8

The large-scale distribution of galaxies

Since the early 1980s, multi-object spectrographs, CCD detectors, and some dedicated telescopes have allowed the mass production of galaxy redshifts. These large surveys have revealed a very surprising picture of the luminous matter in the Universe. Many astronomers had imagined roughly spherical galaxy clusters floating amongst randomly scattered field galaxies, like meatballs in sauce. Instead, they saw galaxies concentrated into enormous walls and long filaments, surrounding huge voids that appear largely empty. The galaxy distribution has been compared to walls of soapy water, surrounding bubbles of air in a basinful of suds; linear filaments appear where the walls of different soap bubbles join, and rich clusters where three or more walls run into each other. A more accurate metaphor is that of a sponge; the voids are interlinked by low-density 'holes' in the walls. Sometimes we think of the filaments as forming a *cosmic web*.

For a star like the Sun in the disk of our Milky Way, the task of finding where it formed is essentially hopeless, because it has already made many orbits about the galaxy, and the memory of its birthplace is largely lost. But the large structures that we discuss in this chapter are still under construction, and the regions where mass is presently concentrated reveal where denser material was laid down in the early Universe. The peculiar motions of groups and clusters of galaxies, their speeds relative to the uniformly expanding cosmos, are motions of infall toward larger concentrations of mass. So the problem of understanding the large-scale structure that we see today becomes one of explaining small variations in the density of the early Universe.

We begin in Section 8.1 by surveying the galaxies around us, mapping out both the local distribution and the larger structures stretching over hundreds of megaparsecs. The following sections discuss the history of our expanding Universe, within which the observed spongy structures grew, and how the expansion and large-scale curvature affect our observations of galaxies. In Section 8.4 we discuss fluctuations in the cosmic microwave background and what they tell us about the initial irregularities that might have given rise to the galaxies that we

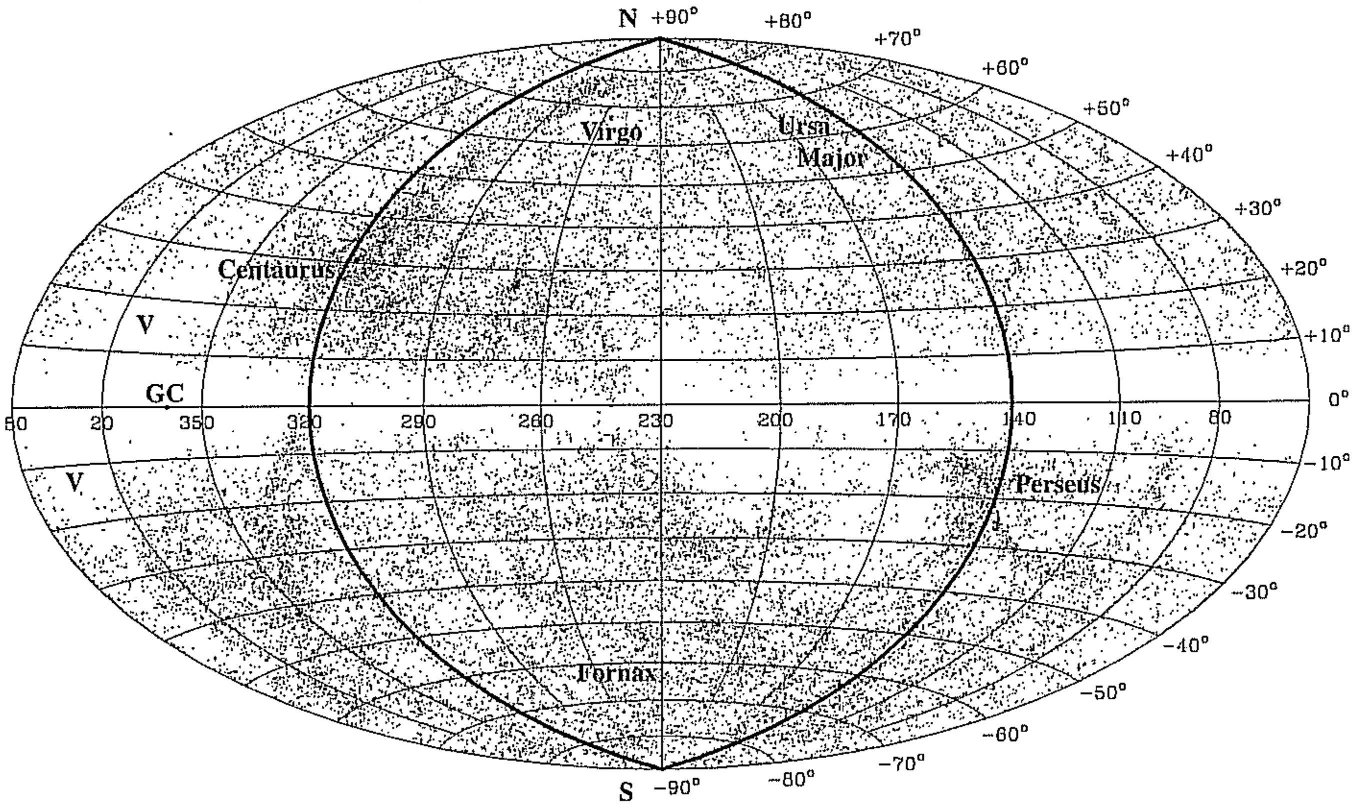

Fig. 8.1. Positions of 14 650 bright galaxies, in Galactic longitude l and latitude b. Many lie near the supergalactic plane, approximately along the Great Circle $l = 140°$ and $l = 320°$ (heavy line); V marks the Local Void. Galaxies near the plane $b = 0$ of the Milky Way's disk are hidden by dust – T. Kolatt and and O. Lahav.

see today. We will see how we can use the observed peculiar motions of galaxies to estimate how much matter is present. The final section asks how dense systems such as galaxies developed from these small beginnings.

Further reading: B. Ryden, 2003, *Introduction to Cosmology* (Addison Wesley, San Francisco, USA) and A. Liddle, 2003, *An Introduction to Modern Cosmology*, 2nd edition (John Wiley & Sons, Chichester, UK) are undergraduate texts on roughly the level of this book. On the graduate level, see M. S. Longair, 1998, *Galaxy Formation* (Springer, Berlin) and T. Padmanabhan, 1993, *Structure Formation in the Universe* (Cambridge University Press, Cambridge, UK).

8.1 Large-scale structure today

As we look out into the sky, it is quite clear that galaxies are not spread uniformly through space. Figure 8.1 shows the positions on the sky of almost 15 000 bright galaxies, taken from three different catalogues compiled from optical photographs. Very few of them are seen close to the plane of the Milky Way's disk at $b = 0$, and this region is sometimes called the *Zone of Avoidance*. The term is unfair: surveys in the 21 cm line of neutral hydrogen, and in far-infrared light, show that galaxies are indeed present, but their visible light is obscured by dust in the Milky Way's disk. Dense areas on the map mark rich clusters: the Virgo cluster is close to the north Galactic pole, at $b = 90°$. Few galaxies are seen in the Local Void, stretching from $l = 40°$, $b = -20°$ across to $l = 0$, $b = 30°$.

The galaxy clusters themselves are not spread evenly on the sky: those within about 100 Mpc form a rough ellipsoid lying almost perpendicular to the Milky Way's disk. Its midplane, the *supergalactic plane*, is well defined in the northern Galactic hemisphere ($b > 0$), but becomes rather scruffy in the south. The pole or Z axis of the supergalactic plane points to $l = 47.4°$, $b = 6.3°$. We take the supergalactic X direction in the Galactic plane, pointing to $l = 137.3°$, $b = 0$, while the Y axis points close to the north Galactic pole at $b = 90°$, so that $Y \approx 0$ along the Zone of Avoidance. The supergalactic plane is close to the Great Circle through Galactic longitude $l = 140°$ and $l = 320°$, shown as a heavy line in Figure 8.1. It passes through the Ursa Major group of Figures 5.6 and 5.8, and the four nearby galaxy clusters described in Section 7.2; the Virgo cluster at right ascension $\alpha = 12^{\mathrm{h}}$, declination $\delta = 12°$; Perseus at $\alpha = 3^{\mathrm{h}}$, $\delta = 40°$; Fornax at $\alpha = 4^{\mathrm{h}}$, $\delta = -35°$; and the Coma cluster at $\alpha = 13^{\mathrm{h}}$, $\delta = 28°$, almost at the north Galactic pole.

Figure 8.2 shows the positions of the elliptical galaxies within about 20 Mpc, tracing out the Virgo and Fornax clusters. The distances to these galaxies have been found by analyzing *surface brightness fluctuations*. Even though they are too far away for us to distinguish individual bright stars, the number N of stars falling within any arcsecond square on the image has some random variation.

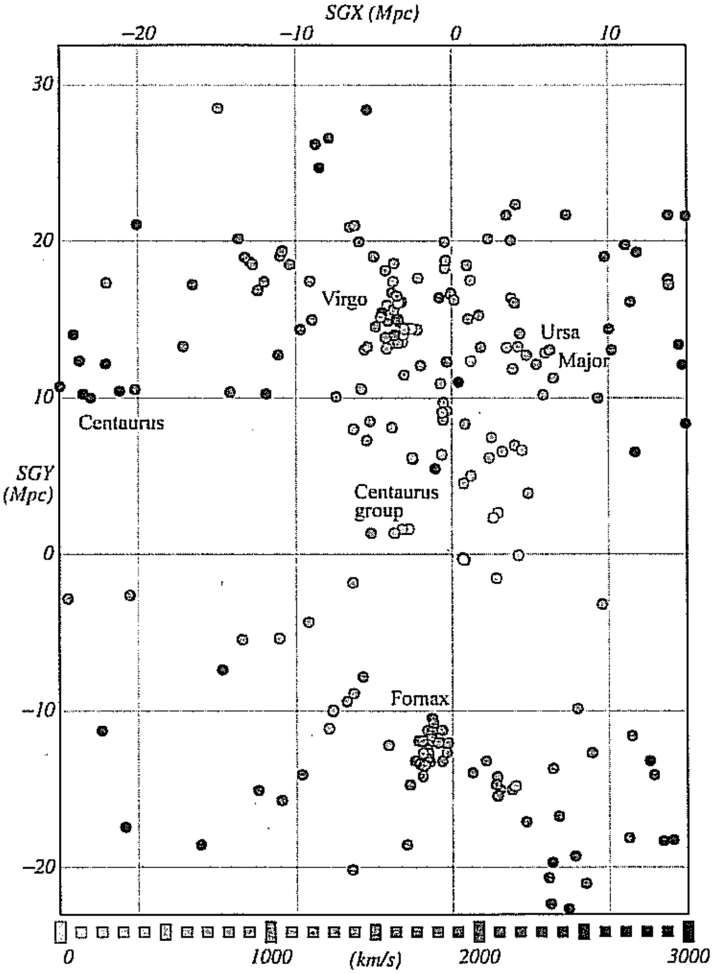

Fig. 8.2. Positions of nearby elliptical galaxies on the supergalactic X–Y plane; the origin is the Milky Way. Shading indicates recession velocity V_r – J. Tonry.

So the surface brightness of any square fluctuates about some average value. The closer the galaxy, the fewer stars lie within each square, and the stronger the fluctuations between neighboring squares: when N is large, the fractional variation is proportional to $1/\sqrt{N}$. So if we measure the surface brightness fluctuations in two galaxies where we know the relative luminosity of the bright stars that emit most of the light, we can find their relative distances.

This method works only for relatively nearby galaxies in which the stars are at least 3–5 Gyr old. In these, nearly all the light comes from stars close to the tip of the red giant branch. As we noted in Section 1.1, these have almost the same luminosity for all stars below about $2\mathcal{M}_\odot$. These stars are old enough that they have made many orbits around the center, so they are dispersed smoothly through the galaxy. The observations are usually made in the I band near 8000 Å, or in the K band at 2.2 μm, to minimize the contribution of the younger bluer stars. The technique fails for spiral galaxies, because their brightest stars are younger: they are red supergiants and the late stages of intermediate-mass stars, and their luminosity depends on the stellar mass, and so on the average age of the stellar population. Since that average changes across the face of the galaxy, so does the luminosity of those bright stars. Also, the luminous stars are too short-lived to move far from the stellar associations where they formed. Their clumpy distribution causes much stronger fluctuations in the galaxy's surface brightness than those from random variations in the number of older stars.

In Figure 8.2, we see that the Virgo cluster is roughly 16 Mpc away. It appears to consist of two separate pieces, which do not coincide exactly with the two velocity clumps around the galaxies M87 and M49 that we discussed in Section 7.2. Here, galaxies in the northern part of the cluster, near M49, lie mainly in the nearer grouping, while those in the south near M86 are more distant; M87 lies between the two clumps. The Fornax cluster, in the south with $Y<0$, is at about the same distance as Virgo. Both these clusters are part of larger complexes of galaxies. Because galaxy groups contain relatively few ellipticals, they do not show up well in this figure. The Local Group is represented only by the elliptical and dwarf elliptical companions of M31, as the overlapping circles just to the right of the origin.

Problem 8.1 In Section 4.5 we saw that the motions of the Milky Way and M31 indicate that the Local Group's mass exceeds $3\times 10^{12}\mathcal{M}_\odot$: taking its radius as 1 Mpc, what is its average density? Show that this is only about $3h^{-2}$ of the critical density ρ_{crit} defined in Equation 1.30 – the Local Group is only just massive enough to collapse on itself.

Problem 8.2 The free-fall time $t_{\mathrm{ff}} = 1/\sqrt{G\rho}$ of Equation 3.23 provides a rough estimate of the time taken for a galaxy or cluster to grow to density ρ. In Problem 4.7 we saw that, for the Milky Way, with average density of $10^5\rho_{\mathrm{crit}}$ within the Sun's orbit, this minimum time is $\sim 3\times 10^8$ years or $0.03\times t_{\mathrm{H}}$, the expansion age given by Equation 1.28. Show that a cluster of galaxies with density $200\rho_{\mathrm{crit}}$ can barely collapse within the age of the Universe. This density divides structures like the Local Group that are still collapsing from those that might have settled into an equilibrium.

To probe further afield, we use a 'wedge diagram' like Figure 8.3 from the 2dF survey, which measured redshifts of galaxies in two large slices across the sky. If we ignore peculiar motions, Equation 1.27 tells us that the recession speed $V_r \approx cz \approx H_0 d$, where H_0 is the Hubble constant; the redshift is roughly proportional to the galaxy's distance d from our position at the apex of each wedge. So this figure gives us a somewhat distorted map of the region out to $600h^{-1}$ Mpc.

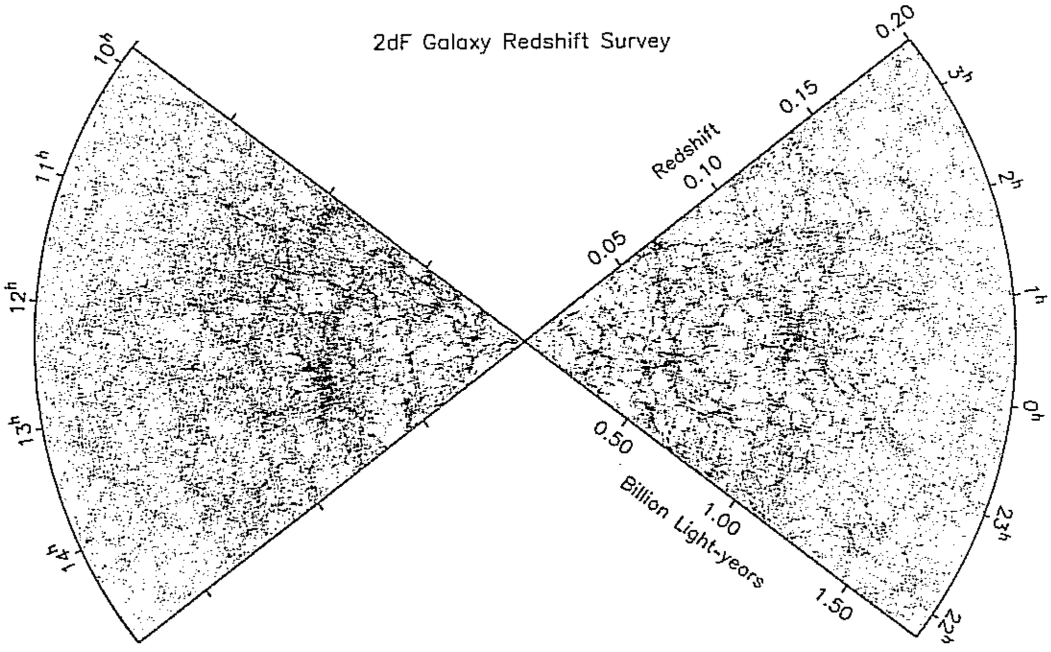

Fig. 8.3. A 'wedge diagram' of 93 170 galaxies from the 2dF survey with the Anglo-Australian 4-meter telescope, in slices $-4° < \delta < 2°$ in the north (left wedge) and $-32° < \delta < -28°$ in the south (right) – M. Colless *et al.* 2001 *MNRAS* **328**, 1039.

The three-dimensional distribution of galaxies in Figure 8.3 has even more pronounced structure than Figure 8.1. We see dense linear features, the walls and stringlike filaments of the cosmic web; at their intersections there are complexes of rich clusters. Between the filaments we find large regions that are almost empty of bright galaxies: these *voids* are typically $\gtrsim 50h^{-1}$ Mpc across. The galaxies appear to thin out beyond $z = 0.15$ because redshifts were measured only for objects that exceeded a fixed apparent brightness. Figure 8.4 shows that, at large distances, just the rarest and most luminous systems have been included. When a solid angle Ω on the sky is surveyed, the volume between distance d and $d + \Delta d$ is $\Delta \mathcal{V} = \Omega d^2 \Delta d$, which increases rapidly with d. Accordingly, we see few galaxies nearby; most of the measured objects lie beyond 25 000 $\mathrm{km\,s^{-1}}$.

Problem 8.3 The Local Group moves at 600 $\mathrm{km\,s^{-1}}$ relative to the cosmic background radiation. At this speed, show that an average galaxy would take $\sim 40h^{-1}$ Gyr to travel from the center to the edge of a typical void. Whatever process removed material from the voids must have taken place very early, when the Universe was far more compact.

In Figures 8.3 and 8.4, the walls appear to be several times denser than the void regions. But ignoring the peculiar motions has exaggerated their narrowness and

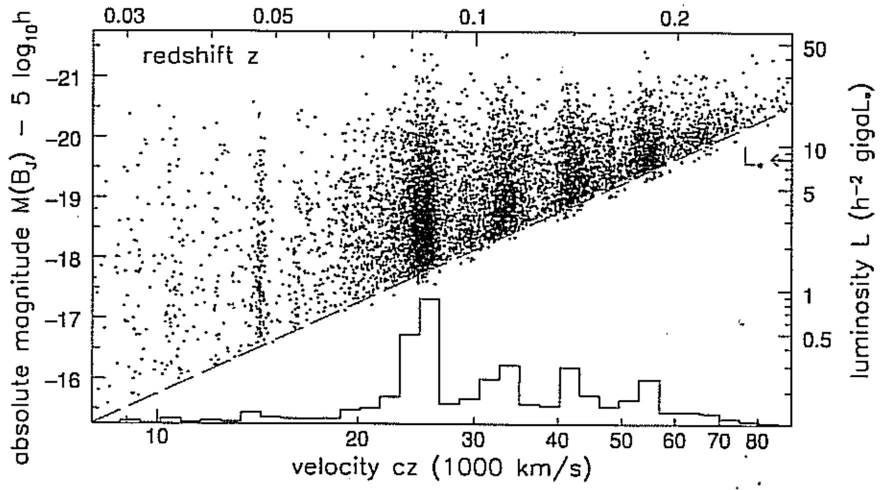

Fig. 8.4. Luminosity (absolute magnitude in B_J) of 8438 galaxies near $13^{\rm h}20^{\rm m}$ in Figure 8.3, showing the number at each redshift. The luminosity L_* of a typical bright galaxy is taken from Figure 1.16; the dashed line at apparent magnitude $m(B_J) = 19.25$ shows the approximate limit of the survey.

sharpness; they would appear less pronounced if we could plot the true distances of the galaxies. The extra mass in a wall or filament attracts nearby galaxies in front of the structure, pulling them toward it and away from us. So the radial velocities of those objects are increased above that of the cosmic expansion, and we overestimate their distances, placing them further from us and closer to the wall. Conversely, galaxies behind the wall are pulled in our direction, reducing their redshifts; these systems appear nearer to us and closer to the wall than they really are. In fact, the walls are only a few times denser than the local average.

By contrast, dense clusters of galaxies appear elongated in the direction toward the observer. The cores of these clusters have completed their collapse, and galaxies are packed tightly together in space. They orbit each other with speeds as large as 1500 km s^{-1}, so their distances inferred from Equation 1.27 can have random errors of $15h^{-1}$ Mpc. In a wedge diagram, rich clusters appear as dense 'fingers' that point toward the observer.

Problem 8.4 How long is the narrow 'finger' in the left panel of Figure 8.5 near $z = 0.12$ and $12^{\rm h}30^{\rm m}$? Show that this represents a large galaxy cluster with $\sigma_r \approx 1500\,\mathrm{km\,s^{-1}}$.

Figure 8.5 shows wedge diagrams for red galaxies, with spectra that show little sign of recent star formation, and blue galaxies, with spectral lines characteristic

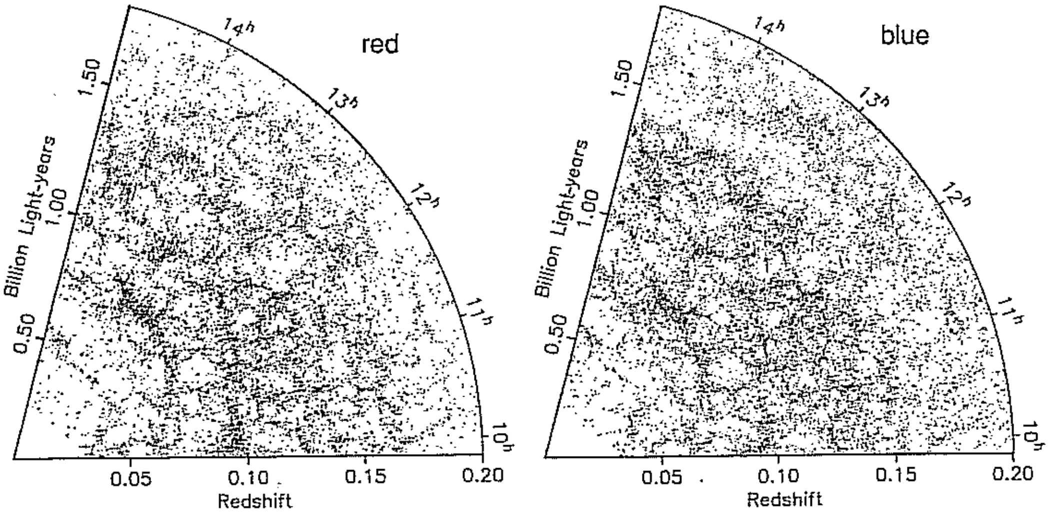

Fig. 8.5. About 27 000 red galaxies (left) with spectra like those of elliptical galaxies, and the same number of star-forming blue galaxies (right), in a slice $-32° < \delta < -28°$ from the 2dF survey. These are luminous galaxies, with $-21 < M(B_J) < -19$. The elliptical and S0 galaxies cluster more strongly than the spiral-like systems.

of young massive stars and the ionized gas around them. In Figure 8.4 we see clumps of galaxies around 13^h20^m at $z = 0.05, 0.08, 0.11$, and 0.15. These are quite clear in the left wedge of Figure 8.5, but much weaker in the right wedge. Similarly, the void at 12^h and $z = 0.08$ is emptier in the left wedge – why? The left-wing galaxies are red elliptical and S0 systems, while on the right are spirals and irregulars. As we saw in Section 7.2, elliptical galaxies live communally in the cores of rich clusters, where spiral galaxies are rare. Accordingly, the clustering of the red galaxies is stronger than that of the bluer systems of the right panel. Whether galaxies are spiral or elliptical is clearly related to how closely packed they are: we see a *morphology–density relation.*

In fact, we should not talk simply of 'the distribution of galaxies', but must be careful to specify which galaxies we are looking at. We never see all the galaxies in a given volume; our surveys are always *biassed* by the way we choose systems for observation. For example, if we select objects that are large enough on the sky that they appear fuzzy and hence distinctly nonstellar, we will omit the most compact galaxies. A survey that finds galaxies by detecting the 21 cm radio emission of their neutral hydrogen gas will readily locate optically dim but gas-rich dwarf irregular galaxies, but will miss the luminous ellipticals which usually lack HI gas. The Malmquist bias of Problem 2.11 is present in any sample selected by apparent magnitude. Even more insidious are the ways in which the bias changes with redshift and apparent brightness. Mapping even the luminous matter of the Universe is no easy task.