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Measuring the Cosmic Microwave Background Radiation

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Summary. — The Cosmic Microwave Background Radiation (CMBR) has over the last four decades been measured to increasingly high precision and with that provided information on the early Universe to shape and scrutinize our current cosmological model. Here we provide an overview on the status and prospects of current and future measurements.

PACS `98.80.Es` – Observational cosmology (including Hubble constant, distance scale, cosmological constant, early Universe, etc.).
PACS `98.70.Vc` – Background radiations.

1. – Introduction

The Cosmic Microwave Background Radiation (CMBR) is a relict from the early Universe from the time of recombination when the Universe became transparent to photons, 400000 years after the Big Bang. It provides a picture of the early Universe and with that rich information on the content and dynamics of the Universe. While its temperature pattern has already been studied in detail and was instrumental in establishing the current cosmological model experiments have only in the last decade reached the sensitivity to additionally access the fainter polarization anisotropy. We will describe the status, prospects and potential of the measurements whereby illustrating the experimental challenge of polarization measurements with a focus on the Q/U Imaging ExperimenT (QUIET [1]).

2. – Temperature anisotropies

The temperature anisotropies reflect the acoustic oscillation pattern in the early Universe due to the density fluctuations at the time of decoupling of photons. After the first detection of the small anisotropies by the COBE satellite a good number of ground-based and balloon experiments contributed to characterizing their detailed characteristics which by now have also been measured on all sky to a very high precision by the WMAP satellite. As a Gaussian homogeneous and isotropic field all information of the

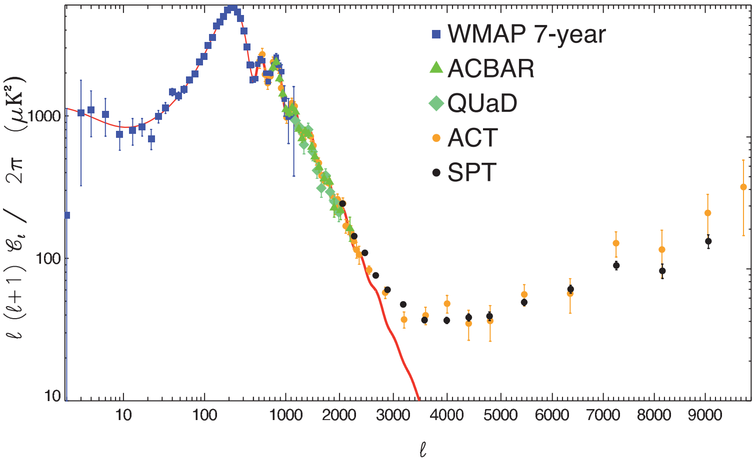

Fig. 1. – (Colour on-line) Measurements of the CMBR temperature power spectrum together with a fit of the best cosmological model in red. Foregrounds dominate above $l = 3000$ (from [2]).

anisotropy pattern can be condensed into the well-known power spectrum which allows the extraction of the parameters characterizing our cosmological model.

$$T(\theta,\phi) = \sum a_{lm} Y_{lm}(\theta,\phi) \qquad C_l = \langle a_{lm} a^*_{lm} \rangle \qquad \Delta T^2 = \frac{l(l+1)}{2\pi} C_l .$$

The Y_{lm} are spherical harmonics where the multipole l defines the angular scale (small l means large angular scale). To date the spectrum has been precisely measured in a multipole range of almost four decades (see fig. 1). Current measurements are fully compatible with Gaussian fluctuations. Future surveys like the Planck satellite will be able to much further constrain the level of possible non-Gaussianities and with that probe the predictions of different inflationary models.

The shape of the spectrum is determined by the content and dynamics of the Universe. The acoustic oscillation pattern of the plasma in the early Universe is imprinted on the photons released at the time of decoupling. The horizon size at that time provides a boundary condition that translates into a series of peaks at certain angular scales in the power spectrum of the CMBR anisotropies. The large power at the first peak of the spectrum is associated with the fluctuations of the size of the horizon at the time of decoupling and thus the position determines the angular size of the horizon as seen by today's observers, about 1 degree. Though seemingly large ($6000\ \mu\mathrm{K}^2$) the power at the first peak corresponds to a fluctuation of only 10^{-5} of the absolute CMBR temperature of $2.7\,\mathrm{K}$. Current CMBR power spectrum measurements allow determining the main parameters of the cosmological model like the baryon and dark matter content to the precision of few percent.

While the CMBR is often perceived as providing a complete picture of the early Universe it is also crucial to appreciate that its pattern can not uniquely be mapped to a single cosmological model but contains degeneracies in the allowed parameter space. The pattern that is visible today is not only affected by the conditions of the early Universe but also by the structure in the line of sight and its development as well as the curvature of the Universe.

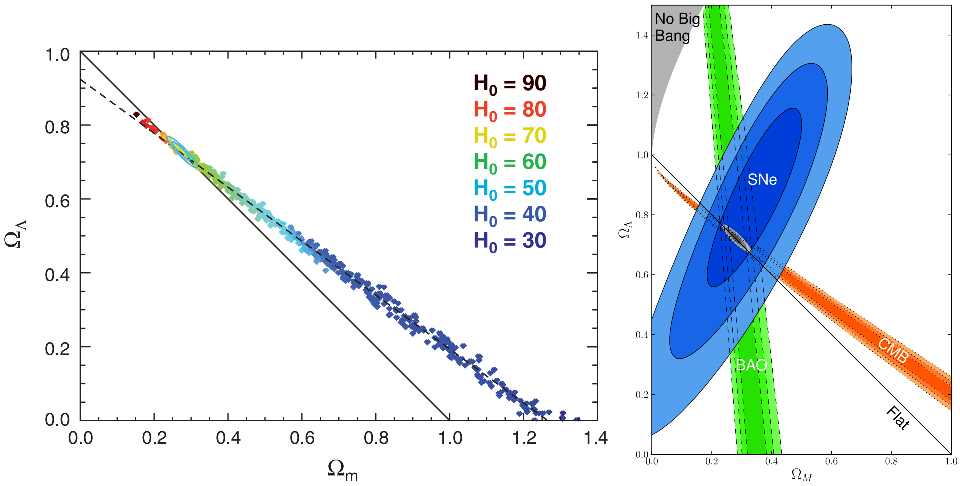

Fig. 2. – Left: Models in the Ω_Λ *vs.* Ω_m plane allowed by WMAP measurements for various values of the Hubble constant (from [5]). Right: Further constraints in the same plane coming also from supernovae and baryonic acoustic oscillations with systematic errors included (from [6]).

A prominent degeneracy is illustrated by the evidence that supports the existence of Dark Energy from CMBR measurements. Figure 2 from [3] shows the phase space of cosmological models in the Ω_Λ *vs.* Ω_m plane (energy densities of Dark Energy and matter) that is allowed by the WMAP measurements. Only when also considering external information like a measurement of the Hubble constant the phase space with no Dark Energy (Ω_Λ=0) is ruled out(1). Measurements of Supernovae distances and baryonic oscillations also complement the information of the CMB to narrow the allowed parameter range considerably towards a flat Universe with a significant content of Dark Energy as seen in the right plot of fig. 2. The increasingly detailed measurements of the temperature anisotropies did not only help establish and specify the current cosmological model at high precision but also provide a rich data set to scrutinize anomalies. As to date several unresolved anomalies have been reported (see, *e.g.*, [7]). A prominent large-scale anomaly is that the quadrupole ($l = 2$) and octupole ($l = 3$) as measured by WMAP are closely aligned also with the ecliptic plane. Though a cosmological origin seems unlikely no instrumental or systematic feature could be proven to account for this distinct feature though the suspicion of possible subtle scan-induced issues has been raised [8]. The new full-sky survey by the Planck satellite will soon be able to shed more light on this with an independent measurement including different scanning and instrumental systematics.

3. – Polarization anisotropies

The polarization pattern is conventionally split into orthogonal contributions named “E”- and “B”-modes which contain gradient and curl components, respectively. E-modes

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(1) By now the first evidence for Dark Energy from CMB measurements alone has been reported by ACT, breaking the previous degeneracy by adding CMBR lensing information [4].

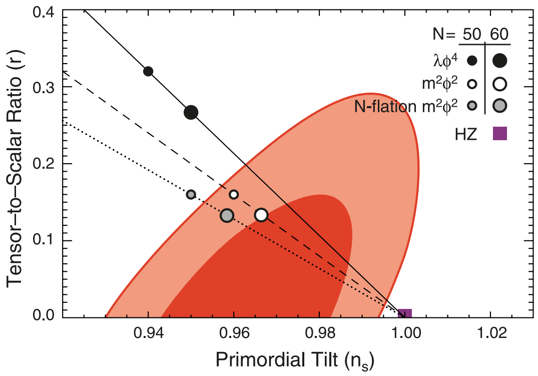

Fig. 3. – (Colour on-line) Various inflationary models are compared in the plane of $r = T/S$ and n_s to the allowed phase space from WMAP measurements which is indicated in red (from [3]).

derive from the same physical origin as the temperature anisotropies, namely the density fluctuations and the associated dynamics and are one order of magnitude smaller than the temperature anisotropies, corresponding to a signal size of μK size. The E-mode polarization directly derives from the flow of the photons between hot and cold spots. As the density fluctuations have by now been measured to high precision by the CMBR temperature data the resulting model predicts also a well-defined polarization pattern with it, that can be cross-checked with the polarization measurements and has been confirmed by current E-mode power spectrum measurements. In stacking the maps of polarization data from hot and cold temperature spots in the WMAP data the expected polarization pattern around those regions could also already be visualized [3].

B-modes are expected from lensing of the E-modes due to matter in the line of sight, but in addition most excitingly also as imprint of primordial gravitational waves in the inflationary era. The B-mode signal due to lensing is expected at more than an order of magnitude smaller size than the E-modes. The size of the B-mode signal deriving from primordial gravitational waves is dependent on the energy scale of inflation and commonly parametrized by the tensor-to-scalar ratio $r = T/S$. Current limits constrain its expected size to smaller than $\sim 100\,\text{nK}$.

The phase space of inflationary models can be parametrized by r together with the slope n_s of the primordial power spectrum whereby n_s is predicted to deviate slightly from 1. Several models are displayed in this parameter space in fig. 3 together with the current best constraints from measurements. The slope n_s has been measured to 0.97 ± 0.012 and the best constraint on r of $r < 0.2$ also still comes from the CMBR temperature measurements together with supernovae and baryonic accoustic oscillation measurements which cannot constrain it further. The best limit on r from polarization data alone comes from the measurements by BICEP at $r < 0.7$ [9].

Upcoming polarization experiments aim at providing sensitivities to reach $r = 10^{-2}$, corresponding to signal sizes of tens of nK and the interesting regime of inflationary energy scales of the order of the GUT energy scale. The CMBR polarization thus provides a unique view on the earliest moments of the Universe and accesses energies that colliders cannot explore, with this complementing the measurements in High Energy Physics laboratories in a highly interesting phase space.

4. – The experimental challenge

In order to access the subtle signature of inflation in the CMBR polarization a significant improvement in sensitivity is needed. As current technologies operate close to fundamental limits this step requires large detector arrays. Large bolometer arrays of the order of several 100 detectors are being built and some already operating. The current most sensitive CMBR array is the successor BICEP 2 of BICEP 1. It is already taking data since 2009 with 512 detectors at the South Pole. In November 2010 it has been followed by the first parts of the Keck array which in 2011 will be complemented to its final size of 5×512 detectors and will then be the most sensitive receiver operating.

Another probe of the inflationary B-modes already in the next year will come from the Planck satellite. Its sensitivity for B-modes from gravity wave reaches $r = 0.1$ and stems from large angular scales ($l = 5$) where also a big signal is expected (its size also depends on the details of reionization). With this different angular reach Planck complements the ground-based measurements in the B-mode search.

Now that the required sensitivity can technically be reached there are still two big obstacles in the way of hunting the primordial B-modes, namely systematics and astrophysical foregrounds. It has yet to be shown that the level of instrumental systematics can be controlled to the required size of nK. And the signal from the sky is not a clean view on the CMBR, but contaminated by signals from, *e.g.*, diffuse emission in our galaxy. The main foregrounds come from synchrotron and dust emission which both are polarized. As the frequency dependence of these foregrounds is different from the CMBR dependence the experiments strive to identify and eliminate the foregrounds by evaluating the sky at several frequencies. The synchrotron emission decreases with frequency and is dominant at frequencies below 100 GHz while the dust contamination is increasing with frequency and dominant above 100 GHz where current bolometer arrays are sensitive. The foregrounds can vary spatially and are at most frequencies expected to have larger signals than the tiny primordial B-mode signal, so it will be a significant challenge to prove the successful cleaning of the CMBR maps.

5. – The Q/U Imaging ExperimenT (QUIET)

The QUIET instrument has in contrast to most other current CMBR polarization experiments been built using coherent amplifier technology. This allows the instantaneous measurement of both linear polarization Stokes parameters Q and U in a single pixel and with this provides an excellent handle for the control of polarization systematics. Building on the planar polarimetry receiver developments at the Jet Propulsion Laboratory (JPL) [10] polarimeters at 40 GHz (Q-band) and 90 GHz (W-band) had been developed which were used to build a 19 and a 91 element receiver array, respectively. Both receivers were subsequently installed from summer 2008 till the end of 2010 on the former CBI platform in the Atacama desert in Chile. With its low frequencies QUIET complements the reach of other CMBR experiments using bolometer arrays, which are measuring at frequencies > 100 GHz. The instantaneous sensitivity of the QUIET arrays of ~ 70 (85) $\mu\mathrm{K}\sqrt{s}$ made them the most sensitive HEMT polarization receivers in the world.

Four patches of the sky of 400 square degrees each were chosen to allow almost continuous observing and at the same time minimize the expected potential foreground contamination from the diffuse galactic emission. Two patches in the galactic plane were observed during the time when none of these selected patches were visible.

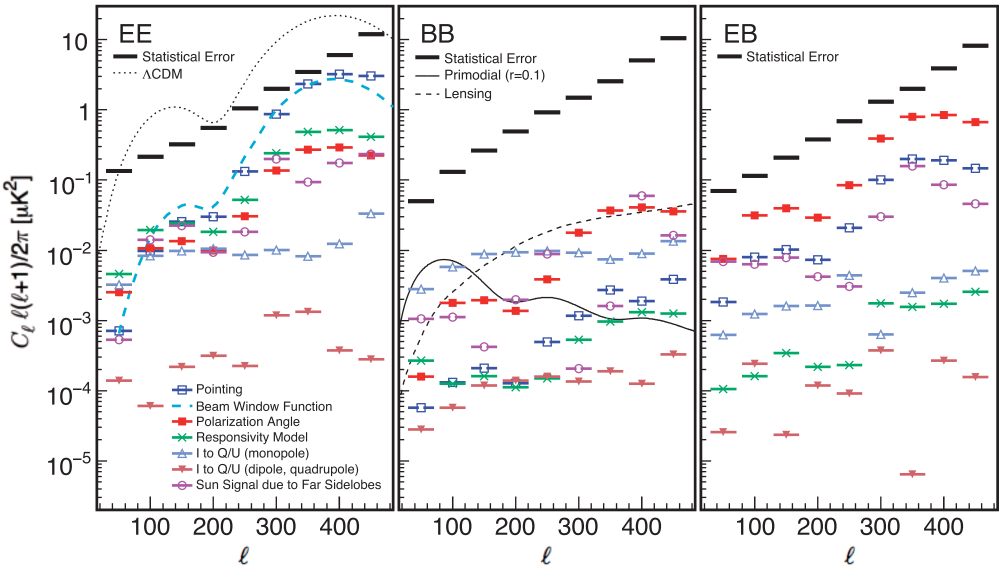

Fig. 4. – The different systematic errors as evaluated in detailed simulations for the QUIET experiment are shown for the E-mode and B-mode spectra as well as the EB-spectra also in comparison to the statistical error (from [11]).

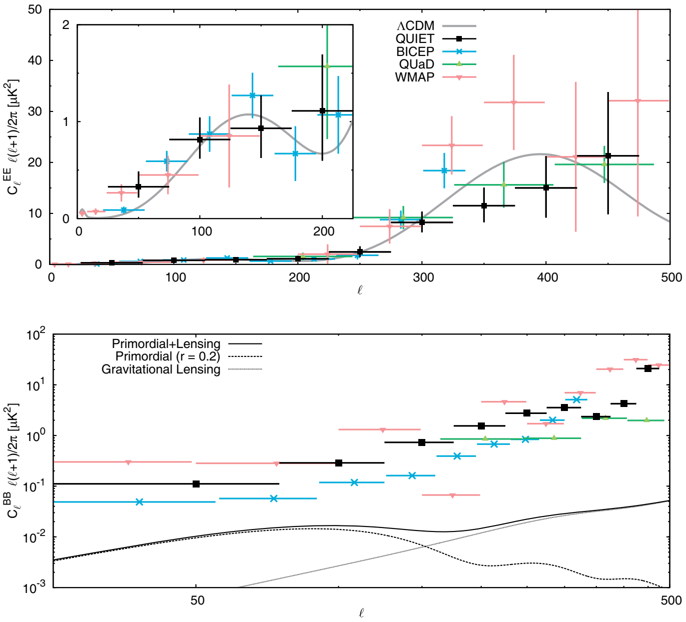

Fig. 5. – Top: Measurements of the E-mode power spectrum with 68% CL error bars together with the ΛCDM model. Bottom: 95% upper limits on the B-mode power spectrum. Expectations from the ΛCDM model are shown with the highest still allowed contribution from primordial gravity waves ($r = 0.2$) (from [11]).

The data streams were switched and differenced at two different frequencies (4 kHz and 50 Hz) in order to suppress the impact of 1/f noise and imperfections of the detection chains in the receiver. In addition possible ground-contamination was minimized through subtraction of ground-templates and the evaluation of the power spectrum by cross-correlating maps observed with different boresight rotations of the receiver.

The analysis of the Q-band data has been finished [11] and the analysis of W-band is underway with a data set with a factor of two better sensitivity. The analysis was performed in a blind way which means that selection criteria were chosen based on the studies of null spectra where two halves of the data were differenced. Though common in high energy physics experiments this philosophy has not yet made its way into the increasingly sophisticated analyses of complex cosmological data and this analysis is one of a few pioneering this approach for CMBR measurements.

The systematics were evaluated through multiple simulations and found to be minor compared to the statistical error. The various contributions are shown in comparison to the statistical error in fig. 4. The main contribution for B-modes comes from instrumental features leading to leakage of the temperature signal into the polarization signal (I to Q/U). The leakage could in the future be corrected for and thus suppress the systematics further by an order of magnitude. For B-modes these systematics are already the lowest reported to date ($< r = 0.1$) at the angular scales relevant for the signature of primordial gravity waves ($l = 100$).

The final Q-band E-mode spectra and limits on the B-spectrum are shown in fig. 5 in comparison to other results. QUIET confirms at lower frequency the only measurement of the first peak in the E-mode power spectrum at 150 GHz. The measured B-mode spectrum is consistent with no signal.

Having successfully proven the potential of the technology with good sensitivity and low systematics the planning for an expansion of the QUIET arrays is now underway to achieve sensitivities for measuring $r \simeq 10^{-2}$.

6. – Outlook

The CMBR measurements have opened a window to rich information on the early Universe. The continuous improvements in the sensitivity allow now to start investigating on the subtle signature from primordial gravity waves from the very first moments of the Universe in the CMBR polarization pattern. Already in the upcoming years an interesting phase space can be explored which will help to shape the theoretical standard models in both cosmology and particle physics.

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