LARGE-SCALE STRUCTURE OF THE UNIVERSE IN UNSTABLE DARK MATTER MODELS

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ABSTRACT

Processes of the formation and the evolution of the large-scale structure are discussed in the framework of unstable dark matter models. Six numerical models are presented. The projected distribution of simulated galaxies on the sky, wedge diagrams, correlation functions and the mean linear scale of voids are presented. Physical background of the hypothesis of unstable particles and possible observational tests are discussed. The level of the microwave background fluctuations is estimated analytically. Special attention is given to late stage of supercluster evolution and galaxy formation.

INTRODUCTION

Simple cosmological scenarios of the large-scale structure formation based on cold dark matter (CDM,axions) or on hot dark matter (HDM, neutrinos) become more and more complicated, invoking biased galaxy formation, unstable dark matter, composite (non flat) spectrum of perturbations, compound inflation, barion bubbles and so on. Evidently these models do not satisfy the criteria of simplicity and elegancy. But the absence of apparent simplicity seems to be reflecting the maturity of the theory - as a rule naive simplicity and elegancy are connected with the deficit of observational data. For example the theory of elementary particles was simple and elegant in early twenties when only two particles (electron and proton) were known. Compare this picture with contemporary theories (GUT, SUSY) with hundreds or thousands of "elementary particles". Today we see in the cosmology the transition from theories exploiting physical effects proved in a laboratory to theories which consider the Universe as a unique laboratory, where we can test predictions of modern high

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energy physics. So, we turn from the picture of the Universe based on the known physical laws to the study of physical laws by cosmological means and in particular by means of large-scale structure analysis.

THE UNSTABLE DARK MATTER (UDM) MODEL

There is now a variety of UDM models differing one from the other by masses and lifetimes of particles, by types of decays, by their solved and unsolved problems. We believe that our model (Doroshkevich et al. 1985, 1987) is well developed and has good perspectives. The main points of the model are as follows:

a) The isotropic Universe with $\Omega = 1$.

b) Particles with rest mass $m \simeq 50-100$ eV and lifetime $\tau \simeq 10^9$ years dominated in the Universe at redshifts $10^4 \geqslant z \geqslant z_\tau \simeq 3-7$. It is very important that particles decay before the begining of the nonlinear stage in the growth of density perturbations when $\delta\rho/\rho$ is less (but not much less) than unit. The formation of the large-scale structure take place after or during decays when homogeneously distributed relativistic products of decays dominate in the Universe and so the perturbations in the cold (non-relativistic) components of the density grow very slowly. This is the reason why the known objections against UDM models (Efstathiou 1985; Hoffman 1986; Vittorio and Silk 1985; Flores et al. 1986) are not relevant to the model under discussion.

c) The observed structure of the Universe was formed by the cold component of the dark matter after the decay of unstable particles. This component may have complicate composition - baryons, massive particles (stable or with large lifetime), axions, familons and other scalar fields, primordial black holes and so on. The stable component amounts $\Omega_{st} \simeq 0.1-0.03$ before it decays. Presently the density of the cold component (galaxies, clusters, superclusters and matter in voids) is about $\Omega_c \simeq 0.2-0.4$. The baryon density is probably $\Omega_b \simeq 0.07-0.1$.

d) At $z = 0$ 70-80% of the mean density of the Universe is in the form of products of the decay of unstable particles (relativistic or not) which maintain the quasiuniform background (perhaps together with cosmological constant). Two- and three-body decays are possible. It is also possible to have small branching (at the level 10^{-5}) to electromagnetic decays.

e) UDM models retain the qualitative picture of the pancake theory. Initial amplitude of perturbations is close to that of HDM models:

$$\sigma_\rho \simeq 4\chi_r(1 + z)^{-1}; \quad z > z_\tau; \; 0.7 \leqq \varkappa_r \leqq 1.3 \qquad (1)$$

At $z = 0$ the amplitude estimated by linear theory (LT) is $\sigma_{LT} \simeq 1.5-2$. The slow growth of perturbations provides the formation of first objects at $z = 3$ and conserves the large-scale structure up to $z = 0$.

PHYSICAL BASIS OF THE MODEL

In the UDM model masses, lifetimes and types of decays are connected with the scale and the rate of evolution of the structure. This enables us to predict either new types of particles having necessary properties or new properties for known particles.

Suggested unstable massive particles (neutrinos) could be related with known spontaneous breakdown of global "horisontal" symmetry between fermion (quark and lepton) generations. In the familon models it is possible to have not only the decay

$$\nu_1 \rightarrow \nu_2 + f; \ W \sim m_\nu^3/F^2; \tau \simeq 10^9 \text{ yr}; \ F \simeq 10^8 \text{ GeV} \qquad (2)$$

but also the decays $\mu \rightarrow e + f$; $K \rightarrow \pi + f$; $D \rightarrow \pi + f$. This provides a sensitive experimental tests for such models. Phenomenologically the breakdown of global horisontal symmetry can imply anomalous four neutrino interaction

$$\nu \rightarrow 3\nu; \ W \sim G_X^2 m_\nu^5; \ \tau \simeq 10^9 \text{ yr}; \ G_X > 10^4 G_F \qquad (3)$$

where G_F is the Fermi constant of four fermion weak interaction. Today we have first attempts of laboratory searches of effects from such interaction in decays of W and D mesons with the use of cosmological limits (3) on its strength. On the basis of the UDM models it seems plausible to find the answer to the question "Why Nature needs several fermion generations?"

NUMERICAL SIMULATIONS

We simulated six numerical models of the formation and the evolution of large-scale structure with massless products of decays. The simulations were made with 64^3 particles in a 64^3 cells using standard Cloud-In-Cell method. We used the "fractal" ("flat") spectrum of Harrison-Zeldovich $b^2(k) = B R_c^4 k(1 + (kR_c)^2)^{-12}$ (FZ) and selfsimilar spectrum (SS) $b^2(k) = B R_c^7 k^4(1 + (kR_c)^2)^{-12}$ where R_c defines damping of perturbations on small scales due to free streaming (Bond and Szalay 1984). Characteristic scale $R_c = 4.8 \ (m/30 \text{ eV})^{-1}$Mpc corresponds to the coherent length $\lambda_c = 40 \ (m/30 \text{ eV})^{-1}$Mpc.

The parameters of the models are presented in the Table, where m and $\tau \cdot 10^9$ years are the mass and the lifetime of unstable particles, z_τ is the redshift at the moment $t = \tau$, Ω_c and Ω_r are present densities of cold and relativistic components, Ω_Λ is the contribution of the cosmological constant, Ω_{st} is the density of stable component before decays, r_c and r_c^* are correlation radii(Mpc) for all particles in a model and particles inside pancakes only. Analytical estimates for expected microwave background fluctuations are given for baryon density $\Omega_b = 0.1$. Here $Q \cdot 10^{-5}$ is quadrupole, $\Delta \cdot 10^{-5}$ and $D\ 10^{-5}$ are two- and three-point estimates for the angle $\theta = 5'$.

Table

N	m_{eV}	τ	$1+z_\tau$	Ω_c	Ω_r	Ω_Λ	Ω_{st}	r_c	r_c^*	Q	Δ	D
1 FZ	70	1.3	3.1	0.16	0.84	-	0.055	7.3	-	2.4	1.2	0.7
2 SS	70	1.3	3.1	0.16	0.84	-	0.055	4.1	6.0	0.02	0.4	0.6
3 SS	85	1.0	3.9	0.19	0.81	-	0.055	3.8	5.1	0.02	0.4	0.8
4 FZ	65	0.3	8.3	0.30	0.30	0.4	0.085	9.1	11.8	2.5	1.2	0.8
5 FZ	85	0.3	8.3	0.15	0.35	0.5	0.05	7.1	9.7	2.0	1.2	0.8
6 FZ	68	1.1	3.7	0.32	0.68	-	0.1	8.4	12.0	2.4	1.2	0.6

A very important problem is the selection of points which could be identified with galaxies. We used a two-step procedure. In the first step we identify all points within pancakes with galaxies. In some models we used the second step which is more realistic and more complicated. It was taken into account that only a small (20-30%) fraction of gas heated by shockwave cools quickly and forms galaxies. Point absorbed by pancake at z larger than $1.2(1 + z)$ $(1 + z_{pan}(r))$ were identified as galaxies ($z_{pan}(r)$ - the moment of pancake formation at every place). In this approximation the space distribution of simulated galaxies better resembles the observed galaxy distribution because outlying parts of pancakes are emphasized and central parts contain a smaller amount of particles.

The simplest characteristic of a model is the projected distribution of galaxies on the sky. Fig. 1 shows CFA galaxies and galaxies of the model N6 with a realistic luminosity function. This representation is rather simple, but the picture is distorted by projection effects and depends essentially on the observer's position.

The comparison of simulated distributions with the observed picture is more useful by means of wedge diagram. Fig. 2 presents wedge diagrams for galaxies in the model N6. The agreement with the observed distribution seems to be very encouraging. Long superclusters and giant empty voids (20-30 Mpc) are clearly seen, but the structure is not so pronounced as it was in the case of standard HDM models. One can find poor groups and separate "galaxies" far from main bodies of superclusters. These objects were born inside weak pancakes formed only recently (at $z \simeq 1$).

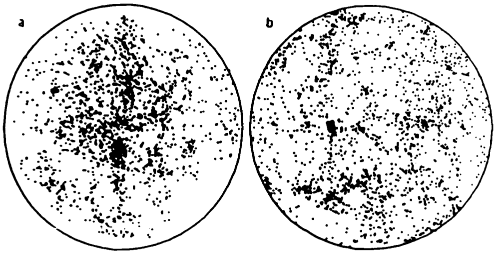

Fig. 1. Projected distribution of galaxies on the sky: a) CFA galaxies ($\sim$2500) in the northen galactic hemisphere with $m < 14^{m}.5$ and $V < 7000$ km/s. The galactic pole is in the centre, b) galaxies in the model N6 (2000) inside a sphere with $R = 70\ h^{-1}$Mpc.

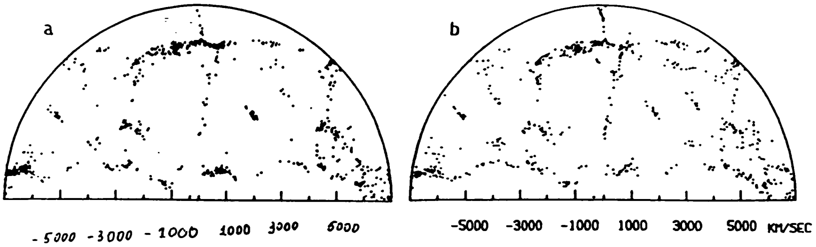

Fig. 2. Distribution of galaxies inside a narrow wedge (6°) for the model N6. a) for points within pancakes, b) for simulated galaxies (first $\sim$30% of points absorbed by pancakes). About 700 objects are plotted.

Most of galaxies in the model N6 were formed at $z = 1.5-2.5$, but a small fraction of galaxies (0.1%) appears at $z = 3.5$ and 6% at $z = 2.5$. The rate of galaxy formation quickly decreases at z smaller than 1.5 although some galaxies can be formed even at present. The epoch of galaxy formation is very sensitive to the type of decay. Better results seem to be obtained for massive products of decays.

The correlation function for all points in a model and for points inside pancakes only are plotted in Fig. 3. For all models the slope of the correlation function is close to the observed value $\sim$1.8 at $\xi > 1$. In the region $\xi < 1$ the correlation function is steeper. It appears that the correlation function weakly depends on the form of initial spectrum of perturbations. Correlation function for all points and only for galaxies differ by a factor of 3-4 in amplitude or by a factor of 1.5-2 in the correlation length. In models with Λ-constant the correlation function is more steep in the region $\xi < 1$ and shows a shoulder at $\xi \gtrsim 1$.

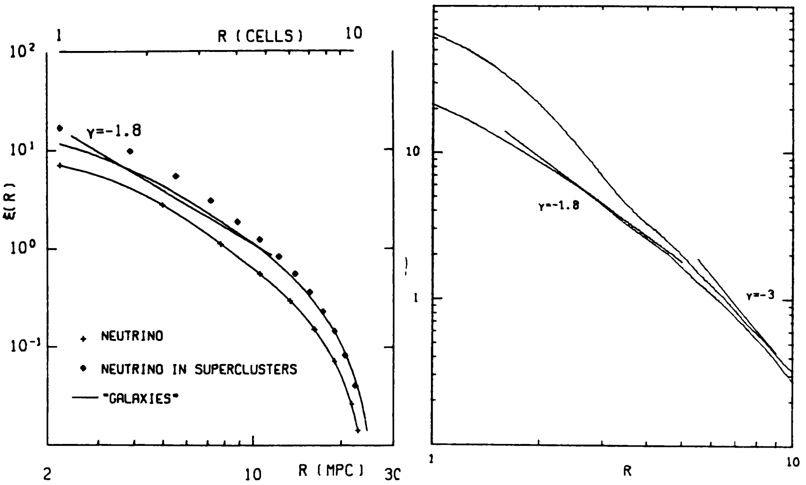

Fig. 3. Two-point correlation function for various types of objects a) in the model N6, b) in the model N4 with positive Λ-constant. For a) "neutrinos" - for all points of the model, "neutrinos in superclusters" - for all matter absorbed by pancakes, "galaxies" - for the distribution of simulated galaxies. For b) the top curve is for all points inside superclusters, the bottom curve is for first fraction (25%) of points absorbed by pancakes, distance scale is in cells, one cell being equal 0.925 h^{-1}Mpc.

An important parameter of the structure is the mean distance between superclusters in deep surveys of galaxies or in one-dimensional catalogs of points. The parameter can be estimated (Doroshkevich and Klypin 1985) using one-dimensional cluster-analysis. The results of the analysis carried out for the deep galaxy survey of Kirshner et al. (1983) and for the model N6 are plotted in Fig. 4. The argument is the filling factor p defined as a ratio of total length of all clusters to total length occupied by points L (i.e. the catalog depth). The ordinate is

$$\ell_0(p) = (1 - p)L/(N_{cl}(p) - 1) \qquad (4)$$

where $N_{cl}(p)$ is the number of clusters. The function $\ell_0(p)$ grows rapidly for $p < 0.15$-0.2 due to clusterrisation of galaxies inside separated superclusters and ℓ_0 is constant for $0.2 < p < 0.4$-0.5. At larger filling factors statistical fluctuations increase very quickly. The value $\ell_0 \simeq$ (25 ± 5) h^{-1}Mpc for the interval p = 0.2-0.4 is the characteristic distance between superclusters. At these filling factors most clusters (75%) consist of a few galaxies (1-5) and probably are related with small groups or poor chains of galaxies.

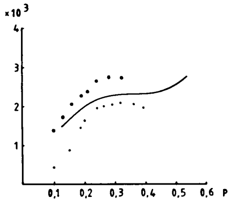

Figure 4. Dependence of normalized mean distance between superclusters ℓ_0 (km/s) on filling factor p. Dots - for points taken from regions with $\rho > 4\bar{\rho}$, circles - for points inside regions with $\rho > 5\bar{\rho}$

FLUCTUATIONS OF THE MICROWAVE BACKGROUND (FMB)

Estimates of FMB depend on the amplitude and spectrum of initial perturbations and on processes in the Universe at $z < 10^3$. In UDM models without secondary ionization the two-point Δ and three-point D estimates of small scale FMB are given by (Doroshkevich 1985):

$$\Delta^2(\theta) = 2\left[C(0)-C(\theta)\right] = 0.64\theta^2\sigma_r^2(R_h^2 l_c^2/R_r^4)\left[1+6.25(10\Omega_\ell\right]^2 \quad (5)$$

$$D^2(\theta) = \Delta^2(\theta)-0.25\,\Delta^2(2\theta) = (\theta^4/7)\,\sigma_r^2(R_h/R_r)^4\left[1+7.1(10\Omega_\ell)^2\right] \quad (6)$$

where $C(\theta)$ is the autocorrelation function of FMB, σ_r is the amplitude of perturbations for $z=10^3$, $l_c^2 = 5/3 < k^{-2}>$ is the averaged over the spectrum the value of k^{-2}, $R_r = 190h^{-1}(\Omega_{st}/\Omega_c)^{1/2}$ Mpc and $R_h = 3\cdot 10^3 h^{-1} I_h$ are the horizons at recombination and at present time $I_h = H_0\int_0^t (1+z)dt$ Multipole harmonics of FMB are determined as

$$\text{(FZ)} \quad a_\ell^2 = 1.5\,\sigma_r^2(l_c/R_r)^4(2\ell+1)/\ell(\ell+1)K_\ell^2 \quad (7)$$

$$\text{(SS)} \quad a_\ell^2 = 4\,\sigma_r^2\left[1+2.5(10\Omega_\ell)^2\right](R_r/R_h)^2 < (kR_r)^{-6} > (2\ell+1) \quad (8)$$

The factor $K_\ell \simeq 3$ takes into account the contribution of the period when relativistic products of decay were dominating in the cosmological density (Kofman et al. 1985).

For comparison with the result of Davis et al. (1987) we present the correlation function of FMB for angles $1° \leq \theta \leq 10°$:

$$\text{(FZ)} \quad C(\theta,\theta_a) = 2.4Q_{FZ}^2 \ln(2/\sqrt{\theta^2+2\theta_a^2}) \quad (9)$$

$$\text{(SS)} \quad C(\theta,\theta_a) = 0.2Q_{SS}^2\,\theta_a^{-2}\exp(-\theta^2/4\theta_a^2) \quad (10)$$

where Q_{FZ} and Q_{SS} are quadrupoles.

Numerical estimates (see Table) show that UDM models with FZ-spectrum predict the quadrupole larger than the most stringent observed upper limit $Q<1.6\ 10^{-5}$ (Strukov et al. 1987). The quadrupole is much smaller in the models with SS-spectrum.

LATE STAGES OF SUPERCLUSTER EVOLUTION AND GALAXY FORMATION

The galaxy formation is a complicated process in UDM models, but some general tendencies common for any pancake picture were discussed by Doroshkevich et al. (1978) and Doroshkevich (1985). Main results are:

a) Our numerical models show that the classical two-dimensional pancake is difficult to find. The main element of the structure is a filament caused by two-dimensional compression of the dark matter but not by intersection of pancakes.

b) Galaxies form quickly after (and during) the formation of a central part for early pancakes, where high density of cooled gas is attained. The process slows down in late pancakes and in outlying parts of early pancakes. In very late pancakes the gas has not time to cool and no galaxies are forming.

c) When stars and galaxies start to form the remain gas of the pancake is heated. It is probable that we observe the trace of this period in the overall abundance of heavy elements and in the observed entropy of hot gas inside galaxy clusters.

d) Besides rich superclusters, filaments and late pancakes (containing only hot gas without galaxies) there should exist an intermediate class of objects which contain both hot gas and poor groups of galaxies or separate galaxies.

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