9. PARTICLES AND THE COSMOS

The vast knowledge gained in the last few decades of high-energy physics has had a major impact on the fields of astrophysics and cosmology. So grand are its accomplishments that scientists can begin to make credible statements about the birth and death of the universe. To understand its earliest moments and some of its most exotic objects and processes, such as neutron stars and supernovae, they need to know how matter behaves at high energies and at short distances—exactly what has been studied for decades at particle accelerators and colliders.

In a similar vein, observations of the cosmos and its astrophysical objects have given particle physicists heavenly laboratories where they can test theories like GUTs, by providing conditions that cannot be replicated on earth. If a theory predicts that the universe or the sun behaves in a certain manner, and that behavior is not observed, the theory must be rejected or modified. By turning to the heavens like this, physicists have been able to study matter at energies, densities, and distance scales that are impossible to produce in earthbound laboratories.

Since the mid-1960's scientists have recognized that we live in an expanding universe, which began about 15 billion years ago in a tremendous explosion called the *Big Bang*. The faint afterglow of that titanic blast was discovered in 1964 by Arno Penzias and Robert Wilson of the Bell Telephone Laboratory. They found that the temperature of this relic radiation was only 3 degrees above absolute zero, or minus 270°C, which can be thought of as the average temperature of the universe today.

If we go back in time to the early moments of the universe, things get steadily hotter and matter becomes increasingly dense. When it was hardly 100,000 years old, the temperature was several thousand degrees—about that of the sun's surface. At this temperature, normal atoms disintegrate into their constituent electrons and nuclei; the universe then was a hot soup of atomic fragments. Still earlier, at about 1 second, it was far too hot (about 10 billion degrees) for even the simplest nuclei like helium to hold together. Under such conditions the universal soup consisted of individual protons, neutrons, electrons, neutrinos, and photons.

Between 1 second and 3 minutes, however, the universe cooled down enough so that the lightest nuclei could begin to form. From knowledge of nuclear and particle physics, scientists from the University of Chicago and Fermilab have calculated the relative amounts of deuterium, helium, and lithium nuclei that should have coalesced. The fact that the abundance of these elements, as measured by astronomers, correspond closely to the calculations is a key proof that the universe began in a hot Big Bang.

One of the assumptions used in these calculations, however, was that there are only *three* families of leptons and quarks having a light (or massless) neutrino as a member. If there were more than four different kinds of light neutrinos, the calculated abundance of helium is too high to be compatible with that measured. Thus cosmology was able to place a constraint on the Standard Model: there could be at most one light neutrino in addition to the three known kinds.

Originally published in the early 1980's, these striking predictions were borne out by the 1989 measurements of the Z particle at the SLC at SLAC. Additional neutrinos would allow the Z ways to disintegrate without leaving a visible trace in the surrounding detector—thus lowering the apparent yield of this massive particle. No such deficit was found. Thus the results are compatible with the three known species of neutrinos, and they exclude the possibility of a fourth.

Predictions of the Standard Model go back even further in time, to tiny fractions of a second after the birth of the universe. At about 0.00001 second (or 10^{-5} second, in scientific notation), conditions were so ultrahot that even hadrons could not survive, disintegrating into quarks and gluons. At earlier moments the universe was a superhot, superdense, seething plasma of quarks, leptons, photons, and gluons. At a trillionth of a second,