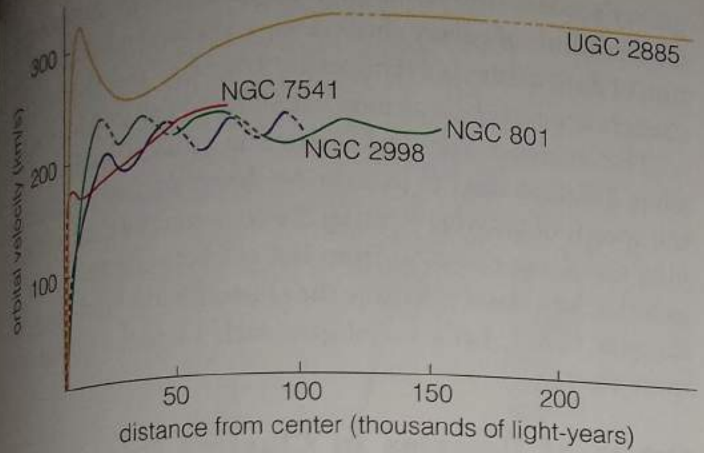


FIGURE 23.4 Graphs of orbital speed versus distance for four spiral galaxies. In each galaxy, the orbital speeds remain nearly constant over a wide range of distances from the center, indicating that dark matter is common in spiral galaxies.

galaxies have at least 10 times as much mass in dark matter as they do in stars. In other words, the composition of typical spiral galaxies is 90% or more dark matter and 10% or less visible matter.

Dark Matter in Elliptical Galaxies We must use a different technique to determine masses of elliptical galaxies, because they do not have large well-organized disks in which we can easily measure how the orbital speeds of stars depend on distance. However, the orbital speeds of their stars still depend on the amount of mass within their orbits, which allows us to measure mass from the width of an elliptical galaxy's spectral lines. If we look at the galaxy as a whole, its spectral lines come from the combination of all its stars. Because each star has its own orbital speed around the center of the galaxy, each produces its own Doppler shift that contributes the overall appearance of the galaxy's spectral lines. Some stars are moving toward the center and others away, so their combined effect is to change any spectral line from a nice narrow line at a particular wavelength to a *broadened* line spanning a range of wavelengths. The greater the broadening of the spectral line, the faster the stars must be moving (**FIGURE 23.5**).

When we compare spectral lines representing regions of elliptical galaxies out to different distances, we find that the speeds of the stars remain fairly constant even quite far from the galaxy's center. Just as in spirals, we conclude that most of

MATHEMATICAL INSIGHT 23.1

Mass-to-Light Ratio

An object's mass-to-light ratio (M/L) is its total mass in units of *solar masses* divided by its total *visible* luminosity in units of *solar luminosities*. For example, the mass-to-light ratio of the Sun is

$$\frac{M}{L} \text{ for Sun} = \frac{1M_{\text{Sun}}}{1L_{\text{Sun}}} = 1\frac{M_{\text{Sun}}}{L_{\text{Sun}}}$$

We read this answer with its units as "1 solar mass per solar luminosity." The following examples clarify the idea of the mass-to-light ratio and explain what it can tell us about the existence of dark matter.

EXAMPLE 1: What is the mass-to-light ratio of a $1M_{\text{Sun}}$ red giant with a luminosity of $100L_{\text{Sun}}$?

SOLUTION:

Step 1 Understand: Finding a mass-to-light ratio simply requires knowing an object's total mass in solar masses and its total luminosity in solar luminosities. We have been given both.

Step 2 Solve: We divide to find the mass-to-light ratio:

$$\frac{M}{L} = \frac{1M_{\text{Sun}}}{100L_{\text{Sun}}} = 0.01\frac{M_{\text{Sun}}}{L_{\text{Sun}}}$$

Step 3 Explain: The red giant has a mass-to-light ratio of 0.01 solar mass per solar luminosity. Note that the ratio is *less* than 1 because a red giant puts out *more* light per unit mass than the Sun. More generally, stars *more luminous* than the Sun have mass-to-light ratios *less* than 1 and stars *less luminous* than the Sun have mass-to-light ratios *greater* than 1.

EXAMPLE 2: The Milky Way Galaxy contains about 90 billion (9×10^{10}) solar masses of material within the Sun's orbit, and the total luminosity of stars within that same region is about 15 billion

SOLUTION:

Step 1 Understand: Again, we simply divide the mass of this region by its luminosity, both in solar units.

Step 2 Solve: The mass-to-light ratio within the Sun's orbit is

$$\frac{M}{L} = \frac{9 \times 10^{10} M_{\text{Sun}}}{1.5 \times 10^{10} L_{\text{Sun}}} = 6\frac{M_{\text{Sun}}}{L_{\text{Sun}}}$$

Step 3 Explain: The mass-to-light ratio of the matter within the Sun's orbit is about 6 solar masses per solar luminosity. This is *greater* than the Sun's ratio of 1 solar mass per solar luminosity, telling us that most matter in this region is *dimmer* per unit mass than our Sun. This is not surprising, because most stars are smaller and dimmer than our Sun.

EXAMPLE 3: Observations of orbital speeds in a spiral galaxy indicate that its total mass is $5 \times 10^{11} M_{\text{Sun}}$; its luminosity is $1.5 \times 10^{10} L_{\text{Sun}}$. What is its mass-to-light ratio?

SOLUTION:

Step 1 Understand: This problem is essentially the same as the others, but with different implications.

Step 2 Solve: We divide the galaxy's mass by its luminosity:

$$\frac{M}{L} = \frac{5 \times 10^{11} M_{\text{Sun}}}{1.5 \times 10^{10} L_{\text{Sun}}} = 33\frac{M_{\text{Sun}}}{L_{\text{Sun}}}$$

Step 3 Explain: The galaxy has a mass-to-light ratio of 33 solar masses per solar luminosity, which is more than five times the mass-to-light ratio for the matter in the Milky Way Galaxy within the Sun's orbit. We conclude that, on average, the mass in this galaxy is *much less* luminous than the mass found in the inner regions of the Milky Way, suggesting that the galaxy must contain a lot of mass that emits little or no light.

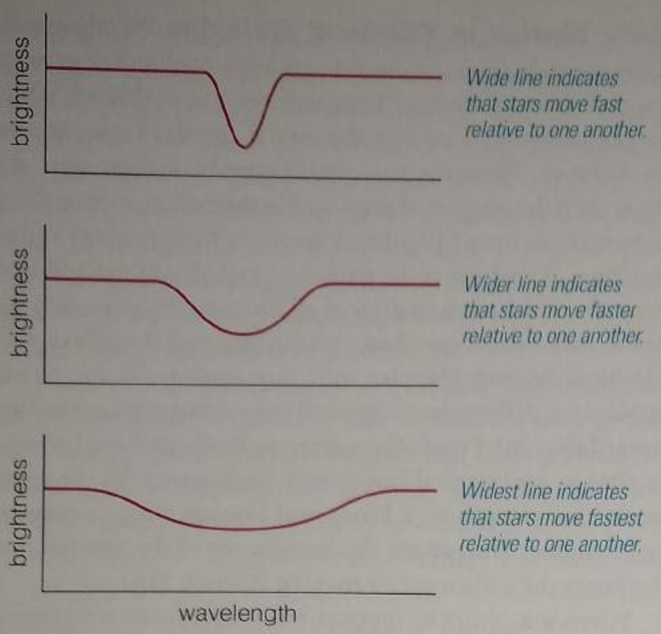


FIGURE 23.5 The broadening of absorption lines in an elliptical galaxy's spectrum tells us how fast its stars move relative to one another.

the matter in elliptical galaxies must lie beyond the distance where the light trails off and hence must be dark matter. The evidence for dark matter is even more convincing for cases in which we can measure the speeds of globular star clusters orbiting at large distances from the center of an elliptical galaxy. These measurements suggest that elliptical galaxies, like spirals, contain 10 times or more as much mass in dark matter as they do in the form of stars.

What is the evidence for dark matter in clusters of galaxies?

The evidence we have discussed so far indicates that stars and gas clouds make up less than 10% of a typical galaxy's mass—the remaining mass consists of dark matter. Observations of galaxy clusters suggest that the total proportion of dark matter is even greater. The mass of dark matter in clusters appears to be as much as 50 times the mass in stars.

The evidence for dark matter in clusters comes from three different ways of measuring cluster masses: measuring the speeds of galaxies orbiting the center of the cluster, studying the X-ray emission from hot gas between the cluster's galaxies, and observing how the clusters bend light as *gravitational lenses.* Let's investigate each of these techniques more closely.

Orbits of Galaxies in Clusters The idea of dark matter is not particularly new. In the 1930s, astronomer Fritz Zwicky was already arguing that clusters of galaxies held enormous amounts of this mysterious stuff (**FIGURE 23.6**). Few of his colleagues paid attention, but later observations supported Zwicky's claims.

Zwicky was one of the first astronomers to think of galaxy clusters as huge swarms of galaxies bound together by gravity. It seemed natural to him that galaxies clumped closely together in space should all be orbiting one another, just like the stars in a star cluster. He therefore assumed that he could measure cluster masses by observing galaxy motions and applying Newton's laws of motion and gravitation.

Armed with a spectrograph, Zwicky measured the redshifts of the galaxies in a particular cluster and used these redshifts to calculate the speeds at which the individual galaxies are moving away from us. He determined the *recession speed* of the cluster as a whole—that is, the speed at which the expansion of the universe carries it away from us—by averaging the speeds of its individual galaxies.

Once he knew the recession speed for the cluster, Zwicky could subtract this speed from each individual galaxy's speed to determine the speeds of galaxies relative to the cluster center. Of course, this method told him only the average

SPECIAL TOPIC

Pioneers of Science

Scientists always take a risk when they publish what they think are groundbreaking results. If their results turn out to be in error, their reputations may suffer. When it came to dark matter, the pioneers in its discovery risked their entire careers. A case in point is Fritz Zwicky and his proclamations in the 1930s about dark matter in clusters of galaxies. Most of his colleagues considered him an eccentric who leapt to premature conclusions.

Another pioneer in the discovery of dark matter was Vera Rubin, an astronomer at the Carnegie Institution. Working in the 1960s, she became the first woman to observe under her own name at California's Palomar Observatory, then the largest telescope in the world. (Another woman, Margaret Burbidge, was permitted to observe at Palomar earlier but was required to apply for time under the name of her husband, also an astronomer.) Rubin first saw the gravitational signature of dark matter in spectra that she recorded of stars in the Andromeda Galaxy. She noticed that stars in the outskirts of Andromeda moved at surprisingly high speeds, suggesting a stronger gravitational attraction than the mass of the galaxy's stars alone could explain.

Working with a colleague, Kent Ford, Rubin went on to measure orbital speeds of hydrogen gas clouds in many other spiral galaxies (by studying Doppler shifts in the spectra of hydrogen gas) and discovered that the behavior seen in Andromeda is common. Although Rubin and Ford did not immediately recognize the significance of the results, they were soon arguing that the universe must contain substantial quantities of dark matter.

For a while, many other astronomers had trouble believing the results. Some astronomers suspected that the bright galaxies studied by Rubin and Ford were unusual for some reason. So Rubin and Ford went back to work, obtaining orbital measurements for fainter galaxies. By the 1980s, the evidence that Rubin, Ford, and other astronomers measuring rotation curves had compiled was so overwhelming that even the critics came around. Either the theory of gravity was wrong or the astronomers measuring these orbital speeds had discovered dark matter in spiral galaxies. In this case, the risks of the pioneers paid off in a groundbreaking discovery.

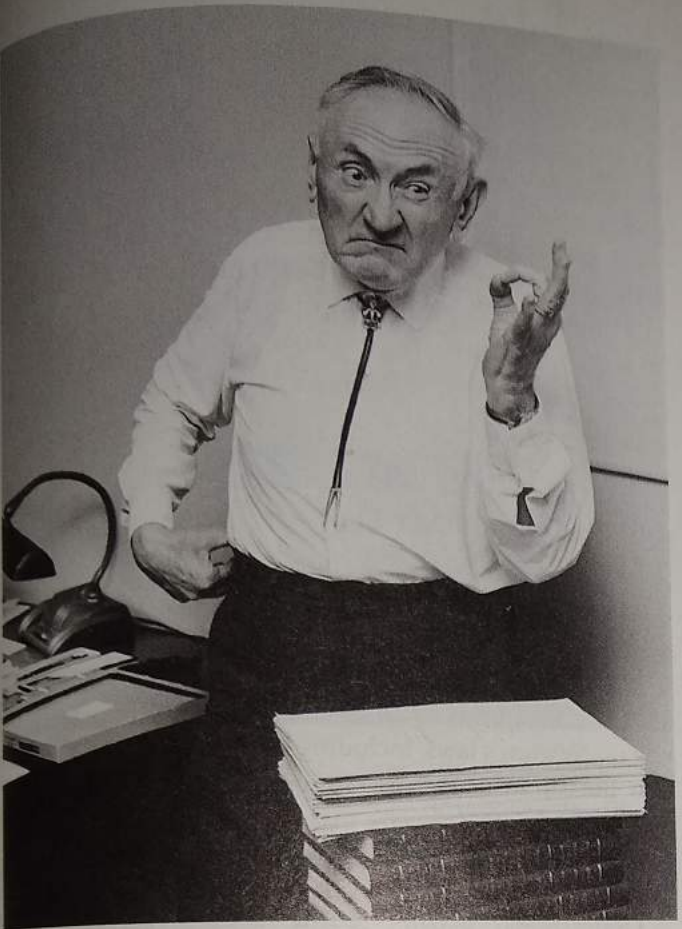


FIGURE 23.6 Fritz Zwicky, discoverer of dark matter in clusters of galaxies. Zwicky had an eccentric personality, but some of his ideas that seemed strange in the 1930s proved correct many decades later.

radial component (the speed toward or away from us) of the actual galaxy velocities [Section 5.4], but by averaging over enough individual galaxies, Zwicky could get a good average orbital velocity for the cluster's galaxies as a whole. Once he knew the average orbital velocity of the galaxies, he could use Newton's universal law of gravitation to estimate the cluster's mass (see Mathematical Insight 23.2). Finally, he compared the cluster's mass to its luminosity.

To his surprise, Zwicky found that clusters of galaxies have much greater masses than their luminosities would suggest. That is, when he estimated the total mass of stars necessary to account for the overall luminosity of a cluster, he found that it was far less than the mass he measured by studying galaxy speeds. He concluded that most of the matter within these clusters must not be in the form of stars and instead must be almost entirely dark. Many astronomers disregarded Zwicky's result, believing that he must have done something wrong to arrive at such a strange result. Today, far more sophisticated measurements of galaxy orbits in clusters confirm Zwicky's original finding.

Hot Gas in Clusters A second method for measuring a cluster's mass relies on observing X rays from the hot gas that fills the space between its galaxies (FIGURE 23.7). This gas (sometimes called the *intracluster medium*) is so hot that it emits primarily X rays and therefore went undetected until the 1960s, when X-ray telescopes were first launched above Earth's atmosphere. The temperature of this gas is tens of millions of degrees in many clusters and can exceed 100 million degrees in the largest clusters. This hot gas represents a great deal of mass. Large clusters have up to seven times as much mass in the form of X ray–emitting gas as they do in the form of stars.

The hot gas can tell us about dark matter because its temperature depends on the total mass of the cluster. The gas in most clusters is nearly in a state of *gravitational equilibrium*—that is, the outward gas pressure balances gravity's inward pull [Section 14.1]. In this state of balance, the average kinetic energies of the gas particles are determined primarily

MATHEMATICAL INSIGHT 23.2

Finding Cluster Masses from Galaxy Orbits

Recall that we can use the *orbital velocity law* (see Mathematical Insight 19.1) to calculate the mass, M_r, contained *within* a distance r of a galaxy's center:

$$M_r = \frac{r \times v^2}{G}$$

This law also applies to galaxy clusters if we consider r as the distance from the center of the cluster and assume the galaxies have circular orbits.

EXAMPLE: A galaxy cluster has a radius of 6.2 million light-years, and Doppler shifts show that galaxies orbit the cluster center at an average speed of approximately 1350 km/s. Find the cluster's mass.

SOLUTION:

Step 1 Understand: We can use the orbital velocity law, but to make the units consistent we must convert the radius into meters and the speed into meters per second.

Step 2 Solve: You can confirm for yourself that the radius of 6.2 million light-years is equivalent to 5.9×10^{22} meters; the speed of 1350 km/s becomes 1.35×10^6 m/s. Substituting, we find

$$\begin{aligned} M_r &= \frac{r \times v^2}{G} \\ &= \frac{(5.9 \times 10^{22}\ \text{m}) \times (1.35 \times 10^6\ \text{m/s})^2}{6.67 \times 10^{-11}\ \text{m}^3/(\text{kg} \times \text{s}^2)} \\ &= 1.6 \times 10^{45}\ \text{kg} \end{aligned}$$

Step 3 Explain: The result is easier to interpret if we convert from kilograms to solar masses ($1M_{\text{Sun}} = 2.0 \times 10^{30}$ kg):

$$M_r = 1.6 \times 10^{45}\ \text{kg} \times \frac{1M_{\text{Sun}}}{2 \times 10^{30}\ \text{kg}} \approx 8.0 \times 10^{14} M_{\text{Sun}}$$

The cluster mass is about 800 trillion solar masses, which is equivalent to about 800 galaxies as large in mass as the Milky Way (including dark matter).

FIGURE 23.7 A distant cluster of galaxies in both visible light and X-ray light. The visible-light photo shows the individual galaxies. The blue-violet overlay shows the X-ray emission from extremely hot gas in the cluster, with blue representing the hottest gas and violet representing cooler gas. Evidence for dark matter comes both from the observed motions of the visible galaxies and from the temperature of the hot gas. (The region shown is about 8 million light-years across.)

by the strength of gravity and hence by the amount of mass within the cluster. Because the temperature of a gas reflects the average kinetic energies of its particles, the gas temperatures we measure with X-ray telescopes tell us the average speeds of the X ray–emitting particles (see Mathematical Insight 23.3). We can then use these particle speeds to determine the cluster's total mass.

The results obtained with this method agree well with the results found by studying the orbital motions of the cluster's galaxies. Even after we account for the mass of the hot gas, we find that the amount of dark matter in clusters of galaxies is up to 50 times the combined mass of the stars in the cluster's galaxies. In other words, the gravity of dark matter seems to be binding the galaxies of a cluster together in much the same way gravity helps bind individual galaxies together.

THINK ABOUT IT

What would happen to a cluster of galaxies if you instantly removed all the dark matter without changing the velocities of the galaxies?

Gravitational Lensing The methods of measuring galaxy and cluster masses that we've discussed so far all ultimately rely on Newton's laws, including his universal law of gravitation. But can we trust these laws on such large size scales? One way to check is to measure masses in a different way. Today, astronomers can do this with observations of *gravitational lensing*.

Gravitational lensing occurs because masses distort spacetime—the "fabric" of the universe [**Section S3.3**]. Massive objects can therefore act as **gravitational lenses** that bend light beams passing nearby. This prediction of Einstein's general theory of relativity was first verified in 1919 during an eclipse of the Sun [**Section S3.4**]. Because the light-bending angle of a gravitational lens depends on

MATHEMATICAL INSIGHT 23.3

Finding Cluster Masses from Gas Temperature

To find a cluster's mass from the temperature of its hot, X ray–emitting gas, we need a formula relating the gas temperature to the speeds of individual particles in the gas, which is mostly hydrogen. Although we will not present a derivation here, the following formula applies:

$$v_H = (140 \text{ m/s}) \times \sqrt{T}$$

where v_H is the average orbital speed of the hydrogen nuclei and T is the temperature on the Kelvin scale. Once we find the speeds of the hydrogen nuclei, we can use them in the orbital velocity law to find the cluster mass.

EXAMPLE: The galaxy cluster from Mathematical Insight 23.2, with a radius of 6.2 million light-years, is filled with hot gas at a temperature of 9×10^7 K. Use this temperature to find the cluster's mass.

SOLUTION:

Step 1 Understand: We can use the formula relating speed and temperature to find the average orbital speed of hydrogen nuclei, which we can then use as the velocity (v) in the orbital velocity law. We already know the cluster's radius, which is the only other information we need.

Step 2 Solve: Using the given formula and the temperature of 9×10^7 K, we find that the average orbital speed of the hydrogen nuclei is

$$\begin{aligned} v_H &= (140 \text{ m/s}) \times \sqrt{T} \\ &= (140 \text{ m/s}) \times \sqrt{9 \times 10^7} \\ &= 1.3 \times 10^6 \text{ m/s} \end{aligned}$$

We now find the cluster's mass from the orbital velocity law, using the above value as v and the cluster's radius ($r = 6.2$ million ly $\approx 5.9 \times 10^{22}$ m):

$$\begin{aligned} M_r &= \frac{r \times v^2}{G} \\ &= \frac{(5.9 \times 10^{22} \text{ m}) \times (1.3 \times 10^6 \text{ m/s})^2}{6.67 \times 10^{-11} \text{ m}^3/(\text{kg} \times \text{s}^2)} \\ &\approx 1.5 \times 10^{45} \text{ kg} \end{aligned}$$

Step 3 Explain: The cluster's mass is 1.5×10^{45} kilograms, which you can confirm to be about 750 trillion solar masses. This is very close to the 800 trillion solar masses found in Mathematical Insight 23.2 from the galaxy speeds, so the two methods of estimating mass agree well.

FIGURE 23.8 **interactive photo** This Hubble Space Telescope photo shows a galaxy cluster acting as a gravitational lens. The yellow elliptical galaxies are cluster members. The small blue ovals (such as those indicated by the arrows) are multiple images of a single galaxy that lies almost directly behind the cluster's center. (The picture shows a region about 1.4 million light-years across.)

the mass of the object doing the bending, we can measure the masses of objects by observing how strongly they distort light paths.

FIGURE 23.8 shows a striking example of how a cluster of galaxies can act as a gravitational lens. Many of the yellow elliptical galaxies concentrated toward the center of the picture belong to the cluster, but at least one of the galaxies pictured does not. At several positions on various sides of the central clump of yellow galaxies, you will notice multiple images of the same blue galaxy. Each one of these images, whose sizes differ, looks like a distorted oval with an off-center smudge.

The blue galaxy seen in these multiple images lies almost directly behind the center of the cluster, at a much greater distance. We see multiple images of this single galaxy because photons do not follow straight paths as they travel from the galaxy to Earth. Instead, the cluster's gravity bends the photon paths, allowing light from the galaxy to arrive at Earth from a few slightly different directions (**FIGURE 23.9**). Each alternative path produces a separate, distorted image of the blue galaxy.

Multiple images of a gravitationally lensed galaxy are rare. They occur only when a distant galaxy lies directly behind the lensing cluster. However, single distorted images of gravitationally lensed galaxies are quite common. **FIGURE 23.10** shows a typical example. This picture shows numerous normal-looking galaxies and several arc-shaped galaxies. The oddly curved galaxies are not members of the cluster, nor are they really curved. They are normal galaxies lying far beyond the cluster whose images have been distorted by the cluster's gravity.

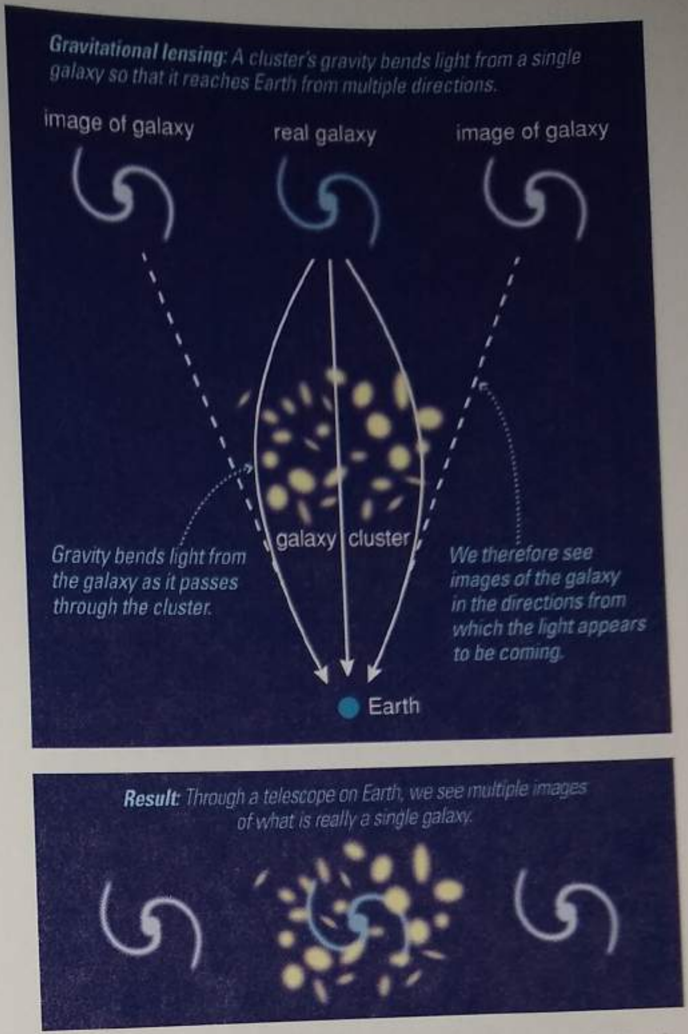


FIGURE 23.9 **interactive figure** A cluster's powerful gravity bends light paths from background galaxies to Earth. If light arrives from several different directions, we see multiple images of the same galaxy.

Careful analyses of the distorted images created by clusters enable us to measure cluster masses without using Newton's laws. Instead, Einstein's general theory of relativity tells us how massive these clusters must be to generate the observed distortions. Cluster masses derived in this way generally agree with those derived from galaxy velocities and X-ray temperatures. It is reassuring that the three different methods all indicate that clusters of galaxies hold substantial amounts of dark matter.

Does dark matter really exist?

Astronomers have made a strong case for the existence of dark matter, but is it possible that there's a completely different explanation for the observations we've discussed? Addressing this question gives us a chance to see how science progresses.

All the evidence for dark matter rests on our understanding of gravity. For individual galaxies, the case for dark matter rests primarily on applying Newton's laws of motion and gravity to observations of the orbital speeds of stars and gas clouds. We've used the same laws to make the case for dark matter in clusters, along with additional evidence based on

FIGURE 23.10 Hubble Space Telescope photo of the cluster Abell 383. The thin, elongated galaxies are images of background galaxies distorted by the cluster's gravity. By measuring these distortions, astronomers can determine the total amount of mass in the cluster. (The region pictured is about 1 million light-years across.)

gravitational lensing predicted by Einstein's general theory of relativity. It therefore seems that one of the following must be true:

1. Dark matter really exists, and we are observing the effects of its gravitational attraction.
2. There is something wrong with our understanding of gravity that is causing us to mistakenly infer the existence of dark matter.

We cannot yet rule out the second possibility, but most astronomers consider it very unlikely. Newton's laws of motion and gravity are among the most trustworthy tools in science. We have used them time and again to measure masses of celestial objects from their orbital properties. We found the masses of Earth and the Sun by applying Newton's version of Kepler's third law to objects that orbit them [**Section 4.4**]. We used this same law to calculate the masses of stars in binary star systems, revealing the general relationships between the masses of stars and their outward appearances. Newton's laws have also told us the masses of things we can't see directly, such as the masses of orbiting neutron stars in X-ray binaries and of black holes in active galactic nuclei. Einstein's general theory of relativity likewise stands on solid ground, having been repeatedly tested and verified to high precision in many observations and experiments. We therefore have good reason to trust our current understanding of gravity.

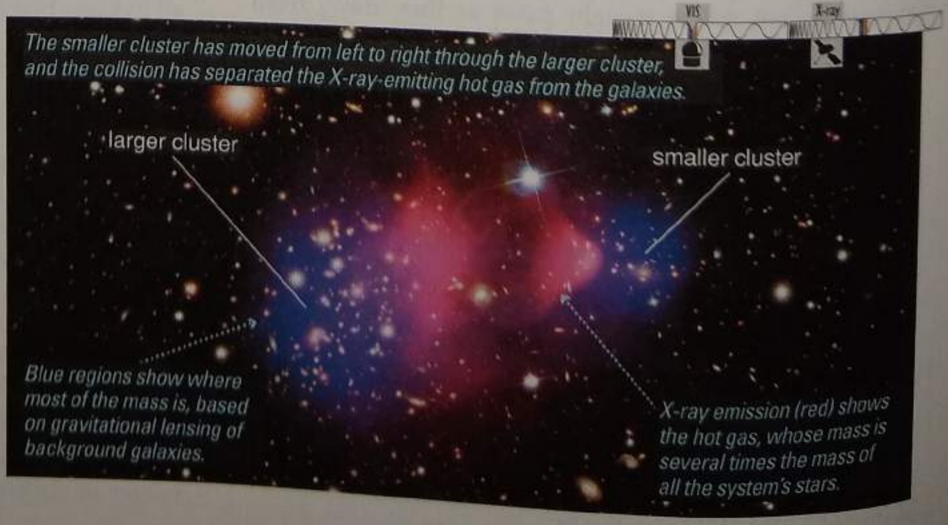
Moreover, many scientists have made valiant efforts to come up with alternative theories of gravity that could account for the observations without invoking dark matter. (After all, there's a Nobel Prize waiting for anyone who can substantiate a new theory of gravity.) So far, no one has succeeded in doing so in a way that can also explain the many other observations accounted for by our current theories of gravity. Meanwhile, astronomers keep making observations that are difficult to explain without dark matter. For example, in observations of colliding galaxy clusters, most of the mass detected by gravitational lensing is *not* in the same place as the hot gas, even though the hot gas is several times more massive than the cluster's stars (**FIGURE 23.11**). This finding is at odds with alternative theories of gravity, which predict that the hot gas should be doing most of the gravitational lensing.

In essence, our high level of confidence in our current understanding of gravity, combined with observations that seem consistent with dark matter but not with alternative hypotheses, gives us high confidence that dark matter really exists. While we should always keep an open mind about the possibility of future changes in our understanding, we will proceed for now under the assumption that dark matter is real.

THINK ABOUT IT

Should the fact that we have three different ways of measuring cluster masses give us greater confidence that we really do understand gravity and that dark matter really does exist? Why or why not?

FIGURE 23.11 interactive photo
Observations of the Bullet Cluster show strong evidence for dark matter. The Bullet Cluster actually consists of two galaxy clusters—the smaller one is emerging from a high-speed collision with the larger one. A map of the system's overall mass (blue) made from gravitational lensing observations does *not* line up with X-ray observations (red) showing the location of the system's hot gas. This fact is difficult to explain without dark matter because the gas contains several times as much mass as all the cluster's stars combined. However, it is easy to explain if dark matter exists: The collision has simply stripped the hot gas away from the dark matter on which it was previously centered.



The smaller cluster has moved from left to right through the larger cluster, and the collision has separated the X-ray-emitting hot gas from the galaxies.

Blue regions show where most of the mass is, based on gravitational lensing of background galaxies.

X-ray emission (red) shows the hot gas, whose mass is several times the mass of all the system's stars.

What [illegible] be made of?

We have seen strong evidence that dark matter really exists and that it contains far more mass than we observe in the stars and gas found in galaxies and clusters of galaxies. But what exactly is all this dark stuff? There are two basic possibilities:

- It could be made of *ordinary matter* (also called *baryonic matter*[*]), meaning the familiar type of matter built from protons, neutrons, and electrons, but in forms too dark for us to detect with current technology.
- It could consist of one or more types of *exotic matter* (also called *nonbaryonic matter*), meaning particles of matter that are different from what we find in ordinary atoms and that do not interact with light at all, in contrast with ordinary matter.

A first step in distinguishing between the two possibilities is to know how much dark matter is out there. When discussing the universe as a whole, astronomers usually focus on density rather than mass. That is, they take the total amount of some type of matter (such as stars, gas, or dark matter) found in a large but typical volume of space and divide by the volume to determine the average density of this type of matter in the universe. These densities are then stated as percentages of the *critical density*—the density of mass-energy needed to make the geometry of the universe flat [**Section 22.3**]. Note that the critical density is quite small: If it were due only to matter (as we'll discuss later, it appears also to have a contribution from dark energy), the critical density would be only 10^{-29} gram per cubic centimeter—roughly equivalent to a few hydrogen atoms in a volume the size of a closet.

The observations we have discussed so far indicate that the total amount of matter in the universe is a significant fraction of the critical density. Only a small proportion of the matter, about 0.5% of the critical density, is in the form of stars. But as we've discussed, observations of galaxy clusters suggest that they contain up to about 50 times as much dark matter as matter in stars. Multiplying the mass in stars by this number leads us to expect the dark matter to amount to about a quarter of the critical density. Clearly, there is a lot of dark matter that needs to be accounted for, and current evidence indicates that most of it must be exotic.

Ordinary Matter: Not Enough Why can't all this dark matter simply be ordinary matter in some hard-to-observe form? After all, matter doesn't necessarily need to be exotic to be dark. Astronomers consider matter to be "dark" as long as it is too dim for us to see at the great distances of the halo of our galaxy or beyond. Your body is dark matter, because our telescopes could not detect you if you were somehow flung into the halo of our galaxy. Similarly, planets, the "failed stars" known as brown dwarfs [**Section 16.3**], and even some faint red main-sequence stars of spectral type M [**Section 15.2**] qualify as dark matter, because they are too dim for current telescopes to see in the halo.

However, calculations made with the Big Bang model allow scientists to place limits on the total amount of ordinary matter in the universe. Recall that, during the era of nucleosynthesis, protons and neutrons first fused into deuterium and the deuterium nuclei then fused into helium [**Section 22.2**]. The fact that some deuterium nuclei still exist in the universe indicates that this process stopped before all the deuterium nuclei were used up. The amount of deuterium in the universe today therefore tells us about the density of protons and neutrons (ordinary matter) during the era of nucleosynthesis: The higher the density, the more efficiently fusion would have proceeded. A higher density in the early universe would have therefore left less deuterium in the universe today, and a lower density would have left more deuterium.

Observations show that about one out of every 40,000 hydrogen atoms in the universe contains a deuterium nucleus—that is, a nucleus with a neutron in addition to its proton. Calculations based on this deuterium abundance indicate that the overall density of ordinary matter in the universe is slightly more than 4% of the critical density (**FIGURE 23.12**), only about one-seventh of the total density of matter. Similar calculations based on the observed abundance of lithium and helium-3 support this conclusion.

Corroborating evidence comes from the temperature patterns in the cosmic microwave background (see Figures 22.9

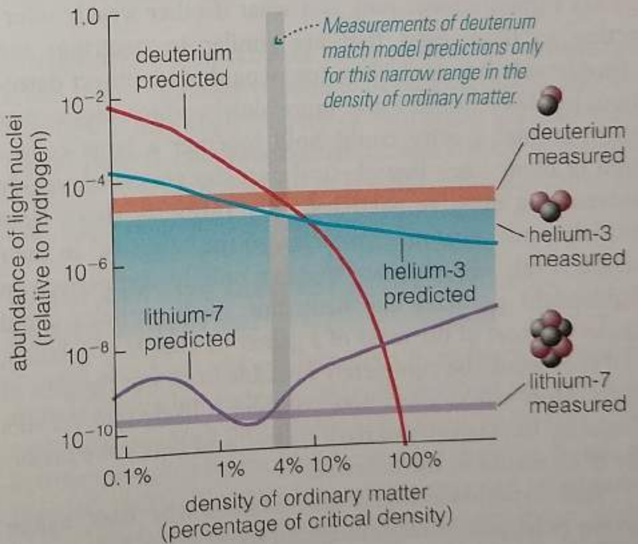


FIGURE 23.12 This graph shows how the measured abundances of deuterium, helium-3, and lithium-7 lead to the conclusion that the density of ordinary matter is about 4% of the critical density. The three horizontal swaths show measured abundances; the thickness of each swath represents the range of uncertainty in the measurements. (The upper edge of the blue swath indicates the upper limit on the helium-3 abundance; a lower limit has not yet been established.) The three curves represent models based on the Big Bang theory; these curves show how the abundance of each type of nucleus is expected to depend on the density of ordinary matter in the universe. Notice that the predictions (curves) match up with the measurements (horizontal swaths) only in the gray vertical strip, which represents a density of about 4% of the critical density.

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[*] Ordinary matter is often called *baryonic* matter, because the protons and neutrons that make up most of its mass belong to a category of particles known as *baryons* (which is the technical term for particles made up of three quarks [**Section S4.2**]). As a result, exotic matter is often called *nonbaryonic* matter.

and 22.17). These patterns are produced as the ordinary matter in the universe moves around in response to the gravitational pull of clumps of dark matter. Careful measurement of these patterns therefore reveals the relative proportions of ordinary and exotic matter, and the results confirm that ordinary matter accounts for only about one-seventh of the total amount of matter.

Exotic Matter: The Leading Hypothesis The fact that ordinary matter appears to fall far short of accounting for the total matter density in the universe has forced astronomers to seriously consider the possibility that most of the matter in the universe is made of exotic particles, and probably of a type of exotic particle that has not yet been discovered. Let's begin to explore this possibility by taking another look at a type of exotic particle that we first encountered in connection with nuclear fusion in the Sun: neutrinos [**Section 14.2**]. Neutrinos are dark by nature because they have no electrical charge and cannot emit electromagnetic radiation of any kind. Moreover, they are never bound together with charged particles in the way that neutrons are bound in atomic nuclei, so their presence cannot be revealed by associated light-emitting particles. In fact, neutrinos interact with other forms of matter through only two of the four forces: gravity and the *weak force* [**Sections S4.2, 22.1**]. For this reason, neutrinos are said to be *weakly interacting particles.*

The dark matter in galaxies cannot be made of neutrinos, because these very-low-mass particles travel through the universe at enormous speeds and can easily escape a galaxy's gravitational pull. But what if other weakly interacting particles exist that are similar to neutrinos but considerably heavier? They, too, would evade direct detection, but they would move more slowly, which means that their mutual gravity could hold together a large collection of them. Such hypothetical particles are called **weakly interacting massive particles**, or **WIMPs** for short. Note that they are subatomic particles, so the "massive" in their name is relative—they are massive only in comparison to lightweight particles like neutrinos. Such particles could make up most of the mass of a galaxy or cluster of galaxies, but they would be completely invisible in all wavelengths of light. Most astronomers now consider it likely that WIMPs make up the majority of dark matter, and hence the majority of all matter in the universe.

This hypothesis would also explain why dark matter seems to be distributed throughout spiral galaxy halos rather than concentrated in flattened disks like the visible matter. Recall that galaxies are thought to have formed as gravity pulled together matter in regions of slightly enhanced density in the early universe [**Section 21.1**]. This matter would have consisted mostly of dark matter mixed with some ordinary hydrogen and helium gas. The ordinary gas could collapse to form a rotating disk because individual gas particles could lose orbital energy: Collisions among many gas particles can convert some of their orbital energy into radiative energy that escapes from the galaxy in the form of photons. In contrast, WIMPs cannot produce photons, and they rarely interact and exchange energy with other particles. As the gas collapsed to form a disk, WIMPs would therefore have remained stuck in orbits far out in the galactic halo—just where most dark matter seems to be located.

Searching for Dark Matter Particles The case for the existence of WIMPs seems fairly strong but is still circumstantial. Detecting the particles directly would be much more convincing, and physicists are currently searching for them in two different ways. The first and most direct way is with detectors that can potentially capture WIMPs from space. Because these particles are thought to interact only very weakly, the search requires building large, sensitive detectors deep underground, where they are shielded from other particles from space. As of 2012, these detectors have provided some tantalizing signals, but so far no proof that dark matter particles really exist.

The second way scientists are currently searching for dark matter particles is with particle accelerators. Recall that particle collisions in these huge machines produce a variety of subatomic particles, because much of the energy in each collision is converted into mass according to $E = mc^2$ [**Sections S4.2, 22.1**]. None of the particles found as of 2012 has the characteristics of a WIMP, but scientists are optimistic that the Large Hadron Collider (see Figure S4.1), the most powerful accelerator in the world, will soon reach collision energies great enough to produce the elusive dark matter particles and finally solve this major scientific mystery.

THINK [illegible]

What do you think of the idea that much of the universe is made of as-yet-undiscovered particles? Can you think of other instances in the history of science in which the existence of something was predicted before it was discovered?

23.3 DARK MATTER AND GALAXY FORMATION

The nature of dark matter remains enigmatic, but we are rapidly learning more about its role in the universe. Because galaxies and clusters of galaxies seem to contain much more dark matter than luminous matter, dark matter's gravitational pull must be the primary force holding these structures together. Therefore, we strongly suspect that the gravitational attraction of dark matter is what pulled galaxies and clusters together in the first place.

What is the role of dark matter in galaxy formation?

Stars, galaxies, and clusters of galaxies are all *gravitationally bound systems*—their gravity is strong enough to hold them together. In most of the gravitationally bound systems we have discussed so far, gravity has completely overwhelmed the expansion of the universe. That is, while the universe as a whole is expanding, space is *not* expanding within our solar system, our galaxy, or our Local Group of galaxies.

Our best guess at how galaxies formed, outlined in Section 21.2, envisions them growing from slight density enhancements that were present in the very early universe. During the first few million years after the Big Bang, the universe expanded everywhere. Gradually, the stronger gravity in regions of enhanced density pulled in matter until these regions stopped expanding and became protogalactic clouds, even as the universe as a whole continued (and still continues) to expand.

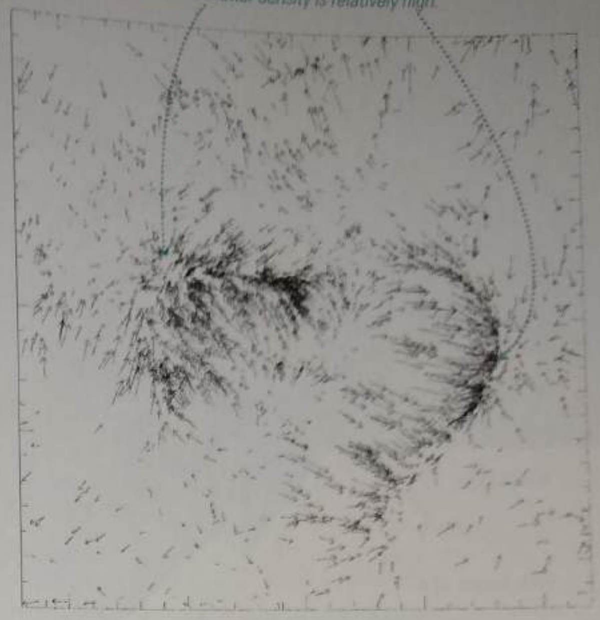
THINK ABOUT IT

State whether each of the following is a gravitationally bound system, and explain why: (a) Earth; (b) a hurricane on Earth; (c) the Orion Nebula; (d) a supernova.

If dark matter is indeed the most common form of mass in galaxies, it must have provided most of the gravitational attraction responsible for creating the protogalactic clouds. The hydrogen and helium gas in the protogalactic clouds collapsed inward and gave birth to stars, while weakly interacting dark matter remained in the outskirts because of its inability to radiate away orbital energy. According to this model, the luminous matter in each galaxy must still be nestled inside the larger cocoon of dark matter that initiated the galaxy's formation (see Figure 23.2), just as observational evidence seems to suggest.

The formation of galaxy clusters probably echoes the formation of galaxies. Early on, all the galaxies that will eventually constitute a cluster are flying apart with the expansion of the universe, but the gravity of the dark matter associated with the cluster eventually reverses the trajectories of these galaxies. The galaxies ultimately fall back inward and start orbiting each other with random orientations, much like the stars in the halo of our galaxy.

Some clusters apparently have not yet finished forming, because their immense gravity is still drawing in new galaxies. For example, the relatively nearby Virgo Cluster of galaxies (about 60 million light-years away) appears to be drawing in the Milky Way and other galaxies of the Local Group. The evidence comes from careful study of galaxy speeds. Plugging the Virgo Cluster's distance into Hubble's law tells us the speed at which the Milky Way and the Virgo Cluster should be drifting apart as a result of universal expansion [**Section 20.3**]. However, the measured speed is about 400 kilometers per second slower than the speed we predict from Hubble's law alone. We conclude that this 400 kilometers per second discrepancy (sometimes called a *peculiar velocity*) arises because the Virgo Cluster's gravity is pulling us back against the flow of universal expansion. In other words, while the Milky Way and other galaxies of our Local Group are still moving away from the Virgo Cluster with the expansion of the universe, the rate at which we are separating from the cluster is slowing with time. Eventually, the cluster's gravity may stop the separation altogether, at which point the cluster will begin pulling in the galaxies of our Local Group, ultimately making them members of the cluster.



Gravity pulls galaxies into regions of the universe where the matter density is relatively high

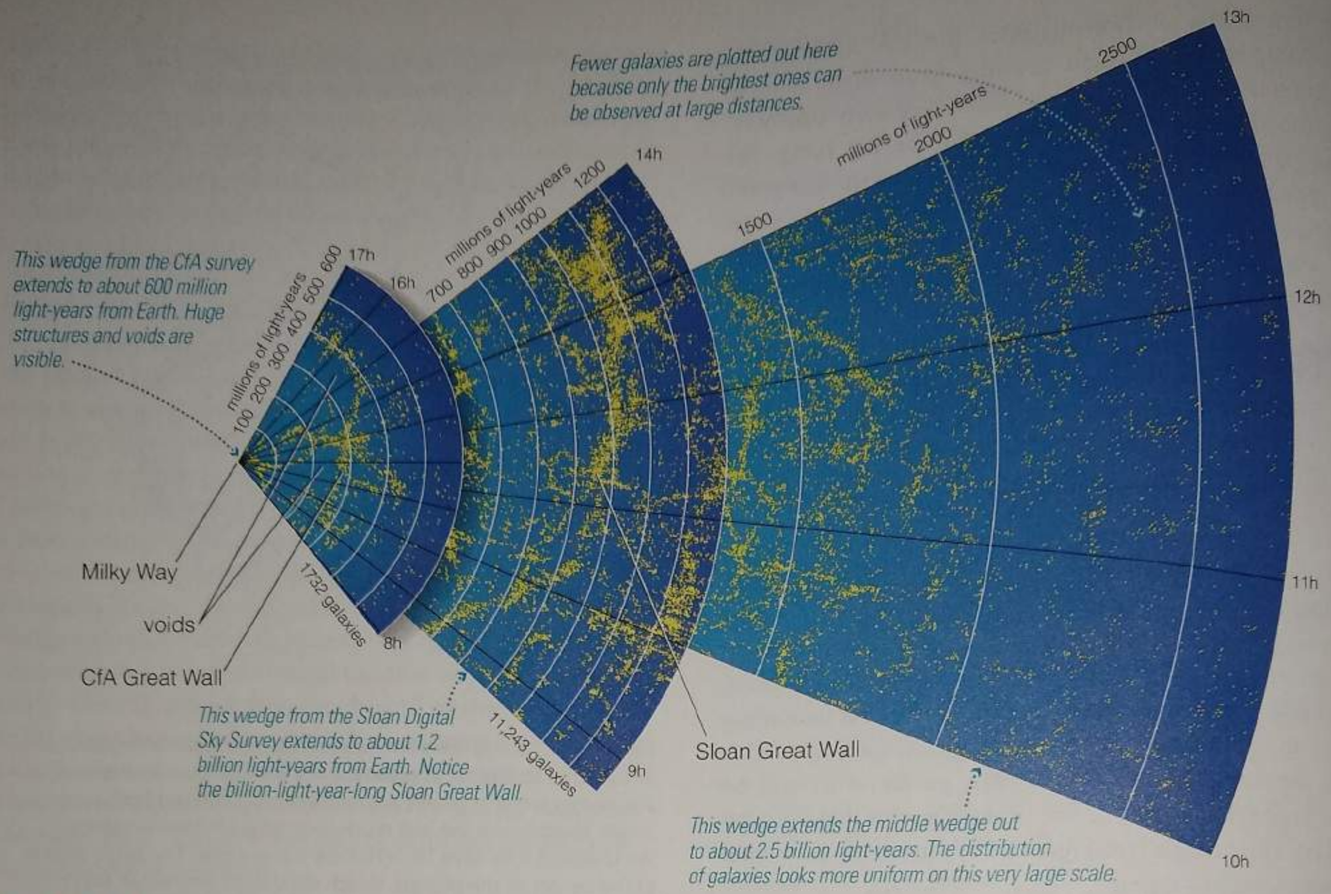
FIGURE 23.13 This diagram represents the motions of galaxies attributable to effects of gravity. Each black arrow represents the amount by which a galaxy's actual velocity (inferred from a combination of observations and modeling) differs from the velocity we'd expect it to have from Hubble's law alone. The Milky Way is at the center of the picture, which shows an area about 600 million light-years across. (Only a representative sample of galaxies is shown.) Notice how the galaxies tend to flow into regions where the density of galaxies is already high. These vast, high-density regions are probably superclusters in the process of formation.

Many other large clusters of galaxies also appear to be drawing in new members, judging from the velocities of galaxies near the outskirts of those clusters. On even larger scales, clusters themselves seem to be tugging on one another, hinting that they might be parts of even bigger gravitationally bound systems, called **superclusters**, that are still in the early stages of formation (**FIGURE 23.13**). But some structures are even larger than superclusters.

What are the largest structures in the universe?

Beyond about 300 million light-years from Earth, deviations from Hubble's law owing to gravitational tugs are insignificant compared with the universal expansion, so Hubble's law becomes our primary method for measuring galaxy distances [**Section 20.3**]. Using this law, astronomers can make maps of the distribution of galaxies in space. Such maps reveal **large-scale structures** much vaster than clusters of galaxies.

Mapping Large-Scale Structures Making maps of galaxy locations requires an enormous amount of data. A long-exposure photo showing galaxy positions is not enough, because it does not tell us the galaxy distances. We must also measure the redshift of each individual galaxy so that we can estimate its distance by applying Hubble's law. These measurements once required intensive labor, and up until a couple decades ago it took years of effort to map the locations of just a few hundred galaxies. However, astronomers have since developed technology that allows redshift measurements for hundreds of galaxies to be made during a single night



Fewer galaxies are plotted out here because only the brightest ones can be observed at large distances.

This wedge from the CfA survey extends to about 600 million light-years from Earth. Huge structures and voids are visible.

This wedge from the Sloan Digital Sky Survey extends to about 1.2 billion light-years from Earth. Notice the billion-light-year-long Sloan Great Wall.

This wedge extends the middle wedge out to about 2.5 billion light-years. The distribution of galaxies looks more uniform on this very large scale.

FIGURE 23.14 Each of these three wedges shows a "slice" of the universe extending outward from our own Milky Way Galaxy. The dots represent galaxies, shown at their measured distances from Earth. We see that galaxies trace out long chains and sheets surrounded by huge voids containing very few galaxies. (The wedges are shown flat but actually are a few angular degrees in thickness; the CfA wedge at left does not actually line up with the two Sloan wedges.)

of telescopic observation. As a result, we now have redshift measurements—and hence estimated distances—for millions of distant galaxies.

FIGURE 23.14 shows the distribution of galaxies in three slices of the universe, each extending farther out in distance. Our Milky Way Galaxy is located at the vertex at the far left, and each dot represents an entire galaxy of stars. The slice at the left comes from one of the first surveys of large-scale structures, performed at the Harvard-Smithsonian Center for Astrophysics (CfA) in the 1980s. This map, which required years of effort by many astronomers, dramatically revealed the complex structure of our corner of the universe. It showed that galaxies are not scattered randomly through space but are instead arranged in huge chains and sheets that span many millions of light-years. Clusters of galaxies are located at the intersections of these chains. Between these chains and sheets of galaxies lie giant empty regions called **voids**. The other two slices show data from the more recent Sloan Digital Sky Survey. The Sloan Survey has measured redshifts for more than a million galaxies spread across about one-fourth of the sky.

Some of the structures in these pictures are amazingly large. The so-called Sloan Great Wall, clearly visible in the center slice, extends more than 1 billion light-years from end to end. Immense structures such as these apparently have not yet collapsed into randomly orbiting, gravitationally bound systems.

The universe may still be growing structures on these very large scales. However, there seems to be a limit to the size of the largest structures. If you look closely at the rightmost slice in Figure 23.14, you'll notice that the overall distribution of galaxies appears nearly uniform on scales larger than about a billion light-years. In other words, on very large scales the universe looks much the same everywhere, in agreement with what we expect from the *Cosmological Principle* [**Section 20.3**].

The Origin of Large Structures Why is gravity collecting matter on such enormous scales? Just as we suspect that galaxies formed from regions of slightly enhanced density in the early universe, we suspect that these larger structures were also regions of enhanced density. Galaxies, clusters, superclusters, and the Sloan Great Wall probably all started as mildly high-density regions of different sizes. The voids in the distribution of galaxies probably started as mildly low-density regions.

If this picture of structure formation is correct, then the structures we see in today's universe mirror the original distribution of dark matter very early in time. Supercomputer models of structure formation in the universe can now simulate the growth of galaxies, clusters, and larger structures from tiny density enhancements as the universe evolves (**FIGURE 23.15**). Models of extremely large regions reveal how dark matter should be distributed throughout the entire observable universe (**FIGURE 23.16**). The results of these models look remarkably similar to the slices of the universe in Figure 23.14, bolstering

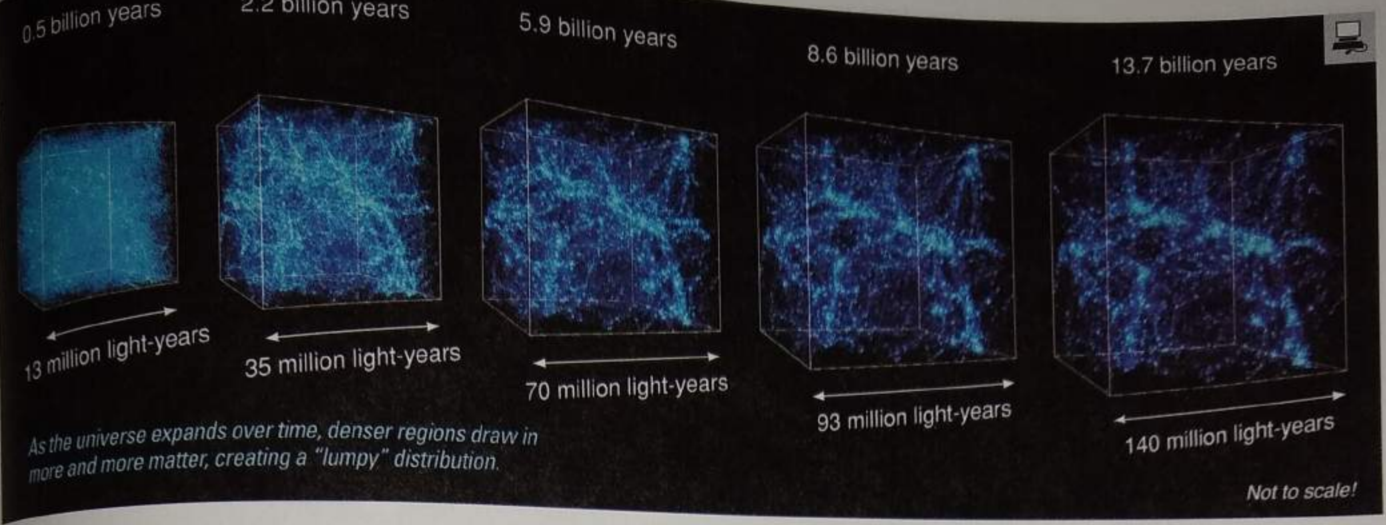


FIGURE 23.15 **interactive figure** Frames from a supercomputer simulation of structure formation. The five boxes depict the development of a cubical region that is now 140 million light-years across. The labels above the boxes give the age of the universe, and the labels below give the size of the box as it expands with time. Notice that the distribution of matter is only slightly lumpy when the universe is young (left frame). Structures grow more pronounced with time as the densest lumps draw in more and more matter.

our confidence in this scenario. Moreover, the patterns of mass distribution are consistent with the patterns of density enhancements revealed in maps of the cosmic microwave background (see Figures 22.9 and 22.17). Overall, we now seem to have a basic picture of how galaxies and large-scale structures formed in the universe, perhaps starting from quantum fluctuations that occurred when the universe was a tiny fraction of a second old [**Section 22.3**].

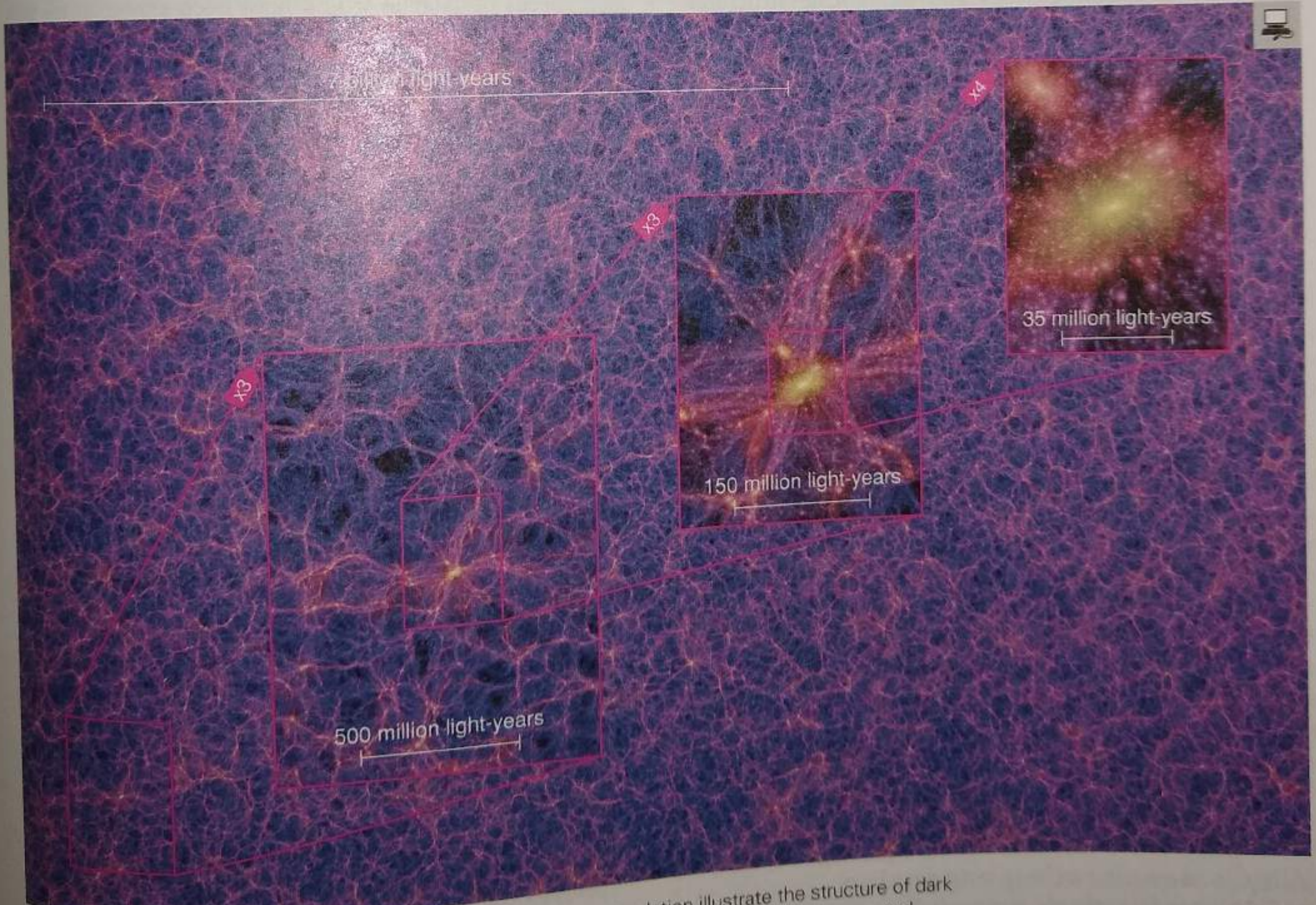


FIGURE 23.16 These images from an extremely large computer simulation illustrate the structure of dark matter in the universe. The main image shows a region similar in size to our observable universe, and the image sequence zooms in on a massive cluster of galaxies. The images show structure as it would appear if we could see dark matter—the brightest clumps in the image represent the highest densities of dark matter. Notice that the large-scale distribution of dark matter has a uniform web-like pattern.

MA Fate of the Universe Tutorial, Lessons 1–3

23.4 DARK ENERGY AND THE FATE OF THE UNIVERSE

Some say the world will end in fire,
Some say in ice.
From what I've tasted of desire
I hold with those who favor fire.
But if it had to perish twice,
I think I know enough of hate
To say that for destruction ice
Is also great
And would suffice.
—*Robert Frost,* Fire and Ice

Over the past few chapters, we have seen that the large-scale development of the universe to date has been governed by two competing processes:

1. the ongoing expansion that began in the Big Bang, which tends to drive galaxies apart from one another, and
2. the gravitational attraction of matter in the universe, which assembles galaxies and larger-scale structures around the density enhancements that emerged from the Big Bang.

These ideas naturally lead us to one of the ultimate questions in astronomy: How will the universe end? After Edwin Hubble discovered the expansion of the universe, astronomers generally assumed that the end would be like one of the two fates in Robert Frost's poem. If gravity were strong enough, the expansion would someday halt and reverse; the universe would then begin collapsing and heating back up, eventually ending in a fiery and cataclysmic crunch. Alternatively, if the total strength of gravity were too weak, gravity would never slow the expansion enough for it to halt and reverse, leading to an icy end in which the universe would grow ever colder as its galaxies moved ever farther apart.

Astronomers therefore began trying to determine whether the gravitational attraction of matter was sufficient to stop the expansion. For many years, the question seemed to hinge on the total amount of dark matter in the universe. However, through a series of observations begun about two decades ago, astronomers have come to realize that the gravity of dark matter might not be the most powerful force in the universe. Much to their surprise, these measurements have shown that the expansion of the universe has been accelerating with time, suggesting that the fate of the universe may be determined by something else—the repulsive force produced by a mysterious form of energy we have come to call *dark energy*.

Why is accelerating expansion evidence for dark energy?

In order to determine how the expansion of the universe changes with time, astronomers need to compare the value of Hubble's constant today to its value at earlier times in the universe's history. Recall that the current value of Hubble's constant is approximately 22 kilometers per second per million light-years [**Section 20.2**]. So, for example, we expect a galaxy located at distance of 100 million light-years to be moving away from us with the expansion of the universe at a speed of about 2200 kilometers per second.

Hubble's constant is called a "constant" because its value is the same across all of space at a particular moment in time. It does not necessarily stay constant with time. In fact, if the galaxies in the universe had always moved away from us at their current speeds, then the reciprocal of Hubble's constant at any given moment in time would always have been equal to the age of the universe at that time (see Mathematical Insight 20.4). In that case, the value of Hubble's constant would continually *decrease* with time. However, the recession speeds of galaxies do not remain the same if forces like gravity or a repulsion driven by dark energy are in play.

For example, if gravity had always been slowing the expansion, then the recession speeds of galaxies would have been greater in the past, meaning that it took *less time* for them to reach their current distances. We would then infer an age for the universe that was *younger* than the age derived from the reciprocal of Hubble's constant. Conversely, if a repulsive force had always accelerated the expansion, then the recession speeds of galaxies would have been slower in the past, so it would have taken them *more* time to reach their current distances and we would infer an *older* age for the universe than we obtain from the reciprocal of Hubble's constant. Therefore, measuring how Hubble's constant has changed with time not only tells us what forces have been acting upon the universe, with implications for its eventual fate, but also is necessary for learning the universe's precise age.

Four Expansion Models To see how different kinds of forces affect the expansion rate and the age for the universe that we infer from it, let's consider four general models for how the expansion rate changes with time, each illustrated in FIGURE 23.17:

- A **recollapsing universe**. In the case of extremely strong gravitational attraction and no repulsive force, the expansion would continually slow down with time and eventually would stop entirely and then reverse. Galaxies would come crashing back together, and the universe would end in a fiery "Big Crunch." We call this a *recollapsing* universe, because the final state, with all matter collapsed together, would look much like the state in which the universe began in the Big Bang.
- A **critical universe**. In the case of gravitational attraction that was not quite strong enough to reverse the expansion in the absence of a repulsive force, the expansion would decelerate forever, leading to a universe that would never collapse but would expand ever more slowly as time progressed. We call this a *critical* universe, because calculations show that it is what we would expect if the total density of the universe were the critical density and only matter (and not dark energy) contributed to this density.

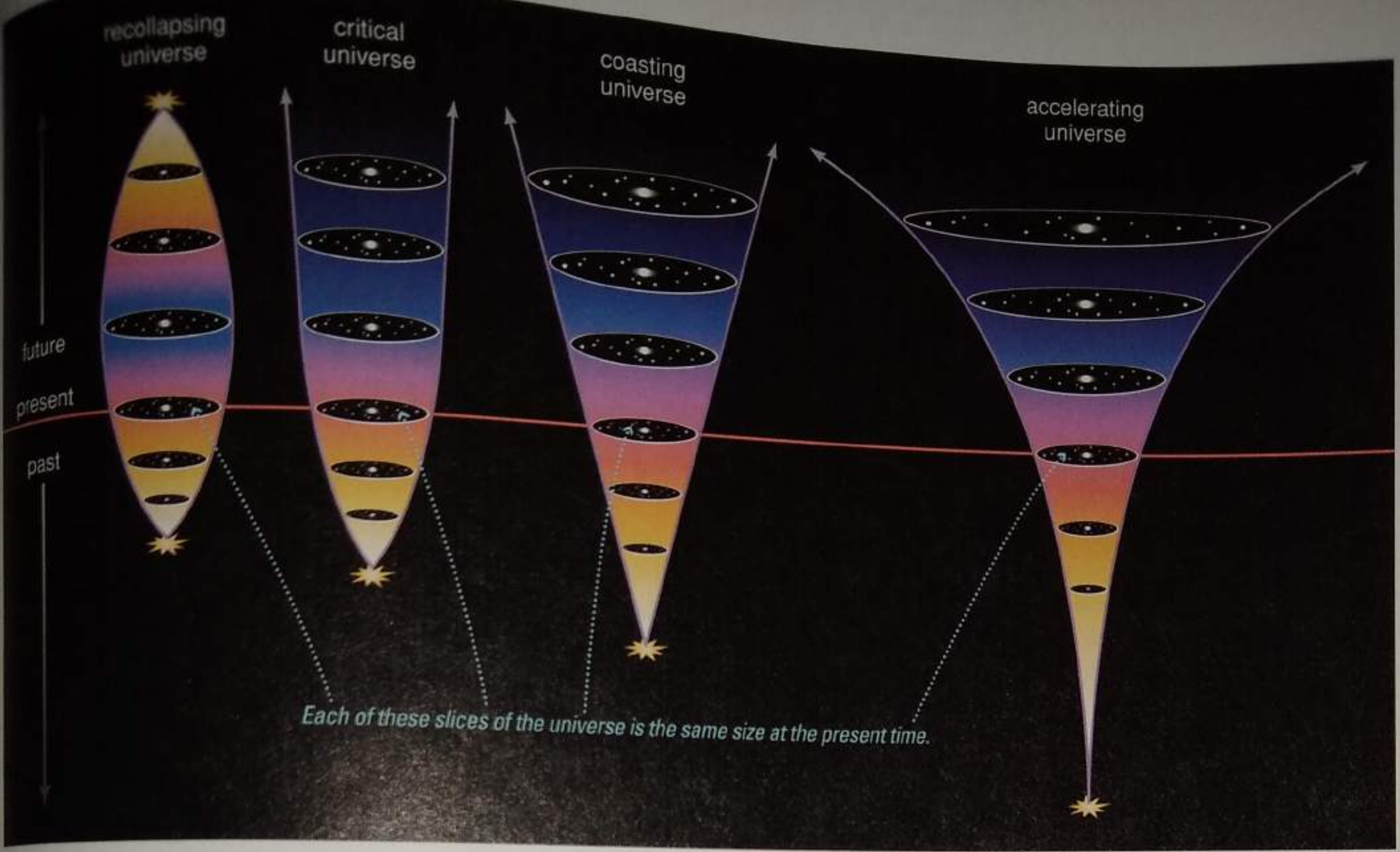


FIGURE 23.17 Four general models for how the universal expansion rate might change with time. Each diagram shows how the size of a circular slice of the universe changes with time in a particular model. The slices are the same size at the present time, marked by the red line, but the models make different predictions about the sizes of the slices in the past and future.

- **A coasting universe.** In the case of weak gravitational attraction and no repulsive force, galaxies would always move apart at approximately the speeds they have today. We call this a *coasting* universe, because it is what we would find if no forces acted to change the expansion rate, much as a spaceship can coast through space at constant speed if no forces act to slow it down or speed it up.
- An **accelerating universe.** In the case of a repulsive force strong enough to overpower gravity, the expansion would *accelerate* with time, causing galaxies to recede from one another with ever-increasing speed.

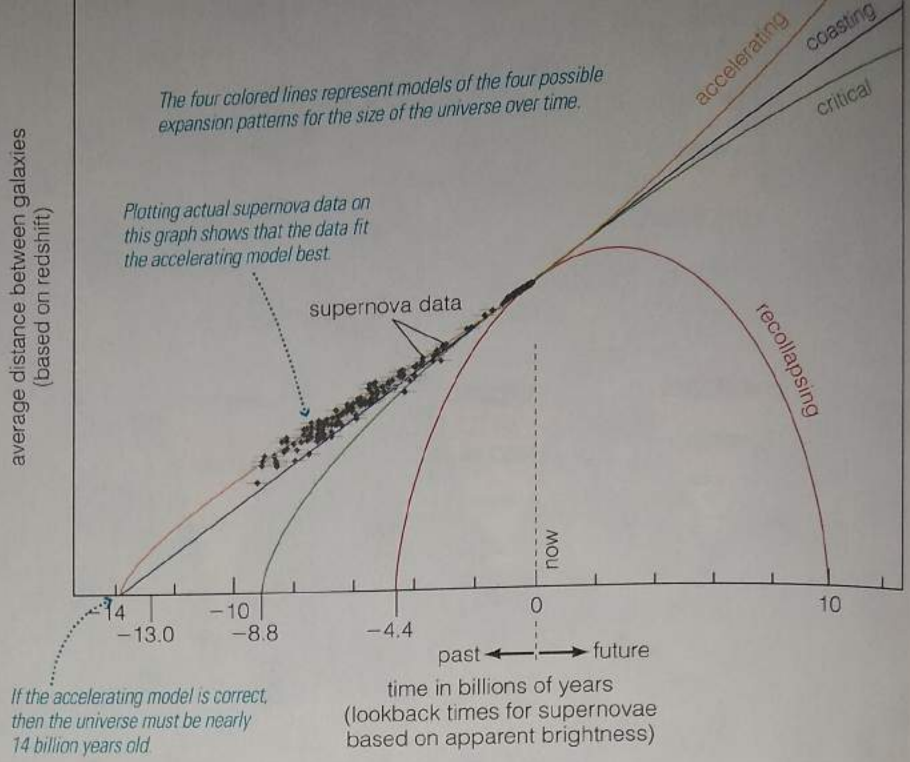
Figure 23.17 also shows that each general model leads to a different age for the universe today. In all four models, the size of a particular region of space and the expansion rate of the universe are the same for the present (indicated by the horizontal red line), because those values must agree with our measurements for the average distance between galaxies today and for Hubble's constant today. However, as we expect, the four models each extend different lengths into the past. The coasting model assumes that the expansion rate never changes, and its starting point therefore indicates the age of the universe that we would infer from Hubble's constant alone. The recollapsing and critical models both give younger ages for the universe (they begin less far into the past), while the accelerating model leads to an older age.

Evidence for Acceleration In principle, it is easy to test which of the four models best corresponds to reality. We simply need to calculate what each one predicts for the universe's expansion rate at different times in the past, and then make observations of how the relationship between redshift and distance changes with time to see which model offers the best match. In practice, measuring how the expansion rate changes through time is quite difficult, because it depends on having reliable standard candles that allow us to determine the distances of extremely distant galaxies. As we discussed in Chapter 20, the most reliable standard candles for great distances are white dwarf supernovae, and in the 1990s two teams of astronomers began large observing programs seeking to detect and measure these stellar explosions.

FIGURE 23.18 shows some of those measurements and compares them with models of how the expansion rate has changed with time. The four solid curves show how the four general models predict that average distance between galaxies should have changed with time; each curve begins at the time at which galaxy distances were zero, which means the time of the Big Bang according to that model. For example, the purple curve for the coasting model shows that if the universe has followed the expansion pattern predicted by this model, then the Big Bang occurred nearly 14 billion years ago; the other curves confirm that the accelerating model would mean a larger age for the universe while the critical and recollapsing models would mean younger ages.

Note that the slopes of the curves represent the predicted expansion rates—the steeper the slope, the faster the expansion—and that only the recollapsing model has a slope that eventually turns downward, indicating a collapsing universe. Also note

FIGURE 23.18 Data from white dwarf supernovae are shown, along with four possible models for the expansion of the universe. Each curve shows how the average distance between galaxies changes with time for a particular model. A rising curve means that the universe is expanding, and a falling curve means that the universe is contracting. Notice that the supernova data fit the accelerating universe better than the other models.



The four colored lines represent models of the four possible expansion patterns for the size of the universe over time.

Plotting actual supernova data on this graph shows that the data fit the accelerating model best.

If the accelerating model is correct, then the universe must be nearly 14 billion years old.

that all the curves pass through the same point and have the same slope at the moment labeled "now," because the current separation between galaxies and the current expansion rate in each case must agree with observations of the present-day universe.

SEE IT FOR YOURSELF

Toss a ball in the air, and observe how it rises and falls. Then make a graph to illustrate your observations, with time on the horizontal axis and height on the vertical axis. Which universe model does your graph most resemble? What is the reason for that resemblance? How would your graph look different if Earth's gravity were not as strong? Would the time for the ball to rise and fall be longer or shorter?

The black dots in Figure 23.18 show actual data from white dwarf supernovae. (The horizontal line through each dot indicates the range of uncertainty in the measured lookback time.) Although there is some scatter in the data points, they clearly fit the curve for the accelerating model better than any of the other models. In other words, the observations agree best with a model of the universe in which the expansion is accelerating with time.

The discovery of an accelerating expansion, first announced in 1998, came as a great surprise to virtually all astronomers. For several years after the announcement, many astronomers feared that these measurements were being misinterpreted, but additional data have only strengthened the evidence of acceleration. In recognition of the importance of this discovery, three of the leaders of the observing teams were awarded the 2011 Nobel Prize in physics.

The Nature of Dark Energy The acceleration of the expansion clearly implies the existence of some force that acts to push galaxies apart, and the source of this force is what we have dubbed *dark energy*. Keep in mind, however, that we have little idea of what the nature of dark energy might actually be. None of the four known forces in nature could

SPECIAL TOPIC

Einstein's Greatest Blunder

Shortly after Einstein completed his general theory of relativity in 1915, he found that it predicted that the universe could not be standing still: The mutual gravitational attraction of all the matter would make the universe collapse. Because Einstein thought at the time that the universe should be eternal and static, he decided to alter his equations. In essence, he inserted a "fudge factor" called the *cosmological constant* that acted as a repulsive force to counteract the attractive force of gravity.

Had he not been so convinced that the universe should be standing still, Einstein might instead have come up with the correct explanation for why the universe is not collapsing: because it is still expanding from the event of its birth. After Hubble discovered universal expansion, Einstein supposedly called his invention of the cosmological constant "the greatest blunder" of his career.

Now that observations of very distant galaxies (using white dwarf supernovae as standard candles) have shown that the universe's expansion is accelerating, Einstein's idea of a universal repulsive force doesn't seem so far-fetched. In fact, observations to date are consistent with the idea that dark energy has properties virtually identical to those that Einstein originally proposed for the cosmological constant. In particular, the amount of dark energy in each volume of space seems to remain unchanged while the universe expands, as if the vacuum of space itself were constantly rippling with energy—which is just what the cosmological constant does in Einstein's equations. We'll need more measurements to know for sure, but it is beginning to seem that Einstein's greatest blunder may not have been a blunder after all.

provide a force to oppose gravity, and while some theories of fundamental physics suggest ways in which energy could fit the bill, no known type of energy produces the right amount of acceleration.

Continued observations of distant supernovae have the potential to tell us exactly how large an effect dark energy has had throughout cosmic history and whether the strength of this effect has changed with time. Already there are some intriguing hints. For example, it appears that the acceleration of the expansion did not begin immediately after the Big Bang, but rather began a few billion years later, indicating that gravity was strong enough to slow the expansion for the first few billion years until dark energy became dominant. (The curve for the accelerating model in Figure 23.18 shows this scenario.) Interestingly, this type of behavior is consistent with an idea that Einstein once introduced but later disavowed in his general theory of relativity, leading some scientists to suggest that dark energy might successfully be described by a term in Einstein's equations that describe gravity (see Special Topic, page 684). Nevertheless, even if this idea turns out to be correct, we remain a long way from an actual understanding of dark energy's nature.

Why is flat geometry evidence for dark energy?

The evidence for the existence of dark energy provided by observations of an accelerating expansion seems quite strong, but it is important to remember that the evidence we have discussed so far comes entirely from measurements of white dwarf supernovae. While we have good reason to think that these supernovae make reliable standard candles, having just a single source of evidence would be cause for at least some concern. Fortunately, during the past decade or so, an entirely different line of evidence for the existence of dark energy has emerged, and it gives results that are fully consistent with the results indicating an accelerating expansion.

Flatness and Dark Energy Recall that Einstein's general theory of relativity tells us that the overall geometry of the universe can take one of three general forms—spherical, flat, or saddle shaped (see Figure 22.15)—and that we can in principle determine which one corresponds to the real universe with careful observations of the cosmic microwave background [**Section 22.3**]. Moreover, these observations now provide strong evidence that the actual geometry is flat (see Figure 22.17), which implies that the total density of *matter plus energy* in the universe must be exactly equal to the critical density.

However, as we have already seen, the total matter density of the universe is not large enough to make the geometry flat on its own, because the total density of matter amounts to only about one-quarter of the critical density. In that case, the remaining three-quarters of the critical density must be in the form of energy. Tellingly, the amount of dark energy required to explain the observed acceleration of the expansion also is about three-quarters of the critical density. The startling conclusion: About three-quarters of the total mass-energy of the universe takes the form of dark energy.

Inventory of the Universe We began this chapter by noting that astronomers today must admit the embarrassing fact that we do not yet know what most of the universe is made of. It appears to be made of things we call dark matter and dark energy, but we do not yet know the true nature of either one. Nevertheless, the observations we have discussed allow us to make quantitative statements about our ignorance. According to the model that best explains the observed temperature patterns in the cosmic microwave background, the total density of matter plus energy in the universe is equal to the critical density, and it is made up of the following components:

- Ordinary matter (made up of protons, neutrons, electrons) makes up slightly more than 4% of the total mass-energy of the universe. Note that this model prediction agrees with what we find from observations of deuterium in the universe. Some of this matter is in the form of stars (about 0.5% of the universe's mass-energy). The rest is presumed to be in the form of intergalactic gas, such as the hot gas found in galaxy clusters.
- Some form of exotic dark matter—most likely weakly interacting massive particles (WIMPs)—makes up about 22% of the mass-energy of the universe, in close agreement with what we infer from measurements of the masses of clusters of galaxies.
- Dark energy makes up the remaining 74% of the mass-energy of the universe, accounting both for the observed acceleration of the expansion and for the pattern of temperatures in the cosmic microwave background.

FIGURE 23.19 shows this inventory of the universe as a pie chart, and **FIGURE 23.20** summarizes the evidence we have discussed for the existence of dark matter and dark energy. We may not yet know what either dark matter or dark energy actually is, but our measurements of how much matter and energy may be out there are becoming quite precise.

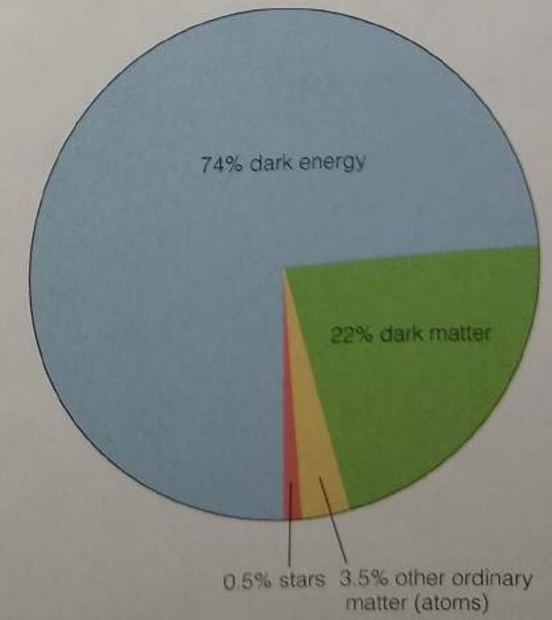


FIGURE 23.19 This pie chart shows the proportion of each of the major components of matter and energy in the universe, based on current evidence.

The Age of the Universe Models that explain the temperature variations in the cosmic microwave background not only give us an inventory of the universe but also make precise predictions about the age of the universe. According to the model that gives the best agreement to the data (the same model used for the inventory above), the age of the universe is about 13.7 billion years, with an uncertainty of about 0.2 billion years (200 million years). That is why, throughout this book, we have said that the universe is "about 14 billion years old." Note that this age is in good agreement with what we infer from Hubble's constant and observed changes in the expansion, and also agrees well with the fact that the oldest stars in the universe appear to be about 13 billion years old.

What is the fate of the universe?

This is the way the world ends
This is the way the world ends
This is the way the world ends
Not with a bang but a whimper.
—*T. S. Eliot, from* The Hollow Men

We are now ready to return to the question of the fate of the universe. If we think in terms of Robert Frost's poetry at the beginning of this section, the recollapsing universe is the only one of our four possible expansion models that has an end in fire, and the data do not fit that model. Therefore, it seems that the universe is doomed to expand forever, its galaxies receding ever more quickly into an icy, empty future. The end, it would seem, is more likely to be like that in T. S. Eliot's excerpt above.

THINK ABOUT IT

Do you think that one of the possible fates (fire or ice) is preferable to the other? Why or why not?

The Next 10^{100} Years What exactly will happen to the universe as time goes on in an ever-expanding universe? We can use our current understanding of physics to hypothesize about the answer.

First, the answer obviously depends on how much the expansion of the universe accelerates in the future. Some scientists speculate that the repulsive force due to dark energy might strengthen with time. In that case, perhaps in a few tens of billions of years, the growing repulsive force would tear apart our galaxy, our solar system, and even matter itself in a catastrophic event sometimes called the "Big Rip." However, evidence for this type of growing repulsion is very weak, and it seems more likely that the expansion will continue to accelerate more gradually.

If the universe continues to expand in this way, galaxies and galaxy clusters will remain gravitationally bound far into the future. Galaxies will not always look the same, however, because the star–gas–star cycle [**Section 19.2**] cannot continue forever. With each generation of stars, more mass becomes locked up in planets, brown dwarfs, white dwarfs, neutron stars, and black holes. Eventually, about a trillion years from now, even the longest-lived stars will burn out, and the galaxies will fade into darkness.

At this point, the only new action in the universe will occur on the rare occasions when two objects—such as two brown dwarfs or two white dwarfs—collide within a galaxy. The vast distances separating star systems in galaxies make such collisions extremely rare. For example, the probability of our Sun (or the white dwarf that it will become) colliding with another star is so small that it would be expected to happen only once in a quadrillion (10^{15}) years. However, given a long enough period of time, even low-probability events will eventually happen many times. If a star system experiences a collision once in a quadrillion years, it will experience about 100 collisions in 100 quadrillion (10^{17}) years. By the time the universe reaches an age of 10^{20} years, star systems will have suffered an average of 100,000 collisions each, making a time-lapse history of any galaxy look like a cosmic game of billiards.

These multiple collisions will severely disrupt galaxies. As in any gravitational encounter, some objects lose energy in such collisions and some gain energy. Objects that lose energy will eventually fall to the galactic center, forming a supermassive black hole where our galaxy used to be. Objects that gain enough energy will be flung into intergalactic space, to be carried away from their home galaxies with the expansion of the universe. The remains of the universe will consist of widely separated black holes with masses as great as a trillion solar masses, and widely scattered planets, brown dwarfs, and stellar corpses. If Earth somehow survives, it will be a frozen chunk of rock in the darkness of the expanding universe, billions of light-years away from any other solid object.

If grand unified theories [**Section 22.1**] are correct, Earth still cannot last forever. These theories predict that protons will eventually fall apart. The predicted lifetime of protons is extremely long: a half-life of at least 10^{33} years. However, if protons really do decay, then by the time the universe is 10^{40} years old, Earth and all other atomic matter will have disintegrated into radiation and subatomic particles.

The final phase may come through a mechanism proposed by physicist Stephen Hawking. Recall that he predicted that black holes must eventually "evaporate," turning their mass-energy into *Hawking radiation* [**Section S4.4**]. The process is so slow that we do not expect to be able to see it from any existing black holes, but if it really occurs, then black holes in the distant future will disappear in brilliant bursts of radiation. The largest black holes will last the longest, but even trillion-solar-mass black holes will evaporate sometime after the universe reaches an age of 10^{100} years. From then on, the universe will consist only of individual photons and subatomic particles, each separated by enormous distances from the others. Nothing new will ever happen, and no events will ever occur that would allow an omniscient observer to distinguish past from future. In a sense, the universe will finally have reached the end of time.

Forever Is a Long Time Lest any of this sound depressing, keep in mind that we are talking about incredibly long times. Remember that 10^{11} years is already nearly 10 times the current age of the universe (because 14 billion years is the same as 1.4×10^{10} years), 10^{12} years is another 10 times that, and so on. A time of 10^{100} years is so long that we can scarcely describe it, but one way to think about it (thanks to the late Carl Sagan) is to imagine that you wanted to write on a piece of paper a number that consisted of a 1 followed by 10^{100} zeros (that is, the number $10^{10^{100}}$). It sounds easy, but a piece of paper large enough to hold all those zeros *would not fit in the observable universe* today. If that still does not alleviate your concerns, you may be glad to know that a few creative thinkers are already speculating about ways in which the universe might avoid an icy fate or undergo rebirth, even after the end of time.

Perhaps of greater significance, speculating about the future of the universe means speculating about forever, and forever leaves us with a very long time in which to make new discoveries. After all, it is only in the past century that we learned that we live in an expanding universe, and only in the past couple of decades that we were surprised to learn that the expansion is accelerating. The universe may yet hold other surprises that might force us to rethink what might happen between now and the end of time.

The Big Picture

Putting Chapter 23 into Context

We have found that there may be much more to the universe than meets the eye. Dark matter too dim for us to see seems to far outweigh the stars, and a mysterious dark energy may be even more prevalent. Together, dark matter and dark energy have probably been the dominant agents of change in the overall history of the universe. Here are some key "big picture" points to remember about this chapter:

- Dark matter and dark energy sound very similar, but they are each hypothesized to explain different observations. Dark matter is thought to exist because we detect its gravitational influence. Dark energy is a term given to the source of the force that may be accelerating the expansion of the universe.
- Either dark matter exists or we do not understand how gravity operates across galaxy-size distances. There are many reasons to be confident about our understanding of gravity, leading most astronomers to conclude that dark matter is real.
- Dark matter seems to be by far the most abundant form of mass in the universe, and therefore the primary source of the gravity that has formed galaxies and larger-scale structures from tiny density enhancements that existed in the early universe. We still do not know what dark matter is, but we suspect it is largely made up of some type of as-yet-undiscovered subatomic particles.
- The existence of dark energy is supported by evidence from observations both of the expansion rate through time and of temperature variations in the cosmic microwave background. Together, these observations have led to a model of the universe that gives us precise values for the inventory of its contents and its age.
- The fate of the universe seems to depend on whether the expansion of the universe continues forever, and the acceleration of the expansion suggests that it will. Nevertheless, forever is a long time, and only time will tell whether new discoveries will alter our speculations about the distant future.

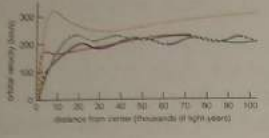
SUMMARY OF KEY CONCEPTS

23.1 UNSEEN INFLUENCES IN THE COSMOS

- **What do we mean by dark matter and dark energy?** Dark matter and dark energy have never been directly observed, but each has been proposed to exist because it seems the simplest way to explain a set of observed motions in the universe. **Dark matter** is the name given to the unseen mass whose gravity governs the observed motions of stars and gas clouds. **Dark energy** is the name given to the form of energy thought to be causing the expansion of the universe to accelerate.

23.2 EVIDENCE FOR DARK MATTER

- **What is the evidence for dark matter in galaxies?** The orbital velocities of stars and gas clouds in galaxies do not change much with distance from the center of the galaxy. Applying Newton's laws of gravitation and motion to these orbits leads to the conclusion that the total mass of a galaxy is far larger than the mass of its stars. Because no detectable visible light is coming from this matter, we call it dark matter.



- **What is the evidence for dark matter in clusters of galaxies?** We have three different ways of measuring the amount of dark matter in clusters of galaxies: from galaxy orbits, from the temperature of the hot gas in clusters, and from the **gravitational lensing** predicted by Einstein. All these methods are in agreement, indicating that the total mass of a galaxy cluster is about 50 times the mass of its stars, implying huge amounts of dark matter.

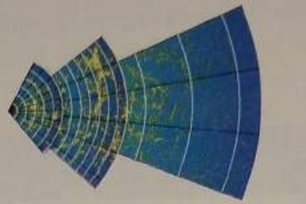
- **Does dark matter really exist?** We infer that dark matter exists from its gravitational influence on the matter we can see, leaving two possibilities: Either dark matter exists or there is something wrong with our understanding of gravity. We cannot rule out the latter possibility, but we have good reason to be confident about our current understanding of gravity and the idea that dark matter is real.

- **What might dark matter be made of?** Some of the dark matter could be ordinary (baryonic) matter in the form of dim stars or planetlike objects, but the amount of deuterium left over from the Big Bang and the patterns in the cosmic microwave background both indicate that ordinary matter adds up to only about one-seventh of the total amount of matter. The rest of the matter is hypothesized to be exotic (nonbaryonic) dark matter consisting of as-yet-undiscovered particles called **WIMPs**.

23.3 DARK MATTER AND GALAXY FORMATION

- **What is the role of dark matter in galaxy formation?** Because most of a galaxy's mass is in the form of dark matter, the gravity of that dark matter is probably what formed protogalactic clouds and then galaxies from slight density enhancements in the early universe.

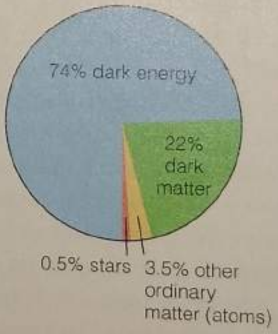
- **What are the largest structures in the universe?** Galaxies appear to be distributed in gigantic chains and sheets that surround great **voids**. These **large-scale structures** trace their origin directly back to regions of slightly enhanced density early in time.



23.4 THE FATE OF THE UNIVERSE

- **Why is accelerating expansion evidence for dark energy?** Observations of distant supernovae show that the expansion of the universe has been speeding up for the last several billion years. No one knows the nature of the mysterious force that could be causing this acceleration. However, its characteristics are consistent with models in which the force is produced by a form of dark energy that pervades the universe.

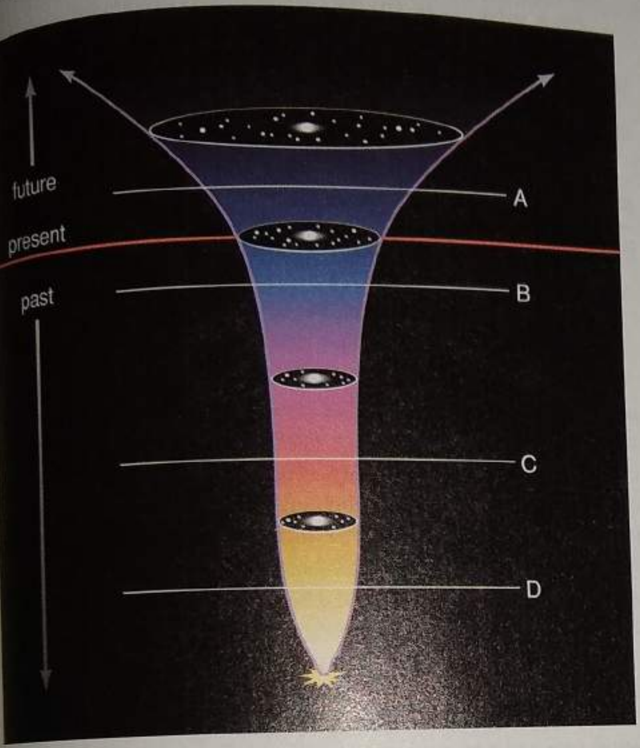
- **Why is flat geometry evidence for dark energy?** Observations of the cosmic microwave background also support the existence of dark energy because they demonstrate that the overall geometry of the universe is nearly flat. According to Einstein's general theory of relativity, the universe can be flat only if the total amount of mass-energy it contains is equal to the critical density, but measurements of the total amount of matter show that it represents only about one-quarter of the critical density. We therefore infer that about three-quarters of the total mass-energy is in the form of dark energy—the same amount implied by the supernova observations.



- **What is the fate of the universe?** If dark energy is indeed what's driving the acceleration of the universe's expansion, then we expect the expansion to continue accelerating into the future, as long as the effects of dark energy do not change with time and there are no other factors that affect the fate of the universe.

VISUAL SKILLS CHECK

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 23 Visual Quiz at MasteringAstronomy®.



The schematic figure to the left shows a more complicated expansion history than the four idealized models shown in Figure 23.17. Answer the following questions, using the information given in this figure.

1. At time A, is the expansion of the universe accelerating, coasting, or decelerating?
2. At time B, is the expansion of the universe accelerating, coasting, or decelerating?
3. At time C, is the expansion of the universe accelerating, coasting, or decelerating?
4. At time D, is the expansion of the universe accelerating, coasting, or decelerating?

EXERCISES AND PROBLEMS

For instructor-assigned homework go to MasteringAstronomy®.

REVIEW QUESTIONS

Short-Answer Questions Based on the Reading

1. Define *dark matter* and *dark energy*, and clearly distinguish between them. What types of observations have led scientists to propose the existence of each of these unseen influences?
2. Describe how orbital speeds in the Milky Way depend on distance from the galactic center. How does this relationship indicate the presence of large amounts of dark matter?
3. How do orbital speeds depend on distance from the galactic center in other spiral galaxies, and what does this tell us about dark matter in spiral galaxies?
4. How do we measure the masses of elliptical galaxies? What do these masses lead us to conclude about dark matter in elliptical galaxies?
5. Briefly describe the three different ways of measuring the mass of a cluster of galaxies. Do the results from the different methods agree? What do they tell us about dark matter in galaxy clusters?
6. What is *gravitational lensing*? Why does it occur? How can we use it to estimate the masses of lensing objects?
7. Briefly explain why the conclusion that dark matter exists rests on assuming that we understand gravity correctly. Is it possible that our understanding of gravity is not correct? Explain.
8. In what sense is dark matter "dark"? Briefly explain why objects like you, planets, and even dim stars qualify as dark matter.
9. What evidence indicates that most of the matter in the universe cannot be ordinary (baryonic) matter?
10. Explain what we mean when we say that a neutrino is a *weakly interacting particle*. Why can't the dark matter in galaxies be made of neutrinos?
11. What do we mean by *WIMPs*? Why does it seem likely that dark matter consists of these particles, even though we do not yet know what they are?
12. Briefly explain why dark matter is thought to have played a major role in the formation of galaxies and larger structures in the universe. What evidence suggests that larger structures are still forming?
13. What do the *large-scale structures* of the universe look like? Explain why we think these structures reflect the density patterns of the early universe.
14. Describe and compare the four general patterns for the expansion of the universe: *recollapsing, critical, coasting,* and *accelerating*. Observationally, how can we decide which of the four general expansion models best describes the present-day universe?
15. How do observations of distant supernovae provide evidence for dark energy?
16. How do observations of the cosmic microwave background provide evidence for dark energy?
17. Based on current evidence, what is the overall inventory of the mass-energy contents of the universe?
18. What implications does the evidence for dark energy have for the fate of the universe?