Anisotropy of CMB & Cosmological Model

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Abstract

In this brief review I will touch upon the main points and trends of observational and theoretical cosmology, that influence and change today our understanding of the Universe.

1 Introduction

My goal is to highlight current situation in building up the true cosmological model. Nowadays, after 30 years of the discovery of the CMB relic radiation, its anisotropy is revealed and provides a basic channel of our information about the World. If to be brief, the cosmology is determined today up to the accuracy 20-30 % which is a great progress since what we had 10-20 years ago when the discussions at best were on the level of a factor of two or even more. The great hope of cosmologists is related with the development of ground based and space based $\Delta T/T$ experiments which will be able to delimit and fix the cosmological model up to few per cent in the nearest future.

2 Basics of the Problem of LSS Formation

The seeds of the visible Large Scale Structure in the Universe are the Cosmological Density Perturbations which grow due to the gravitational instability in the late, cold period of the Universe expansion when the density is dominated by Cold Dark Matter ($z < 10^5$). These primordial CDPs must have been created since the inflationary Big Bang epoch, as after the end of inflation – the inflaton decay and the primeval reheating of cosmic medium – the Universe became predominant by relativistic particles and radiation which remnant today as the fossil CMB. Such an early hot Universe was absolutely gravitationally stable against small perturbations of the matter density and gravitation field: the CDPs were a
kind of frozen, just presenting the 'gravitating sound waves' propagating across the relativistic matter with a constant amplitude. Thus, the CDPs started growing only after the equality epoch when the pressure diminished in comparison with the third fraction of the matter density. The required CDP amplitude for galaxy clusters could form by now, has therefore been predicted to consist $\delta \sim 10^{-5}$, which was finally confirmed by COBE on this same level but the two orders of magnitude larger scale (that in turn appeared to be in a successful consistency with another famous prediction known as the Harrison-Zel’dovich scale-invariant perturbation spectrum).

This optimistic situation has created a great impetus for the observational and theoretical cosmology extending dramatically by continuing progress in the improved technology of deep-sky surveys and CMB temperature detections. The ultimate goal has come for the reconstruction of the primordial CDP spectrum from 1 Mpc scales up to the horizon, the scope straightforwardly related to the high energy physics at inflation capable by observational tests today.

Three points should be emphasised in connection with the problem of LSS formation: Theoretical, Model, and Observational. The first point means that the creation of the LSS in the Universe is as fundamental problem as the creation of the Universe as whole: both features, the small CDPs and the background Friedmann model (the Cosmological Principle), are produced in the process of inflation in the very early Universe. The theory works at very high energies ($\sim 10^{16}$ GeV) whereas the observations proceed in the low-energy limit ($\sim 10^{-4}$ eV). To provide a fair comparison in such a situation one needs a model to know how the perturbations evolved during the whole history of the Universe. Any confrontation in cosmology between theory and observations is thus model dependent.

To fix the model one needs priorities and the fundamental constants. The former conventionally assume the gravitational instability mechanism as a principal tool for the CDP dynamics on large scale and the Gaussian primordial perturbations (with random spatial phase). The latter requires the knowledge of the current time when the structure is observed ($H_0$), the abundance of cosmic matter components ($\Omega_M$, $\Omega_\Lambda$, $\Omega_b$) and Cosmic Gravitational Waves (T/S), and the nature of the dark matter (e.g. relic scale field, CDM, HDM, the number of species of massive neutrinos and relativistic particles, etc.). Today, cosmologists venture the following approach: if the dark matter model is stated as fairly simple (with small number of the parameters, e.g. the one with zero spatial curvature or zero $\Lambda$-term, or other) then the recovering of both the CDP spectrum and the model fundamental parameters, can be provided by observational data on $\Delta T/T$ and LSS.

Below, I come to discussion of the models in such a conventional probability sense. However, there is no principal restrictions: any theory could be tested to the limit if we have enough data. The more data will be available, the less uncertainties will remain in the model and more parameters can be finally determined. Actually, we are in the beginning on the way
of getting the data. Today we may do a model restoration exercise facing
the observations we just have.

3 Dark Matter Models

Until recently there were two basic theories claiming to approach the cor-
er stones of the LSS formation: inflation and defects. While being very
much different in their grounds on galaxy seeds – the linear Gaussian
scalar perturbations in the one case and the non-linear non-Gaussian cos-
omic defects (strings, monopoles, textures) in the second scenario – both
models presented the fundamental inevitable perturbations produced by
the physics of the very early Universe: the parametrically amplified quan-
tum vacuum fluctuations of the inflaton and the topological defects left
after phase transitions, respectively.

However, the defect model normalised by the CMB fluctuations proved
to fail to meet the LSS formation\textsuperscript{[2]}. The reason is that the non-linear
matter perturbations generate all three types of the metric fluctuations -
Scalar, Vortex and Tensor ones, which all contribute to the Sachs-Wolfe
$\Delta T/T$ anisotropy on large angular scale, so the residual S-mode ampli-
tude appeared to have no sufficient power to develop the observed galaxy
distribution.

At the moment, only the inflation theories got through ordeals fitting
the LSS and $\Delta T/T$ observations. The principal quest here is the predicted
Gaussian nature of small CDPs, which faces a satisfactory consistency
with the real distribution of galaxies on scales $\sim 20 \, h^{-1} \, \text{Mpc}$\textsuperscript{[3]}. The only
obstacle to test reliably this important feature of the CDP seeds is the
limited depth of the available galaxy surveys.

The deep galaxy surveys would be highly welcome to solve also other
challenge of the modern cosmology: the fractal model attacking persis-
tently the cosmological principle. The point is that the huge voids seen
in the galaxy distributions extend up to scales $\sim 100 \, h^{-1} \, \text{Mpc}$ which is
close to the catalogues’ sizes, thus, leaving a room for discussions on the
homogeneity scale\textsuperscript{[4]}. Nevertheless, I would like to stress that the fractal
challenge is still a question for distribution of the baryonic matter (the
optical galaxies) rather than for the total mass of the Universe. The lat-
ter should be pretty homogeneous on scale larger than few tens of Mpc
to fit the beautiful Hubble diagrams. Not to speak on the uniform mi-
crowave and X-ray backgrounds evidencing the cosmic homogeneity on
larger scales.

Thus, we consider only models backed on the inflationary theories.
The main tool for the Gaussian perturbations is the second moment of
their distribution related to the power-spectrum:

$$\langle \delta^2 \rangle = \int_0^\infty P(k) k^3 dk = \int_0^\infty \Delta_k^2 \frac{dk}{k}$$

(1)
The dimensionless CDP spectrum $\Delta^2_k$ has a simple meaning of the variance of density contrast in the scale $k$ (the wave number) within the scale band $dk \sim k$, it is evidently additive ($\delta^2 \sim \Sigma \Delta^2_k$).

Before coming to discussion on the spectrum observational reconstruction let me sketch briefly the situation with the model parameters.

## 4 Cosmological Parameters

It seems that the long strong debate on $H_0$ is approaching to its end and we are going to learn the value of the Hubble constant during nearest years. Today, very promising seem two methods: measuring Cepheids in distant galaxies and the supernovae type Ia method. I would not like to fix here the number since it is not yet time for any consensus between the groups about systematic and selection bias effects for all methods employed. For us, it is important to note that standard cosmological models (with the critical dynamical matter density, $\Omega_M = 1$, and negligible $\Lambda$-term) are consistent only with small Hubble constant ($H_0 < 65 \text{ km s}^{-1}\text{Mpc}^{-1}$) regarding the low limit for the age of the Universe coming from globular clusters.

A much more optimistic point stands on the current progress in determination of $\Omega_M$ and the baryonic content of the Universe $\Omega_b$. At the first glance the situation looks similar: again we have two groups of experiment resulting in different conclusions. However, here the consensus is possible.

The first experiment deals with megaparsec scales – galaxy halos, groups and X-ray clusters, $- l < l_D$ (the dynamical scale in the Universe $l_D \sim 10h^{-1}\text{Mpc}$, which is the largest pass of a galaxy for the current Hubble time, just the scale of the richest collapsing clusters). The assumption on the hydrostatic equilibrium yields a low dynamical mass responsible for the formation of the gravitational potential on small scales: $\Omega_M \sim 0.3$.

Another important observation is large fraction of baryons inside X-ray clusters reaching somehow $\sim 20\%$ within scale $\sim 1\text{ Mpc}$:

$$\frac{M_b}{M_M} \sim 0.2, \quad (2)$$

which is also consistent with a low matter density involved dynamically in megaparsec scales (as $\Omega_b \leq 0.1$ due to the primordial nucleasynthesis and $M_b/M_M$ may be $\sim \Omega_b/\Omega_M$ on the dynamical scale).

The other experiment deals with LSS ($l > l_D$) and argues that the Universe may be matter dominated, $\Omega_M \approx 1$. There are few principal arguments for this (still a more detail model dependent ones in comparison with the small scale arguments):

- the existence of substructures in the majority of galaxy clusters evi-
dencing that the clusters are just forming systems which is possible only in the Universe dynamical close to the critical density,
- the large coherence velocities obviously of the cosmological origin,

thus allowing for the reconstruction of the total density contrast
(and as a consequence, the consistency with the "standard" model \( \Omega_M \simeq 1 \) and the galaxy biasing factor \( b \simeq 1 \)),

- the fact that the Gaussian nature of the linear primordial cosmological perturbations may be recovered (after going back in time from the actual non-linear distribution of matter density and velocity) only for the parabolically expanding Universe (\( \Omega_M \sim 1 \)),

- the weak gravitational lensing confirming high dynamical mass abundance around some X-ray clusters,

- the lensing argument on the fraction of splitting quasars, still much dependent on the model assumptions,

- the evolutionary argument on the galaxy clusters abundance,

- the geometrical argument from the distant supernovae type Ia,

- the point coming from \( \Delta T/T \) anisotropy (mainly, the location of the first acoustic peak).

The last three points got some dramatic turns in the recent time which I cannot help mentioning here.

It is the ENACS identification of the nearby galaxy clusters by the dispersion velocities of their optical galaxies that has shown the previous underestimate of the Abell cluster abundance (which employed the method of counting the number galaxy concentrations in the sky). At the moment we may state the consistency of the cluster number density evolution in redshifts with the \( \Omega_M = 1 \) Universe. At least, the low evolution argument that for many years was considered as a basic argument in favour of the low density Universe, is not any more as strong as it seemed before.

The breakthrough in the problem of the model geometry restoration is being done today by the classical Hubble diagrams (the redshifts vs apparent magnitudes) composed from distant supernovae of type Ia. Contrary to galaxies, such sources look amazingly standard candles which is well supported by the distance measurements to nearby supernovae. The candidate model for this class of supernovae could be exploding white dwarfs that would clearly fix their mass and chemical composition and thus provide theoretical understanding of their observable luminosity stability. Tested by the distant supernovae, the deviations of the Hubble diagram from the linear law hint on the real geometry of the Universe. While more statistics is still needed to come to the reliable conclusions, the first conditional estimates of the model parameters seem very much impressive: if \( \Lambda = 0 \) then \( \Omega_M < 0.6 \), whereas for the flat models \( \Omega_\Lambda < 0.5 \). The latter inequality is especially interesting as it improves dramatically the best lensing upper limit for the \( \Lambda \)-term (\( \Omega_\Lambda < 0.6 \)).

The reconstruction of the cosmological parameters from CMB temperature fluctuations recall today an exercise as the strongest effect comes from the location and amplitude of the 'Doppler peak' (the first Sakharov oscillation) whose observational detection leaves something to be desired. However, not discussing here the numbers, it is worth while remembering
the tendency for the model parameters limits constrained by all the $\Delta T/T$ data available in the literature: it is for low $H_0$ ($\sim 0.5$) and high $\Omega_b$ ($\sim 0.1$) and $\Omega_M$ (consistent with the flat Universe) that comes somehow larger than the local astrophysical predictions. The low density Universe ($\Omega_M < 0.3$) is rejected by current $\Delta T/T$ data.

Finally, a possible reconciliation between the DM experiments on small and large scales can be the following: some fraction of dark matter in the Universe is distributed on large scales and does not enter the galaxy halos and groups. How it can be arranged? Today we have purely theoretical ideas on such model. The most frequently discussed are that with mixed dark matter (hot+cold, with the hot particles like massive neutrinos with a few eV rest mass and the corresponding density parameter $\Omega_\nu \in (0.2, 0.4)$), and the model with non-zero $\Lambda$-term ($\Omega_\Lambda \in (0.6, 0.7)$). For both cases, the cold particles form the dynamical structure beginning from small scales while on the large scale there is additional contribution coming from light neutrinos or vacuum density (the $\Lambda$-term), respectively. A very sceptical point concerning these and other cosmological models considered currently as possible candidates for the real Universe is as follows: all they are multi-parameter and thus non-fundamental models, which differ them drastically from the purely hot or purely cold dark matter models.

Is there something very important which we miss in our discussion on the formation of the Universe structure? May be. I can only conclude here saying than none of the models under discussion meets all the observational tests. Say, regarding the two previous examples, for $\Lambda \neq 0$ models one can expect a large fraction of old (relaxed) galaxy clusters and lensed quasars whereas the hot+cold models require $H_0 < 65 \, \text{km s}^{-1} \text{Mpc}^{-1}$ and too a small abundance of X-ray clusters and high-redshift quasars. Probably, the dark matter can exist in the form of the relic scalar field left after inflation or in some other exotic form, which require a more detail analysis.

In such a situation, the observational verifications become extremely important. The principal tests is LSS of the early Universe.

5 The spectrum of density perturbations

The cosmological models of LSS formation discussed today are aimed to fit the observational data at $z = 0$. So, we cannot distinguish between them without going to the evolution at medium and high redshifts where the models demonstrate their essential difference. Two main experiments promote a snow ball progress in the reconstruction of CDP spectrum, that was impossible in previous years: $\Delta T/T(\theta > 1')$ and direct investigation of the evolution and hierarchy of LSSs. The reason for stimulating such a progress is that these two experiments confront and overlap each other: the $\Delta T/T$ investigations go nowadays to small comoving scales up to $\ell \sim 10 \, h^{-1} \, \text{Mpc}$ (recall the corresponding angular scale in arcmin $\theta \sim \ell h$), at the same time we observe a developed structure of clusters, filaments,
voids, and superclusters coming up to scales $\sim 100\ h^{-1}\ Mpc$.

Any reasonable assumption on the "formation" of large voids and superclusters in Gaussian perturbation theories inevitably leads to $\Delta T/T$ predictions at $\sim 1^0$ capable of current detection. There is a great puzzle that namely this scale specifies the horizon at the decoupling era, therefore, the angular scale of the first acoustic peaks. Its existence was predicted by the theory long ago. Now, the time came for the observations: it is just on agenda, a matter of the improved instrument’s technology and foreground separations that will precisely determine the peak parameters and ultimately prove and fix the theory.

Today, we are aware of the cosmological temperature anisotropy on large scale and have some information on the whole spectrum of the CMB fluctuations\[7\]. Fortunately, the small angular scales ($\theta < 1^0$) can be effectively tested from the ground. The hope is that such the ground based instruments as SK, CAT, VSI, RATAN-600, together with the balloon experiments as well as the MAP, RELICT2 and Planck Surveyor satellites will provide an advance sensitivity to put the point in the cosmology model reconstruction.

Meanwhile, the situation with the CDP spectrum looks rather dramatic. On large scale ($\sim 1000\ h^{-1}\ Mpc$) the fundamental spectrum is small in amplitude and consistent with the HZ one:

$$\Delta^2_k \sim k^{3+n_S}; \quad n_S = 1.1 \pm 0.1. \ (3)$$

However, in close scales ($\leq 100\ h^{-1}\ Mpc$) the power should be boosted as we observe a rich structure in the spatial distribution of galaxies, clusters, Ly$\alpha$-forest, and distant sources like quasars. The latter is especially important. We live in the period of the decay of quasar and star formation activity\[9\]. So, we have a unique opportunity to use these numerous early sources to observe the past dynamics of the LSS formation. This would be extremely informative as the LSS perturbation amplitude, being still small today at $\ell \sim 100\ h^{-1}\ Mpc$, were even lower in the past, which predicts a strong inverse evolution of such huge systems as superclusters and voids.

It seems that quasars, the active galactic nuclei of distant galaxies, form the LSS at medium redshifts ($z \sim 1 - 2$) which is provided by their correlation function and the existence of huge QSO groups recalling in properties (the comoving size and abundance) local superclusters\[10\]. Actually, distant bright quasars may originate in merging galaxies in protoclusters, and thus can trace the sites of enhanced matter density at medium and high redshifts analogous to how galaxy clusters trace them in nearly space. If so, then the dynamical formation of these early LSSs suggests that the spectral amplitude on superclusters scale ($\sim 100\ h^{-1}\ Mpc$) should be comparable and pretty close to that on cluster scale ($\sim 10\ h^{-1}\ Mpc$), i.e. the CDP spectrum is nearly flat between those scales\[11\]:

$$\Delta^2_k \sim k^{0.9 \pm 0.2}. \ (4)$$

This estimate for the spectrum slope is also indicated by the local observations of galaxy and galaxy cluster distributions\[12\], \[13\], \[14\].

7
A drastic break in the spectrum slope from the HZ asymptotic to the flat part (4) should have happened at supercluster scale ($\sim 100 - 150 \, h^{-1}\text{Mpc}$) which is obviously a real feature of the primordial CDP spectrum. (Contrary to the scale of galaxy clusters to be a mere consequence of current dynamical time.) This 'signature of the God' in the primordial spectrum requires its explanation in physics of the very early Universe.

I cannot help mentioning another connection to the very early Universe through the primordial perturbation spectrum. This is a possibility to have high abundance of cosmic gravitation waves contributing to large-scale CMB anisotropy.

There are at least two reasons for such discussion.

The first is theoretical one. Inflation theory is not discriminative to any of the perturbation modes\cite{15}: both $S$ (CDP) and $T$ (CGW) modes can be produced with similar amplitudes and thus comparable contribution to the CMB anisotropy,

$$\left(\frac{\Delta T}{T}\right)^2 = S + T.$$ (5)

The second reason comes from observations. If the scalar perturbation spectrum is 'blue' ($n_S > 1$) then the non-zero $T/S$ is needed to reconcile the COBE $\Delta T/T$ measurement with the galaxy cluster abundance.

The problem of $T/S$ is fundamental but can be treated at the moment only theoretically. A serious discussion on the observational detection of $T/S$ could be launched after polarization CMB measurements, that would require the instrumental sensitivity $\sim 1\mu K$ currently non-reachable.

6 Conclusions and Tendencies

As never before, the cosmologists are very close today to recover the real model of our Universe and the post-recombination CDP spectrum directly from observations, both $\Delta T/T$ and LSS, and make exciting link to the very early Universe physics. We are going to get data from the advanced ground and space based CMB explorers as well as huge surveys of spatial distribution of galaxies, to delimit the cosmological model with unprecedented precision.

The list of current conclusions may not be full:

- extreme open models ($\Omega_M < 0.3$) are rejected by CMB and cluster evolution data;
- from point of view of distant supernovae Ia the vacuum density of our Universe may not be dynamically important ($\Omega_\Lambda < 0.5$);
- current data on the Doppler peak indicate small $H_0$ ($\sim 60 \, \text{km} \, \text{s}^{-1}\text{Mpc}^{-1}$) and large $\Omega_b$ ($\sim 0.1$) and $\Omega_M$ ($> 0.5$);
- the $S$-mode fundamental spectrum is consistent with HZ ($n_S \simeq 1 - 1.2$);
- CMB together with LSS data indicate the CDP spectrum break at scale $\sim 150$ Mpc, which demands new physical explanation;
• the T/S problem cannot be ignored and needs a careful treatment.

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