
  - cleaned B-modes lensing-dominated

Errard, Feeney (joint first authors), Peiris, Jaffe (JCAP, 2016)
• 3’ beam, $0.01 < f_{\text{sky}} < 1.0$ ($f_{\text{sky}}$ floor without delensing)
• CIB/LSS better for noisy expts; CMB delenses to zero if noiseless.

Errard, Feeney (joint first authors), Peiris, Jaffe (JCAP 2016)
Delensing: selected real experiments

Pre-2020: ground x balloon
CIB delensing

Post-2020: ground x satellite
CMB delensing

Errard, Feeney (joint first authors), Peiris, Jaffe (JCAP, 2016)
B-mode delensing demonstration

SPT-pol and Herschel 500 micron CIB map
(28% reduction; efficiency limited by noise in lensing potential map)
CMB at commercial aircraft altitudes?

- ground
- balloon
- satellite

Airlander (Hybrid Air Vehicles) (300 ft megablimp) ??

10 km flight altitude
3 week flights
2.5T payload
• half-sky, 10,000 detectors distributed equally @ [40, 94, 150, 220, 270, 350] GHz, synch+dust cleaning, no delensing
**Cosmological Highlights**

**Pre-2020:**
- **inflation:**
  - $\sigma(r=0.001) \sim 0.003$
  - $\sigma(n_t) \sim 0.2 \ (r = 0.1)$

- **neutrinos:**
  - $\sigma(M_\nu) \sim 60 \ meV$
    
    *CMBxCIB deflection estimate*

**Post-2020:**
- **inflation:**
  - $\sigma(r=0.001) \sim 2 \times 10^{-4}$
    
    *5-\sigma measurement (<80% delensing)*
  - $\sigma(n_t) \sim 0.03 \ (r = 0.1)$

- **neutrinos:**
  - $\sigma(M_\nu) \sim 30 \ meV$
    
    *(normal vs inverted hierarchies…)*
  - $\sigma(N_{\text{eff}}) \sim 0.024$
    
    *(thermal history 1 sec after Big Bang!)*

Errard, Feeney (joint first authors), Peiris, Jaffe (JCAP, 2016)
Summary

• Next generation CMB surveys: discovery potential for new physics if systematics under control

Transition between precision and accuracy
The Cosmic Microwave Background as seen by Planck and WMAP