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TESTS OF THE PARTICLE PHYSICS-PHYSICAL COSMOLOGY INTERFACE *

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Abstract

Three interrelated interfaces of particle physics and physical cosmology are discussed: (1) inflation and other phase transitions; (2) Big Bang Nucleosynthesis (and also the quark-hadron transition); and (3) structure formation (including dark matter). Recent observations that affect each of these topics are discussed. Topic number 1 is shown to be consistent with the COBE observations but not proven and it may be having problems with some age-expansion data. Topic number 2 has now been well-tested and is an established "pillar" of the Big Bang. Topic number 3 is the prime arena of current physical cosmological activity. Experiments to resolve the current exciting, but still ambiguous, situation following the COBE results are discussed.

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1. Introduction

The particle-cosmology interface has grown over the last decade to become one of the most exciting and active areas of all of physical science. Rather than attempt to review the entire field, this paper will focus on three very active areas at the interface of particle physics with physical cosmology—physical cosmology being defined here as that subset of cosmological problems which have experimentally testable consequences (experimentally testable in our lifetime!).

The three topics that are chosen are:

(1) Inflation,

(2) Big Bang Nucleosynthesis (BBN),

(3) Cosmic Structure Formation.

These three topics are intimately and symbiotically interrelated and all three have been affected profoundly by recent experiments and astrophysical observations. In particular, we will discuss the impact of the COBE anisotropy measurements on inflation and on structure formation. We will note the current potential problem of the age-expansion relations for inflations. And we will note the recent ^{6}Li measurement along with the LEP neutrino counting results which give even greater confidence in the standard BBN model which has now become one of the three principle pillars of the Big Bang itself. Of course, one critical prediction of BBN is that the baryon density is low so that the critical density universe required by inflations mandates non-baryonic dark matter. This latter point unites all three of our topics.

2. Inflation

It us well known (c.f. Linde 1990, Kolb and Turner, 1990) that inflation (Guth 1981, Albrecht and Steinhardt 1982, Linde 1982) predicts a flat universe and produces gaussian density fluctuations with a power spectrum

$$(\frac{\delta\rho}{\rho})^2_k \sim k^n \text{ with } n \sim 1$$

where k is the wave number of the fluctuation ($k \equiv 2\pi/L$ where L is the length scale). Standard inflation yields the flat, $n = 1$, Harrison-Zeldovich spectrum with equal power on all scales. However, variants such as "natural inflation" (Freese, Frieman, and Olinto, 1990) can yield a "tilted" spectrum with n slightly less than unity.

The recent COBE results (Wright et al. 1992, Smoot et al. 1992) are certainly consistent with a gaussian spectrum and thus yield

$$n = 1.2^{+0.5}_{-0.6}$$

which is also consistent with a flat spectrum (or a slightly tilted one). Furthermore, since COBE observes fluctuations only on large angular scales, $\theta \gtrsim 7°$, which are outside the causal horizon ($\theta \sim 2°$) at the time of radiation decoupling, the observed fluctuations do support the need for inflation or something like it. In fact, minimal fluctuations, which exist only on the scales where galaxies and structures are seen, would naively add together in an incoherent manner on larger scales and would thus yield a power spectrum of $\sim k^4$. Therefore, COBE is telling us that the primordial spectrum is not just a superposition of the fluctuations that specifically made galaxies, clusters, etc., but that some larger scale primordial fluctuations did indeed exist. Whether or not some additional small scale (non-gaussian?) seeds also existed remains to be seen, but there is no question that COBE is consistent with inflation.

This consistency is a necessary but not sufficient statement. The idea of a flat $n = 1$ spectrum existed prior to the inflation idea. Obtaining such a spectrum then may not be unique to inflation. Another necessary but not sufficient prediction of inflation is a flat universe, which, in its most natural mode, is just saying $\Omega = 1$. This prediction has gained support recently from the large scale velocity flow data (Dekel, Bertschinger et al. 1993, Fisher et al. 1993) from the IRAS survey and the Great Attractor and potent work which seems to require $\Omega \sim 1$ and appears inconsistent with $\Omega \lesssim 0.3$. A further hint in this direction comes from the recent angular size versus redshift work of Kellerman (1993) (see Figure 1) which is best fit by a flat universe, although evolutionary effects could alter such a conclusion (Krauss and Schramm 1993). The one potential cloud on the inflationary horizon is the value of the Hubble constant. Recall that the age of the universe is $t = \frac{2}{3H_0}$ for an $\Omega = 1$, matter-dominated universe. But globular cluster ages are best fit by $t_{GC} = 15 \pm 3$ Gyr (Schramm 1990, Deliyannis et al. 1992). Although recently Dearborn and Schramm (1993) have argured that mass loss to fit a subset of the Pop II Li observations would create a downward shift of ~ 2 Gyr, nonetheless t_{GC} can still be fit only by an $\Omega = 1$ universe if $H_0 \lesssim 60$ km/sec/Mpc. (There is also a firm lower bound on t from nuclear chronology (Schramm 1990), $t > 10$ Gyr.) Thus, if astronomers determine a large H_0, then there is a problem with $\Omega = 1$. The simplest loophole of adding a cosmological constant to keep the universe flat may still be allowed but only if the large scale velocity flow data and the angular size data are shown to be wrong. The cosmological constant also has the repugnanace that its invocation today requires tuning at the level of $\sim 10^{-121}$.

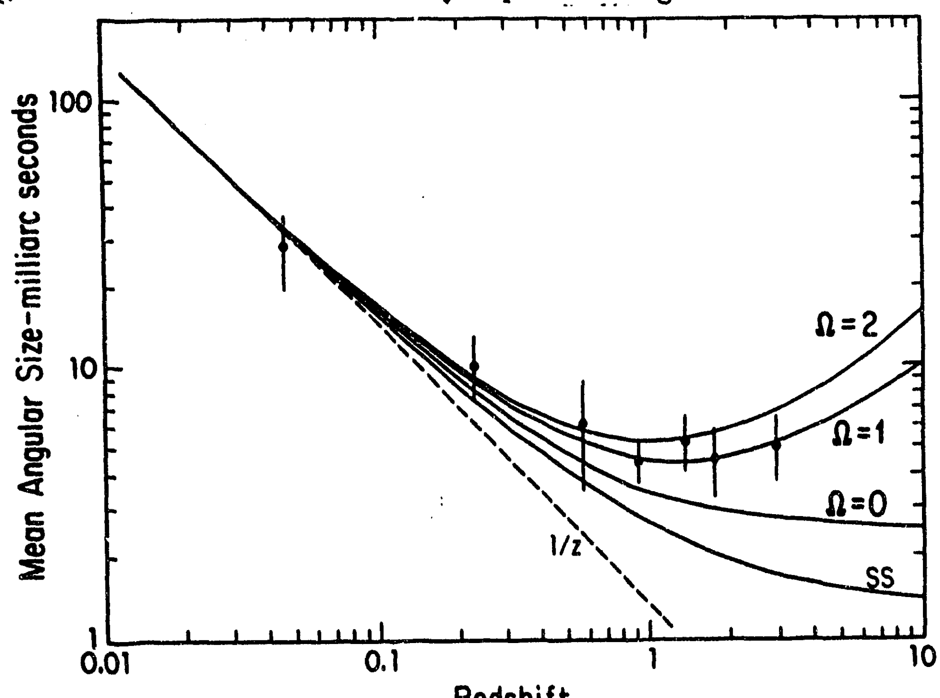

Figure 1. This is the recent angular size test performed using compact radio jets measured with very long baseline interferometry. The graph is from Ken Kellerman of the National Radio Astronomy Observatory.

At present, the various techniques for determining H_0 fall into two distinct clumps, with most of the empirically calibrated astronomical methods yielding $H_0 \sim 85$ and most of the physically derived but statistically poorer techniques yielding $H_0 \sim 50$. Obviously, inflation favors the $H_0 \sim 50$ camp, but only the future will truly decide.

3. Big Bang Nucleosynthesis

The third pillar of the Big Bang (after the Hubble expansion and the microwave background) comes from the light element abundance measurements and, most recently, the measurement at LEP of the number of families of neutrinos. In particular, the Big Bang predicts (Walker et al. 1991 and references therein) that when the universe was at a temperature of $\sim$ 10 billion degrees and was about one second old, it should have started nuclear processes that would eventually yield certain well-specified abundances for the light isotopes (see Table 1). The abundances of these light elements have all been accurately determined to be in impressive agreement with the Big Bang predictions to the accuracy of the measurements. Of special interest is that even the one part in 10 billion for lithium works. Furthermore, the Big Bang predicted that the abundances would fit well only if there were no more than three families of neutrinos, and that was exactly what was observed at LEP. Thus, as is frequently emphasized, the Big Bang has made a variety of detailed predictions based on the nature of the universe at $\sim$ 1 sec, and the predictions have been confirmed by observation and experiment.

TABLE 1
Light Element Abundances

Element (isotope)	Predicted Primordial Abundance	When Observed
^{1}H	$\sim$76% by mass	1960's
^{4}He	$\sim$24% by mass	1960's
^{2}H/H	2×10^{-5}	1970's
^{7}Li/H	10^{-10}	1980's
Neutrinos	$N_\nu = 3$	1990

A recent detection of ^{6}Li in a metal-poor star (Smith, Lambert and Nissen 1993) has confirmed that the Spite Lithium Plateau is probably not the result of stellar depletion but is a true measurement for the primordial value (Olive and Schramm 1992). This gives us even greater confidence in the basic BBN arguments and we can use the Li constraint as well as the D and ^{3}He constraint on the density. The light elements with abundances, ranging from $\sim$ 76% for hydrogen to one part in 10^{10} for lithium, all fit with the cosmological predictions, with the one adjustable parameter being the baryon density,

$$\Omega_B \sim 0.05 \pm 0.03.$$

Thus, if one prefers a universe with $\Omega_{TOTAL} = 1$, one must also demand that the bulk of the matter in the universe (greater than 90%) be something other than baryons.

Recent attempts to find alternatives to this conclusion by introducing an inhomogeneous baryon distribution at the nucleosynthesis epoch have ended up reaching essentially the same constraint on Ω_B as in the standard homogeneous model (Kurki-Suonio et al. 1990).

The baryon density, Ω_B, deduced from the abundances of light elements is within the range of dynamical estimates of the mean mass density in and around the bright parts of galaxies, including the dark massive halos associated with galaxies (Gott and Turner 1976, Gott, Gunn, Schramm and Tinsley 1974) (see Figure 2). The IRAS/GA point mentioned in the previous section shows that we are beginning to have some experimental/observational evidence that Ω_{TOTAL} exceeds Ω_B and that some non-baryonic dark matter is truly needed.

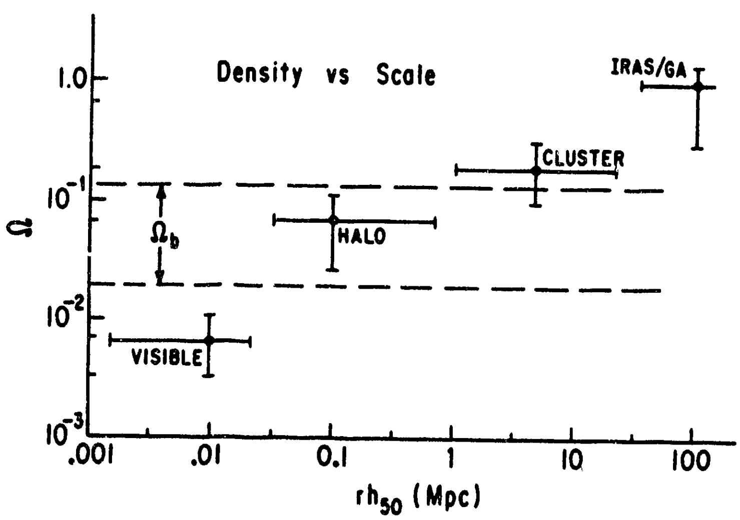

Figure 2. The density paramater Ω versus the scale on which it is determined. Note that the baryon density is consistent with galactic halo densities but exceeds visible matter densities. Note also that only on the largest scales is there any hint that Ω exceeds Ω_B.

An interesting additional bit of information on the distribution and relative proportions of matter in the universe has come from the ROSAT x-ray satellite. In particular, Mushotzky (1992) has shown that rich clusters of galaxies have a mass fraction, $\sim 0.3h_{50}^{-3/2}$, of hot x-ray gas. Since $\Omega_{cluster} \sim 0.2$, this yields $\Omega_{baryon} \sim 0.06$ for these clusters in reasonable agreement with BBN (but only for $h_{50} = H_0/50 \sim 1$). However, such a high ratio of baryons to non-baryons in rich clusters and yet an overall low cosmic average would imply that even on the scale of clusters, baryons are preferentially being selected. Such selection is not present in most models for cluster formation and may turn out to be an important discriminator of structure formation models.

4. Cosmic Structure Formation

To make the observed objects in the universe such as galaxies, clusters, stars, planets and people requires something beyond just some combination of baryons and hot and/or cold exotic dark matter. There also had to be some "seeds" to get the matter, both baryonic and exotic, to begin clumping in some fashion. Having additional exotic matter does help accelerate the clumping process to form observable lumps, but all models require some sort of "seed" or density fluctuation to get from the smooth, early universe to the lumpy universe in which we live today. All seeds that are capable of producing the observed objects, even the most carefully contrived ones, inevitably induce fluctuations in the microwave background on different angular scales at the minimal level of $\sim 10^{-6}$ and in most cases at the level of $\sim 10^{-5}$. (This is sometimes noted with the analogy that "you can't make an omelet without cracking eggs." i.e., you can't make galaxies without disturbing the microwave background.)

A "model" consists of some assumption about the seeds and some assumptions about Ω_B plus Ω_{HDM} plus Ω_{CDM} and, for some people, assumptions about Λ. (HDM and CDM refer to hot and cold non-baryonic dark matter, hot being rapidly moving at galaxy formation and cold being slow at that epoch.)

Table 2

Seeds for Structure Formation and Minimal Microwave Anisotropy

Seed	$\frac{\delta T}{T}$
Density Fluctuations [Quantum Gaussian Fluctuations From the End of Inflation]	$\geq 6 \times 10^{-6}$
Topological Defects* [structures form directly in cosmic phase transitions]	
A. "Cosmic Strings" from early phase transitions before decoupling of the cosmic background	$\gtrsim 5 \times 10^{-6}$
B. Defects from "late-time transitions" after decoupling	$\gtrsim 1 \times 10^{-6}$

*For topological defects, the fluctuations are not "randomly" distributed, so statistics on the average $\frac{\delta T}{T}$ do not directly apply.

Table 2 summarizes the minimal predictions for some different possible "seeds." Note that these minimal predictions are actually below the level that the DMR (Differential Microwave Radiometer) experiment (Wright et al. 1992, Smoot et al. 1992) on COBE detected: $\frac{\delta T}{T} \sim 10^{-5}$. This brings to mind two points. The first is that if COBE had failed to detect a signal, it would not yet have caused a serious problem since models existed which could generate structure with smaller values of $\frac{\delta T}{T}$ than COBE was capable of measuring. The second is that we are very lucky that the DMR experiment was so well-designed that it could reach the level of sensitivity of 10^{-5}. At the time COBE was proposed 20 years ago, theories focused on anisotropy values near 10^{-3}. Fortunately, COBE was not designed to check just the in-vogue theories of the times, but went as far as it could go technically.

The general cause of the microwave fluctuations in apparent temperature from density fluctuations is merely gravity. If the density is higher than the average, then the gravitational field is higher and hence the background radiation climbing out of that higher potential well will be redshifted. (Note that regions of high density which eventually form structure would have produced temperature fluctuations to the low side, whereas low density fluctuations would yield "hot spots.") Different structure formation models have different distributions of the gravitational seeds or density fluctuations and hence predict different patterns and amplitudes for the temperature variations.

An additional difference between models is the relative size of fluctuations on different angular scales. For example, the density fluctuation model with CDM and $h = 1$ tends to predict a distribution something like Figure 3.

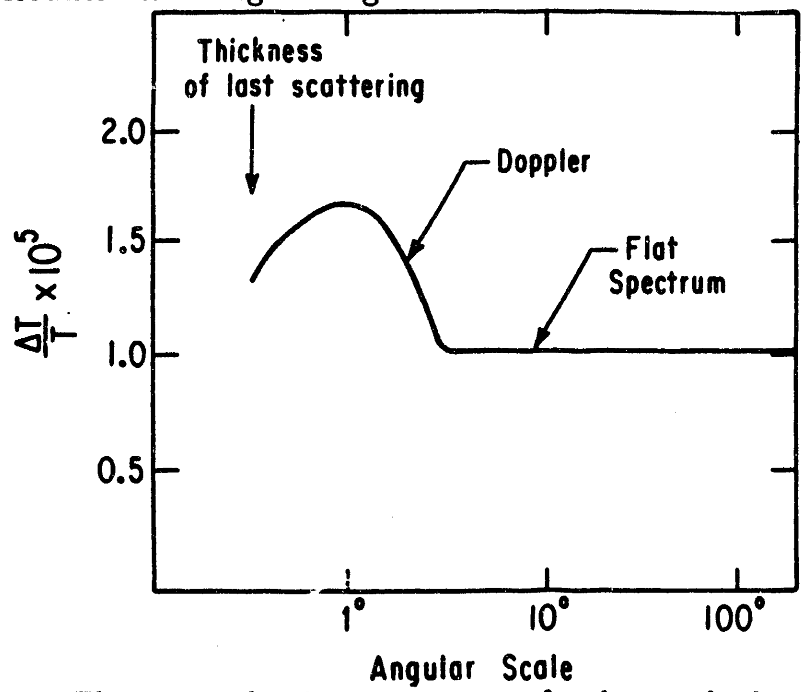

Figure 3. The expected anisotropy pattern for the standard gaussian flat density fluctuation model.

Note in Figure 3 that the flat spectrum does directly yield a "flat" prediction for large angles, but as the angular separation gets down to $\sim 2°$, the expected level of fluctations increases. As mentioned earlier, this is the angular size today of material that could be "causally connected" at the time the background radiation last interacted with matter. Since causally connected material could be influenced by the other material in that volume, significant motion and structure formation cannot occur on distance scales beyond the causally connected scale. Matter within the causally connected region is moving in a significant way and hence can create additional disturbances of the background radiation via the Doppler effect. On very small scales, the fluctuations in the radiation will get smeared out to uniformity due to the fact that the time, temperature and density of the last scattering of the photons with the matter is not a single, unique point but is spread out in these parameters. This causes the expected microwave anisotropy to be less on scales smaller than about 8 minutes of arc.

As mentioned earlier, the COBE measurement is consistent with a $n \sim 1$ spectrum with

$$\frac{\delta T}{T} \sim 10^{-5}$$

for angular scales from 7° to 180°.

Of course, no scientific observation is believable until it is checked. Fortunately, the large scale COBE anisotropy has now been dramatically checked by a balloon experiment designed and built by a collaboration led by Stephan Meyer (1992) of MIT (and Chicago). Their balloon mission also measured the anisotropy at large angular scales, and they found an anisotropy that both correlated with the directions of the COBE data and also had about the same size fluctuations. This dramatic confirmation means that we now seem to know that there really were primordial fluctuations on large angular scales. This has been further confirmed by the 2nd year of COBE data which shows essentially the same result as the first year, but with better statistics (Wright 1992).

With the large angular scales now relatively fixed (to experimental accuracy), attention has now turned to the smaller angular scales that directly correspond to the scales that eventually formed galaxies, clusters, etc. An important test is to see if the anisotropies do look like Figure 3 or if there is some other sort of behavior occurring at the smaller angular scales which affects structure formation. Of course, it is also important to see how "flat" the large angular scale anisotropy is since slightly "tilted" anisotropies which favor large or small scales can also be produced in some models and could still be allowed by the COBE measurements. One also would like to know how gaussian are the anisotropies at a given angular scale. For example, the topological seed models, while also predicting anisotropies, expect to have special characteristic spatial patterns rather than a purely random distribution. Luo and Schramm (1993) have presented tests for gaussianity.

Two groups recently announced somewhat ambiguous results about the 1-to-2 degree scale anisotropies. One of the groups (Lubin et al. 1992), led by Lubin of UC Santa Cruz, reported results from their previous year's South Pole observations. The second group, known as the MAX collaboration (1992), reported on their balloon-borne measurements. Each group reported that there were anisotropies observed at levels not too different from that predicted by Figure 3, although the relative levels reported were not uniform in all directions, hinting either to non-gaussianity or to source contamindation, but the error bars are also still quite large when fit to COBE's large angle data. Hopefully, with more South Pole and balloon data, the important 1-to-2 degree scales will be unabiguously mapped out in the near future. All microwave data on these scales can be directly compared with how galaxies cluster on the equivalent scales.

Several major surveys of the 3-dimensional positions of galaxies have mapped out some interesting nearby structure. For example, the Center for Astrophysics (Vogeley et al. 1992) survey has found a "Great Wall" of galaxies stretching for about 150 Mpc, and the APM survey (Peacock, Efstathiou et al. 1991) have also found evidence for very large structures of galaxies.

One general feature of all of these galaxy surveys is that they seem to find more really big structures than might have been estimated if galaxies were randomly distributed and if the mass of the systems really traced the emitted light. However, many have argued that it is possible that light is not a good tracer of the underlying mass distribution. Such a shift between light and mass distributions (biasing) makes it difficult to compare unambiguously galaxy distributions with theories. Furthermore, different types of galaxies (or clusters) may have different biasing factors and, at present, the statistics on large separations are poor since the numbers of objects studied is limiting. This latter point should be alleviated with the Sloan Digital Sky Survey (a Chicago-Princeton-Fermilab-Johns Hopkins-Japanese collaboration) when the 3-D positions for about a million galaxies will be determined (as contrasted with current surveys that see at most about ten thousand).

One way of comparing the microwave anisotropy data with the galaxy data is to look at the relative power implied on different separation scales. Because of the horizon cut-off, it is expected with flat gaussian density seeds that the power will peak on scales of about 1 or 2 degrees (see Figure 4) which today would correspond to distance scales of a few hundred Mpc. The dotted line in Figure 4 shows this behavior. The absolute amplitude of the initial fluctuations is very uncertain so the dotted curve is free to be moved up or down. For Figure 4, it has been fixed by the additional requirement that it fit the large scale data of COBE. The curves for the different galaxy surveys may be moved up or down, but not left or right via biasing and/or selection effects. Note that if the dotted curve is made to fit the small scale end of the galaxy data, then the large scale end doesn't fit. Note also that if we use the COBE fit at large scales and fit the IRAS or APM data at a couple of hundred Mpc, then the small scale IRAS and APM data falls below the dotted curve. Thus, no simple constant biasing can enable the dotted curve to work. Furthermore, there are hints from the radio galaxy (Peacock and Nicholson 1991) and cluster data (Bahcall and Bugett 1986) that there may be even more power near 100 to 200 Mpc, although the uncertainties are large and biasing may move the points coherently up and down.

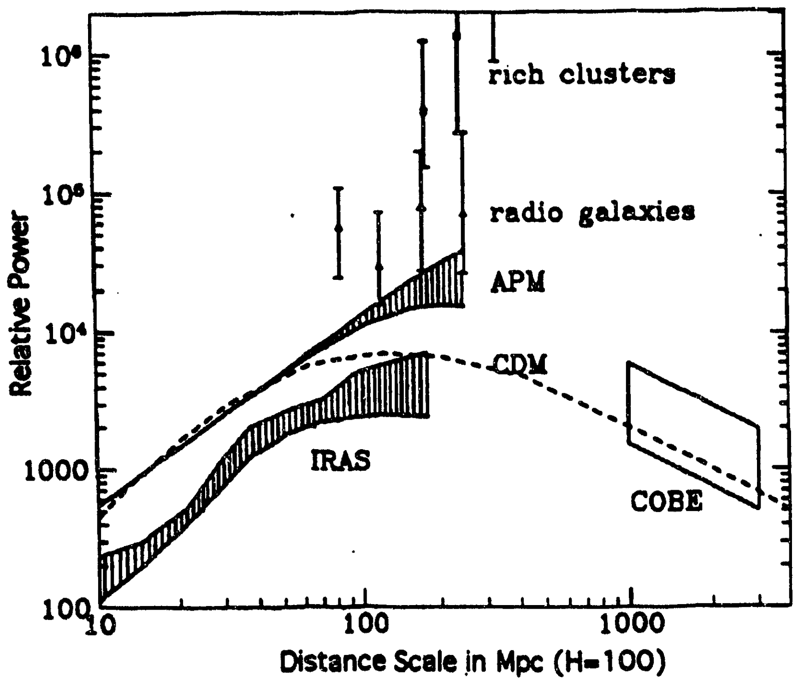

Figure 4. The relative power of producing structures on different scales. The dotted curve is for a traditional CDM model with gaussian density seeds. The galaxy data from different samples can be moved up and down via biasing and/or selection effects but the shapes are fixed. This figure was prepared by Jean Quashnock of the University of Chicago.

This conflict with the simple "CDM model" of an $n = 1$, gaussian density seed spectrum with CDM and constant biasing has led to several alternatives, all designed to fit the COBE data on large scales and the shape of the galaxy data on smaller scales. The possible models are shown in Table 3. As seen from the table, the surviving models each involve some assumptions beyond or instead of the traditional CDM constant biased model. For example, one can retain the gaussian density fluctuation picture by either adding a variable scale dependent biasing (that goes negative at small scales!), or by adding some HDM to smooth out the small scale fluctuations and thereby decrease the small scale power, or by tilting the initial spectrum enough to fit the small scales but not violate the COBE error box. Another alternative is to go to topological defects. These can be either cosmic strings if the defects form in the early universe or almost any defect if the defects form after the microwave radiation decouples, but in this latter case, the COBE spectrum still requires some gaussian primordial fluctuations. The advantages of the defects plus HDM is that they tend to give a larger bump in the power spectrum near the epoch of galaxy formation which leads to an easier fit to the rich cluster and radio galaxy data (although this is the most uncertain part of the structure data and many models choose to ignore it at present).

Table 3

Models After COBE
With Critical Total Density and ~ 5% Baryons

Model Name	Non-Baryonic Dark Matter	Seed Type	Biasing
Modified CDM	CDM	flat-gaussian density	variable, going negative at small scales
Mixed (MDM)	CDM plus HDM	flat-gaussian density	negligible, except for cluster data
Tilted	CDM	slightly tilted spectrum increasing towards large scale	negligible, except for cluster data
Cosmic Strings	HDM	cosmic strings	negligible, may even fit cluster data
Late-Time Phase Transition	HDM	topological defects plus background flat-gaussian density	negligible

Note: models with cosmological constant or pure baryons are excluded here for reasons mentioned previously in text. Also, it is not obvious how many of the above models will fit the cluster x-ray gas analysis of Mushotzky (1992).

A resolution of which of the surviving models is correct (if any) can be accomplished with the next round of experiments and observations. Table 4 lists some key new pieces of information we should have by the end of the decade.

Table 4
Projects to Answer the Unsolved Questions

Topic	Projects
DARK MATTER	
• Baryonic Dark Matter	Gravitational Micro-lensing
• Cold Dark Matter	
-WIMPS	Underground direct searches Accelerator searches
-AXIONS	Direct Searches with Cavity
• Hot Dark Matter	Accelerator Neutrino Mixing
DISTRIBUTION OF GALAXIES	Dedicated Redshift Surveys
GALAXIES AT FORMATION	HST, Keck, AXAF, ROSAT, etc.
MICROWAVE ANISOTROPIES	South Pole, Balloons Future space mapping mission (away from Earth background)

This exciting and rapidly moving field may even come to some resolution of the problem of structure formation in the universe in the not-too-distant future. This resoution will come by an interdisciplinary effort of particle physicsts, nuclear physicists, radio, IR, optical, UV and x-ray astronomers and theorists. It is exciting to be doing cosmology in this "Golden Age" where progress really occurs.

5. Acknowledgements

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6. References

Albrecht, A. and Steinhardt, P.J., 1982, *Phys. Rev. Lett.*, 48, 1220.

Bahcall, J. and Bugett, W., 1986, *ApJ*, 300, L35.

Dearborn, D. and Schramm, D.N., 1993, Fermilab preprint.

Dekel, A., Bertschinger, et al., 1993, *ApJ*, in press.

Delyannis, C. et al., 1992, Yale University preprint.

Fisher, C., Davis, M., Strauss, M., Yahil, A., and Huchra, J., 1993, *ApJ*, in press.

Freese, K., Frieman, J.A., and Olinto, A.V., 1990, *Phys. Rev. Lett*, 65, 3233.

Gott, J.R. and Turner, E.L., 1976, *ApJ*, 209, 1.

Gott, J.R., Gunn, J., Schramm, D., and Tinsley, B., 1974, *ApJ*, 194, 543.

Guth, A., 1981, *Phys. Rev*, D23, 347.

Kellerman, K., 1993, *Nature*, in press.

Kolb, E.W. and Turner, M.S., 1990, *The Early Universe* (Redwood City, CA: Addison-Wesley).

Krauss, L. and Schramm, D.N., 1993, *ApJ*, in press.

Kurki-Suonio, H., Matzner, R., Olive, K., and Schramm, D., 1990, *ApJ*, 353, 406.

Linde, A., 1982, *Phys. Lett.*, 108B, 389.

Linde, A., 1990, *Particle Physics and Inflationary Cosmology* (Chur, Switzerland: Harwood Academic Pub.).

Lubin, P. et al., 1992, Talks at Texas/PASCOS Meeting, Berkeley, CA, December 1992.

Luo, X. and Schramm, D.N., 1993, *ApJ*, in press.

MAX collaboration, 1992, Talks at Texas/PASCOS Meeting, Berkeley, CA, December 1992.

Meyer, S., 1992, Review talk at Texas/PASCOS Meeting, Berkeley, CA, December 1992.

Mushotzky, R., 1992, Review talk at Texas/PASCOS Meeting, Berkeley, CA, December 1992.

Olive, K. and Schramm, D.N., 1992 *Nature*, 360, 434.

Peacock, J.A., Efstathiou, G., et al., 1991, *MNRAS*, 253, 1.

Peacock, J.A. and Nicholson, D., 1991, *MNRAS*, 253, 307.

Schramm, D., 1990, in *Astrophysical Ages and Dating Methods*, eds. Vangioni-Flam, E. et al. (Gif-sur-Yvette, France: Editions Frontières) 365-383.

Smith, V., Lambert, D., and Nissen, R., 1993, *ApJ*, in press.

Smoot, G. et al., 1992, *ApJ*, 396, L1.

Vogeley, M.S., Park, C., Geller, M., and Huchra, J., 1992, *ApJ*, 391, L5.

Walker, T., Steigman, G., Schramm, D., Olive, K., and Kang, H.-S., 1991, *ApJ*, 376, 51.

Wright, E., 1992, Talk at Texas/PASCOS Meeting, Berkeley, CA, December 1992.

Wright, E. et al., 1992, *ApJ*, 396, L13.

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