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GROWTH OF PERTURBATIONS BETWEEN HORIZON CROSSING AND MATTER DOMINANCE: IMPLICATIONS FOR GALAXY FORMATION

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The dark matter (DM) that appears to be gravitationally dominant on all astronomical scales larger than the cores of galaxies can be classified, on the basis of its characteristic free-streaming damping mass M_D, as hot ($M_D \sim 10^{15} M_\odot$), warm ($M_D \sim 10^{11} M_\odot$), or cold ($M_D < 10^8 M_\odot$) (Bond and Szalay, 1983; Primack and Blumenthal, 1983). For the case of cold DM, the shape of the DM fluctuation spectrum is determined by (a) the primordial spectrum (on scales larger than the horizon), which is usually assumed to have a power spectrum of the form $|\delta_k|^2 \propto k^n$ (inflationary models predict the "Zeldovich spectrum" $n = 1$); and (b) "stagspansion", the stagnation of growth of DM fluctuations which enter the horizon while the universe is still radiation-dominated. Stagspansion flattens the fluctuation spectrum for $M \lesssim 10^{15} M_\odot$. We report here the results of a numerical evaluation of the fluctuation spectrum in which all relevant physical effects have been included (Blumenthal and Primack, in preparation), together with implications for galaxy formation (Blumenthal, Faber, Primack, and Rees, in preparation; hereafter BFPR).

1. WHY COLD DM IS INTERESTING

If a species of neutrino is the gravitationally dominant component of the universe, its mass $m_\nu = 100\,\Omega h^2\,\mathrm{eV}$ (where $h = H_o/100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ lies in the range $1/2 \leq h \leq 1$) implies a free-streaming damping mass $M_D \sim 10^{15} M_\odot$ corresponding to hot DM. Probably because this type of DM has been the most intensively studied, a number of potential problems have been identified - for example the late formation of supercluster "pancakes", at $z_p \lesssim 2$ (see, e.g., Frenk, White, and Davis, 1983), which later fragment into galaxies, in contradiction to the observed abundance of QSOs with $z > 2$, which implies earlier galaxy formation.

We would like to call attention to another discrepancy between the hot DM hypothesis and observations, including data presented at this conference: namely the absence of evidence for growth of the DM/baryon ratio from the scale of ordinary galaxies to rich clusters. If the DM is composed of neutrinos, which first collapse gravitationally on supercluster scales with corresponding velocities $\sim 10^3$km/s, only a small fraction of the neutrinos can be captured to form the DM halos of galaxies having escape velocities typically $\sim 10^2$km/s, while a much larger fraction will be bound in rich clusters. One-dimensional simulations (Bond, Szalay, and White, 1983) confirm this expectation. The most relevant observational parameter is not the oft-discussed M_{tot}/L but rather $M_{tot}/M_{\ell um}$, where M_{tot} is the total mass determined dynamically and $M_{\ell um}$ is the mass in stars plus that in x-ray emitting gas. The available data, including that on our galaxy (which imply that its massive halo extends at least to ~50kpc), on small spiral groups, on small cD groups, and on rich clusters, is all consistent with $M_{tot}/M_{\ell um} \approx 10$ (BFPR).

Yet another problem for the hypothesis that the DM is neutrinos is the recent prediction (Faber and Lin, 1983) that the dwarf spheroidal galaxies near the Milky Way have heavy halos; this is supported by recent observational determinations of the velocity dispersion of Draco (Aronson, 1983; Lin and Faber, 1983) and Carina (Aronson, private communication to Faber). The phase space constraint (Tremaine and Gunn, 1979) implies that $m_\nu \gtrsim 500$ eV. This is of course inconsistent with the cosmological density bound on m_ν, implying that the DM in these dwarf spheroidal halos is not hot. It is probably not warm DM either. Warm DM first collapses on a scale $\sim 10^{12} M_\odot$ with $\sigma \sim 10^2$ km/s (Blumenthal, Pagels, and Primack, 1982; Bond, Szalay, and Turner, 1982), and too little could be captured by dwarf spheroidals, having $\sigma \sim 10$ km/s, to form the heavy halos indicated by the observations.

Besides the evidence just summarized against hot and warm DM, a further reason to consider cold DM is the existence of several plausible physical candidates, including axions of mass $\sim 10^{-5}$ eV (Preskill, Wise, and Wilczek, 1983; Abbott and Sikivie, 1983; Dine and Fischler, 1983; Ipser and Sikivie, 1983); heavy stable particles, such as the photino, with a mass ~10 GeV and very weak interactions; and primordial black holes with $10^{17}\,\mathrm{g} \lesssim m_{PBH} \lesssim M_\odot$.

2. CALCULATION AND IMPLICATIONS OF THE FLUCTUATION SPECTRUM

We will follow the current conventional wisdom and assume that the primordial fluctuations were adiabatic. In the standard formulation (e.g. Peebles, 1980), fluctuations $\delta \equiv \delta\rho/\rho$ grow as $\delta \sim a^2$ on scales larger than the horizon, where a = scale factor = $(1+z)^{-1}$. When a fluctuation enters the horizon in the radiation-dominated era, the photons (together with the charged particles) oscillate as an acoustic wave, and the neutrinos (assumed to have negligible mass) free stream away. As a result, the main driving terms for the growth of δ_{DM}

disappear, and the growth of δ_{DM} stagnates ("stagspansion") until matter dominates (Guyot and Zeldovich, 1970; Meszaros, 1974; Groth and Peebles, 1975); see Fig. 1. Matter domination first occurs at $z = z_{eq}$, where

$$\begin{aligned} z_{eq} &= 4.2 \times 10^4 h^2 \Omega (1 + 0.68\, n_\nu)^{-1} \\ &= 2.5 \times 10^4 h^2 \Omega \text{ for } n_\nu = 3 \end{aligned} \tag{1}$$

The first study of the growth of cold DM fluctuations was the numerical calculation of Peebles (1982), who for simplicity ignored neutrinos: $n_\nu = 0$ in (1). We have done numerical calculations including the effects of the known neutrino species ($n_\nu = 3$, $m_\nu \approx 0$) both outside and inside the horizon. Numerically, the largest effect of including neutrinos is the change in z_{eq}.

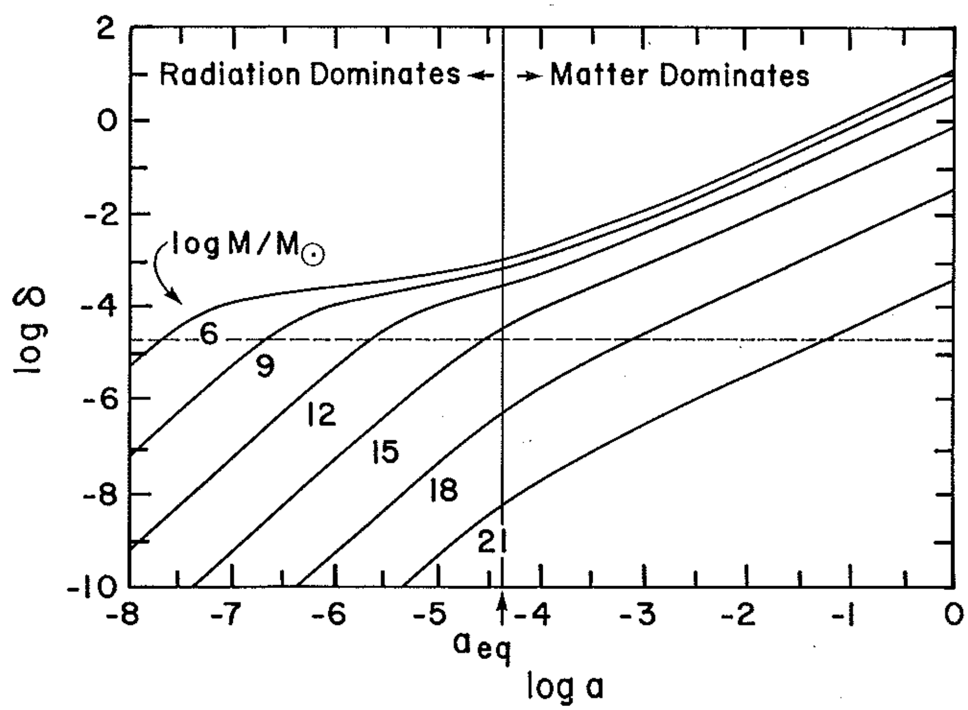

Figure 1. Numerical results for the growth of $\delta = k^{3/2}\delta_k$ versus scale factor a for fluctuations of various masses $M = 4\pi^4 k^{-3}\rho_c/3$. The curves are drawn for $n = 1$, $\Omega = h = 1$, and a baryonic to total mass ratio of 0.1. The vertical line represents the value of a when the universe becomes matter dominated, and the dashed line shows the (constant, for $n = 1$) value of δ when each mass scale crosses the horizon. These curves illustrate the stagnation of perturbation growth after small mass scales cross the horizon and show why at late times $\delta(k)$ is nearly flat for large k (small M).

It is instructive to make the further approximation of setting $\delta_{\gamma+b} = \delta_\nu = 0$ once a fluctuation is inside the horizon. Then one can analytically match the solution for $a > a_{horizon}$ (Peebles, 1980, p.58)

$$\delta_{DM}(a) = A_1 D_1(a) + A_2 D_2(a) = \delta_1 + \delta_2, \tag{2}$$

$$D_1 = 1 + 1.5y, \quad \text{where } y = a/a_{eq}, \tag{3a}$$

$$D_2 = D_1 \ln\left[\frac{(1+y)^{1/2}+1}{(1+y)^{1/2}-1}\right] - 3(1+y)^{1/2}. \tag{3b}$$

to the growing mode $\delta_{DM} \sim a^2$ for $a < a_{horizon}$. Matching the derivatives requires δ_2 comparable to δ_1 but opposite in sign. For $a \gg a_{horizon}$ only the growing mode D_1 survives, which explains the moderate growth in δ_{DM} between horizon crossing and matter dominance. In the limit of large k, one finds $\delta_k \propto k^{n/2-2} \ln k$. Correspondingly, for $M \ll M_{eq} \approx 10^{16} M_\odot$, the rms fluctuation in the mass within a random sphere containing average mass M is $\delta M/M \propto |\ln M|^{3/2}$. Turner, Wilczek, and Zee (1983) considered only the Meszaros solution (3a) and erroneously inferred that the fluctuation spectrum would be essentially flat for $M < M_{eq}$ for a Zeldovich primordial spectrum, which would then be inconsistent with observations.

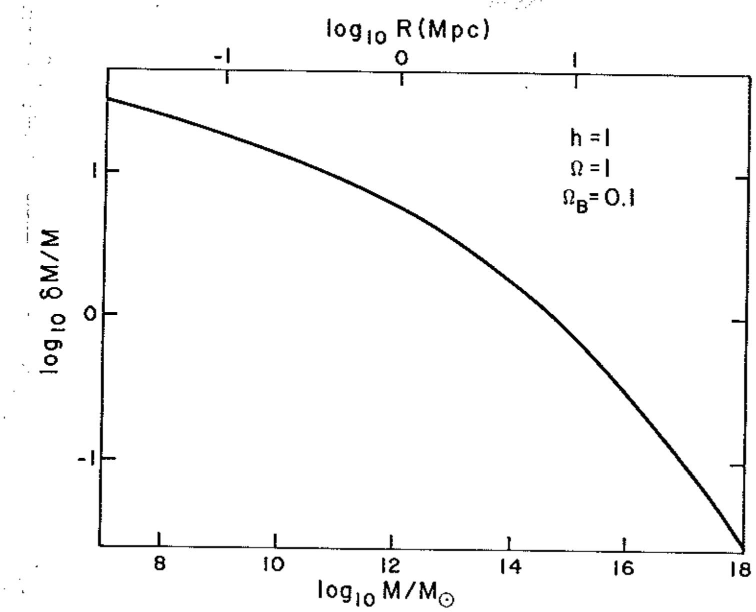

Figure 2. The r.m.s mass fluctuations within a randomly placed sphere of radius R in a cold DM universe. The curve is normalized at 8 Mpc and assumes an initial Zeldovich (n = 1) fluctuation spectrum, and $h = \Omega = 1$.

Our numerical results for $\delta M/M$ are shown in Fig. 2 for $\Omega = h = 1$, assuming a Zeldovich ($n = 1$) spectrum (reflected in $\delta M/M \propto M^{-2/3}$ for $M > M_{eq}$). We have followed Peebles (1982) in normalizing $\delta M/M = 1$ at $8h^{-1}$ Mpc. For either h or Ω less than unity, $\delta M/M$ is somewhat flatter.

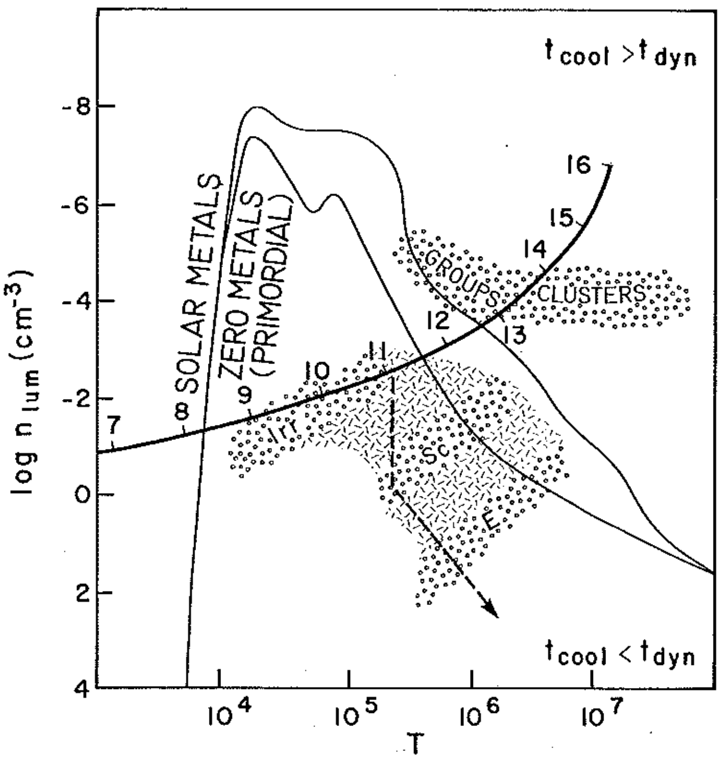

Figure 3. The baryonic density versus temperature as average perturbations having total mass M become nonlinear and virialize. The numbers on the tick marks are the logarithm of M in solar units. This curve assumes $n = 1$, $\Omega = h = 1$, and a baryonic to total mass ratio of 0.07. The region where baryons can cool within a dynamical time lies below the cooling curves. Also shown are the positions of observed galaxies, groups, and clusters of galaxies. The dashed line represents a possible evolutionary path for dissipating baryons.

Fig. 3 (Primack and Blumenthal, 1983) shows the density of ordinary (baryonic) matter vs. internal kinetic energy (temperature) of typical fluctuations of various sizes, just after virialization, calculated from $\delta M/M$ of Fig. 2. This is superimposed upon the Rees-Ostriker (1977) cooling curves (for which cooling time equals gravitational free fall time) and data on galaxies (with kinetic energy determined from rotation velocity for spirals and velocity dispersion for ellipticals). Fluctuations that start with greater amplitude than average will turn around earlier, at higher density, and thus lie below the virilization curve on Fig. 3. As the baryons in a virialized fluctuation dissipate, their density will initially increase at constant T within the surrounding isothermal halo of dissipationless material (DM), and then T will increase as well when the baryon density exceeds the DM density, as suggested by the dashed line in the figure. Note that the galaxy data lies below the virialization curve (the curve is somewhat higher for $h = \frac{1}{2}, \Omega = 1$). In this respect, the Zeldovich primordial spectrum is more consistent with the data than an $n = 2$ (or $n = 0$) primordial spectrum, which lies too low (too high) on the figure compared to the galaxies (see BFPR for more details). With the Zeldovich spectrum, the important conclusion is that one should observe dissipated systems with large halos having total mass $10^8 M_\odot \lesssim M \lesssim 10^{12} M_\odot$. This is essentially the range of observed galaxy masses.

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