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LARGE SCALE STRUCTURES AND INTEGRATED SACHS–WOLFE EFFECT IN NON-ZERO Λ COSMOLOGIES

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Some interesting features of the large scale structure formation in the model of the Universe with the cosmological constant are discussed. In the framework of such a model we consider the evolution of small scalar perturbations of metrics, density and velocity of the matter for the dust-like medium.

On the basis of the corresponding solutions of the Einstein equations the analysis of the long distance correlations of clusters of galaxies, contribution of the integrated Sachs–Wolfe (ISW) effect into microwave background temperature fluctuations and the Great Attractor problem in a non-zero Λ cosmology is carried out. It is shown that the data on long distance correlations in spatial distribution of clusters of galaxies are well explained in the framework of such models when $\Omega_\Lambda \geq 0.5$. On the other hand, the possibility of a nearly convergent flow of the galaxies in the neighborhood of the Local Group to be generated by the gravitational action of single large scale matter density perturbation is even more insignificant in the $\Lambda \neq 0$ case in comparison with the models without Λ. It is shown also, that the main contribution to the microwave background temperature fluctuations due to ISW effect is formed at $0.05 \leq z \leq 1$. Its value for models with different Ω_Λ is estimated.

Key words: non-zero Λ models: cosmic microwave background and large scale structures.

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I. INTRODUCTION

The cosmological constant has a physical interpretation of the energy density of zero-point quantum vacuum fluctuations of the fundamental fields. In cosmology it can be considered as a specific kind of non-baryonic dark matter, that is not clustered at all the scales and has a negative effective pressure. Actually, there is no possibility for the direct detection of Λ, but the growing amount of indirect evidences suggests the existence of the Λ-term.

Non-zero Λ cosmological models have been in the centre of attention in the last few years due to their ability to resolve some problems of the standard cold dark matter (sCDM) and the standard mixed dark matter (sMDM) scenarios [1,13,22]. Including $\Lambda > 0$ into cosmology allows to keep the inflation paradigm $\Omega = 1$ and avoid any contradiction between the age of the oldest stars in globular clusters [8] and the age of the Universe for the present value of the Hubble constant $H_0 \geq 50$ kms^{-1}Mpc^{-1}, $h \equiv \frac{H_0}{100 \text{ km/s Mpc}} \geq 0.5$. Also such a class of cosmological models explains the low values of the clustered matter fraction, obtained by most of the dynamical estimates, and fits the whole set of the observable data much better (see for review [19]).

Furthermore, current experiments on high redshift SNIa [18] directly indicate a positive cosmological constant, and can be considered as an independent confirmation. Also the data on gravitational lensing [9] and current analyses of the cosmic microwave background (CMB) temperature fluctuations [23,16] provide us with additional evidence. Thus, the specific features of $\Lambda \neq 0$ models must be of great interest for cosmologists.

The most important problem in modern cosmology is to determine the cosmological model (or the class of cosmological models) whose predictions agree with the whole set of the available observational data in the best way. The so-called standard scenario imply that the observable large scale structures of the Universe have been formed via the growth of small primordial inhomogeneities due to the gravitational instability. The physical properties of initial random field of density fluctuations are defined by the physics of very early epochs in the evolution of the Universe, and described by primordial power spectrum. Most of modern inflationary scenarios predict the primordial power spectrum to be scale-free $P(k) = A\ k^n$ with $n \simeq 1$. Further evolution of perturbations is determined by the global characteristics of the Universe (i. e. curvature, Hubble constant, presence of cosmological constant) as well as by the material content of the Universe (i. e. fractions of baryons, hot and cold dark matter, numbers of species of massive and massless neutrinos). In such a framework the characteristics of the large scale structure can be precalculated and confronted to observations, and conclusions about the likelihood of a certain cosmological model with a particular set of parameters can be made (see [17,22] and references therein).

This paper is concerned with the consideration of some features of the cosmological models with non-zero cosmological term. The outline of the paper is as follows: in section II we give the solutions of the linearized Einstein equations for the fluctuations of the matter density, velocity and gravitational potential in the longitudinal Newtonian gauge for dust-like medium with the cosmological constant. Also in this section a two-point correlation function of a cluster of galaxies is calculated and compared with the observable one. Section III is devoted to the analysis of the influence of the cosmological constant onto microwave background anisotropy. In section IV we analyse the Great Attractor problem in the $\Lambda \neq 0$ cosmology. The conclusions are given in section V.

II. EVOLUTION OF PERTURBATIONS. POWER SPECTRA AND LONG DISTANCE CORRELATIONS OF CLUSTERS

Let us consider the evolution of small scalar perturbations in the framework of a simple dust-like $\Lambda \neq 0$ model. For comparing theoretical predictions and observable data on the large scale structure of the Universe more convenient gauge to use for scalar perturbations is Newtonian (longitudinal) one with the line element

$$\begin{aligned} ds^2 &= g_{ik} dx^i dx^k \\ &= (1 + 2\phi/c^2) c^2 dt^2 - a(t)^2 (1 - 2\phi/c^2) \delta_{\alpha\beta} dx^\alpha dx^\beta, \quad (1) \end{aligned}$$

where i, $k = 0, 1, 2, 3$, α, $\beta = 1, 2, 3$, and ϕ plays the role of the gravitational potential in the Newtonian limit.

Einstein equations for flat, unperturbed $\Lambda \neq 0$ Universe give the following solution for the evolution of the scale factor [13,19]

$$a(t) = \left(\frac{\Omega_m}{1 - \Omega_m}\right)^{\frac{1}{3}} \mathrm{sh}^{\frac{2}{3}} \left(\frac{3H_0 t\sqrt{1 - \Omega_m}}{2}\right),$$

where Ω_m is the density parameter at present ($\Omega_m = \frac{8\pi G}{3H_0^2}\rho(t_0)$).

The age of the Universe in such a model for the same present Hubble constant is larger than in the $\Lambda \equiv 0$ case by the factor

$$K_t = \frac{1}{2\sqrt{1 - \Omega_m}} \ln \frac{1 + \sqrt{1 - \Omega_m}}{1 - \sqrt{1 - \Omega_m}} > 1.$$

The age of the Universe predicted by the model for the currently measured values of Hubble constant $H_0 \geq 50$ km s^{-1} Mpc^{-1} agrees with the data on the age of globular clusters $t_0 = 13 \pm 3$ Gyrs [8] for $\Omega_m \leq 1$.

From Einstein equations in Newtonian gauge, with energy-momentum tensor for the dust-like medium $T_i^k = c^2 \rho U_i U^k$, we have obtained solutions in Fourier space for the matter density perturbations $\delta\rho/\rho$, 3-velocity δV^α and gravitational potential ϕ, (growing mode only):

$$\begin{aligned} \frac{\delta\rho}{\rho}(k, t) &= -\frac{2C_k k^2}{3H_0^2 \Omega_m} a K_\rho, \\ \delta V^\alpha(k, t) &= -ik^\alpha \frac{2C_k a\dot{a}}{3H_0^2\Omega_m} K_V, \\ \phi(k, t) &= C_k K_\rho, \end{aligned} \qquad (2)$$

where C_k is a constant of integration, $a = a(t)$ is the scale factor in unperturbed $\Lambda \neq 0$ model.

$$K_\rho \equiv \frac{5}{3}\left(1 - \dot{a}/a^2 \int_0^t a dt\right),$$

$$K_V \equiv \frac{5}{3}\left(\dot{a}/a^2 - \ddot{a}/a\dot{a}\right) \int_0^t a\, dt, \ (0 < K_\rho, K_V \leq 1)$$

are suppressing factors for density and velocity perturbations correspondingly. For the models without the cosmological constant both factors are equal to unity.

Here $\phi(k, t)$ and $\frac{\delta\rho}{\rho}(k, t)$ are gauge-invariant values Φ_A and ϵ_m respectively, as introduced by Bardeen [2]. The proper solution for the density perturbations in the Newtonian (longitudinal) gauge, gauge-invariant value ϵ_g was transformed to the ϵ_m using relations from [2]. The analogous solutions in synchronous gauge was obtained and analyzed in details by [14]. At the early epoch $z > z_\Lambda \geq 0$ for $\Omega_m \leq 0.5$, where $z_\Lambda = \left(\frac{1-\Omega_m}{\Omega_m}\right)^{1/3} - 1$ is the redshift at the moment of equality of matter density to cosmological constant density, the suppressing factors were close to unity. At later epoch $z < z_\Lambda$ they decrease fast as z goes to 0 or Ω_m decreases (see Table 1).

Ω_m	K_ρ	K_V	K_2^2	K_3^2	K_4^2	K_5^2	K_{10}^2	K_{20}^2	K_Δ	K_U	K_ϕ
0.70	0.93	0.77	1.00	1.02	1.02	1.02	1.01	0.99	1.30	1.09	0.91
0.55	0.89	0.64	1.06	1.07	1.06	1.05	1.02	1.00	1.56	1.16	0.86
0.35	0.81	0.45	1.28	1.25	1.21	1.18	1.08	1.01	2.22	1.31	0.78
0.25	0.75	0.35	1.51	1.43	1.35	1.29	1.13	1.03	2.86	1.43	0.71

Table 1. Suppressing factors at $z = 0$, ISW and GA amplification coefficients for different Ω_m.

The approximations for the suppressing factors K_ρ and K_V are given also by [7,15]. As we can see, in all the models $K_\rho/\Omega_m > 1$ and $K_V/\Omega_m > 1$, so that the amplitudes of density and velocity perturbations will be higher in $\Lambda \neq 0$ models in comparison with $\Lambda = 0$ ones for the same C_k (normalization to CMB quadrupole). According to these solutions power spectra for the density, velocity and potential perturbations are as follows:

$$P_\rho(k) = Ak^nT^2(k)\frac{K_\rho^2}{\Omega_m^2},$$

$$P_V(k) = \frac{H_0^2}{k^2}P_\rho(k)\frac{K_V^2}{K_\rho^2},$$

$$P_\phi(k) = \frac{9H_0^2}{4k^4}P_\rho(k)\Omega_m^2,$$

where $T(k)$ is a transfer function, A is a constant of normalization ($C_kC_k^* = 9H_0AT^2(k)/4k^3$). The power spectra normalized to 4-year COBE data [5] for different value of Ω_m and scale-invariant primordial spectrum with $n = 1$ are shown in Fig. 1. We have used the normalization procedure proposed by [4].

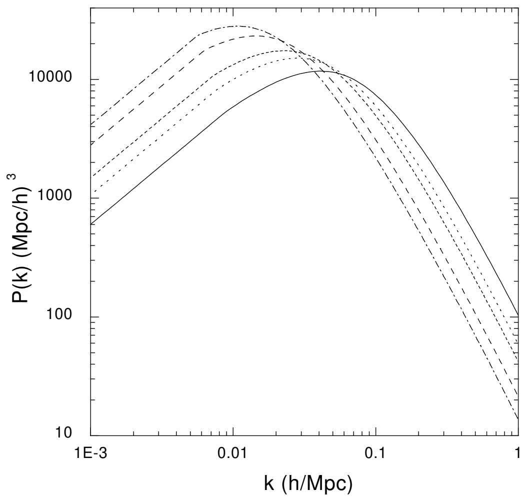

Fig. 1. The power spectra of density perturbations normalized to 4-year COBE data for MDM+Λ models with H_0=50 km s^{-1} Mpc^{-1}, $\Omega_H/\Omega_m = 0.2$ (Ω_H is a content of hot dark matter), 1 species of massive and 2 species of massless neutrinos, and different Ω_Λ: 0 (solid line), 0.3 (dotted), 0.45 (short dashed), 0.65 (long dashed), 0.75 (dot-short dashed).

The transfer functions used here for different models were taken from [22]. The horizontal shift of the maximum of power spectra toward large scales when Ω_m decreases (horizon scale at the increasing equality epoch) and the growth of amplitude at larger than horizon scales can resolve the problem of the positive long distance ($> 50h^{-1}$ Mpc) correlations in a spatial distribution of clusters of galaxies. The correlation function of clusters is calculated as

$$\xi_{cc}(r) = \frac{b_c^2}{2\pi^2}\int_0^\infty P(k)k^2W^2(kR_c)\frac{\sin\, kr}{kr}dk,$$

where $W(kR_c)$ is a window function, which filters the structures of scales larger than R_c out of the density field, b_c is their biasing parameter, which takes into account the statistical correlation of peaks above the given threshold [3], and this correlation function matches very well observational data for $\Omega_m h \sim 0.15 - 0.30$ (Fig. 2).

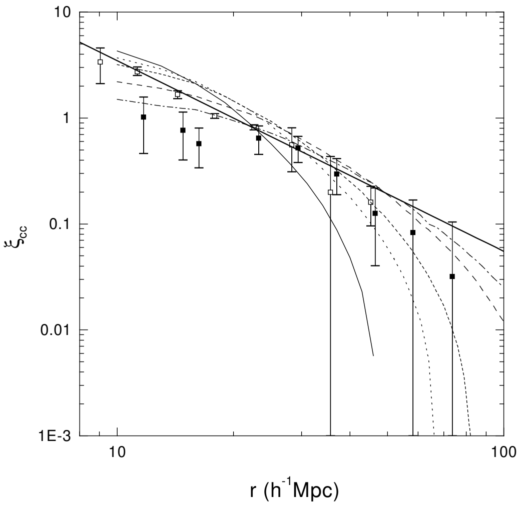

Fig. 2. The cluster-cluster correlation functions for spectra from Fig. 1, along with observational data points, given by [12]. Solid straight line represents the well-known approximation $\xi_{cc} = (r/r_0)^{-1.8}$.

III. $\Delta T/T$ ANISOTROPY: THE LOCALIZATION OF CONTRIBUTION OF ISW EFFECT

Now we shall use these solutions for the analysis of temperature fluctuations of CMB radiation in $\Lambda \neq 0$ models. The observable temperature fluctuations of CMB radiation can be connected with density, velocity and metrics perturbations at the last scattering surface by means of integrating geodesic equation in a fashion similar to classical paper [20] and taking into consideration adiabatic process:

$$\frac{\delta T}{T}(\mathbf{n}) = \frac{1}{3}\phi(\mathbf{n}R_h)$$
$$+2\int_0^{\omega_e}\frac{\partial\phi}{\partial\eta}(x^\alpha(\omega))d\omega + n_\alpha\delta V^\alpha(\mathbf{n}R_h) + \frac{1}{3}\frac{\delta\rho_b}{\rho_b}(\mathbf{n}R_h),$$

where $\mathbf{n}$ is unit vector, $\omega(\eta)$ is affine parameter along geodesic curve which begins from observer and finishes in the emission point, η is conformal time ($d\eta = c\, dt/a$), R_h is a distance to the last-scattering surface. The first term is well known Sachs–Wolfe effect (SW), the second is integrated Sachs–Wolfe (ISW), essential for $\frac{\partial\phi}{\partial\eta} \neq 0$ only, the third is Doppler one and the last is adiabatic one. At a large angular scale ($\simeq 10°$), where such anisotropy has been registered by COBE [5], SW and ISW effects dominate. For this case $\Delta T/T$ in expansion into spherical harmonics will be

$$\left(\frac{\Delta T}{T}\right)_l^2 = \frac{2l+1}{8\pi^2}\frac{H_0^2}{c^4}\int_0^\infty\frac{P_\rho(k)}{k^2}\Big[j_l(kR_h)$$
$$+\,6\int_{\eta_0}^{\eta_{rec}}\frac{dK_\rho}{d\eta}j_l\left(k(\eta_0-\eta)\right)d\eta\Big]^2 dk, \qquad (3)$$

where j_l is spherical Bessel function of l-th order, $\eta_{\rm rec}$ is the conformal time of recombination, η_0 is the present conformal time. It also can be expressed in a symbolic form:

$$\langle \Delta T/T\rangle^2 = SW * SW + 2 * SW * ISW + ISW * ISW.$$

It is clear that $\frac{dK_\rho}{d\eta} \to 0$ when $\eta \to \eta_{\rm rec}$ and its moduli are maximal at $\eta = \eta_0$ (physical factor). It means that the main contribution into the monopole ISW term ($l = 0$) is being formed now. But higher harmonics ($l \geq 1$) are formed between $z_{\rm rec}$ and $z = 0$, because $j_{l\geq 1}\left(k(\eta_0 - \eta)\right) \to 0$ when $\eta \to \eta_0$ (the geometrical factor). A question arises: where at the time scale is the main contribution of ISW effect to angular power spectrum formed and how does its localization depend on Ω_m and l? In order to answer this question we have altered the order of integration in (3) and calculated integrand (function of contribution) as a function of time for different Ω_m and l. The results are shown in Fig. 3 and Fig. 4, for primordial spectrum $P_\rho(k) = A\ k$ with arbitrary normalization.

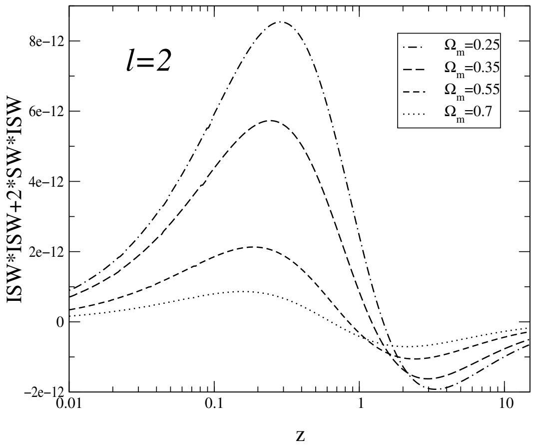

Fig. 3. Contribution function of the ISW effect against z for quadrupole in models with different Ω_m.

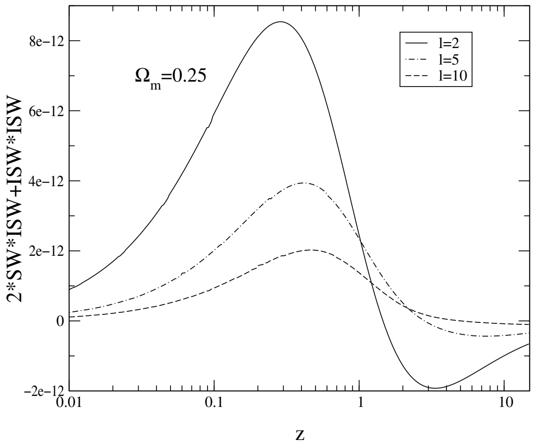

Fig. 4. Localization of contribution function of ISW on z for different harmonics.

As we can see, the maximum of contribution function shifts to an earlier epoch when either $\Omega_\Lambda = 1 - \Omega_m$ or l is growing. The main contribution to $\Delta T/T$ caused by the cosmological constant localized in the redshift range $z \simeq 0.05 - 1$ and this localization does not depend strongly on Ω_m, because it is caused mainly by the geometrical factor.

The coefficients of $\Delta T/T$ amplification owing to the cosmological constant are defined as $K_l^2 = \left(\frac{\Delta T}{T}\right)_l^2 (SW + ISW)/\left(\frac{\Delta T}{T}\right)_l^2 (SW)$ and presented in Table 1 for some harmonics. The ISW contribution to quadrupole is rapidly growing with the Ω_Λ increase (from 6% for $\Omega_m = 0.55$ to 50% for $\Omega_m = 0.25$). It is more essential for lower harmonics and lower Ω_m. K_l^2 is not sensible to the transfer function: after the transfer function has been substituted by 1 in (3), K_l^2 arises 6% for $l = 20$, 4% for $l = 10$ and only 1% for $l = 2$ in model with $\Omega_m = 0.25$.

IV. GREAT ATTRACTOR-LIKE FLUCTUATIONS

Let us appeal to the Great Attractor (GA) problem in $\Lambda \neq 0$ cosmology. The core of problem is an explanation of a roughly convergent flow in the neighborhood of the Local Group (LG) of galaxies ($\geq 50h^{-1}$ Mpc) with increasing velocity toward the centre which is placed at $\simeq 45h^{-1}$ Mpc from us. The peculiar velocity of LG is ~ 535 km/s (see [6,10,24] and references therein). If we introduce the potential for a peculiar velocity field, such as was proposed by [6] $\delta \mathbf{V}(\mathbf{x}) = -\boldsymbol{\nabla} U_0(\mathbf{x})$ and use solutions (2) then amplitudes of matter density perturbation and gravitational potential are given by:

$$\frac{\Delta\rho}{\rho}(\mathbf{x}) = H_0^{-1}\nabla^2 U_0(\mathbf{x})\frac{K_\rho}{K_V}$$

$$\phi(\mathbf{x}) = \frac{3}{2}H_0 U_0(\mathbf{x})\Omega_m\frac{K_\rho}{K_V}.$$

The velocity potential is provided by observational peculiar velocity field and does not depend on the model. So, in $\Lambda \neq 0$ models gravitational potential will be less and density perturbation higher than in $\Lambda = 0$ models with the same U_0 and H_0. It can be understood easily. As the source of $\phi(\mathbf{x})$ is $\Delta\rho(\mathbf{x})$, which in $\Lambda \neq 0$ models is lesser by $\Omega_m \frac{K_\rho}{K_V}$, so that $\phi(\mathbf{x})$ lessens by the same factor. Thus, the same peculiar velocity potential $U_0(\mathbf{x})$ in $\Lambda \neq 0$ models is generated by lower $\Delta\rho(\mathbf{x})$ and $\phi(\mathbf{x})$, because Hubble constant for $\Lambda \neq 0$ was lower in the past in comparison with $\Lambda = 0$: $H_{\Lambda=0} = H_0(1+z)^{3/2}$, $H_{\Lambda\neq 0} = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$. Since the power spectrum of density perturbations decreases at these scales with decreasing Ω_m the probability of realizing such fluctuations will decrease too. If GA is not a unique object similar fluctuations should be seen at the last scattering surface and they must have generated hot and cold spots in the CMB sky. The scale of GA at the recombination epoch is close to the acoustic horizon so that the angular size of such spots is in the same range where the first acoustic peak is expected to be. In order to calculate the amplitudes or profiles of such spots one must recalculate velocity, density and gravitational potential perturbations at $z = z_{\rm rec}$. Using of solutions (2) it can be obtained that

$$U(\mathbf{x}) = \frac{U_0(\mathbf{x})}{\sqrt{z_{rec}+1}} \frac{\sqrt{\Omega_m}}{K_V},$$

$$\phi(\mathbf{x}) = \frac{3}{2} H_0 U_0(\mathbf{x}) \frac{\Omega_m}{K_V},$$

$$\frac{\Delta\rho}{\rho}(\mathbf{x}) = \frac{1}{H_0} \frac{\nabla^2 U_0(\mathbf{x})}{z_{rec}+1} \frac{1}{K_V}.$$

In comparison with the $\Omega_m = 1$ models, at LSS the velocity potential U is higher by the factor $K_U = \sqrt{\Omega_m}/K_V$, ϕ is lesser by the factor $K_\phi = \Omega_m/K_V$ and density perturbations are higher by the factor $K_\Delta = 1/K_V$ (see Table 1). Therefore, the GA-like fluctuations will generate more contrast hot and cold spots because at the GA scale (full width at half maximum is $\sim 30'$) the main contribution is given by Doppler and Silk effects. We have calculated profiles for such spots in the $\Omega_m = 1$ model and shown that their amplitudes are $\leq 1.4\ 10^{-4}$ for the GA precursors [10]. The rms $\Delta T/T$ at this scale, calculated by means of the analytical approach by [11], is $\langle (\frac{\Delta T}{T})^2 \rangle^{1/2} = 2.8\ 10^{-5}$ (here and below we suppose the baryon content $\Omega_b = 0.06$ and cold dark matter content $\Omega_{\rm CDM} = 1 - \Omega_\Lambda - \Omega_b$). An analogous calculation for $\Omega_m = 0.3$ model gives the amplitude $\leq 2.2\ 10^{-4}$. Here it was taken into account that at the scale of GA ($k \simeq 0.03$) the damping factor $D(k) \simeq 0.75$ [11] and the amplitude of baryon density perturbations is lower by the factor $\simeq 0.4$ in comparison with the CDM component (estimated using the code from [21]). The estimation of $\Delta T/T$, caused by Great Attractor and measured at LSS carried out by [24] for $\Omega_m = 0.3$ is close to our own estimation. The rms $\Delta T/T$ at this scale in such a model is $3.3\ 10^{-5}$. So, the hot and cold spots caused by GA are more rare in $\Lambda \neq 0$ as compared with the $\Lambda = 0$ case. It means that the possibility of generating a large scale peculiar velocity field with the value ~ 540 km/s for Local Group via gravitational action of the large scale matter density perturbation is even more insignificant in the $\Lambda \neq 0$ models.

V. CONCLUSION

Changes in the form and amplitude of the initial power spectra in $\Lambda > 0$ cosmology along with the best features of sCDM and/or sMDM scenario allow us to achieve better agreement between the theoretical predictions and observable data on a large scale structure of the Universe (for more details see [17,22]).

The main contribution of the ISW effect to $\langle (\frac{\Delta T}{T})^2 \rangle$ is formed at the redshift range 0.05–1. It is maximal for lower spherical garmonics and increases fast when Ω_m decreases (from 6% for $\Omega_m = 0.55$ to 50% for $\Omega_m = 0.25$).

The GA like fluctuations which are probably responsible for the convergent flow with $V \geq 500$ km/s in the bulk of $\sim 50h^{-1}$ Mpc in these models are less possible than in the models without Λ. Taking into account the positive long distance correlation in these models, the observable disturbance of the uniform Hubble flow in the vicinity of Local Group is suggested to be a result of superposition of gravitational action of a few extended low amplitude density perturbations.

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ВЕЛИКОМАСШТАБНІ СТРУКТУРИ ТА ІНТЕҐРОВАНИЙ ЕФЕКТ САКСА-ВОЛЬФА В МОДЕЛЯХ ІЗ КОСМОЛОГІЧНОЮ ПОСТІЙНОЮ

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Космологічні моделі з ненульовою Λ-константою останніми роками привернули увагу дослідників можливістю розв'язати деякі проблеми стандартних моделей із холодною та змішаною темною матерією (sCDM та sMDM). Включення в модель $\Lambda > 0$ дає змогу не порушувати стандартного припущення інфляційних теорій $\Omega = 1$ і уникнути протиріччя між віком найстарших зір у кулястих скупченнях та віком Всесвіту для сучасних значень постійної Габбла $H_0 \geq 50$ км с$^{-1}$ Мпк$^{-1}$. У межах такого класу моделей добре пояснюються низькі значення долі кластеризованої матерії, які випливають з більшости динамічних оцінок, і в загальному передбачення таких моделей ліпше відповідають усій сукупності спостережуваних даних. Щобільше, останні експерименти з визначення відстаней за Надновими Ia прямо вказують на наявність додатної космологічної постійної і їх можна розглядати як незалежне підтвердження $\Lambda > 0$.

У цій праці обговорено деякі аспекти формування великомасштабної структури Всесвіту в моделях із космологічною константою. Вивчено особливості еволюції скалярних збурень, спектр потужности густини таких збурень у цьому класі моделей. Теоретично обчислена кореляційна функція скупчень галактик добре узгоджується зі спостережуваною при $\Omega_\Lambda \geq 0.5$.

Проаналізовано підсилення низьких гармонік у флюктуаціях температури реліктового фонового випромінювання внаслідок присутности космологічної постійної та визначено, що основний внесок у підсилення формується в діяпазоні червоних зміщень $0.05 < z < 1$.

Також виявлено, що ймовірність утворення такого явища, як Великий Атрактор (майже збіжний потік галактик до центру, що знаходиться на відстані $\sim 50h^{-1}$ Мпк від нашої Галактики), як результат ґравітаційного притягання великомасштабної флюктуації густини в моделях із космологічною постійною, менша, ніж у моделях з $\Lambda = 0$.