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17 PARTICLE PHYSICS AND COSMOLOGY

John Ellis

Editor's Introduction: The 'Big Bang' picture of the origin of the Universe, one of the major scientific contributions of the twentieth century, was slowly pieced together as the interests of astronomers, astrophysicists, cosmologists and particle and nuclear physicists converged.

For centuries, astronomers had to be content with the faint light which manages to pierce the Earth's atmosphere. While huge new terrestrial telescopes continue to be a major weapon in the astronomers' armoury, the technological advances of the twentieth century, particularly following the Second World War, enabled astronomers to view the Universe's 'light' over a wide range of the electromagnetic spectrum, and to mount sensitive detectors aboard satellites which orbit in 'empty' space. The outcome was a radical reappraisal of our understanding of the Universe around us, a reappraisal in which particle physics has played a major role.

Einstein's development of the General Theory of Relativity in 1915 refined the classical ideas of Newtonian gravity, which still remained exactly as Newton had published them in 1686. Einstein's new theory set the stage for a new understanding of the Universe around us and provided a framework for the new science of cosmology—the study of the origin and structure of the large-scale Universe. Very soon afterwards, astronomers led by Edwin Hubble discovered that the Universe is much bigger than had been thought, and that the distant galaxies are receding at a rate proportional to their distance.

These two important developments ushered in a new concept of the origin of the Universe in a massive initial cataclysmic explosion—what is now called the Big Bang. The ingredients of this Big Bang were the same particles and forces which particle physicists study, but under very different conditions.

It took about half a century before particle physics was sufficiently well explored and its mechanisms understood for it to be ready for use as a cosmological tool. Most of the material in this book can be considered as necessary 'input' for modern cosmology. In his book *Before the Beginning* (New York: Simon and Schuster), Cambridge astrophysicist and cosmologist Sir Martin Rees says 'Cosmology's current buoyancy owes a lot to the incursion of particle physicists with (their) robust intellectual confidence'. In the next two chapters John Ellis and Qaisar Shafi describe this 'incursion' and the new insights it has produced.

INTRODUCTION

The Universe is, by definition, the largest possible physics laboratory, able to produce conditions more extreme than those achieved with our accelerators. Almost all conceivable experiments are presumably being carried out somewhere in the Universe, but the problems are to discover where, and to observe and interpret the results. The crucial difference between cosmological and accelerator experiments is that we have direct control over the conditions of the latter, whereas we are passive observers of whatever the Universe chooses to show us.

Before accelerator experiments gained their present sophistication, many particle discoveries were made in cosmic rays. As we shall see in the section on cosmic rays, these are now providing tantalizing hints of possible physics beyond the Standard Model, which may also have profound implications for the conventional Big Bang cosmology, developed in the subsequent two sections. A generation ago, advances in nuclear physics revolutionized our understanding of astrophysics, enabling us to calculate the properties of stars and their evolution. Analogously, particle physics provides the framework in which fundamental issues in cosmology may be resolved, including the origin and dominance of matter in the Universe, discussed in the section on Big Bang baryosynthesis, and possible candidates for dark matter, discussed in the subsequent section. Together with the primordial density perturbations revealed by the COBE satellite, this dark matter provides us with a theory for the formation of structures in the Universe, including galaxies and their clusters, as discussed in the section on cosmological inflation and structure formation. The earliest epoch that we can discuss rationally with our current physical theories is the Planck time, when the Universe was about 10^{-43} s old; typical particle energies would have been of order around 10^{19} GeV, and quantum gravity reigned. This may leave traces such as gravitational waves and superheavy relic particles in the present Universe, as discussed in the penultimate section. The final section reviews some speculations about the symbiosis of particle physics and cosmology in the new millennium.

COSMIC RAYS

These messengers from space played a formative rôle in the early days of particle physics, before accelerators were developed (see the chapter by Lock). They revealed antimatter with the discovery of the positron, mesons with the discovery of the pion, the second generation of fundamental particles with the discovery of the muon, and strange particles. However, during the past 50 years, the development of the Standard Model of particle physics has largely been the achievement of experiments at accelerators. Charm, the third-generation particles (bottom and top), the gluon, the W and the Z were all discovered in accelerator experiments, and the details of the Standard Model could not have been unravelled without the controlled environment which they provide.

However, hints of new physics beyond the Standard Model are now emerging from a new generation of cosmic-ray experiments using neutrinos. Historically, the first of these were those looking for neutrinos emitted by nuclear reactions in the Sun. Their observation was an experimental *tour de force*, but the remarkable fact for us is that all experiments find electron neutrino fluxes considerably below the predictions based on the known energy output of the Sun. No explanation based on modified solar physics, such as a different equation of state or lowered central temperature, seems able to explain this deficit. The least unlikely interpretation may now be that neutrinos have properties not predicted by the Standard Model; perhaps the electron neutrinos produced in the solar core change into some other, less detectable species before they reach our detectors? Such transformations would be possible if the neutrinos had masses (figure 17.1).

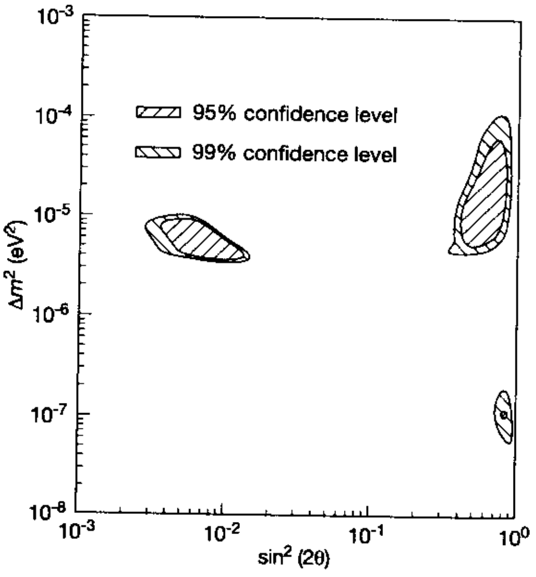

Figure 17.1. Possible scenarios for neutrino transformations ('oscillations') using input data from several experiments. Several allowed regions emerge for the neutrino mass and mixing parameters. The confidence level for the outer regions is 99% and for the inner regions 95%.

An analogous phenomenon has recently appeared in neutrinos produced by cosmic-ray collisions in the Earth's atmosphere. In this case, it is the flux of muon neutrinos that appears to be deficient, and transformations between neutrinos of different masses again provide the most plausible interpretation.

Such neutrino masses could have dramatic consequences for cosmology. According to the standard Big Bang theory of cosmology reviewed later, there should be a billion times more neutrinos in the Universe than conventional matter particles. Thus, if individual neutrinos weighed 1 eV or more, collectively they would outweigh all the matter in the Universe, providing a possible explanation for the dark matter long advocated by astrophysicists.

Other types of cosmic-ray experiment also have the potential to reveal new physics beyond the Standard Model. For example, many underground experiments around the world are looking for weakly interacting massive nonrelativistic particles (WIMPs) arriving from space. If such particles existed in numbers comparable with protons and neutrons, and with masses around 30–100 times larger, they could provide all the dark matter suggested in current cosmological models based on inflation, as discussed later. However, so far as there is no experimental confirmation of the existence of any such WIMPs.

At the other end of the energy spectrum, there are puzzles concerning ultrahigh-energy cosmic rays with energies around 10^{20} eV (figure 17.2). Clearly, their production requires some very powerful astrophysical accelerators whose identification is still enigmatic. Moreover, these sources cannot be too far away, or they would be absorbed by interactions with the microwave background radiation discussed in the next section. One very speculative possibility is that they might originate from the decays of supermassive relic particles from the very early Universe, as discussed in the final section.

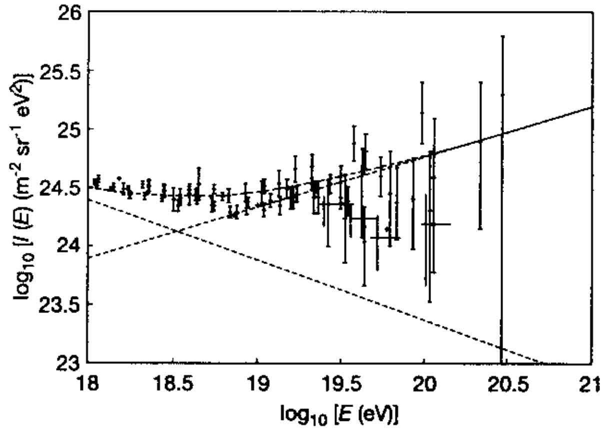

Figure 17.2. The measured spectrum of the highest energy cosmic rays. The upper broken curve is a superposition of the steeply falling power law combined with a flatter distribution at higher energy.

BIG BANG COSMOLOGY

We now pass from the direct observation of particles from space to their indirect manifestations in cosmology. Since the 1920s, it has been known that our Universe is expanding, and the standard model for this is the Big Bang. Historically, the first evidence for this was the recession of the distant galaxies observed by the astronomer Hubble, now known to occur at a rate of about 50–80 km s^{-1} Mparsec^{-1} of distance. Viewed on a sufficiently large scale above about 100 Mparsec, the Universe appears approximately homogeneous and isotropic.

One immediate question is whether this expansion will continue for ever. Certainly the observable matter would not exert sufficient gravitational attraction to halt and reverse the expansion; it has a density which is less than one tenth of the critical density required to cause such a collapse. However, astrophysicists observing the motions of stars and galaxies have long insisted that these are being pulled around by the gravitational attraction of more (invisible) matter out there, the dark matter mentioned earlier. Current determinations of the total density of matter come out at around one third of the critical density. To my mind, it is premature to exclude the possibility that the density may even be critical, in which case the Universe might eventually recollapse.

Setting the cosmological videocassette recorder now on ‘fast rewind’, we find two crucial additional pieces of evidence for the Big Bang theory of cosmology (figure 17.3). Earlier in the history of the Universe, when it was less than a million years old, its matter would have been much hotter and denser than it is today. When it was more than about 1000 times smaller and hotter, atoms could not have existed, and all the matter in the Universe would have been ionized into nuclei and free electrons. As these electrons cooled and settled into atoms, they would have emitted photons which should be visible today as a diffuse background of microwaves. Predicted by Gamow, this cosmic microwave background was first observed by Penzias and Wilson in 1965. The most complete

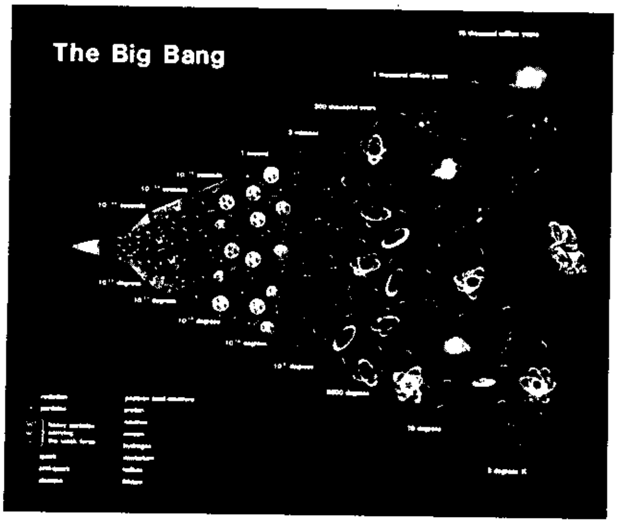

Figure 17.3. Milestones in the evolution of the Universe from the Big Bang. (Photograph CERN.) (See colour plate 2.)

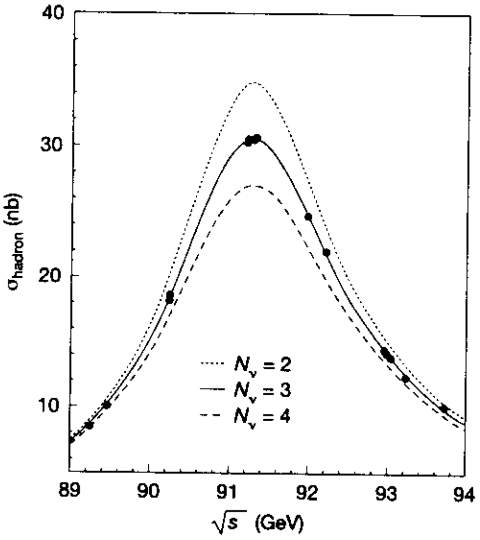

Figure 17.4. The shape of the Z resonance measured at CERN's LEP, compared with predictions using different numbers of light neutrinos. Only the three-neutrino solution (•) corresponds to the observed data.

observations of it have been with the COBE satellite, which demonstrated that it had (to an excellent approximation) a thermal spectrum, and that it was isotropic to one part in 10^5. At this level, minuscule fluctuations appear that may be an exciting window on primordial particle physics, as discussed in the section on cosmological inflation and structure formation.

Rewinding the Universe further, when it was aged less than a minute and about 10^8 times smaller and hotter still, even nuclei would no longer have been sacrosanct, and thermonuclear reactions would have occurred throughout the Universe. Before this epoch, the dominant forms of matter would have been protons, neutrons, electrons, positrons and neutrinos. The Big Bang nuclear interactions would have synthesized deuterium, helium, lithium and other light elements. The efficiencies of these interactions would have depended on the rate of expansion of the Universe, which was controlled by the density of protons and neutrons and the number of different species of neutrinos.

In recent years, there have been extensive calculations of this Big Bang nucleosynthesis and their confrontations with observations of the cosmological abundances of light-element abundances. These are in concordance if the density of protons and neutrons is about one billionth that of photons, corresponding to a present matter density below one tenth of the critical density, as observed. This concordance also requires that there be no more than a handful of species of light neutrinos. Laboratory experiments at the Large Electron–Positron Collider (LEP) and elsewhere have now determined that there are precisely three neutrino species, leading to successful calculations of the abundances of light elements (figure 17.4).

This agreement constitutes the most successful confirmation of the Big Bang theory; when it was less than a minute old, the Universe was a thousand million times smaller and hotter than it is today, and the fundamental laws of microphysics describe its behaviour. The next sections will extrapolate this success back to earlier times when the Universe was orders of magnitude smaller and hotter, the experimental evidence correspondingly smaller and the theoretical speculation correspondingly hotter.

THE PRE-HISTORY OF THE UNIVERSE

Before the 'written records' provided by the microwave background radiation and the cosmological light elements, the Universe experienced several periods of smooth expansion in a state close to thermodynamic equilibrium, punctuated by the occasional phase transition.

In everyday life, we are familiar with the transitions from the frozen to the liquid to the gaseous state as matter is heated. The ionization of atoms to the plasma phase of nuclei and free electrons is another example that we have already met in the early Universe. The next transition we meet as we go back in time is probably the transition from ordinary matter such as protons and neutrons to an analogous plasma phase of quarks and gluons. Theoretical calculations suggest that this should have occurred when the Universe was a few microseconds old, with a temperature of around 10^{12} K!

This quark–gluon plasma phase transition is currently the object of intense experimental searches at accelerators colliding beams of heavy nuclei. Experiments at CERN have recently found tantalizing evidence for this new phase of matter (figure 17.5). Certain bound states of heavy quarks and antiquarks are produced less copiously than expected naïvely on the basis of individual proton–proton collisions. Is this because the collisions of heavy nuclei produced an extended hot plasma region where these bound states cannot exist? Only future rounds of experiments at Brookhaven and with CERN's Large Hadron Collider (LHC) will be able to answer this question definitively.

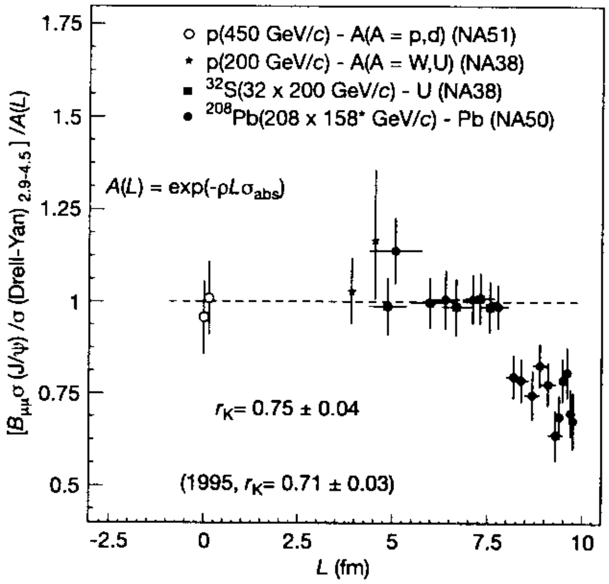

Figure 17.5. The NA50 experiment at CERN studies the production of J/ψ particles in high-energy nucleus–nucleus collisions. Under certain conditions (right), the production of J/ψ particles falls, suggesting that conditions are nearing those required to create the quark–gluon plasma.

The results of these experiments will confirm our understanding of the Universe back to when it was less than a microsecond old and may also be relevant to the interiors of dense astrophysical objects such as neutron stars. However, it is not yet clear what the observational signatures of the cosmological quark–gluon plasma transition might be.

The next step back is to the electroweak transition, where the quarks, leptons, W and Z acquired their masses. The Standard Model says that these were generated by interactions with a universal Higgs scalar field. However, there is no direct evidence for this mechanism; in particular, LEP experiments have searched intensively for a particle associated with this Higgs field and have so far only been able to establish a lower limit that is currently just below 90 GeV.

Going even further back, to higher temperatures above about 10^{15} K, when the Universe was about 10^{-10} s old, thermal fluctuations would have disrupted the normal Higgs mechanism for mass generation, and the quarks, leptons, W and Z would have lost their masses. The LEP lower limit on the mass of the Higgs particle suggests that this transition was probably relatively smooth and uneventful, but this conclusion could be reversed if LEP or another accelerator such as the LHC discovers additional particles beyond the Standard Model, such as those suggested by supersymmetry. An abrupt (first-order) transition could have interesting consequences for the history of the Universe; in particular, it could explain the origin of the matter in the Universe, as discussed in the next section.

Before the electroweak phase transition, the prehistory of the Universe becomes more speculative and less subject to experimental test. Within the framework of conventional Grand Unified Theories (GUTs), the next phase transition would have been associated with the recovery of an underlying symmetry between the strong and electroweak interactions. In simple models, this occurs at an energy of around 10^{15} GeV, corresponding to a temperature of around 10^{28} K. There are two possible observable implications of this conjectured phase transition; one is the synthesis of matter already mentioned, and the other is the suggestion of cosmological inflation discussed later.

If one wishes to speculate even more outrageously, one is restricted by the fact that our conventional notions of space and time probably break down when quantum gravity effects become important and particle energies reach the Planck energy of around 10^{19} GeV, corresponding to an ultimate temperature of around 10^{32} K. Beyond this mark, the notions of distance and time probably break down under the incessant impacts of high-energy particle collisions. Since the concept of time breaks down, it does not make sense to ask: what happened before the Big Bang? In my view, the appropriate framework for discussing this Planck epoch is provided by string (perhaps in its latest incarnation of M theory), which is the only candidate we have for a Theory of Everything (TOE) (see the chapter by Ross). Does this lead to a 'pre-Big Bang' or a phase in which only mathematical topology is meaningful?

Let us try to get our feet back on the ground by discussing some concrete cosmological probes of this pre-historical framework.

BIG BANG BARYOSYNTHESIS

Where does all the matter in the Universe come from, and why does it predominate over antimatter? This is typical of the sort of fundamental issue that would have been left to theologians until the advent of modern particle physics and cosmology. It was the physicist Sakharov in 1967 who set out the necessary and sufficient conditions for generating such an asymmetry between matter and antimatter.

First and foremost, one needs particle interactions that change quarks into leptons and vice versa. These are explicitly present in most GUTs and should also lead to proton decay. Unfortunately, despite intense experimental searches, protons remain stubbornly stable. However, all is not lost, even if one is GUT-less, because it has been realized that even the Standard Model should have hidden interactions that induce quark–lepton transitions, although these are not vulnerable to direct experimental observation.

Secondly, Sakharov pointed out that these interactions should distinguish between matter and antimatter. Such a distinction has been observed in the electroweak interactions of neutral kaons since 1964, although its origins are not yet established. There is now a vigorous campaign of experiments on heavier particles containing bottom quarks to study in more detail this matter–antimatter distinction. The Standard Model makes detailed and specific predictions for what should be observed. Regardless of whether these are confirmed or refuted, the new experimental campaign should provide us with understanding of the matter–antimatter distinction that should be essential for any mechanism for Big Bang baryosynthesis.

The third Sakharov condition is that there should be a breakdown of thermal equilibrium. This is because, in equilibrium, particle and antiparticle densities are fated to be equal following Boltzmann's law. Subsequent annihilation of these equal densities would yield a relic matter density that is at least 10 orders of magnitude smaller than indicated by observation. We conclude that a breakdown of thermal equilibrium is essential, and this could only have occurred at a phase transition that was abrupt (first order) and too rapid for the particle and antiparticle densities to keep together.

Two of the transitions identified in the previous section could provide this opportunity: the electroweak transition and the GUT transition. The electroweak scenario has the merit of being closer to experimental test. According to this idea, prior to the transition, the 'hidden' electroweak interactions would have enforced matter–antimatter equality. Then, if the electroweak transition was sufficiently abrupt, residual electroweak interactions could have favoured matter creation, e.g. in the collisions of particles with nucleating bubbles of the low-temperature phase. This scenario is subject to test in the ongoing matter–antimatter experiments, as well as being severely constrained by LEP searches for the Higgs and other particles.

The GUT scenario invokes the out-of-equilibrium decays of some massive particles X spawned by the GUT phase transition. For example, if GUTs produce equal numbers of X particles and their antiparticles $\overline{X}$, but the probability that X decays into matter is larger than the probability that $\overline{X}$ decays into antimatter, a net matter–antimatter asymmetry will be produced. Examples of such massive X particles could include superheavy neutrino-like particles that are associated with the possible neutrino masses mentioned earlier in connection with the deficits of solar and atmospheric neutrinos. As also mentioned there, massive neutrinos are among the particle candidates for dark matter, but there are other candidates as well, as we now discuss.

PARTICLE CANDIDATES FOR DARK MATTER

Astrophysicists have long argued that the Universe must contain large amounts of invisible dark matter. Could this be ordinary matter that does not shine in stars, for some reason? Big Bang nucleosynthesis tells us that there could not be enough ordinary matter to provide the fraction of about one third of the critical density apparently present in clusters of galaxies. However, ordinary dark matter could be significant locally, e.g. in the halo of our own galaxy. Indeed, observations of the Magellanic Clouds have revealed a few stars whose light is briefly amplified by gravitational lensing owing to the passage of an intermediate dark object with mass a fraction of that of the Sun. Indications are that these massive compact halo objects (MACHOs) could not constitute the whole of our galactic halo, but the jury is still out. Theoretically, MACHOs would not help to explain the formation of galaxies, and clusters surely need some extra matter, as already mentioned.

Neutrinos are good candidates, since they certainly exist, may have mass, as discussed earlier, and are only weakly interacting, and so they would escape collapse into concentrations of ordinary matter such as the discs of galaxies. Unfortunately, the indications are that they would also not populate sufficiently galactic haloes, although they might be a significant source of dark matter in clusters.

For many astrophysicists and cosmologists, the favoured dark matter candidates are WIMPs. These would have been non-relativistic ever since they froze out early in the expansion of the Big Bang. As such, they would easily have gravitated together and catalysed the formation of structures in the Universe. They would fill up galactic haloes as well as clusters. The only snag is, no such particles are known to exist!

Many speculative candidates for WIMPs have been proposed; my own favourite is the lightest supersymmetric particle (LSP). The motivations for a supersymmetric extension of the Standard Model are reviewed elsewhere (see the chapter by Ross). Suffice it to say here that it postulates partners of all the known particles with spins that differ by half a unit, but with the same internal properties such as electric charges, baryon and lepton numbers. If the interactions of these supersymmetric particles conserve these quantum numbers, the LSP would be stable, and an excellent candidate for dark matter, since it would have neither nuclear nor electromagnetic interactions. Calculations indicate that the overall density of LSPs in the Universe might be comparable with those of protons or neutrons, whereas the failures of searches for supersymmetric particles at LEP so far indicate that it must weigh more than about 40 GeV. Hence its relic density today might well approach the critical density.

As already mentioned, many underground experiments are searching for LSPs from the galactic halo scattering off nuclei with the deposit of detectable nuclear recoil energy. At the time of writing, the sensitivity of such experiments is beginning to probe some theoretical predictions. Other experiments are looking for high-energy neutrinos released by the annihilations of LSPs or other WIMPs captured at the centres of the Earth or the Sun. Yet another class of experiments is looking for antiprotons, positrons and γ-rays that may be produced by LSP annihilations in the galactic halo.

Before leaving particle candidates for dark matter, it is worth mentioning the axion, a very light bosonic particle that might be present in the Universe in very large numbers in coherent waves. There are also experiments probing whether our galactic halo may be composed of axions.

There seems every likelihood that the dark-matter particles in our galactic halo may be detected within the next decade. Accelerator experiments will also be looking for supersymmetric particles, in particular. LEP will probe LSP masses up to about 50 GeV, and in the long run the LHC will explore all the likely range of supersymmetric particle masses. It will be interesting to see who wins the race between accelerator and dark-matter experiments; super-optimists do not admit the possibility that supersymmetric particles do not exist!

COSMOLOGICAL INFLATION AND STRUCTURE FORMATION

We commented in the section on Big Bang cosmology that the density of matter in the Universe appears to be less than an order of magnitude below the critical density. *A priori*, this is surprising, because the density of a subcritical Universe tends to fall rapidly far below the critical density as the Hubble expansion proceeds. Related questions are why the Universe is so old and large. Its expansion is controlled by Einstein's equations, in which the only dimensional parameter is the Planck mass, which corresponds to a time scale of order 10^{-43} s and a length scale of order 10^{-33} cm. Clearly our Universe must be a very special solution of Einstein's equations, in order to have survived so long and grown so large.

The solution of these conundra may also explain why the Universe is so homogeneous and isotropic. Cosmic microwave background photons, from opposite directions in the sky, when they were emitted during the combination of nuclei to form atoms, started from points that were separated by about a hundred times further than the maximum distance that a light wave could have travelled since the beginning of the Universe. Yet these opposite regions of the sky look identical to one part in 10^5. How did they succeed in coordinating their behaviour?

The answer proposed by cosmological inflation is that the very early Universe underwent a phase of exponential expansion, perhaps driven by energy stored in a Higgs-like field associated with some GUT (figure 17.6). This mechanism would suggest that the density of the Universe be very close to the critical density and explain its age and size by this enormous exponential kick. The isotropy of the cosmic microwave background radiation would be made possible by coordinating the behaviours of different regions of the Universe before they were blown apart.

One of the beauties of cosmological inflation is that it not only predicts the homogeneity and isotropy of the Universe but also their breakdown. During the phase of exponential expansion, quantum fluctuations in the driving field are imprinted on the Universe as variations in its density, and their magnitude is related to the density of energy during inflation. The COBE satellite detected for the first time fluctuations in the cosmic microwave background radiation that could be due to this inflationary mechanism. If so, their magnitude of about one part in 10^5 corresponds naïvely to an energy density around the GUT energy scale. Even if this particular identification eventually fails, there is little doubt that fluctuations in the cosmic microwave background probe particle physics at an energy scale far beyond those attainable directly with accelerators.

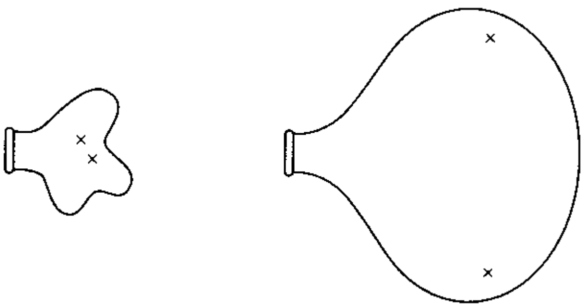

Figure 17.6. As a balloon is inflated, points on its two-dimensional surface appear to move apart. Analogously points in a higher dimensional Universe appear to move away from each other: the 'Hubble expansion'.

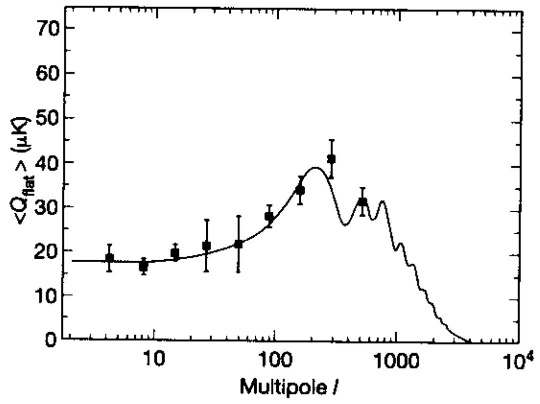

Figure 17.7. Data from a number of experiments measuring the cosmic background radiation, showing the variation in temperature seen over various angles (higher multipoles imply smaller angles).

Many experiments have by now confirmed the COBE discovery and mapped out the microwave background fluctuations at a wide range of angular scales (figure 17.7). They will be able to measure in detail the spectrum of perturbations and may tell us how they are composed into simple density perturbations and gravitational waves. Within the inflationary paradigm, these measurements should enable us to map out a significant part of the potential energy of the field driving inflation and test different GUT and other models.

The COBE discovery has also caused effervescence in attempts to understand the formation of structures such as galaxies and clusters. Armed with the COBE input and large N-body simulation codes, theoretical astrophysicists have tested many models of structure formation. The most successful has combined inflationary perturbations with some species of massive dark-matter particle such as the LSP or some other WIMP. Not all the detailed comparisons work perfectly, and it may be that this basic recipe requires some spice, perhaps in the form of massive neutrinos, a modification of the fluctuation spectrum, or some energy density in the present-day vacuum—a cosmological constant.

With all the cosmological measurements to be made over the next decade, particularly by the MAP and *Planck Surveyor* satellites, there is good reason to expect soon to have a detailed and quantitative theory of structure formation. This theory will rely upon inputs from particle physics, notably the theory of inflation and the experimental observation of some species of dark-matter particles, either at an accelerator and/or in the galactic halo.

GRAVITATIONAL RELICS FROM THE BIG BANG?

So far we have emphasized the links between cosmology and the non-gravitational interactions of elementary particles. Are there any hopes for observing direct consequences of their gravitational interactions?

One strong hope is that of observing directly gravitational waves, which have already been observed indirectly via their effects on the orbits of binary pulsars. Large laser interferometer devices are now being built that have a fair chance of observing gravitational waves emitted by coalescing binary systems, star capture by black holes and perhaps supernova explosions. The next step would be a laser interferometer array in space. This might even be able to observe gravitational waves emanating from the primordial Universe, as occurs in some 'pre-Big Bang' models.

The evidence for astrophysical black holes is also growing more impressive, with claims being made for hints of a surrounding event horizon, and distortions of the surrounding space–time that are characteristic of a strong field in general relativity. However, direct observation of a quantum particle phenomenon such as Hawking radiation does not seem within reach at present. A recurrent theme is the possible existence of primordial black holes left over from the Big Bang. Suggestions that they might be made during the quark–hadron phase transition are not convincing, and it is difficult to imagine other sources subsequent to cosmological inflation (if this occurred). On the other hand, inflation would have diluted to undetectability any primordial black holes made previously.

The question then arises whether black holes or any other massive relics might have been fabricated during inflation. In the context of current inflationary models, this is unlikely unless their mass is of order 10^{13} GeV. If such relics carry quantum numbers that prevent or inhibit their decays, they could be around today as superheavy relics from the Big Bang. Decay products of such supermassive relics could conceivably be at the origin of the mysterious ultrahigh-energy cosmic rays mentioned earlier.

THE SYMBIOSIS OF PARTICLE PHYSICS AND COSMOLOGY

Microphysics and macrophysics have become so intertwined that it is now impossible to distinguish them. Particle physics provides the building blocks with which cosmologists must work. Cosmology constrains the properties of particles, e.g. the masses of neutrinos or the abundance of WIMPs, that are inaccessible to accelerator experiments. Researchers working in the fields of particle physics and cosmology use arguments from each other's fields as naturally as they draw breath. Experiments at LEP and the LHC provide key inputs to cosmological theories, and our greatest challenge may be the identification of dark matter. The present period of particle cosmology will, in retrospect, surely be considered as seminal as was nuclear astrophysics in a previous generation. Astronomy has already been extended from the electromagnetic spectrum to neutrinos, and perhaps soon to gravitational waves. Many of the most fundamental problems in cosmology may soon find solutions based on particle physics, whereas many particle theories may only be tested by cosmological observations. Within the contexts of the discussions of the previous sections of this chapter, which are the major developments that may be expected in the foreseeable future?

- We shall soon know from the Superkamiokande and other experiments whether neutrinos mix, as expected if they have non-zero masses.
- Underground or other non-accelerator experiments are likely to identify any WIMP component of the galactic halo, if LEP, the LHC and other accelerator experiments do not discover them first.
- We shall soon know to high precision the basic cosmological parameters such as the Hubble expansion rate and the present densities of baryons, other matter and the vacuum, in particular from the data of the MAP and *Planck Surveyor* satellites.
- Laboratory experiments will identify the quark–gluon plasma and will predict the nature of the electroweak phase transition.
- Laboratory experiments will also identify the origin of the matter–antimatter distinction observed in the weak interactions. Together with the electroweak phase transition measurements, these may provide a calculable theory of the matter–antimatter symmetry in the Universe.
- Accelerator experiments at LEP or the LHC will discover supersymmetry, if dark-matter experiments do not beat them to it.
- Observations by MAP and *Planck Surveyor*, together with sky surveys and the discovery of dark matter will provide a tested theory of the formation of structure in the Universe.
- Gravitational waves will be detected.

This list is impressive, but I prefer to end on a more humble note. The most exciting developments will surely be those that I have failed to foresee or predicted wrongly. The reader is invited to laugh at my hubris and myopia when the Universe outsmarts me.

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ABOUT THE AUTHOR

Educated in England, John Ellis obtained his BA in 1967 and his PhD in 1971, both from the University of Cambridge. After a couple of years at the Stanford Linear Accelerator Center and the California Institute of Technology, he settled at CERN in 1973, where he was leader of the Division of Theoretical Physics for six years and is currently a senior staff member. He is the author of over 500 scientific articles, mainly in particle physics and some related areas of astrophysics and cosmology. Most of his research work has been on the possible experimental consequences and tests of new theoretical ideas such as gauge theories of the strong and electroweak interactions, grand unified theories, supersymmetry and string theory. He was awarded the Maxwell Medal of the Institute of Physics in 1983 and was elected a Fellow of the Royal Society in 1985. The University of Southampton awarded him an Honorary Doctorate in 1994, and he has held visiting appointments at Berkeley, Cambridge, Oxford, Melbourne and Stanford.