1 PRELUDE: THE MYSTERY OF THE MISSING ANTIMATTER

In the beginning—what was the beginning? Every culture asks this question. Traditionally each finds some answer, a creation myth, a cosmology. These stories satisfy an innate human longing to know about our origins. Only recently has our scientific understanding of the history of the Universe progressed to the point that we can begin to formulate a scientifically based answer—a scientific cosmology. We know that the Universe is evolving and we understand many facets of its history. We know its age, about fourteen billion years! We can ask, and often even answer, detailed questions about the very earliest times, times immediately after the Big Bang. We can test our ideas by comparing detailed observation of the Universe to detailed simulation of its evolution built on our modern understanding of physics. Today our technology for probing physics on both the tiniest and the largest imaginable scales can take us closer to the beginning of the known Universe than ever before. Much has been learned. Big questions remain; each new answer reveals new questions. What a wondrous time this is for cosmology.

Our story centers on a question that links cosmology and particle physics. Experiments in high energy physics laboratories have demonstrated that, in addition to the stuff we call *matter*, there is another set of stuff. It is just like matter except with a reversal of charges. It interacts, with itself and with matter, in ways that we understand. Physicists call this stuff *antimatter*. We make it and study it in our laboratories, but find very little of it in nature. The laws of physics for antimatter are almost an exact mirror of those for matter. That makes the imbalance between matter and antimatter in the Universe a deep mystery. This mystery is the central topic of our book.

For each type of matter particle there is a matching type of antimatter particle. Given the right conditions, we can convert energy from radiation into a matched pair of newly formed matter and antimatter particles; that is how we produce antimatter in our laboratory experiments. Conversely, whenever an antimatter particle meets its matching matter twin they can both disappear, converting all their energy into a flash of radiation. Thus any antimatter particles produced in the laboratory, or in naturally occurring high energy processes, disappear again very shortly. In a matter-dominated environment their chances for longevity are very slim!

In probing the Universe today, experiments from the ground or on satellites can achieve sensitivity to times long before any structure and form evolved within it. They observe radiation that has been traveling through space for a very long time, almost as long as the Universe has existed. We can use these observations to find out about the Universe at the time this radiation began its journey. We can explore even earlier stages by modeling them according to our theories and asking whether the model can match the Universe as we observe it. The observations show a Universe that is expanding, and therefore it is cooling, and becoming, on average, less densely populated by particles.

Our theories suggest that, at very early times in the development of this evolving Universe, matter and antimatter, all possible types of particles and antiparticles, existed equally in a hot, dense, and very uniform plasma. If equal amounts of matter and antimatter had persisted, then today the Universe would be a very dull place. At the early high temperatures, creation and annihilation of energetic matter and antimatter particles would have served not only to keep their numbers equal, but also to keep those numbers large. However, as the Universe expanded and cooled, it reached a stage where annihilation could still occur whenever a particle met an antiparticle, but the reverse process, creation of a particle and an antiparticle, became more and more rare. There was essentially no radiation remaining with sufficiently high energy to cause it. Gradually all the particles and antiparticles would have disappeared. The Universe would have no visible objects in it.

Today, however, we do see a universe with huge structures made of matter: earth, solar system, galaxies, clusters of galaxies; all matter, with very little antimatter, governed on large scales chiefly by gravitational effects. All these visible parts of the structure, the stars and galaxies that light up the heavens with many forms of electromagnetic radiation, from radio waves to gamma rays (including, of course, their beautiful visible light), would not exist today if somehow matter had not won out over antimatter at some very early time in the evolution of the Universe.

How and when did the histories of matter and antimatter take such different courses? This is one of the great mysteries of science today. A question at the root of our very existence, it is one for which, as yet, science has no clear answer. Our purpose in this book is to discuss the issues around this question, explaining what we physicists do and do not understand at present, and how we hope to learn more.

We can describe the history of the very early Universe with some confidence for events that occurred from a millionth of a millionth of a second (10^{-12} seconds) after the Big Bang. The reason is that in our high energy laboratories we can produce particles with energies similar to those that prevailed in the Universe at those times. We know how particles behave under those conditions. Thus, for example, the wisdom of nuclear physics allows us to model the primordial production of small nuclei from collisions starting with protons and neutrons, long before stars began to form. Because we know very well what energies are required for collisions to take apart each of the light elements into its constituents, protons and neutrons, we can identify rather precisely the time at which the Universe became cold enough that this destruction practically ceased, and thus production of elements started in earnest. This was about three minutes after the Big Bang. The success of our model of the early Universe in predicting the relative amounts of deuterium, helium, tritium, and lithium produced in this primordial nucleosynthesis is one of the great triumphs of cosmology.

For earlier events, back to as early as 10^{-40} seconds (a ten-billionth of a ten-billionth of a ten-billionth of a ten-billionth of a second—an unimaginably small time!) after the Big Bang, the conditions were considerably more extreme than anything that we can create in our laboratories. But, amazingly, our *theoretical* understanding of particle physics can be used to develop a reasonable (even if hypothetical) picture of events that happened at such early times, when the Universe was hot and dense beyond imagination. Our picture may not be completely right, but it builds on what we do know and tells us what issues it is critical to study further.

For yet earlier times, before about 10^{-40} seconds after the Big Bang, we do not even have any theory we can use; we run into contradictions if we try to apply our best current knowledge to such extreme conditions. At this time the Universe was an unimaginably hot and dense plasma of particles, interacting rapidly and energetically. The best we can do is start a moment after the Big Bang, immediately after the first rapid stage of Universal expansion (known as inflation), and follow the history of the Universe forward from then. Questions about how the Big Bang began, or what, if anything, was there before it, fascinating as they are to speculate about, cannot be addressed with any certainty at the current stage of our understanding, though they are an active topic of current work.

This much we do know: The fate of antimatter to disappear was sealed by the time the Universe was no older than a millionth of a second. At that time, matter particles and antiparticles were both still very abundant, but there must have been a tiny edge for particles over antiparticles, about one extra particle for every ten billion particle–antiparticle pairs. This tiny excess is all that matter needed for a total victory over antimatter in the present Universe. All the visible structures in the Universe that we observe today—planets, stars, galaxies, clusters of galaxies—are made from that surplus of particles over antiparticles. While we know for sure that the tiny excess of matter over antimatter existed when the Universe was a millionth of a second old, it is very likely that the crucial events that created this excess happened well before, sometime between 10^{-40} and 10^{-12} seconds, the period that is accessible to our theories but not to experiments. This makes the mystery of the missing antimatter a very exciting one: it gives us a window into extremely early times, and tests our particle physics theories under conditions that we cannot recreate in our experiments.

Matter and antimatter obey very similar but not quite identical physical laws. We know that a tiny difference between the laws of nature for matter and antimatter exists because we have seen it in experiments. It is now incorporated into our theories of particle physics. We can use these theories to develop a picture of how and when an imbalance of matter and antimatter could develop. We can even calculate how big the imbalance should be. That calculation makes predictions for conditions we can observe today, for the amount of matter in stars and galaxies compared to the amount of radiation in the background microwave signal that we see from all directions in space.

But the mystery of the missing antimatter is not solved! Our modeling tells us that the present theory of elementary particles and their interactions, the so-called *Standard Model*, which matches correctly the results of numerous laboratory experiments, must be flawed or incomplete. For, if it were the full story, the disappearing antimatter would have taken along with it too much of the matter; too few protons and neutrons would persist to make just a single galaxy, such as our own Milky Way. So this is the mystery of the missing antimatter in its modern variation: What laws of nature, not yet manifest in experiments and not part of our current Standard Model, were active in the early Universe, allowing the observed amount of matter to persist while all antimatter disappeared from the Universe?

The question of the imbalance between matter and antimatter focuses our attention on a particular early stage in the history of the Universe. Much has recently been learned about other episodes. Beautiful experiments have tested and refined our understanding of the big picture of how the Universe developed and is still developing. Along the way these experiments tell us there are two more mysteries to solve.

One is the mystery of the *dark matter*, stuff that is neither matter nor antimatter but some as yet unknown type of particle. This mysterious dark matter is also essential in the history of the Universe, but it interacts so little that it does not form stars or produce any visible emanations. We know that dark matter exists because we observe its gravitational effects. All our modeling of the motions of stars within galaxies, of the patterns of multiple images of the same distant galaxy formed by gravitational lensing as the light paths are bent by the mass of nearer galaxies, and of the evolution of structure in the Universe cannot be made to work (that, is to match the observations) without it. There is roughly six times as much mass in dark matter particles today as there is in matter particles. We cannot at present specify further what the dark matter is. All we know is that it has mass and interacts very little with itself or with matter and antimatter, except via gravitation. It is most likely some kind of particle, but we do not know enough about it yet to say what kind.

The third mystery is the most recently discovered, and hence, as yet, the least understood. The rate of expansion of the Universe is not slowing down, as we expected it should. Instead, it is accelerating. Whatever causes this is not yet part of our particle theories at all, though very speculative extensions suggest ways it might be added. This effect is generally called *dark energy*. The mysteries of dark matter and dark energy are both exciting and still developing detective stories. We will tell you what little we know about them too, though our stress in this book is on the matter–antimatter puzzle.

To develop the story of matter and antimatter in the Universe we will develop a number of themes; the Universe itself is of course one of them, along with the story of matter and antimatter. But we will also need to develop the themes of symmetries and of energy before we can tell our story in a meaningful way. Then too the theme of experiments, of how we know what we claim to know, must enter the story. We hope you will find the development of each of themes interesting in its own right; they are the basics of modern particle physics, and to understand the Universe we must understand them all.