Topics at the Interface of Particle Physics and Cosmology

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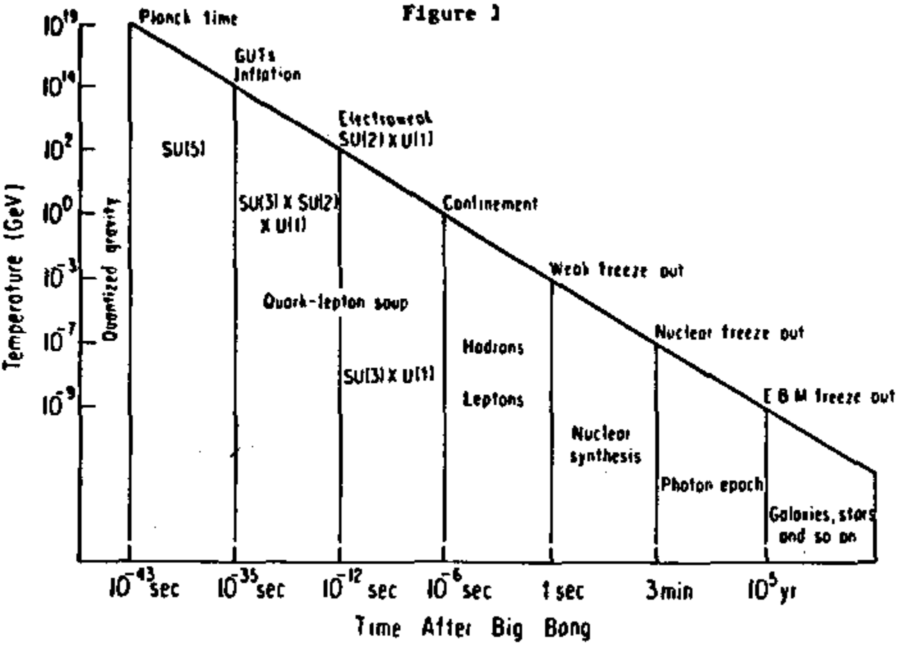
ABSTRACT

Emphasis is placed on topics at the interface of particle physics and cosmology in this review of the cosmological timeline. The importance of phase transitions in producing observables in the early universe will readily become apparent. The flow of information between particle physics and cosmology is no longer one way, as will be illustrated with many examples.

1. Introduction

Over the past few years, the fields of cosmology and particle physics have developed very rapidly. For several decades now, developments in particle theory have explained long standing cosmological problems. It is not until recently, however, that cosmology has been able to place constraints on particle properties, constraints that can be tested by experiment. Thus the flow of information at the interface of particle physics and cosmology is no longer just one way. Many examples of the interchange will be described in this review. The timeline of cosmology is rapidly filling in as later events find their explanations in earlier events. We shall see that phase transitions in the early universe produce observables which can be used as evidence of the occurrence of a transition or as a way of working out the details of the transition. Figure 1 depicts the timeline of the early universe, emphasizing the occurrence of phase transitions. In this review, we will describe what is known about each epoch. Since a great deal of effort is currently devoted to the study of the dark matter problem, special emphasis will

Figure 1



be placed on this issue. This study of dark matter and galaxy formation will allow us to draw upon much of what was discussed in earlier epochs.

2. Quantum gravity

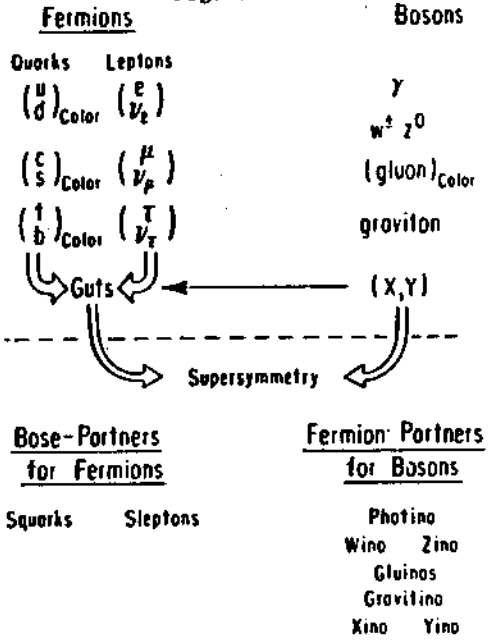
We begin by discussing the least understood epoch of the universe, the era of quantized gravity. Before the Planck time, 10^{-43} sec, at energies exceeding 10^{19} GeV, it is expected that gravity is unified with the other forces. The physics of this time period cannot be described, because no reliable quantum field theory for gravity exists. It has been suggested by Steven Hawking that, at the Planck time, all of space-time is a foam of mini black holes, each with a mass of around 10^{19} GeV. These black holes will evaporate and re-form on a time scale of 10^{-43}

seconds. Cocconi[1] has proposed that the gravitational constant may vary at temperatures greater than 10^{19} GeV in analogy with other gauge coupling constants which vary above an appropriate critical energy. On an even more speculative note, it is hoped that the expansion rate H_0 and the deceleration rate q_0 are observables produced at the 'freezeout' of quantum gravity. The basis for this hope is the many examples of observables produced when an interaction decouples from the background. Perhaps further study of the quantum gravity epoch will add H_0 and q_0 to the growing list of those properties of the universe, once thought to be initial conditions, which now have explanations, just as study of the GUTs epoch has yielded the cosmologically-observed baryon to photon ratio. Most theories of supergravity involve more than four dimensions. The extra dimensions are not observed today, so the theories operate on the assumption that they are compactified on the scale of the Planck length. Perhaps this will lead to an explanation of the origin of 3 + 1 dimensions.

3. GUTS

In the epoch following the Planck time the strong, weak and electromagnetic forces remain unified until the energy drops below 10^{14} GeV at 10^{-35} seconds. Above this energy, the Grand Unified Theory (GUT) gauge particles X and Y, which carry the grand unified force, exist. The X's and Y's would be able to interconvert quarks and leptons. Thus at the GUTs epoch there would be nonconservation of baryon number and lepton number, quantities conserved at lower energies. The nonconservation of baryon number led to the GUTs' prediction of proton decay. Experiments to measure the proton lifetime are a way of exploring which quantum field theory describes the GUTs epoch correctly. The simplest GUT which can be considered is SU(5)[2]. SU(5) predicts proton decay with the lifetime $\sim 10^{30}$ years by the dominant mode $p \rightarrow e + \pi^0$. As we will see, even before the experiment cosmologists already doubted SU(5) from baryosynthesis arguments. The Irvine-Michigan Brookhaven (IMB) proton decay experiment has essentially ruled out the minimal SU(5) model. In this experiment, no decays the mode $p\rightarrow e+\pi^0$ were found for about one year in 10^4 tons of water, giving a lifetime for $p\geq 10^{32}$ years. Although SU(5) was the simplest GUT, another class of GUT, supersymmetric or (SUSY) GUTs have a different and perhaps more significant appeal. In SUSY, each fermion (boson) is required to have a boson (fermion) partner. New families of particles were created since existing particles did not match up correctly. Fig. 2 is a summary of the particle types including their supersymmetric partners which have not been seen since terrestrial accelerators have not yet reached sufficiently high energies, (a few TeV). SUSY seems to point the way somewhat more clearly to unification of GUTs with gravity and also seems to explain the mass differences between the various gauge bosons.

Figure 2



Masses of gauge particles are produced by the Higgs field during a phase transition. We will describe the transition further when discussing inflation. SUSY models predict proton decay via the mode $p \rightarrow \mu^+ K^0$ with somewhat larger range in lifetimes than the 10^{30} years required by minimal SU(5). SUSY favors μK because in it the decay goes via a Higgs particle which couples to mass, thus favoring the most massive quark that is less massive than the proton, the strange quark, which is in kaons. The IMB experiment is not particularly sensitive to decay via this mode, but it does have one possible candidate[3]. The experiment, NUSEX, conducted at Mont Blanc Tunnel, also has a candidate. The Kamioka experiment has two possible $\mu\eta$ events which also involve strange quarks. New μK sensitive proton detectors should give a definite result, but it is tentatively possible that the proton lifetime is on the order of a few times 10^{31} years. This is in accordance with the predictions of SUSY, but these few events aren't sufficient to prove anything yet.

3.1. Baryogenesis

One of the most attractive characteristics of GUTs is that they are able to yield a net n_b/n_γ for the universe[4]. Direct observations of cosmic rays and of the γ-ray background demonstrate a net baryon assymetry. Nucleosynthesis arguments, to be discussed later in this paper, constrain the baryon to photon ratio to the range $(4\text{-}7)\times 10^{-10}$. Sakharov[5] outlined the three ingredients needed for baryogenesis: baryon non-conservation, C and CP violation and departure from thermal equilibrium. Baryon non-conservation is clearly required if an initially symmetric universe is to develop a net n_b/n_γ. Unless both C (charge conjugation) and CP (charge conservation combined with parity) are violated, B (the net baryon number) is zero since it changes sign under C and CP. Departure from thermal equilibrium is required, since, in thermal equilibrium, the baryon density depends only on the temperature and the particle mass which is the same for a particle and an antiparticle. We have already seen that baryon nonconservation follows from GUTs. C is violated in weak interactions, but, thus far, CP violation has only been observed in the $K^0\overline{K^0}$ system. The axion may provide an explanation for the strong CP problem: why the strong interaction conserves CP and the weak does not[6]. It seems likely that CP is also violated at very high energies in the decays of superheavy bosons. An upper limit for the magnitude of CP violation can be found from a measurement of the electric dipole moment of the neutron since the two quantities are related[7]. Thermal equilibrium is maintained only if reaction rates are much greater than the Hubble constant. As the universe expands and cools, reaction rates drop to values lower than expansion rates and processes drop out of equilibrium. Detailed calculations of specific GUTs models[8,9] have yielded a net baryon to photon ratio in the observed range. It was noted that minimal SU(5) made too small a baryon to photon ratio unless an additional generation, a richer Higgs sector or an axion U_1 field was added[10]. One important consequence of the GUTs determination of n_b/n_γ as a unique function of temperature was the requirement that primordial fluctuations must be adiabatic[11,12]. Isothermal fluctuations were ruled out since n_γ = constant implies n_b = constant. We will return to this point later.

3.2. Inflation

Another consequence of the GUTs transition is the generation of magnetic monopoles. When the group SU(5) is broken to yield the U(1) subgroup, electromagnetism, monopoles are produced[13,14]. The number of monopoles produced should be quite high, comparable to the number of baryons produced[15,16]. Observations clearly rule out the existence of this many monopoles. Some adjustment is needed to solve this problem. This adjustment leads to the theory of inflation.

Inflation solves the monopole problem as well as three other significant cosmological problems: the horizon problem, the flatness problem and the clumping problem. The horizon problem deals with the question of why the universe is so smooth on large scales. Recent limits on the 3K anisotropy give $\delta T/T \leq 2.1\times10^{-5}$ at the decoupling of radiation from matter at $T = 3000K$[17] At that time opposite parts of the sky were apparently causally disconnected even more so than at the present. Why is the universe so homogeneous and isotropic if separate regions were causally disconnected, that is, each outside the others horizon? The second problem, the flatness problem, is finding an explanation for why the cosmological density parameter, $\Omega = \rho/\rho_{crit}$, is so finely tuned to one. At the Planck time, this parameter should evolve on a dynamical timescale of 10^{-43} seconds. By the present time it would have evolved to ∞ or 0 depending on whether $\Omega > 1$ or $\Omega < 1$ unless it was 1.000... to over 50 decimal places. Finally, why does the universe contain density perturbations, ('bumps'), such as stars, galaxies, and clusters of galaxies, on a small scale if the universe is so smooth on a large scale?

In 1981, Guth[18] proposed the theory of inflation as a solution to these problems. Although buds of inflation existed as early as 1975[19,20,21], Guth was the first to put all the pieces together and to realize that inflation could solve cosmological problems. The idea is based on the existence of a non-zero vacuum energy produced by the Higgs field in GUTs. When the radiation density is no longer higher than the energy density of this false vacuum, the universe enters a phase in which the scale factor grows exponentially, a deSitter phase. When symmetry is broken in the GUTs phase transition, the energy in the Higgs field produces the masses of the gauge particles, the vacuum energy goes to zero and inflation stops. The horizon problem is solved since opposite parts of the universe were causally connected before inflation. Inflation also solves the monopole problem. Since each horizon prior to inflation would contain less than one monopole, thus less than one monopole generated in the GUTs transition would exist in the universe today. Inflation would make the scale factor $R \to \infty$, so the curvature term k/R^2 would be suppressed and the universe would be flat, $\Omega = 1$. Finally, bumps could be generated in the phase transition as different domains mixed to create our present space. The problem with this original inflation theory is that the phase transition is unable to go to completion, because the bubbles of broken symmetry inflate away from each other faster than they expand.

This problem was solved in the theory of new inflation proposed by Linde[22] and Albrecht and Steinhardt[23]. In this theory, the transition is a smooth Coleman-Weinberg type in which, during the vacuum-dominated era, the universe is evolving towards the true vacuum. The result of this kind of a transition is that our universe is a single bubble. As in the original inflation, the horizon, flatness and monopole problems are solved. But since we must live in a single bubble, all perturbations must be generated within this bubble. Numerous investigators[24] found that fluctuations could be generated with the Harrison-Zeldovich spectrum[15] which put equal power on all scales as observed. Standard GUTs, however, resulted in $\delta\rho/\rho \gtrsim 10$, a factor of 10^5 more than observed limits required by 3K anisotropy[25,26,27]. Such large fluctuations would collapse to black holes rather than to galaxies. Possible solutions to this problem are supersymmetry (SUSY), supergravity or extra Higgs sectors[28,29,30,31]. These all require what presently seems to be ad hoc tuning. Despite the fact that the details of inflation have yet to be worked out, it is currently viewed with a great deal of certainty, since it has been so successful in solving the cosmological problems discussed above.

Finally, the GUTs transition may produce strings rather than bubbles if the vacuum in the model has the correct topology. This is analogous to phase transitions in crystalization which produce filaments. Strings will later be discussed as a possible solution to the dark matter problem.

Recently, much attention has been devoted to the study of multidimensional universes. As a simple example, let us consider a five-dimensional universe which can be described by the Kasner metric. It is the property of this metric that the three spatial dimensions begin to grow, and the fifth dimension shrinks at approximately the Planck time. In five dimensions the symmetry of the fifth dimension corresponds to the electromagnetic U(1) gauge symmetry. It is possible that 3 + 1 dimensions are able to inflate while the fifth does not. These ideas can be extended to cosmologies with a larger number of dimensions, with the result that the spatial dimensions inflate and the remaining dimensions representing the GUTs force and gravity remain small. In particular SUSY looks best in 10 + 1 dimensions where the compactified dimensions have all the symmetries of the four observed forces.

4. Quark lepton soup

After the GUTs transition we enter a somewhat more familiar epoch, that of SU(3)×SU(2)×U(1) phase space. In this epoch, above 100 GeV, the weak and electromagnetic interactions remain unified as predicted over a decade ago by Weinberg, Salem and Glashow and verified in 1983 by the discoveries of the intermediate vector bosons (W^+, W^- and Z^0) by Rubbia *etal.*[32] in 1983. Quarks and leptons are no longer interconverted since baryon number is conserved and the universe exists as a 'soup' of quarks and leptons. At 100 GeV, (10^{-12}sec), the Weinberg-Salem transition occurs, and the symmetry between the weak and the electromagnetic forces, (SU(2)×U(1)), is broken. The next event is the quark-hadron symmetry transition at 1 GeV (10^{-6}sec). Although the quark-hadron transition (quark confinement) and chiral symmetry breaking (quarks obtaining mass) seem to be quite different physical processes, calculations have shown that they probably occur at the same time. It is thought that the transition is first order, although the word on this subject is not definite. Details on this subject can be found in the Quark Matter '83 proceedings[33].

The possibility of black hole formation at both the electroweak and the quark-hadron-chiral symmetry transitions has been discussed, the former by Crawford[34] and Novikov[35] and the later by Crawford and Schramm[36] and Schramm and Olive[37]. These black holes would be of planetary mass and thus would not explode by the Hawking process in the age of the universe. They also form before Big Bang nucleosynthesis so they are not limited as later black holes are. Production of such black holes would require a first order phase transition. The electroweak transition does not seem to be capable of producing many black holes[34]. The quark-hadron-chiral transition, however, may generate planetary mass black holes. Such black holes will be of interest when discussing the dark matter problem.

5. Weak freezeout

In the early universe, neutrinos are produced by neutral-current weak interactions via reactions of the type:

$$e^+ e^- \longleftrightarrow \nu_i + \bar{\nu}_i \quad (i=e,\mu,\tau)$$

This equilibrium is maintained until the temperature drops below a few MeV. At lower temperatures the weak interaction rate is too slow to keep up with the expansion of the universe, so neutrinos are decoupled from the hadron-lepton soup. These neutrinos would have a temperature of 2K today, compared to 3K for photons, because the decoupled neutrinos are not heated by e^+e^- annihilation at $T \leq m_e/3$ as the photons are.

Soon after the neutrinos decouple, the charged-current weak interactions,

$$p + e^- \longleftrightarrow n + \nu_e, \quad n + e^+ \longleftrightarrow p + \bar{\nu}_e, \quad n \longleftrightarrow p + e^- + \bar{\nu}_e$$

are no longer able to maintain chemical equilibrium between neutrons and protons. The equilibrium ratio of n/p is given by $\exp(-\Delta m/T)$. When the rates of the charged-current weak interactions become small compared to the universal expansion rate, the n/p ratio essentially freezes out. Since nearly all neutrons are incorporated into ^{4}He, the value of n/p will determine the abundance of ^{4}He produced in the nucleosynthesis period.

Nucleosynthesis begins with the production of deuterons via the reaction $n + p \longleftrightarrow d + \gamma$. At energies greater than 0.1 MeV the abundance of deuterons is very small because energetic photons rapidly dissociate any deuterons which are formed. This deuterium bottleneck to nucleosynthesis breaks at $T \approx 0.1$ MeV, and the epoch of nucleosynthesis begins.

6. Nucleosynthesis

When the deuterium abundance becomes significant, reactions with n, p and d occur, leading to the synthesis of ^{3}H, ^{3}He, ^{4}He and a small amount of ^{7}Li. The agreement of the predictions of primordial nucleosynthesis with the observed abundances is one of the profound successes of the Big Bang theory. We shall begin by discussing the dependence of the various abundances on the baryon to photon ratio, n_b/n_γ, the neutron half-life, $\tau_{1/2}$, and the number of neutrino flavors, N_ν. These dependences will then allow us to examine the constraints placed on n_b/n_γ, N_ν and Ω_b, the baryon density parameter. For a detailed current review of nucleosynthesis see Yang *etal.*[38] and references therein.

As mentioned in section 5, the production of ^{4}He depends upon the value of n/p which is determined by a balance of the weak interaction rate with the expansion of the universe. The weak interaction rate varies as $(\tau_{1/2})^{-1}$. The expansion rate increases with an increasing number of light particle species and thus with increasing N_ν. Finally, if n_b/n_γ is large the deuterium bottleneck is broken sooner, so n/p is higher, and more ^{4}He can be produced.

The abundances of D and ^{3}He are much smaller than that of ^{4}He. Nuclear reactions tend to burn both of these elements to ^{4}He, since it is more tightly bound. The surviving abundances are determined by a competition between the reaction rates and the expansion rate of the universe. The higher the value of n_b/n_γ, the more nucleons available to react with D or ^{3}He, so the lower the abundances of the remaining D and ^{3}He.

Few elements heavier than ^{4}He are produced primordially, because the expansion rate overtakes the rate of reactions producing heavier elements. The absence of stable nuclei at mass-5 and mass-8 inhibits the production of heavier nuclei. Only small amounts of ^{7}Li are synthesized via the reaction $^4\mathrm{He} + {}^3\mathrm{H} \rightarrow {}^7\mathrm{Li} + \gamma$ at low nuclear abundance, ($n_b/n_\gamma \leq 3 \times 10^{-10}$), and from the decay of ^{7}Be produced in the reaction $^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$ at higher abundances. The curve of ^{7}Li/H vs. n_b/n_γ goes through a minimum at $n_b/n_\gamma \approx 3 \times 10^{-10}$.

All of the abundances discussed above can be used to place various constraints on n_b/n_γ. Since the deuteron is barely bound and is thus easily destroyed in stars, the observed abundance of deuterium provides a lower limit to the primordial abundance. Since the abundance decreases with increasing n_b/n_γ, the observed value can be used to place an upper limit on n_b/n_γ. A lower limit on n_b/n_γ can be obtained using the observed abundances of D and ^{3}He. Nearly all the deuterium in stars is burned to ^{3}He, and a fraction of the ^{3}He in stars is burned to ^{4}He. It follows that:

$$\left(\frac{D}{H}\right)_\odot + \left(\frac{1}{1-f}\right)\left(\frac{{}^3He}{H}\right)_\odot$$

provides an upper limit for the primordial value of $(D+{}^3He)/H$, and thus a lower limit for n_b/n_γ. Similar observations can be made for ^{7}Li and ^{4}He. All are in agreement with a conservative estimate of $n_b/n_\gamma = 3\text{-}10 \times 10^{-10}$ and a best value of $n_b/n_\gamma = 4\text{-}7 \times 10^{-10}$.

As mentioned earlier, the abundance of ^{4}He depends upon the number of neutrino flavors as well as $\tau_{1/2}$ and n_b/n_γ. Since we have a constraint on n_b/n_γ and a value $\tau_{1/2} = 10.6$ min ± 0.2 we can limit the number of neutrino species if given a range of possible values for the primordial ^{4}He abundance Y_p. An upper limit for Y_p from observations of low Z objects is 0.25. It is more difficult to bound Y_p from below, but observations show that $Y_p \geq 0.22$ is a reasonable value. (See Yang, *etal.*[38] and references therein). The conclusion of such studies[39] is that $N_\nu < 4$ with a best fit value of $N_\nu = 3$. $N_\nu = 4$ is allowed only if $Y_p \geq 0.253$. Predictions on N_ν can be verified[39] by high-energy particle physics experiments currently being conducted to determine the width of Z^0, at CERN and in the near future at SLAC and Fermilab.

The density parameter is related to the value of n_b/n_γ by:

$$\Omega_b = 3.53 \times 10^{-3} h_0^{-2} (T_0/2.7\mathrm{K})^3 n_b/n_\gamma$$

The conservative range is $0.011 \leq \Omega_b \leq 0.19$ using the values of n_b/n_γ quoted above. A best value range is $0.014 \leq \Omega_b \leq 0.14$. If $\Omega = 1$, as predicted by inflation, then we see that the universe must be dominated by non-baryonic matter. If constraints on the age of the universe are used, the range tightens to $0.03 \leq \Omega_b \leq 0.14$.[40]. This subject, including the possible identities of the dark matter, will be discussed later in this paper.

We have seen that nucleosynthesis is able to place a constraint on the value of N_ν, thus predicting a quantity of great interest to particle physics, before such a constraint can be determined experimentally. (The best value from the width of the Z^0 thus far has been $N_\nu \leq$ 18-31[41]). This is yet another example of the rich interchange between the fields of cosmology and particle physics.

7. Electricity and magnetism freezeout

When the temperature of the universe dropped below $\sim$ 1eV at $\sim 10^5$ years, two important things happened. First, since 1eV is approximately the binding energy of the electron, at this time electrons combined with nuclei to form atoms. Charged particles which had been capable of scattering or absorbing radiation were no longer abundant, so the universe became transparent. The second event was that the universe became matter dominated, that is, the energy density in radiation dropped below that in matter. The significance of this is that density perturbations could begin growing without being smeared out by the radiation. The photons at 10^4K that were able to propagate freely after the E&M freezeout are observed today as the 3K blackbody radiation.

8. Dark matter

We have seen that inflation seems to require that $\Omega = 1$, while nucleosynthesis requires the density in baryons to be in the range $0.011 \leq \Omega_b \leq 0.19$. This leads us to the conclusion that the universe is dominated by non-baryonic matter. This is one of the three distinct cosmological dark matter problems. First, we will describe the other two problems, dark halos of galaxies and galaxy formation. Correlation functions and galaxy clustering will be briefly reviewed. Then possible solutions to the problems shall be discussed.

8.1. Halos

The problem of dark matter in halos of galaxies has been well established and described in detail[42,43]. Characteristic masses of galaxies can be found using the simple dynamical relationship, $M \sim v^2 r/G$, where v is the orbital velocity and r is the separation distance. For spiral galaxies a typical value for M is 10^{11} $M_\odot$ with a mass to luminosity ratio $M/L \sim 10\ h_0$ where h_0 is the Hubble constant in units of 100 km/sec/Mpc. In our galaxy, this value is approximately twice that accounted for by matter visible in the optical such as stars, gas, dust, etc. in the disk[44]. This problem in our galaxy, however, probably does not have a cosmological origin. When we look at larger scales such as binaries and small groups, the characteristic mass increases by ~ 10 while the light/galaxy does not change. The resulting M/L is approximately 100 h_0. As the scale increases M/L seems to increase, although uncertainties in the data are large. Values of M/L for large clusters and superclusters range from $\sim 100\ h_0$ to $\sim 500\ h_0$. This problem of dark halos has been referred to as the 'missing light problem,' because the problem is not mass which is missing, but the existence of nonluminous mass[45].

A value of M/L can be related to the density parameter if it is assumed to be an average M/L for the universe. To do this, we must introduce the average luminosity density, $\mathbf{L} = 2 \times 10^8 h_0 L_{\odot}/\mathrm{Mpc}^3$. The implied matter density is given by $\rho = \mathrm{M/L} \times \mathbf{L}$. The result for the largest scale gives an Ω in the range 0.07-0.4. In theory, it is possible that this dark halo problem could be solved by baryonic matter. It is known that non-optical baryons provide at least a partial solution to the problem since some are seen in the X-ray region[46]. It is difficult to find a type of baryonic object that is not excluded by other considerations[47]. Jupiters and low mass stars are a contributing factor, but observed stellar initial mass functions indicate they do not come close to providing a complete solution unless extreme production occurs at very low mass with no high mass tail. The number of stellar mass black holes required to solve the problem would require the existence of heavy elements produced in supernovae in excess of the abundances observed. Although a baryonic universe cannot be ruled out by the dark halo problem, no solution without non-baryonic matter has yet been found. Note, however, that some of the dark matter must be baryonic since $\Omega_b \lesssim 0.03$ whereas $\Omega_{visible}$ is 0.01. It is intriguing that $\Omega \sim 0.1$ is still consistent with all dynamical and baryonic arguments[48].

It is interesting to note that even on the largest scale, that of superclusters, $\Omega \sim 0.4$ is the largest value observed. The only way to reach $\Omega = 1$ (the value required by inflation) is to distribute more dark matter on even larger scales than those of giant superclusters.

8.2. Galaxy formation

For galaxy formation to occur, a density fluctuation, δn_b, in the baryon density, n_b is required. The fluctuation can arise via adiabatic or isothermal modes or from seeds formed at earlier times[49]. If planetary mass black holes were formed in the quark-hadron transition they may serve as seeds, first clustering baryons and then exploding[50].

We saw, when discussing GUTs and baryogenesis, that primordial fluctuations must be adiabatic. In adiabatic fluctuations there is a connection between the variations in baryon density $\delta n_b/n_b$, and the fluctuations in the 3K background, $\delta T/T$, since baryons are coupled to the radiation field. Naively $\delta\rho/\rho \sim 3\delta T/T$ and detailed calculations show that $\delta\rho/\rho$ does track $\delta T/T$[51,52]. Recent observations set the limit on the 3K background anisotropy as $\delta T/T \leq 2.1 \times 10^{-5}$ at the E&M decoupling, $T \sim 3000$K. The requirement for density perturbations at decoupling is thus $\delta n_b/n_b \lesssim 6\times 10^{-5}$. If we assume linear growth this would imply $\delta n_b/n_b \leq 6 \times 10^{-2}$ today at $T \sim 3$K. This is much smaller than the observed value of $\delta\rho/\rho \sim 1$ on scales up to at least clusters of galaxies. For $\delta\rho/\rho$ to be this large requires growth to begin earlier than the time when baryonic matter decouples from the radiation so non-baryonic matter is needed. Detailed calculations show that $\Omega \sim 1$ (at least $\Omega > 0.2$) is required to be consistent with $\delta\rho/\rho \sim 1$. Non-linear growth can occur when $\delta\rho/\rho \geq 1$ so some objects with $\delta\rho/\rho >> 1$ can easily be explained.

6.3. Galaxy clustering

Two, three and four point correlation functions, developed by Peebles and his co-workers, are an invaluable method for describing the distribution of matter. Later, we will use this to examine the plausibility of various candidates for the dark matter. The 2-point correlation function is defined as the probability over random for a galaxy to be a distance r from another galaxy. This probability is found to be proportional to $r^{-1.8}$. On large scales the correlation function no longer has this r dependence but decreases and may be negative for $r \geq 40$ Mpc[53]. The correlation function for clusters has the same r dependence, $r^{-1.8}$, but it is ~ 20 times larger in magnitude than that for galaxies[54,55]. The cluster-cluster correlation function is non-zero up to scales of at least 100 Mpc. This kind of distribution seems to be difficult to explain[56]. An alternative way of looking at the cluster-cluster correlation is using a renormalized approach, using the average separation distance between the objects as units for r rather than using the same r for clusters and galaxies. The result is that the correlation function for clusters is $\sim$ three times weaker than that for galaxies[57]. With the renormalized approach, the galaxy-galaxy correlation becomes negative at ~ 40 Mpc, while the cluster-cluster function remains positive out to ~ 200 Mpc. This would indicate that different physical processes are acting at different scales. Strings[58,30], pancakes[59], or explosive galaxy formation[60] have been proposed as possible processes yielding the large scale.

The 3-point correlation function implies density perturbations growing from small scales. This was once thought to be an argument in favor of isothermal fluctuations, but it is now known that adiabatic scenarios with cold matter can produce such hierarchical clustering. Fry[61] has shown that large scale filaments will produce 3-point correlation functions in agreement with the data. Recent observations indicate that the large scale holes and filaments are quite common[62].

8.4. Possible solutions

We have seen that inflation requires $\Omega \sim 1$ and leads to the conclusion th the universe is dominated by non-baryonic matter. It is also difficult but not impossible to explain dark matter in halos without invoking non-baryonic solutions. Finally the discrepancy between perturbations in matter density and temperature implies the existence of non-baryonic matter so that perturbations in matter can begin growing before decoupling.

Single particle non-baryonic candidates are described as hot, warm or cold matter following Bond[63]. Cold matter is non-relativistic at the time it decouples from matter so it can condense on small scales. The smallest scales that can collapse when particle i first dominates the mass density of the universe is the effective Jeans mass

$$(\mathrm{M}_J)_i = 3\times 10^{18}\frac{M_\odot}{m_i^2(eV)}.$$

Hot matter is relativistic at decoupling, and it remains relativistic until shortly before it becomes the dominant matter of the universe. The Jeans mass for hot matter is large, so large cluster scales form first and eventually fragment to form smaller scales. It has been argued that warm matter behaves essentially the same as hot matter except that it decouples before the neutrinos decouple, and thus has a lower temperature than the neutrinos at present.

Massive neutrinos are the least exotic of the hot matter solutions. Schramm and Freese[40] have found a mass $10\mathrm{eV} \leq \mathrm{m}_\nu \leq 25\mathrm{eV}$ for the most massive neutrino eigenstate. They considered mass density constraints, age of the universe arguments, phase-space density arguments, large-scale structure, the requirement of damping on small scales and Big-Bang nucleosynthesis in reaching this conclusion. Hot matter solutions give the large scale structure, but they have difficulty making galaxies. Perhaps fragmentation could occur in a neutrino pancake or in a series of explosions, but no such model has been worked out. Also, phase-space arguments prevent hot matter from solving the dark halo problem particularly for dwarf spheroidals. Finally, they have galaxies forming after $z = 1$ which is in conflict with observations of quasars with $z \geq 3.5$. Various other light 'inos' also fall under the classification of hot matter.

The many examples of cold matter include neutral heavy leptons, various heavy 'inos', axions and planetary mass black holes that have been discussed in connection with the quark-hadron-chiral symmetry transition. More massive black holes would still be in the form of baryons at the time of nucleosynthesis while less massive black holes would evaporate via the Hawking process. Cold matter has major advantages[64,65] in that it is able to explain galaxy formation, to fit galaxy-galaxy correlation functions and to solve the problem of dark matter in halos. The serious flaw in cold matter models is that they place all the mass on small scales. If $\Omega \sim 1$ as predicted by inflation, then $\Omega_{cluster} \sim 1$ in conflict with observations of $\Omega_{cluster} \leq 0.4$[66].

All warm particles that have been suggested have the same difficulties as either the hot or cold matter. Hybrid cold particle and hot particle models also fail because the hot particles, while relativistic, damp out growth of the cold density fluctuations[40,67].

Various more speculative solutions have been proposed. If a cold or warm particle was to decay to a hot one after galaxy formation, all the dark matter problems could be solved[62,68,69,70,71]. Unfortunately, it requires a finely-tuned particle for which there is no other evidence. Another possibility is shock-enhanced galaxy formation in which planetary mass black holes or other seeds clustered baryons and subsequently exploded[50]. If planetary mass black holes exist then this model is perhaps a plausible solution, but it requires a first-order transition at either electroweak of quark-hadron-chiral transitions. A non-zero cosmological constant is also a possible solution, but it requires that we live in a special epoch[69]. Another possibility has been suggested by Beckenstein. Perhaps gravity does not fall like r^{-2} on large scales, although there is no reason to think that the dependence of the gravitational force would vary at such a large scale since the only known scale to gravity is the Planck scale and no other evidence has been found.

Strings have received much attention recently as a dark matter candidate[72,58]. As mentioned before, strings could have been formed in the GUTs epoch. The strings would be stretched by the expansion of the universe, and they could form loops with long lifetimes. The strings would accrete matter due to their gravitational field. Thus they could provide the primordial density fluctuations needed for galaxy formation. The important point is that the string model creates real spatial correlation between density fluctuations of all sizes. The 3 and 4-point correlation functions are fit by a filamentary structure characteristic of strings[61]. Although more work is necessary, strings seem to have promise as a solution to the dark matter problems. Even without non-random phases, strings alter the standard assumptions. For example, hot matter with the fluctuations carried by strings will not have small scales smoothed so galaxy formation can occur right away rather than later.

9. Conclusion

When two branches of science are able to pool their resources, an exciting and productive era of scientific study results. At the interface of particle physics and cosmology, such an era is beginning. Many examples of invaluable interchange between these two fields have been described in this review. We will reiterate some of the more significant examples:

1. Cosmologists have used abundances of elements synthesized in the Big Bang to constrain the range of values for n_b/n_γ to 3-10 $\times 10^{-10}$. The baryon to

photon ratio given by the minimal SU(5) field is smaller than the lower bound of this constraint. This gave cosmologists reason to doubt SU(5) before proton decay experiments were conducted and confirmed this result.

2. The idea of inflation is based on the existence of the Higgs field which was proposed in connection with GUTs. Inflation is able to solve long standing problems in cosmology such as the horizon problem, the flatness problem and the clumping problem.
3. Big Bang nucleosynthesis arguments have enabled cosmologists to find a best fit value of 3 for the number of neutrino flavors, with 4 as an upper limit. If the best fit value is correct, we expect no more quarks after top to be found in experimental particle physics. Measurement of the width of the Z^0 will soon test this constraint.
4. A mass range of $10\text{eV} \leq m_\nu \leq 25\text{eV}$ for the most massive neutrino eigenstate has been found using a variety of considerations including mass density, age of the universe, phase-space density, large-scale structure, small-scale damping and Big Bang nucleosynthesis.

Many other entries for this list rapidly come to mind, such as the origin of planetary mass black holes, constraints of number densities, fluxes and coupling constants of fundamental particles, solutions to the dark matter problem, etc. It seems that this is only the beginning of a rapidly growing list, with entries inspired by developments both in particle physics and in cosmology.

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