12

Structure Formation

The universe is lit up with stars, which are scattered through space, forming a hierarchy of structure. Stars are assembled into galaxies, and galaxies are grouped in clusters, which are in turn grouped into still larger structures, called superclusters. The formation of cosmic structures is an active area of research, and we now believe we have a good idea of how they emerged.

12.1 Cosmic Structure

Galaxies come in three main types: spiral, elliptical and irregular, as shown in Fig. 12.1. The main components of a spiral galaxy are the central bulge, the flattened disk with spiral arms, and a huge dark matter halo. The disk of our Milky Way galaxy is roughly 100,000 light years across and about 10,000 light years thick. The halo is nearly spherical, with a diameter about ten times larger than that of the disk. The Sun sits in the disk and is located about 25,000 light years from the galactic center. Large galaxies like the Milky Way contain of order 100 billion stars. The typical distance between stars in a galaxy is a few light years; this is much larger than the size of a star. If you imagine the Sun to be pea sized, the nearest star would be 160 km away! Thus galaxies are mostly empty.

Galaxies group together to form clusters. The Milky Way belongs to a small cluster called the Local Group (see Fig. 12.2). The Andromeda galaxy also resides in the Local Group, some 2.5 million light years away. Although

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Fig. 12.1 Spiral, elliptical and irregular galaxies. Spiral Image (NGC 6814) *Credit* ESA/Hubble & NASA; *Acknowledgement* Judy Schmidt (Geckzilla). Elliptical (M87) *Credit* Canada-France-Hawaii Telescope, J.-C. Cuillandre (CFHT), Coelum. Irregular (NGC 1427A) *Credit* NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

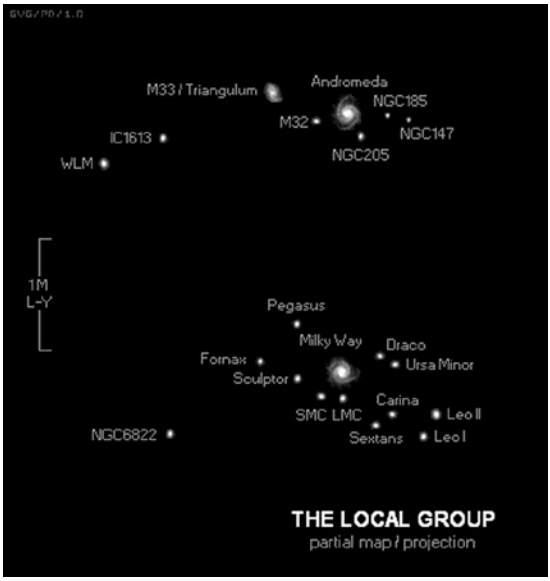

Fig. 12.2 The Local Group. *Credit* www.wikipedia.org

the Local Group has less than 40 galaxies, some rich clusters contain thousands of galaxies. The closest cluster to the Local Group is the Virgo cluster, which lies about 60 million light years away and contains over a thousand galaxies (Fig. 12.3).

Clusters are further grouped into superclusters, some of which contain hundreds of clusters (the Local Group is part of the Local Supercluster).

Fig. 12.3 The virgo cluster of galaxies (by the Hubble Space Telescope). *Credit NASA/ESA*

Automated galaxy surveys, pioneered in the late 1980s at the Harvard Center for Astrophysics (CfA), also revealed that the galaxy distribution has a frothy appearance, with filaments and sheet-like walls of galaxies straddling huge voids (Fig. 12.4).

What happens on still larger scales? Does the hierarchy of structure continue to grow, with superclusters grouping together and so on? Or does the distribution of galaxies become uniform above a certain scale? The Anglo-Australian Observatory "Two Degree Field" (or 2dF) galaxy survey and the Sloan Digital Sky Survey (SDSS) set out to answer these questions. Extending out to 2 billion light years, these enormous surveys show that the large-scale distribution of galaxies exhibits a web-like structure with filaments, sheets, clusters and voids (see Fig. 12.5). Consistent with the CfA results, the largest structures are roughly 300 million light years in size, and have a mass of about 10^{17} Solar masses (or 10^5 galactic masses). On still larger scales, the universe is homogeneous. There are no "super-superclusters". Thus, if the matter distribution were smoothed over distance scales of 300 million light years, the universe would be homogeneous and isotropic, as assumed in the Friedmann models.

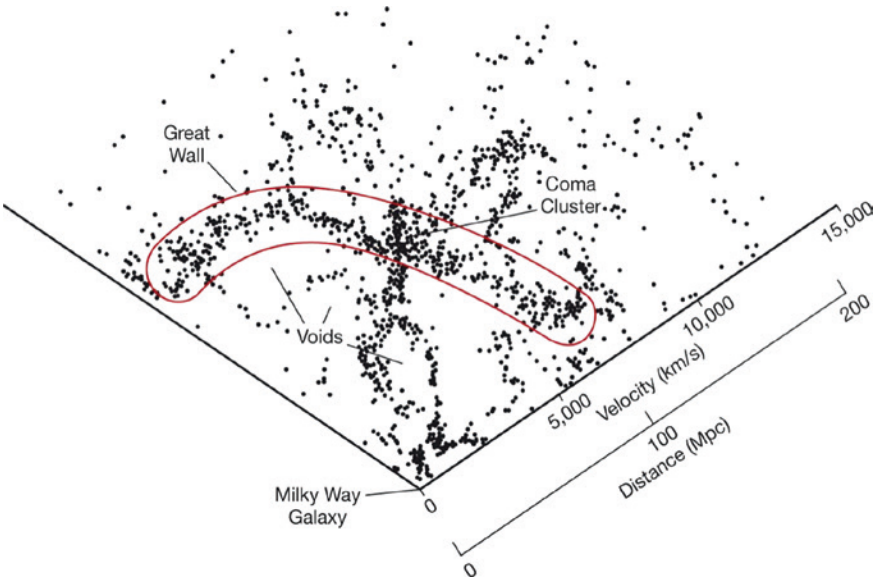

Fig. 12.4 CfA map of a thin (6°) slice of the universe. Each *dot* represents a galaxy. Some of the apparently filamentary structures in the map are actually slices through sheet-like walls. One of them is the "Great Wall" outlined in *red* on the map. *Credit* Smithsonian Astrophysical Observatory. De Lapparent, V.; Geller, M. J.; Huchra, J. P. (1986). "A slice of the universe". The Astrophysical Journal. 302: L1

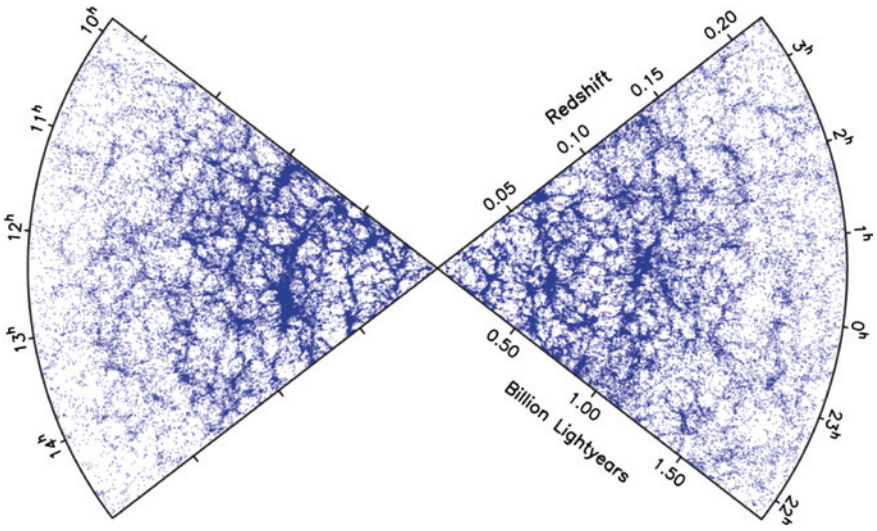

Fig. 12.5 The large-scale distribution of galaxies, as observed by the 2dF survey (2002). *Credit* 2dF Galaxy Redshift Survey

12.2 Assembling Structure

Now that we are familiar with the hierarchical structure of the universe, we are faced with an inevitable question: *How did all these structures arise?* We know that the universe was very homogeneous when the CMB radiation was produced, at $t_{rec} = 380{,}000$ years. If it were perfectly homogeneous, having the same density everywhere, then it would remain that way forever. But we know from CMB observations that there were tiny deviations from perfect homogeneity (about one part in a hundred thousand). This is all that was needed to seed structure formation.

A region that is denser than average will attract matter gravitationally from its surroundings. It thus gets even denser relative to the average, and its gravitational pull gets stronger, attracting even more matter. An overdense expanding region initially continues to expand, but eventually it turns around and collapses back on itself, forming a gravitationally bound object. This effect is called *gravitational instability*; it causes the matter distribution to become more and more lumpy. Only a tiny fluctuation is needed to get the process started.

The basic idea is simple, but as it often happens, the details are rather complicated. It took several decades to sort them out, ultimately the following picture has emerged:

- The gravitational instability is effective only if the expansion of the universe is sufficiently slow. During the radiation era the universe is expanding too fast, so the growth of density fluctuations can begin in earnest only at $t_{eq} \approx 60{,}000$ years, when the matter era begins.
- The clustering of atomic matter develops differently from that of dark matter. The hot atomic gas has a high pressure, which prevents it from being pulled into clumps less massive than about 10^6 Solar masses. On larger mass scales, gravity wins and pressure does not play an important role. Dark matter, on the other hand, is influenced only by gravity,[1] so its lumpiness begins to grow right after t_{eq}. (Here we assume that the dark matter is "cold", in the sense that its particles move slowly and cannot escape the gravitational pull of the developing clumps. This is naturally satisfied if the dark matter particles are sufficiently massive).

[1]Another difference of atomic gas from dark matter is that gas particles often collide, emitting photons in the process. As a result the gas loses energy, cools and sinks deeper towards the centers of dark matter clumps. This cooling process is important on galactic mass scales, up to 10^{12} Solar masses. Dark matter particles, on the other hand, interact very weakly and lose almost no energy in collisions. This explains why stars and gas are localized near the centers of dark matter halos.

- Smaller clumps take a shorter time to form; as a result structure formation proceeds in a hierarchical, bottom-up fashion. It begins with the formation of small dark matter clumps, which then merge to form larger and larger structures. Atomic matter starts falling into dark matter clumps at about 0.5 billion years ABB[2] (after the big bang), when the typical mass of a clump exceeds 10^6 Solar masses. This is when the first stars are formed. Their light illuminates the universe, ending the cosmic dark age.
- A spherical overdense region would collapse to a localized gravitationally bound object. But a typical overdense region is more like an ellipsoid, which has different sizes along three orthogonal axes. It first collapses along its smallest axis to form an approximately 2-dimensional sheet. The sheet then collapses to form a filament, and finally the filament collapses to a localized halo. The observed galaxies and clusters are well localized, gravitationally bound objects, while superclusters are caught in the process of their formation. Some of them resemble filaments or sheets, while others have a rather irregular appearance.
- About 5 billion years ago, when the matter era gave way to the current vacuum dominated era, the expansion of the universe started to accelerate, causing further gravitational clumping to be quenched. This is why there will never be cosmic structures that are larger than superclusters.

It is interesting to note that dark matter played a crucial role in structure formation. In the absence of dark matter, density fluctuations would start growing only much later than t_{eq}. The amount of growth that could occur by the onset of the vacuum era would then be insufficient for the formation of bound structures. Thus, if it were not for dark matter, the universe would be almost devoid of galaxies today.

12.3 Watching Cosmic Structures Evolve

The hierarchical scenario of structure formation has been tested by direct observation of distant galaxies. We can see what early galaxies looked like by taking galaxy images at higher and higher redshifts, that is, by looking deeper and deeper into space. The image in Fig. 12.6 was obtained by pointing the Hubble Space Telescope to a totally blank spot in the sky and tak-

[2]We will use the notation ABB to mean "after the big bang" throughout the rest of the book.

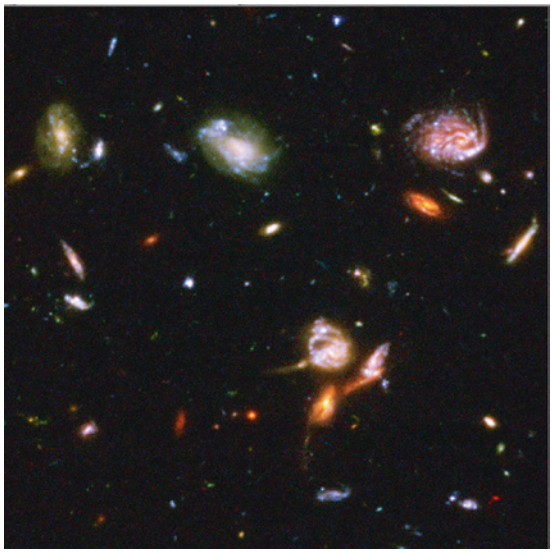

Fig. 12.6 The Hubble Ultra Deep Field *Credit* NASA; ESA; G. Illingworth, D. Magee, and P. Oesch, University of California, Santa Cruz; R. Bouwens, Leiden University; and the HUDF09 Team

ing a very long exposure. This is known as the Hubble Ultra Deep Field. It shows a multitude of early galaxies—some of them date back to less than a billion years ABB.

These infant galaxies differ from today's galaxies in a number of ways. They are much smaller, with a typical size of 10,000 light years across, and generally appear to be chaotic and irregular. Furthermore, almost all infant galaxies are colliding or interacting gravitationally with their neighbors (see Fig. 12.7), compared to about 2% that are colliding today. All these features strongly suggest that present-day galaxies formed by collisions and mergers of smaller early galaxies.

Another way to see cosmic structure formation unfold in front of you is to use a computer simulation. A few frames from one such simulation are shown in Fig. 12.8. The simulation follows the history of a large cubic volume as it expands to the present size of 160 million light years. It starts with a nearly uniform distribution of particles in the volume and includes only gravitational interactions of the particles and the gravitational effect of dark energy. This is a good approximation on the largest scales (galaxy clusters

Fig. 12.7 Colliding early galaxies *Credit* NASA, ESA, the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration, and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)

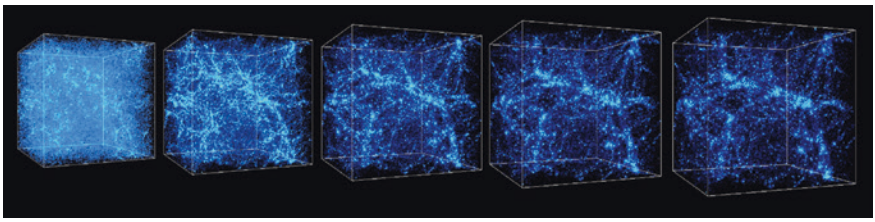

Fig. 12.8 Computer simulation of structure formation. The evolution of a cubic volume is followed from 0.5 billion years ABB ($z = 10$) to the present epoch. The cube expands with the universe (by a factor of 11), but the expansion has been factored out in the figure, so all "snapshots" of the cube have the same apparent size. The snapshots are at redshifts 10, 4, 1, 0.5 and 0. (This simulation was performed by A. Kravtsov and A. Klypin at the National Center for Supercomputer Applications at the University of Chicago)

and above), where gravity is the dominant force. The web-like distribution of matter in the last frame closely resembles the large-scale galaxy distribution observed today.

On galactic and smaller scales, the complicated dynamics of atomic gas cannot be ignored. Cosmologists are making progress simulating these dynamics on computers, but some details of galaxy and star formation are still not fully understood. This is now an active area of research.

12.4 Primordial Density Fluctuations

The picture of structure formation by gravitational instability relies on the existence of small primordial density fluctuations. The magnitude of these fluctuations can be different for regions of different size (or mass). In order

to fully characterize the fluctuations, one has to specify their *spectrum*—that is, the typical strength of the fluctuation as a function of mass. If the spectrum is peaked at some particular mass, then the first bound objects to form are likely to have this mass.[3] Thus the evolution of structure in the universe depends on the form of the primordial fluctuation spectrum.

The structure formation scenario outlined in this chapter and computer simulations, like the one in Fig. 12.8, assume the fluctuation strength to be approximately the same for all relevant mass scales. This is called the *scale-invariant* fluctuation spectrum. *But what is the origin of the primordial fluctuations? And what determined their spectrum?* These questions are addressed by the theory of cosmic inflation. We shall see in Chap. 17 that the fluctuation spectrum predicted by this theory is indeed nearly scale-invariant. Moreover, we shall see that this form of the spectrum is supported by observations.

12.5 Supermassive Black Holes and Active Galaxies

General relativity predicts that if we cram a large enough amount of mass into a small enough volume, we can create a black hole (see Chap. 4). Stellar mass black holes can form at the final stages of stellar evolution. There is also strong observational evidence for the existence of colossal, supermassive black holes with masses of millions and even billions of Solar masses. Velocities of stars and gas close to galactic centers have been measured using Doppler shifts. These measurements reveal the presence of extremely massive compact objects lurking at the center of most galaxies—they are black holes! The black hole at the center of our Milky Way has a mass of about 3.7 million Solar masses, while black holes in some other galaxies are more massive than a billion Solar masses.

These monstrous black holes lie dormant most of the time. But when there is some gas near the galactic center, it falls into the black hole. The gas heats up and emits vast amounts of radiation as it spirals down into the hole. Radiation continues until the supply of gas is exhausted. During their explosive periods, supermassive black holes are the most luminous objects in the universe. Depending on the amount of energy released, and the type of radiation, we call them quasars or active galactic nuclei (Fig. 12.9).

[3]There are also some additional factors that determine the mass (or size) of the first collapsed objects; we do not need to discuss this here in more detail.

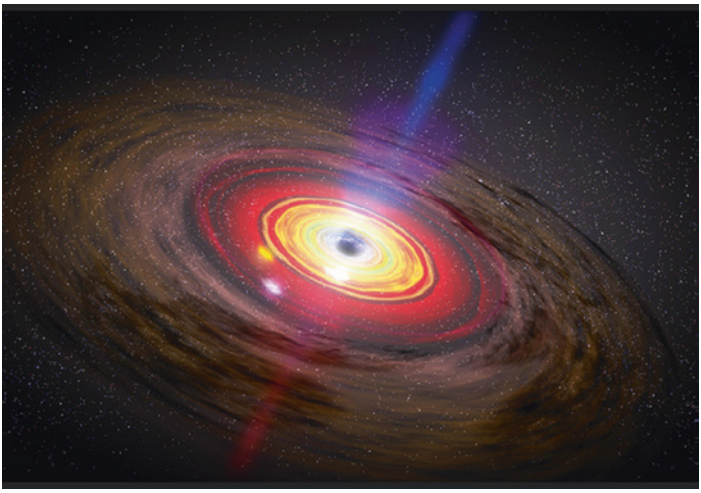

Fig. 12.9 Artist's impression of a supermassive black hole. Infalling gas forms a thin accretion disk as it spirals into the hole. Powerful jets of gas emanate from the black hole vicinity in the directions orthogonal to the disk. Such jets are often observed in active galactic nuclei, but the mechanism of their formation is not well understood. *Credit* NASA / Dana Berry, SkyWorks Digital

Galaxy collisions perturb the gas distribution in the galaxies and trigger black hole feeding. Thus black hole activity should have been more common in the young universe, when the collision rate was high. Observations of quasars support this hypothesis. The quasars we observe are very distant, thus they are very old. Quasar formation rates peaked at about 2–3 billion years ABB. They represent an early stage in galaxy development.

Summary

The origin of galaxies can be traced to tiny inhomogeneities in the primordial fireball. Some regions of the fireball had a slightly higher density than others. The mass of these regions grew as they attracted matter from the surrounding space, and over the course of billions of years they evolved into galaxies and larger structures.

The scenario of structure formation suggested by combining mathematical analysis with simulations is that the first stars formed around 0.5 billion years after the big bang, followed by the birth of infant irregular galaxies. Large galaxies were formed via hierarchical assembly, from the merger of smaller ones. Galaxies then clumped into clusters, which further grouped into superclusters. On the largest scales, the universe exhibits a web-like

structure with filaments, sheets, and voids, up to scales of roughly 300 million light years. On still larger scales, the growth of structure is quenched by gravitational repulsion due to dark energy, so there is no further clumping, and the universe is homogeneous.

Questions

1. The largest structures in the universe have sizes of about 300 million light years. On still larger scales what does the universe look like? What does the galaxy distribution look like on smaller scales?
2. What is gravitational instability? Describe how it can turn small density fluctuations into structures like stars and galaxies.
3. Describe how gravitational instability is different for dark matter and for atomic gas.
4. What is hierarchical clustering?
5. Can you explain why the large-scale distribution of galaxies has a web-like appearance, with filaments, walls and voids?
6. What observational evidence do we have for hierarchical structure formation?
7. Given that the radius of a Solar mass black hole is 3 km, what is the radius of a billion Solar mass supermassive black hole? Compare it to the radius of Earth's orbit around the Sun (1.5×10^{11} m). (Recall the formula for the Schwarzschild radius in Chap. 4).
8. Imagine you live at an earlier cosmic epoch, when galaxies were much younger than they are today. How would the galaxies that you observe be different from the present galaxies? Would they be larger, smaller, or about the same size? Would they be closer or farther apart? What other differences would you expect?
9. What is a quasar? Why are most of the quasars observed at early cosmic times?
10. How do we deduce that there is a supermassive black hole in the center of a galaxy? How do we measure the mass of black holes?
11. How do cosmologists map out the 3-dimensional distribution of galaxies from the 2-dimensional pattern observed on the sky?