Mean density of matter in the Local Universe

Dmitry Makarov[1],*

[1]Special astrophysical observatory of the Russian academy of sciences, Nizhnij Arkhyz, Russia; dim@sao.ru

Abstract The Local Supercluster is an ideal laboratory to study distribution of luminous and dark matter in the nearby Universe. In total, 54% of galaxies in the Local Universe are gathered into groups. The groups collect 82% of the K-band light. The local matter density is Ωm=0.08 within a distance of ~40 Mpc assuming H_0=73 km s^{-1} Mpc^{-1}. It is significantly smaller than the cosmic value, 0.32, in the standard ΛCDM model. The discrepancy between the global and local quantities of Ωm may be caused by the existence of a dark matter component unrelated to the virial masses of the galaxy systems.

Keywords: Local supercluster, dark matter, matter density

1. Introduction

Despite the fact that more than 80 years have passed since the first works, which found that the kinematics of galaxy systems can not be explained by visible matter, until now, the question of the nature of the dark matter, its properties and distribution remains one of the key in modern cosmology. Modern standard cosmology, according to the results of the Plank mission, considers that "dark energy" accounts for 68%, "dark matter" - 27%, and the ordinary baryonic substance is only 5% of the average density of the Universe. The ΛCDM model has achieved great success in explaining a wide range of observations, such as the formation of galaxies and parameters of the large-scale structure of the Universe. However, many problems of standard cosmology appear on small scales and small masses of objects (for example, the problem of cusps in the dark matter halos and the problem of "missing" satellites of giant galaxies).

2. The Local Volume

The sample of Local Volume galaxies gives a unique opportunity to study properties of galaxies till to very small scales, down to the absolute magnitude MB=-10 and virial mass $M=10^9 M_\odot$. In the Local Volume, conventionally limited to a radius of 10 Mpc, a large number of dwarf galaxies are detected, whose velocities and distances make it possible to investigate the Hubble flow with unprecedented accuracy compared to distant objects. The study of the stellar population of nearby galaxies allows us to restore the star formation history from the moment of their origin to the present time. In fact, the study of local Universe formed over the last 10-15 years in an independent and productive branch of observational cosmology.

Until recently, a serious obstacle in the study of the nearby Universe was the scarcity of distance estimations even for the nearest galaxies. Using the Hubble Space Telescope in combination with a new method of distance determination by the luminosity of the tip of the red giant branch (TRGB), the mass measurements of distances were preformed to about 300 nearby galaxies with an accuracy of 5-10%. ***Fig1*** shows the Hubble diagram and the distribution of galaxies inside 10 Mpc in projection on the plane of the Local Supercluster. The different distance determination methods are color-coded. The stars correspond to the contribution of our team in the distance estimation to the nearby galaxies.

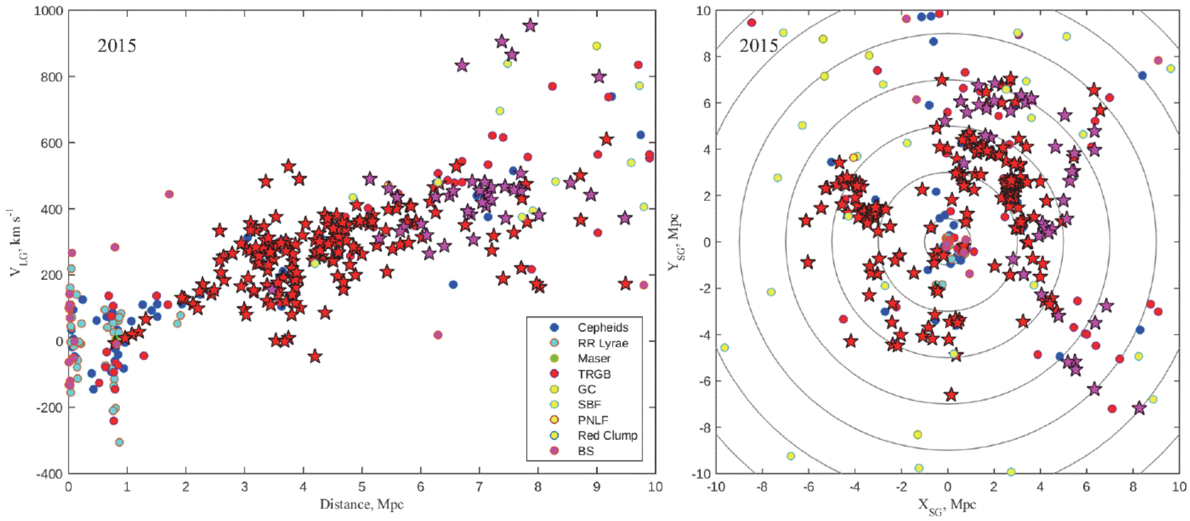

Fig1.: *The distribution of the Local Volume galaxies with redshift independent distance estimations. Different distance determination methods are code by a color. The Cepheids, RR Lyrae, Maser and TRGB methods give accuracy better that 10%. The contribution of our team is marked by stars. Left: the velocity-distance diagram of the Hubble flow. Right: the distribution of galaxies in the projection on the plane of the Local Supercluster.*

A detailed study of the motions of galaxies in the vicinity of nearby groups, including the Local Group, revealed unexpected features of the near Hubble flow. The velocity-distance diagrams outside the central regions of the groups are characterized by a small dispersion of the radial velocities about 30 km s-1. Such small chaotic motions together with high accuracy of distance determination allow us to see the deviation from the simple linear Hubble law caused by the gravitational retardation of galaxies by the mass of the group itself. The example of the Hubble flow around the Local Group is demonstrated on the ***Fig2***, where distances are measured from the center of mass of the Local Group. The zone of virial motions around our Galaxy and Andromeda galaxy is separated from the cold Hubble flow, which stars just behind the radius of a zero velocity surface of $R_0=(0.96\pm0.03)$ Mpc [1]. This radius determines the total mass of the Local Group, $M_{R0}=(1.9\pm0.2)\times10^{12}\ M_{\odot}$, which is in good agreement with virial estimation of the total mass $M(MW+M31)=(1.6\text{-}2.2)\times10^{12}\ M_{\odot}$. It is necessary to note, that these estimations are obtained on different characteristic scale lengths of 1 Mpc and 0.2 Mpc respectively. Thus, we can conclude that majority of the mass in the group is concentrated inside the virial zone. Similar conclusion can be drawn from the motion of galaxies around nearby giant galaxies, Centaurus A and M 81.

3. The Local Universe

Detailed observational data on the Local Volume galaxies give a fairly complete picture of the spatial distribution of luminous and dark matter. However, the Local Volume can not be considered as a representative sample of the Universe due to large density fluctuations at 10 Mpc scales. For better representation, Makarov and Karachentsev [2] examined much bigger volume around our Galaxy, which includes Local Supercluster with its vicinities.

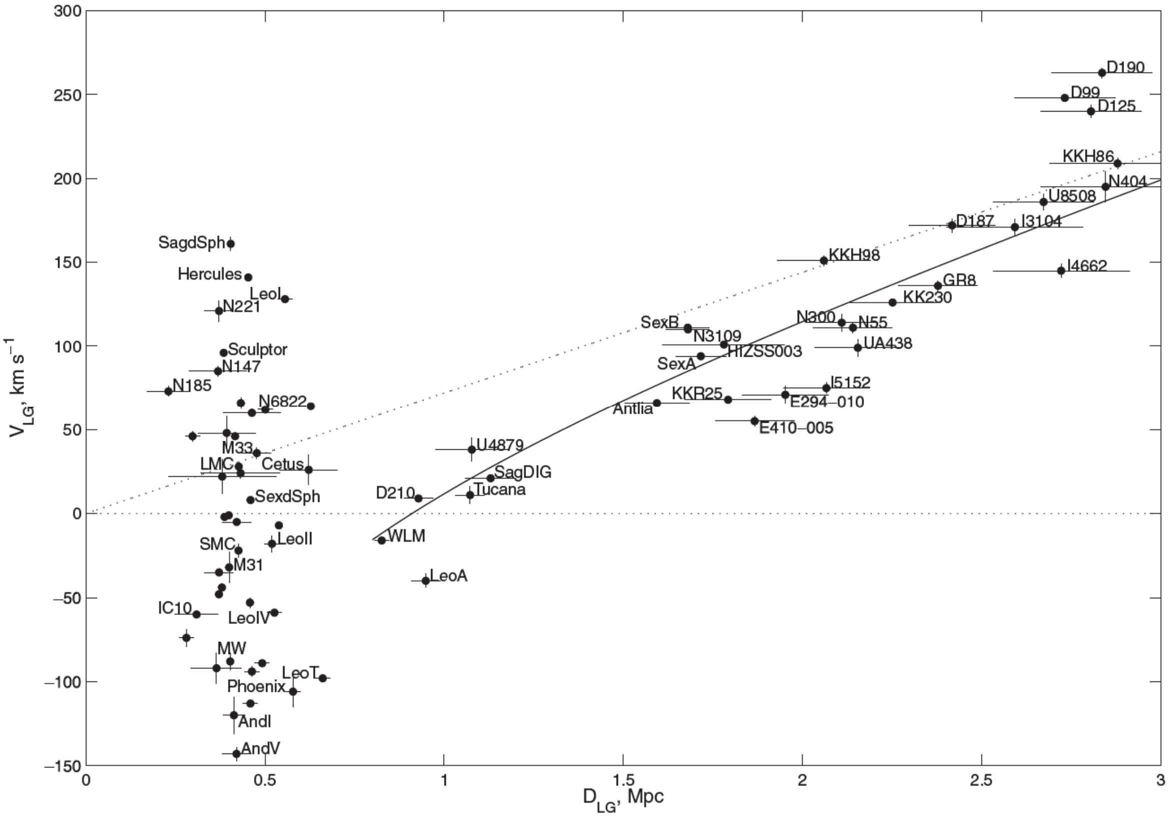

Fig2.: *The Hubble diagram in the vicinity of the Local Group. The distances and velocities of galaxies are given with respect to the centroid of the Local Group. The undistorted Hubble flow is shown by the dashed line. The solid line describes the influence of the Local Group on the motion of nearby galaxies. It allow us to estimate the mass of the Local Group of 1.9×10^{12} $M_\odot$.*

Recent huge redshift surveys like 6dF [3], SDSS [4], HIPASS [5], ALFALFA [6] significantly improved quantity and quality of the data about galaxies in the Local Universe. We gathered information on all known galaxies with radial velocities V_{LG}<3500 km s^{-1} in the rest frame of the Local Group excluding the zone of strong Galactic extinction, |b|<15º. The main efforts in our program were aimed at the systematization of data on radial velocities, apparent magnitudes and morphological types of galaxies. Moreover, we carried out a search for new dwarf galaxies and performed optical identification of HI radio sources from the HIPASS [5], ALFALFA [6] and other blind surveys. We paid special attention to cleaning the list from spurious objects and erroneous measurements. Unfortunately, because of observational specific, majority of the wrong data is dumped to the Local Universe. The most popular errors are: misclassification of star and distant galaxies as well as influence of superimposed star in optical redshift surveys, contamination of HI spectra by gas of our own Galaxy or by near galaxies because of low spatial resolution in radio observations, splitting of a galaxy on several objects in automatic image processing, as well as different kind of misprints, wrong measurements and data analysis The visual control and purification of the data was the most time consuming part of the work. The all sky distribution in equatorial coordinates of the sample of galaxies in the Local Universe is presented in ***Fig3***. The most prominent structure is the concentration of galaxies to the Supergalactic plane. Fortunately, the center of the Local Supercluster in Virgo constellation locates near the north Galactic pole, making it easy for observations and one of the most studied galaxy clusters.

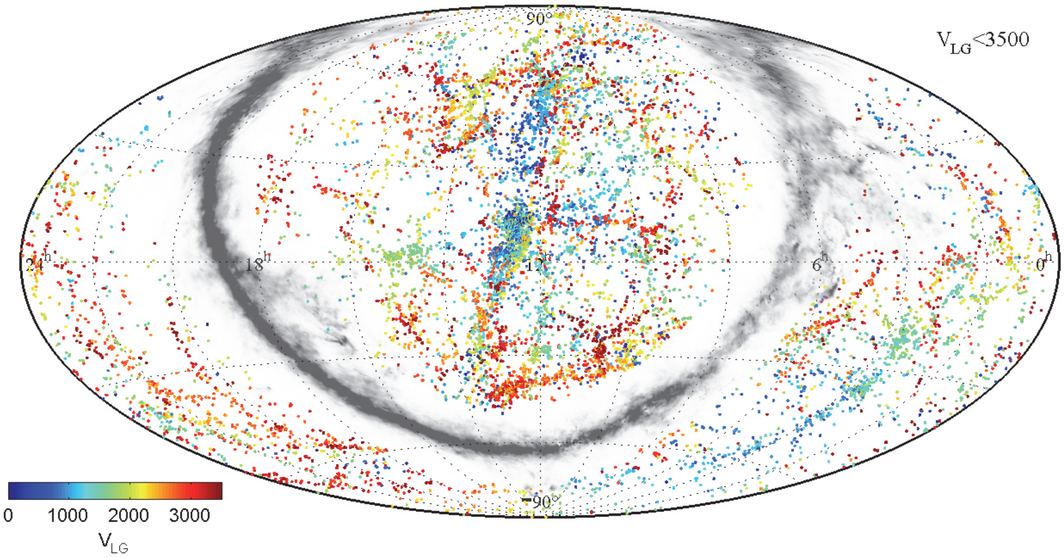

Fig3.: *All sky map of galaxies in the Local Universe. The radial velocity is color coded from the blue for nearby galaxies to the brown for distant ones. The "zone of Avoidance" in the Milky Way is shown by clumpy gray belt, which represents the extinction map in our Galaxy.*

Makarov and Karachentsev [2] have applied a new group finding algorithm to the updated and cleaned sample of 10 900 galaxies. In contrast to the simple "friends of friends" percolation algorithm, we take into account the individual luminosities of galaxies for identifying the groups of different population. Obviously, we can not consider giant and dwarf galaxies as objects with equal rights in the group. As well as bounding criteria for pair of dwarfs and for pair of giants can not be the same. Our method is based on idea that bounded system of galaxies has to have negative total energy and whole system has to reside inside a radius of zero velocity surface. Because in observations we know only brightness of the galaxy, the projection of the position of the galaxy on the sky and the projection of spatial velocity on the line of sight, we need to calibrate the grouping criteria with a standard. As such a standard, we selected nearby groups of galaxies with a well-known structure from direct measurements of photometric distances to group members. These distances were measured during our long term program on the study of 3D structure of the Local Volume.

As a result, we have created catalogs of 509 pairs [7], 168 triplets [8] and 395 more populated groups [2] as well as 520 very isolated galaxies [9]. The subsequent analysis showed that the algorithm [2] identifies groups with approximately the same characteristics for nearby as well as for distant volumes of the Local Universe. The algorithm gathers galaxies into aggregates, which are in good correspondence with the previously known systems.

In total, 54% of known galaxies reside in groups. They gather 82% of the K-band luminosity of the Local Universe. The sample of well populated groups (number of members $n \geq 4$) is characterized by the following medians parameteras: mean projected radius R=268 kpc, radial velocity dispersion $\sigma_V = 74$ km s^{-1}, K-band luminosity $L_K = 1.2\times10^{11} L_\odot$, virial and projected masses $M_{vir} = 2.4\times10^{12}$ and $M_p = 3.3\times10^{12} M_\odot$, respectively. Taking into account measurement error of radial velocities reduces the median masses by 30%. It corresponds to median mass-to-light ratio of groups, corrected for errors, $M_{pc}/L_K = 22\ M_\odot L_\odot^{-1}$. For 97% of identified groups the crossing time does not exceed the cosmic time, 13.7 Gyr, with the median at 3.8 Gyr. This means that the algorithm forms well-evolved systems that are in the virialized state.

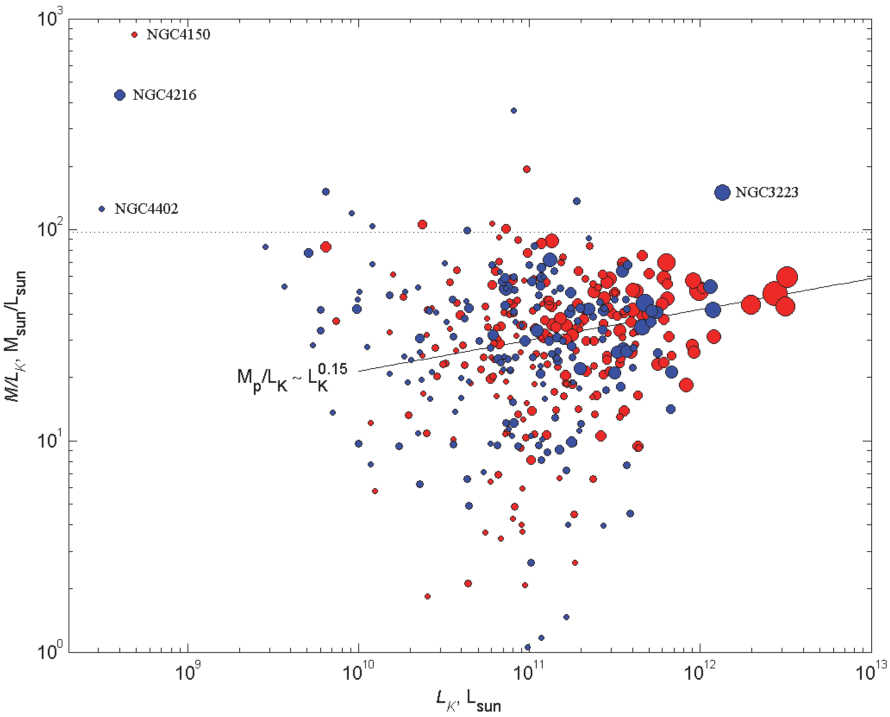

Fig4.: *Mass-to-K-light ratio of the groups as a function of K-luminosity. The groups are represented by circles scaled by population. The groups with a bulge-dominated main member are shown by red circles. The horizontal dotted line traces the global cosmic ratio, 97 M_Θ/L_Θ, corresponding to $\Omega m = 0.28$. The regression (solid) line is drawn taking into account the K-luminosity as a statistical weight.*

The distribution of 395 groups by the projected mass-to-luminosity ratio versus the total K-band luminosity, L_K, is demonstrated in ***Fig4***. The groups with the bulge dominant main galaxy ($T \leq 2$) are shown with red circles, and the rest of the groups with blue ones. The size of the circles is proportional to the group population. The horizontal dotted line represents the ratio $M/L_K = 97\ M_\Theta/L_\Theta$, which corresponds to K-luminosity density $j_K = 4.28\times10^8\ L_\Theta\,Mpc^{-3}$ [10] assuming a Hubble constant $H_0 = 73$ km s^{-1} Mpc^{-1} and the cosmic parameter of matter density $\Omega m = 0.32$ in the standard ΛCDM model. A significant spread of galactic systems in this diagram is due to the projection factors. Despite the large variations, the average ratio of virial mass to luminosity increases with the population of the system, its luminosity and correlates with the morphological type of the brightest member. All these features are well known from other catalogs of groups and clusters of galaxies.

The mean K-band luminosity density in the Local Universe inside a sphere of 40-45 Mpc is in good agreement with the global value of mean luminosity density obtained by different authors from deeper samples of galaxies. This fact supports our expectation that the sample of galaxies in the Local Universe can be considered as representative sample of the Universe. Summing the virial masses of the groups and clusters, Makarov and Karachentsev [2] mapped the distribution of the average density of dark matter around our Galaxy up to 40-45 Mpc. The shape of distribution of mass approximately repeats the shape of distribution of luminous matter. However, in almost all regions the density $\Omega m = \rho_m/\rho_c$ is below the global value $\Omega m = 0.32$ from the space CMB experiments. The mean matter density, $\Omega m = 0.08 \pm 0.02$, on the scale of 40-45 Mpc.

4. Missing dark matter problem

The observational fact that the virial masses of groups and clusters of galaxies are not able to provide the global density is not new. Similar estimates were obtained by different authors [11,12,13]. The estimation of Ωm varies from 0.05 to 0.2 for different methodologies and different samples of galaxies. The most refined methods of the virial mass estimation in the systems of different scale and population lead to the local ($D \leq 40$ Mpc) value of the mean matter density $\Omega m=0.08\pm0.02$, which is 3-4 times lower than the global value $\Omega m=0.32$ in standard ΛCDM cosmology. Various possible explanations of this contradiction were proposed:

1) Dark matter in groups and clusters extends far beyond their virial radius traced by galaxies. To reduce the Ωm discrepancy, one have to assume that the total mass of each group and cluster is about three times its virial mass. However, as was shown by the example of the Local Group, the masses of groups and clusters within the virial radius are in good agreement with the total mass inside the radius of zero velocity. Note that R_0 is ~(3.5-4.0) R_{vir}. Therefore, the existence of a large amount of dark matter at the periphery of the systems is inconsistent with the observational data.
2) There is possibility that we reside inside a giant under density region where the mean matter density is 3 to 4 times lower than the global value. However, it seems unlikely in standard ΛCDM theory to generate a giant void of 100-500 Mpc in diameter with such density contrast. Moreover, numerous K-band counts of galaxies in the range of K=12-19 mag do not show the presence of any significant cosmic lacuna around us within ~2000 Mpc.
3) The essential part of the dark matter in the Universe (about 2/3) is not associated with groups and clusters of galaxies and scattered outside the virial (and even collapsing) regions. It can be distributed in form of massive dark clumps or as a smooth dark "sea". The modern N-body simulations shows that about 2/3 of particles involved in model remain outside the dark matter halos. This number is roughly in agreement with our estimate.

5. Comparison theory and observations

Table1. *The properties of groups in different tests*

Sample	Local Universe	Best mock sample		Random mock sample	
			σ		σ
R, kpc	268	302.9	7.8	287.7	22.7
σ_V, km s^{-1}	74	61.5	2.0	65.6	4.0
M_p, $\times10^{12}$ M_Θ	3.3	2.73	0.22	2.92	0.52
M_p/L_K, M_Θ/L_Θ	31	24.8	1.1	26.2	2.1

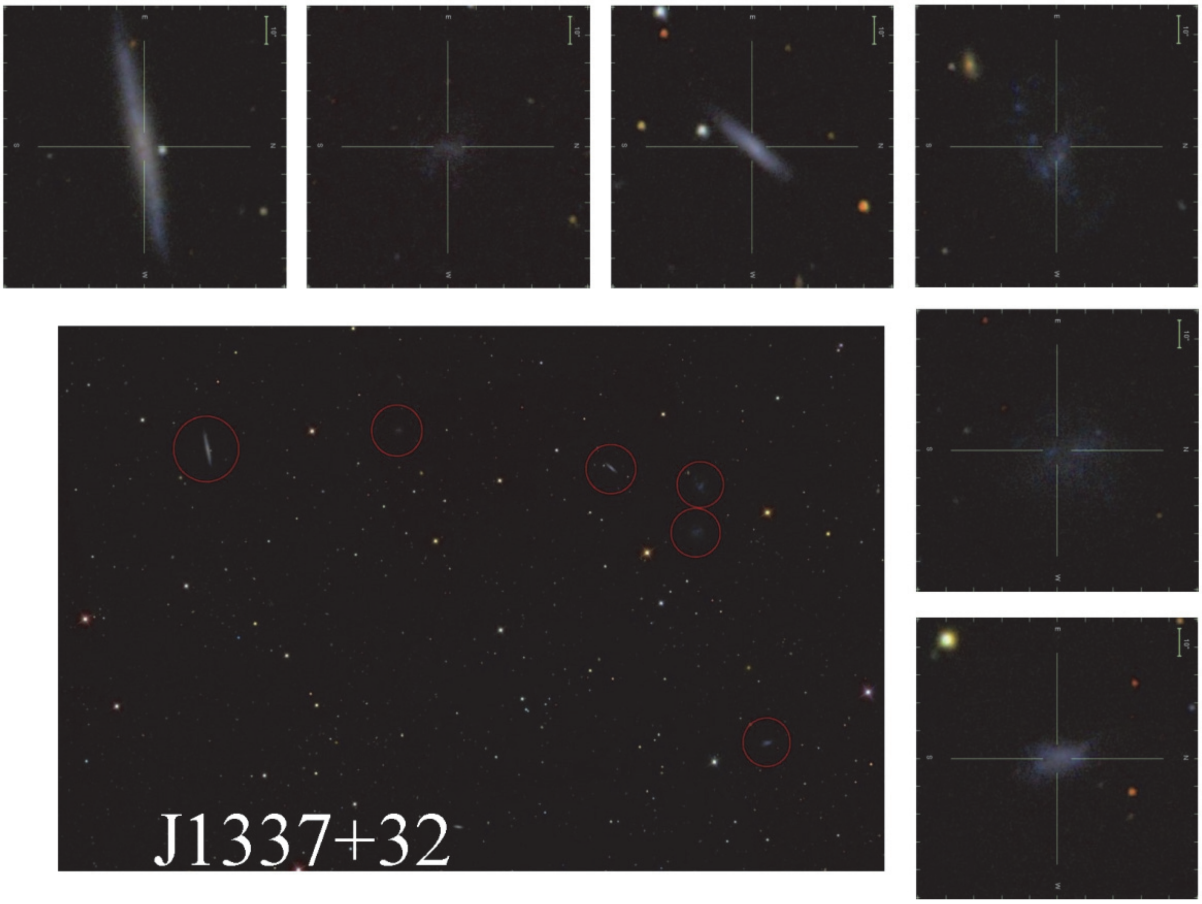

Fig5.: *Example of the most populated group of dwarf galaxies.*

We used the CLUES constrained N-body simulations [14] with 1024^3 particles of $2.554\times10^8\ h^{-1}\ M_\odot$ inside a 160 h^{-1} Mpc box. We generated mock catalogs which reproduce the properties of the distribution of galaxies in the Local Universe, taking into account completeness function of the real galaxy sample and a position of an observer around nearby structures in the Universe. We have applied our group selection algorithm [2] to the mock catalogs to test the properties of groups in the N-body simulations and compare them with real groups in the Local Universe. As can be seen from ***Table1***, the properties of groups in different tests are in good agreement each other as well as in good agreement with the groups in the real sample of galaxies. It supports the idea that significant part of dark matter can be not connected with luminous matter.

6. Examples of systems with high mass-to-light ratio

In the framework of studying the three-dimensional distribution of galaxies in the Local Volume, Makarov et al. [17] measured distances to 30 galaxies in the Canes Venatici cloud I (CVn I). The system is mostly populated by dwarf galaxies and clearly differs from the other nearby galaxy groups, such as the Local Group, M81 or Centaurus A. It does not show a prominent gravitational center and looks diffuse. The high quality of distance measurements allows us to identify an area of chaotic motions around the galaxy M94 and estimate the mass

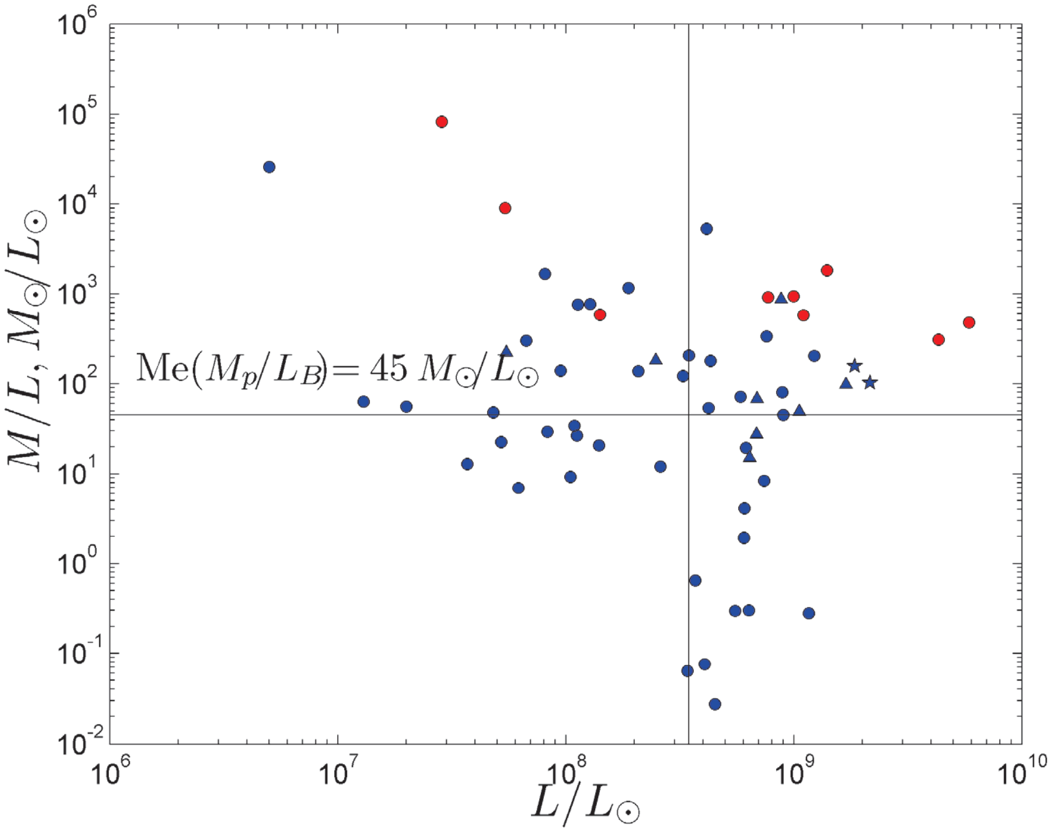

Fig6.: *Distribution of systems consisting dwarf galaxy only by their mass-to-light ration and luminosity. Red dots corresponds to the associations of Tully et al. [15] and blue ones represents the groups of dwarf galaxies found by Makarov and Uklein [16].*

of the system using virial theorem. Estimation of the mass-to-light ration, $M_p/L=159\ M_\odot/L_\odot$ for the CVn I cloud of galaxies greatly exceeds the typical ratio $M/L_B\sim30$ for the nearby groups of galaxies, such as the Local Group (M/L_B=15-20) and M81 group (M/L_B=19-32). Note that compared with the well-known nearby groups, such as the Local Group ($L_B=10.1\times10^{10}\ L_\odot$), M81 ($L_B=6.1\times10^{10}\ L_\odot$) and Centaurus A ($L_B=5.5\times10^{10}\ L_\odot$), the CVn I cloud ($L_B=1.61\times10^{10}\ L_\odot$) contains about 4-5 times less luminous matter, and M94 is at least 1 mag fainter than any other central galaxy of these groups. However, the concentration of galaxies in the Canes Venatici may have a comparable total mass.

Tully et al. [15] identified systems of dwarf galaxies in the neighborhood of the Local Group using high-precision photometric distances of nearby galaxies on the 3 Mpc scale. Such structures, which were called the associations of dwarf galaxies, have the mass-to-luminosity ratios in the range from 100 to1000 M/L and contain large amounts of dark matter. Karachentsev and Makarov [7] pointed out the existence of an unexpectedly large number of pairs consisting of dwarf galaxies. Makarov and Uklein [16] compiled the list of of groups consisting of dwarf galaxies only. The sample contains 126 objects, mainly combined in pairs. The most populated group contains six dwarf galaxies (***Fig5***). The majority of these systems reside in the low-density regions and evolve unaffected by massive galaxies. The dwarf galaxy groups forms a continuous sequence in the mass and luminosity along with the associations identified by Tully et al. [15]. The groups and associations of dwarfs have similar luminosities, however, the groups are by one order of magnitude more compact (see ***Fig6***). The median mass-to-luminosity ratio for the groups of dwarfs is equal to 45 M/L, which indicate a greater amount of dark matter comparable to the normal groups. The systems of dwarf galaxies may contain substantial amounts of dark matter. Such "dark" aggregates may be quite numerous. They are difficult to reveal and study, and can therefore "hide" a substantial fraction of dark matter, which remains undiscovered in the studies of groups of galaxies. This may partially solve the problem of "missing" mass.

Acknowledgements

This work was supported by the Russian Science Foundation (grant 14-12-00965).

References

[1] Karachentsev I.D., Kashibadze O.G., Makarov D.I., Tully R.B. 2009; MNRAS; 393; 1265

[2] Makarov D., Karachentsev I. 2011; MNRAS; 412; 2498

[3] Jones D.H., Read M.A., Saunders W. et al. 2009; MNRAS; 399; 683

[4] Ahn C.P., Alexandroff R., Allende Prieto C. et al. 2012; ApJS; 203; 21

[5] Meyer M.J., Zwaan M.A., Webster R.L. et al. 2004; MNRAS; 350; 1195

[6] Haynes M.P., Giovanelli R., Martin A.M. et al. 2011; AJ; 142; 170

[7] Karachentsev I.D., Makarov D.I., 2008; Astrophysical Bulletin; 63; 299

[8] Makarov D.I., Karachentsev I.D., 2009; Astrophysical Bulletin; 64; 24

[9] Karachentsev I.D., Makarov D.I., Karachentseva V. E., Melnyk O.V., 2011; Astrophysical Bulletin; 66; 1

[10] Jones D.H., Peterson B.A., Colless M., Saunders W. 2006; MNRAS; 369; 25

[11] Tully R.B., 1987; AphJ; 321; 280

[12] Vennik J., 1984; Tartu Astron. Obs. Publ.; 73; 1

[13] Magtesian A., Astrofizika. 1988; 28; 150

[14] Yepes G., Martínez-Vaquero L. A., Gottlöber S., Hoffman Y., 2009, in American Institute of Physics Conference Series, Vol. 1178, American Institute of Physics Conference Series, Balazs C., Wang F., eds., pp. 64-75

[15] Tully R.B., Rizzi L., Dolphin A.E. et al. 2006; AJ; 132; 729

[16] Makarov D.I., Uklein R.I. 2012; Astrophysical Bulletin; 67; 135

[17] Makarov D.I., Makarova L.N., Uklein R.I. 2013; Astrophysical Bulletin; 68; 125