The polarized CMB: from neutrinos to gravitational waves

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• What is the physics of the neutrino (or sub-eV) sector?
  
  *How many relativistic species are there?*
  
  *What are the masses of the neutrino particles?*

• What physics describes the initial expansion of space (~$10^{16}$ GeV)?
  
  *Did inflation happen, and what drove it?*
Neutrinos

Minimum mass sum = 0.06 eV
Inflation

Predict scalar and tensor fluctuations
Quantify gravitational wave with tensor-to-scalar ratio, $r$

$E \sim (r/0.01)^{1/4} \times 10^{16}$ GeV
Fig. 19. The temperature angular power spectrum of the primary CMB from Planck, showing a precise measurement of seven acoustic peaks, that are well fit by a simple six-parameter $\Lambda$CDM theoretical model (the model plotted is the one labelled [Planck + WP + highL] in Planck Collaboration XVI (2013)). The shaded area around the best-fit curve represents cosmic variance, including the sky cut used. The error bars on individual points also include cosmic variance. The horizontal axis is logarithmic up to $\ell = 50$, and linear beyond. The vertical scale is $D_\ell/2\pi$. The measured spectrum shown here is exactly the same as the one shown in Fig. 1 of Planck Collaboration XVI (2013), but it has been rebinned to show better the low-$\ell$ region.

Fig. 20. The temperature angular power spectrum of the CMB, estimated from the SMICA Planck map. The model plotted is the one labelled [Planck + WP + highL] in Planck Collaboration XVI (2013). The shaded area around the best-fit curve represents cosmic variance, including the sky cut used. The error bars on individual points do not include cosmic variance. The horizontal axis is logarithmic up to $\ell = 50$, and linear beyond. The vertical scale is $D_\ell/2\pi$. The binning scheme is the same as in Fig. 19.

8.1.1. Main catalogue
The Planck Catalogue of Compact Sources (PCCS, Planck Collaboration XXVIII (2013)) is a list of compact sources detected by Planck over the entire sky, and which therefore contains both Galactic and extragalactic objects. No polarization information is provided for the sources at this time. The PCCS differs from the ERCSC in its extraction philosophy: more effort has been made on the completeness of the catalogue, without reducing notably the reliability of the detected sources, whereas the ERCSC was built in the spirit of releasing a reliable catalog suitable for quick follow-up (in particular with the short-lived Herschel telescope). The greater amount of data, different selection process and the improvements in the calibration and map-making processing (references) help the PCCS to improve the performance (in depth and numbers) with respect to the previous ERCSC.

The sources were extracted from the 2013 Planck frequency maps (Sect. 6), which include data acquired over more than two sky coverages. This implies that the flux densities of most of the sources are an average of three or more different observations over a period of 15.5 months. The Mexican Hat Wavelet algorithm (López-Caniego et al. 2006) has been selected as the baseline method for the production of the PCCS. However, one additional method, MTXF (González-Nuevo et al. 2006) was implemented in order to support the validation and characterization of the PCCS.

The source selection for the PCCS is made on the basis of Signal-to-Noise Ratio (SNR). However, the properties of the background in the Planck maps vary substantially depending on frequency and part of the sky. Up to 217 GHz, the CMB is the...
Cerro Toco, Northern Chile

High and dry: 5200m, 0.49mm PWV

6m off-axis Gregorian primary 1'

Currently ACTPol:
148 GHz (plus 90 GHz to come)

Atacama Cosmology Telescope

The Atacama Cosmology Telescope: Results and Future Prospects
Blake D. & Sherwin (Miller Fellow, UC Berkeley) & ACT collaboration [+ POLARBEAR collaboration]

ACTPol Collaboration (2014):

1.) Argon National Laboratory
2.) Arizona State University
3.) Canadian Institute for Theoretical Astrophysics (CITA)
4.) Cardiff University
5.) Carnegie Mellon University
6.) Cornell University
7.) Florida State University
8.) Haverford College
9.) Johns Hopkins University
10.) Leiden University
11.) National Aeronautics and Space Administration Goddard Space Flight Center (NASA GSFC)
12.) National Institute of Standards and Technology (NIST)
13.) Pontificia Universidad Católica de Chile
14.) Princeton University
15.) Rutgers, The State University of New Jersey
16.) Stanford University
17.) Stony Brook University
18.) University of British Columbia
19.) University of California, Berkeley
20.) University of Illinois at Urbana-Champaign
21.) University of KwaZulu-Natal
22.) University of Michigan
23.) University of Oxford
24.) University of Pennsylvania
25.) University of Pittsburgh
26.) West Chester University of Pennsylvania

PI: Lyman Page, Suzanne Staggs

Stage 1: 2007-10
Stage 2: 2013-15
Stage 3: 2016-19
CMB temperature

Variance in CMB map

\[ D_\ell [\mu K^2] \]

\( \theta \) K

10

Planck

ACT

SPT

Multipole moment, \( \ell \)

0.07

0.05

0.03

0.01

0.2

0.1

0.07

0.05

0.03

0.01

0.2

0.1

0.07

0.05

0.03

0.01

0.2

0.1

0.07

0.05

0.03

0.01
How does number of neutrinos affect CMB?

Increasing number of species = more non-photon relativistic particles
Photon-baryon oscillations more damped, and acoustic peaks shifted

ACT+WMAP9: \( N_{\text{eff}} = 2.9 \pm 0.5 \) (Calabrese et al 2013)
Planck: \( N_{\text{eff}} = 3.1 \pm 0.3 \) (Planck Collab 2015)
CMB lensing potential

\[ T(n) = \tilde{T}(n + \nabla \phi) \]
How does mass of neutrinos affect CMB?

Neutrinos start relativistic, suppressing growth compared to cold dark matter.
More suppression, less lensing, if more of the dark matter density is in neutrinos.

Neutrino mass sum < 0.7 eV (Planck Collab 2015)
How does mass of neutrinos affect cosmic distances?

- Neutrinos behave like cold dark matter at late times ($z<\sim 100$).
- Angular diameter distances and $H(z)$ measure total matter

![Graph showing the effect of neutrino mass on cosmic distances]

**Fixed CDM density**

- **BAO**: measures total dark matter
- **CMB**: measures growth of structure
Comparison to lab-based measurements

Current limits < 2 eV. Katrin aims for < 0.2 eV.

- HOLMES (ECHO) (2017+)
- KATRIN (ongoing)
- MARE-2 (ongoing)
- PROJECT8 (2018+)
New information: CMB polarization
Atacama

Stage 1: 2007-10
Stage 2: 2013-15
Stage 3: 2016-19
Number of neutrino species:

Polarized peaks are more pronounced, so effects more visible.

Fig by Erminia Calabrese
Lensing turns E-modes to B-modes

Lensing from <half of two-season 2013-14 ACTPol

Also 9-sigma in correlation with infrared galaxy emission

New measurement at smaller angular scales than planck —> tighter neutrino mass limit

Variance in lensing potential

Angular scale

[Sherwin et al in prep. 2015]
How do gravitational waves affect CMB?

Limit from BICEP2/Keck $r < 0.09$ (2015)
Planck Collaboration: The Planck mission

Fig. 15. Maximum posterior amplitude polarization maps derived from the Planck observations between 30 and 353 GHz (Planck Collaboration X 2015). The left and right columns show the Stokes $Q$ and $U$ parameters, respectively. Rows show, from top to bottom: CMB; synchrotron polarization at 30 GHz; and thermal dust polarization at 353 GHz. The CMB map has been highpass-filtered with a cosine-apodized filter between $\lambda = 20$ and 40, and the Galactic plane (defined by the 17% CPM83 mask) has been replaced with a constrained Gaussian realization (Planck Collaboration IX 2015).

Fig. 16. Brightness temperature rms as a function of frequency and astrophysical component for temperature (left) and polarization (right). For temperature, each component is smoothed to an angular resolution of 1 FWHM, and the lower and upper edges of each line are defined by masks covering 81 and 93% of the sky, respectively. For polarization, the corresponding smoothing scale is 40.0, and the sky fractions are 73 and 93%.

10. Planck 2015 cosmology results

Since their discovery, anisotropies in the CMB have contributed significantly to defining our cosmological model and measuring its key parameters. The standard model of cosmology is based upon a spatially flat, expanding Universe whose dynamics are governed by General Relativity and dominated by cold dark matter and a cosmological constant ($\Lambda$). The seeds of structure have Gaussian statistics and form an almost scale-invariant spectrum of adiabatic fluctuations. The 2015 Planck data remain in excellent agreement with this paradigm, and continue to tighten the constraints on deviations and reduce the uncertainty on the key cosmological parameters.

The major methodological changes in the steps going from sky maps to cosmological parameters are discussed in Planck Collaboration XII (2015); Planck Collaboration XIII (2015). These include the use of Planck polarization data instead of WMAP, changes to the foreground masks to include more sky and dramatically reduce the number of point source "holes," minor changes to the foreground models, improve...
of adiabatic fluctuations. The 2015 Gaussian statistics and form an almost scale-invariant spectrum key parameters. The standard model of cosmology is based significantly to defining our cosmological model and measuring Since their discovery, anisotropies in the CMB have contributed

![Planck Collaboration 2015](image)

Brightness temperature rms as a function of frequency and astrophysical component for temperature

![Planck Collaboration 2015](image)

The major methodological changes in the steps going from sky maps to cosmological parameters are discussed

![Planck Collaboration 2015](image)

Planck Collaboration: The

![Planck Collaboration 2015](image)

Planck Collaboration IX

![Planck Collaboration 2015](image)

Planck Collaboration X

![Planck Collaboration 2015](image)

Planck Collaboration XI

![Planck Collaboration 2015](image)

Planck Collaboration XII

![Planck Collaboration 2015](image)

Planck Collaboration XIII

![Planck Collaboration 2015](image)

Planck Collaboration 2015
Five channels: 28, 41, 90, 150, 230 GHz
Same telescope, new detectors
Estimated noise levels after foreground removal: ~ 8 uK/arcmin
Three year survey starting 2016
AdvACT: neutrinos and inflation

Neutrino mass: error of 45/25 meV
Neutrino number: shrink error 6 times, to 0.05

Inflation: reduce error on $r$ to 0.003*

Also, complete overlap with LSST, so exciting dark energy science through correlations
What might future look like?

Ground-based suite of ‘S4’ telescopes
+ JAXA-led LiteBIRD satellite
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*How many relativistic species are there?*

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*Did inflation happen, and what drove it?*

*Improved measurements of CMB polarisation is central to both of these; AdvACT will measure half sky from Chile starting 2016.*