ASTRONOMY

Chapter 29 THE BIG BANG

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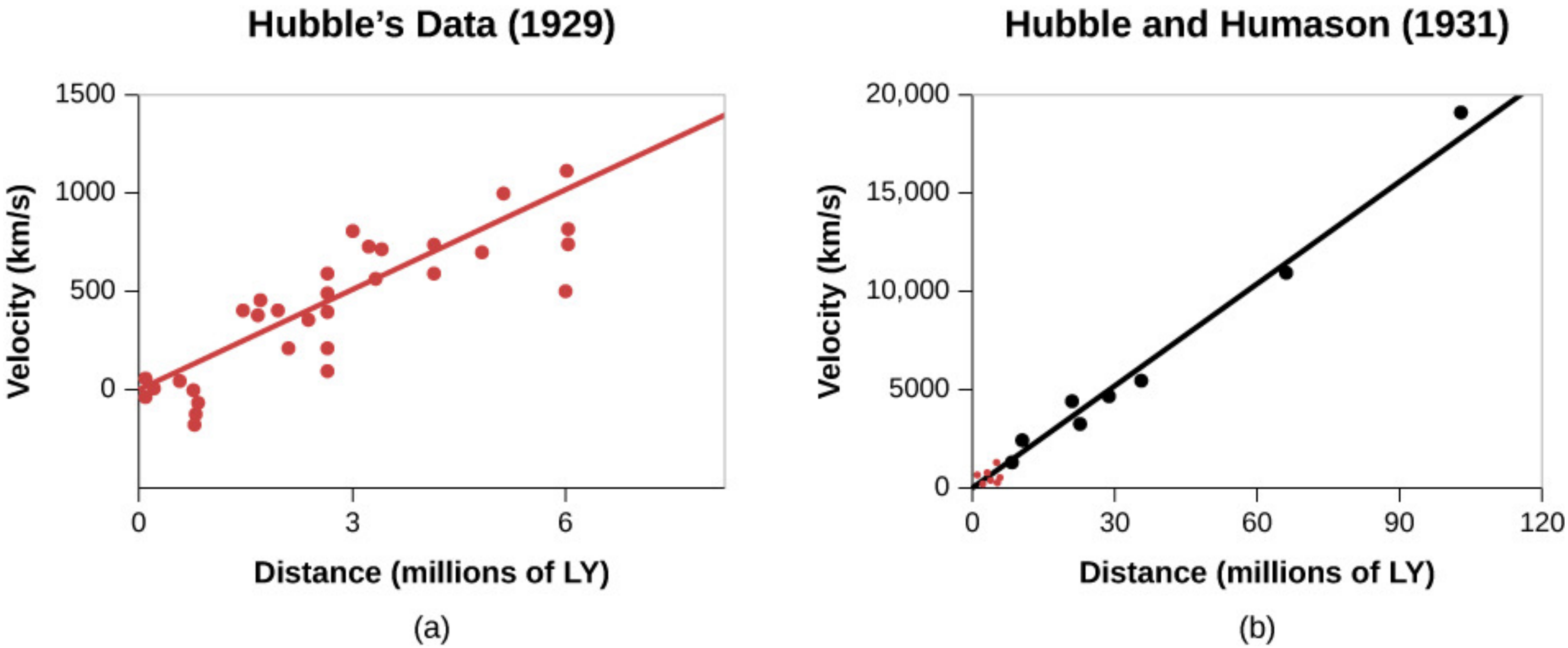
WHERE DID MATTER COME FROM?

Up to this point, we've discussed how the matter produced in the early universe gradually assembled into planets, stars, and galaxies.

However, we have not yet answered one big question: Where did matter itself come from?

To answer this question, we must go beyond even the most distant galaxies. We must go back not only to the origins of matter and energy but to the beginning of time itself.

FIGURE 26.15



Hubble's Law.

(a) These data show Hubble's original velocity-distance relation, adapted from his 1929 paper in the *Proceedings of the National Academy of Sciences*.

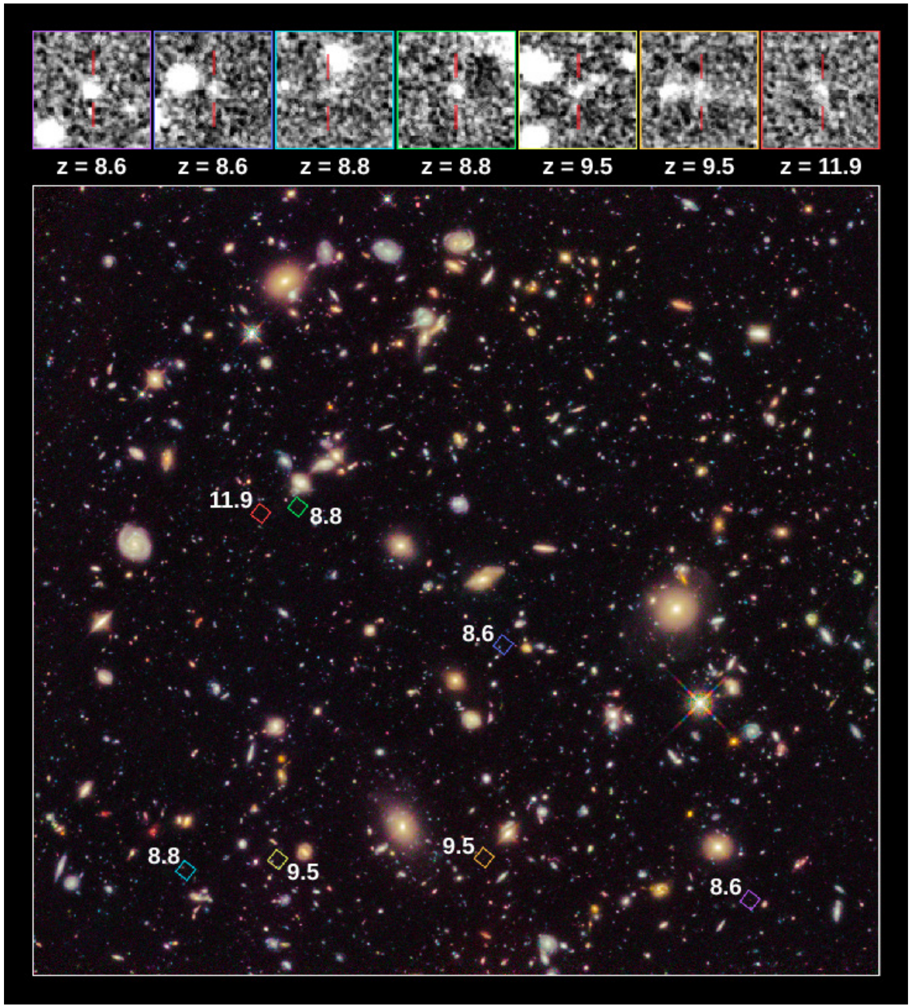
(b) These data show Hubble and Humason's velocity-distance relation, adapted from their 1931 paper in *The Astrophysical Journal*. The red dots at the lower left are the points in the diagram in the 1929 paper. Comparison of the two graphs shows how rapidly the determination of galactic distances and redshifts progressed in the 2 years between these publications.

THE BIG BANG THEORY

This theory is based on applying known and tested laws of physics to the idea that all we see today, from Earth to the cosmic horizon, began as an incredibly tiny, hot, and dense collection of matter and radiation.

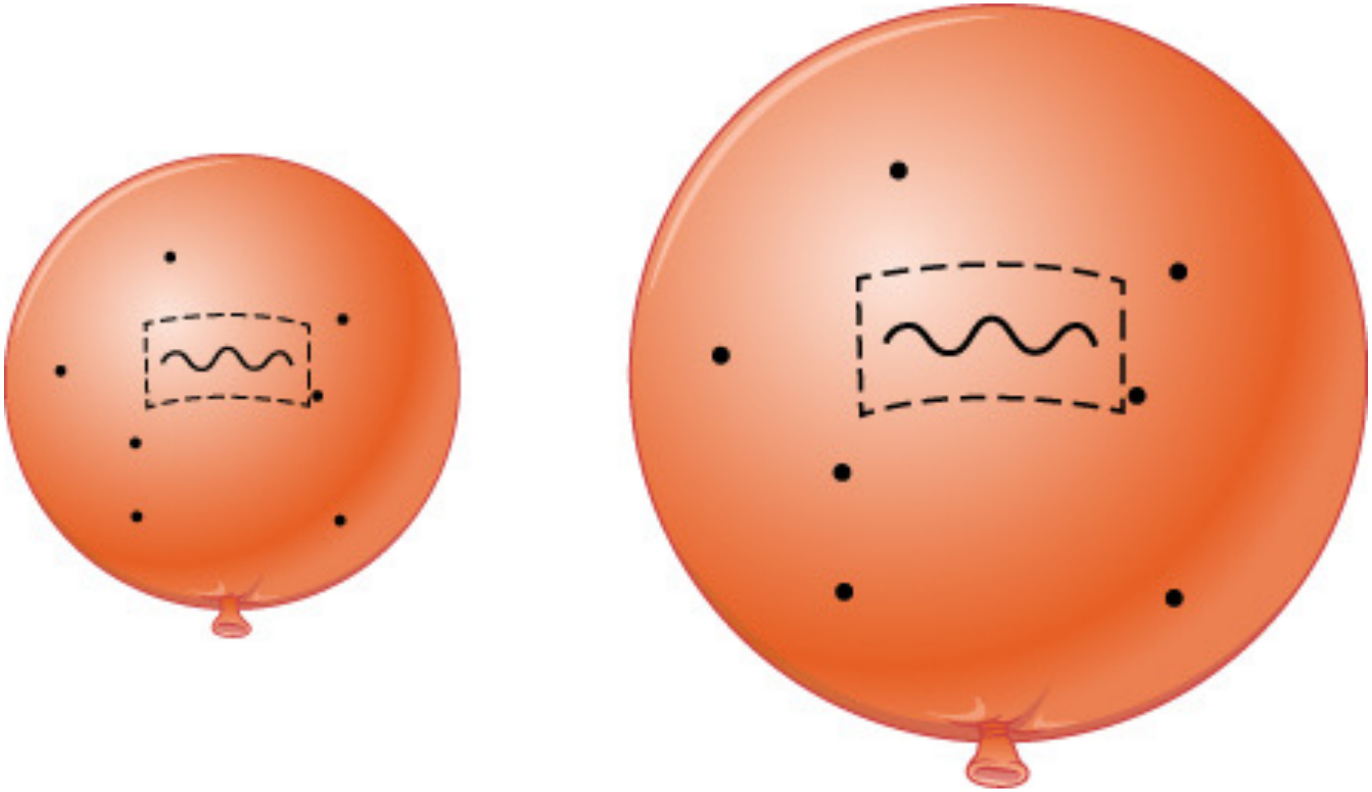
The Big Bang theory successfully describes how the expansion and cooling of this intense mixture of particles and photons could have led to the present universe of stars and galaxies, and it explains many aspects of today’s universe with impressive accuracy.

FIGURE 29.10



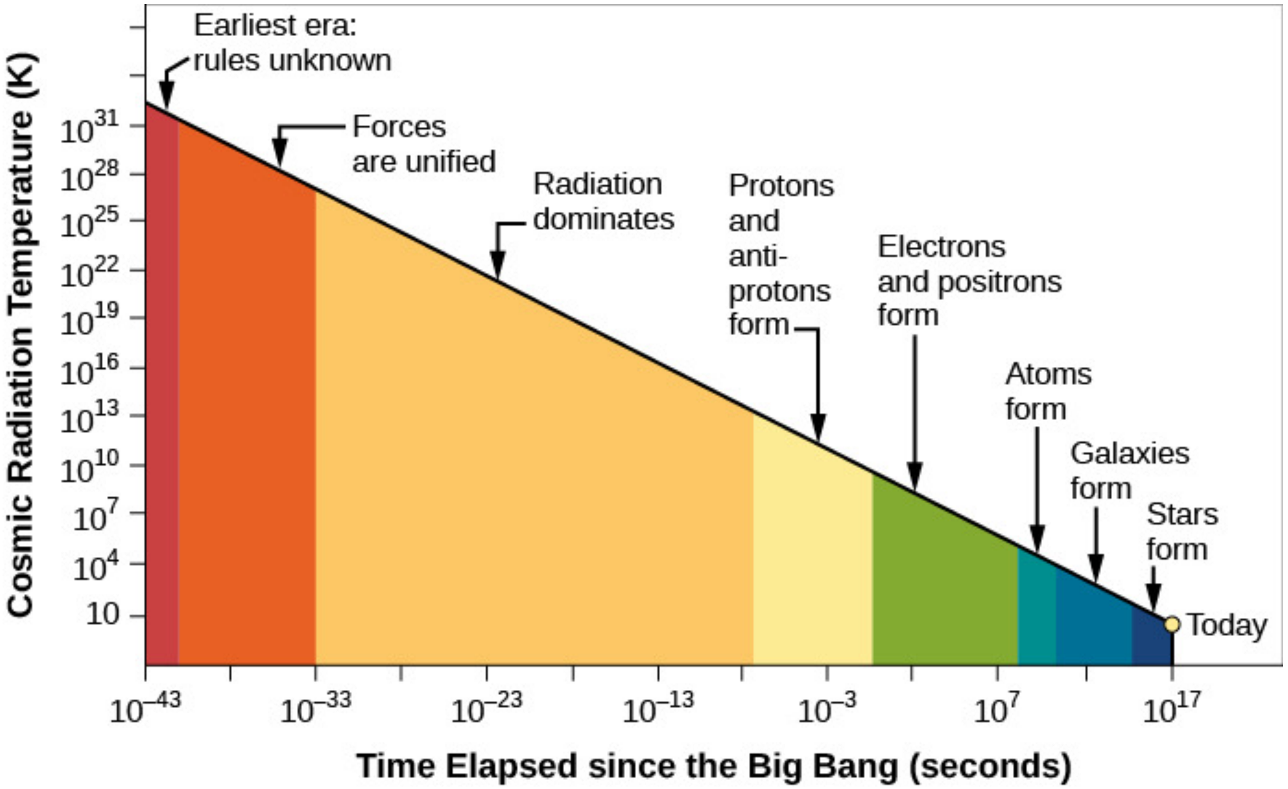
Hubble Ultra-Deep Field. This image, called the Hubble Ultra Deep Field, shows faint galaxies, seen very far away and therefore very far back in time. The colored squares in the main image outline the locations of the galaxies. Enlarged views of each galaxy are shown in the black-and-white images. The red lines mark each galaxy's location. The "redshift" of each galaxy is indicated below each box, denoted by the symbol "z." The redshift measures how much a galaxy's ultraviolet and visible light has been stretched to infrared wavelengths by the universe's expansion. The larger the redshift, the more distant the galaxy, and therefore the further astronomers are seeing back in time. One of the seven galaxies may be a distance breaker, observed at a redshift of 11.9. If this redshift is confirmed by additional measurements, the galaxy is seen as it appeared only 380 million years after the Big Bang, when the universe was less than 3% of its present age. (credit: modification of work by NASA, ESA, R. Ellis (Caltech), and the UDF 2012 Team)

FIGURE 29.7



Expansion and Redshift. As an elastic surface expands, a wave on its surface stretches. For light waves, the increase in wavelength would be seen as a redshift.

FIGURE 29.13



Temperature of the Universe. This graph shows how the temperature of the universe varies with time as predicted by the standard model of the Big Bang. Note that both the temperature (vertical axis) and the time in seconds (horizontal axis) change over vast scales on this compressed diagram.

PARTICLE CREATION AND ANNIHILATION

The universe was so hot during the first few seconds after the Big Bang that photons could transform themselves into matter, and vice versa, in accordance with Einstein's formula E=mc^2

Reactions that create and destroy matter are now relatively rare in the universe, but physicists can reproduce such reactions in laboratories

A HOT, DENSE MIX OF PHOTONS, MATTER, AND ANTIMATTER

Similar reactions can produce or destroy any particle-antiparticle pair, such as a proton and antiproton or a neutron and antineutron.

The early universe therefore was filled with an extremely hot, dense mix of photons, matter, and antimatter, converting furiously back and forth.

Despite all these vigorous reactions, describing conditions in the early universe is straightforward, at least in principle. We can use the laws of physics to calculate the proportions of the various forms of radiation and matter at each moment in the universe's early history.

The only difficulty is our incomplete understanding of the laws of physics.

THE PARTICLE ERA

As long as the universe was hot enough for the spontaneous creation and annihilation of particles, the total number of particles was roughly in balance with the total number of photons.

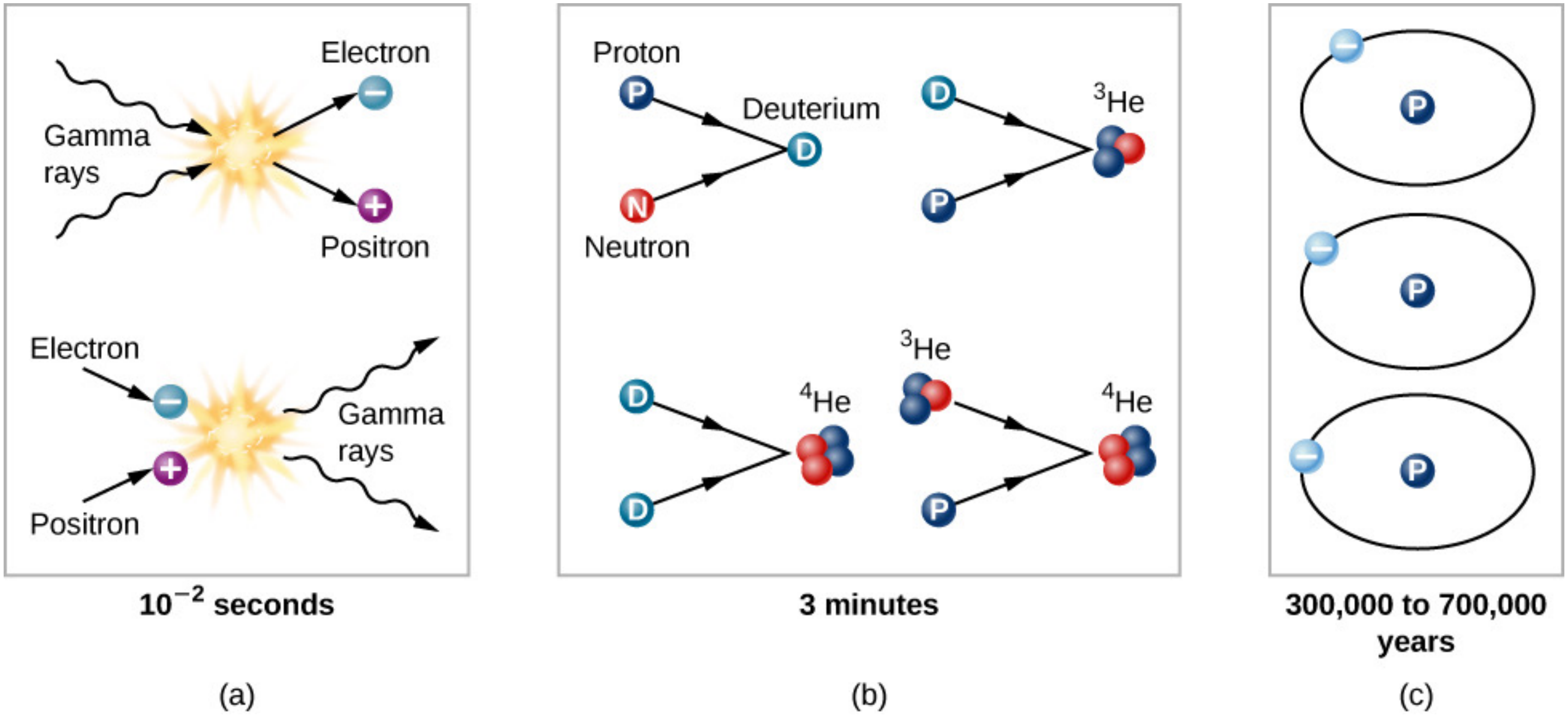
Once it became too cool for this spontaneous exchange of matter and energy to continue, photons became the dominant form of energy in the universe.

<u>The Particle Era ended when the age of the universe was about 1 millisecond -- at the moment when spontaneous particle production ceased.</u>

During the early parts of the particle era (and earlier eras), photons produced all sorts of exotic particles that we no longer find freely existing in the universe today, including quarks—the building blocks of protons and neutrons.

As the universe cooled, all the quarks eventually combined into protons and neutrons, which then shared the universe with other particles such as electrons and neutrinos.

FIGURE 29.14



Particle Interactions in the Early Universe.

(a) In the first fractions of a second, when the universe was very hot, energy was converted into particles and antiparticles. The reverse reaction also happened: a particle and antiparticle could collide and produce energy.

(b) As the temperature of the universe decreased, the energy of typical photons became too low to create matter. Instead, existing particles fused to create such nuclei as deuterium and helium.

(c) Later, it became cool enough for electrons to settle down with nuclei and make neutral atoms. Most of the universe was still hydrogen.

PROTONS SLIGHTLY OUTNUMBERED ANTIPROTONS

The particle era ended when the universe reached an age of 1 millisecond (0.001 second), at which point it was no longer hot enough to produce protons and antiprotons spontaneously from pure energy.

If the universe had contained equal numbers of protons and antiprotons at that time, they all would have annihilated each other, creating photons and leaving essentially no matter in the universe.

Since the universe contains a significant amount of matter today, we conclude that protons must have slightly outnumbered antiprotons at the end of the particle era.

THE ERA OF NUCLEOSYNTHESIS

The physics we have discussed so far all occurred within the first 0.001 second of the universe’s existence—less time than it takes you to blink an eye.

At this point, the protons and neutrons left over after the annihilation of antimatter began to fuse into heavier nuclei.

However, the temperature of the universe remained so high that most nuclei were blasted apart by gamma rays as fast as they formed.

This dance of fusion and demolition marked the era of nucleosynthesis, which ended when the universe was about 5 minutes old.

THE CHEMICAL COMPOSITION OF THE UNIVERSE

When the universe was about 5 minutes old, the density in the expanding universe had dropped so much that fusion no longer occurred, even though the temperature was still about a billion Kelvin —much hotter than the temperature of the Sun's core.

When fusion ceased at the end of the era of nucleosynthesis, the chemical content of the universe had become (by mass) about 75% hydrogen and 25% helium, along with trace amounts of deuterium (hydrogen with a neutron) and lithium (the next heaviest element after hydrogen and helium).

Except for the small proportion of matter (2%) that stars later forged into heavier elements, the chemical composition of the universe remains the same today.

THE ERA OF NUCLEI

After fusion ceased, the universe consisted of a very hot plasma of hydrogen nuclei, helium nuclei, and free electrons. The fully ionized nuclei moved independently of electrons during this period (rather than being bound with electrons in neutral atoms), so we call it the era of nuclei.

Throughout this era, photons bounced rapidly from one electron to the next, just as they do deep inside the Sun today, never traveling far between collisions. Any time a nucleus managed to capture an electron to form a complete atom, one of the photons quickly ionized it.

The era of nuclei lasted until the universe was about 380,000 years old, by which point the universe had cooled to a temperature of about 3000 K—roughly half the temperature of the Sun's surface today.

Hydrogen and helium nuclei finally captured electrons for good, forming stable, neutral atoms for the first time. With electrons now bound into atoms, the universe became transparent, as if a thick fog had suddenly lifted.

- These photons are the cosmic microwave background!

EVIDENCE FOR THE BIG BANG THEORY

What makes us think that the Big Bang theory really describes events that occurred nearly 14 billion years ago? Like any scientific theory, the Big Bang theory is a model of nature designed to explain a set of observations.

The model was inspired by Edwin Hubble's discovery of the universe's expansion: If the universe has been expanding for billions of years, then simple physical reasoning suggests that conditions ought to have been much denser and hotter in the past.

However, the model was not accepted as a valid scientific theory until its major predictions were verified through additional observations and experiments.

TWO KEY REASONS

The Big Bang theory has gained wide scientific acceptance for two key reasons:

It predicts that the radiation **[light]** released at the end of the era of nuclei should still be present today in the form of a cosmic microwave background.

- **We have detected this background and find that its characteristics precisely match those predicted by the theory.**

It predicts the precise fraction of the original hydrogen in the universe that should have fused into helium during the era of nucleosynthesis.

- **Observations of the actual helium content of the universe closely match the predicted value.**

RADIATION LEFT OVER FROM THE BIG BANG

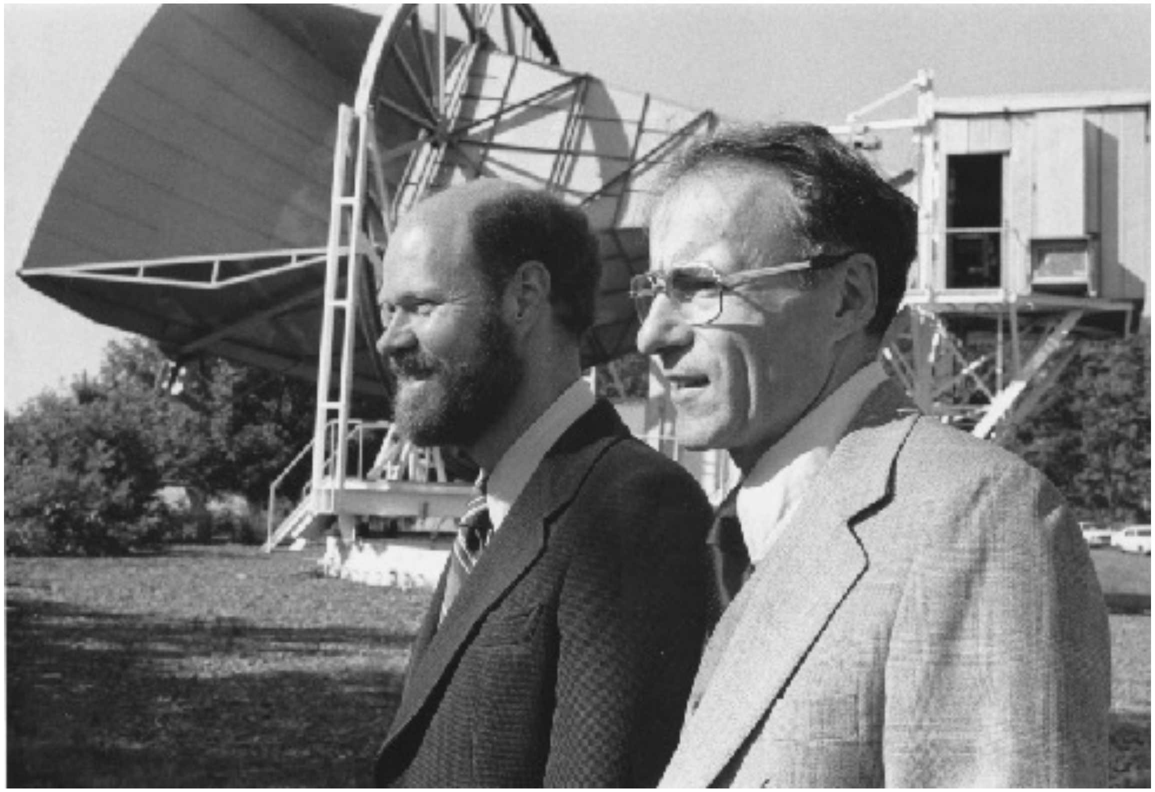
The discovery of the cosmic microwave background was announced in 1965.

Arno Penzias and Robert Wilson, two physicists working at Bell Laboratories in New Jersey, were calibrating a sensitive microwave antenna designed for satellite communications.

Much to their annoyance, they kept finding unexpected “noise” in every measurement they made. The noise was the same no matter where they pointed their antenna, indicating that it came from all directions in the sky and ruling out the possibility that it came from any particular astronomical object or from any place on Earth.

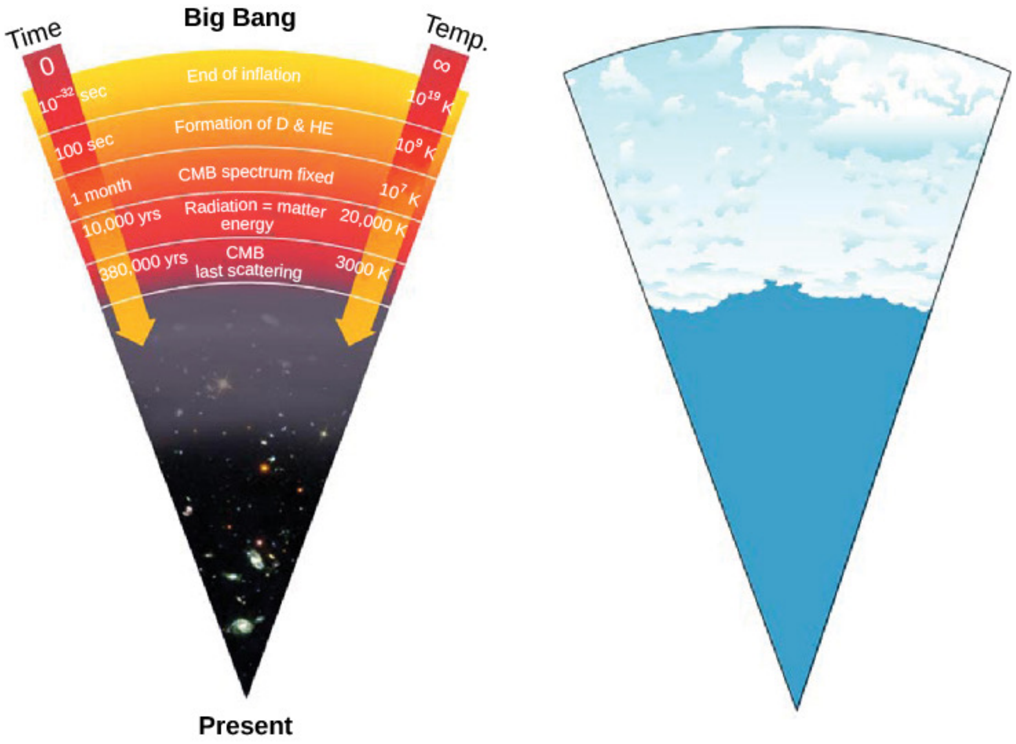
Figure 13.6. Page 218. *The Cosmic Perspective Fundamentals*. Publisher: Addison-Wesley. © 2010

FIGURE 29.16



Robert Wilson (left) and Arno Penzias (right). These two scientists are standing in front of the horn-shaped antenna with which they discovered the cosmic background radiation. The photo was taken in 1978, just after they received the Nobel Prize in physics.

FIGURE 29.15



(a) (b)

Cosmic Microwave Background and Clouds Compared.

(a) Early in the universe, photons (electromagnetic energy) were scattering off the crowded, hot, charged particles and could not get very far without colliding with another particle. But after electrons and photons settled into neutral atoms, there was far less scattering, and photons could travel over vast distances. The universe became transparent. As we look out in space and back in time, we can't see back beyond this time.

(b) This is similar to what happens when we see clouds in Earth's atmosphere. Water droplets in a cloud scatter light very efficiently, but clear air lets light travel over long distances. So as we look up into the atmosphere, our vision is blocked by the cloud layers and we can't see beyond them. (credit: modification of work by NASA)

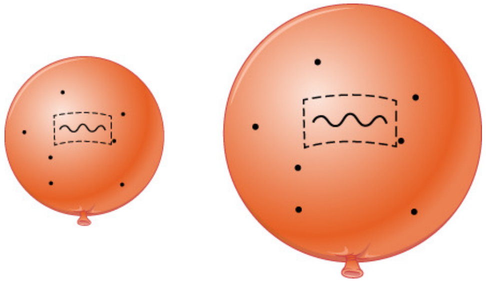
THEORY MEETS PRACTICE

Meanwhile, physicists at nearby Princeton University were busy calculating the expected characteristics of the radiation left over from the heat of the Big Bang.

They concluded that, if the Big Bang had really occurred, this radiation should be permeating the entire universe and should be detectable with a microwave antenna.

The Princeton group soon met with Penzias and Wilson to compare notes, and both teams realized that the “noise” from the Bell Labs antenna was the predicted cosmic microwave background—the first strong evidence that the Big Bang really did happen.

THEORY PREDICTS



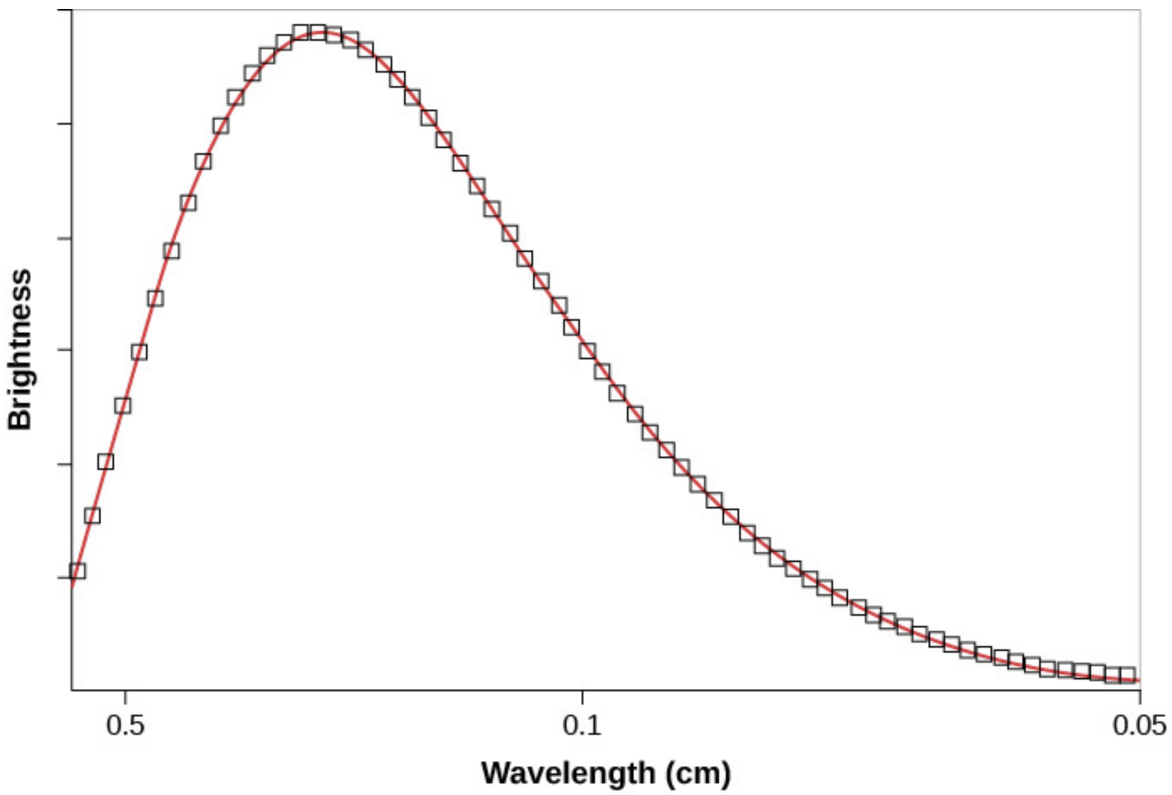
The Big Bang theory predicts that the cosmic microwave background should have an essentially perfect thermal radiation spectrum because it came from the heat of the universe itself.

- the theory predicts the approximate wavelength at which this thermal radiation spectrum should peak. When the radiation of the cosmic microwave background broke free, the temperature of the universe was about 3000 K, similar to the surface temperature of a red giant star.

The spectrum of the cosmic microwave background therefore originally peaked in visible light, just like the thermal radiation from a red star.

- However, the universe has expanded by a factor of about 1000 since that time, stretching the wavelengths of these photons by the same amount.
- Their wavelengths have therefore shifted to the microwave portion of the spectrum and corresponding to a temperature of a few degrees above absolute zero.

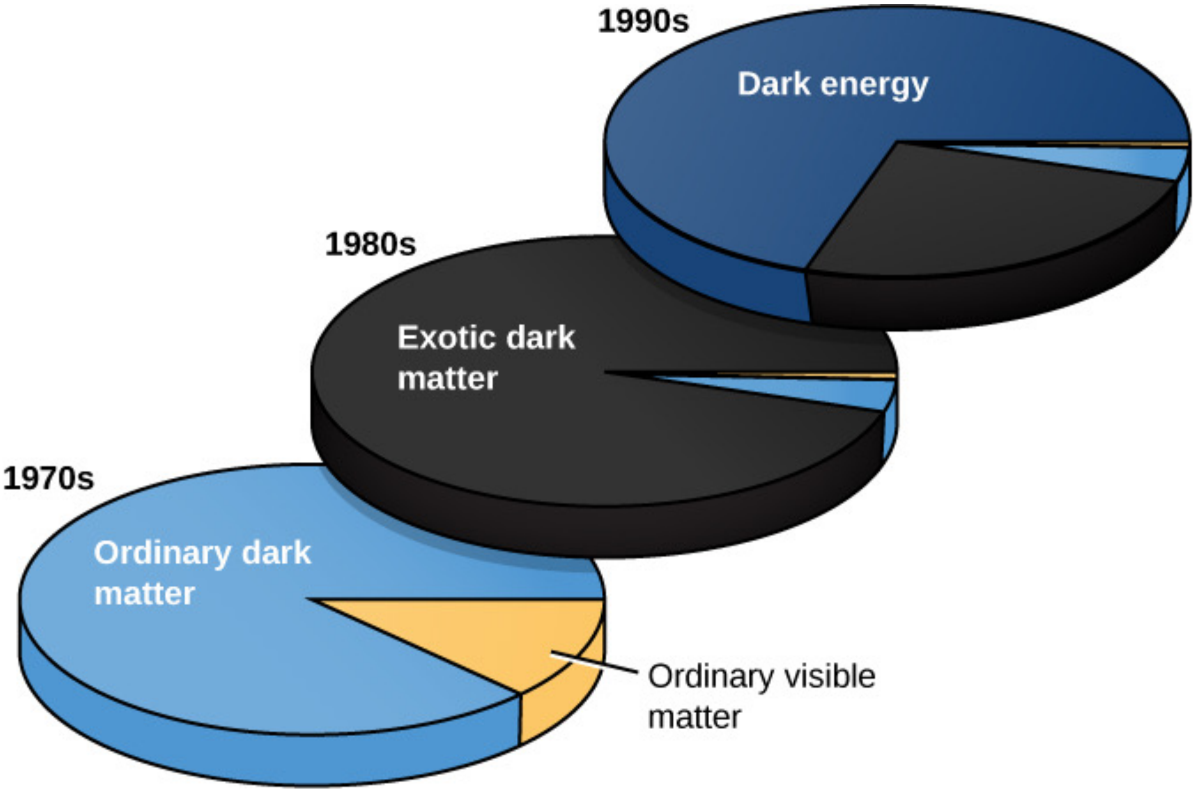
FIGURE 29.17



Cosmic Background Radiation. The solid line shows how the intensity of radiation should change with wavelength for a blackbody with a temperature of 2.73 K. The boxes show the intensity of the cosmic background radiation as measured at various wavelengths by COBE's instruments. The fit is perfect. When this graph was first shown at a meeting of astronomers, they gave it a standing ovation.

HELIUM FORMATION IN THE EARLY UNIVERSE

FIGURE 29.22



Changing Estimates of the Content of the Universe. This diagram shows the changes in our understanding of the contents of the universe over the past three decades. In the 1970s, we suspected that most of the matter in the universe was invisible, but we thought that this matter might be ordinary matter (protons, neutrons, etc.) that was simply not producing electromagnetic radiation. By the 1980s, it was becoming likely that most of the dark matter was made of something we had not yet detected on Earth. By the late 1990s, a variety of experiments had shown that we live in a critical -density universe and that dark energy contributes about 70% of what is required to reach critical density. Note how the estimate of the relative importance of ordinary luminous matter (shown in yellow) has diminished over time.

DARK MATTER

Astronomers consider matter to be “dark” as long as it is too dim to be visible in the halo of our galaxy or beyond.

Your body is dark matter, because you would be far too dim for our telescopes to detect if you were somehow flung into the halo of our galaxy.

Similarly, Earth and other planets are dark matter because we could not see them at great distances either. The “failed stars” known as brown dwarfs and even faint red main-sequence stars of spectral type M also qualify as dark matter, because they are too dim for current telescopes to see in the halo.

WHAT MIGHT DARK MATTER BE MADE OF?

What is all this dark stuff in galaxies and clusters of galaxies? There are two basic possibilities:

- (1) It could be made of ordinary matter that is built from protons, neutrons, and electrons, but in forms too dark for us to detect with current technology
- (2) it could be made of exotic particles that we have yet to discover.

Current evidence indicates that while some of the dark matter might be ordinary, most of it must be exotic.

SUGGESTION 1: MACHOS (MASSIVE COMPACT HALO OBJECTS)

Every once in a while, “something” drifts across our line of sight to a more distant star, its gravity can focus more of the distant star’s light directly toward Earth.

The distant star appears much brighter than usual for several days or weeks as the lensing object passes in front of it.

We cannot see the lensing object itself, but the duration of the lensing event reveals its mass.

MACHOS (MASSIVE COMPACT HALO OBJECTS)

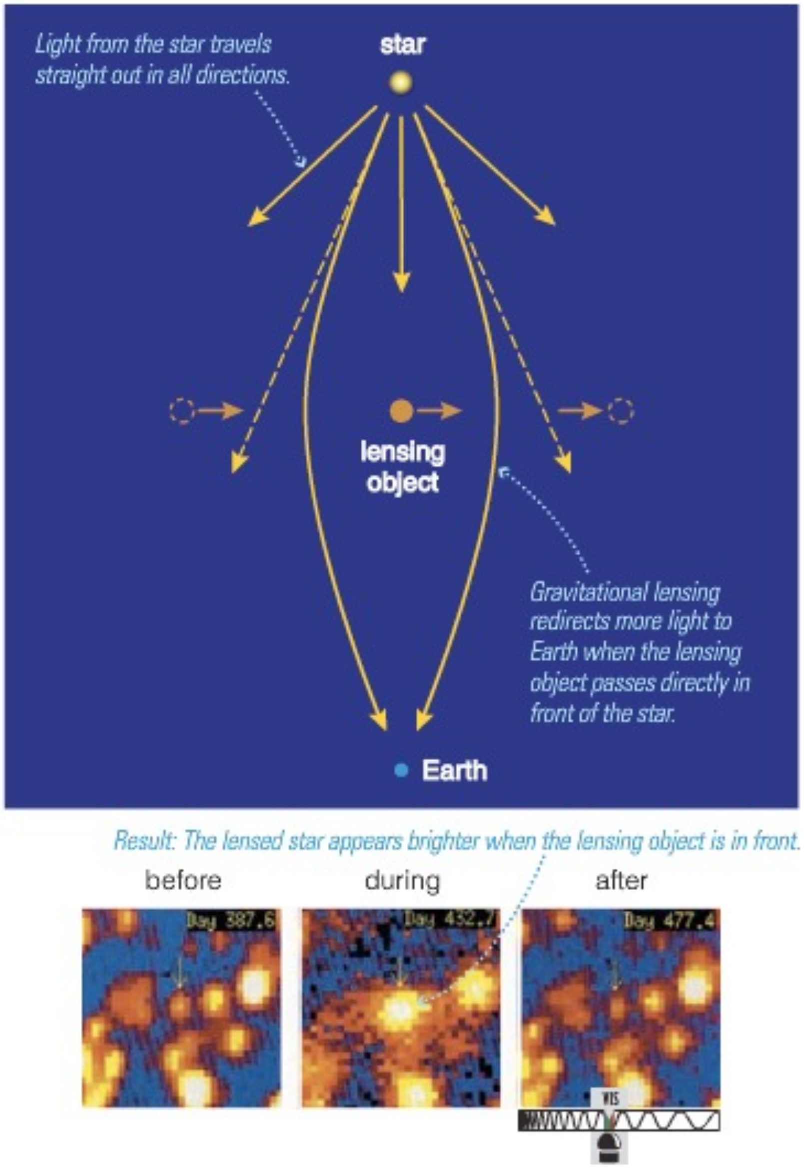


Figure 14.9. Page 232. *The Cosmic Perspective Fundamentals*. Publisher: Addison-Wesley. © 2010

WE DO KNOW THAT DARK MATTER ISN’T NEUTRINOS

Large numbers of neutrinos were made in the Big Bang, and they 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.

Particles like neutrinos interact with other forms of matter through only two of the four forces: gravity and the weak force. For this reason, they 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.

SUGGESTION 2: WIMPS

What if other weakly interacting particles exist that are similar to neutrinos but considerably more massive?

They, too, would have been made in the Big Bang and would evade direct detection, but they would move more slowly, so 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 with 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.

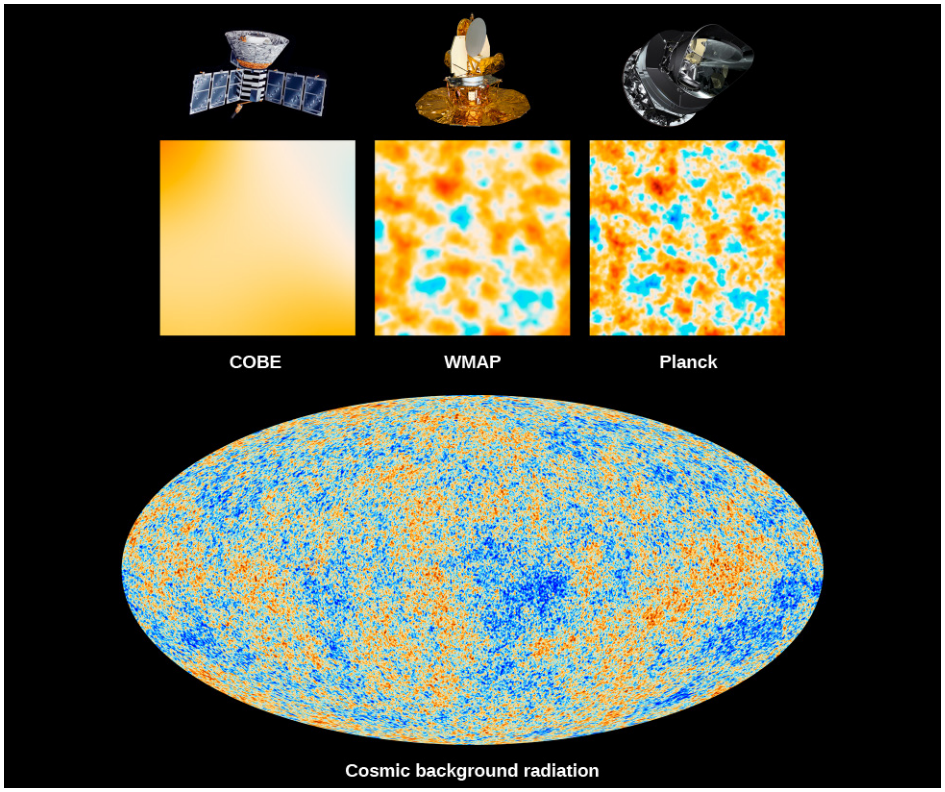
SUPPORTING EVIDENCE

Supporting evidence for weakly interacting massive particles comes from careful analysis of the cosmic microwave background.

In the model that best explains observed temperature patterns in this background radiation, one-sixth of the matter in the universe consists of ordinary matter made from protons and neutrons and five-sixths consists of WIMPs, in agreement with the conclusions we have drawn from deuterium observations and the proportions of dark matter and hot gas in clusters of galaxies.

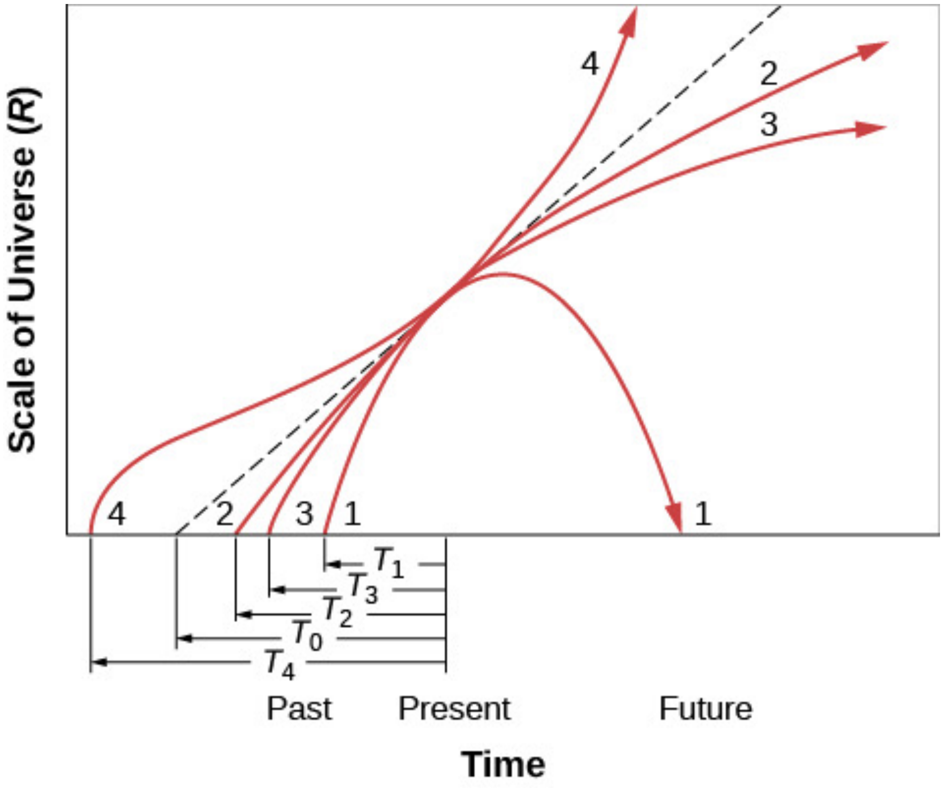
If the proportion of ordinary matter were greater, the model would no longer fit the microwave data. Astronomers therefore consider it likely that weakly interacting massive particles make up the vast majority of dark matter and hence the majority of all matter in the universe.

FIGURE 29.18



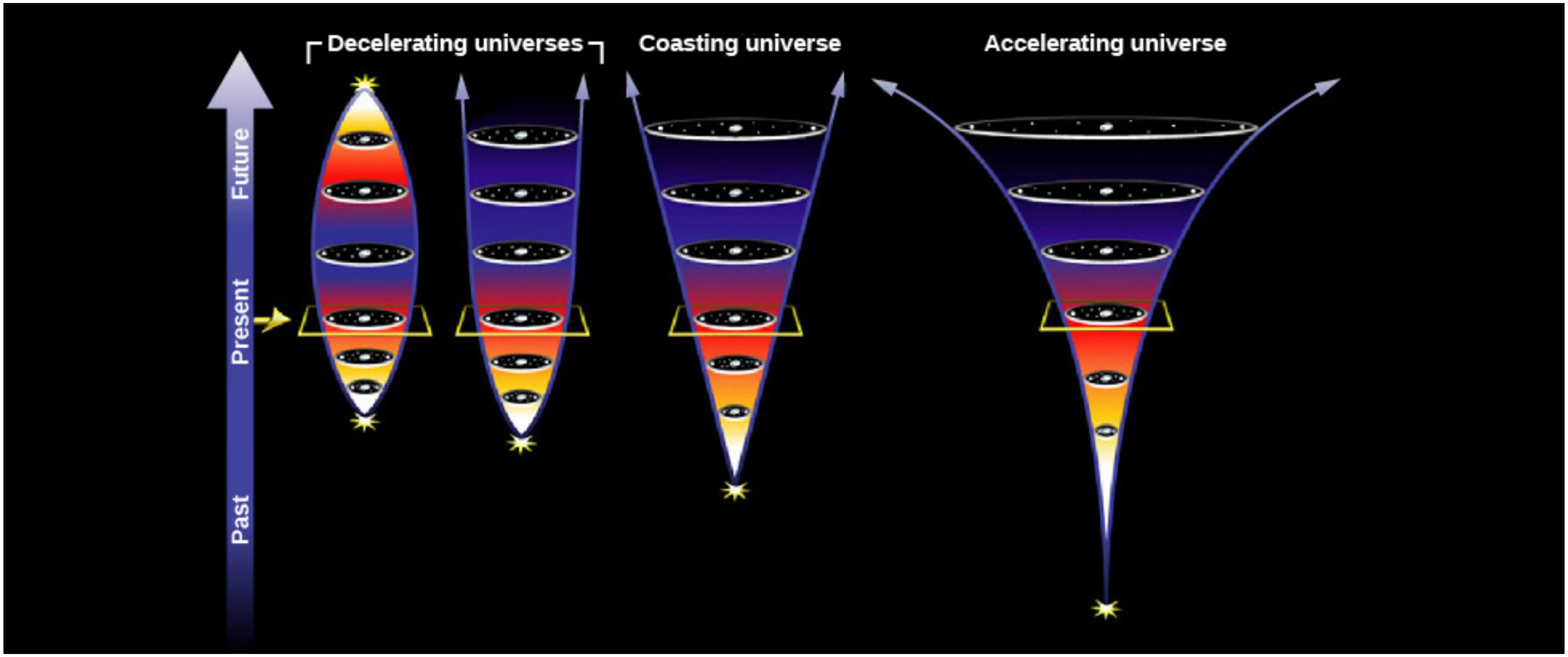
CMB Observations. This comparison shows how much detail can be seen in the observations of three satellites used to measure the CMB. The CMB is a snapshot of the oldest light in our universe, imprinted on the sky when the universe was just about 380,000 years old. The first spacecraft, launched in 1989, is NASA’s Cosmic Background Explorer, or COBE. WMAP was launched in 2001, and Planck was launched in 2009. The three panels show 10-square-degree patches of all-sky maps. This cosmic background radiation image (bottom) is an all-sky map of the CMB as observed by the Planck mission. The colors in the map represent different temperatures: red for warmer and blue for cooler. These tiny temperature fluctuations correspond to regions of slightly different densities, representing the seeds of all future structures: the stars, galaxies, and galaxy clusters of today. (credit top: modification of work by NASA/JPL-Caltech/ESA; credit bottom: modification of work by ESA and the Planck Collaboration)

FIGURE 29.9



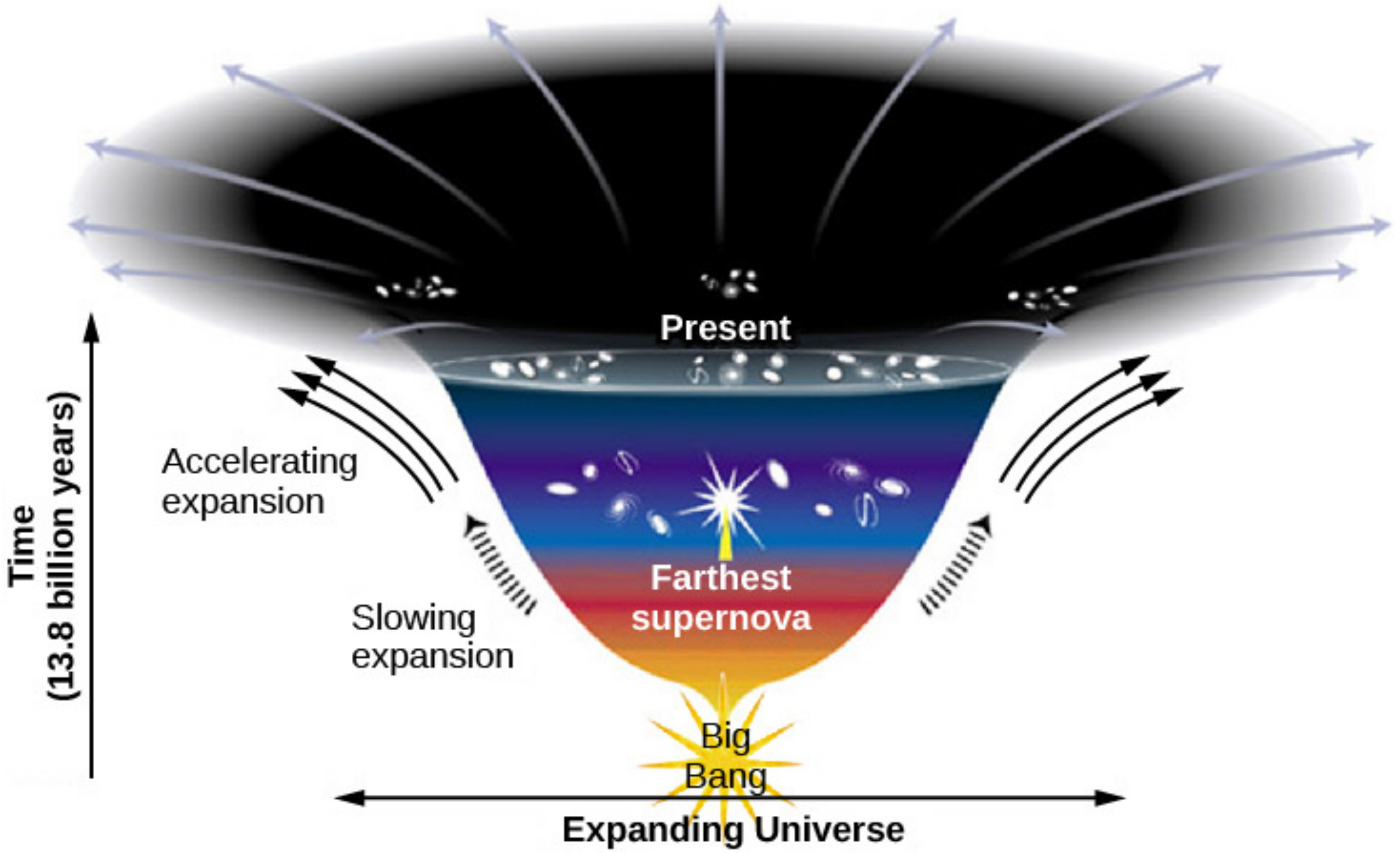
Models of the Universe. This graph plots *R*, the scale of the universe, against time for various cosmological models. Curve 1 represents a universe where the density is greater than the critical value; this model predicts that the universe will eventually collapse. Curve 2 represents a universe with a density lower than critical; the universe will continue to expand but at an ever-slower rate. Curve 3 is a critical-density universe; in this universe, the expansion will gradually slow to a stop infinitely far in the future. Curve 4 represents a universe that is accelerating because of the effects of dark energy. The dashed line is for an empty universe, one in which the expansion is not slowed by gravity or accelerated by dark energy. Time is very compressed on this graph.

FIGURE 29.8



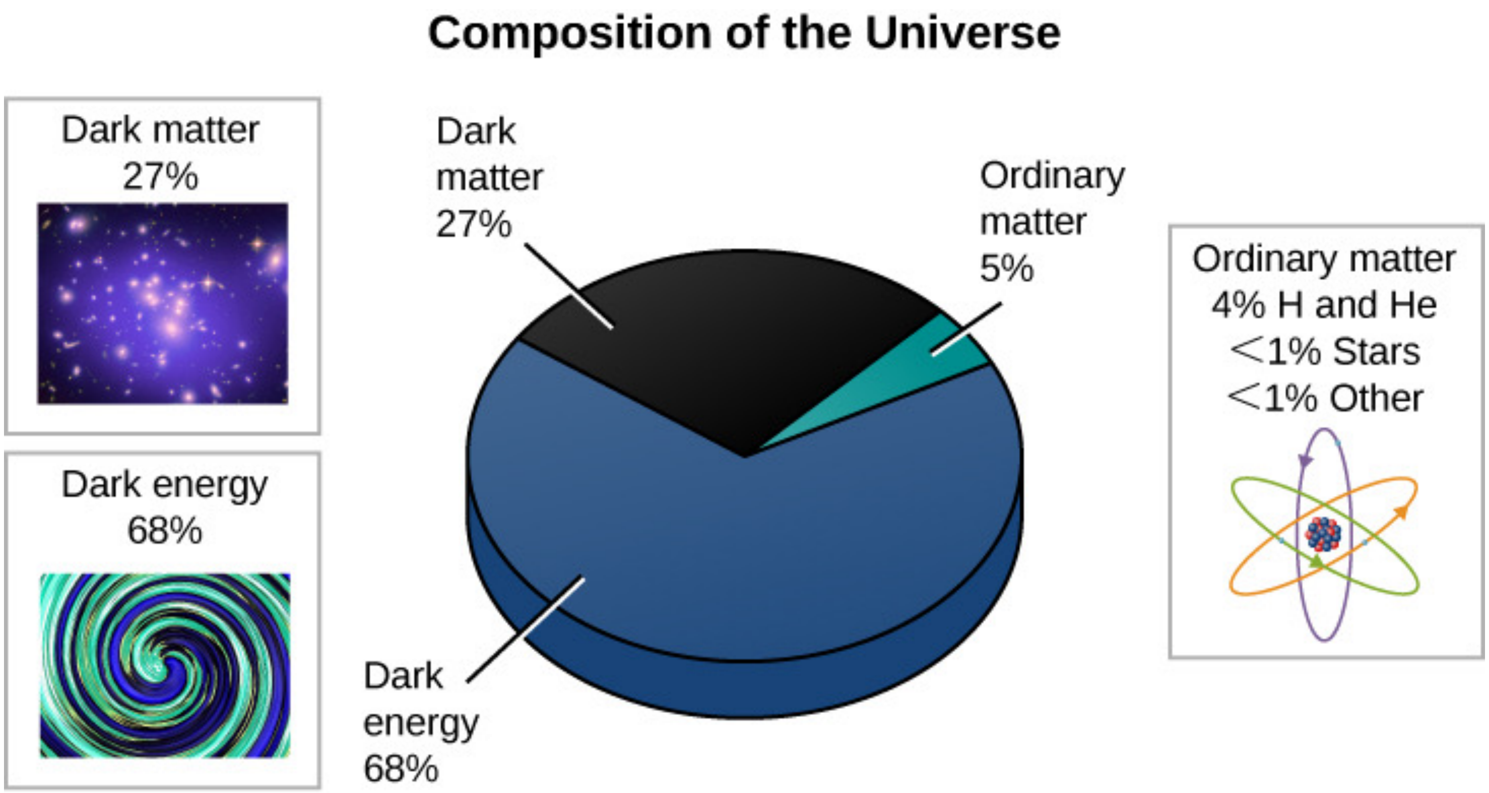
Four Possible Models of the Universe. The yellow square marks the present in all four cases, and for all four, the Hubble constant is equal to the same value at the present time. Time is measured in the vertical direction. The first two universes on the left are ones in which the rate of expansion slows over time. The one on the left will eventually slow, come to a stop and reverse, ending up in a “big crunch,” while the one next to it will continue to expand forever, but ever-more slowly as time passes. The “coasting” universe is one that expands at a constant rate given by the Hubble constant throughout all of cosmic time. The accelerating universe on the right will continue to expand faster and faster forever. (credit: modification of work by NASA/ESA)

FIGURE 29.4



Changes in the Rate of Expansion of the Universe Since Its Beginning 13.8 Billion Years Ago. The more the diagram spreads out horizontally, the faster the change in the velocity of expansion. After a period of very rapid expansion at the beginning, which scientists call inflation and which we will discuss later in this chapter, the expansion began to decelerate. Galaxies were then close together, and their mutual gravitational attraction slowed the expansion. After a few billion years, when galaxies were farther apart, the influence of gravity began to weaken. Dark energy then took over and caused the expansion to accelerate. (credit: modification of work by Ann Feild (STScI))

FIGURE 29.21



Composition of the Universe. Only about 5% of all the mass and energy in the universe is matter with which we are familiar here on Earth. Most ordinary matter consists of hydrogen and helium located in interstellar and intergalactic space. Only about one-half of 1% of the critical density of the universe is found in stars. Dark matter and dark energy, which have not yet been detected in earthbound laboratories, account for 95% of the contents of the universe.