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ASTROPHYSICS, COSMOLOGY, AND UNIFICATION OF FORCES

BARRY C. BARISH

California Institute of Technology, Pasadena, CA 91125

MICHAEL S. TURNER

The University of Chicago, Chicago, IL 60637
and
Fermi National Accelerator Laboratory, Batavia, IL 60510

FRANK WILCZEK

Institute for Advanced Study, Princeton, NJ 08540

1 Executive Summary

The fields of astrophysics, cosmology, and unification are growing areas of research that are at the intellectual frontier of particle physics. Because the "energy reach" of theory has exceeded that of terrestrial experiment, the pursuit of fundamental physics has more and more come to involve astrophysics and cosmology. Today many particle physicists, both theorists and experimentalists, are working at the interface of particle physics with astrophysics and cosmology, and this trend is likely to increase.

The boundaries of particle physics now touch on cosmology, astrophysics and gravity. Our best attempts to understand the origin of the cosmic asymmetry between matter and antimatter, the tiny primordial inhomogeneities that seed the growth of all structure in the Universe, and the nature of the mysterious dark matter involve fundamental physics. Studies of the highest-energy cosmic rays or of the low-energy solar neutrinos already hint at physics beyond the Standard Model. The unification of the strong, weak and electromagnetic forces seems to implicate gravity and to force the question of its quantization.

Large-scale experiments addressing these fundamental problems have already been undertaken and many more are planned. They include the search for proton decay and particle dark matter, measurements of the solar-neutrino flux, large redshift surveys, programs to observe gravity waves, map out the anisotropy of the cosmic background radiation, and study the highest-energy cosmic-ray particles.

Increasingly these experimental efforts have come to involve scientists from diverse disciplines (*e.g.*, astronomy, space science, nuclear physics, and high-energy physics). The growing scope and importance of efforts in particle astrophysics requires that difficult structural issues facing an inter-disciplinary field be addressed. Some of these include determining the role of the national laboratories, developing methods for planning and setting priorities, and coordinating with other disciplines and several funding agencies (*e.g.*, Divisions of Physics and of Astronomy at NSF, Divisions of High Energy and of Nuclear Physics at DOE, and various programs at NASA).

2 Cosmology

2.1 Status

The standard model of cosmology, the hot big-bang model, provides a remarkably successful account of the history of the Universe from about 0.01 sec (temperature $\sim 10\,\mathrm{MeV}$) until the present (about 15 billion years later and temperature 2.726 K). The standard cosmology supplemented by modern ideas in particle physics has allowed sensible speculations about the earliest history of the Universe which address a deeper set of cosmological questions. Conversely, the early Universe provides a unique "laboratory" in which physics at unification energies (say, greater than $10^{10}\,\mathrm{GeV}$) can be studied.

Four pillars provide the observational support on which the standard cosmology rests: (1) The uniform distribution of matter on large scales and the isotropic expansion that maintains this uniformity; (2) The existence of a nearly uniform and accurately thermal cosmic background radiation (CBR); (3) The abundance (relative to hydrogen) of the light elements D, ^{3}He, ^{4}He and ^{7}Li; and (4) The existence of small fluctuations in the temperature of the CBR across the sky at the level of about 10^{-5}.

The nearly linear relationship between velocity and distance (Hubble's expansion law) has been established out to distances of about 300 Mpc (5% of the distance to the edge of the observable Universe). Except for a handful of nearby galaxies, all galaxies are observed to have redshifted, as opposed to blueshifted, spectral features, indicating a universal expansion. [The shift of spectral lines toward longer wavelength, $\lambda_{\rm detected} \equiv (1+z)\lambda_{\rm emitted}$, is related to the size of the Universe when the radiation was emitted: $R_{\rm today}/R_{\rm emission} = (1+z)$.] Hundreds of objects with redshifts in excess of unity have been seen, and the most distant of these is a quasar with redshift $z = 4.9$. There is no doubt that the Universe is expanding in accord with the big-bang model. Unfortunately, the very important proportionality constant in Hubble's law, the present expansion rate $H_0 = 100h\,$km/sec/Mpc which sets the scale for cosmic distances as well as cosmic times, has yet to be determined accurately.

Measurements made by the Far Infrared Absolute Spectrometer (FIRAS) on the Cosmic Background Explorer (COBE) spacecraft have established the blackbody nature of the CBR spectrum to better than 0.03%, leaving little room to question that the radiation is a relic of an early, hotter and denser epoch. The dipolar variation of the CBR temperature on the sky indicates that our galaxy is moving with respect to the cosmic rest frame at a speed of 620 km/s. Remarkably, the yearly modulation of the CBR temperature due to orbital motion about the sun at 30 km/s has also been measured by COBE (the earth really does move!).

According to the big-bang model the temperature of the CBR decreases as the Universe expands, and a recent measurement has confirmed this. The relative populations of hyperfine states in neutral Carbon atoms seen in a gas cloud at redshift $z = 1.776$ indicated a thermodynamic temperature, $7.4 \pm 0.8\,$K, which is consistent with the big-bang prediction for the CBR temperature at this earlier time $T(z) = (1+z)2.726\,{\rm K} = 7.58\,{\rm K}$.

The earliest and perhaps most impressive test of the standard cosmology involves the light elements D, ^{3}He, ^{4}He and ^{7}Li which were synthesized when the Universe was seconds old. The predictions for the "primeval" (just after big-bang nucleosynthesis) abundances of these elements depend upon the number of light neutrino species (now known to be three) and a handful of nuclear matrix elements (which for the most part are relatively well determined). The comparison between the predicted abundances and the light-element abundances measured today is not a simple matter; it is complicated by 15 Gyr of "chemical evolution" (astrophysical processes destroy D, produce ^{4}He, and destroy or produce ^{3}He and ^{7}Li). However, three decades of careful theoretical and observational work has put the comparison on a firm footing, and there is excellent agreement provided that the ratio of baryons to photons is between 2.5×10^{-10} and 6×10^{-10} (see Fig. 1).

Accepting the validity of the standard cosmology, this then provides the most accurate determination of the density of ordinary matter, between about $1.5 \times 10^{-31}\,{\rm g/cm}^3$ and $4.1 \times 10^{-31}\,{\rm g/cm}^3$. However, because the value of the critical density depends upon the Hubble constant, $\rho_{\rm crit} = 3H_0^2/8\pi G$, the fraction of critical density contributed by baryons is not as well determined, between about $0.01h^{-2}$ and $0.02h^{-2}$ or 1% and 15% for a generous range of the Hubble constant ($h = 0.35 - 1.0$).

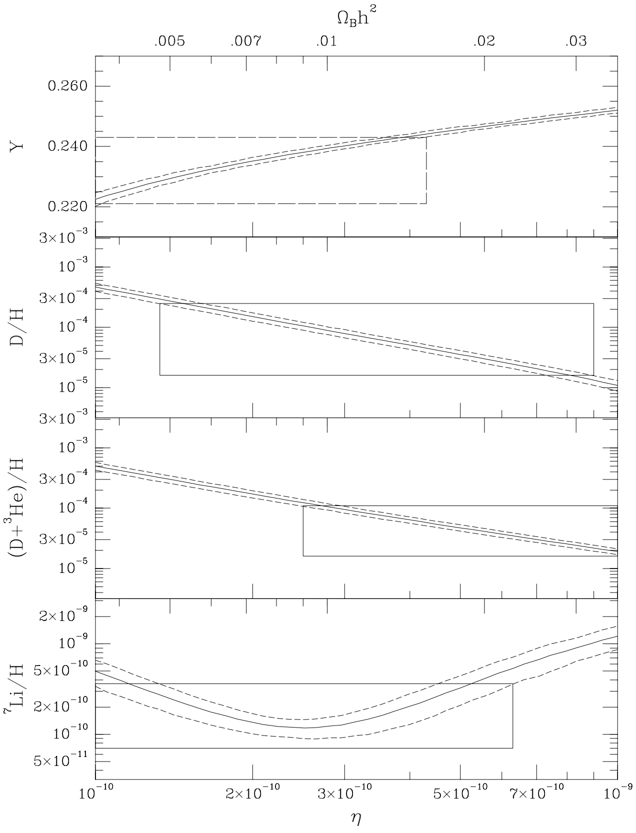

Figure 1: The predicted light-element abundances as a function of the baryon-to-photon ratio η and $\Omega_B h^2$. The broken curves delineate the two-sigma theoretical uncertainties and the boxes delineate the acceptable range for η as allowed by measured abundances. The predictions for all four light elements are consistent with the observations for $\eta \simeq 2.5 \times 10^{-10} - 6 \times 10^{-10}$. (Figure courtesy of C. Copi.)

The final pillar involves the existence of small variations in the CBR temperature (around 30μK) at points on the sky separated by angles from about 0.5° to 90° (see Fig. 2). These fluctuations imply the presence of inhomogeneity (of about the same magnitude) at early times. These tiny seed inhomogeneities, amplified by gravity over the life of the Universe, develop into the rich variety of structures we observe today—galaxies, clusters of galaxies, superclusters, voids, and great walls. This picture for how structure evolved is an essential aspect of the standard cosmology as it links the smooth early Universe with the markedly inhomogeneous Universe today.

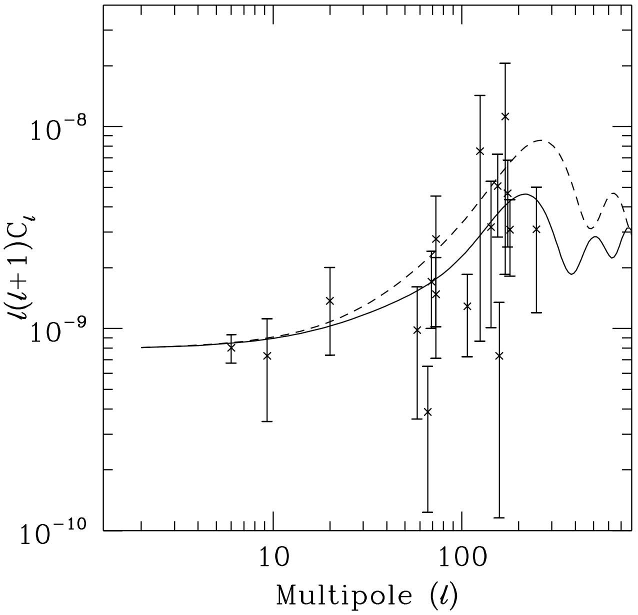

Figure 2: Summary of current measurements of CBR anisotropy in terms of a spherical-harmonic decomposition, $C_l \equiv \langle|a_{lm}|^2\rangle$. The rms temperature fluctuation measured between two points separated by an angle θ is roughly given by: $(\delta T/T)_\theta \simeq \sqrt{l(l+1)C_l}$ with $l \simeq 200^\circ/\theta$. The curves are the cold dark matter predictions, normalized to the COBE detection, for Hubble constants of 50 km/s/Mpc (solid) and 35 km/s/Mpc (broken). (Figure courtesy of M. White.)

2.2 Open problems

Building upon the success of the standard cosmology we can now address questions that involve the most fundamental aspects of the Universe. Our best efforts to answer these questions involve events occurring during the earliest moments and physics at the highest energies. Today, cosmologists and particle physicists are involved in a common quest to understand physics beyond the Standard Model.

Here we highlight some pressing issues. An exciting common theme is that data are pouring in from a variety of efforts—observations made by telescopes to particle searches at the highest-energy accelerators—and are testing both early-Universe cosmology and fundamental physics at the highest energies. We are poised for major advances in our understanding of both cosmology and fundamental physics.

2.2.1 Nature of the Dark Matter

The mean density of the Universe, expressed as a fraction of the critical density ($\bar{\rho}/\rho_{\rm crit} \equiv \Omega_0$), is a very important cosmological parameter which, like the Hubble parameter, is still not known with good precision. With confidence it is only possible to say that Ω_0 is between 0.1 and 2. The value of Ω_0 takes on additional importance because nucleosynthesis indicates that ordinary matter can account for between about 1% and 15% of critical density. Thus, if the total density is significantly greater than 15% of critical, a strong case exists for an additional, exotic component. There is a ready candidate for this exotic component: elementary particles that remain today from the earliest moments.

To be more specific, it is known that: (i) luminous matter (that closely associated with stars) contributes much less than 1% of the critical density; (ii) based upon nucleosynthesis, ordinary matter contributes between about 1% and 15% of critical density; (iii) dynamical measurements of the mean mass density indicate that it is certainly greater than 10% of the critical density, probably at least as large as 20% to 30% of the critical density, and a few measurements even suggest that it is close to the critical density. These dynamical measurements include: determinations of the masses of rich clusters from x-ray measurements, galactic motions (virial theorem), and gravitational lensing; estimates of the mean density based upon relating the peculiar motions of galaxies to the inhomogeneous distribution of matter; and measurements of the masses of spiral galaxies based upon rotation curves and gravitational lensing by their halos. It is important to state again, no method has yet provided a definitive answer for the mean density.

A number of indirect arguments favor the spatially flat, critical Universe; among them, structure formation—the most successful models involve a flat Universe—and theoretical notions—inflation and the Eddington-Dicke-Peebles naturalness argument (regardless of the value of Ω today, at early times Ω approaches unity, and if $\Omega \neq 0$, we are living at the special epoch when it is first beginning to deviate from unity).

Two dark-matter problems are indicated: the form of the dark baryons, and the form of the exotic dark matter—provided the density of the Universe is greater than that which ordinary matter can contribute. If the density of the Universe is equal to the critical density, then exotic matter is the dominant form of matter in the Universe.

The "dark" baryons are likely to exist in different forms in different places. In rich clusters the majority of baryons exist in the form of hot, x-ray emitting gas, and thus by "optical standards" are dark. The abundance of hot gas in clusters has measured by satellite-borne x-ray instruments (Einstein, ROSAT and ASCA) and is only around 5% to 10% of the total cluster mass, supporting the idea of nonbaryonic dark matter.

In spiral galaxies like own Milky Way, the bulk of the baryons are certainly not hot gas and are likely to be dark stars, objects not massive enough to have ignited their nuclear fuels (mass less than about $0.08M_\odot$) or stars that have exhausted their nuclear fuels (old neutron stars, white dwarfs or black holes). Three large-scale efforts are underway (MACHO, EROS, and OGLE collaborations) to search for dark stars in our galaxy through the effects of microlensing, and more than fifty microlensing events have now been seen. The event rates suggest that dark stars can only account for about 10% of the mass of the dark halo of our galaxy, further strengthening the case for nonbaryonic dark matter.

The second dark matter problem seems to directly involves fundamental physics, and the idea that the dark matter is something exotic receives support from such considerations. For three particles, the axion, the lightest supersymmetric partner (usually the neutralino), and the neutrino, the relic mass density contributed by these particles can be about equal to the critical density.

The axion and neutralino are hypothetical particles that arise from attempts to solve problems in particle physics (strong-CP problem for the axion and mass hierarchy problem for the neutralino). In the case of the neutrino, three species are known to exist and their relic abundance is accurately known ($113\,\mathrm{cm}^{-3}$); the issue is mass. To be cosmologically interesting, a neutrino mass of order 3 eV to 30 eV is required. Virtually all attempts to unify the forces and particles lead to the prediction that neutrinos have mass; while the predictions vary wildly, in some instances they fall into this range.

2.2.2 Structure Formation

The basic picture of how structure developed has been established: Small inhomogeneities in the density of the Universe were amplified by gravity and ultimately grew into the structure seen today. The challenge is to formulate a coherent and detailed picture. The two basic elements of such a description are a specification of the quantity and composition of the dark matter and a quantitative description of the density perturbations. We have just discussed the relationship of the dark matter problem to fundamental physics; the most attractive models for the origin of the density perturbations also involve fundamental physics.

The first and probably most attractive possibility is that the density perturbations arose from quantum-mechanical fluctuations during inflation (see below). Inflation-produced density perturbations and a critical-density Universe comprised mainly of "cold dark matter" (slowly moving particle dark matter—axions or neutralinos) leads to the most successful and well studied picture for structure formation, known as the cold dark matter theory. (The other alternative with inflationary perturbations, hot dark matter, where the bulk of the mass density is in fast-moving neutrinos does not lead to a viable picture of structure formation because galaxies and even smaller structures form far too late.)

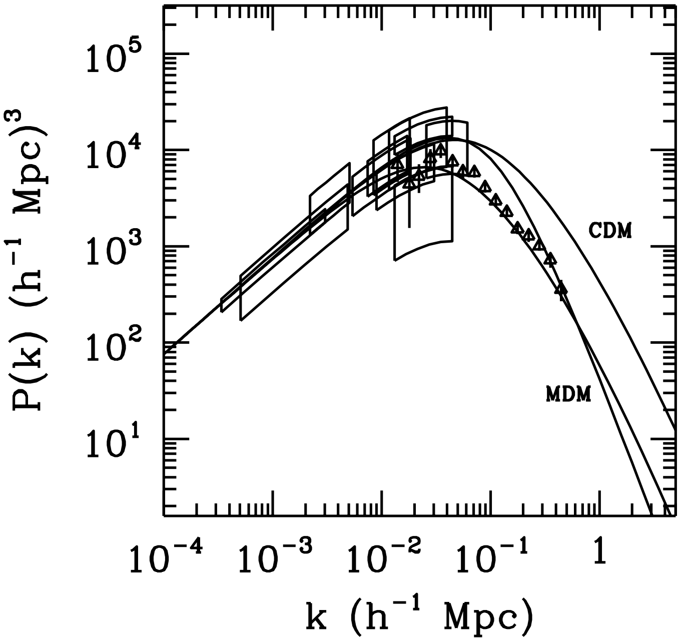

Figure 3: Comparison of the cold dark matter perturbation spectrum, $P(k) \equiv |\delta_k|^2$, with CBR anisotropy measurements (boxes) and the distribution of galaxies today (triangles). Wavenumber k is related to length scale by: $k = 2\pi/\lambda$; error flags are not shown for the galaxy distribution (since it is indicative of the distribution of "light" as opposed to mass there could well be a systematic offset). The curve labeled MDM is hot + cold dark matter ("5 eV" worth of neutrinos); the other two curves are cold dark matter models with Hubble constants of 50 km/s/Mpc (labeled CDM) and 35 km/s/Mpc. (Figure courtesy of M. White.)

The measured CBR anisotropy and the distribution of galaxies in the Universe today (as determined by redshift surveys) generally agree with the predictions of cold dark matter (see Fig. 3). However, there is evidence for a discrepancy: when the spectrum of density perturbations is normalized to agree with the CBR anisotropy as measured by COBE, the level of inhomogeneity predicted on small scales seems to be too large. This discrepancy, which is supported by several other observations (including the abundance of clusters and their clustering properties), suggests that the cold dark matter theory needs to be modified slightly. A number of "fixes" which lead to a better fit to the observations have been proposed: hot + cold dark matter, cosmological constant + cold dark matter, unstable tau neutrino + cold dark matter. It is interesting to note that the discrepancy would vanish if the Hubble constant were around 35 km/s/Mpc; however, such a value is significantly lower than the current range of measurements.

The second possibility is that the seeds are topological defects (cosmic string, textures, or global monopoles) produced in an early-Universe phase transition. An attractive feature of this idea is that the energy scale desired for these defects, around 10^{16} GeV, is close to estimates for the unification scale. In these models the dark matter could either be neutrinos (in the case of cosmic string) or cold dark matter (in the case of textures). It is technically much more challenging to make sharp predictions for these models because density perturbations arise due to the defect network which constantly evolves with time. However, based upon the work done to date, defect models appear to be less successful in accounting for the observed structure and measured CBR anisotropy.

The first two pictures involve fundamental physics; a third, more conservative picture of structure formation has been advocated by Peebles and is known as the primeval baryon isocurvature scenario (PBI). This model begins with a sub-critical Universe comprised of baryons only and an ad-hoc spectrum of perturbations in the distribution of baryons. At the very least PBI provides a "standard" against which the two early-Universe scenarios can be judged. Thus far it has been less successful, requiring a baryon density that is higher than the nucleosynthesis limit and having difficulty conforming to CBR anisotropy measurements.

In sum, because the density perturbations that seed structure may well trace their origins to the earliest moments of the Universe, the study of large-scale structure has become an important window on physics beyond the Standard Model.

2.2.3 Inflation

Guth proposed the idea of cosmic inflation to address three vexing problems associated with the standard cosmology:

- Why is the observable Universe so smooth (horizon problem)?
- Why has the Universe not recollapsed or gone into free expansion long ago (flatness problem)?
- The extreme overproduction of magnetic monopoles in the early Universe (monopole problem).

Inflation not only squarely addresses these three problems, but it also provides an explanation for the origin of the tiny primeval density perturbations.

The key to inflation's beneficial effects is a very rapid period of expansion driven by the false-vacuum energy associated with a scalar field that is displaced from the minimum of its potential-energy curve. During the inflationary period the Universe grows in size by a larger factor than it has since. This tremendous growth allows a small smooth part of the Universe to become large enough to encompass all that we see today; it also allows quantum-mechanical fluctuations on very small scales ($< 10^{-23}$ cm) to become density fluctuations on astrophysical scales ($> 10^{25}$ cm). (Quantum-mechanical fluctuations also lead to a spectrum of relic gravitational waves.)

Inflation ends with the enormous entropy production associated with the conversion of the false-vacuum energy into a thermal bath of radiation (that ultimately becomes the CBR) and exponentially dilutes the abundance of any unwanted relic such as magnetic monopoles. Any baryon number the Universe possessed before inflation is also exponentially diluted and baryogenesis (see below) is a necessity.

Inflation has revolutionized the way cosmologists think about the early Universe as well as the Universe today. It has been one of, if not the most, important ideas in cosmology in the past two decades. At the moment, there is no standard model of inflation; there are many viable models, most of which involve energy scales of 10^{14} GeV and greater (although there is at least one model where inflation occurs at the electroweak energy scale). Great effort is being given to "connecting" the inflationary scalar-field potential which drives inflation to models for unification or to superstring theory.

One of the best prospects for testing inflation and learning about the underlying inflationary model is by testing the cold dark matter theory of structure formation. Observations of large-scale structure and the anisotropy of the CBR can be used to determine the spectra of density and gravity-wave perturbations (amplitudes and power-law indices). They in turn can be used to determine the shape and scale of the scalar-field potential. Such information would surely provide valuable insights about physics at energies well beyond those accessible in terrestrial laboratories.

Inflation not only holds the promise of extending the standard cosmology to very early times but also of providing a "bridge" from cosmological observations to unification-scale physics.

2.2.4 Baryogenesis

There is good evidence that the Universe contains only matter and thus has a net baryon number, about 10^{-10} relative to the photon number. The matter-antimatter asymmetry is very small, very mysterious, and very important—without it, matter and antimatter would have annihilated to negligibly small levels when the Universe was a fraction of a second old. In 1967 Sakharov suggested that this asymmetry could have evolved dynamically in the early Universe due to interactions that do not conserve baryon number, do not respect C and CP symmetry (matter/antimatter symmetry) and occurred out of thermal equilibrium. For a decade the paper went unnoticed, in part because there was little motivation for the nonconservation of baryon number. The advent of grand unification and its prediction of baryon-number violation led to the first working model for the origin of the baryon asymmetry (baryogenesis). It involves the out of equilibrium decay of a superheavy Higgs boson which mediates baryon-number violation (such bosons are predicted to exist in virtually all grand unified theories).

Almost two decades after Sakharov's paper, it was suggested that the required baryon-number violation could arise due to nonperturbative effects in the Standard Model. Since, a great deal of activity has focussed on whether or not physics at the electroweak scale—perhaps even within the Standard Model itself—can account for the baryon asymmetry of the Universe. The issue, which is a pivotal one, has yet to be resolved.

The baryon asymmetry of the Universe appears to be deeply connected to the physics of baryon-number violation and C, CP violation. Conversely, the existence of a cosmic baryon asymmetry provides strong circumstantial evidence for baryon-number violation and C, CP violation beyond the K-meson system. It seems certain that advances in the understanding of both baryon-number violation and CP violation and the origin of the cosmic baryon asymmetry will be closely linked.

2.2.5 Relic neutrinos

Neutrinos have provided and continue to provide a pivotal connection between particle physics, astrophysics and cosmology. The success of primordial nucleosynthesis (as well as our understanding of the weak interactions) gives us confidence that the relic abundance of neutrinos is $113\,\mathrm{cm}^{-3}$ with temperature equal to $(4/11)^{1/3}$ that of the CBR. The fraction of critical density contributed by neutrinos is related to the sum of their masses, $\Omega_\nu h^2 = \sum m_\nu/93\,\mathrm{eV}$, and if the sum of neutrino masses is a few eV or greater neutrinos contribute at least as much mass density as baryons do. If they are unstable, then they can have variety of interesting effects for a much wider range of masses (*e.g.*, their decays can reionize the Universe after decoupling or raise the level of relativistic particles and improve the agreement between the cold dark matter theory and observations).

In any case, neutrinos are a cosmological relic that we are confident must exist, and, if detected, they would provide a window on the Universe at an age of around 1 sec (the surface of last scattering for neutrinos). Unfortunately, there are no practical ideas for their detection (yet!).

2.2.6 Phase transitions

It is very likely that the Universe has undergone two phase transitions (quark/hadron and electroweak symmetry breaking) and perhaps several others (*e.g.*, symmetry breaking associated with grand unification and compactification of extra dimensions). There may be remnants left over from these phase transitions (*e.g.*, topological defects) or other important consequences (production of the baryon asymmetry or inflation). The early Universe provides one of the few "laboratories" where the full nonperturbative effects of this physics can be studied.

2.2.7 Planck Epoch

General relativity together with current ideas in particle physics allows us to self-consistently extrapolate to times as early as 10^{-43} sec. Earlier than about 10^{-43} sec (temperatures greater than 10^{19} GeV) quantum corrections to general relativity should be very significant and must be considered. Thus, the very early Universe offers one of the few venues for studying the quantum effects of gravity. Superstring theory and other attempts to unify/quantize gravity make some notable predictions, *e.g.*, the existence of extra spatial dimensions or that gravity at high energies differs from general relativity. The hope exists that through extra dimensions or connections to inflationary theory or something else cosmology will allow the exploration of the quantum gravity regime.

2.2.8 Cosmological Parameters

From the discussion of open problems it is clear that more precise knowledge of the cosmological parameters, H_0, Ω_0, the deceleration parameter q_0, the age of the Universe t_0, and the cosmological constant Λ, is crucial to testing many of our most interesting ideas about the earliest history of the Universe, *e.g.*, nonbaryonic dark matter, the cold dark matter theory, and inflation. The need to know these parameters is so pressing that physicists have become involved in trying to determine some of them, *e.g.*, the use of distant (redshifts $z \sim 0.3$) type Ia supernovae to determine q_0. It is likely that there will be even more interest in using new techniques to measure these important parameters.

3 Unification

3.1 The Case for Unification

One primary goal of physics is to achieve an integrated description of Nature. History teaches us that progress toward this goal is not continuous. Rather, long periods of piecemeal accumulation of insight within limited domains of experience have been punctuated by a few bold syntheses which suddenly connect what had seemed quite separate. Historical examples include Newton's synthesis of terrestrial mechanics and celestial dynamics, and Maxwell's synthesis of electricity, magnetism, and optics. More recent examples include Einstein's synthesis of space, time, and gravitation; and the profound synthesis, made possible by quantum theory, of chemistry, material science and fundamental physical law.

Each of these great syntheses not only formed connections between what was previously known, but produced essentially new, unanticipated consequences, which often did not become fully apparent for many years. Thus Newtonian mechanics leads directly to modern structural engineering on the one hand and inertial guidance on the other; Maxwellian electrodynamics underlies every aspect of modern telecommunications; and the insights provided by quantum theory provide the foundation for lasers, transistors, and a host of other innovations. Even Einstein's general relativity theory, which was deduced by "thought experiments" and for many years was notorious for being difficult to test, has become the foundation of modern cosmology and a workhorse of contemporary astrophysics, describing in exquisite detail beautiful observations regarding pulsar timing and gravitational lensing, among other things.

As documented in an earlier Chapter, a remarkable new synthesis between what previously appeared to be widely disparate areas of physics—electrodynamics and the weak nuclear force—has evolved, over the last thirty years or so, from a tentative, schematic suggestion into a fully predictive and experimentally verified theory. This synthesis, together with the modern theory of the strong nuclear force, quantum chromodynamics or QCD, forms the basis for the Standard Model of particle physics. The Standard Model accurately describes an astonishing range of phenomena in terms of a few deep principles, and by any measure represents one of the greatest intellectual achievements of all time.

The guiding principle of the Standard Model is the symmetry of physical law. To be more precise, the principle of gauge invariance dictates how many gauge bosons exist and how they interact. And precisely these interactions are responsible for the structure of matter. It is impossible to do justice to the elegance and power of these mathematical principles in a small number of ordinary words; but one can fairly say that the fundamental laws governing (in Dirac's phrase) "all of chemistry and most of physics" are embodied, within their own appropriate language, in a few lines of poetry.

Yet there are important clues leading us to suspect that the Standard Model is but a way-station on the road to a still grander and more complete synthesis, some of whose far-reaching implications—for cosmology, in particular—we can already begin to discern.

To put these clues in context, we must now mention another central feature of the Standard Model, a feature that is perhaps unique in the history of physics. Very roughly speaking, in the past one has arrived at successively deeper and more complete levels of understanding matter by discovering and analyzing ever smaller and more basic building blocks. Thus ordinary matter was analyzed into molecules, molecules into atoms, atoms into electrons and nuclei, nuclei into protons and neutrons, protons and neutrons into quarks and color gluons. Thinking along these lines, one might anticipate that the next thing that will happen would be that electrons, quarks, gluons, and the other "fundamental particles" of the Standard Model will be further analyzed into smaller, more basic entities. There are important reasons to believe, however, that this is not the case—that electrons, quarks, and gluons are in a real sense truly fundamental, and that the next step beyond the Standard Model will be profoundly different from those that went before.

What suggests this extraordinary conclusion? First, of course, there is the fact that experiments attempting to find substructure have uniformly failed. Second, within the Standard Model itself one finds that all interactions turn off at short distances or high energies. This asymptotic freedom property is central to the modern theory of the strong interaction, and has been very extensively checked, as is discussed elsewhere in this Report. This property implies that it is internally consistent to assume that the Standard Model is valid down to arbitrarily short distances. Indeed not only does the assumption of simplicity and closure avoid contradictions—it becomes ever more accurate, as the interactions turn off completely.

Just because the Standard Model is potentially so accurate and complete, we must judge it by the highest standards. Every imperfection, in a theory which presents itself as potentially a nearly complete description of the fundamental laws of the material world, must be cause for pain and puzzlement.

Upon critically scrutinizing the Standard Model, one does readily discern imperfections. The gauge bosons fall into three unrelated sets, associated with the three different gauge groups $SU(3) \times SU(2) \times U(1)$ that appear in the mathematical formulation of the theory. Similarly, the fundamental fermions fall into fifteen different unrelated sets—three identical repeats of five essentially different structures. One cannot be satisfied with such a proliferation of structures. The situation becomes even more disturbing when one considers the electric charges of the different particles, which likewise appear rather helter-skelter.

A considerable effort of focussed imagination is required to discern any pattern implicit in this apparent jumble. Fortunately, an extremely attractive and convincing one was found for us by Georgi and Glashow. They showed that the various gauge bosons could be grouped into a single larger structure, $SU(5)$, and that when this was done the fundamental fermions fell into just six groups (three identical families each with two different groups), and furthermore that when this was done the electric charges were determined uniquely and correctly. Many variants and extensions of this idea have been proposed since, but all successful ones employ the same core pattern. The idea, then, is that at some very short distance (or, equivalently, in interactions at very high energies) the full symmetry of the world is larger than that of the Standard Model. The Standard Model as we see it at comparatively large distances, or in interactions at low energies, descends from the larger, more symmetric model by a process of spontaneous symmetry breaking. The sub-idea of spontaneous symmetry breaking, of course, is partially inspired by the similar mechanism known to be at to work in the electroweak sector of the Standard Model.

Most remarkably, these bold speculations involve a concrete, testable numerical consequence. For the gauge bosons of $SU(3) \times SU(2) \times U(1)$ to unify into the single structure $SU(5)$ (or any of its variants), it is necessary that their coupling strengths become equal. One can compute how the actual coupling strengths change with distance, following the procedures known and tested in QCD, to see if they do indeed become equal. When this is done a stunning—and most encouraging—result emerges.

It appears that straightforward extrapolation of the couplings measured at low energies, incorporating the effect of known particles only, comes very close to insuring the unification of coupling strengths at high energies. This gives us confidence that our ideas about unification are on the right track. Recent extremely accurate measurements of the couplings allow us to discriminate further among unified models. It now appears that the minimal extension of the Standard Model does not quite allow unification, but that its minimal extension supporting supersymmetry does. Supersymmetry is a very attractive idea, that was proposed for other independent reasons, and is discussed in an earlier Chapter. Taken at face value, then, the unification of couplings seems to encourage not only the quest for a unification of gauge forces, but also the quest for a further unification of gauge bosons, fundamental fermions, and Higgs particles all together in the framework of supersymmetry.

3.2 Open Questions

The main open question regarding these ambitious ideas of unification is simply: Are they true? Most physicists regard the clues discussed above: that the gauge bosons and fermions fit beautifully into a unified framework, and that the couplings do appear to approach a common value at short distances, as extremely encouraging—but perhaps not yet compelling. Will we be able to elevate our present tentative, schematic suggestions into the scientific realm of predictions and verifications? There are good reasons to hope that, given new tools and some hard work, we can.

As was mentioned above, the unification of couplings works best quantitatively if one assumes that supersymmetry is only mildly broken. More precisely, one requires that the supersymmetric partners of the known particles, as yet undetected, should not be much heavier than the W bosons. This is also desirable from other points of view, slightly too technical for discussion here, having to do with subtler details of unification. It is an exciting prospect, because it implies that the discovery of these partners, so pregnant with meaning for the unification of fundamental forces, is almost within our grasp.

Unified theories also suggest the possibility of certain small but very significant effects that are altogether forbidden within the Standard Model. One is the spontaneous decay of protons. This process is mediated, at a small but potentially detectable level, by the extra gauge bosons and Higgs particles needed to consummate the unification. Supersymmetric theories support additional decay mechanisms, which specifically facilitate decay into strange particles. Another is the existence of neutrino masses and the concomitant possibility of neutrino oscillations. There may already be evidence for this effect, from the long-standing but still not completely elucidated discrepancy between the predicted rate of arrival of neutrinos from the sun and the rate actually observed. A third prediction of unified theories is the existence of superheavy magnetic monopoles; a large-scale search for such particles is being carried out in an underground laboratory in the Gran Sasso tunnel.

There is a remarkable connection between all these ideas and cosmology. The production of supersymmetric particles during the Big Bang can be estimated with some confidence. Indeed, the methods used for these estimates are not very different from the methods used to estimate—with great success—the production of different light nuclear species and of the microwave background radiation. When this is done, it is found that for a wide range of parameters the lightest supersymmetric partner is a stable particle (usually the neutralino, a combination of the supersymmetric partners of the gauge and Higgs particles), and that it would have been produced during the Big Bang in such abundance as to presently contribute a significant fraction of the total mass density of the Universe. In this way, theoretical considerations concerning unified theories have produced a plausible candidate to solve the "dark matter" or "missing mass" problem of cosmology. The relic particles, though they are predicted to be omnipresent, are also predicted to be so feebly interacting that they are very difficult to detect. Several heroic, technologically innovative experiments are being mounted in response to this challenge. It is also possible that some or all of the missing mass is provided by relic massive neutrinos, or by axions, another particle species whose existence is suggested by unified theories.

The ideas we have just sketched regarding unification of gauge forces seem to us—given their scope—both astonishingly specific, and in their broad outline persuasive. They are not complete, however, and in concluding this brief survey of open problems it seems appropriate to mention two of their most obvious omissions.

First, although they succeed in organizing fundamental fermions into large families, existing unified gauge theories leave unexplained the fact that three such families of particles are known to exist, identical except for their masses. Are there additional families yet to be discovered? Or additional symmetries and interactions that group the known families, together perhaps with other particles, into a larger, more coherent whole? Experimental searches for the tell-tale signs of such interactions, including especially hypothetical rare processes in which members of one family spontaneously decay into members of another, could help us decipher the meaning of this cryptic but doubtless profound message from Nature.

Second, the unified gauge theories do not include gravity. Some promising but as yet highly speculative attempts to construct fully unified theories, including both the interactions of the Standard Model and gravity, are discussed in the previous Chapter.

4 Gravity

4.1 Status

Gravity is central to the interface of astrophysics, cosmology, and particle physics. It is fundamental to cosmology and to the understanding of many objects in the Universe. Further, the unification of gravity with the other forces is a major focus in theoretical particle physics.

Our current understanding of gravity is embodied in general relativity. It provides the theoretical foundation for the big-bang cosmology as well as the means for understanding many of the most interesting objects and phenomena in the Universe—neutron stars, black holes, gravitational waves, and gravitational lenses.

While general relativity has passed a long succession of tests, starting with Eddington's measuring the bending of starlight in 1919 to a host of more recent tests involving the binary pulsar (PSR 1913+16), most theorists are confident that it is at best the classical limit of a more complete theory that brings together quantum mechanics and gravity. Superstring theory provides the first example of a theory that does this self consistently, and at the same time unifies gravity with the other forces of nature.

4.2 Open Problems

Relativity is a vibrant area of research in its own right. Here we only mention the topics that overlap significantly with particle astrophysics, cosmology, and unification. To be sure, there is much interesting work going on beyond this, from the formal aspects of relativity (cosmic censorship hypothesis, entropy of gravitating systems, possibility of time machines, and the application of supercomputers to address numerically important problems in relativity) to the application of general relativity to astrophysical systems (massive accreting black holes that power quasars, colliding black holes).

4.2.1 Fundamental Aspects of Gravitation

It could well be that the classical description of gravity is a theory that closely resembles general relativity, but is not general relativity. This is because none of the tests of general relativity have yet probed the strong-field regime (*e.g.*, near black holes) or its limits of applicability (*e.g.*, in the very early Universe when quantum corrections to general relativity are important). There is a hint from superstring theory that the classical gravitation theory that emerges might be more similar to Brans-Dicke theory (where the gravitational constant is determined by the expectation value of a scalar field), and a class of very interesting models of inflation are based upon the idea that at the time of inflation gravity is not described by general relativity. The formulation, study, and testing of alternative theories of gravity continues to be an important area of research.

Black holes are a possible key to understanding the quantum nature of gravity. Hawking showed that a black hole should radiate a thermal spectrum of particles due to quantum processes near its horizon and in the process reduce its mass. This semi-classical calculation (quantum fields are treated on the classical background of a black hole) provided a crucial first link between gravity, quantum mechanics and thermodynamics, and in the process has raised many issues. What is left when a black hole evaporates? What happens to information (*e.g.*, coherent radiation or an encyclopedia) that falls into a black hole; is it lost? As a result of ideas from string theory two-dimensional black-hole models have been developed to describe the formation of a black hole, the "turning on" of Hawking radiation, and the evaporation process itself. This has allowed fundamental questions about black-hole physics to be addressed quantitatively.

The interest in the unification of gravity with the other forces has stirred theorists to address other fundamental issues, *e.g.*, topology change and wormholes. (Many of these issues are discussed in more detail in the previous Chapter.)

4.2.2 Phenomenological Aspects

Gravitational waves have yet to be detected directly, though there is strong evidence for their existence: The measured decrease in the orbital period of the binary pulsar agrees to a precision of better than 1% with the prediction of general relativity based upon energy loss due to the emission of gravitational radiation. When the LIGO and VIRGO facilities that are currently under construction become operational, the chances for direct detection of gravitational waves will improve dramatically. Not only can the detection of gravitational radiation probe the behaviour of gravity in a new regime, but it can also open a new window to the Universe.

The "bread and butter" source for these broad-band laser interferometric detectors are coalescing compact objects: neutron-star binaries, neutron star–black hole binaries, and black hole-black hole binaries. These sources can all be detected at cosmological distances and have potential for probing the Universe (*e.g.*, a measurement of the Hubble constant or even the deceleration parameter). In addition to a variety of astrophysical sources (pulsars and supernovae), there are interesting early-Universe sources, *e.g.*, gravity waves from first-order phase transitions, inflation, or cosmic strings. The detection of gravity waves from the early Universe would reveal a wealth of information about the earliest moments of the Universe. While these early-Universe sources are probably too weak and in the wrong frequency band to be detected by earth-based interferometers, they might be detectable with future space-based interferometers (*e.g.*, LISA).

5 Interface with Cosmic Rays, Nuclear Physics, and Astrophysics

The interface between these fields with particle physics is both scientifically rich and very complex. We highlight some of the connections.

5.1 Cosmic rays

Cosmic rays in our galaxy have energies from less than 10^6 eV to more than 10^{20} eV, and include the highest energy particles we have access to. The particles in the cosmic rays include photons, neutrinos, electrons, positrons, protons, antiprotons, nuclei from the lightest to the heaviest elements, and perhaps exotic particles yet to be identified. There is good evidence that cosmic-ray particles of energy up to 10^{13} eV (or even 10^{15} eV) were produced and accelerated by supernovae. Likewise, the propagation of these particles throughout the galaxy is relatively well understood.

The change in the shape of the spectrum of cosmic rays around 10^{16} eV (the knee region) is still not understood (it could involve the escape of cosmic rays from the galaxy or a change in composition or something else). The origin, composition, and acceleration of the highest-energy cosmic rays remain a mystery. They could be produced by topological defects (such as cosmic string) remaining from the early Universe, or by astrophysical accelerators whose interworkings are still not understood at the crudest level. The gamma-ray spectrum above 10^{12} eV remains a mystery: Are there ultra-high energy point sources? Is there a diffuse background of ultra-high energy gamma rays; if so, what is its origin?

Even the low-energy cosmic rays could provide important insights on new physics. For example they could include the annihilation products from neutralinos that may comprise the dark halo of our galaxy. Low-energy cosmic rays offer us the best opportunity for searching for antimatter in the Universe (antiprotons and antinuclei).

5.2 Astrophysical phenomena

Aspects of fundamental physics (*e.g.*, ordinary weak interactions, a variety of nuclear cross sections, and new phenomena such as neutrino oscillations or the existence of particles such as axions or righthanded neutrino states) provide important "input microphysics" for astrophysical situations, *e.g.*, structure of neutron stars, cooling of white dwarfs, red giant stars or newly born neutron stars, explosion of massive stars (supernovae) and explosive synthesis of heavy elements. In some instances the input microphysics might better be described as nuclear physics, *e.g.*, in neutron stars, in the synthesis of the light elements in the early Universe, or in the synthesis of heavy elements in supernovae. Likewise, some of the speculative physics is more closely related to nuclear physics, such as pion or Kaon condensates at high density, or strange quark matter.

Because astrophysical and cosmological phenomena in a wide range of circumstances—from the cosmic rays to the early Universe—depend upon input microphysics they can be exploited to study fundamental physics in regimes beyond the reach of terrestrial laboratories. The knowledge derived in the past has been very useful: hadronic cross sections at very high energies; nucleosynthesis limit to the number of light neutrino species (and other light particle species); cosmological limits to neutrino masses and other properties; constraints to the mass of the axion based upon the cooling of hot neutron stars, white dwarfs, and red giant stars; limits to the flux of superheavy magnetic monopoles based upon the existence of magnetic fields in neutron stars, galaxies and clusters of galaxies; a host of limits to neutrino properties based upon SN 1987A.

Since the energy reach of theorists continues to exceed that of accelerators and other terrestrial-based experiments, the "heavenly laboratory" is certain to continue to play an important role in the quest for our understanding of the most fundamental aspects of physics.

6 Experiment

Our focus here is on experiments not involving high-energy accelerators. That is not to say that accelerator-based experiments are of no interest for astroparticle physics, cosmology, and unification. They are of great interest; accelerator-based experiments have the potential to discover new phenomena that bear on important issues for this discipline, *e.g.*, neutrino oscillations, supersymmetric particles (including the neutralino), Higgs particles, and evidence for physics beyond the Standard Model.

Experiments addressing a broad range of questions involving astroparticle physics, cosmology and unification have been implemented in the past decade, more are underway, and still more are planned for the future. Since the experiments address such a wide range of questions they are very diverse in approach, techniques and scale. However, some trends stand out. Many such experiments in this general area require a quiet environment, and, as a consequence, we have seen major facilities develop underground at the Gran Sasso Laboratory in Italy, at the Baksan Laboratory in Russia, at Kamiokande in Japan, and at the Soudan and IMB facilities in the U.S.

The experiments often employ techniques from high-energy physics, such as the use of tracking chambers and scintillators. However, in addition, very important and successful new techniques were pioneered for this research, the most visible being large-scale, imaging H_2O Cherenkov detectors. Also, detector development is crucial to efforts to directly detect particle dark matter. Experiments addressing the questions discussed here are by no means limited to underground facilities and very challenging experiments that require advanced instrumentation are being done on the earth's surface.

There are a number of exciting new projects under construction, such as a next generation H_2O Cherenkov detector (SuperKamiokande), a heavy-water detector (SNO), and an interferometer facility to detect gravitational waves (LIGO/VIRGO). In the planning stage are very-large neutrino detectors for deep underwater, DUMAND and NESTOR, or under ice, AMANDA. In addition to these very-large facilities, special efforts to build sensitive and massive dark-matter detectors are underway. Space-based experiments (high-resolution mapping of the CBR anisotropy, search for antimatter using a large magnet in space, a small telescope in space to study microlensing by dark stars in our galaxy) and large-scale astronomical observational efforts (large redshift surveys, a dedicated cosmology telescope) are beginning to emerge.

Below, we highlight some of these experimental efforts.

6.1 High-Energy Cosmic-ray Physics

High-energy cosmic rays have been of common interest to particle physics and astrophysics for many years. Many important questions remain to be answered. Moreover, their answers could well shed light on fundamental physics.

At the lower end of the energy scale for cosmic-ray studies, satellite experiments have been very successful. The Gamma Ray Observatory (GRO) for instance has detected γ-rays from pulsars and active galactic nuclei, as well as from unidentified objects, most notably, the mysterious gamma-ray bursters. Are they neutron-star collisions seen out to the edge of the Universe or accretion instabilities associated with neutron stars in the halo of our own galaxy?

At energies above 10 GeV or so, the rates are too low for satellites and ground-based instruments are used. Large electromagnetic shower arrays only become useful well above 1 TeV. To partially fill the gap, advanced imaging Cherenkov techniques have been developed and are quite successful. The imaging Cherenkov detector at Whipple Observatory has detected the Crab Nebula, a galactic source, and an extragalactic source, Mrk 421, in the 200 GeV to 1 TeV energy range. However, an important gap—between about 20 GeV and 200 GeV—still remains.

At higher energies, above 10 TeV, searches using large-scale surface shower arrays like CASA-MIA and the MILAGRO H_20 water-Cherenkov detector have thus far failed to find gamma-ray point sources or evidence for a diffuse gamma-ray background. It is interesting to note that the origin of gamma rays at such very high energies may be hadronic, rather then electromagnetic. Such sources would provide a window on particle acceleration at very high energies. These large-scale devices are also very useful in studying another important problem: the composition in the "knee" region of the cosmic-ray spectrum near 10^{16} eV. The origin of the knee is unknown and these experiments are aimed at resolving whether it is due to particles escaping the galaxy or another mechanism.

Finally, the very-highest energy cosmic rays are detected using very-large air-shower arrays (Akeno in Japan) and a different technique (fluorescence in the atmosphere) with a Cherenkov array (Fly's Eye). These arrays have detected many more cosmic rays with energies in excess of 10^{19} eV than expected (hadrons at these energies have very short mean-free paths for inelastic scattering with CBR photons). Future improvements (Hi Res at Fly Eye's) will investigate this interesting puzzle with improved sensitivity that hopefully will confirm previous results and shed light on the origin of the highest-energy cosmic rays.

Complementary investigations are performed deep underground by studies of penetrating multiple muons in large detectors like MACRO, and these also yield primary composition information at very-high energies through muon multiplicity and the transverse distributions. Such studies are now beginning to include hybrid experiments that use coincidences of muons in a large underground detector with the signal from a large area surface electromagnetic shower array. This added information is very promising for composition studies.

Future plans in high-energy cosmic-ray physics are focussed around the development of a very-large hybrid (air shower/fluorescence) array (about $10^4\,\mathrm{km}^2$), and presently involves an international design effort. Such a facility will provide greatly improved sensitivity directed at searches for point-like sources of high energy γ-rays at levels where detection is expected as well as studies of the cosmic ray cut-off.

6.2 Neutrinos

The range of physics and large number of different facilities developed to explore neutrino physics make this area a major focus of astroparticle physics. The implementation of large-scale underground detectors has opened up a large range of studies involving neutrinos. These studies cover a very-large dynamic range of energies ranging from an MeV to several TeV, presenting a large experimental challenge.

At the lowest energies (less than one MeV), solar neutrinos have been detected by radiochemical techniques (using Chlorine and Gallium) and at somewhat higher energy by water Cherenkov techniques. The experiments indicate a deficit of neutrinos whose best explanation involves neutrino oscillations. The next generation experiments at SuperKamiokande, using a much larger volume of H_2O, at Sudbury, Canada (SNO), using D_2O, which allows the observation of the neutral-current channel, and at Gran Sasso (Borexino and ICARUS) should shed important new light on this question. It seems likely that a resolution of the solar-neutrino problem is near and will advance our understanding of both neutrino physics and the detailed interworkings of the sun.

At somewhat higher energies ($> 5\,\mathrm{MeV}$), large-volume underground detectors (*e.g.*, SuperKamiokande and MACRO) are sensitive to a supernova collapse in our galaxy. Observation of SN 1987A validated the idea that the collapse of a massive star to a neutron star liberates most of its energy in neutrinos, but the source was too distant and therefore the rate too small to enable detailed studies. A future stellar collapse will be observed by several complimentary detectors and will yield hundreds to thousands of events if it is in our own galaxy. Detection of neutrinos from a galactic supernova would greatly improve our understanding of type II supernovae and perhaps the equation of state of matter at supernuclear density, as well as provide useful information about the fundamental properties of neutrinos.

The primary source of neutrinos in the GeV range comes from atmospheric showers created when a high-energy primary cosmic ray interacts at the top of the atmosphere producing a shower of secondary, tertiary, etc. particles. Such a cascade should yield ν_μ's and ν_e's in an approximate ratio of two to one. At present, the observations of stopping muons from a number of underground detectors indicate a ratio closer to unity. This is yet another hint of neutrino oscillations. Further investigations of this anomaly appear best done through a hybrid experiment, where neutrinos are produced at a high-energy accelerator, and are detected at a distant detector. The distance and neutrino energy can be chosen to explore the same region as available with atmospheric neutrinos. Experiments are presently being considered for Fermilab/Soudan or BNL, CERN/Gran Sasso, and KEK/SuperKamiokande. These are all in the proposal stage and involve intense new beams and sophisticated new detectors.

For many years there has been an ongoing program to develop a very-large scale (*e.g.*, 1 km^3) underwater or under-ice detector that could sensitively search for astrophysical point sources of ultra high-energy neutrinos. Prototypes are under study, and sites and detectors under ice at the South Pole (AMANDA) or under water near Hawaii (DUMAND) or Greece (NESTOR) are being considered.

The window to the Universe provided by ultra-low and ultra-high energy neutrinos has yet to be opened. It is interesting to note that ultra-high energy neutrinos offer one of the only plausible means of detecting the cosmic background of ultra-low energy neutrinos: at the Z-pole the neutrino seas provide about a mean-free path for absorption and the dip in the spectrum of an ultra-high neutrino source could reveal their presence.

6.3 Particle/Nuclear Physics

Another important interface is between particle and nuclear physics where experiments are directed at fundamental-physics questions, but involve nuclear physics or nuclear physics techniques. For example, direct studies of the electron-neutrino mass involve precision measurements of the nuclear beta-decay spectrum. These have yielded a sensitivity for the electron neutrino with a current best limit of about $7\mathrm{eV/c}^2$. These measurements are limited by our knowledge of atomic and molecular physics effects.

In addition to experiments directly sensitive to neutrino mass, effects are expected that involve the mass differences between different neutrino types. The solar-neutrino and atmospheric-neutrino experiments are important examples, and both show hints of evidence for neutrino oscillations. However, systematic uncertainties—both theoretical and instrumental in character—preclude a definite statement at present.

Another important class of nuclear physics experiments are the double beta-decay experiments. In particular, new physics beyond the Standard Model can involve massive Majorana-type neutrinos which do not distinguish between neutrino and antineutrino. One consequence of this that would be observable are neutrinoless double-beta decays that yield two electrons but no neutrinos in the final state. Sensitive searches have been performed setting the present limits (less than around $1\,\mathrm{eV/c^2}$) and future improvements are expected.

Finally, there are experiments done at reactors and small accelerator facilities (some involving radioactive beams) that make crucial measurements for particle astrophysics and cosmology. These measurements include: cross sections for reactions that are key to the solar-neutrino problem (*e.g.*, $^7\mathrm{Be(p,\gamma)^8B}$), to stellar physics (*e.g.*, $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$), to explosive nucleosynthesis (*e.g.*, r-process reactions and neutrino cross sections); and to big-bang nucleosynthesis (*e.g.*, neutron mean lifetime, $^4\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$, $^3\mathrm{H}(\alpha,\gamma)^7\mathrm{Li}$, and $^7\mathrm{Li\,(p,\alpha)^4He}$).

6.4 Particle Dark-Matter Detectors

The search for dark matter is a central theme of particle astrophysics. The evidence for dark matter based on cosmological and astronomical observations is very strong. In addition, there are compelling cosmological and astrophysical arguments that suggest that the bulk of the dark matter is nonbaryonic. Searches for baryonic dark matter have been performed, including the search for Massive Astrophysical Compact Halo Objects (MACHOs) using the gravitational microlensing technique.

Of most interest to particle physics, however, are the class of candidates that involve new elementary particles or massive neutrinos. The simplest solution to the dark matter problem involving particle physics is finite-mass neutrinos. Light neutrinos of mass in the few to 20 eV could represent some or all of the dark matter. Neutrino-oscillation experiments, involving accelerators with short and long baselines and nonaccelerator experiments are addressing the possibility of such neutrino oscillations, both in this mass range and in those indicated by the atmospheric neutrino data.

Cold dark matter is favored from the point of view of structure formation. Weakly Interacting Massive Particles (WIMPs) are an attractive solution, especially the lightest supersymmetric particle (usually the neutralino). Direct detection of such particles requires technological detector developments before a large-scale direct searches with sufficient sensitivity are possible. Such developmental work is underway and the first generation detectors of small scale have already been used to set limits. This program is planned to evolve in stages to larger and more sophisticated detectors to be installed deep underground with improved sensitivity. A definitive search at the expected sensitivity level will require a major initiative.

There are specialized experiments for other dark-matter candidates, *e.g.*, $10^{-6} - 10^{-5}\,\mathrm{eV}$ axions (Livermore and Kyoto) and superheavy magnetic monopoles (MACRO), and improved results are expected in the next few years.

Complementary to these direct searches, indirect searches, through WIMP-antiWIMP annihilation in the earth and sun that yield high-energy neutrinos, are being performed using data from the large underground detectors (*e.g.*, Kamiokande and MACRO). These searches have already ruled out large regions of neutralino parameter space, but eventually are limited by background. The best prospect for indirect detection in the future probably involves the search for annihilation products (positrons, antiprotons, and gamma rays) from WIMP-antiWIMP annihilations in the halo.

6.5 Gravitational Waves

Two projects (LIGO, VIRGO) are under construction with the goal to observe cosmic gravitational waves. These novel scientific facilities are directed first at direct detection and then at becoming gravitational-wave observatories that will open a new window on the Universe. The method is to detect small displacements between widely separated suspended test masses that result from the passage of a gravitational wave. The LIGO and VIRGO projects use laser interferometers with arm lengths of 3-4 kilometers which are capable of resolving 10^{-18} meter change in arm length due to the passage of a gravitational wave.

The best understood source of gravitational waves is the inspiral of binary neutron-star systems. The design sensitivity of VIRGO and LIGO are such as to produce a few events per year from these sources by the initial interferometers with substantial long-term improvements envisioned. The LIGO detectors are located in Hanford, Washington and Livingston, Louisiana, and are used in coincidence. These will also be combined with the VIRGO detector near Pisa, Italy to decompose the polarizations of the gravitational waves and for pointing to the sources. The time scale for initial physics with these detectors is about 2002.

6.6 CBR Studies, Redshift Surveys, Gravitational Lensing, Etc.

Some of the most decisive tests of the predictions of new physics beyond the Standard Model involve observations that are more astronomical in character. However, even here the boundaries between fields have become blurred, and techniques and people move freely across traditional boundaries in the quest to answer fundamental questions. We briefly mention some of the most exciting work.

The anisotropy of the CBR provides the best record of density perturbations on very-large scales and thereby probably the most powerful test of inflation and topological-defect theories. Measuring the anisotropy of the CBR is a rapidly developing field (see Fig. 2) and more experiments, including high-resolution, balloon-borne and space-based experiments to map the CBR sky, are being proposed.

On small scales the spectrum of inhomogeneity is probably best probed by directly "mapping the Universe," *i.e.*, determining the redshifts of galaxies (and through Hubble's law their distances) in a representative sample of the Universe. An effort to obtain a million redshifts and involving astronomers at a number of universities as well as high-energy physicists at Fermilab is well underway (Sloan Digital Sky Survey).

The MACHO and Sloan projects represent a new style. For the MACHO project a special CCD camera was built for a telescope dedicated to searching for microlensing; in the case of the Sloan Survey a special purpose 2.5 meter telescope and instruments are being built to map the Universe. Similar initiatives on the horizon. For example, a diverse group of scientists (astronomers, high-energy physicists, experimental physicists) has discussed a dedicated cosmology telescope to probe the Universe using gravitational-lensing techniques. Such an instrument could map dark matter in clusters and the halos of individual galaxies as well as determining the clustering properties of dark matter.

7 Structural Issues

High-energy physics research is built around strong partnerships between the national laboratories devoted to HEP (Fermilab, SLAC, and BNL) and university-based research groups. In recent years, we have seen a growing centralization of major facilities for research in particle physics resulting from the development of high-energy accelerators and colliders, coupled with the construction of very-large detector facilities. As a result, the laboratories now both provide the location and the focus of activity, including much of the resources, technical expertise, and infrastructure required. A system of peer review through program advisory committees, long-range planning, and the necessary management has developed in each laboratory.

The increased importance of particle astrophysics and other nonaccelerator experiments, coupled with the growing scale and technical challenges, presents new challenges. In terms of planning, a method for setting priorities and the ability to monitor and track the execution of complicated nonaccelerator projects does not naturally fit into the current mode of operation where this is done through the national laboratories. In particular, many of the current projects have no direct national laboratory involvement and are located elsewhere.

Presently, about 20% of the experimental program in HEP involves experiments not using the major accelerators at the national laboratories. This research is conducted by individual groups and by large collaborations. Some centers for these studies (*e.g.*, NASA/Fermilab Astrophysics Center, Experimental Astrophysics Group at Fermilab, Center for Particle Astrophysics in Berkeley, Institute for Nuclear/Particle Astrophysics at LBL) have emerged in recent years, responding to the need to provide coherence to these efforts and, also, to increased interest in pursuing this research. The Baksan Laboratory in Russia, and most notably, the Gran Sasso Laboratory in Italy, have developed as major laboratories providing facilities and infrastructure for such experiments. Most of the major projects are conducted through large international collaborations (*e.g.*, SuperKamiokande is U.S./Japan; MACRO is Italian/U.S.; GALLEX is German, French, Italian and U.S.; SAGE/RAGE is Russian and U.S.). It is also worth noting that these large experiments often involve funding by multiple agencies, either in the U.S. or in different countries, which presents additional logistical problems.

Conducting this research which has no host national laboratory presents a number of new problems. Perhaps the most important is to find a satisfactory mechanism for long-range planning and to set priorities. Given the diversity of the field and the number of funding agencies involved this is a difficult challenge. In high-energy physics such planning is generally provided by laboratory long-range planning and program advisory committees, with HEPAP and DPF Workshops used for global studies and to set global priorities. There are no standing committees to help set priorities and provide oversight for particle-astrophysics experiments and especially with limited resources this might be of value. A related problem is how best to make available or provide the technical and project expertise that is centralized in our national laboratories for this research.

An emerging problem involves the fact that the collaborations that are developing are becoming even more diverse. For example, the Sloan Digital Sky Survey involves astronomers, astrophysicists, high-energy physicists, and computer scientists at universities, Fermilab, the Naval Observatory, and the National Astronomical Observatory in Japan. The funding comes from NSF, the Sloan Foundation, the DOE (through Fermilab), the universities, and Japan. The challenges include the merging of scientific cultures, the usual ones associated with international collaboration, and dealing with several funding agencies.

The research opportunities in particle astrophysics, cosmology, and unification address some of the most important and exciting problems in our field. The future will involve implementation of the next generation of facilities (*e.g.*, SNO, SuperKamiokande, LIGO/VIRGO, etc.) as well as choosing and implementing new large projects now under design (long-baseline neutrino oscillation experiments, large-scale cosmic-ray arrays, large underwater or under ice neutrino detectors, large-scale dark-matter detectors, CBR anisotropy). To select the best projects, obtain funding, and successfully implement them is an increasing challenge. The creation of infrastructure for planning and technical support may be well be needed.

Selected Bibliography

1. *Proceedings of Snowmass 1994: Nuclear and Particle Astrophysics and Cosmology in the Next Millennium*, eds. E.W. Kolb and R.D. Peccei (World Scientific, Singapore, 1995).
2. E.W. Kolb and M.S. Turner, *The Early Universe* (Addison-Wesley, Redwood City, CA, 1990).
3. P.J.E. Peebles, *Principles of Physical Cosmology* (Princeton University Press, Princeton, 1993).
4. *The Birth and Early Evolution of Our Universe (Nobel Symposium 79)*, *Physica Scripta* **T36** (1991).
5. C. Copi, D.N. Schramm, and M.S. Turner, "Big-bang Nucleosynthesis and the Baryon Density of the Universe," *Science* **267**, 192 (1995).
6. J.C. Mather *et al.*, "Measurement of the Cosmic Microwave Background Spectrum by the COBE FIRAS Instrument," *Astrophys. J.* **420**, 439 (1994).
7. M. White, D. Scott, and J. Silk, "Anisotropies in the Cosmic Microwave Background," *Annu. Rev. Astron. Astrophys.* **32**, 319 (1994).
8. A. Cohen, D. Kaplan, and A. Nelson, "Progress in Electroweak Baryogenesis," *Annu. Rev. Nucl. Part. Sci.* **43**, 27 (1992).
9. G.G. Ross, *Grand Unified Theories* (Addison-Wesley, Reading, MA, 1984).
10. C.W. Misner, K.S. Thorne, and J.A. Wheeler, *Gravitation* (Freeman, San Francisco, 1973).
11. T.K. Gaisser, *Cosmic Rays and Particle Physics* (Cambridge University Press, Cambridge, 1990).
12. J.W. Cronin, K.G. Gibbs, and T.C. Weekes, "The Search for Discrete Astrophysical Sources of Energetic Gamma Radiation," *Annu. Rev. Nucl. Part. Sci.* **43**, 883 (1993).
13. J. Wdowczyk and A.W. Wolfendale, "The Highest Energy Cosmic Rays," *Annu. Rev. Nucl. Part. Sci.* **39**, 43 (1989).
14. G.G. Raffelt, "Astrophysical Methods to Constrain Axions and Other Novel Particle Phenomena," *Phys. Repts.* **198**, 1 (1990).