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## COSMOLOGICAL STRUCTURE FORMATION \*

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### ABSTRACT

A summary is presented of the current forefront problem of physical cosmology, the formation of structures (galaxies, clusters, great walls, etc.) in the universe. Solutions require two key ingredients: (1) matter; and (2) seeds. Regarding the matter, it now seems clear that both baryonic and non-baryonic matter are required. Whether the non-baryonic matter is "hot" or "cold" depends on the choice of seeds. Regarding the seeds, both density fluctuations and topological defects are discussed. The combination of the isotropy of the microwave background and the recent observations indicating more power on large scales have severely constrained, if not eliminated, gaussian fluctuations with equal power on all scales, regardless of the eventual resolution of both the matter and seed questions. It is important to note that all current structure formation ideas require new physics beyond  $SU(3) \times SU(2) \times U(1)$ .

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## Introduction

The most active problem in physical cosmology today is that of structure formation. This problem is the central arena in which the juggernaut of particle physics-inspired, early universe theories collides with the growing mass of real observational data. Because of this wealth of new data, modern cosmology has shifted from being a branch of mathematics or philosophy to being a true experimentally testable science. The collision of ideas and data has created numerous headlines in the popular media. Unfortunately, many of these headlines are inaccurate or misleading.

The purpose of this talk (see also similar presentations in ref. 1 and ref. 2) is to attempt to summarize the dynamic current situation. However, before discussing the problems and recent observations regarding large-scale structure and galaxy formation, let us first review how observations and experiments have now established the basic hot Big Bang universe to a remarkable level of confidence so that any reasonable model for structure formation must operate in the Big Bang framework. Contrary to some recent headlines, it is not the Big Bang that is being challenged; rather, it is specific models of structure formation that are being challenged. These models, by necessity, operate within the Big Bang framework, just as earthquake predictors continue to operate within the framework of a round Earth even though they sometimes have difficulties in their predictions.

After briefly reviewing the basic Big Bang arguments, we will then discuss the generic features that any structure formation model must have: (1) matter, and (2) seeds to clump the matter. We will see that the bulk of the matter is dark (non-shining) and that some of the dark matter must be just non-shining ordinary matter in, say, brown dwarfs or some other low luminosity form, but the bulk of the dark matter is probably in some new exotic form such as low-mass neutrinos, "axions," or supersymmetric "neutralinos." We will also see that the "seeds" can be either small, gaussian density fluctuations or they could also be topological defects such as cosmic "strings," "walls," or "textures."

Observations and experiments are beginning to test the various combinations of matter and seeds. In particular, different combinations predict different patterns for the resultant structure and different levels and distributions for residual fluctuations in the cosmic microwave background radiation. We will examine where the current situation lies, what combinations are eliminated and which still look promising. We will conclude by discussing what future observations and experiments should resolve the problems and lead us to convergence on a model for how structure forms in the universe.

## The Establishment of the Hot Big Bang

While Hubble's<sup>3</sup> work in the 1920's established an expanding universe, the establishment of modern physical cosmology and the hot Big Bang naturally focuses on two key quantitative observational tests:

- (1) the cosmic microwave background radiation (CBR); and
- (2) Big Bang Nucleosynthesis (BBN) and the light element abundances.

The magnificent agreement of the 1990 COBE satellite measurements<sup>4</sup> with a perfect 2.735K blackbody radiation spectrum has been well discussed in the press (see also ref. 5). We should remember that this spectral shape is exactly what the hot Big Bang

predicts and no other theory naturally yields such a precise black body shape with only one free parameter,  $T$ , the temperature. A second precision test of the standard model is the consistency of light element abundance measurements and also the recent accelerator measurements of the number of neutrino species with the predictions of nucleosynthesis calculations in the Big Bang model.<sup>6</sup> Figure 1 shows the abundances produced in the standard BBN calculation as a function of the fraction of the critical density (that density required to make the universe's gravitational binding energy equal to its expansion kinetic energy) in baryons,  $\Omega_b$ . The vertical band in Figure 1 is the allowed values that are simultaneously consistent with the observed light element abundances of  $^4\text{He}$ ,  $^2\text{H}$ ,  $^3\text{He}$  and  $^7\text{Li}$  extrapolated to their primordial values unassociated with any heavier elements. Since  $^2\text{H}$  cannot be produced significantly in any non-cosmological process, only destroyed,<sup>7</sup> the present abundance of  $^2\text{H}$  puts an upper limit on the baryon density. Conversely,  $^3\text{He}$  is made in stars, and since the bulk of the excess cosmological  $^2\text{H}$  over the present value burns to  $^3\text{He}$  in stars, the sum of  $^2\text{H}$  plus  $^3\text{He}$  provides a lower bound on the baryon density. The allowed range of baryon density that is consistent with these bounds requires  $^7\text{Li}$  to be at the minimum in its production curve (as shown in Figure 1). The measurements of the Spites,<sup>8</sup> subsequently verified by others,<sup>9,10</sup> giving  $^7\text{Li}/\text{H} \sim 10^{-10}$  in the primitive (Pop II) stars, further substantiates these arguments. Thus, the light elements with abundances ranging from  $\sim 24\%$  to one part in  $10^{10}$  all fit with the cosmological predictions, with the one adjustable parameter giving baryon density

$$\Omega_b \simeq 0.06 .$$

Recent attempts to find alternatives to this conclusion by introducing variations in the assumptions have ended up (once the models are treated in detail) reaching essentially the same constraint on  $\Omega_b$  as in the standard model.<sup>11</sup> Thus, the conclusions have proven remarkably robust.

Added to the impressive agreement of the abundances has been the measurement using high energy colliders of the number of neutrino families,  $N_\nu = 2.98 \pm 0.06$ .<sup>12</sup> Nucleosynthesis arguments, developed in the 1970s, show that the cosmological  $^4\text{He}$  abundance is quantitatively related<sup>13</sup> to  $N_\nu$ . The current parameter values yield the cosmological prediction  $N_\nu \lesssim 3.3$ , specifically ruling out any light neutrinos beyond  $e$ ,  $\mu$  and  $\tau$ , and consistent with the collider measurements. This experimental particle physics test of the cosmological model is a "first" and effectively "consummates the marriage" of particle physics and cosmology. It also gives us even further confidence that we understand cosmological nucleosynthesis and thus know the cosmological baryon density as well as giving us confidence in the basic hot Big Bang model of the universe.

## Dark Matter Requirements

The narrow range in baryon density for which concordance occurs is very interesting. Note that the constraint on  $\Omega_b$  means that the universe *cannot be closed with normal matter*. If the universe is truly at its critical density, then nonbaryonic matter is required.

The arguments requiring some sort of dark matter fall into separate and possibly distinct areas. (For a more complete qualitative discussion of the various dark matter problems, see ref. 14.) The visible matter in the universe (stars) yields a fraction of

# BIG BANG NUCLEOSYNTHESIS

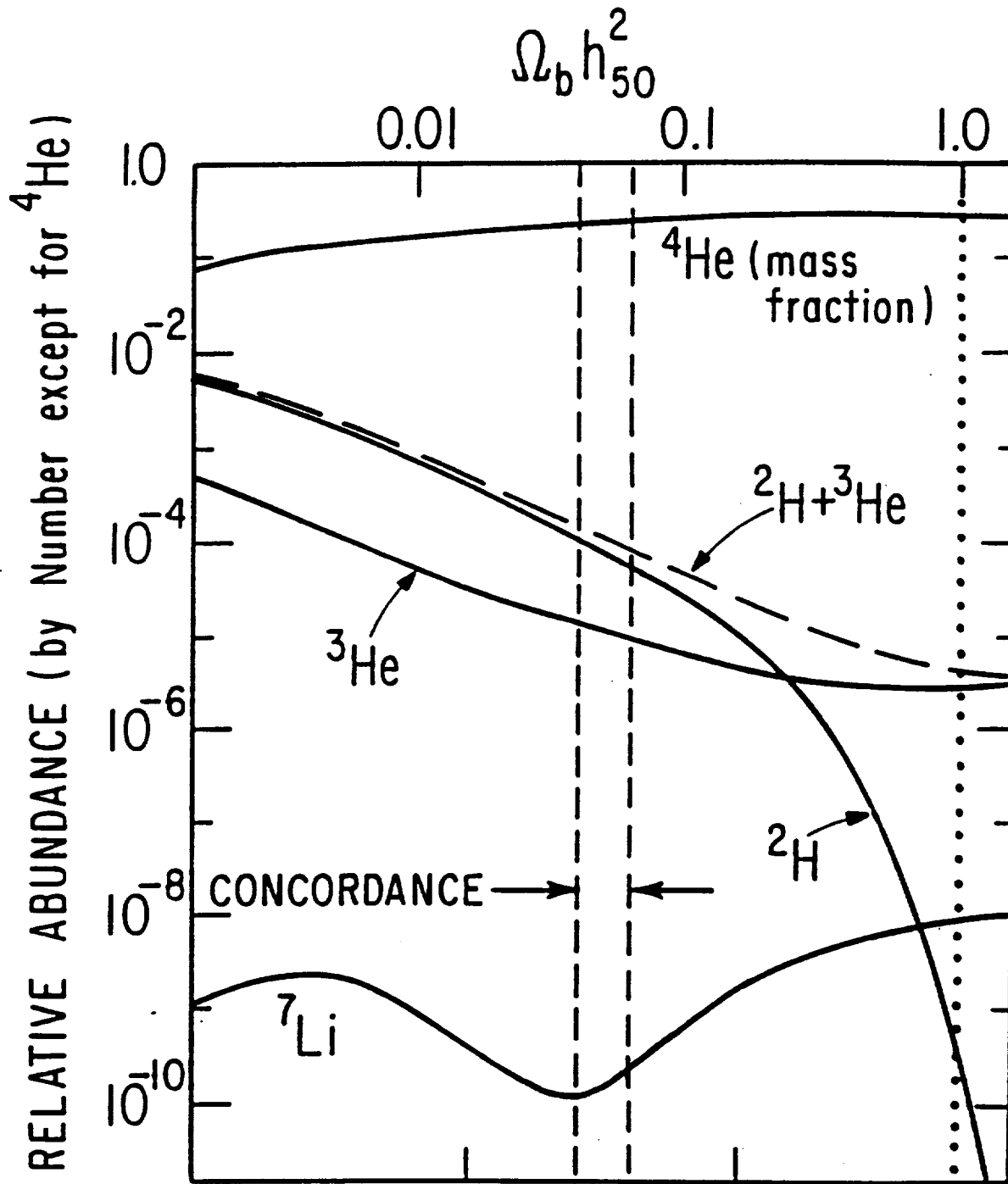


Figure 1. The abundances of light isotopes produced in the standard Big Bang model as a function of the fraction of the critical density in baryons,  $\Omega_b$ . Note the agreement with all abundance determinations is for  $\Omega_b \sim 0.06$ .<sup>9</sup>

the critical density of only about 0.007. This can be compared to the implied densities using Newtonian mechanics applied to various astronomical systems. These arguments are summarized in Figure 2.<sup>1,2</sup> It should be noted that these arguments (flat rotation curves, dynamics of binary galaxies, etc.) reliably demonstrate that galactic halos seem to have a mass  $\sim 10$  times the visible mass.

Note, however, that Big Bang nucleosynthesis requires that the bulk of the baryons in the universe be dark since  $\Omega_{vis} \ll \Omega_b$  and  $\Omega_b \sim \Omega_{halo}$ . Thus, the dark halos could, in principle, be baryonic (and if they are not, there is an interesting coincidence between  $\Omega_b$  and  $\Omega_{halo}$ , as noted by Gott *et al.*<sup>15</sup>). However, when similar dynamical arguments are applied to larger systems such as clusters of galaxies, the implied  $\Omega$  rises to about 0.2. (This same value of  $\Omega$  can also be obtained from gravitational lensing of distant quasars and galaxies by intervening clusters of galaxies. While the uncertainties might marginally allow an overlap between  $\Omega_b$  and  $\Omega_{cluster}$  at  $\sim 0.1$ , the central values are already hinting that, on the scales of clusters of galaxies (about 1 to 10 Mpc), there appears to be something more than baryonic matter.

A new and very dramatic development on even larger scales than clusters now suggests that on these very large scales (50 to 100 Mpc), the density approaches the critical value<sup>16,17</sup> ( $\Omega \sim 1$ ). This new development utilizes the combined velocity and distance estimates for galaxies out to and slightly beyond the Seven Samurai's so-called "Great Attractor."<sup>18</sup> This team determined the so-called peculiar velocities for galaxies out to about 100 Mpc. They did this by estimating the distance and using this to determine the cosmological expansion velocity. The difference between the galaxy's actual velocity as determined by the redshift and the inferred expansion velocity is known as the "peculiar velocity." From analyzing these peculiar velocities, it became apparent that there was a large flow of galaxies (including our local group) towards something they called the Great Attractor. They have now even shown possible infall from the far side of the Great Attractor.<sup>19</sup> Recently the galaxy flows have been mapped out in much greater detail using redshifts measured for the catalogue of galaxies found by the Infrared Astronomy Satellite (IRAS). This data has been analyzed by teams from MIT, Israel, Toronto, England, Stony Brook, Berkeley and Fermilab, and the universal conclusion to date is that the observed dynamics on this scale require  $\Omega = 1 \pm 0.3$ . This result forces us to need some sort of non-baryonic dark matter.

Of course, theoretical cosmologists have long assumed that  $\Omega$  is unity, so these recent (and still preliminary) results may prove to be a confirmation of this theoretical assumption. The theoretical argument is essentially that the only long-lived natural value for  $\Omega$  is unity, and that inflation or something like it provided the early universe with the mechanism to achieve that value and thereby solve the so-called flatness and smoothness problems. (The flatness problem is simply the fact that universes with  $\Omega$  not equal to unity rapidly either collapse to an infinite density "big crunch" or expand to a zero density "big chill" in a very short time. The  $\Omega = 1$  solution corresponds to a flat Euclidean space time. The "smoothness" or "horizon" problem is the uniformity of the microwave background radiation on scales that are farther apart than the distance light could have traveled in the age of the universe.)

Before turning to exotic non-baryonic matter, we should note that some baryonic dark matter must exist since the lower bound from Big Bang nucleosynthesis is greater than the upper limits on the amount of visible matter in the universe. We do not know what form this baryonic dark matter is in. It could be either in condensed objects in the halo,

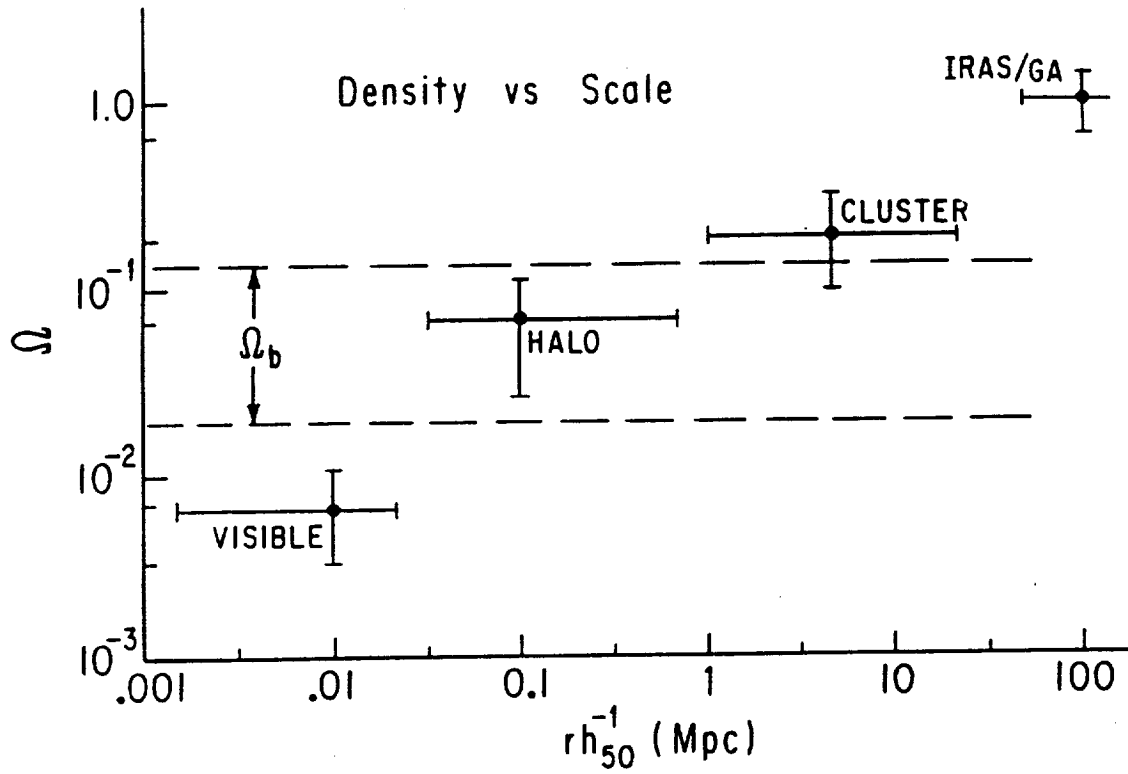


Figure 2. The inferred density in units of the critical density as a function of the scale on which it is "measured." Note the increase in  $\Omega$  towards unity as larger scales are probed. Note also that  $\Omega_b$  agrees with densities on the scale of galactic halos and is greater than the amount of visible matter.<sup>1</sup>

defects generated at the transition. Small quantum fluctuations in the position of water molecules in the ice crystals may be thought of as the random fluctuations. For the universe, the medium undergoing the phase transition is the vacuum itself. Proposed transitions are associated with the unification of forces. For example, the Grand Unified Transition (GUT) can, in principle, create both types of seeds when the universe was at a temperature of about  $10^{28}$  K. Recently, it has also been proposed that a cosmological phase transition may occur as late as a temperature of  $\sim 100$  K (after the decoupling of the cosmic background radiation) and also be able to generate either type of seed.<sup>23</sup>

It is interesting to realize that all models for generating structure in the universe require some new fundamental physics, both in the form of exotic matter and some vacuum phase transition to produce seeds. Thus, the study of the structure of the universe should teach us new physics as well as astronomy.

For readers who remember the discussions of seeds and structure formation of twenty years ago, it is useful to put the current ideas into the former framework.<sup>24</sup> Prior to the introduction of Grand Unified or microphysics models for generating fluctuations, one merely noted that density fluctuations in matter could be divided into two general classes:

- 1) adiabatic;  
and
- 2) "isocurvature" (or almost equivalently "isothermal", since in the early universe

$$\rho_b \ll \rho_r).$$

In the adiabatic case, the ratio of baryon density,  $n_b$ , to radiation density,  $n_\gamma$ , is unchanging, so any variation in  $n_b$  is accompanied by a variation in  $n_\gamma$ . In the isothermal case,  $n_\gamma$  remains fixed, so only  $n_b$  varies, and in the isocurvature case, the total energy density (which yields cosmic curvature) is fixed so that variations in the energy density are accompanied by opposite compensating variations in the energy density of photons,  $\rho_\gamma$ . But since  $\rho_\gamma \gg \rho_b$ , the variations in  $\rho_b$  don't really affect  $\rho_\gamma$ , so isocurvature behaves just like isothermal, with the development of grand unified models and particularly the realization that baryons were probably produced by some variant of the Sakharov process (see review in ref. 25). It was noted<sup>26</sup> that, in such models for baryosynthesis, adiabatic fluctuations were preferred for baryon density fluctuation. If baryons are generated by temperature-dependent microphysics processes, then a constant isothermal temperature everywhere would result in the same baryon density everywhere and yield no baryon density fluctuation. A way around this would be to have the "seed" not be a matter density fluctuation itself, but, instead, be some separate physical seed. This latter role is the function of a topological defect. Such a defect does not alter the thermal background, so in the old classification it is isothermal or isocurvature. However, topological seeds do not yield gaussian distribution, but, instead, are patterns. Thus, if one wishes to use the old language, the random quantum seeds are the old gaussian adiabatic fluctuations and topological seeds are the old isothermal/isocurvature seeds with the added constraint of being non-gaussian. The key new point is that these models are motivated by fundamental physics ideas rather than just mathematical formalism.

Figure 3 shows how density fluctuations grow as the universe expands. If the seed is produced by a phase transition prior to the decoupling of the CBR, then the observed isotropy of that radiation constrains the initial fluctuation amplitude to be quite small and small fluctuations grow linearly, as indicated,  $\frac{\delta\rho}{\rho} \propto \frac{1}{1+z}$ . Such a linear growth means that

# Structure Growth

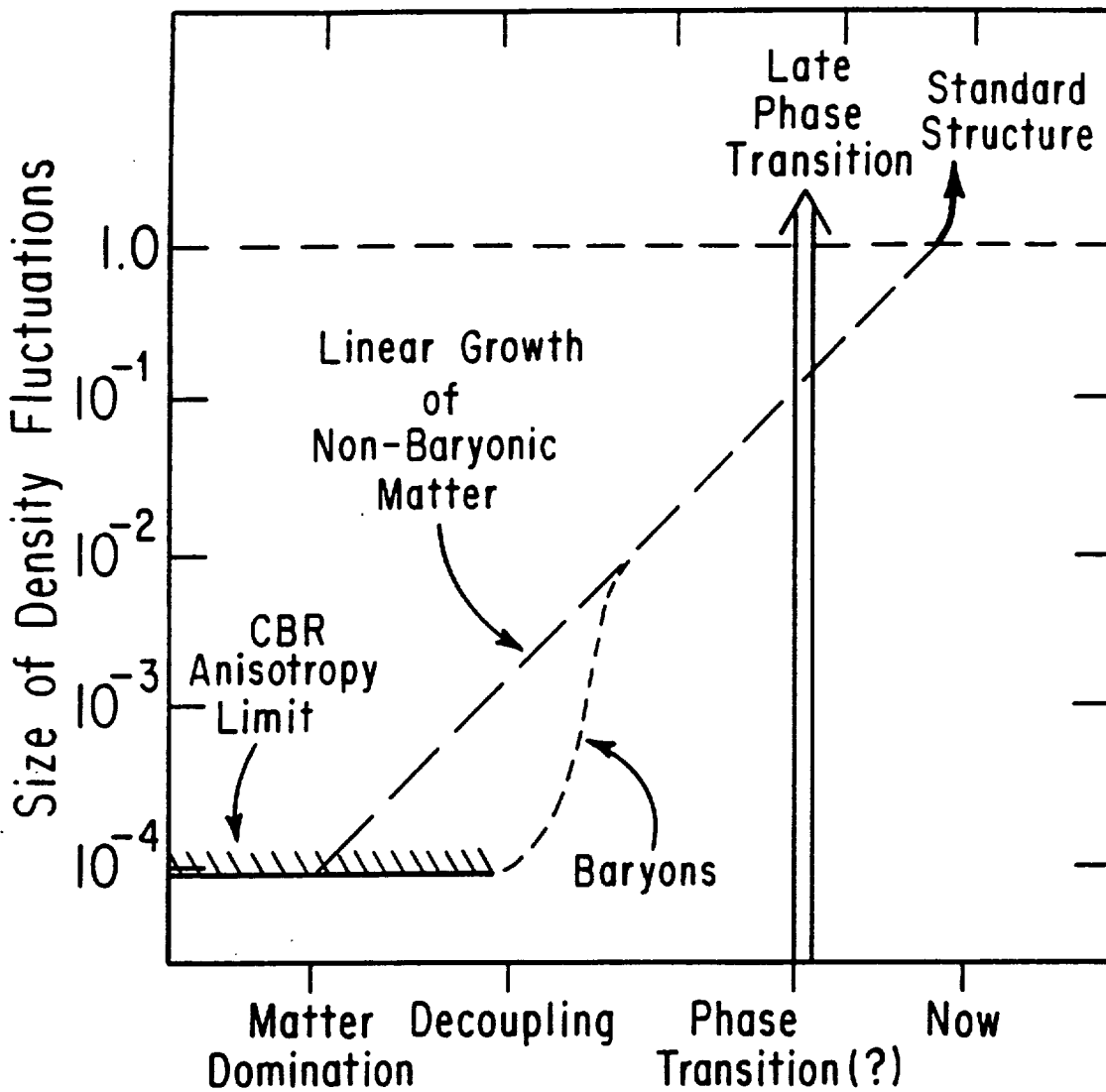


Figure 3. Diagram shows structure growth as a function of the redshift epoch. Note that any model which starts with primordial seeds that are constrained by the isotropy of the cosmic background radiation produce most of their structure relatively late.



the bulk of the objects form relatively late when the average fluctuation size is comparable to the average density itself. (Only after  $\frac{\delta\rho}{\rho} \sim 1$  can non-linear rapid growth occur.) This slow growth is a serious constraint on such models and is one of the motivations behind recent models with a late phase transition occurring after the decoupling of the background radiation. In this latter case, the growth can be much faster without violating the isotropy limits.

The favorite structure formation model until recently has been a combination of (1) random density fluctuations with a spectrum of equal amplitude on all scales as might be expected from quantum fluctuations at the end of inflation (see discussion in ref. 27 or ref. 28), and (2) CDM. Although the model is known simply as the “cold dark matter model,” it is important to remember that a critical (and perhaps fatal) part of this model is actually its assumption about the nature of the seeds. (The model also requires something known as “biasing” so that only a small fraction of the baryons ends up in shining regions). The alternative of random density fluctuations with HDM fails because it doesn’t produce “small” objects like galaxies fast enough. We will see that a similar problem may occur for the CDM model, given the recent observations of large numbers of high redshift objects. However, HDM (and CDM) can avoid this problem if the seeds are topological (or if there is a late-time phase transition).

## Large-Scale Structure Observations

Let us now turn to the actual large-scale structure observations which, we hope, will select among the different models. (It is worth noting that other than for these recent large-scale structure observations, the CDM model with random fluctuation seeds has done a remarkably good job of explaining most extragalactic observations, including the basic observed properties of individual galaxies. Even bizarre “cosmologies” which fail to fit the 3K background or light element abundances and are designed in an *ad hoc* way to make galaxies [the so-called “plasma cosmology” comes to mind] don’t do as good a job as the CDM model in this regard.)

The key recent observations pertain to the following:

- (1) cosmic background isotropy;
- (2) quasars found at large redshifts;
- (3) large coherent velocity flows;
- (4) structures with scales of  $\gtrsim 100 Mpc$ ;
- (5) large correlations of clusters of galaxies.

The first one of these we’ve already noted on Figure 3. While the present limits marginally allow structures to form by the present epoch, it is clear that if the limit gets pushed down much further, no model with primordial density fluctuations will survive<sup>29</sup> (unless the power on large scales is truncated completely).

If the fluctuation amplitude on different scales is expressed as a Fourier co-efficient,  $\delta_k$  (where  $K$  is the inverse of the lengthy scale being considered), then we can express various power spectra using  $\delta_k^2 = k^n$  (see ref. 24). The Harrison-Zeldovich-equal-power-on-all-scales spectrum has  $n = 1$ . Present microwave limits seem to require  $n \gtrsim 0.5$  (or that all  $\delta_k$  for present scales  $\gtrsim 100 Mpc$  be set to zero). The current temperature variation limits when observing in different directions are at the level of a couple parts in  $10^5$  (which

translates into the density fluctuation limits shown in Figure 3 and  $n \gtrsim 0.5$ ). The Cosmic Background Explorer (COBE) satellite expects to push the limit down to about 5 parts in a million, which should be able to test  $n = 1$ . Furthermore, independent cosmic radiation studies to be carried out at the South Pole by a Chicago-Princeton team and by a University of California team expect eventually to push the limit down to a single part in a million. This should either see something or force us to a late generation of seeds.

Pushing the opposite direction on the “zone of mystery” epoch between the background radiation and the existence of objects at high redshift is the discovery of objects at higher and higher redshift. The higher the redshift of objects found, the harder it is to have the linear growth of Figure 3 explain their existence. A few high redshift objects could be dismissed as statistical fluctuations if the bulk of objects still formed late, but we may already be running into problems. In the last year, the number of quasars with redshifts  $> 4$  has gone to 30, with one having a redshift<sup>30</sup> as large as 4.9. Furthermore, there appears to be no significant intergalactic gas near these quasars. Thus, either the bulk of the gas has already been incorporated into objects (contrary to the linear growth picture) or the gas has somehow been heated and/or kept hot enough to be ionized (but not so hot as to emit observable x-rays).

The large velocity flows have already been discussed with regard to the implication of  $\Omega = 1$  on scales of  $\sim 100$  Mpc. To generate structures as large as the Great Attractor and the associated high velocity flows on those scales can be a problem since it tends to require large amplitude fluctuations if the seeds are random fluctuations but the CBR limits go in the opposite direction.

The large-scale observations which have gotten the most publicity recently are the direct maps of the large structures in the universe.<sup>31</sup> In particular, note that the CfA maps show objects such as the “Great Wall” which stretch for over 100 Mpc. Furthermore, the deep pencil beam surveys of Broadhurst, Ellis, Koo and Szalay<sup>32</sup> (see Figure 4) show that the great walls appear to be ubiquitous in the universe and may have a quasi-regular spacing of about 100 Mpc. Thus, again we see indications of significant structure on scales of about 100 Mpc.

While these maps certainly show us large-scale structure in a graphic way, the question up until last year had been “what’s the statistical significance?” In other words, could these big things be relatively rare statistical flukes or are they common? Random seed models with CDM and a spectrum that has equal size fluctuations on all scales ( $n = 1$ ) can give occasional large structures, but was there more “power” on large scales than such a spectrum could yield. The answer to this latter question has come from some new large surveys of galaxy positions. In particular, the Automatic Plate Measuring (APM) survey headed by Efsthathiou of Oxford and the Queen Mary-Durham-Oxford-Toronto (QDOT) survey of IRAS galaxies<sup>33</sup> and the 2nd Palomar sky survey (POSS II) analysis of Picard<sup>34</sup> all now have statistically significant samples that show that indeed there is more power on large scales than can be accommodated by the Harrison-Zeldovich seed spectrum assumed in the so-called CDM model (see Figure 5). In fact, these surveys seem to require  $n \lesssim 0.5$ . Note that it is the seed part of the model that is having difficulties, not the matter itself. While the limits on  $n$  from the structure and the microwave background might still be marginally fit at  $n \sim 0.5$ , it looks like the days of a simple, single power spectrum with primordial gaussian fluctuations may be almost over.

Of course, a complete, statistically significant mapping out of the structures requires

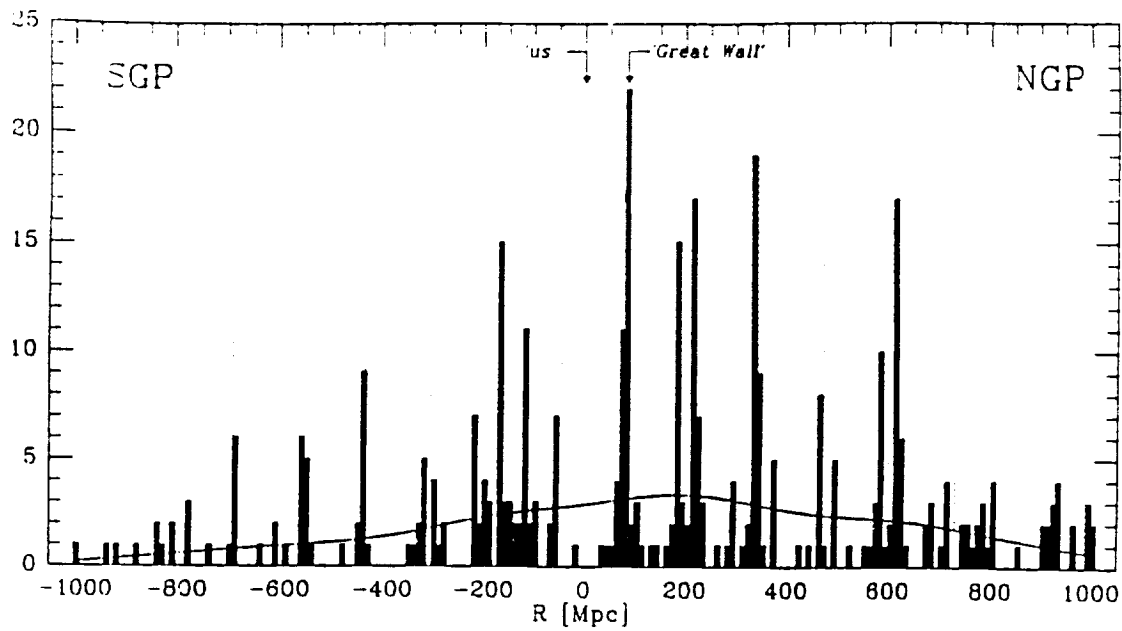


Figure 4. Data from the pencil beam surveys of Broadhurst, Ellis, Koo and Szalay using the Anglo-Australian Telescope for the South Galactic Pole (SGP) pencil and the Kitt Peak Telescope for the North Galactic Pole (NGP) pencil. The plot shows numbers of galaxies versus distance. The solid line and shaded region would be a random distribution of galaxies. The spikes appear to show the pencil penetrating walls of galaxies. The average spacing of the spikes is about 130 Mpc.<sup>32</sup>

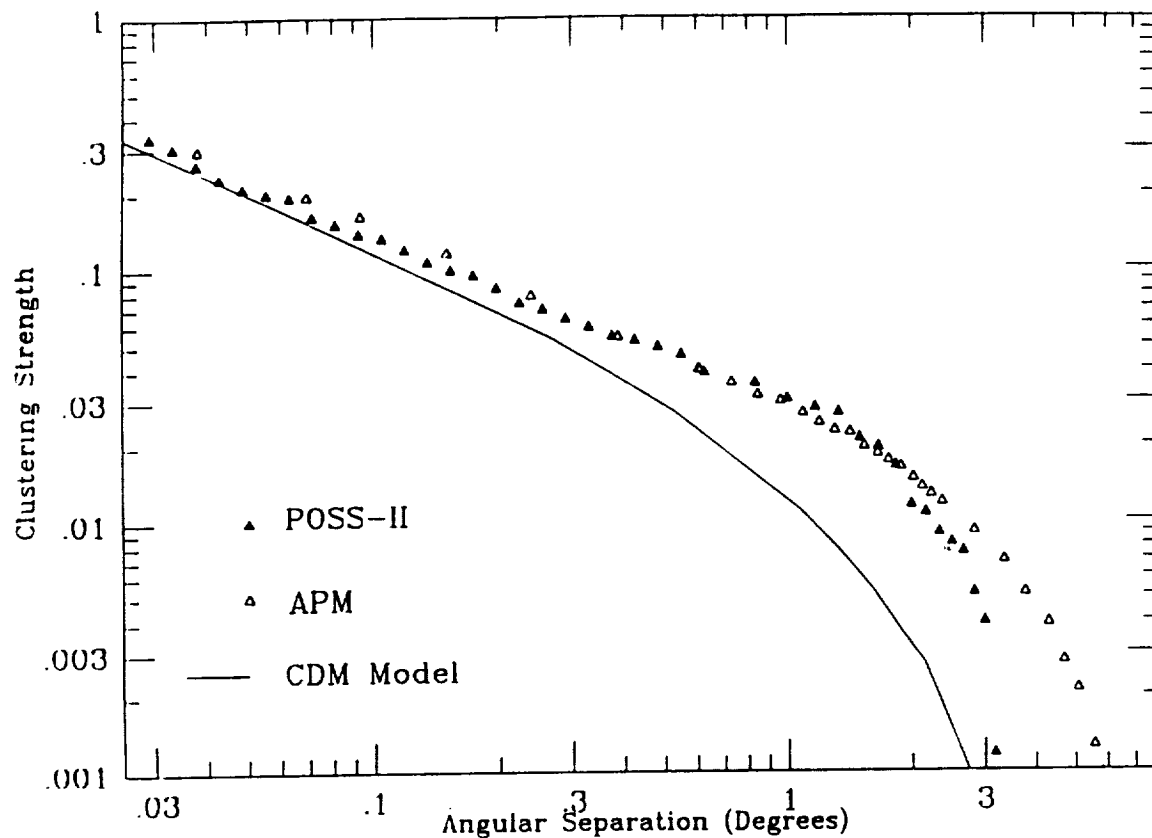


Figure 5. Galaxy clustering strength versus angular separation for the second Palomar Sky Survey (POSS-II)<sup>34</sup> and Automatic Plate Measuring (APM) Survey.<sup>33</sup> Solid curve shows prediction of Cold Dark Matter (CDM) theoretical model with a flat  $n = 1$  gaussian initial fluctuation spectrum.

the three dimensional positions of far more galaxies than any of the current surveys provide ( $\sim 10,000$  at most). The University of Chicago, Princeton University, the Institute for Advanced Study and Fermilab are now building a dedicated telescope which will get the three dimensional positions of a million galaxies and thus, to some extent, fill in the pencil beams to see how regular the structures really are.

The last large-scale structure item to be discussed is the apparent predilection that clusters of galaxies have to be near each other rather than randomly distributed. In fact, Bahcall and Soneira<sup>35</sup> showed that it is more likely to find a cluster near another cluster than a galaxy near another galaxy. If gravity alone is responsible for the grouping, this sounds backwards. The average density of galaxies is higher and the distance to move is smaller to get clumping. Thus, if gravity alone were at play, then clusters should not be so strongly correlated with each other. At first, people tried to get around this point by arguing that projection effects might explain it. However, recent work by West and van den Bergh<sup>36</sup> attempted to surmount this problem using *cD* galaxies that are found at the centers of these clusters, and they found that the *cD*'s are strongly correlated. However, Efstathiou *et al.*,<sup>37</sup> using the APM data, do not find as strong a correlation as Bahcall and Soneira, although they still seem to find more power on large scales than a flat ( $n = 1$ ), random seed spectrum would give. Complete resolution will require the new million-galaxy surveys or with cluster correlations using clusters identified by their x-ray emission from the ROSAT and AXAF satellites. If correlations are stronger than random, then we would have to conclude that galaxies and clusters do not form from just random seeds and gravity but, instead, the seeds are laid out in some pattern.<sup>38</sup> A pattern is exactly what topological defect models tend to predict.

## Conclusion

Galaxy and structure formation is obviously a very active field. By necessity, the models work in the Big Bang framework. The details for the models all invoke new fundamental physics, both for the generation of seeds and for the non-baryonic dark matter. Which new physics is right remains to be seen. The model with CDM and random seeds was the front runner, but it is running into problems with the new large-scale structure observations. However, variants on this model, putting higher amplitude fluctuations on large scales (but truncating the still larger scales to avoid anisotropy problems), may still survive. Other models with late phase transitions generating the seeds or with topological defects as seeds are also looking quite attractive. These latter models may work with either HDM or CDM.

Fortunately, in the near future, a battery of experiments and observations will be carried out which should resolve the problem. In addition to the million galaxy maps, the improved CBR limits and the x-ray satellite observations, we will also profit by the new large ground telescopes and HST observations of galaxies near the time of their formation. Furthermore, new dedicated telescopes are being developed to search for dark baryonic matter in the Galactic Halo, using gravitational microlensing techniques. (It is interesting that the move towards more and more dedicated rather than general purpose telescopes is the direction being taken for cosmological problems). But cosmology is no longer tackled with telescopes alone. Experimental particle physicists have also gotten in the game.

Direct search experiments are being built to try to detect WIMPS and axions. Also, new accelerator experiments, including the SSC and LHC, will put new, tighter constraints on WIMPS, and the upgrade at Fermilab may find the mass of the tau neutrino through its mixing with other neutrinos. Many of these questions should be resolved before the end of the decade.

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such as brown dwarfs and jupiters (objects with  $\lesssim 0.08M_{\odot}$  so they are not bright shining stars), or in black holes (which at the time of nucleosynthesis would have been baryons). Or, if the baryonic dark matter is not in the halo, it could be in hot intergalactic gas, hot enough not to show absorption lines, but not so hot as to be seen in x-rays. Evidence for some hot gas is found in clusters of galaxies. However, the amount of gas in clusters would not be enough to make up the entire non-visible baryonic matter. Another possible hiding place for the dark baryons would be failed galaxies, large clumps of baryons that condense gravitationally but did not produce stars.

The more exotic non-baryonic dark matter can be divided into two major categories for cosmological purposes: hot dark matter (HDM) and cold dark matter (CDM). Hot dark matter is matter that is moving near the speed of light until just before the epoch of galaxy formation, the best example being low mass neutrinos with  $m_{\nu}c^2 \sim 25\text{eV}$ . Cold dark matter is matter that is moving slowly at the epoch of galaxy formation. Because it is moving slowly, it can clump on very small scales, whereas HDM tends to have more difficulty in being confined on small scales. Examples of CDM could be massive neutrino-like particles with masses greater than several times the mass of a proton or the lightest super-symmetric particle which is presumed to be stable and might also have a mass of several GeV. Following Michael Turner, all such Weakly Interacting Massive Particles are called “WIMPS” and, in the case of the supersymmetric candidates, they are also referred to “neutralinos” or “INOS” for short. Axions are very light but would also be moving very slowly and, thus, would clump on small scales. Or, for CDM, there are non-elementary particle candidates, such as planetary mass blackholes or “nuggets” of strange quark matter. Note that CDM would clump in halos, thus requiring the dark baryonic matter to be out between galaxies, whereas HDM would allow baryonic halos. Table 1 summarizes the various dark matter candidates, both baryonic and non-baryonic.

A few years ago the favorite dark matter candidate was probably a few GeV mass WIMP. However, the lack of discovery of any new particles in the high energy collider experiments now means that the only massive particles which could serve as CDM must have masses greater than about 20GeV and interactions weaker than that of a neutrino.<sup>20</sup> While discussing dark matter candidates, it is worth noting that recent hints from new solar neutrino observations suggest that neutrinos may indeed have small masses.<sup>21</sup> Although the mass directly implied is too small to yield  $\Omega$  of unity, reasonable “see-saw” scaling of the results to the less constrained tau neutrino would put its mass in the range where it could yield  $\Omega$  of unity.<sup>22</sup> This has created a renewed interest in HDM models.

## Seeds for Making Structure

In addition to matter, all models for making galaxies and larger structures require some sort of “seeds” to stimulate the matter to clump. The seeds can be divided into two generic categories:

- (a) Random Density Fluctuations; and
- (b) Topological Defects (cosmic strings, walls, textures, etc.).

Both random density fluctuations and topological defects are assumed to be generated by some sort of vacuum phase transition in the early universe. A familiar phase transition is water freezing to ice; the little white lines in an ice cube are equivalent to topological

Table 1

MATTER

Baryonic (  $\Omega_b \sim 0.06$  )

VISIBLE  $\Omega_{vis} \lesssim 0.01$

DARK

Halo

Jupiters

Brown Dwarfs

Stellar Black Holes

Intergalactic

Hot gas at  $T \sim 10^5 K$

Stillborn Galaxies

Non Baryonic (  $\Omega_{nb} \sim 0.94$  )

HOT

$m_{\nu_\tau} \sim 25 eV$

COLD

WIMPS/Inos  $\sim 100 GeV$

Axions  $\sim 10^{-5} eV$

Planetary Mass Black Holes



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