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Cosmological quests in the CMB sky

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Abstract

Observational Cosmology has indeed made very rapid progress in recent years. The ability to quantify the universe has largely improved due to observational constraints coming from structure formation Measurements of CMB anisotropy and, more recently, polarization have played a very important role. Besides precise determination of various parameters of the 'standard' cosmological model, observations have also established some important basic tenets that underlie models of cosmology and structure formation in the universe – 'acausally' correlated initial perturbations in a flat, statistically isotropic universe, adiabatic nature of primordial density perturbations. These are consistent with the expectation of the paradigm of inflation and the generic prediction of the simplest realization of inflationary scenario in the early universe. Further, gravitational instability is the established mechanism for structure formation from these initial perturbations. In the next decade, future experiments promise to strengthen these deductions and uncover the remaining crucial signature of inflation – the primordial gravitational wave background.

1 Introduction

The 'standard' model of cosmology must not only explain the dynamics of the homogeneous background universe, but also satisfactorily describe the perturbed universe – the generation, evolution and finally, the formation of large scale structures in the universe. It is fair to say much of the recent progress in cosmology has come from the interplay between refinement of the theories of structure formation and the improvement of the observations.

The transition to precision cosmology has been spearheaded by measurements of CMB anisotropy and, more recently, polarization. Despite its remarkable success, the 'standard' model of cosmology remains largely tied to a number of fundamental assumptions that have yet to find precise observational verification : the Cosmological Principle, the paradigm of inflation in the early universe and its observable consequences (flat spatial geometry, scale invariant spectrum of primordial seed perturbations, cosmic gravitational radiation background etc.). Our understanding of cosmology and structure formation necessarily depends on the relatively unexplored physics of the early universe that

[1]Invited plenary talk at the International Conference on *Einstein's Legacy in the New Millennium*, Dec.15-22,2005, Puri, India.

provides the stage for scenarios of inflation (or related alternatives). The CMB anisotropy and polarization contains 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 depend 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 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 a predominant form of 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 section 2 The article only briefly touches on the important aspect of precision cosmology and summarizes the recent estimates of the cosmological parameters. This information is available in more detail in many recent literature, eg. Ref.[2, 20]. The main theme of the article is to highlight [1] the quest cosmological observations in establishing some of the fundamental tenets of cosmology and structure :

- Statistical Isotropy of the universe (Sec. 3);
- Gravitational instability mechanism for structure formation(Sec. 4);
- Primordial perturbations from Inflation.(Sec. 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 the C_ℓ are sensitive to important cosmological parameters, such as, the relative density of

[1] The article does *not* attempt at a review and is far from being exhaustive in the coverage of the science and literature.

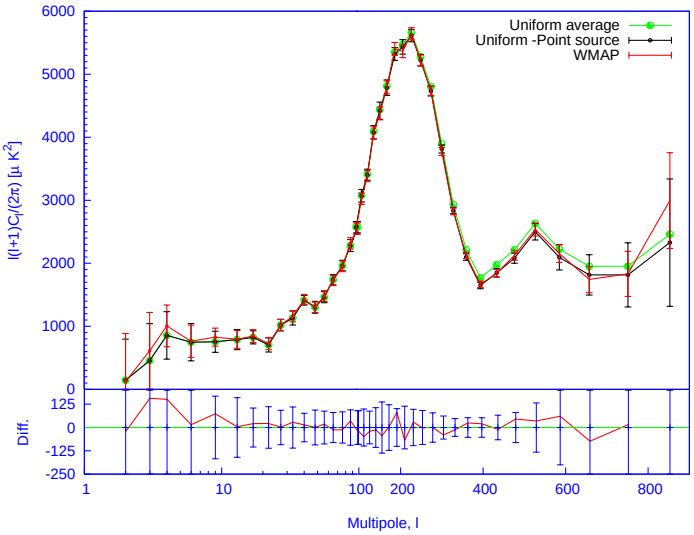


Figure 1: The angular power spectrum estimated from the WMAP multi-frequency using a self-contained model free approach to foreground removal (black curve) is compared to the WMAP team estimate (red).The published binned WMAP power spectrum plotted in red line with error bars for comparison. The lower 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.

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 [4], while smaller angular scales have been probed by ground and balloon-based CMB experiments [5, 6, 7, 8, 9]. These data are broadly consistent with a ΛCDM 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 [10]. 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 [12].

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 decoupling [13]. This arises from the polarization dependence of the differential cross section: $d\sigma/d\Omega \propto |\epsilon' \cdot \epsilon|^2$, where ϵ and ϵ' are the incoming and outgoing polarization states [14] involving linear polarization only. A local quadrupole temperature anisotropy produces a net polarization, because of the $\cos^2\theta$ dependence of the cross section. A net pattern of linear polarization is

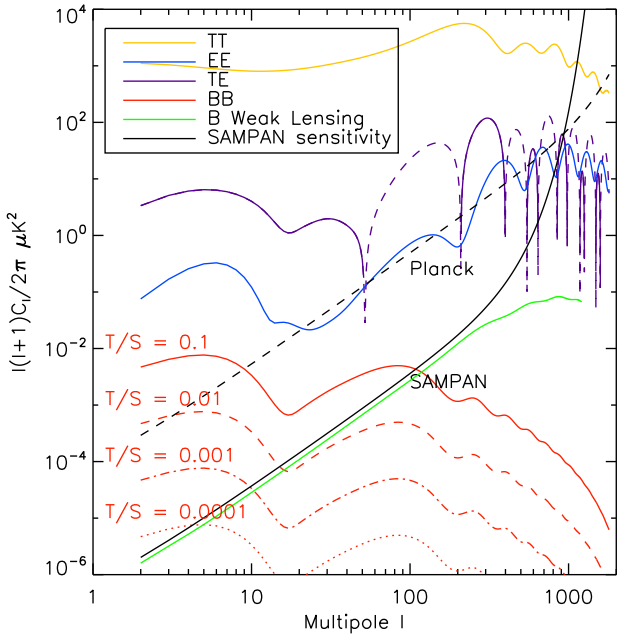


Figure 2: Figure taken from Ref. [15] shows the CMB anisotropy (TT) and the three polarization power spectra (TE,EE,BB) that can be extracted from CMB sky. The $C_\ell^{\rm BB}$ spectra being the weakest, presents the toughest challenge. The three $C_\ell^{\rm BB}$ curves correspond to a specific energy scale of inflation ranging from 2.2 to 0.4 in units of $(10^{16} GeV)$. These predictions will be within reach of dedicated satellite missions presently under study both at ESA and NASA.

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 4 power spectra to determine: $C_\ell^{\rm TT}, C_\ell^{\rm TE}, C_\ell^{\rm EE}, C_\ell^{\rm BB}$. Parity conservation [2] eliminates the two other possible power spectra, $C_\ell^{\rm TB}$ & $C_\ell^{\rm EB}$. 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. As seen in figure 2, the CMB polarization signal is much smaller

[2] On the other hand, a non-zero detection of $C_\ell^{\rm TB}$ or $C_\ell^{\rm EB}$, over and above observational artifacts, could be tell-tale signatures of exotic parity violating physics [11].

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 ($l \sim 200 - 440$) in late 2002 [16]. The DASI experiment recently published results of much refined measurements with 3 years of data [18]. More recently, the Boomerang collaboration reports measurements of $C_\ell^{\rm TT}$, $C_\ell^{\rm TE}$ and $C_\ell^{\rm EE}$ and a non–detection of B–modes [20]. The recent release of full sky E-mode polarization maps and polarization spectra by WMAP are a new milestone in CMB research [3, 17]. 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 $C_\ell^{\rm TE}$ and $C_\ell^{\rm EE}$ 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.

Table 1: The table taken from Ref.[2] summarizes the estimated values of the cosmological parameters of the ΛCDM Model. The best fit parameters correspond to the maximum of the joint likelihoods of various combinations of CMB anisotropy and large scale structure data.

Data combo.→ Parameters ↓	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	$0.238^{+0.030}_{-0.041}$	$0.226^{+0.026}_{-0.036}$	$0.233^{+0.029}_{-0.041}$	$0.236^{+0.016}_{-0.024}$

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 redshift 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 best to look up in the parameter estimation paper accompanying the most recent results announcement of a major experiment, such as recent WMAP release [2]. Using WMAP data only, the best fit values for cosmological parameters for the power-law, flat, ΛCDM model are $(\Omega_m h^2, \Omega_b h^2, h, n_s, \tau, \sigma_8) = (0.127^{+0.007}_{-0.013}, 0.0223^{+0.0007}_{-0.0009}, 0.73^{+0.03}_{-0.03}, 0.951^{+0.015}_{-0.019}, 0.09^{+0.03}_{-0.03}, 0.74^{+0.05}_{-0.06})$. 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 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.

The CMB anisotropy and its polarization is currently the most promising observational probe of the global spatial structure of the universe on length scales near to and even somewhat beyond the 'horizon' scale ($\sim cH_0^{-1}$). The exquisite measurement of the temperature fluctuations in the CMB provide an excellent test bed for establishing the statistical isotropy (SI) and homogeneity of the universe. In 'standard' cosmology, CMB anisotropy signal is expected to be statistically isotropic, i.e., statistical expectation values of the temperature fluctuations $\Delta T(\hat{q})$ are preserved under rotations of the sky. In particular, the angular correlation function $C(\hat{q}, \hat{q}') \equiv \langle \Delta T(\hat{q}) \Delta T(\hat{q}') \rangle$ is rotationally invariant for Gaussian fields. In spherical harmonic space, where $\Delta T(\hat{q}) = \sum_{lm} a_{lm} Y_{lm}(\hat{q})$, the condition of *statistical isotropy* (SI) translates to a diagonal $\langle a_{lm} a^*_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'}$ where C_l, is the widely used angular power spectrum of CMB anisotropy. The C_l is a complete description of (Gaussian) SI CMB sky CMB anisotropy and hence would be (in principle) an inadequate measure for comparing models when SI is violated [19].

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 octopole are aligned [21]. Further "multipole-vector" directions associated with these multipoles (and some other low multipoles as well) appear to be anomalously correlated [22, 23]. There are indications of asymmetry in the power spectrum at low multipoles in opposite hemispheres [24]. 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 [25, 26, 27]. Analysis of the

distribution of extrema in *WMAP* sky maps has indicated non-gaussianity, and to some extent, violation of SI [28]. 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 [4]. 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 aposteriori 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.

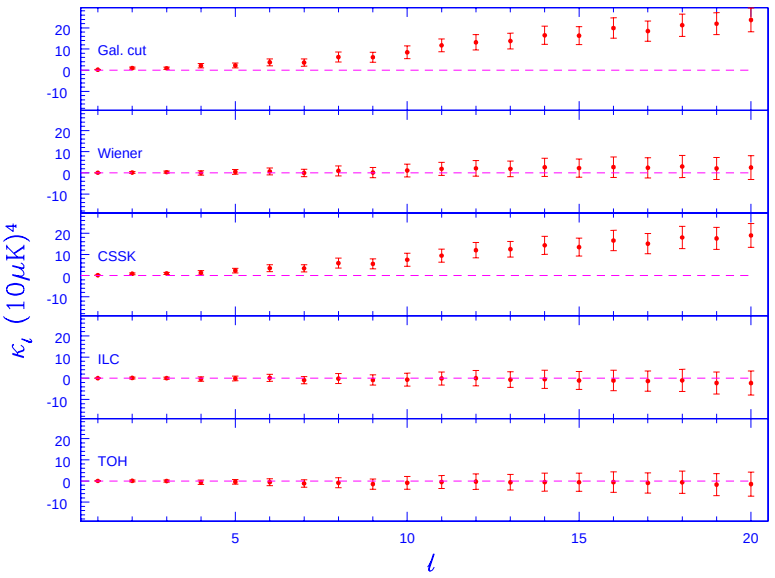


Figure 3: BiPS measurements for different CMB maps based on the WMAP-1year data filtered with a window with $l_s = 30$, $l_t = 20$. This measures the statistical isotropy of the WMAP in the modest $20 < l < 40$ range in the multipole space where certain anomalies have been reported. The bottom two panels show that BiPS of WMAP-1 is consistent with SI. ILC with a 10° galactic cut (top) has the same BiPS as CSSK ($l_s = 30$, $l_t = 20$) and explains that the raising tail of CSSK map is because of the mask. Although the Weiner filtered map shows a null BiPS in this filter, it shows a rising tail just like CSSK in a filter peaking a slightly larger l. This reflects the measurable SI violation created by Weiner filtering that the suppresses power in the foreground contaminated regions along a band around the galactic plane [32].

The observed CMB sky is a single realization of the underlying correlation, hence the detection of SI violation, or correlation patterns, pose a great observational challenge. It is essential to develop a 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 ($\ell = 1, 2, 3, \ldots$) of the CMB map was proposed as a statistical tool of detecting and measuring departure from SI [29, 30]. The non-zero value of the BiPS spectrum imply the break down of statistical isotropy

$$\text{STATISTICAL ISOTROPY} \quad \Longrightarrow \quad \kappa_\ell = 0 \quad \forall \ell \neq 0. \tag{1}$$

BiPS is sensitive to structures and patterns in the underlying total two-point correlation function [29, 30]. The BiPS is particularly sensitive to real space correlation patterns (preferred directions, etc.) on characteristic angular scales. In harmonic space, the BiPS at multipole ℓ sums power in off-diagonal elements of the covariance matrix, $\langle a_{lm} a_{l'm'} \rangle$, in the same way that the 'angular momentum' addition of states lm, $l'm'$ have non-zero overlap with a state with angular momentum $|l - l'| < \ell < l + l'$. Signatures, like a_{lm} and $a_{(l+n)\ m}$ being correlated over a significant range l are ideal targets for BiPS. These are typical of SI violation due to cosmic topology and the predicted BiPS in these models have a strong spectral signature in the bipolar multipole ℓ space [33]. The orientation independence of BiPS is an advantage since one can obtain constraints on cosmic topology that do not depend on the unknown specific orientation of the pattern (*e.g.*, preferred directions). Measurement of the BiPS on the following CMB anisotropy maps based the first year WMAP data : A) a foreground cleaned map (denoted as 'TOH') [21]; B) the Internal Linear Combination map (denoted as 'ILC' in the figures) [52], and C) a customized linear combination of the QVW maps of WMAP with a galactic cut (denoted as 'CSSK'). Fig. 3 shows that the measured BiPS for all the WMAP sky maps are consistent with statistical isotropy [31, 32]. The ongoing BIPS analysis on WMAP-3yr data indicates that BiPS of the three years maps show an improvement in SI – the deviations are smaller and fewer [40].

CMB polarization maps over large areas of the sky have been recently delivered by experiments in the near future. The statistical isotropy of the CMB polarization maps will be an independent probe of the cosmological principle. Since CMB polarization is generated on at the surface of 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 [41].

BiPS is a promising probe to detect the topology of the universe.The underlying correlation patterns in the CMB anisotropy in a multiply connected universe is related to the symmetry of the Dirichlet domain. The BiPS expected in flat, toroidal models of the universe has been computed and shown to be related to the principle directions in the Dirichlet domain [33]. As a tool for constraining cosmic topology, the BiPS has the advantage of being independent of the overall orientation of the Dirichlet domain with respect to the sky. Hence, the null result of BiPS have important implication for cosmic topology. This approach complements other direct search for signature of cosmic topology [35, 36] and our results are consistent with the absence of the matched circles and the null S-map test of the WMAP CMB maps [37, 38, 39]. Full Bayesian likelihood comparison to the data of specific cosmic topology models is another approach that has applied to COBE-DMR data [19]. The BiPS has also been used to constrain anisotropic models of cosmology using SI violating CMB patterns that arise in them [42].

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 [43, 44].

The acoustic peaks occur because the cosmological perturbations excite acoustic waves in the relativistic plasma of the early universe [45, 46, 47, 48, 49]. The recombination of baryons at redshift $z \approx 1100$ effectively decouples the baryon and photons in the plasma abruptly switching off the wave propagation. In the time between the excitation of the perturbations and the epoch of recombination, modes of different wavelength can complete different numbers of oscillation periods. This translates the characteristic time into a characteristic length scale and produces a harmonic series of maxima and minima in the CMB anisotropy power spectrum. The acoustic oscillations have a characteristic scale known as the sound horizon, which is the comoving distance that a sound wave could have traveled up to the epoch of recombination. This physical scale is determined by the expansion history of the early universe and the baryon density that determines the speed of acoustic waves in the baryon-photon plasma.

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. This is easier understood in a real space description of the response of the CDM and baryon-photon fluid to metric perturbations [43]. An initial small delta-function (sharp spike) adiabatic perturbation ($\delta \ln a|_H$) at a point leads to corresponding spikes in the distribution of cold dark matter (CDM), neutrinos, baryons and radiation (in the 'adiabatic' proportion, $1 + w_i$, of the species). The CDM perturbation grows in place while the baryonic perturbation being strongly coupled to radiation is carried outward in an expanding spherical wave. At recombination, this shell is roughly $105h^{-1}$ Mpc in (comoving) radius when the propagation of baryons ceases. Afterward, the combined dark matter and baryon perturbation seeds the formation of large-scale structure. 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 wavenumber translates 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 redshift 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. Figure 4 shows the correlation function derived from SDSS data that clearly shows the acoustic 'bump' feature at a fairly good statistical significance [43]. 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

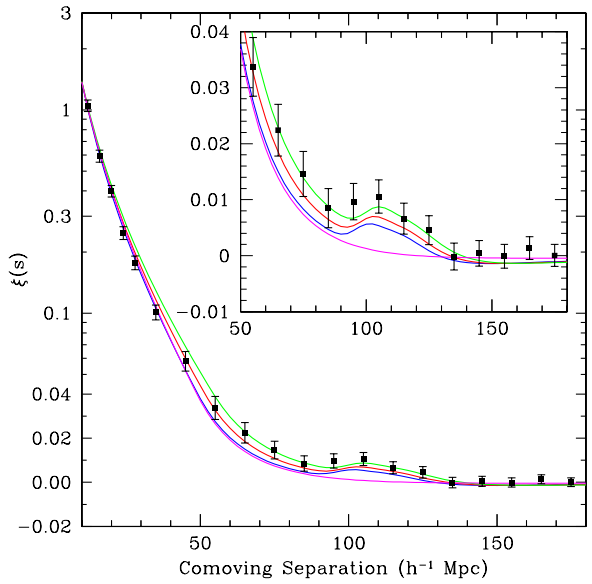


Figure 4: The large-scale redshift-space correlation function of the SDSS LRG sample taken from Ref. [43]. The inset shows an expanded view with a linear vertical axis. The magenta line shows a pure CDM model ($\Omega_m h^2 = 0.105$), which lacks the acoustic peak. The models are $\Omega_m h^2 = 0.12$ (top, green), 0.13 (red), and 0.14 (bottom with peak, blue), all with $\Omega_b h^2 = 0.024$ and $n = 0.98$ and with a mild non-linear prescription folded in. The clearly visible bump at $\sim 100h^{-1}$ Mpc scale is statistically significant.

instability.

5 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 [50].

The power in the CMB temperature anisotropy at low multipoles ($l \lesssim 60$) first measured by the COBE-DMR [51] 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 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 [3, 17, 52].

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.

5.1 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 curvature. Inflation dilutes the curvature of the universe to negliglible values and generically predicts a (nearly) Euclidean spatial section.

The CMB data [20] alone places a constraint on the curvature which is $\Omega_k = -0.037^{+0.033}_{-0.039}$. 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 previous CMB results was $\Omega_k = -0.015 \pm 0.016$. A constraint $\Omega_k = -0.010 \pm 0.009$ obtained by combining CMB data with the red luminous galaxy clustering data, which has its own signature of baryon acoustic oscillations [43]. The WMAP 3 year data can (jointly) constrain $\Omega_k = -0.024^{+0.016}_{-0.013}$ even when allowing for dark energy with arbitrary (constant) equation state w [2]. (The corresponding joint limit from WMAP-3yr on the equation of state is also impressive, $w = -1.062^{+0.128}_{-0.079}$).

5.2 Adiabatic primordial perturbation

The polarization measurements provides an important test on the adiabatic nature primordial scaler fluctuations [3]. 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 figure 5 taken from Ref. [20] on the Boomerang 2000 flight data reflects the current observational status of CMB E-mode polarization measurements. The recent measurements of the angular power spectrum the E-mode of CMB polarization at large l have confirmed that the peaks in the spectra are out of phase with that of the temperature anisotropy spectrum. Data from other

[3] Another independent observable is the baryon oscillation in LSS discussed in sec 4

experiments such as DASI, CAPMAP and CBI are comparable. The data is 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 [20]. The null BB detection of primary CMB signal from gravity waves is expected given the ratio of tensor to scalar perturbations but contain good tidings for the level of foregrounds and the ability to deal with it. These conclusions are further borne out in the recent polarization results from the three years of WMAP data [3].

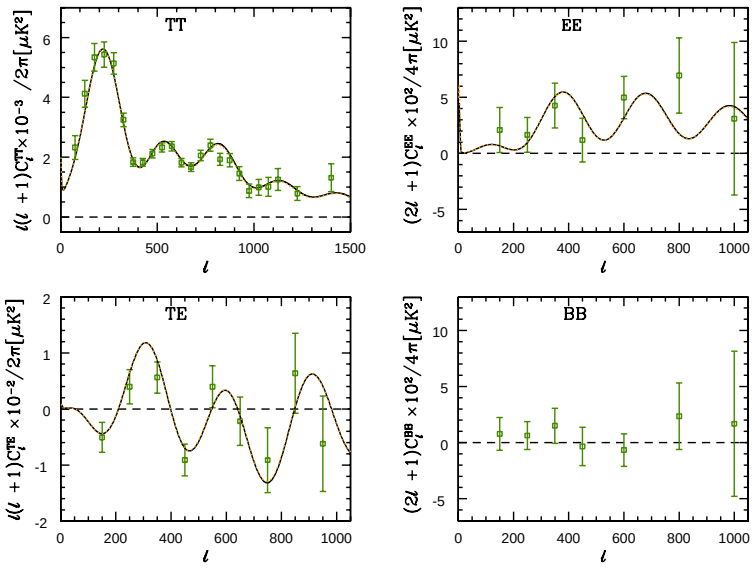


Figure 5: Figure taken from Ref. [20] show the measurement of the angular power spectrum CMB anisotropy and polarization from Boomerang balloon 2000 flight. The CMB anisotropy (TT) spectra has been measured at larger as well smaller angular scales. Data from other experiments such as DASI, CAPMAP and CBI are comparable. The data is 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. The null BB detection of primary CMB signal from gravity waves is not unexpected (given the ratio of tensor to scalar perturbations) but contains good tiding for level of foregrounds and the ability to deal with it.

5.3 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 [53]. Current observations favor a value of $n_s = 0.98 \pm 0.02\,(99.9\%CL)$ very close to unity are consistent with a nearly scale invariant power spectrum.

The current combined CMB and LSS data is good enough to constrain the

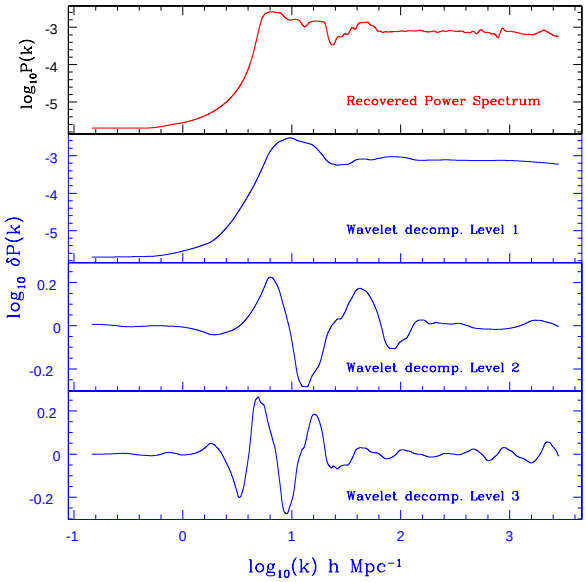


Figure 6: The primordial power spectrum recovered from the angular power spectrum of CMB anisotropy measured by WMAP is shown in the top panel [60]. Wavelet decomposition allows for clean separation of the 'features' in the recovered power spectrum on different scales. The lower three panels show a Daubechies-4 wavelet decomposition from ongoing research work (Manimaran, Panigrahi, Rangarajan, Souradeep). The most significant feature at the coarsest resolution is a compensated infrared cutoff shown in the second panel (from top). The statistical significance of the small superimposed oscillations is under closer study.

'running' of the spectral index, $\alpha = dn_s/d\ln k = 0.003 \pm 0.01\,(99.9\%CL)$. These results are remarkably consistent with the generic predictions of the simplest models of inflation. While the simplest inflationary models predict that the spectral index varies slowly with scale, inflationary models can produce strong scale dependent fluctuations. The first year WMAP observations provided some motivation for considering these models as the data, particularly when combined with the (first version of) measurements of the power spectrum at much larger wavenumbers from the distribution of absorption lines (Lyman-α forest) in the spectra of distant quasars, were better fit by models with running spectral index. Subsequent reanalysis of revised Lyman-α based measurements showed the spectral index to be close to unity with no hint of running [53].

Many model-independent searches have also been made to look for features in the CMB power spectrum [54, 55, 56, 57]. Accurate measurements of the angular power spectrum over a wide range of multipoles from the WMAP has opened up the possibility to deconvolve the primordial power spectrum for a given set of cosmological parameters [58, 59, 60, 62]. 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 [60]. The most prominent feature of the recovered primordial power spectrum shown in Figure 6 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. 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 inflaton potential [63].

5.4 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 [64, 65] that is theoretically motivated by inflation [50]. 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 [66]) have been found to be consistent with a Gaussian random field. Consistent with the predictions of simple inflationary theories, no significant deviations from Gaussianity in the CMB maps using general tests such as Minkowski functionals, the bispectrum, trispectrum in the three year WMAP data [2]. There have however been numerous claims of anomalies in specific forms of non-Gaussian signals in the CMB data from WMAP at large scales (see discussion in sec. 3).

5.5 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 parameterize the tensor component by the ratio $r_{k_*} = A_{\rm t}/A_{\rm s}$, ratio of $A_{\rm t}$, the primordial power in the transverse traceless part of the metric tensor perturbations, and $A_{\rm s}$, the amplitude scalar perturbation at a comoving wavenumber, k_* (in $\rm Mpc^{-1}$). For power-law models, recent WMAP data alone puts 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) [20].

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 $\mathcal{E}_{\rm Inf} = 3.4 \times 10^{16}$ GeV $r^{1/4}$. A

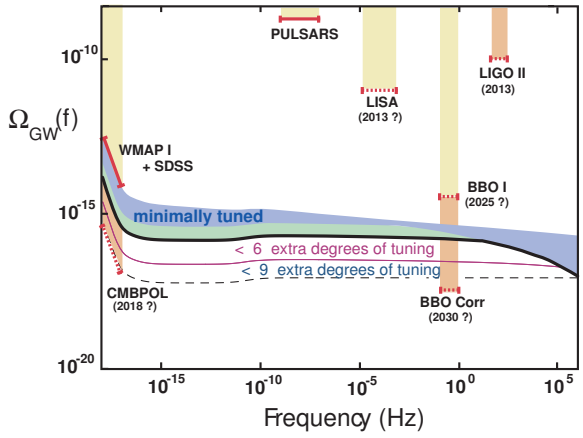


Figure 7: The figure taken from Ref. [67] shows the theoretical predictions and observational constraints on primordial gravitational waves from inflation. The gravitational wave energy density per logarithmic frequency interval, (in units of the critical density) is plotted versus frequency. The blue 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 the projected sensitivity of a future space mission for CMB polarization (CMBPol).

measurement 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 7 summarizes the current theoretical understanding, observational constraints and future possibilities for the stochastic gravity wave background from Inflation.

6 Conclusions

The past few years has seen the emergence of a 'concordant' cosmological model that is consistent both with observational constraints from the background evolution of the universe as well that from the formation of large sale 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 [68].

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 with 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 up coming 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 best achievable sensitivity.

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