Particle Astrophysics from the Particle Perspective*

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INTRODUCTION

During the last decade, particle astrophysics has developed into a discipline by itself, encompassing a large array of interesting phenomena. I am certainly not an expert on what we might refer to as the “hard core” astrophysics aspects of the subject, particularly those associated with structure formation and the detailed interpretation of the COBE data, or of detailed theories of inflation. What I would like to do today, after briefly surveying the standard big bang theory, inflation, and the marvelous results from COBE, is largely to quote uncritically from the experts on such topics, and turn to those aspects of the subject which have the most immediate implications for present day particle physics.

Even here, one could make a large list. In my briefcase, I am carrying literally hundreds of papers, and if one followed their references, the number would surely extend into the thousands. To narrow this list further, I would like to focus in this talk on a few principle topics:

1. **Neutralino cold dark matter.** There are two particularly well-motivated candidates from particle physics at the present time. The first of these, which has direct relevance for accelerator experiments, is the neutralino, likely to be the lightest new particle if supersymmetry is correct. I will review why this is such a wonderful dark matter candidate, and some of the proposals for searching for this component of the dark matter directly. During the past year or so, a major industry has developed trying to constrain the parameters of supersymmetry—the squark and gaugino masses, and so forth, and the idea of supersymmetric dark matter has been a major component of these efforts. I will discuss briefly some of the assumptions that go into these analyses and their plausibility; this is also important to understanding the constraints set by present and future direct dark matter searches.

2. **The second of these candidates is the axion.** The axion is the subject of experimental searches of growing sophistication and power. The situation, however, is qualitatively different than that of the neutralino; if the axion is not the dark matter, it is probably impossible to find. Indeed, if an axion is found, this will be particularly exciting because it will provide a window on an energy scale that is otherwise completely inaccessible. I will review the axion idea and the related experiments. Recently, the plausibility of the axion idea has been “attacked;” I will review these arguments, and give some counterarguments.

3. **Neutrinos.** The question of neutrino mass is a long-standing one, and there are a variety of theoretical ideas which suggest that one neutrino might have a mass in the few eV range. Experimentally, there are a number of hints, of varying degrees of credibility, of neutrino mass: the solar neutrino problem and the
lower than expected flux of muon neutrinos from cosmic rays being the most impressive. Moreover, among astrophysicists and cosmologists, a model with a mix of cold (70%) and hot (30%) dark matter has become very popular in light of the COBE results. A light (e.g., 7 eV) neutrino is an often-mentioned candidate for this dark matter. These subjects have been reviewed in the talk by Smirnov at this meeting, and I will only say a few words about them here.

4. Electroweak baryogenesis: In the past few years, it has become clear that the observed baryon asymmetry may have been produced at the electroweak phase transition. If so, this might resolve a number of questions in particle astrophysics. It also has bearing on extensions of the standard model, in particular on questions of $CP$-violation. I will give a brief overview of this subject here, and mention some efforts which it has (in part) motivated to understand the problem of $CP$-violation at high energy colliders.

5. Exotica: Under this heading, I will discuss a variety of more speculative topics. These include: the fate of domain walls; axion cosmology in the framework of supersymmetry (axinos, saxions, etc.); cosmological constraints on models of dynamical supersymmetry breaking; the possibility that much of the dark matter is in the form of a very small cosmological constant.

Perhaps before beginning, however, since this is at best a “mixed audience,” it is worth recalling some of the highlights of the standard big bang theory. The big bang cosmology starts with the observation that, on the average, the galaxies are all moving away from us at a rate proportional to their distance, and with the “cosmological principle,” the idea that our position in the universe is in no sense special, and that on very large scales, the universe is homogeneous and isotropic. There is strong observational evidence for this; the most dramatic being the COBE results on the fluctuations in the microwave background temperature. This, plus Einstein’s equations, lead to a model of space-time with metric of the form

$$ds^2 = -dt^2 + a^2(t) \left[ \frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2(\theta)d\phi^2) \right]. \tag{1.1}$$

Here $a$ is the scale factor, and satisfies the equation

$$\left( \frac{\dot{a}}{a} \right)^2 = \frac{8}{3} \pi G \rho - \frac{k}{a^2} \tag{1.2}$$

where $G$ is Newton’s constant and $\rho$ is the energy density of matter. $k = \pm 1, 0$. The Hubble “constant” is $H = \dot{a}/a$; today, $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$. The “critical
density” is determined by the requirement that $k = 0$ in eq. (1.2):

$$\rho_c = \frac{3H_0^2}{8\pi G} = 1.054 \times 10^{-5} h^2 \text{ GeV cm}^{-3}.$$  \hspace{1cm} (1.3)

Extremely important in all of these quantities is the parameter $\Omega = \rho_o/\rho_c$.

Now if one runs this picture backwards in time, matter becomes more and more compressed, and the temperature rises. In fact, we can think of the temperature as a sort of clock, labeling the important moments in the history of the universe. There are two particularly relevant periods: that of radiation domination and that of matter domination of the energy density. Radiation domination lasts from the earliest times until temperatures of order a few eV (when the universe is of order $10^5$ years old or so). During the radiation dominated era, the energy and entropy densities are:

$$\rho = \frac{\pi^2}{30} g T^4 \quad s = \frac{2}{45} \pi^2 g T^3 \quad g = g_B + 7/8 g_F.$$  \hspace{1cm} (1.4)

During this period, $t \sim T^{-2}$. We can now list a few highlights in the history of the universe:

1. $T \approx 2.7 K$: the present moment ($t \approx 13 \times 10^9$ yrs)
2. $T \sim 10^9 K$ ($t \sim 10^9$ yrs): earliest formation of galaxies.
3. $T \approx$ few eV ($t \sim 10^4$ yrs): transition from radiation to matter domination
4. $T \approx$ MeV ($t \sim 1$ sec): this is the moment of neutrino decoupling. At this point, weak interactions no longer maintain the equilibrium between protons and neutrons. Subsequently, at $T \approx 0.1$ MeV ($t \approx 3$ minutes) those neutrons which have not yet decayed are bound into the light nuclei $^4\text{He}, ^2\text{D}, ^3\text{He}, ^7\text{Li}$. One of the great triumphs of the standard cosmology is its successful prediction (through detailed calculations) of the abundances of these “primordial” elements. This success, however, only holds if the density of baryons lies in a narrow range:\footnote{1}

$$0.011 < \Omega_b h^2 < 0.048 \quad N_\nu < 5$$  \hspace{1cm} (1.5)

where $\Omega_b$ is the fraction of the critical density in baryons.

5. $T \approx 200$ MeV: The QCD phase transition – QCD passes from an unconfined, quark-gluon plasma phase to a confined phase (gas of nucleons and pions).

6. $T \approx 100$ GeV: The electroweak phase transition. Above this temperature, the $W$ and $Z$ bosons are essentially massless, and the Higgs particles (or whatever)
have no vacuum expectation values. Perhaps the baryon asymmetry, $n_b/n_\gamma \sim 10^{-10}$ is created at this temperature.

7. Still higher temperatures: Here we enter into a still more speculative realm.

If a Peccei-Quinn symmetry exists, there is a phase transition associated with this, presumably (but not necessarily) at a temperature of order $f_a$, the axion decay constant. Many other phenomena may occur as well.

8. At some very high temperature (perhaps as low as the weak scale, but probably higher), inflation occurs.

Inflation is not really the subject of this talk, but let me say a few words about it here. Inflation, at the present time, is a generic term, referring to a class of phenomena which could solve a number of serious puzzles with big bang cosmology. (Indeed, it has recently been argued that inflation is the unique solution to these problems.)

Briefly, these problems are:

1. The universe is remarkably homogeneous and isotropic on very large scales. From COBE, we know that the temperature of the microwave background exhibits only tiny variations on angular scales of 10 degrees or so. If we just run the big bang clock backwards, this means that about $10^5$ regions which were causally disconnected at recombination have nearly the same temperature. This would seem to violate causality. A similar statement applies to the synthesis of the light elements (at the time of nucleosynthesis, our present universe corresponds to about $10^{25}$ causally disconnected regions).

2. The $\Omega$ problem: $\Omega$ behaves with time as

$$\Omega = \frac{1}{1 - x(t)} \quad x = \frac{k}{a^2} \frac{1}{8\pi G \rho/3} \quad (1.6)$$

where $a$ here is normalized so as to be 1 today. But since in the far past, $a$ was many orders of magnitude smaller (e.g., 10 orders of magnitude at nucleosynthesis), and given that $\Omega$ is within a few orders of magnitude of unity today, it was extremely close to unity at early times.

3. Particle physics models often predict stable, heavy particles, such as monopoles, and topological objects, such as domain walls. These would yield far more mass than is currently observed.

In inflationary schemes, there is a period in which the energy density of the universe is dominated neither by radiation nor by matter, but by a cosmological constant – essentially vacuum energy. During such a period, Einstein’s equations yield that $a \sim e^{Ht}$ where $H^2 = 8\pi G V/3 V$. A simple model for such a process is provided by the “new inflationary scenario” (by now a misnomer). In this scenario, there is a scalar field, $\phi$ (the “inflaton”). By assumption, the potential of this field
is extremely flat. At early times, the inflaton does not sit at the minimum of its potential, due, for example, to thermal effects. Instead, it sits near the origin. At some time, it begins to roll, very slowly, towards the minimum. During this period, there is, effectively, a non-zero cosmological constant. If the period of exponential growth lasts for a sufficient number of e-foldings (e.g., 100’s), all of the problems mentioned above are solved. First, small, causally connected regions of the universe grow to enormous size – sizes larger than our observable universe. This solves the homogeneity and flatness problems. Second, if such a region contains, say a single monopole, then there is at most one monopole in our observable universe; more generally, any stable objects will be diluted away. Third, provided the universe reheats significantly after inflation, a great deal of entropy is created. This occurs, for example, if the inflaton is reasonably strongly coupled at the end of inflation. In this case, as it sloshes around near the minimum, its motion damps, and the energy is dissipated into heating of the ambient plasma. A vast amount of entropy can be created in this way.

There are many problems with this particular scenario, and many variants are currently on the market. I don’t want to review these here, but simply stress that there are two predictions generic to these schemes:

1. $\Omega = 1$. (See eq. (1.1); essentially, the $k$ term becomes irrelevant due to the large value of $a$.)

2. The description I gave of the inflationary model above was completely classical. Quantum effects lead to fluctuations (e.g., in the position of the field, $\phi$, in time) and these lead to fluctuations in the density as a function of wavenumber, $k$. The wavelength is “stretched” by expansion; once these fluctuations are larger than the horizon size (essentially $H^{-1}$), they are frozen. In this way one obtains an essentially scale-invariant fluctuation of density fluctuations (“Harrison-Zeldovich spectrum”). Once inflation is over, the universe continues to expand. As a result, at any given time, fluctuations on a scale of order the horizon size reenter the horizon. When they do, they can begin to grow. However, this growth is only significant during the matter dominated era, when $\delta \rho / \rho \propto a(t)$. Once $\delta \rho / \rho \sim 1$, the system becomes non-linear, and structure begins to form. (The reader should be aware that there exist competing, so-called “non-Gaussian” models of structure formation, such as textures and cosmic strings.)

Where does COBE fit into this? COBE found fluctuations in the sky in the microwave temperature of approximately a part in $10^{-5}$. The fluctuations in the energy density are related to fluctuations in the temperature by an equation of the
As we will see when we discuss dark matter, the COBE result is consistent (to at least a factor of two) with a picture in which galaxies begin to form when these fluctuations became non-linear. Moreover, COBE observed a power spectrum, \( P(k) = A k^{1.1 \pm 0.5} \), consistent with Harrison-Zeldovich. (See fig. 1.)
the force on the outlying stars is much too large to be accounted for by the visible matter. Indeed, the galaxy has a halo, usually assumed to be spherical, with a density which falls more slowly than the visible density. From general studies of such rotation curves, astronomers estimate that this missing matter contributes to $\Omega$ an amount between 0.03 and 0.1. On larger scales, there is evidence for even larger densities of dark matter. (The issue, here, is how the dark matter has “clumped.”) From studies of groups and clusters of galaxies, one obtains $\Omega = 0.05–0.3$. Perhaps most interesting are recent studies of peculiar velocities (IRAS and POTENT) One studies the motion of galaxies (particularly ours) relative to the CMBR (about 620 km/sec), and assumes that this can be understood as arising from the galaxies in a large galaxy survey. These studies give $\Omega/b \approx 1.2 \pm 0.6$. Here $b$ is the so-called biasing factor; it is related to how luminous mass traces the dark matter.

So it is well established that most of the matter in the universe is non-luminous, and it may well be true that $\Omega = 1$. Recalling eq. (1.5), we see that big bang nucleosynthesis allows a baryon number density consistent with the missing mass in the galactic halo, but not with $\Omega = 1$. For the rest of this talk, I will adopt the working assumption that there is non-baryonic missing matter. Even then, however, there is the question of whether the matter in the galactic halo is baryonic (perhaps the non-baryonic matter clumps only on scales larger than galaxy scales).

This question of whether the galactic halo contains baryonic matter is subject to experimental test. In particular, the baryonic matter might be in the form of MACHO’s, “massive compact halo objects.” These could be “jupiters,” objects with mass of order $0.001M_\odot$, or brown dwarfs, with mass $0.01M_\odot$. In either case, these objects, consisting principally of hydrogen and helium, would be too light to ignite nuclear burning. There are already several searches for such objects under- way. The idea is to look for “microlensing,” multiple images (actually enhanced images, since the multiple image, or ring, cannot be resolved on earth) which result when one of these objects passes between our line of sight and a star. Because the distribution of non-luminous matter in the galaxy is known, one can predict the expected rate. There are actually three searches underway, looking for MACHO’s in our own galactic halo by looking for intensity variations of stars in the Large Magellenic Cloud. The typical time scale for these variations are of order one week (one week for $0.1M_\odot$ objects; the time varies as $\sqrt{M}$). The MACHO collaboration, for example, (LLNL, CPA, Mt. Stromlo Observatory) has exclusive use of a 1.3 m telescope for at least 4 years. They observe about 10–20 million stars per night. They would expect something of order 500 events per year for a halo density of jupiter mass objects ($0.001M$) (with events lasting about 30 days). So far, they have analyzed one data set, containing 1.7 million stars, observed for about nine months. In this sample, they would have expected to see a few brown dwarfs; with
their cuts, however, they have no candidates. If the cuts are relaxed, there are a handful of candidates. These they believe are probably variable stars; if they are real microlensing events, there will be many candidates in the next set. Within about four years time, definitive results can probably be obtained for objects with masses between $10^{-5} - 10^2 \, M_\odot$. This is, in fact, the entire interesting range; smaller objects would have already evaporated, while larger ones would disrupt the galactic disk. So it is possible that within a few years we will know with some certainty whether the dark matter in the galaxy is baryonic or not. Indeed, as this document was “going to press,” there were preliminary announcements of macho candidates.\footnote{8}

COBE provides indirect evidence that the dark matter is not baryonic. In a baryon-dominated universe, fluctuations which enter the horizon prior to decoupling are washed out. Since decoupling, the scale factor has grown by about $10^3$, so fluctuations as small as $10^{-5}$ would not even now be non-linear. An $\Omega = 1$ universe, dominated by non-baryonic matter does much better, because the fluctuations start to grow upon matter domination, and matter domination occurs earlier.

Assuming that most of the matter in the universe is non-baryonic, one usually distinguishes two types of dark matter. Cold dark matter is defined as matter which is relativistic when it drops out of equilibrium (“freeze out”), while hot dark matter is relativistic at freeze out. In the case of cold dark matter, this leads to a quite compelling theory of structure on the scale of galaxies and clusters of galaxies. Hot dark matter does not appear to clump enough on galactic scales, particularly of small dwarf galaxies. However, cold dark matter has trouble with the recent COBE results, if one makes the standard assumption—motivated by the simplest inflationary models—of a scale-invariant spectrum (there is too little power at large scales, too much at small if CDM normalized to galaxy-galaxy two-point function). To fix this, there have been various proposals. These include modification of the fluctuation spectrum. This does not seem unreasonable, given that most present theories of inflation are not completely satisfactory. For example, if the potential responsible for inflation changes during the inflationary epoch, this can lead to departures from scale invariance.\footnote{9} Another possibility is that the “bias,” which we have discussed earlier, is not constant with scale. Perhaps the most popular alternative at the moment, however, is to suppose that there is actually a mixture of cold (70%) and hot (30%) dark matter, where the hot dark matter might be a neutrino with mass of order 7 eV.\footnote{2} Of course, this requires a quite remarkable coincidence, and I will leave it to you to decide how plausible such a coincidence might be. Still, 7 eV is not an unreasonable value for a neutrino mass (\textit{e.g.,} see-saw mechanisms), and this model has the virtue that it fits quite a range of data with only one extra parameter. Since I am not going to focus heavily on neutrinos in this talk, for the rest I will simply adopt the viewpoint that dark matter certainly
exists, and there is a good chance that some of it is in an exotic form. Note that even in this cold plus hot scenario, on galactic scales, the dark matter is principally cold, so experiments designed to look for the dark matter in the halo are unaffected.

For the moment, let us not worry about the details of primordial fluctuations and the development of structure, but rather consider some of the dark matter candidates suggested by particle physics. The two which will interest us here are WIMP’s (Weakly Interacting Massive Particles) and axions. As we will see, massive particles with cross sections of weak interaction magnitude are ideal dark matter candidates. It is very easy to cook up models with such particles, but only a small number are very well motivated. Of these, Majorana and Dirac neutrinos are ruled out by LEP and direct dark matter searches. This leaves the neutralino, a particle suggested by supersymmetry, as the most promising of the (currently) well-motivated candidates. This candidate is so plausible that over the last year or so model builders have been using the condition Ω = 1 to constrain the supersymmetry parameters. Meanwhile, a variety of terrestrial searches have a very real prospect of seeing this dark matter, if it exists.

The second well-motivated candidate for dark matter is the axion. Its role as dark matter arises in a quite different way from that of WIMP’s, and if it is found it will provide a window on physics at much higher energies than we can contemplate exploring with accelerators – 10^{12} GeV or so. We will turn to this particle first.

AXIONS

QCD is a quite successful theory of strong interactions. However, in addition to the well-known Λ parameter, this theory has another parameter: it is possible to add to the lagrangian a term

$$\theta g^2 \frac{F^a_{\mu\nu} \bar{F}^a_{\mu\nu}}{32\pi^2}.$$ (3.1)

This term is CP-violating. Formally, it is a total divergence, but arguments based on current algebra can be used to show that it has a definite effect on physics: it leads to too large a value of the electric dipole moment unless θ < 10^{-9}. One can view this as just one more small coupling (like the electron Yukawa coupling) which we don’t know how to explain. But in fact there are three proposals for understanding the small value of this number:

1. m_u = 0. This contradicts the usual, first order current algebra analysis of the pseudoscalar masses, which gives m_u/m_d ≈ 0.55. But it has been argued (rather convincingy in my view) that second order corrections to this relation are large, and that one cannot rule out m_u = 0.10. It is also often argued that it
is unnatural to have $m_u = 0$. Any symmetry which might protect the $u$ quark mass would necessarily be anomalous (in a moment, however, we will see that a similar argument applies – in spades – to axions), and rather puzzling from the perspective of, say, grand unification. It has recently been pointed out, however, that such anomalous discrete symmetries do arise in string theory. Recently proposed schemes for understanding quark mass matrices also frequently lead to $m_u = 0$.\(^{11}\) Thus, while our focus here will be on axions, one should keep in mind that this first solution of the strong $CP$ problem is quite plausible.

2. $CP$ is a good symmetry of nature, so there is no “bare” $\theta$, and is spontaneously broken in such a way that the effective $\theta$ is small. Some time ago, Nelson and Barr suggested a mechanism which would give a non-zero KM phase, while at the same time giving a very small $\theta$.\(^{12,13}\) Unfortunately, in the framework of supersymmetry, it has recently been shown that loop corrections to $\theta$ are generically quite large in such schemes.\(^{14}\)

3. Axions.\(^{15,16}\) The basic idea for solving the axion problem, due to Peccei and Quinn, is to make $\theta$ a dynamical variable, by introducing a field $a(x)$, which couples to $F\tilde{F}$:

$$[Na(x)/f_a + \theta] \frac{g^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^a_{\mu\nu}. \quad (3.2)$$

$f_a$ is called the axion decay constant. The rest of the lagrangian is assumed to be symmetric under the shift (“Peccei-Quinn symmetry”)

$$\frac{a}{f_a} \to \frac{a}{f_a} + \delta. \quad (3.3)$$

By a symmetry transformation we can remove $\theta$; the effective $\theta$ is then just the expectation value of $a$. In QCD, it is easy to show that this vev is very tiny, because, in the absence of $\theta$ the theory conserves $CP$.

To actually construct models of this phenomenon, one typically considers theories with a scalar field, $\phi$, which transforms under an anomalous $U(1)$ symmetry. $\phi$ is assumed to obtain a vev, $v = f_a$. One then writes

$$\phi = \frac{v}{\sqrt{2}} e^{ia(x)/v}. \quad (3.4)$$

The coupling to $F\tilde{F}$ then arises through then anomaly. QCD effects give rise to a potential for the axion, which can be computed using ordinary current algebra. One finds

$$m_a = |N| f_{\pi} m_{\pi} \sqrt{m_u m_d} = 0.6 \text{ eV} \frac{10^7 \text{ GeV}}{f_a/|N|}, \quad (3.5)$$

where $N = 2 \sum_f t_f Q_f^{PQ}$, the sum is over fermion species, and $t_f$ is an appropriate
Casimir. There is also, typically, a coupling to two photons,
\[ \mathcal{L}_{a\gamma\gamma} = \frac{\alpha}{8\pi} \frac{a}{f_a} \left[ N_{\text{e}}/N - \left( \frac{5}{3} + \frac{m_d - m_u}{m_d + m_u} \right) \right] F\tilde{F}. \] (3.6)

\( N_{\text{e}} \) reflects the QED anomaly of the Peccei-Quinn symmetry; 8/3 is a value which typifies a broad class of models. With this choice,
\[ \mathcal{L}_{a\gamma\gamma} \approx \frac{\alpha}{\pi} \frac{m_a}{0.6 \times 10^{16} \text{eV}^2} a(x) \vec{E} \cdot \vec{B}. \] (3.7)

One can also work out couplings of axions to fermions.

Note that if \( f_a = M_p \), the axion is extremely weakly coupled, but also extremely light, so assuming initially a thermal distribution of axions, their density today would be comparable to that of photons. Why, then, are axions a plausible dark matter candidate? Suppose that inflation occurs after the PQ phase transition, \textit{i.e.}, at temperatures such that \( \phi \) has a non-zero vev. At extremely high temperatures, the QCD effects which give rise to the axion potential are so small (due to asymptotic freedom) that \( \langle a \rangle \) is essentially a random variable. In particular, prior to inflation, regions of the order of the horizon size have different values of \( \langle a \rangle \) (\( \theta \)). After inflation, the region which will become our present universe has a single value of \( \langle a \rangle \). As the universe cools towards QCD temperatures, the axion potential “turns on.” The axion field will then roll towards its minimum. However, because of its weak coupling, it cannot dissipate energy effectively, and simply oscillates. Indeed, the axion field carries an energy of order
\[ V = m_a^2 a^2 \sim (100 \text{ MeV})^4 \frac{a^2}{f_a^2}. \] (3.8)

One can think of this field as a coherent state of axions, where the density of axions is \( |V|/m_a \), a huge number! This axion density dilutes like matter (it falls as \( T^3 \), whereas the radiation falls as \( T^4 \)), so the axions eventually come to dominate the energy density. Putting in the numbers, one finds
\[ \rho_a = \rho_{\text{crit}} \theta_o^2 \left( \frac{0.6 \times 10^{-5} \text{eV}}{m_a} \right) \left( \frac{200 \text{MeV}}{\Lambda_{\text{QCD}}} \right)^{3/4} \left( \frac{75 \text{ km s}^{-1} \text{Mpc}^{-1}}{H_o} \right)^2 \] (3.9)

where \( \theta_o = a_o/f_a \) is the initial value of the effective \( \theta \) angle. One sees that axions overclose the universe unless the axion mass is not too small, or we happen to be living in a part of the universe where \( \theta_o \) happens to be very small. For a range of axion masses around \( 10^{-5} \text{ eV} \), the axions are a dark matter candidate. They are cold dark matter because they are highly non-relativistic.
\( m_a > 10^{-5} \) corresponds to \( f_a < 10^{12} \) GeV, so it is possible that the Peccei-Quinn transition occurs after inflation. If this is the case, the situation is distinctly more complicated. First, there is the danger of forming domain walls. The point is that, in general, QCD does not break the Peccei-Quinn symmetry completely, but typically leaves over a discrete \( Z_N \) symmetry. I know of two solutions to this problem. First, there is the possibility that \( N \) is simply equal to one. Second, as Sikivie pointed out long ago, if one had small effects which explicitly break the Peccei-Quinn symmetry, these could lead to collapse of the domain walls. As we will discuss shortly, the Peccei-Quinn symmetry, if it exists, is likely to be an accidental, approximate symmetry. It is almost certainly violated by higher dimension operators, so the symmetry-violating terms envisioned by Sikivie are quite plausible. Because the Hubble constant at this time is about 19 orders of magnitude smaller than the QCD scale, quite small corrections can cause the collapse of the walls on a cosmologically short time scale.

As stressed by Davis, and discussed by Sikivie and collaborators at the, Peccei-Quinn phase transition, one expects to form networks of axion strings, which in turn are a coherent source of axions. There seems to be some controversy in the literature about just how large an axion density one makes, with estimates ranging from values similar to those of eq. (3.9) to values 100 times a large (which might rule out axions all together). For the rest of this discussion, we will simply assume inflation occurs first, but these other possibilities should be kept in mind.

There is an upper bound on the axion mass, which comes from more conventional astrophysics. The axion mass is proportional to the strength of the axion interaction (inversely proportional to \( f_a \)). As a result, if axions are too heavy, they are copiously produced in stars. However, they still interact sufficiently weakly that they escape the star, carrying off energy. The strongest bounds of this type come from supernova SN 1987a. (It should be noted, however, that these bounds are probably weakened somewhat by the “LPM effect,” as pointed out by Raffelt and Seckel. The first experimental observation of this effect was described in S. Klein’s talk at this meeting.) This combination of bounds is indicated in fig. 2. So if axions exist at all, and the cosmological arguments are correct, they are in the right range to be a dark matter candidate.

Can axions be detected if they constitute the halo of our galaxy? Pierre Sikivie has for some years been advocating searches for such axions, and by now there have been at least two prototype experiments, and a full scale experiment which can study an interesting range of parameters has been proposed and approved.

\* Recently, Lythe has pointed out that if during inflation, \( H \sim f_a \), there can still be problems with strings.
The idea is to stimulate axion conversions to photons in a cavity placed in a strong magnetic field, using the coupling in $L_{a\gamma\gamma}$. The axions can then, in the presence of the field, excite a mode of the cavity (a $T_M{nl}$ mode, since the size of the cavity is typically much less than the de Broglie wavelength of the axion, $\lambda_a \sim 2\pi10^3 m_a^{-1}$, where the first factor reflects the typical velocity of axions in the halo).

One can then compute the power in this mode; it behaves as

$$P_{nl} = 2 \times 10^{-26} \text{ watt} \left(\frac{V}{500 \text{ liter}}\right) \left(\frac{B_o}{8 \text{ Tesla}}\right)^2 C_{nl} \frac{\rho_a}{10^{-24} \text{ gm/cm}^3} \frac{m_a}{2\pi \times 3 \text{ GHz}} \times \min[Q_L, Q_a]$$

(3.10)
where $Q_L$ and $Q_a$ are respectively the quality factors of the cavity and the galactic signal (the ratio of energy to energy spread), and $C_{nl}$ is a geometric factor. Part of the difficulty of these experiments comes from the fact that one must study a large range of frequencies in very small intervals. The cavity must thus be tunable. Prototype experiments have already been carried out at BNL (Rochester, Brookhaven, Fermilab) and at Florida. The results are shown in fig. 3, where they are compared with the predictions of two popular axion models. Note that the sensitivity of these experiments is about two orders of magnitude too low to rule out (or establish!) these two models. These experiments both had $B^2V$ about $0.4T^2m^3$. The Florida experiment had somewhat greater sensitivity due to more efficient data taking and better microwave equipment.

Fig. 3. Results of prototype experiments showing the parameter range ruled out. This is taken from the proposal described in the text. Range which may be excluded by future experiments is indicated.

There is now an approved proposal for an experiment using a new, much larger magnet, with $B = 8.5T$ and a 60 cm diameter (permitting installation of a 50 cm cavity). (The original proposal involved a decommissioned magnet from a mirror fusion test facility at LLNL.) Delivery of the magnet is expected in April of '94. Eventually, with multiple cavities, it should be possible to search to a mass of 12.6 $\mu$eV, and possibly higher. There is also the possibility of installing cavities in a 14T magnet at the National Magnet Lab. However, this magnet is only available for a brief period, so there is discussion of building a dedicated magnet of this size, as well. Other suggestions have been made for observing axions of larger mass.24 These proposals involve cavity detectors, but also involve various
alternative detectors, \textit{e.g.}, involving superconducting wires. Current in the wires gives a spatially varying magnetic field, which is used to enhance axion production.

Having described a little bit these wonderful experiments, let me step back and ask a rather embarrassing question, which has been raised by a number of authors recently: just how plausible is the axion solution of the strong \textit{CP} problem? The question is not really a new one. After all, the Peccei-Quinn symmetry is a puzzling one: a symmetry which is not really a symmetry. Moreover, as we have already mentioned, the attitude has developed among theorists in recent years that there should be no global symmetries in nature. More precisely, any global symmetries which exist should be accidents of renormalizability, just as baryon number is an accidental symmetry of the standard model. What the recent discussions have made clear is that if the Peccei-Quinn symmetry is an accident of this type, the accident must be an extraordinarily good one; operators of very high dimension must be suppressed.

The difficulty is easy to understand; it was noted in passing by Georgi, Glashow and Wise.\footnote{25} More recently, it has been discussed in a general and quantitative fashion by several authors.\footnote{26} To gain some appreciation of the difficulty, suppose that the lowest dimension, gauge-invariant operator which violates the symmetry is $O(4+n)$, of dimension $4+n$. Then the leading symmetry-violating term which can occur in a low-energy effective field theory is

$$\mathcal{L}_{SB} = \frac{\gamma}{M_P} O^{(4+n)}$$

(3.11)

where $\gamma$ is a dimensionless coupling constant. On dimensional grounds, this gives rise to a linear term in the axion potential,

$$V_{SB} \propto \gamma \frac{f_a^{n+3}}{M_P^2} a(x).$$

(3.12)

Since $m_a^2 \sim m_{\pi}^2 f_{\pi}^2 / f_a^2$ the resulting shift in $\theta$ is

$$\delta \theta = \frac{\delta a}{f_a} \sim \frac{\gamma f_a^{n+4}}{m_{\pi}^2 f_{\pi}^2 M_P^8} < 10^{-9}.$$  

(3.13)

For $f_a = 10^{11}$, this gives $n > 7$ (\textit{i.e.}, the symmetry-violating operator must at least be of dimension 12!) If $f_a = 10^{10}$, things are slightly better; one needs to suppress all operators of dimension less than 9. Of course, if $f_a$ is larger, one must forbid an even larger number of operators.
This all sounds rather hopeless. But in string theory, it has long been known that, in perturbation theory, the Peccei-Quinn symmetry is exact! One way to understand this is as an accidental consequence of another gauge symmetry of the theory, involving the antisymmetric tensor field. Unfortunately for our present considerations, this axion has $f_a \sim M_p$. Only if we give up the cosmological bound is such an axion acceptable. One can imagine a number of ways in which this bound might be relaxed. For example, there might be some generation of entropy after the QCD phase transition. Or perhaps, as a result of some sort of anthropic considerations, the initial value of the $\theta$-angle in our observable universe is small, of order $10^{-3}$ or less (the axion energy density is proportional to the square of this angle, though we have not indicated it explicitly above). One proposal for such an anthropic explanation has been made in ref. 28. However, such an axion would be too weakly coupled to be detectable in any of these experiments, even if it did make up the dark matter of the halo.

If we do take the cosmological bound seriously, the lesson of all this is that if one wants a Peccei-Quinn symmetry to arise by accident, one must forbid operators up to very high dimensions. How might such a thing occur? The authors of refs. 26 noted that with a sufficiently complicated continuous gauge symmetry, one could indeed suppress operators of very high dimension. However, by their own admission, the resulting models were not particularly beautiful.

In my view, a more plausible explanation for an axion with a decay constant of order $10^{12}$ or so is as an accidental consequence of a discrete symmetry. In fact, in the framework of string theory, such a possibility was considered long ago by Lazarides et al. and by Ross and Casas. The latter authors also attempted to estimate how large a $\theta$ would be induced by higher-dimension operators which violated the Peccei-Quinn symmetry, in precisely the spirit described above (it turns out that they neglected an important class of operators, but this difficulty is easily remedied). Rather than review these models in detail, however, it is useful to illustrate just how powerful discrete symmetries are in this respect by considering theories in which the Peccei-Quinn symmetry is dynamically broken by fermion condensates. As an example, consider a theory with (unbroken) gauge group (in addition to the standard model gauge group) $SU(4)_{AC}$ ($AC$ is for “axi-color”), with scale $\Lambda_{AC} \sim f_a$. In addition to the usual quarks and leptons, we suppose that the theory contains additional fields $Q$ and $\bar{Q}$, transforming as $(4, 3)$ and $(\bar{4}, 3)$ under $SU(4)_{AC} \times SU(3)_c$, and fields $\mathcal{Q}$ and $\bar{\mathcal{Q}}$ transforming as a $(4, 1)$ and a $(\bar{4}, 1)$. Now suppose that the model possesses a discrete symmetry (gauged

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* This has been noted independently, and much earlier, by A. Nelson (unpublished).
or global) under which

\[ Q \rightarrow \alpha Q \quad \bar{Q} \rightarrow \alpha \bar{Q} \]  

(3.14)

where \( \alpha = e^{2\pi i/N} \); all other fields are neutral. If, for example, \( N = 3 \), the lowest dimension chirality-violating operators one can write are of the form \((\bar{Q}Q)^3\)

which is dimension 9; suppression of still higher dimension operators is achieved by choosing larger \( N \). In this theory, the would-be PQ symmetry is

\[ Q \rightarrow e^{i\omega Q} \quad \bar{Q} \rightarrow e^{-3i\omega Q} \]  

(3.15)

This symmetry has no \( SU(4) \) anomaly, but it does have a QCD anomaly. One expects that this symmetry will be broken by the condensates

\[ \langle \bar{Q}Q \rangle \sim \langle Q\bar{Q} \rangle \sim f_a^3. \]  

(3.16)

This gives rise to an axion with decay constant \( f_a \), which solves the strong \( CP \) problem.

Lazarides \textit{et al.} and Casas and Ross wrote down string inspired models which accomplished the same objective as in the model above. Again, discrete symmetries suppressed operators up to very high dimension. These models have a major virtue: the axion decay constant is naturally of order \( M_{INT} = \sqrt{M_W M_P} \), \textit{i.e.}, within the allowed axion window.

If, for the moment, we accept this picture as the origin of the Peccei-Quinn symmetry, there is one interesting cosmological consequence, which we have already alluded to. This is the point that the symmetry is not likely to be exact, and is likely to be violated by operators of dimension just higher than that permitted by our earlier arguments. As Sikivie noted long ago, under these circumstances, it is quite possible that any domain walls formed at the PQ phase transition would harmlessly disappear (\textit{i.e.}, before nucleosynthesis).

What are we to make of all of this? My attitude is that there are two, and possibly three, plausible mechanisms for solving the strong \( CP \)-problem. Thanks to the heroic efforts of a now rather large number of physicists, we have a real hope of getting an experimental handle on the axion some time soon. The discovery of this particle would be an extraordinary event, a connection with physics at vastly higher energies than we have ever studied. Perhaps, in light of all of these criticisms, the probability of success is not 50%, but even at 10% the payoff seems worth it.
NEUTRALINO COLD DARK MATTER

We have remarked that massive particles with weak interaction cross sections are ideal dark matter candidates. It is easy to understand why this is so.\textsuperscript{33} Let us call our WIMP $w$. At extremely early times, when the temperature is well above its mass, $w$ will be in thermal equilibrium. Equilibrium is maintained, typically, by pair annihilation ($w + w \rightarrow q + \bar{q}$, say), and the reverse process of WIMP pair production. At these temperatures, the $w$ density goes as $n_w \propto T^3$. As the temperature drops below the $w$ mass, however, the $w$ density falls as

$$n_w \propto \left(\frac{m_w T}{m_w T}\right)^{3/2} \exp(-m_w T).$$  \hfill (4.1)

(The density of $f\bar{f}$ pairs, where $f$ denotes light fermions, with sufficient energy to produce $w$ pairs falls similarly). Eventually, annihilation and production reactions are too slow to maintain equilibrium, and one is left with some density of $w$’s. The density is clearly inversely proportional to the cross section. Detailed calculations give for the final density, as a fraction of closure density,

$$\Omega_w h^2 \approx 3 \times 10^{-27} \text{cm}^3\text{sec}^{-1} / \sigma_A v.$$ \hfill (4.2)

This is a wonderful result: to be a suitable dark matter candidate, the cross section should be roughly of weak interaction strength. In other words, it is possible that if this particle exists, we have a chance of discovering it in the laboratory. Moreover, in our menu of present theoretical ideas, we have several candidates.

What about detection of these particles? Of course, in some cases one can hope to observe them in accelerators. If such particles actually make up the halo of our galaxy, then there is a significant flux of these particles on earth, which one might hope to observe. One expects that the typical velocities will be of order 220 km/sec. Passing through quantities of matter, these particles can scatter off nuclei. Typical interaction rates are of order 1/kg/day for particles with principally spin-dependent, incoherent interactions with nuclei (such as majorana particles), while they can be orders of magnitude larger for particles with coherent interactions. We have mentioned that two obvious candidates of this type are already ruled out: Majorana and Dirac neutrinos. Majorana neutrinos are ruled out by the fact that if they constitute cold dark matter, their masses are necessarily in the few GeV range, and this is ruled out by LEP. Dirac neutrinos can play the role of dark matter over a large range of mass, since they can have associated with them an approximately conserved quantum number (like baryon number). However, they are ruled out, for masses from about 20 GeV to 1000 TeV by direct searches of the type which will be discussed below, while lower masses are ruled out by LEP.
But aside from these rather conventional(?) extensions of the known particles of the standard model, other candidates have emerged from studies of extensions of the standard model. Probably the most popular extension of the standard model is supersymmetry. Supersymmetry near the weak scale, as you have all heard many times, is of interest for a variety of reasons: it potentially solves the hierarchy problem; it leads to a far better unification of couplings than non-supersymmetric theories; it provides an attractive mechanism for $SU(2) \times U(1)$ breaking, and more. Certainly one attractive feature of these models is that they provide an excellent dark matter candidate.

Just to remind you briefly of the basics of supersymmetry, supersymmetry is a symmetry between bosons and fermions. If it is a symmetry of nature, for each of the fields we currently know, there must be a bosonic or fermionic partner as appropriate. For example, for all of the gauge bosons of the standard model, there must be a gauge fermion (gaugino) in the adjoint representation of the gauge group; there must be scalar quarks (squarks) and scalar leptons (sleptons). From LEP and CDF we have lower limits on the masses of many of these particles. If supersymmetry has anything to do with the solution of the hierarchy problem, these particles cannot be too heavy. Of course, the fact that particles are not degenerate with their supersymmetry partners means that supersymmetry is a broken symmetry. Little is known about this breaking, and there are only a few models where the breaking can be understood dynamically. As a result, almost all analyses to date proceed by making a set of simplifying assumptions. First, one assumes that the particle content of the model is the minimal one consistent with supersymmetry and the states we currently observe. This just means that one has, in fact, a superpartner for all of the ordinary quarks, leptons and gauge bosons, and that one has two Higgs doublets and their “Higgsino” partners. One also typically makes some assumptions about how supersymmetry is broken, i.e., about the “soft breaking” parameters, the masses and (superrenormalizable) couplings of the superfields. In particular, most workers assume that at the scale of unification, the masses of all of the scalar fields are identical, and that there is a proportionality between soft breaking cubic couplings and Yukawa couplings. With these assumptions, one has a model specified by a relatively small number of parameters: the top quark Yukawa coupling, $h_t$, the gaugino masses, $m_{1/2}$, the common squark and slepton masses, $m_0^2$, a supersymmetric Higgs mass term, $\mu$, and quantities $A$ and $B$ which describe the relations between the Yukawa couplings and the cubic terms (and a certain term involving the Higgs masses). The low energy parameters are then determined by running the masses and couplings down to low energies using the renormalization group (usually after having determined the unification scale and coupling by the standard renormalization group analysis.) One of the exciting features of these models is that, for a range of parameters, this running leads to a
negative mass for the Higgs field which couples to the top quark, which triggers $SU(2) \times U(1)$ breaking.

There is one other, critical assumption which is usually made in these models. This is that the models should possess a discrete symmetry known as $R$-parity, under which all ordinary fields are neutral (including the two Higgs doublets) while all of the new superfields change sign. This is necessary to forbid vertices which would lead to rapid proton decay. (Alternatives to $R$-parity will not be considered here.) This symmetry has an immediate consequence: the lightest of the new particles is stable; it is this particle which is a candidate for dark matter. Which of these states it is depends on the parameters of the model. One possibility which has been ruled out is the “sneutrino,” the scalar partner of the neutrino. From LEP we know that this state, if it exists, has a mass larger than about 42 GeV. $\tilde{\nu}$ annihilation would proceed through “zino” exchange. But this interaction is rather strong, and as a result, the $\tilde{\nu}$ abundance is too small to make it a dark matter candidate.

For a good part of the parameter space, however, the LSP is the “neutralino,” a linear combination of the Higgsino, the “photino” and the “zino.” We will denote this state by $\chi$. In the MSSM, for a significant range of parameters, one finds that $\chi$ is a good dark matter candidate. This problem has been studied by many authors, and I will not attempt a complete survey here. For example, in fig. 4 one sees, for somewhat different assumptions about the parameters, that $\Omega \sim 1$ for a significant range of parameter space. Based on this, many have argued that if supersymmetry exists, the LSP is the dark matter.

Over the past year, there have been two significant developments. First, the problem of neutralino annihilation and detection has been studied with great sophistication and power. Much of the MSSM parameter space has been ruled out; gaugino-like LSP’s have been seen to be favored. Second, it has been appreciated that with some assumptions, one can even use the hypothesis of neutralino dark matter to constrain the supersymmetry parameters. Typically, one doesn’t want masses of squarks, etc., to be too small, since in that case the annihilation cross sections are too large. Roberts and Roszkowski, for example, find the following sorts of parameters (assuming, in addition to unification of gauge couplings, $SU(5)$-type unification of $m_b$ and $m_\tau$):

\begin{align*}
60 < m_\chi < 200 \text{ GeV} & \quad 150 < m_{\chi^\pm} < 300 \text{ GeV} & \quad 200 < m_{\tilde{\tau}} < 500 \text{ GeV} \quad (4.3) \\
250 < m_{\tilde{q}} < 850 \text{ GeV} & \quad 350 < m_{\tilde{g}} < 900 \text{ GeV}.
\end{align*}

The heavy Higgs fields have masses of order 250–700 GeV. Considerations of naturalness probably prefer the lower values of these masses.
What are the prospects for detecting this dark matter? If nature is supersymmetric at low energies, we are certain (given sufficient cooperation from the taxpayers) to find it in accelerators in the not too distant future. But can we hope to see the dark matter directly? This turns out not to be as easy as in the case of neutrinos, mentioned above. The problem is that $\chi$ is a Majorana particle, with only axial couplings to ordinary quarks at low momenta. As a result, one does not have the sort of coherent effects which permit heavy neutrino detection. Actually, the situation is more subtle than this. Once one considers couplings to gluons through loops, coherent couplings do arise. Even then, the event rates are small; typically one is talking of rates of order $1/\text{kg/day}$ This is problematic, given that backgrounds from photons are typically of order $0.5/\text{kg/day/keV}$. Still, there are many groups trying to search for these events. Recently, the feasibility of measuring the phonon signal from nuclear recoil has been demonstrated. A larger pilot experiment is currently in progress (involving LBL, CPA, UCSB, Stanford and San Francisco State; the studies are being performed at SLAC, using $1/2$ kg of $^{76}\text{Ge}$, brought over from the FSU in a suitcase). This gives significantly greater sensitivity, since photons deposit $33\%$ of their energy in ionization, and $66\%$ in phonons, while recoiling nuclei deposit $90\%$ of their energy in phonons. As a result, one can examine a significant part of the neutralino parameter space, as indicated in fig. 5.

An alternative method of searching for neutralinos from the halo is also being actively pursued. Neutralinos (and similar WIMP’s) can be captured in the earth and the sun, where they can subsequently annihilate. Since the sun and the earth
have been around for a long time, the total numbers of captured particles can be substantial. Capture occurs when a neutralino scatters elastically on a particle in the sun, emerging with a velocity smaller than the escape velocity. (The most thorough calculations of the capture rate are probably those by Gould.\textsuperscript{40}) The typical velocities of these particles are of order \(200\ \text{km/sec}\). Because of the earth’s low escape velocity, and because most of the nuclei in the earth are spinless, capture is rare for particles with mass greater than about \(80\ \text{GeV}\) (for pure gauginos). In the sun, capture is much more probable. The subsequent annihilation of these WIMP’s in the sun leads to production of \(\nu\)’s. For neutralinos, these \(\nu\)’s are produced principally in cascade decays of heavy quarks; most are \(\nu_\mu\)’s, with typical energies \(20–30\ \text{GeV}\). To date, the best experimental results come from IMB and Kamiokande. There are significant backgrounds from cosmic rays. Kamiokande, I understand, is currently doing a careful analysis. MACRO, in the Gran Sasso, is currently running; it covers an area something of the order of a football field in size. Future experiments include DUMAND and AMANDA. This last experiment involves looking for \(\nu\)’s by sinking an array of phototubes in the south pole ice; some pilot experiments have already been done. In principle, this experiment should cover an area about 100 times as big as that of MACRO. Eventually one
can hope to rule out a significant part of the MSSM parameter space.

What sort of uncertainties exist in these experiments? They are surprisingly small. The local density is known to within a factor of two. Uncertainties in the elastic cross sections are of a similar order; perhaps slightly larger. Some sense of what part of the parameter space can be ruled out (or discovered) by these types of experiments is indicated in fig. 6.

Fig. 6. Some of the parameter space which can be covered by indirect searches.

Finally, I would like to turn to two more theoretical questions. Most of the analyses which I have described involve the MSSM. They make quite specific assumptions about the mass spectrum. Just how plausible are these assumptions? And how important are they to these analyses?

In the absence of data, the answer to the first question depends a good deal on personal prejudice. For example, consider the assumptions that squarks and sleptons are degenerate at the highest energy scale, and that the gaugino masses are identical at this scale. Some assumption like this, apart from its plausibility, is essential in order to understand the absence of flavor changing neutral currents. In virtually all models which have been studied to date, however, all of these masses are parameters, which are not constrained by any principles of symmetry. Recently, a variety of scenarios have been proposed which might give rise to the phenomenologically required degree of degeneracy and proportionality. In string
BARYOGENESIS

In the last few years, it has become clear that the standard model violates baryon number significantly at high temperatures. This opens the possibility that the electroweak phase transition, if it is first order, could be the origin of the baryon asymmetry. Several mechanisms have been suggested which could lead to the asymmetry. The subject has recently been the subject of an excellent review, so I will only mention here two recent developments, and areas where further work is needed.

In order to obtain a departure from equilibrium, it is necessary that the phase transition be first order. Over the last year, there has been a great deal of work attempting to understand the phase transition. Perhaps the most thorough of these studies is that due to Arnold and Espinosa. (A somewhat simpler version of this analysis, which yields the largest contribution, is due to myself and my student J. Bagnasco). This work suggests that, for the relevant range of parameters, perturbation theory is not too bad a guide. Still, many serious questions have been raised about the validity of the perturbative analyses, and further work is necessary. There has been a great deal of other work on the phase transition as well, and controversy still seems to rein about such questions as: how strongly first order is the transition? how do bubbles propagate?

Most discussions of the subject of electroweak baryogenesis begin with the remark that there is not enough $CP$-violation in the minimal standard model
(MSM) to give the observed asymmetry. Since three generations are required to obtain $CP$-violation, one expects suppression by mixing angles and quark masses; even before one begins this yields a number like $10^{-20}$. Recently, however, Farrar and Shaposhnikov have argued that the suppression may not be nearly so severe. The argument involves careful treatment of quasi particle excitations in the plasma and resonant phenomena similar to the MSW effect. I think it is safe to say that the verdict is not yet in. Even if the suppression is not at great as one might have imagined, as these authors note, there are still a number of obstacles to obtaining a reasonable asymmetry in the MSM. First, a perturbative analysis gives that the baryon asymmetry is washed out unless the Higgs mass is less than about 35 GeV. The recent analyses referred to above indicate that higher order corrections give only a small change in this limit. Against this, one might argue that for heavy enough Higgs, the finite temperature perturbation theory is not under control at all. Second, there is the question of the rate. In ref. 48, similar dynamics in an extended model gave a maximum asymmetry of about $10^{-4}$. In comparing the analysis of ref. 49 with this, one sees that in the MSM one must pay at least a factor of $10^{-5}$ for mixing angles, and a factor of $m_s/T \sim 10^{-3}$. While their analysis differs somewhat, the main source of the larger answer seems to be in the choice of the baryon number violating rate. Such a large value is not implausible (indeed I have argued for it elsewhere$^{50}$).

There are some other developments which I would like to briefly mention:

1. The baryon number violating rate in the broken phase has been recalculated,$^{51}$ yielding a larger value than earlier calculations.$^{52}$ This is suggestive that the rate in the unbroken phase may be larger than previously assumed.

2. There has been an interesting proposal for how a suitable asymmetry might arise in a theory like the MSSM where $CP$-violating phases are small.$^{53}$ The point is that in many theories there is a range of parameters for which $CP$ is spontaneously violated at high temperatures. One might expect that this would lead to equal numbers of regions with one sign or the other of the baryon number, and that there would be no net asymmetry. However, because the bubble nucleation rate is exponentially sensitive to a large, three-dimensional tunneling action, small fractional changes in this action due to a small, $CP$-violating asymmetry can significantly bias the rate of bubble formation.

3. Motivated by the possibility of electroweak baryogenesis, a number of authors have begun to study the observability of various $CP$-violating phenomena in different experimental environments, including the SSC$^{54}$ and NLC$^{55}$.

Despite the progress of the last few years, as the confusion about baryogenesis in the MSM illustrates, it remains important to have improved calculations of baryon number violating rates, particularly in the unbroken phase, and to better
understand the electroweak phase transition and specific mechanisms for producing the asymmetry.

**EXOTICA**

Finally, I would like to turn to a number of more exotic problems, somewhat further removed from direct observation. Necessarily, because time is limited, these choices reflect more personal interests. Cosmology, in principal, can provide many interesting constraints on model building. If we assume that at temperatures of order, say, the weak scale and above, the universe was always in thermal equilibrium, these constraints can be quite severe. We have already mentioned one example: gravitinos lead to trouble, unless the reheat temperature after inflation is sufficiently low. Let me mention some examples which have been of relevance recently:

1. Domain walls. In models with spontaneously broken discrete symmetries, domain walls form. If they do not somehow decay, these come to dominate the energy density of the universe, and are unacceptable. A simple example of this problem is provided by a model with two Higgs doublets, $\phi_1$ and $\phi_2$ (non-supersymmetric). In such a model, one usually imposes a discrete symmetry which prevents flavor changing neutral currents. Because of this symmetry, the theory would appear to have a pair of degenerate vacua at tree level. However, Preskill et al\textsuperscript{56} pointed out that once QCD effects are taken into account, these vacua are not quite degenerate; they are split by an amount of order $m_\pi^2 f_\pi^2$. At first sight, this would appear irrelevant; it is to be compared with $m_W^4$. However, because the expansion of the universe goes as $H \sim m_W^2/M_P$, there is plenty of time for the domain walls to collapse. This suggests a more general point which was first raised, to my knowledge, by Sikivie\textsuperscript{17} in the context of axion physics. Suppose one has an approximate (accidental) discrete symmetry, broken by dimension 5 operators. Then these operators can also lead to collapse of domain walls. Thus it is not clear that domain walls are such a problem for model building. This idea was recently revived by Ral and Senjanovic\textsuperscript{57} in a different context, and by myself and A. Nelson in the framework of models of dynamical supersymmetry breaking, where accidental discrete symmetries (i.e., symmetries which are accidental consequences of gauge invariance and renormalizability) are common.\textsuperscript{44}

2. Problems with an earlier model: In my discussion of axions, I described a class of models in which discrete symmetries gave rise to an accidental Peccei-Quinn symmetry good enough to solve the strong $CP$-problem. However, I did not go into great detail about these models, and I neglected to point out...
another cosmological problem that these raise. One of the attractive features
of these models turns out to be that the scale $f_a$ is automatically of the desired
order of magnitude, $f_a \sim m_W m_P$. However, there is another side to this
good feature. In these theories, the PQ symmetry is broken by the vev of a
field whose potential has a characteristic curvature of order $m_{3/2}$. How does
the PQ-violating phase transition arise in this model? If the field, $S$, is in
thermal equilibrium at high temperature, than near the origin its potential has
a curvature of order $T^2$. But this means that the field gets hung up for a while
in a false vacuum. Eventually, it rolls to its minimum, but at the minimum
all of the fields to which it couples are very massive, so it can only dissipate
its energy with great difficulty. This is potentially a catastrophe. While this
problem is worthy of further investigation, one solution is to suppose that the
field does not “start” near its minimum. In this case, when it starts to oscillate
it carries only a tiny fraction of the total energy density, and this is still true
when it decays.

3. Axinos: Related to the problem described above is a perhaps more general
set of issues which have been extensively discussed in the literature. In su-
persymmetric theories in which the strong $CP$-problem is solved by an axion,
the axion will have a scalar and a spinor superpartner. The spinor is refe-
red to as the axino, the scalar as the saxion. Both of these particles are, like the
axion, extremely weakly interacting, with interaction strengths proportional to
$1/f_a$. Thus they have potentially significant phenomenological implications.
It is generally agreed that the saxion will have a weak-interaction type mass
after supersymmetry breaking. About the axino, the literature is more varied,
with many claims that this particle can be quite light, with a mass of order
$m_{3/2}^2/f_a \sim \text{keV}$. This would have implications, for example, for the stability
of neutralinos, and thus for their role as dark matter; they might well decay
on cosmologically interesting time scales (if their decays are due to operators
of dimension 5, for example, their lifetimes could well be of order seconds; if
higher dimensions, they could be of order the age of the universe). These axi-
os, in turn, could play the role of “warm” dark matter. In fact, Masiero et al.
have recently pointed out that they could provide a form of HCDM, with one
component arising from neutralino decay, another from the simple equilibration
of these particles.\textsuperscript{59}

It should be noted, however, that these axinos are likely to have weak inter-
action size masses. In the context of particular models, this has been discussed
before.\textsuperscript{61} In general, a supersymmetric mass term for these fields can appear
in the effective lagrangian with a coefficient of order $m_W (m_{3/2})$ by essentially
the same mechanisms which have been discussed for the Higgs particles. (For
a nice review of this latter problem, see ref. 42.) If \( \phi = \tilde{s} + ia + \theta \tilde{a} + \ldots \) denotes the axion superfield, and \( Z \) is some hidden sector field responsible for supersymmetry breaking, the operator

\[
\int d^4 \theta Z^\dagger (\phi + \phi^\dagger)^2
\]

would give a mass to the axino of order \( m_{3/2} \); in the context of supergravity, other terms can appear as well. It is difficult to suppress these operators by any symmetry, since such a symmetry would also forbid gaugino masses. If they are heavy, the cosmology of the axino and saxino fields is potentially catastrophic, since these fields drop out of equilibrium while they are still relativistic, and easily provide far too much matter today. This problem, however, may be solved if inflation occurs below the Peccei-Quinn scale, at least if the reheating temperature is low enough that not too many of these particles are produced later (this constraint is analogous to constraints on gravitinos).

4. Cosmological constraints on models with dynamical supersymmetry breaking.

Recently, Banks et al.\(^{58}\) have surveyed a number of issues in models with dynamical supersymmetry breaking. They point out that, making again the sort of cosmological assumptions I have described above, many supersymmetry breaking scenarios have trouble. In particular, gluino condensation scenarios for string theory run into difficulties analogous to some of those I have described above. One has, at early times, weakly coupled fields which have no reason to sit near the minima of their potentials. As a result, huge amounts of energy are stored in them, and it is difficult to dissipate this energy. Instead, one is forced to a particular class of models in which supersymmetry is broken strongly. These models have their own special difficulties, in particular in generating gaugino masses.

5. Still other features of models with dynamical supersymmetry breaking. Recently, Ann Nelson and I have considered a class of models in which supersymmetry is broken dynamically at TeV energies.\(^{44}\) The only feature of these models I want to mention is that in these theories, the neutralinos and similar particles can decay with weak interaction lifetimes to gravitinos; the gravitinos, in turn, are very light (typically with eV-ish masses). These particles in themselves are a potential problem. They are like a fourth generation of neutrinos (with two helicity states) and can spoil nucleosynthesis. These models have other problems as well, which have been alluded to earlier. They can give rise to domain walls (though the particular example we studied does not) which must be removed by the higher dimension operator mechanism I described earlier. Also, these models often contain massive, stable particles associated
with supersymmetry breaking. These are probably not suitable dark matter
candidates; in fact, there are likely to be far too many of them unless higher
dimension operators render them unstable.

Earlier, I stressed that all of these problems presume that we can simply run
the clock backwards on the big bang. This is not necessarily so. Since we now know
that the baryon asymmetry may have been created rather late, one can contemplate
the possibility that there was a severe departure from thermal equilibrium at
temperatures far below any GUT scale. The most extreme possibility, which has
been developed recently by Knox and Turner is that inflation itself occurred at the
weak scale. Before the advent of electroweak baryogenesis, this would have been
deemed impossible; there would be no way to generate the observed asymmetry.
Now, it appears that if the final temperature after inflation is of order the weak
scale, it is possible to generate the asymmetry. It is probably fair to say that no
very attractive model of this type exists. However, many would argue that the
same is true of inflation at any scale, so this possibility should be born in mind.

Let me close by mentioning another class of puzzles. I have, so far, been almost
taking for granted that \( \Omega = 1 \). But there is a problem with such a value of \( \Omega \): the
age of the universe. We know from a variety of sources (long-lived radioisotopes,
oldest stars, cooling of white dwarfs) that the age of the universe is almost certainly
greater than about 12 billion years. On the other hand, most measures of \( h \) give
\( H \approx 80 \text{ km sec}^{-1} \text{ Mpc}^{-1} \). Assuming \( \Omega = 1 \), this gives for the expansion age of the
universe \( t = 8 \) billion years. Some measurements of \( H \) give values around 50, giving
something closer to the 13 billion years or so inferred from other measurements.
Many astrophysicists believe that the lower value will eventually be seen to be the
correct one, but one should keep in mind that this is not necessarily the case. In
principle, this question will be settled eventually by HST.

One model which has been proposed to explain a larger value of \( H \) has \( \Omega = 0.2–0.3 \)
in cold dark matter or baryons, while the universe is flat as a result of a
cosmological constant. Such a model can provide for growth of structure while at
the same time accommodating the larger values for the age of the universe.\(^{62}\)

In any case, this dilemma has created interest in models with a non-vanishing
cosmological constant. Of course, it is one of the great mysteries of particle physics
why the cosmological constant is small. It is perhaps doubly mysterious why
\( \Lambda \) might take on just the value of cosmological interest. Recently, Carlson and
Garretson have noted that this value might not be unreasonable in a theory which
could solve the cosmological constant problem, but in their scenario such a value
is not in any sense preferred (the cosmological constant is just a function of some
mass scales which are adjustable).\(^{63}\) My own belief, if the cosmological constant
is non-zero, is that some sort of anthropic explanation is called for (perhaps the
cosmological constant takes different values in different parts of the universe, and for some reason—which I certainly don’t claim to know—we can only exist in a universe with such a small cosmological constant.

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