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Super-Large-Scale Structures in the Sloan Digital Sky Survey *

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Abstract We study the super-large-scale structures in the Sloan Digital Sky Survey by cluster analysis, and examine the geometry and the properties of the member galaxies. Two subsamples are selected from the SDSS, Subsample 1 at the celestial equator and Subsample 2 further north. In Subsample 1 we discover two compact super-large-scale structures: the Sloan Great Wall and the CfA Great Wall. The Sloan Great Wall, located at a median redshift of $z = 0.07804$, has a total length of about 433 Mpc and a mean galaxy density of about six times that of the whole sample. Most of its member galaxies are of medium size and brightness. The CfA Great Wall, located at a median redshift of $z = 0.03058$, has a total length of about 251 Mpc and includes large percentages of faint and small galaxies and relatively fewer early-type galaxies.

Key words: galaxy: distances and redshifts — large-scale structure of universe

1 INTRODUCTION

In the distribution of extragalactic bodies, the existence of super-large-scale structures is an important discovery. In the early 80's, the clustering of galaxy clusters (Bahcall & Soneira 1983) and voids (Kirshner et al. 1981) were observed. Soon after that, astronomers successively discovered "The Strings" (Haynes & Giovarelli 1986), "The Great Wall" (Geller & Huchra 1989), "The Great Attractor" (Lynden-Bell et al. 1988), and super-large-scale structures on the scale of $\geq 100\,h^{-1}$ Mpc in the distribution of galaxies. In order to explore the existence of super-large-scale structures in the distribution of the clusters, Deng et al. (1996) studied the structure in the two-dimensional distribution of Abell-ACO clusters of distance classes $D = 5$ and $D = 6$ by cluster analysis. The results showed that there are real structures on the scale of $\geq 100\,h^{-1}$ Mpc in the distribution of rich clusters. In the Southern Galactic Subsample of $D = 5$, Deng et al. discovered "The Great Wall of galaxy clusters", about $400\,h^{-1}$ Mpc in length.

The Great Wall, the most extended megastructure ever discovered, which was discovered by Geller & Huchra (1989) in the CfA survey, stretches from $9^{\rm h}$ to $16.7^{\rm h}$ in right ascension, is a system of thousands of galaxies arrayed across the cosmos in the form of a vast, crumpled membrane, and is far too large and too massive to have formed by the mutual gravitational attraction of its member galaxies. It is located at a median redshift of $z = 0.02918$, with a length of about 240 Mpc in

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co-moving coordinates. In the Sloan Digital Sky Survey (SDSS),a larger Great Wall was discovered (Gott et al. 2005). It is located at a redshift of $z = 0.0734$, almost a factor of 3 further than the Great Wall of Geller & Huchra (1989). Its total length in co-moving coordinates is 450 Mpc, thus 80% greater than the Great Wall of Geller & Huchra.

Geller & Huchra (1989) discovered the Great Wall by observing the cone diagram of slices in a certain declination range, while Gott et al. (2005) discovered such super-large-scale structures in the conformal map of the universe. They roughly studied the geometrical property of the structures by two-dimensional survey results. In this paper, we intend to separate such super-large-scale structures from the whole galaxy sample by the three-dimensional cluster analysis (Einasto et al. 1984). This makes it possible that many properties of the Great Wall can be studied further. We examine its geometry and the properties of member galaxies. Hopefully, this research will be helpful to the understanding of the properties of such super-large-scale structures.

This paper is organized as follows. In Section 2, we describe the data to be used. The cluster analysis is discussed in Section 3. In Section 4, we present the basic properties of the Great Wall. Our main results and conclusions are summarized in Section 5.

2 DATA

SDSS is one of the largest astronomical surveys to date. The completed survey will cover approximately 10 000 square degrees. York et al. (2000) provided a technical summary of the SDSS. The SDSS observes galaxies in five photometric bands (u, g, r, i and z) centered at 3540, 4770, 6230, 7630 and 9130 Å, respectively. The imaging camera was described by Gunn et al. (1998), while the photometric system and the photometric calibration of the SDSS imaging data were roughly described by Fukugita et al. (1996), Hogg et al. (2001) and Smith et al. (2002), respectively. Pier et al. (2003) described the methods and algorithms involved in the astrometric calibration of the survey, and presented a detailed analysis of the accuracy achieved. Many of the survey properties were discussed in detail in the Early Data Release paper (Stoughton et al. 2002). Galaxy spectroscopic target selection can be implemented by two algorithms. The primary sample (Strauss et al. 2002), referred to here as the MAIN sample, targets galaxies brighter than $r < 17.77$ (r-band apparent Petrosian magnitude). The surface density of such galaxies is about 90 per square degree. This sample has a median redshift of 0.10 and few galaxies are beyond $z = 0.25$. The Luminous Red Galaxy (LRG) algorithm (Eisenstein et al. 2001) selects ~ 12 additional galaxies per square degree, using color-magnitude cuts in g, r, and i to select galaxies to $r < 19.5$ that are likely to be luminous early-types at redshifts up to ~ 0.5.

The SDSS has adopted a modified form of the Petrosian (1976)'s system of galaxy photometry, which is designed to measure a constant fraction of the total light independent of the surface-brightness limit. The Petrosian radius r_p is defined to be the radius where the local surface-brightness averaged in an annulus equals 20 percent of the mean surface-brightness interior to this annulus, i.e.,

$$\frac{\int_{0.8r_p}^{1.25r_p} dr2\pi rI(r)/[\pi(1.25^2 - 0.8^2)r^2]}{\int_0^{r_p} dr2\pi rI(r)/[\pi r^2]} = 0.2\,,$$

where $I(r)$ is the azimuthally averaged surface-brightness profile. The Petrosian flux F_p is then defined as the total flux within a radius of $2r_p$, $F_p = \int_0^{2r_p} 2\pi r dr I(r)$. With this definition, the Petrosian flux (magnitude) is about 98 percent of the total flux for an exponential profile and about 80 percent for a de Vaucouleurs profile. The other two Petrosian radii listed in the Photo output, R_{50} and R_{90}, are the radii enclosing 50 percent and 90 percent of the Petrosian flux, respectively.

The SDSS sky coverage can be separated into three regions. Two of them are located north of the Galactic plane, with one region at the celestial equator and another at high declination. The third lies south of the Galactic plane. Each of these regions covers a wide range of longitude. For the purpose of studying super-large-scale structures, we only use the first two regions, the one at the celestial equator is labelled Subsample 1, the other one further north, Subsample 2.

We downloaded the data of the main galaxy sample from the Catalog Archive Server of SDSS Data Release 3 (Abazajian et al. 2005) using the SDSS SQL Search (http://www.sdss.org). From this basic sample, we produce the two subsamples described above. Subsample 1 comprises 68 386 galaxies, and Subsample 2, 113 354. When calculating the luminosity distance we use a cosmological model with a matter density $\Omega_0 = 0.3$, cosmological constant $\Omega_\Lambda = 0.7$, and Hubble's constant $H_0 = 100\,h\,\mathrm{km\ s^{-1}\ Mpc^{-1}}$ with $h = 0.7$.

3 CLUSTER ANALYSIS

As a general method, cluster analysis (Einasto et al. 1984) has been applied to the study of the geometry of point samples in many fields. The key idea of this method is to separate the sample into individual systems by an objective, automatic procedure. Let us first draw a sphere of radius R around each sample point (in our case, galaxy). If within this sphere there are other galaxies, then these galaxies are considered to be neighbors or friends belonging to the same system. Now draw a sphere around each friend and continue the procedure using the rule "any friend of a friend is a friend". When no more friends can be added, then the procedure stops and a system is identified. The system then consists either of a single, isolated galaxy or of a number of galaxies, each of which has at least one neighbour within a distance not exceeding R.

The mean density of galaxies is $\bar{\rho} = N/V$ (N is the number of galaxies contained in the volume V) and the radius of the sphere with unit population is $R_0 = [3/(4\pi\bar{\rho})]^{1/3}$. In our analysis, we express all distances in dimensionless radii $r = R/R_0$. According to the redshift distribution more than 96% galaxies in our sample are in the redshift range $0.02 \leq z \leq 0.2$. For this selected redshift range, our calculated result is $R_0 = 7.712\,\mathrm{Mpc}$.

4 BASIC RESULTS

First, we analyse how the size (expressed by the number of member galaxies, or the "galaxy number") of the richest system varies as a function of the dimensionless radius r. Figure 1 shows the results for the two subsamples. For small radii ($r < 0.6$), the systems resulting from the cluster analysis are mostly isolated galaxies or close double and multiple galaxies. A few form the cores of groups and conventional clusters of galaxies. For very large radii, the previous systems merge into very large, less dense regions. As we are interested in compact super-large-scale structures, we limit the dimensionless radius to the range $0.6 \leq r \leq 0.9$. In Subsample 1, we discover that the richest system forming in $0.62 \leq r \leq 0.64$ and $0.67 \leq r \leq 0.76$ is around redshift $z = 0.07804$, and the richest system forming at $r = 0.65$–0.66 is around redshift $z = 0.03058$. At $r = 0.77$, the two systems at different distances merge into one. So we preliminarily confirm that there are two compact super-large-scale structures in Subsample 1. Figure 1(a) shows a platform in the region $0.69 \leq r \leq 0.75$. This presents that the super-large-scale structure at $z = 0.07804$ is a very dense and relatively isolated system. In Subsample 2, we do not find any compact and isolated structures as in Subsample 1. From $r = 0.62$ to $r = 0.77$, the formed richest system varies almost smoothly from a dense one to an extended one in a certain space.

In order to illustrate the super-large-scale structures in Subsample 1, we show the richest systems forming at $r = 0.65$ and $r = 0.69$ in the polar plot Figure 2 (redshift distance cz versus right ascension). The $r = 0.69$ system is around cz=23412 km s^{-1}, the $r = 0.65$ system, around cz=9174 km s^{-1}. The super-large-scale structure around cz=23412 km s^{-1} is the Great Wall discovered in the SDSS (Gott et al. 2005, hereafter, refers to The Sloan Great Wall). It contains 8902 galaxies at a median redshift of $z = 0.07804$ and stretches from 139.2° to 211.8° in right ascension. Its total length is about 433 Mpc (luminosity distance), and the thickness at the median redshift approximately 55.7 Mpc. We calculate the mean galaxy density of the Sloan Great Wall in the region $0.065 \leq z \leq 0.09$, $150° \leq \mathrm{RA} \leq 210°$, $-3° \leq \mathrm{DEC} \leq 6°$ (the Sloan Great Wall contains 7482 galaxies in this region, about 84% of the total galaxy number of the Sloan Great Wall) , and compare it with the mean galaxy density of the whole sample in the redshift region $0.02 \leq z \leq 0.2$. The result shows that the mean galaxy density of the Sloan Great Wall is about six times that of the whole sample. The super-large-scale structure around cz=9174 km s^{-1} is the Great Wall discovered in the CfA survey (Geller & Huchra 1989, hereafter, refers to The CfA Great Wall). It contains 2691 galaxies at a median redshift of $z = 0.03058$ and stretches from 129.1° to 236.2° in right ascension. Its total length is about 251 Mpc. The Sloan Great Wall is 1.73 times as long as the CfA Great Wall.

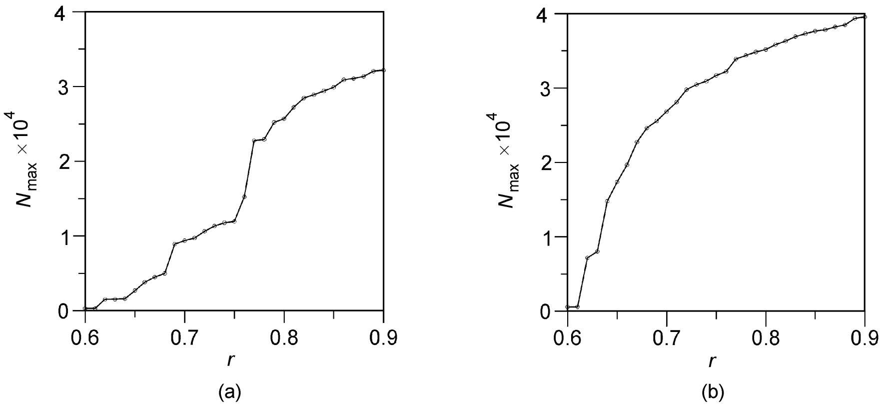

Fig. 1 Galaxy number $N_{\max}$ of the richest system as a function of the dimensionless radius r, (a) for Subsample 1 and (b) for Subsample 2.

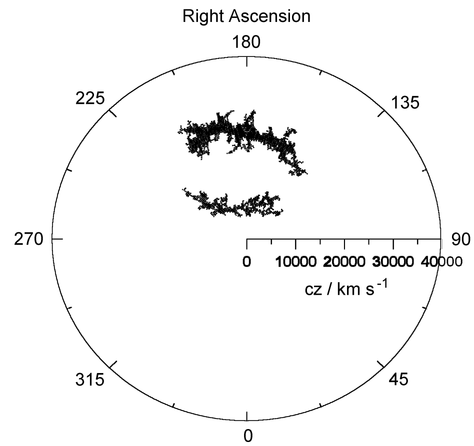

Fig. 2 Distribution of right ascension and redshift distance cz for the super-large-scale structures forming at $r = 0.69$ and $r = 0.65$. They respectively are around cz=23412 km s^{-1} (forming at $r = 0.69$) and cz=9174 km s^{-1} (forming at $r = 0.65$).

Several studies have shown that the 3D topology of large scale structure is sponge-like (Gott, Dickinson & Melott 1986; Vogeley et al. 1994; Hikage et al. 2002). So, it should not be surprising that as we look at larger samples we would find examples of larger connected structures. Simulations have presented that the Great Wall can be produced from random phase Gaussian fluctuations in a standard flat-ΛCDM model which also predicts a sponge-like topology of high density regions in 3D (Colley et al. 2000; Cole et al. 1998)

The luminosity, size, and morphological type are the most basic properties of a galaxy. Observed galaxies cover large ranges in these properties, for example, the effective radius falls between 0.1 kpc and 50 kpc, the morphology ranges from pure disk systems to pure ellipsoidal systems. The study of the distribution of galaxy properties is crucial to our understanding of the formation and evolution of the galaxy population.

Figure 3 displays separately the distributions of absolute magnitudes in Subsample 1, the Sloan Great Wall, and the CfA Great Wall. The absolute magnitude M_r can be calculated from the r-band

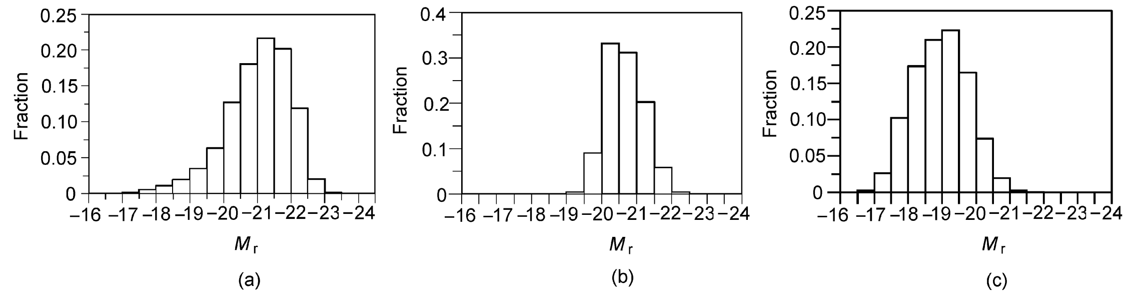

Fig. 3 Distribution of the absolute magnitudes of galaxies for Subsample 1, the Sloan Great Wall, and the CfA Great Wall, respectively. (a) for Subsample 1; (b) for the Sloan Great Wall; (c) for the CfA Great Wall.

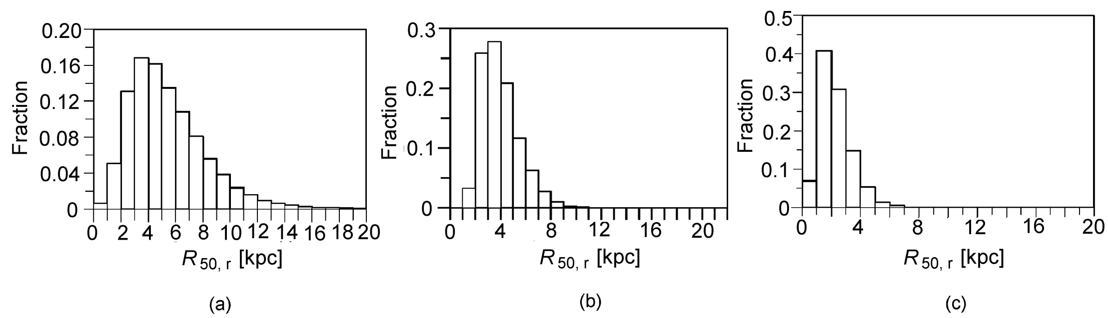

Fig. 4 Histogram of the size distribution of galaxies of Subsample 1 (a), the Sloan Great Wall (b), and the CfA Great Wall (c).

apparent Petrosian magnitude. Because our analysis is rough, we have ignored the K-correction (Blanton et al. 2003). We discover that, in the Sloan Great Wall, both faint and bright galaxies are few: only about 0.39% are fainter than $M_r = -19.5$ (to compare with 7.2% in Subsample 1), and only about 0.38% are brighter than $M_r = -22$ (14% in Subsample 1). Interestingly, the proportion of faint galaxies in the CfA Great Wall is very high: about 51.2% are fainter than $M_r = -19$ and as high as 73.5% are fainter than $M_r = -19.5$.

In Figure 4, we plot the histogram of the size distribution of galaxies for Subsample 1, the Sloan Great Wall, and the CfA Great Wall. Of the two Petrosian radii listed, R_{50} and R_{90}, we selected the r-band $R_{50}(R_{50,r})$ to represent the galaxy size. In the Sloan Great Wall, most (86.1%) galaxies have sizes from 2 to 6 kpc, and there is almost no galaxies smaller than 1 kpc, and the proportion of galaxies larger than 9 kpc is relatively small (in Subsample 1, this proportion is 10.4%). In the CfA Great Wall, most (about 71.4%) galaxies have sizes from 1 to 3 kpc, about 6.9% are smaller than 1 kpc, and only 2% are larger than 5 kpc.

For small (compact) galaxies in SDSS, the size measurement is seriously affected by the PSF (point-spread-function), or they are misclassified as stars. In our main galaxy sample, the lower limit of angular sizes R50 of galaxies is $0.596''$. At this limit galaxies in the Sloan Great Wall almost have projected sizes $R_{50} > 1$ kpc. Therefore, it is completely due to this lower limit of angular size that there are almost no galaxies smaller than 1 kpc in the Sloan Great Wall.

There have been attempts to classify SDSS galaxies into morphological classes through direct inspection of the galaxy images (Shimasaku et al. 2001; Nakamura et al. 2003). While such eyeball classification should match the original Hubble morphological sequence, it is quite tedious and has so far been carried out only for about 1500 larger galaxies in the SDSS. However, it has

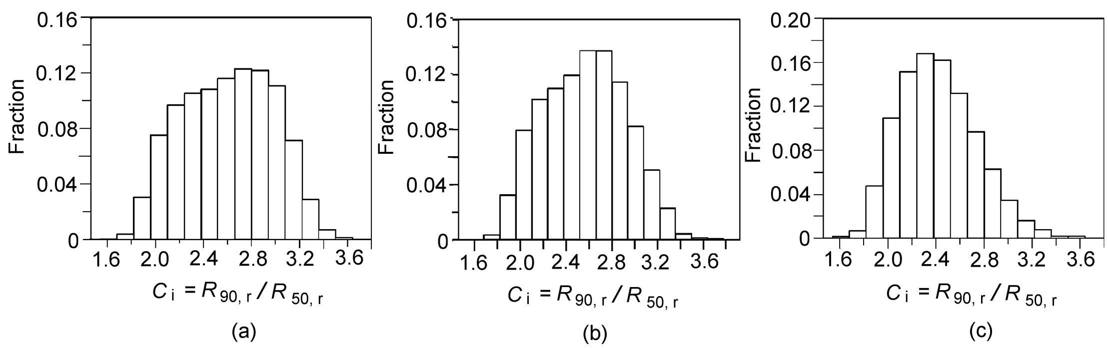

Fig. 5 Histogram of the concentration index c_i for Subsample 1 (a), the Sloan Great Wall (b), and the CfA Great Wall (c).

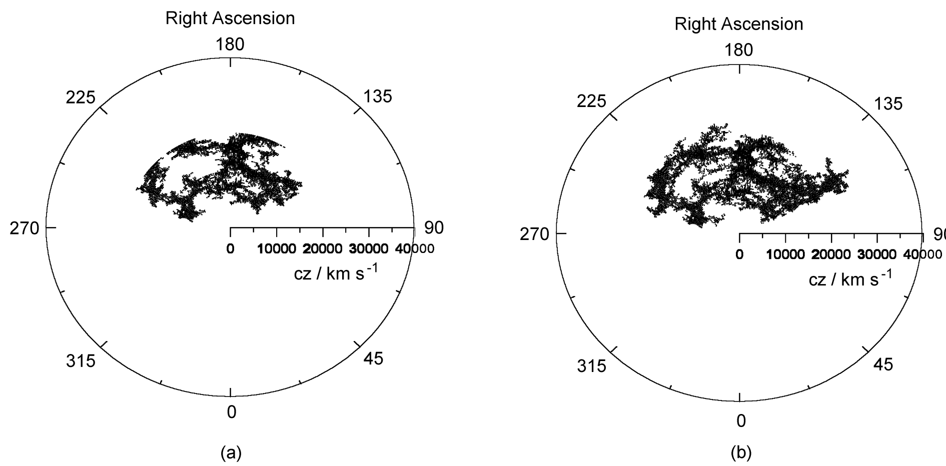

Fig. 6 Polar plot of the richest systems formed at $r = 0.65$ (a) and $r = 0.69$ (b) in Subsample 2.

been suggested that some photometric and spectroscopic properties may be closely correlated with the morphological type, and so can be used as morphology indicators. For example, Shimasaku et al. (2001) showed that the concentration index $c_i = R_{90}/R_{50}$ can be used to separate early-type (E/S0) galaxies from late-type (Sa/b/c, Irr) galaxies. Using about 1500 galaxies with eye-ball classifications, Nakamura et al. (2003) confirmed that $c_i = 2.86$ separates galaxies at S0/a with a completeness of about 0.82 for both late and early types. In Subsample 1, 28.9% of galaxies are included in the early types ($c_i > 2.86$). Figure 5 shows the histogram of the concentration index c_i distribution in the three data sets. We notice that the proportion of early-type galaxies in the CfA Great Wall is smaller at about 9.8%, and is about 22.3% in the Sloan Great Wall, approximately the same as in the whole sample.

The galaxy size has been found to be correlated with the luminosity (Kormendy 1977; Shen et al. 2003). Shen et al. (2003) argued that the dependence of galaxy size $R_{50,r}$ on the luminosity is quite different for early- and late-type galaxies: for the early-type galaxies ($c_i > 2.86$), $R_{50,r} \propto L^{0.6}$; for the late-type galaxies ($c_i < 2.86$), $R_{50,r} \propto L^{0.21}$ at the faint end ($L \ll L_0$) (L_0 being the luminosity corresponding to $M_0 = -20.52$), and $R_{50,r} \propto L^{0.53}$ at the bright end ($L \gg L_0$). We notice that most galaxies are smaller and fainter in the CfA Great Wall, while in the Sloan Great

Wall bright medium size galaxies account for a high proportion. This result accords with the correlation of the galaxy size with luminosity stated above.

We also analyse the super-large-scale structures in Subsample 2. Figure 6 is a polar plot of the richest systems formed at $r = 0.65$ and $r = 0.69$ in Subsample 2. Here, we do not see such compact structures as in Subsample 1.

5 SUMMARY

Since the Great Wall was discovered, its geometry was explored mainly by some two-dimensional views (Geller & Huchra 1989; Gott et al. 2005). In our work, we separate such super-large-scale structures from the galaxy background by three-dimensional cluster analysis (Einasto et al. 1984). This makes it possible that many properties of the Great Wall can be studied fully. To explore the Great Wall in the SDSS data we select two subsamples north of the Galactic plane: one at the celestial equator (Subsample 1) and one at the higher declination (Subsample 2), and study its geometry and the properties of the member galaxies of the Great Wall.

Because we use galaxy redshifts as radial distance indicators, our results refer to the redshift space. The main conclusions can be summarized as follows:

(1) In Subsample 1, we discover two compact super-large-scale structures: the Sloan Great Wall and the CfA Great Wall, while in Subsample 2 we do not observe any such compact structures.
(2) The Sloan Great Wall, located at a median redshift of $z = 0.07804$, has a total length of about 433 Mpc, and a mean galaxy density about six times that of the whole sample. We analysed the distributions of luminosity and galaxy size. In the Sloan Great Wall, 86.1% of the member galaxies have sizes from 2 to 6 kpc, and galaxies fainter than $M_r = -19.5$ or brighter than $M_r = -22$ are both rare.
(3) The CfA Great Wall, located at a median redshift of $z = 0.03058$, has a total length of about 251 Mpc. About 71.4% of the members have sizes between 1 and 3 kpc. The proportion of galaxies fainter than $M_r = -19$ is about 51.2% and that of galaxies fainter than $M_r = -19.5$ is as high as 73.5%.
(4) We separate early-type (E/S0) galaxies from late-type (Sa/b/c, Irr) galaxies according as the concentration index c_i is greater or less than 2.86. We discover that there are relatively few early-type galaxies in the CfA Great Wall.

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