Chapter 1
Prologue: Inside the Energy Walls of Our "Cradle"

We often say that the physics of "small distances" is equivalent to the physics of "high energies." This is indeed true, as a direct consequence of the celebrated Heisenberg's principle (or uncertainty principle) stating that, in order to explore (and measure) smaller and smaller distances, we need probes with higher and higher momenta, namely with larger and larger kinetic energies. According to the uncertainty principle, in particular, the required energy E turns out to be inversely proportional to the considered distance d, so that E tends to infinity when the distance d goes to zero.

Even in the case of very large distances, however, we are unavoidably lead to the high-energy regime. This basically occurs for two reasons: one reason, of accidental type, is related to the expansion of our Universe; the other reason, of more fundamental nature, is related to the fact that all information and signals (of all types) are characterized by a finite speed of propagation.

According to this second (important) property of Nature, in fact, looking "far away in space" also means looking "back in time," because the signals we receive from more and more distant sources have been emitted at increasingly remote epochs. If a galaxy is millions of light-years away from Earth, for instance, its light has been traveling for millions of years to get to us, and the information it can provide is referred to the epoch when the light left the galaxy—namely, to millions of years ago.[1]

Because of the expansion of our Universe, on the other hand, looking back in time implies considering epochs in which matter and radiation were concentrated in increasingly smaller volumes of space, so that the temperature and the kinetic energy of their elementary components were higher and higher. Hence, the more remote is the signal which reaches us, the greater is the energy scale corresponding to the emission epoch.

[1]The famous *Andromeda Galaxy*, whose picture is also used as a desktop background in recent versions of Mac computers, is one of the nearest galaxies, and is approximately 2.5 million light-years away from Earth (corresponding to a distance of about 2.4×10^{19} km).

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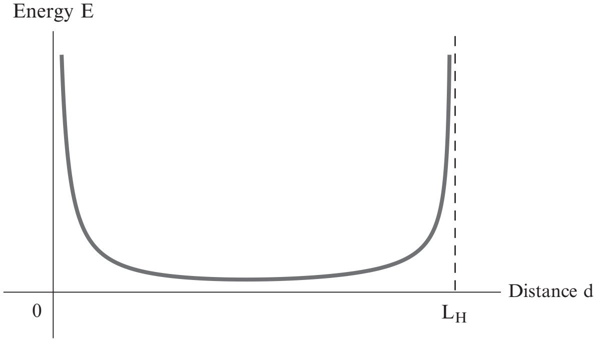

Fig. 1.1 The energy scale E as a function of the corresponding distance scale d. The physically accessible range of distances seems to be bounded by two walls of infinitely high energy

It follows that our observations cannot be extended back in time (and out in space) at our will: beyond a given epoch, for instance, the Universe is so dense as to be no longer transparent to the electromagnetic radiation[2] (the emitted light is immediately reabsorbed, hence it cannot get to us today and bring us information about those eras).

We might consider different types of radiation (for instance, gravitational waves) which are more penetrating than light, and can reach us from more remote eras. Even proceeding in this way, however, standard cosmology tells us that we *must* encounter, at a given time and to a given distance, an impassable barrier due to the so-called "initial singularity:" the famous Big Bang.

The Big bang singularity, which marks the beginning of the cosmological expansion, and which is characterized by an arbitrarily high-energy scale, is not infinitely remote in time (and distant in space): it is localized at an epoch that approximately dates back to 14 billion years ago, and that corresponds to a spatial distance of the order of the so-called "Hubble radius," L_H. Such a distance is time dependent, and its present value is just about 14 billion light-years. For spatial distances approaching L_H the corresponding energy scale tends to infinity.

In order to summarize the previous discussion, and synthesize our findings, we can produce a (empirical) plot of the energy scale E as a function of the distance d. We obtain in this way a curve like the one reported in Fig. 1.1, characterized by an unbounded growth of the energy in the limit of both very small distances ($d \to 0$) and very large distances ($d \to L_H$), approaching the Hubble radius.

Such a behavior of E seems to keep our observation capability confined within a limited range, bounded by two physically insourmountable walls. In fact, an

[2]This occurs when the radiation reaches a temperature that is about a 1,000 times larger than the current one: more precisely, a temperature of 2,973 K. Such a temperature is reached at the so-called "decoupling epoch," see for instance the textbooks by Durrer [1], Weinberg [2], Gasperini [3] (in Italian).

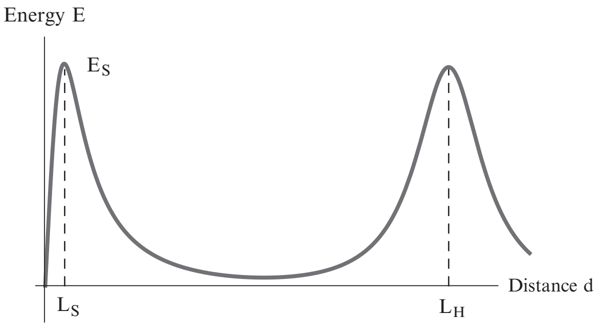

Fig. 1.2 The energy scale E as a function of the corresponding distance scale d, including the energy bounds suggested by string theory. The physically accessible distances now range from zero to arbitrarily high values

infinitely high energy would seem to be required to get access to arbitrarily small and/or arbitrarily large distances, just as if Nature had prepared for us a "cradle" from which we cannot escape.

As every cradle, however, also the "energy cradle" we are considering might prove effective to confine and protect a "newborn" physical science, becoming however inadequate, and no longer impassable, with the growth and the ripening of our scientific knowledge. There are indeed recent developments in theoretical physics, to be illustrated in the following chapters, suggesting that the energy walls of Fig. 1.1 might be "smoothed out"—at both large and small distances—and replaced by barriers of very high but *finite* energy.

Anticipating some results, and considering first the "cosmological" barrier associated with the Big Bang, we may recall that the modern string theory allows to formulate models of the Universe in which the initial singularity is replaced by a transition phase—the so-called "string phase"—with typical values of temperature and density much higher than those of ordinary macroscopic matter, but *not infinite*. In that case the energy scale E is no longer divergent as the distance approaches L_H, but it is limited to a maximum value E_S (determined by string theory). At larger distances the energy goes back to the decreasing regime, allowing (at least in principle) the observation of spatial distances (and time intervals) of arbitrarily large extension (see Fig. 1.2).

We may expect a similar change also for the energy barrier located at small distances. In fact, the scale of maximum energy E_S is inversely proportional to a distance scale which we shall call L_S, and which is typical of the theories of strings and extended objects in their quantum version. Below that distance, which represents the minimal length of the quantized string (or extended object), we may expect that the uncertainty relation may acquire corrections able to remove the infinite amount of energy fluctuations associated with the presence of infinitely small distances, so as to fix a maximum energy scale in correspondence of the string length L_S.

The outcome of the above modifications is qualitatively illustrated in Fig. 1.2, showing how the two energy barriers might be smoothed around the two critical distances L_S and L_H, as a consequence of the corrections induced by string theory.

Given that the above figure is not in scale and does not reflect the actual proportions, it is appropriate to stress that the two distance scales L_S and L_H are tremendously different from each other: L_S corresponds to a very small length, of the order of 10^{-32} cm, while L_H is extremely large and (as already mentioned) is of the order of 10^{28} cm (approximately 14 billion light-years).

Also, the peak value of the energy barrier, E_S, is enormous with respect to the typical energy scales of nuclear and subnuclear physics. String theory, in fact, suggests for E_S a value of the order of 10^{15} TeV: this is a million billion times larger than the maximum energy presently reached by the world’s biggest accelerator “Large Hadron Collider” (LHC), operating at the CERN laboratories near Geneva.

The two barriers we are considering are thus of finite but very large height and are located at an enormous distance from each other. Which other worlds, and what new natural phenomena, are waiting for us beyond those barriers regarded as impassable by the physics of the last century?

We are a bit intrigued and a bit intimidated, just like an infant raising his head for the first time to look over the walls of his cradle.

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