

Cosmology with cosmic microwave background anisotropy

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Abstract. Measurements of CMB anisotropy and, more recently, polarization have played a very important role in allowing precise determination of various parameters of the ‘standard’ cosmological model. The expectation of the paradigm of inflation and the generic prediction of the simplest realization of inflationary scenario in the early Universe have also been established – ‘acausally’ correlated initial perturbations in a flat, statistically isotropic Universe, adiabatic nature of primordial density perturbations. Direct evidence for gravitational instability mechanism for structure formation from primordial perturbations has been established. In the next decade, future experiments promise to strengthen these deductions and uncover the remaining crucial signature of inflation – the primordial gravitational wave background.

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1. Introduction

The transition to precision cosmology has been spearheaded by measurements of CMB anisotropy and, more recently, polarization. Our understanding of cosmology and structure formation necessarily depends on the relatively unexplored physics of the early Universe that provides the stage for scenarios of inflation (or related alternatives). The CMB anisotropy and polarization contain information about the hypothesized nature of random primordial/initial metric perturbations – (Gaussian) statistics, (nearly scale invariant) power spectrum, (largely) adiabatic vs. iso-curvature and (largely) scalar vs. tensor component. The ‘default’ settings in bracket are motivated by inflation. Estimation of cosmological parameters implicitly depends on the assumed values of the initial conditions, or, explicitly on the scenario of generation of initial perturbations [1]. Besides precise determination of various parameters of the ‘standard’ cosmological model, observations have also established some important basic tenets of cosmology and structure formation in the Universe – ‘acausally’ correlated initial perturbations, adiabatic nature of primordial density perturbations, gravitational instability as the mechanism for structure formation. We have inferred a spatially flat Universe where structures form by the

gravitational evolution of nearly scale invariant, adiabatic perturbations in non-baryonic cold dark matter which is sub-dominant to a form dark energy that does not cluster (on astrophysical scales).

The signature of primordial perturbations on super-horizon scales at decoupling in the CMB anisotropy and polarization are the most definite evidence for new physics (eg., inflation) in the early Universe that needs to be uncovered. We briefly review the observables from the CMB sky and importance to understanding cosmology in §2. The article briefly summarizes the recent estimates of the cosmological parameters and highlight the success of recent cosmological observations in establishing some of the fundamental tenets of cosmology and structure:

- Primordial perturbations from inflation (§3);
- Gravitational instability mechanism for structure formation (§4);
- Statistical isotropy of the Universe (§5).

At this time, the attention of the community is largely focused on estimating the cosmological parameters. The next decade would see increasing efforts to observationally test fundamental tenets of the cosmological model using the CMB anisotropy and polarization measurements (and related LSS observations, galaxy survey, gravitational lensing, etc.).

2. CMB observations and cosmological parameters

The angular power spectra of the cosmic microwave background temperature fluctuations (C_ℓ) have become invaluable observables for constraining cosmological models. The position and amplitude of the peaks and dips of C_ℓ are sensitive to important cosmological parameters, such as, the relative density of matter (Ω_0), cosmological constant (Ω_Λ), baryon content (Ω_B), Hubble constant (H_0) and deviation from flatness (curvature) (Ω_K).

The angular spectrum of CMB temperature fluctuations has been measured with high precision on large angular scales ($\ell < 800$) by the WMAP experiment [2], while smaller angular scales have been probed by ground and balloon-based CMB experiments [3–7]. These data are broadly consistent with a Λ CDM model in which the Universe is spatially flat and is composed of radiation, baryons, neutrinos and, the exotic, cold dark matter and dark energy. The exquisite measurements by the Wilkinson microwave anisotropy probe (WMAP) mark a successful decade of exciting CMB anisotropy measurements and are considered a milestone because they combine high angular resolution with full sky coverage and extremely stable ambient condition (that control systematics) allowed by a space mission. Figure 1 shows the angular power spectrum of CMB temperature fluctuations obtained from the first year of WMAP data [8]. The third year of WMAP observations have also included CMB polarization results. The WMAP results are of excellent quality and show robustness to different analysis methods [9].

One of the firm predictions of this working ‘standard’ cosmological model is linear polarization pattern (Q and U Stokes parameters) imprinted on the CMB at last scattering surface. Thomson scattering generates CMB polarization anisotropy at

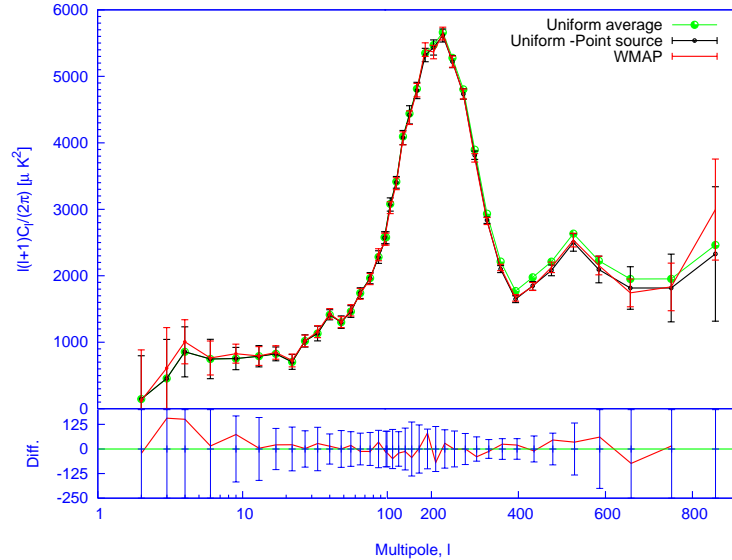


Figure 1. The angular power spectrum estimated from the WMAP multi-frequency using a self-contained model free approach to foreground removal [8] (black curve) is compared to the WMAP team estimate (red). The published binned WMAP power spectrum is plotted in red line with error bars for comparison. The lower panel shows the difference in the estimated power spectra. The method holds great promise for CMB polarization where modeling uncertainties for foregrounds are much higher.

decoupling [10]. A net pattern of linear polarization is retained due to local quadrupole intensity anisotropy of the CMB radiation impinging on the electrons at z_{rec} . The coordinate-free description decomposes the two kinds of polarization pattern on the sky based on their different parities. In the spinor approach, the even parity pattern is called the E -mode and the odd parity pattern the B -mode. With the introduction of polarization, there are a total of four power spectra to determine: C_ℓ^{TT} , C_ℓ^{TE} , C_ℓ^{EE} , C_ℓ^{BB} . Parity conservation [10a] eliminates the two other possible power spectra, C_ℓ^{TB} and C_ℓ^{EB} . While CMB temperature anisotropy can also be generated during the propagation of the radiation from the last scattering surface, the CMB polarization signal can be generated only at the last scattering surface, where the optical depth transits from large to small values. The polarization information complements the CMB temperature anisotropy by isolating the effect at the last scattering surface from effects along the line of sight.

The CMB polarization is an even cleaner probe of early Universe scenarios, that promises to complement the remarkable successes of CMB anisotropy measurements. The CMB polarization signal is much smaller than the anisotropy signal. Measurements of polarization at sensitivities of μK (E -mode) to tens of nK level (B -mode) pose spectacular challenges for ongoing and future experiments.

After the first detection of CMB polarization by DASI in 2003, the field has rapidly grown, with measurements coming in from a host of ground-based and

balloon-borne dedicated CMB polarization experiments. The degree angular scale interferometer (DASI) measured the CMB polarization spectrum over a limited band of angular scales ($l \sim 200\text{--}440$) in late 2002 [12]. The DASI experiment recently published results of much refined measurements with three years of data [13]. More recently, the Boomerang Collaboration reports measurements of C_ℓ^{TT} , C_ℓ^{TE} and C_ℓ^{EE} and a non-detection of B -modes [14]. The recent release of full sky E -mode polarization maps and polarization spectra by WMAP are a new milestone in CMB research [15,16]. As expected, there has been no detection of cosmological signal in B -mode of polarization. The lack of B -mode power suggests that foreground contamination is at a manageable level which is good news for future measurements. Scheduled for launch in 2007, the Planck satellite will greatly advance our knowledge of CMB polarization by providing foreground/cosmic variance-limited measurements of C_ℓ^{TE} and C_ℓ^{EE} out beyond $l \sim 1000$. We also expect to detect the lensing signal, although with relatively low precision, and could see gravity waves at a level of $r \sim 0.1$. In the future, a dedicated CMB polarization mission has been listed as a priority by both NASA (beyond Einstein) and ESA (cosmic vision) in the time frame 2015–2020. These primarily target the B -mode polarization signature of gravity waves, and consequently, identify the viable sectors in the space of inflationary parameters.

The measurements of the anisotropy in the cosmic microwave background (CMB) over the past decade has led to ‘precision cosmology’. Observations of the large-scale structure in the distribution of galaxies, high red-shift supernova, and more recently, CMB polarization, have provided the required complementary information. The current up-to-date status of cosmological parameter estimates from joint analysis of CMB anisotropy and large scale structure (LSS) data is usually found in the parameter estimation paper accompanying the most recent results announcement of a major experiment, such as recent WMAP release [17]. Using WMAP data only, the best-fit values for cosmological parameters for the power-law, flat, Λ CDM model are $(\Omega_m h^2, \Omega_b h^2, h, n_s, \tau, \sigma_8) = (0.127_{-0.013}^{+0.007}, 0.0223_{-0.0009}^{+0.0007}, 0.73_{-0.03}^{+0.03}, 0.951_{-0.019}^{+0.015}, 0.09_{-0.03}^{+0.03}, 0.74_{-0.06}^{+0.05})$. Table 1 summarizes best-fit parameters that correspond to the maximum of the joint likelihoods (in a multi-dimensional parameter space) of various combinations of CMB anisotropy and large scale structure data.

3. Primordial perturbations from inflation

Any observational comparison based on the structure formation in the Universe necessarily depends on the assumed initial conditions describing the primordial seed perturbations. It is well-appreciated that in ‘classical’ Big Bang model the initial perturbations would have had to be generated ‘acausally’. Besides resolving a number of other problems of classical Big Bang, inflation provides a mechanism for generating these apparently ‘acausally’ correlated primordial perturbations [18].

The power in the CMB temperature anisotropy at low multipoles ($l \lesssim 60$) first measured by the COBE-DMR [19] did indicate the existence of correlated cosmological perturbations on super Hubble-radius scales at the epoch of last scattering, except for the (rather unlikely) possibility of all the power arising from the integrated Sachs–Wolfe effect along the line of sight. Since the polarization anisotropy

Table 1. The table taken from ref. [17] summarizes the estimated values of the cosmological parameters of the Λ CDM Model. The best-fit parameters correspond to the maximum of the joint likelihoods of various combinations of CMB anisotropy and large-scale structure data.

Parameters	Data combination			
	WMAP only	WMAP +CBI+VSA	WMAP+ACBAR +BOOMERanG	WMAP + 2dFGRS
$100\Omega_b h^2$	$2.233^{+0.072}_{-0.091}$	$2.212^{+0.066}_{-0.084}$	$2.231^{+0.070}_{-0.088}$	$2.223^{+0.066}_{-0.083}$
$\Omega_m h^2$	$0.1268^{+0.0072}_{-0.0095}$	$0.1233^{+0.0070}_{-0.0086}$	$0.1259^{+0.0077}_{-0.0095}$	$0.1262^{+0.0045}_{-0.0062}$
h	$0.734^{+0.028}_{-0.038}$	$0.743^{+0.027}_{-0.037}$	$0.739^{+0.028}_{-0.038}$	$0.732^{+0.018}_{-0.025}$
A	$0.801^{+0.043}_{-0.054}$	$0.796^{+0.042}_{-0.052}$	$0.798^{+0.046}_{-0.054}$	$0.799^{+0.042}_{-0.051}$
τ	$0.088^{+0.028}_{-0.034}$	$0.088^{+0.027}_{-0.033}$	$0.088^{+0.030}_{-0.033}$	$0.083^{+0.027}_{-0.031}$
n_s	$0.951^{+0.015}_{-0.019}$	$0.947^{+0.014}_{-0.017}$	$0.951^{+0.015}_{-0.020}$	$0.948^{+0.014}_{-0.018}$
σ_8	$0.744^{+0.050}_{-0.060}$	$0.722^{+0.043}_{-0.053}$	$0.739^{+0.047}_{-0.059}$	$0.737^{+0.033}_{-0.045}$
Ω_m	$0.238^{+0.030}_{-0.041}$	$0.226^{+0.026}_{-0.036}$	$0.233^{+0.029}_{-0.041}$	$0.236^{+0.016}_{-0.024}$

is generated only at the last scattering surface, the negative trough in the C_l^{TE} spectrum at $l \sim 130$ (that corresponds to a scale larger than the horizon at the epoch of last scattering) measured by WMAP first sealed this loophole, and provides an unambiguous proof of apparently ‘acausal’ correlations in the cosmological perturbations [15,16,20].

Besides, the entirely theoretical motivation of the paradigm of inflation, the assumption of Gaussian, random adiabatic scalar perturbations with a nearly scale-invariant power spectrum is arguably also the simplest possible choice for the initial perturbations. What has been truly remarkable is the extent to which recent cosmological observations have been consistent with and, in certain cases, even vindicated the simplest set of assumptions for the initial conditions for the (perturbed) Universe discussed below.

3.1 Nearly zero curvature of space

The most interesting and robust constraint obtained in our quests in the CMB sky is that on the spatial curvature of the Universe. The combination of CMB anisotropy, LSS and other observations can pin down the Universe to be flat, $\Omega_k \approx -0.02 \pm 0.02$. This is based on the basic geometrical fact that angular scale subtended in the sky by the acoustic horizon would be different in a Universe with uniform positive (spherical), negative (hyperbolic), or, zero (Euclidean) spatial curvatures. Inflation dilutes the curvature of the Universe to negligible values and generically predicts a (nearly) Euclidean spatial section.

The CMB data [14] alone places a constraint on the curvature which is $\Omega_k = -0.037_{-0.039}^{+0.033}$. Addition of the LSS data, yields a median value of $\Omega_k = -0.027 \pm 0.016$. Restricting H_0 by the application of a Gaussian HST prior, the curvature density determined from the Boom2K flight data set and all the previous CMB results was $\Omega_k = -0.015 \pm 0.016$. A constraint $\Omega_k = -0.010 \pm 0.009$ is obtained by combining CMB data with the red luminous galaxy clustering data, which has its own signature of baryon acoustic oscillations [21]. The WMAP 3-year data can (jointly) constrain $\Omega_k = -0.024_{-0.013}^{+0.016}$ even when allowing for dark energy with arbitrary (constant) equation of state w [17]. (The corresponding joint limit from WMAP-3 yr on the equation of state is also impressive, $w = -1.062_{-0.079}^{+0.128}$.)

3.2 Adiabatic primordial perturbation

The polarization measurements provides an important test on the adiabatic nature of primordial scalar fluctuations [21a]. CMB polarization is sourced by the anisotropy of the CMB at recombination, z_{rec} , the angular power spectra of temperature and polarization are closely linked. Peaks in the polarization spectra are sourced by the velocity term in the same acoustic oscillations of the baryon-photon fluid at last scattering. Hence, a clear indication of the adiabatic initial conditions is the compression and rarefaction peaks in the temperature anisotropy spectrum be ‘out-of-phase’ with the gradient (velocity) driven peaks in the polarization spectra.

The recent measurements of the angular power spectrum of the E -mode of CMB polarization at large l from experiments such as Boomerang2K, DASI, CAPMAP and CBI have confirmed that the peaks in the spectra are out-of-phase with that of the temperature anisotropy spectrum. Data from others are comparable. The data are good enough to indicate that the peaks in EE and TE are out-of-phase with that of TT as expected for adiabatic initial conditions [14]. These conclusions are further borne out in the recent polarization results from the three years of WMAP data [16].

3.3 Nearly scale-invariant power spectrum?

In a simple power-law parametrization of the primordial spectrum of density perturbation ($|\delta_k|^2 = Ak^{n_s}$), the scale-invariant spectrum corresponds to $n_s = 1$. Recent estimation of (smooth) deviations from scale invariance favor a nearly scale-invariant spectrum [22].

Many model-independent searches have also been made to look for features in the CMB power spectrum [23–26]. Accurate measurements of the angular power spectrum over a wide range of multipoles from the WMAP have opened up the possibility to deconvolve the primordial power spectrum for a given set of cosmological parameters [27–31]. The primordial power spectrum has been deconvolved from the angular power spectrum of CMB anisotropy measured by WMAP using an improved implementation of the Richardson–Lucy algorithm [30]. The most prominent feature of the recovered primordial power spectrum is a sharp, infra-red cut-off on the horizon scale. It also has a localized excess just above the cut-off

which leads to great improvement of likelihood over the simple monotonic forms of model infra-red cut-off spectra considered in the post-WMAP literature. The form of infra-red cut-off is robust to small changes in cosmological parameters. Theoretical motivation and models that give features in the power spectrum have also been studied and compared in recent post-WMAP literature [32–34]. Remarkably similar form of infra-red cutoff is known to arise in very reasonable extensions and refinement of the predictions from simple inflationary scenarios, such as the modification to the power spectrum from a pre-inflationary radiation dominated epoch or from a sharp change in slope of the inflation potential [35].

3.4 *Gaussian primordial perturbations*

The detection of primordial non-Gaussian fluctuations in the CMB would have a profound impact on our understanding of the physics of the early Universe. The Gaussianity of the CMB anisotropy on large angular scales directly implies Gaussian primordial perturbations [36,37] that is theoretically motivated by inflation [18]. The simplest inflationary models predict only very mild non-Gaussianity that should be undetectable in the WMAP data.

The CMB anisotropy maps (including the non-Gaussianity analysis carried out by the WMAP team on the first year data [38]) have been found to be consistent with a Gaussian random field. Consistent with the predictions of simple inflationary theories, no significant deviations from Gaussianity has been found in the CMB maps using general tests such as Minkowski functionals, the bispectrum, trispectrum in the three year WMAP data [17].

3.5 *Primordial tensor (GW) perturbations*

Inflationary models can produce tensor perturbations from gravitational waves that are predicted to evolve independently of the scalar perturbations, with an uncorrelated power spectrum. The amplitude of a tensor mode falls off rapidly on sub-Hubble radius scales. The tensor modes on the scales of Hubble-radius the line of sight to the last scattering distort the photon propagation and generate an additional anisotropy pattern predominantly on the largest scales. It is common to parametrize the tensor component by the ratio $r_{k_*} = A_t/A_s$, where A_t is the primordial power in the transverse traceless part of the metric tensor perturbations, A_s is the amplitude scalar perturbation at a comoving wave number, k_* (in Mpc^{-1}). For power-law models, recent WMAP data alone put an improved upper limit on the tensor-to-scalar ratio, $r_{0.002} < 0.55$ (95% CL) and the combination of WMAP and the lensing-normalized SDSS galaxy survey implies $r_{0.002} < 0.28$ (95% CL) [14].

On large angular scales, the curl component of CMB polarization is a unique signature of tensor perturbations. The CMB polarization is a direct probe of the energy scale of early Universe physics that generate the primordial metric perturbations. Inflation generates both (scalar) density perturbations and (tensor) gravity wave perturbations. The relative amplitude of tensor-to-scalar perturbations, r , sets the energy scale for inflation as $\mathcal{E}_{\text{inf}} = 3.4 \times 10^{16} \text{ GeV } r^{1/4}$. A measurement

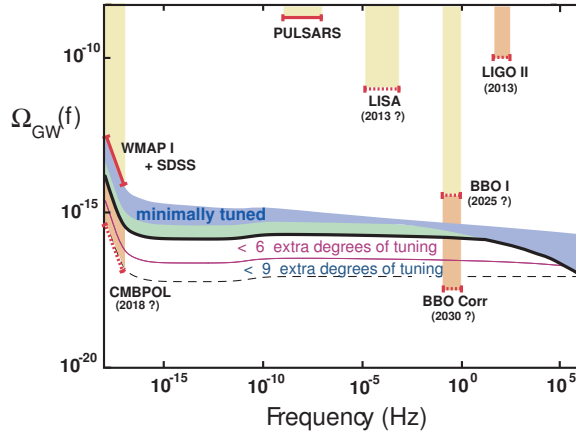


Figure 2. The figure taken from ref. [40] shows the theoretical predictions and observational constraints on primordial gravitational waves from inflation. The gravitational wave energy density per logarithmic frequency interval, (in units of the critical density) is plotted versus frequency. The blue region represents the range predicted for simple inflation models with the minimal number of parameters and tunings. The dashed curves have lower values of tensor contribution, r , that is possible with more fine-tuned inflationary scenarios. The currently existing experimental constraints shown are due to: Big Bang nucleosynthesis (BBN), binary pulsars, and WMAP-1 (first year) with SDSS. Also shown are the projections for LIGO (both LIGO-I, after one year running, and LIGO-II), LISA, and BBO (both initial sensitivity, BBO-I, and after cross-correlating receivers, BBO-Corr). Also seen is the projected sensitivity of a future space mission for CMB polarization (CMBPol).

of B -mode polarization on large scales would give us this amplitude, and hence *a direct determination of the energy scale of inflation*. Besides being a generic prediction of inflation, the cosmological gravity wave background from inflation would be a fundamental test of GR on cosmic scales and the semi-classical behavior of gravity. Figure 2 summarizes the current theoretical understanding, observational constraints and future possibilities for the stochastic gravity wave background from inflation.

4. Gravitational instability mechanism for structure formation

It is a well-accepted notion that the large-scale structure in the distribution of matter in the present Universe arose due to gravitational instability from the same primordial perturbation seen in the CMB anisotropy at the epoch of recombination. This fundamental assumption in our understanding of structure formation has recently found an irrefutable direct observational evidence [21,39].

For baryonic density comparable to that expected from Big Bang nucleosynthesis, acoustic oscillations in the baryon–photon plasma will also be observably imprinted onto the late-time power spectrum of the non-relativistic matter. The

remnants of the acoustic feature in the matter correlations are weak (10% contrast in the power spectrum) and on large scales. The acoustic oscillations of characteristic wave numbers translate to a bump (a spike softened by gravitational clustering of baryon into the well-developed dark matter over-densities) in the correlation function at $105h^{-1}$ Mpc separation. The large-scale correlation function of a large spectroscopic sample of luminous, red galaxies (LRGs) from the Sloan digital sky survey that covers ~ 4000 square degrees out to a red-shift of $z \sim 0.5$ with $\sim 50,000$ galaxies has allowed a clean detection of the acoustic bump in distribution of matter in the present Universe. The acoustic signatures in the large-scale clustering of galaxies provide direct, irrefutable evidence for the theory of gravitational clustering, notably the idea that large-scale fluctuations grow by linear perturbation theory from $z \sim 1000$ to the present due to gravitational instability.

5. Statistical isotropy of the Universe

The *cosmological principle* that led to the idealized FRW Universe found its strongest support in the discovery of the (nearly) isotropic, Planckian, cosmic microwave background. The isotropy around every observer leads to spatially homogeneous cosmological models. The large scale structure in the distribution of matter in the Universe (LSS) implies that the symmetries incorporated in FRW cosmological models are to be interpreted statistically.

Interestingly enough, the statistical isotropy of CMB has come under a lot of scrutiny after the WMAP results. Tantalizing evidence of SI breakdown (albeit, in very different guises) has mounted in the WMAP first year sky maps, using a variety of different statistics. It was pointed out that the suppression of power in the quadrupole and octupole are aligned [41]. Further ‘multipole-vector’ directions associated with these multipoles (and some other low multipoles as well) appear to be anomalously correlated [42,43]. There are indications of asymmetry in the power spectrum at low multipoles in opposite hemispheres [44]. Possibly related, are the results of tests of Gaussianity that show asymmetry in the amplitude of the measured genus amplitude (at about 2 to 3σ significance) between the north and south galactic hemispheres [45–47]. Analysis of the distribution of extrema in WMAP sky maps has indicated non-Gaussianity, and to some extent, violation of SI [48]. The three-year WMAP maps are consistent with the first-year maps up to a small quadrupole difference. The two additional years of data and the improvements in analysis has not significantly altered the low multipole structures in the maps [2]. Hence, ‘anomalies’ are expected to persist at the same modest level of significance and are unlikely to be artifacts of noise, systematics, or the analysis in the first year data. The cosmic significance of these ‘anomalies’ remains debatable also because of the *a posteriori* statistics employed to ferret them out of the data. More importantly, what is missing is a common, well-defined, mathematical language to quantify SI (as distinct from non Gaussianity) and the ability to ascribe statistical significance to the anomalies unambiguously.

Recently, the bipolar power spectrum (BiPS) κ_ℓ ($\ell = 1, 2, 3, \dots$) of the CMB map was proposed as a statistical tool of detecting and measuring departure from SI [49,50]. The non-zero value of the BiPS spectrum imply the breakdown of

statistical isotropy

$$\text{Statistical isotropy} \implies \kappa_\ell = 0 \quad \forall \ell \neq 0. \quad (1)$$

BiPS is sensitive to structures and patterns in the underlying total two-point correlation function [49,50,53].

Measurement of the BiPS on the CMB anisotropy maps based on the first year WMAP data shows that the measured BiPS for all the WMAP sky maps are consistent with statistical isotropy [51,52,54]. The ongoing BiPS analysis on WMAP-3 yr data indicates that BiPS of the three years' maps show an improvement in SI – the deviations are smaller and fewer [55].

CMB polarization maps over large areas of the sky have been recently delivered by WMAP. The statistical isotropy of the CMB polarization maps will be an independent probe of the cosmological principle. Since CMB polarization is generated at the surface of the last scattering, violations of statistical isotropy are pristine cosmic signatures and more difficult to attribute to the local Universe. The bipolar power spectrum has been defined and implemented for CMB polarization and show great promise [56].

6. Conclusions

The past few years has seen the emergence of a ‘concordant’ cosmological model that is consistent with observational constraints both from the background evolution of the Universe, as well that, from the formation of large scale structures. It is certainly fair to say that the present edifice of the ‘standard’ cosmological models is robust. A set of foundation and pillars of cosmology have emerged and are each supported by a number of distinct observations [57].

The community is now looking beyond the estimation of parameters of a working ‘standard’ model of cosmology. There is increasing effort towards establishing the basic principles and assumptions. The feasibility and promise of this ambitious goal is based on the grand success in the recent years of the CMB anisotropy measurements. The quest in the CMB sky from ground, balloon and space have indeed yielded great results! While the ongoing WMAP and upcoming Planck space missions will further improve the CMB polarization measurements, there are already proposals for the next generation dedicated satellite mission in 2015–20 for CMB polarization measurements at the best achievable sensitivity.

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