

The fate of this expanding and smooth universe is an open question. According to the general theory of relativity, an important way to characterize the state of the universe is through the space-time metric:

$$ds^2 = c^2 dt^2 - a(t)^2 d\Sigma^2, \quad (11.13)$$

where c is the speed of light, a is a scale factor (a function of time), and $d\Sigma$ is the length element of the space. In spherical coordinates (r, θ, ϕ), this length element can be written

$$d\Sigma^2 = \frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2), \quad (11.14)$$

where k is a constant with units of inverse area that describes the curvature of space. This constant distinguishes between open, closed, and flat universes:

- $k = 0$ (flat universe)
- $k > 0$ (closed universe, such as a sphere)
- $k < 0$ (open universe, such as a hyperbola)

In terms of the scale factor a , this metric also distinguishes between static, expanding, and shrinking universes:

- $a = 1$ (static universe)
- $da/dt > 0$ (expanding universe)
- $da/dt < 0$ (shrinking universe)

The scale factor a and the curvature k are determined from Einstein's general theory of relativity. If we treat the universe as a gas of galaxies of density ρ and pressure p , and assume $k = 0$ (a flat universe), then the scale factor a is given by

$$\frac{d^2a}{dt^2} = -\frac{4\pi G}{3}(\rho + 3p)a, \quad (11.15)$$

where G is the universal gravitational constant. (For ordinary matter, we expect the quantity $\rho + 3p$ to be greater than zero.) If the scale factor is positive ($a > 0$), the value of the scale factor “decelerates” ($d^2a/dt^2 < 0$), and the expansion of the universe slows down over time. If the numerator is less than zero (somehow, the pressure of the universe is negative), the value of the scale factor “accelerates,” and the expansion of the universe speeds up over time. According to recent cosmological data, the universe appears to be expanding. Many scientists explain the current state of the universe in terms of a very rapid expansion in the early universe. This expansion is called inflation.

11.7 | Evolution of the Early Universe

Learning Objectives

By the end of this section, you will be able to:

- Describe the evolution of the early universe in terms of the four fundamental forces
- Use the concept of gravitational lensing to explain astronomical phenomena
- Provide evidence of the Big Bang in terms of cosmic background radiation
- Distinguish between dark matter and dark energy

In the previous section, we discussed the structure and dynamics of universe. In particular, the universe appears to be expanding and even accelerating. But what was the universe like at the beginning of time? In this section, we discuss what evidence scientists have been able to gather about the early universe and its evolution to present time.

The Early Universe

Before the short period of cosmic inflation, cosmologists believe that all matter in the universe was squeezed into a space much smaller than an atom. Cosmologists further believe that the universe was extremely dense and hot, and interactions between particles were governed by a single force. In other words, the four fundamental forces (strong nuclear, electromagnetic, weak nuclear, and gravitational) merge into one at these energies (**Figure 11.21**). How and why this “unity” breaks down at lower energies is an important unsolved problem in physics.

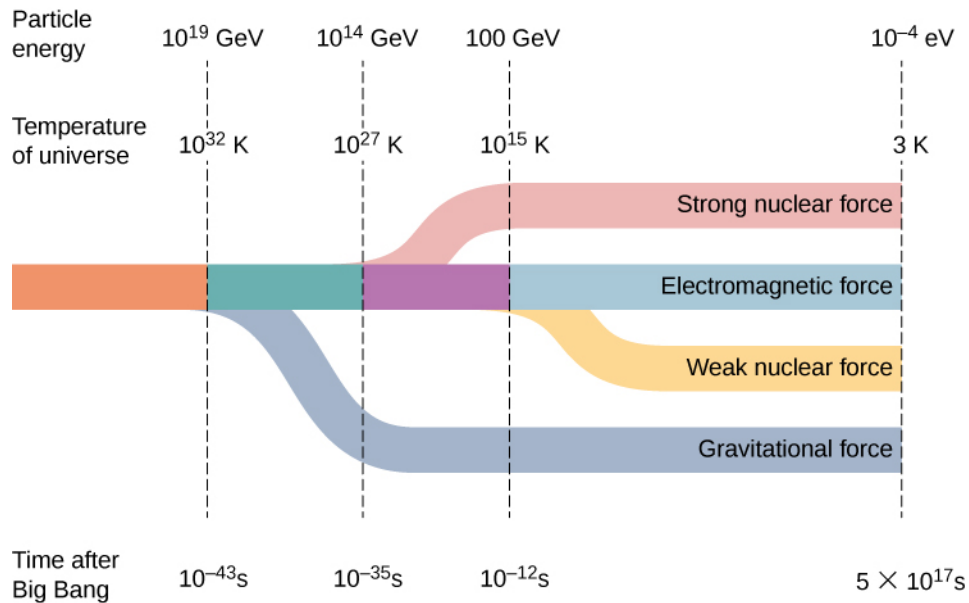


Figure 11.21 The separation of the four fundamental forces in the early universe.

Scientific models of the early universe are highly speculative. **Figure 11.22** shows a sketch of one possible timeline of events.

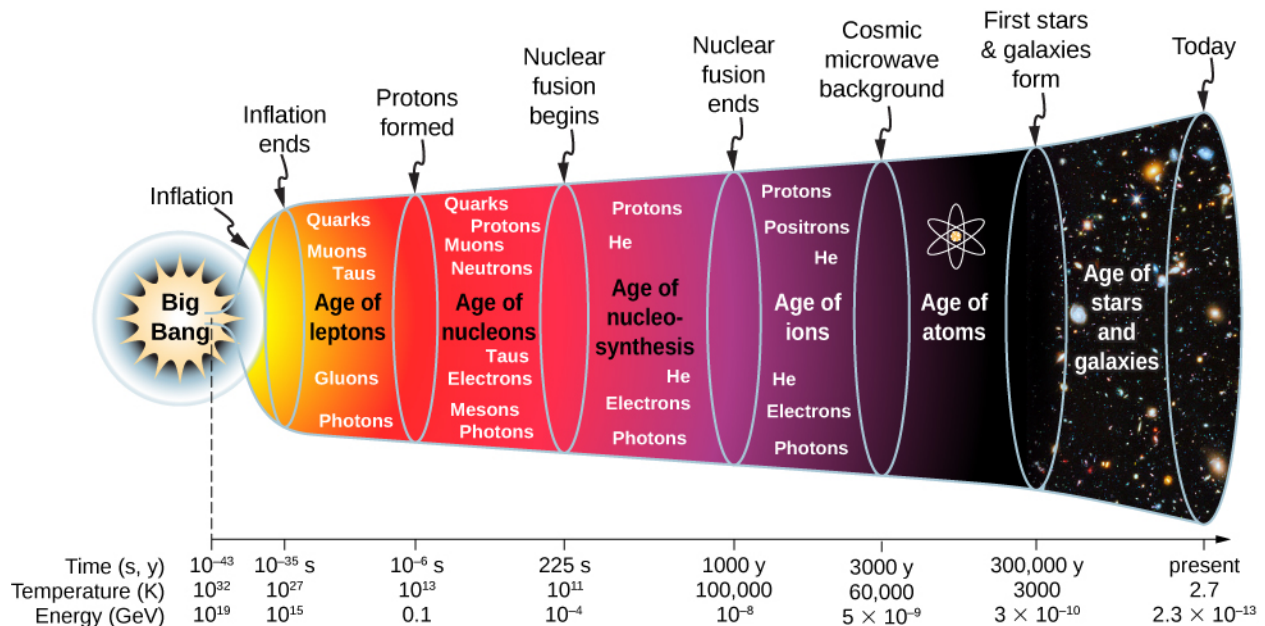


Figure 11.22 An approximate timeline for the evolution of the universe from the Big Bang to the present.

1. **Big Bang** ($t < 10^{-43}$ s): The current laws of physics break down. At the end of the initial Big Bang event, the temperature of the universe is approximately $T = 10^{32}$ K.

2. *Inflationary phase* ($t = 10^{-43}$ to 10^{-35} s): The universe expands exponentially, and gravity separates from the other forces. The universe cools to approximately $T = 10^{27}$ K.
3. *Age of leptons* ($t = 10^{-35}$ to 10^{-6} s): As the universe continues to expand, the strong nuclear force separates from the electromagnetic and weak nuclear forces (or electroweak force). Soon after, the weak nuclear force separates from the electromagnetic force. The universe is a hot soup of quarks, leptons, photons, and other particles.
4. *Age of nucleons* ($t = 10^{-6}$ to 225 s): The universe consists of leptons and hadrons (such as protons, neutrons, and mesons) in thermal equilibrium. Pair production and pair annihilation occurs with equal ease, so photons remain in thermal equilibrium:

$$\gamma + \gamma \leftrightarrow e^- + e^+$$

$$\gamma + \gamma \leftrightarrow p + \bar{p}$$

$$\gamma + \gamma \leftrightarrow n + \bar{n}.$$

The number of protons is approximately equal to the number of neutrons through interactions with neutrinos:

$$\nu_e + n \leftrightarrow e^- + p$$

$$\bar{\nu}_e + p \leftrightarrow e^+ + n.$$

The temperature of the universe settles to approximately 10^{11} K —much too cool for the continued production of nucleon-antinucleon pairs. The numbers of protons and neutrons begin to dominate over their anti-particles, so proton-antiproton ($p\bar{p}$) and neutron-antineutron ($n\bar{n}$) annihilations decline. Deuterons (proton-neutron pairs) begin to form.

5. *Age of nucleosynthesis* ($t = 225$ s to 1000 years): As the universe continues to expand, deuterons react with protons and neutrons to form larger nuclei; these larger nuclei react with protons and neutrons to form still larger nuclei. At the end of this period, about 1/4 of the mass of the universe is helium. (This explains the current amount of helium in the universe.) Photons lack the energy to continue electron-positron production, so electrons and positrons annihilate each other to photons only.
6. *Age of ions* ($t = 1000$ to 3000 years): The universe is hot enough to ionize any atoms formed. The universe consists of electrons, positrons, protons, light nuclei, and photons.
7. *Age of atoms* ($t = 3000$ to 300,000 years): The universe cools below 10^5 K and atoms form. Photons do not interact strongly with neutral atoms, so they “decouple” (separate) from atoms. These photons constitute the **cosmic microwave background radiation** to be discussed later.
8. *Age of stars and galaxies* ($t = 300,000$ years to present): The atoms and particles are pulled together by gravity and form large lumps. The atoms and particles in stars undergo nuclear fusion reaction.



Watch this **video** (<https://openstaxcollege.org/l/21bigbang>) to learn more about Big Bang cosmology.

To describe the conditions of the early universe quantitatively, recall the relationship between the average thermal energy of particle (E) in a system of interacting particles and equilibrium temperature (T) of that system:

$$E = k_B T, \quad (11.16)$$

where k_B is Boltzmann's constant. In the hot conditions of the early universe, particle energies were unimaginably large.

Example 11.9

What Was the Average Thermal Energy of a Particle just after the Big Bang?

Strategy

The average thermal energy of a particle in a system of interacting particles depends on the equilibrium temperature of that system **Equation 11.1**. We are given this approximate temperature in the above timeline.

Solution

Cosmologists think the temperature of the universe just after the Big Bang was approximately $T = 10^{32}$ K. Therefore, the average thermal energy of a particle would have been

$$k_B T \approx (10^{-4} \text{ eV/K})(10^{32} \text{ K}) = 10^{28} \text{ eV} = 10^{19} \text{ GeV}.$$

Significance

This energy is many orders of magnitude larger than particle energies produced by human-made particle accelerators. Currently, these accelerators operate at energies less than 10^4 GeV.



11.9 Check Your Understanding Compare the abundance of helium by mass 10,000 years after the Big Bang and now.

Nucleons form at energies approximately equal to the rest mass of a proton, or 1000 MeV. The temperature corresponding to this energy is therefore

$$T = \frac{1000 \text{ MeV}}{8.62 \times 10^{11} \text{ MeV} \cdot \text{K}^{-1}} = 1.2 \times 10^{13} \text{ K}.$$

Temperatures of this value or higher existed within the first second of the early universe. A similar analysis can be done for atoms. Atoms form at an energy equal to the ionization energy of ground-state hydrogen (13 eV). The effective temperature for atom formation is therefore

$$T = \frac{13 \text{ eV}}{8.62 \times 10^5 \text{ eV} \cdot \text{K}^{-1}} = 1.6 \times 10^5 \text{ K}.$$

This occurs well after the four fundamental forces have separated, including forces necessary to bind the protons and neutrons in the nucleus (strong nuclear force), and bind electrons to the nucleus (electromagnetic force).

Nucleosynthesis of Light Elements

The relative abundances of the light elements hydrogen, helium, lithium, and beryllium in the universe provide key evidence for the Big Bang. The data suggest that much of the helium in the universe is primordial. For instance, it turns out that that 25% of the matter in the universe is helium, which is too high an abundance and cannot be explained based on the production of helium in stars.

How much of the elements in the universe were created in the Big Bang? If you run the clock backward, the universe becomes more and more compressed, and hotter and hotter. Eventually, temperatures are reached that permit **nucleosynthesis**, the period of formation of nuclei, similar to what occurs at the core of the Sun. Big Bang nucleosynthesis is believed to have occurred within a few hundred seconds of the Big Bang.

How did Big Bang nucleosynthesis occur? At first, protons and neutrons combined to form deuterons, ${}^2\text{H}$. The deuteron captured a neutron to form triton, ${}^3\text{H}$ —the nucleus of the radioactive hydrogen called tritium. Deuterons also captured protons to make helium ${}^3\text{He}$. When ${}^3\text{H}$ captures a proton or ${}^3\text{He}$ captures a neutron, helium ${}^4\text{He}$ results. At this stage in the Big Bang, the ratio of protons to neutrons was about 7:1. Thus, the process of conversion to ${}^4\text{He}$ used up almost all neutrons. The process lasted about 3 minutes and almost 25% of all the matter turned into ${}^4\text{He}$, along with small percentages of ${}^2\text{H}$, ${}^3\text{H}$, and ${}^3\text{He}$. Tiny amounts of ${}^7\text{Li}$ and ${}^7\text{Be}$ were also formed. The expansion during this time

cooled the universe enough that the nuclear reactions stopped. The abundances of the light nuclei ^2H , ^4He , and ^7Li created after the Big Bang are very dependent on the matter density.

The predicted abundances of the elements in the universe provide a stringent test of the Big Bang and the Big Bang nucleosynthesis. Recent experimental estimates of the matter density from the Wilkinson Microwave Anisotropy Probe (WMAP) agree with model predictions. This agreement provides convincing evidence of the Big Bang model.

Cosmic Microwave Background Radiation

According to cosmological models, the Big Bang event should have left behind thermal radiation called the cosmic microwave background radiation (CMBR). The intensity of this radiation should follow the blackbody radiation curve (**Photons and Matter Waves**). Wien's law states that the wavelength of the radiation at peak intensity is

$$\lambda_{\text{max}} = \frac{2.898 \times 10^{-3} \text{ m-K}}{T}, \quad (11.17)$$

where T is temperature in kelvins. Scientists expected the expansion of the universe to “stretch the light,” and the temperature to be very low, so cosmic background radiation should be long-wavelength and low energy.

In the 1960s, Arno Penzias and Robert Wilson of Bell Laboratories noticed that no matter what they did, they could not get rid of a faint background noise in their satellite communication system. The noise was due to radiation with wavelengths in the centimeter range (the microwave region). Later, this noise was associated with the cosmic background radiation. An intensity map of the cosmic background radiation appears in **Figure 11.23**. The thermal spectrum is modeled well by a blackbody curve that corresponds to a temperature $T = 2.7\text{K}$ (**Figure 11.24**).

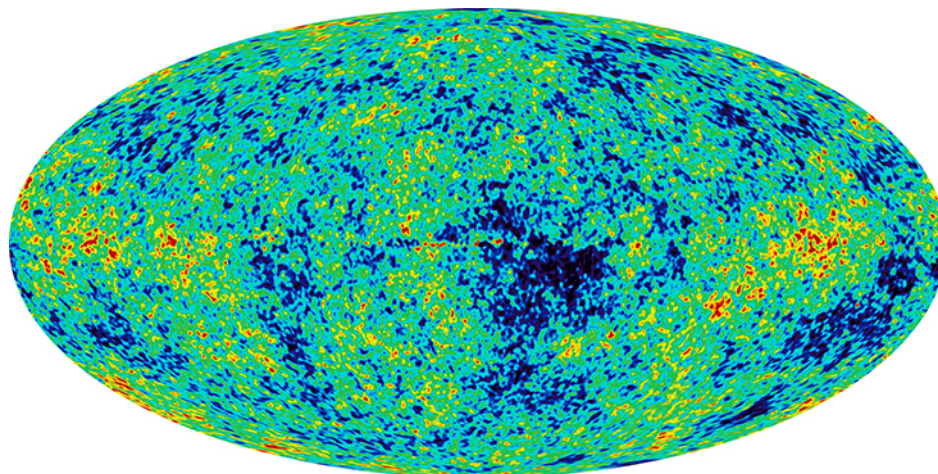


Figure 11.23 This map of the sky uses color to show fluctuations, or wrinkles, in the cosmic microwave background observed with the WMAP spacecraft. The Milky Way has been removed for clarity. Red represents higher temperature and higher density, whereas blue indicates lower temperature and density. This map does not contradict the earlier claim of smoothness because the largest fluctuations are only one part in one million. (credit: NASA/WMAP Science Team)

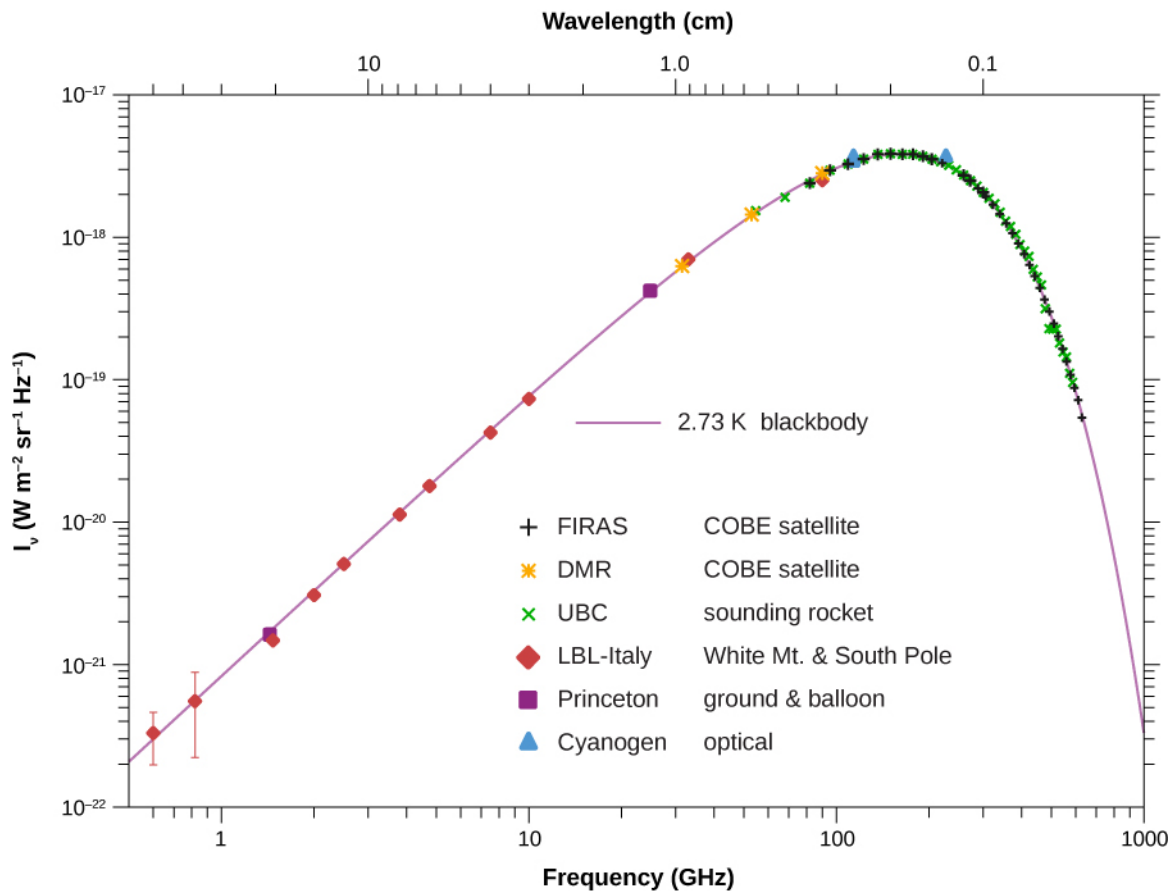


Figure 11.24 Intensity distribution of cosmic microwave background radiation. The model predictions (the line) agree extremely well with the experimental results (the dots). Frequency and brightness values are shown on a log axis. (credit: modification of work by George Smoot/NASA COBE Project)

The formation of atoms in the early universe makes these atoms less likely to interact with light. Therefore, photons that belong to the cosmic background radiation must have separated from matter at a temperature T associated with 1 eV (the approximate ionization energy of an atom). The temperature of the universe at this point was

$$k_B T \sim 1 \text{ eV} \Rightarrow T = \frac{1 \text{ eV}}{8.617 \times 10^5 \text{ eV/K}} \sim 10^4 \text{ K}.$$

According to cosmological models, the time when photons last scattered off charged particles was approximately 380,000 years after the Big Bang. Before that time, matter in the universe was in the plasma form and the photons were “thermalized.”

Antimatter and Matter

We know from direct observation that antimatter is rare. Earth and the solar system are nearly pure matter, and most of the universe also seems dominated by matter. This is proven by the lack of annihilation radiation coming to us from space, particularly the relative absence of 0.511-MeV γ rays created by the mutual annihilation of electrons and positrons.

(Antimatter in nature is created in particle collisions and in β^+ decays, but only in small amounts that quickly annihilate, leaving almost pure matter surviving.)

Despite the observed dominance of matter over antimatter in the universe, the Standard Model of particle interactions and experimental measurement suggests only small differences in the ways that matter and antimatter interact. For example, neutral kaon decays produce only slightly more matter than antimatter. Yet, if through such decay, slightly more matter than antimatter was produced in the early universe, the rest could annihilate pair by pair, leaving mostly ordinary matter to form the stars and galaxies. In this way, the vast number of stars we observe may be only a tiny remnant of the original matter created in the Big Bang.

Dark Matter and Dark Energy

In the last two decades, new and more powerful techniques have revealed that the universe is filled with **dark matter**. This type of matter is interesting and important because, currently, scientists do not know what it is! However, we can infer its existence by the deflection of distant starlight. For example, if light from a distant galaxy is bent by the gravitational field of a clump of dark matter between us and the galaxy, it is possible that two images of the same galaxy can be produced (**Figure 11.25**). The bending of light by the gravitational field of matter is called gravitational lensing. In some cases, the starlight travels to an observer by multiple paths around the galaxy, producing a ring (**Figure 11.26**).

Based on current research, scientists know only that dark matter is cold, slow moving, and interacts weakly with ordinary matter. Dark matter candidates include neutralinos (partners of Z bosons, photons, and Higgs bosons in “supersymmetry theory”) and particles that circulate in tiny rings set up by extra spatial dimensions.

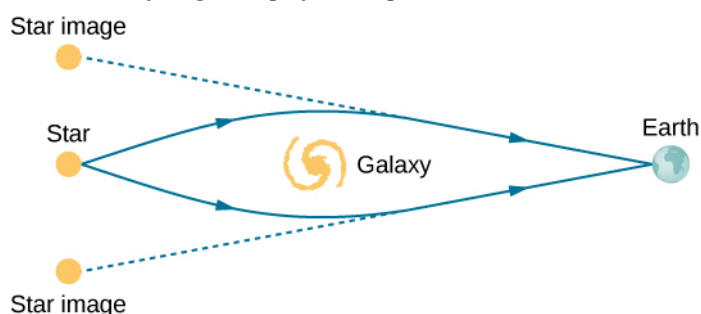


Figure 11.25 Light from a distant star is bent around a galaxy. Under the right conditions, two duplicate images of the same star can be seen.

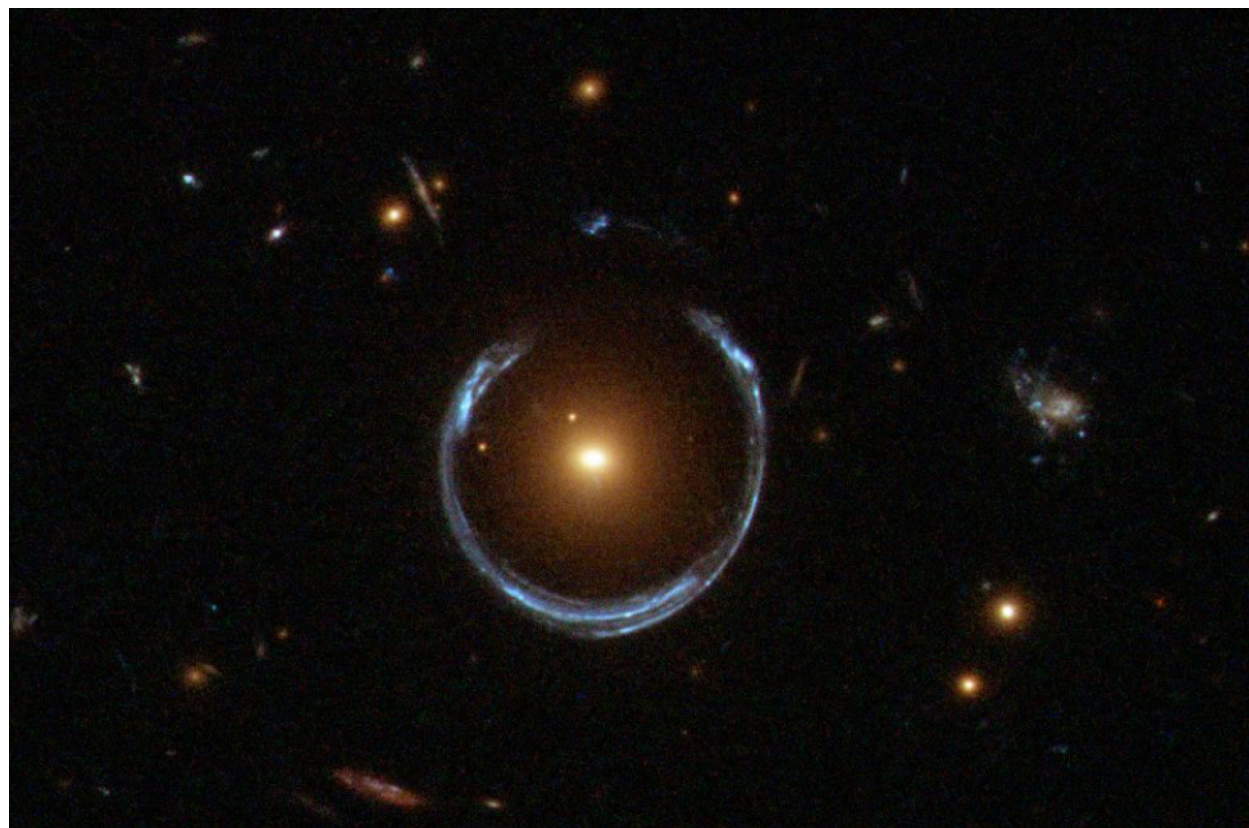


Figure 11.26 Light from a distant star is bent around a galaxy. Under the right conditions, we can see a ring of light instead of a single star. (credit: modification of work by ESA/Hubble & NASA)

Increasingly precise astronomical measurements of the expanding universe also reveal the presence of a new form of energy called **dark energy**. This energy is thought to explain larger-than-expected values for the observed galactic redshifts

for distant galaxies. These redshifts suggest that the universe is not only expanding, but expanding at an increasing rate. Virtually nothing is known about the nature and properties of dark energy. Together, dark energy and dark matter represent two of the most interesting and unsolved puzzles of modern physics. Scientists attribute 68.3% of the energy of the universe to dark energy, 26.8% to dark matter, and just 4.9% to the mass-energy of ordinary particles (**Figure 11.27**). Given the current great mystery over the nature of dark matter and dark energy, Isaac Newton's humble words are as true now as they were centuries ago:

"I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the sea-shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me."

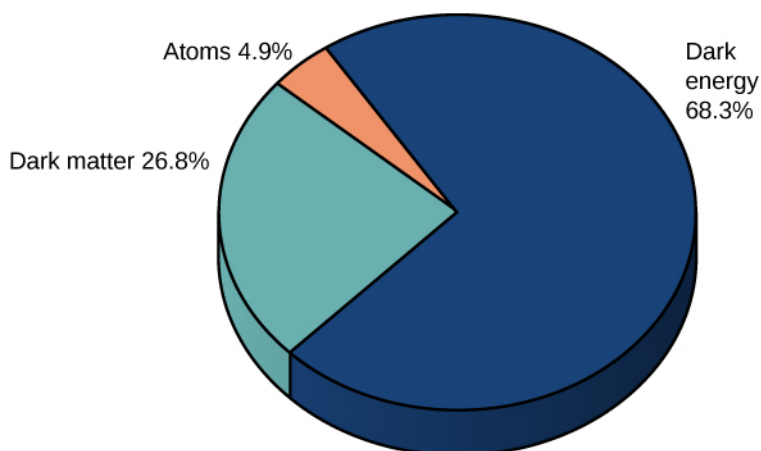


Figure 11.27 Estimated distribution of matter and energy in the universe.
(credit: NASA/WMAP Science Team)