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THE ABDUS SALAM INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

LARGE SCALE STRUCTURE AND BARYOGENESIS

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Abstract

We discuss a possible connection between the very large scale structure formation and the baryogenesis in the universe.

An update review of the observational indications for the presence of a very large scale $120h^{-1}$ Mpc in the distribution of the visible matter of the universe is provided. The possibility to generate a periodic distribution with the characteristic scale $120h^{-1}$ Mpc through a mechanism producing quasi-periodic baryon density perturbations during inflationary stage, is discussed. The evolution of the baryon charge density distribution is explored in the framework of a low temperature boson condensate baryogenesis scenario. Both the observed very large scale of the visible matter distribution in the universe and the observed baryon asymmetry value could naturally appear as a result of the evolution of a complex scalar field condensate, formed at the inflationary stage. Moreover, for some model's parameters a natural separation of matter superclusters from antimatter ones can be achieved.

MIRAMARE – TRIESTE
August 2001

1 Introduction

The universe is not homogeneous even over large scales of about $100h^{-1}$ Mpc [1, 2, 3]. On large scales the universe texture shows an intricate pattern of observed structures: filaments, voids and walls, forming the so-called supercluster-void network. Besides, in the last 10 years, evidence is accumulating for the presence of a characteristic very large scale in the supercluster-void distribution: different types of observational data and theoretical analysis point to the existence of a characteristic scale of about $120h^{-1}$ Mpc in the large scale structure (LSS) and moreover, a regular density distribution of the luminous matter in the universe.

Numerous works discussed the very large scale and the periodicity. This scale is significantly larger than predicted by standard models of structure formation by gravitational instability. Besides, no generally accepted theory of structure formation yields a regular structure. The presence of the observed periodicity up to a great distance and in different directions and its physical origin is still an open question.

Here we discuss the possibility that this periodicity is a new feature, characteristic only for very large scales and it is a result of a quasi-periodic baryon density fluctuations, produced in the early universe, through the mechanism of Dolgov (1992) [4, 5]. We explore the evolution of the baryon density perturbations in the scalar field condensate baryogenesis scenario [6]. We show that this scenario can successfully reproduce the observed periodic distribution of the visible matter.

The basic idea was first proposed in ref. [7], and more detail investigations were provided in refs. [8, 9]. In the framework of this scenario an attractive possibility can be realized: the scalar field relevant for the baryogenesis in the universe could also be the creator of the observed large scale periodicity of the visible matter. Moreover, for some model parameters it proposes a natural mechanism of separation of vast domains of matter from antimatter, which are formed without domain walls.

In the next section we review the observational evidence for the existence of the characteristic very large scale and periodicity in LSS. The last section discusses the generation of the spatial periodicity.

2 Indications for 120 - $130h^{-1}$ Mpc scale in LSS

There are many observational indications for the presence of a very large scale, 120 - $130h^{-1}$ Mpc, in LSS of the universe. We discuss briefly some of them below.

- **Galaxy deep pencil beam surveys.**

The galaxy deep pencil beam survey of Broadhurst et al. (1988, 1990) [10, 11] found an intriguing periodicity in the very large scale distribution of the high-density regions of luminous matter. The data consisted of several hundred redshifts of galaxies, in two narrow cylindrical volumes into the directions of the North and the South Galactic poles of our Galaxy, up to redshifts of more than $z \sim 0.3$. These were combined to produce a well sampled distribution of galaxies by redshift on a linear scale extending to $2000h^{-1}$ Mpc. The plot of the numbers of galaxies as a function of redshifts displayed a remarkably regular redshift distribution, with most galaxies lying in discrete peaks, with a periodicity over a scale of about $128h^{-1}$ Mpc comoving size, extending over 13 periods.

Though initially rejected and thought a statistical anomaly, the periodicity was confirmed in the following studies [12, 13, 14, 15].

The density peaks in the regular space distribution of galaxies in the redshift survey of Broadhurst et al. were shown to coincide in position and redshift with the location of rich superclusters, as defined by rich clusters of galaxies in the given direction [16].

The *survey of samples in other directions, located near the South Galactic pole*, also gave indications for a regular distribution on slightly different scales near $100h^{-1}$ Mpc [17, 18, 19, 20]. This discovery of a large scale pattern at the galactic poles was confirmed in *a wider angle survey* of 21 new pencil beams distributed over 10 degree field at both galactic caps [21] and also by the *new pencil-beam galaxy redshift data around the South Galactic pole region* [22].

In the following studies different objects and methods were used to characterize the regularity. The analysis of observations of different objects confirmed the existence of this very large scale, namely:

- **quasars and radio galaxies** [23]$^{-}$[28]

- **peculiar velocity information** [29, 30, 31]

- **Lyman-α break galaxies**

The line-of-sight correlation function of Lyman-α break galaxies at high redshift, $z \sim 3$, has secondary peaks at a redshift separation $\delta z = 0.22 \pm 0.02$ corresponding to the comoving scale $120(1+z)^{-1}$ Mpc in ΛCDM cosmological model with $\Omega_m = 1 - \Omega_\Lambda \sim 0.4 \pm 0.1$ [32, 33].

- **optical and IRAS galaxies and clusters of galaxies**

The regularity traced by galaxies and galaxy clusters was discussed in many works [13, 34]-[48].

Studies of the correlation functions and power spectrum of clusters of galaxies: The 3 dimensional data of the distribution of clusters of galaxies has been used to calculate the correlation function and the power spectrum of these [45, 47]. The results confirmed the existence of regularity: the correlation analysis showed an evidence for a secondary peak at $125h^{-1}$ Mpc of the correlation function of clusters of galaxies. It was shown that the period of the correlation function oscillations equals the period of the supercluster-void network [48].

Oscillations with a low amplitude were also registered in the correlation function of *the Las Campanas redshift survey of galaxies* [49, 50, 51, 52, 53, 54]. An oscillating correlation function corresponds to a peaked power spectrum. A strong peak in the 2-dimensional power spectrum, corresponding to an excess power at about 100 Mpc, was obtained.

A peak near wavelength $\lambda = 120 \pm 15h^{-1}$ Mpc or wave number $k = 0.05h$ Mpc^{-1} in the three dimensional power spectrum was also found from the projected distribution of *APM galaxies* [55, 56], power spectrum of *Abell clusters* was obtained by Einasto et al. [47], Retzlaf et al. [57] with a well defined peak at $k = 0.052h$ Mpc^{-1} and calculated for *APM clusters* by Tadros et al. [58].

So, the study of *the whole-sky distribution of very rich Abell and APM clusters of galaxies* (see also refs. [59, 60]) confirmed from 3-dimensional data that the high-density regions form quasi-regular lattice with $120h^{-1}$ Mpc characteristic scale.

- **X-ray clusters of galaxies**

The distribution of X-ray clusters of galaxies was studied using *the ROSAT Bright survey of X-ray clusters.* X-ray clusters were shown to follow the supercluster-void network in a similar way like Abell clusters [61, 62]. The correlation function of X-ray clusters provides evidence for $120h^{-1}$ Mpc in the distribution of X-ray clusters. A similar result has been obtained by comparing the *REFLEX cluster survey* with the Las Campanas galaxy redshift survey [63].

- **the supercluster-void distribution**

The supercluster distribution was shown also to be not random but rather described as some network of superclusters and voids with typical mean separation of $120h^{-1}$ Mpc.

First in ref. [3] it was noted that the mean diameters of voids between clusters is about $\sim 100h^{-1}$ Mpc. The cluster correlation function was calculated in refs. [64, 12] and a secondary peak at $\sim 125h^{-1}$ Mpc was found.

Analysis of *new Abell sample of clusters* confirmed that the supercluster-void network has a period of $120h^{-1}$ Mpc. The distributions of rich superclusters was analyzed using 1304 rich Abell clusters with a redshift up to $z = 0.12$ by a novel geometrical method sensitive to the geometry of the location of clusters [65]. The supercluster-void network was found to resemble a rectangular lattice with a period of about $120 - 130h^{-1}$ Mpc. Direction dependence of the periodicity was found: the distribution of rich superclusters is periodic along supergalactic coordinates with a step $130h^{-1}$ Mpc, while in other directions the regularity is less pronounced (see also refs. [17, 66, 18, 19, 22]).

APM clusters, X-ray selected clusters and active galaxies were analyzed for comparison [60].

- **Cosmic Microwave Background data**

The fact, that the universe is not homogeneous and fully isotropic at scales $\sim 120h^{-1}$ Mpc, does not contradict the observed degree of isotropy of the cosmic background radiation. The large-scale periodicity is compatible with recent CMB data. The combined evidence from cluster and CMB data, namely CAT2 data [67] as well as CAT1 [68] also favors the presence of a peak at $120h^{-1}$ Mpc and a subsequent break in the initial power spectrum [69, 70, 71, 65].

The analysis [72] using a model independent measurement of the primordial power spectrum from recent MAXIMA and BOOMERANG microwave background anisotropy data indicates the presence of features in the spectrum, consistent with the large scale data, indicating a peak in the matter power spectrum at $k \sim 0.05h$ Mpc^{-1}.

Thus, the observations and their theoretical analysis present a growing evidence for the regularity of the supercluster-void network: different objects trace the same high-density regions at large scales and suggest the existence of a typical large scale of the matter distribution of the universe. Rich superclusters and voids form a quasi-rectangular lattice with a mean separation of rich superclusters across voids $120 - 130h^{-1}$ *Mpc.* [1]

This scale is significantly larger than predicted by standard models of structure formation by gravitational instability. Besides, no generally accepted theory of structure formation yields a regular structure.

3 Generation of the spatial periodicity

Numerous works discussed the periodicity in the density distribution of luminous matter at large scales. It was shown that a random structure could not explain the observed distribution. The assumption of an intrinsic scale in the structure also was found not sufficient to explain the observed periodicity: In ref. [74] it was shown that the existence of a specific scale in the mass density distribution is not sufficient to achieve reasonable probabilities for the observations of the detected periodicities in a given direction. Recent results from very large cosmological N-body simulations of deep pencil beam surveys [75] in Cold Dark Matter cosmogonies (τCDM and ΛCDM) showed that the regularity is incompatible with CDM paradigm, as far as the observed regularity has a probability well below 10^{-3} in these CDM models. I.e. τCDM and ΛCDM are unsuccessful in reproducing the observed periodicity.

The presence of the periodicity up to a great distance and in different directions is rather amazing. Its physical origin, its scale and extend is an open question. Therefore, we consider interesting to discuss here a baryogenesis scenario which is capable to answer these questions rather naturally. In this scenario the observed $120 - 130h^{-1}$ Mpc scale is a typical new feature characteristic only for very large scales ($> 100h^{-1}$ Mpc) and is a result of quasi-periodic isocurvature density perturbations, generated through the mechanism of Dolgov (1992) [4, 5]. Here we will discuss the results of refs.[8, 9], where the generation and evolution of periodic space distribution of primordial baryon density fluctuations was studied for the case of baryogenesis model with baryon charge condensate [6]. The case of high-temperature baryogenesis was discussed in

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[1] The existence of the maximum in the power spectrum at wavenumber $\sim 130h^{-1}$ Mpc is so convincing, that it has been recently used as a powerful standard ruler and applied to measure the universe curvature [73].

ref. [4].

3.1 Description of the baryogenesis model.

Here we present a brief review of the baryogenesis model of Dolgov and Kirilova, described in detail in ref. [6], based on the Affleck and Dine SUSY GUT mechanism [76].

The essential ingredient of the model is a scalar field ϕ (electrically neutral colorless combination of squarks and sleptons) with a nonzero baryon charge. It may form a classical condensate $< \phi > \neq 0$ at the inflationary stage if there are flat directions in its potential, as a result of the enhancement of quantum fluctuations of the ϕ field [77, 78, 79, 80]: $< \phi^2 >= H^3 t/4\pi^2$. As a result, a condensate of a baryon charge (stored in $< \phi >$) is developed during inflation.

When inflation is over, ϕ evolves down to its equilibrium point, rotating clockwise or anticlockwise (depending on its initial condition). These oscillations around its equilibrium point proceed with a decreasing amplitude. The decrease is due to the universe expansion and to the particle production by the oscillating scalar field. The subsequent decay of the condensate at the advent of the baryon conservation epoch t_B results into a baryon asymmetry of order 1. [81, 6].

The evolution of the complex scalar field in the expanding universe ϕ is described by the equation:

$$\ddot{\phi} - a^{-2}\partial_i^2\phi + 3H\dot{\phi} + \frac{1}{4}\Gamma\dot{\phi} + U'_\phi = 0, \tag{1}$$

where $a(t)$ is the scale factor and $H = \dot{a}/a$.

$$U(\phi) = m^2|\phi|^2 + \frac{\lambda_1}{2}|\phi|^4 + \frac{\lambda_2}{4}(\phi^4 + \phi^{*4}) + \frac{\lambda_3}{4}|\phi|^2(\phi^2 + \phi^{*2}) \tag{2}$$

The potential is spherically symmetric at small values of the field and is asymmetric and may have flat directions at high values. Therefore, for high ϕ there is strong baryon charge non-conservation, while for small ϕ baryon charge is conserved. In the model $m \ll H_I$ and a natural value of m is $10^2 \div 10^4$ GeV. In super-symmetric theories the constants λ_i are of the order of the gauge coupling constant α. The initial values for the field variables are derived from the assumption that the energy density of ϕ at the inflationary stage is of the order H_I^4: $\phi_o^{max} \sim H_I \lambda^{-1/4}$ and $\dot{\phi}_o = 0$.

In our toy model fast oscillations of ϕ after inflation result in particle creation due to the coupling of the scalar field to fermions [82] $g\phi\bar{f}_1 f_2$, where $g^2/4\pi = \alpha_{SUSY}$. Therefore, the amplitude of ϕ is damped as $\phi \rightarrow \phi \exp(-\Gamma t/4)$ and the baryon charge, contained in the ϕ condensate, is considerably reduced.

For a constant Γ this reduction is exponential and the baryon asymmetry is waved away till baryogenesis epoch. In the case without flat directions, the production rate is a decreasing function of time. Hence, the damping process may be slow enough and the baryon charge contained in ϕ may survive until the advent of the B-conservation epoch.

The evolution of baryon charge contained in the scalar field for different initial values of the field is shown in Figs. 1 and also in ref. [9] (Fig.2 there) and ref. [7] (Fig.1. there).

So, for a considerable range of acceptable model parameters values of m, H, α, and λ, sufficient baryon asymmetry is created without the need of an explicit or spontaneous CP-violation. It is a result of the asymmetric initial conditions, created by the rise of quantum fluctuations of ϕ during inflation, i.e. due to stochastic CP-violation.

The level of damping and hence, the results concerning the asymmetry will considerably differ in case of coupling to bosons. In any case future more realistic models should also precisely account for the back reaction of the produced particles, discussed in ref. [83].

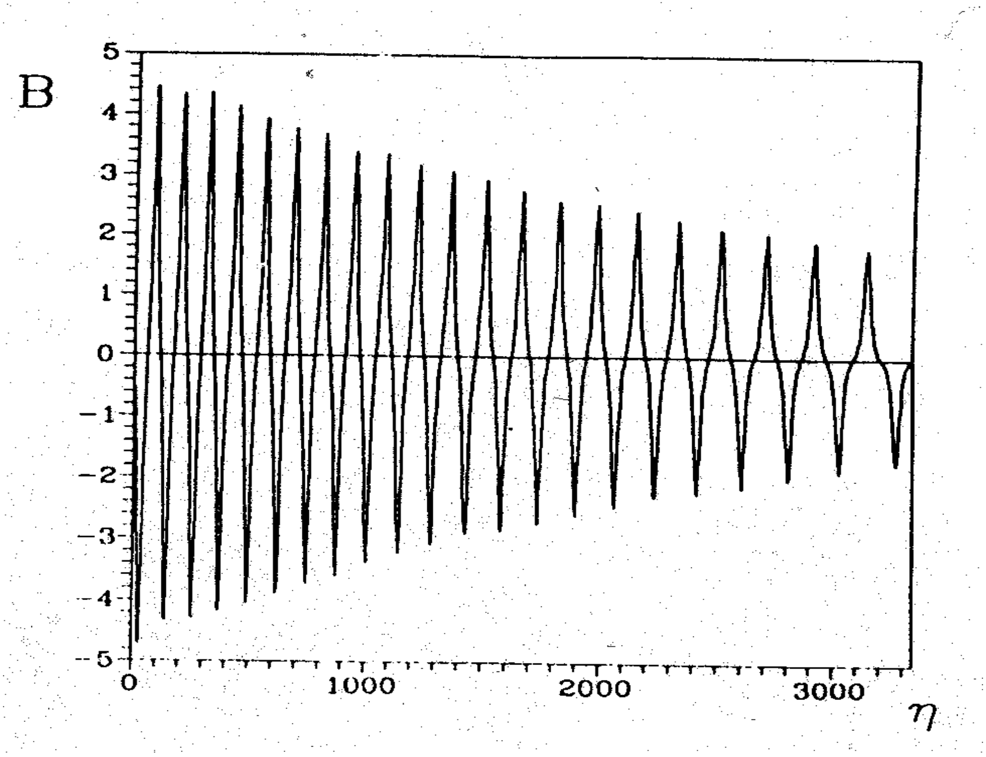

Figure 1: The evolution of the baryon charge $B(\eta)$ contained in the condensate $< \phi >$ for $\lambda_1 = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = \alpha = 10^{-3}$, $H_I/m = 10^7$, $\phi_o = H_I \lambda^{-1/4}$, and $\dot{\phi}_o = 0$.

3.2 Generation of the baryon density periodicity.

The modification of the baryogenesis model, namely the natural assumption that initially ϕ is a slowly varying function of the space coordinates $\phi(r, t)$, allows to obtain periodic distribution of the baryonic matter in the universe. The generation of the baryon density periodicity in the framework of the discussed baryogenesis model, was analyzed in refs.[7, 8, 9].

The equations of motion for $\phi = x + iy$ read

$$\begin{aligned}\ddot{x}+3H\dot{x}+\frac{1}{4}\Gamma_x\dot{x}+(\lambda+\lambda_3)x^3+\lambda' xy^2=0\\ \ddot{y}+3H\dot{y}+\frac{1}{4}\Gamma_y\dot{y}+(\lambda-\lambda_3)y^3+\lambda' yx^2=0\end{aligned} \tag{3}$$

where $\lambda=\lambda_1+\lambda_2$, $\lambda'=\lambda_1-3\lambda_2$.

In case when at the end of inflation the universe is dominated by a coherent oscillations of the inflaton field $\psi=m_{PL}(3\pi)^{-1/2}\sin(m_\psi t)$, the Hubble parameter is $H=2/(3t)$.

For each set of parameter values of the model λ_i we have numerically calculated the baryon charge evolution $B(\eta)$ for hundreds different initial conditions of the field corresponding to its initial monotonic space distribution $\phi(t_i,r_i)$, where $r\in[0,1]$.

The next step was to determine the baryogenesis epoch t_B, which was defined as the later epoch, when the B-conserving terms of the potential become comparable with the B-violating ones. Then the space distribution of the baryon charge $B(t_B,r)$ was obtained for the moment t_B from the evolution analysis $B(\eta)$ for hundreds different initial values of the field $\phi(t_i,r)$, corresponding to its initial space distribution.

Due to the nonharmonic field's potential, the initially monotonic space behavior is quickly replaced by space oscillations of ϕ, because of the dependence of the period on the amplitude, which on its turn is a function of r. As a result in different points different periods are observed and space behavior of ϕ becomes quasi-periodic. Correspondingly, the space distribution of the baryon charge contained in ϕ becomes quasi-periodic as well. The calculated space distribution of baryons at the moment of baryogenesis for one set of model's parameters is shown in Fig. 2, the distribution for another set of parameters is presented in ref. [8] (in Fig.2 there).

During the universe expansion the characteristic scale of the variation of the baryon charge was inflated to a cosmologically interesting size. Thus the present periodic distribution of the visible matter may date from the spatial distribution of the baryon charge $B(t_B,r)$, contained in ϕ at the advent of the B-conservation epoch t_B. And at present the visible part of the universe consists of baryonic shells and antibaryonic ones, divided by vast under dense regions.

For a wide range of parameters' values the observed average distance of $120h^{-1}$ Mpc between high-density regions in the universe can be obtained. The parameters of the model ensuring that scale belong to the range of parameters for which the generation of the observed value of the baryon asymmetry is possible. For example, taking the characteristic size of spatial variation to equal the present-day horizon size $r=10^{28}$ cm, for $\lambda_1\sim10^{-2}$ and $\lambda_2\sim\lambda_3\sim10^{-3}$ and $\alpha\sim10^{-4}$, $H_I t_B\sim10^{11}$, the voids size is around $120h^{-1}$ Mpc. Within the discussed model of baryogenesis there is interesting connection between the LSS scale $120h^{-1}$ Mpc and the baryogenesis time t_B. I.e. knowing from observations the characteristic scale $120h^{-1}$ Mpc, it is possible for a given t_B value to fix the parameters λ_i, and vice versa: concrete SUSY parameters will fix the time of baryogenesis.

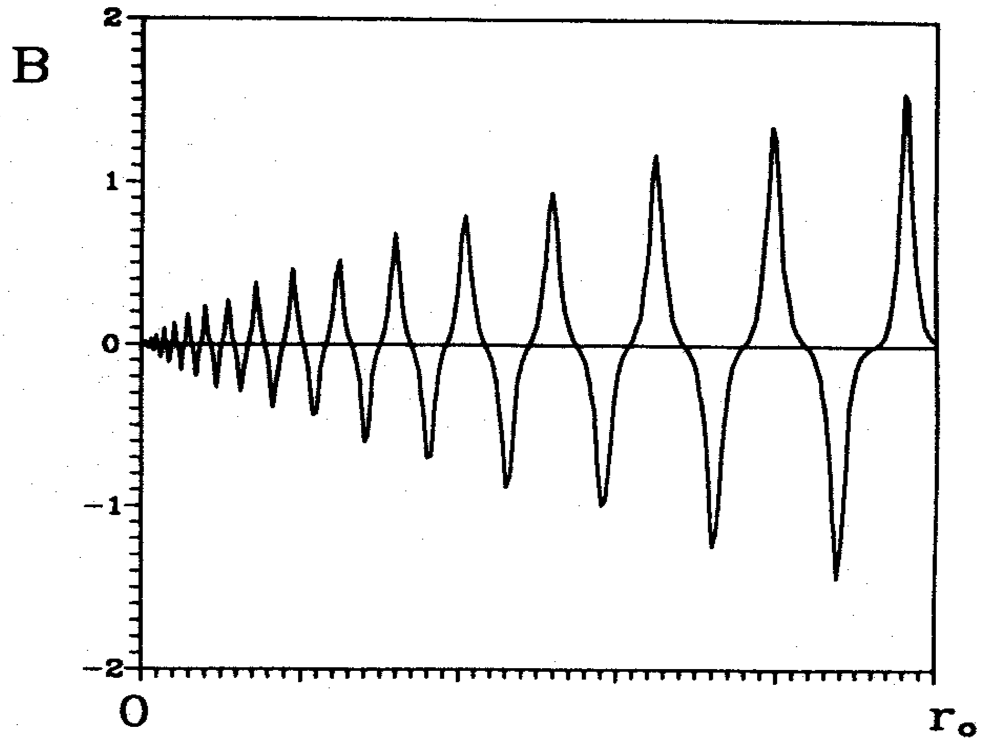

Figure 2: The space distribution of baryon charge at the moment of baryogenesis for $\lambda_1 = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = \alpha = 10^{-3}$, $H_I/m = 10^7$.

Thus in the proposed toy model both the baryogenesis and the large scale structure periodicity of the universe can be explained through the evolution of a single scalar field.

For some model's variations a presence of vast antibaryonic regions is predicted (see Fig.2). This is interesting because the observational data do not rule out the possibility of antimatter superclusters of galaxies in the universe. Thus the model proposes also an elegant mechanism for achieving a sufficient separation between domains of matter and antimatter, necessary to inhibit the contact of matter and antimatter regions with considerable density [84]. Besides, as far as neither explicit nor spontaneous charge symmetry violation is needed (charge symmetry is broken stochastically by quantum fluctuations during inflation), the domain wall problem is evaded.

Hopefully, the future largest projects, providing much larger and more complete samples like: the Sloan Digital Sky Survey, tending to cover the whole northern sky in five photometric bands to m=23 with a total number of galaxies with measured redshifts more than a million; the 2-degree Field Survey of Anglo-Australian Telescope, based on APM galaxy catalogue, that intends to measure about 250 000 redshifts; the VIRMOS Deep Survey, 6 Degree Field Galaxy Survey, as well as large quasar surveys: the 2 Degree Field Quasar Survey and the Sloan Digital Sky Survey quasar sample, together with the upcoming data from CMB satellite missions MAP and Planck will help to understand the nature of the LSS periodicity and to choose among the different theoretical models suggested to explain this LSS puzzle, thus providing constraints on physics of the very early universe.

Acknowledgments

We are glad to thank A. Dolgov, J. Einasto and B. Roukema for fruitful discussions. We highly appreciate the excellent stimulating atmosphere of the Workshop provided by J. Tran Thanh Van, Doris Neumann and the Organizing Committee of the XXXVIth Rencontres de Morion "Galaxy Clusters and the High-Redshift Universe". We are grateful for the financial support of our participation.

D.K. thanks Theory Division of CERN for the one month visiting position and High Energy and Astroparticle Section of ICTP for the two months visiting position during which this work was finalized.

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