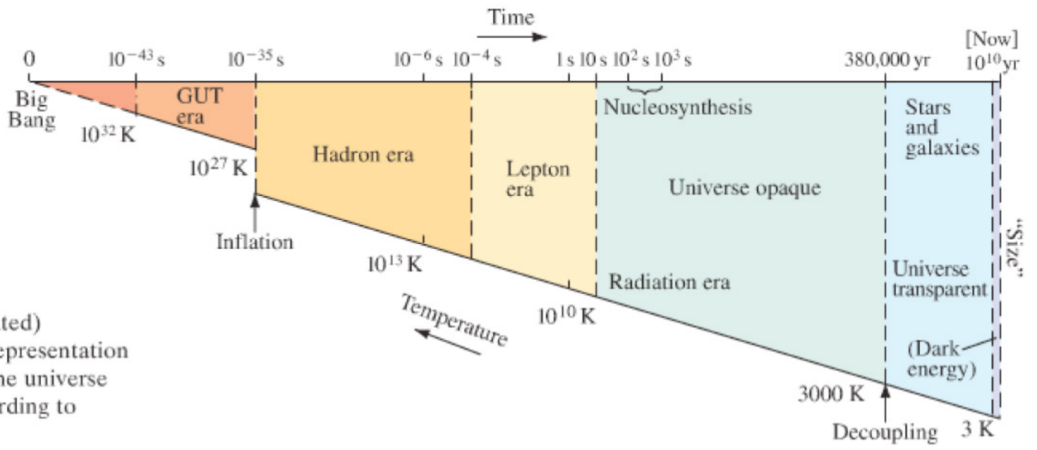

**FIGURE 33–25** (repeated) Compressed graphical representation of the development of the universe after the Big Bang, according to modern cosmology.

have resulted in a slight excess of nucleons over antinucleons. And it is these "leftover" nucleons that we are made of today. The excess of nucleons over antinucleons was about one part in $10^9$. Earlier, during the hadron era, there should have been about as many nucleons as photons. After it ended, the "left-over" nucleons thus numbered only about one nucleon per $10^9$ photons, and this ratio has persisted to this day. Protons, neutrons, and all other heavier particles were thus tremendously reduced in number by about $10^{-6}$ s after the Big Bang. The lightest hadrons, the pions, disappeared as the nucleons had; because they are the lightest mass hadrons (140 MeV), they were the last hadrons to go, about $10^{-4}$ s after the Big Bang. Lighter particles, including electrons and neutrinos, were the dominant form of matter, and the universe entered the **lepton era**.

*Lepton era*

By the time the first full second had passed (clearly the most eventful second in history!), the universe had cooled to about 10 billion degrees, $10^{10}$ K. The average kinetic energy was about 1 MeV. This was still sufficient energy to create electrons and positrons and balance their annihilation reactions, since their masses correspond to about 0.5 MeV. So there were about as many $e^+$ and $e^-$ as there were photons. But within a few more seconds, the temperature had dropped sufficiently so that $e^+$ and $e^-$ could no longer be formed. Annihilation ($e^+ + e^- \rightarrow$ photons) continued. And, like nucleons before them, electrons and positrons all but disappeared from the universe—except for a slight excess of electrons over positrons (later to join with nuclei to form atoms). Thus, about $t = 10$ s after the Big Bang, the universe entered the **radiation era**. Its major constituents were photons and neutrinos. But the neutrinos, partaking only in the weak force, rarely interacted. So the universe, until then experiencing significant amounts of energy in matter and in radiation, now became **radiation-dominated**: much more energy was contained in radiation than in matter, a situation that would last tens of thousands of years (Fig. 33–25).

*Radiation-dominated universe*

*Making He nuclei*

Meanwhile, during the next few minutes, crucial events were taking place. Beginning about 2 or 3 minutes after the Big Bang, nuclear fusion began to occur. The temperature had dropped to about $10^9$ K, corresponding to an average kinetic energy $\overline{\mathrm{KE}} \approx 100$ keV, where nucleons could strike each other and be able to fuse (Section 31–3), but now cool enough so newly formed nuclei would not be immediately broken apart by subsequent collisions. Deuterium, helium, and very tiny amounts of lithium nuclei were probably made. But the universe was cooling too quickly, and larger nuclei were not made. After only a few minutes, probably not even a quarter of an hour after the Big Bang, the temperature dropped far enough that nucleosynthesis stopped, not to start again for millions of years (in stars). Thus, after the first hour or so of the universe,