The Universe after *Planck* 2013

Martin BUCHER, Laboratoire Astroparticles & Cosmologie,
Université Paris 7 (Denis-Diderot)

for the PLANCK Collaboration

16 May 2013, IST Lisboa

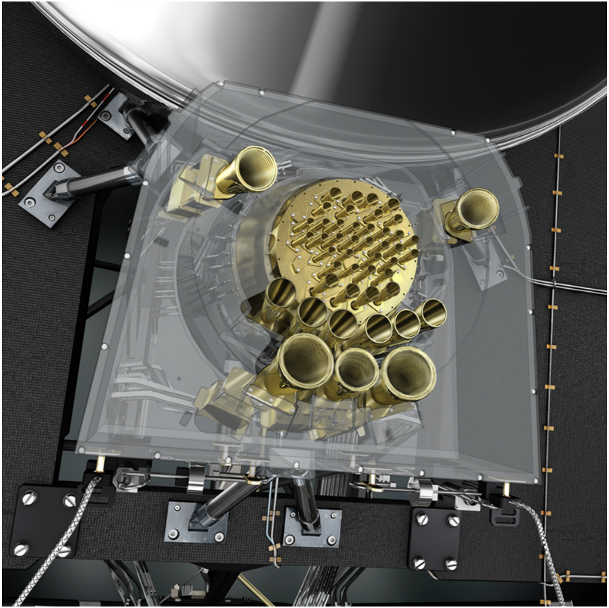
Outline

1. What is Planck?
2. A brief history of CMB observation
3. First release of cosmology results
4. Power spectrum
5. Gravitational lensing
6. Non-Gaussianity
7. Statistical isotropy
8. Alignments
9. Clusters
10. What's next

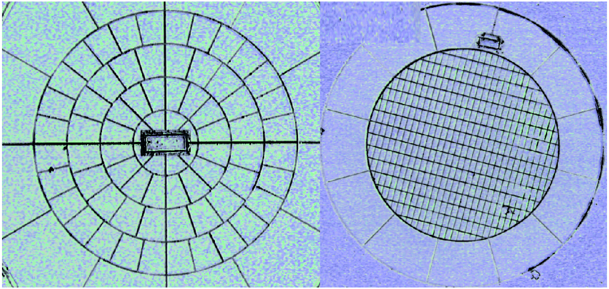
What is Planck?

The *Planck* mission

PLANCK Focal Plane

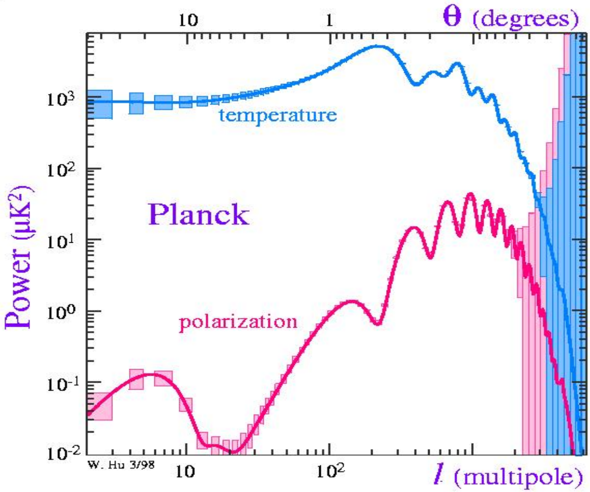


The workhorse of Planck: spiderweb and polarization sensitive bolometers



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

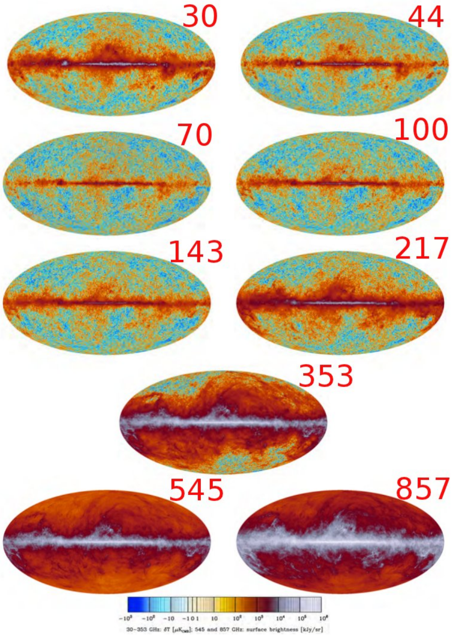
Planck Capabilities

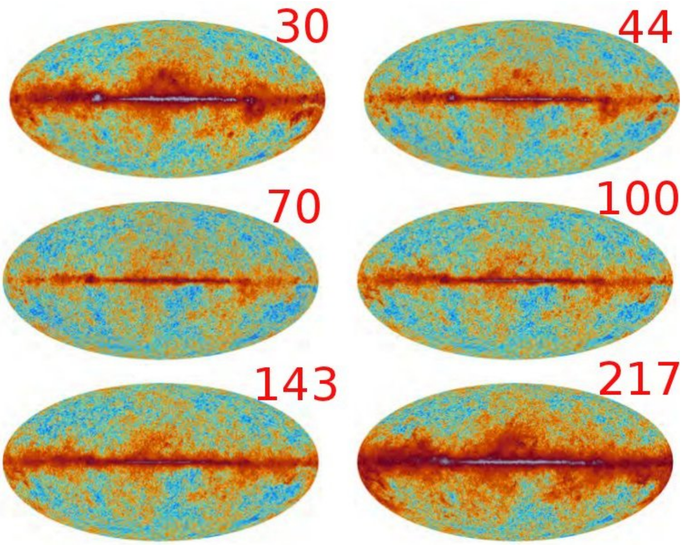


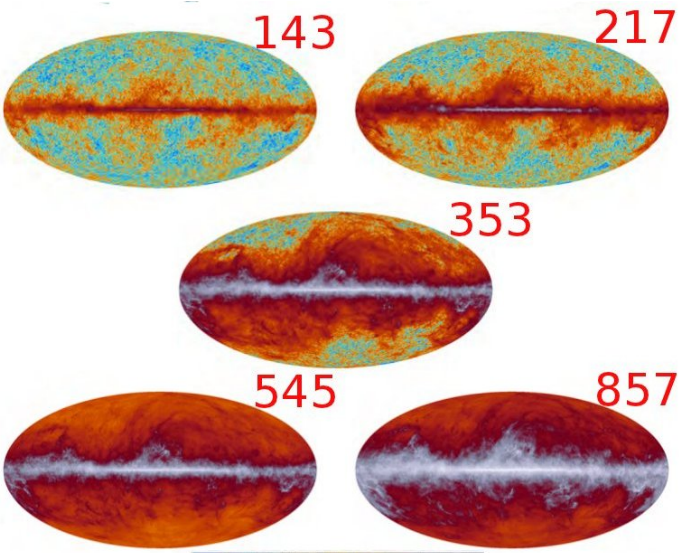
Planck Capabilities

Table 2. *Planck* performance parameters determined from flight data.

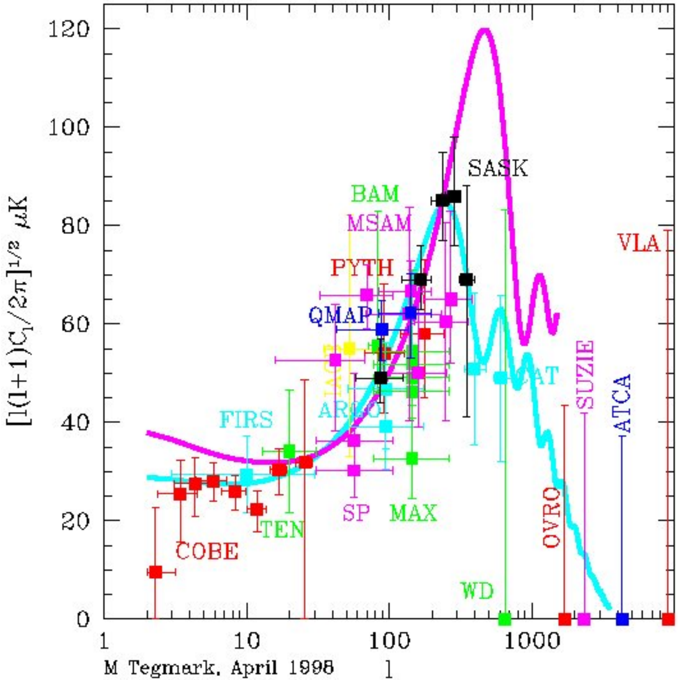
Channel	$N_{detectors}$[a]	ν_{center}[b] [GHz]	Scanning Beam[c] FWHM [arcm]	Ellipticity	Noise[d] Sensitivity [μK_{RJ} $s^{1/2}$]	[μK_{CMB} $s^{1/2}$]
30 GHz	4	28.4	33.16	1.37	145.4	148.5
44 GHz	6	44.1	28.09	1.25	164.8	173.2
70 GHz	12	70.4	13.08	1.27	133.9	151.9
100 GHz	8	100	9.59	1.21	31.52	41.3
143 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]


30
44
70
100
143
217
353
545
857
−10³ −10² −10 −1 0 1 10 10² 10³ 10⁴ 10⁵ 10⁶
30–353 GHz: δT [μK_CMB]; 545 and 857 GHz: surface brightness [kJy/sr]


30
44
70
100
143
217


143
217
353
545
857

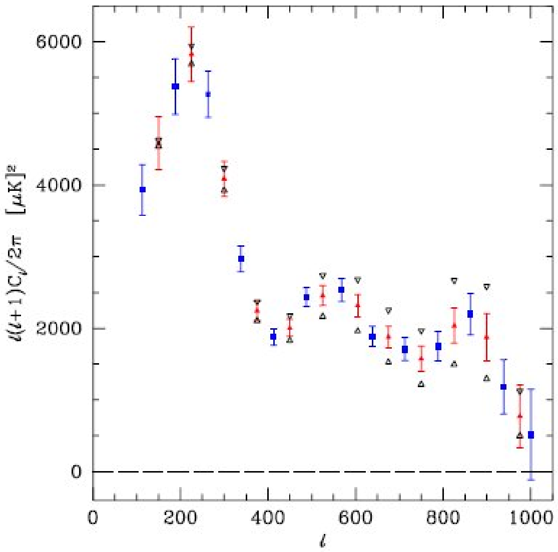
A brief history of CMB observation



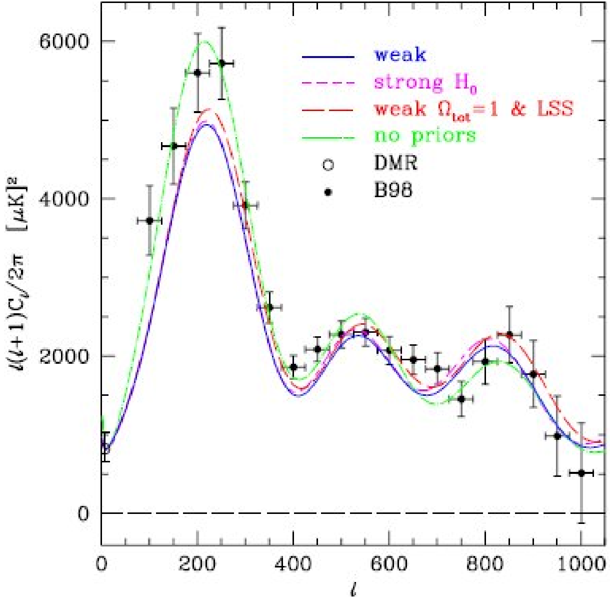
[l(l+1)C_l/2π]^{1/2} μK
120
100
80
60
40
20
0
1
10
100
1000
SASK
BAM
MSAM
PYTH
QMAP
FIRS
TEN
COBE
SP
MAX
WD
OVRO
SUZIE
ATCA
VLA
M Tegmark, April 1998
l

Boomerang baloon

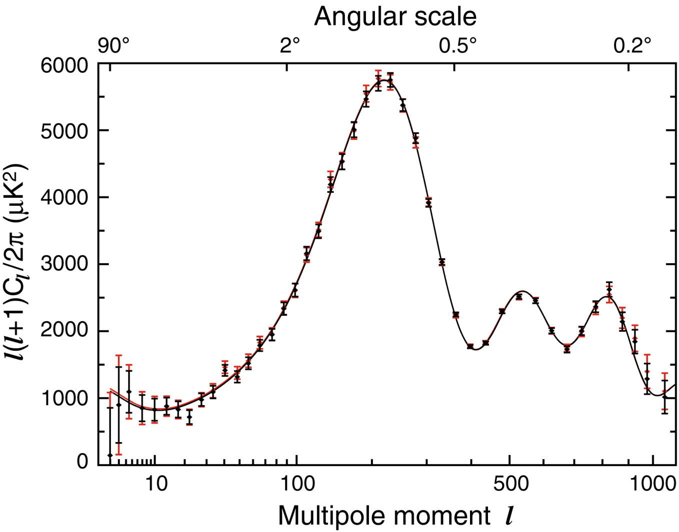
Boomerang mutipole spectrum (no theory)



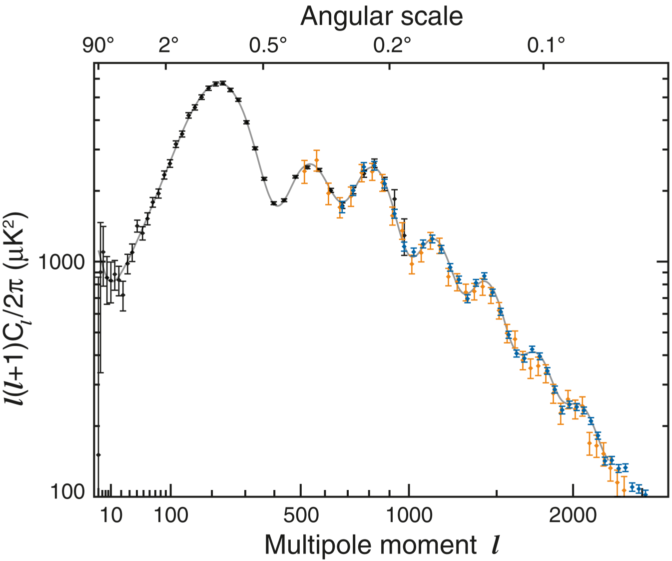
Boomerang mutipole spectrum (with theory)



WMAP 9-year alone



WMAP 9-year +SPT+ACT



Basic statistical approach—interesting outcome case

1. No popular model provides good fit to data.
2. Former agreement with "concordance" model (sufficient to explain WMAP power spectrum and the loose constraints at very large ℓ from ACT and SPT) falls apart owing to factor 2 improvement in resolution and factor 10 improvement in sensitivity of Planck.
3. No simple, theoretically motivated model works, although baroque models with epicycles and many parameters can be made to work.
4. Theorists sent back to drawing board.

This did not happen, but polarization data still being analyzed. Still room for some surprises in future releases.

Basic statistical approach—boring outcome case

1. After having constructed a **likelihood function** whose input is the predicted theoretical power spectrum, find the simplest model with a **good fit** to the power spectrum.
2. Consider extensions to this model and see whether the improvement in the quality of fit is statistically significant. (E.g., isocurvature modes, extra neutrino species, varying α, ...
3. Study the residuals to the minimal models to test for statistical significance.

The Planck Temperature-Temperature Power Spectrum $C_{TT}(\ell)$

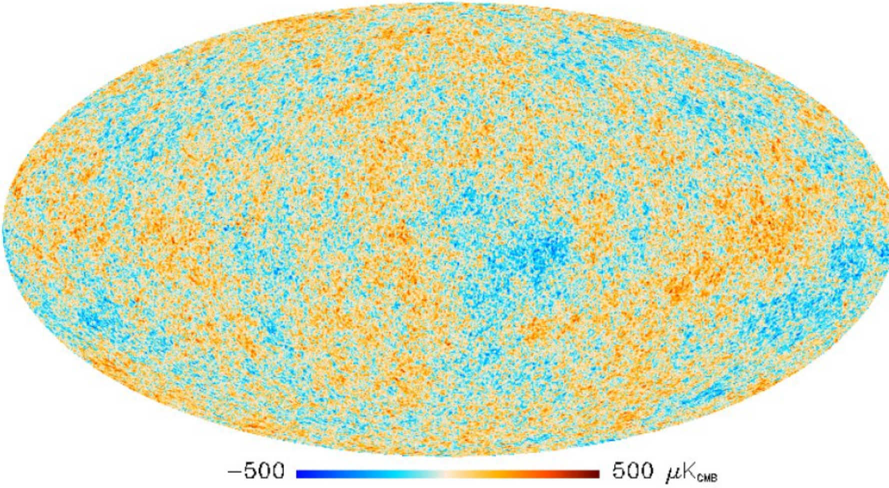
Base model—sampling parameters

	Planck		*Planck*+lensing		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$

Base model—derived parameters

Ω_Λ	0.6825	0.686 ± 0.020
Ω_m	0.3175	0.314 ± 0.020
σ_8	0.8344	0.834 ± 0.027
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$
H_0	67.11	67.4 ± 1.4
$10^9 A_s$	2.215	2.23 ± 0.16
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059
Y_P	0.247710	0.24771 ± 0.00014
Age/Gyr	13.819	13.813 ± 0.058

Planck ILC map



Planck Gravitational lensing spectrum

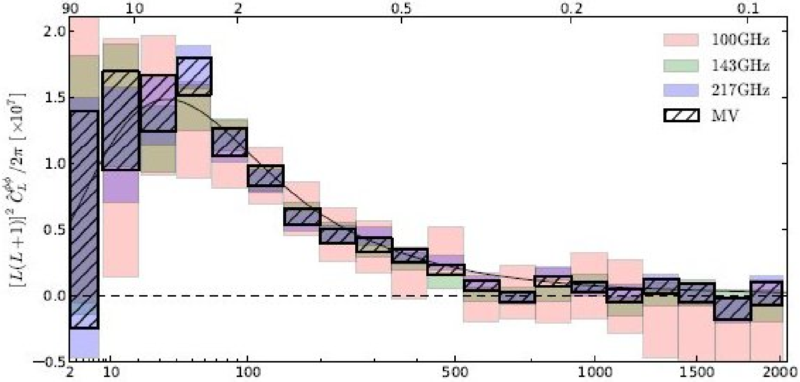
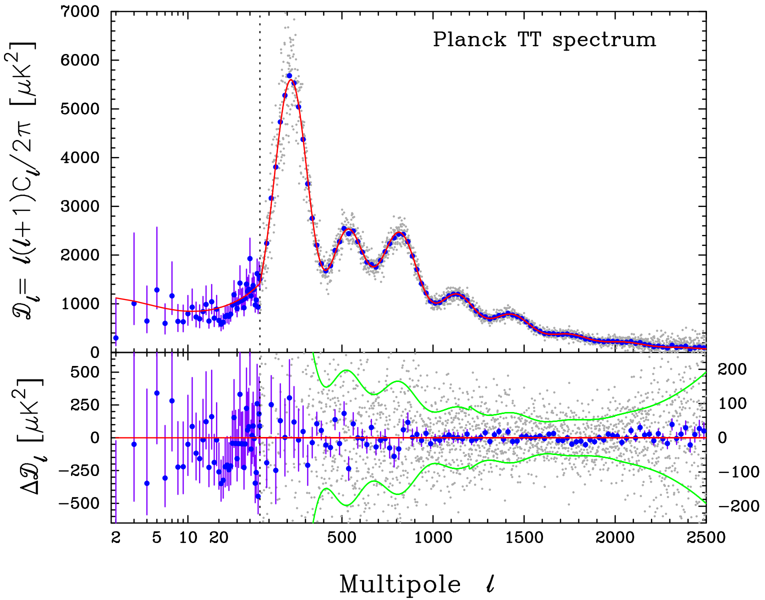
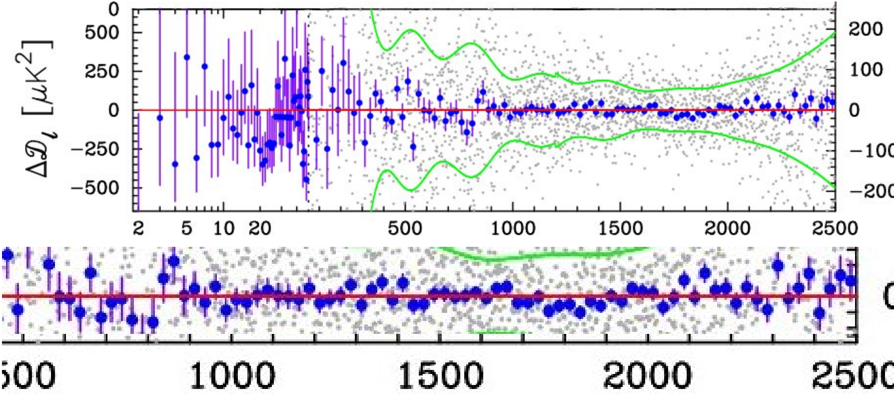
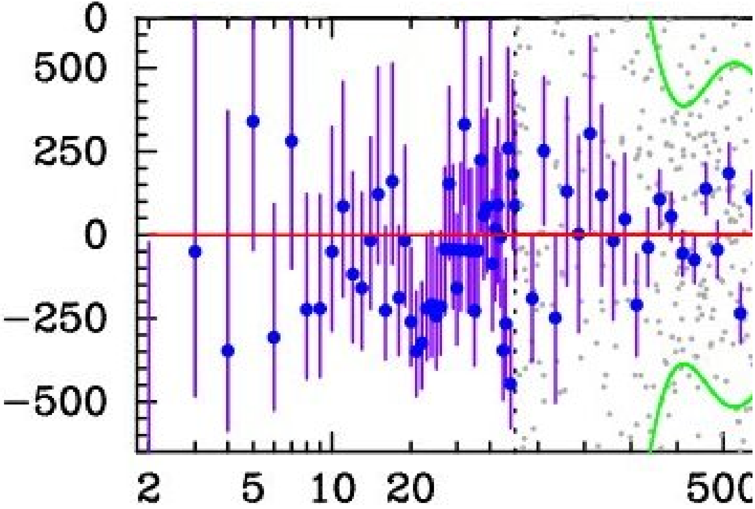


Fig. 18. Fiducial lensing power spectrum estimates based on the 100, 143, and 217 GHz frequency reconstructions, as well as the minimum-variance reconstruction that forms the basis for the *Planck* lensing likelihood.


Planck TT spectrum
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500



$\Delta\mathcal{D}_\ell\ [\mu K^2]$
0
500
250
0
−250
−500
2 5 10 20 500 1000 1500 2000 2500
200
100
0
1000 1500 2000


0
500
250
0
−250
−500
2
5
10
20
500

Underlying question: conventional parameterization

What is the primordial power spectrum?

- For lack of a fundamental theory, expand in powers of $\ln(k)$

$$
\begin{aligned}
\ln\left(\mathcal{P}(\ln k)\right) &= \mathcal{P}_0 \left(\ln(k/k_{piv})\right)^0 + \mathcal{P}_1 \left(\ln(k/k_{piv})\right)^1 + \mathcal{P}_2 \left(\ln(k/k_{piv})\right)^2 + \dots \\
\mathcal{P}(k) &= A(k/k_{piv})^{(n_s-1)} \\
&\text{or} \\
\mathcal{P}(k) &= A(k/k_{piv})^{(n_s-1)+\alpha \ln(k/k_{piv})+\dots}
\end{aligned}
$$

- *Planck* seems to be telling us that the first two terms suffice, and using just the first term can be ruled out at a respectable statistical significance. $n_S \neq 1$ implies exact scale invariance needs to be downgraded to an approximate symmetry. No statistically significant evidence for running of the spectral index.

Underlying question: searching for features

- Two approaches
  - Parameterized approaches : make Ansätze with a small number of extra parameters and compare quality of fit to simpler model to determine whether extra parameters are justified by the data (Aikake Information Criterion, Bayesian Information Criterion, Bayesian Evidence, . . .). (Approach followed in Planck paper XXII, section 8)
  - Non-parameterized approaches: penalized likelihoods,.... [Details of approach followed in Planck XXII paper follow: Gauthier, Christopher; Bucher, Martin; Reconstructing the primordial power spectrum from the CMB, JCAP 10, 050 (2012) (arXiv:1209.2147) (Approach followed in Planck paper XXII, section 7)

Tentative conclusion of Planck Parameters paper

> *To the extremely high accuracy afforded by the Planck data, the power spectrum at high multipoles is compatible with the predictions of the base six parameter ΛCDM cosmology.* This is the main result of this paper. Fig. 1 does, however, suggest that the power spectrum of the best-fit base ΛCDM cosmology has a higher amplitude than the observed power spectrum at multipoles $\ell \lesssim 30$. We will return to this point in Sect. 7.

- Conclusion based on looking at overall χ^2 with a very large number of degrees of freedom.
- We want to examine whether this conclusion is really justified.

Penalized likelihood

Let $\mathcal{P}_0(k) = A_\mathrm{s}(k/k_*)^{n_\mathrm{s}-1}$ be the best fit power spectrum of the six parameter model. We define a general Ansatz for the power spectrum in terms of a fractional variation, $f(k)$, relative to this fiducial model, so that

$$\mathcal{P}_\mathcal{R}(k) = \mathcal{P}_0(k)\Big[1 + f(k)\Big]. \tag{1}$$

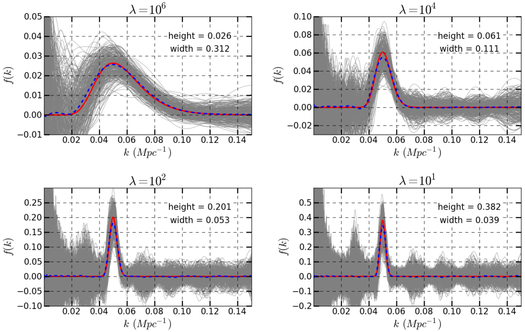
Any features are then described in terms of $f(k)$.

In this analysis we use the Planck+WP likelihood supplemented by the following prior, which is added to $-2\ln\mathcal{L}$:

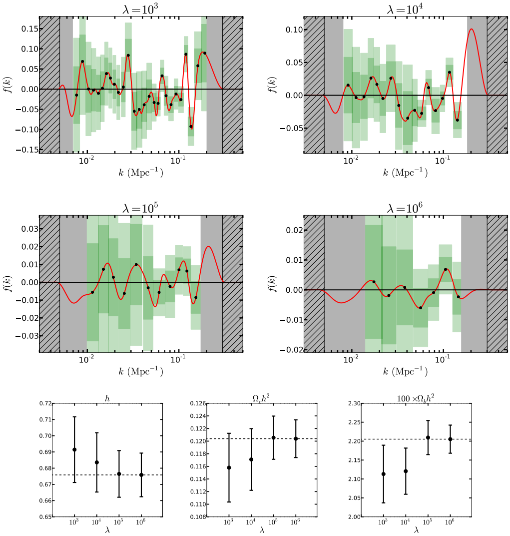
$$\begin{aligned}\mathbf{f}^T\mathbf{R}(\lambda,\alpha)\mathbf{f} &= \lambda\int \mathrm{d}\kappa\ \left(\frac{\partial^2 f(\kappa)}{\partial\kappa^2}\right)^2 \\ &+ \alpha\int_{-\infty}^{\kappa_\mathrm{min}} \mathrm{d}\kappa\ f^2(\kappa) + \alpha\int_{\kappa_\mathrm{max}}^{+\infty} \mathrm{d}\kappa\ f^2(\kappa).\end{aligned} \tag{2}$$

where $\kappa = \ln k$.

Validation of method

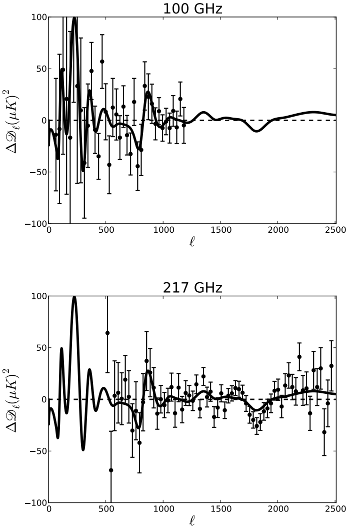


Results on Planck “Nominal mission" likeklihood

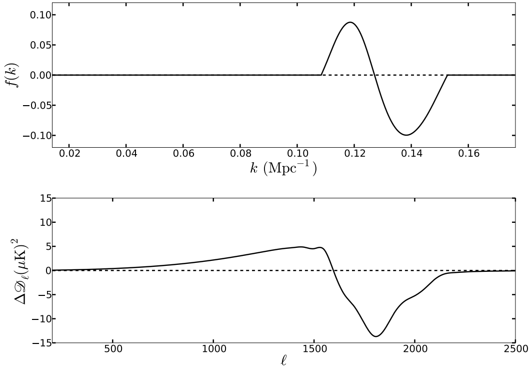


Maximum excursions locally 3.2σ and 3.9σ for $\lambda = 10^4$ and 10^3, respectively. After look-elsewhere-effect translates into $p = 1.74\%$ and $p = 0.21\%$, or 2.4σ and 3.1σ.

Where does this come from in the CMB multipole power spectrum?



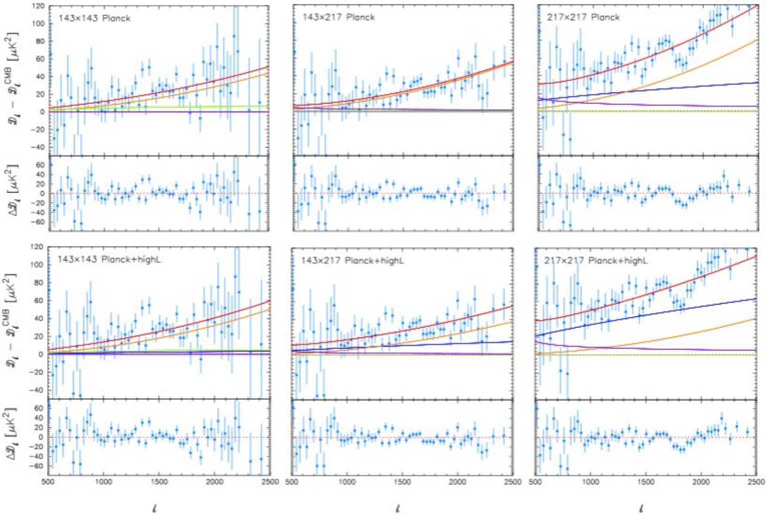
Proof that signal is from around $\ell \approx 1800$



(Extract from parameters paper)

To the extremely high accuracy afforded by the Planck data, the power spectrum at high multipoles is compatible with the predictions of the base six parameter ΛCDM cosmology. This is the main result of this paper. Fig. 1 does, however, suggest that the power spectrum of the best-fit base ΛCDM cosmology has a higher amplitude than the observed power spectrum at multipoles $\ell \lesssim 30$. We will return to this point in Sect. 7.

(Extract from parameters paper)



(Extract from parameters paper)

Table 6. Goodness-of-fit tests for the *Planck* spectra. The $\Delta\chi^2 = \chi^2 - N_\ell$ is the difference from the mean assuming the model is correct, and the last column expresses $\Delta\chi^2$ in units of the dispersion $\sqrt{2N_\ell}$.

Spectrum	ℓ_{min}	ℓ_{max}	χ^2	χ^2/N_ℓ	$\Delta\chi^2/\sqrt{2N_\ell}$
100×100	50	1200	1158	1.01	0.14
143×143	50	2000	1883	0.97	−1.09
217×217	500	2500	2079	1.04	1.23
143×217	500	2500	1930	0.96	−1.13
All	50	2500	2564	1.05	1.62

Comic interlude: testing for nontrivial topology

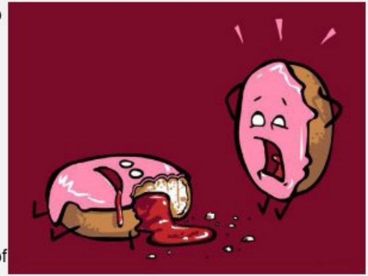
Stephen Hawking : Your theory of a donut shaped universe is intriguing, Homer. I may have to steal it.

Homer Simpson : Wow, I can't believe someone I never heard of is hanging out with a guy like me.

Homer Simpson's suggestion that the universe is doughnut shaped may not be that far from the truth!

Like 25

The universe may accidently be paying tribute to "The Simpsons" with its shape.



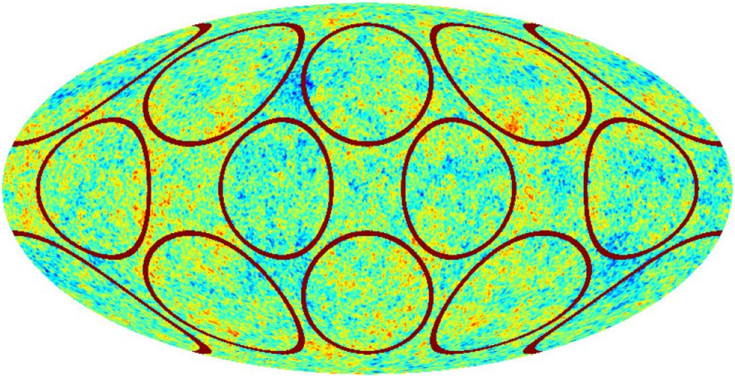
The idea that the universe is finite and relatively small rather than infinitely large first became popular in 2003 when cosmologists noticed unexpected patterns in the cosmic microwave background- radiation residue left from the Big Bang.

An infinite universe should contain CMB waves of all sizes but cosmologists found that longer wavelengths were missing from measurements made by NASA's Wilkinson Microwave Anisotropy Probe.

This meant that the universe could be finite. When cosmologists set out to determine the shape of this finite universe, it was suggested that the universe could be doughnut shaped.

While the doughnut is a likely candidate, there are some other possibilities (e.g. the universe may be shaped like a football).

Planck tests Homer's theory—overlapping great circles



Prediction : Up to noise and some smearing coincidences on overlapping circles should be apparent.

Planck result : These coincidences are not observed ruling out a large class of models with nontrivial topology.

Constraints on neutrino physics

Impact of neutrinos on CMB

1. Actual (precision) analysis is somewhat mindless. (1) Incorporate new physics in Boltzmann solver (e.g., CAMB, CLASS,....) (2) Run Monte Carlo Marco Chain (MCMC) (2) Check for convergence, prior dependence, ... (3) Compare quality of fits.
2. Precision approach gives no intuition. Difficult to understand what is really being tested. Difficult to know what new models to look for in order to explain possible anomalies.
3. Neutrinos affect model CMB primarily in three ways: (1) number of relativistic species shifts moment of matter-radiation equality, affecting the damping tail. (Early recombination means more "viscosity"), (2) "early" integrated Sachs-Wolfe effect, extending visibility surface, (3) gravitational lensing (aka late-time integrated Sachs-Wolfe at large ℓ). Deficit of halo structure on small-scales.
4. While non-cosmological neutrino experiments depend sensitively on the coupling of neutrinos to the Standard Model, cosmological probes are sensitive to neutrino because of the gravitational coupling. Thus "active" and "sterile" neutrinos imprint the same CMB anisotropies.

Planck neutrino constraints

WMAP Seven-year claim:

$N_{eff} = 4.34 \pm 0.87$

WMAP Nine-year claim:

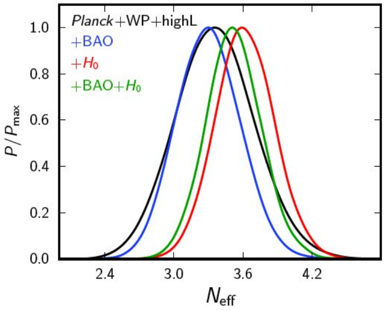
$N_{eff} = 3.84 \pm 0.40$

$\sum m_v < 0.44 eV$ 95% confidence.

Planck:

$N_{eff} = 3.52^{+0.48}_{-0.45}$ (95% *Confidence*; *Planck* + *WP* + H_0 + *BAO*)

$\sum m_v < 0.28 eV$ 95% confidence.



Evidence of Primordial Non-Gaussianity (f_{NL}) in the Wilkinson Microwave Anisotropy Probe 3-Year Data at 2.8σ

Amit P. S. Yadav[1] and Benjamin D. Wandelt[1,2]

[1]*Department of Astronomy, University of Illinois at Urbana-Champaign, 1002 W. Green Street, Urbana, Illinois 61801, USA*
[2]*Department of Physics, University of Illinois at Urbana-Champaign, 1110 W. Green Street, Urbana, Illinois 61801, USA*
(Received 7 December 2007; revised manuscript received 6 March 2008; published 7 May 2008)

We present evidence for primordial non-Gaussianity of the local type (f_{NL}) in the temperature anisotropy of the cosmic microwave background. Analyzing the bispectrum of the Wilkinson Microwave Anisotropy Probe 3-year data up to $\ell_{max} = 750$ we find $27 < f_{NL} < 147$ (95% C.L.). This amounts to a rejection of $f_{NL} = 0$ at 2.8σ, disfavoring canonical single-field slow-roll inflation. The signal is robust to variations in l_{max}, frequency and masks. No known foreground, instrument systematic, or secondary anisotropy explains it. We explore the impact of several analysis choices on the quoted significance and find 2.5σ to be conservative.

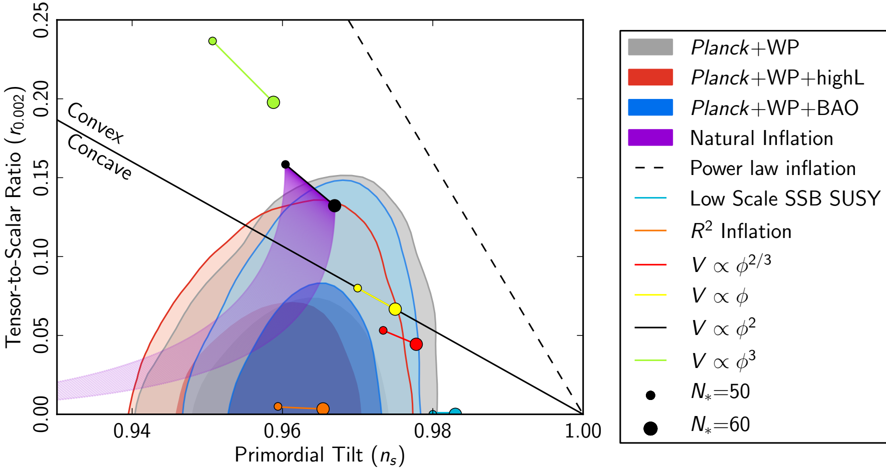
DOI: 10.1103/PhysRevLett.100.181301 PACS numbers: 98.70.Vc, 98.80.Es

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 $f_{NL}^{local} = 2.7 \pm 5.8$, $f_{NL}^{equil} = -42 \pm 75$, and $f_{NL}^{ortho} = -25 \pm 39$ (68% CL statistical); and we find the integrated Sachs-Wolfe lensing bispectrum expected in the ΛCDM 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_l, 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, $c_s \geq 0.02 (95\% CL)$, in an effective field theory parametrization, and the curvaton decay fraction $r_D \geq 0.15 (95\% CL)$. 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.

Implications for inflation—summary plot



Constraints on isocurvature modes

Model	$\beta_{iso}(k_{low})$	$\beta_{iso}(k_{mid})$	$\beta_{iso}(k_{high})$	$\alpha^{(2,2500)}_{\mathcal{RR}}$	$\alpha^{(2,2500)}_{\mathcal{II}}$	$\alpha^{(2,2500)}_{\mathcal{RI}}$	Δn	$-2\Delta \ln \mathcal{L}_{max}$
General model:								
CDM isocurvature	0.075	0.39	0.60	[0.98:1.07]	0.039	[-0.093:0.014]	4	-4.6
ND isocurvature	0.27	0.27	0.32	[0.99:1.09]	0.093	[-0.18:0]	4	-4.2
NV isocurvature	0.18	0.14	0.17	[0.96:1.05]	0.068	[-0.090:0.026]	4	-2.5
Special CDM isocurvature cases:								
Uncorrelated, $n_{\mathcal{II}} = 1$, ("axion")	0.036	0.039	0.040	[0.98:1]	0.016	–	1	0
Fully correlated, $n_{\mathcal{II}} = n_{\mathcal{RR}}$, ("curvaton")	0.0025	0.0025	0.0025	[0.97:1]	0.0011	[0:0.028]	1	0
Fully anti-correlated, $n_{\mathcal{II}} = n_{\mathcal{RR}}$	0.0087	0.0087	0.0087	[1:1.06]	0.0046	[-0.067:0]	1	-1.3

Statistical Isotropy?

Table 23. Summary of dipole modulation likelihood results as a function of scale for all four *Planck* CMB solutions.

Data set	FWHM [°]	A	(l,b) [°]	$\Delta \ln \mathcal{L}$	Significance
Commander	5	$0.078^{+0.020}_{-0.021}$	$(227,-15) \pm 19$	8.8	3.5σ
NILC	5	$0.069^{+0.020}_{-0.021}$	$(226,-16) \pm 22$	7.1	3.0σ
SEVEM	5	$0.066^{+0.021}_{-0.021}$	$(227,-16) \pm 24$	6.7	2.9σ
SMICA	5	$0.065^{+0.021}_{-0.021}$	$(226,-17) \pm 24$	6.6	2.9σ
WMAP5 ILC	4.5	0.072 ± 0.022	$(224,-22) \pm 24$	7.3	3.3σ
Commander	6	$0.076^{+0.024}_{-0.025}$	$(223,-16) \pm 25$	6.4	2.8σ
NILC	6	$0.062^{+0.025}_{-0.026}$	$(223,-19) \pm 38$	4.7	2.3σ
SEVEM	6	$0.060^{+0.025}_{-0.026}$	$(225,-19) \pm 40$	4.6	2.2σ
SMICA	6	$0.058^{+0.025}_{-0.027}$	$(223,-21) \pm 43$	4.2	2.1σ
Commander	7	$0.062^{+0.028}_{-0.030}$	$(223,-8) \pm 45$	4.0	2.0σ
NILC	7	$0.055^{+0.029}_{-0.030}$	$(225,-10) \pm 53$	3.4	1.7σ
SEVEM	7	$0.055^{+0.029}_{-0.030}$	$(226,-10) \pm 54$	3.3	1.7σ
SMICA	7	$0.048^{+0.029}_{-0.029}$	$(226,-11) \pm 58$	2.8	1.5σ
Commander	8	$0.043^{+0.032}_{-0.029}$	$(218,-15) \pm 62$	2.1	1.2σ
NILC	8	$0.049^{+0.032}_{-0.031}$	$(223,-16) \pm 59$	2.5	1.4σ
SEVEM	8	$0.050^{+0.032}_{-0.031}$	$(223,-15) \pm 60$	2.5	1.4σ
SMICA	8	$0.041^{+0.032}_{-0.029}$	$(225,-16) \pm 63$	2.0	1.1σ
Commander	9	$0.068^{+0.035}_{-0.037}$	$(210,-24) \pm 52$	3.3	1.7σ
NILC	9	$0.076^{+0.035}_{-0.037}$	$(216,-25) \pm 45$	3.9	1.9σ
SEVEM	9	$0.078^{+0.035}_{-0.037}$	$(215,-24) \pm 43$	4.0	2.0σ
SMICA	9	$0.070^{+0.035}_{-0.037}$	$(216,-25) \pm 50$	3.4	1.8σ
WMAP3 ILC	9	0.114	$(225,-27)$	6.1	2.8σ
Commander	10	$0.092^{+0.037}_{-0.040}$	$(215,-29) \pm 38$	4.5	2.2σ
NILC	10	$0.098^{+0.037}_{-0.039}$	$(217,-29) \pm 33$	5.0	2.3σ
SEVEM	10	$0.103^{+0.037}_{-0.039}$	$(217,-28) \pm 30$	5.4	2.5σ
SMICA	10	$0.094^{+0.037}_{-0.040}$	$(218,-29) \pm 37$	4.6	2.2σ