Chapter 2
Structure of Matter and Fundamental Forces

The previous section provided a rough description of the large structures in the observable universe. We now go inside matter.

2.1 The Fundamentals at Subatomic Distances

When we look inside matter, at sizes much smaller than our natural sizes, as we go deeper and deeper into the subatomic scales, we discover entire new worlds of molecules, atoms, nuclei, quarks, and leptons. This is illustrated in Figs. 2.1 and 2.2.

During its early stages right after the Big Bang, the entire universe is imagined to be extremely dense, extremely energetic, and extremely hot. According to our current understanding of cosmology, a tiny speck of the early universe will eventually develop to become our present *visible* universe. So, to understand the status of our visible universe at the time of the Big Bang, you need to imagine squeezing all the mass and energy of the present universe into an unimaginably small region. During such early stages of the universe, elementary matter collides with huge energies within volumes 10^{20} times smaller than the sizes of nuclei or protons depicted in Figs. 2.1 and 2.2. Therefore the evolution of the universe from the Big Bang into what it is today must have been determined by the fundamental laws of physics that govern the smallest elementary particles, namely quarks, leptons, and force particles, moving in extremely small regions at huge energies. This is well beyond the levels of energies in so-called high-energy physics experiments at modern accelerators. So, we need to look deep into the structure of matter and understand thoroughly its elementary constituents and the fundamental forces acting on them, in order to explain our origins.

It has been experimentally established that all known matter in our environment is made up of quarks, leptons, and "force particles" that hold them together, as illustrated in Figs. 2.1, 2.3, 2.4 and 2.6. The behavior of these elementary constituents is controlled by four fundamental forces. The strong and weak forces are short range and can be felt only by tiny particles moving at subnuclear distances. However, the electromagnetic and gravitational forces are long range, and act at both small and large distances, including macroscopic distances typical of our everyday life.

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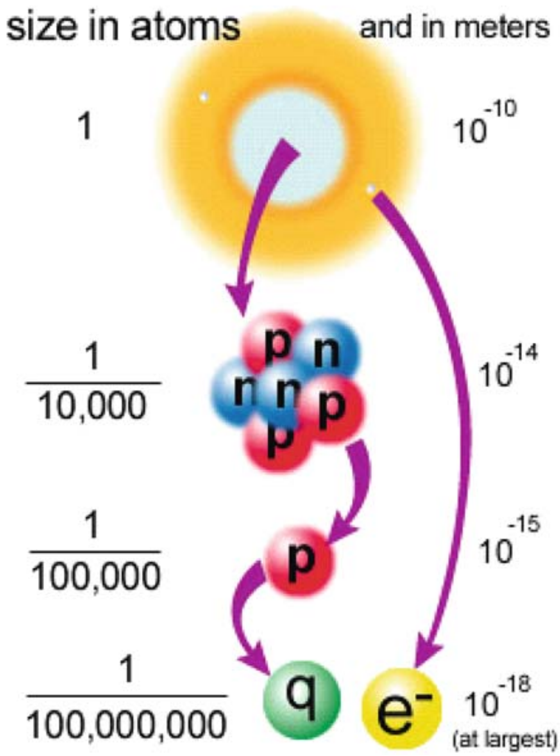

Fig 2.1 Structure of matter (Credits, Particle Data Group.)

For this reason we are more easily aware of the electromagnetic and gravitational forces.

The strong force, whose influence dominates within matter of the size of a proton (10^{-15} m in Fig. 2.1), holds quarks and gluons inside protons and neutrons and other similar strongly interacting particles called hadrons. The strong force is transmitted by the gluons.

The weak force has an even smaller range of influence (within 10^{-17} m) and it is responsible for the decay of matter, such as *neutron* → *proton*+*electron* + *anti-neutrino*. It is transmitted by the $W^{\pm}$ and Z^0 particles.

The electromagnetic force is responsible for holding the electrons around a nucleus in atoms (10^{-10} m in Fig. 2.1) and also for the formation of molecules from atoms. The range of the electromagnetic force is infinite; therefore, we can experience it also in the macroscopic world, such as when it acts to pull magnets together, or the attraction/repulsion of electric charges, as well as in all phenomena that involve light. The electromagnetic force is transmitted by photons, which are the smallest bits of light. Photons make up the electromagnetic waves in the entire spectrum of frequencies, including radar, radio, TV, X-rays, and the visible spectrum that is interpreted by the human eye as the colors from red to violet light.

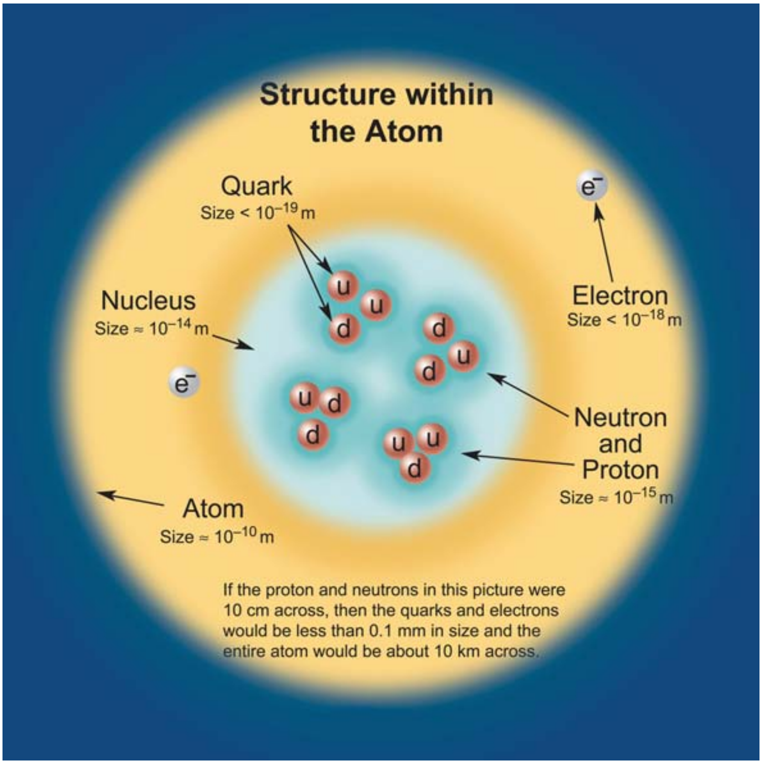

Fig. 2.2 Atom, nucleus, proton, neutron, *u, d* quarks, and electron (Credits, Particle Data Group.)

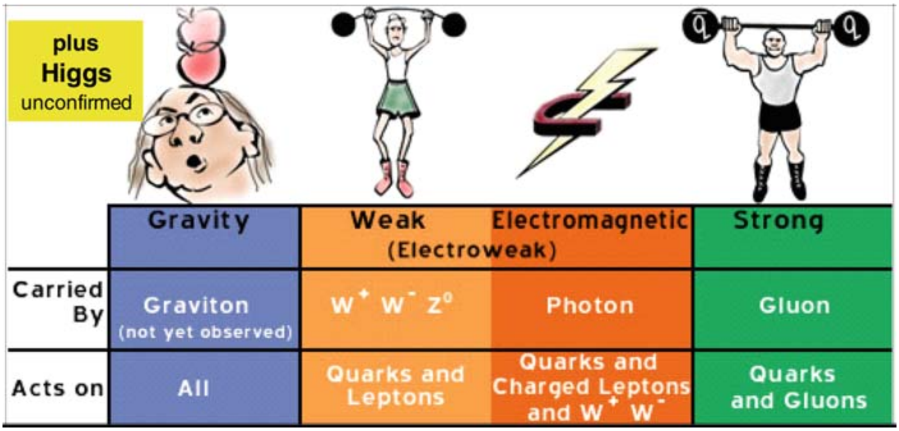

Fig. 2.3 The four interactions, force particles, and Higgs (Credits, Particle Data Group.)

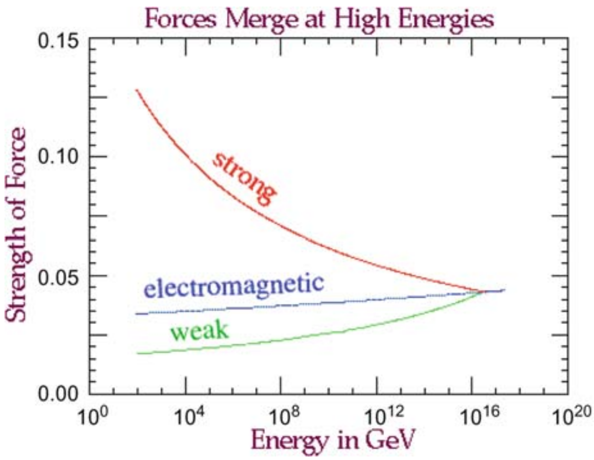

Fig. 2.4 Grand unification of strong, weak, and electromagnetic forces (Credits, Particle Data Group.)

The remaining known force is gravity which is the most familiar in everyday life. It is responsible for holding people and animals on the surface of the Earth, or holding planets around the Sun or other stars, or controlling the motion of stars within galaxies, or of the motion of galaxies within the universe. In fact, the gravitational force controls the expansion of the entire universe starting from the very initial Big Bang. The graviton is the particle responsible for transmitting the gravitational force.

Properties of the known forces are summarized in Figs. 2.3 and 2.4. Although described as separate forces with different roles in today's universe, there is some evidence that these forces possibly arise from a common origin and are unified at some deep level. As we go deeper inside matter through higher energy experiments, it is known that the weak force becomes comparable in strength to the electromagnetic force when particles collide with energy about 100 GeV, as shown in Fig. 2.4. With this amount of energy we can probe the structure of matter as deeply as 10^{-18} m. It has been established experimentally that at that scale there is a common origin of both weak and electromagnetic forces. The unified force is called the "electroweak force" and is described by a precise mathematical structure called a Yang–Mills gauge field theory based on the gauge symmetry $SU(2) \times U(1)$, as formulated by Weinberg, Salam, and Glashow. The meaning of a "gauge symmetry" and symbols like $SU(2) \times U(1)$ will be explained later in this book. Theoretically, a "grand unification" is envisaged between the electroweak and strong forces at around 10^{17} GeV in energy as shown in Fig. 2.4, which corresponds to probing up to 10^{-32} m deep inside matter. An even deeper unification that includes the gravitational force is expected at around 10^{-35} m, known as the Planck length, a typical length scale at the Big Bang, which is probed with energy of about 10^{19} GeV.

In addition to the force particles associated with the familiar four forces, there is an additional hypothetical particle called the Higgs particle as shown in Fig. 2.3. The Higgs particle is so far mysterious. It is needed to understand the origin of mass for all elementary particles; however, its precise nature remains to be clarified experimentally, which could possibly occur during the years 2009–2011 in experiments to be conducted at the Large Hadron Collider at CERN . The Higgs could be simply a single additional elementary particle or it could be analogous to the tip of an iceberg (Fig. 2.5) waiting to reveal a lot more of the secrets of the universe, including the possibility of new forces acting at deeper levels inside matter. We will return to the Higgs particle in a later section.

Turning now to the matter particles, quarks, and leptons, shown in Fig. 2.6, can be compared to the bricks that make up a house. By contrast, the force particles described above can be compared to the mortar that holds the bricks together. Both the bricks and the mortar come in several varieties, thus making up the properties of the various parts of the house as well as giving its overall character.

One of the distinguishing properties of elementary particles is their spin, which is a property similar to the amount of rotation of the Earth around its own axis. All quarks and leptons, and their anti-particles which make up anti-matter, have spin 1/2. On the other hand, the force particles have integer spins: the graviton has spin 2; the gluons, photon, $W^{\pm}, Z^0$ all have spin 1; the Higgs particle has spin 0. All half-integer spin particles are called *fermions* in honor of the great physicist Fermi. Similarly, all integer spin particles are called *bosons* in honor of another great physicist, Bose. Fermions and bosons behave in certain distinguishing ways according to the laws of quantum mechanics as well as according to the roles they play in the structure of

Fig 2.5 Higgs particle, the tip of an iceberg? (Credits, Brian Zaikowski.)

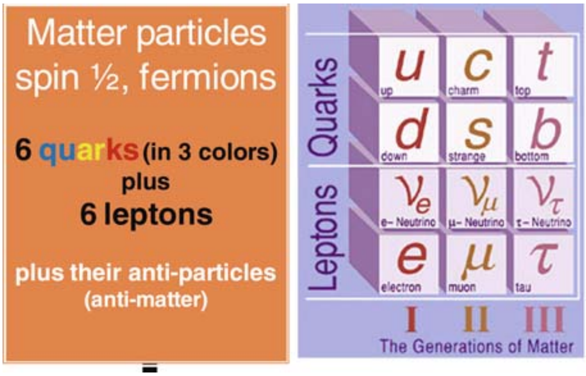

Fig 2.6 Three generations of quarks and leptons (Credits, Particle Data Group.)

matter, and this provides a basis for classifying them in separate sets of elementary constituents.

These "elementary" particles have various quantum numbers, which generalize the concept of the electric charge, that whimsically are called "flavors" and "colors." The various quarks and leptons are distinguished from one another by their colors and flavors, somewhat like distinguishing different ice creams in a Baskin–Robbins store, or like distinguishing people or animals from one another by certain characteristics.

There are six flavors of quarks called up (u), down (d), strange (s), charm (c), bottom (b), and top (t). These silly sounding names developed historically in the process of building models to characterize in words certain physical and mathematical properties that summarized experimental observations. There are also six flavors of leptons called electron (e), muon (μ), tau (τ), and the corresponding neutrinos called electron-neutrino ν_e, muon-neutrino ν_μ, and tau-neutrino ν_τ. There are three color charges: red, blue, and yellow. All quarks come in every variety of color. Therefore there are altogether 18 distinct quarks that can be distinguished by their flavor and color charges ($6 \times 3 = 18$). On the other hand the six leptons have no color charges, they are color neutral.

Anti-matter is as fundamental as matter. For every quark, lepton, or force particle, there exists also a corresponding anti-particle that carries the opposite values of the flavor and color charges (anti-up, anti-down, etc.). This is a prediction made by Paul Dirac on the basis of quantum field theory, before anyone knew of the concept of anti-matter. Today it is commonly observed in accelerators that, at sufficiently high-energy collisions among matter particles, both matter and anti-matter particles are produced, just with the predicted properties. Why don't we see much anti-matter in our common experience? Where is your anti-self-made of anti-matter? There are plausible, but not fully settled, cosmological explanations for why in today's universe the amount of anti-matter is greatly suppressed compared to the amount of matter, as further explained in later sections.

The 6×3 quarks and the 6 leptons make certain patterns of flavor and color charges that are repeated 3 times. This repetition defines the concept of three generations of quarks and leptons as organized in Fig. 2.6. The members in the third generation are heavier than the corresponding members in the second generation and those are heavier than the corresponding ones in the first generation.

The concept of generation is also related to how all of these particles interact in certain symmetric patterns with each other under the influence of the strong, weak, and electromagnetic interactions. The symmetry patterns have a mathematical structure[1] called SU(3) × SU(2) × U(1), where 3 stands for triplets of color SU(3), 2 stands for doublets of flavor SU(2), and U(1) is another structure related to both electromagnetic and weak interactions. The doublet structure is made evident in Fig. 2.6, where the quarks and the leptons of each generation come separately as doublets of flavor, and triplets or singlets of color, such as

$$\underbrace{\binom{u}{d}_L^{red}, \binom{u}{d}_L^{blue}, \binom{u}{d}_L^{yellow},}_{\text{triplets of color}} \quad \underbrace{\binom{\nu_e}{e}_L}_{\text{singlets of color}} \quad \left.\right\} \begin{matrix}\text{doublets of flavor, } L \text{ stands} \\ \text{for left-handed chirality}\end{matrix} .$$

The color triplet structure of SU(3) dictates precisely how quarks interact with the eight gluons that create the strong force. Similarly the doublet/singlet structure of SU(2) × U(1) dictates precisely how all quarks and leptons interact with the $W^{\pm}$, Z^0 and the *photon* that create the weak and electromagnetic interactions, respectively. Only the left-handed chirality components of quarks and leptons interact with $W^{\pm}$, while Z^0 and the photon interact with both the left and right chirality components. "Chirality" is related to spin, such that, for a *massless* particle it coincides with "helicity." Helicity is that component of spin in the same direction (right handed) or in the opposite direction (left handed) of its momentum.

Why there are only three generations, and why we see these peculiar patterns of flavors and colors within each generation, remains as an unsolved mystery. There are some tentative proposals to explain these patterns as a property of higher dimensions in string theory.

The mass pattern of the observed quarks, leptons, and force particles is rather uneven and cover a fairly big range from almost zero for neutrinos, to 5×10^{-3} GeV/c^2 for the electron, to 175 GeV/c^2 for the top quark. The exactly zero masses of the graviton, photon, and gluons are explained by gauge symmetry (discussed later), but the non-zero mass patterns of quark and leptons so far has defied an explanation.

Closely related to the *origin of mass*, an additional particle called the Higgs particle, or some more complicated structure that imitates it, is postulated to exist. According to theory, the patterns of interactions of the Higgs particle with all of

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[1] In the Cartan classification of symmetry groups outlined in footnote 1 of Chapter 5, the group SU(3) corresponds to A_2 and the group SU(2) corresponds to A_1, both taken in their compact versions. The group U(1), which corresponds to just phase transformations, is not included in the Cartan's list of "simple" Lie groups. All of the "simple" groups are non-Abelian, while U(1) is Abelian, thus explaining why it is not included.

the other particles parallels precisely the observed mass patterns. There are indirect effects of the Higgs particle that explain several observations, and in this sense there is indirect evidence for its existence. But the Higgs particle has not yet been seen directly in accelerators because it is presumably too heavy to be produced with the available accelerator energies.

However, the new Large Hadron Collider (LHC) at CERN, that will begin to conduct crucial experiments in late 2009 or early 2010, will have sufficient energy to produce the Higgs particle. We don't really know whether what we call "Higgs" is just a single isolated particle or whether understanding it will uncover deeper structures. Seeing the Higgs, and clarifying its nature, is expected to be among the very first triumphs of the LHC.

Currently we don't know the true sizes of the quarks, leptons, and force particles force particles (graviton, photon, W, Z, gluons), but we do know that their sizes must be smaller than 10^{-18} m. This is 1000 times smaller than the size of the proton or neutron as indicated in Fig. 2.1. The LHC will be able to probe into distances 1000 times smaller than that and learn more about the properties of these tiny structures.

Are these particles point-like without any structures inside them or do they contain some smaller and more elementary constituents? There are several theories about that.

The most popular point of view is that quarks, leptons, and force particles are all made up of tiny strings. We will discuss some aspects of string theory later. String theory tries to answer simultaneously other puzzles of the universe, so it can serve as a useful guide when we don't have definitive answers. However, even if string theory is completely right, the strings may be so tiny that even the LHC would not be a sufficiently powerful "microscope" to detect them.

There are string-related "brane-world" scenarios that are more hopeful about the prospects of seeing string theory structures at the LHC. This will be discussed in the second part of this book authored by Prof. Terning.

The fundamentals of string theory are still under development so its attractive proposals are not yet firm conclusions. There are also less popular but nevertheless viable possibilities of inner structure, such as "preons" bound by a new strong force, that the LHC could discover.

Therefore we are still uncertain what, if anything, is inside quarks, leptons, or force particles. Perhaps the LHC will shed new light on this very important issue, but maybe not?

The computational framework of all known interactions in Figs. 2.3 and 2.4, including the Higgs, are precisely given by the *standard model of particles and forces*. This is a theory that has a mathematical structure dictated by *relativistic quantum Yang–Mills field theory* in 3-space plus 1-time dimensions. Each word here is loaded with deep mathematical and physical meanings.

"Relativistic" refers to the fact that it is a theory in the framework of Einstein's theory of special theory of relativity in 3-space and 1-time dimensions. Some aspects of relativity will be discussed in a later section.

"Yang–Mills field theory" is the local gauge symmetry framework that extends Maxwell's theory of electromagnetism to include and unify the other known interactions. The fundamental role of local gauge symmetry will be explained later, and this will be essential in the construction of two-time physics in 4 + 2 dimensions.

"Quantum" implies that all aspects of quantum mechanics, that accounts for the correct rules of motion with some probabilistic features at subatomic distances, have been incorporated, as long as gravity is ignored.

Quantum effects of gravity are indeed ignorable up to the energy level of all experiments conducted so far. It is only at much higher energies, far beyond those accessible in accelerators, that quantum effects of gravity can play a significant role to explain the physical phenomena (see later Fig. 9.1 and footnote 1 in Chapter 9). Within the present "low-energy" limitation of accelerators or other available detection capabilities, Einstein's theory of general relativity at the classical (rather than quantum) level has agreed perfectly well with all aspects of gravity measured so far.

It is known that at the theoretical level general relativity poses some severe problems in the context of quantum mechanics. Even though this is not of experimental consequence at the energy level of current or foreseeable accelerators, at the much larger Big Bang energy level it is a stumbling block that prevents us from deciphering the very origin of the universe. For this very essential reason, as well as a matter of principle, quantum gravity is a major theoretical problem that requires solution. String theory appears to be the only viable framework that could deliver the answer according to current understanding.

The precise formalism of the standard model, as a relativistic quantum field theory, provides the tools to perform computations and make quantitative predictions that extend our understanding beyond just a qualitative description of what is observed. It is a beautiful, compact, and simple structure that makes thousands of detailed predictions all of which are in exquisite agreement with very precise measurements so far. Some of these computations and measurements are so accurate that they agree up to 12 decimal places. There has not been a single experiment that has contradicted the predictions of the standard model up to now. The standard model of particles and forces is an amazing feat of the 20th century.

Despite its enormous success, the standard model leaves many questions unanswered. We will discuss these later.

2.2 Large Distances and Cosmology

We know that the laws of physics that govern the subatomic world seem to be rather different from the laws of physics that govern the big universe. Quantum mechanics and special relativity are part of the rules that govern the universe at the small scale. Actually the correct rules that apply everywhere, large or small, as we know them today, are the laws of particle physics in the subatomic world. It can be shown that the laws that apply at larger scales arise from the fundamental ones as an approximation that is effectively valid for the large structures. So, the *fundamental* laws of physics are unique and the same everywhere; they should not be confused with the effective approximations.

The fundamental laws are incorporated as part of the standard model of particles and forces outlined above. This correctly describes the subatomic world with great precision and great success. The standard model is experimentally verified and is today the most precise theory ever known to mankind.

Since the universe was so tiny during its early stages starting with the Big Bang, it must have been governed by the same laws of physics at small distances, as prescribed by the standard model. By applying this well-established knowledge we can give a very detailed description of what happened at each stage of structure formation described in Fig. 2.7. This makes a quantitative prediction of what we should expect to see in today's universe. The great success is that the prediction matches the experimental observation in quantitative detail as outlined below.

The details of the Big Bang itself still needs clarification, but the physics and history of the universe, starting right after the Big Bang, is pretty much under control.

During its early stages, right after the Big Bang, the entire known universe was very dense, so the elementary constituents of matter were squeezed into distances much smaller than the sizes shown in Figs. 2.1 and 2.2. They were moving at huge energies, much larger than those attainable in today's accelerators. There was so much energy that matter and anti-matter were continually created from energy and also under collisions they continually destroyed each other back into energy (all according to Einstein's formula, $E \Leftrightarrow mc^2$). The forces acting on matter were not sufficient to overcome the very energetic motion; therefore the quarks, leptons, force particles, and their anti-particles were roaming around almost as free (that is, not bound) particles. As shown in Fig. 2.7, as the universe expanded and cooled down, the existing matter, moving at lesser energies, started to coalesce under the influence of the strong, electromagnetic, and finally gravitational forces.

By applying the established laws of physics up to the level of quarks and leptons, and with some additional educated theoretical guesses, physicists can trace the evolution of the universe quantitatively starting as soon as 10^{-45} s after the Big Bang, as outlined below partly following the events depicted in Fig. 2.7.

Some thinkers like to identify the Big Bang as the beginning of time, at least for our universe, but so far we really do not understand the meaning of space–time at the Big Bang. The universe was then extremely small, dense, hot, and energetic. The laws of physics at those extreme conditions are not fully understood yet; therefore, some of the current views about what exactly happened could change as we learn more in the future. It is thought that matter and anti-matter were created in equal amounts from the energy available in the huge explosion ($E = mc^2$).

Shortly after the Big Bang, asymmetry developed in favor of matter due to asymmetric interactions known to exist among elementary particles as measured in the laboratory. This is why in today's universe we see mostly matter as illustrated in Fig. 2.8. There are remaining questions. The precise mechanism for how the matter–anti-matter asymmetry originated is still under debate. In the cosmological evolution, did matter/anti-matter asymmetry start with the quarks (this is called baryogenesis) or with the leptons (this is called leptogenesis) or both?

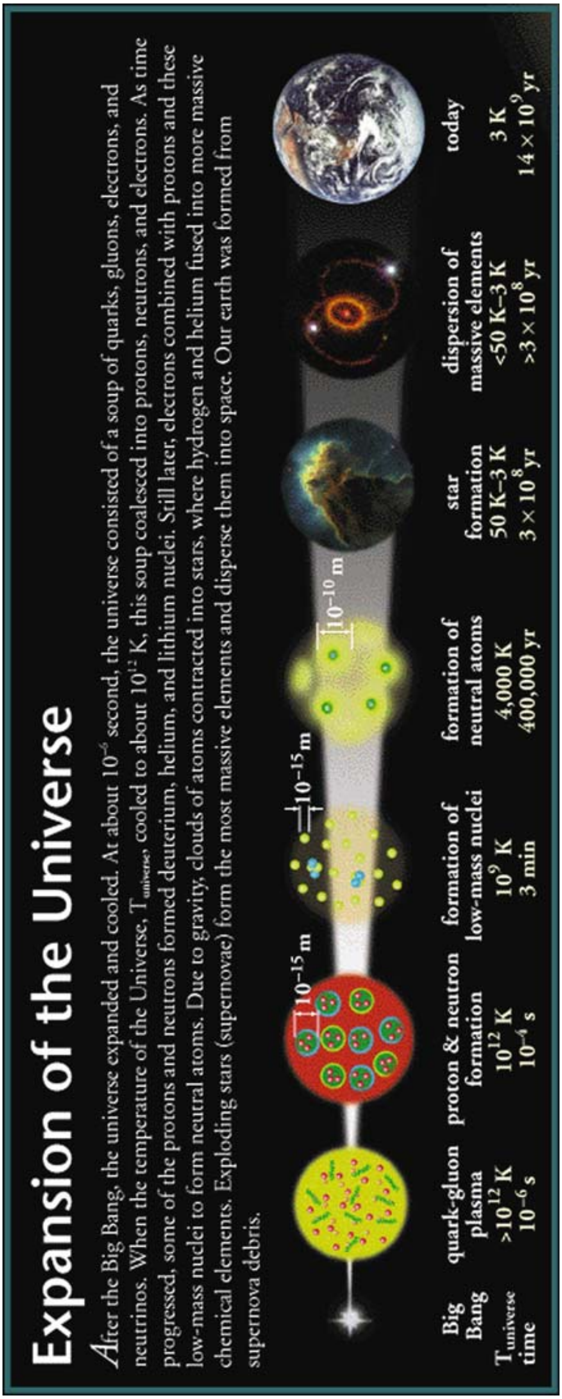

Fig. 2.7 Expansion of the Universe (Credits, Particle Data Group.)

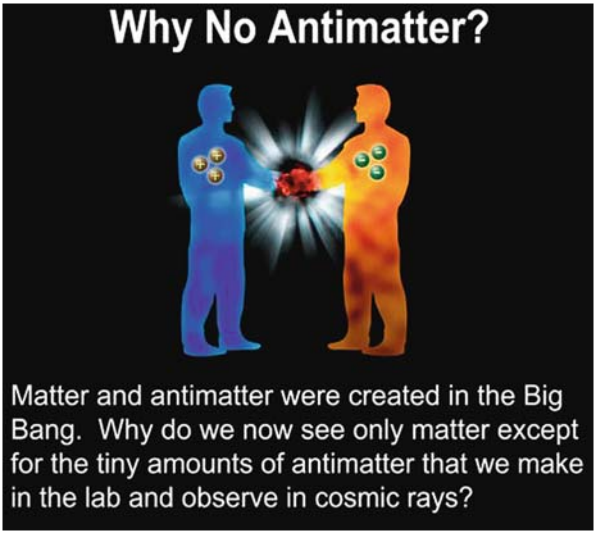

Fig. 2.8 Anti-matter is produced in accelerators when matter particles collide with each other at very high energies. But anti-matter is not found in abundance in the universe like matter is (Credits, Particle Data Group.)

Also a phase transition is thought to occur that split the unified force into three components as shown in Fig. 2.4. These eventually became the strong, weak, and electromagnetic forces that act on matter as recognized in today's universe.

The size of the universe underwent a sudden exponential inflation, like a bubble, at *speeds much larger than the speed of light*, which is permitted under the influence of strong gravitational fields as described by general relativity. This happened perhaps around 10^{-35} s after the Big Bang. Today we live in the space of what used to be only a speck of the original universe just before inflation. The fact that our "bubble" developed from a speck explains why the energy distribution, or temperature, in today's universe is isotropic and homogeneous and looks the same everywhere we look in the sky. It is because within a speck there is not much possibility to have significant variations in the energy distributions. Conceivably, there are other universes disconnected from ours in other inflation bubbles that may have developed from other specs with possibly different conditions than ours. Such other bubble universes are disconnected from ours because we cannot observe them. Our ability to observe is limited by the speed of light. In today's universe, the gravitational fields are non-existent in what is mostly empty space, so no signal can travel faster than light. Hence, we are unable to obtain information from other parts of the original universe that moved away from our bubble at speeds larger than light's. This inflation scenario is formulated mathematically in the context of general relativity.

After inflation, matter was in the most elementary form we see today in accelerators, including the quarks, leptons, gluons, photons, which we discussed above. These elementary particles were still so energetic that they managed to roam around almost freely, since the attraction produced by forces could not be overcome due to the great speeds.

Around 10^{-6} s after the Big Bang, while the universe was as hot as 10^{12} degrees, it was like a soup of somewhat interacting quarks and gluons, while photons, electrons, neutrinos, and other weakly interacting particles continued to move freely.

At around 10^{-4} s, under the influence of the strong force generated by the color charges of gluons and quarks, color neutral bound states that are called *hadrons* were formed. According to the theory of quantum chromodynamics those color neutral hadrons contain (quark + quark + quark) or (anti-quark + anti-quark + anti-quark) or (quark + anti-quark), where each quark or anti-quark can be any of the six flavors (u, d, s, c, b, t) in Fig. 2.6. Indeed these are the only types of hadrons that have been observed in accelerators. Most of these hadrons are short lived and decay quickly after they get created in collisions, but the proton which contains (up + up + down) and the neutron which contains (up + down + down), and their anti-matter counterparts are survivors. A free neutron lives about 1000 s while a free proton has never been seen to decay. Their sizes are about 10^{-15} m.

At around 3 min, or 10^9 degrees in temperature, the strong force pulled together the protons and neutrons to form small stable nuclei 10^{-14} m in size. Inside the nucleus, the neutron is slightly less massive and then it can no longer decay. So these small nuclei survive basically forever.

After about 380,000 years, at much cooler temperatures and slower motions, the electromagnetic attraction created by the positively charged nuclei managed to finally capture the, by then more sluggish, negatively charged electrons to form neutral atoms of 10^{-10} m in size.

Photons cannot bounce off neutral matter. Therefore once the matter coalesced into neutral atoms, the existing photons continued to move freely and filled the expanding universe. These relic photons are the origin of the *cosmic background radiation* that is detected today everywhere throughout the sky in the form of a background temperature of 2.7 K distributed *uniformly* across the universe.

The degree to which this temperature is homogeneously and isotropically distributed everywhere puzzled cosmologists who proposed that at a much earlier stage the universe underwent the rapid expansion mentioned above. *Inflation* explains the uniformity of this temperature distribution simply by making it plausible that we come from a small speck that could not have much variation within that small distance.

Modern telescopes can measure tiny fluctuations in this background temperature, as shown in Fig. 2.9. This image is captured by the satellite telescope called Wilkinson Microwave Anisotropy Probe (WMAP). It represents the temperature distribution across the sky in all directions. Colors have been exaggerated to represent very tiny deviations from the average 2.7 K, with blue indicating cooler temperatures. These precision measurements can be related to certain additional details in cosmological observations that confirm the theory of inflation.

The electromagnetic force cannot act on *neutral* matter over distances larger than molecules. So, after the formation of neutral matter, gravitational attraction eventually dominated over the other forces in shaping the universe. This led to the

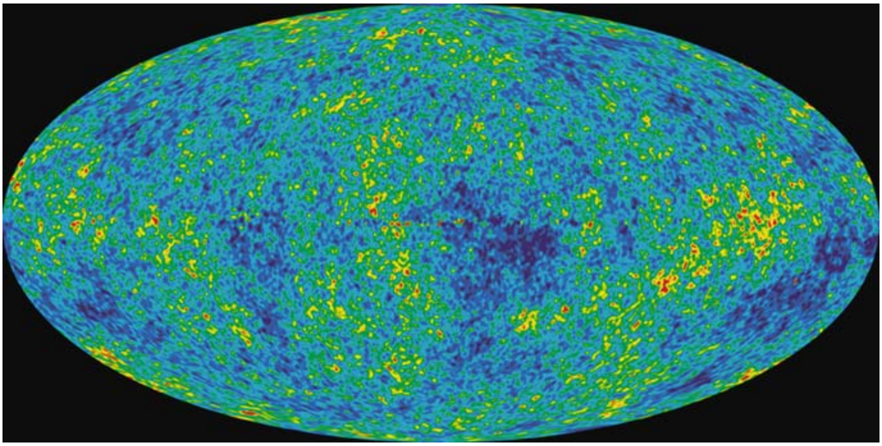

Fig. 2.9 WMAP image of temperature fluctuations (Credits, Particle Data Group.)

formation of the first stars and galaxies by starting from slight inhomogeneities in the distribution of energy. According to the theory of star formation, to reach today's state of the universe, the required amounts and distribution of inhomogeneity are in agreement with the tiny temperature fluctuations measured by WMAP in Fig. 2.9, and as predicted by the theory of inflation. Such inhomogeneities slowly coalesced in parts of the universe under the influence of gravity, leading to the condensation of hydrogen and helium into stars, and then into galaxies, after about 1–300 million years.

In the core of stars, gravity can create sufficiently huge pressures to fuse small nuclei into larger ones through processes called *stellar nucleosynthesis*. Nuclear fusion reactions at the cores of massive stars create more massive nuclei in a series of nuclear reactions. The heavier elements, up to as heavy as iron (Fe, with 26 protons and 30 neutrons), are formed in this way inside stars. The formation of the heavier elements requires more violent processes produced in star-like structures called red giants or astronomical processes called supernovae to fuse the smaller nuclei into larger ones. This is why iron and nickel are among the more abundant heavy elements found in the cores of planets such as the Earth and in metallic meteorites.

Stellar nucleosynthesis is the origin of the energy of the Sun and other stars. As long as there is enough matter to burn into energy ($E = mc^2$), the outward pressure created by the nuclear reactions keeps the remaining matter from collapsing under the influence of gravity.

When an aging star can no longer generate sufficient energy from nuclear fusion, it may undergo a gravitational collapse because the outward pressure from the nuclear explosions diminish. Through this collapse, and related gravitational processes, *red giants*, *white dwarfs*, or *neutron stars* are created. Spinning neutron stars may also form *pulsars*. If the star is too large, its life ends with a *supernova* explosion before becoming a neutron star and then finally a *black hole*. As measured today, in a galaxy the size of the Milky Way, supernovae occur about once every 50 years.

There may be black holes of various sizes roaming around a galaxy, but the small ones are hard to detect. However, large black holes create a large gravitational attraction that affects the motion and the distribution of stars in a galaxy. In fact, every galaxy is expected to contain at least one large giant black hole at its center. Experiments conducted during 1995–2003 established that the giant black hole at the center of our own Milky Way galaxy has an estimated mass of 4 million times the mass of our Sun and measures about 23 million km across, which is smaller than the orbit of Mercury around the Sun. Evidently a huge amount of mass is packed into the small region that makes up this black hole. In 2004 astronomers detected another intermediate-sized black hole of 1300 solar masses near the center of the Milky Way.

In the history of the universe, the expanding shock waves from supernovae explosions scattered the heavier elements into space where they later combined with interstellar gas to produce new stars and their planets.

Over time, clusters of galaxies formed and then superclusters formed, etc., leading to the larger structures in the universe, including strings of galaxies, sheets of galaxies, and large voids where there are nearly no stars.

Today the diameter of the observable universe is estimated to be 28 billion parsecs (about 93 billion light-years). This diameter is increasing at a rate of about 1.96 million km/s, which is about 6.5 times faster than the speed of light in empty space.[2] The age of this huge universe is estimated as 13.73 billion years since the Big Bang, with an uncertainty of about 120 million years.

The solar system, the Earth, and all its occupants, animate and inanimate, are the products of nuclear astrophysical processes followed by biological ones. The Sun formed about 4.6 billion years ago. The oldest rocks found on the Earth give an estimate of 4.54 billion years for the age of the Earth. Life developed in an elementary form in a primordial earth under special circumstances some 3.5 billions years ago. The first organisms made up of many cells appeared about 1.8 billion years ago, while it took mammals until about 200 million years ago to develop. Modern humans emerged much later, some 30,000 years ago.

[2]This expansion rate is calculated from the Hubble parameter $H_0 = (\dot{R}/R)$ whose value today is measured as $H_0 \simeq 70.1$ (km/s)/Mpc, where 1 Mpc $= 3.08 \times 10^{19}$ km. The inverse of the Hubble constant gives a rough estimate of the age of the universe. One finds $(\mathrm{H}_0)^{-1} = 0.44 \times 10^{18}$ s, or equivalently 13.9 billion years. Inserting the diameter of the universe today, $2R = 28{,}000$ Mpc, one obtains from the formula $2\dot{R} \simeq 1.96 \times 10^6$ km/s. This faster than light motion is possible in curved space–time, or equivalently under the influence of the gravitational force.

Extra Dimensions in Space and Time
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