Testing Inflation with the CMB: Past and Future

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The *Planck* mission



PLANCK Focal Plane



The workhorse of Planck : spiderweb and polarization sensitive bolometers



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Made by JPL, Caltech Cooled to $\approx 100 \, mK$

Planck Capabilities

Channel	$N_{ m detectors}$ ^a	v _{center} ^b [GHz]	SCANNING BEAM ^C		Noised	
			FWHM [arcm]	Ellipticity	$\frac{1}{[\mu K_{RJ} s^{1/2}]}$	$[\mu K_{CMB} s^{1/2}]$
30 GHz	4	28.4	33.16	1.37	145.4	148.5
44 GHz	6	44.1	28.09	1.25	164.8	173.2
70 GHz	12	70.4	13.08	1.27	133.9	151.9
100 GHz	8	100	9.59	1.21	31.52	41.3
143 GHz	11	143	7.18	1.04	10.38	17.4
217 GHz	12	217	4.87	1.22	7.45	23.8
353 GHz	12	353	4.7	1.2	5.52	78.8
545 GHz	3	545	4.73	1.18	2.66	0.0259^{d}
857 GHz	4	857	4.51	1.38	1.33	0.0259 ^d

Table 2. Planck performance parameters determined from flight data.



30-353 GHz: 67 [aK_{cab}]: 545 and 857 GHz: surface brightness [kJy/sr]

Planck ILC map



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Theory – origin of the CMB anisotropy Sachs-Wolfe formula

$$\frac{\delta T}{T}(\hat{\mathbf{n}}) = \left[\frac{1}{4}\delta_{\gamma} + \mathbf{v}_{\gamma} \cdot \mathbf{n} + \Phi i\right]_{i}^{f} + 2\int_{i}^{f} d\eta \frac{\partial \Phi}{\partial \eta}'(\eta, \hat{\mathbf{n}}(\eta_{0} - \eta)$$

 $\Phi \equiv \text{Newtonian gravitational potential (dimensionless)}$ δ_{γ} and \mathbf{v}_{γ} describe the fractional density contrast and peculiar 3-velocity of of the photon component.



This treatment is somewhat naive because it assumes that the surface of last scatter is infinitely thin.

In reality the surface of last scatter has a width the smears the anisotropies on small scales.

Single-Field Inflation

In the beginning there was a scalar field that dominated the universe. Everything came from this scalar field and there was nothing without the scalar field. The quantum fluctuations of this field (that is, those of the vacuum) generated small fluctuations that advanced or retarded the instant of re-heating. These were the seeds of the large-scale structure.



Perturbations generated during inflation

$$\begin{split} \boxed{\begin{split} \hbar &= c = 1, M_{\rho l}^{-2} \end{split}} \qquad \delta \phi \approx H \qquad \frac{\delta \rho}{\bar{\rho}} \approx H \cdot \delta t, \quad \delta t \approx \frac{\delta \phi}{\bar{\phi}} \\ H \dot{\phi} \approx V_{,\phi}, \quad \dot{\phi} \approx V_{,\phi}/H, \quad H^2 \approx \frac{1}{M_{\rho l}^2} V, \frac{\delta \rho}{\bar{\rho}} \approx \frac{V^{3/2}[\phi(k)]}{M_{\rho l}^3 V_{,\phi}} \\ \\ \text{Scalar perturbations :} \qquad \qquad \boxed{\begin{split} \mathcal{P}_5^{1/2}(k) \approx \mathcal{O}(1) \cdot \frac{V^{3/2}[\phi(k)]}{M_{\rho l}^3 V_{,\phi}[\phi(k)]}. \end{split}}$$

Tensor perturbations :

$$\mathcal{P}_T^{1/2}(k) \approx O(1) \cdot \frac{H}{M_{pl}} \approx O(1) \cdot \frac{V^{1/2}}{M_{pl}^2}$$

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 $\phi(k) \equiv$ value of ϕ at horizon crossing of the mode k

Reconstruction of the inflationary potential : the tensors measure the height of the potential, the scalars the slope.

Planck temperature (TT) power spectrum+residuals



Fig. 1. The *Planck* 2015 temperature power spectrum. At multipoles $\ell \ge 30$ we show the maximum likelihood frequency averaged temperature spectrum computed from the P11k cross-half-mission likelihood with foreground and other nuisance parameters determined from the MCMC analysis of the base ACDM cosmology. In the multipole range $2 \le \ell \le 29$, we plot the power spectrum estimates from the Commander component-separation algorithm computed over 94% of the sky. The best-fit base ACDM theoretical spectrum fitted to the *Planck* TT+lowP likelihood is plotted in the upper panel. Residuals with respect to this model are shown in the lower panel. The error bars show $\pm 1 \sigma$ uncertainties.

Planck polarization (TE+EE) power spectra+residuals



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The six-parameter concordance model

[1] Parameter	[2] 2013N(DS)	[3] 2013F(DS)	[4] 2013F(CY)	[5] 2015F(CHM)	[6] 2015F(CHM) (Plik)	$([2]-[6])/\sigma_{[6]}$	$([5]-[6])/\sigma_{[5]}$
1000 _{MC}	1.04131 ± 0.00063	1.04126 ± 0.00047	1.04121 ± 0.00048	1.04094 ± 0.00048	1.04086 ± 0.00048	0.71	0.17
$\Omega_b h^2$	0.02205 ± 0.00028	0.02234 ± 0.00023	0.02230 ± 0.00023	0.02225 ± 0.00023	0.02222 ± 0.00023	-0.61	0.13
$\Omega_c h^2$	0.1199 ± 0.0027	0.1189 ± 0.0022	0.1188 ± 0.0022	0.1194 ± 0.0022	0.1199 ± 0.0022	0.00	-0.23
H ₀	67.3 ± 1.2	67.8 ± 1.0	67.8 ± 1.0	67.48 ± 0.98	67.26 ± 0.98	0.03	0.22
n _s	0.9603 ± 0.0073	0.9665 ± 0.0062	0.9655 ± 0.0062	0.9682 ± 0.0062	0.9652 ± 0.0062	-0.67	0.48
Ω _m	0.315 ± 0.017	0.308 ± 0.013	0.308 ± 0.013	0.313 ± 0.013	0.316 ± 0.014	-0.06	-0.23
σ_8	0.829 ± 0.012	0.831 ± 0.011	0.828 ± 0.012	0.829 ± 0.015	0.830 ± 0.015	-0.08	-0.07
τ	0.089 ± 0.013	0.096 ± 0.013	0.094 ± 0.013	0.079 ± 0.019	0.078 ± 0.019	0.85	0.05
$10^{9}A_{s}e^{-2\tau}$	1.836 ± 0.013	1.833 ± 0.011	1.831 ± 0.011	1.875 ± 0.014	1.881 ± 0.014	-3.46	-0.42

Parameterization of primordial power spectrum used here :

 $P(k) = A_S (k/k_p)^{n_S}$

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Consistency of P with T?



Fig. 6. Comparison of the base ACDM model parameter constraints from Planck temperature and polarization data.

Constraints on inflationary models





Planck Gravitational lensing spectrum



Fig. 18. Fiducial lensing power spectrum estimates based on the 100, 143, and 217 GHz frequency reconstructions, as well as the minimum-variance reconstruction that forms the basis for the *Planck* lensing like-lihood.

Planck 2013 Results. XXIV. Constraints on primordial non-Gaussianity Planck Collaboration : P. A. R. Ade, N. Aghanim, C. Armitage-Caplan, M. Arnaud, M. Ashdown, F. Atrio-Barandela, J. Aumont, C. Baccigalupi, A. J. Banday, R. B. Barreiro, J. G. Bartlett, N. Bartolo, E. Battaner, K. Benabed, A. Benoît, A. Benoit-Lévy, J.-P. Bernard, M. Bersanelli, P. Bielewicz, J. Bobin, J. J. Bock, A. Bonaldi, L. Bonavera, J. R. Bond, J. Borrill, F. R. Bouchet, M. Bridges, M. Bucher, C. Burigana, R. C. Butler, J.-F. Cardoso, A. Catalano, A. Challinor, A. Chamballu, L.-Y Chiang, H. C. Chiang, P. R. Christensen, S. Church, D. L. Clements, S. Colombi, L. P. L. Colombo, F. Couchot, A. Coulais, B. P. Crill, A. Curto, F. Cuttaia, R. D. Davies, R. J. Davis, P. de Bernardis, A. de Rosa, G. de Zotti, J. Delabrouille, J.-M. Delouis, F.-X. Désert, J. M. Diego, H. Dole, S. Donzelli, et al. (175 additional authors not shown) (Submitted on 20 Mar 2013)

The Planck nominal mission cosmic microwave background (CMB) maps yield unprecedented constraints on primordial non-Gaussianity (NG). Using three optimal bispectrum estimators, separable template-fitting (KSW), binned, and modal, we obtain consistent values for the primordial local,

equilateral, and orthogonal bispectrum amplitudes, quoting as our final result $f_{NI}^{local} = 2.7 \pm 5.8$,

 $f_{NL}^{equil} = -42 \pm 75$, and $f_{NL}^{ortho} = -25 \pm 39$ (68% CL statistical); and we find the integrated Sachs-Wolfe lensing bispectrum expected in the Λ CDM scenario. The results are based on comprehensive cross-validation of these estimators on Gaussian and non-Gaussian simulations, are stable across component separation techniques, pass an extensive suite of tests, and are confirmed by skew- C_I , wavelet bispectrum and Minkowski functional estimators. Beyond estimates of individual shape amplitudes, we present model-independent, three-dimensional reconstructions of the Planck CMB bispectrum and thus derive constraints on early-Universe scenarios that generate primordial NG, including general single-field models of inflation, excited initial states (non-Bunch-Davies vacua), and directionally-dependent vector models. We provide an initial survey of scale-dependent feature and resonance models. These results bound both general single-field and multi-field model parameter ranges, such as the speed of sound, $c_S = 0.02(95\% CL)$. The Planck data put severe pressure on ekpyrotic/cyclic scenarios. The amplitude of the four-point function in the local model $\tau_{NL} < 2800(95\% CL)$. Taken together, these constraints represent the highest precision tests to date of physical mechanisms for the origin of cosmic structure.

NEW RESULTS ON THE REIONIZATION OPTICAL DEPTH

Planck 2016. Planck constraints on reionization history (astro-ph/1605.03507) Planck 2016. Reduction of large-scale systematic effects in HFI polarization maps and estimation of the reionization optical depth (astro-ph/1605.02985)

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Reionization optical depth (au) / scalar perturbation amplitude (A_S) degeneracy

 \blacktriangleright The overall amplitude of the high- ℓ CMB anisotropies depends on the combination

 $A_S \exp[-\tau].$

Only effects at very low ℓ break this degeneracy.

The E-mode polarization is the cleanest way to break this degeneracy. The height of the reionization bump is proportional to τ (assuming τ ≤ 1.)

 Some other independent determination of A_S can likewise break this degeneracy (e.g., CMB lensing).

The Reionization Bump



It turns out that

$$P \propto (1- au) d_{lastscatter}^2 rac{\partial^2 T}{\partial x^2}$$

is small compared to

$$P \propto au d_{
m reion}^2 rac{\partial^2 T}{\partial x^2}$$

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even when au is small.

CMB polarization and the Reionization Bump



 $\tau = 0.0, 0.5, 0.10, 0.15 \text{ (bottom} \rightarrow \text{top)}$

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CMB measurements of the reionization optical depth

- ▶ WMAP first year (based on TE, because EE was not available) $\tau = 0.17 \pm 0.04$
- \blacktriangleright WMAP third year (mainly based on low- ℓ EE) au= 0.09 \pm 0.03
- WMAP nine-year (last word from WMAP) $au = 0.089 \pm 0.014$
- \blacktriangleright WMAP cleaned with Planck 353 GHz dust map $au = 0.075 \pm 0.013$
- Planck 2013 (not really an independent measurement, because Planck low-*l* polarization not available)

 $au = 0.089 \pm 0.032$ Planck TT+lensing

Planck 2015 release

 $au = 0.078 \pm 0.019$ LFI 70 GHz Polar only $au = 0.066 \pm 0.016$ (with lensing added) $au = 0.067 \pm 0.016$ PlanckTT+lensing+BAO (no P)

- ▶ Planck HFI low- ℓ polarization : $\tau = 0.053^{+0.014}_{-0.016}$ (E only) $\tau = 0.058 \pm 0.012$ (with T data included)
- \blacktriangleright The future....limited by cosmic variance ($\Delta aupprox$ 0.006, i.e., pprox 10%)

SEARCHING FOR B MODES

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E and B Mode Polarization



E mode

B mode

$$\mathbf{Y}_{\ell m,ab}^{(E)} = \sqrt{\frac{2}{(\ell-1)\ell(\ell+1)(\ell+2)}} \Big[\nabla_{a} \nabla_{b} - \frac{1}{2} \delta_{ab} \nabla^{2} \Big] Y_{\ell m}(\hat{\Omega})$$

$$\mathbf{Y}_{\ell m,ab}^{(B)} = \sqrt{\frac{2}{(\ell-1)\ell(\ell+1)(\ell+2)}} \frac{1}{2} \Big[\epsilon_{ac} \nabla_c \nabla_b + \nabla_a \epsilon_{bc} \nabla_c \Big] \mathbf{Y}_{\ell m}(\hat{\Omega})$$

Inflationary Prediction for Scalar & Tensor Anisotropies



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Breaking news 22 March 2014



ONE useful feature of a scientific theory is that it makes testable predictions. Such predictions, though, do not have to be testable straight away. Physics is replete with prophecies that could be confirmed or denied only decades later, nore the technology to examine them had aught up. The Higgs boson, for example, was 50 years in the confirming.

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BICEP2 summary plot :

"Smoking gun" of gravitational waves from inflation?



Why they said that dust cannot explain observed signal?



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Planck Collaboration: Dust polarization at high latitudes



From Planck Collaboration : Dust polarization at high latitudes (astro-ph/1409.5738) Top : polarized dust as equivalent *r*. Bottom : error in dust pol. measurement.



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r<0.12 at 95 % now from B modes



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FIG. 6. Likelihood results from a basic lensed-ACDM+r+d-ust model, fitting BB auto- and cross-spectra taken between maps at 150 GHz, 217, and 353 GHz. The 217 and 353 GHz maps come from *Planck*. The primary results (heavy black) use the 150 GHz combined maps from BICEP2/*Keck*. Alternate curves (light blue and red) show how the results vary when the BICEP2 and *Keck* Array only maps are used. In all cases a Gaussian prior is placed on the dust frequency spectrum parameter $\beta_a = 1.59 \pm 0.11$. In the right panel the two dimensional contours enclose 66% and 95% of the total likelihood.

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r<0.12 at 95 % now from B modes

COrE : Cosmic Origins Explorer A space mission for measuring microwave band polarization on the full sky





LiteBIRD Mission Summary

Lite (Light) Satellite for the Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection

- CMB B-mode satellite proposed to JAXA
 - Also to NASA for US participation
 - Both proposals passed initial selection
- Proposed launch year: JFY 2022
- Mission Requirements
 - Total uncertainty on r < 0.001*
 - Multipole coverage: $2 \le \ell \le 200$
 - Each bump (reionization, recombination) with >5sigma if r > 0.01
- Orbit: L2
- Observing time: 3 years

*Our current studies yield $\sigma(r) = 2 \times 10^{-4}$ (for r=0) for 3 year observation

2015/12/14

Masashi Hazumi (KEK, Kavli IPMU)

15 frequency bands as global Phase-A baseline

Polarization sensitivity



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LiteBIRD constraints on r vs. n_s plane (15 bands)



2015/12/14

For more details on the CMB :

Physics of the cosmic microwave background anisotropy^{*}

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Abstract

Observations of the cosmic microwave background (CMB), especially of its frequency spectrum and its anisotropies, both in temperature and in polarization, have played a key role in the development of modern cosmology and our understanding of the very early universe. We review the underlying physics of the CAB and how the primordial temperature and polarization anisotropies were imprinted. Possibilities for distinguishing computing cosmological models are emphasized. The current status of CMB experiments and experimental reforminges with an emphasis toward future observations, particularly in polarization, is reviewed. The physics of foreground emissions, especially of polarized dust, is discussed in detail, since this area is likely to become crucial for measurements of the *B* modes of the CMB polarization at ever greater sensitivity.

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