Prologue

The athletes who participate in the Olympic Games run and swim ever faster, even if, with the passing of time, it becomes ever more challenging to beat former records. The same can be said of the particles that travel at (almost!) the speed of light in accelerators, those microscopes of the infinitely small. Everyone understands the motivations of athletes and Olympic organisers; physicists' reasons are instead much less clear to non-experts.

The question "why accelerate particles?" has become even more frequent since – in July 2012 – physicists from the *Large Hadron Collider* (or LHC) at the CERN laboratory near Geneva announced the discovery of the *Higgs boson*. It is a question which I will try to answer in this book, beginning with the history of a few important physical discoveries and some of the main characters involved.

As we will see, it is a story in which research on fundamental aspects of nature – from the structure of matter to the origin of the universe – is interwoven with applications of great practical value, in particular for diagnosis and treatment of our illnesses.

Subatomic Microscopes, Particle Factories

The important development of particle accelerators, devices that usually have a circular shape, began about 80 years ago.

Initially, for some decades, they were used to study the structure of matter: fast particles, once accelerated, were directed onto a target, for example a small piece of metal. Observing the products of the collisions provided information on the structure of atomic nuclei in the bombarded material. It was rather like exploring the contents of a darkened room by throwing a lot of marbles into it and observing the rebounds.

Subsequently, the attention of physicists turned to the new particles produced in the collision between a fast particle and an atomic nucleus. Energy can be transformed into mass, as predicted by the relationship $E = mc^2$ discovered by

Einstein, and the energy released in collisions frequently gave rise to the creation of new particles. Most of these particles are 'unstable' in the sense that they live very briefly and then give rise to two, three, four... particles of smaller masses. These unstable particles, which before 'decaying' into other particles survive for less than a millionth of a second after the collision, are not found in the matter making up the world around us and can be studied in detail only by producing them artificially with an accelerator.

Thus accelerators, as well as being 'microscopes' of the subatomic world (that is of the nucleus and whatever exists inside the nucleus), can also be viewed as 'factories' of these particles that – having mass, and therefore energy, greater than the particles which make up ordinary matter – are unstable and decay extremely rapidly, transforming into the well known stable particles.

However, there is a *third* reason for studying the fleeting existence of particles that are so difficult to produce and observe; physicists would like to interpret the picture of Fig. 1. This is not just any picture: rather it can be described as the most ancient 'photograph' that we will ever have of our universe. Let us understand better what that means.

Why We Cannot See the Big Bang

When we point the most powerful telescopes deep into space, we observe light originating from stars of our galaxy and from other galaxies. With the naked eye we can see only some thousands of stars in our galaxy, that in reality contains several hundred billions of them and, even though the other galaxies of the universe are also numbered in hundreds of billions, we can hardly distinguish Andromeda, the closest one.

The light emitted by the farthest galaxies has travelled for billions of years before being detected by telescopes, so the photographs describe today how those galaxies were billions of years ago; in the meantime they could even have disappeared. Hence the furthest galaxies are the oldest and those closest, the youngest; comparing images, therefore, it is possible to study the evolution of the galaxies with time.

But there is more; in the last century it was discovered that galaxies are moving away from each other, and this observation shows that space itself is expanding; it is as if galaxies were tiny specks of paper stuck to the surface of a balloon that is being inflated. Extrapolating this motion in reverse, if the balloon were deflated, one can conclude that about 14 billion years ago all the energy of the universe occupied a tiny volume and the temperature of the matter contained within it was extremely high; this was the universe produced in the Big Bang.

A millionth of a microsecond after the Big Bang matter had a temperature of millions of billions of degrees. Then however, with the passage of time and the expansion of space, the temperature gradually decreased. There are places in the universe in which the temperatures today are still high; for example the photosphere

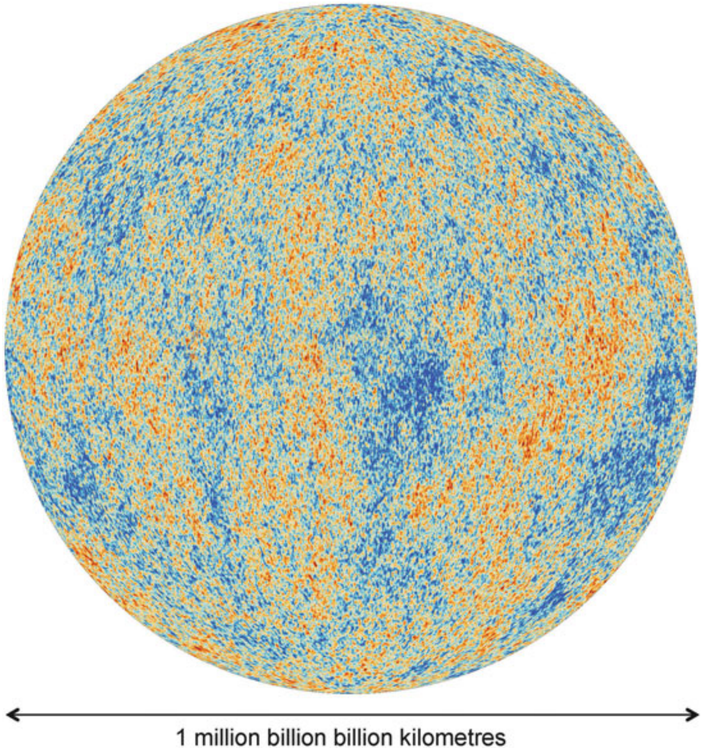

Fig. 1 This 'photograph' shows the distribution of the temperature of the gas constituting our universe when it was 380,000 years old. It was obtained in 2013 by the Planck space probe which had been sent into space 4 years before by the European Space Agency (ESA). The different colours represent tiny fluctuations in the temperature of the gas, mainly hydrogen (Courtesy of European Space Agency, Planck Collaboration)

of the Sun is around 6,000 degrees, and its interior reaches 10 million degrees. However, if one could carry a thermometer into the space between the galaxies – where the heating due to the light emitted by stars and intergalactic matter is negligible – the measured value would be -270 °C, or 3 K.[1]

Up to temperatures of several thousand Kelvin, matter is solid or liquid or gaseous, as we know from experience on Earth. Heating beyond that begins to produce a fourth state of matter, the so-called *atomic plasma*, in which continuous and violent collisions between atoms strip some of the electrons from the nuclei around which they normally orbit.

Increasing the temperature actually means to increase proportionately the energy with which atoms of matter collide, in that frenetic and uncoordinated dance that physicists call *thermal motion*. At 10,000 degrees, the collisions detach electrons

[1] Physicists prefer to use as a reference the minimum possible temperature, zero degrees Kelvin or 0 K, equal to -273 °C.

only from the lightest atoms, such as hydrogen or helium; to strip electrons that orbit close to the nuclei of heavy atoms like iron it is necessary to exceed millions of degrees.

In any case above 10,000 degrees, a significant fraction of the plasma is made up of electrically charged particles, in particular free negative electrons and residual positively charged atoms deprived of one or more electrons, and called *ions*. These electrical charges immediately absorb the packets of luminous energy, or *photons*, which are continuously emitted by atoms and ions themselves at these high temperatures; an atomic plasma is therefore not transparent to light, like a slab of iron.[2]

Thus, the *primordial cosmic soup* of particles – which shortly after the Big Bang was at billions of billions of billions of degrees – cooled while expanding, but remained impenetrable to the light emitted by the same particles until the temperature fell below a few thousand degrees.

Theories of the birth of the universe are called *cosmological models* and today are supported by numerous precise measurements. The models tell us that starting only 380,000 years after the Big Bang – when the cosmos was about a thousand times smaller than at present – the temperature became low enough that most electrons became bound to atoms that are electrically neutral and the whole universe became transparent in a very short time. Matter consisted mainly of hydrogen atoms, hydrogen being the simplest atom, made of a positively charged proton encircled by a negative electron.

Thus, when the temperature decreased to the present level of the Sun's photosphere, the cosmos became the source of an extremely intense white light, whose unabsorbed photons began to travel in every direction at the speed of light. Instead the light emitted *before* this instant, absorbed by the primordial cosmic soup, will never reach our instruments, however sensitive they are; looking from Earth we are not able to 'see' the Big Bang.

Relic Radiation

To understand the significance of Fig. 1 ignore, for the moment, the expansion of the universe and imagine that, for a brief instant, a dazzling white light were to be emitted from every point of an enormous sphere of extremely hot gas, at whose centre the Planck space probe – taking the picture – is found.

Later – say a thousand years after the instant of emission – the photons which have travelled undisturbed for all that time arrive at its detectors, having been emitted by atoms which were located, at the moment of emission, at a distance of

[2] Iron is opaque to light because two of 26 electrons of each Fe atom move freely within the metal, and therefore 'devour' every photon that penetrates. Instead glass is transparent because all the electrons are attached to their atoms.

1,000 light years away. The images then captured by Planck therefore describe the state of a thin layer of gas – of 1,000 light years in radius – as it was 1,000 years earlier.

After a million years the photons which have travelled a thousand times further arrive, corresponding in the images to gas which was located one million light years away. After a billion years the same instruments provide a picture of the gas found one billion light years away.

Similarly, when the Planck instruments observe the universe today, they see those photons that were produced 380,000 years after the Big Bang (when the emitted light was no longer absorbed by the plasma) and have travelled undisturbed for 13.8 billion years. They were emitted by the plasma contained in a very thin spherical layer that today is an enormous distance away from us, illustrated in Fig. 1. That distance is actually larger than 13.8 billion light years because, in the meantime, the universe has expanded, a phenomenon that I ignored in the preceding explanation.

The expansion of the universe has a second important effect which influences the observation of photons emitted by the cosmic gas. In fact, during their long transit these packets of electromagnetic waves are changed; the continuous expansion of space, that increased a thousandfold the dimensions of the visible universe, also stretched the peaks of the waves a thousand times further apart. In this way the photons of white light, which initially had a wavelength of little less than a micrometre, have now reached a wavelength of about a millimetre; they are *microwaves* instead of visible light. In order to 'see' them Planck's instruments are not standard cameras but sophisticated microwave detectors.

The image of Fig. 1 was obtained by observing this *microwave background radiation,* which comes from every part of the sky. The average wavelength is practically the same in every direction, and coincides with what would be measured on Earth inside a container held at 3 K, that is -270 °C.

Hence the cosmic space which separates the galaxies is traversed in every direction by a radiation that is a *relic* of a remote era; 380,000 years after the Big Bang it was at a uniform temperature of 3,000 degrees, while today it is much, much colder. The picture shows that the uniformity was however not absolute. In small regions of the sky, appearing as red spots in Fig. 1, the temperature of the background radiation exceeded the average value by a few hundred-thousandths of a degree, while in other parts – the blue spots – it was a few hundred-thousandths of a degree below the average; the intermediate temperatures are shown in the figure by different colours.

The coldest regions were also those which had the highest density; the gravitational attraction there was stronger, therefore the first stars and galaxies, which began to form several hundred million years after the Big Bang, had their origins in those darker spots. Their light required almost 14 billion years to reach the Planck space observatory.

A Time Machine

Even if our descendants were to observe the heavens with highly advanced instruments, capable of detecting electromagnetic waves of any wavelength with maximum sensitivity, they still would never succeed to 'see' what happened earlier than 380,000 years from the Big Bang.

They are prevented – and always will be prevented – by the opaqueness of the particle soup, which absorbed all photons when it was at temperatures higher than several thousand degrees. But physicists do not give up easily, and for three decades they have chosen the only possible way to overcome this difficulty: by constructing models.

These models are based on experimental studies of the reactions which took place between particles during the first 380,000 years of the life of the universe. The experiments were carried out using particle accelerators, devices in which tiny granules of matter, brought to speeds close to the velocity of light, are made to collide.

Thanks to Einstein's equivalence between mass and energy, the collisions in an accelerator enable the creation of new particles (provided that they have masses lower than the combined energy of the colliding particles) and the observation of their subsequent *decay*, which is the process that transforms them back into particles of ordinary matter.

By using a sufficiently powerful accelerator, it is possible to observe the creation and decays of particles that existed in the early universe when the temperature was higher. In other words, ever more powerful accelerators allow to reproduce in the laboratory some of the reactions among particles that happened further and further back in time. The accelerators are therefore not only subatomic microscopes and factories of unstable particles; they are also 'time machines'.

When 50 years ago, shortly after arriving at CERN, I made my first, small contribution to these studies, the energies released in collisions were of the order of one GeV, or one billion electron-volts. Today we know that such energies are characteristic of collisions which took place a *microsecond* after the Big Bang.

At the end of 2000, the group which I coordinated at the LEP (Large Electron Positron) collider accelerator at CERN in Geneva, collected data from collisions at 100 GeV. An increase of 100 times in energy allows to go further back in time by a factor $100^2 = 10{,}000$; thanks to LEP we could therefore understand in detail what happened just a *ten thousandth of a microsecond* after the Big Bang. (Physicists quantify such a small number by writing 10^{-10} s, which corresponds to 1 divided by 1 followed by 10 zeros.)

This information, combining what was known from experimental studies carried out at lower energies with some new and important theoretical progress, allowed the formulation of a mathematical model that explains the observed data contained in Fig. 1 that, as we have seen, goes back to 380,000 years after the Big Bang.

But we aim at learning more, at exploring times even more remote, earlier than 10^{-10} s, to search for confirmation of theoretical intuitions and to approach even closer to the instant in which everything began.

The new LHC accelerator at CERN has allowed us to make another step back in time by a factor 100, to a *millionth of a microsecond* (10^{-12} s) from the Big Bang.

From Cosmology to Medicine

More than a hundred years have passed since the discovery of X-rays, made possible by one of the most sophisticated particle accelerators available at the time; that was where modern physics began.

The following chapters retrace the principal events – which, following that discovery, have brought into being more and more powerful accelerators – and introduce the accelerator experts, who made possible the collisions of particles of larger and larger energies. We will get also to know the experimentalists, who invented, built and used the particle detectors needed to ‘see’ the particle collisions; and the theorists, who constructed the mathematical theories that best explain the experimental data. Accelerator experts have been instrumental in the understanding of both the matter around us and the history of the early universe. Since they are the least known of all these scientists, in this book I devote special attention to them and their inventions while I mention only cursorily the contributions of the experimentalists and I pass over most of the theorists, who usually get the largest credits.

The fascinating story of accelerators leads us up to the 2012 announcement of the discovery of the *Higgs boson* and the real frontiers of *high energy physics*, that the LHC – the extraordinary CERN apparatus – will enable to explore.

In the last two chapters we will also see that particle accelerators, invented and used for pure research in the field of fundamental physics, turn out also to be highly valuable in medicine, making possible the realisation of new techniques for diagnosis and treatment of numerous illnesses.

This is an interesting example that illustrates a very general fact; instruments developed by physicists for fundamental research have found – and, I am convinced, always will find – practical applications that go well beyond the intentions of their creators and that, perhaps in the long term, will bring benefits to everyone.

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