An overview of the current status of CMB observations

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Abstract In this paper we briefly review the current status of the Cosmic Microwave Background (CMB) observations, summarising the latest results obtained from CMB experiments, both in intensity and polarization, and the constraints imposed on the cosmological parameters. We also present a summary of current and future CMB experiments, with a special focus on the quest for the CMB B-mode polarization.

1 Introduction

In the last years, a series of high-quality cosmological data sets have provided a consistent picture of our universe, the so-called concordance model. This model presents a flat universe with an energy content of about 70 per cent of dark energy, 25 per cent of cold dark matter and only around 5 per cent of baryonic matter. The data also indicate that the primordial density fluctuations are primarily adiabatic and close to Gaussian distributed with a nearly scale invariant power spectrum.

The Cosmic Microwave Background (CMB) observations are playing a key role in this era of precision cosmology. The data collected from a large number of experiments measuring the intensity and, more recently, the polarization of the CMB anisotropies are in very good agreement with the predictions of the inflationary paradigm. Most notably, the NASA WMAP (Wilkinson Microwave Anisotropy Probe) satellite, launched in June 2001, has constrained the cosmological parameters down to a few per cent [35]. The detection of the E-mode polarization of the CMB, first by DASI [37] and later by a handful of experiments, also provided strong support to the concordance model.

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The major challenge in current CMB Astronomy is the detection of the primordial B-mode polarization, which would constitute a direct proof of the existence of a primordial background of gravitational waves, as predicted by inflation. A large effort is currently being put within the CMB community in order to achieve this goal. Some experiments are already putting limits on the amplitude of the B-mode, while many others are in preparation. Complementary, a good number of CMB experiments are dedicated to the study of the CMB at very small scales, which will provide very valuable information about secondary anisotropies, such as those due to the Sunyaev-Zeldovich (SZ) effects or gravitational lensing. Moreover, the ESA Planck satellite [67], that has been launched in May 2009, will provide all-sky CMB observations, both in intensity and polarization, with unprecedented sensitivity, resolution and frequency coverage.

Another very active field of research is the study of the temperature distribution of the CMB. The standard inflationary scenario together with the cosmological principle predict that the CMB anisotropies should follow an isotropic Gaussian field. However, alternative theories predict the presence of non-Gaussian signatures in the cosmological signal. Interestingly, different works have found deviations of Gaussianity and/or isotropy in the WMAP data whose origin, at the moment, is uncertain (see [43] for a review and references therein). Future Planck data is expected to shed light on the origin of these anomalies.

The outline of the paper is as follows. Section 2 reviews some recent CMB observational results, both in intensity and polarization. Section 3 discusses current and future CMB experiments, including the Planck satellite.

2 Observational results

In the last decade, there has been an explosion of CMB data that has allowed a strong progress in the characterisation of the CMB fluctuations. In particular, the unambiguous detection of the position of the first peak by different experiments (Boomerang [19], MAXIMA [26]) determined that the geometry of the universe is close to flat. In subsequent years, other experiments such as Archeops [3], VSA [23] and, most notably, the NASA WMAP satellite confirmed these results and, in conjunction with other cosmological data sets [22, 60, 49, 38], imposed strong constraints on the cosmological parameters [35]. In addition, a series of experiments are measuring the polarization power spectrum with increasing sensitivity, confirming further the current consistent picture of the universe.

WMAP consists of five instruments (with a total of 10 differencing assemblies) observing at frequencies ranging from 23 to 94 GHz, with a best resolution of 13 arcminutes. The latest published results are based in 5-year of data, although the satellite continues in operation. The WMAP team found that the simple six-parameter ΛCDM model – a flat model dominated by dark energy and dark matter, seeded by nearly scale-invariant, adiabatic, Gaussian fluctuations – continues to provide a good fit to the data. In addition, the model is also consistent with other cosmological

Table 1 Cosmological parameters, with the corresponding 68 per cent intervals, for the 6-parameter ΛCDM model derived using only WMAP 5-yr data and combined WMAP, baryon acoustic oscillations and supernovae data (see [35] for details).

Parameter	WMAP	Combined
$100\Omega_b h^2$	2.273 ± 0.062	$2.267^{+0.058}_{-0.059}$
$\Omega_c h^2$	0.1099 ± 0.0062	0.1131 ± 0.0034
Ω_Λ	0.742 ± 0.030	0.726 ± 0.015
n_s	$0.963^{+0.014}_{-0.015}$	0.960 ± 0.013
τ	0.087 ± 0.017	0.084 ± 0.016
$\Delta^2_R(k_0)^a$	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.445 \pm 0.096) \times 10^{-9}$

^{a} k_0=0.002 Mpc^{-1}.

data sets. Table 1 shows the cosmological parameters for the simple ΛCDM model as obtained by [35] using only WMAP and combining data from WMAP, baryon acoustic oscillations [49] and supernovae [38]. Moving beyond this simple model, the combined data set also constrains additional parameters such as the tensor to scalar ratio $r < 0.22$ (95 per cent CL) and put simultaneous limits on the spatial curvature of the universe $-0.0179 < \Omega_k < 0.0081$ and the dark energy equation of state $-0.14 < 1 + w < 0.12$ (both at the 95 per cent CL).

Fig. 1 shows the temperature power spectrum measured by different experiments. The solid line is the best-fit ΛCDM model to the WMAP 5-yr data, which also agrees well with the additional CMB data sets up to $\ell \approx 2000$. However, some high resolution experiments have found an excess of power at multipoles $\ell \gtrsim 2000$, in particular, CBI [63] and BIMA [17] (which observe at 30 GHz) and, at a lower level, ACBAR [56] (at 150 GHz). The spectrum of the reported excess could be consistent with Sunyaev-Zeldovich emission from cluster of galaxies but this would imply a value of σ_8 larger than the one favoured by other measurements [35, 73]. Another possible origin of this excess is the presence of unsubtracted extragalactic sources [68]. Very recently, two experiments, QUAD and SZA, have reported new measurements of the CMB power spectrum at small scales, finding no excess. In particular, QUAD [54] reports that, after masking the brightest point sources, the results at 150 GHz are consistent with the primary fluctuations expected for the ΛCDM model. The SZA experiment [61], that observes at 30 GHz, finds that the level of SZ emission is in agreement with the expected value of $\sigma_8 \approx 0.8$. The latter work also suggests that the excess found by CBI and BIMA experiments could be due to an underestimation of the effect of extragalactic point sources. In any case, further observations will be needed to clarify the origin of this excess.

Regarding polarization, several experiments have obtained very valuable data in recent years, providing a further test of the concordance model. In particular, the large angle anticorrelation seen by WMAP in the cross power spectrum between temperature and polarization (TE) implies that the density fluctuations are primarily adiabatic, ruling out defect models and isocurvature models as the primary source of

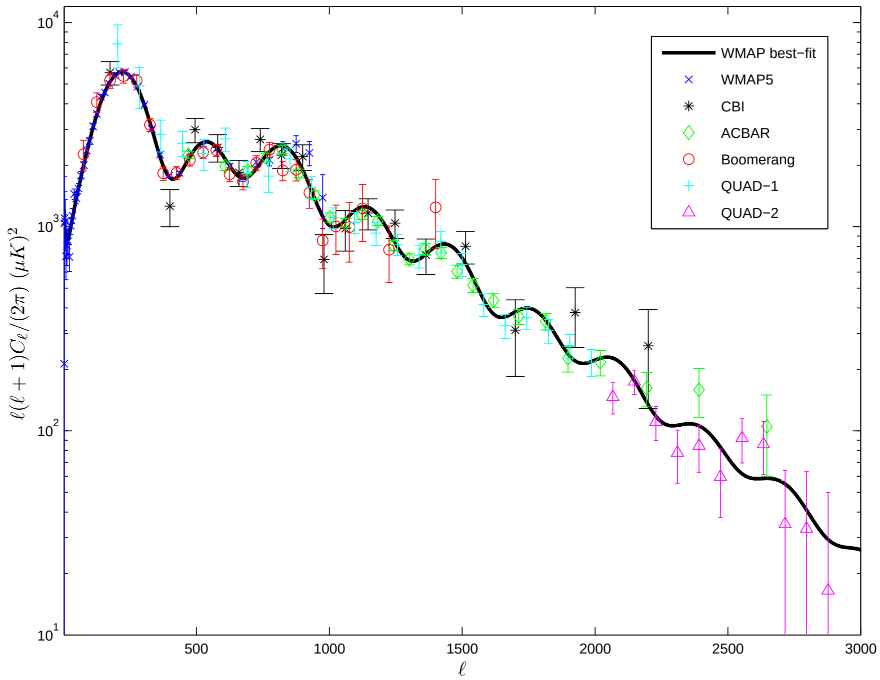

Fig. 1 CMB temperature power spectrum measured by different experiments: WMAP [46], CBI [63], ACBAR [56], Boomerang [33] and QUAD [52, 54]. The solid line corresponds to the best-fit model obtained using the WMAP 5-yr data [35].

fluctuations [48]. In addition to WMAP [46], the TE cross power spectrum has also been measured by a number of experiments: DASI [42], CBI [62], BOOMERANG [50] and QUAD [52]. A compilation of these measurements are shown in Fig. 2. Regarding the E-mode of polarization, after its first detection by DASI [37, 42], several experiments have delivered further measurements covering different ranges of angular scales: WMAP [46], CBI [62], CAPMAP [5], BOOMERANG [45] and QUAD [52]. Fig. 3 shows the E-mode power spectrum measured by these experiments, where acoustic oscillations are already seen. Conversely, no detection of the B-mode polarization has been found up to date, although several experiments have imposed upper limits, including the polarization experiments previously mentioned. In particular, QUAD [52] has recently provided the tightest upper limits for the B-mode power spectrum at $\ell \gtrsim 200$ (for a compilation of current B-mode constraints see e.g. [7]).

Although most observational results show consistency with the concordance model, it is also interesting to point out that QUAD has recently found some tension between their polarization data and the simple ΛCDM model, which seems to be originated by the TE power spectrum [53]. Although this deviation is not highly

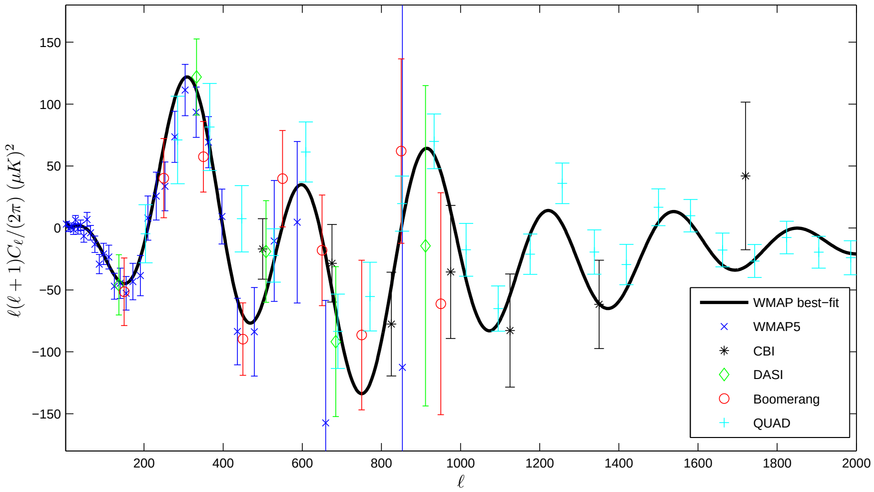

Fig. 2 TE cross power spectrum measured by different experiments: WMAP [46], CBI [62], DASI [42], Boomerang [50] and QUAD [52].

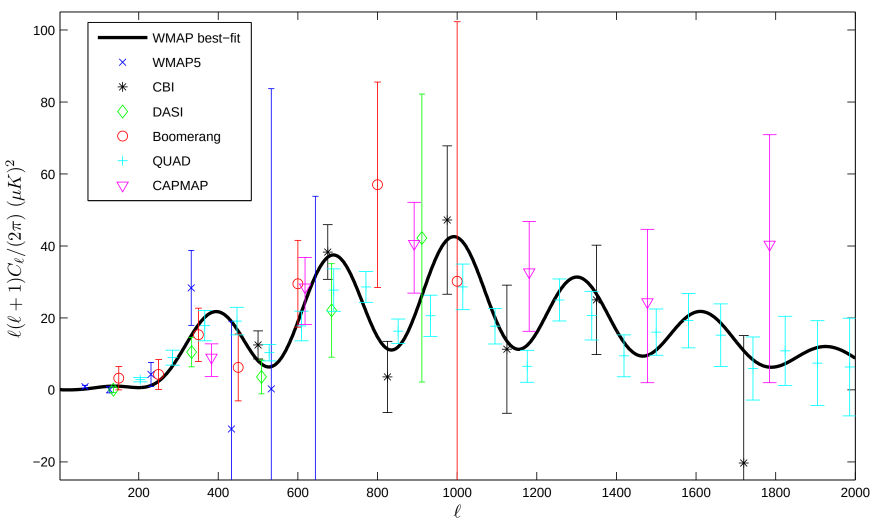

Fig. 3 CMB E-mode power spectrum measured by WMAP [46], CBI [62], DASI [42], Boomerang [45], QUAD [52] and CAPMAP [5].

significant, it will be interesting to see whether it is confirmed or not by future polarization experiments.

A number of works have also found deviations from Gaussianity and/or isotropy in the WMAP data, including, among others, a large cold spot in the southern hemisphere [70, 12] north-south asymmetries [21, 55, 27, 29], anomalies in the low multipoles [20, 4, 9, 10, 39], anisotropies in the amplitude and orientation of CMB features [72, 74], an anomalously low CMB variance [44] or anomalous properties of CMB spots [40, 30, 1]. Although several possibilities have been considered to explain some of the anomalies, e.g. [32, 14, 13, 31, 25], their origin is still uncertain. The future Planck data, with a larger frequency coverage and better sensitivity than WMAP, as well as a different scanning strategy, will allow one to carry out a more detailed study of the temperature distribution of the CMB, helping to shed light on these results.

Different groups have also placed constraints on some physically-motivated non-Gaussian models characterised by the f_{NL} parameter [2] finding, in general, consistency with Gaussianity, e.g. [35, 16, 15, 51, 71, 64, 28]. In particular, the best limits up to date are $-4 < f_{NL}^{local} < 80$ [64] and $151 < f_{NL}^{equil} < 253$ [35], for the local and equilateral models respectively, at the 95 per cent CL. However, [76] have found a deviation from the Gaussian hypothesis at the 2.8σ for the local model, in disagreement with the previous mentioned results. Planck data, as well as future WMAP data with higher sensitivity, will help to confirm or discard the presence of such deviation.

3 Summary of CMB experiments

The most notable CMB experiment to operate in the near future is the ESA Planck satellite [67], that has been launched in May 2009. Planck will measure the CMB fluctuations over the whole sky, in intensity and polarization, with an unprecedented combination of sensitivity ($\Delta T/T \sim 2 \times 10^{-6}$), angular resolution (up to 5 arcminutes), and frequency coverage (30-857 GHz). The main characteristics of Planck are summarised in Table 2. Planck will allow the fundamental cosmological parameters to be determined with a precision of ~ 1 per cent and will set constraints on fundamental physics at energies larger than 10^{15} GeV, which cannot be reached by any conceivable experiment on Earth. In addition, it will provide a catalogue of thousands of galaxy clusters through the SZ effect and very valuable information on the properties of radio and infrared extragalactic sources as well as on our own galaxy.

Complementary, a good number of ground-based and balloon-borne experiments are operating, or in preparation, in order to measure the intensity and polarization of the CMB with increasing sensitivity and resolution. Some of these experiments are devoted to the study of the CMB fluctuations at very small scales (a few arcminutes or below) and, in particular, to the study of the CMB secondary anisotropies, including those produced by the SZ effects and gravitational lensing. This will allow a further test of the concordance model as well as to clarify the possible excess

Table 2 Summary of Planck instrument characteristics (taken from [67])

	LFI			HFI					
Detector Technology	HEMT arrays			Bolometer arrays					
Center Frequency (GHz)	30	44	70	100	143	217	353	545	857
Angular Resolution (arcmin)	33	24	14	10	7.1	5.0	5.0	5.0	5.0
$\Delta T/T$ per pixel (Stokes I)[a]	2.0	2.7	4.7	2.5	2.2	4.8	14.7	147	6700
$\Delta T/T$ per pixel (Stokes Q & U)[a]	2.8	3.9	6.7	4.0	4.2	9.8	29.8	–	–

[a] Goal (in μK/K) for 14 months integration, 1σ, for square pixels whose sides are given in the row angular resolution.

of power found at small angular scales by previous CMB observations. Within this type of experiments we can mention AMI [77], SPT [36], ACT [58] or AMiBA [75].

However, the major challenge of current CMB Astronomy is the detection of the primordial B-mode polarization, which will imply the existence of a primordial background of gravitational waves, as predicted by inflation. Table 3 summarises some of the main on-going and future experiments targeted to study the CMB B-mode polarization. For comparison, we also include the Planck satellite in the table, as well as the C-Bass experiment which is devoted to the study of the synchrotron polarization and will provide complementary information to other experiments. The different experiments cover a wide range of frequencies, resolutions and technologies and will allow to detect (or to constrain) values of $r \approx 0.01$ in the next few years. In addition, design studies for the next generation of satellite missions are being conducted (BPol [18], EPIC[6]), which aim to achieve a sensitivity of $r \approx 0.001$, provided that foreground contamination can be properly removed.

Table 3 Summary of the main characteristics of some B-mode polarization experiments

Experiment	Angular resolution (arcmin)	Frequency (GHz)	Goal (r)	Starting Year
Ground Based				
ABS [65]	30	145	0.1	2010
BICEP [66]	54 - 36	100, 150	0.1	2006
BRAIN [8]	~ 60	90, 150, 220	0.01	2010
C-BASS [47]	51	5	–	2009
KECK	60 -30	100, 150, 220	0.01	2010
MBI [69]	~ 60	90	–	2008
QUIET [59]	28 - 12	40, 90	0.01	2008
QUIJOTE [57]	55 - 22	11, 13, 17, 19, 30	0.05	2009
PolarBear [41]	4 - 2.7	150, 220	0.025	2009
Balloon Borne				
EBEX [24]	8	150, 250, 410	0.02	2009
PAPPA [34]	30	90, 210, 300	0.01	2010
PIPER	~ 15	200, 270, 350, 600	0.007	2013
SPIDER [11]	58 - 21	100, 145, 225, 275	0.01	2010
Satellite				
Planck	33 - 5	30 - 353	0.05	2009

4 Conclusions

During the last years, a consistent picture of our universe, the so-called concordance model, has emerged due to the availability of several high quality data sets. In particular, CMB observations have significantly contributed to improve our description of the universe. However, some fundamental questions still remain to be answered such as which is the nature of dark matter and dark energy, which parameters characterise the inflationary era or which is the origin of the WMAP anomalies. The future CMB data from the Planck satellite, as well as from other CMB experiments, will help to answer these open questions. In addition, the quest for the B-mode of polarization has already started and, if the scalar-to-tensor ratio is $r \approx 0.01$ or larger, the primordial background of gravitational waves – expected from inflation – could be detected in the next years. This would constitute a major breakthrough in our understanding of the early universe.

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References

1. Ayaita, Y., Weber, M., Wetterich, C.: Too few spots in the Cosmic Microwave Background. ArXiv e-prints (2009)
2. Bartolo, N., Komatsu, E., Matarrese, S., Riotto, A.: Non-Gaussianity from inflation: theory and observations. Phys. Rept. **402**, 103–266 (2004)
3. Benoît, A., et al.: The cosmic microwave background anisotropy power spectrum measured by Archeops. A&A **399**, L19–L23 (2003)
4. Bielewicz, P., Eriksen, H.K., Banday, A.J., Górski, K.M., Lilje, P.B.: Multipole Vector Anomalies in the First-Year WMAP Data: A Cut-Sky Analysis. ApJ **635**, 750–760 (2005)
5. Bischoff, C., et al.: New Measurements of Fine-Scale CMB Polarization Power Spectra from CAPMAP at Both 40 and 90 GHz. ApJ **684**, 771–789 (2008)
6. Bock, J., et al.: The Experimental Probe of Inflationary Cosmology (EPIC): A Mission Concept Study for NASA's Einstein Inflation Probe. ArXiv e-prints (2008)
7. Challinor, A., Peiris, H.: Lecture notes on the physics of cosmic microwave background anisotropies. ArXiv e-prints (2009)
8. Charlassier, R., for the BRAIN Collaboration: The BRAIN experiment, a bolometric interferometer dedicated to the CMB B-mode measurement. ArXiv e-prints (2008)
9. Chiang, L.Y., Naselsky, P.D., Coles, P.: Departure from Gaussianity of the Cosmic Microwave Background Temperature Anisotropies in the Three-Year WMAP Data. ApJ **664**, 8–13 (2007)
10. Copi, C.J., Huterer, D., Schwarz, D.J., Starkman, G.D.: Uncorrelated universe: Statistical anisotropy and the vanishing angular correlation function in WMAP years 1-3. Phys. Rev. D **75**(2), 023,507–+ (2007)
11. Crill, B.P., et al.: SPIDER: a balloon-borne large-scale CMB polarimeter. In: Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, vol. 7010 (2008)
12. Cruz, M., Cayón, L., Martínez-González, E., Vielva, P., Jin, J.: The Non-Gaussian Cold Spot in the 3 Year Wilkinson Microwave Anisotropy Probe Data. ApJ **655**, 11–20 (2007)

13. Cruz, M., Martínez-González, E., Vielva, P., Diego, J.M., Hobson, M., Turok, N.: The CMB cold spot: texture, cluster or void? MNRAS **390**, 913–919 (2008)
14. Cruz, M., Turok, N., Vielva, P., Martínez-González, E., Hobson, M.: A Cosmic Microwave Background Feature Consistent with a Cosmic Texture. Science **318**, 1612– (2007)
15. Curto, A., Martinez-Gonzalez, E., Barreiro, R.B.: Improved constraints on primordial non-Gaussianity for the Wilkinson Microwave Anisotropy Probe 5-yr data. ArXiv e-prints (2009)
16. Curto, A., Martínez-Gonzélez, E., Mukherjee, P., Barreiro, R.B., Hansen, F.K., Liguori, M., Matarrese, S.: Wilkinson Microwave Anisotropy Probe 5-yr constraints on f_{nl} with wavelets. MNRAS **393**, 615–622 (2009)
17. Dawson, K.S., Holzapfel, W.L., Carlstrom, J.E., Joy, M., LaRoque, S.J.: Final Results from the BIMA CMB Anisotropy Survey and Search for a Signature of the Sunyaev-Zel'dovich Effect. ApJ **647**, 13–24 (2006)
18. De Bernardis, P., Bucher, M., Burigana, C., Piccirillo, L.: B-Pol: detecting primordial gravitational waves generated during inflation. Experimental Astronomy **23**, 5–16 (2009)
19. de Bernardis, P., et al.: A flat Universe from high-resolution maps of the cosmic microwave background radiation. Nature **404**, 955–959 (2000)
20. de Oliveira-Costa, A., Tegmark, M., Zaldarriaga, M., Hamilton, A.: Significance of the largest scale CMB fluctuations in WMAP. Phys. Rev. D **69**(6), 063,516–+ (2004)
21. Eriksen, H.K., Banday, A.J., Górski, K.M., Hansen, F.K., Lilje, P.B.: Hemispherical Power Asymmetry in the Third-Year Wilkinson Microwave Anisotropy Probe Sky Maps. ApJ **660**, L81–L84 (2007)
22. Freedman, W.L., et al.: Final Results from the Hubble Space Telescope Key Project to Measure the Hubble Constant. ApJ **553**, 47–72 (2001)
23. Grainge, K., et al.: The cosmic microwave background power spectrum out to l= 1400 measured by the Very Small Array. MNRAS **341**, L23–L28 (2003)
24. Grainger, W., et al.: EBEX: the E and B Experiment. In: Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, vol. 7020 (2008)
25. Groeneboom, N.E., Eriksen, H.K.: Bayesian Analysis of Sparse Anisotropic Universe Models and Application to the Five-Year WMAP Data. ApJ **690**, 1807–1819 (2009)
26. Hanany, S., et al.: MAXIMA-1: A Measurement of the Cosmic Microwave Background Anisotropy on Angular Scales of 10'-5°. ApJ **545**, L5–L9 (2000)
27. Hansen, F.K., Banday, A.J., Gorski, K.M., Eriksen, H.K., Lilje, P.B.: Power Asymmetry in Cosmic Microwave Background Fluctuations from Full Sky to Sub-degree Scales: Is the Universe Isotropic? ArXiv e-prints (2008)
28. Hikage, C., Matsubara, T., Coles, P., Liguori, M., Hansen, F.K., Matarrese, S.: Limits on primordial non-Gaussianity from Minkowski Functionals of the WMAP temperature anisotropies. MNRAS **389**, 1439–1446 (2008)
29. Hoftuft, J., Eriksen, H.K., Banday, A.J., Gorski, K.M., Hansen, F.K., Lilje, P.B.: Increasing evidence for hemispherical power asymmetry in the five-year WMAP data. ArXiv e-prints (2009)
30. Hou, Z., Banday, A.J., Gorski, K.M.: The Hot and Cold Spots in Five-Year WMAP Data. ArXiv e-prints (2009)
31. Inoue, K.T., Silk, J.: Local Voids as the Origin of Large-Angle Cosmic Microwave Background Anomalies: The Effect of a Cosmological Constant. ApJ **664**, 650–659 (2007)
32. Jaffe, T.R., Hervik, S., Banday, A.J., Górski, K.M.: On the Viability of Bianchi Type VII_h Models with Dark Energy. ApJ **644**, 701–708 (2006)
33. Jones, W.C., et al.: A Measurement of the Angular Power Spectrum of the CMB Temperature Anisotropy from the 2003 Flight of BOOMERANG. ApJ **647**, 823–832 (2006)
34. Kogut, A., et al.: PAPPA: Primordial anisotropy polarization pathfinder array. New Astronomy Review **50**, 1009–1014 (2006)
35. Komatsu, E., et al.: Five-Year Wilkinson Microwave Anisotropy Probe Observations: Cosmological Interpretation. ApJS **180**, 330–376 (2009)
36. Kosowsky, A.: The Atacama Cosmology Telescope project: A progress report. New Astronomy Review **50**, 969–976 (2006)

37. Kovac, J.M., Leitch, E.M., Pryke, C., Carlstrom, J.E., Halverson, N.W., Holzapfel, W.L.: Detection of polarization in the cosmic microwave background using DASI. Nature **420**, 772–787 (2002)
38. Kowalski, M., et al.: Improved Cosmological Constraints from New, Old, and Combined Supernova Data Sets. ApJ **686**, 749–778 (2008)
39. Land, K., Magueijo, J.: The Axis of Evil revisited. MNRAS **378**, 153–158 (2007)
40. Larson, D.L., Wandelt, B.D.: The Hot and Cold Spots in the Wilkinson Microwave Anisotropy Probe Data Are Not Hot and Cold Enough. ApJ **613**, L85–L88 (2004)
41. Lee, A.T., et al.: POLARBEAR: Ultra-high Energy Physics with Measurements of CMB Polarization. In: American Institute of Physics Conference Series, *American Institute of Physics Conference Series*, vol. 1040, pp. 66–77 (2008)
42. Leitch, E.M., Kovac, J.M., Halverson, N.W., Carlstrom, J.E., Pryke, C., Smith, M.W.E.: Degree Angular Scale Interferometer 3 Year Cosmic Microwave Background Polarization Results. ApJ **624**, 10–20 (2005)
43. Martínez-González, E.: Gaussianity. ArXiv e-prints (2008)
44. Monteserín, C., Barreiro, R.B., Vielva, P., Martínez-González, E., Hobson, M.P., Lasenby, A.N.: A low cosmic microwave background variance in the Wilkinson Microwave Anisotropy Probe data. MNRAS **387**, 209–219 (2008)
45. Montroy, T.E., et al.: A Measurement of the CMB $< EE >$ Spectrum from the 2003 Flight of BOOMERANG. ApJ **647**, 813–822 (2006)
46. Nolta, M.R., et al.: Five-Year Wilkinson Microwave Anisotropy Probe Observations: Angular Power Spectra. ApJS **180**, 296–305 (2009)
47. Pearson, T.J., C-BASS collaboration: C-BASS: C-Band All-Sky Survey. In: Bulletin of the American Astronomical Society, *Bulletin of the American Astronomical Society*, vol. 38, pp. 883–+ (2007)
48. Peiris, H.V., et al.: First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Implications For Inflation. ApJS **148**, 213–231 (2003)
49. Percival, W.J., Cole, S., Eisenstein, D.J., Nichol, R.C., Peacock, J.A., Pope, A.C., Szalay, A.S.: Measuring the Baryon Acoustic Oscillation scale using the Sloan Digital Sky Survey and 2dF Galaxy Redshift Survey. MNRAS **381**, 1053–1066 (2007)
50. Piacentini, F., et al.: A Measurement of the Polarization-Temperature Angular Cross-Power Spectrum of the Cosmic Microwave Background from the 2003 Flight of BOOMERANG. ApJ **647**, 833–839 (2006)
51. Pietrobon, D., Cabella, P., Balbi, A., de Gasperis, G., Vittorio, N.: Constraints on Primordial Non-Gaussianity from a Needlet Analysis of the WMAP-5 Data. ArXiv e-prints (2008)
52. Pryke, C., et al.: Second and Third Season QUaD Cosmic Microwave Background Temperature and Polarization Power Spectra. ApJ **692**, 1247–1270 (2009)
53. QUaD collaboration: P. G. Castro, et al.: Cosmological Parameters from the QUaD CMB polarization experiment. ArXiv e-prints (2009)
54. QUaD collaboration: R. B. Friedman, et al.: Small Angular Scale Measurements of the CMB Temperature Power Spectrum from QUaD. ArXiv e-prints (2009)
55. Räth, C., Schuecker, P., Banday, A.J.: A scaling index analysis of the Wilkinson Microwave Anisotropy Probe three-year data: signatures of non-Gaussianities and asymmetries in the cosmic microwave background. MNRAS **380**, 466–478 (2007)
56. Reichardt, C.L., et al.: High-Resolution CMB Power Spectrum from the Complete ACBAR Data Set. ApJ **694**, 1200–1219 (2009)
57. Rubino-Martin, J.A., et al.: The Quijote CMB Experiment. ArXiv e-prints (2008)
58. Ruhl, J., et al.: The South Pole Telescope. In: C.M. Bradford, P.A.R. Ade, J.E. Aguirre, J.J. Bock, M. Dragovan, L. Duband, L. Earle, J. Glenn, H. Matsuhara, B.J. Naylor, H.T. Nguyen, M. Yun, J. Zmuidzinas (eds.) Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, vol. 5498, pp. 11–29 (2004)
59. Samtleben, D., for the QUIET collaboration: QUIET - Measuring the CMB polarization with coherent detector arrays. ArXiv e-prints (2008)

60. Seljak, U., Slosar, A., McDonald, P.: Cosmological parameters from combining the Lyman-α forest with CMB, galaxy clustering and SN constraints. Journal of Cosmology and Astro-Particle Physics **10**, 14–+ (2006)
61. Sharp, M.K., et al.: A Measurement of Arcminute Anisotropy in the Cosmic Microwave Background with the Sunyaev-Zel'dovich Array. ArXiv e-prints (2009)
62. Sievers, J.L., et al.: Implications of the Cosmic Background Imager Polarization Data. ApJ **660**, 976–987 (2007)
63. Sievers, J.L., et al.: Cosmological Results from Five Years of 30 GHz CMB Intensity Measurements with the Cosmic Background Imager. ArXiv e-prints (2009)
64. Smith, K.M., Senatore, L., Zaldarriaga, M.: Optimal limits on f_{NL}^{local} from WMAP 5-year data. ArXiv e-prints (2009)
65. Staggs, S.T., et al.: The Atacama B-mode Search: an experiment to measure the polarization of the cosmic microwave background at large angular scales. In: Proceedings of Mitigating Systematic Errors in Space-based CMB Polarization Measurements (2008)
66. Takahashi, Y.D., et al.: CMB polarimetry with BICEP: instrument characterization, calibration, and performance. In: Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, vol. 7020 (2008)
67. The Planck Collaboration: The Scientific Programme of Planck. ArXiv Astrophysics e-prints (2006)
68. Toffolatti, L., Negrello, M., González-Nuevo, J., de Zotti, G., Silva, L., Granato, G.L., Argüeso, F.: Extragalactic source contributions to arcminute-scale Cosmic Microwave Background anisotropies. A&A **438**, 475–480 (2005)
69. Tucker, G.S., et al.: The millimeter-wave bolometric interferometer (MBI). In: Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, vol. 7020 (2008)
70. Vielva, P., Martínez-González, E., Barreiro, R.B., Sanz, J.L., Cayón, L.: Detection of Non-Gaussianity in the Wilkinson Microwave Anisotropy Probe First-Year Data Using Spherical Wavelets. ApJ **609**, 22–34 (2004)
71. Vielva, P., Sanz, J.L.: Analysis of non-Gaussian CMB maps based on the N-pdf. Application to WMAP data. ArXiv e-prints (2008)
72. Vielva, P., Wiaux, Y., Martínez-González, E., Vandergheynst, P.: Alignment and signed-intensity anomalies in Wilkinson Microwave Anisotropy Probe data. MNRAS **381**, 932–942 (2007)
73. Vikhlinin, A., et al.: Chandra Cluster Cosmology Project III: Cosmological Parameter Constraints. ApJ **692**, 1060–1074 (2009)
74. Wiaux, Y., Vielva, P., Barreiro, R.B., Martínez-González, E., Vandergheynst, P.: Non-Gaussianity analysis on local morphological measures of WMAP data. MNRAS **385**, 939–947 (2008)
75. Wu, J.H.P., et al.: Array for Microwave Background Anisotropy: Observations, Data Analysis, and Results for Sunyaev-Zel'Dovich Effects. ApJ **694**, 1619–1628 (2009)
76. Yadav, A.P.S., Wandelt, B.D.: Evidence of Primordial Non-Gaussianity (f_{NL}) in the Wilkinson Microwave Anisotropy Probe 3-Year Data at 2.8σ. Phys. Rev. Lett. **100**(18), 181,301–+ (2008)
77. Zwart, J.T.L., et al.: The Arcminute Microkelvin Imager. MNRAS **391**, 1545–1558 (2008)