International Journal of Advances in Engineering and Management (IJAEM)
Volume 8, Issue 11 November. 2026, pp:49-54 www.ijaem.net ISSN: 2395-5252

A Study of Anisotropy IN CMB And LSS In Modified Gravity Models

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Date of Submission: 01-11-2026 Date of Acceptance: 10-11-2026

ABSTRACT
Recent years have brought strong observational evidences for the standard LCDM cosmological model. Cosmic microwave background (CMB) anisotropy and large scale structure (LSS) probes do not favour any extensions of the standard model. Nevertheless, in this framework, the prefered cosmological parameters may differ from probe to probe, from experiment to experiment. In this context, the Cosmic Microwave Background (CMB) and Large-Scale Structure (LSS) provide complementary probes of the expansion history, gravitational potentials, matter distribution, and primordial fluctuations. CMB anisotropies preserve information about the early Universe, while LSS observations trace the subsequent growth and evolution of cosmic structures over a wide range of scales. Particular importance is associated with ultra-large scales, where relativistic effects become significant and the commonly used quasi-static approximation may no longer be valid. Modified gravity can alter the evolution of metric perturbations, matter clustering, gravitational lensing, and the relationship between CMB and LSS observables. Cross-correlations between CMB and galaxy surveys, together with galaxy number counts and other large-scale observables, therefore provide powerful methods for testing deviations from the standard ΛCDM framework.

Keywords: Anisotropies, Modified Gravity, Cosmic, Galaxy, Cosmological

I. INTRODUCTION

One of the biggest mysteries in modern science is how cosmic acceleration works. The answer to this question could help us understand basic physics better. An example of this kind of mechanism could be Einstein's General Relativity (GR) breaking down on cosmic scales because of the extra degrees of freedom. Observations of the universe's expansion and the formation of large scale structure (LSS) will allow us to test gravity in many ways that other theories predict. This is true even if there are no connections between what we are seeing and the acceleration of the universe. Future scans will cover more land and deeper depths, so the search for strange gravity effects will cover bigger and bigger areas, finally hitting very large sizes like the Hubble radius.

When looking at the universe as a whole, Newton's theory of gravity doesn't work well, so relativistic effects can happen that wouldn't be noticed otherwise. It takes cosmologically long for gravitational information to move over such long distances. This means that the system's rest time is about the same as its normal evolution rate. The observables can also be changed by gravitational potentials that bend the light cone. At least in theory, this and other effects need to be taken into account. There is more and more writing about how these effects affect LSS findings and how to find them in the next generation of star surveys.

Making relativistic changes to cosmological observables can give us new ways to test gravity. These changes become more important at very large sizes, which makes them interesting. They also have a number of benefits for cosmic tests of gravity. The biggest scales that can be seen today crossed the Hubble horizon at the start of cosmic acceleration. They are now in tune with the energy scale of any extra degree of freedom that may be connected to this event. Large scales like these fit the linear theory very well and are the best way to avoid screening mechanisms that strongly stop changes in gravity caused by non-linear effects. Many theories of gravity predict these screening processes, which can be very good at getting rid of the signs we see on small and medium scales. Finally, relativistic effects depend directly on metric perturbations and how they change over time, which in turn depends on the theory of gravity.

Galaxy Number Counts (GNCs) are one of the most important things that can be seen in galaxy studies. They can be studied mathematically using n-point correlation functions. All effects of relativity can be modelled in the theoretical predictions. The GNCs only depend on things that can be directly observed, like the angles and redshifts of galaxies.

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This means that angle and redshift dependent spectra can be consistently linked to observations on arbitrary angular scales and redshift slicings without assuming a fiducial background expansion. This is a big improvement over correlation functions in comoving space. In this way, GNC angular statistics are like cosmic microwave background (CMB) spectra, but they depend on redshift to account for the fact that galaxies are spread out in three dimensions. Future polls like DESI, Euclid, SKA, and the LSST should be able to measure these kinds of things more accurately.

Putting together different observables is another good way to limit gravity. By looking at the CMB integrated Sachs-Wolfe (ISW) effect, galaxy and cosmic microwave background cross-correlations help us figure out how Bardeen potentials changed in late time. Small-scale non-linearities change correlation functions, but linear theory can be used to study large enough angle scales and give useful details about how Dark Energy has changed over time. It is expected that connecting CMB data to future large-scale surveys will make it much easier to tell the difference between different Dark Energy models.

To study the effects of changed gravity on scales like the Hubble radius, we need to go beyond the usual approximations that work on small scales. Most research on LSS formation in different theories has been based on the idea of quasi-static (QS) evolution, which doesn't take into account how the field moves. This approach has been shown to work on linear scales that are small enough that the dynamics have slowed down to the values of equilibrium. The sound horizon of the new degrees of freedom defines the regime of validity. Because of this, the QS approach doesn't always work on very large scales, and the whole system needs to be solved, either from a real theory or an effective version like the effective field theory of dark energy (EFT-DE). Horndeski's theory is the most general local, Lorentz-invariant, scalar-tensor theory described by second order equations of motion. It has been used to make a very clear application of the EFT-DE.

II. REVIEW OF LITERATURE

Sun, Chenghao. (2025) The cosmic microwave background (CMB) anisotropies are a useful tool for evaluating inflationary theories and for understanding the early universe's mechanics. Recent results from COBE, WMAP, Plank, and BICEP/Keck, especially a virtually scale-invariant and adiabatic spectrum, have offered evidence in favour of inflationary theories. The theories also have to address unsolved issues like as where beginning circumstances came from, the trans-Planckian conundrum, and how the inflaton potential was fine-tuned. In addition, issues like as cosmic variance and foreground contamination persist. Given that next-generation systems such as CMB-S4 and LiteBIRD are capable of overcoming these challenges, the future seems promising. Their sensitivity will make it possible to probe primordial B-modes, μ-distortions, and non-Gaussianity with much greater precision.

Devi, Lambamayum et al., (2023) We study modified f (R, T) gravity in isotropic and homogeneous Bianchi type-I cosmological models using the function f (R, T) = R + 2ΛT, where R and T are the Ricci scalar and the trace of the energy momentum tensor, respectively. By including a novel generalised time-varying deceleration parameter of third degree and the relationship between the shear scalar and expansion scalar, the precise solutions to the field equations of the universe may be found (i.e.,). At time t = 3n, the universe undergoes Big Crunch after having progressed from original singularity and Big Rips. The change from positive to negative pressure (p), energy density (ρ), and the EoS parameter entering the phantom epoch phase are all clearly visible. Evaluation of the model's energy conditions and Om(z) diagnostic is carried out. Consistent with the current concept of an expanding Universe, the phantom character of dark energy is confirmed, and the energy conditions of NEC and DEC are determined to be accurate, whereas SEC is not obeyed.

Tiwari, Rishi et al., (2021) As far as we can tell from our present data, the cosmos is flat and uniform on sufficiently vast scales. Nevertheless, this doesn't rule out the chance that the cosmos may have experienced some anisotropy in its early phases of development, which may have been subsequently reduced. Interest in the homogeneous but anisotropic Bianchi models has been sparked by this hypothesis. Secondly, the typical ΛCDM model encounters challenges in general relativity, which is why modified gravity is now attracting a lot of attention. Thus, the Bianchi type-I cosmological model in f(R,T)-modified gravity was the subject of the investigation presented in this work. Adopting a particular shape for the deceleration parameter in accordance with cosmological principles resulted in a model showing a change from early deceleration to late-time acceleration. In the latter stages, the resulting model came close to isotropy. Expressions for the different model parameters were generated, and the physical features of the model were explored. A variable cosmological-type parameter emerged in this model in f(R,T) gravity, which was initially huge but ultimately dropped to a constant value,

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suggesting that progress toward addressing the cosmological constant issue is also conceivable.

Bucher, Martin. (2015) Modern cosmology and our knowledge of the early universe owe a great deal on observations of the cosmic microwave background (CMB), particularly of its frequency spectrum and its temperature and polarisation anisotropies. We examine the fundamental principles of the cosmic microwave background (CMB) and the imprinting of the primordial temperature and polarisation anisotropies. Emphasis is placed on potential ways to differentiate conflicting cosmological theories. Future observations, especially in polarisation, are the focus of this review, which examines the present state of CMB investigations and experimental methods. This region is expected to play a pivotal role in the future, when measuring the B modes of the CMB polarisation with ever-increasing sensitivity, therefore the physics of foreground emissions, particularly of polarised dust, is thoroughly examined.

Challinor, Anthony. (2013) Our most direct observational window to the early cosmos is provided by the cosmic microwave background (CMB). Important contributions to the now-standard cosmological model have been made by observations of the temperature and polarisation anisotropies in the CMB. In this contribution, we go over the fundamentals of cosmic microwave background (CMB) research, with an emphasis on the significance of data collected by both terrestrial and aerial Antarctic observatories. From a basic physics perspective, most of the components of the mainstream cosmological model are not well understood. We go over the ways in which past, present, and future CMB observations may tackle some of these problems, with a special emphasis on two that are pertinent to Antarctic programs: the hunt for gravity waves originating from inflation using B-mode polarisation and the mapping of dark matter using CMB lensing.

Hu, Wayne & Dodelson, Scott. (2001) Our knowledge of the cosmos has been and will be profoundly altered by cosmic microwave background (CMB) temperature anisotropies. The recently found acoustic peaks in the power spectrum, which were predicted earlier, have given rise to a functional cosmological model: a critical density universe with dark matter and dark energy as its main components, which was structured during inflationary epoch by gravitational instability from quantum fluctuations. This model should be tested and its essential cosmological parameters measured with remarkable accuracy in future observations. The cosmological and phenomenological consequences of the sonic peaks are elaborated. The mechanics of inflation and dark energy may be studied via the secondary anisotropies and polarisation that have not yet been identified, which lie beyond the peaks. Because CMB data sets are becoming more important in experimental cosmology, the methods used to extract cosmic information from them are detailed.

III. COSMIC MICROWAVE BACKGROUND (CMB) AS A PROBE OF EARLY UNIVERSE PHYSICS

The cosmic structure formation issue is most likely to have its fluctuations rooted in the early universe physics. Following these first variations, we want to quantify the CMB's [and LSS's] reaction. The aspirational objective is to peep into the physical process that created the variations. Potential mechanisms for production include (i) "zero point" quantum noise in scalar and tensor fields, which should exist in the early cosmos according to quantum mechanics, and (ii) topological defects that might result from the predicted phase transitions in that time.

The following is what we are hoping to deduce from CMB and LSS observations: the mode, which might be adiabatic or isocurvature scalar perturbations; the statistics of the fluctuations, which may be Gaussian or non-Gaussian; and the presence or absence of a substantial component in gravitational wave tensor perturbations; the power spectra for these modes, $\mathcal{P}_{\Phi}(k)$, $\mathcal{P}_{is}(k)$, $\mathcal{P}_{GW}(k)$ as a function of comoving wavenumber k. Sample initial and evolved power spectra for the gravitational potential $\mathcal{P}_{\Phi}(k)$ ($\equiv d\sigma_{\Phi}^2/d\ln k$, the rms power in each dln k band) are shown in Fig. 1. The unique scales imprinted on the initial form of $\boldsymbol{l}$ as the Universe changes reflect the values of cosmological parameters including the energy densities of baryons, cold and hot dark matter, the cosmological constant in the vacuum, and curvature. The density parameters and initial fluctuation parameters may be probed by several observables, which can be represented as weighted integrals over k of the power spectra.

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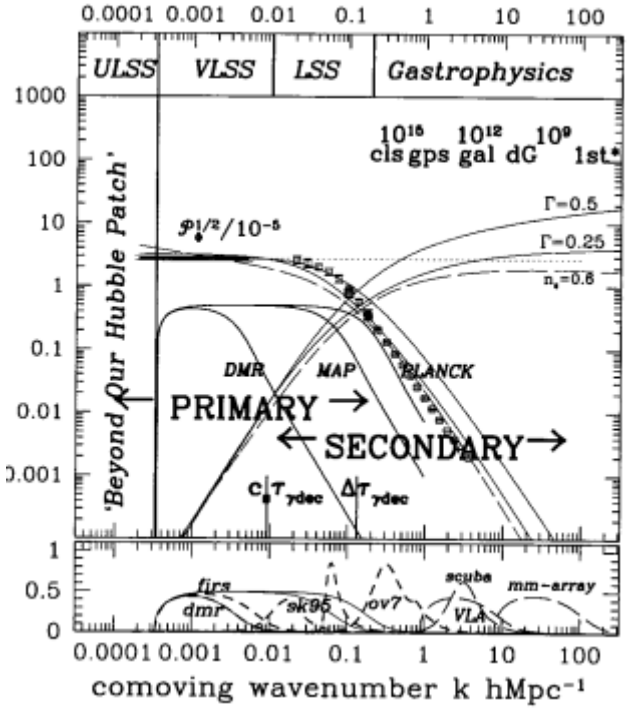


Figure 1. CMB and LSS Wavenumber Ranges

The (linear) density power spectra, $\mathcal{P}_\rho(k) \propto k^4\mathcal{P}_\Phi(k)$, are also shown in Fig. 1. In hierarchical structure formation models such as those considered here, the nonlinear wavenumber $k_{NL}(t)$, defined by $\int_0^{k_{NL}} \mathcal{P}_\rho(k)d\ln k = 1$, grows as the universe expands. $k_{NL}(t)$ was in the galaxy band at redshift 3 and is currently in the cluster band. At $k > k_{NL}(t)$, nonlinearities and complications associated with dissipative gas processes can obscure the direct connection to the early universe physics. Most easily interpretable are observables probing the linear regime now, $k < k_{NL}(t_0)$. Primary CMB anisotropies are those that originate in the linear domain and, as shown in Fig. 1, extend throughout a wavelength range of 30–40 GHz. The region that LSS observations at low redshift cover is less, yet it overlaps. Gas dynamics may affect the link between the observable and power spectrum in various ways, but we believe that z~3 LSS observations, when $k_{NL}(t)$ was greater, can increase the range.

IV. COSMIC PARAMETERS

Power spectrum amplitudes at some normalisation wavenumber k_n for the modes available are among the many early universe characteristics that we would want to discover, even for basic Gaussian inflation-generated fluctuations for structure creation, $[\mathcal{P}_\Phi(k_n), \mathcal{P}_{is}(k_n), \mathcal{P}_{GW}(k_n)]$; shape functions for the "tilts" $[\nu_s(k), \nu_{is}(k), \nu_t(k)]$, usually chosen to be constant or with a logarithmic correction—e.g., $\nu_s(k_n)$, $d\nu_s(k_n)/d\ln k$. [The scalar tilt for adiabatic fluctuations, $\nu_s(k) \equiv d\ln \mathcal{P}_\Phi/d\ln k$, is related to the usual index, n_s, by $\nu_s = n_s - 1$.] When it comes to the transport dilemma, physical processes—and by extension, physical parameters—are crucial. Included in a partial list is the Hubble parameter h, various mean energy densities $[\Omega_{tot}, \Omega_B, \Omega_\Lambda, \Omega_{cdm}, \Omega_{hdm}]h^2$, and parameters characterizing the ionization history of the Universe—e.g., the Compton optical depth τ_C from a reheating redshift z_{reh} to the present. Instead of Ω_{tot}, we prefer to use the curvature energy parameter, $\Omega_k \equiv 1 - \Omega_{tot}$, thus zero for the flat case. In this space, the Hubble parameter $h = (\Sigma_j(\Omega_j h^2))^{1/2}$, and the age of the Universe, t_0, are functions of the $\Omega_j h^2$. The density in nonrelativistic (clustering) particles is $\Omega_{nr} = \Omega_B + \Omega_{cdm} + \Omega_{hdm}$. Photons, relativistic neutrinos, and decaying particle products are all part of the relativistic particle density, Ω_{er}. Other parameters that need to be calculated include the amount of primordial helium, etc. So far, we have 17 confirmed cases. The last part provides error estimates for the MAP and Planck spacecraft using a reduced 9-parameter inflation set.

The anisotropic power spectrum in multipole space (Fig. 2), where CMB theory and observation clash, illustrates the relationship between these cosmic parameters and the variation of primary $C\ell$ values. Here $\mathcal{C}_\ell \equiv \ell(\ell + 1)\langle|(\Delta T/T)_{\ell m}|^2\rangle/(2\pi)$. The $\mathcal{C}_\ell$ values are normalized to the 4-yr DMR(53 + 90 + 31) (A + B) data. The arena for LSS theory is the $\mathcal{P}_\rho$ of Fig. 1.

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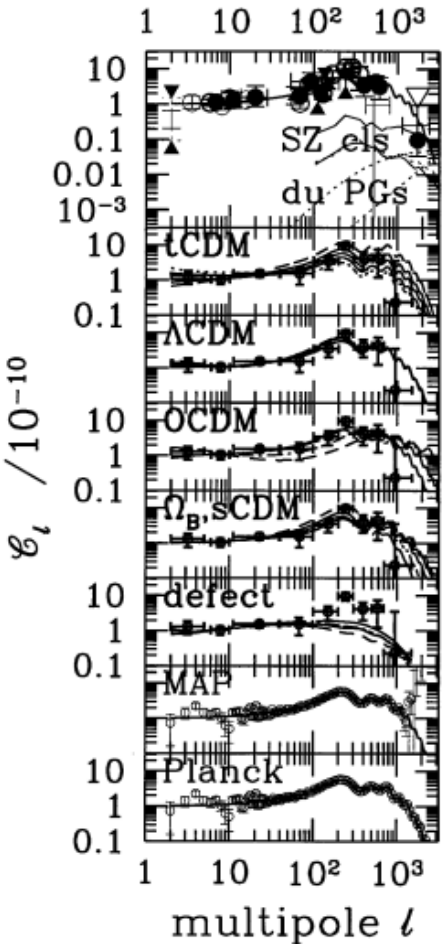


Figure 2. CMB Anisotropy Data and Cosmological Model Predictions

For a given model, the early universe $\mathcal{P}_\Phi$ is uniquely related to late-time power spectrum measures of relevance for the CMB, such as the quadrupole $\mathcal{C}_2^{1/2}$ or averages over ℓ-bands B, $\langle \mathcal{C}_\ell \rangle_B^{1/2}$, and to LSS measures, such as the rms density fluctuation level on the 8 h^{-1} Mpc (cluster) scale, σ_8, so any of these can be used in place of the primordial power amplitudes in the parameter set. In inflation, the ratio of gravitational wave power to scalar adiabatic power is $\mathcal{P}_{GW}/\mathcal{P}_\Phi \approx -(100/9)n_t/(1 - n_t/2)$, with small corrections depending upon $n_s - n_t$. If such a relationship is assumed, the parameter count is lowered by one.

V. LSS CONSTRAINTS ON THE POWER SPECTRUM

In order to find good models, we have always used both CMB and LSS data. A connection between the two is seen in Fig. 1. For every model that is taken into consideration, DMR normalisation exactly finds σ_8; comparing with the $\sigma_8 \sim 0.6\Omega_{nr}^{-0.56}$ the cosmological parameters that define the models are heavily constrained by the goal value that is determined from measurements of cluster abundance. In Fig. 1, this means the COBE-normalized $\mathcal{P}_\Phi(k)$ must thread the "eye of the needle" in the cluster-band.

Similar constrictions arise from galaxy–galaxy and cluster–cluster clustering observations: the shape of the linear $\mathcal{P}_\Phi$ must match the shape reconstructed from the data. The clustering observations are roughly compatible with an allowed range $0.15 \lesssim \Gamma + n_s/2 \lesssim 0.3$, where $\Gamma \approx \Omega_{nr} h[\Omega_{er}/(1.68\Omega_\gamma)]^{-1/2} e^{-(\Omega_B(1+\Omega_{nr}^{-1}(2h)1/2)-0.06)}$ characterizes the density transfer function shape. The standard CDM (SCDM) model has $\Gamma \approx 0.5$. To get $\Gamma + n_s/2$ in the observed range one can: lower h, lower Ω_{nr} (ΛCDM, OCDM), raise Ω_{er}, the density parameter in relativistic particles ($1.68\Omega_\gamma$ with three species of massless neutrinos and the photons)—e.g., as in τCDM, with a decaying ν of lifetime τ_d and $\Gamma \approx 1.08\Omega_{nr}h(1 + 0.96(m_\nu\tau_d/\text{keV yr})^{2/3})^{-1/2}$; raise Ω_B; tilt $n_s < 0$ (TCDM), for standard CDM parameters—e.g., $0.3 \lesssim n_s \lesssim 0.7$ would be required. Adding a hot dark matter component gives a power spectrum characterized by more than just Γ.

VI. CONCLUSION

The CMB and LSS provide complementary probes for understanding the evolution and fundamental physics of the Universe. CMB anisotropies preserve information about the early Universe and primordial fluctuations, while LSS observations trace the growth of matter and cosmic structures. The observed accelerated expansion and the limitations of the standard ΛCDM framework motivate the study of modified gravity theories as possible alternatives to General Relativity. Such theories can produce observable signatures in gravitational potentials, matter clustering, galaxy number counts, lensing, and the growth of structure, particularly on ultra-large scales where relativistic effects become important. The combined analysis of CMB and LSS anisotropies and their cross-correlations can therefore provide stronger constraints on modified gravity models and help distinguish them from the standard cosmological scenario. With the increasing precision of forthcoming CMB and galaxy surveys, these observations are expected to provide valuable insights into the origin of cosmic acceleration and the nature of gravity on cosmological scales.

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