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LARGE-SCALE STRUCTURE OF THE UNIVERSE AND INITIAL FLUCTUATION SPECTRA

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ABSTRACT. *It is shown that observations of galaxy and cluster correlation functions and large-scale bulk motions indicate the extra power of initial Gaussian density perturbation spectrum. Upper limits of cosmic microwave background (CMB) anisotropy at a few degrees restrict such extra power from above. CDM+Z spectrum which satisfies recently reported observations without any contradictions with the modern observable upper limits of CMB anisotropy is constructed. It contains additional power of ~170% relative to CDM-spectrum on the scale* $(3\text{-}10^3)h^{-1}$*Mpc. The amplitude of the spectrum and its slope in this region are determined by the observed characteristics of the large-scale structure.*

INTRODUCTION

The data of observational cosmology which have been obtained during the last years on the large-scale structure of the Universe (distances to far galaxies measured without Hubble law, their peculiar velocities, voids, Great attractor, etc.) give a chance to progress in solution of the reverse problem of cosmology - reconstruction of the initial power spectrum of density perturbations from all the observable characteristics of the large-scale structure of the Universe. Solution of this problem permits to clear up the nature of the matter and/or physical processes in the early Universe when this spectrum was formed. Meanwhile only the first attempts of such reconstruction have been undertaken (Bardeen et al., 1987; Turner et al., 1987;

Juszkiewicz et al., 1987; Martinez-Gonzales & Sanz, 1989; Dekel, 1991).

The purpose of this paper is to analyse the requirements imposed on the initial power spectrum of density perturbation for securing conformity of both theoretical and observable large-scale structure characteristics of the Universe. Most important from such characteristics are:

- anisotropy of the microwave background radiation temperature;
- galaxy and cluster correlation functions;
- bulk motion;
- mean distances beetwen bright galaxies, clusters or their concentrations;
- biasing or ratio of the galaxy to mass correlation functions.

SPECTRA AND THEIR NORMALIZATION

We analyze the following initial power spectra of the density perturbations:

1) HDM(1)-spectrum with one sort of massive neutrinos and HDM(3)- spectrum with three sorts of them (Bond & Szalay, 1983);

2) CDM-spectrum (Davis et al., 1985);

3) Hybrid HC-spectrum, which is a combination of both HDM-spectrum with Ω_{HDM}=0.4 and CDM-spectrum with Ω_{CDM}=0.5 (Bardeen et al., 1987);

4) CDM+X-spectrum with additional power on scales $5\ h^{-1} \leqslant k^{-1} \leqslant 1000h^{-1}$ Mpc relative to CDM-spectrum (Bardeen et al., 1987);

5) DI (double inflation) spectrum proposed by Turner et al. (1987), which is a combination of the long-wave neutrino spectrum (after the first inflation) and phenomenological short-wave spectrum (after second inflation).

The procedure of normalization of the spectrum is very importante. There are several ways of realization of such procedure:

a) Normalization to the galaxy correlation function (N1) - $\xi_{gg}(5h^{-1}\mathrm{Mpc})=1$;

b) Normalization to the second moment of the correlation function $J_{3g}(R)$ at $R=10h^{-1}$Mpc (N2);

c) Normalization to the mean square amplitude of mass fluctuations $(\Delta M/M)_{rms}=1$ at $8h^{-1}$ Mpc (N3).

The calculation has been executed at J_{3g} normalization for all spectra. Coefficients for transformation to another type of normalization are presented in Table 1 without DI-spectrum, because the long-wave part of this spectrum has been normalized by J_{3g} normalization, but the short-wave part - by the galaxy correlation function. The characteristics of the models are presented in Table 2, where Ω_b, Ω_{CDM}, Ω_{HDM} are the density (in units of the critical density) of baryons, cold dark matter and hot dark matter, respectively, σ_{og} is the root mean square density fluctuations on the galaxy scales.

Table 1. **Coefficients for transformation from N2 to N1 and N3 normalization for each spectrum**

	A(N1)	A(N2)	A(N3)
HDM(1)	0.84	1	1.36
HDM(3)	1.08	1	1.32
CDM	0.77	1	1.17
HC	0.61	1	1.27
CDM+X	0.81	1	1.19
CDM+Z	0.83	1	1.19

According to the hypothesis of the large-scale structure of the Universe as a result of development of Gaussian random density perturbations the galaxies, clusters and more large-scale objects were formed in the density peaks of such perturbation field. Obvious question is whether the space distribution of both peaks (bright objects) and total density (baryons and dark matter) coincide or they are displaced relative to each other by the value of the biasing parameter (b).

Fruitful turns out the approach when all observable objects in the Universe are formed in the density peaks which have amplitudes larger than some threshold value: $\delta_0 \geq \nu_t \sigma_0$. Formalizm of such approach has been developed by Politzer & Wyse (1984) and Bardeen et al. (1986). The order of the calculation of the biasing parameters for galaxies and clusters has been described in detail in our paper (Hnatyk et al., 1991). We have calculated the biasing for each model using the observed galaxy and cluster concentrations $n^g \simeq (h/4.6\ \mathrm{Mpc})^3$ and $n^c \simeq (h/55\ \mathrm{Mpc})^3$, accordingly. Thus all models conform to the observed concentrations of bright galaxies and clusters. HDM-models are exceptions, because galaxies in such models are formed by fragmentation of larger objects. In this case the equation for ν_t has no solutions for such observed concentration of galaxies, therefore the galaxy biasing obtained using such method is uncertain. The biasing for HC model we assumed to be equal to 1 so far as in that case the moment of galaxy formations is consistent with modern data about the age of galaxies and old stars.

Results of calculations are presented in Table 2. The mean height of the peaks $\langle\nu\rangle_a$ from which bright galaxies and rich clusters are formed in any models of the Universe as well as the moment of appearance of the first counterflow in dark matter and generation of shock wave in baryon component, $z_a = \langle\nu\rangle_a \sigma_0(R_a)/1.69-1$, are presented too.

TESTS OF FLUCTUATION SPECTRA

Measure of matter clustering on scales $\leq 20h^{-1}$Mpc is two-point bulk galaxy-galaxy correlation function (Davis & Peebles, 1983), which has the correlation radius

$r_g \simeq 5.4h^{-1}$Mpc and the power exponent $n \simeq 1.8$.

Table 2. Parameters of cosmological models

	HDM(1)	HDM(3)	HDM(3)	CDM	HC	DI	CDM+X	CDM+Z
Ω_b	0.1	0.1	$\ll$ 0.1	0.1	0.1	0.1	0.1	0.1
Ω_{CDM}	-	-	-	0.9	0.5	0.9	0.9	0.9
Ω_{HDM}	0.9	0.9	$\simeq$ 1.0	-	0.4	-	-	-
b_g	0.64	0.51	0.52	1.62	1.00	1.47	1.69	1.76
b_{cl}	2.69	1.79	1.96	5.54	3.08	3.70	5.51	5.58
σ_{og}	2.00	2.00	2.00	2.89	2.25	3.03	2.58	2.34
$\langle\nu\rangle_g$	-	-	-	2.80	2.85	2.53	2.80	2.80
z_g	-	-	-	3.78	2.80	3.53	3.27	2.87
σ_{ocl}	1.08	1.54	1.46	0.44	0.76	0.67	0.43	0.42
$\langle\nu\rangle_c$	3.00	2.58	2.71	3.10	2.76	2.92	3.02	2.98
z_c	0.91	1.35	1.34	- 0.19	0.24	0.16	- 0.23	- 0.26

On larger scales ($\gtrsim 20h^{-1}$Mpc) the two-point cluster-cluster correlation function is similar measure. It is calculated for Abell clusters and approximated by a power law (Klypin & Kopylov, 1983; Bahcal & Soneira, 1983) with the correlation radius $r_c \simeq 20 \div 25h^{-1}$ Mpc and power exponent $n \simeq 1.3 \div 1.9$.

The tendency to clustering of galaxies in the neighbourhood of Abell clusters ($r \lesssim 40h^{-1}$Mpc) is described by two-point cluster-galaxy crosscorrelation function (Peebles, 1980). It is approximately equal to the root square of the product of both the galaxy and the cluster correlation functions that follows from the essence of the cross-correlation (Bahcal, 1988).

Thus, the observed two-point correlation functions of galaxies and clusters with ratio between them $\xi_{gg}:\xi_{cg}:\xi_{cc} \simeq 1:(2 \div 5):(9 \div 18)$ are observable characteristics of the large-scale structure of the Universe. Scatter of these values stipulated by errors of determination of r_g, r_{cg}, r_c and slope of the correlation functions.

In the theory of structure formation of the Universe from Gaussian random perturbation all correlation functions can be calculated if the initial power spectrum $P(k)$ is known:

$$\xi_{ab}(r) = \frac{b_a b_b}{(2\pi^2)} \int_0^\infty P(k)\, k^2\, W(kR_a)\, W(kR_b)\, \frac{\sin(kr)}{kr}\, dk,$$

where indices a, b mark either correlation of perturbation of galaxy scales (g) or cluster scales (c), $W(kr)$, the filter function for a- or b-scales, b_a, b_b, the biasing for peaks of these scales. In this paper we defined $R_g=0.35h^{-1}$Mpc and $R_c=5h^{-1}$Mpc that correspond to full masses of these objects $M_g=2\cdot10^{11}M_\odot$ and $M_c\simeq5\cdot10^{14}M_\odot$, accordingly.

For analysis of the dependence of correlation functions from the initial spectrum we calculated them for all models. Results of the calculation are presented in Fig.1.

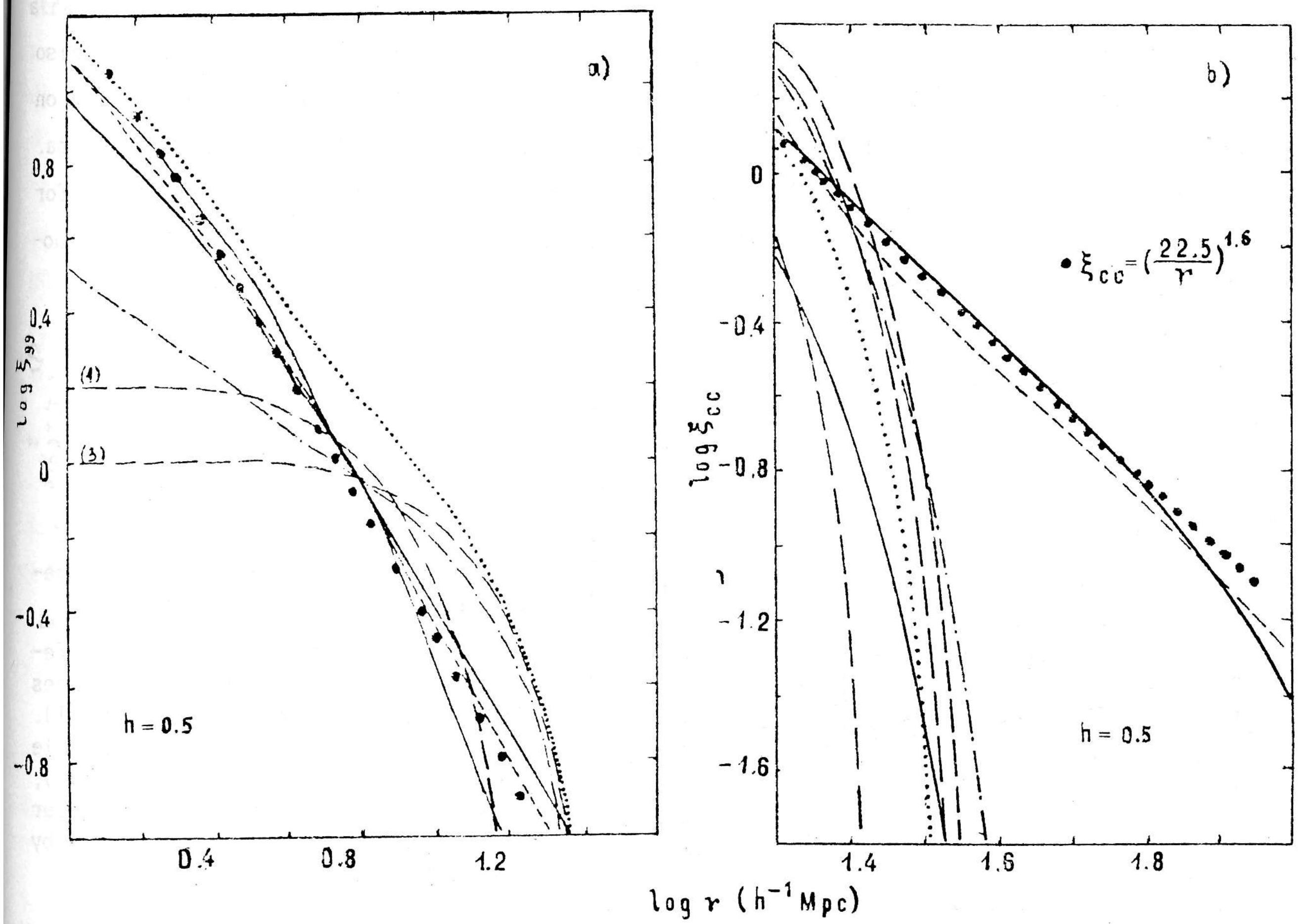

Fig.1. Galaxy (a) and cluster (b) two-point correlation function for different density fluctuation spectra. Dashed line corresponds to HDM models with one (1) and (3) sort of massive neutrinos, solid line - CDM spectrum, dashed-dotted - HC, dotted - DI, short-dashed - CDM+X, thick solid - CDM+Z. Black circle shows correlation functions which are defined by Davis & Peebles (1983) from galaxy catalog - (a) and by Klypin & Kopylov (1983) from cluster catalog - (b).

We can see here that only the spectrum which has $P(k)\propto k^{-1}$ in the region $3h^{-1}\leqslant k^{-1}\leqslant100h^{-1}$ Mpc may explain the observed correlations.

Space distribution of galaxies and clusters gives the main information about the large-scale structure of the Universe. Observational data about bulk motion of galaxies are also important because they can give additional information about the distribution of dark matter.

From the data on the distribution of matter on scales $\geqslant10h^{-1}$Mpc it follows that perturbations on these scales are small and therefore are described by the linear theory of perturbations. In this case root mean square bulk velocity of matter is defined by the power spectrum which is smoothed on the corresponding scale. The basis for such an approach has been elaborated by Vittorio et al. (1980) and Kaiser (1988). In the theory of structure formation of the Universe from adiabatic Gaussian perturbation the root mean square bulk motion of the region of radius R is equal to

$$V_{rms}(R) = \left[H^2/2\pi^2 \int_0^\infty P(k)\, W^2(kR)\, dk \right]^{1/2}.$$

The dependence of $V_{rms}(R)$ on the smoothing radius R is shown in Fig. 2. It shows also the observational data for the bulk motion. We can see that the peculiar velocity on short scales agrees with the observational data only for HDM(1) and CDM+X spectra. But the bulk motion on scales $\sim 40h^{-1}$Mpc is more natural for CDM+X spectrum than for HDM(1) so far as the former can explain it by the local peak ~1.5 σ height and another ~3 σ. The data by Collins et al. (1986) do not agree with any spectrum.

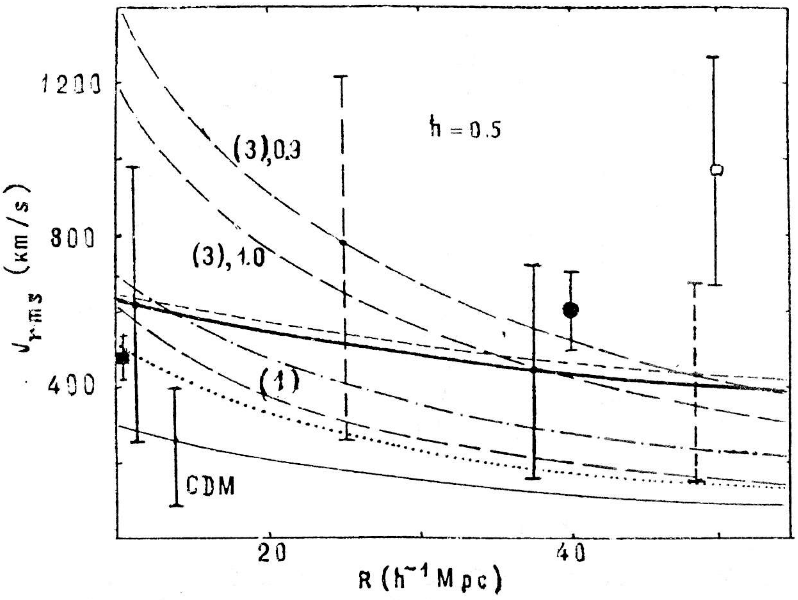

Fig. 2. The dependence of root mean square peculiar velocity V_{rms} on filtering radius R for different spectra (character of lines is similar to that in Fig. 1). Black circle shows observable data by Lubin & Villela (1986), black square - data by Dressler et al. (1987), empty square - by Collinz et al. (1986).

Comparison of the theoretical value of the bulk motion with the observed one leads to the conclusion that for explanation of the observed bulk peculiar velocity the spectrum with additional power relative to CDM-spectrum on scales $5h^{-1} \leqslant k^{-1} \leqslant 200h^{-1}$ Mpc is necessary.

More important test for any theory of formation of the large-scale structure of the Universe is a comparison of both the predicted and observed restrictions of anisotropy of cosmic microwave background radiation $\Delta T/T(\theta)$ for all angle scales. A more stringent limit on quadrupole component has been got obtained from the cosmic experiment "Relic 1": $\frac{\Delta T}{T}(\simeq 90^\circ) \leqslant 2\cdot 10^{-5}$. For the angle scale at $\sim 8^\circ$ a lower restriction on CMB anisotropy has been got by Davies et al. (1987): $\frac{\Delta T}{T}(\simeq 8^\circ) \leqslant 4\cdot 10^{-5}$. On a scale which is proportional to the horizon the upper limit has been obtained by the RATAN-600 in the experiment "Cold": $\frac{\Delta T}{T}(\simeq 2^\circ) \leqslant 1.5\cdot 10^{-5}$ (1σ level).

In the present paper we would be interested only in the large scale of angles consistent with CMB anisotropy $\frac{\Delta T}{T}(\theta \geqslant 2^\circ)$, so far as it is exactly on this scale that it is necessary to introduce a change in the CDM-spectrum for explanation of both the observed cluster correlation function and the bulk motion. It is known that the Sachs-Wolfe effect is the main contributor to CMB anisotropy on these angle scales. It can be calculated by means of the method suggested by Doroshkewich & Klypin (1988). The dependence $\frac{\Delta T}{T}(\theta)$ in the region 2°-90° for the analysed spectra is demonstrated in Fig. 3.

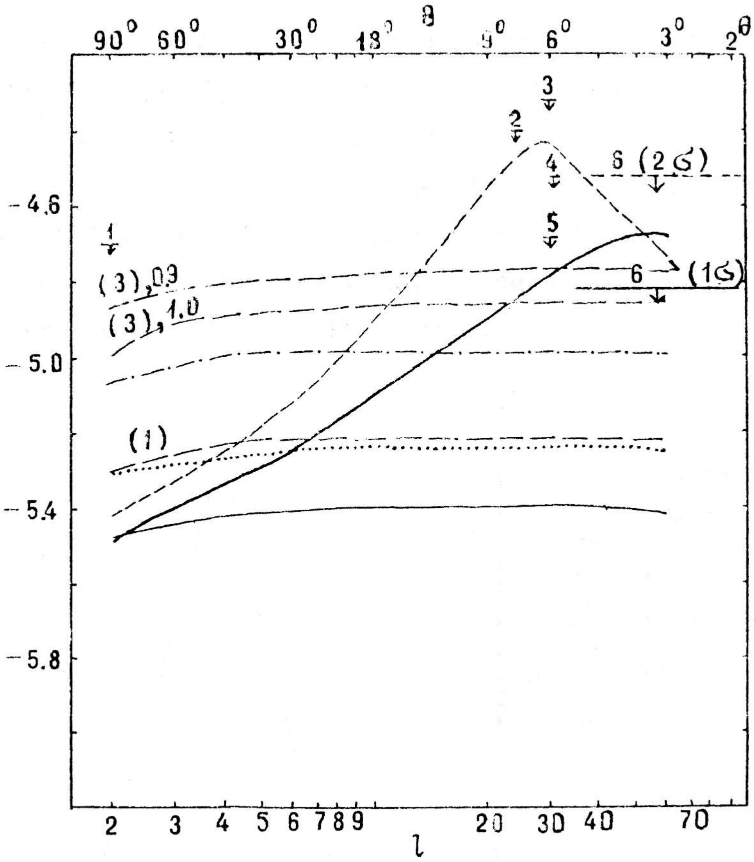

Fig. 3. The angle power spectra of the cosmic microwave background temperature fluctuations $\Delta T/T$ for different spectra (character of lines is similar to that in Fig. 1). Arrows show upper limit on $\Delta T/T$ given by: 1 - Klypin et al., (1987) ("Relic 1"), 2 - Davies et al. (1987), 3 - Melchiorri et al. (1981), 4 - Fabbri et al. (1980), 5 - Wilkinson (1983), 6 - Berlin et al., 1984 ("Cold").

We can see from this figure that CDM, HC, DI and HDM(1) models predict rather a low level of fluctuations of $\Delta T/T$ which does not contradict the observed restrictions. The model with three sorts of massive neutrinos is already at the limit of its experimental refutation on large angle scales too. CDM+X spectrum which is suggested by Bardeen et al. (1987) contradicts the observed restrictions for $\Delta T/T$ on a scale of $\sim 5^\circ$ and is at the limit of restrictions on a scale of $\sim 2^\circ$.

CONSTRUCTION OF OPTIMUM SPECTRUM

Thus for explanation of the galaxy and cluster correlation functions, bulk motion without contradiction to observable restrictions for CMB anisotropy the initial power spectrum must have the power law $P(k) \propto k^{-1}$ in the region $3\ h^{-1} \leqslant k^{-1} \leqslant 100\ h^{-1}$ Mpc, must be sufficiently slightly sloping $(P(k) \propto k^2)$ in region $k^{-1} > 100 h^{-1}$Mpc in order to satisfy the observational requirement on the value of the bulk motion V_{rms} and must become the scale-invariant ($P(k) \propto k$) at $k^{-1} \geq 10^{3} h^{-1}$Mpc. From the large number of trial approximations of such spectrum the following turns out most successful:

$$P(k)= \frac{Ak}{(1+C_1 k+C_2 k^{1.5}+C_3 k^2)^2} \left(1+\Psi(k)\right),$$

$$\Psi(k)= \begin{cases} 0.055\ [(k_1/k)^2-1], & k_2 \leq k \leq k_1, \\ \Psi(k_2)\ (k/k_2)^2, & k \leq k_2, \end{cases}$$

where k_1=3h^{-1}Mpc, k_2=100h^{-1}Mpc, but C_1, C_2, C_3 correspond to CDM- spectrum (Davis et al., 1985) and are: $C_1=1.7/(h\cdot\Omega_{DM})$, $C_2=9.0/(h\cdot\Omega_{DM})^{3/2}$, $C_3=1.0/(h\cdot\Omega_{DM})$. By analogy with CDM+X spectrum we marked this spectrum CDM+Z. Galaxy and cluster correlation functions for this spectrum are presented in Fig. 1, bulk motion - in Fig. 2 and angle power spectrum of cosmic background anisotropy - in Fig. 3. Ratio of CDM+Z and CDM power spectra are shown in Fig. 4. Additional power which is contained in this outburst has a value which is twice larger than the filtered at ~10h^{-1}Mpc CDM-spectrum.

It should be noted that this spectrum is most optimum since even insignificant change of it in the region k>0.1h^{-1} Mpc leads to increase of divergence between the predicted and observed characteristics of the large-scale structure of the Universe.

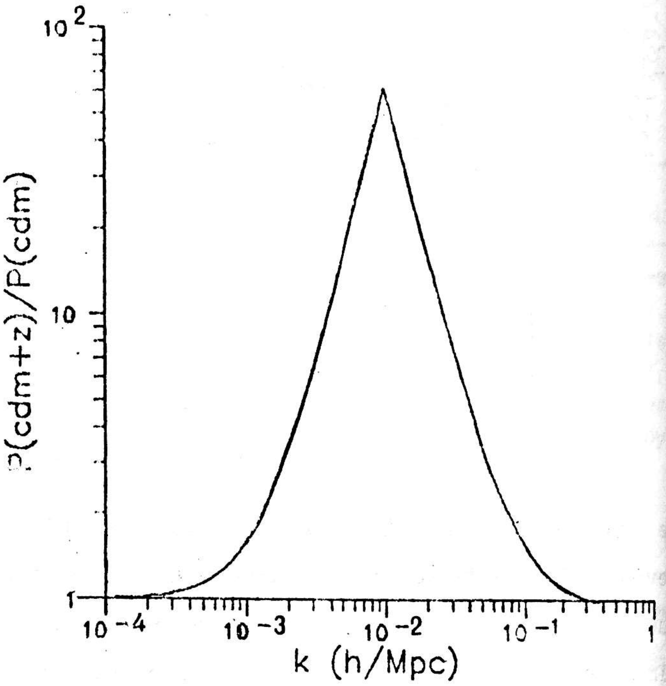

Fig. 4. The ratio of CDM+Z to CDM power spectra.

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