Fermi National Accelerator Laboratory

FERMILAB-Conf-94/344-A
September 1994

Particle astrophysics and cosmology

Edward W Kolb†§

† NASA/Fermilab Astrophysics Center,
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
§ Department of Astronomy and Astrophysics, Enrico Fermi Institute,
The University of Chicago, Chicago, Illinois 60637, USA

Abstract

This paper discusses the possibility that astronomical observations of the present Universe can be used as a tool to discover information about fundamental processes that occurred in the early Universe, and the corresponding physics behind the processes. Potential information includes symmetry breaking patterns at energy scales of 10^{16}GeV or so, or a region of a scalar potential corresponding to energy densities of $(10^{16}\text{GeV})^4$. Also outlined are the necessary observations, as well as the required theoretical and phenomenological advances, to implement this program.

1. Introduction

The organizing principle of this talk is that observations of the present Universe provide information about the early Universe, and since the evolution of the early Universe depends upon the fundamental laws of physics, we can learn something about high-energy physics from present-day astronomical observations.

The observational program necessary before meaningful information about particle processes in the early Universe can be obtained has been divided into four categories; 1) large-scale structure, 2) the cosmic microwave background radiation, 3) the matter content of the Universe, and 4) the cosmological parameters that describe our world model.

In sections 2 through 5 I will highlight recent observations in these four categories. I will then turn to theories of the early Universe, discussing two possibilities for the origin of structure closely allied with high-energy physics: inflation and defects. Then I will discuss the phenomenology necessary to connect these theories of the early Universe to observations. With sufficient knowledge of the present Universe, it should be possible to test these theories for the origin of structure. I will discuss some of the methods by which we can discriminate between the two theories and discover whether either is correct. Finally, I will speculate about the possibility of learning something about fundamental physics from this program.

As a glimpse of what the conclusions will be, I propose that it will soon be possible to learn something about physics at distance scales as small as 10^{-28}cm (corresponding to energy scales as large as 10^{16}GeV) from cosmological observation of the present Universe on distance scales as large as 10^{+28}cm.

2. Large-Scale Structure

One goal of large-scale structure observations is to determine the nature and the spectrum of the density field of the Universe. To a theorist, the density field of the Universe is simple: $\rho(\mathbf{x}) = \text{const} \equiv \langle\rho\rangle = \Omega_0\rho_C$, where Ω_0 is the present ratio of the mass density of the Universe to its critical density $\rho_C = 3H_0^2/8\pi G$, with H_0 the Hubble constant ($H_0 = 100h\text{km s}^{-1}\text{Mpc}$, $1 > h > 0.4$). If we live in a flat Universe, $\Omega_0 = 1$, and $\langle\rho\rangle = 1.88 \times 10^{-29}h^2\text{g cm}^{-3}$.

Of course we do not live in a Universe that is exactly homogeneous and isotropic because the density field has spatial dependence. However the concept of

Paper presented at the *27th International Conference on High Energy Physics*, Glasgow, Scotland, July 20-27, 1994

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

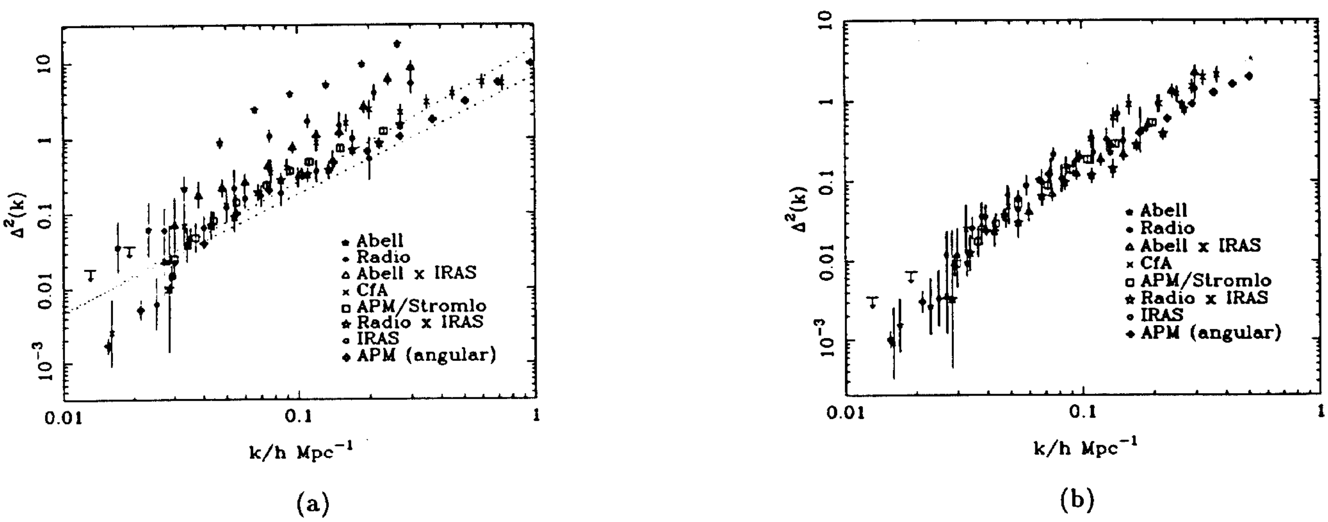

Figure 1. On the left is the power spectrum inferred from the indicated surveys of large-scale structure. On the right is the same data, corrected for red-shift space distortions, with individual bias factors, and properly linearized. Recall that small k corresponds to large scales. The figure and analysis is from Peacock and Dodds [1]; references to the different surveys can be found there.

an average density for the Universe is still a useful concept, and the density field is typically described in terms of fluctuations about the mean density $\langle\rho\rangle$. The fluctuations in the density field, $\delta\rho(\mathbf{x}) \equiv \rho(\mathbf{x}) - \langle\rho\rangle$ can be expanded in terms of Fourier components δ_k:

$$\frac{\delta\rho(\mathbf{x})}{\rho} \propto \int d^3k\; e^{-i\mathbf{k}\cdot\mathbf{x}}\delta_k. \qquad (1)$$

So long as the power spectrum is isotropic, the *rms* density fluctuation can be expressed as

$$\left\langle\left(\frac{\delta\rho(\mathbf{x})}{\langle\rho\rangle}\right)^2\right\rangle \propto \int \frac{dk}{k}\, k^3\,|\delta_k|^2 . \qquad (2)$$

The power spectrum, either expressed as $P(k)$ or $\Delta(k)$, where

$$P(k) \equiv |\delta_k|^2, \qquad \Delta(k) \equiv k^3|\delta_k|^2, \qquad (3)$$

is directly related to the Fourier transform of the two-point autocorrelation function of the mass distribution. $\Delta(k)$ is the power per logarithmic interval in k space, and is what is usually meant by the amplitude of the mass fluctuation on scale λ, where $k\lambda \sim 2\pi$

Determination of the power spectrum, over a range of say few h^{-1}Mpc to a few $100h^{-1}$Mpc, is one of the primary goals of observational cosmology.

2.1. Large-scale structure surveys

The traditional method to obtain the power spectrum is through large-scale structure surveys. The procedure is straightforward in concept (but exceedingly complex in execution). One looks at a sample of objects, determines a mean density, then calculates the *rms* fluctuations in the number counts of objects on some scale λ, performs the Fourier transform, and obtains the power spectrum.

A survey of surveys of power spectra is displayed in Fig. 1a, taken from the work of Peacock and Dodds [1]. On the left-hand side of the figure is the "raw" data from various surveys. The goal is to extract from the data a consistent value for the linear power spectrum of the mass fluctuations, which is what is predicted by early-Universe cosmology. There are three major corrections that must be applied to the data: (i) For large k (small scales) the spectrum has undergone some degree of non-linear evolution and the observed spectrum deviates from a linear extrapolation of the initial spectrum. (ii) Three-dimensional data sets, which use redshift as the radial coordinate, must be corrected for the existence of peculiar velocities (defined and discussed in section 2.3). (iii) Actually measured are the fluctuations in the *number density* of the objects surveyed, while what is desired are the fluctuations in the *mass density*. There are astrophysical effects that suggest that the relationship between the number density and the mass density might be different for different objects. This is known as the bias factor.

Peacock and Dodds have attempted to make these corrections; their result is shown in Fig. 1b. While the procedure is involved, and while some corrections such as the relative bias factors are phenomenological and yet not well understood on a physical basis, the resulting power spectrum in Fig. 1b is fairly well determined. Of course one of the goals in large-scale structure is to understand better the corrections necessary to

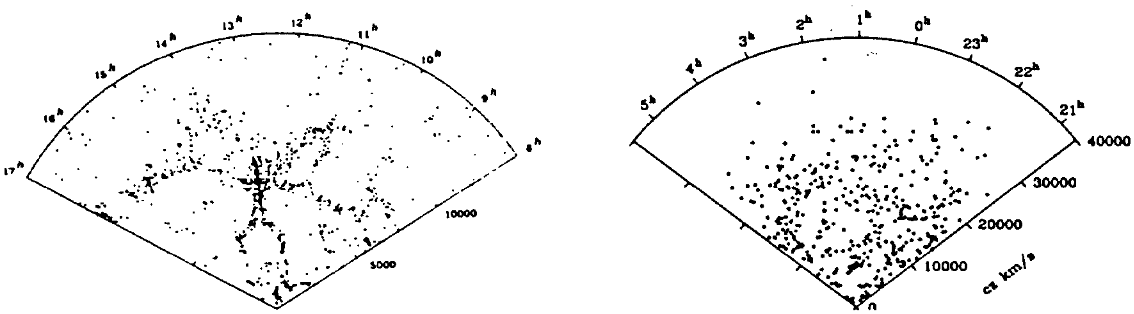

Figure 2. On the left is the map of the location of bright galaxies produced by the CfA survey of galaxies [2] covering a slice 6° in declination and 135° in right ascension, while on the right is the map produced by a sparse sampling of the APM survey [3], covering about 12° in declination and 135° in right ascension. The radial direction is redshift. Note that the APM survey is nearly three times deeper than the CfA survey.

convert the observed power spectra into a single power spectrum. However we have every expectation that eventually we will be able to extract an accurate power spectrum from large-scale structure surveys.

2.2. Maps

If the fluctuations in the matter distribution are Gaussian distributed, then in principle it is possible to extract all the information from the two-point autocorrelation function, or its Fourier transform, the power spectrum. However if the fluctuations are non-Gaussian, then it is necessary to analyze maps of the mass distribution to extract the desired physics.

We know that through gravitational collapse, non-linear processes will take an initially Gaussian spectrum and turn it into a non-Gaussian distribution of matter. One of the challenges of large-scale structure is to determine whether the obviously non-Gaussian distribution of structure on smallish scales, for instance as seen in the CfA redshift survey [2] as shown in Fig. 2, is the result of non-Gaussian initial conditions, or if the observed non-Gaussian features were impressed upon an initially Gaussian distribution by non-linear effects in the course of gravitational collapse. Perhaps we are starting to be able to answer this question, for there are now hints that if we look at deeper samples, such as in the APM survey [3], also shown in Fig. 2, the non-Gaussian features are less pronounced, leading most cosmologists to conclude that the initial spectrum was Gaussian. It is also clear that the Universe becomes smoother on large scales, unlike a fractal.

2.3. Peculiar velocity fields

Another tool to probe the nature and spectrum of the mass distribution is the observation of the "peculiar" velocities (departures of the apparent velocities from that due to the linear relationship of the Hubble expansion) of objects caused by the gravitational pull of density perturbations. One important advantage of determining the mass distribution by this method is that the peculiar velocity is a probe of the total mass distribution, dark plus visible matter. Thus velocities should be a relatively unbiased probe of the power spectrum.

Bertschinger, Deckel, and collaborators have pioneered a method to extract the density distribution from measurements of peculiar velocities [4]. From information about peculiar velocities, Bertschinger et al. are able to reconstruct the matter distribution that gives rise to the observed velocities. The reconstructed matter distribution looks a lot like the true matter distribution, leading one to hope that the technique may be extended in the future to larger scales, and information about the power spectrum can result.

2.4. Early structure formation

Early-Universe cosmologies consider the Universe at redshifts of about 10^{28}, corresponding to temperatures of 10^{16}GeV or so. We can directly see galaxies out to redshift of order unity. Although a redshift of unity corresponds to a look-back time of about 65% of the age of the Universe, it is a far cry from $z \sim 10^{28}$. One might think that observations of the Universe at redshift of order one might not shed light on the early Universe. However the development of structure at moderate redshifts is different in early-Universe models. Knowledge of the Universe at redshift of order unity can give information about the spectrum of the fluctuations, and whether they arose as the result of a Gaussian distribution of fluctuations.

There are two new instruments that should be particularly useful in high-redshift astronomy. The Hubble space telescope can resolve galaxies and clusters at high redshift. Information as simple as the morphological type of galaxies at that redshift can be used to give information about the development of structure.

The first Keck 10-meter telescope has started operations, and a second one is under construction. These telescopes are large enough to take the spectra of galaxies at redshifts $z \sim 0.5$. With this information one can hope to learn of the evolution of galaxies in mass, luminosity, and rate of mergers, measure the evolution of large-scale structure, and if evolution is understood, use galaxies as a probe to measure the curvature of space by classical tests like number vs. redshift or angular diameter vs. redshift of the galaxies.

2.5. *Weak gravitational lensing*

Recent deep CCD (charged coupled device) images have shown that there are as many as 10^6 faint blue objects per square degree of the sky [5]. While we are not certain what these objects are, they are believed to be a population of galaxies at redshift of order 1 to 3, which are extremely blue because they are star-forming galaxies, perhaps dwarf galaxies. They have an angular diameter of about 1 arc second.

Although they are very interesting objects for study in their own right, they are useful even now as a probe of the distribution of matter in the nearby Universe by acting as background image sources for gravitational lensing by nearby matter concentrations. In Section 4.1.1 I will discuss how they can be used to give information about the mass of clusters of galaxies, but in the future it may be possible to map the distribution of matter in the Universe by observing the distortions of the images of the faint blue objects caused by the gravitational effect of the matter between us and the sources. This would probably require the construction of a large 4-meter class telescope dedicated to the project.

2.6. *Structure Outlook*

The outlook for advances in our understanding of the nature and the spectrum of fluctuations in the density field of the Universe have never been better. Not only are there more surveys today than just a few years ago, covering a larger fraction of the Universe, but by the end of the decade even larger surveys should have information. For instance, the Sloan Digital Sky Survey (SDSS), which will eventually record the redshift of 10^6 galaxies, will greatly extend the reach of structure surveys to distance scales where we can connect with the information about fluctuations in the microwave background radiation.

If the structure we see in the Universe today resulted from events in the early Universe, then the structure should be a sensitive probe of the events in the early Universe. But structure, by itself, will not give the complete picture. We require information from the microwave background, as well as knowledge of the dark matter and cosmological parameters. Let us turn now to the microwave background.

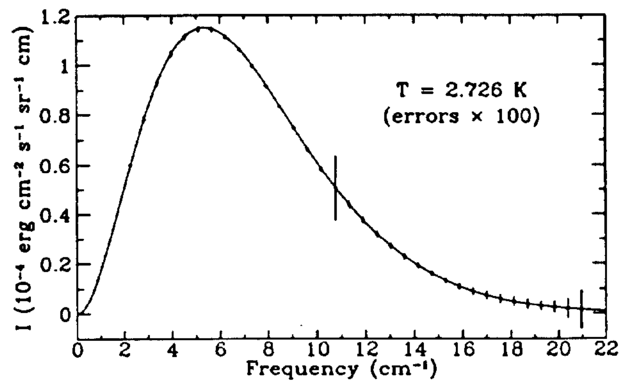

Figure 3. The spectrum of the CMBR from [6].

3. Cosmic Microwave Background Radiation

The Cosmic Microwave Background Radiation (CMBR) is a fundamental probe of the early Universe. The photons in the CMBR last interacted around the time of recombination (redshift $1+z = 1100$; age about 300,000 years) when it became cool enough for the electrons and nuclei to form atoms. Although the CMBR provides direct evidence about conditions in the Universe at recombination, small fluctuations in the temperature of the Universe at recombination may be the result of process that occurred much earlier in the history of the Universe.

3.1. *Spectrum*

The best blackbody in the Universe is the Universe. The far infrared radiation absolute spectrometer instrument on the Cosmic Background Explorer (COBE) satellite measured the spectrum of the CMBR around the peak, in a wavelength region containing about 90% of the total energy in the CMBR. The resulting spectrum is shown in Fig. 3 [6].

There are no detectable departures from a blackbody spectrum. However at some level that have to be there, since anything that injects energy into the Universe, such as the energy release in galaxy formation, should lead to a distortion of the spectrum.

3.2. *Temperature Fluctuations*

Anisotropies in the CMBR provide valuable clues to processes in the early Universe. In 1992 the first measurement of anisotropies were made by the DMR

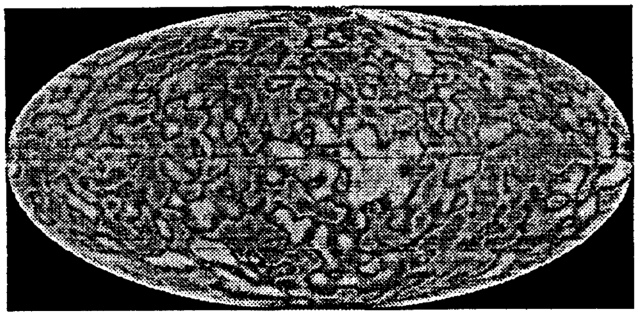

Figure 4. The map of fluctuations in the CMBR as seen by COBE. Lighter regions correspond to low-temperature regions. The typical scale of fluctuations about the average temperature is a few parts in 10^5 [7].

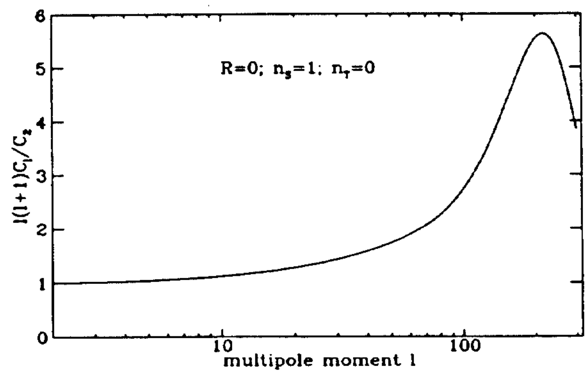

Figure 5. The spectrum of temperature fluctuations predicted in a sample inflationary model containing no tensor perturbations and a primordial scalar perturbation spectrum of the Harrison-Zel'dovich form $P(k) \propto k$, normalized to C_2. Note the flat region at small l and the Doppler peak around $l = 200$. [Data courtesy of Scott Dodelson.]

detector on COBE [7]. The familiar map of temperature fluctuations is shown in Fig. 4.

Maps of the anisotropy are useful for testing whether the temperature fluctuations are Gaussian distributed, or whether there is an excess of large fluctuations in the temperature. From a map of the temperature we also can construct the quantity analogous to the power spectrum for density perturbations.

Since a map of temperature variations forms a two-sphere, a location on the sky can be expressed in terms of angles. One can form the temperature–temperature autocorrelation function at an angle θ (similar to, say, the galaxy-galaxy autocorrelation function) by measuring the temperature at some angle α, comparing it to the temperature at angle $\alpha+\theta$, and averaging over positions α: in equations, $C(\theta) = \langle \delta T(\alpha)\, \delta T(\alpha+\theta)\rangle_\alpha$. Just as the two-point autocorrelation function in large-scale structure is expanded in a Fourier series, it is useful to expand $C(\theta)$ in Legendre polynomials: $C(\theta) = (4\pi)^{-1}\sum_l (2l+1)C_l P_l(\cos\theta)$. The C_l are the multipole moments, and C_l as a function of l is known as the spectrum of the temperature fluctuations.

There are some important features to look for in the spectrum of temperature fluctuations [8]. If inflation is correct, then at large angular scale (small multipole moment l) the spectrum should be roughly flat, because these scales were outside the horizon at last scattering and we are seeing the unprocessed spectrum. However multipole moment of $l \sim 100$ corresponds to an angular scale which subtended the horizon on the last scattering surface. On sub-horizon scales matter can move under the influence of the density perturbations. Matter moves toward regions of high density, away from regions of low density. Photons last scattering from moving matter will pick up an additional energy shift due to the Doppler effect. This effect peaks around multipole moment of 200 for the canonical value of the baryon density, but can shift around if the baryon density changes or if Ω changes, simply because the horizon size at last scattering depends upon Ω.

The spectrum from a sample inflationary model is shown in Fig. 5. Note the flat region at small l, and the Doppler peak at $l \sim 200$.

Additional information may be available from polarization observations [9]. Since scattering at the surface of last scattering is polarized (it is simply Thomson scattering), the fluctuations in the CMBR should be correlated with some polarization. The polarization is only a percent or so at its largest around the Doppler peak, so detection would be very difficult.

3.3. CMBR outlook

The detection of CMBR fluctuations by no means proves inflation, or any other early-Universe scenario. However the detailed study of the fluctuation spectrum in the future can make quite a convincing case for inflation. The first step would be a clear indication of a Doppler peak in the spectrum. So far the evidence one way or the other is unclear, but experiments are in the early stages, and we can look for the situation to improve in the near future. Eventually we want the spectrum from $l = 2$ to l of a few times 10^4. We also require maps on angular scales with higher spatial resolution than the COBE maps to test whether the fluctuations in the temperature are Gaussian distributed.

4. The matter content of the Universe

Any attempt to infer the primordial perturbation spectrum from the present structure of the Universe depends upon knowledge of the nature of the matter content of the Universe. Complicating this issue is the fact that there is more to the Universe than we can see, in fact most of the mass of the Universe is in the form of dark matter.

The traditional methods for determining the mass of objects in the Universe involve measuring the velocities of test particles moving in the gravitational potential resulting from the mass distribution. Evidence for dark matter in our own galactic halo, as well as the halos of other galaxies, is well known, as is the evidence that an even larger fraction of the mass in clusters of galaxies is dark based upon measurements of the velocity dispersion of galaxies in the cluster [10].

Recently, evidence for dark matter in clusters has been found by a different method. In a deep exposure of a relatively distant cluster, say at redshift $z \sim 0.2$ to 0.5, one can see that the cluster acts as a gravitational lens and distorts the images of the background faint blue galaxies. By measuring the distortion of the background images caused by the cluster, the mass distribution of the cluster (light + dark) may be inferred. Although this is a telescope-intensive project (several nights per cluster on a 4-meter telescope), preliminary results seem to be consistent with the total mass and mass distribution inferred by traditional velocity dispersion measurements. In other words, there is a second detection method that sees dark matter in the halos of clusters.

The evidence for dark matter continues to grow, we have to find out what it is.

4.1. The non-baryonic side

There is no shortage of candidates for non-baryonic particle dark matter. The mass of the candidates vary from 10^{-5}eV for axions all the way to the Planck mass. There are three ways the non-baryonic dark matter problem is being attacked: by direct searches for the cosmic dark matter, by indirect searches for the decay products or annihilation products of the dark matter, and by terrestrial experiments searching for confirmation of theories which contain dark matter.

4.1.1. Direct searches: If the Universe is dominated by a particle that was once in thermal equilibrium and is very non-relativistic when it decouples from the heat bath, its present abundance is determined by its annihilation cross section and its mass m, with the abundance roughly proportional to $(\sigma_A m m_{Pl})^{-1}$ where m_{Pl} is the Planck mass and σ_A is the annihilation cross section [11]. The present energy density for the non-relativistic species is its mass times its present abundance, so it should be proportional to σ_A^{-1} and roughly independent of the mass. Therefore for a wide range of masses, very general arguments suggest that its annihilation cross section should be of the order of 10^{-38} cm^2 for its present density to be close to the critical value [11]. Since by crossing symmetry we expect the scattering cross section of the dark matter particle to be comparable to its annihilation cross section, they may interact strongly enough to be seen in sensitive, low-background experiments.

Of course this broad-brush picture requires many refinements: if the particle is a fermion, the abundance depends upon whether it is a Dirac or Majorana particle, not only because of numbers of degrees of freedom, but whether the annihilation is s-wave as for Dirac particle or p-wave as for Majorana particles; whether the annihilation proceeds near a resonance region; the expected flux of the dark matter particle depends upon the mass, as does the energy transfer in scattering; and whether the scattering is spin-dependent or not is a crucial factor in strategies for detection.

Progress in the construction of low-temperature, low-background detectors has been slow (it is often said that low-temperature physics is slow-temperature physics [12]), but eventually dark matter with such an annihilation cross section will be ruled out, or discovered [13]!

4.1.2. Indirect searches: Dark matter should be all around us, and the decay or annihilation of the dark matter into visible particles could be a signature of their existence. Decay possibilities include phenomena as disparate as the decay of cosmic axions into photons through the anomaly or decay of cosmic neutrinos into photons through a non-diagonal magnetic moment. If the dark matter particle can interact and lose a small amount of energy when passing through the Sun or the Earth, they can be captured. They would eventually be concentrated in the center of the Earth or the Sun, and possibly annihilate. If the annihilation process includes neutrinos, then the Sun and the Earth would be a source of energetic neutrino that might be detected in underground detectors [14].

4.1.3. Accelerator searches: There are several accelerator searches that bear on the dark matter problem. Light neutrinos contribute a fraction of the closure density $\Omega_\nu h^2 = m_\nu/91.5\ eV$. Since h could be as small as 0.4, any neutrino with a mass greater than an eV or two would play a rôle in the dynamics of the expansion of the Universe and would have to be included in the inventory of dark matter. If neutrino oscillations are observed, then neutrinos have mass, and we could potentially learn the nature of the dark matter from these experiments.

For the type of particle dark matter with an annihilation cross section in the 10^{-38} cm^2, the most popular candidate is the neutralino. Whether the first hints will come from direct detection or from accelerator evidence for SUSY is anybody's guess.

4.2. The baryonic side

The density of baryons in the Universe is an important cosmological parameter. If we truly understood high-energy physics, we should be able to predict the present baryon density from the fundamental parameters of the processes that produced the baryon asymmetry. Since the baryon density is a parameter in big-bang nucleosynthesis (BBN), if we had true knowledge about the primordial abundance of the elements, we could also pin down the baryon number. Finally, if we are clever enough we could take a true inventory of baryons in the Universe today and check for consistency. Although a lot of effort has gone into these three efforts, we have not yet put together a consistent picture. Let me discuss each in turn.

4.2.1. Baryogenesis: There are two places where it seems likely that a baryon asymmetry could be generated: the grand unified theory (GUT) era, and the electroweak (EWK) era. The GUT scenarios typically involve the decay of a supermassive Higgs (or possibly a gauge) boson in baryon-number violating decays out of equilibrium (for a review, see [15]).

However simply generating a baryon number may not be sufficient. Kuzmin, Rubakov, and Shaposhnikov pointed out that baryon number is also violated by the electroweak anomaly until the rate becomes exponentially small at temperatures below the weak scale, and any baryon number would be wiped out before the electroweak era. Since the anomaly violates B+L and conserves B−L, any baryon number with a zero projection onto B−L will be destroyed.

Of course some GUTs, like $SO(10)$, can produce a non-zero B−L, so it is possible that the baryon number is generated at the GUT scale and is only re-distributed among B and L at the electroweak scale.

However another possibility is that the baryon number itself is generated at the electroweak scale. This has been the subject of a lot of recent work (for a review of some of the ideas and models, see [16]). Part of the reason this scenario has attracted so much attention is that if this is the origin of the baryon asymmetry, in principle it is possible to measure all the parameters necessary to calculate baryogenesis in high-energy physics experiments.

The basic ideas of electroweak baryogenesis are given in [16]. I would just like to mention the implications of the crucial question of whether the minimal standard model can account for the baryon asymmetry. (Here by minimal I mean the standard model with a single Higgs doublet.)

There are two potential problems for minimal model electroweak baryogenesis. The first problem is the weakness of the transition. If the Higgs mass exceeds about 50 GeV, the transition is very weakly first order, and the weakness of the transition increases with increasing Higgs mass. One of the requirements for baryogenesis is a departure from equilibrium, and there is little in a second-order transition. There is a lot of disagreement about how small the Higgs mass could be and still have a strong enough transition, but everyone agrees that if the Higgs mass is greater than about 90 GeV the scenario can't work in the minimal model (some people would put the value as low as 40 GeV, which is below the current bound).

The second problem is that it seems difficult to have adequate CP violation via the CKM mechanism. Since this issue is discussed at length in the contribution of M. Shaposhnikov and B. Gavela in these proceedings I will not detail it here.

Although it is still unclear whether minimal model electroweak baryogenesis is possible or some departure from the minimal model is required, the experimental implications of the two scenarios are clear. If minimal model works, then the crucial experimental ingredients are the mass of the Higgs (it must be less than about 90 GeV for the scenario to get off the ground) and the CKM angles. If some non-minimal model is required, then in general CP violation in the electron and neutron electric dipole moments should be just below present experimental limits.

4.2.2. The baryon fraction from BBN: The abundance of the light elements depends upon the baryon density, and the most sensitive probe of the baryon density is the fraction of deuterium produced in the big bang. If we knew the primordial abundance of deuterium then we would have a very good idea of the present baryon density. Unfortunately, deuterium is a fragile nucleus because its binding energy is so low, and it is difficult to infer its primordial abundance from present observations. (Of course it is the very fact that its binding energy is so low that makes it such a sensitive probe of the conditions in the Universe at the time of nucleosynthesis.) Until recently, most of the information about the primordial deuterium abundance has come from measurements in the solar system or our solar neighborhood. However very recently another technique has emerged to determine the primordial deuterium abundance.

Light from high-redshift quasars can be absorbed by intervening gas clouds. If the clouds are at very high redshift, they should be a fair indication of the primordial, unprocessed elemental abundances. One particular system that has recently been studied is the high-redshift ($z = 3.41$) quasar Q0014+813, which has an intervening cloud at redshift $z = 3.32$. (The

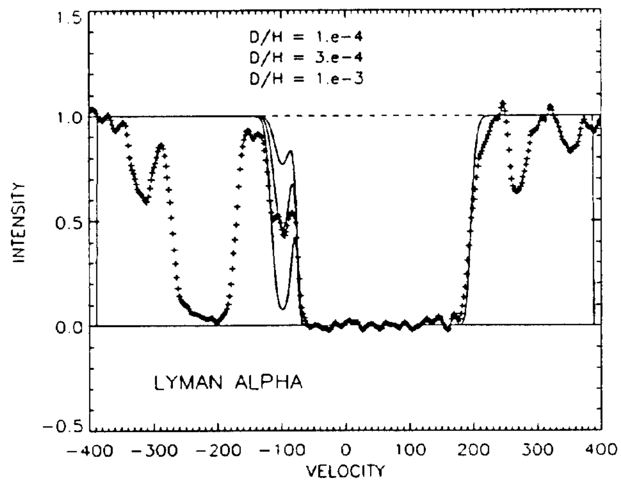

Figure 6. A region of the spectrum of the quasar Q0014+813. The crosses mark data points, while the three curves are fits to the deuterium absorption for the indicated values of the D/H [17].

redshift of the cloud is known from the position of the Lyman-α absorption line.) By searching for the effect of absorption lines due to deuterium, an upper limit on the deuterium-to-hydrogen (D/H) can be found [17, 18].

The relevant part of the spectrum of Q0014+813 is shown in Fig. 6. If the absorption feature at -82 km s^{-1} is interpreted as the presence of deuterium in the cloud, it would imply D/H $= 3 \times 10^{-4}$, higher than the usual range of standard BBN. This would result in a present baryon density of about 10^{-31}g cm^{-3}, slightly lower than usually assumed. However there is the possibility that the absorption feature is not due to deuterium in the cloud at $z = 3.32$, but due to hydrogen absorption in another cloud at a lower redshift.

Until measurements of other quasar absorption systems are made, this result should be considered as an upper limit to the primordial D/H abundance, and a demonstration that eventually a quite accurate value of primordial D/H, and therefore the baryon density, will come from this technique.

4.2.3. Dark baryons in our halo: If one had to hide a large number of baryons from observers, a good place to put them would be in objects in the mass range 0.001 to $0.1 M_\odot$. These objects are known as MACHOS (MAssive Compact Halo ObjectS). Paczynski [19] suggested that the way to detect them is through microlensing of background stars, where the MACHOS act as gravitational microlenses, temporarily increasing the apparent brightness of background stars.

Although millions of stars have to be monitored to see a single microlensing event, the signature of such an event is pretty clear. It should be achromatic, with equal amplification as a function of wavelength, and the amplification should be symmetric in time. The mass of the MACHO can be estimated from the duration of the event if the relative velocity transverse to the line of sight and the distance to the lens is known. Neither of these things are known for any individual event, but from halo models one can calculate the distribution of the widths of the light curves. Thus if one has many events and a model of the halo, one can estimate the mass of the lenses.

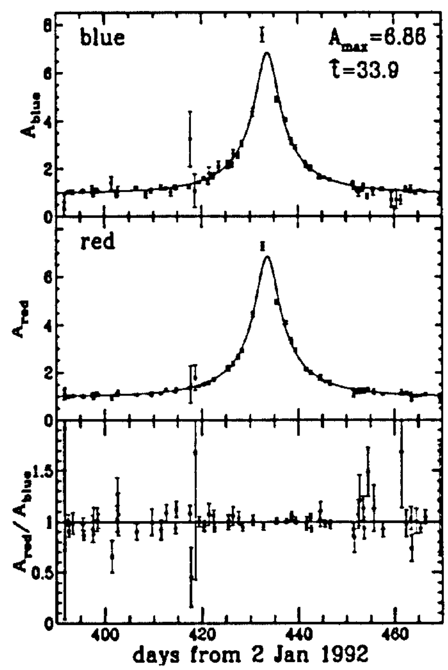

Figure 7. An example of the signal of a star undergoing microlensing as observed by the MACHO collaboration [20]. A_{RED} and A_{BLUE} are the amplitudes in red and blue channels. Microlensing events should be achromatic and time symmetric.

In the past year three groups have seen evidence of gravitational microlensing [20]. An example of such an event is shown in Fig. 7. Although now a handful of events have been seen in the direction of the Large Magellanic Cloud, as well as toward the galactic bulge, it is still too early to know for sure the value of the lens mass, the contribution of the MACHOS to the halo density, or even if the lenses are really a halo population or a disk population.

We can expect in a couple of years to have sufficient data to learn if MACHOS are a significant fraction of the halo mass, which has bearing on the dark matter problem, as well as the consistency of BBN.

4.3. Matter content outlook

It is impossible to say where the breakthrough on dark matter will come. It may well be direct detection, or evidence from indirect detection, or perhaps something from accelerators like the discovery of supersymmetry or neutrino oscillations will point the way. The only thing to do is to push on as many different fronts as possible.

On the issue of the baryon density, we seem no closer now to having the ability to make a prediction of the baryon number from electroweak physics than we were from GUT physics. In fact the physics behind the generation of the baryon asymmetry was simpler for the GUT scenario, and it was easier to make a prediction in a model. The scenario of EWK baryogenesis may be too complicated for a clean prediction ever to result.

The outlook seems much brighter with respect to observational determination of the baryon density. Eventually the situation of the D/H ratio from quasar absorption systems will clear up, yielding an accurate number for the baryon density.

Whether there is the necessity of dark baryons or not depends upon the D/H result. If it is the canonical range, $7 \times 10^{-5} > \mathrm{D/H} > 2 \times 10^{-5}$, then $4 \times 10^{-31} > \rho_B > 2 \times 10^{-31}\mathrm{g\ cm^{-3}}$, and there are almost certainly dark baryons. However if one interprets the Songaila et al., measurement as a D/H determination, rather than an upper limit, then $\rho_B \sim 10^{-31}\mathrm{g\ cm^{-3}}$, and dark baryons are not required. This is an important issue that will be settled by observations, sooner rather than later.

Of course complicating the picture is the fact that MACHO/EROS/OGLE have all seen evidence for dark baryons from microlensing events. However early results seem to suggest that the fraction of dark baryons in MACHOS is not very large. Again, more observations are needed, and they should be arriving soon.

5. Cosmological parameters

There are several parameters that are necessary to describe our world model: the age of the Universe, t_0; the Hubble constant, H_0; the ratio of the present energy density to critical density, Ω_0; as well as the contributions of the individual components; the present temperature of the Universe, T_0; the present value of the cosmological constant, Λ_0; and the deceleration parameter, $q_0 = -(1 + \dot{H}_0/H_0^2)$.

Of these, only the temperature of the Universe is well determined, $T_0 = 2.726 \pm 0.01$ K. The age of the Universe is estimated anywhere from 12 to 20 billion years. The Hubble constant is between 100 and 40 km $\mathrm{s^{-1}\ Mpc^{-1}}$. Limits on Ω_0 are from a few percent to one. From QSO lensing we can probably say that $\Omega_\Lambda < 0.6$ which places a limit on $\Lambda = 8\pi G\rho_\Lambda$. Limits to Ω_B were discussed above, and the limits to q_0 we have now are not very useful.

These are all parameters that determine our world model and they should be determined for this reason alone, but there are two other reasons related to early-Universe physics that they must be known. The parameters are important input parameters in the phenomenology of comparing early-Universe theories with present observations. Until we know the parameters, meaningful comparisons of theory and observation cannot be made. Secondly, inflation makes a prediction for some of the parameters. The inflationary prediction that the Universe is spatially flat implies $\Omega_0 + \Omega_\Lambda = 1$. If we make the reasonable assumption that $\Omega_\Lambda = 0$, this implies that $\Omega_0 = 1$. In a flat Universe with $\Omega_\Lambda = 0$ there is a relationship between the age of the Universe and the Hubble constant: $t_0 \simeq 2H_0^{-1}/3$. This means that large values of H_0 and small values of t_0 are at odds with inflation.

6. Theories of the early Universe

Perhaps the most important things that have come from the last 15 years of early-Universe cosmology are theories for dark matter and the origin of the seed fluctuations responsible for CMBR fluctuations and large-scale structure.

6.1. Dark matter

From a particle physics prospective, the most attractive candidate for dark matter is a massive neutrino; after all, we know they exist. The most popular candidate for dark matter represented by a new particle is probably the neutralino (the lightest supersymmetric particle) from the minimal supersymmetric standard model (MSSM).

Part of the attractiveness of the neutralino as dark matter are the manifold implications of its existence. Supersymmetry (SUSY) would be extremely interesting for particle phenomenology, for model building, and for physics beyond the standard model. If SUSY exists near the electroweak scale, it is almost impossible for the neutralino not to be important in the mass density of the Universe today [21]. (SUSY might also be an important ingredient in generating the CP violation required for EWK baryogenesis.)

For some applications it is not necessary to know the exact form of the dark matter, only whether it is "hot," "cold," or "mixed." If the particle is extremely non-relativistic when it comes to dominate the radiation density the particle is said to be cold dark matter. If the particle is still semi-relativistic when it dominates it is said to be hot. The only reasonable candidate for hot dark matter is a neutrino of mass several to several dozen eV. Of course there is an intermediate case known as warm. A mixed dark matter model is when the Universe contains both hot and cold dark matter and they both are dynamically important.

6.2. *Fluctuations*

There are two well developed scenarios for the generation of primordial fluctuations: inflation and defects. Both are capable of producing fluctuations on large angular scales as seen by COBE, and both are capable of producing large-scale structure (whether the large-scale structure produced by either model resembles the structure observed in our Universe is not completely clear).

6.2.1. Inflation: Just as fluctuations in the density field may be expanded in a Fourier series, fluctuations in the scalar field driving inflation, known as the ***inflaton*** field, may be expanded in terms of its Fourier coefficients $\delta\phi_{\mathbf{k}}$: $\delta\phi(\mathbf{x}) \propto \int \delta\phi_{\mathbf{k}} \exp(-i\mathbf{k}\cdot\mathbf{x}) d^3k$. During inflation there is an event horizon, and quantum-mechanical fluctuations in the Fourier components of the inflaton field are given by [22] $k^3 \left|\delta\phi_{\mathbf{k}}\right|^2 / 2\pi^2 = (H/2\pi)^2$, where $H/2\pi$ plays a role similar to the Hawking temperature of black holes. Thus, when a given mode of the inflaton field leaves the Hubble radius during inflation, it has impressed upon it quantum mechanical fluctuations. Fluctuations in the inflaton field on scale k are proportional to $k^{3/2}|\delta\phi_{\mathbf{k}}|$, which in turn is proportional to $H/2\pi$. Fluctuations in ϕ lead to perturbations in the energy density: $\delta\rho_\phi = \delta\phi(\partial V/\partial\phi)$. Now considering the fluctuations as a particular mode leaves the Hubble radius during inflation we may construct the quantity $\zeta = \delta\rho/(\rho + p)$, which is constant outside the Hubble radius in the uniform Hubble gauge, using the fact that during inflation $\rho_0 + p_0 = \dot{\phi}^2$: $\zeta = \delta\phi\,(\partial V/\partial\phi)\,\dot{\phi}^{-2}$. Now the amplitude of the density perturbation when it crosses the Hubble radius *after* inflation is related to ζ and is given by [23] (prime denotes $d/d\phi$)

$$\left(\frac{\delta\rho}{\rho}\right)_\lambda^{\mathrm{HOR}} \equiv \frac{m}{\sqrt{2}} A_S(\phi) = \frac{m\kappa^2}{8\pi^{3/2}} \frac{H^2(\phi)}{|H'(\phi)|} \propto \frac{V^{3/2}(\phi)}{m_{Pl}^3 V'(\phi)}, \qquad (4)$$

where $H(\phi)$ and $H'(\phi)$ are to be evaluated when the scale λ crossed the Hubble radius *during* inflation. The constant m equals 2/5 or 4 if the perturbation re-enters during the matter or radiation dominated eras respectively, and $\kappa^2 = 8\pi G$.

In addition to the scalar density perturbations caused by de Sitter fluctuations in the inflaton field, there are gravitational mode perturbations, $g_{\mu\nu} \rightarrow g_{\mu\nu}^{\mathrm{FRW}} + h_{\mu\nu}$, caused by de Sitter fluctuations in the metric tensor [24]. Here, $g_{\mu\nu}^{\mathrm{FRW}}$ is the Friedmann–Robertson–Walker metric and $h_{\mu\nu}$ are the metric perturbations. That de Sitter space fluctuations should lead to fluctuations in the metric tensor is not surprising, since after all, gravitons are the propagating modes associated with transverse, traceless metric perturbations, and they too behave as minimally

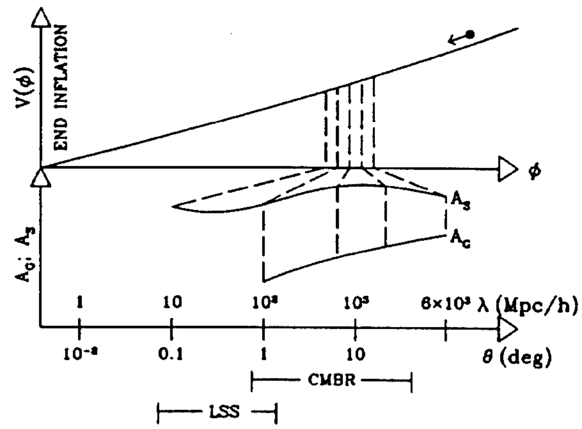

Figure 8. The basic idea of inflation is that as the field evolves in the potential, quantum fluctuations in the inflaton field produce scalar density perturbations A_S, while fluctuations in the transverse, traceless metric components produce tensor gravitational wave perturbations, A_G. Also indicated is the main observational information from the cosmic microwave background, roughly over the range indicated by CMBR, and structure surveys, roughly over the range noted LSS.

coupled scalar fields. The dimensionless tensor metric perturbations can be expressed in terms of two graviton modes we will denote as h. Performing a Fourier decomposition of h, $h(\vec{x}) \propto \int \delta h_k \exp(-i\vec{k}\cdot\vec{x}) d^3k$, we can use the formalism for scalar field perturbations simply by the identification $\delta\phi_{\mathbf{k}} \rightarrow h_{\mathbf{k}}/\kappa\sqrt{2}$, with resulting quantum fluctuations $k^3|h_{\mathbf{k}}|^2/2\pi^2 = 2\kappa^2(H/2\pi)^2$. While outside the Hubble radius, the amplitude of a given mode remains constant, so the amplitude of the dimensionless strain on scale λ when it crosses the Hubble radius after inflation is

$$\left|k^{3/2} h_{\mathbf{k}}\right|_\lambda^{\mathrm{HOR}} \equiv A_G(\phi) = \frac{\kappa}{4\pi^{3/2}} H(\phi) \sim \frac{V^{1/2}(\phi)}{m_{Pl}^2}, \qquad (5)$$

where once again $H(\phi)$ is to be evaluated when the scale λ crossed the Hubble radius *during* inflation.

The basic picture of fluctuations in the evolving inflaton field giving rise to scalar and tensor fluctuations is illustrated in Fig. 8.

All inflationary calculations rely on the use of a ***slow-roll*** approximation, which assumes that quantities like A_S and A_G may be expressed as an expansion in terms of derivatives of the Hubble parameter H. If one defines $\epsilon_0(\phi) = 2\left[H'(\phi)/H(\phi)\right]^2/\kappa^2$, then the expansion variables are $\epsilon_n \equiv \sqrt[n]{2}\,\kappa^{-n}\epsilon_0^{-n/2} d^n\epsilon_0/d\phi^n$. In general there are an infinite hierarchy of these derivatives which can in principle all enter at the same order in an expansion. In practice one assumes that since the potential is flat, only the first few terms are important. The slow-roll approximation applies when these slow-roll parameters are small in comparison to unity. The lowest-order expressions for the scalar (A_S)

and tensor (A_G) amplitudes above assume only ϵ_0 and ϵ_1 are important, and that they are much less than one. Improved expressions for the scalar and tensor amplitudes for finite but small $\{\epsilon_0,\ \epsilon_1\}$ were found by Stewart and Lyth [25].

Since the potential must be flat in order for inflation to occur, H and H' will not vary much over accessible length scales. Therefore it is often convenient to assume that the scalar and tensor fluctuations are given by a power law: $d\ln A_S^2(\lambda)/d\ln\lambda \equiv 1 - n_S$ and $d\ln A_G^2(\lambda)/d\ln\lambda \equiv -n_T$, where n_S and n_T are called the spectral indices. The CDM model assumes $n_S = n_T = 0$.

6.2.2. Defects: Perhaps the most important concept in modern particle theory is that of spontaneous symmetry breaking (SSB). The idea that there are underlying symmetries of nature that are not manifest in the structure of the vacuum appears to play a crucial role in the unification of the forces. In all unified gauge theories—including the standard electroweak model—the underlying gauge symmetry is larger than the unbroken $SU(3)_C \otimes U(1)_{EM}$. Of particular interest for cosmology is the theoretical expectation that at high temperatures, symmetries that are spontaneously broken today were restored, and that during the evolution of the Universe there were phase transitions associated with spontaneous breakdown of gauge (and perhaps global) symmetries. For example, we can be reasonably confident that there was such a phase transition at a temperature of order 100 GeV and a time of order 10^{-11} sec, associated with the breakdown of $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{EM}$. Moreover, the vacuum structure in many spontaneously broken gauge theories is very rich: topologically stable configurations of gauge and Higgs fields exist as domain walls, cosmic strings, and monopoles. In addition, classical configurations that are not topologically stable, so-called non-topological solitons, may exist and be stable for dynamical reasons. Interesting examples include soliton stars, Q-balls, non-topological cosmic strings, sphalerons, and so on.

How can we tell if the Universe underwent a series of SSB phase transitions? One possibility is that symmetry-breaking transitions were not "perfect," and that false vacuum remnants were left behind, frozen in the form of topological defects.

Domain walls arise from the spontaneous breaking of a discrete symmetry. The general mathematical criterion for the existence of topologically stable domain walls for the symmetry-breaking pattern $\mathcal{G} \rightarrow \mathcal{H}$ is that $\Pi_0(\mathcal{M}) \neq \mathcal{I}$, where $\mathcal{M}$ is the manifold of equivalent vacuum states $\mathcal{M} \equiv \mathcal{G}/\mathcal{H}$, and Π_0 is the homotopy group that counts disconnected components.

In general, there will be string solutions associated with the symmetry breaking of a gauge group $\mathcal{G} \rightarrow \mathcal{H}$, if the manifold of degenerate vacuum states, $\mathcal{M} = \mathcal{G}/\mathcal{H}$, contains unshrinkable loops, i.e., if the mapping of $\mathcal{M}$ onto the circle is non-trivial. This is formally expressed by the statement that topologically stable string solutions exist if $\Pi_1(\mathcal{M}) \neq \mathcal{I}$. Such a mapping is typically characterized by the winding number of the mapping, i.e., $\theta \rightarrow N\theta$ ($N = 0,\ 1,\ \cdots$), so that $\Pi_1(\mathcal{M}) = \mathcal{Z}$, the set of integers.

Gauge and Higgs field configurations corresponding to a magnetic monopole exist if the vacuum manifold ($\mathcal{M} = \mathcal{G}/\mathcal{H}$) associated with the symmetry-breaking pattern $\mathcal{G} \rightarrow \mathcal{H}$ contains non-shrinkable surfaces, i.e., if the mapping of $\mathcal{M}$ onto the two-sphere is non-trivial. Mathematically, this is expressed by the statement that monopole solutions arise in the theory if $\Pi_2(\mathcal{M}) \neq \mathcal{I}$. If $\mathcal{G}$ is simply connected, then $\Pi_2(\mathcal{G}/\mathcal{H}) = \Pi_1(\mathcal{H})$. If $\mathcal{G}$ is not simply connected, then the generalization of the above expression is $\Pi_2(\mathcal{G}/\mathcal{H}) = \Pi_1(\mathcal{H})/\Pi_1(\mathcal{G})$.

Defects can also arise in the spontaneous breaking of *global* symmetries. The analogies of the defects discussed above are global strings and global monopoles. The global field configurations look like their local counterparts for the scalar field, but of course there is no vector field. This means that formally the string and monopole solutions have infinite energy (recall for the local defects the energy in the gauge fields cancels the energy in the Higgs field far from the defect.) This is really not a problem, because there the divergence in the energy is only logarithmic, and there are many physical effects to cut it off (such as the inter-defect separation). There are just two main differences in the behavior of gauge and global defects: (1) the energy of the global defects are slightly more spread out, (2) the global strings can radiate energy by the emission of Nambu–Goldstone bosons.

However there are new types of defects in global symmetry breaking that do not appear in the breaking of gauge symmetries. For example, in the spontaneous breaking of a global $O(N)$ model to $O(N-1)$, for $N = 1$ walls appear, for $N = 2$ global strings result, for $N = 3$ global monopoles are produced. These all have counterparts in local theories. However for $N > 3$ global defects also exist: for $N = 4$ the defect is called global texture (for gauge theories the texture configuration resembles instantons), and for $N > 4$ they are called Kibble gradients. Texture corresponds to knots in the Higgs field that arise when the field winds around the three sphere. These knots are generally formed by misalignment of the field on scales larger than the horizon at the symmetry-breaking phase transition because of the Kibble mechanism [26]. As the knots enter the horizon, they collapse at roughly the speed of light, giving rise to nearly spherical energy density perturbations. New knots are constantly coming into the horizon and collapsing, leading to a scale invariant spectrum of density perturbations. The magnitude of the perturbations is set by the scale of the symmetry breaking, and for scenarios of structure formation involving texture, the scale of symmetry breaking must be about 10^{16}GeV.

In the past few years defects produced in the electroweak transition has attracted a lot of interest. Although the breaking scheme $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{EM}$ does not produce stable topological defects, unstable defects are produced: strings that end on monopoles, called electroweak strings. These non-perturbative objects are quite interesting, although their rôle in cosmology (and particle physics for that matter) is still unclear (for a review, see [27]).

7. Phenomenology—connecting theories of the early Universe to present observations

What is predicted from inflation and defects is a primordial scalar (and possibly) tensor perturbation spectrum. The phenomenological exercise is to obtain this information from observations.

It is not too difficult to understand how to obtain the power spectrum from large-scale structure surveys. This was discussed in section 2.1. Of course understanding how to do something in principle is far from obtaining useful results. As discussed in section 2.1, astrophysical effects such as biasing, redshift space distortions, non-linear evolution, etc., has to be understood.

Obtaining the primordial power spectrum from CMBR fluctuations is not as straightforward, even in principle. Let's assume that what is known is the spectrum of CMBR fluctuations, C_l as a function of l as discussed in section 3.2. Now in order to go from the observed C_l to the primordial power spectrum requires a knowledge of the dark matter, as well as the value of the cosmological parameters. To illustrate this, write the observed C_ls as

$$C_l = \int_0^\infty dk\, P(k) T(k) K_l(k), \qquad (6)$$

where $P(k)$ is the primordial spectrum, $T(k)$ is the transfer function which describes how the primordial spectrum is modified by collisionless damping (free-streaming), collisional damping (Silk damping), scattering, etc. $T(k)$ depends upon the nature of the dark matter, the value of Ω, H_0, etc. An example of how $P(k)$ would be modified by a transfer function is shown in Fig. 9.

The function $K_l(k)$ in Eq. (6) represents the fact that any given C_l receives a contribution from all momentum modes (although dominated by modes around $k \propto l$). The form of $K_l(k)$ is quite complicated, and depends upon the physical process giving rise to

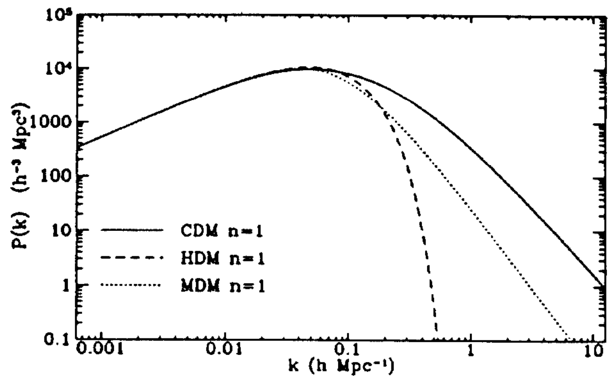

Figure 9. The processed power spectrum depends upon the type of dark matter. All three power spectra started with a primordial flat, Harrison–Zel'dovich spectrum. The solid line is power spectrum if the dark matter is cold (CDM), for instance a SUSY neutralino, the dashed line is hot dark matter (HDM), say a neutrino-dominated Universe, and a mixed model (MDM) containing both a hot and a cold component. [Transfer functions courtesy of M. S. Turner.]

how perturbations in the matter on a given scale k leads to fluctuations in the CMBR with a given multipole moment l. Calculation of $K_l(k)$ involves solving the Boltzmann equation for the evolution of the coupled matter and radiation fluid in the expanding Universe. If the primordial perturbations are curvature fluctuations as expected from inflation, then at large angular scales (small l), $K_l(k)$ is just related to the perturbation in the Newtonian potential on the last scattering surface, while around the Doppler peak in the spectrum of inflation, $K_l(k)$ is determined by Thomson scattering of the photons from moving electrons.

Although calculating the C_l given a theory for the primordial perturbation spectrum $P(k)$ is something that has been done for several years, for the above reasons the inverse problem of deducing the primordial spectrum from measurements of C_l is a more difficult undertaking (as inverse problems usually are). The first steps in this direction are illustrated in Fig. 10 from the work of White, Scott, and Silk [28].

8. Testing theories of the early Universe

Once the primordial fluctuation spectrum is known from CMBR and large-scale structure surveys, and de-convolved with the transfer function to obtain the primordial, unprocessed spectrum, we can compare the result to what is expected from early-Universe theories.

8.1. *Inflation*

The prime observational consequences of inflation derive from the stochastic spectra of density (scalar) perturbations and gravitational wave (tensor) modes

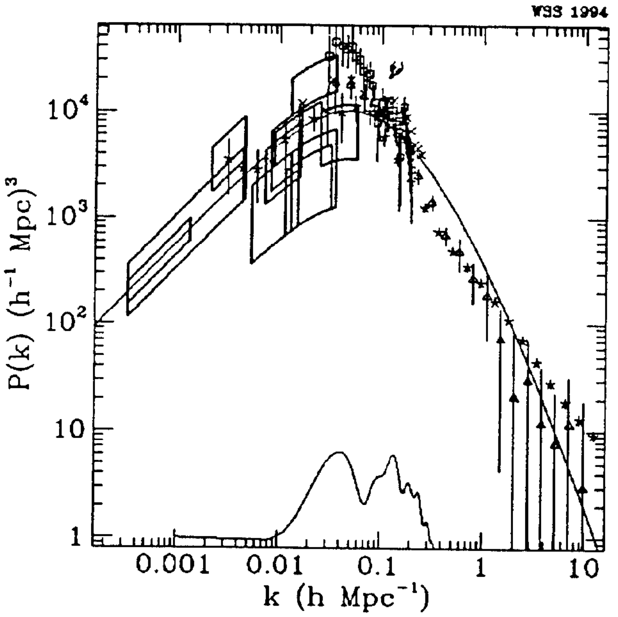

Figure 10. The power spectrum as constructed by White, Scott, and Silk [28]. The solid line is the prediction of a simple CDM model. Clearly what is needed is more information around the peak in the area indicated by the finger.

generated during inflation. Each stretches from scales of order centimeters to scales well in excess of the size of the presently observable Universe. Once within the Hubble radius, gravitational waves redshift away so their main influence is on the large-scale microwave background anisotropies, such as those probed by COBE. The scalar density perturbations are thought to lead to structure formation in the Universe. They produce microwave background anisotropies across a much wider range of angular scales than do the tensor modes, and constraints on the scalar spectrum are also available from the clustering of galaxies and galaxy clusters, peculiar velocity flows and a host of other measurable quantities as discussed in section 2.

Broadly speaking, inflation predicts a very nearly Gaussian spectrum of density perturbations that is *scale dependent*, i.e., the amplitude of the perturbation depends upon the length scale. Such a dependence typically arises because the Hubble expansion rate during the inflationary epoch changes, albeit slowly, as the field driving the expansion rolls towards the minimum of the scalar potential. This implies that the amplitude of the fluctuations as they cross the Hubble radius will be weakly time-dependent.

These primordial scalar and tensor perturbations are processed by various processes, particularly around the time of last-scattering of the CMBR.

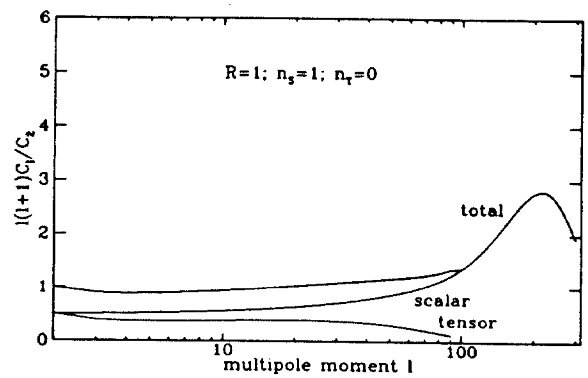

Figure 11. The spectrum of temperature fluctuations predicted in a sample inflationary model with equal tensor and scalar perturbations on large scales with the indicated primordial spectral indices. Note the suppression of the Doppler peak compared to the result with no tensor component [data courtesy of Scott Dodelson and Lloyd Knox].

8.2. Defects

If defects from early-Universe phase transitions play a role in large-scale structure, their most striking signature would be in the CMBR. There would be no Doppler peak in the spectrum, and at some level the fluctuations would be non-Gaussian, with substantial hot and cold spots.

Sufficiently large maps of the microwave sky with small enough angular resolution are not yet available to settle the question of the Gaussian nature of the fluctuations. Not only is there insufficient data to say for sure whether there is a Doppler peak in the spectrum, but without knowledge of the cosmological parameters, including the degree of tilt in the scalar spectrum and the contribution of the tensor component to the fluctuations, it is impossible to estimate the height of the Doppler peak expected in inflation models (see Fig. 11).

However within the next few years the situation could change, particularly with respect to the Doppler peak, where there is already weak evidence for its existence.

How defects lead to structure formation is less developed than in the inflation scenario. The most promising discriminant might be early structure formation, where defects seem to produce non-linear structures at fairly early times.

9. The Payoff

If the early-Universe program proves successful, then basic physics will give us information about the origin and nature of large-scale structure in the Universe. However it is possible that the nature of large-scale structure of the Universe will give us information about basic physics.

If the primordial fluctuations arise from topological defects produced in the early Universe, then detailed study of the CMBR fluctuations should reveal the following information about the symmetry breaking phase transition.

1 The scale of SSB: The scale of symmetry breaking and the Planck mass are the only scales in the problem. Quantities such as the mass per unit length of a cosmic string is proportional to the SSB breaking scale, σ, and observables such as the CMBR fluctuations are proportional to some power of σ/m_{Pl}. In order to be important for structure formation σ must be in the neighborhood of 10^{16}GeV. If defects are discovered, then it should be possible to pin down σ to within a factor of two or so.

2 The nature of the symmetry: Defects arising from the breaking of a global symmetry have a different character than defects arising from the breaking of a local symmetry, because without the gauge field to compensate the energy in the scalar field, the mass of a global defect is logarithmically divergent (cutoff by the inter-defect separation). Detailed simulations show a difference between global and local defects that should eventually be distinguishable.

3 The rank of the broken symmetry: If we consider the breaking of global symmetries, say $O(N) \to O(N-1)$, the resulting defect depends upon N. As the simulations show that the pattern of anisotropies in the CMBR are different for the various types of defects, N is, in principle, a measurable quantity.

4 The fate of global symmetries in quantum gravity: The scenario of defects arising from the spontaneous breaking of global symmetries requires that any explicit breaking of the global symmetry be extraordinarily small. One might expect a slight breaking of the global symmetry if quantum-gravitational effects do not respect global symmetry. These would appear as high-dimensional operators in the Lagrangian that explicitly break the global symmetry. If global defects are discovered, it would imply that either the coefficient of these higher-dimensional operators are unnaturally small, or quantum gravity respects global symmetry.

If the primordial fluctuations arise from quantum fluctuations generated during inflation, then there is also information about fundamental physics we can learn from observations:

1 Can the equation of state giving $\rho + 3p < 0$ be described by the dynamics of a *single* scalar field ϕ evolving under the influence of a canonical potential $V(\phi)$? One might think that there are many scalar fields in the fundamental theory contributing to the energy density, with many possible directions for evolution. Whether this will have any effect on the predictions of inflation with regard to $A_G(\lambda)$ and $A_S(\lambda)$ remains to be seen.

2 The parameters of slow roll: The spectral indices n_S and n_T as well as the ratio of tensor modes to scalar modes depends on the inflaton potential. We can deduce the parameters of slow roll from observations.

3 Prove the existence of gravitons: If unambiguous evidence for the existence of tensor perturbations is discovered, then we will know that gravity is quantized. More specifically, the production of the tensor perturbations depends upon the canonical quantization condition for the metric tensor. In the calculation it is assumed that one can write the metric as a perturbation of the FRW metric: $g_{\mu\nu} = g^{\mathrm{FRW}}_{\mu\nu} + h_{\mu\nu}$. What is required is a quantization condition for $h_{\mu\nu}$: something like $[h, \dot{h}] = i\hbar\delta$ in cryptic notation. Therefore CMBR observation could provide the first evidence that small fluctuations of the metric tensor about the FRW background are quantized: in other words, gravitons exist.

4 Finally, if some evidence that $A_G(\lambda) \neq 0$ is found, then it might be possible to reconstruct the potential.

Potential reconstruction has recently received some attention [29, 30], here I can only give the basics. For simplicity I will work only to first order in the slow-roll parameters. Now for reconstruction. From Eq. (5) it is clear that if $A_G(\lambda)$ is known, the value of the potential V corresponding to the value of ϕ corresponding to present distance scale λ is known. So knowledge of $A_G(\lambda)$ is the key to potential reconstruction. However as discussed in section 8.1, once inside the horizon the contribution to the C_ls from the tensor component rapidly decreases. Therefore we can anticipate information about $A_G(\lambda)$ only on the largest scales.

However if we know $A_G(\lambda)$ on one scale, and $A_S(\lambda)$ on a variety of scales, we can deduce $A_G(\lambda)$ on the scales spanned by $A_S(\lambda)$ [29]. Recall that the result for $A_G(\lambda)$ depends only upon $V(\phi)$ (to lowest order), while the result for $A_S(\lambda)$ depends upon $V(\phi)$ and its derivative $V'(\phi)$. We can express this schematically ~~as~~ $A_G = A_G(V)$ and $A_S = A_S(V, V')$. Clearly $A'_G(\lambda)$ can be expressed as some combination of A_S and A_G. To

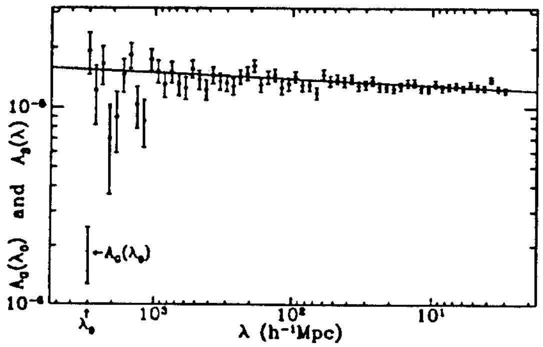

Figure 12. The illustration of an anticipated data set limited by cosmic variance [31]. The data was generated with a $\lambda_\phi \phi^4$ potential with $\lambda_\phi = 4 \times 10^{-14}$. The upper points are $A_S(\lambda)$, while the single lower point is $A_G(\lambda)$. The solid line is the mean $A_S(\lambda)$, while the mean $A_G(\lambda_0)$ is 2×10^{-6}.

first order in the slow-roll parameters it is

$$\frac{\lambda}{A_G(\lambda)} \frac{dA_G(\lambda)}{d\lambda} = \frac{A_G^2(\lambda)}{A_S^2(\lambda)}. \tag{7}$$

Thus if we know $A_G(\lambda)$ at one scale, we can use this equation as an evolution equation to find $A_G(\lambda)$ and hence $V(\phi)$.

To illustrate reconstruction, let's assume a simple power-law potential of the form $V(\phi) = \lambda_\phi \phi^4$ with $\lambda_\phi = 4 \times 10^{-14}$. This generates perturbation spectra of the form (evaluated at horizon crossing after inflation)

$$\begin{aligned} A_S(\lambda) &= 4 \times 10^{-8} \left[50 + \ln(\lambda/\lambda_0)\right]^{3/2} \\ A_G(\lambda) &= 4 \times 10^{-8} \left[50 + \ln(\lambda/\lambda_0)\right]. \end{aligned} \tag{8}$$

On any scale, the number of statistically independent sample measurements of the spectra that can be made is finite. Given that the underlying inflationary fluctuations are stochastic, one obtains only a limited set of realizations from the complete probability distribution function. Such a subset may insufficiently specify the underlying distribution, which is the quantity predicted by an inflationary model. This cosmic variance is an important matter of principle, being a source of uncertainty which remains even if perfectly accurate experiments could be carried out. At any stage in the history of the Universe, it is impossible to specify accurately the properties (most significantly the variance, which is what the spectrum specifies assuming Gaussian statistics) of the probability distribution function pertaining to perturbations on scales close to that of the observable Universe.

Even assuming "perfect" observations, cosmic variance sets a lower limit on the uncertainty at any one scale. Assuming that the only errors come from cosmic variance, the determination of the spectra might look like in Fig. 12. In the realization generated by the random number generator, the value of $A_G(\lambda_0)$ is 1.87×10^{-6}, slightly below the ensemble mean of 2×10^{-6}.

As a first exercise, we simply perform a first-order reconstruction by doing a simple trapezoidal integration, and making the naïve assumption that the errors are uncorrelated. If we do that we obtain the reconstructed potential shown in Fig. 13. Also shown in Fig. 13 by the solid curve is the actual potential used to generate the synthetic data from which the potential was reconstructed.

There are several things we can notice in Fig. 13. First of all, reconstruction works: the true potential is within the error bars. The second obvious feature is that the slope of the reconstructed data is better than one might expect given the errors. This feature can be explored by taking another approach to the uncertainty introduced in $A_G(\lambda_0)$ by cosmic variance. Let's ignore that error, and pick three realizations of $A_G(\lambda_0)$, one at the "measured" value, one 1σ above the measured value, and one 1σ below the measured value. (Here "σ" is the value determined by cosmic variance.) If we do that, we generate the three curves shown in Fig. 13. Although we can't tell which of the curves is the true potential, we know that the true potential is one of a family of curves bounded by the two extremes in the figure. We can understand why this occurs, because if we look at the slope of V^{-1}, the initial value of $A_G(\lambda)$ drops out, and the contribution comes from adding together a large number of different $A_S(\lambda)$. Since we are combining a large number of data points, the central limit theorem tells us that the errors in the reconstructed potential will become small.

10. Could we be wrong?

Cosmology has traditionally been a science poor in data, but rich in speculation. At least with regard to the lack of data, the situation is changing. And as has been discussed in this paper, perhaps some of the speculations in early-Universe cosmology have turned out to be surprisingly rich in content.

But as data comes pouring in, it is useful occasionally to take a reality check and see if there is anything that would completely change our belief in the relevance of early-Universe cosmology, or even more surprisingly, our basic picture of the big-bang.

Here I would like to highlight some possible ways our picture can be dramatically changed in order of increasing shock to cosmologists:

1 Does the temperature increase with the redshift? In addition to detecting deuterium in quasar absorption systems, carbon can be discovered. If the absorbers are at relatively high redshift, transitions

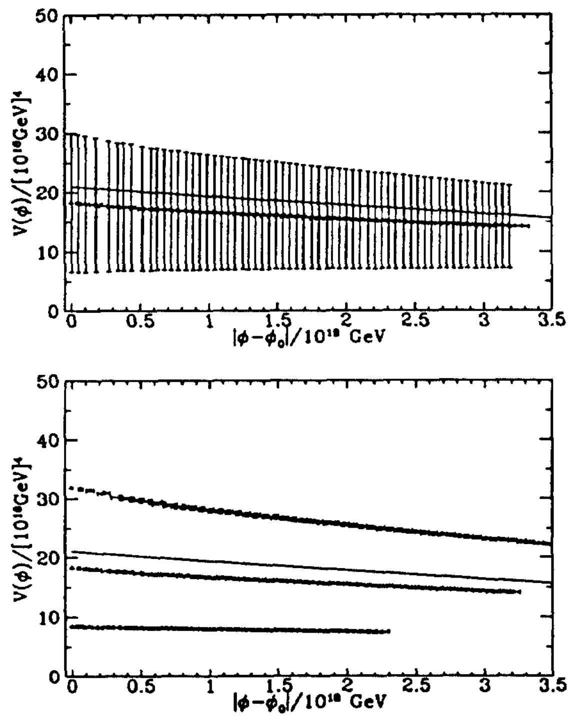

Figure 13. The upper graph is a first-order reconstruction of the example $\lambda_\phi \phi^4$ potential [31]. The solid line is the actual potential, while the points and associated errors were generated from the data above. The lower curve is the reconstructed potential ignoring uncertainty in $A_G(\lambda_0)$ for three choices of $A_G(\lambda_0)$ corresponding to the midpoint and $\pm 1\sigma$.

from the ground state of singly ionized atomic carbon (CII) can be seen. There should also be transitions from the fine-structure-split state of singly ionized atomic carbon (CII*), which lies just 64 cm^{-1}, or about 10^{3}eV, above the ground state. The temperature of the Universe scales with redshift as $T = T_0(1+z)$ where T_0 is the present temperature. Therefore the temperature as a function of redshift should be $T = 2.35 \times 10^{-4}(1+z)$eV. At z larger than about unity, there are enough photons in the blackbody distribution to populate the CII* state, and eventually transitions will be seen. By measuring the relative line strengths of CII/CII*, the relative populations of the two states can be determined, and hence the temperature of the Universe as a function of redshift can be measured. Any departure of $T(z)$ from the expected $1+z$ dependence would have profound implications and shake our very belief in the big bang model.

2 Could CMBR fluctuations be non-cosmological in origin? One year ago it was possible to say that perhaps the CMBR fluctuations reported by COBE were spurious. The original 1992 announcement was based upon one year's data which gave a map of the sky that was 12σ above what could be expected for a blank sky. Now in the 2-year data, with better understanding of systematic errors in addition to an increase in statistics, the statistical significance is even greater (of course much, much greater than 2.8σ) compared to a blank-sky map. With the fact that many other experiments see microwave fluctuations (in particular the FIRS experiment [32] sees fluctuations correlated with regions of the sky where COBE sees fluctuations), it is now impossible to say that the sky is featureless. Detection of anisotropies is not the whole game however, it is necessary to demonstrate that the fluctuations are not caused by any foreground contamination. Most CMBR experiments have some spectral information to differentiate between a spectrum of fluctuations caused by dust, synchrotron, or bremsstrahlung. We're close to having a spectrum of the fluctuations will prove that they are thermal as expected for CMBR fluctuations.

3 Is the Universe too old? There is a relationship between the age of the Universe, the Hubble constant, and Ω_0. Eventually these will be measured, and if the age relation is not satisfied, it will either prove the existence of a cosmological constant large enough to curve space sufficiently to be detectable, or the big bang is wrong. If one believes in inflation, then the dependence upon Ω_0 drops out (since it is one), and the situation is easier to compare to observations. A measurement of a high Hubble constant (h greater than 0.85 or so), or unambiguous evidence that the age of the Universe is large (greater than 17×10^{9}yr or so) would ether rule out inflation or demand a cosmological constant.

4 There is a standard range for the light element (H, ^{2}H, ^{3}He, ^{4}He, and ^{7}Li) abundances from nucleosynthesis. If the Songaila et al. result is correct, then the ^{2}H abundance lies outside this accepted range. This would mean that either standard primordial nucleosynthesis is wrong, or what we believe to be the range of the primordial abundances of the other light elements are slightly off. It would be surprising (to me), but not impossible, to imagine the second possibility, but the lack of *any* possible agreement among the light elements would invalidate the simple picture of BBN and would really change the way we view the early Universe.

5 Finally, as discussed in the second section, evidence that all the structure we see in the Universe emerged as a result of a single primordial fluctuation spectrum seems to be building. However it may turn out that this is not so. Evidence that the

structure we see in the Universe did not result from seed perturbations would invalidate all of the early-Universe scenarios and truly leave us in the dark about the origin of light in the Universe.

11. Conclusions

Early-Universe cosmology, motivated by particle physics, has been remarkably influential in the development of models for the origin of large-scale structure and CMBR fluctuations. One particular version of a simple model, CDM, which is cold dark matter dominating the Universe and fluctuations produced by inflation, has emerged as the standard picture for structure formation and CMBR fluctuations.

This simple picture has a primordial curvature fluctuation spectrum of fluctuations that is scale free, and has a power-law index of $|\delta_k|^2 \propto k^{1-n_S}$ with $n_S = 1$. It is remarkable how well this simple model does in reproducing the basic features of $P(k)$. This can be seen in Fig. 10, where the solid line is the CDM spectrum processed with a CDM transfer function. Any model of $P(k)$ must look a lot like CDM.

However most cosmologists believe that CDM cannot be the complete story, and many variants of CDM have been developed, including tilting the primordial spectrum away from $n_S = 1$ as predicted by some inflation models, or by changing the transfer function by adding a bit of hot dark matter to the mix.

In the near-term future, we can expect the observational situation to improve greatly: new large-scale structure surveys for a more accurate determination of $P(k)$ and determination of it over a larger range of k, as well as much improved information of the spectrum of CMBR fluctuations.

It is fair to say that we do not yet have a standard model of large-scale structure formation and CMBR fluctuations, but perhaps we can see the emergence of a standard scenario, involving primordial curvature fluctuations. It would be like in a particle physics situation where we know that the standard model involves spontaneously broken and unbroken gauge symmetries, but don't know the gauge groups involved or the particle content. However the observations are coming in at such a rapid pace, and phenomenology and theory are being developed so quickly, that we should soon be able to turn the standard scenario into a standard model.

Once a standard model for large-scale structure and CMBR fluctuations are in hand, then we can truly confront early-Universe scenarios with the observations. In so doing we can learn about fundamental physics. Inflation and defects seem to point to energy scales of 10^{16}GeV or so, and the first information about fundamental processes at these energies may well come from cosmology.

Information about fundamental physics is written upon the sky, it is our job to read it.

Acknowledgements

I would like to thank Toni Cowie, Craig Hogan, Jon Loveday, John Peacock, Douglas Scott, Joe Silk, Martin White, and the MACHO collaboration for allowing me to incorporate figures from their work. I would also like to thank Scott Dodelson, Llyod Knox, and Mike Turner for unpublished data. This work was supported in part by DOE and NASA under grant NAGW–2381.

References

[1] J. A. Peacock and S. J. Dodds, *Mon. Not. R. astr. Soc.* **267**, 1020 (1994).

[2] V. de Lapparent, M. J. Geller, and J. Huchra, *Ap. J.* **302**, L1 (1986); *ibid*, **332**, 44 (1988); M. J. Geller, J. Huchra, and V. de Lapparent, in *Observational Cosmology* (IAU Symposium 124), eds. A. Hewitt, G. Burbidge, and Li-Zhi Fang (Reidel, Dordrecht, 1987), p. 301.

[3] J. Loveday, B. A. Peterson, G. Efstathiou, and S. J. Maddox, *Ap. J.* **390**, 338 (1992).

[4] E. Bertschinger and A. Deckel, Astrophys. J. **336**, **L5** (1989).

[5] For a brief review, see J. A. Tyson, in *Cosmology and Large Scale Structure (Les Houches 1993*, R. Schaeffer, ed. (Elsevier Science Publishers, 1994).

[6] J. C. Mather et al., Astrophys. J. **354**, L37 (1990).

[7] G. Smoot et al., Astrophys. J. **396**, L1 (1992).

[8] J. R. Bond and G. E. Efstathiou, Astrophys. J. **285**, L45 (1984).

[9] D. Coulson , R.G. Crittenden, and N.G. Turok , Princeton University report PUPT-1473; R. Crittenden, R. L. Davis, P. J. Steinhardt, astro-ph/9306027.

[10] V. Trimble, *Ann. Rev. Astron. and Astrophys.* **25**, 425 (1987).

[11] E. W. Kolb and M. S. Turner, *The Early Universe* (Addison-Wesley, Reading, Ma., 1990).

[12] B. Sadoulet, private communication.

[13] B. Sadoulet, in *Current topics in astrofundamental physics*, proceedings of Erice 1991.

[14] For a review, see e.g., M. Kamionkowski, in *29th Rencontres de Moriond: Perspectives in Particle Physics, Atomic Physics and Gravitation* Jan 1994.

[15] E. W. Kolb and M. S. Turner, *Ann. Rev. Nucl. Part. Sci.* **33**, 645 (1983).

[16] Cohen, Kaplan, Nelson, *Ann. Rev. Nucl. Part. Sci.* **43**, 27 (1993).

[17] A. Songaila et al., *Nature* **368**, 599 (1994).

[18] R. F. Carswell et al., *Mon. Not. R. ast. Soc.* in press (1994).

[19] B. Paczynski, *Ap. J.* **304**, 1 (1986).

[20] C. Alcock et al., *Nature* **365**, 621 (1993); E. Aubourg et al., *ibid* **365**, 623 (1993); A. Udalski et al., *Acta Astronomica* **43**, 289 (1993).

[21] In addition to contributions at this conference, see e.g., K. Griest and L. Roszkowski, Phys. Rev. D**46**, 3309 (1992).

[22] T. Bunch and P. C. W. Davies, *Proc. Roy. Soc. London* **A360**, 117 (1978).

[23] A. H. Guth and S.-Y. Pi, *Phys. Rev. Lett.* **49**, 1110 (1982); A. A. Starobinskii, *Phys. Lett.* **117B**, 175 (1982); and S. W. Hawking, *Phys. Lett.* **115B**, 295 (1982); J. M. Bardeen, P. J. Steinhardt, and M. S. Turner, *Phys. Rev. D* **28**, 679 (1983).

[24] V. A. Rubakov, M. Sazhin, and A. Veryaskin, Phys. Lett. **115B**, 189 (1982); R. Fabbri and M. Pollock, Phys. Lett. **125B**, 445 (1983); B. Allen, Phys. Rev. D **37**, 2078 (1988); and L. Abbott and M. Wise, Nucl. Phys. **B244**, 541 (1984).

[25] E. D. Stewart and D. H. Lyth, Phys. Lett. **302B**, 171 (1993).

[26] See e.g., T. W. B. Kibble, *Phys. Rep.* 67, 183 (1980).

[27] T. Vachaspati and A. Achucarro, Phys. Rev. D**44**, 3067 (1991).

[28] M. White, D. Scott, and J. Silk, *Ann. Rev. Astron. and Astrophys.* **32**, 319 (1994).

[29] E. J. Copeland, E. W. Kolb, A. R. Liddle and J. E. Lidsey, Phys. Rev. Lett. **71**, 219 (1993); Phys. Rev. D**48**, 2529 (1993); Phys. Rev. D**49**, 1840 (1994).

[30] H. M. Hodges and G. R. Blumenthal, Phys. Rev. D**42**, 3329 (1990); and M. S. Turner, Phys. Rev. D**48**, 5539 (1993); A. R. Liddle and M. S. Turner, Phys. Rev. D**50**, 758 (1994)

[31] M. Abney, E. J. Copeland, E. W. Kolb, A. R. Liddle and J. E. Lidsey, in *Proceedings of the 1994 Coral Gables Conference*, Fermilab report FERMILAB-CONF-94-189-A, astro-ph/940721.

[32] K. M. Ganga et al., Astrophys. J. **410**, L57 (1993).