COSMOLOGY SOLVED? MAYBE.

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Abstract

For two decades the hot big-bang model as been referred to as the standard cosmology – and for good reason. For just as long cosmologists have known that there are fundamental questions that are not answered by the standard cosmology and point to a grander theory. The best candidate for that grander theory is inflation + cold dark matter; it can extend our understanding of the Universe back to 10^{-32} sec. There is now prima facie evidence that supports the two basic tenets of this new paradigm: flat Universe and scale-invariant spectrum of Gaussian density perturbations. An avalanche of high-quality cosmological observations will soon make this case stronger or will break it. If inflation + cold dark matter is correct, then there are new, fundamental questions to be answered, most notably the nature of the dark energy that seems to account for 60% of the critical density and how inflation fits into a unified theory of the forces and particles. These are exciting times in cosmology!

1. 1998, A Memorable Year for Cosmology

The birth of the hot big-bang model dates back to the work of Gamow and his collaborators in the 1940s. The emergence of the hot big-bang as the standard cosmology began in the late 1960s, with the discovery of the microwave background radiation, the establishment of its black-body spectrum, and the success of big-bang nucleosynthesis. By the 1970s, the hot big-bang was being referred to as the standard cosmology. Today, it is well established and provides an accounting of the Universe from a fraction of a second after the beginning when the Universe was a hot, smooth soup of quarks and leptons to the present, some 13 Gyr later. The standard cosmology rests upon three strong observational pillars: the expansion of the Universe; the cosmic microwave background radiation (CBR); and the abundance pattern of the light elements, D, ^{3}He, ^{4}He, and ^{7}Li, produced seconds after the bang (see e.g., Peebles et al, 1991).

The standard cosmology leaves fundamental questions unexplained: the matter/antimatter asymmetry, the origin of the smoothness and flatness of the Universe, the nature and origin of the primeval density inhomogeneities that seeded all the structure in the Universe, the quantity and composition of the dark matter that holds the Universe together, and the nature of the big-bang event itself. This has motivated the search for a more expansive cosmological theory.

In the 1980s, a new paradigm emerged, deeply rooted in fundamental physics with the potential to extend our understanding of the Universe back to 10^{-32} sec and to address the fundamental questions poised by the hot big-bang model. That paradigm, known as inflation + cold dark matter, holds that most of the dark matter consists of slowly moving elementary particles (cold dark matter), that the Universe is flat and that the density perturbations that seeded all the structure seen today arose from quantum mechanical fluctuations on scales of 10^{-23} cm or smaller. It took awhile for the observers and experimentalists to take this theory seriously enough to try to disprove it, and in the 1990s it began to be tested in a serious way.

1998 could prove to be a watershed year in cosmology, as important as 1964, when the CBR was discovered. The crucial new data include a precision measurement of the density of ordinary matter and of the total amount of matter, both derived from a measurement of the primeval deuterium abundance and the theory of BBN; and the first fine-scale (down to 0.3°) measurements of the anisotropy of the CBR; and a measurement of the deceleration of the Universe based upon distance measurements of type Ia supernovae (SNe1a) out to redshift of close to unity. Together, these measurements, which are harbingers for the precision era of cosmology that is coming, provide the first plausible, complete accounting of the matter/energy density in the Universe and evidence that the primeval density perturbations arose from quantum fluctuations during inflation. In addition, there exists a body of evidence in support of the cold dark matter theory of structure formation.

The accounting of matter and energy goes like this (in units of the critical density): light neutrinos, at least 0.3%; bright stars and related material, 0.5%; baryons, 5%; cold dark matter, 35%; and vacuum energy (or something similar), 60%; for a total equalling the critical density (see Fig. 1). The recently measured primeval deuterium abundance (Burles & Tytler, 1998) and the theory of big-bang

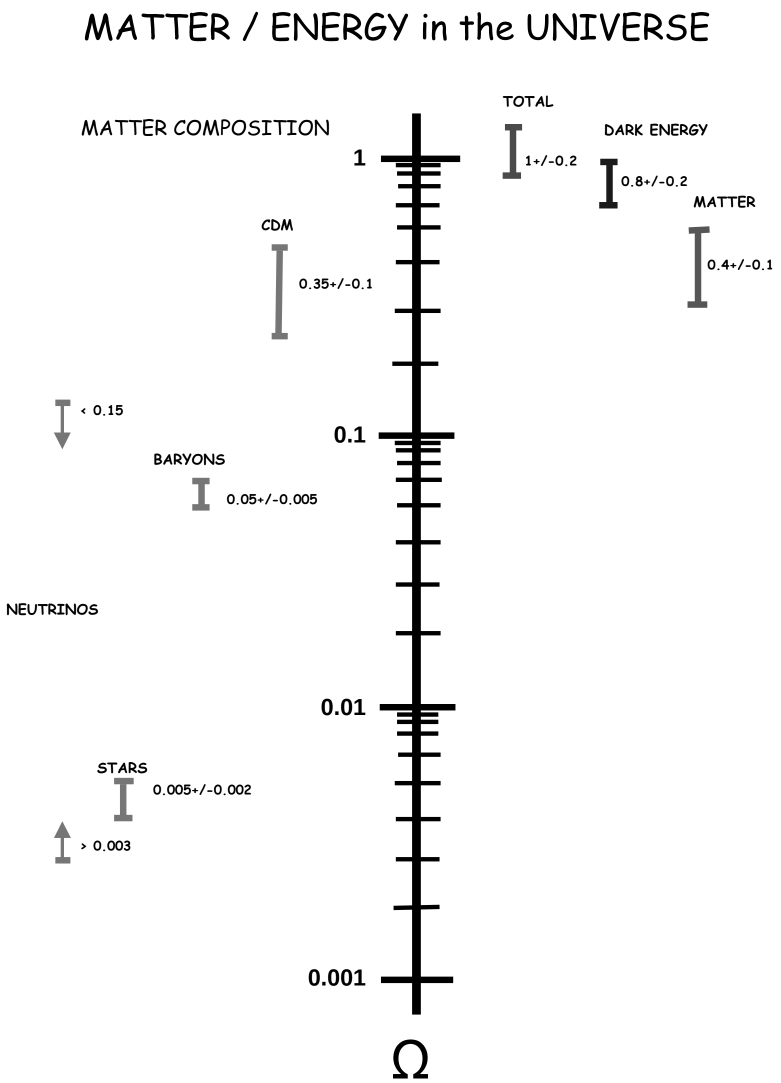

Fig. 1. Summary of matter/energy in the Universe. The right side refers to an overall accounting of matter and energy; the left refers to the composition of the matter component. The upper limit to mass density contributed by neutrinos is based upon the failure of the hot dark matter model and the lower limit follows from the evidence for neutrino oscillations (Fukuda et al, 1998).

nucleosynthesis accurately determine the baryon density (Schramm & Turner, 1998), $\Omega_B = (0.02 \pm 0.002)h^{-2} \simeq 0.05$ (for $h = 0.65$). Using the cluster baryon fraction, determined from x-ray measurements, $f_B = M_{\rm baryon}/M_{\rm TOT} = 0.07 \pm 0.007$ (Evrard, 1996), and assuming that clusters provide a fair sample of matter in the Universe, $\Omega_B/\Omega_M = f_B$, it follows that $\Omega_M = (0.3 \pm 0.05)h^{-1/2} \simeq 0.4 \pm 0.1$. That $\Omega_M \gg \Omega_B$ is strong evidence for nonbaryonic dark matter; the leading candidates are axions, neutralinos and neutrinos.

The position of the first acoustic peak in the angular power spectrum of temperature fluctuations of the CBR is a sensitive indicator of the curvature of the Universe: $l_{\rm peak} \simeq 200/\sqrt{\Omega_0}$, where $R^2_{\rm curv} = H_0^{-2}/|\Omega_0 - 1|$. Measurements now span multipole number $l = 2$ to around $l = 1000$ (see Fig. 2); while the data do not yet speak definitively, it is clear that $\Omega_0 \sim 1$ is preferred. Several experiments have new results around $l = 30 - 300$, and should be reporting them soon. Ultimately, the MAP (launch in 2000) and Planck (launch in 2007) satellites will cover $l = 2$ to $l = 3000$ with precision limited essentially by sampling variance, and should determine Ω_0 to a precision of 1% or better.

The same angular power spectrum that indicates $\Omega_0 \sim 1$ also provides evidence that the primeval density perturbations are of the kind predicted by inflation. The inflation-produced Gaussian curvature fluctuations lead to an angular power spectrum with a series of well defined acoustic peaks. While the data at best define the first peak, they are good enough to exclude models where the density perturbations are isocurvature (e.g., cosmic strings and textures): in these models the predicted spectrum is devoid of acoustic peaks (Allen et al, 1997; Pen et al, 1997).

The oldest approach to determining Ω_0 is by measuring the deceleration of the expansion. Sandage's deceleration parameter, $q_0 \equiv -(\ddot{R}/R)/H_0^2 = \frac{\Omega_0}{2}[1 + 3p/\rho]$, depends upon both Ω_0 and the equation of state. Accurate measurements of the (luminosity) distance as a function of redshift allow the deceleration to be determined. Accurate distant measurements to some fifty or so SNe1a, with redshifts as large as one, carried out by two groups (Riess et al, 1998; Perlmutter et al, 1998) indicate that the Universe is speeding up, not slowing down (i.e., $q_0 < 0$). The simplest explanation is a cosmological constant, with $\Omega_\Lambda \sim 0.6$. This result fits neatly with the CBR determination that $\Omega_0 = 1$ and dynamical measures that indicate $\Omega_M \sim 0.4$: the "missing energy" exists in a smooth component that cannot clump and thus is not found in clusters of galaxies.

While the evidence for inflation + cold dark matter is not definitive and we should be cautious, 1998 could well mark a turning point in cosmology as important as 1964. Recall, after the discovery of the CBR it took a decade or more to firmly establish the cosmological origin of the CBR and the hot big-bang

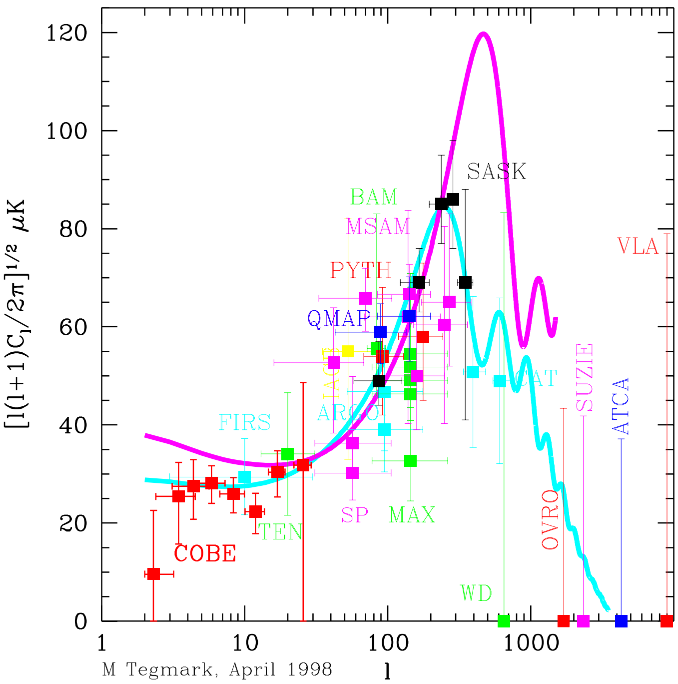

Fig. 2. Summary of current CBR anisotropy measurements, where the temperature variation across the sky has been expanded in spherical harmonics, $\delta T(\theta,\phi) = \sum_i a_{lm} Y_{lm}$ and $C_l \equiv \langle |a_{lm}|^2 \rangle$. The curves illustrate CDM models with $\Omega_0 = 1$ and $\Omega_0 = 0.3$. Note the preference of the data for a flat Universe (Figure courtesy of M. Tegmark).

cosmology as the standard cosmology.

2. Inflation + Cold Dark Matter

Inflation has revolutionized the way cosmologists view the Universe and provides the current working hypothesis for extending the standard cosmology. It explains how a region of size much, much greater than our Hubble volume could have become smooth and flat without recourse to special initial conditions (Guth 1981), as well as the origin of the density inhomogeneities needed to seed structure (Hawking, 1982; Starobinsky, 1982; Guth & Pi, 1982; and Bardeen et al, 1983). Inflation is based upon well defined, albeit speculative physics – the semi-classical evolution of a weakly coupled scalar field – and this physics may well be connected to the unification of the particles and forces of Nature.

It would be nice if there were a standard model of inflation, but there isn't. What is important, is that almost all inflationary models make three very testable predictions: flat Universe, nearly scale-invariant spectrum of Gaussian density perturbations, and nearly scale-invariant spectrum of gravitational waves.

These three predictions allow the inflationary paradigm to be decisively tested. While the gravitational waves are an extremely important and challenging test, I do not have space to mention them again here (see e.g., Turner 1997).

The tremendous expansion that occurs during inflation is key to its beneficial effects and robust predictions: A small, subhorizon-sized bit of the Universe can grow large enough to encompass the entire observable Universe and much more. Because all that we can see today was once so extraordinarily small, it appears flat and smooth. This is unaffected by the expansion since then and so the Hubble radius today is much, much smaller than the curvature radius, implying $\Omega_0 = 1$. Lastly, the tremendous expansion stretches quantum fluctuations on truly microscopic scales ($\lesssim 10^{-23}$ cm) to astrophysical scales ($\gtrsim$ Mpc).

The curvature perturbations created by inflation are characterized by two important features: 1) they are almost scale-invariant, which refers to the fluctuations in the gravitational potential being independent of scale – and not the density perturbations themselves; 2) because they arise from fluctuations in an essentially noninteracting quantum field, their statistical properties are that of a Gaussian random field.

Scale invariance specifies the dependence of the spectrum of density perturbations upon scale. The normalization (overall amplitude) depends upon the specific inflationary model (i.e., scalar-field potential). Ignoring numerical factors for the moment, the fluctuation amplitude is given by: $\delta\phi \simeq (\delta\rho/\rho)_{\rm HOR} \sim V^{3/2}/m_{\rm PL}^3 V'$. (The amplitude of the density perturbation on a given scale at horizon crossing is equal to the fluctuation in the gravitational potential $\delta\phi$.) To be consistent with the COBE measurement of CBR anisotropy on the 10° scale, $\delta\phi$ must be around 2×10^{-5}. Not only did COBE produce the first evidence for the existence of the density perturbations that seeded all structure (Smoot et al, 1992), but also, for a theory like inflation that predicts the shape of the spectrum of density perturbations, it provides the overall normalization that fixes the amplitude of density perturbations on all scales. The COBE normalization began precision testing of inflation.

3. Inflation + CDM in the Era of Precision Cosmology

As we look forward to the abundance (avalanche!) of high-quality observations that will test Inflation + CDM, we have to make sure the predictions of the theory match the precision of the data. In so doing, CDM + Inflation becomes a ten (or more) parameter theory. For astrophysicists, and especially cosmologists, this is daunting, as it may seem that a ten-parameter theory can be made to fit any set of observations. This is not the case when one has the quality and quantity of data that will be coming. The standard model of particle physics offers an excellent example: it is a nineteen-parameter theory and because of the high-quality of data from experiments at Fermilab's Tevatron, SLAC's SLC, CERN's LEP and other facilities it has been rigorously tested and the parameters measured to a precision of better than 1% in some cases. My worry as an inflationist is not that many different sets of parameters will fit the upcoming data, but rather that no set of parameters will!

In fact, the ten parameters of CDM + Inflation are an opportunity rather than a curse: Because the parameters depend upon the underlying inflationary model and fundamental aspects of the Universe, we have the very real possibility of learning much about the Universe and inflation. The ten parameters can be organized into two groups: cosmological and dark-matter (Dodelson et al, 1996).

Cosmological Parameters

1. h, the Hubble constant in units of $100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.
2. $\Omega_B h^2$, the baryon density. Primeval deuterium measurements and together with the theory of BBN imply: $\Omega_B h^2 = 0.02 \pm 0.002$.
3. n, the power-law index of the scalar density perturbations. CBR measurements indicate $n = 1.1 \pm 0.2$; $n = 1$ corresponds to scale-invariant density perturbations. Several popular inflationary models predict $n \simeq 0.95$; range of predictions runs from 0.7 to 1.2 (Lyth & Riotto, 1996).
4. $dn/d\ln k$, "running" of the scalar index with comoving scale (k = wavenumber). Inflationary models predict a value of $\mathcal{O}(\pm 10^{-3})$ or smaller (Kosowsky & Turner, 1995).
5. S, the overall amplitude squared of density perturbations, quantified by their contribution to the variance of the CBR quadrupole anisotropy.
6. T, the overall amplitude squared of gravity waves, quantified by their contribution to the variance of the CBR quadrupole anisotropy. Note, the COBE normalization determines $T + S$ (see below).
7. n_T, the power-law index of the gravity wave spectrum. Scale-invariance corresponds to $n_T = 0$; for inflation, n_T is given by $-\frac{1}{7}\frac{T}{S}$.

Dark-matter Parameters

1. Ω_ν, the fraction of critical density in neutrinos ($= \sum_i m_{\nu_i}/90h^2$). While the hot dark matter theory of structure formation is not viable, it is possible that a small fraction of the matter density exists in the form of neutrinos.

Further, small – but nonzero – neutrino masses are a generic prediction of theories that unify the strong, weak and electromagnetic interactions – and the Super-Kamiokande Collaboration has presented evidence that the at least one of the neutrino species has a mass of greater than about 0.1 eV, based upon the deficit of atmospheric muon neutrinos (Fukuda et al, 1998).

2. Ω_X, the fraction of critical density in a smooth component of unknown composition and negative pressure ($w_X \lesssim -0.3$). There is mounting evidence for such a component, with the simplest example being a cosmological constant ($w_X = -1$).

3. g_*, the quantity that counts the number of ultra-relativistic degrees of freedom (around the time of matter-radiation equality). The standard cosmology/standard model of particle physics predicts $g_* = 3.3626$ (photons in the CBR + 3 massless neutrino species with temperature $(4/11)^{1/3}$ times that of the photons). The amount of radiation controls when the Universe became matter dominated and thus affects the present spectrum of density inhomogeneity.

3.1. Present status of Inflation + CDM

A useful way to organize the different CDM models is by their dark-matter content; within each CDM family, the cosmological parameters vary. One list of models is:

1. sCDM (for simple): Only CDM and baryons; no additional radiation ($g_* = 3.36$). The original standard CDM is a member of this family ($h = 0.50$, $n = 1.00$, $\Omega_B = 0.05$), but is now ruled out (see Fig. 3).

2. τCDM: This model has extra radiation, e.g., produced by the decay of an unstable massive tau neutrino (hence the name); here we take $g_* = 7.45$.

3. νCDM (for neutrinos): This model has a dash of hot dark matter; here we take $\Omega_\nu = 0.2$ (about 5 eV worth of neutrinos).

4. ΛCDM (for cosmological constant): This model has a smooth component in the form of a cosmological constant; here we take $\Omega_\Lambda = 0.6$.

Figure 3 summarizes the viability of these different CDM models, based upon CBR measurements and current determinations of the present power spectrum of inhomogeneity derived from redshift surveys. sCDM is only viable for low values of the Hubble constant (less than $55\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$) and/or significant tilt (deviation from scale invariance); the region of viability for τCDM is

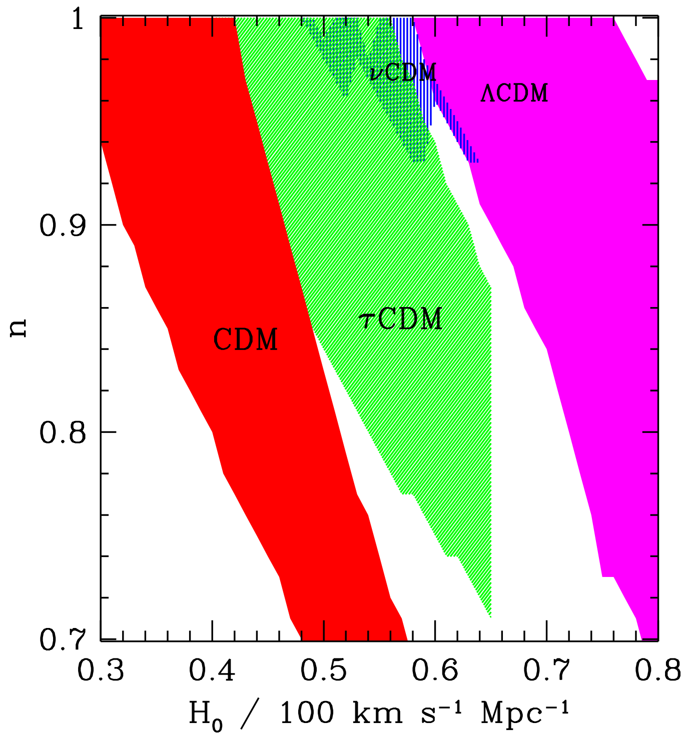

Fig. 3. Summary of viable CDM models, based upon CBR anisotropy and determinations of the present power spectrum of inhomogeneity (Dodelson et al, 1996).

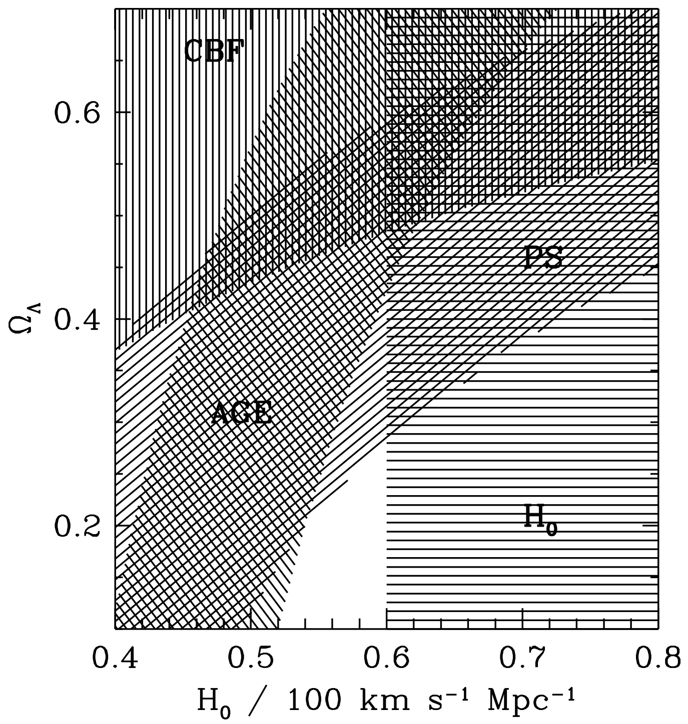

Fig. 4. Constraints used to determine the best-fit CDM model: PS = large-scale structure + CBR anisotropy; AGE = age of the Universe; CBF = cluster-baryon fraction; and H_0= Hubble constant measurements. The best-fit model, indicated by the darkest region, has $h \simeq 0.60 - 0.65$ and $\Omega_\Lambda \simeq 0.55 - 0.65$.

similar to sCDM, but shifted to larger values of the Hubble constant (as large as $65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$). νCDM has an island of viability around $H_0 \sim 60\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $n \sim 0.95$. ΛCDM can tolerate the largest values of the Hubble constant.

Considering other relevant data too – e.g., age of the Universe, determinations of Ω_M, measurements of the Hubble constant, and limits to Ω_Λ – ΛCDM emerges as the 'best-fit CDM model' (Krauss & Turner, 1995; Ostriker & Steinhardt, 1995; Liddle et al, 1996); see Fig. 4. Moreover, its 'smoking gun signature,' negative q_0, has apparently been confirmed (Riess et al, 1998; Perlmutter et al, 1998). Despite my general enthusiasm, I would caution that it is premature to conclude that ΛCDM is anything but the model to take aim at.

4. Checklist for the Next Decade

As I have been careful to stress the basic tenets of Inflation + Cold Dark Matter have not yet been confirmed definitively. However, a flood of high-quality cosmological data is coming, and could make the case in the next decade. Here is my version of how "maybe" becomes "yes."

- Map of the Universe at 300,000 yrs. COBE mapped the CMB with an angular resolution of around 10°; two new satellite missions, NASA's MAP (launch 2000) and ESA's Planck Surveyor (launch 2007), will map the CMB with 100 times better resolution (0.1°). From these maps of the Universe as it existed at a simpler time, long before the first stars and galaxies, will come a gold mine of information: Among other things, a definitive measurement of Ω_0; a determination of the Hubble constant to a precision of better than 5%; a characterization of the primeval lumpiness; and possible detection of the relic gravity waves from inflation. The precision maps of the CMB that will be made are crucial to establishing Inflation + Cold Dark Matter.

- Map of the Universe today. Our knowledge of the structure of the Universe is based upon maps constructed from the positions of some 30,000 galaxies in our own backyard. The Sloan Digital Sky Survey will produce a map of a representative portion of the Universe, based upon the positions of a million galaxies. The Anglo-Australian 2-degree Field survey will determine the position of several hundred thousand galaxies. These surveys will define precisely the large-scale structure that exists today, answering questions such as, "What are the largest structures that exist?" Used together with the CMB maps, this will definitively test the Cold Dark Matter theory of structure formation, and much more.

- Present expansion rate H_0. Direct measurements of the expansion rate using standard candles, gravitational time delay, SZ imaging and the CMB maps will pin down the elusive Hubble constant once and for all. It is the fundamental parameter that sets the size – in time and space – of the observable Universe. Its value is critical to testing the self consistency of Cold Dark Matter.

- Cold dark matter. A key element of theory is the cold dark matter particles that hold the Universe together; until we actually detect cold dark matter particles, it will be difficult to argue that cosmology is solved. Experiments designed to detect the dark matter that holds are own galaxy together are now operating with sufficient sensitivity to detect both neutralinos and axions. In addition, experiments at particle accelerators (Fermilab and CERN) will be hunting for the neutralino and its other supersymmetric cousins.

- Nature of the dark energy. If the Universe is indeed accelerating, then most of the critical density exists in the form of dark energy. This component is poorly understood. Vacuum energy is only the simplest possibly for the smooth dark component; there are other possibilities: frustrated topological defects or an evolving scalar field (see e.g., Caldwell et al, 1998; Turner & White, 1997). Independent evidence for the existence of this dark energy, e.g., by CMB anisotropy, the SDSS and 2dF surveys, or gravitational lensing, is crucial for verifying the accounting of matter and energy in the Universe I have advocated. Additional measurements of SNe1a could help shed light on the precise nature of the dark energy. The dark energy problem is not only of great importance for cosmology, but for fundamental physics as well. Whether it is vacuum energy or quintessence, it is a puzzle for fundamental physics and possibly a clue about the unification of the forces and particles.

5. New Questions; Some Surprises?

Will cosmologists look back on 1998 as a year that rivals 1964 in importance? I think it is quite possible. In any case, the flood of data that is coming will make the next twenty years in cosmology very exciting. It could be that my younger theoretical colleagues will get their wish – inflation + cold dark matter is falsified and it's back to the drawing board. Or, it may be that it is roughly correct, but the real story is richer and even more interesting. This happened in particle physics. The quark model of the 1960s was based upon an approximate $SU(3)$ global flavor symmetry, which shed no light on the dynamics of how quarks are held together. The standard model of particle physics that emerged and which provides a fundamental description of physics at energies less than a few hundred GeV, is based upon the $SU(3)$ color gauge theory of quarks and gluons (QCD) and the $SU(2)\otimes U(1)$ gauge theory of the electroweak interactions. The difference between global and local $SU(3)$ symmetry was profound.

Even if Inflation + Cold Dark Matter does pass the series of stringent tests that will confront it in the next decade, there will be questions to address and issues to work out. Exactly how does inflation work and fit into the scheme of the unification of the forces and particles? Does the quantum gravity era of cosmology, which occurs before inflation, leave a detectable imprint on the Universe? What is the topology of the Universe and are there additional spatial dimensions? Precisely how did the excess of matter over antimatter develop? What happened before inflation? What does Inflation + Cold Dark Matter teach us about the unification of the forces and particles of Nature? We live in exciting times!

6. References

1. Allen, B. et al, 1997, Phys. Rev. Lett. 79, 2624.
2. Bardeen, J., P. J. Steinhardt, and M. S. Turner, 1983, Phys. Rev. D 28, 679.
3. Burles, S. & Tytler, D. 1998, Astrophys. J. 499, 699.
4. Caldwell, R., Dave, R., & Steinhardt, P.J. 1998, Phys. Rev. Lett. 80, 1582.
5. Dodelson, S., E.I. Gates, and M.S. Turner, 1996, Science 274, 69.
6. Evrard, A.E. 1996, MNRAS 292, 289.
7. Fukuda, Y. et al (SuperKamiokande Collaboration) 1998, Phys. Rev. Lett. 81, 1562.
8. Guth, A., 1982, Phys. Rev. D 23, 347.
9. Guth, A. and S.-Y. Pi, 1982, Phys. Rev. Lett. 49, 1110.
10. Hawking, S.W. 1982, Phys. Lett. B 115, 295.
11. Kosowsky, A. & Turner, M.S. 1995, Phys. Rev. D 52, R1739.
12. Krauss, L. & M.S. Turner, 1995, Gen. Rel. Grav. 27, 1137.
13. Liddle, A.R. et al 1996, MNRAS 282, 281.
14. Lyth, D. H. & Riotto, A. 1998, Phys. Rep., in press.
15. Ostriker, J.P. & Steinhardt, P.J. 1995, Nature 377, 600.
16. Peebles, P.J.E., Schramm, D. N., Turner, E. L., & Kron, R.G. 1991, Nature 352, 769.
17. Pen, U.-L. et al, 1997, Phys. Rev. Lett. 79, 1611.
18. Perlmutter, S. et al 1998, Astrophys. J., in press.
19. Reiss, A. et al 1998, Astron. J., in press.
20. Schramm, D.N. & Turner, M.S. 1998, Rev. Mod. Phys. 70, 303.
21. Smoot, G. et al 1992, Astrophys. J. 396, L1.
22. Starobinskii, A.A., 1982, Phys. Lett. B 117, 175.
23. Turner, M.S. 1997, Phys. Rev. 55, R435.
24. Turner, M.S. & White, M. 1997, Phys. Rev. D 56, R4439.