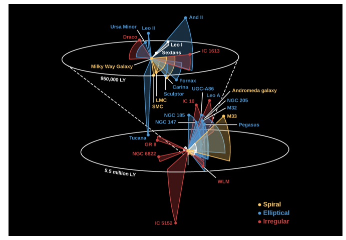
28.3 THE DISTRIBUTION OF GALAXIES IN SPACE

- **Hubble at Work.** Edwin Hubble at the 100-inch telescope on Mount Wilson.

Figure 28.14

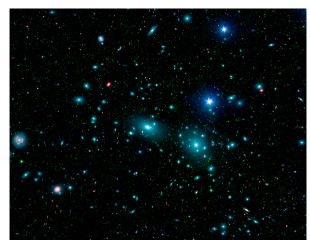


- **Local Group.** This illustration shows some members of the Local Group of galaxies, with our Milky Way at the center. The exploded view at the top shows the region closest to the Milky Way and fits into the bigger view at the bottom as shown by the dashed lines. The three largest galaxies among the three dozen or so members of the Local Group are all spirals; the others are small irregular galaxies and dwarf ellipticals. A number of new members of the group have been found since this map was made.

Figure 28.15

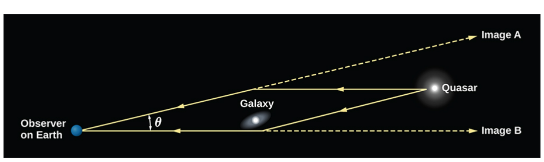
- **Central Region of the Virgo Cluster.** Virgo is the nearest rich cluster and is at a distance of about 50 million light-years. It contains hundreds of bright galaxies. In this picture you can see only the central part of the cluster, including the giant elliptical galaxy M87, just below center. Other spirals and ellipticals are visible; the two galaxies to the top right are known as "The Eyes." (credit: modification of work by Chris Mihos (Case Western Reserve University)/ESO)

Figure 28.16



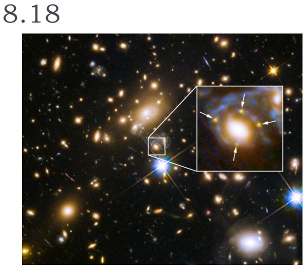
- **Central Region of the Coma Cluster.** This combined visible-light (from the Sloan Digital Sky Survey) and infrared (from the Spitzer Space Telescope) image has been color coded so that faint dwarf galaxies are seen as green. Note the number of little green smudges on the image. The cluster is roughly 320 million light-years away from us.

Figure 28.17



- **Gravitational Lensing.** This drawing shows how a gravitational lens can make two images. Two light rays from a distant quasar are shown being bent while passing a foreground galaxy; they then arrive together at Earth. Although the two beams of light contain the same information, they now appear to come from two different points on the sky. This sketch is oversimplified and not to scale, but it gives a rough idea of the lensing phenomenon.

Figure 28.18



- **Multiple Images of a Gravitationally Lensed Supernova.** Light from a supernova at a distance of 9 billion light-years passed near a galaxy in a cluster at a distance of about 5 billion light-years. In the enlarged inset view of the galaxy, the arrows point to the multiple images of the exploding star. The images are arranged around the galaxy in a cross-shaped pattern called an Einstein Cross. The blue streaks wrapping around the galaxy are the stretched images of the supernova's host spiral galaxy, which has been distorted by the warping of space.

Figure 28.19

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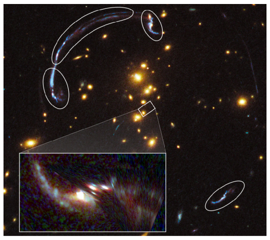

- **Distorted Images of a Distant Galaxy Produced by Gravitational Lensing in a Galaxy Cluster.** The rounded outlines show the location of distinct, distorted images of the background galaxy resulting from lensing by the mass in the cluster. The image in the box at lower left is a reconstruction of what the lensed galaxy would look like in the absence of the cluster, based on a model of the cluster's mass distribution, which can be derived from studying the distorted galaxy images. The reconstruction shows far more detail about the galaxy than could have been seen in the absence of lensing. As the image shows, this galaxy contains regions of star formation glowing like bright Christmas tree bulbs. These are much brighter than any star-formation regions in our Milky Way Galaxy.

Figure 28.21

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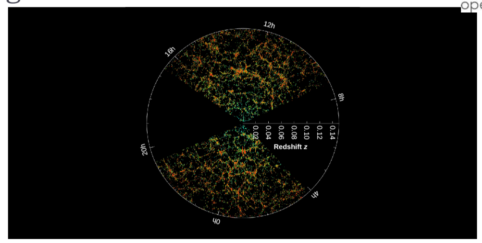

- **Sloan Digital Sky Survey Map of the Large-Scale Structure of the Universe.** This image shows slices from the SDSS map. The point at the center corresponds to the Milky Way and might say "You Are Here!" Points on the map moving outward from the center are farther away. The distance to the galaxies is indicated by their redshifts The colors of the galaxies indicate the ages of their stars, with the redder color showing galaxies that are made of older stars. The outer circle is at a distance of two billion light-years from us. Note that red (older stars) galaxies are more strongly clustered than blue galaxies (young stars). The unmapped areas are where our view of the universe is obstructed by dust in our own Galaxy. (credit: modification of work by M. Blanton and the Sloan Digital Sky Survey)

Figure 28.22

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(a) (b)

- **Sloan Digital Sky Survey.**

(a) The Sloan Digital Sky Survey telescope is seen here in front of the Sacramento Mountains in New Mexico.

(b) Astronomer Richard Kron inserts some of the optical fibers into the pre-drilled plate to enable the instruments to make many spectra of galaxies at the same time. (credit a, b: modification of work by the Sloan Digital Sky Survey)

28.4 THE CHALLENGE OF DARK MATTER

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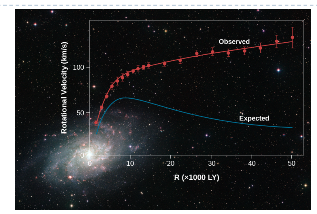

- **Rotation Indicates Dark Matter.** We see the Milky Way's sister, the spiral Andromeda galaxy, with a graph that shows the velocity at which stars and clouds of gas orbit the galaxy at different distances from the center (red line). As is true of the Milky Way, the rotational velocity (or orbital speed) does not decrease with distance from the center, which is what you would expect if an assembly of objects rotates around a common center. A calculation (blue line) based on the total mass visible as stars, gas, and dust predicts that the velocity should be much lower at larger distances from the center. The discrepancy between the two curves implies the presence of a halo of massive dark matter extending outside the boundary of the luminous matter. This dark matter causes everything in the galaxy to orbit faster than the observed matter alone could explain

Figure 28.24

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- **Cluster Abell 2218.** This view from the Hubble Space Telescope shows the massive galaxy cluster Abell 2218 at a distance of about 2 billion light-years. Most of the yellowish objects are galaxies belonging to the cluster. But notice the numerous long, thin streaks, many of them blue; those are the distorted and magnified images of even more distant background galaxies, gravitationally lensed by the enormous mass of the intervening cluster. By carefully analyzing the lensed images, astronomers can construct a map of the dark matter that dominates the mass of the cluster.

Figure 28.25

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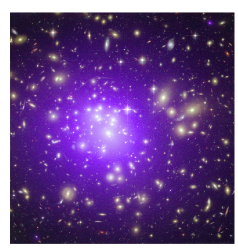
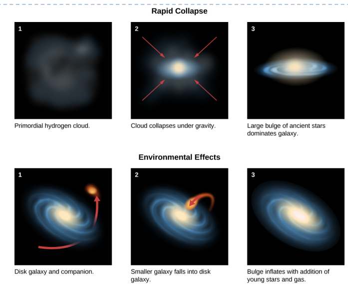


- **X-Ray Image of a Galaxy Cluster.** This composite image shows the galaxy cluster Abell 1689 at a distance of 2.3 billion light-years. The finely detailed views of the galaxies, most of them yellow, are in visible and near-infrared light from the Hubble Space Telescope, while the diffuse purple haze shows X-rays as seen by Chandra X-ray Observatory. The abundant X-rays, the gravitationally lensed images (thin curving arcs) of background galaxies, and the measured velocities of galaxies in the clusters all show that the total mass of Abell 1689—most of it dark matter—is about 10^{15} solar masses.

Figure 28.26

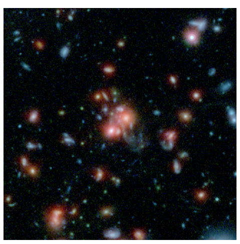
- **Large and Small Magellanic Clouds.** Here, the two small galaxies we call the Large Magellanic Cloud and Small Magellanic Cloud can be seen above the auxiliary telescopes for the Very Large Telescope Array on Cerro Paranal in Chile. You can see from the number of stars that are visible that this is a very dark site for doing astronomy. (credit: ESO/J. Colosimo)

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



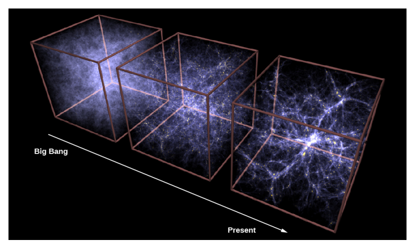
- **Growth of Spiral Bulges.** The nuclear bulges of some spiral galaxies formed through the collapse of a single protogalactic cloud (top row). Others grew over time through mergers with other smaller galaxies (bottom row).

Figure 28.28



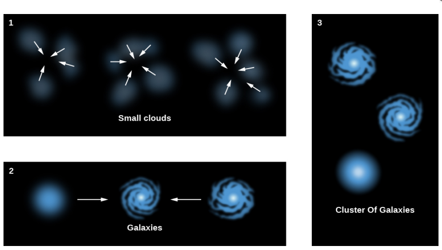
- **Merging Galaxies in a Distant Cluster.** This Hubble image shows the core of one of the most distant galaxy clusters yet discovered, SpARCS 1049+56; we are seeing it as it was nearly 10 billion years ago. The surprise delivered by the image was the "train wreck" of chaotic galaxy shapes and blue 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)

Figure 28.29

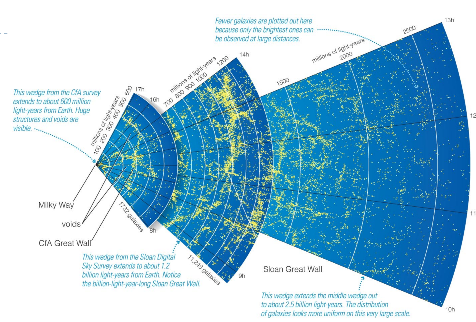


- **Growth of Large-Scale Structure as Calculated by Supercomputers.** The boxes show how filaments and superclusters of galaxies grow over time, from a relatively smooth distribution of dark matter and gas, with few galaxies formed in the first 2 billion years after the Big Bang, to the very clumpy 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**.

Figure 28.30



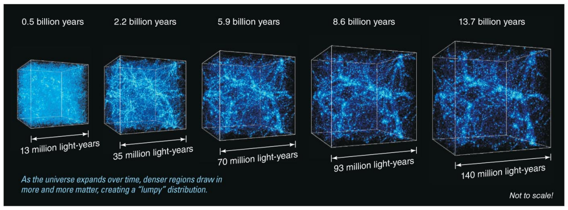
- **Formation of Cluster of Galaxies.** This schematic diagram shows how galaxies might have formed if small clouds formed first and then congregated to form galaxies and then clusters of galaxies.



Maps of galaxy positions reveal extremely large structures: ***superclusters*** and ***voids.***

Time in billions of years

0.5 2.2 5.9 8.6 13.7



13 35 70 93 140

Size of expanding box in millions of light-years

Models show that the gravity of dark matter pulls mass into denser regions—the universe grows lumpier with time.

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Links

- galaxies 5 min
- structure 5

Reading

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- 22.2
- 28.3
- 28.4
- 28.5