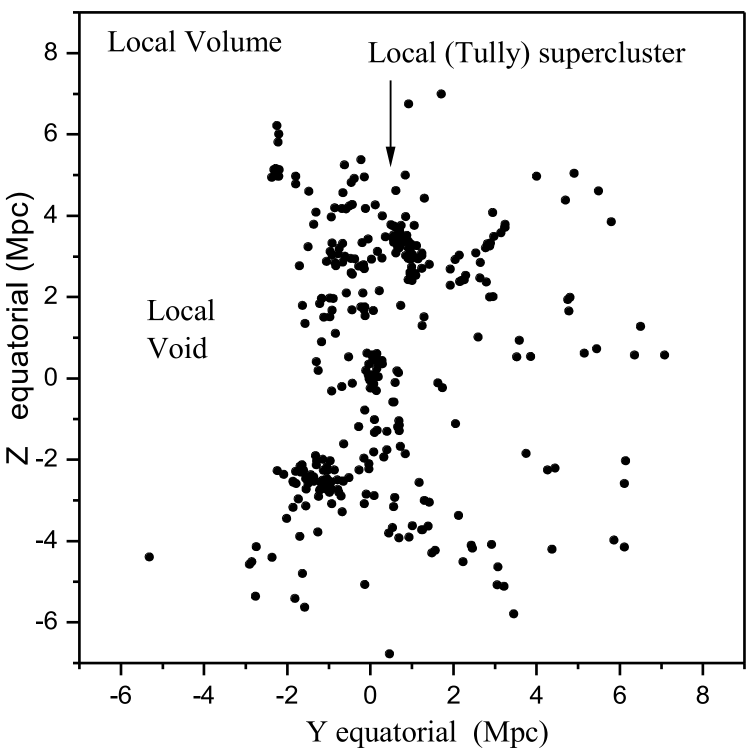
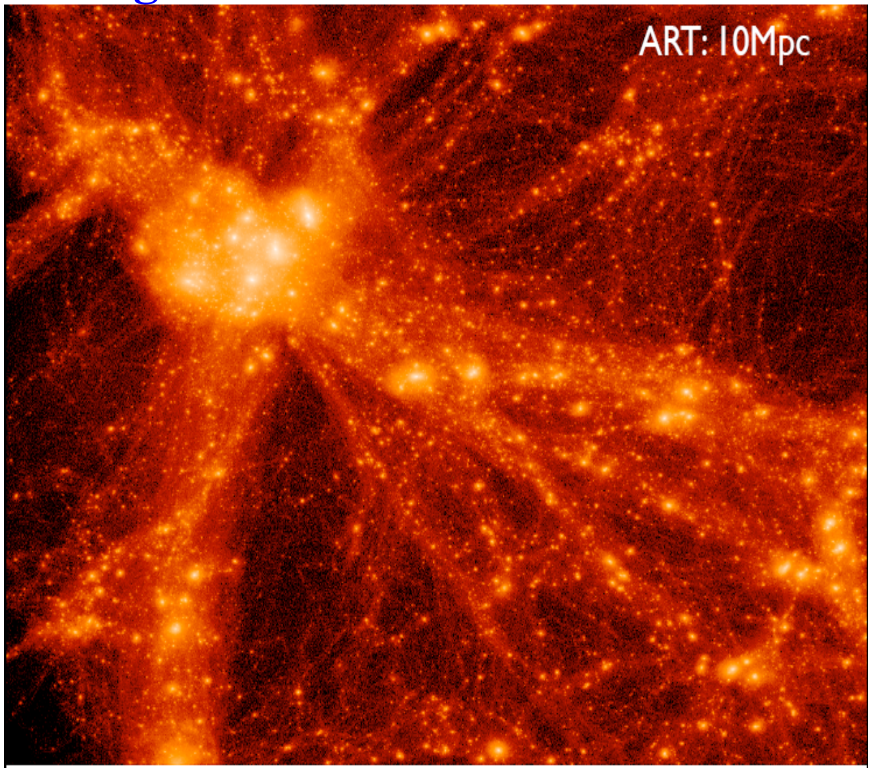
Anton Tikhonov / **Saint Petersburg State University**

Voids and Dwarf galaxies in the Local Volume: yet another LCDM-overabundance

14th Paris Cosmology Colloquium 2010

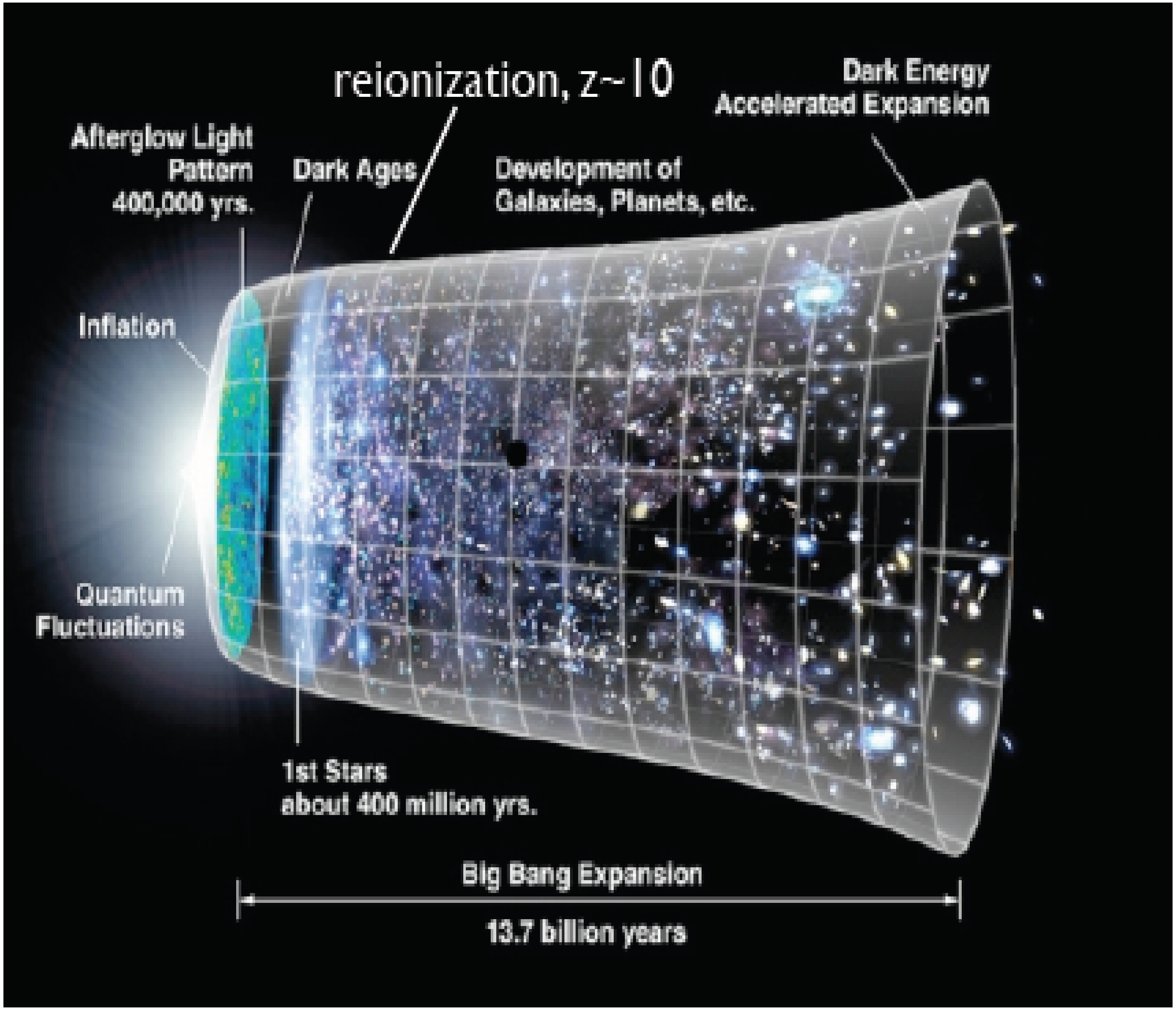
LCDM-*model* faces the same overabundance problem, which it had with the number of satellites in the LG: the theory predicts a **factor of 10** more **DM halos** in voids as compared with the observed number of **dwarf galaxies**.

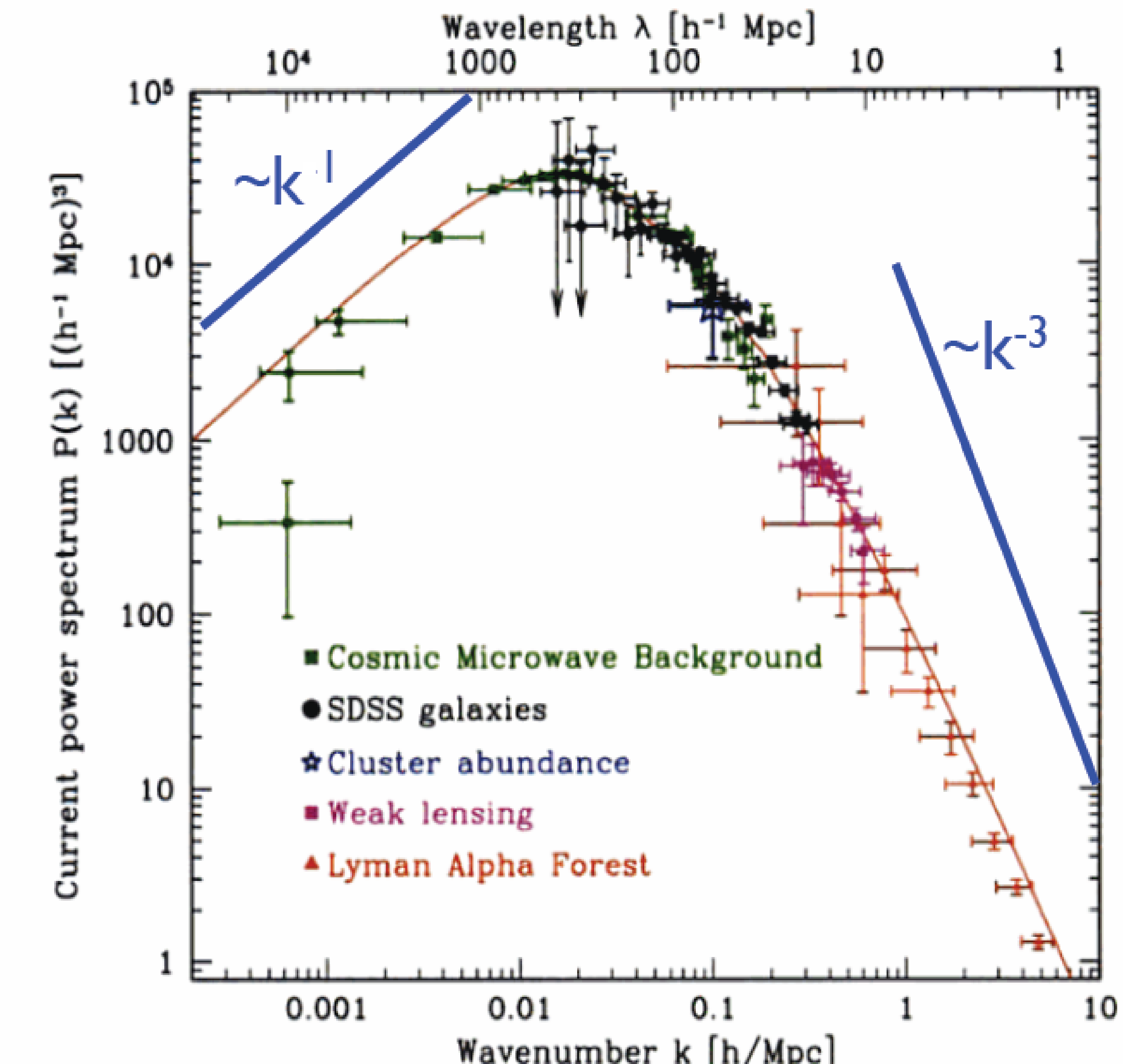




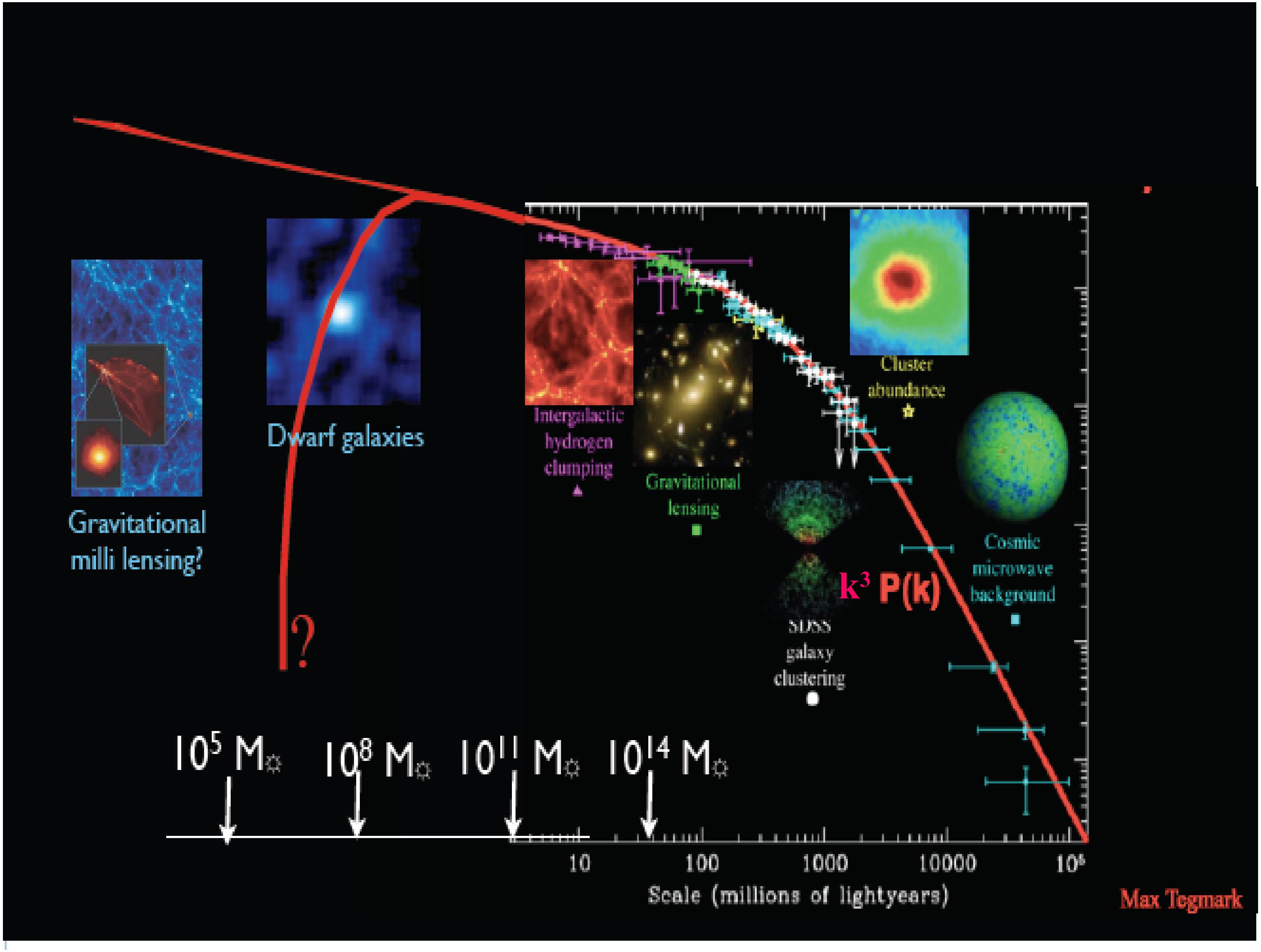
Klypin

Timeline of the Universe

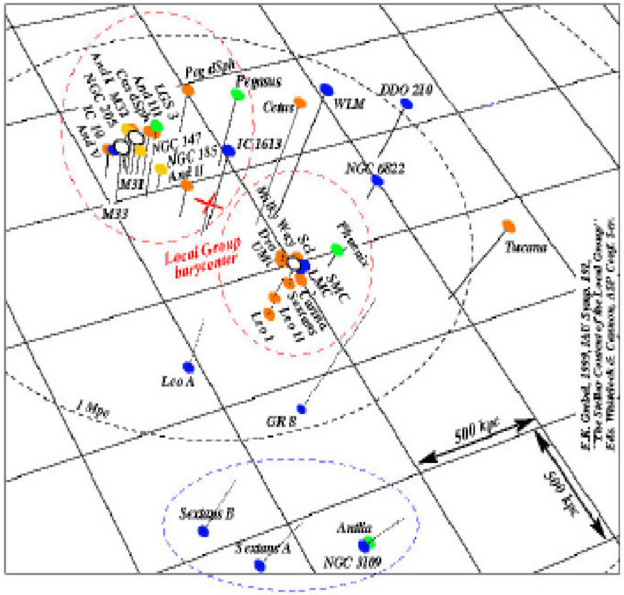


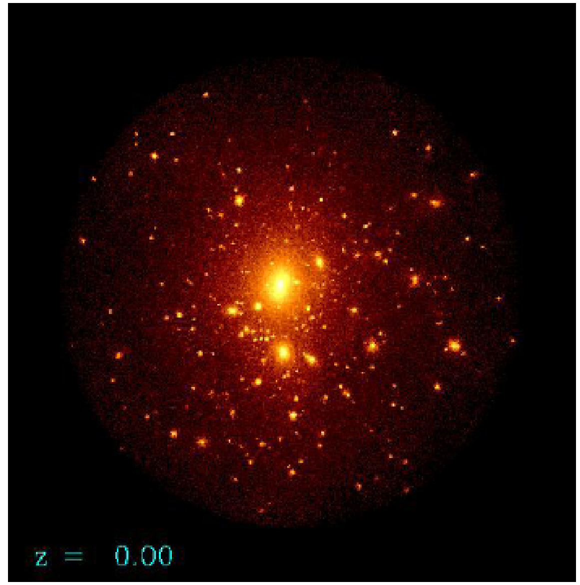


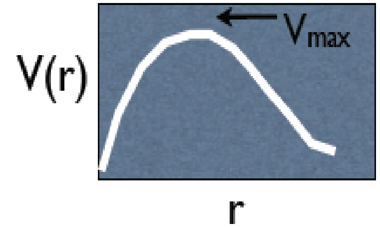
Tegmark, 2004


Gravitational milli lensing?
Dwarf galaxies
?
Intergalactic hydrogen clumping
Gravitational lensing
Cluster abundance
SDSS galaxy clustering
k³ P(k)
Cosmic microwave background
10⁵ M☉
10⁸ M☉
10¹¹ M☉
10¹⁴ M☉
10
100
1000
10000
10⁵
Scale (millions of lightyears)
Max Tegmark

WHERE ARE THE MISSING GALACTIC SATELLITES?

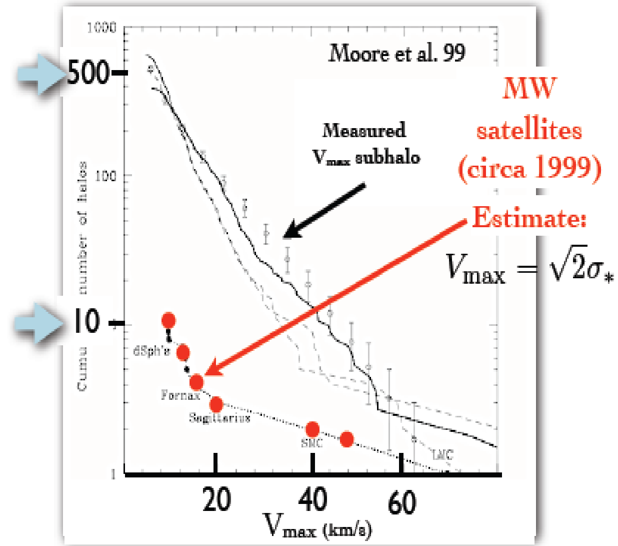






$V(r) = (GM(r)/r)^{1/2}$

count subhalos within virial radius of a simulated $M \sim 10^{12}\ M_{sun}$ halo



The LCDM model predicts that thousands of dwarf DM haloes should exist in the Local Group while only ~50 are observed.

Klypin et al.,1999, Moore et al.,1999, Madau et al., 2008

Currently favored scenario for explanation of the overabundance of the dark matter subhaloes assumes that dwarf haloes above V_{max} ~ 30-50 km/s were forming stars before they fall into the Milky Way or M31 and that smaller haloes never formed any substantial amount of stars.

Bullock et al., 2000, Kravtsov et al., 2004

THE VOID PHENOMENON P. J. E. PEEBLES 2001, ApJ, 557, 495

From continuity one might have thought the more likely picture is that gravity has emptied the voids of mass as well as galaxies. This does not happen in the CDM model, however. Simulations show, between the concentrations of large dark mass halos, clumps of mass that seem to be capable of developing into void objects observable as clumps of stars or gas, contrary to what is observed.

The structure of voids Stefan Gottlöber et al. 2003, MNRAS, 344, 715

that voids in the distribution of $10^{12}h^{-1}M_\odot$ haloes (expected galactic magnitudes $\sim M_*$) are almost the same as the voids in $10^{11}h^{-1}M_\odot$ haloes. Yet, much smaller haloes with masses $10^9h^{-1}M_\odot$ and circular velocities $v_{\rm circ} \sim 20$ km/s readily fill the voids: there should be almost 1000 of these haloes in a $20h^{-1}$Mpc–diameter void. A typical void of diameter $20h^{-1}$Mpc contains about 50 haloes with $v_{\rm circ} > 50$ km/s. The haloes are arranged in a pattern, which looks like a miniature Universe: it has the same structural elements as the large-scale structure of the galactic distribution of

THE VOID PHENOMENON EXPLAINED 2009, ApJ, 691, 633

JEREMY L. TINKER[1] & CHARLIE CONROY[2]

The void phenomenon consists of two observational facts: that voids contain few, if any, low-luminosity galaxies, and that the few void objects tend to have similar properties to the overall galaxy population. The controversial aspect is whether these facts are at odds with the current cosmology. Although the depth of voids and homogeneity of void objects are striking features of the cosmic web, they are readily explainable within the context of ΛCDM, combined with a straightforward model to connect galaxies and dark matter at all luminosities and mass scales.

How small can be a galaxy?

Below some mass the halos are expected to **stop producing galaxies** inside them.

stellar feedback (Dekel & Silk, 1986)
photoionization (Bullock et al., 2000)
may play a significant role in **quenching starformation** in **too small halos**.

(**Loeb, 2008**): V_{lim} below which halos have essentially **no gas infall** due to **increase of Jeans mass** caused by **UV background** at the **epoch of reionization**:

$$V_{lim} = 34 \cdot (T_{IGM} / 1.5 \cdot 10^4 \, K)^{1/2} \ km/s,$$

T_{IGM} is the temperature of intergalactic medium gas ionized by stars.

(**Hoeft et al., 2006**): high-resolution hydrodynamic simulations, assuming that **cosmological UV-background photo-evaporates baryons out of halos of dwarf galaxies**, and thereby limits their cooling and starformation rate.

(**Hoeft et al., 2006**) give characteristic mass

$$M_C = 6 \cdot 10^9 \ h^{-1} M_{sun}$$

below which haloes start to fail accreting gas.

We compare the spectrum of void sizes in the **Local Volume galaxy sample** with the distribution of voids in **high-resolution cosmological simulations**.

$$V_{\rm circ} = \sqrt{\frac{GM(<r)}{r}}\Bigg|_{\rm max}.$$

V_c = 20km/s – $M_{vir} \sim 10^9\, M_o$
V_c = 50km/s – $M_{vir} \sim 10^{10}\, M_o$

Theoretical predictions of the luminosity of a galaxy hosted by a halo with given mass, circular velocity and merging history are quite uncertain and cannot be used for our analysis

Instead, we ask a more simple question:

What luminosity a halo or subhalo with given circular velocity *should have* in order to reproduce the observed spectrum of void sizes?

We assume that halos with larger circular velocities should host more luminous galaxies.

Local Volume (LV) galaxy sample

Over the last decade, *Hubble Space Telescope* observations have provided distances to many nearby galaxies which were measured with the tip of the red giant branch (TRGB) stars. Special searches for new nearby dwarf galaxies have been undertaken by Karachentsev et al. (1990s - 2009). Also, special cross-check has been done with infrared and blind HI surveys (Karachentsev et al. 2007).

The distances were measured from TRGB stars, Cepheids, the Tully–Fisher relation and some other secondary distance indicators. Since the distances of galaxies in the LV are measured independent of redshifts, we know their true three-dimensional spatial distribution and their radial velocities.

A substantial fraction of the distances have been measured with accuracies as good as 8–10 percent (Karachentsev et al. 2004).

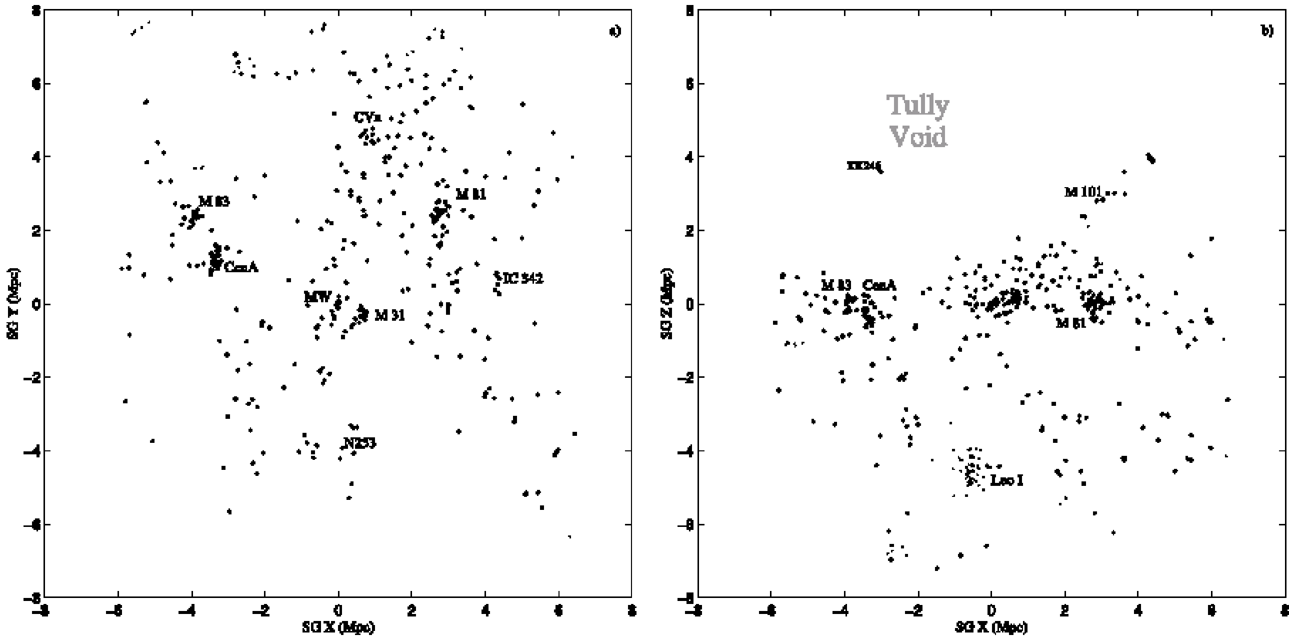
Within the LV, dwarf systems have been observed down to extremely low luminosities. This gives us a unique chance to detect voids, which may be empty of rather faint galaxies. Here, we used the updated Catalog of Neighboring Galaxies (Karachentsev et al. 2004, private communication). We analysed a volume-limited sample of galaxies with absolute magnitudes M_B **<-**12 within 8-Mpc radius.

The overall completeness of the sample has been discussed in Tikhonov & Klypin (2009).

B-band luminosity density within the radius of 8 Mpc around us exceeds **1.8 - 2.0** times the global luminosity density.

About **2/3** of the LV galaxies belong to the LV groups

Karachentsev et al., 2007



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

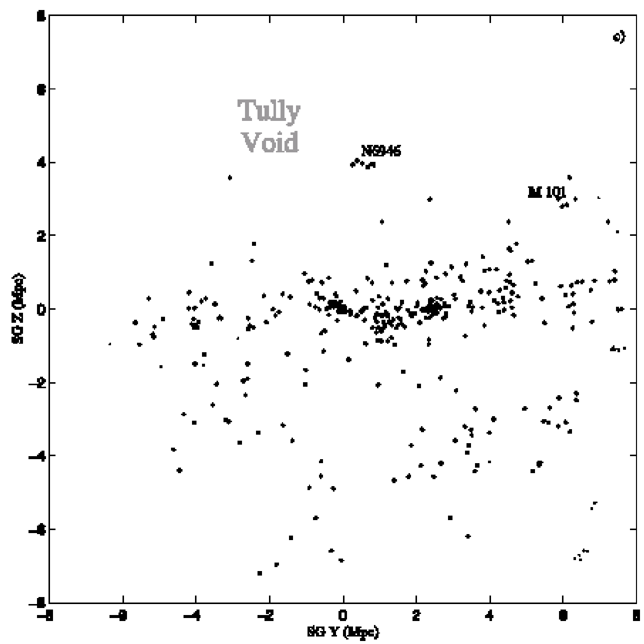
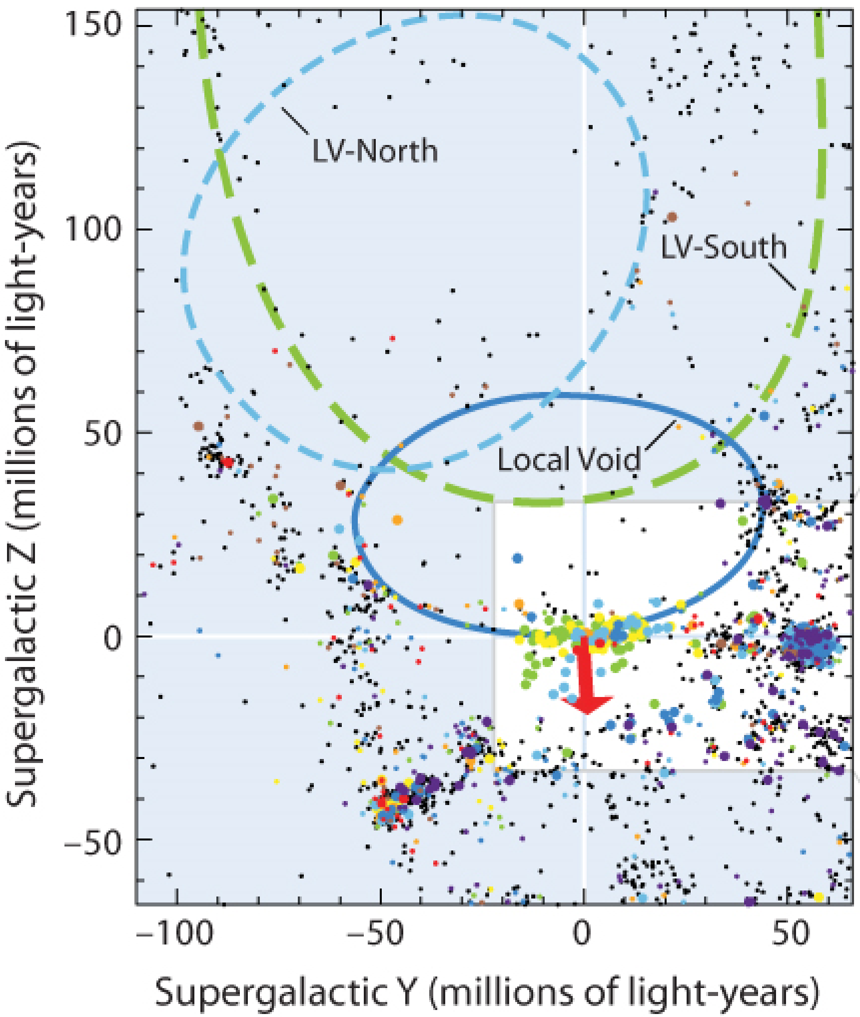
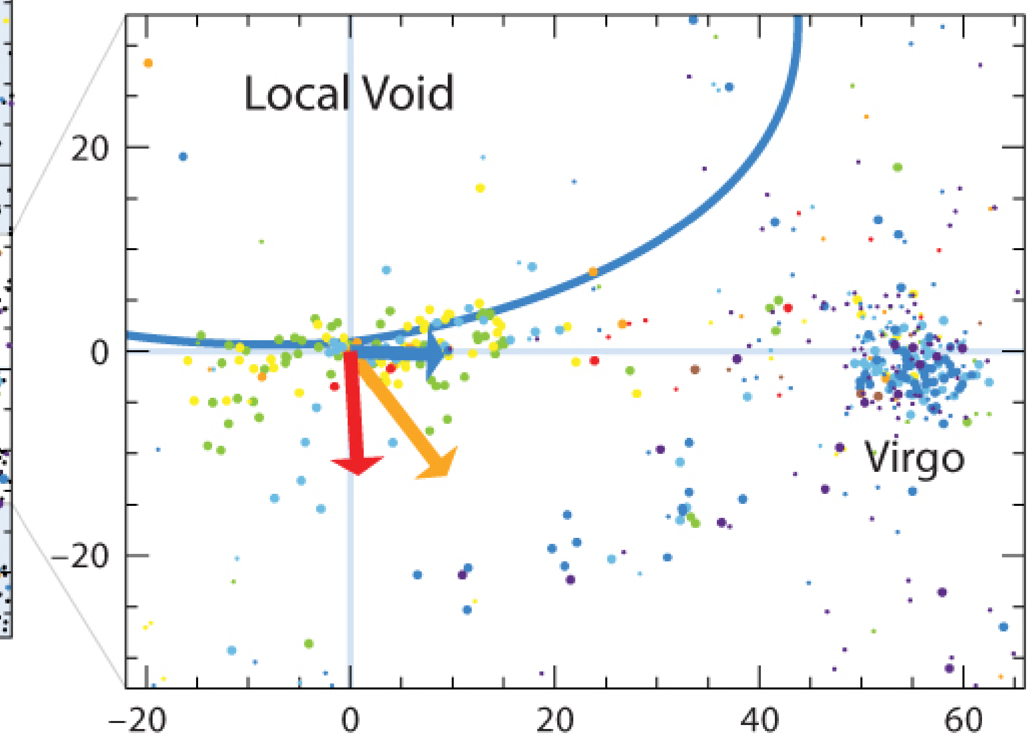


FIG. 5.—Panorama of the LV within a radius of 8 Mpc in Cartesian supergalactic coordinates. Galaxies from Table 1 with $D > 8$ Mpc are shown as small circl
(*a*) SGX-SGY, galaxies projected onto the plane of the Local Supercluster; (*b*) SGX-SGZ, the distribution in Z (perpendicular to the plane of the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

Tully et al.



Our motion with the respect to galaxies in the Local Supercluster *Tully et al. 2008, ApJ, 676, 184*

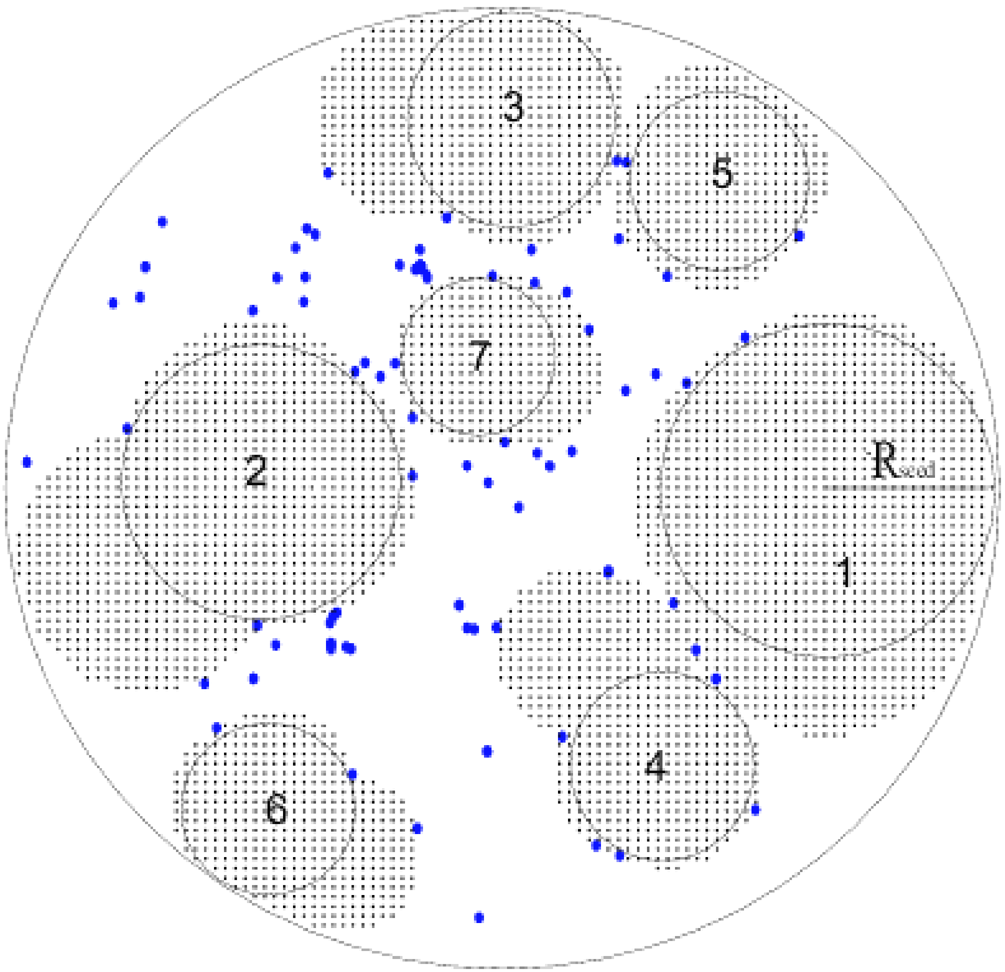


Void Finder

- **3D grid**.
- **Empty seed sphere** of largest possible radius R_{seed} 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 $R_{seed} > R_{threshold}$.
- **Voids have flexible but still regular shapes and are thick enough** throughout their volumes.
- **Voids are defined to be completely inside** sample boundaries.

Then we considered

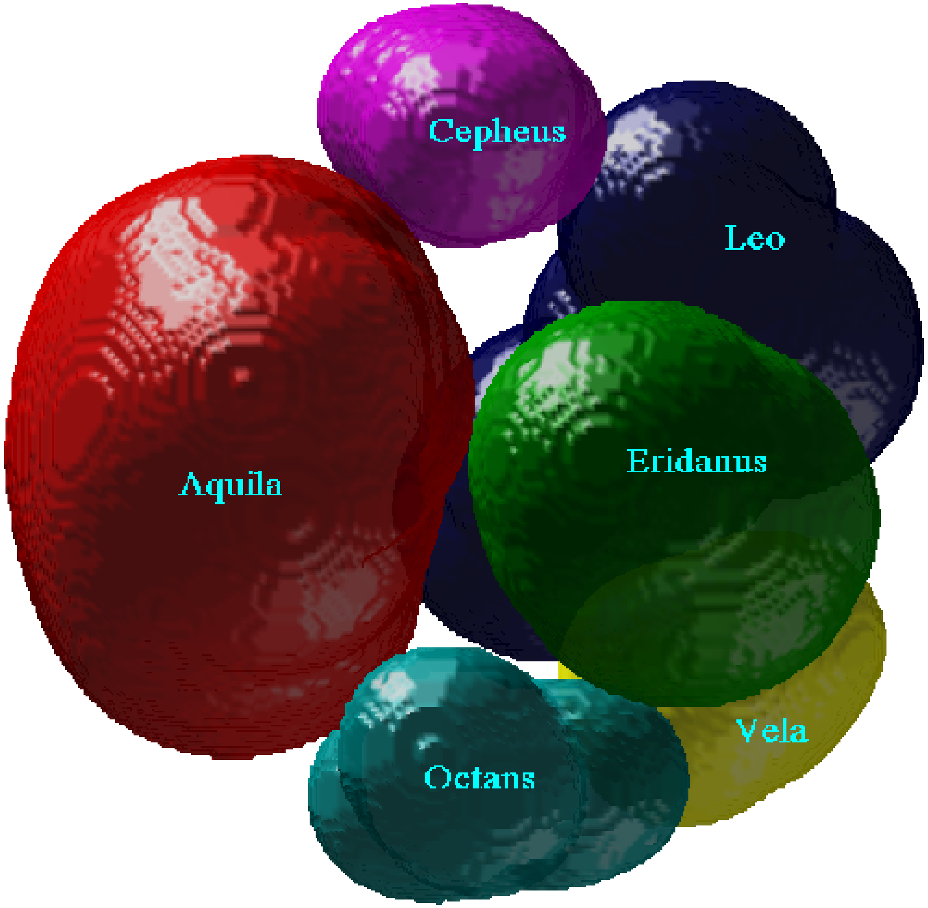
Cumulative void function ΔV/V(>Rvoid)



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

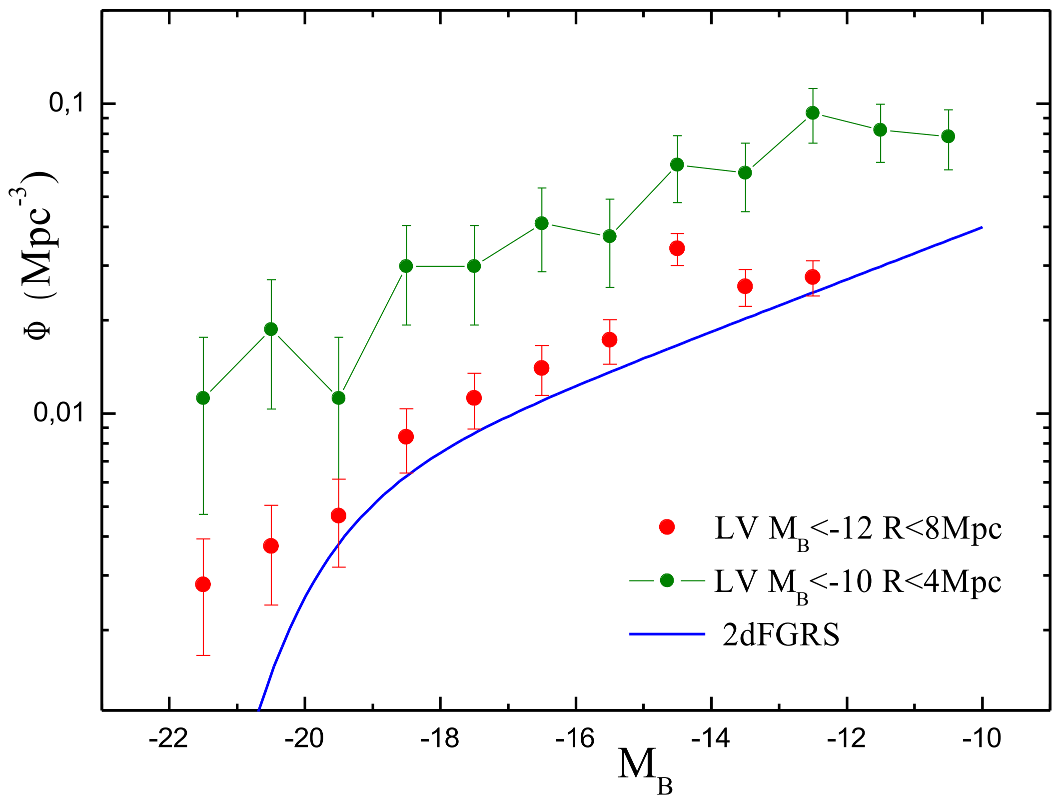
6 largest minivoids within the LV.

¼ of the Local Volume is occupied by Void in Aquila - front part of the Local (Tully) Void
(Tikhonov & Karachentsev, 2006)



Luminosity functions of LV galaxies

2 volume limited samples in LV
1) M_B **< -12** within **8Mpc** 2) M_B **< -10** within **4Mpc**.

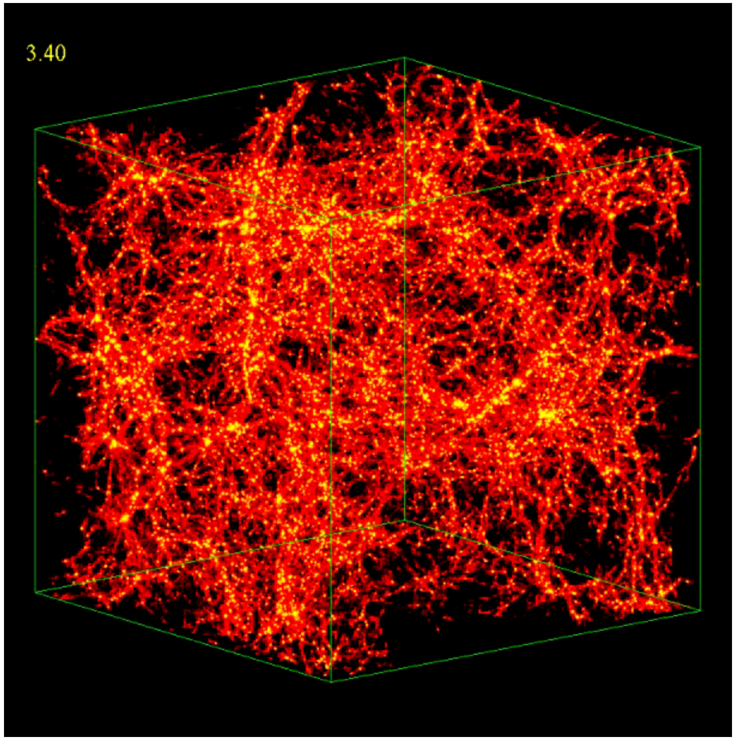


α ~ 1.2

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.

Simulations

Simulation	S_1	S_2	S_3
Box Size (h^{-1}Mpc)	80	160	64
σ_8	0.90	0.75	0.75
Mass of a high resolution particle ($h^{-1}M_\odot$)	4.91×10^6	3.18×10^8	1.6×10^7
Spatial Resolution (h^{-1}kpc)	0.52	1.2	1.6
Number of high resolution particles	1.6×10^8	1024^3	1024^3
Circular velocity of the smallest resolved halo (km/s)	9	27	15



Selection of model LV-candidates

(i) We put a sphere of radius 8 Mpc on a Local Group candidate.

(ii) No haloes with $m_{vir} > 2 \times 10^{13}$ $M_\odot$ are inside this sphere.

(iii) There are no haloes more massive than 5.0×10^{11} $M_\odot$ in a distance between 1 and 3 Mpc.

(iv) The centres of the spheres (the Local Group candidates) are located at distances larger than 5 Mpc one from the other.

(v) The number density of haloes with $V_c > 100\,\mathrm{km\,s^{-1}}$ inside this sphere exceeds the mean value in the whole box by a factor in the range 1.4–1.8.

RMS Peculiar Velocity – deviations from the HUBBLE FLOW - σ_H

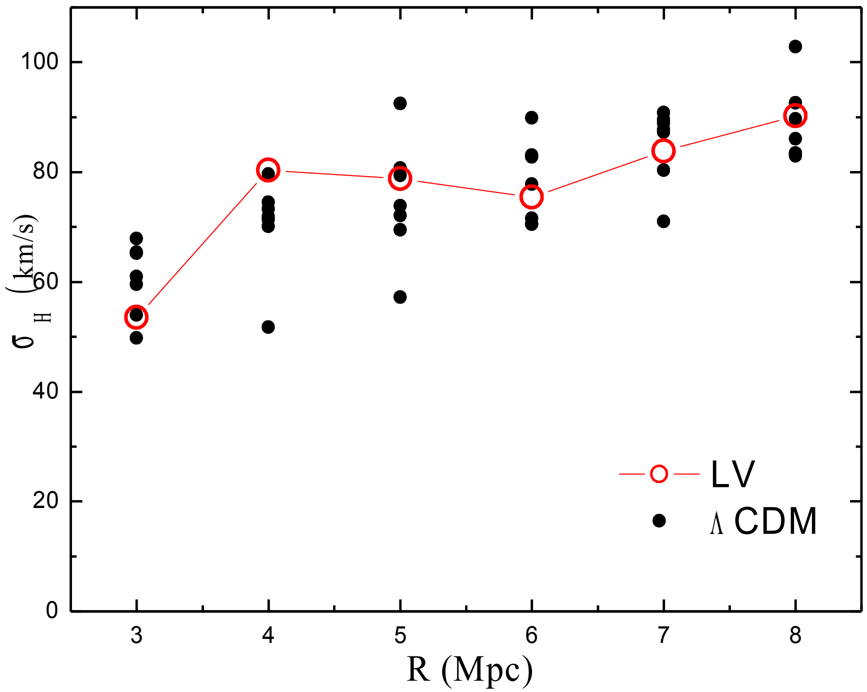


Figure 2. The rms radial velocity deviations from the Hubble flow σ_H for galaxies in the Local Volume with distances from 1 Mpc up to R (full red curve with open circles). The estimates are corrected for the apex motion and for distance errors. Black filled circles show theoretical predictions for 7 LV candidates in the simulation S_2.

Note that the spherical top-hat collapse model predicts that a sphere with overdensity 5.5 is at the turn-around radius (Peebles 1980) and does not expand. If the model were applicable to the motion of galaxies in the Local Volume, than we should have observed random motions comparable to the Hubble velocities for the 4 Mpc sample. In reality we have rather cold Hubble flow in the Local Volume implying that the top-hat model gives an extremely poor approximation of the dynamics of galaxies in the LV.

Void Function $\Delta V/V(>R_{void}) = V_{voids}(>R_{void})/V_{sample}$

Local Volume

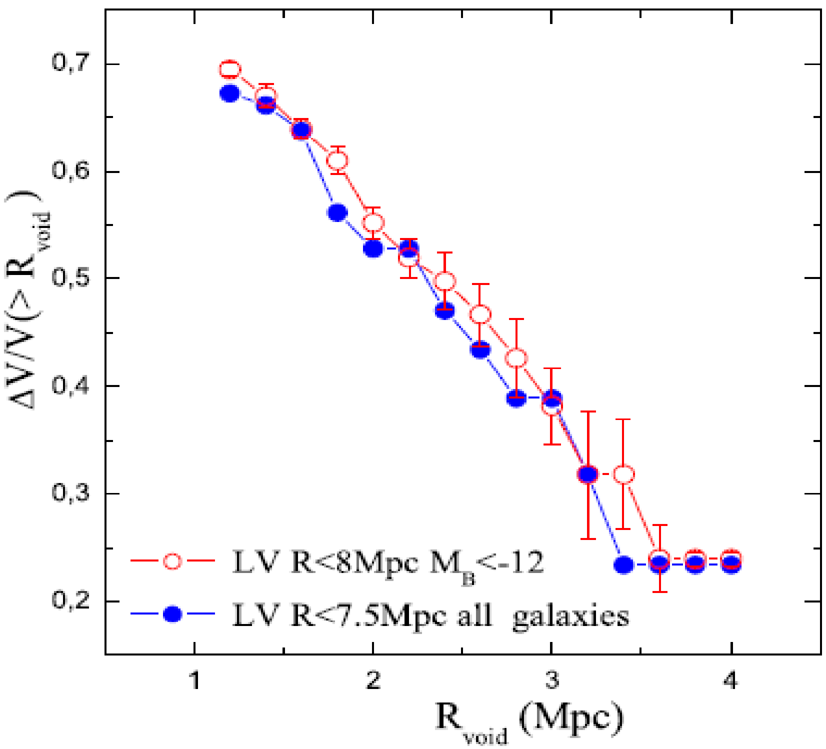


Figure 4. the void function for two observational samples. The full curve with open circles are for a complete volume limited sample with $M_B < -12$ and $R < 8\,\mathrm{Mpc}$. 1σ errors obtained by Monte Carlo resampling distances from catalog by means of additon gaussian distributed characteristic 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 $\sigma_8 = 0.9$

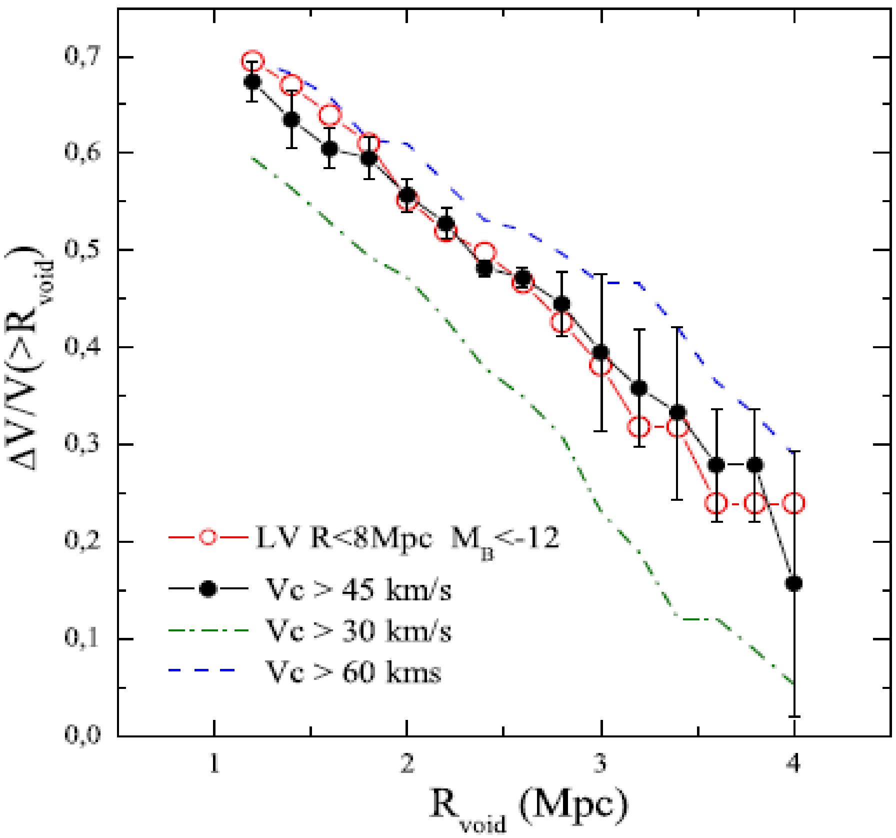


Figure 3. Observational data (the complete sample, circles) are compared with the distribution of voids in samples of halos with different limits on halo circular velocity. VF for $V_c = 45\,\mathrm{km/s}$ provides a remarkably good fit to observations. Note that the LCDM model predicts very large empty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

CLUES Box64CR $\sigma_8 = 0.75$

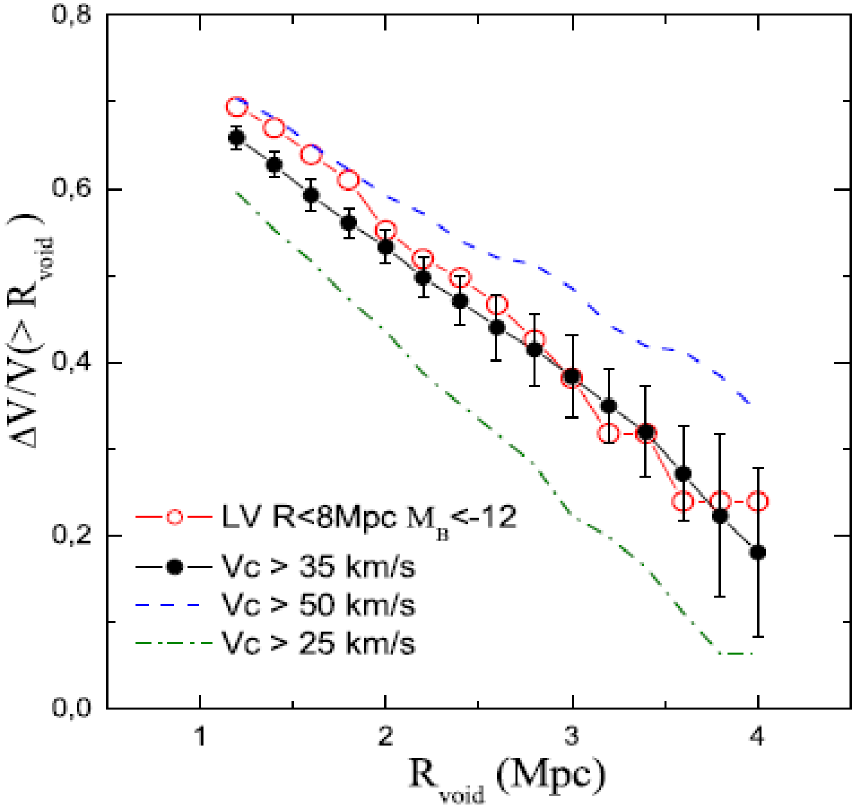


Figure 5. Observational data (the complete sample $M_B < -12$) are compared with the distribution of voids in 14 samples from Box64CR of halos with different limits on halo circular velocity. In this case VF for $V_c = 35\,\mathrm{km/s}$ (shown with 1σ scatter) provides a better fit to observations.

Box160CR $\sigma_8 = 0.75$

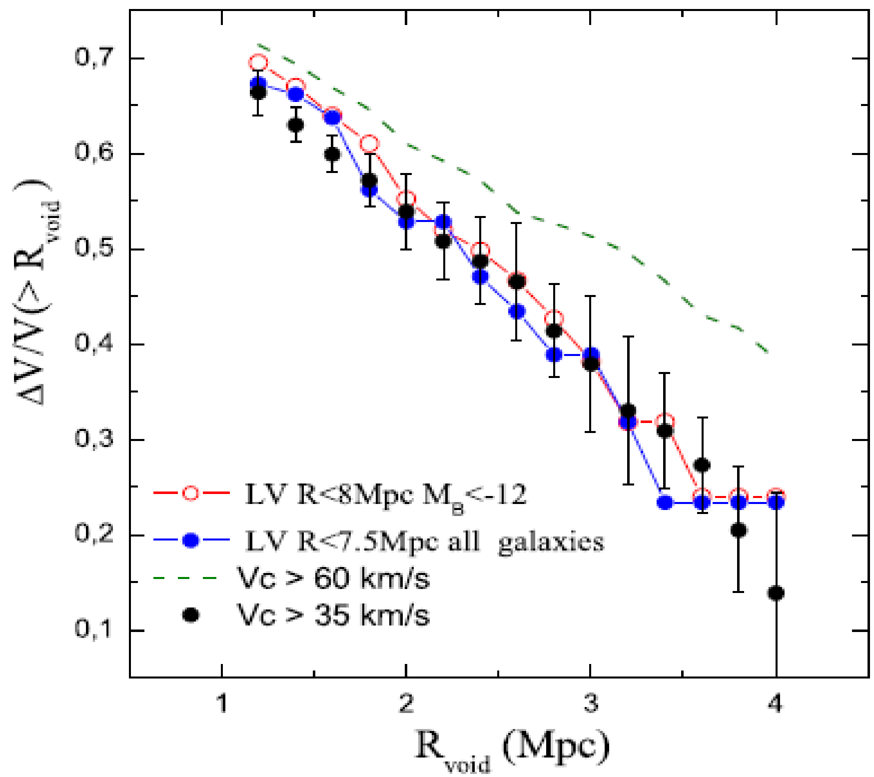


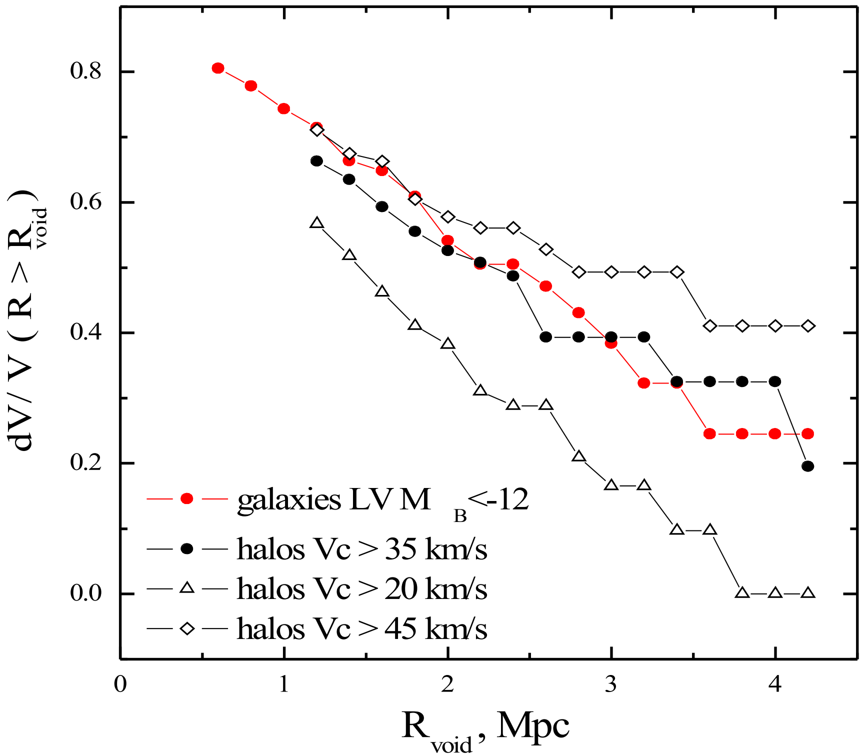
Figure 6. Observational data (the complete sample $M_B < -12$) are compared with the distribution of voids in 7 samples from Box160CR of halos with different limits on halo circular velocity. CVF for $V_c = 35\,\mathrm{km/s}$ (shown with 1σ scatter) provides a remarkably good fit to observations. Because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

CLUES (S. Gottloeber, G. Yepes, Y.Hoffman, A. Klypin)

CR run WMAP5 cosmology

7 Mpc/h resimulated sphere with 2048^3 resolution

Complete downto Vc=10km/s



Vc > 35km/s fit the observations

The disagreement with the LCDM theory is staggering.

Examples of LV galaxies with Vrot < 25km/s

Table 4. Properties of isolated dwarf galaxies with $M_B = -11.8 - 13.2$

Name	M_B	axial ratio	W_{50}	V_{rot}	Distance
E349-031,SDIG	-12.10	0.82	20.0	17.5	3.21
KKH5	-12.27	0.62	37.0	23.6	4.26
KKH6	-12.38	0.60	31.0	19.4	3.73
KK16	-12.65	0.37	24.0	12.9	5.40
KKH18	-12.39	0.57	34.0	20.7	4.43
KKH34,Mai13	-12.30	0.56	24.0	14.5	4.61
E489-56,KK54	-13.07	0.53	33.8	19.9	4.99
KKH46	-11.93	0.86	25.0	24.5	5.70
U5186	-12.98	0.23	42.0	21.6	6.90
E321-014	-12.70	0.43	39.8	22.0	3.19
KK144	-12.59	0.33	44.0	23.3	6.30
E443-09,KK170	-12.03	0.75	29.0	21.9	5.78
KK182,Cen6	-11.89	0.60	16.0	10.0	5.78
DDO181,U8651	-12.97	0.57	42	23.7	3.02
DDO183,U8760	-13.13	0.32	30.0	15.8	3.18
HIPASS1351-47	-11.88	0.60	38.8	24.2	5.65

The observed spectrum of void sizes strongly disagrees from the theoretical void spectrum if halos with Vc > 20 km/s host galaxies brighter than MB = −12.

In the LCDM model with σ8 = 0.9 there are 320 haloes with Vc > 45 km/s – the same number as the number of galaxies in the Local Volume with the MB = −12 limit. In the same volume in the LCDM model there are 3500 haloes with Vc > 20 km/s.

If all these halos host galaxies brighter than MB = −12, the theory predicts a ***factor of 10*** more haloes as compared with the observations.

The emptiness of voids: yet another over-abundance problem for the LCDM model.

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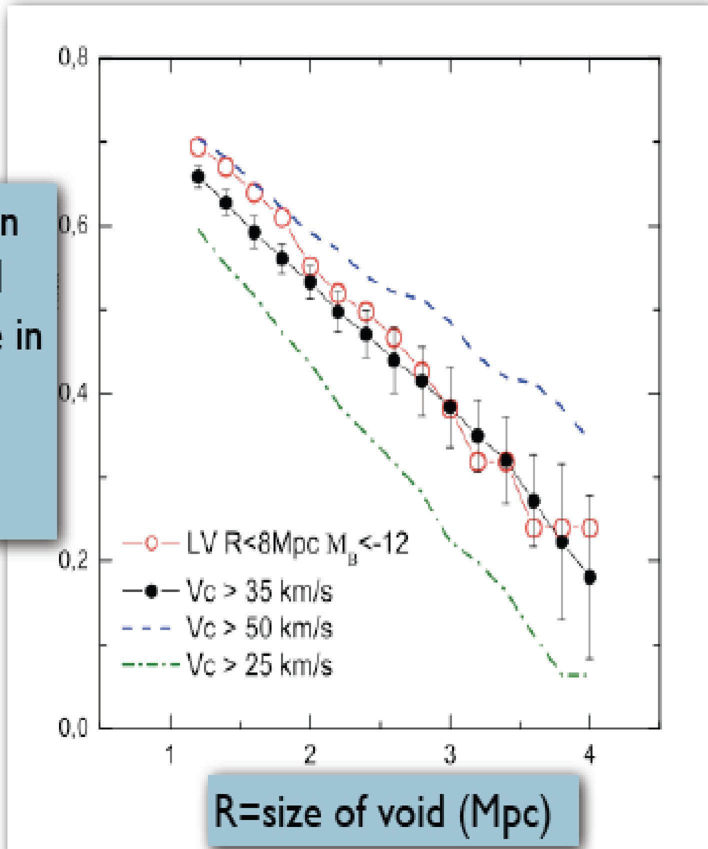
Fraction of local volume in voids bigger than R



R=size of void (Mpc)

~Fornax's ~Leo I's

Voids are empty enough only if $M_B < -12$ galaxies are big:

→ $V_{max} > 35$ km/s

→ $M_{vir} \sim 10^{9.5} M_{sun}$

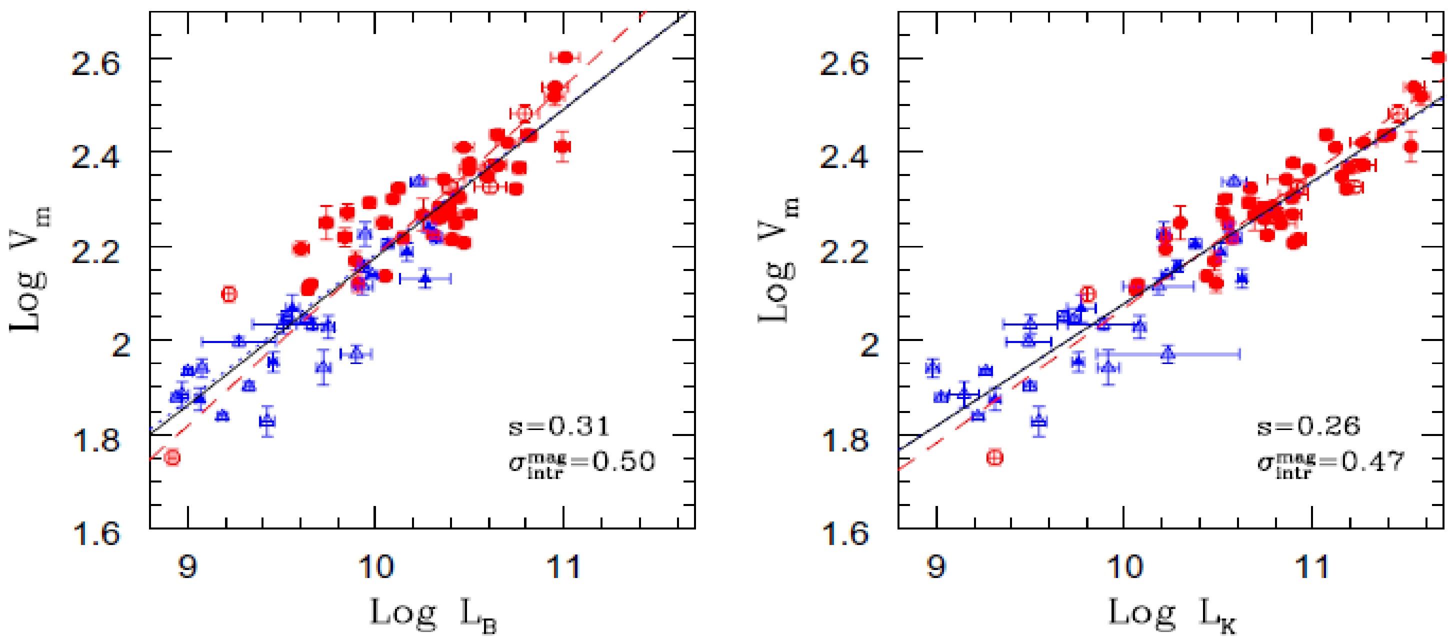
→ $M_{300} \sim 10^{7.15} M_{sun}$

Name	M_B	V_{rot}
E349-031,SDIG	-12.10	17.5
KKH5	-12.27	23.6
KKH6	-12.38	19.4
KK16	-12.65	12.9
KKH18	-12.39	20.7
KKH34,Mai13	-12.30	14.5
E489-56,KK54	-13.07	19.9
KKH46	-11.93	24.5
U5186	-12.98	21.6
E321-014	-12.70	22.0
KK144	-12.59	23.3
E443-09,KK170	-12.03	21.9
KK182,Cen6	-11.89	10.0
DDO181,U8651	-12.97	23.7
DDO183,U8760	-13.13	15.6
HIPASS1351-47	-11.88	24.2

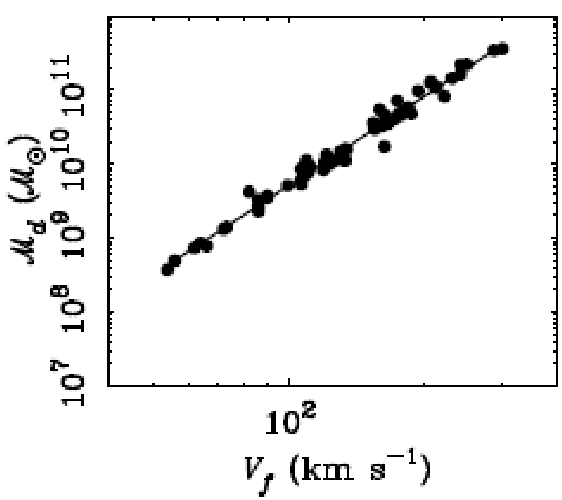
but: $V_{HI} \sim$ 20 km/s

Tully-Fisher relation

Avila-Reese et al.



Barionic Tully-Fisher relation



The physical basis of the Tully-Fisher relation is widely presumed to be a relation between a galaxy's total mass and rotation velocity (e.g., Freeman 1999). Luminosity is a proxy, being proportional to stellar mass, which in turn depends on the total mass. McGaugh et al. (2000) found that a more fundamental relationship between the baryonic mass and rotation velocity does indeed exist, provided that both stellar and gas mass are considered (Milgrom & Braun 1998).

Stacy S. McGaugh

Klypin et al. 2010 Luminosity-Vcirc relation

An outstanding challenge for the ΛCDM model that we address here is to reproduce the observed abundance of galaxies as a function of their overall properties such as dynamical mass, luminosity, stellar mass, and morphology, both nearby and at higher redshifts. A successful cosmological model should produce agreement with various observed galaxy dynamical scaling laws such as the Faber-Jackson (Faber & Jackson 1976) and Tully-Fisher (Tully & Fisher 1977) relations.

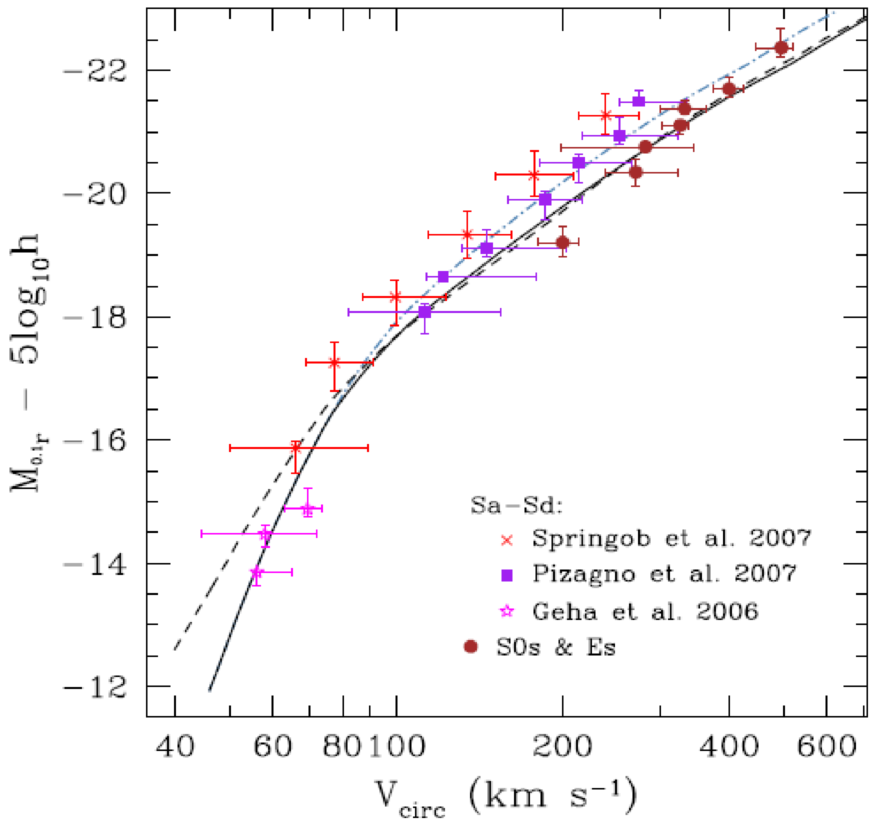
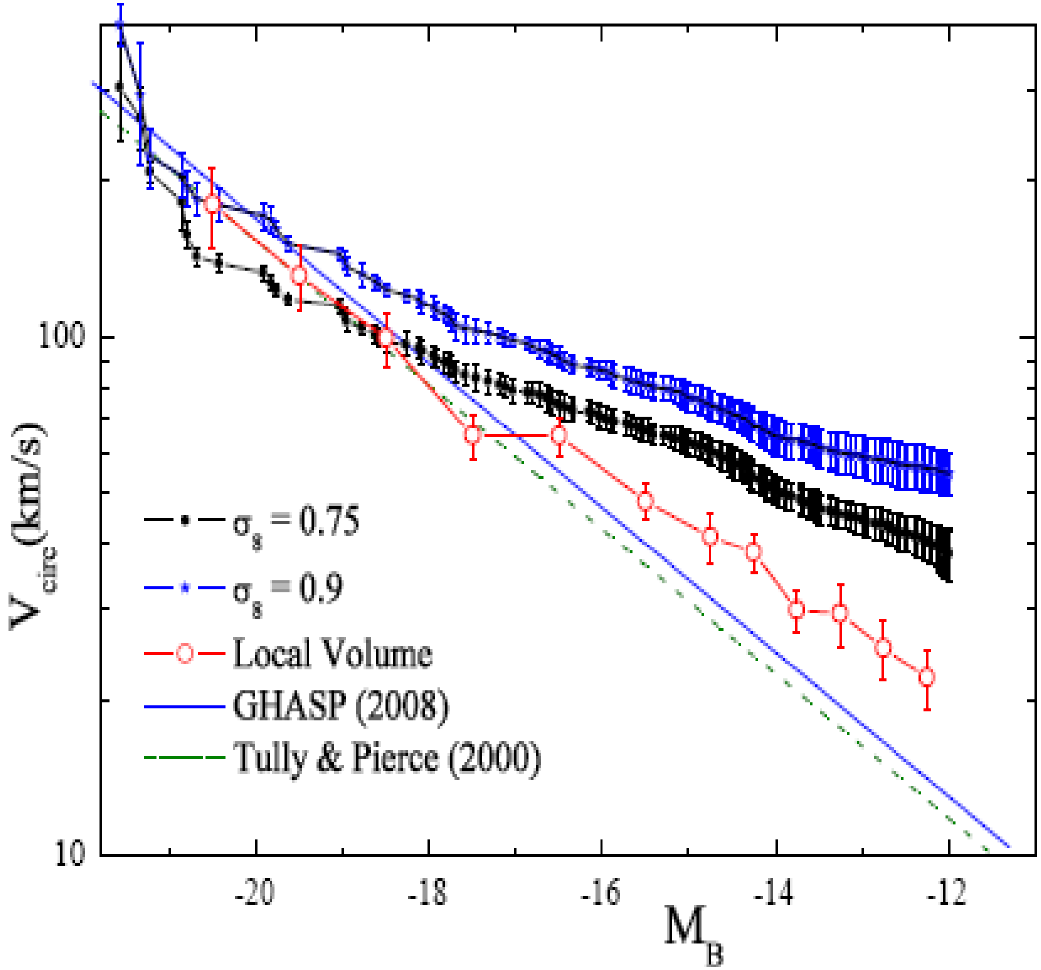


Fig. 4.— Comparison of the observed Luminosity–Velocity relation with the predictions of the ΛCDM model. The solid curve shows the median values of $^{0.1}r$-band luminosity vs. circular velocity for the model galaxy sample assuming adiabatic compression. The dot-dashed curve shows predictions after adding the baryon mass without adiabatic contraction. The dashed curve show results for a steeper ($\alpha = -1.34$) slope of the LF. The circular velocity for each model galaxy is based on the peak circular velocity of its host halo over its entire history, measured at a distance of 10 kpc from the center including the cold baryonic mass and the standard correction due to adiabatic halo contraction. We also include the most representative observational samples.

LCDM- Overabundance in terms of TF-relation

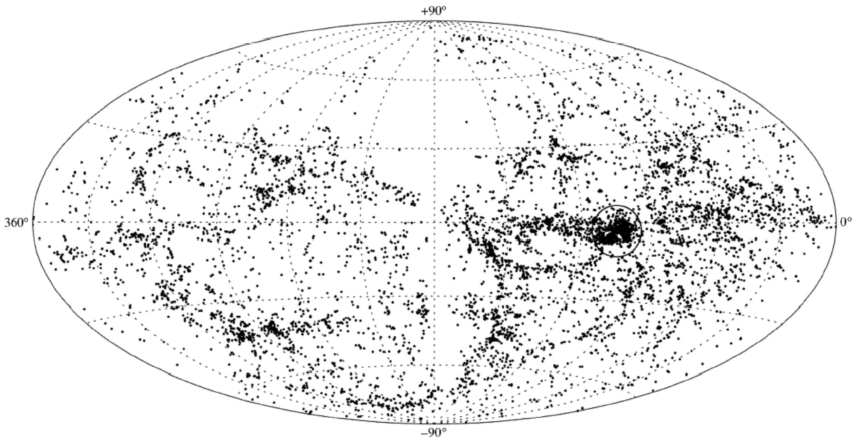
LV Spirals + Irregulars



Local Supercluster Galaxy Sample

D. Makarov and I. Karachentsev 2010

D < 25Mpc MK <-17.5 (Vrot>50km/s)



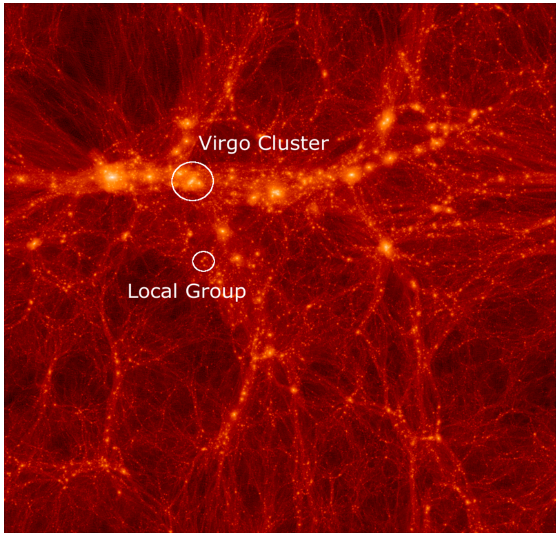
For Vcirc > 50km/s objects

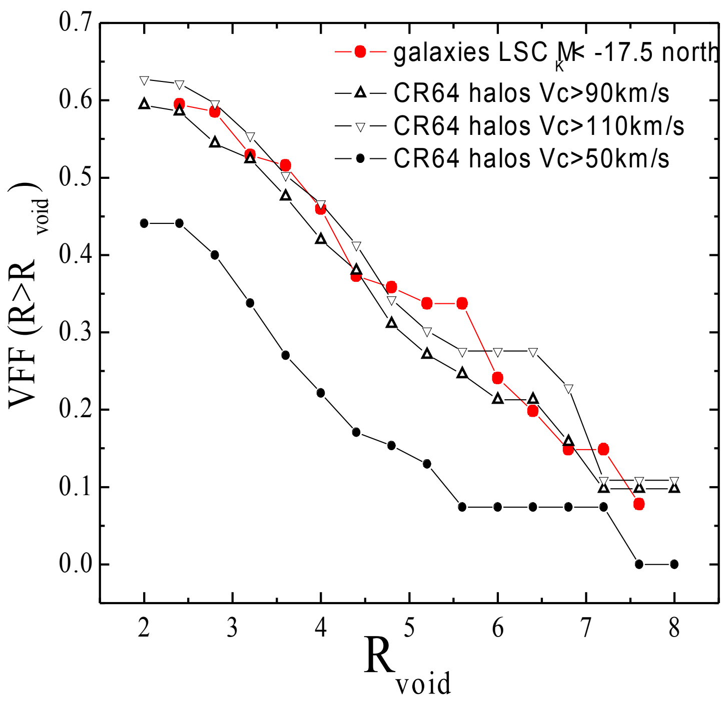
N of halos = 6104

N of galaxies = 2006

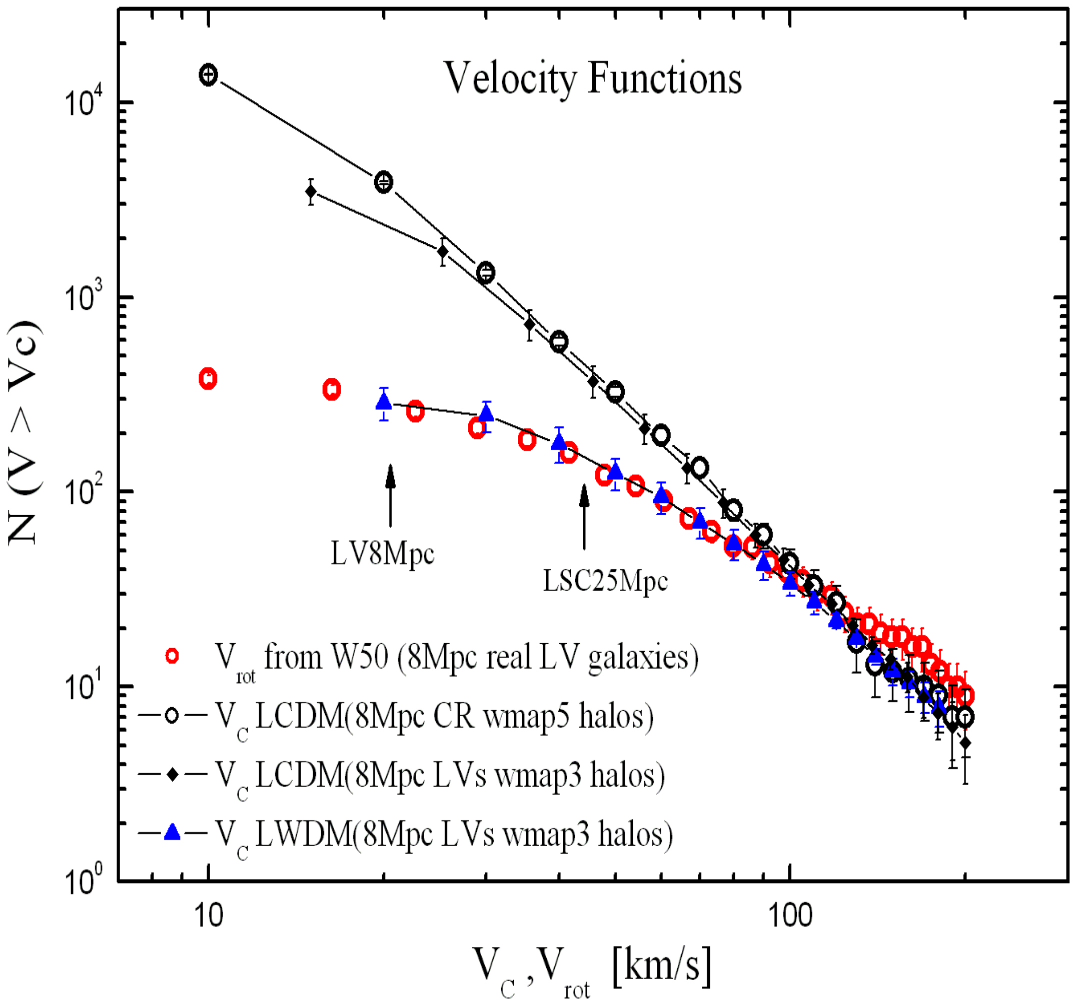
Factor of 3 LCDM excess

CLUES Box64/h

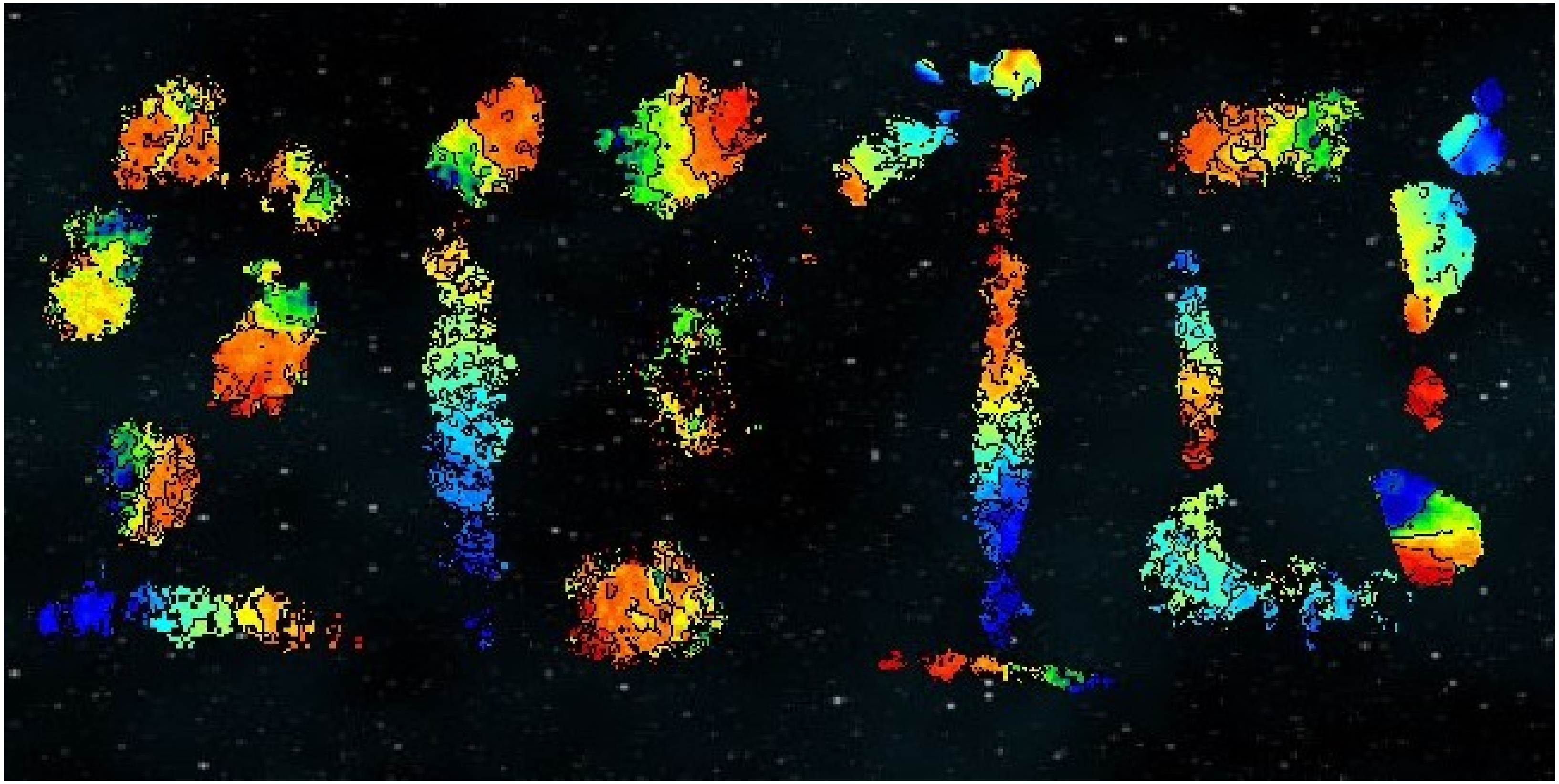




Galaxies in 8Mpc MB<-12 (vl-sample)
Halos in 8Mpc wmap5 and wmap3



Dwarf galaxies from the Zone of Overabundance
Halpha velocity fields PI: A.Klypin.



A.Moiseev

6 meter Russian telescope

Observations: Scanning Fabry-Perot interferometer

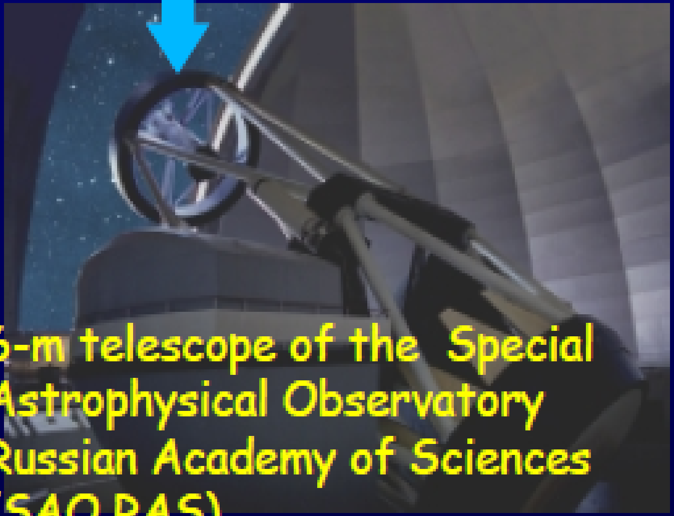
SCORPIO multi-mode focal reducer with scanning FPI (Afanasiev & Moiseev, 2005):

2D velocity fields of the ionized gas in the Hα emission line

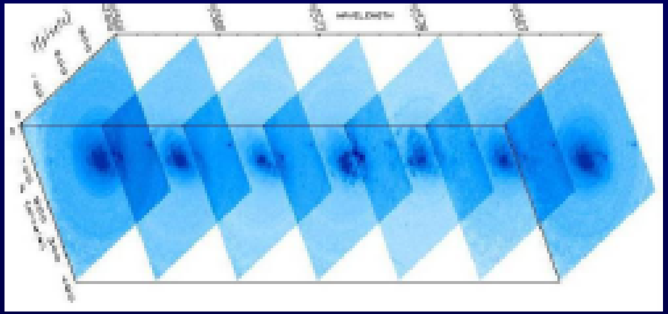
Field of view: 6 arcmin

Spatial sampling: 0.35-0.70 arcsec/px

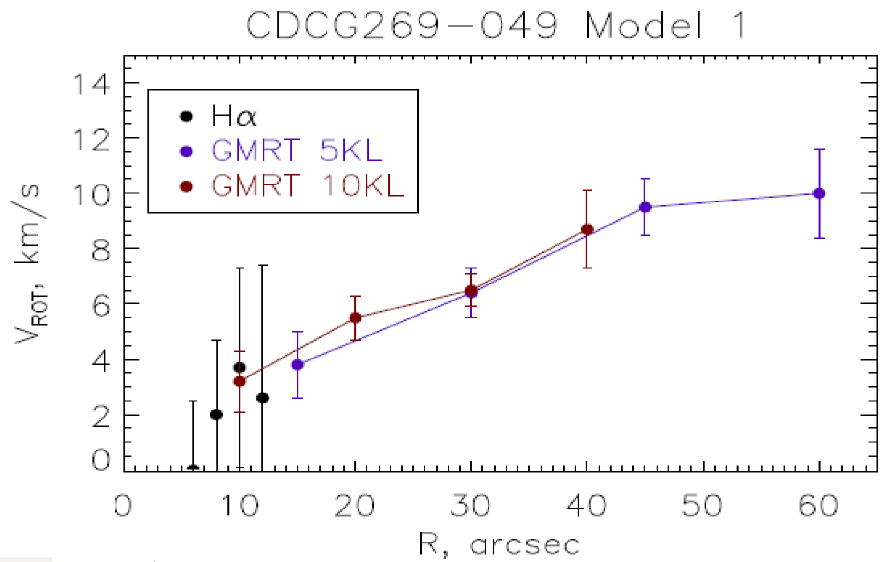
Spectral resolution: 0.5 and 0.8 Å (σ=9.5 and 14.5 km/s)



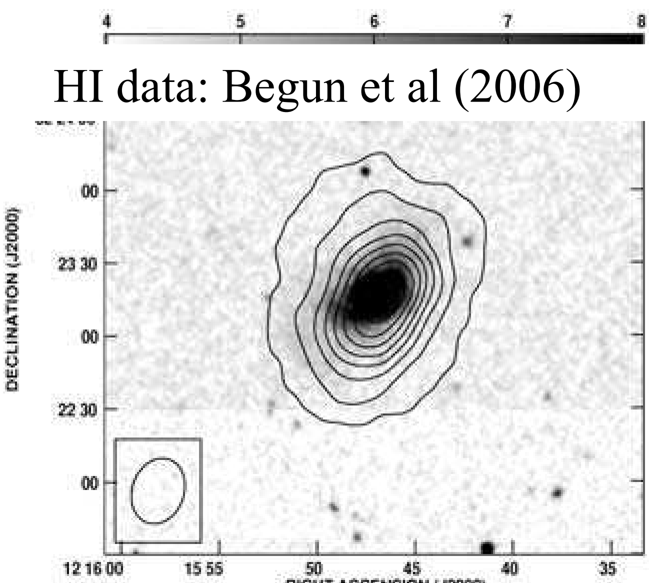
6-m telescope of the Special Astrophysical Observatory Russian Academy of Sciences (SAO RAS).

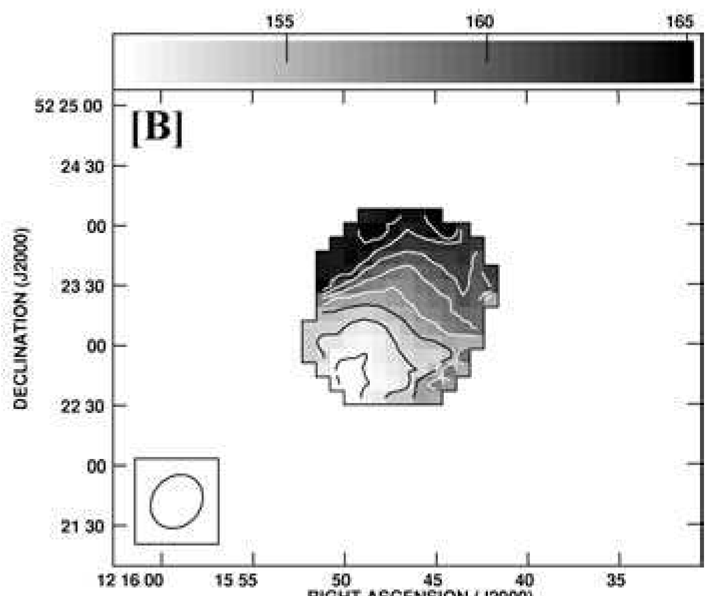


CGCG 269-049: an example of Vmax~10 km/s



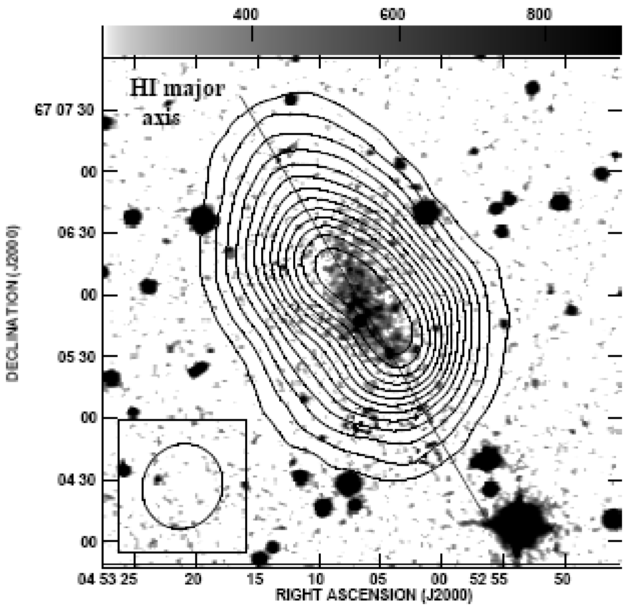
HI data: Begun et al (2006)

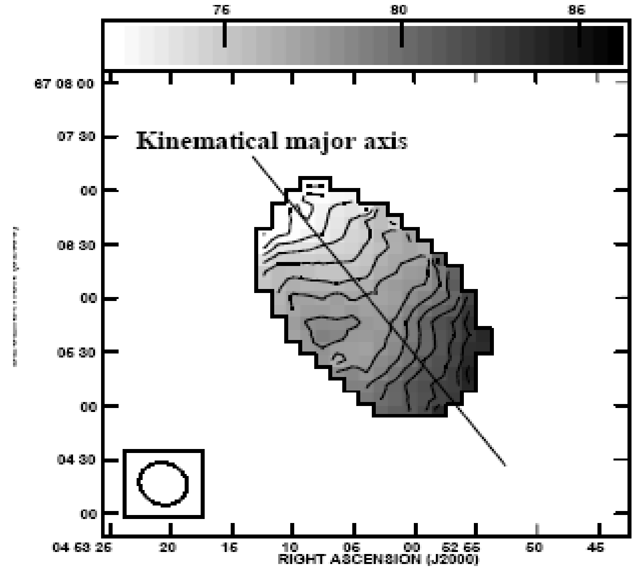




dIrr Camelopardalis B; D=2.2Mpc; $M_B = -10.9$

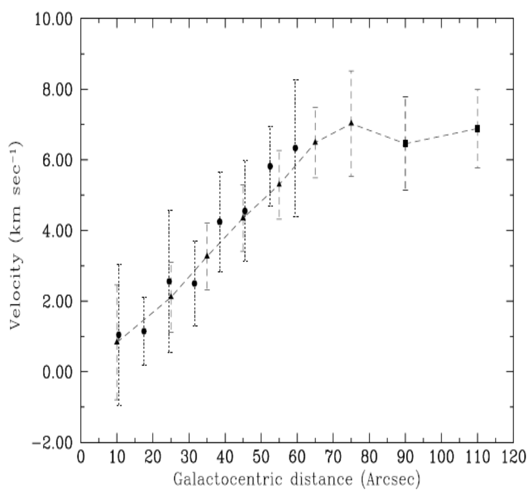
$V_{rot} \sim 10$ km s^{-1}



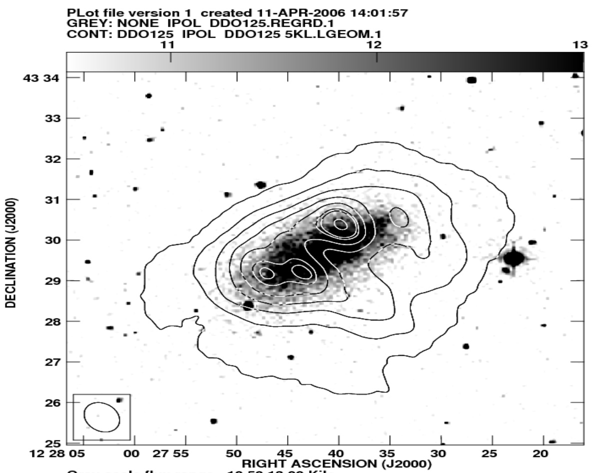


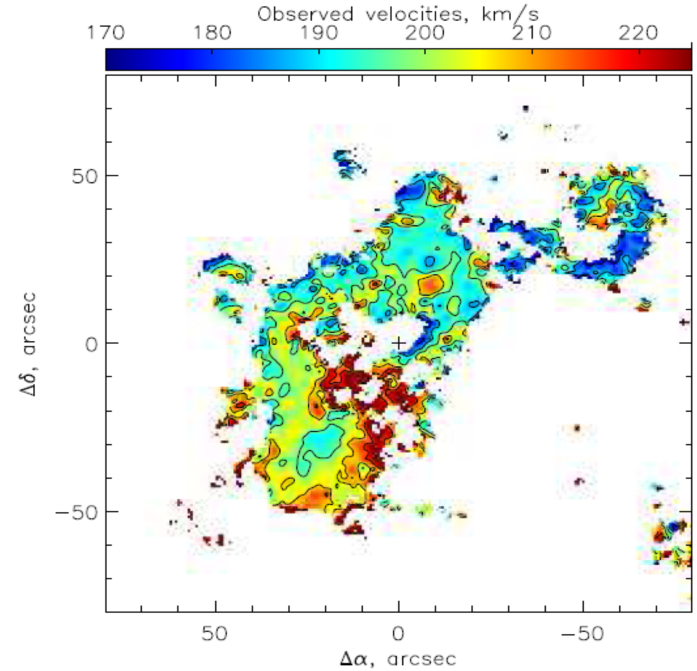
J.Chengalur and A.Begum

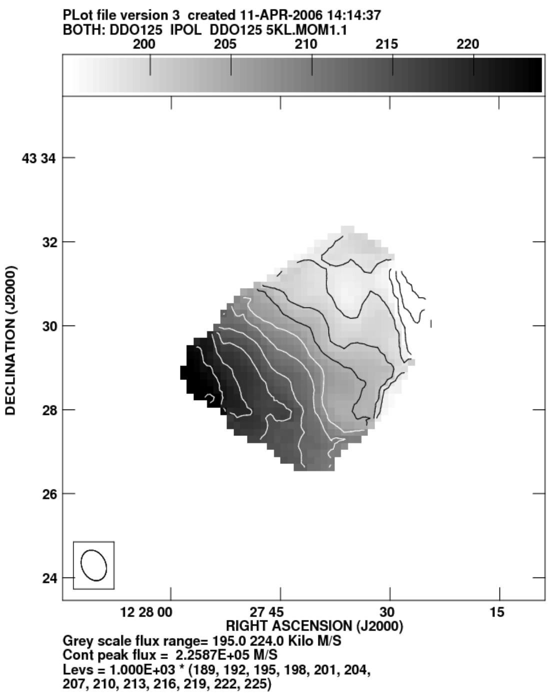
GMRT

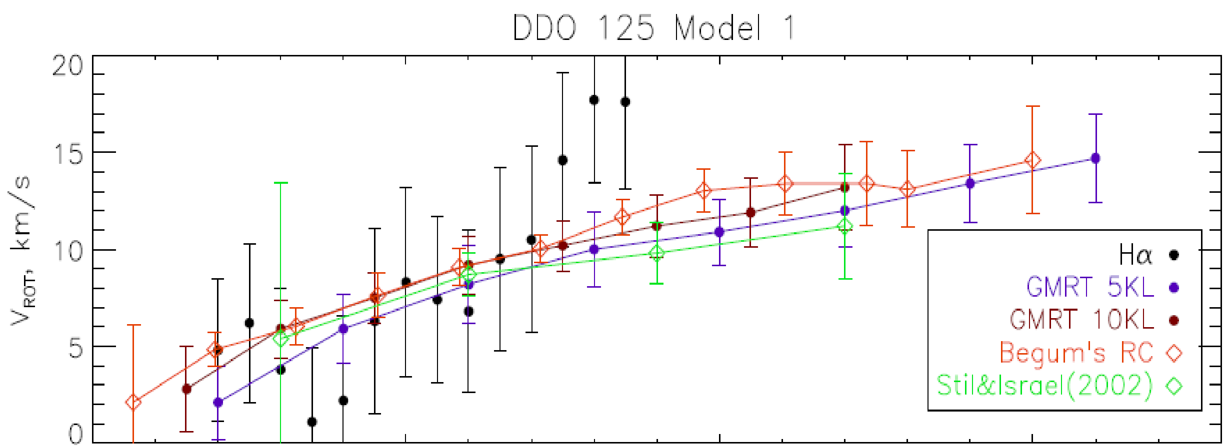


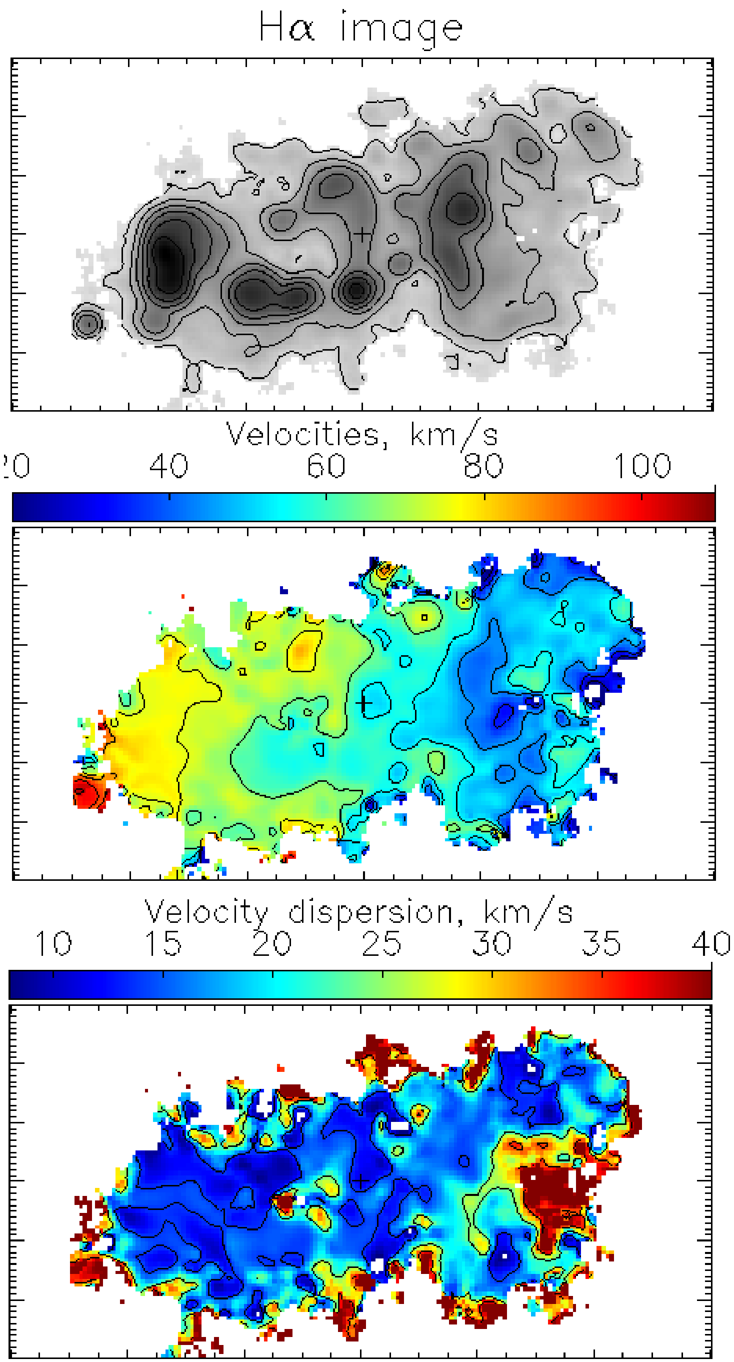
dIrr DDO125 D=2.54Mpc M_B=-14.16



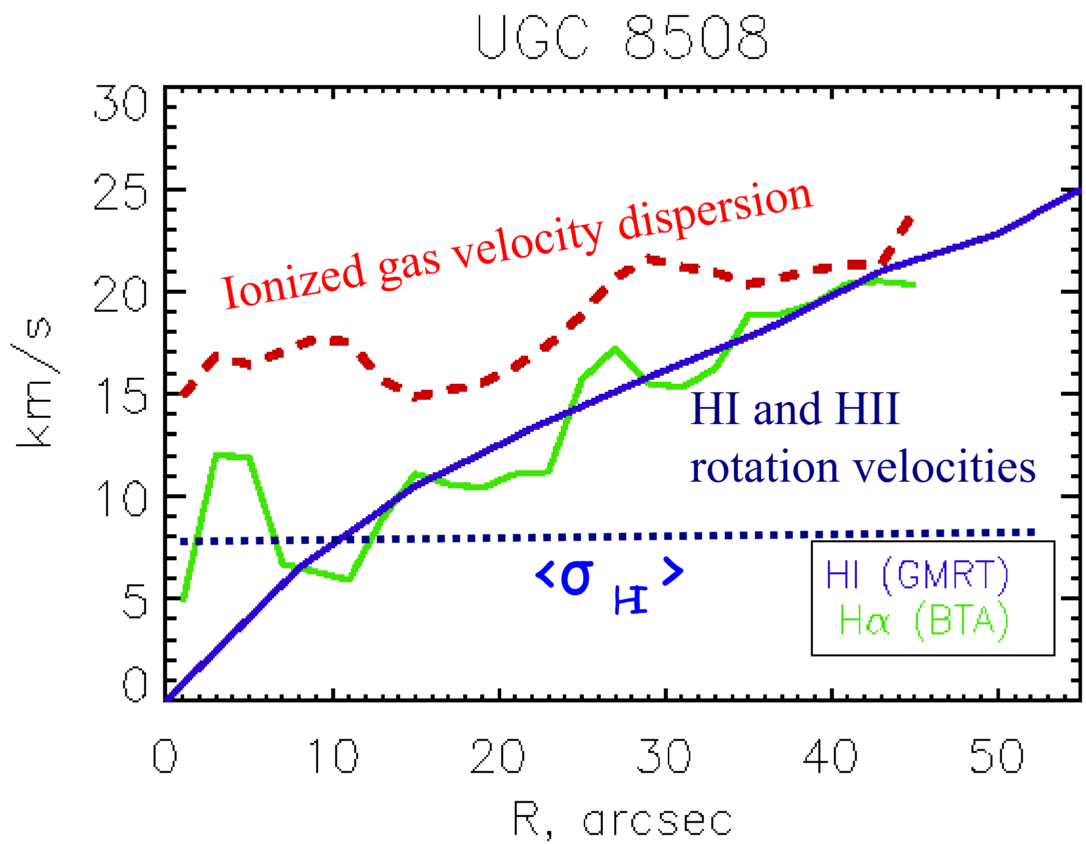




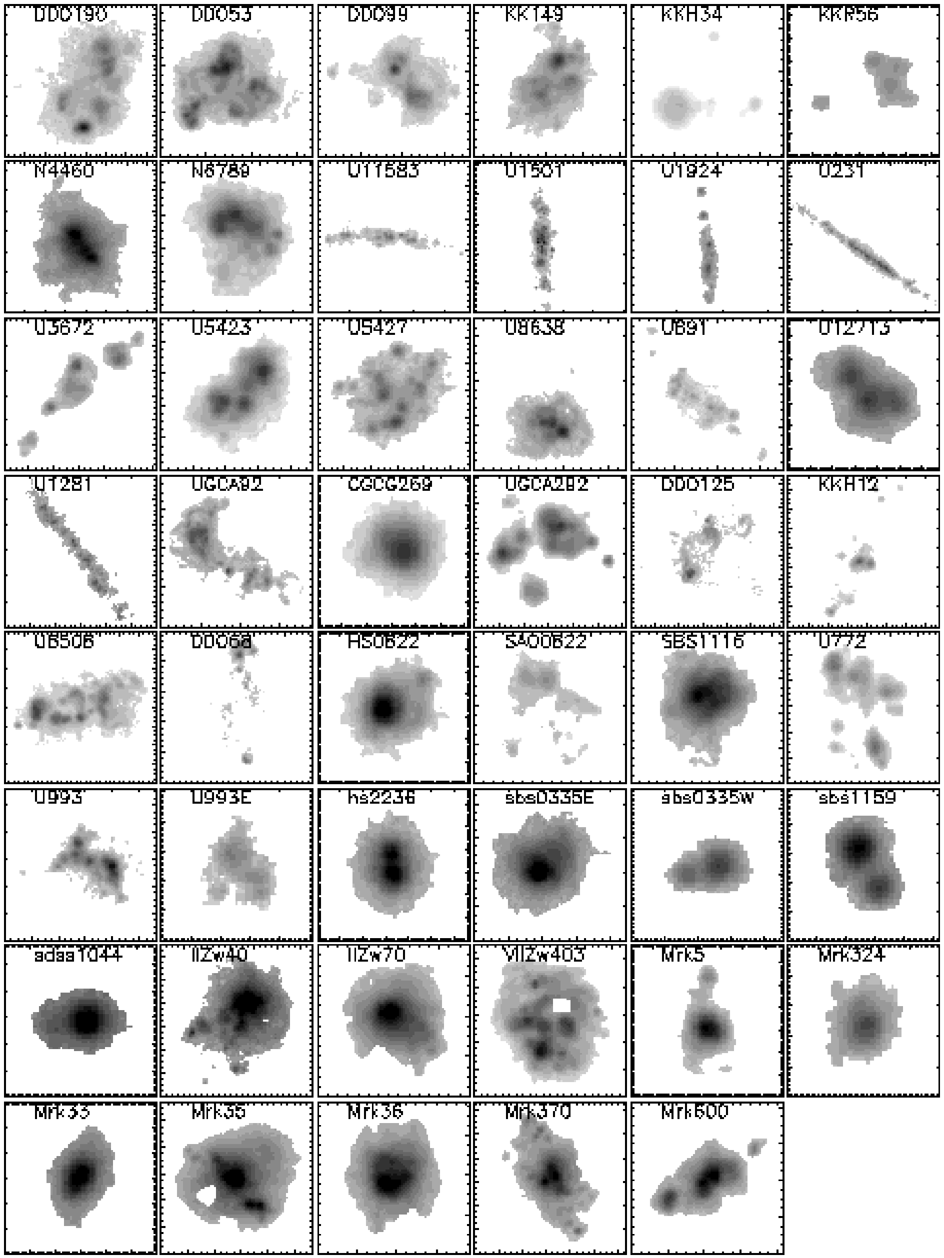



Hα image
Velocities, km/s
20 40 60 80 100
Velocity dispersion, km/s
10 15 20 25 30 35 40

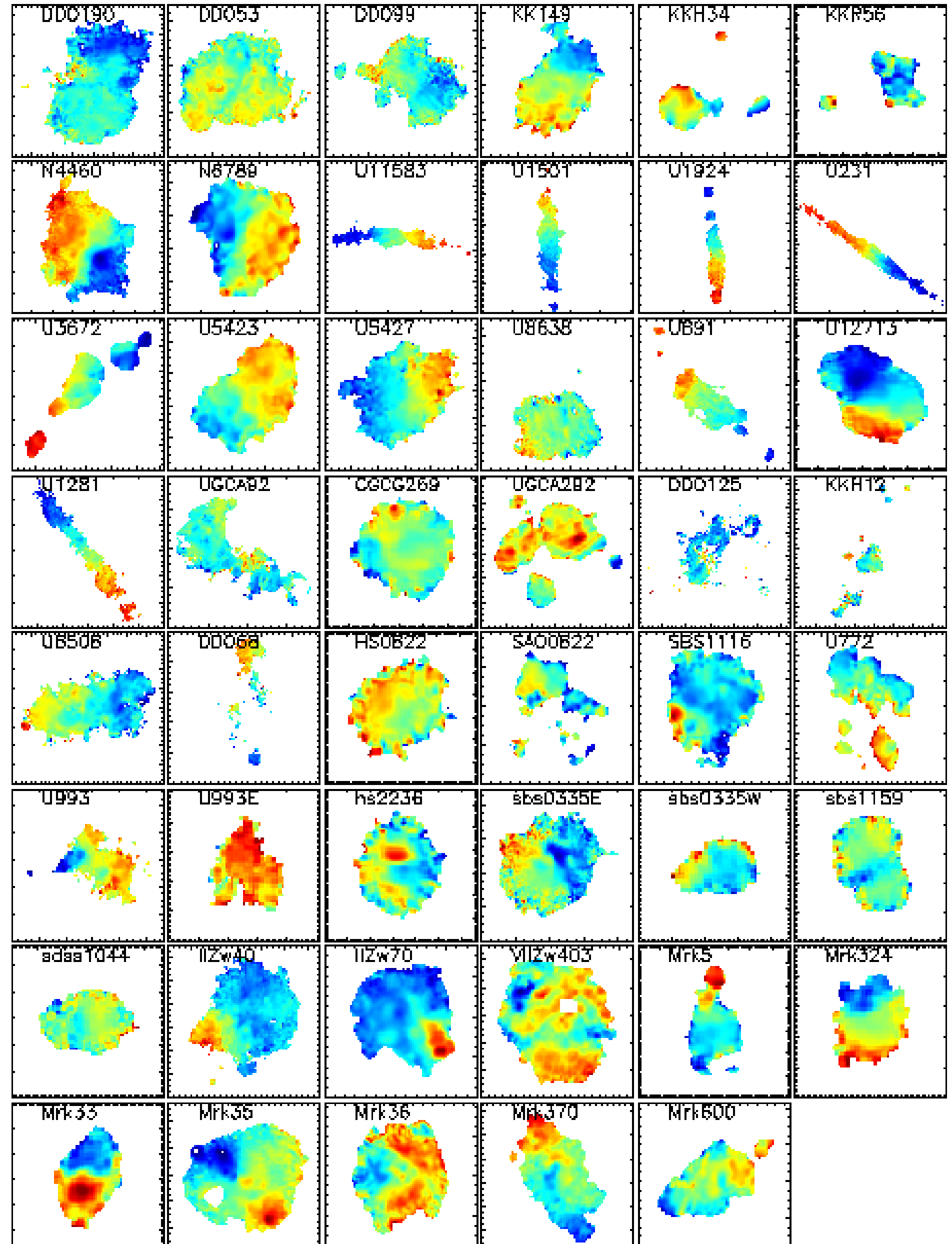

UGC 8508 (SDSS)


UGC 8508
Ionized gas velocity dispersion
HI and HII
rotation velocities
‹σ HI›
HI (GMRT)
Hα (BTA)
km/s
R, arcsec
0 5 10 15 20 25 30
0 10 20 30 40 50

Hα images

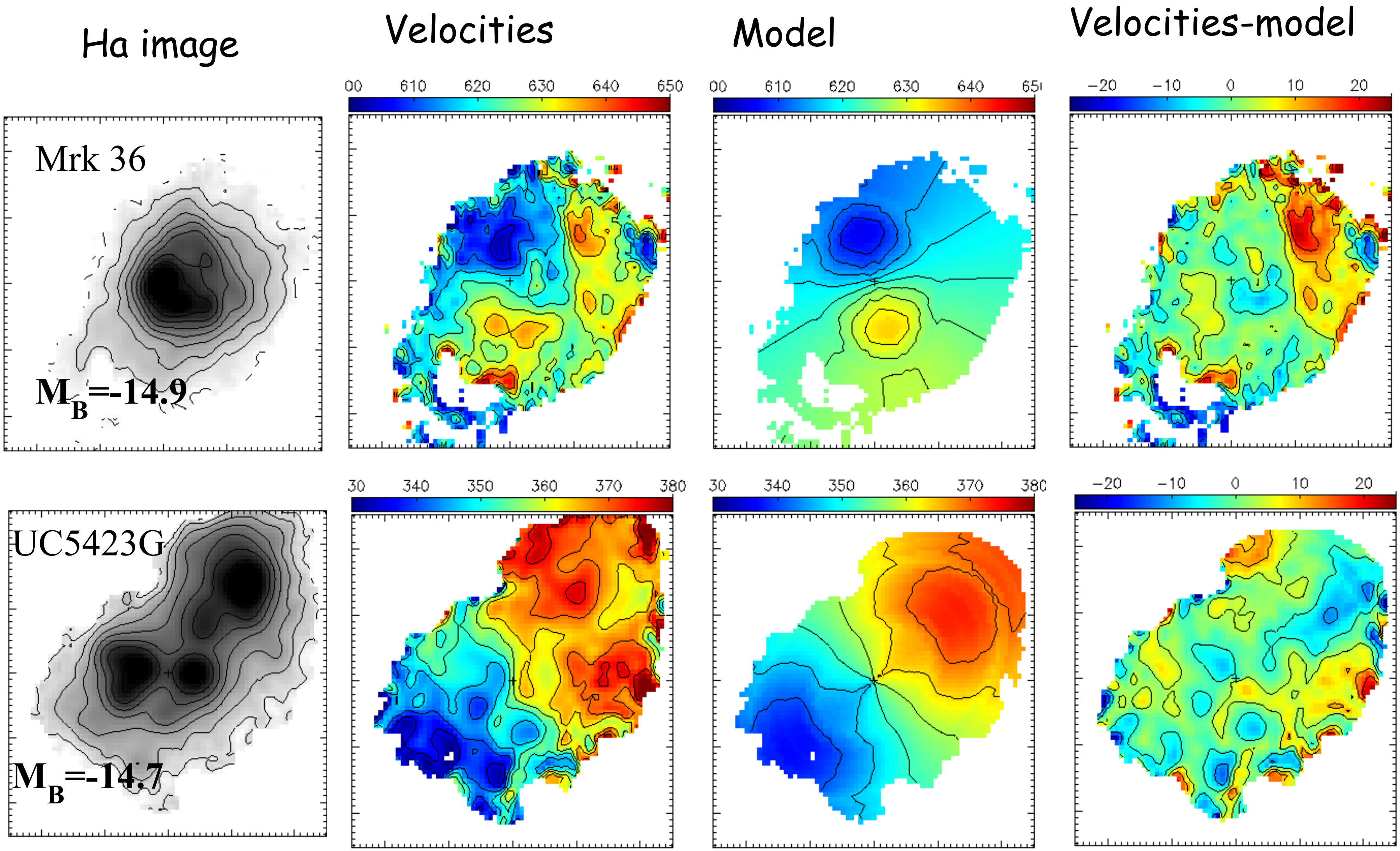


Velocity fields



Regular circular rotation

Major part of the sample (43/47=91%) has regular velocity pattern that is described by the model of circular rotation: Vmax>>Vres



Conclusions

The LCDM model faces the same overabundance problem, which it had with the number of satellites in the LG: the theory predicts a much more halos as compared with the observed number of dwarf galaxies.

Possible Solutions:

1. Hundreds of **dSph**s or another type of LSBs in the field to find out

2. Halo $\mathbf{V_c \sim 2V_{rot}}$:dwarf galaxies are hosted by significantly more massive halos.

3. Dwarfs formation was **suppressed** by e.g. UV- background after reionization

4. L**WD**M-models (P(k) - truncation) $m_X \sim 1$keV

And... others

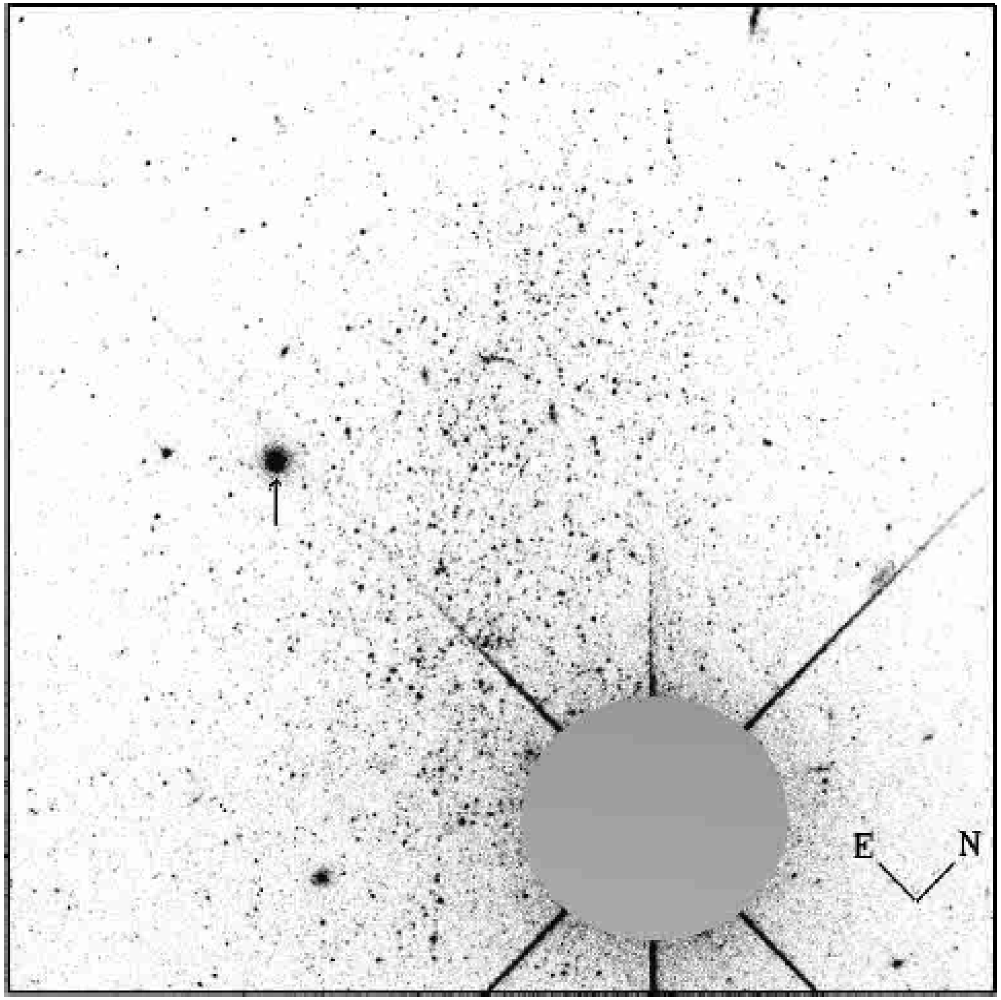
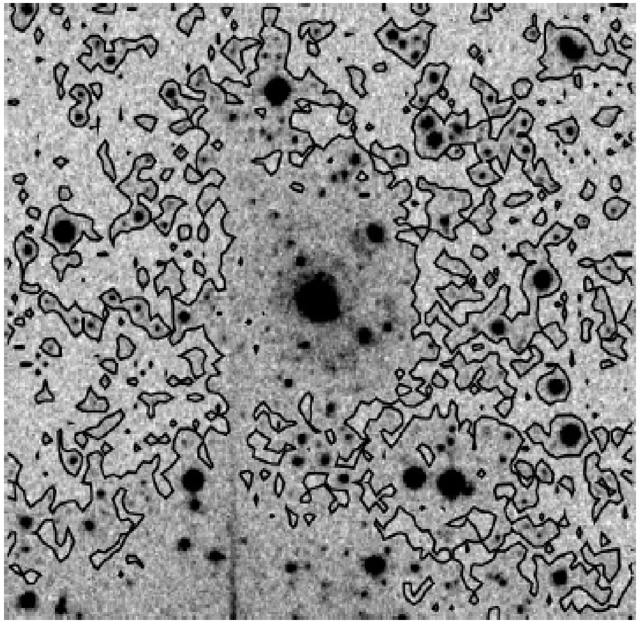


Fig. 2. WF3 image of KKR 25 produced by combining the two 600 s exposures taken through the F606W and F814W filters. A globular cluster candidate is indicated by the arrow.

KKR25
dSph in the field
blueshifted!!
M_B = -9.94
D = 1.86 Mpc (TRGB)
Central SB, Σ_V =24^m/□"

Karachentsev et al.
2001 A&A, 379, 407



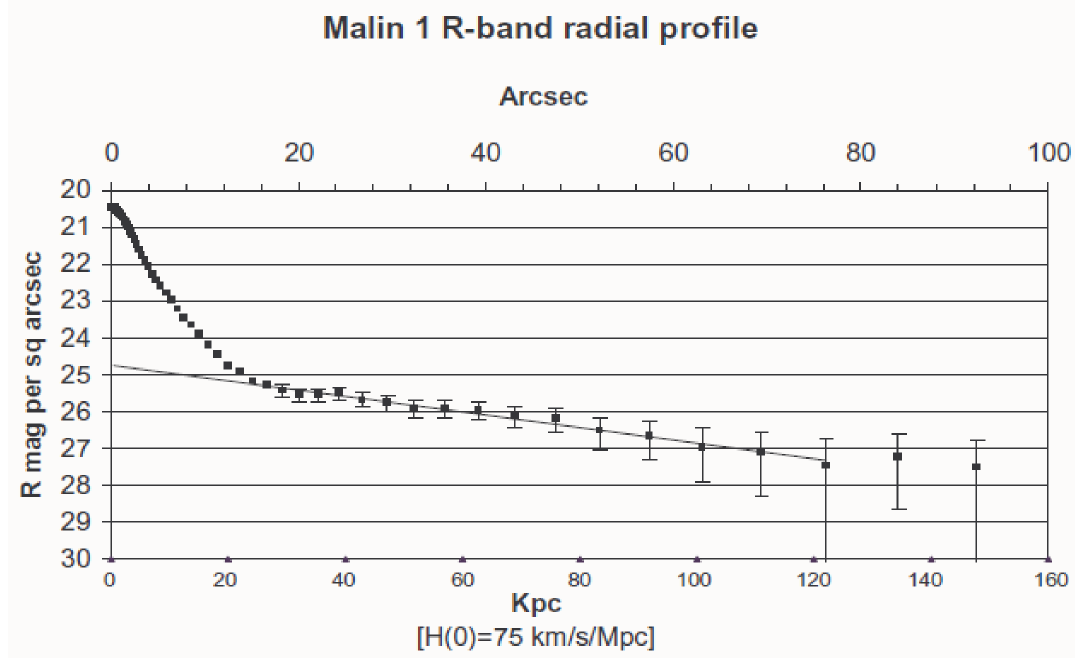
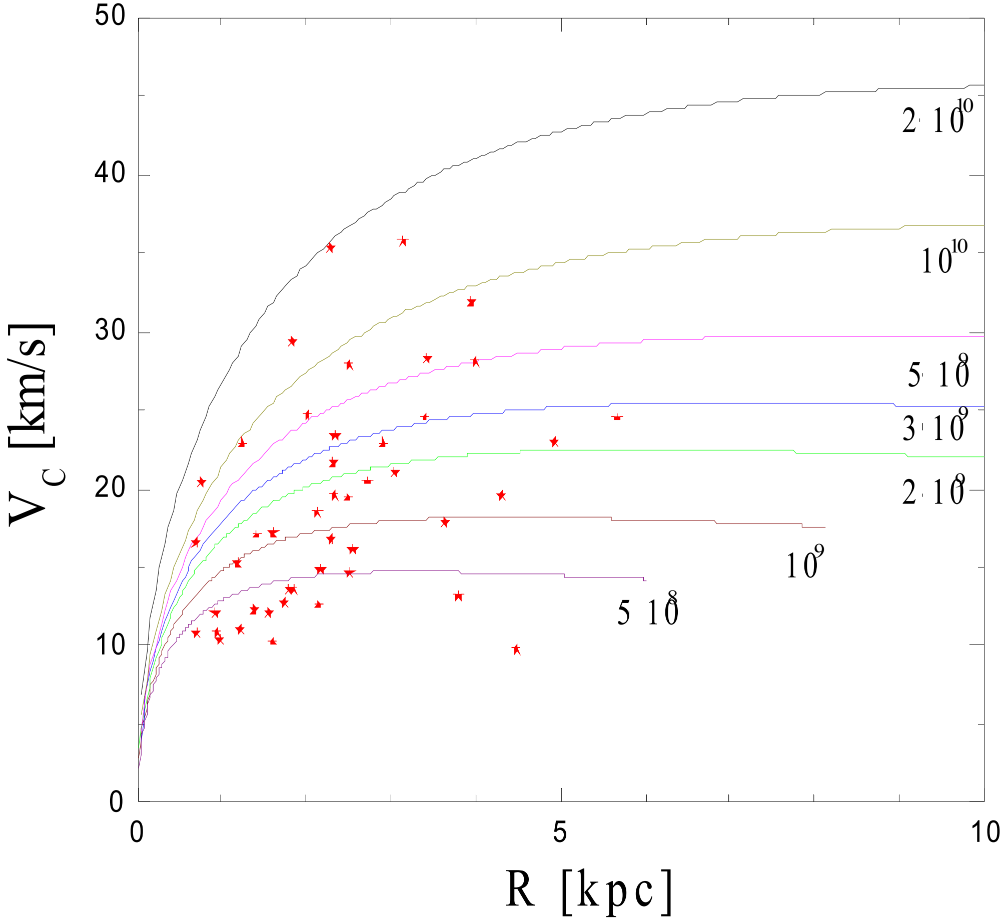


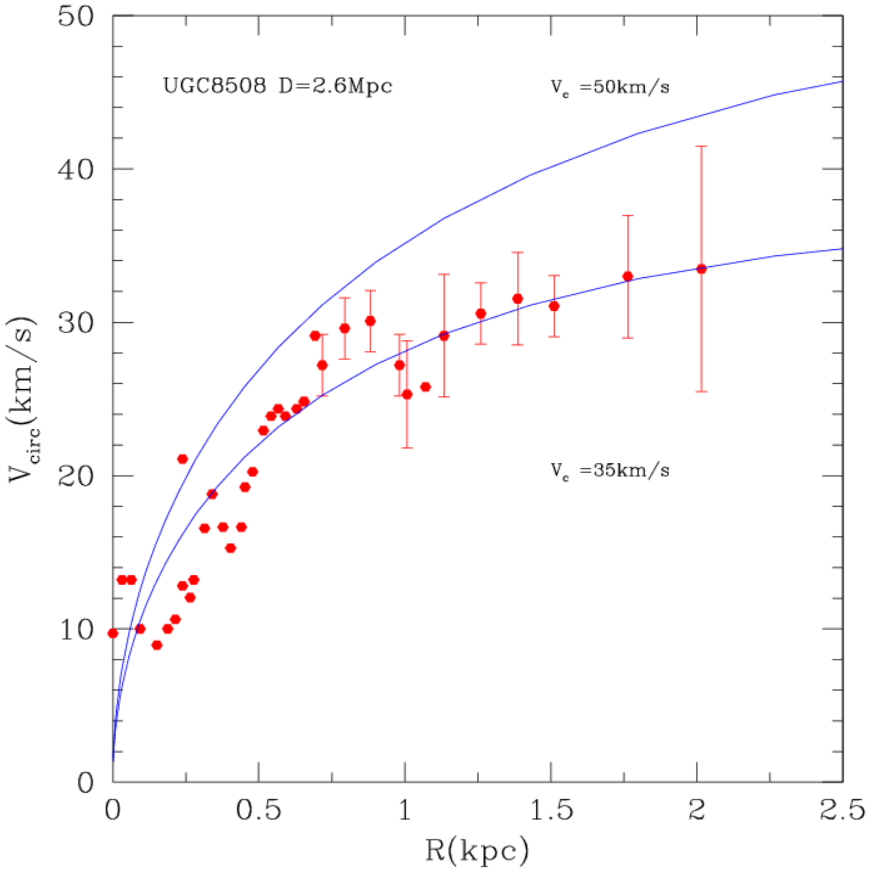
Figure 1: Malin 1 with contours at 6380 data counts to delineate the extent of the optical disk.

Optical radius	65 arcsec [b]
Inclination	45 ± 15^{o}
HI diameter	up to 3.3 arcmin

Figure 2: *Top*: The *R*-band radial profile shows that the optical disk (solid squares) is visible to a semi-major axis of ∼ 80 arcsec before reaching the background level. The upper scale shows arcsec. The lower scale shows kpc based on the redshift give in Table 1 and assuming $H_0 = 75$ km s^{-1} Mpc^{-1}. A fit to the exponential part of the profile is shown as a solid line. The last two data points on the right are not included in the fit as these are clearly beyond the point where the galaxy light can be distinguished from sky and adjacent objects. The fit is extrapolated to the left to show central surface brightness of 24.74 *R* mag arcsec^{-2}. See text for explanation of the calculation of the error bars on the exponential part of the

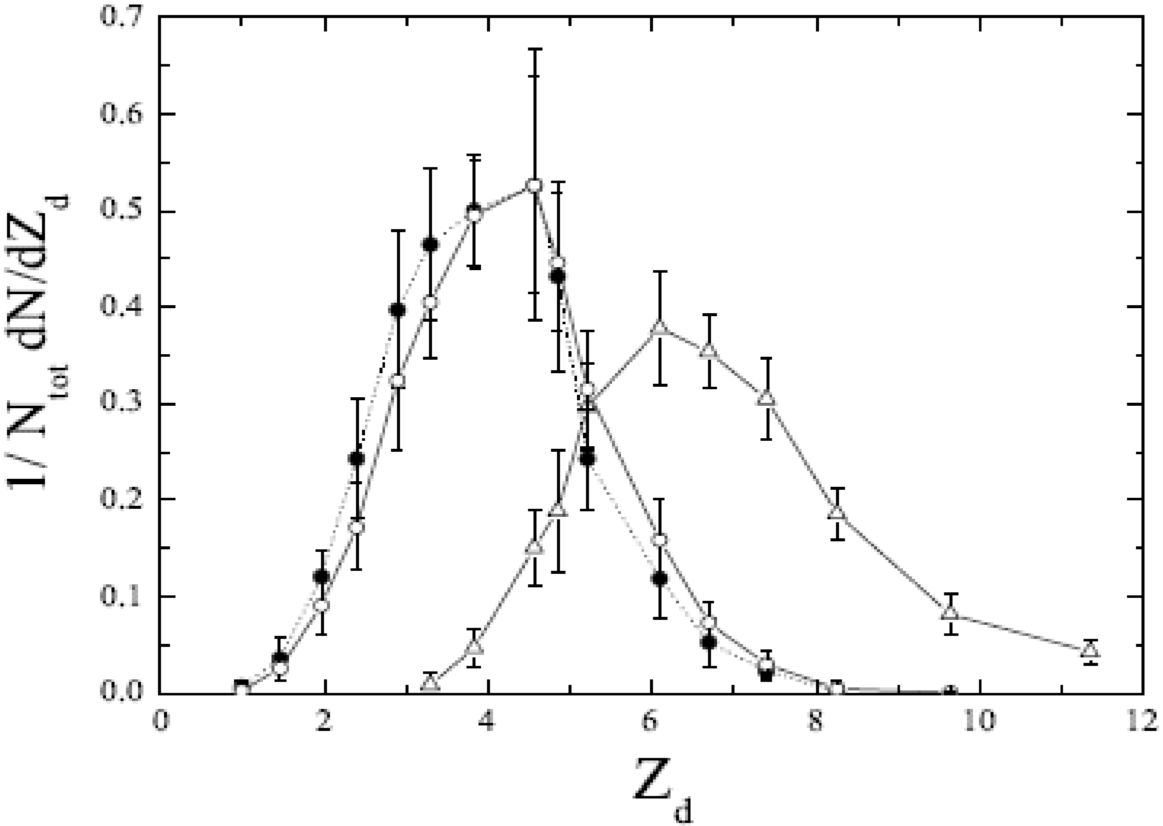


NFW circular velocity profiles for DM halos with masses between 5e8/h and 2e10/h Msun. Red stars: observed *V*rot versus HI radii taken from the **FIGGS** LV galaxy sample (Chengalur et al.)



It is clear that the more massive halo
can not fit the data.

We cannot place the galaxy
into a large halo



The differential number fraction of progenitors of haloes which became more massive than 3e8/h at redshift **Z**d.

Filled diamonds: haloes with **Vc** < 35 km/s at $z = 0$ inside minivoids;

Open diamonds: haloes with **Vc** < 35 km/s outside minivoids;

Triangles: halos with **Vc**> 35 km/ s.

Error bars are 1σ deviations

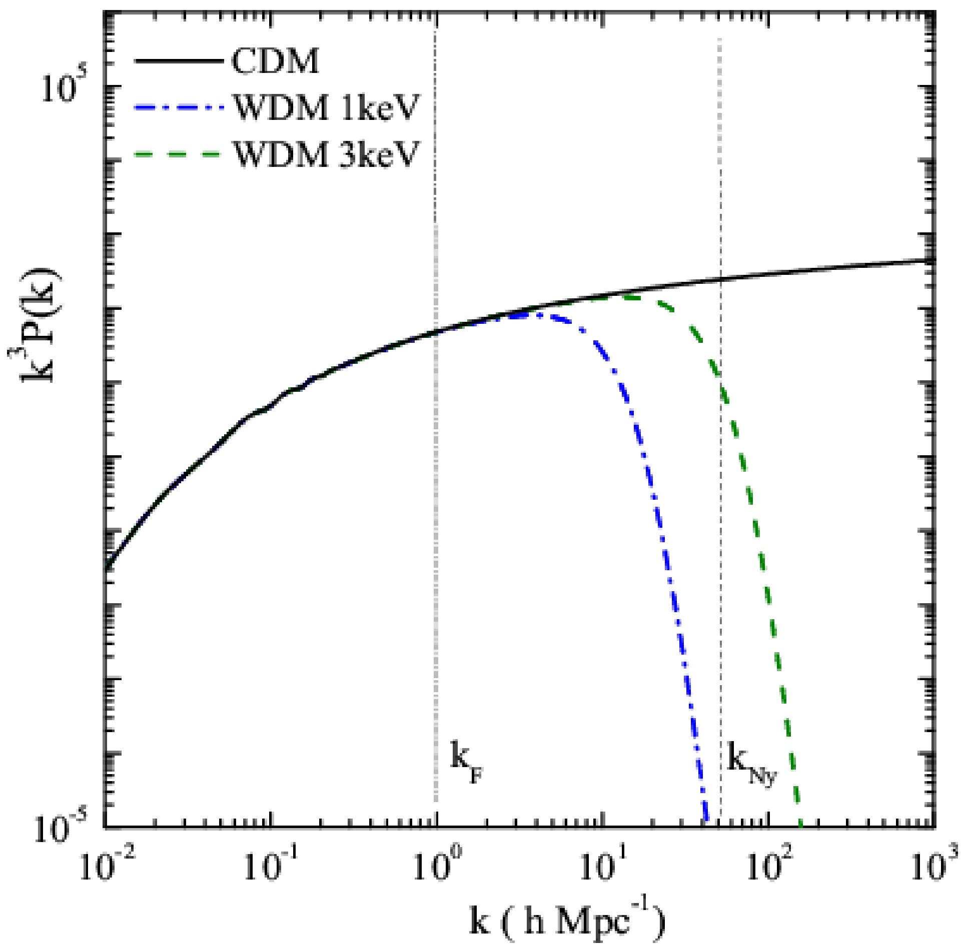
The sizes of minivoids in the local Universe: an argument in favour of a warm dark matter model?

A. V. Tikhonov, S. Gottloeber, G. Yepes, Y. Hoffman

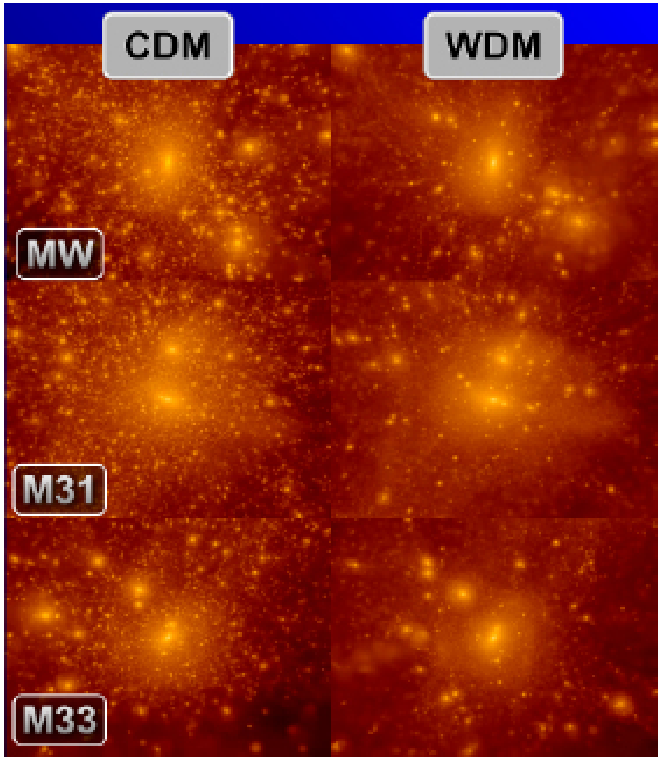
WDM-paradigm with m_X=1keV

Box 64h^{-1} Mpc, h=0.72 WDM and CDM WMAP3

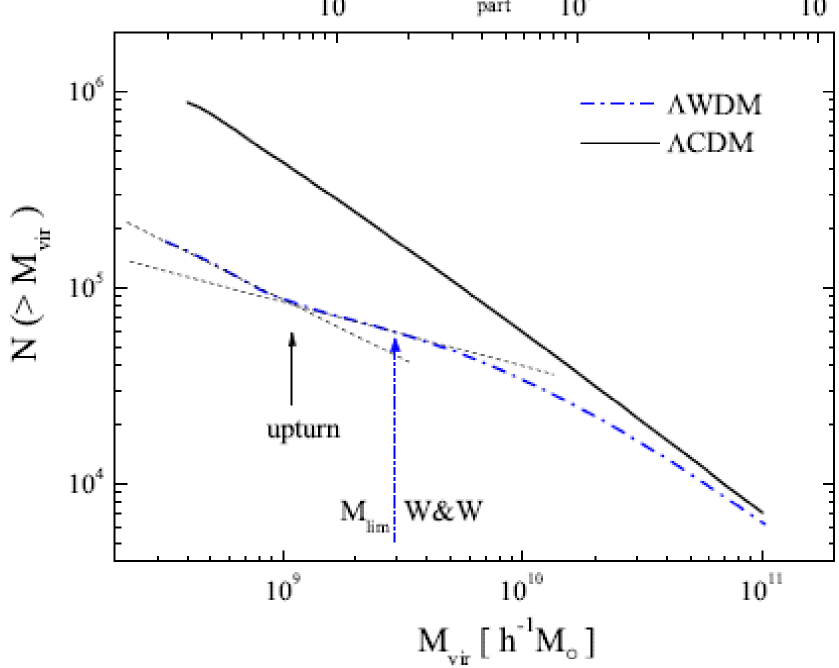
Initial conditions

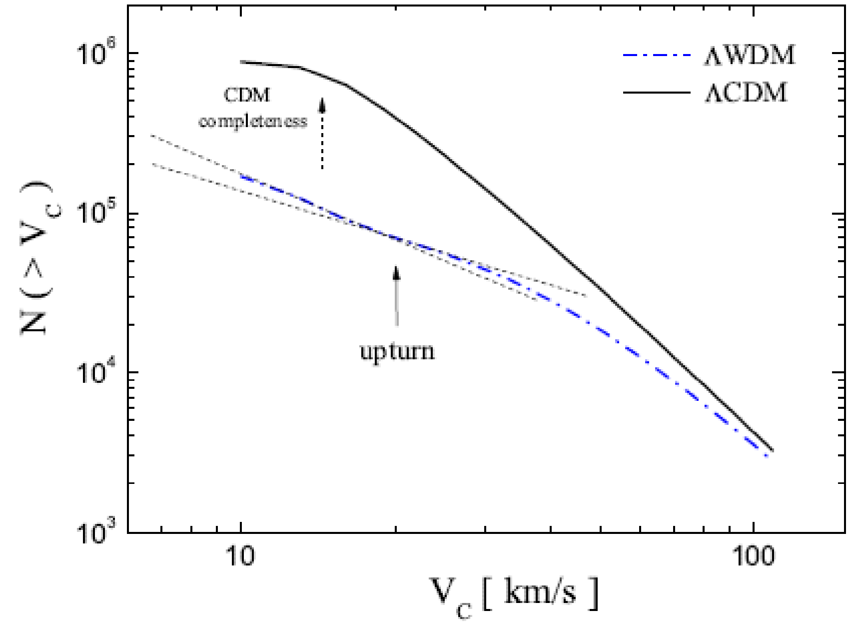


Resulting haloes



Arman Khalatyan





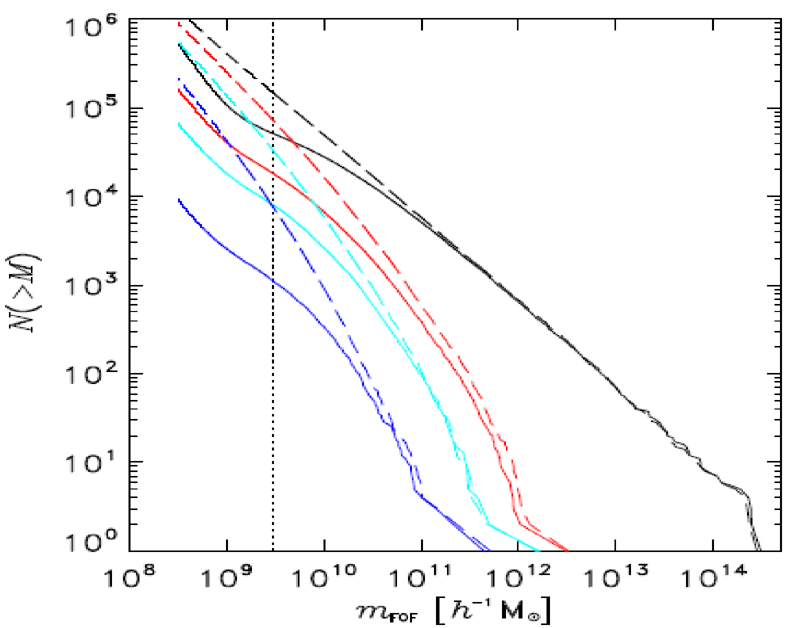
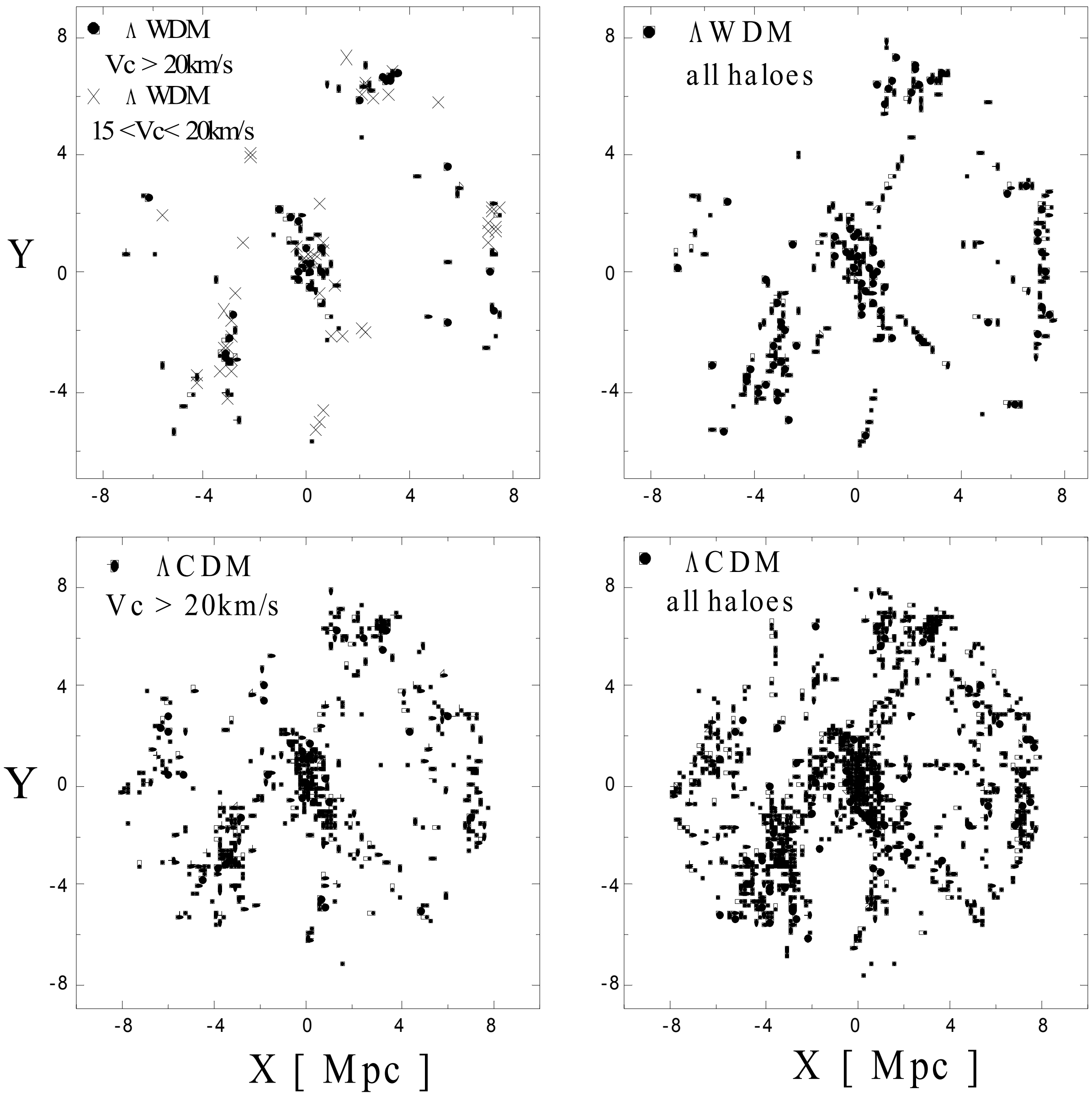


Figure 2. Cumulative FOF halo mass functions with more than 20 particles for the ΛCDM (dashed line) and ΛWDM (solid line) models. From left to right the mass functions are shown at redshifts z = 8, 6, 5, and 0. The dotted line marks $M_{\rm lim} = 3 \times 10^9 h^{-1} {\rm M}_\odot$.

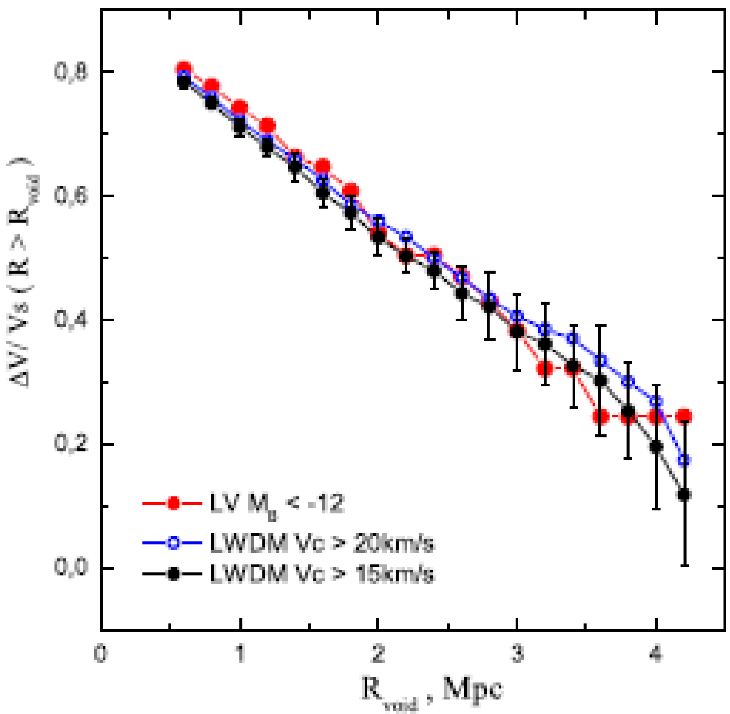


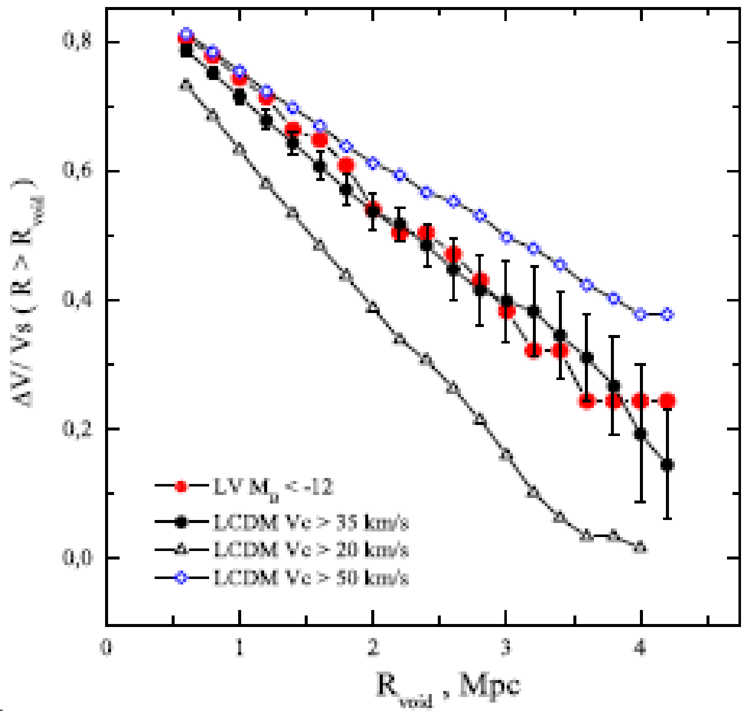
Λ WDM
Vc > 20km/s
Λ WDM
15 <Vc< 20km/s
Λ WDM
all haloes
Λ CDM
Vc > 20km/s
Λ CDM
all haloes
Y
Y
X [Mpc]
X [Mpc]

Void-functions

WDM

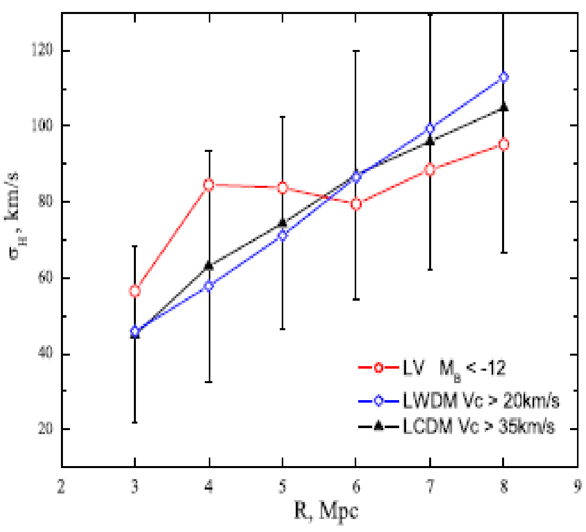
CDM





V^{lim} = 15-20 km/s

σ_H



V^{lim} = 35 km/s