matter consisted mainly of bare nuclei of hydrogen (about 75%) and helium (about 25%)† and electrons. But radiation (photons) continued to dominate.

Our story is almost complete. The next important event is presumed to have occurred 380,000 years later. The universe had expanded to about $\frac{1}{1000}$ of its present size, and the temperature had cooled to about 3000 K. The average kinetic energy of nuclei, electrons, and photons was less than an electron volt. Since ionization energies of atoms are on the order of eV, then as the temperature dropped below this point, electrons could orbit the bare nuclei and remain there (without being ejected by collisions), thus forming atoms. With the birth of atoms, the photons—which had been continually scattering from the free electrons—now became free to spread nearly unhindered throughout the universe. As mentioned in the previous Section, the photons became **decoupled** from matter. The total energy contained in radiation had been decreasing (lengthening in wavelength as the universe expanded), and even before decoupling (at about $t = 56{,}000$ yr) the total energy contained in matter became dominant. The universe was said to have become **matter-dominated**. As the universe continued to expand, the electromagnetic radiation cooled further, to 2.7 K today, forming the cosmic microwave background radiation we detect from everywhere in the universe.

Birth of stable atoms

Matter-dominated universe

After the birth of atoms, then stars and galaxies could begin to form—presumably by self-gravitation around mass concentrations (inhomogeneities). Stars began to form about 200 million years after the Big Bang, galaxies after almost 10^9 years. The universe continued to evolve until today, some 13.7 billion years later.

* * *

This scenario is by no means "proven." But it does provide a workable picture, for the first time, of how the universe may have begun and evolved.

A major event, and something only discovered very recently, is that when the universe was about half as old as it is now (5–7 Gyr ago), its expansion began to accelerate. This was a big surprise because it was assumed the expansion of the universe would slow down due to gravitational attraction of all objects to each other. Indeed, another major recent discovery is that ordinary matter makes up very little of the total mass–energy of the universe ($\approx 4\%$). Instead, as we discuss in the next Section, the major contributors to the energy density of the universe are *dark matter* and *dark energy*. On the right in Fig. 33–25 is a narrow vertical strip that represents the most recent 5 to 7 billion years of the universe, during which *dark energy* seems to have dominated.

33–8 Dark Matter and Dark Energy

According to the standard Big Bang model, the universe is evolving and changing. Individual stars are being created, evolving, and dying as white dwarfs, neutron stars, black holes. At the same time, the universe as a whole is expanding. One important question is whether the universe will continue to expand forever. Until the late 1990s, the universe was thought to be dominated by matter which interacts by gravity, and this question was connected to the curvature of space-time (Section 33–4). If the universe had *negative* curvature, the expansion of the universe would never stop, although the rate of expansion would decrease due to the gravitational attraction of its parts. Such a universe would be *open* and infinite. If the universe is *flat* (no curvature), it would still be open and infinite but its expansion would slowly approach a zero rate. Finally, if the universe had *positive* curvature, it would be *closed* and finite; the effect of gravity would be strong enough that the expansion would eventually stop and the universe would begin to contract, collapsing back onto itself in a **big crunch**.

†This standard model prediction of a 25% primordial production of helium agrees with what we observe today—the universe *does* contain about 25% He—and it is strong evidence in support of the standard Big Bang model. Furthermore, the theory says that 25% He abundance is fully consistent with there being three neutrino types, which is the number we observe. And it sets an upper limit of four to the maximum number of possible neutrino types. Here we have a situation where cosmology actually makes a specific prediction about fundamental physics.