SLAC – PUB – 3307
March 1984
T

FORMATION OF GALAXIES AND LARGE SCALE STRUCTURE WITH COLD DARK MATTER*

GEORGE R. BLUMENTHAL AND S. M. FABER

Lick Observatory, Board of Studies in Astronomy and Astrophysics
University of California, Santa Cruz, California 95064

JOEL R. PRIMACK

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

and

Santa Cruz Institute of Particle Physics
University of California, Santa Cruz, California 95064 †

and

MARTIN J. REES

Institute of Theoretical Physics
University of California, Santa Barbara, California 93106

and

Institute of Astronomy
Madingley Road, Cambridge CB3 0HA, England †

Submitted to *Nature*

---

* This work was supported by the Department of Energy under Contract Number DE-AC03-76SF00515 and in part by National Science Foundation grants AST-82-11551 and PHY-81-15541.

† Permanent address.

ABSTRACT

The dark matter that appears to be gravitationally dominant on all scales larger than galactic cores may consist of axions, stable photinos, or other collisionless particles whose velocity dispersion in the early universe is so small that fluctuations of galactic size or larger are not damped by free streaming. An attractive feature of this cold dark matter hypothesis is its considerable predictive power: the post-recombination fluctuation spectrum is calculable, and it in turn governs the formation of galaxies and clusters. Good agreement with the data is obtained for a Zeldovich ($|\delta_k|^2 \propto k$) spectrum of primordial fluctuations.

1. Introduction

Why are there galaxies, and why do they have the sizes and shapes we observe? Why are galaxies clustered hierarchically in clusters and superclusters, separated by enormous voids in which bright galaxies are almost entirely absent? And what is the nature of the invisible mass, or dark matter, that we detect gravitationally roundabout galaxies and clusters but cannot see directly in any wavelength of electromagnetic radiation? Of the great mysteries of modern cosmology, these three may now be among the ripest for solution.

Since there is evidence that the amount of dark matter in the universe exceeds that of the visible matter by at least an order of magnitude,[1] the third question may hold the key to the first two. This paper considers the hypothesis that the dark matter is *cold*,[2–6] that is, that its velocity dispersion is cosmologically negligible in the early universe.

Most modern theories of the origin of structure in the universe assume that the extreme inhomogeneity of the present universe grew gravitationally from initially very small density fluctuations. [7–8] At early times the universe is gravitationally dominated by photons and other relativistic particles, but as the temperature drops the average kinetic energy per particle decreases. One hypothesis extensively explored of late is that the dark matter (hereafter DM) consists of neutrinos of mass about 30 eV. [9–10] Since these particles would still be relativistic when galaxy-size masses come within the horizon, they would freely stream away, smoothing out small scale fluctuations. We refer to such particles as *hot* DM. The mass of the neutrinos inside the horizon when they first become non-relativistic is roughly $10^{15} M_{\odot}$, about the mass of a supercluster. This is the mass of the first structures to collapse gravitationally in a neutrino-dominated universe.

It is also possible that the DM consists of elementary particles that decoupled thermally from the big bang much earlier than neutrinos. These particles would have correspondingly lower number density, and thus could be more massive ($\sim$ 1 keV) and become nonrelativistic sooner than neutrinos. [11–12] We refer to this as *warm* DM. The first structures to form in such a universe weigh about $10^{11} M_{\odot}$, about the mass of a typical galaxy. Fluctuations smaller than this are damped by free streaming.[13–15]

In contrast, in a universe dominated by cold DM, the free streaming damping mass is, by definition, smaller than galaxy masses. In the next section, we will discuss possible particle physics candidates for cold DM and explain why we believe it is more plausible that the universe is dominated gravitationally by cold DM than by ordinary matter ("baryons") or hot or warm DM. The next two sections consider galaxy formation in the cold DM picture, and show that galaxy and cluster data compare favorably with the predictions of this model. We then discuss the extent to which the data constrain the cosmological density in the cold DM picture, and the evolution of superclusters and voids. The last section summarizes our conclusions. To anticipate briefly, the cold DM hypothesis seems to lead to a remarkably attractive theory for galaxy formation and to account for large scale structure at least as well as any competing theory.

2. Evidence that the dark matter is cold

Cold dark matter consists of particles having an insignificant velocity dispersion with respect to the Hubble flow and having nongravitational interactions that are much weaker than the weak interactions.[3] A currently popular cold DM candidate is the axion,[16] a pseudoscalar field proposed originally to avoid large CP violation in the strong interactions (which would imply for example much too large a value for the neutron electric dipole moment).[17–19] Instanton effects generate a nonzero axion mass at the quark deconfinement temperature ($T \sim 10^2$ MeV), below which the axions act as a nonrelativistic, massive, pressureless fluid. The requirement that the axion density be less than the critical density implies that the axion mass $m_a \gtrsim 10^{-5}$ eV,[20–22] while the longevity of helium burning stars implies that $m_a < 10^{-1}$ eV.[23] Thus, if axions exist, they may be cosmologically important, and, for $m_a \approx 10^{-5}$ eV, they would be gravitationally dominant.

Another cold DM candidate particle is the photino, the spin $\frac{1}{2}$ supersymmetric partner of the photon. Photinos are thought to be the lightest supersymmetric particle with $m_{\tilde{\gamma}} \gtrsim 0.5$ GeV (the lower limit corresponding to cosmological critical density).[24] Since photino annihilation at high temperatures is incomplete, the remnant photinos can, because of their large mass, contribute a critical density today.

Yet a third cold DM candidate is black holes of mass

$$10^{-16} M_\odot \lesssim M_{BH} \lesssim 10^6 M_\odot,$$

the lower limit implied by the non-observation of γ-rays from black hole decay by Hawking radiation, and the upper limit required to avoid disruption of galactic disks and star clusters.[25–27] A stronger but more controversial upper limit $M_{BH} < 10^{-2} M_{\odot}$ follows from the non-observation of focusing of quasar cores.[28]

Still another exotic cold DM candidate has recently been proposed by Witten: "nuggets" of $u-s-d$ symmetric quark matter.[29] There is thus no shortage of cold DM candidate particles—although each of them is highly speculative, to say the least. Our motivation for considering the hypothesis that the universe is dominated by cold DM is twofold. First, as we discuss in the following sections, a cold DM universe correctly predicts many of the observed properties of galaxies, including their range of masses, irrespective of the identity of the cold particle. Moreover, there is more than a little evidence against all other forms of DM.

The most conventional assumption might be that DM is baryonic, since we know that baryons pervade the universe. There are, however, three arguments that make a nonbaryonic form of DM more plausible. First, if DM consists of baryons, it must be clumped into objects with mass $\ll M_{\odot}$ in order to avoid nuclear burning and the emission of too much radiation,[30] and there is as yet no compelling theory for the formation of such a large density of objects of planetary mass or smaller. The difficulties with other possible forms of baryonic dark matter have been reviewed recently.[31] The second argument involves the observed deuterium abundance, $D/H = (1-4) \times 10^{-5}$ (by number), which provides a lower limit on the primordial D abundance since deuterium is readily consumed but not produced in stars. This then corresponds to an upper limit for the *baryonic* density parameter (ratio of baryon density to critical density) of[32] $\Omega_b \leq 0.035 h^{-2} (T_o/2.7)^3$, where T_o is the present temperature of the microwave background radiation and h is Hubble's constant expressed in units of 100 km/sec/Mpc. (Observationally, $1/2 \leq h \leq 1$.) However, there is also strong observational evidence that the *total* density parameter $\Omega \geq 0.1$. Therefore a baryon dominated universe ($\Omega = \Omega_b$) is consistent with the deuterium limit only for Ω and h very near their observational lower limits. Finally, the existence of galaxies and clusters today requires that perturbations in the density must have become nonlinear before the present epoch. In a baryonic universe, for adiabatic perturbations at recombination, this implies present-day fluctuations in the microwave background of $\delta T/T \gtrsim 10^{-3}$ on scales $> 2'$. Such temperature fluctuations are an order of magnitude larger than the present observational upper limits.[33] For baryonic DM, this problem can be avoided only if there is significant reheating of the intergalactic medium after recombination or if the primordial fluctuation spectrum is isothermal rather than adiabatic.[34] (However, grand unified models of baryosynthesis favor adiabatic fluctuations.[35–36]) For nonbaryonic DM, on the other hand, the predicted fluctuations in the microwave background are consistent with the observations since the baryonic fluctuations are small at recombination and only later grow to the same size as fluctuations in the dark matter (see below).

The neutrino dominated picture of galaxy formation also has serious weaknesses. Studies of nonlinear clustering (on scales $\lambda < 10$ Mpc) show that supercluster collapse must have occurred quite recently, at redshift $z_{sc} < 2$.[37–38] This is also consistent with a study of streaming velocity in the linear regime ($\lambda > 10$ Mpc), which indicates $z_{sc} < 0.5$.[39] However, the best limits on galaxy ages coming from globular clusters and other stellar populations, plus the possible association of QSO's with galactic nuclei, indicate that galaxy formation took place before $z = 3$.[40] This is inconsistent with the neutrino "top-down" theory, in which superclusters form before galaxies rather than after them.

Another problem with the neutrino picture is that large clusters of galaxies can accrete neutrinos more efficiently than ordinary galactic halos, which have lower escape velocities. One-dimensional numerical simulations predict that the ratio of total to baryonic mass M/M_b should be ~ 5 times larger for clusters ($\sim 10^{14} M_{\odot}$) than for ordinary galaxies ($M \sim 10^{12} M_{\odot}$).[41] While there is evidence that the mass-to-light ratio M/L does increase with scale, there is also considerable evidence that the more physically meaningful ratio of total to luminous mass M/M_{lum} remains constant from large clusters through groups of galaxies, binary galaxies, and ordinary spirals. (M_{lum}, which is the mass visible in galactic stars and gas plus hot, X-ray emitting gas, is $\leq M_b$, since an unknown fraction of the baryons is invisible—*e.g.*, in the form of diffuse ionized intergalactic gas at $T \sim 10^4$ K.) This is illustrated in Table 1 and Fig. 1, where we have plotted observed data for M/L and M/M_{lum}. The fact that the total-to-luminous mass of rich clusters is similar to that of galaxies including their massive halos, even though the clusters' mass-to-light ratio is larger, is due mainly to the different stellar population in the ellipticals in rich clusters plus the large contribution of X-ray emitting gas to M_{lum}. In very rich clusters such as Coma, there is perhaps $\sim 2-5$ times as much mass in hot gas as there is in stars.

Finally, preliminary velocity dispersion data for Draco, Carina, and Ursa Minor[42–44] as well as theoretical arguments[45] suggest that a significant amount of DM may reside in dwarf spheroidal galaxies. Because of the low velocity dispersion of dwarf galaxies, phase space constraints give a lower limit of $m > 500$ eV for the mass of particles comprising this DM.[46] The present velocity dispersion estimates are uncertain owing to possible stellar oscillations, mass outflow, and binary motions, but these effects can be discovered and eliminated monitoring. Taken at face value, however, the existing mass limit of 500 eV would rule out neutrinos completely.

Although warm DM does provide a natural (free streaming) scale for ordinary galaxies, it cannot account for massive halos in dwarf spheroidals even though the warm DM mass is actually, if barely, consistent with the phase space constraint. Free streaming damps out fluctuations with mass $< 10^{11} M_{\odot}$, so dwarf galaxies with mass $\sim 10^7 M_{\odot}$ can form in this picture only by the fragmentation of much larger scale galactic masses. Since dwarf galaxies with escape velocity $\sim$ 10 km/sec would capture only a small fraction of the warm DM particles, whose velocity dispersion is $\sim$ 100 km/sec, typical of ordinary spirals, one would expect M/M_{lum} to be much smaller in dwarf galaxies than in spirals. However, the dynamical mass data on dwarf spheroidals shown in Fig. 1 suggest a similar value for the ratio of total to luminous mass. In view of the great importance of dwarf spheroidal halos to constraints on warm as well as hot DM, it is clearly urgent to continue the monitoring program on velocity dispersions mentioned above.

3. Galaxy formation with cold dark matter

To calculate the growth of initially small perturbations and their ultimate gravitational collapse into condensed systems, one must first determine an initial spectrum for density perturbations in the very early universe. We assume here that the initial fluctuations are adiabatic, which is consistent with currently fashionable particle theories in which a small excess of baryons over antibaryons is generated by the decay of supermassive grand unified theory particles.[35,36] Then the mass (or energy) density at any point can be written as $\rho(r,t) = \rho_o(1+\delta)$, where $\rho_o(t)$ is the average density in the universe and δ represents the fractional density perturbation in the synchronous gauge. If the fluctuation spectrum is characterized by a power law distribution, then the rms fluctuation on mass scale M can be written

$$\delta \propto M^{-\frac{1}{2}-\frac{n}{6}},$$

which corresponds to a Fourier power spectrum $|\delta_k|^2 \propto k^n$. Alternatively, we can characterize the perturbations on mass scale M when that mass scale crosses the horizon as

$$\delta_H = \epsilon (M/M_o)^{-\gamma},$$

where M_o is the present horizon mass and $n = 6\gamma + 1$. To avoid having too much power on either large or small scales requires $\gamma \approx 0$, which corresponds to $n \approx 1$. Limits on the large scale variation of the microwave background imply $\epsilon \lesssim 10^{-4}$. The $n = 1$ fluctuation spectrum, which we assume here, is commonly referred to as the (Harrison-Peebles-)Zeldovich [47–49] spectrum and is predicted in inflationary models. It has recently been shown that not only inflation but also $\epsilon \approx 10^{-4}$ can be arranged in suitably fine-tuned grand unified theories. [50–52]

The Zeldovich spectrum also arises automatically if the fluctuations are due to cosmic strings. [53–54]

The first study of the growth of cold DM fluctuations was the numerical calculation of Peebles,[2] who for simplicity ignored the neutrinos but included cold DM, photons, baryons and electrons. Blumenthal and Primack[3,4,6] extended these numerical calculations to include three massless neutrino species. Fluctuations having mass $M < M_{eq} = 2 \times 10^{15}(\Omega h^2)^{-2} M_\odot$ cross the horizon when the universe is still radiation dominated, that is, when $z > z_{eq} = 2.5 \times 10^4 \Omega h^2$. After such fluctuations cross the horizon, the neutrino components of the perturbations dissipate by free streaming, and the photon and charged particle perturbations oscillate as an acoustic wave (whose amplitude is ultimately damped by photon diffusion for[55] $M < M_{Silk} \approx 3 \times 10^{13} \Omega_b^{-1/2} \Omega^{-3/4} h^{-5/2} M_\odot$). As a result, the main driving terms for the growth of cold dark matter fluctuations δ_{DM} decrease, and consequently δ_{DM} soon begins to grow only very slowly until the universe becomes (dark) matter dominated at z_{eq}, after which $\delta_{DM} \propto a = 1/(1+z)$ until $z \approx \Omega^{-1}$. This stagnation of the growth of DM fluctuations between the epochs of horizon crossing and matter domination is called "stagspansion".[3] It has been erroneously asserted that because of this effect, δ_{DM} can grow only by a factor of 5/2 between horizon crossing and the epoch t_{eq}. [56–57] In fact, there is somewhat more growth than this for DM fluctuations during the stagspansion era because of the initially large growth rate at horizon crossing, because the neutrino fluctuations do not instantaneously free stream away, and because the oscillating photon perturbations still provide a net driving term for a finite time.[3,4]

Since fluctuations with $M < M_{eq}$ grow very little during the stagspansion era and since fluctuations on all scales grow at essentially the same rate after the universe becomes matter dominated, an initial Zeldovich spectrum, $\delta_{DM} \propto M^{-2/3}$, evolves to a much flatter spectrum for $M < M_{eq}$ by the time of recombination. In Fig. 2 we plot the resulting cold DM fluctuation spectrum at the present time (ignoring the nonlinear evolution which is important for $\delta \gtrsim 1$, as discussed below; thus the plotted spectrum δ_k is larger than the spectrum at recombination by a constant factor). The quantity plotted in Fig. 2a, $k^{3/2}|\delta_k|$, roughly represents the spatial density fluctuation δ as a function of total mass $M = 4\pi^4\rho_o/3k^3$. Also sketched schematically are the fluctuation spectra in the hot DM scenario and in an isothermal scenario with white noise fluctuations. Note that the hot DM model requires more power on large scales today in order to form superclusters by $z \approx 2$. In Fig. 2b we have plotted cold DM fluctuation spectra in another form, $\delta M/M$, which represents the rms mass fluctuation within a randomly placed sphere of radius R containing mass M. Following Peebles,[2] we have normalized the curves so that, at the present epoch, $\delta M/M = 1$ at $R = 8h^{-1}$ Mpc.

Even though baryonic fluctuations do not grow (and are damped for $M < M_{Silk}$) before recombination, after recombination the baryons "fall into" the DM perturbations so that quickly $\delta_b = \delta_{DM}$.[58–59] This will occur if $\Omega_{DM}\delta_{DM} \gg \Omega_b\delta_b$, as we expect, and if the baryonic fluctuation mass exceeds the baryonic Jeans mass $M_{J,b}$:[5]

$$M_b > M_{J,b} \sim 10^6\Omega_b\Omega^{-3/2}h^{-1}(T_b/T)^{3/2}M_\odot,$$

where T_b is the temperature of the baryonic gas and T is the photon temperature. On scales smaller than this, the pressure of the baryonic gas prevents it from developing the same density contrast δ as the cold DM. The value of T_b/T is kept close to unity for $z > 100$ by the coupling of the residual free electrons with the radiation, but for smaller z it falls off approximately as $(1 + z)$. This means that at $z \approx 10$, $M_{J,b}$ may be as small as $\sim 10^3 M_\odot$.

At any mass scale M, when the fluctuation $\delta M/M$ approaches unity, nonlinear gravitational effects become important. The fluctuation then separates from the Hubble expansion, reaches a maximum radius, and begins to contract. Spherically symmetric fluctuations contract to about half their maximum radii. During this contraction, violent relaxation due to the rapidly varying gravitational field converts enough potential energy into kinetic energy for the virial theorem, $\langle PE \rangle = -2\langle KE \rangle$, to be satisfied. After virialization, the mean density within a fluctuation is roughly eight times the density corresponding to the maximum radius of expansion.[7]

Since the cold-DM fluctuation spectrum $\delta M/M$ is a decreasing function of M, smaller mass fluctuations will, on the average, become nonlinear and begin to collapse at earlier times than larger mass fluctuations. (Of course, if the fluctuations $\delta M/M$ have a Gaussian distribution at each mass scale, then for a given M the high magnitude tail of the distribution will become nonlinear first. See ref. 5 for a more complete discussion of this.) On the average, smaller mass fluctuations are themselves subsequently clustered within larger mass perturbations, which go nonlinear at a later time. This hierarchical clustering of smaller systems into larger and yet larger gravitationally bound systems begins at the baryon Jeans mass, $M_{J,b}$, and continues until the present time. The baryonic substructures within larger mass clusters will then be disrupted by virialization of the clusters unless significant mass segregation between baryons and DM has occured prior to cluster virialization. Hence, in order to maintain their existence as a separate substructure, the baryons must cool and gravitationally condense within their massive DM halos *before* virialization occurs on larger scales.[60]

In Fig. 3 we have plotted the baryonic number density n_b versus temperature T (or halo velocity dispersion) for spherically symmetric protocondensations resulting from an initial Zeldovich spectrum of cold DM fluctuations. Two cases are considered: $\Omega = 1$ and $h = 0.5$ (represented by the solid lines in the figure), and $\Omega = 0.2$ and $h = 1$ (dashed lines). The curves assume that the protocondensations have already virialized, but that the baryons have not yet cooled and condensed. The curves labeled 1σ assume that for each mass scale, $\delta M/M$ has the appropriate normalized rms value; those labeled 2σ correspond to fluctuations $\delta M/M$ twice as great; and so on. For given total mass M, the distribution of values of $\delta M/M$ spreads out along lines of constant M, represented in the figure by the light diagonal lines. We have also shown in Fig. 3 the present positions of clusters and groups of galaxies and of individual galaxies, including dwarf spheroidals. It is noteworthy that different types of galaxies, the Hubble sequence, are spread out in this diagram.

Baryons can radiatively cool through collisional excitation of either atoms or molecules. Fig. 3 is correspondingly divided into two regions by the medium solid curves labeled "No Metals" and "Solar Metals"; below these curves, the baryonic cooling time is shorter than the dynamical time and above them the reverse is true.[61] The figure immediately shows that, while the Hubble sequence of galaxies shows strong evidence for baryonic cooling and dissipation (core condensation in heavy halos), dwarf spheroidals are only marginally able to cool, and groups and clusters of galaxies have too long a cooling time to have dissipated much energy on their scale. [62–63]

On the average, for the cold DM fluctuation spectrum, what range of total masses yields baryon condensation within a massive halo? Let us first consider large galaxies. Naively, Fig. 3 suggests that there is an upper bound for galactic masses of $M \lesssim 10^{12} M_{\odot}$, where the baryonic cooling time for gas of primordial composition begins to exceed the dynamical time. Somewhat more massive galaxies could form in dense regions, where perhaps an early generation of Population III stars enriched the remaining baryonic gas with metals. Actually, the situation is likely to be more complicated, with many large galaxies formed by the merger of smaller ones. The resulting galaxy mass distribution arises from competition between hierarchical clustering and decreasing galaxy collision cross sections due to dissipation, and it is thus difficult to calculate reliably. Regarding the smallest galaxies, collisional excitation of atomic hydrogen provides a lower limit of $M \gtrsim 10^8 M_{\odot}$, corresponding to virialized baryonic temperature $T_b \gtrsim 10^4$ K. This range of protogalactic total masses, $10^8 M_{\odot} \lesssim M \lesssim 10^{12} M_{\odot}$, encompasses virtually all the mass that is observed to comprise galaxies. For protogalaxies in this mass range, the velocity dispersion of the baryons will initially remain nearly constant ($T \approx$ const.) as they condense within the gravitational potential of the virialized (and presumably roughly isothermal) DM halo. When the baryon density increases enough that their gravitational potential dominates that of the halo, the baryons' velocity dispersion will rise as they continue to dissipate energy and condense. Baryonic contraction is finally halted by rotation and perhaps, in some protogalaxies, by star formation (see below).

The collapse of fluctuations with mass $M > 10^{13} M_{\odot}$ leads to clusters of galaxies in this picture. In clusters, only the outer parts of member galactic halos are stripped off by collisions—the inner baryonic cores are able to contract to form the observed stellar systems. More of the baryons in the richest clusters are observed to be in the form of hot gas than in galaxies, as we have already mentioned in connection with Fig. 1. Perhaps this is because rich clusters tend to contain high-density cores, which collapse early, simultaneously with many of the galaxies they contain.

It is interesting to ask whether the cold DM picture can account for the wide range of morphologies displayed by clusters of galaxies in X-ray[64] and optical-band[65] observations, ranging from regular, apparently relaxed configurations to complex, multicomponent structures. Preliminary results are encouraging. In particular, simulations show that large central condensations form quickly and can grow by subsequent mergers to form cD galaxies if most of the DM is in halos around the baryonic substructures, as expected for cold DM, but not if the DM is distributed diffusely.[66–67]

What happens to small clouds whose baryonic mass M_b lies in the range $M_{J,b} < M_b < 10^{7-8} M_\odot$ and for which $T_b < 10^4$ K after virialization? For a primordial element abundance, the molecular cooling time (primarily due to H_2) is less than the dynamical time for fluctuations that satisfy

$$M_b > M_{C,b} \approx 4.1 \times 10^6 (\Omega h^2)^{-.917} \left(\frac{Y_e}{10^{-4}}\right)^{-0.625} \left(\frac{\Omega_B}{0.1\Omega}\right)^{-.04} \left(\frac{1+z_t}{10}\right)^{-2.75} M_\odot,$$

where z_t is the redshift of maximum expansion of the fluctuation. (This result uses the cooling rates given by Yoneyama[68] and assumes the simple "top hat" model of collapsing fluctuations. It corrects an equation given in ref. 15.) The quantity Y_e, the fraction of free electrons, is essentially the fraction that escapes recombination as the universe cools below $\sim$ 1000 K, and is roughly $10^{-4}(\Omega_b/0.1)^{-1}\Omega^{\frac{1}{2}} h^{-1}$. Systems with $M_b < M_{C,b}$ will persist as pressure supported clouds until they are disrupted by the virialization of larger scale clusters. Clouds having $M_b > M_{C,b}$ can dissipate energy and collapse, although the influence of rotation and the efficiency of fragmentation are poorly understood. The end product may be an irregular or dwarf spheroidal galaxy. Other possibilities such as a protoglobular cluster or one or more very massive objects (VMOs) would require greater contraction and are likely to be inhibited by angular momentum.

Moreover, it is unclear what fraction of the original baryonic mass can be retained by such small clouds rather than expelled. There is—despite the uncertainties—a strong probability that energy output from fragmented subsystems can influence the gas that remains uncondensed, thereby exerting a feedback on further condensation. In particular, UV emission from massive or supermassive stars can photoionize the remaining diffuse baryons, raising T_b up to 10^4 K. If such stars radiate a fraction q_{UV} of their Eddington luminosity in Lyman continuum photons, then the entire baryonic medium can be ionized even by a mass fraction of stars as low as $\sim 3 \times 10^{-5}/q_{UV}$. If the baryonic gas is re-ionized in systems with total mass $M \lesssim 10^8 M_\odot$, the baryons become so hot that they flow out of the cloud, whose gravitational field is not strong enough to bind them.

This may explain the origin of dwarf spheroidal galaxies, with $10^6 M_\odot < M < 10^8 M_\odot$, which show little evidence of dissipation in Fig. 3. As the baryons in these systems begin to condense through molecular cooling, if fragmentation and star formation are very efficient the baryons quickly turn into stars and condensation ceases. On the other hand, if a fraction of the baryons fragment into stars having strong UV luminosity, the remaining baryons are heated until they leave the system, and dissipation will again cease. The apparent absence of dissipation in dwarf spheroidals could also be due to stripping of their baryons in encounters with more massive systems,[46] which would move the dwarfs upward in Fig. 3.

In the cold DM scenario, globular clusters are probably not primordial objects. For one thing, there is no evidence that they have massive halos (although, as Peebles[69] points out, there is not much direct contrary evidence either). Furthermore, if truly primordial, they should be distributed in the universe like DM whereas, at least within galaxies, they seem to have dissipated and condensed like the other baryonic matter. However, the existence of "standard objects" inside galaxies with mass $\sim 10^6 M_\odot$ demands some explanation. In the model discussed here, there is a natural mass scale of order $M_{g,b} \sim M_{Gal,b}(T_{virial}/10^4\ K)^2$, where $M_{Gal,b}$ is the baryonic mass within a galaxy; $M_{g,b}$ is the Jeans mass of a cloud at 10^4 K in pressure balance with protogalactic gas at the virial temperature.[70] During the dissipation phase of galaxy formation, the gas might be likely to have a two-phase structure with a hot phase at T_{virial} and a cool phase at $\sim 10^4$ K, in which case subcondensations of mass $M_{g,b}$ would be expected with density contrast $\approx T_{virial}/10^4$ K. We identify these with protoglobular clusters (noting that the considerations of Fall and Rees[71] could further limit the mass range). Notice that this hypothesis predicts that galaxies of larger mass will have globular clusters of larger mass.

4. Galaxies and clusters

While the n_b–T diagram (Fig. 3) is useful for comparing data and predictions with the cooling curves, it is also useful to consider total mass M versus T, as in Fig. 4. This avoids having to take into account the differing amounts of baryonic dissipation suffered by various galaxies. The heavy solid and dashed curves again correspond to the $n = 1$ cold DM spectrum, for $(\Omega = 1, h = 0.5)$ and $(\Omega = 0.2, h = 1)$ respectively. It is striking that the galaxies in the $M - T$ diagram lie along lines of roughly the same slope as these curves. This occurs because the effective slope of the $n = 1$ cold DM fluctuation spectrum in the galaxy mass range is $n_{eff} \approx -2$, which corresponds to the empirical Tully-Fisher and Faber-Jackson laws: $M \propto v^4$. The light dashed lines in Fig. 4 are the post-virialization curves for primordial fluctuation spectra with $n = 0$ (white noise) and $n = 2$. The $n = 1$ (Zeldovich) spectrum is evidently the one that is most consistent with the data.

The points in Fig. 4 represent essentially all of the clusters identified by Geller and Huchra[72] in the CfA catalog within 5000 km s^{-1}. The cluster data lie about where they should on the diagram, and even the statistics of the distribution seem roughly to correspond to the expectations represented by the $0.5, 1, 2$, and 3σ curves.

Notice that spiral galaxies lie roughly along the 1σ curve while elliptical galaxies lie along the 2σ curve. Although this displacement is not large compared to the uncertainties, it is consistent with the fact that more than half of all galaxies are spirals, while only about 15 percent are ellipticals. We have elsewhere[73] suggested that, in hierarchical clustering scenarios, the higher σ fluctuations will develop rather smaller angular momenta, as measured by the dimensionless parameter λ ($= JE^{\frac{1}{2}}G^{-1}M^{-\frac{5}{2}}$). This difference appears to exist with either white noise or a flatter spectrum, but to be somewhat larger in the latter case. If high σ fluctuations have little angular momentum, their baryons can collapse by a large factor in radius, forming high-density ellipticals and spheroidal bulges, as shown in Fig. 3. Since, with a flat spectrum, higher σ fluctuations occur preferentially in denser regions destined to become rich clusters (the statistics of such correlations can be treated[74] by the methods of Peebles[5]), one expects to find more ellipicals there—as is observed. Indeed, the rich clusters lie along the same 2 and 3σ curves in Fig. 4 as do the elliptical galaxies.

Presumably the collapse of the low-λ protoellipical galaxies is halted by star formation well before a flattened disk can form, yielding a stellar system of spheroidal shape. The mechanism governing the onset of star formation in these systems is unfortunately not yet understood, but may involve a threshold effect which sets in when the baryon density exceeds the DM halo density by a sufficient factor.[60,62] Disks (spirals and irregulars) form from average, higher-λ protogalaxies, which, for a given mass, are larger and more diffuse than their protoelliptical counterparts. The collapse of disks thus occurs via relatively slow infall of baryons from $\sim 10^2$ kpc, halted by angular momentum. Infall from such distances is consistent both with the extent of dark halos inferred from observations and with the high angular momenta of present-day disks ($\lambda \sim 0.4$). The location of the galaxies in Fig. 3 is consistent with these ideas if the baryons in all galaxies collapsed by roughly the same factor, about an order of magnitude, but somewhat less for late-type irregulars and somewhat more for early-type E's and spheroidal bulges.

It has been theorized that the Hubble sequence originates in the distribution of either the initial angular momenta [75–76] or else the initial densities[77] of protogalaxies. However, if overdensity and angular momentum are linked, with the high-σ fluctuations having lower λ, then these two apparently competitive theories become the opposite sides of the same coin.

Consider finally the difference in Fig. 4 between the solid and dashed lines. The dashed lines, representing a lower-density universe ($\Omega = 0.2$), curve backward at the largest masses and lie far away from the circle representing the cores of the richest clusters, Abell classes 2 and 3. Since these regions of very high galaxy density contain at least several percent of the mass in the universe, the circle should lie between the 2 and 3σ lines (assuming Gaussian statistics). It does so for the solid ($\Omega = 1$) lines, but not for the dashed lines. At face value, this is evidence favoring an Einstein-de Sitter universe for cold DM. However, there are at least two reasons why this argument should probably not be taken too seriously. First, the velocity dispersions represented by the Abell cluster circle in Fig. 4 correspond to the cluster cores. The model curves on the other hand refer to the entire virialized cluster, over which the velocity dispersion is considerably lower (as indicated by the arrow attached to the circle in Fig. 4). Second, the assumption of spherical symmetry used in obtaining both sets of curves in the figure is only an approximation. The initial collapse is probably often quite anisotropic—more like a Zeldovich pancake than a sphere. It is therefore preferable to compare these data with N-body simulations than with the simple model represented by the curves in Fig. 4. Until this becomes possible we do not believe that the data in the figure allow a clear-cut discrimination between the $\Omega = 0.2$ and $\Omega = 1$ cases, especially if the Hubble parameter h is allowed to vary simultaneously within the observationally allowed range, as we have assumed. However, the preponderance of the data seems to favor $\Omega \approx 0.2$ for a universe dominated by cold DM, as we discuss in the next section.

5. The cosmological density, Ω

The most straightforward interpretation of the approximate constancy of $M/M_{lum} \approx 10$ from galaxy through rich cluster scales (Fig. 1) is that dark matter clusters with galaxies. This is precisely what *cold* DM is expected to do. One then expects the density parameter

$$\Omega = (M/M_{lum})\Omega_{galaxies} \approx 10 \times 0.02 = 0.2,$$

in agreement with $\Omega = 0.2 \times 1.5^{\pm 1}$ from the cosmic energy equation and the stability of clustering.[78]

The value $\Omega \approx 0.2$ is consistent with all reliable measurements and furthermore gives an age for the universe, t_o, consistent with globular cluster age estimates[79] ($\gtrsim$ 15 Gyr) if $h \lesssim 0.7$. The observed abundance of deuterium plus helium-3 implies a lower limit[32] $\Omega_b h^2 \geq 0.01$, which is also consistent with $\Omega = 0.2$ and $\Omega_b \approx 0.02$ if $h \gtrsim 0.7$.

Another argument favoring $\Omega = 0.2$ for cold DM is based on preliminary N-body results,[80] which indicate that superclusters and voids form on the observed scale for $\Omega = 0.2$, but on too small a scale for $\Omega = 1$ unless the Hubble constant is unrealistically small. However, this conclusion follows from comparing the N-body mass autocorrelation function $\xi_m(r)$ with the observed galaxy autocorrelation function $\xi_g(r)$. This is justified only if the galaxies are a good tracer of mass—*i.e.*, if $M/L \approx$ constant. This is certainly not true for rich clusters, as illustrated in the top part of Fig. 1 and in Table 1, where M/L for very rich clusters is roughly six times larger than it is for small groups and for the Milky

Way (including its DM halo). This means that some of the actual small-distance mass autocorrelation is not included in the galaxy autocorrelation function; *i.e.,* that $\xi_m(r)$ is somewhat steeper for $r \lesssim 1$Mpc than $\xi_g(r)$. This effect is in the right direction to bring the $\Omega = 1$ N-body simulations into consistency with observations. Note that galaxy velocity dispersion averages also underestimate the actual mass-weighted velocity dispersion, since the high-velocity, dense regions of rich clusters are under-represented in the counts. This effect is also compatible with higher Ω.

The absence of measurable fluctuations in the cosmic microwave background also restricts Ω, since in a low-Ω universe there is less growth of fluctuations both before and after recombination. A universe with $\Omega \gtrsim 0.2$ is consistent with the present limits on $\Delta T/T$ but $\Omega \approx 0.2$ will be ruled out if these limits are pushed much further, unless the universe was reionized after recombination.

Both prejudice and the inflationary hypothesis favor the Einstein-de Sitter value $\Omega = 1$. (Actually, inflation implies more generally that[81]

$$\Omega = 1 - \frac{\Lambda}{3H^2},$$

where Λ is the cosmological constant and H is Hubble's constant, but we assume here that $\Lambda = 0$.) For $\Omega = 1$, $t_o = 6.5h^{-1}$ Gyr, so consistency with globular cluster age estimates requires the Hubble constant to be perhaps unrealistically small. As we have discussed, the Zeldovich ($n = 1$) spectrum of primordial adiabatic fluctuations, which also follows from inflation, is quite compatible with models of galaxy formation in the cold DM scenario. Of course, the Zeldovich spectrum does not necessarily entail inflation. Moreover, inflation does not necessarily imply $\Omega = 1$: if there is a great deal of inflation, then of course Ω is very close to unity (assuming vanishing cosmological constant); but if we speculate that greater amounts of inflation are increasingly unlikely, then our horizon might just happen to lie in a patch with $\Omega = 0.2$.

Could $\Omega = 1$ in the cold DM model? Based on Fig. 1, this could happen only if M/M_{lum} increases substantially on scales larger than rich clusters. Perhaps galaxy formation is suppressed in the voids, and the resulting luminosity contrast is so strong, for reasons we do not yet understand, that $M/L > 1500$ there (see below). Alternatively, if the virial mass of clusters of galaxies is significantly underestimated, as suggested recently by Kaiser, and if galactic halos extend much further than $\sim$ 70 kpc, then the ratio M/M_{lum} may be substantially underestimated in Fig. 1, leading to a larger value for Ω. We conclude that a straightforward interpretation of the evidence summarized above favors $\Omega \approx 0.2$ in the cold DM picture, but that $\Omega = 1$ is not beyond the realm of possibility.

It is noteworthy that the cold DM model may require some means of suppressing galaxy formation in voids for $\Omega \approx 0.2$ as well as for $\Omega = 1$. As noted, this is required in the latter case to hide most of the mass. In a low-Ω universe, on the other hand, large, very underdense regions cannot form by gravitation alone;[82–83] and galaxy formation must be suppressed somehow in regions of moderately low density if the density of galaxies in voids is less than $\frac{1}{4}$ the average density, the quoted upper limit for the Boötes void.[84–85] Suppression of galaxy formation may occur partly because of the substantial difference at $z < \Omega^{-1}$ between $\langle\rho\rangle$ and ρ_c in a low-density universe. This and other mechanisms are discussed further in the next section.

6. Superclusters and voids

Recent, accurate redshift measurements of several thousand galaxies have revealed the presence of voids with linear dimensions ranging up to $\sim 50h^{-1}$ Mpc that are almost completely empty of bright galaxies. Most galaxies are concentrated in irregularly shaped, flattened, or elongated superclusters (see Oort's recent review[86] for fuller discussion and references). Two related observations are particularly interesting for their possible bearing on the origin of this large scale structure: a correlation of galaxy type with galaxy number density [87–88] and, possibly, a correlation between the orientation of cluster major axes and the direction to neighboring clusters within $\sim 15h^{-1}$ Mpc.[89]

In the hot DM picture, the fluctuation spectrum is rather sharply peaked at masses $\sim 4 \times 10^{15}(30\mathrm{eV}/m)^2$. The suppression of smaller scale structure results in an essentially pressure-free collapse on the supercluster scale, with the formation of sharp caustics—Zeldovich pancakes. If galaxies form only in the densest regions, where the shocked baryons have cooled sufficiently, [90–91] most of the universe would be essentially devoid of galaxies. Simulations[92] also show large scale cluster orientation correlations resembling those observed. On the other hand, as discussed above, the rapid evolution of the autocorrelation function requires that the pancakes form at $z \lesssim 2$, which is uncomfortably recent if smaller structures including galaxies must form subsequently.

The cold DM scenario avoids this latter problem since galaxies and clusters would already have formed by the time of supercluster collapse. Would superclusters and voids arise in a cold DM universe? There are good reasons to believe that pancakes, filaments, and voids would indeed form, and preliminary indications from N-body simulations suggest that they do.[80,93] The cold and hot DM fluctuation spectra are identical on the very largest scales, differing only in that the latter is cut off below $\sim 10^{15} M_\odot$ by neutrino free streaming and normalized somewhat larger above this scale (see Fig. 2a). The presence of already-formed and partially virialized substructure in the cold DM case causes supercluster collapse to be less dissipative than in the neutrino picture because the caustics are thickened and because a smaller fraction of the baryons remains as cold, uncondensed gas. Nevertheless, as Dekel[94] has shown, persistent flattened or elongated structures can form even in the absence of dissipation as a result of continued expansion in directions orthogonal to the collapse. Indeed, the sharp caustics and highly dissipative shocks in the neutrino picture may produce superclusters that are too flat compared to the observations, even when gravitational interactions with neighboring superclusters are taken into account.

Another related difference between hot and cold DM is that the hot DM universe is predicted to have a rather simple cellular structure while the cold DM universe probably has a considerably richer structure, perhaps more like that observed. In particular, the sizes of superclusters and voids in the cold case should span a fairly broad range. This will be an important test of the models when enough galaxy redshift data become available to indicate the statistics of the void distribution.

What should one expect to find in the voids? In the hot DM picture, all galaxies form from the dense gas along the caustics. Hence, the centers of voids should be entirely empty of galaxies and should contain only low density DM and hot primordial gas (heated by radiation from pancake shocks and too dilute to have cooled).[95] In the cold DM picture, one might at first suppose that galaxies form more or less uniformly in space, with their density subsequently enhanced by gravitational clustering and the pancake distortion of the Hubble flow. One would then expect to find galaxies in the voids, although with lower density than in superclusters.

In a low density universe, say $\Omega \lesssim 0.5$, both analytic calculations[82,83] and N-body simulations[80] suggest that large regions having $\rho/\langle\rho\rangle \leq 0.2$ cannot form by gravitational clustering alone. Nonetheless, large regions with few bright galaxies may be *more* likely in a low density cold DM universe, for several reasons. For one thing, on average large galaxies form late, when the average density has dropped well below the critical density. Larger initial fluctuations are thus required in order to form large galaxies in low-density regions. But larger fluctuations are statistically less likely to occur in low-density regions. This suppresses formation of large galaxies in moderate-size voids, and formation of clusters in larger voids.[74] Finally, since the density oscillates around $\langle\rho\rangle < \rho_{crit}$ when $\Omega < 1$, density minima will on the average go nonlinear before density maxima turn around. It is conceivable that this effect will tend to heat up the DM preferentially in the protovoids, inhibiting galactic condensations there.

In addition, feedback from a number of nongravitational processes could amplify the number density contrast of bright galaxies compared to the underlying density of dark and baryonic matter. For example, at $z \sim 10$ the average density is highest where pancakes will later occur. This is where most of the earliest galaxies and rich clusters form, and these will be the regions earliest enriched in metals. Radiation from these early galaxies (and quasars, and possibly Population III stars or VMOs) could heat the gas in lower density regions, raising the Jeans mass as discussed above and suppressing small galaxy formation. Indeed, if this early radiation has a hard enough spectrum and heats the gas sufficiently rapidly, it could raise the gas temperature throughout the univese to 10^6 K and essentially halt galaxy formation outside pancakes. Rees[96] has recently discussed processes for suppressing galaxy formation in protovoids. Finally, explosive shocks could also enhance galaxy formation in denser regions.[97] Although the efficacy of all these processes is uncertain and in need of further investigation, we conclude that the existence of large regions in which the density of bright galaxies is low is probably not a serious problem for the cold DM picture.

Now let us briefly discuss the two types of correlations mentioned above. The observed correlation of galaxy type with galaxy number density[87,88] can at least partly be understood as a consequence of the greater statistical likelihood of large-σ fluctuations in regions of greater density (protoclusters), together with the effect discussed above that results in higher-σ fluctuations acquiring lower angular momenta on average and becoming elliptical galaxies or spheroidal bulges. There is also an environmental effect: lower-σ fluctuations yield dark halos that are physically larger and more diffuse than higher-σ fluctuations. Disks, which form from such fluctuations, thus form slowly, by infall of gas from large radii within these extended halos. Because large halos have correspondingly large collision cross sections, few disks can form in regions of high galaxy number density. In dense regions, the halo gas is stripped by collisions and is mixed with enriched gas from galactic winds to become the hot intergalactic medium observed in X-rays. It will be interesting to investigate these effects with N-body simulations and a more detailed theory of galaxy formation.

Regarding the second type of correlation, Binggeli[89] has found that the position angles of nearby, elongated Abell clusters are within 45^o of the direction to the nearest cluster, provided the two clusters are separated by less than $\sim 15h^{-1}$

Mpc. He found a similar, though less significant, correlation between the position angle of the brightest cluster galaxy's major axis and the direction to the nearest cluster. In the hot DM picture, where superclusters form before clusters and galaxies, such correlations arise naturally. Indeed an N-body simulation[92] has shown that such correlations also occur, but more weakly, even with a fluctuation spectrum having an adiabatic peak at $\sim 10^{15} M_{\odot}$ superimposed upon an $n = 0$ spectrum, so that rich clusters and superclusters form almost simultaneously. Two related physical processes could produce such correlations in the cold DM picture: the coherent velocity field of a supercluster-scale density fluctuation will contribute to cluster velocity anisotropies (and therefore the direction of the cluster major axis), and clusters with position correlated anisotropies may also arise from mergers of smaller clusters formed preferentially along the pancake axis. For $\Omega h^2 \lesssim 0.3$, the fluctuation spectrum is sufficiently flat that rich cluster virialization (which occurs at $\delta M/M \approx 5$) occurs *after* supercluster pancake collapse.

It is important to find other observationally accessible information that can discriminate between cosmological models. The large scale velocity fields of superclusters should be rather different in the hot and cold DM schemes because of the much greater dissipation in the former. With new instruments it will be possible to study also the $z < 2$ evolution of superclustering of quasars and of Ly α-absorbing clouds, and perhaps the density and composition of the gas in voids.

It was once hoped that percolation analysis of the large scale galaxy distribution could help distinguish between different cosmological models.[9] However, when this analysis is applied to the CfA galaxy data, the results are found to be a sensitive function of the depth of the survey.[98] Moreover, realistic N-body simulations of isothermal and adiabatic scenarios (*i.e.*, with accurate treatment of gravitational interactions on small as well as large scales) have nearly identical percolation properties.[92,99] Obviously, better statistical tests are needed to compare objectively the large scale distribution of matter in models and observations.

7. Conclusions

We have shown that a universe with ~ 10 times as much cold dark matter as baryonic matter provides a remarkably good fit to the observed universe. This model predicts roughly the observed mass range of galaxies, the dissipational nature of galaxy collapse, and the observed Faber-Jackson and Tully-Fisher relations. It also gives dissipationless galactic halos and clusters. In addition, it may also provide natural explanations for galaxy-environment correlations and for the differences in angular momenta between ellipticals and spiral galaxies. At present, cold DM seems at best marginally consistent with an Einstein-deSitter $\Omega = 1$ universe, but for $\Omega \approx 0.2$ it appears to give a good fit to the observed large scale clustering, including filamentary superclusters and voids. In short, it is the best model presently available and merits close scrutiny and testing in the future.

ACKNOWLEDGEMENTS

It is a pleasant duty to acknowledge valuable conversations with Dick Bond, Jim Bardeen, Marc Davis, Avishai Dekel, George Efstathiou, Carlos Frenk, Margaret Geller, Jim Gunn, Jim Peebles, Nicola Vittorio, and Simon White. In addition, J. R. P. acknowledges the hospitality of the Max Planck Institute for Physics and Astrophysics, Munich, in summer 1983.

REFERENCES

1) Faber, S. M. and Gallagher, J. S. *Ann. Rev. Astron. Astrophys.* **17**, 135-187 (1979).

2) Peebles, P. J. E. *Astrophys. J. Lett.* **263**, L1-L5 (1982).

3) Primack, J. R. and Blumenthal, G. R. *Fourth Workshop on Grand Unification* (eds. Weldon, H. A., Langacker, P. and Steinhardt, P. J.) 256-288 (Birkhauser, Boston, 1983).

4) Primack, J. R. and Blumenthal, G. R. *Clusters and Groups of Galaxies* (eds. Mardirossian, F., Giuricin, G., and Mezzetti, M., Reidel, Dordrecht, Holland, in the press).

5) Peebles, P. J. E. *Astrophys. J.* **277**, 470-477 (1984).

6) Blumenthal, G. R. and Primack, J. R., in prep. (1984).

7) Peebles, P. J. E. *The Large Scale Structure of the Universe* (Princeton University Press, 1980).

8) Efstathiou, G. and Silk, J. *Fundamentals of Cosmic Phys.* **9**, 1-138 (1983).

9) Zeldovich, Ya. B., Einasto, J. and Shandarin, S. F. *Nature* **300**, 407-413 (1982).

10) Shandarin, S. F., Doroshkevich, A. G. and Zeldovich, Ya. B. *Sov. Phys. Usp.* **26**, 46-76 (1983).

11) Pagels, H. R. and Primack, J. R. *Phys. Rev. Lett.* **48**, 223-226 (1982).

12) Olive, K. A. and Turner, M. S. *Phys. Rev.* *D***25**, 213-216 (1982).

13) Blumenthal, G. R., Pagels, H. and Primack, J. R. *Nature* **299**, 37-38 (1982).

14) Bond, J. R., Szalay, A. S. and Turner, M. S. *Phys. Rev. Lett.* **48**, 1636-1639 (1982).

15) J. R. Bond and A. Szalay, *Astrophys. J.* **274**, 443-468 (1984).

16) Ipser, J. and Sikivie, P. *Phys. Rev. Lett.* **50**, 925-927 (1983).

17) Peccei, R. and Quinn, H. *Phys. Rev. D* **16**, 1791-1797 (1977).

18) Weinberg, S. *Phys. Rev. Lett.* **40**, 223-226 (1978).

19) Wilczek, F. *Phys. Rev. Lett.* **40**, 279-282 (1978).

20) Preskill, J., Wise, M. and Wilczek, F. *Phys. Lett.* **120B**, 127-132 (1983).

21) Abbott, L. and Sikivie, P. *Phys. Lett.* **120B**, 133-136 (1983).

22) Dine, M. and Fischler, W. *Phys. Lett.* **120B**, 137-141 (1983).

23) Fukugita, M., Watamura, S. and Yoshimura, M. *Phys. Rev. Lett.* **48**, 1522-1525 (1982).

24) Ellis, J., Hagelin, J. S., Nanopoulos, D. V., Olive, K. and Srednicki, M. *Nucl. Phys. B*(in the press).

25) Carr, B. J. *Comments on Astrophys.* **7**, 161-173 (1978).

26) Lacey, C. G. *Formation and Evolution of Galaxies and Large Scale Structures in the Universe* (eds. Audouze, J. and Tran Thanh Van, J.) 351-360 (Reidel, Dordrecht, 1984).

27) Freese, K., Price, R. and Schramm, D. N. *Astrophys. J.* **275**, 405-412 (1983).

28) Canizares, C. R. *Astrophys. J.* **263**, 508-517 (1982).

29) Witten, E. (preprint).

30) Carr, B. J., Bond, J. R. and Arnett, W. D. *Astrophys. J.* **277**, 445-469 (1984).

31) Hegyi, D. J. and Olive, K. A. *Phys. Lett.* **126B**, 28-32 (1983).

32) Yang, J., Turner, M. S., Steigman, G., Schramm, D. N. and Olive, K. A. *Astrophys. J.* (in the press).

33) Uson, J. M. and Wilkinson, D. T. *Astrophys. J. Lett.* **277**, L1- L4 (1984).

34) Rees, M. J. *The Very Early Universe,* (eds. Gibbons, G., Hawking, S. and Siklos, S.), 29-58 (Cambridge University Press, 1983).

35) Weinberg, S. *Astrophysical Cosmology: Proceedings of the Study Week on Cosmology and Fundamental Physics* (eds. Brück, H. A., Coyne, G. V. and Longair, M. S.) 503-528 (Pontifical Scientific Academy, Vatican, 1982).

36) Kolb, E. W. and Turner, M. S. *Ann. Rev. Nucl. Part. Sci.* **33**, 645-696 (1983).

37) Frenk, C., White, S. D. M. and Davis, M. *Astrophys. J.* **271**, 417-430 (1983)

38) Dekel, A. and Aarseth, S. *Astrophys. J.* **283** (in the press).

39) Kaiser, N. *Astrophys. J.* **273**, L17-L20 (1983).

40) Faber, S. M. *Proc. of the First ESO-CERN Symposium, Large Scale Structure of the Universe, Cosmology, and Fundamental Physics* (in the press).

41) Bond, J. R., Szalay, A. S. and White, S. D. M. *Nature* **301**, 584-585 (1983).

42) Aaronson, M. *Astrophys. J. Lett.* **266**, L11-L15 (1983).

43) Aaronson, M. and Cook, K. *Bull. Am. Astron. Soc.* **15**, 907 (1983).

44) Cook, K., Schechter, P. and Aaronson, M. *Bull. Am. Astron. Soc.* **15**, 907 (1983).

45) Faber, S. M. and Lin, D. N. C. *Astrophys. J. Lett.* **266**, L17-L20 (1983).

46) Lin, D. N. C. and Faber, S. M. *Astrophys. J. Lett.* **266**, L21-L25 (1983).

47) Harrison, E. R. *Phys. Rev.* *D***1**, 2726-2730 (1970).

48) Peebles, P. J. E. and Yu, J. T. *Astrophys. J.* **162**, 815-836 (1970).

49) Zeldovich, Ya. B. *Mon. Not. R. astr. Soc.* **160**, 1P-3P (1972).

50) Shafi, Q. and Vilenkin, A. *Phys. Rev. Lett.* **52**, 691-694 (1984).

51) Steinhardt, P. J. and Turner, M. S. (preprint).

52) Quinn, H. R. and and Gupta, S. (preprint SLAC-PUB-3269).

53) Zeldovich, Ya. B. *Mon. Not. R. astr. Soc.* **192**, 663-667 (1980).

54) Vilenkin, A. *Phys, Rev.* *D***24**, 2082-2089 (1981).

55) Bond, J. R., Efstathiou, G. and Silk, J. *Phys. Rev. Lett.* **45**, 1980-1984 (1980).

56) Turner, M. S., Wilczek, F. and Zee, A. *Phys. Lett.* **125B**, 35-40 and (E) 519 (1983).

57) Hara, T. *Prog. Theor. Phys.* **6**, 1556-1568 (1983).

58) Doroshkevich, A. G., Zeldovich, Ya. B., Sunyaev, R. A. and Khlopov, M. Yu. *Sov. Astron. Lett.* **6**, 252-256 (1980).

59) Chernin, A. D. *Sov. Astron.* **25**, 14-16 (1981).

60) White, S. D. M. and Rees, M. J. *Mon. Not. R. astr. Soc.* **183**, 341-358 (1978).

61) Rees, M. J. and Ostriker, J. P. *Mon. Not. R. astr. Soc.* **179**, 541-559 (1977).

62) Faber, S. M. *Astrophysical Cosmology: Proceedings of the Study Week on Cosmology and Fundamental Physics* (eds. Brück, H. A., Coyne, G. V. and Longair, M. S.) 191-234 (Pontifical Scientific Academy, Vatican, 1982).

63) Silk, J. *Nature* **301**, 574-578 (1983).

64) Forman, W. and Jones, C. *Ann. Rev. Astron. Astrophys.* **20**, 547-585 (1982).

65) Geller, M. J. and Beers, T. C. *Proc. Astron. Soc. Pacific* **94**, 421-439 (1982).

66) Thuan, T. X. and Romanishin, W. *Astrophys. J.* **248**, 439-459 (1981).

67) Cavaliere, A., Santangelo, P., Tarquini, G. and Vittorio, N. *Clusters and Groups of Galaxies* (eds. Mardirossian, F., Giuricin, G., and Mezzetti, M., Reidel, Dordrecht, Holland, in the press).

68) Yoneyama, T. *Publ. Astron. Soc. Japan* **24**, 87-98 (1972).

69) Peebles, P. J. E. (preprint).

70) Fall, S. M. and Rees, M. J. (in prep.).

71) Fall, S. M. and Rees, M. J. *Mon. Not. R. astr. Soc.* **181**, 37P-42P (1977).

72) Geller, M. and Huchra, J. *Astrophys. J. Suppl.* **52**, 61-87 (1983).

73) Faber, S. M., Blumenthal, G. R. and Primack, J. R. *Astrophys. J. Lett.* (submitted).

74) Blumenthal, G. R., Faber, S. M. and Primack, J. R. (in prep.).

75) Sandage, A., Freeman, K. C. and Stokes, N. R. *Astrophys. J.* **160**, 831-844 (1970).

76) Efstathiou, G. and Barnes, J. *Formation and Evolution of Galaxies and Large Scale Structures in the Universe* (eds. Audouze, J. and Tran Thanh Van, J.) 361-377 (Reidel, Dordrecht, 1984).

77) Gott, J. R. and Thuan, T. X. *Astrophys. J.* **204**, 649-667 (1976).

78) Davis, M. and Peebles, P. J. E. *Astrophys. J.* **267**, 465-482 (1983).

79) Sandage, A. *Proc. First ESO-CERN Symposium, Large Scale Structure of the Universe, Cosmology, and Fundamental Physics* (in the press).

80) Davis, M., Efstathiou, G., Frenk, C. and White, S. D. M. (in prep.).

81) Peebles, P. J. E. (preprint).

82) Hoffman, G. L., Salpeter, E. E. and Wasserman, I. *Astrophys. J.* **268**, 527-539 (1983).

83) Hoffman, Y. and Shaham, J. *Astrophys. J. Lett.* **262**, L23-L26 (1982).

84) Kirshner, R. F., Oemler, A., Schechter, P. L. and Schectman, S. A. *Astrophys. J. Lett.* **248**, L57-L60 (1981).

85) Kirshner, R. F., Oemler, A., Schechter, P. L. and Schectman, S. A. *Early Evolution of the Universe and Its Present Structure, IAU Symposium No. 104* (eds. Abell, G. O. and Chincarini, G.) 197-202 (Reidel, Dordrecht, Holland, 1983).

86) Oort, J. H. *Ann. Rev. Astron. Astrophys.* **21**, 373-428 (1983).

87) Dressler, A. *Astrophys. J.* **236**, 351-365 (1980).

88) Geller, M. J. and Huchra, J. (preprint).

89) Binggeli, B. *Astron. Astrophys.* **107**, 338-349 (1982).

90) Bond, J. R., Centrella, J., Szalay, A. S. and Wilson, J. R. *Formation and Evolution of Galaxies and Large Structures in the Universe* (eds. Audouze, J. and Tran Thanh Van, J.) 87-99 (Reidel, Dordrecht, Holland, 1984).

91) Shapiro, P. R., Struck-Marcell, C. and Melott, A. L. *Astrophys. J.* **275**, 413-429 (1983).

92) Dekel, A., West, M. J. and Aarseth, S. J., *Astrophys. J.* **279** , 1 (1984).

93) Melott, A., Einasto, J., Saar, E., Suisalu, I., Klypin, A. A. and Shandarin, S. F. *Phys. Rev. Lett.* **51**, 935-938 (1983).

94) Dekel, A. *Astrophys. J.* **264**, 373-391 (1983).

95) Doroshkevich, A. G., Shandarin, S. F. and Zeldovich, Ya. B. *Comments on Astrophys.* **9**, 265-273 (1982).

96) Rees, M. J. *Clusters and Groups of Galaxies* (eds. Mardirossian, F., Giuricin, G., and Mezzetti, M., Reidel, Dordrecht, Holland, in the press).

97) Ostriker, J. P. *Astrophysical Cosmology: Proceedings of the Study Week on Cosmology and Fundamental Physics* (eds. Brück, H. A., Coyne, G. V. and Longair, M. S.) 473-493 (Pontifical Scientific Academy, Vatican, 1982).

98) Barrow, J. D. and Bhavsar, S. P. *Mon. Not. R. Astr. Soc.* **205,** 61p (1983).

99) Dekel, A. and West, M. J. (preprint NSF-ITP-84-44).

100) Dressler, A. *Astrophys. J.* **226**, 55-69 (1978).

101) Jones, C. and Forman, W. *Astrophys. J.* **272**, 439-448 (1983).

102) Kriss, G. A., Cioffi, D. F. and Canizares, C. R. *Astrophys. J.* **272**, 439-448 (1983).

103) Beers, T. C., Geller, M. J., Huchra, J. P., Latham, D. W. and Davis, R.J., preprint (1984).

104) Gunn, J.E. *Astrophysical Cosmology* (eds. Brück, H.A., Coyne, G.V., and Longair, M.S.) 233-259 (Pontifical Scientific Academy, Vatican, 1982).

105) Young, P.J. *Astron. J.* **81**, 807-816 (1976).

106) Kent, S. M. and Gunn, J. E. *Astron. J.* **87**, 945-971 (1982).

107) Kent, S. M. and Sargent, W. L. W. *Astron. J.* **88**, 697-708 (1983).

108) de Vaucouleurs, G., de Vaucouleurs, A., and Corwin, H. R. *Second Reference Catalogue of Bright Galaxies* (University of Texas, Austin, 1976).

109) Dressler, A. and Sandage, A. R. *Astrophys. J.* **265**, 664-680 (1983).

110) Rubin, V. C. *Internal Kinematics and Dynamics of Galaxies* (ed. Athanassoula, E.) 3-6 (Reidel, Dordrecht, 1983).

111) Rubin, V. C., Ford, W. K., Thonnard, N. and Burstein, D. *Astrophys. J.* **261**, 439-456 (1982).

112) Tonry, J. and Davis, M. *Astrophys. J.* **246**, 680-695 (1981).

113) Thuan, T. X. and Seitzer, P. O. *Astrophys. J.* **231**, 680-687 (1979).

114) Burstein, D., Rubin, V. C., Thonnard, N. and Ford, W.K. *Astrophys. J.* **253**, 70-85 (1982).

115) Raymond, J. C., Cox, D. P. and Smith, B. W. *Astrophys. J.* **204**, 290-292 (1976).

116) Dalgarno, A. and McCray, R. A. *Ann. Rev. Astron. Astrophys.* **10**, 375-426 (1972).

TABLE 1

M/L_B and M/M_{lum} on Various Mass Scales

Unit	M^a	M/L_B [b]	M_{gas}/M_{lum}	M/M_{lum}
Large Clusters	$10^{15}\ M_\odot$	316±40[c]	$0.84^{+0.0}_{-0.1}$ [d]	$8.4^{+7.0}_{-1.0}$
Small E-dominated Groups	5×10^{13}	83^{+80}_{-10} [e]	$0.61^{+0.1}_{-0.1}$ [e]	$5.4^{+10.0}_{-2.0}$ [e]
Small Spiral-dominated Groups	2×10^{13}	40^{+50}_{-10} [f]	0 (?)	14.2^{+36}_{-6} [g]
Whole Milky Way	10^{12} [h]	50[i]	0 (?)	14[j]
Dwarf Spheroidals[k]				
Stellar ~~Masses~~:	10^{5-7}	2.5	0	1
Dynamical Masses:	10^{6-8}	30	0	12

Notes:

[a]Total mass including dark matter. $H = 50$ km s^{-1} Mpc.

[b]Mass-to-light ratio on B(O) magnitude system as described by Faber and Gallagher[1]

[c]Dressler[100]

[d]M_{gas}/M_{lum} is calculated as the product of two factors: $(M_{gas}/M) \times (M_{lum}/M)^{-1}$. $M_{gas}/M = 0.10^{+0.02}_{-0.05}$ from Jones and Forman for 14 X-ray clusters.[101] Formal clusters have been increased to allow for the unknown gas distribution outside the core and possible settling of gas relative to galaxies or vice versa. M_{lum}/M is $(M_*+M_{gas})/M$, where M_*/M is the fractional mass in stars. It may be calculated as $(M/L_B)_*(M/L_B)^{-1}$, where $(M/L_B)_*$ is the stellar mass-to-light ratio. For E and SO galaxies in large clusters, $(M/L_B)_*$ appears to be about 6.[1]

Notes (continued):

[e] L_V, M_{gas}, and M from Kriss, Cioffi, and Canizares[102] based on five groups. L_V corrected to B(0) system based on data provided by Kriss (private communication). Comparison with Beers et al.[103] suggests that M may be underestimated by a factor of two. Quoted errors take this into account.

[f] Faber and Gallagher.[1]

[g] Faber.[62] Includes baryonic mass in stars and neutral gas.

[h] Mass assumed to be 1/3 total mass of Local Group.[1]

[i] B(0) luminosity from Faber and Gallagher.[1]

[j] M_{lum} from Gunn.[104]

[k] Basic data from Faber and Lin.[45] Upper line assumes that only stars are present. Lower line includes excess dark matter, based on mean dynamical masses of Faber and Lin[45] and Aaronson et al.[42-44]

Figure Captions

Fig. 1. Mass-to-light ratio, M/L_B, and total-to-luminous mass, M/M_{lum}, for structures of various size in the universe. The data come from Table 1. Although M/L_B increases systematically with mass, the more physically meaningful ratio M/M_{lum} appears to be constant on all scales within the errors.

If the velocity dispersion data for the dwarf spheroidal galaxies are interpreted to imply heavy halos, the upper estimates in the figure result. The lower estimates follow from assuming that all the mass is visible. We believe the former estimate to be more realistic, as discussed in the text.

Fig. 2. Density fluctuations as a function of mass. a) $k^{3/2}|\delta_k| = \delta\rho/\rho(M)$, where $M = 4\pi^4\rho_o/3k^3$, for isothermal white noise ($n = 0$), and adiabatic Zeldovich ($n = 1$) neutrino[14] and cold dark matter spectra. b) Root-mean-square mass fluctuation within a randomly placed sphere containing mass M for cold dark matter, $n = 1$, and ($\Omega = 1$, $h = 0.5$), ($\Omega = 0.2$, $h = 1$).

Fig. 3. Baryon density n_b versus three-dimensional, rms velocity dispersion V and virial temperature T for structures of various size in the universe. The quantity T is $\mu V^2/3k$, where μ is mean molecular weight (≈ 0.6 for ionized, primordial H + He) and k is Boltzmann's constant. Dots at upper right represent nearly all groups and clusters within 5000 km s^{-1} in the CfA catalog.[72] Baryon density is obtained from total density assuming $\rho_b/\rho = 0.1$ (cf. Table 1), where ρ is defined as $M/(4\pi R_{vir}^3/3)$, M is total mass, and R_{vir} is GM/V^2. Catalog groups are chosen to exceed a minimum threshold luminosity density. Their minimum baryon density should thus fall on a horizontal line, slightly modified by the higher M/L of rich clusters, as is observed. Point A represents Abell

clusters of richness 2 and 3 studied by Dressler.[100] Here $R_{vir} = 3.0\ R_{eff}$, valid for a deVaucouleurs cluster profile.[105] The quantity T for clusters corresponds to central velocity dispersion, with the arrow indicating the effect of the falloff in velocity dispersion at large radii observed in the Coma cluster.[106]

For galaxies, M_{lum} is set equal to $(M_{lum}/L_B) \times L_B$, where L_B is blue luminosity. Assumed values of (M_{lum}/L_B): E = 8, S0 = 6, Sa = 4, Sb = 2.5, Sc = 1.5, Dw. Irr = 1.00, Dw. Spheroidal = 2.5 (all but the last are based on h = 0.5). Galaxy radii are approximate virial radii, assuming that the baryonic components of galaxies are self-gravitating (to obtain a radius consistent with the definition used for groups and clusters above). To achieve this, isophotal radii from various sources have been appropriately scaled, as follows: E-Sb, $R_{vir} = R_{25}$ [108–111] ; Sc, $R_{vir} = 1.24\ R_{25}$ [114] ; Dw. Irr, $R_{vir} = 1.24\ R_H$ [113] ; Dw. Sph., $R_{vir} = 0.70\ R_{tid}$ [45] . Velocities: E-S0, $V = \sqrt{3} \times \sigma(\text{nucleus})$[112,109] ; Sa-Sc, $V = v_{rot}^{max}$ [110,111,114] ; Dw. Irr, $V = 1/2$ FWHM (Δv),[113] corrected for inclination. Dw. spheroidals are plotted twice; open circles, $M = 2.5\ L_B$ (stars only) and $V = (GM/R_{vir})^{1/2}$; large dots, $M = 30\ L_B$ (stars plus dark matter[42–45]), with V as before.

Light diagonal lines represent the masses of self-gravitating bodies with the indicated values of n_b and T and assuming $\rho_b = 0.1\rho$. The discontinuities near 10^4 K are due to the effects of H and He ionization.

Cooling curves[115,116,68] (medium lines) separate regions where cooling is efficient ($\tau_{cool} < \tau_{dyn}$, lower region) from regions where it is inefficient ($\tau_{cool} > \tau_{dyn}$, upper region). All curves assume a residual electron fraction after recombination of 10^{-4}, consistent with $\Omega_b/\Omega = 0.1$. Further discussion of molecular cooling below 10^4 K is given in the text.

Model curves represent the equilibria of structures that collapse dissipationlessly from the cold dark matter initial fluctuation spectra of Fig. 2 with $n = 1$. DM halos and groups and clusters of galaxies should lie on these curves, whereas the baryon components of galaxies should lie below due to baryonic dissipation. The curve labeled 1σ refers to fluctuations with $\delta M/M$ equal to the rms value shown in Fig. 2. Curves labeled 0.5σ, 2σ, and 3σ refer to fluctuations having 0.5, 2, and 3 times the rms value. Heavy curves: $\Omega = 1$, $h = 0.5$; dashed curves: $\Omega = 0.2$, $h = 1$.

Major conclusions from the figure: 1) Model curves appear to pass through groups and clusters in about the right place, and the horizontal spread is roughly as expected for a Gaussian distribution in $\delta M/M$. 2) Baryon components of galaxies lie below the loci for dissipationless collapse and generally within the region where strong baryonic cooling is expected. 3) Dwarf spheroidal galaxies lie near the beginning of the clustering hierarchy and may be typical of the earliest structures to collapse (cf. Silk[63]). 4) Hubble types are spread out along different loci, perhaps due in part to different baryon collapse factors (E's larger, Irr's smaller) and in part to intrinsic differences in initial $\delta M/M$ (see also Fig. 4).

Fig. 4. Total mass M versus virial temperature T . Data sources and symbols are the same as in Fig. 3. M for groups and clusters is total dynamical mass. For galaxies, M is assumed to be 10 M_{lum} (see caption, Fig. 3). If Dw. spheroidals actually have $M/L_B = 30$, they may have suffered baryon stripping[46] , in which case M is a lower limit (arrows). Details of the region occupied by massive galaxies are shown in the inset in upper left. In addition to the n = 1 models from Fig. 3, two 1σ curves for $n = 0$ and $n = 2$ are also shown (light dashes).

Major conclusions from the figure: 1) Either set of curves for $n = 1$ (Zeldovich spectrum) provides a good fit to the observations over 9 orders of magnitude in mass. Curves with $n = 0$ and $n = 2$ do not fit as well. 2) The apparent gap between galaxies and groups and clusters in Fig. 3 (which stems from baryonic dissipation) vanishes in this figure, and the clustering hierarchy is smooth and unbroken from the smallest structures to the largest ones. 3) The Fisher-Tully and Faber-Jackson laws for galaxies ($M \propto V^4$ or T^2) arise naturally as a consequence of the slope of the cold DM fluctuation spectrum in the mass region of galaxies. 4) Groups and clusters are distributed around the $n = 1$ loci about as expected. The apparent upward trend among the groups is not physically meaningful but arises from their selection as minimum-density enhancements (see caption, Fig. 3, and constant-density arrow, this figure). 5) The exact locations of galaxies are somewhat uncertain. In particular, the temperatures of E's and S0's may be overestimated owing to the use of nuclear rather than global velocity dispersions. The masses of Dw. Irr's may also be too low owing to too small HI masses. Taken at face value, however, the data suggest that early-type galaxies (E's and S0's) arise from high-$\delta M/M$ fluctuations, whereas late-type galaxies (Sc's and Irr's) arise from low-$\delta M/M$ fluctuations. 6) Groups and clusters appear to fill a wider band than galaxies. If real, this difference may indicate that very weak, low-$\delta M/M$ fluctuations on the mass scale of galaxies once existed but did not give rise to visible galaxies. This suggests further that galaxy formation, at least in some regions of the universe, may not have been fully complete and that galaxies are therefore not a reliable tracer of total mass. 7) There seems to be a real trend along the Hubble sequence to increasing mass among early-type galaxies. Neither this trend nor the rather sharp demarcation between galaxies and groups and clusters is fully understood.

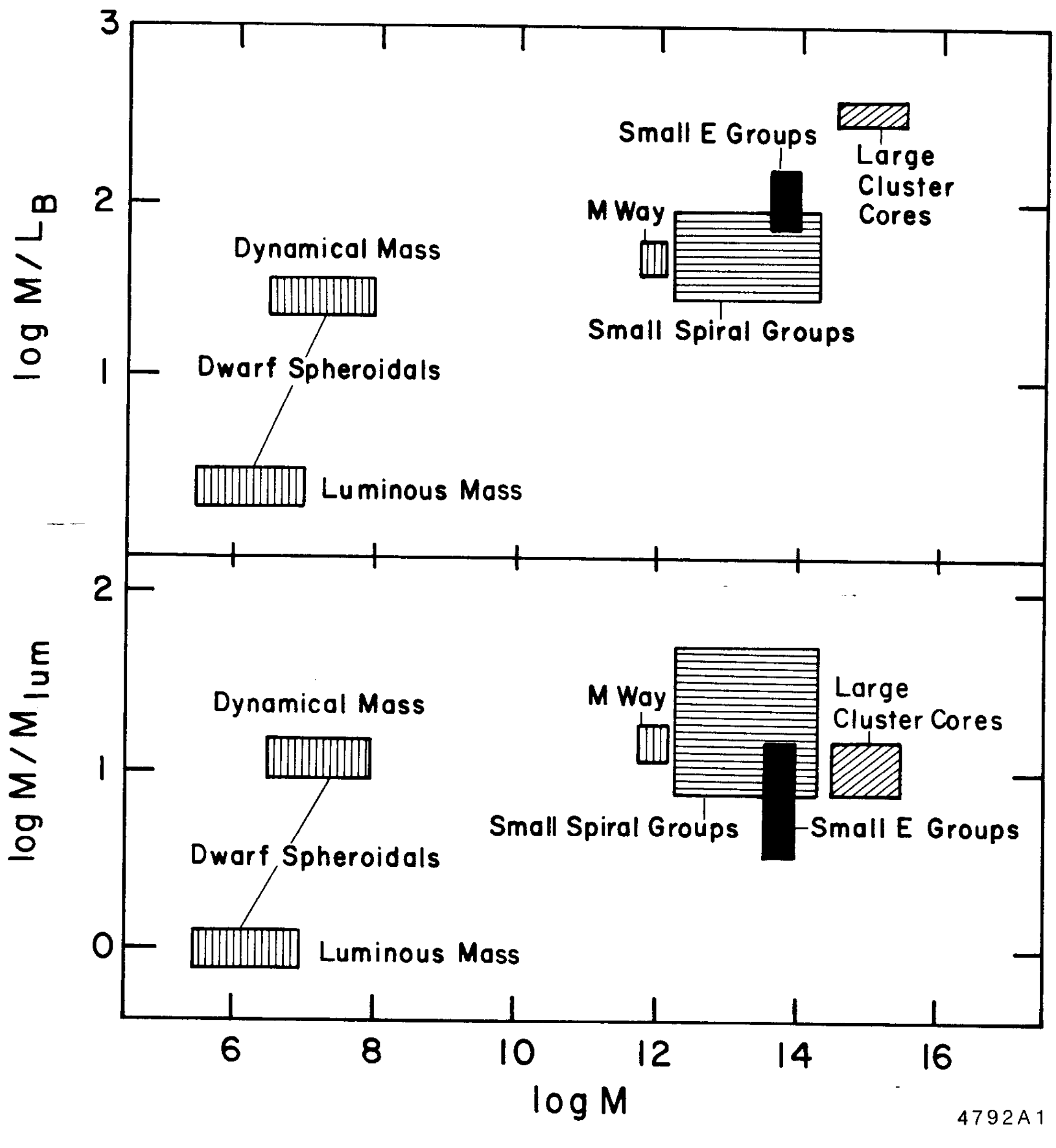
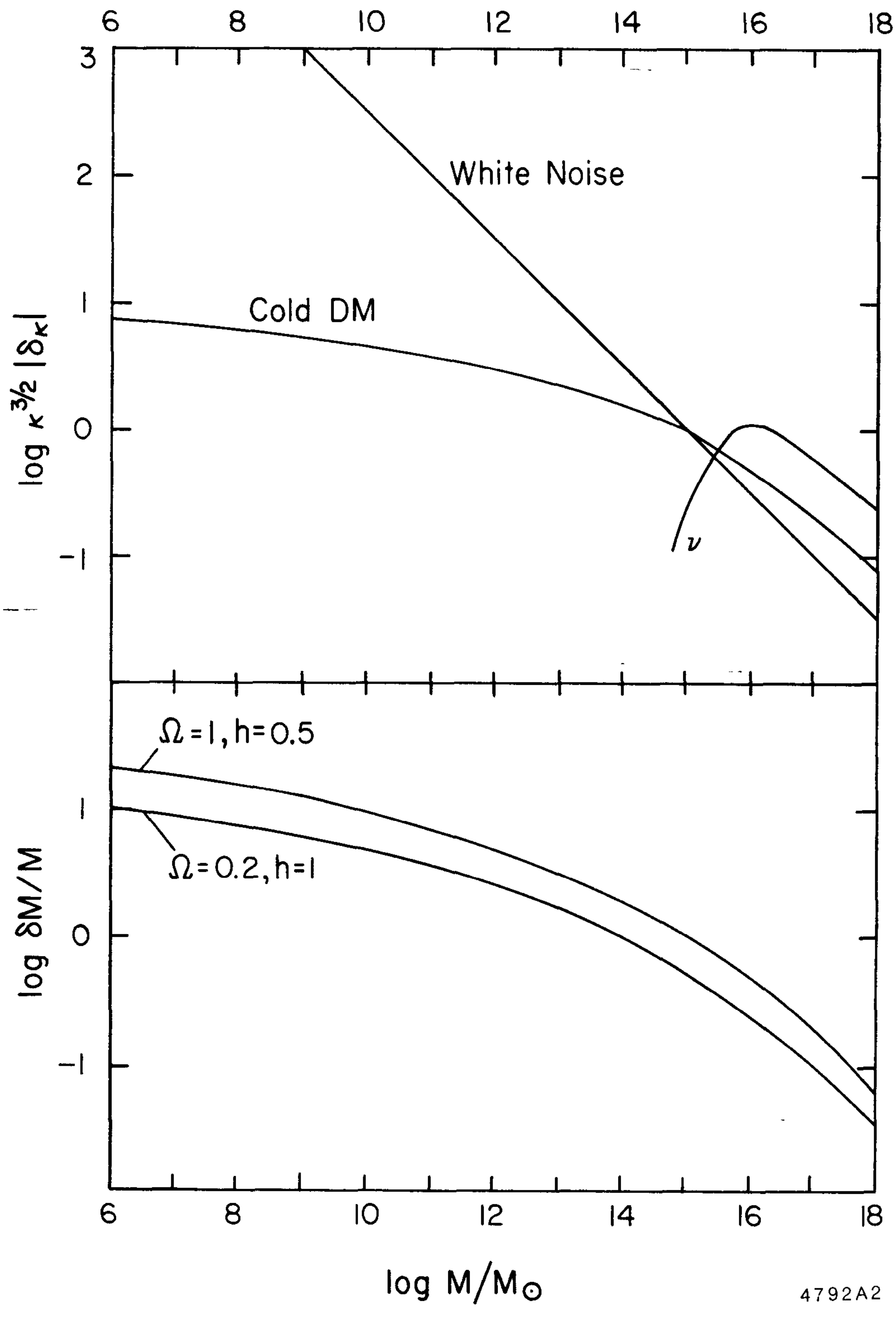

3
2
1
log M/L_B
Small E Groups
Large
Cluster
Cores
M Way
Dynamical Mass
Small Spiral Groups
Dwarf Spheroidals
Luminous Mass
2
1
0
log M/M_lum
Dynamical Mass
M Way
Large
Cluster Cores
Small Spiral Groups
Small E Groups
Dwarf Spheroidals
Luminous Mass
6
8
10
12
14
16
log M
4792A1

Fig. 1



White Noise
Cold DM
ν
$\log \kappa^{3/2}|\delta_\kappa|$
$\Omega=1, h=0.5$
$\Omega=0.2, h=1$
$\log \delta M/M$
$\log M/M_\odot$
4792A2

Fig. 2

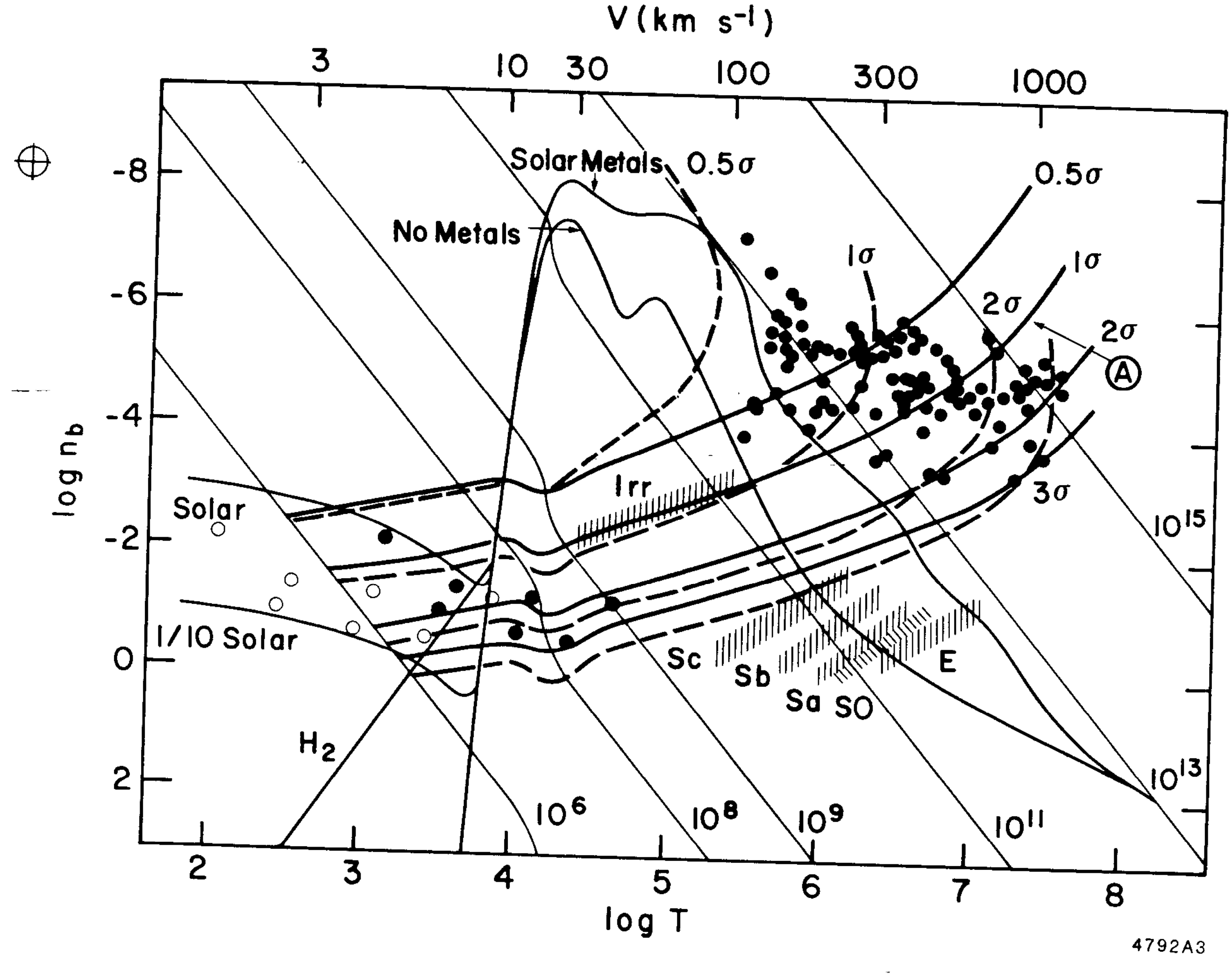
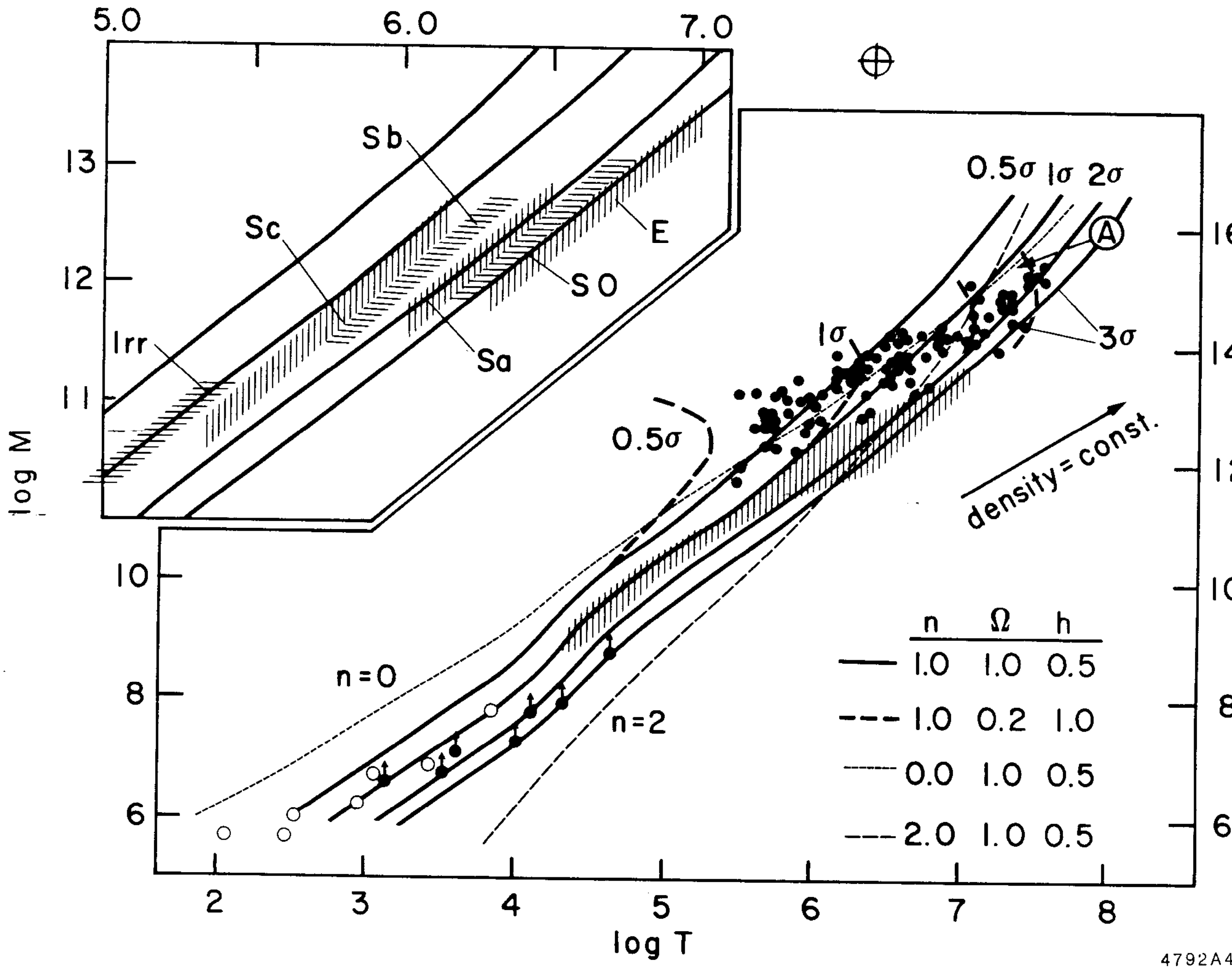

V (km s⁻¹)
3
10
30
100
300
1000
Solar Metals
0.5σ
No Metals
1σ
2σ
A
3σ
Irr
Sc
Sb
Sa
SO
E
Solar
1/10 Solar
H$_2$
10^6
10^8
10^9
10^{11}
10^{13}
10^{15}
log n_b
-8
-6
-4
-2
0
2
log T
4
5
6
7
8
4792A3

Fig. 3



5.0
6.0
7.0
13
12
11
Sb
Sc
Irr
E
S0
Sa
log M
0.5σ
1σ
2σ
A
3σ
16
14
12
10
8
6
density = const.
n=0
n=2
n Ω h
1.0 1.0 0.5
1.0 0.2 1.0
0.0 1.0 0.5
2.0 1.0 0.5
2
3
4
5
6
7
8
log T
4792A4

Fig. 4