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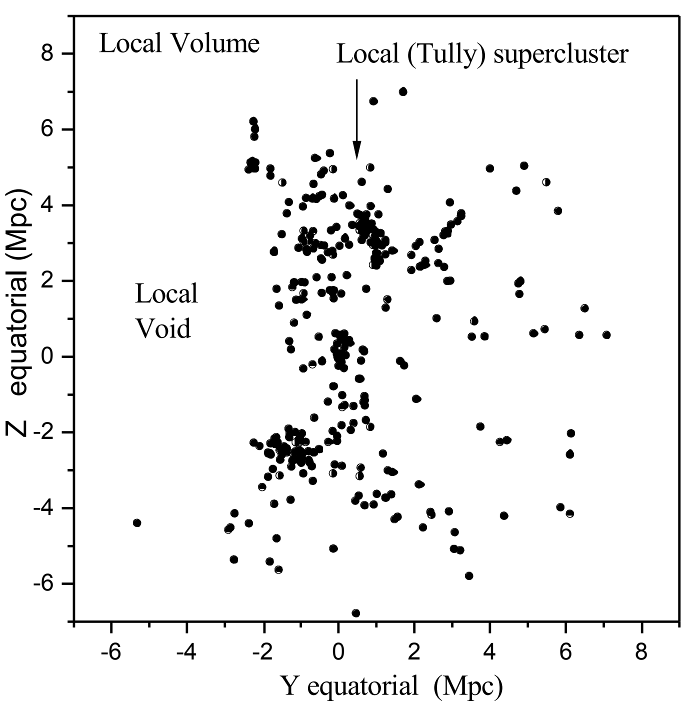
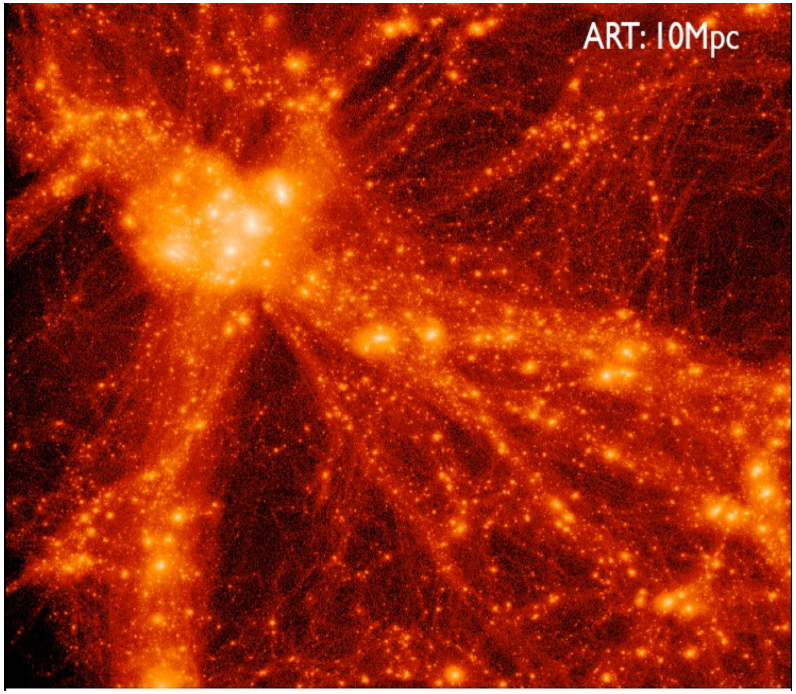
Voids and Hubble flow in the Local Volume and the Limit of appearance of a galaxy in DM halo

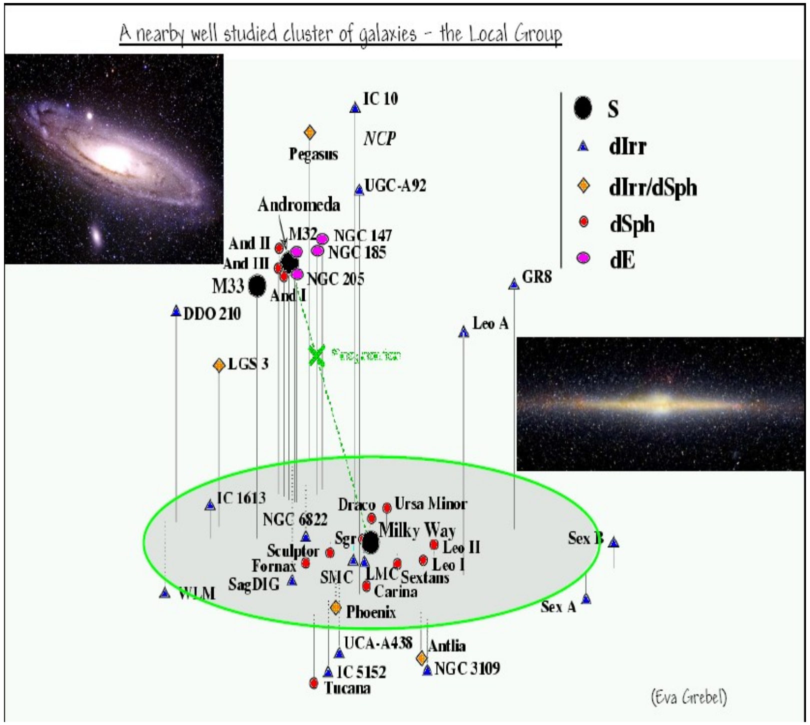
The observational discovery ((Gregory & Thompson 1978; Joeveer et al. 1978; Kirshner et al. 1981) was soon followed by the **theoretical understanding** that voids constitute a natural outcome of structure formation via gravitational instability (Peebles 1982; Hoffman & Shaham 1982).

Emptiness of voids: do we have a problem? Cosmological simulations predict many small DM halos in voids and it seems that observations are failing to find a substantial number of dwarf galaxies inside voids. Statistics of voids in catalogs of galaxies; formation of DM structures in voids; physics of galaxies in voids.





WHERE ARE THE MISSING GALACTIC SATELLITES?



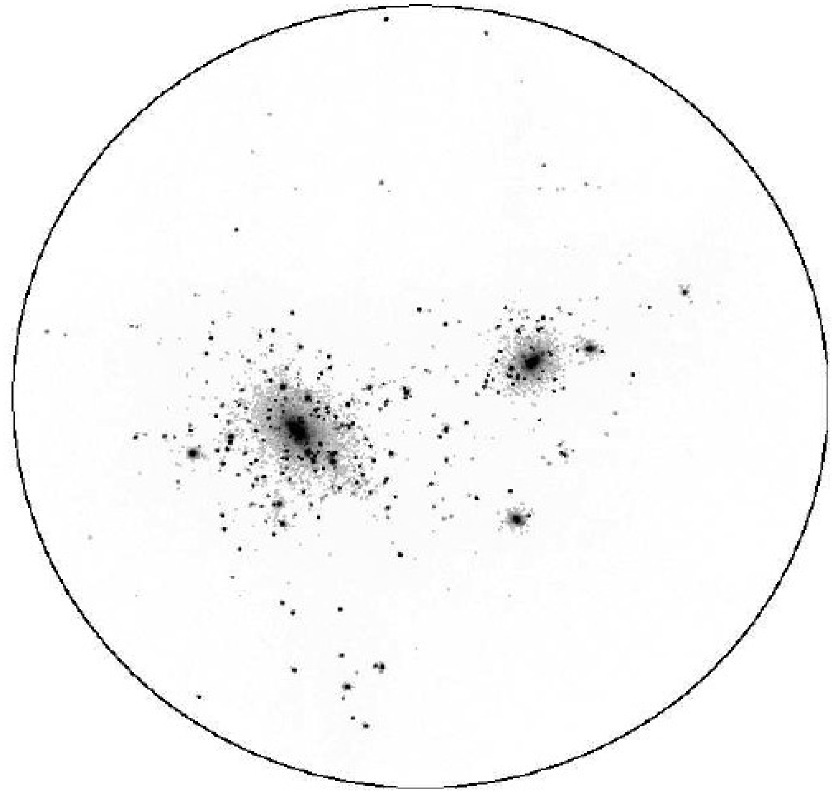


FIG. 2.— Distribution of dark matter particles inside a sphere of the radius of $1.5h^{-1}$Mpc (solid circle) for a small group of dark matter halos (similar in mass to the Local Group) in the ΛCDM simulation. The group consists of two massive halos with circular velocities of 280km s^{-1} and 205km s^{-1} (masses of $1.7 \times 10^{12} h^{-1} M_\odot$ and $7.9 \times 10^{11} h^{-1} M_\odot$ inside $100h^{-1}$ kpc radius) and 281 halos with circular velocities > 10 km s^{-1} inside $1.5h^{-1}$Mpc. The distance between the halos is $1.05h^{-1}$Mpc.

13.3 The Local Group

- The Milky Way belongs to a loose collection of galaxies called the **Local Group**.
- The brightest members of the Local Group are the Andromeda Galaxy (M31), the Milky Way, and M33, three spiral galaxies. Apart from M32 (which is not very typical) there are no elliptical galaxies found in the Local Group. The most frequent galaxy types in the Local Group members are the irregulars (like the Large and the Small Magellanic Cloud) and dwarf ellipticals.
- The total number of galaxies known to belong to the Local Group is about 40, but there probably exists a number of dwarf galaxies which may have remained undetected (especially behind the Milky Way plane).
- All Local Group galaxies are gravitationally bound (M31 approaches the Milky Way with 120 km/s).

Description of the Local Volume galaxy sample

The first compilation of a Local volume (LV) sample of galaxies situated within 10Mpc was made by Kraan-Korteweg & Tammann (1979) who published a list of 179 nearby galaxies with radial velocities $V_{LG} < 500$ km/s

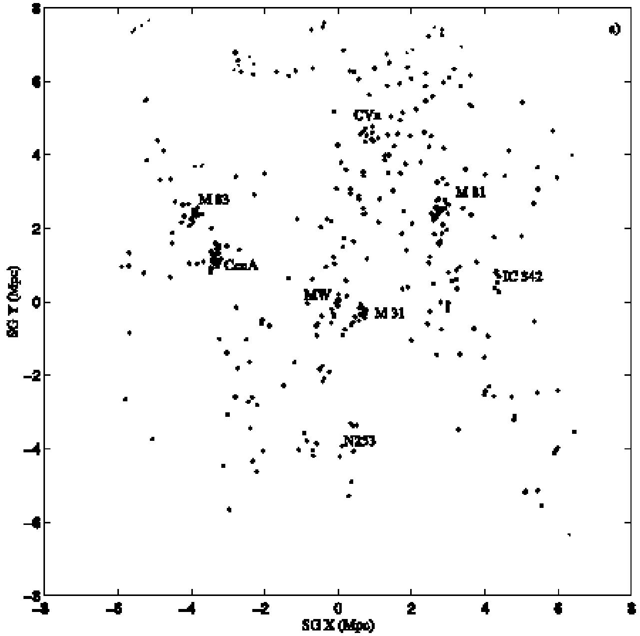
In his **Catalog and Atlas of Nearby Galaxies, Tully (1988)** noted the presence in the Local Supercluster (LSC) that consists of number of intersecting filaments of the so-called Local void which begins directly from the boundaries of the Local Group and extends in the direction of North Pole of the LSC by ~ 20 Mpc. The Local void looks practically free from galaxies.

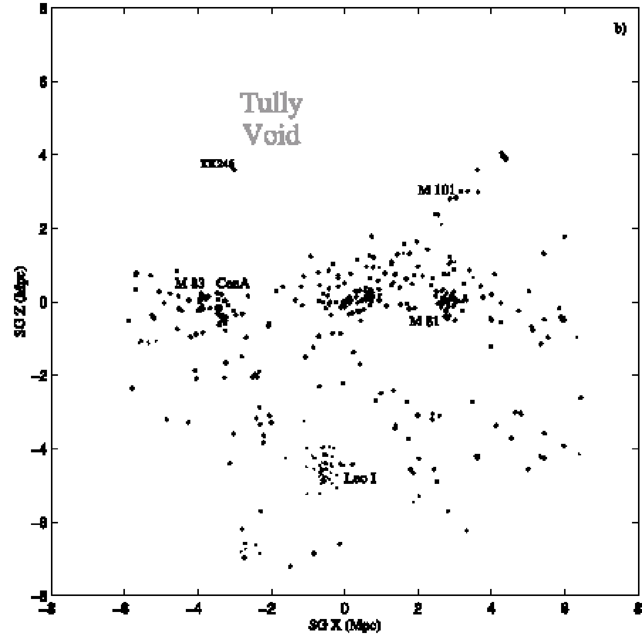
Later, **Karachentsev (1994) published an updated version of the LV list**, which contained 226 galaxies with $V_{LG} < 500$ km/s. Over the past few years, special searches for new nearby dwarf galaxies have been undertaken basing on the optical sky survey POSS-II/ESO/SERC, HI and infrared surveys of the zone of avoidance, ''blind'' sky surveys in the 21 cm line, HIPASS and HIJASS.

At the present time, the sample of galaxies with distances less than 10 Mpc numbers about 550 galaxies. For half of them the distances have been measured to an accuracy as high as 8-10% (**Karachentsev et al., 2004=Catalog of Neighboring Galaxies**). 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 effect of "God's fingers"" in the Local Volume because of the virial motions of galaxies simplifies the analysis of the shape and orientation of nearby voids.

In spite from the presence of local voids, the average density of luminosity within the radius of 8 Mpc around us exceeds 1.8 - 2.0 times the global luminosity density. Almost the same excess is also seen in the local HI mass density. About 2/3 of the LV galaxies belong to the known virialized groups like the LG.





Parameter	M.Way	M31	M81	CenA	M83	IC342	Maffei
D, Mpc	0.01	0.78	3.63	3.66	4.56	3.28	3.01
Nv	18	18	24	29	13	8	8
σ_v,km/s	76	77	91	136	61	54	59
R_p, Mpc	.16	.25	.21	.29	.16	.32	.10
T_{cross}, Gyr	2.1	3.3	2.3	2.2	2.7	5.9	1.8
M_{vir}, 10^{10}	95	84	157	725	86	76	100
L_B, 10^{10}	3.3	6.8	6.1	6.0	2.5	3.2	2.7
M/L, solar	29	12	26	121	34	24	37

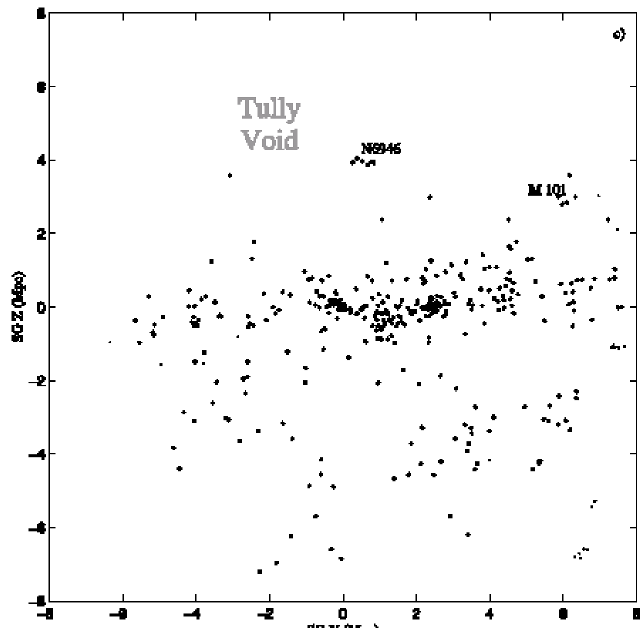


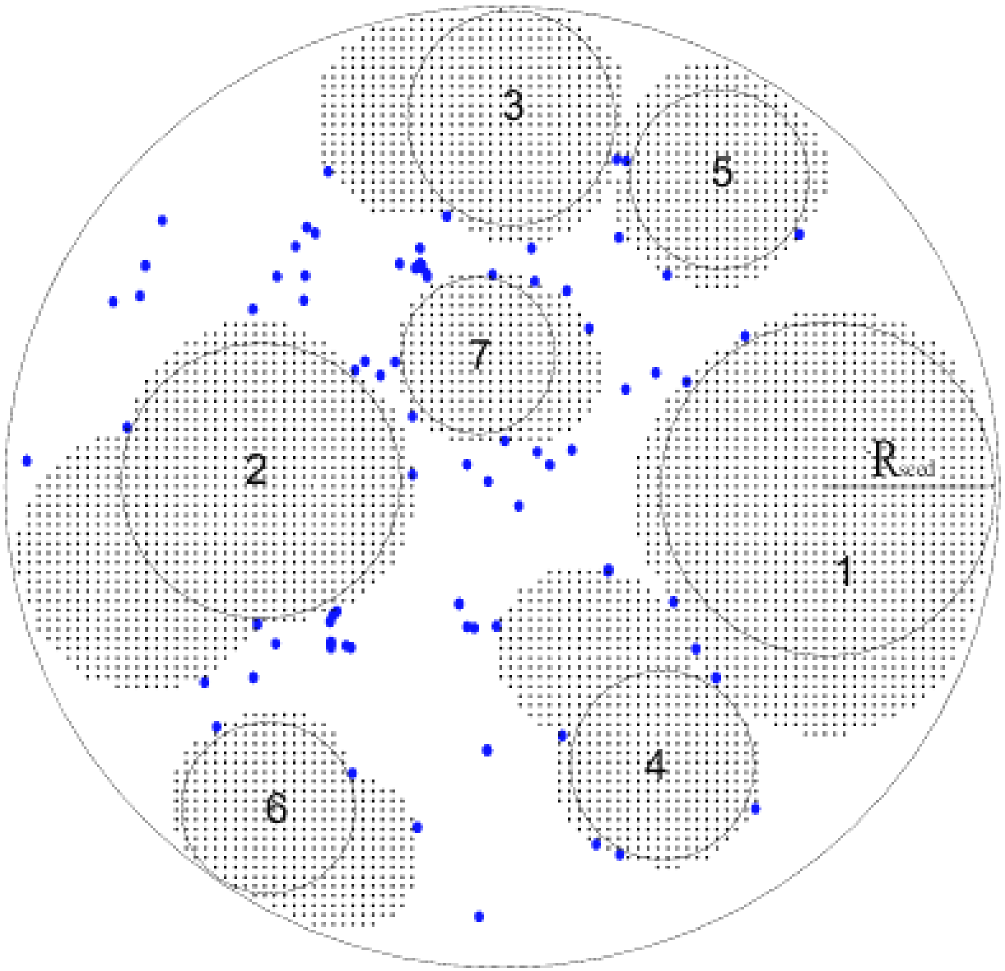
FIG. 5.—Panorama of the LV within a radius of 8 Mpc in Cartesian supergalactic coordinates. Galaxies from Table 1 with $D > 8$ Mpc are shown as small circl
(*a*) SGX-SGY, galaxies projected onto the plane of the Local Supercluster; (*b*) SGX-SGZ, the distribution in Z (perpendicular to the plane of the Local Superclust

Void detection algorithm

• **3D grid** (to refer the nodes of this grid to this or that void).
• **Empty seed sphere** of largest possible radius is identified.
• **Expansion of seed spheres** by spheres with radius

$$R_{sph} > 0.9\ R_{seed}$$

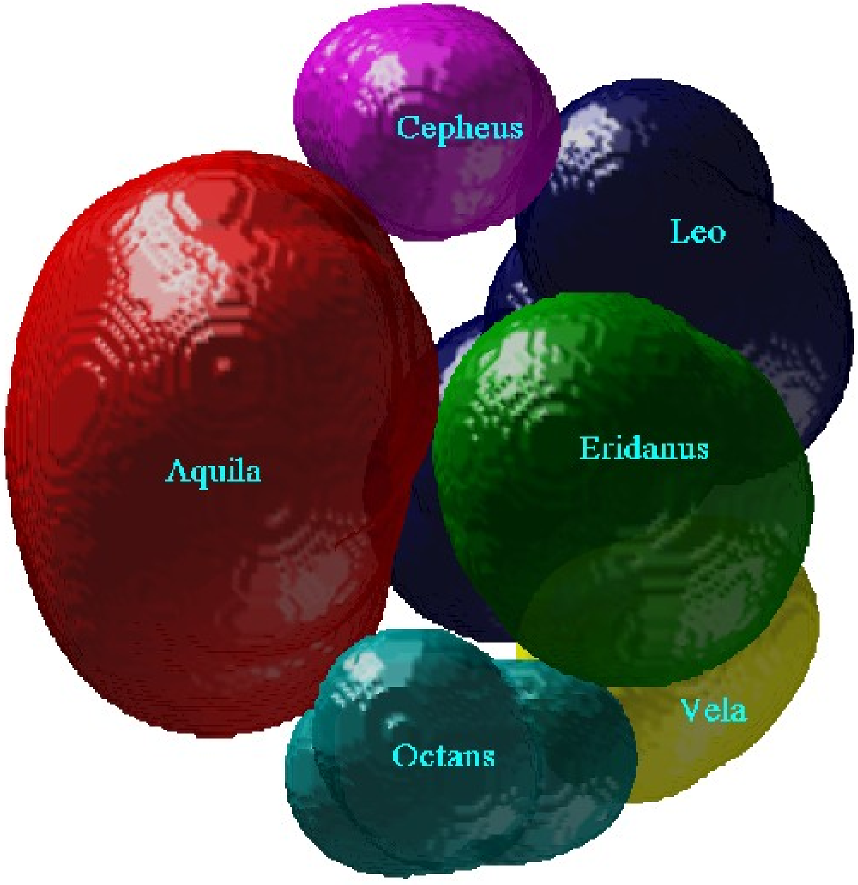
and with centers inside already fixed part of a void.
• **Next seed sphere** is determined. Process continues until R_{seed} > threshold.
• **Voids are thick enough** throughout their volumes.
• Voids are divided into lying completely inside boundaries and voids touching when constructed the sample boundaries.



2D-case of point-like distribution. Seed circles and voids growing from them are shown. The numerals indicate the order of identification of voids

Distribution of six large minivoids within the LV-sphere of radius 7.5 Mpc.

¼ of Local Volume is occupied by Void N1 in Aquila. It is the front part of the Local (Tully) void



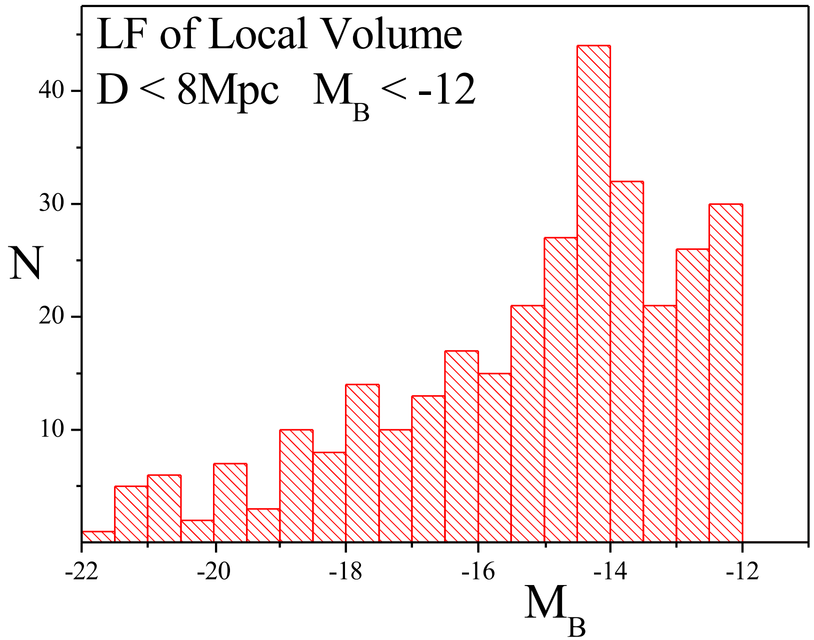
The peak in luminosity function, isolated galaxies.

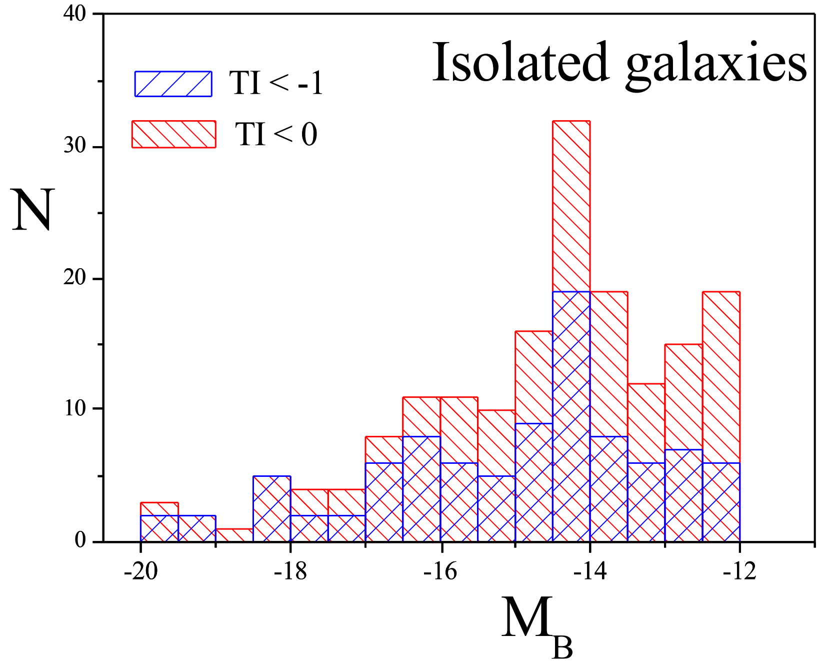
Tidal Index $\mathbf{TI_i = max[\,log(M_k/D^3_{ik})\,] + C}$

For every galaxy i, we found its main disturber, producing the highest tidal action or a maximum density enhancement $\Delta\rho_k \sim M_k/D^3_{ik}$

$M_{25}/L = 3.8\ M_{sun}/L_{sun}$, total galaxy mass $M_T = 2.5\ M_{25}$

Inside 8 Mpc around MW there are about 420 galaxies (known today). Galaxies in the peak ($B_{abs} \sim -14$) have morphological de Vaucouleur type 7-10 (dwarf Irregulars). Large $M(HI)/M_{total}$. Isolated galaxies with $B_{abs} \sim -14$ have large M/L>~30, an order higher HI/L_B and SFR/L_B with the respect to galaxies in more dense environment.





Luminosity functions of LV galaxies

The volume limited sample is complete for galaxies with abs. magnitudes **M_B < -12 within 8Mpc** radius. Another volume limited sample is **M_B < -10 within 4Mpc**. Karachentsev (2004)noted that luminosity density in LV in **B**-band with respect to the mean in the Universe about **1.8 - 2** times higher (he used two different estimates of global density). By the sample of **K**-magnitudes provided by D.I. Makarov we obtained $\rho_K / \rho_{mean} >$ **1.5** inside 7 Mpc of LV. Note that luminosity in K-band gives estimate of stellar mass content. Luminosity density is rather unstable characteristic in such a small volume as LV.

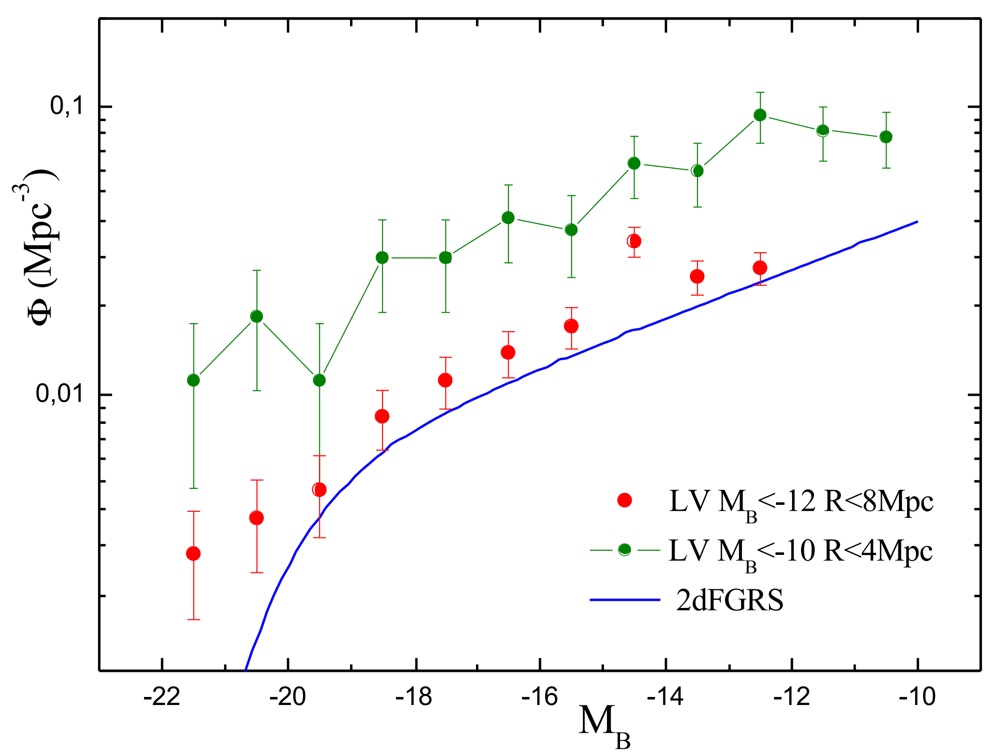


Figure 1. Luminosity function of galaxies. Circles with errors show results for 8 Mpc sample. The full curve is for 4 Mpc sample. The dashed curve is for the Schechter approximation of 2dFGRS b_j band LF scaled to h=0.72

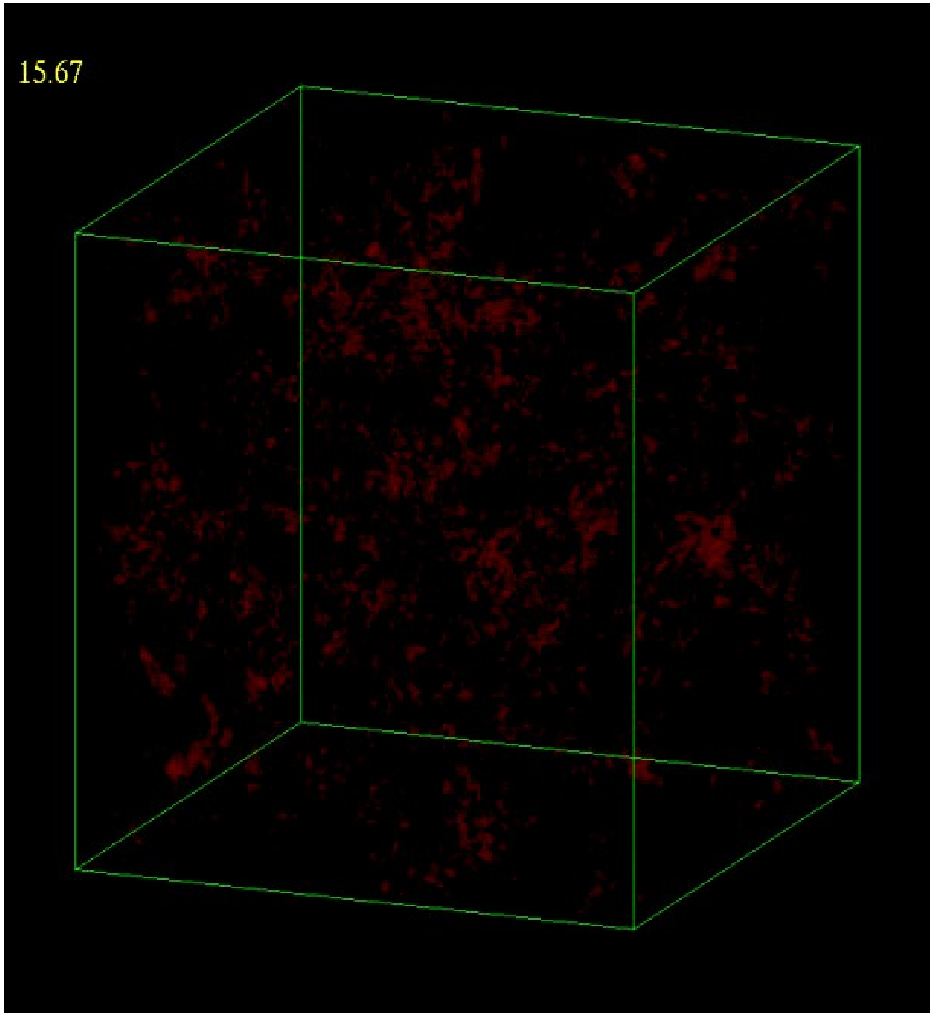
In order to to get overdensity criteria for LV sample we integrated all 3 LF in the range M_B (–17 : –22). We obtained following number overdensity ratios: in 8 Mpc $N_8/ < N >= 1.4 \pm 0.17$; in 4 Mpc $N_4/ < N >\sim 5.3$, where $< N >$ value is obtained from universal Schechter approximation of 2dFGRS LF.

This values give us reasonable criteria for selection of **"LV-candidates"**-8Mpc spheres from simulations. Since we observe that largest part of number and luminosity overdensity in LV with respect to the universal values comes from brightest galaxies we used number overdensity criteria for ratio of number density of halos with **circular velocity Vc > 100 km/s** in 8Mpc sphere to the mean density of such halos in the whole simulated box – halos that must contain luminous galaxies.

3 SIMULATIONS

We use N-body simulations (1) and (2) done with the Adaptive Refinement Tree code (9) and (3) done with GADGET2 code. As a measure of how large is a halo we typically use the maxumum circular velocity V_c, which is easier to relate to observatons as compared with the virial mass. For reference, halos with $V_c = 50\,\mathrm{km/s}$ have virial mass about $10^{10} M_\odot$ and halos with $V_c = 20\,\mathrm{km/s}$ have virial mass about $10^9 M_\odot$. We use three simulations: (1) (Box80S); spherical region of 14 Mpc inside 80Mpc/h box (mass per particle $3 \times 10^8 h^{-1} M_\odot$) resolved with $5 \times 10^6 h^{-1} M_\odot$ particles; (2) Box160CR 160 Mpc/h aside constrained realization with mass resolution $1.2 \cdot 10^9$; (3) Box64CR 64Mpc/h aside constrained realization with mass resolution $1.6 \cdot 10^7$. The simulations are for a spatially flat cosmological LCDM model with following parameters: (1) $\Omega_0 = 0.3, \Omega_\Lambda = 0.7; \sigma_8 = 0.9; h = 0.7$ (WMAP1 parameters). (2) and (3): $\Omega_0 = 0.24, \Omega_\Lambda = 0.76; \sigma_8 = 0.75; h = 0.73$ (WMAP3 parameters).

We scaled all data (coordinates and masses of halos) to "real" $H_0 = 72$ km/s/Mpc that is the mean value of Hubble flow in the Local Volume and close to the value that comes from WMAP parameters.



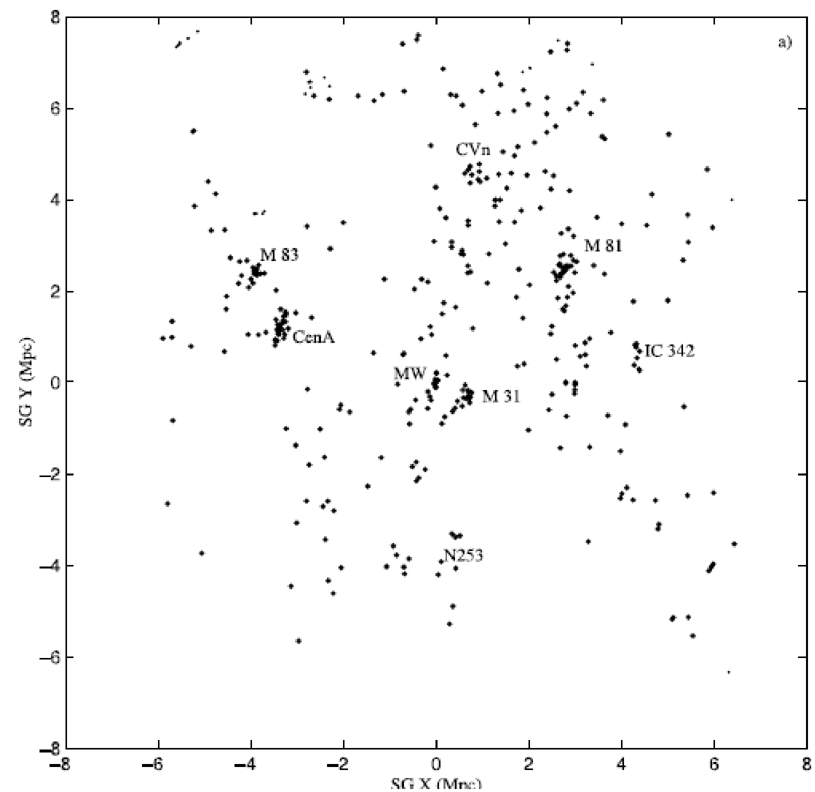
4 SELECTING MODEL LV-CANDIDATES

To mimic main features of real Local Volume galaxy sample we used number of criteria to select from our simulations some 8 Mpc spheres that we can consider as "LV-candidates". Criteria differ slightly from one simulation box to another to select at least some samples.

Box160CR: here we tried to mimic LV features more closely.(1) no halos with $Mass > 2 \cdot 10^{13} M_{\odot}$ inside a 8 Mpc sphere; (2) the sphere must be centered on a halo with $1.5 \cdot 10^{13} M_{\odot} < Mass < 3 \cdot 10^{13} M_{\odot}$ km/s (Local Group analog); (3) The number density of halos found inside 8$\tilde{M}$pc sphere with $V_c > 100$ km/s exceeds mean value in the whole box by factor in the range $1.5 - 1.7$; (4) The number density of halos found inside 4.5$\tilde{M}$pc sphere with $V_c > 100$ km/s exceeds mean value in the whole box by factor greater then 3.5; (5) There are no halos more massive than $5.0 \cdot 10^{11} M_{\odot}$ with distances in the range (1-3 Mpc). (5) no halos with $Mass > 2 \cdot 10^{14} M_{\odot}$ (no clusters like Virgo nearby); (6) Central halos of different samples are located on distance more then 8$\tilde{M}$pc. We've found 7 such samples in Box160CR.

We note that the number overdensity criterium $1.5 - 1.7$ of halos with $V_c > 100$ km/s in 8 Mpc with respect to the mean in the box, give for selected samples from Box64CR and BOX160CR ~ 20 such halos that is comparable to the number of galaxies in LV having maximum rotational speed $V_{max} > 120$ km/s taking into account rough estimation of increase in rotational speed produced by gas infall into DM halo.

For all selected LV-candidates we checked that rms velocity dispersion should be reasonably consistent with values obtained from LV galaxy sample.



Some LV-candidates fit geometry of LV-galaxy distribution

RMS VELOCITY DISPERSION AROUND HUBBLE FLOW

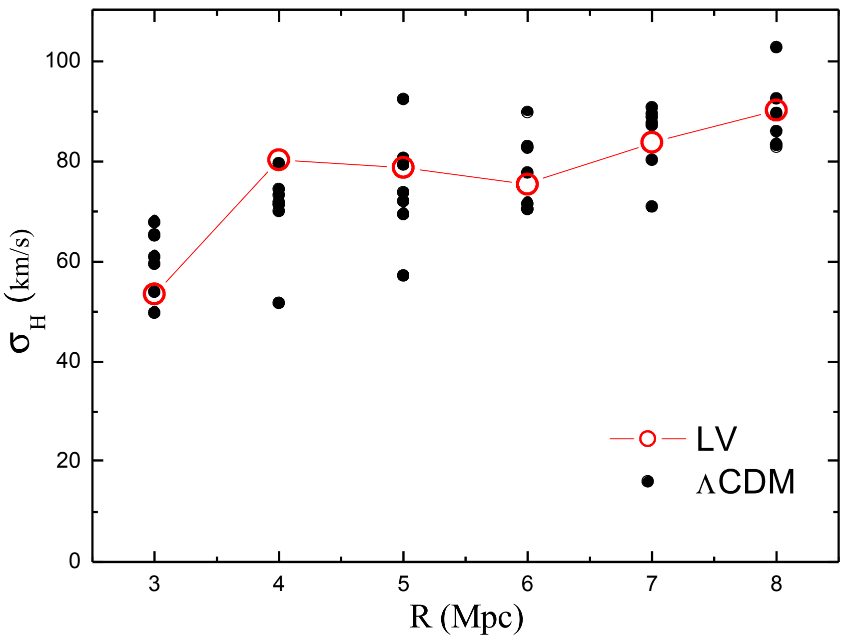


Figure 2. σ_H^{true} with apex and error correction for LV in the volume from 1 Mpc up to R Mpc with σ_H in corresponding volume for 7 model LV-candidates from Box160CR

We started our estimation just outside 1Mpc {approximate virial radius of Local Group and calculated σ_H for galaxies with distances **1Mpc < D < R**. We applied **correction for apex** (mean motion of surrounding volume with respect to Local Group in simple interpretation), estimated by minimization of the sum

$$\sum_{i=1}^{N}(v_i - H_0 \cdot D_i + (Ax \cdot x_i + Ay \cdot y_i + Az \cdot z_i)/D_i)\,,$$

Table 1. Velocity scatter around Hubble flow with H_0 = 72km/s/Mpc in Local Volume beyond 1 Mpc.

Db (Mpc)	N	σ_H	σ_H^{error}	σ_H^{apex}	σ_H^{true}	V_{apex}(km/s)	error
3.0	43	73.73	71.66	56.24	53.49	65.48	17.363
4.0	106	84.58	81.56	83.37	80.30	26.69	22.427
5.0	162	84.31	80.11	83.07	78.80	21.89	26.280
6.0	214	83.65	78.10	81.17	75.44	32.00	29.956
7.0	273	96.76	90.44	90.62	83.83	54.87	34.413
8.0	335	106.64	99.34	98.22	90.24	68.78	38.792
9.0	360	107.55	99.57	99.43	90.73	68.50	40.665

$$\Delta^2\sigma_H = \frac{\alpha^2 \cdot H_0^2 \cdot \sum_{i=1}^{N}(D_i^2)}{N}.$$

Results

Cumulative void function $\Delta V/V(>R_{void}) = V_{voids}(>R_{void})/V_{sample}$, V_{voids} - total volume of voids with $R_{eff} > R_{void}$, V_{sample}- total volume of a sample, $R_{eff} = (3V_{void}/4\pi)^{-1/3}$.

Local Volume

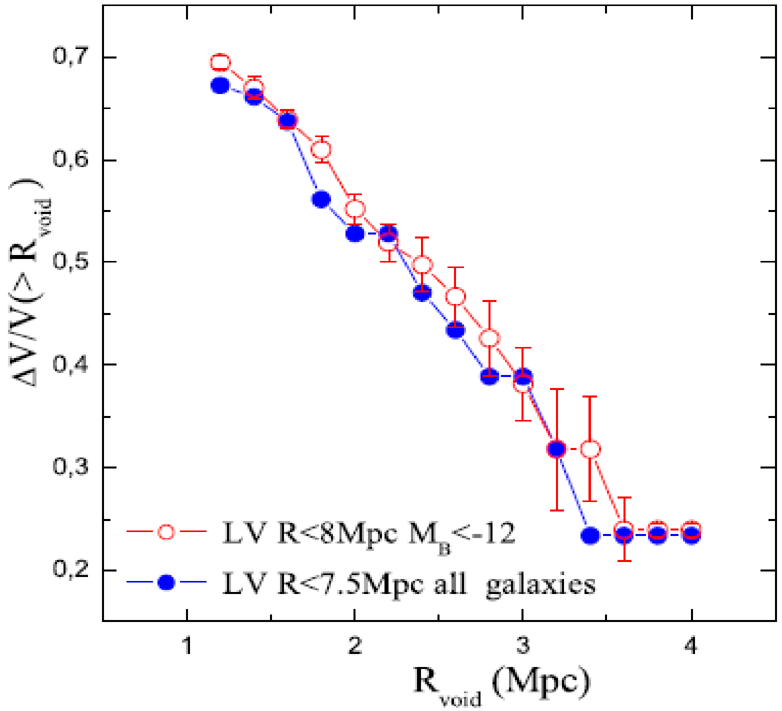


Figure 4. the void function for two observational samples. The full curve with open circles are for a complete volume limited sample with $M_B < -12$ and $R < 8\,\mathrm{Mpc}$. 1σ errors obtained by Monte Carlo resampling distances from catalog by means of additon gaussian distributed characteristic error of distance measurements. The filled circles are for all observed galaxies inside 7.5 Mpc. Comparison of the samples shows reasonable stability of the void function.

Box80S

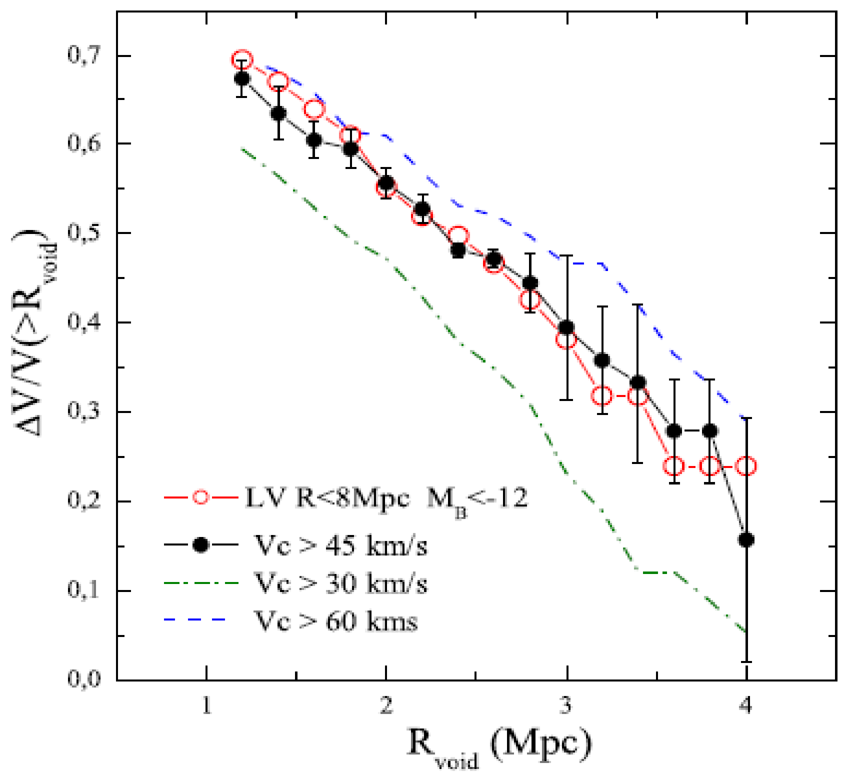


Figure 3. Observational data (the complete sample, circles) are compared with the distribution of voids in samples of halos with different limits on halo circular velocity. VF for $V_c = 45\,\mathrm{km/s}$ provides a remarkably good fit to observations. Note that the LCDM model predicts very large empty regions.

Box64CR

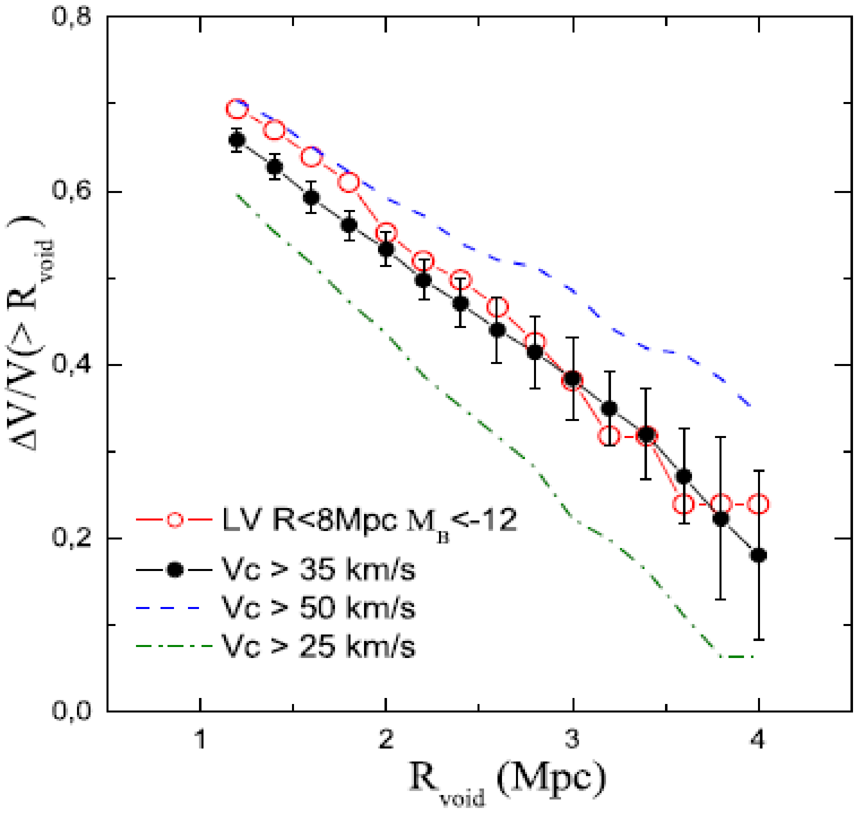


Figure 5. Observational data (the complete sample $M_B < -12$) are compared with the distribution of voids in 14 samples from Box64CR of halos with different limits on halo circular velocity. In this case VF for $V_c = 35\,\mathrm{km/s}$ (shown with 1σ scatter) provides a better fit to observations.

Box160CR

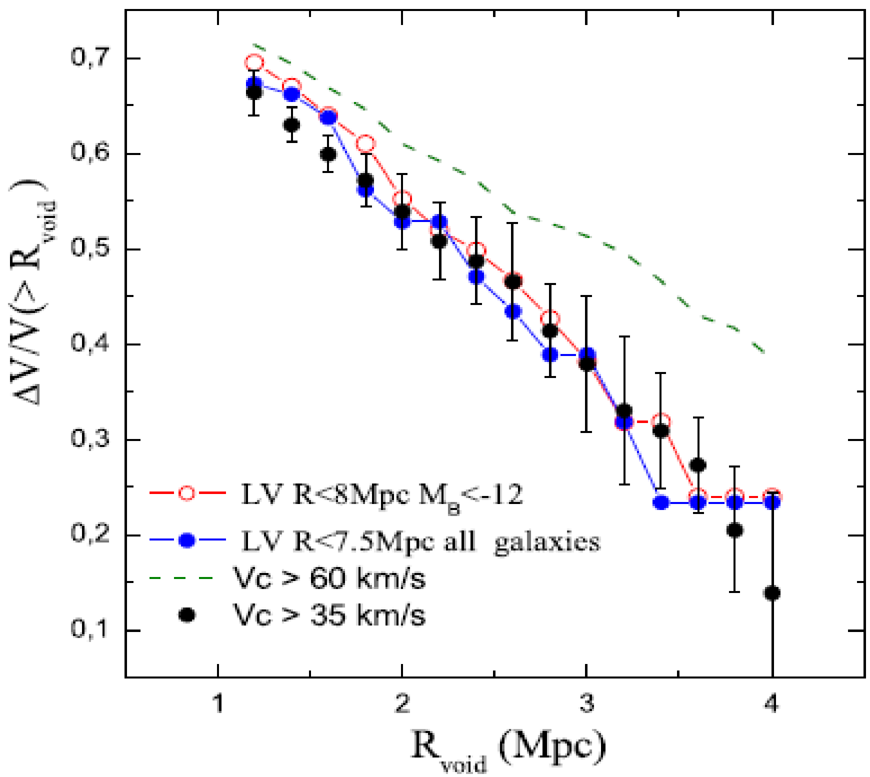
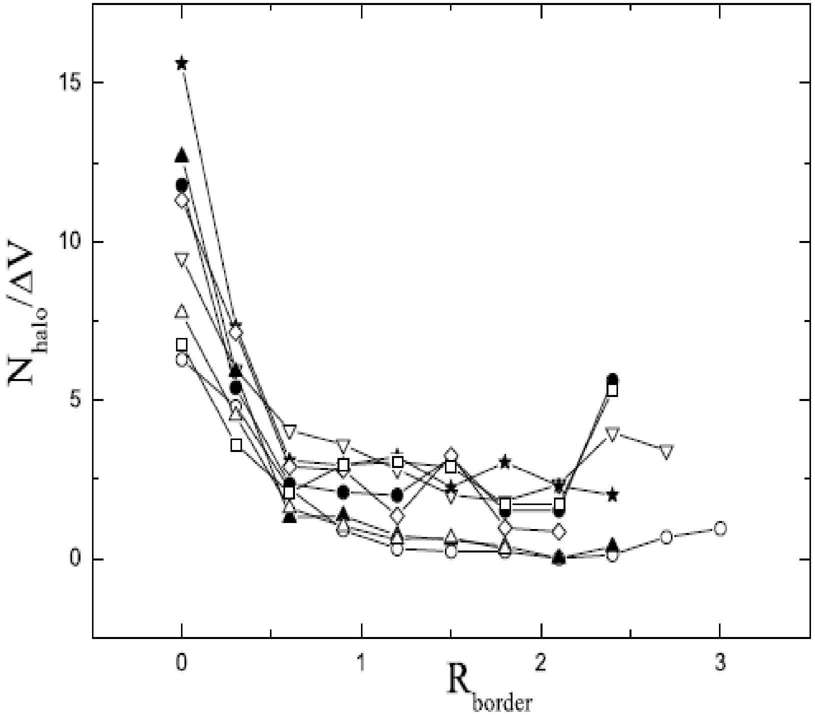
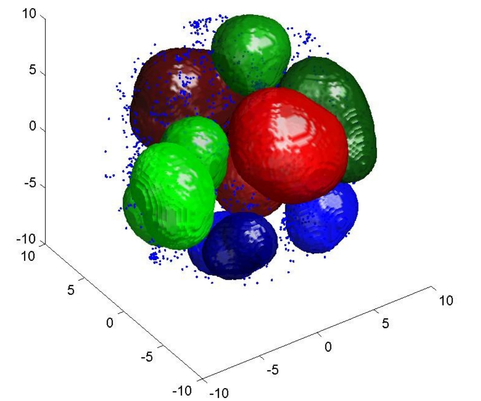


Figure 6. Observational data (the complete sample $M_B < -12$) are compared with the distribution of voids in 7 samples from Box160CR of halos with different limits on halo circular velocity. CVF for $V_c = 35\,\mathrm{km/s}$ (shown with 1σ scatter) provides a remarkably good fit to observations. Because of resolution here we can not plot curves below observational VF

Density profiles of dark halos inside voids





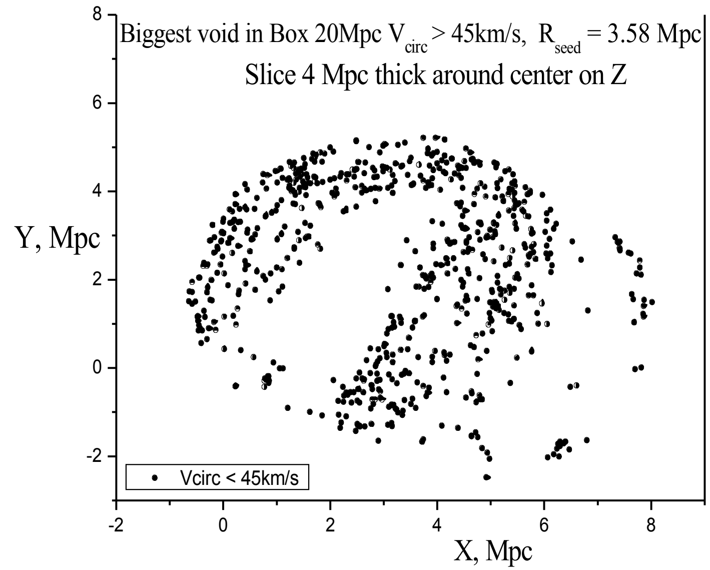


Figure 7. Density profiles in 8 largest voids found in 10 Mpc spherical region from Box80S defined by haloes with $V_c > 45$ km/s. $N/\Delta V$ – halo ($V_c < 45$ km/s) number density in shells 0.3 Mpc thick inside voids that located on the constant distances from the void borders. D_{border} – distance of first shell edge from void border.

Conclusions

- ***ΛCDM is consistent*** *with volume functions of voids in distribution of galaxies above some luminosity in a large luminosity range. There are significant (up to few Mpc) holes in ΛCDM that are free from haloes with $V_{circ} > 10$km/s – any haloes of astronomical interest.*
- ***rms peculiar velocity*** *of model LV candidates is consistent with observational values*

when we closely mimic main features of real Local Volume.
- *Voids in distribution of halos (**wmap3 cosmplogy**) with $V_{circ} > 35 \pm 5$ **km/s** reproduce 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.***
- *Luminosity functions in the Local Volume (8Mpc) together with luminosity density in Local volume give us indication that overdensity of matter inside 4-5Mpc of Local Volume according to **conception of spherical collapse** should decouple from Hubble flow, but we don't see rms peculiar velocities comparable to Hubble expansion (on the contrary Hubble flow is rather cold).*
- ***$M_B \sim -14$ isolated galaxies*** *(having $V_{circ} \sim 30$-40 km/s) may be on the limit of appearance. Then the bump in Luminosity Function is natural.*
- ***Dark galaxies*** *are probably located close to borders of voids.*
- *According to ΛCDM large empty voids in Local Volume like **front part of Tully Void** are probable.*