Properties of voids in the Local Volume

Anton Tikhonov\textsuperscript{1} and Anatoly Klypin\textsuperscript{2}

\textsuperscript{1} Department of Mathematics and Mechanics, St. Petersburg State University
avt@gtnt.ru
\textsuperscript{2} Astronomy Department, NMSU aklypin@nmsu.edu

\textbf{Summary.} Current explanation of the overabundance of dark matter subhalos in the Local Group (LG) indicates that there maybe a limit on mass of a halo, which can host a galaxy. This idea can be tested using voids in the distribution of galaxies: at some level small voids should not contain any (even dwarf) galaxies. We use observational samples complete to $M_B = -12$ with distances less than 8 Mpc to construct the void function (VF): the distribution of sizes of voids empty of any galaxies. There are $\sim 30$ voids with sizes ranging from 1 to 5 Mpc. We also study the distribution of dark matter halos in very high resolution simulations of the LCDM model. The theoretical VF matches the observations remarkably well only if we use halos with circular velocities larger than 45 $\pm$ 10 km/s. This agrees with the Local Group predictions. Small voids look quite similar to their giant cousins: the density has a minimum at the center of a void and it increases as we get closer to the border. Thus, both the Local Group data and the nearby voids indicate that isolated halos below 45 $\pm$ 10 km/s must not host galaxies and that small (few Mpc) voids are truly dark.

\textbf{Key words:} galaxies: structure, statistics, halos; cosmology: large-scale structure of universe, dark matter

\section{1 Introduction}

The observational discovery of giant voids was soon followed by the theoretical understanding that voids constitute a natural outcome of structure formation via gravitational instability. Emptiness of voids – the number of small galaxies in the voids – is an interesting question for both the observations and the theory to tackle [1]. Cosmological simulations predict (e.g., [2]) that many small DM halos should reside in voids. There seems to be no disagreement between the LCDM theory and the observations regarding the giant voids defined by $M_*$ galaxies or by $10^{12} M_\odot$ halos [3]. The situation is less clear on smaller scales. In the region of $\sim 10$ Mpc around the Milky Way, where observations go to remarkably low luminosities, small voids look very empty: dwarf
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galaxies do not show a tendency to fill the voids and voids are still relatively large. The theory predicts that many dwarf dark matter halos should be in the voids, which puts it in the collision course with observations. Yet, below some mass the halos are expected to stop producing galaxies inside them. There are different arguments for that: stellar feedback [4] or photoionization may play significant role in quenching star formation in too small halos. Still, it is difficult to get a definite answer because the physics of dwarfs at high redshifts is quite complicated.

Satellites of the Local Group give a more definite answer. Current explanation of the overabundance of the dark matter subhalos [5] assumes that dwarf halos above $V_c \approx 50 \text{ km/s}$ were forming stars before they fall into the Milky Way or M31. Once they fall in, they get severely stripped and may substantially reduce their circular velocity producing galaxies such as Draco or Fornax with the rms line-of-sight velocities only few km/s. The largest subhalos retain their gas and continue form stars, while smaller ones may lose the gas and become dwarf spheroidals. Halos below the limit never had substantial star formation. They are truly dark. This scenario implies that $V_c \approx 50 \text{ km/s}$ is the limit for star formation in halos. If this picture is correct, it can be tested with small-size voids: they must be empty of any galaxies and are filled with gas and dark matter halos.

Tully [6] noted that the Local Supercluster contains a number of filaments and that those outline the so-called Local Void, which begins just outside the Local Group and extends in the direction of the North Pole of the LSC. The Local Void looks practically free from galaxies. Over the past few years special searches for new nearby dwarf galaxies have been undertaken using numerous observational data. At present, the sample of galaxies with distances less than 10 Mpc lists about 500 galaxies. For half of them the distances have been measured to an accuracy as high as 8-10% [7]. Over the last 5 years snapshot surveys with Hubble Space Telescope (HST) have provided us with the TRGB distances for many nearby galaxies. The absence of the “finger of God” effect in the Local Volume simplifies the analysis of the shape and orientation of nearby voids. Observations of the Local Volume have detected dwarf systems down to extremely low luminosity. This gives us unique possibility to detect voids which may be empty of any galaxies. Tikhonov & Karachentsev [8] analyzed nearby voids. Here we continue the analysis using an updated list of galaxies (Karachentsev, private communication). The volume limited sample is complete for galaxies with abs. magnitudes $M_B = -12$ within 8 Mpc radius.

We use N-body simulations done with the Adaptive Refinement Tree code [9]. The simulations are for spatially flat cosmological LCDM model with following parameters: $\Omega_0 = 0.7, \Omega_A = 0.3; \sigma_8 = 0.9; H_0 = 70 \text{ km/s/Mpc}$. As a measure of how large is a halo we typically use the maximum circular velocity $V_c$, which is easier to relate to observators as compared with the virial mass. For reference, halos with $V_c = 50 \text{ km/s}$ have virial mass about $10^{10}M_\odot$ and halos with $V_c = 20 \text{ km/s}$ have virial mass about $10^9M_\odot$. We use two simulations: (1) Box 80Mpc/h (Box80); mass per particle $3 \times 10^8h^{-1}M_\odot$;
simulations cover the whole volume and (2) Box 80Mpc/h (Box80S); spherical region of 10 Mpc inside 80Mpc/h box resolved with $5 \times 10^6 h^{-1} M_\odot$ particles.

In order to detect voids, we place a 3d mesh on the observational or simulation volume. We then find initial centers of voids as the mesh centers having the largest distances to nearest objects. In the next iteration, an initial spherical void may be increased by adding additional off-center empty spheres with smaller radius. The radius of the spheres is limited to be larger than 0.9 of the initial sphere and their centers must stay inside the volume of the first sphere. The process is repeated few times. It produces voids which are slightly aspherical, but voids never become more flattened than 1:2 axial ratio. Artificial objects are placed on the boundaries of the sample to prevent voids getting out of the boundaries of the sample. We define the cumulative void function (CVF) as the fraction of the total volume occupied by voids with effective radius larger than $R_{\text{eff}} = (3V_{\text{void}}/4\pi)^{-1/3}$.

2 Results

We use two samples to construct CVF of the Local Volume: (1) Galaxies brighter than $M_B = -12$ inside sphere of radius 8 Mpc and (2) all galaxies inside 7.5 Mpc. Results are present in the right bottom panel of Figure 1. There are about 30 voids in the observational sample. We limit the radius of voids to be more than 1 Mpc. The two subsamples indicate some degree of stability: inclusion of few low-luminocity galaxies does not change the void function.

We use the Box80 simulation (full volume) to construct a sample of 40 “Local Volumes”. The selecton criteria are: (1) no halos with $M > 10^{14} M_\odot$ inside a 8 Mpc sphere (thus, no clusters in a sample); (2) the sphere must be centered on a halo with $150 < V_c < 200$ km/s (Milky Way analog); (3)The number of halos found inside 8Mpc sphere with $V_c > 180$ km/s within 10% is the average number expected for a sphere of this radius. The halo catalogs are complete down to halos with circular velocity $V_c = 40$ km/s. The second simulation (Box80S) provides one sample and it is complete down to 20 km/s. The left bottom panel in the Figure 1 shows CVF for different samples of halos and the observed CVF. Results indicate that voids in the distribution of halos with $V_c > 45$ km/s give the best fit to the observed CVF. The theoretical CVF goes above the observational data if we use circular velocities larger than 60 km/s. If we use significantly lower limits, than the theory predicts too few large voids. The theoretical results match the observations if we use $V_{\text{circ}} = 45 \pm 10$ km/s. In this case, the match is remarkably good: the whole spectrum of voids is reproduced by the theory.

According to LCDM simulations totally empty front part of the Local Void is probable. In a sample of ten 8 Mpc “Local Volumes” a half of cases have voids comparable to the largest voids in LV if we consider entire LV sample.
Fig. 1. **Bottom Right panel:** the void function for two observational samples. The full curve and filled circles are for a complete volume limited sample with $M_B < -12$ and $R < 8$ Mpc. The open circles are for all observed galaxies inside 7.5 Mpc. Comparison of the samples shows reasonable stability of the void function. **Bottom Left panel:** Observational data (the complete sample) are compared with the distribution of voids in samples of halos with different limits on halo circular velocity. CVF for $V_c = 45$ km/s provides a remarkably good fit to observations. Note that the LCDM model predicts very large empty regions. **Top panel:** Luminosity function of galaxies. Circles with errors show results for 8 Mpc sample. The full curve is for 4 Mpc sample scaled down by factor 2.7. The dashed curve is for the Schechter approximation.

The top panel in Figure 1 shows the luminosity function of galaxies. We also show the Schechter approximation with parameters: $\alpha = -1.21$, $M_* = -19.9 + 5 \log h$, $\Phi_* = 1.9 \times 10^{-2} h^3 \text{Mpc}^{-3}$. The approximation is the average luminosity function of galaxies in the B-band in the Universe (not in our sample). It provides a very good fit to our data. This means that the sphere of radius 8 Mpc contains the average number of galaxies:
We also show the luminosity function for another complete sample: $R < 4 \text{ Mpc}$. In this case, the shape of the luminosity function is the same, but its normalization is different: $N_{\text{4Mpc sample}}/N_{\text{average}} = 2.7$.

### 3 Conclusions

- The LCDM model is consistent with the cumulative volume functions of voids in the distribution of galaxies for a large luminosity range. According to LCDM, large empty voids in Local Volume such as the Local Void are probable.
- There are significant (up to few Mpc) holes in the distribution of halos predicted by LCDM that are free from haloes with $V_c > 20 \text{ km/s}$: any haloes of astronomical interest.
- Voids in the distribution of halos with $V_c > 45 \pm 10 \text{ km/s}$ reproduce the Cumulative Void Function of Local Volume galaxy sample. We can treat this value as a limit of appearance of a galaxy in a DM halo.
- The luminosity function in the Local Volume (8 Mpc) has the shape and the normalization of the average LF in the Universe. There is substantial overdensity of galaxies inside sphere of radius 4 Mpc. It has 2.7 time more galaxies than the average expected for a sphere of this size.

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### References

1. P. J. E. Peebles: *ApJ*, **557**, 495 (2001)
2. S. Gottl"ober, E. L. Lokas, A. Klypin, & Y. Hoffman: *MNRAS*, **344**, 715 (2003)
3. S. G. Patiri et al: *MNRAS*, **372**, 1710 (2006)
4. A. Dekel, & J. Silk: *ApJ* **303**, 39 (1986)
5. A. V. Kravtsov, O. Y. Gnedin, & A. Klypin: *ApJ*, **609**, 482 (2004)
6. R. B. Tully, & J. R. Fisher: *Atlas of Nearby Galaxies* (Cambridge University Press 1987)
7. I. D. Karachentsev, V. E.Karachentseva, W. K Huchtmeier, & D. I.Makarov: *AJ*, **127**, 2031 (2004)
8. A. V. Tikhonov, & I. D. Karachentsev: *ApJ*, **653**, 969 (2006)
9. A. V. Kravtsov, A. Klypin, & A. M. Khokhlov: *ApJ Suppl.*, **111**, 73 (1997)