

halos made of dark matter, how does this affect their interactions with one another and the shapes and types of galaxies that their collisions create?

Astronomers armed with various theories are working hard to produce models of galaxy structure and evolution that take dark matter into account in just the right way. Even though we don't know what the dark matter is, we do have some clues about how it affected the formation of the very first galaxies. As we will see in **The Big Bang**, careful measurements of the microwave radiation left over after the Big Bang have allowed astronomers to set very tight limits on the actual sizes of those early seeds that led to the formation of the large galaxies that we see in today's universe. Astronomers have also measured the relative numbers and distances between galaxies and clusters of different sizes in the universe today. So far, most of the evidence seems to weigh heavily in favor of cold dark matter, and most current models of galaxy and large-scale structure formation use cold dark matter as their main ingredient.

As if the presence of dark matter—a mysterious substance that exerts gravity and outweighs all the known stars and galaxies in the universe but does not emit or absorb light—were not enough, there is an even more baffling and equally important constituent of the universe that has only recently been discovered: we have called it **dark energy** in parallel with dark matter. We will say more about it and explore its effects on the evolution of the universe in **The Big Bang**. For now, we can complete our inventory of the contents of the universe by noting that it appears that the entire universe contains some mysterious energy that pushes spacetime apart, taking galaxies and the larger structures made of galaxies along with it. Observations show that dark energy becomes more and more important relative to gravity as the universe ages. As a result, the expansion of the universe is accelerating, and this acceleration seems to be happening mostly since the universe was about half its current age.

What we see when we peer out into the universe—the light from trillions of stars in hundreds of billions of galaxies wrapped in intricate veils of gas and dust—is therefore actually only a sprinkling of icing on top of the cake: as we will see in **The Big Bang**, when we look outside galaxies and clusters of galaxies at the universe as a whole, astronomers find that for every gram of luminous normal matter, such as protons, neutrons, electrons, and atoms in the universe, there are about 4 grams of nonluminous normal matter, mainly intergalactic hydrogen and helium. There are about 27 grams of dark matter, and the energy equivalent (remember Einstein's famous $E = mc^2$) of about 68 grams of dark energy. Dark matter, and (as we will see) even more so dark energy, are dramatic demonstrations of what we have tried to emphasize throughout this book: science is always a "progress report," and we often encounter areas where we have more questions than answers.

Let's next put together all these clues to trace the life history of galaxies and large-scale structure in the universe. What follows is the current consensus, but research in this field is moving rapidly, and some of these ideas will probably be modified as new observations are made.

28.5 THE FORMATION AND EVOLUTION OF GALAXIES AND STRUCTURE IN THE UNIVERSE

Learning Objectives

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

- › Summarize the main theories attempting to explain how individual galaxies formed
- › Explain how tiny "seeds" of dark matter in the early universe grew by gravitational attraction over billions of years into the largest structures observed in the universe: galaxy clusters and superclusters, filaments, and voids

As with most branches of natural science, astronomers and cosmologists always want to know the answer to the question, “How did it get that way?” What made galaxies and galaxy clusters, superclusters, voids, and filaments look the way they do? The existence of such large filaments of galaxies and voids is an interesting puzzle because we have evidence (to be discussed in [The Big Bang](#)) that the universe was extremely smooth even a few hundred thousand years after forming. The challenge for theoreticians is to understand how a nearly featureless universe changed into the complex and lumpy one that we see today. Armed with our observations and current understanding of galaxy evolution over cosmic time, dark matter, and large-scale structure, we are now prepared to try to answer that question on some of the largest possible scales in the universe. As we will see, the short answer to how the universe got this way is “dark matter + gravity + time.”

How Galaxies Form and Grow

We’ve already seen that galaxies were more numerous, but smaller, bluer, and clumpier, in the distant past than they are today, and that galaxy mergers play a significant role in their evolution. At the same time, we have observed quasars and galaxies that emitted their light when the universe was less than a billion years old—so we know that large condensations of matter had begun to form at least that early. We also saw in [Active Galaxies, Quasars, and Supermassive Black Holes](#) that many quasars are found in the centers of elliptical galaxies. This means that some of the first large concentrations of matter must have evolved into the elliptical galaxies that we see in today’s universe. It seems likely that the supermassive black holes in the centers of galaxies and the spherical distribution of ordinary matter around them formed at the same time and through related physical processes.

Dramatic confirmation of that picture arrived only in the last decade, when astronomers discovered a curious empirical relationship: as we saw in [Active Galaxies, Quasars, and Supermassive Black Holes](#), the more massive a galaxy is, the more massive its central black hole is. Somehow, the black hole and the galaxy “know” enough about each other to match their growth rates.

There have been two main types of galaxy formation models to explain all those observations. The first asserts that massive elliptical galaxies formed in a single, rapid collapse of gas and dark matter, during which virtually all the gas was turned quickly into stars. Afterward the galaxies changed only slowly as the stars evolved. This is what astronomers call a “top-down” scenario.

The second model suggests that today’s giant ellipticals were formed mostly through mergers of smaller galaxies that had already converted at least some of their gas into stars—a “bottom-up” scenario. In other words, astronomers have debated whether giant ellipticals formed most of their stars in the large galaxy that we see today or in separate small galaxies that subsequently merged.

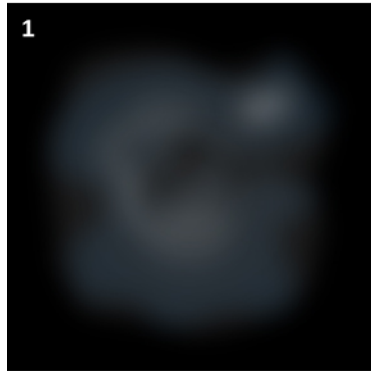
Since we see some luminous quasars from when the universe was less than a billion years old, it is likely that at least some giant ellipticals began their evolution very early through the collapse of a single cloud. However, the best evidence also seems to show that mature *giant* elliptical galaxies like the ones we see nearby were rare before the universe was about 6 billion years old and that they are much more common today than they were when the universe was young. Observations also indicate that most of the gas in elliptical galaxies was converted to stars by the time the universe was about 3 billion years old, so it appears that elliptical galaxies have not formed many new stars since then. They are often said to be “red and dead”—that is, they mostly contain old, cool, red stars, and there is little or no new star formation going on.

These observations (when considered together) suggest that the giant elliptical galaxies that we see nearby formed from a combination of both top-down and bottom-up mechanisms, with the most massive galaxies forming in the densest clusters where both processes happened very early and quickly in the history of the universe.

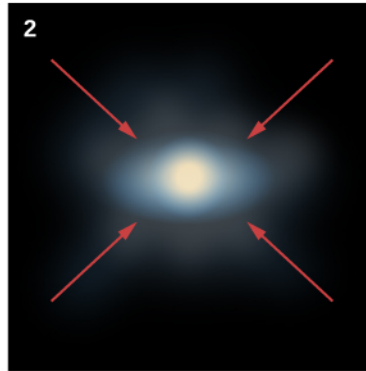
The situation with spiral galaxies is apparently very different. The bulges of these galaxies formed early, like the

elliptical galaxies (**Figure 28.27**). However, the disks formed later (remember that the stars in the disk of the Milky Way are younger than the stars in the bulge and the halo) and still contain gas and dust. However, the rate of star formation in spirals today is about ten times lower than it was 8 billion years ago. The number of stars being formed drops as the gas is used up. So spirals seem to form mostly “bottom up” but over a longer time than ellipticals and in a more complex way, with at least two distinct phases.

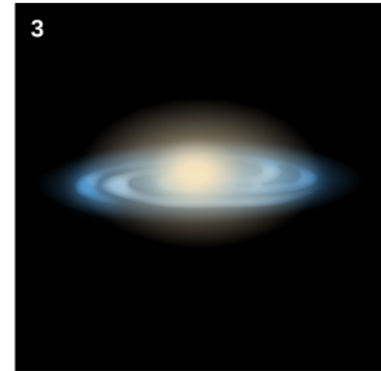
Rapid Collapse



1
Primordial hydrogen cloud.

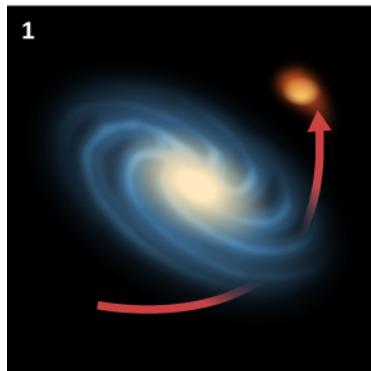


2
Cloud collapses under gravity.

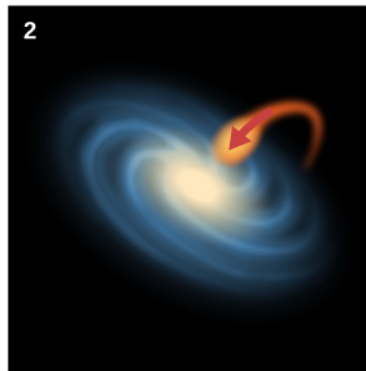


3
Large bulge of ancient stars dominates galaxy.

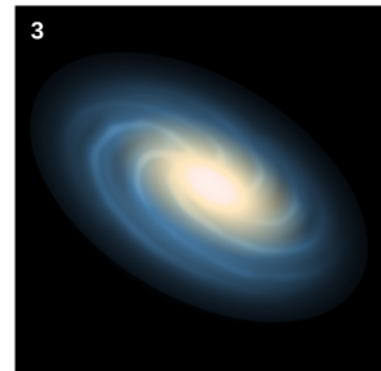
Environmental Effects



1
Disk galaxy and companion.



2
Smaller galaxy falls into disk galaxy.



3
Bulge inflates with addition of young stars and gas.

Figure 28.27 Growth of Spiral Bulges. The nuclear bulges of some spiral galaxies formed through the collapse of a single protogalactic cloud (top row). Others grew over time through mergers with other smaller galaxies (bottom row).

Hubble originally thought that elliptical galaxies were young and would eventually turn into spirals, an idea we now know is not true. In fact, as we saw above, it's more likely the other way around: two spirals that crash together under their mutual gravity can turn into an elliptical.

Despite these advances in our understanding of how galaxies form and evolve, many questions remain. For example, it's even possible, given current evidence, that spiral galaxies could lose their spiral arms and disks in a merger event, making them look more like an elliptical or irregular galaxy, and then regain the disk and arms again later if enough gas remains available. The story of how galaxies assume their final shapes is still being written as we learn more about galaxies and their environment.

Forming Galaxy Clusters, Superclusters, Voids, and Filaments

If individual galaxies seem to grow mostly by assembling smaller pieces together gravitationally over cosmic time, what about the clusters of galaxies and larger structures such as those seen in [Figure 28.21](#)? How do we explain the large-scale maps that show galaxies distributed on the walls of huge sponge- or bubble-like structures spanning hundreds of millions of light-years?

As we saw, observations have found increasing evidence for concentrations, filaments, clusters, and superclusters of galaxies when the universe was less than 3 billion years old ([Figure 28.28](#)). This means that large concentrations of galaxies had already come together when the universe was less than a quarter as old as it is now.

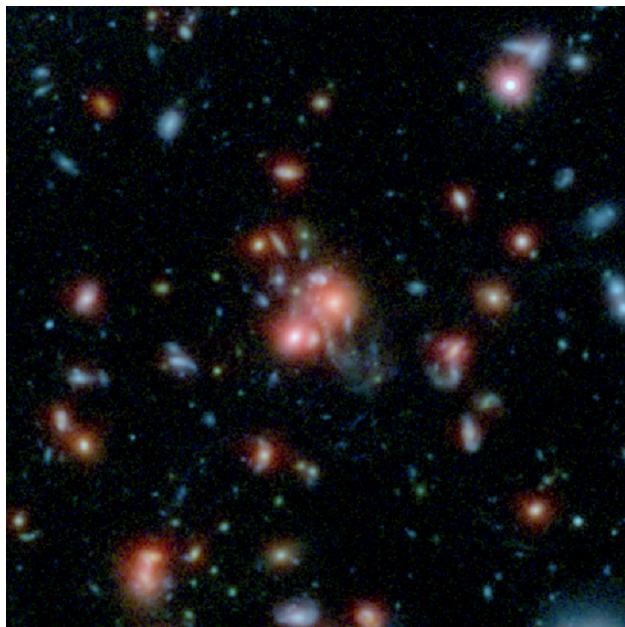


Figure 28.28 Merging Galaxies in a Distant Cluster. This Hubble image shows the core of one of the most distant galaxy clusters yet discovered, SpARCS 1049+56; we are seeing it as it was nearly 10 billion years ago. The surprise delivered by the image was the “train wreck” of chaotic galaxy shapes and blue tidal tails: apparently there are several galaxies right in the core that are merging together, the probable cause of a massive burst of star formation and bright infrared emission from the cluster. (credit: modification of work by NASA/STScI/ESA/JPL-Caltech/McGill)

Almost all the currently favored models of how large-scale structure formed in the universe tell a story similar to that for individual galaxies: tiny dark matter “seeds” in the hot cosmic soup after the Big Bang grew by gravity into larger and larger structures as cosmic time ticked on ([Figure 28.29](#)). The final models we construct will need to be able to explain the size, shape, age, number, and spatial distribution of galaxies, clusters, and filaments—not only today, but also far back in time. Therefore, astronomers are working hard to measure and then to model those features of large-scale structure as accurately as possible. So far, a mixture of 5% normal atoms, 27% cold dark matter, and 68% dark energy seems to be the best way to explain all the evidence currently available (see [The Big Bang](#)).

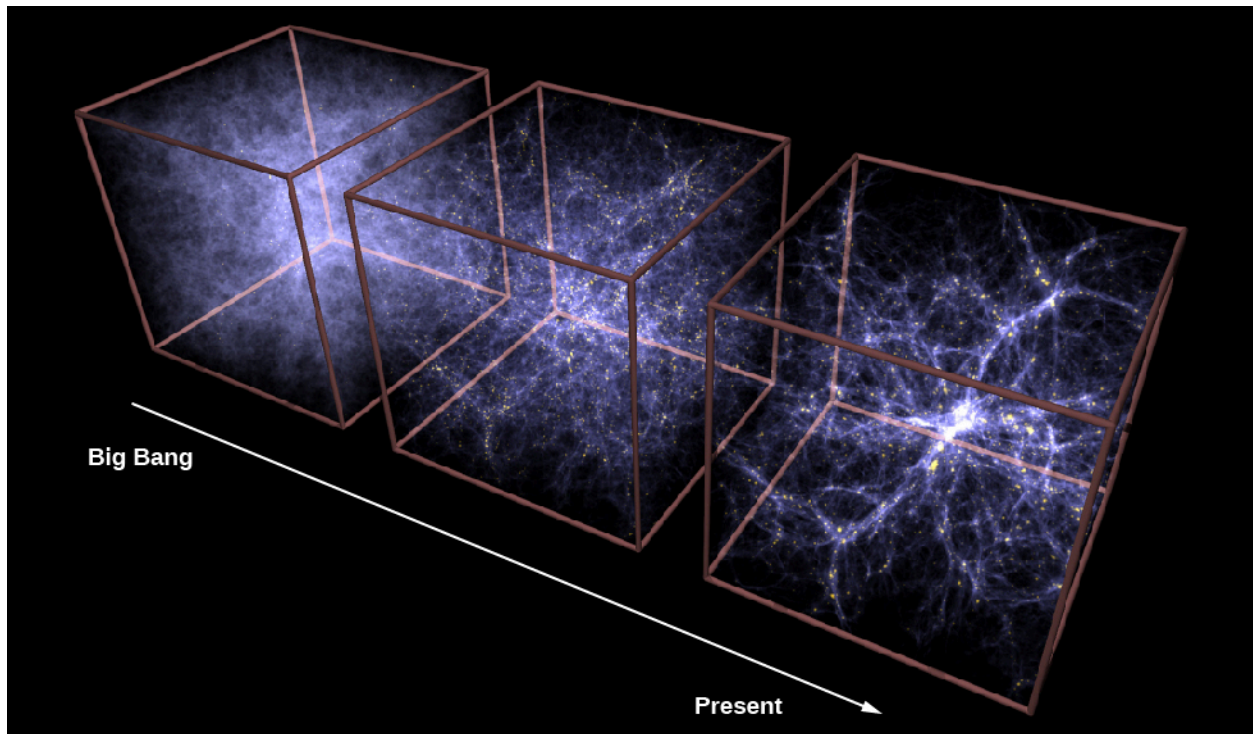


Figure 28.29 Growth of Large-Scale Structure as Calculated by Supercomputers. The boxes show how filaments and superclusters of galaxies grow over time, from a relatively smooth distribution of dark matter and gas, with few galaxies formed in the first 2 billion years after the Big Bang, to the very clumpy strings of galaxies with large voids today. Compare the last image in this sequence with the actual distribution of nearby galaxies shown in [Figure 28.21](#). (credit: modification of work by CXC/MPE/V.Springel)

The box at left is labeled “Big Bang,” the box at center is unlabeled and the box at right is labeled “Present”. A white arrow points from left to right representing the direction of time.

Scientists even have a model to explain how a nearly uniform, hot “soup” of particles and energy at the beginning of time acquired the Swiss-cheese-like structure that we now see on the largest scales. As we will see in [The Big Bang](#), when the universe was only a few hundred thousand years old, *everything* was at a temperature of a few thousand degrees. Theorists suggest that at that early time, all the hot gas was vibrating, much as sound waves vibrate the air of a nightclub with an especially loud band. This vibrating could have concentrated matter into high-density peaks and created emptier spaces between them. When the universe cooled, the concentrations of matter were “frozen in,” and galaxies ultimately formed from the matter in these high-density regions.

The Big Picture

To finish this chapter, let’s put all these ideas together to tell a coherent story of how the universe came to look the way it does. Initially, as we said, the distribution of matter (both luminous and dark) was nearly, but not quite exactly, smooth and uniform. That “not quite” is the key to everything. Here and there were lumps where the density of matter (both luminous and dark) was ever so slightly higher than average.

Initially, each individual lump expanded because the whole universe was expanding. However, as the universe continued to expand, the regions of higher density acquired still more mass because they exerted a slightly larger than average gravitational force on surrounding material. If the inward pull of gravity was high enough, the denser individual regions ultimately stopped expanding. They then began to collapse into irregularly shaped blobs (that’s the technical term astronomers use!). In many regions the collapse was more rapid in one direction, so the concentrations of matter were not spherical but came to resemble giant clumps, pancakes, and

rope-like filaments—each much larger than individual galaxies.

These elongated clumps existed throughout the early universe, oriented in different directions and collapsing at different rates. The clumps provided the framework for the large-scale filamentary and bubble-like structures that we see preserved in the universe today.

The universe then proceeded to “build itself” from the bottom up. Within the clumps, smaller structures formed first, then merged to build larger ones, like Lego pieces being put together one by one to create a giant Lego metropolis. The first dense concentrations of matter that collapsed were the size of small dwarf galaxies or globular clusters—which helps explain why globular clusters are the oldest things in the Milky Way and most other galaxies. These fragments then gradually assembled to build galaxies, galaxy clusters, and, ultimately, superclusters of galaxies.

According to this picture, small galaxies and large star clusters first formed in the highest density regions of all—the filaments and nodes where the pancakes intersect—when the universe was about two percent of its current age. Some stars may have formed even before the first star clusters and galaxies came into existence. Some galaxy-galaxy collisions triggered massive bursts of star formation, and some of these led to the formation of black holes. In that rich, crowded environment, black holes found constant food and grew in mass. The development of massive black holes then triggered quasars and other active galactic nuclei whose powerful outflows of energy and matter shut off the star formation in their host galaxies. The early universe must have been an exciting place!

Clusters of galaxies then formed as individual galaxies congregated, drawn together by their mutual gravitational attraction (**Figure 28.30**). First, a few galaxies came together to form groups, much like our own Local Group. Then the groups began combining to form clusters and, eventually, superclusters. This model predicts that clusters and superclusters should still be in the process of gathering together, and observations do in fact suggest that clusters are still gathering up their flocks of galaxies and collecting more gas as it flows in along filaments. In some instances we even see entire clusters of galaxies merging together.

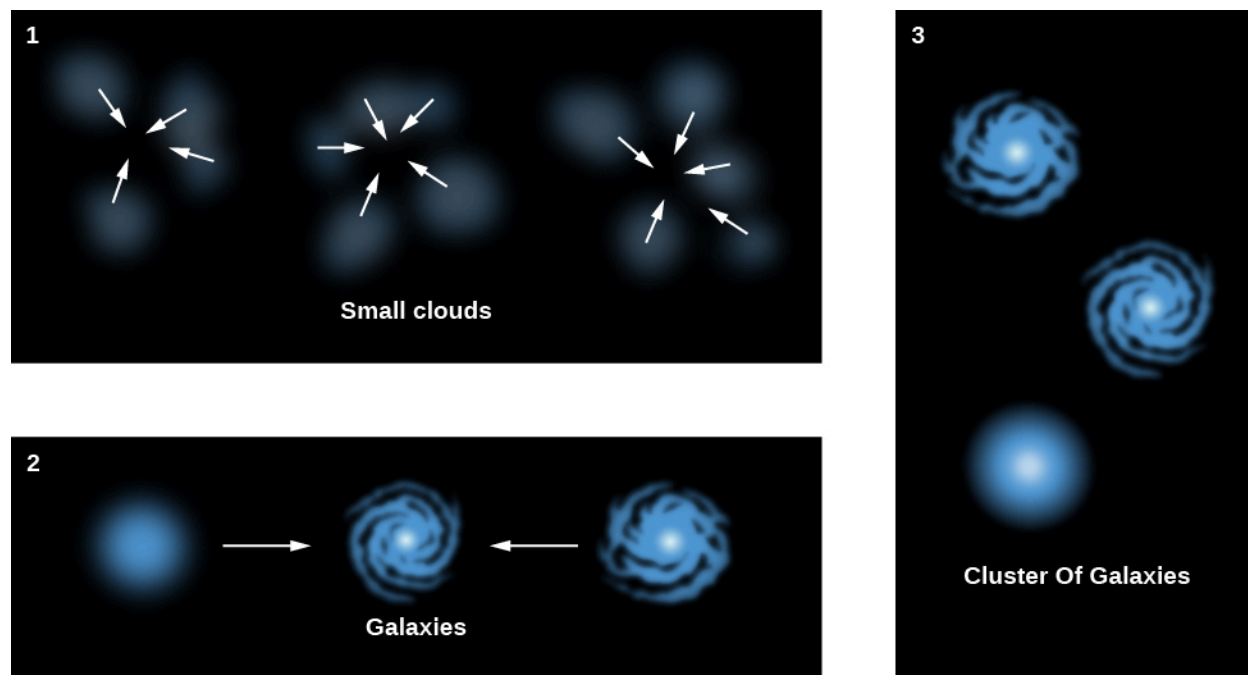


Figure 28.30 Formation of Cluster of Galaxies. This schematic diagram shows how galaxies might have formed if small clouds formed first and then congregated to form galaxies and then clusters of galaxies.

Most giant elliptical galaxies formed through the collision and merger of many smaller fragments. Some spiral galaxies may have formed in relatively isolated regions from a single cloud of gas that collapsed to make a flattened disk, but others acquired additional stars, gas, and dark matter through collisions, and the stars acquired through these collisions now populate their halos and bulges. As we have seen, our Milky Way is still capturing small galaxies and adding them to its halo, and probably also pulling fresh gas from these galaxies into its disk.