The Astrophysical Journal Letters, 759:L7 (6pp), 2012 November 1 doi:10.1088/2041-8205/759/1/L7
© 2012. The American Astronomical Society. All rights reserved. Printed in the U.S.A.

THE CHALLENGE OF THE LARGEST STRUCTURES IN THE UNIVERSE TO COSMOLOGY

Changbom Park[1], Yun-Young Choi[2], Juhan Kim[3], J. Richard Gott III[4], Sungsoo S. Kim[2,5], and Kap-Sung Kim[2,5]
[1] School of Physics, Korea Institute for Advanced Study, Heogiro 85, Seoul 130-722, Republic of Korea
[2] Department of Astronomy & Space Science, Kyung Hee University, Gyeonggi 446-701, Republic of Korea; yy.choi@khu.ac.kr
[3] Center for Advanced Computation, Korea Institute for Advanced Study, Heogiro 85, Seoul 130-722, Republic of Korea
[4] Department of Astrophysical Sciences, Peyton Hall, Princeton University, Princeton, NJ 08544-1001, USA
[5] School of Space Research, Kyung Hee University, Gyeonggi 446-701, Republic of Korea
Received 2012 September 5; accepted 2012 September 25; published 2012 October 10

ABSTRACT

Large galaxy redshift surveys have long been used to constrain cosmological models and structure formation scenarios. In particular, the largest structures discovered observationally are thought to carry critical information on the amplitude of large-scale density fluctuations or homogeneity of the universe, and have often challenged the standard cosmological framework. The Sloan Great Wall (SGW) recently found in the Sloan Digital Sky Survey (SDSS) region casts doubt on the concordance cosmological model with a cosmological constant (i.e., the flat ΛCDM model). Here we show that the existence of the SGW is perfectly consistent with the ΛCDM model, a result that only our very large cosmological *N*-body simulation (the Horizon Run 2, HR2) could supply. In addition, we report on the discovery of a void complex in the SDSS much larger than the SGW, and show that such size of the largest void is also predicted in the ΛCDM paradigm. Our results demonstrate that an initially homogeneous isotropic universe with primordial Gaussian random phase density fluctuations growing in accordance with the general relativity can explain the richness and size of the observed large-scale structures in the SDSS. Using the HR2 simulation we predict that a future galaxy redshift survey about four times deeper or with 3 mag fainter limit than the SDSS should reveal a largest structure of bright galaxies about twice as big as the SGW.

Key words: cosmology: observations – galaxies: statistics – large-scale structure of universe – methods: numerical – methods: observational

Online-only material: color figures

1. INTRODUCTION

The Sloan Great Wall (SGW; Gott et al. 2005) found in the Sloan Digital Sky Survey (SDSS; Aihara et al. 2011) is a thick filamentary structure of galaxies located at a distance of about 300 Mpc from the Earth. Its densest part spans about 200 Mpc, and the whole filament projected on a slice appears to be contiguous over a scale of more than 400 Mpc. It is likely to be longer since the structure is cut by the survey boundaries. The SGW is reminiscent of the CfA Great Wall (Geller & Huchra 1989) which triggered an intense dispute against the "standard" cold dark matter (SCDM) model (White et al. 1987) or even the whole class of gravitational instability models of structure formation (Park 1990 and references therein). The cosmological principle of homogeneity and isotropy of the universe was also doubted since structures as big as the survey size were always found as the survey size was increased.

The skepticism was relieved when Park (1990) demonstrated that large-scale structures (LSSs) with sizes up to 200 Mpc can appear in the standard CDM cosmological model in surveys like the CfA survey. About 20 years later, the SGW revived the doubt on the cosmological principle and the current standard model (ΛCDM model), since it is even larger than the CfA Wall and comparable to the survey size again (Sheth & Diaferio 2011).

In this Letter we ask whether or not the existence of the LSSs observed in the SDSS is consistent with the ΛCDM model that adopts a homogeneous isotropic universe with primordial Gaussian random phase density fluctuations as predicted by inflation and a reasonably successful galaxy assignment scheme. The comparison of real superclusters with simulated ones has been made in several previous studies (Einasto et al. 2006, 2007b, 2007c; Araya-Melo et al. 2009). We also make predictions on the properties of the LSSs to be observed in the future deeper surveys. A Hubble constant of 72 km s^{-1} Mpc^{-1} is used in this Letter.

2. THE SDSS SAMPLE

To identify the LSSs in an observational sample we use the SDSS Main galaxy sample (Strauss et al. 2002), which is currently the largest three-dimensional sample of galaxies with a high sampling density. A volume-limited subsample of 116,877 galaxies with absolute *r*-band magnitude brighter than −21.6 is generated from the KIAS value-added catalog (Choi et al. 2010a), which supplements the bright galaxies missing in the SDSS sample. The magnitude limit is about 0.6 mag brighter than the critical magnitude M_* of the SDSS Main galaxy sample (Choi et al. 2007), and corresponds to the sample depth of 689 Mpc for the given apparent magnitude of 17.77. The mean separation between galaxies is $\bar{d} = 12.5$ Mpc. The sample is large enough to reduce the cosmic variance in the number of SGW-like structures, and yet the galaxy number density is high enough to trace major LSSs. We calculate the comoving distances *R* of galaxies using the *Wilkinson Microwave Anisotropy Probe* 5 year cosmological parameters (Komatsu et al. 2009), and the Cartesian coordinates are calculated as in Park et al. (2007),

$$x = -R\sin\lambda,\ y = R\cos\lambda\cos\eta,\ z = R\cos\lambda\sin\eta, \qquad (1)$$

where λ and η are the SDSS survey coordinates.

3. IDENTIFICATION OF THE LARGE-SCALE STRUCTURES

Superclusters of galaxies have been identified by many previous studies, which typically use the smoothed luminosity density of galaxies and apply a threshold level to define

structures (Basilakos et al. 2001; Einasto et al. 2007a; Luparello et al. 2011; Liivamagi et al. 2012). Here we adopt the friend-of-friend (FoF) algorithm to identify high-density LSSs by connecting close galaxies because the results convey the visual impression well and the method effectively uses only one free parameter.

Before we search for structures in a sample of galaxies, we first reduce the finger-of-god effects. We apply the FoF algorithm with the linking length of 3000 km^{-1} s to the sample to find massive groups. The dispersion of each group along the line of sight is forced to be equal to that across the line of sight if the former is larger than the latter. We then search for LSSs by connecting galaxies separated by less than the connection length d_c. A very small d_c results in no LSS, and a very large d_c gives just one LSS connecting all galaxies. We choose to use the critical linking length that results in the maximum number of structures (Basilakos 2003). In the case of our volume-limited sample we find the critical linking length of $d_c = 7.78\,\mathrm{Mpc} = 0.622\,\bar{d}$ when the minimum number of member galaxies is set to 20.

The left column of Figure 1 shows the four richest high-density LSSs found in the SDSS sample using the FoF method. The richest one among all 873 structures discovered within our sample is a dense part of the SGW containing 822 bright galaxies (the top left panel). However, the largest one is the second richest structure with the maximum extent of 226 Mpc containing 601 galaxies. The part of the SGW identified by our FoF method is 207 Mpc long. The richest structures are typically filamentary, and filaments are often looping. Superclusters are also occasionally found attaching a few spreading filaments. The relatively poor structures are usually single superclusters or doubles connected by a thin filament. Some LSSs contain one or a few superclusters found by previous studies (Einasto et al. 2011a, 2011b; Liivamagi et al. 2012).

The low-density LSSs are found in a similar fashion. We tessellate the SDSS region with cubic pixels, and then mark the void core pixels from which there is no or only one galaxy within a radius of r_{ball}. Note that the high-density structures are regions where a ball with a radius of d_c contains two or more galaxies. Therefore, our definition for void core pixels is consistent with and complementary to the definition of the high-density structures. To identify voids, these void pixels contacting their faces are grouped together by using the FoF algorithm. We then expand each void out to the distance of $r_{\mathrm{ball}} - d_c$ to account for the buffer region with high-density structures, where d_c is the linking length used to identify the high-density structures. We adopt the critical $r_{\mathrm{ball}} = 18.14\,\mathrm{Mpc} = 1.45\,\bar{d}$ that results in the maximum number of independent voids with volume of the core pixel region larger than $(15\,\mathrm{Mpc})^3$.

On the right of Figure 1, the three largest-volume void complexes found in our SDSS sample are shown. The largest one among the 385 voids found is located just behind and above (in y- and z-directions) the SGW (the top right panel; see also Einasto et al. 2011c, 2012 for a large void at similar location). Its total volume is as big as $(157\,\mathrm{Mpc})^3$ and its maximum extent is 464 Mpc, more than twice larger than the dense part of the SGW. The largest few void complexes have very complicated topology showing many voids multiply connected by tunnels. The relatively smaller low-density structures are usually single voids.

4. *N*-BODY COSMOLOGICAL SIMULATION

Our main concern is to know how often these largest structures are expected to be observed in the currently popular model of the universe. Taking one more step further we ask if the whole distribution of richness or size of the observed LSSs is consistent with the prediction of the standard model.

We use a very large cosmological *N*-body simulation, Horizon Run 2 (HR2; Kim et al. 2011), for the comparison. The simulation evolved 6000^3 particles in a box with a side length of 10 Gpc to calculate the gravitational evolution of primordial density fluctuations generated in accordance with a ΛCDM model (Komatsu et al. 2009). The matter, baryon, and cosmological constant density parameters are set to 0.26, 0.044, and 0.74, respectively (see Kim et al. 2011). The minimum mass of dark matter subhalos identified in the simulation is $5.2 \times 10^{12}\ M_\odot$, and the mean subhalo separation is 12.5 Mpc, equal to that of our SDSS galaxy sample. We assume that each dark matter subhalo above the minimum mass contains one galaxy. This subhalo–galaxy one-to-one correspondence model has been proven to work well in terms of one-point function and its local density dependence (Kim et al. 2008), two-point function (Kim et al. 2009), and also topology (Gott et al. 2009; Choi et al. 2010b). Using this galaxy assignment scheme and the idea of abundance matching, we assume that the subhalos with mass above $5.2 \times 10^{12}\ M_\odot$ compare with our SDSS galaxies brighter than $M_r = -21.6$ as they both have the same mean number density of $5.11 \times 10^{-4}\,\mathrm{Mpc}^{-3}$.

The total volume of our SDSS sample is $(615\,\mathrm{Mpc})^3$ effectively. Our HR2 simulation, about 16 times larger in linear size, is for the first time large enough to capture the large-scale power actually present in the standard model of cosmology and at the same time has a mass resolution high enough to simulate the SDSS Main galaxy sample. This uniqueness of the simulation enables us to estimate the statistical likelihood of the LSSs found in the observations.

5. COMPARISON BETWEEN THE OBSERVATIONS AND THE ΛCDM MODEL

We make 200 SDSS-like surveys of the "galaxies" in the simulation at the present epoch and analyze the mock survey samples in exactly the same way the observational data are analyzed.

Therefore, there are no evolutionary effects in our simulated samples, but we expect them to be small as the sample depth is still quite small ($\Delta z = 0.161$ with z from 0.01 to 0.171). For each mock sample the fingers of god are identified and compressed, and the critical linking length giving the maximum number of LSSs is found. We find that the mean and standard deviation of the linking lengths from the 200 mock SDSS samples are $d_c = 7.71 \pm 0.18\,\mathrm{Mpc}$, quite close to that of the observational sample. Figure 2 shows the four largest typical high-density LSSs and three largest typical low-density structures selected from the 200 mock samples. For example, the largest one in the figure is the structure having the approximately median maximum extent and also the median richness (or volume in the case of low-density structures) among the 200 largest structures found in each of the 200 mock samples. The second largest structure is the median among the 200 second largest ones.

Out of the 200 mocks, 137 samples contain a high-density structure richer than the SGW. We also find that the largest high-density structure is longer than the SGW identified in the same way in 155 cases. Therefore, we conclude that structures like the SGW can be easily found in surveys like the SDSS in the ΛCDM universe even though the LSSs grew from primordial Gaussian fluctuations in a homogeneous isotropic background. On the other hand, none of the mock samples have the sixth richest or largest structure richer or larger than the SGW. This

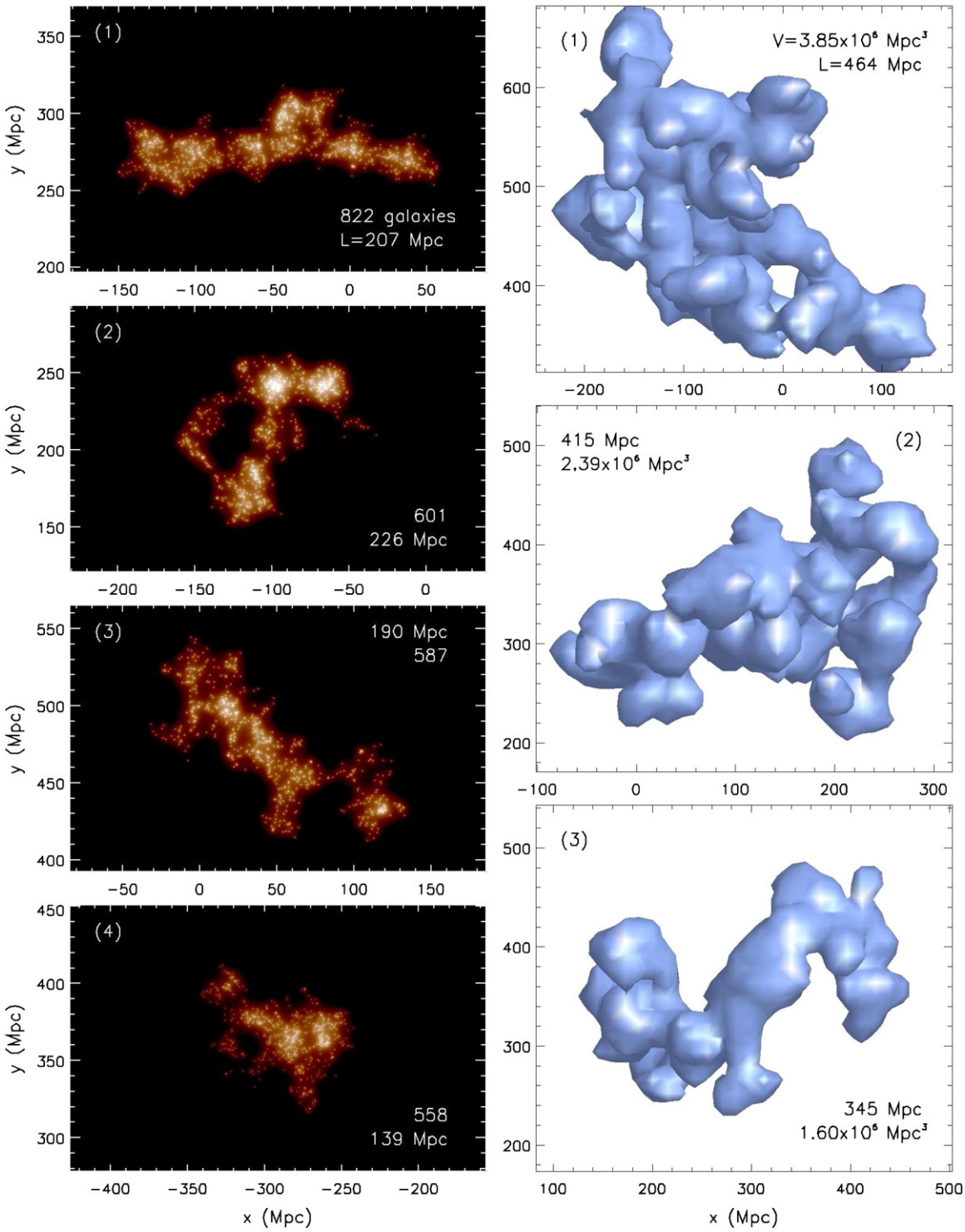

Figure 1. Left: the four richest high-density large-scale structures found using the friend-of-friend method with the linking length of 7.78 Mpc. Galaxies belonging to each structure are projected onto the *x*–*y* plane of the SDSS survey coordinates (Choi et al. 2010b). *L* is the maximum extent of each structure. Right: three largest volume low-density large-scale structures (void complexes). The total volume *V* is calculated by expanding 10.4 Mpc to all directions from the core region shown in the plot to take into account the boundary regions with the high-density structures.

means that even though the SGW-like structures can be found quite often in an SDSS-like survey, such large structures are always one of the top six richest and largest structures. The SGW is indeed a rare object, and was found because of the large survey volume of the SDSS.

Our conclusion is opposite to that of Sheth & Diaferio (2011), who used the extreme value statistics to estimate the likelihood of finding an SGW-like object in the SDSS. They claimed that the existence of the SGW is a 4σ event in the flat ΛCDM universe with the rms amplitude of density fluctuation in a 11.1 Mpc radius sphere of $\sigma_8 = 0.8$, and is difficult to reconcile with the model.

To further inspect the consistency between the observations and the ΛCDM model we calculate the distribution functions

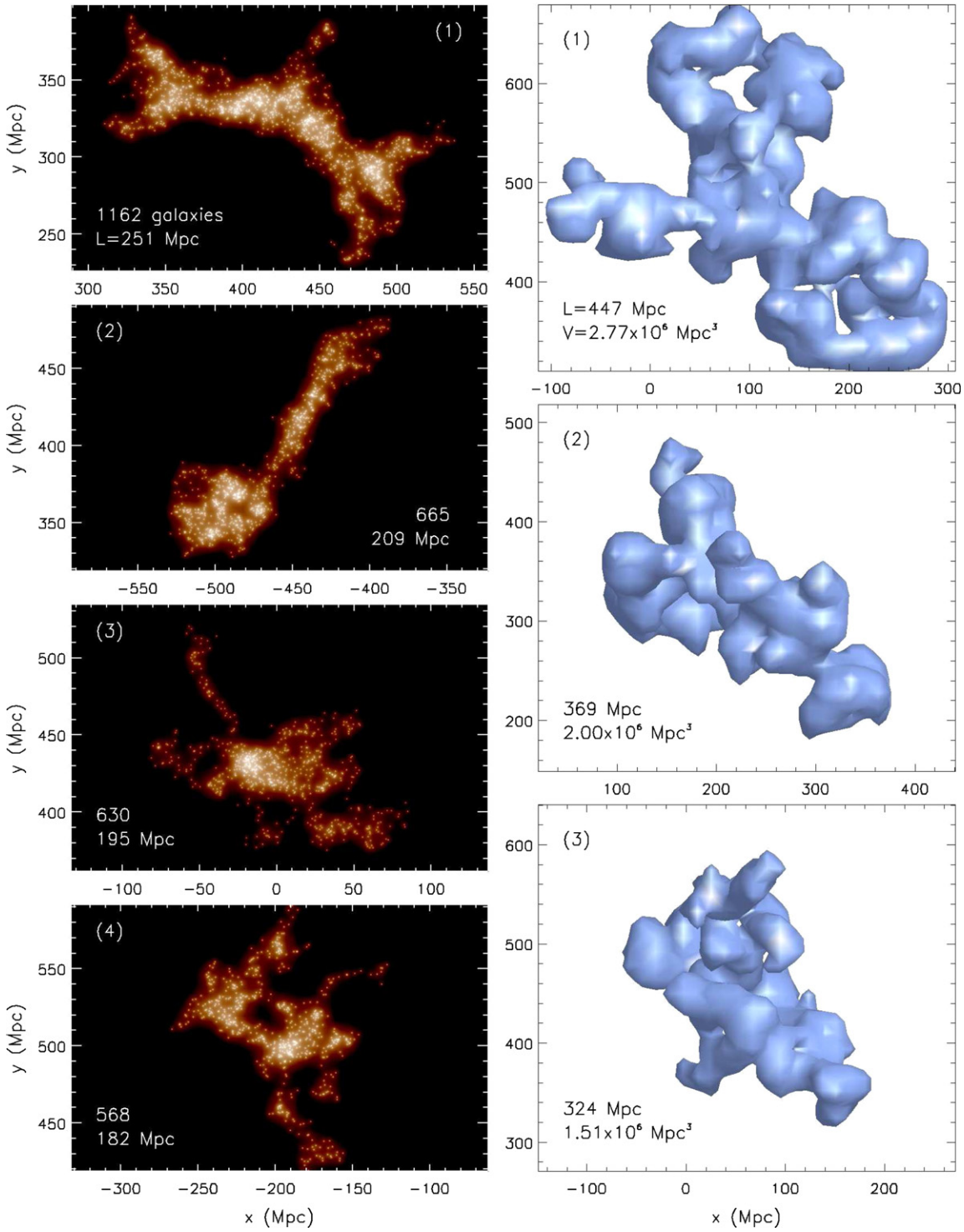

Figure 2. Four largest typical high-density LSSs (left) and three largest typical low-density structures (right) selected from the 200 mock samples. The high-density LSSs show superclusters and filaments connected quite similarly to the observed ones. Likewise, the low-density structures show topology of voids very much like the observed void complexes.

of the richness and size of the LSSs. Figure 3 shows the distributions of the number of structures with member galaxies more than N_g (open circles in the top panel) and with a maximum extent larger than L (open circles in the bottom panel). The y-axis Φ is the number of structures per unit SDSS volume. The mean and standard deviation of the cumulative histograms from 200 mock surveys are shown as lower solid lines and error bars. It can be seen that the observed richness and size distributions agree astonishingly well with the simulation.

Our ΛCDM simulation tells us that on average the richest high-density LSS in the flat ΛCDM universe in an SDSS volume is expected to contain 957 galaxies brighter than $M_r = -21.6$ when the linking length is 7.78 Mpc, and that the typical size of the largest structure is 255 Mpc. These values compare with 822 galaxies and 226 Mpc for the SDSS sample. Therefore, the largest structures in the observations are actually a little smaller than the ΛCDM expectations both in the richness and size. The triangles and upper solid lines are the cumulative histograms for

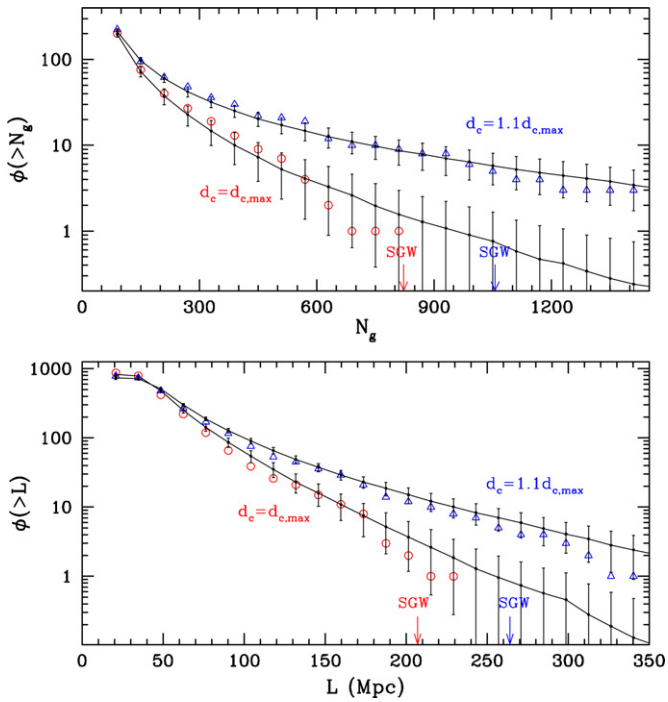

Figure 3. Richness (top) and size distributions (bottom) of high-density large-scale structures in the observations and simulations. Cumulative distribution functions of the richness and size of the high-density LSSs identified in the SDSS sample (circles). The richness N_g is the number of member galaxies belonging to each LSS. The triangles are the distribution functions when the linking length is increased by 10%. The corresponding solid lines and the error bars attached are the means and the standard deviations obtained from 200 mock surveys in the Horizon Run 2 simulation. The red arrows on the left are the locations of the SGW when the linking length d_c is set to the critical value while the right ones are when d_c is 10% larger. Note the SGW is the fifth richest and largest structure for this larger linking length.

(A color version of this figure is available in the online journal.)

the observation and the simulation when the linking length is increased by 10% above the critical value. The plots demonstrate that the agreement does not depend on the choice of the linking length even though the histograms and thus the LSSs found change significantly.

Springel et al. (2006) claimed that an SGW-like object was found in their Millennium Simulation to support their view that a LSS does not provide the strongest challenge to ΛCDM. However, considering the fact that the matter fluctuation power spectrum of their simulation deviated largely from the ΛCDM theory near the simulation box scales due to incorrect normalization and statistical fluctuations (Springel et al. 2005) and also having only one simulation whose volume is roughly equal to SDSS, it would be difficult to draw such a conclusion on the prevalence of an SGW-like structure in the SDSS-like surveys in the ΛCDM universe. Our HR2 is about 4300 times larger than the volume of the SDSS sample with the fundamental mode more than 15 times larger than the depth of SDSS, and accurate statistical comparisons as presented here are possible.

The impressive agreement between the observations and the ΛCDM model is also found for the volume and size of void complexes. Figure 4 shows the number of the void complexes in the SDSS sample with volume larger than V (open circles in the upper panel) and that with the maximum extent larger than L (open circles in the bottom panel). The cumulative distribution functions agree very well with the mean of the 200 mock surveys in the HR2 (solid lines with error bars).

To find how the size of the largest LSS scales as the survey size increases, we made 27 non-overlapping mock surveys in the HR2 simulation having the SDSS angular mask but with the outer boundary located at 2767 Mpc or redshift 0.8. These surveys are about four times deeper or 3 mag fainter than the SDSS. We use these mock surveys to correctly account for the survey boundary effects on the scaling of the LSS. We find that the largest LSS typically has the mean number of galaxies of 2480 and the maximum extent of 430 Mpc. Therefore, the maximum richness and size will increase by a factor of only about 3 and 1.7, respectively, if the evolution effects are not large and the universe will look more homogeneous over the scale of the survey size.

6. CONCLUSIONS

We identify high-density and low-density LSSs in the SDSS to test whether or not the current standard ΛCDM model of the universe can explain the observed structures of bright galaxies (Choi et al. 2010b). The LSSs used in this comparison are those when the characteristic connection lengths result in the maximum number of structures. It is found that the richest high-density structure is the dense part of the SGW, which is also the second largest structure. The low-density LSSs are typically much larger than the high-density counterparts, and the largest one is found to be 464 Mpc long.

The HR2 simulation of the ΛCDM universe is used to make a set of mock SDSS surveys. Galaxies are assigned to dark matter subhalos assuming that each halo contains one galaxy and adopting the abundance matching (Kim et al. 2008). LSSs are identified in exactly the same way that the SDSS data are analyzed. We find that the structures with richness and size similar to the SGW are usually one of the richest and/or the largest structures in the mock samples. To estimate the statistical significance of the largest observed LSSs and to check the consistency of the properties of the observed LSSs with those of the structures found in ΛCDM, we measure the distribution functions of the richness and maximum extent of LSSs. We found that the observed distribution functions agree with those of the simulation astonishingly well. We conclude that both observed high-density and low-density LSSs have the richness/volume and size distributions consistent with the ΛCDM universe. This agreement between the observations and the theoretical predictions should be considered as one of the great successes of the ΛCDM cosmological model coupled with the subhalo–galaxy correspondence model.

Einasto et al. (2006, 2007b, 2007c) compared properties of 2dFGRS and SDSS superclusters with those of superclusters identified from the Millennium Run mock galaxy catalogue. They showed that the geometric properties of real superclusters such as the size, the degree of asymmetry and compactness, and the mass of the richest superclusters are similar to those of simulated ones (see also Araya-Melo et al. 2009). It was found that the fraction of such extremely massive and richest superclusters is too small in the simulated samples when compared to the observed samples, and the morphology of the richest supercluster in the SGW is not recovered in simulation (see also Einasto et al. 2011b). Richness and luminosity function of LSSs depend sensitively on three things: first, the initial conditions such as the primordial power spectrum; second, the galaxy properties (or the galaxy assignment scheme in the simulation); and third, the LSS identification method. Therefore, for a fair comparison between observations and simulations, it is very important to use the same mass objects and to identify the LSSs using the

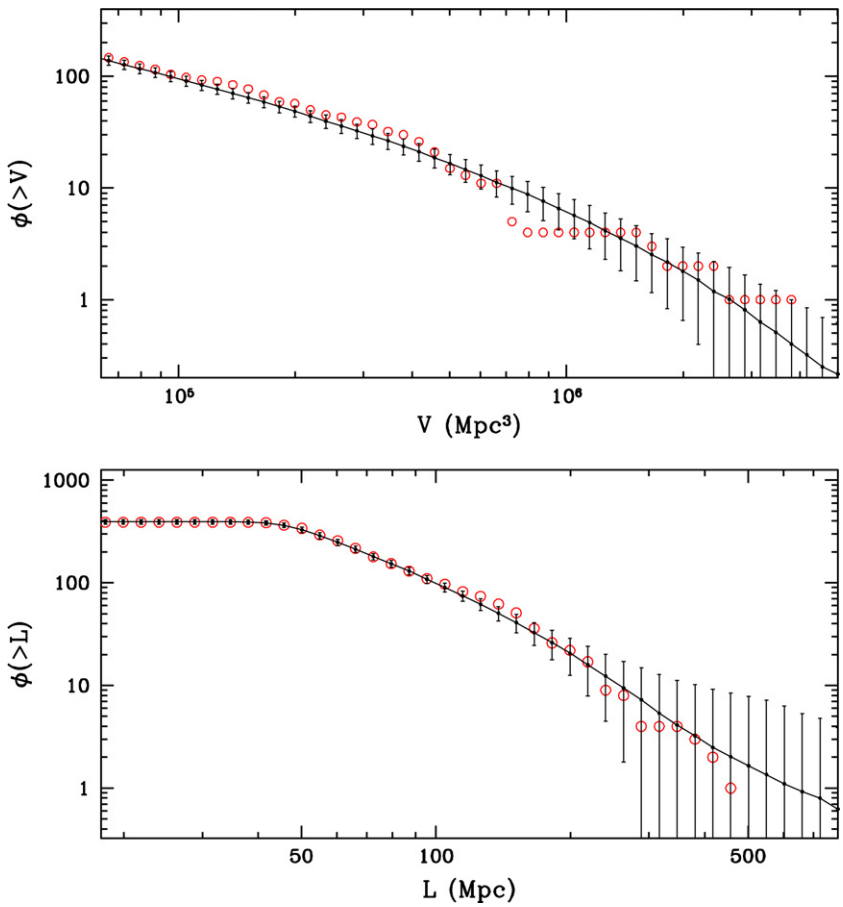

Figure 4. Volume (top) and size distributions (bottom) of voids in the observations and simulations. Cumulative distribution functions of the volume and size of the void complexes identified from the SDSS sample (circles). 200 mock surveys in the Horizon Run 2 simulation are used to calculate the mean (solid lines) and standard deviations (error bars).

(A color version of this figure is available in the online journal.)

same criteria. Whether or not the largest LSSs of the ΛCDM universe have properties different from the observed ones in previous studies remain to be studied further.

We note in this study that the properties of LSSs depend sensitively on the initial power spectrum and the growth of structures and can be a powerful tool to discriminate among cosmological models and galaxy formation scenarios. We plan to further explore the usefulness of using LSS properties in cosmology in future studies.

This work was supported by a grant from the Kyung Hee University in 2011 (KHU-20100179). We thank Graziano Rossi for helpful comments and Korea Institute for Advanced Study for providing computing resources (KIAS Center for Advanced Computation Linux Cluster System) for this work.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web site is http://www.sdss.org/.

REFERENCES

Aihara, H., Allende Prieto, C., An, D., et al. 2011, ApJS, 193, 29
Araya-Melo, P. A., Reisenegger, A., Meza, A., et al. 2009, MNRAS, 399, 97
Basilakos, S. 2003, MNRAS, 344, 602
Basilakos, S., Plionis, M., & Rowan-Robinson, M. 2001, MNRAS, 323, 47
Choi, Y.-Y., Han, D.-H., & Kim, S. S. 2010a, J. Korean Astron. Soc., 43, 191
Choi, Y.-Y., Park, C., Kim, J., et al. 2010b, ApJS, 190, 181
Choi, Y.-Y., Park, C., & Vogeley, M. S. 2007, ApJ, 658, 884
Einasto, J., Einasto, M., Saar, E., et al. 2006, A&A, 459, L1
Einasto, J., Einasto, M., Saar, E., et al. 2007a, A&A, 462, 811
Einasto, J., Einasto, M., Saar, E., et al. 2007b, A&A, 462, 397
Einasto, J. M., Saar, E., Liivamagi, L. J., et al. 2007c, A&A, 476, 697
Einasto, M., Liivamagi, L. J., Tago, E., et al. 2011a, A&A, 532, 5
Einasto, M., Liivamagi, L. J., Tempel, E., et al. 2011b, ApJ, 736, 51
Einasto, J., Suhhonenko, I., Hutsi, G., et al. 2011c, A&A, 534, 128
Einasto, M., Liivamagi, L. J., Tempel, E., et al. 2012, A&A, 542, 36
Geller, M. J., & Huchra, J. P. 1989, Science, 246, 897
Gott, J. R., Choi, Y.-Y., Park, C., & Kim, J. 2009, ApJ, 695, L45
Gott, J. R., III, Jurić, M., Schlegel, D., et al. 2005, ApJ, 624, 463
Kim, J., Park, C., & Choi, Y. Y. 2008, ApJ, 683, 123
Kim, J., Park, C., Gott, J. R., III, & Dubinski, J. 2009, ApJ, 701, 1547
Kim, J., Park, C., Rossi, G., Lee, S. M., & Gott, J. R. 2011, J. Korean Astron. Soc., 44, 217
Komatsu, E., Dunkley, J., Nolta, M. R., et al. 2009, ApJS, 180, 330
Liivamagi, L. J., Tempel, E., & Saar, E. 2012, A&A, 539, 80
Luparello, H., Lares, M., Lambas, D. G., & Padilla, M. D. 2011, MNRAS, 415, 964
Park, C. 1990, MNRAS, 242, 59
Park, C., Choi, Y.-Y., Vogeley, M. S., Gott, J. R., & Blanton, M. R. 2007, ApJ, 658, 898
Sheth, R. K., & Diaferio, A. 2011, MNRAS, 417, 2938
Springel, V., Frenk, C. S., & White, S. D. M. 2006, Nature, 440, 1137
Springel, V., White, S. D. M., Jenkins, A., et al. 2005, Nature, 435, 629
Strauss, M. A., Weinberg, D. H., Lupton, R. H., et al. 2002, AJ, 124, 1810
White, S. D. M., Frenk, C. S., Davis, M., & Efstathiou, G. 1987, ApJ, 313, 505