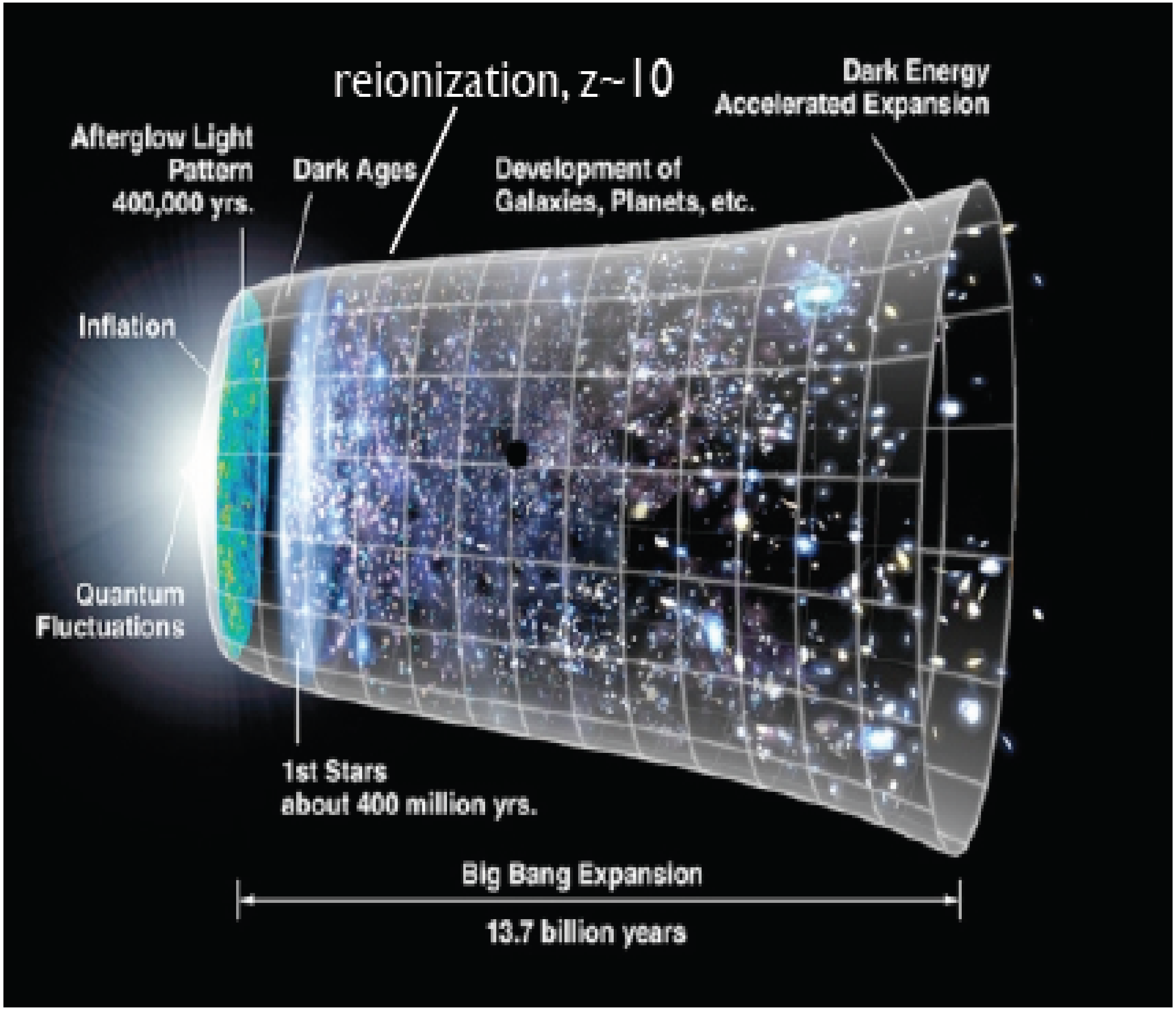
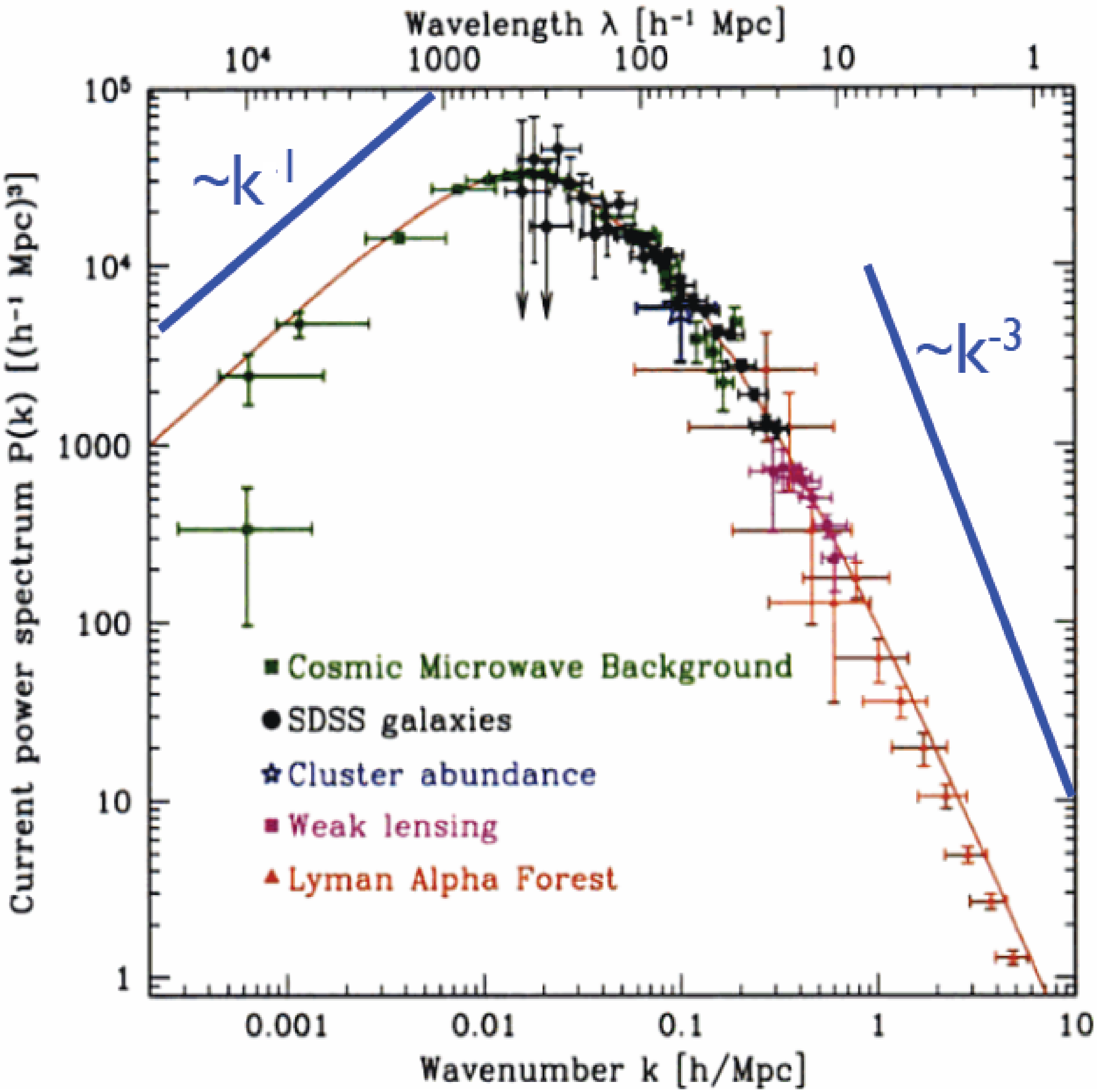
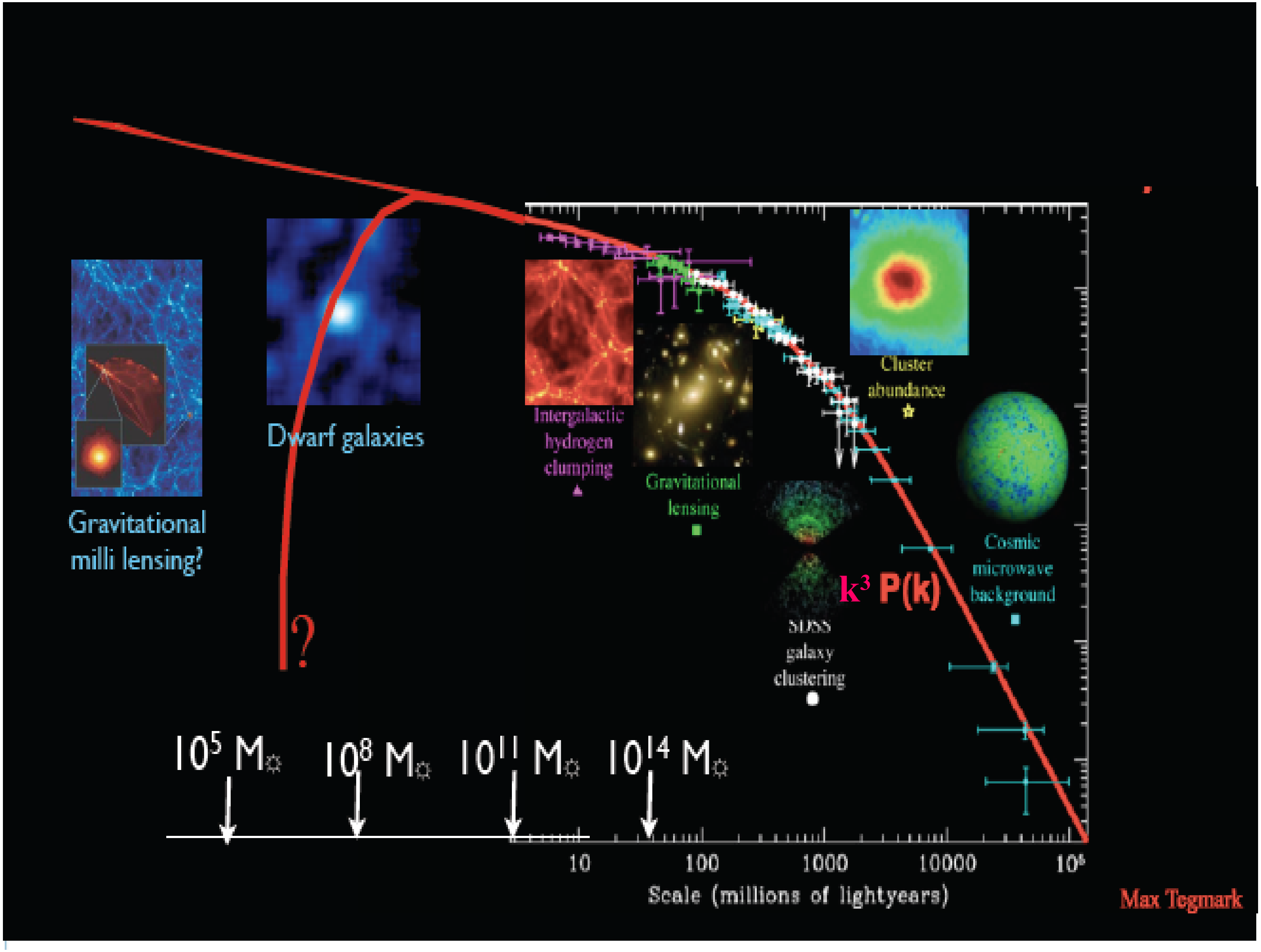
Timeline of the Universe





Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
10⁵
10⁴
1000
100
10
1
Current power spectrum P(k) [(h⁻¹ Mpc)³]
~k⁻¹
~k⁻³
Cosmic Microwave Background
SDSS galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest
0.001
0.01
0.1
1
10
Wavenumber k [h/Mpc]


Gravitational
milli lensing?
Dwarf galaxies
Intergalactic
hydrogen
clumping
Gravitational
lensing
Cluster
abundance
Cosmic
microwave
background
SDSS
galaxy
clustering
k³ P(k)
?
10⁵ M☼
10⁸ M☼
10¹¹ M☼
10¹⁴ M☼
10
100
1000
10000
10⁶
Scale (millions of lightyears)
Max Tegmark

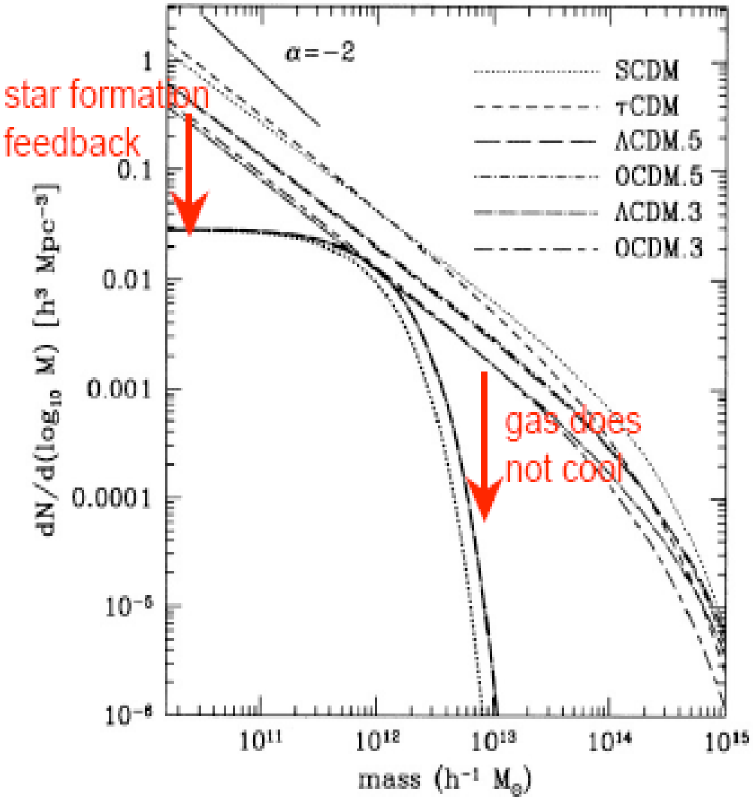


Figure 9. The mass function of dark matter haloes predicted by the standard Press–Schechter model for various CDM cosmologies (light broken lines). The bold lines show the mass function of galactic haloes, estimated from the observed APM luminosity function as described in the text, for an SCDM or τCDM cosmology (dotted), and for the ΛCDM.3 cosmology (long dashed-dotted line); other cosmologies lie between these two cases. The short solid line shows a power law with slope $\alpha = -2$.

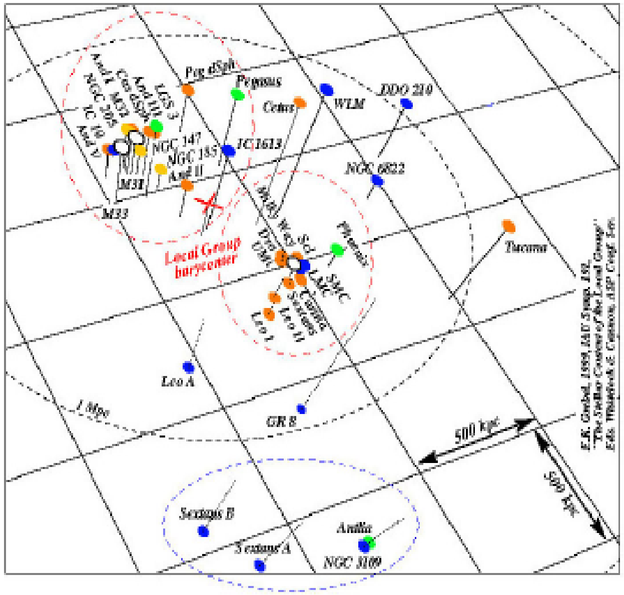
Dark halo mass function versus visible galaxy halo mass function at z=0:

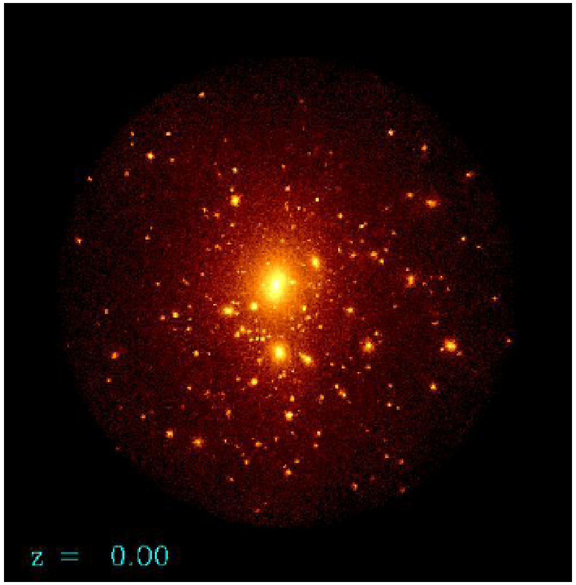
The challenge for galaxy formation models is to explain why only around

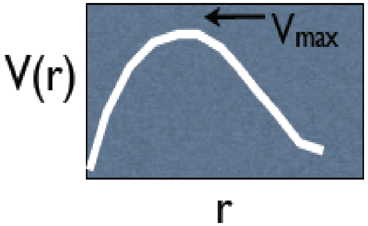
10^{12} M_{sun} the number of galaxies is consistent with the number of halos expected at this mass. At higher and at lower masses we find less galaxies than expected in a hierarchical CDM universe. Possible explanations are indicated.

Somerville & Primack 1999, MNRAS 310, 1087

WHERE ARE THE MISSING GALACTIC SATELLITES?

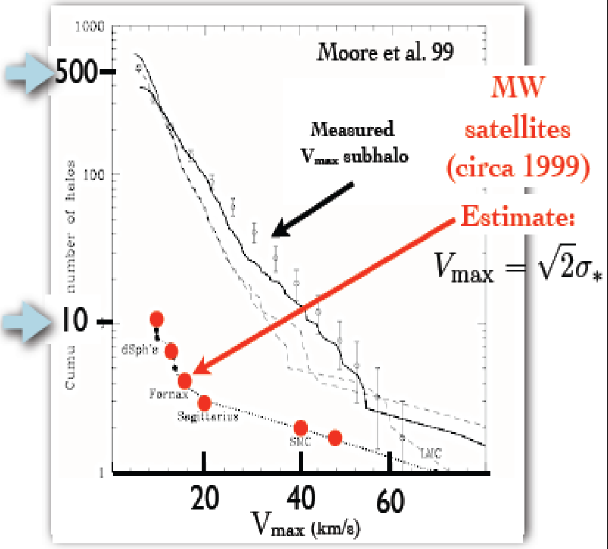






$V(r) = (GM(r)/r)^{1/2}$

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

2001

THE VOID PHENOMENON

astro-ph/0101127

P. J. E. PEEBLES

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.

2008

THE VOID PHENOMENON EXPLAINED

astro-ph/0804.2475

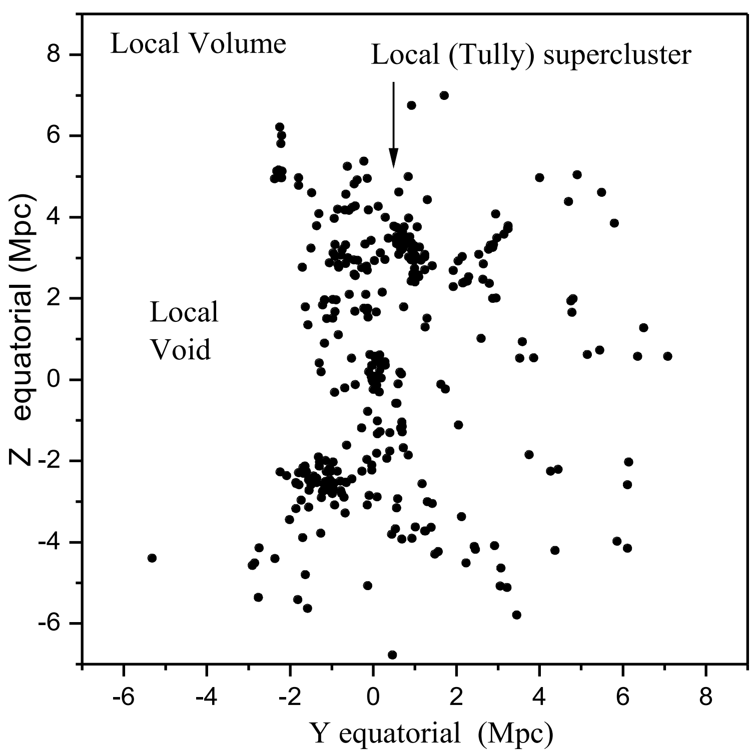
JEREMY L. TINKER[1] & CHARLIE CONROY[2]

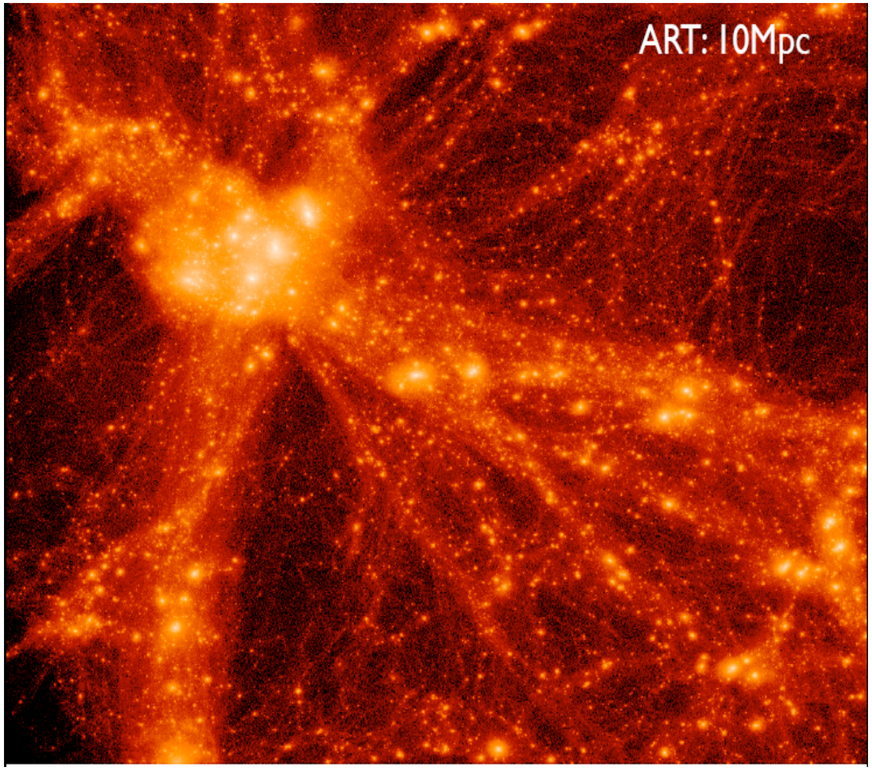
The void phenomenon consists of two observational facts: that voids contain few, if any, low-luminosity galaxies, and that the few void objects tend to have similar properties to the overall galaxy population. The controversial aspect is whether these facts are at odds with the current cosmology. Although 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.

Anton Tikhonov / Saint Petersburg State University
Anatoly Klypin / New Mexico State University

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

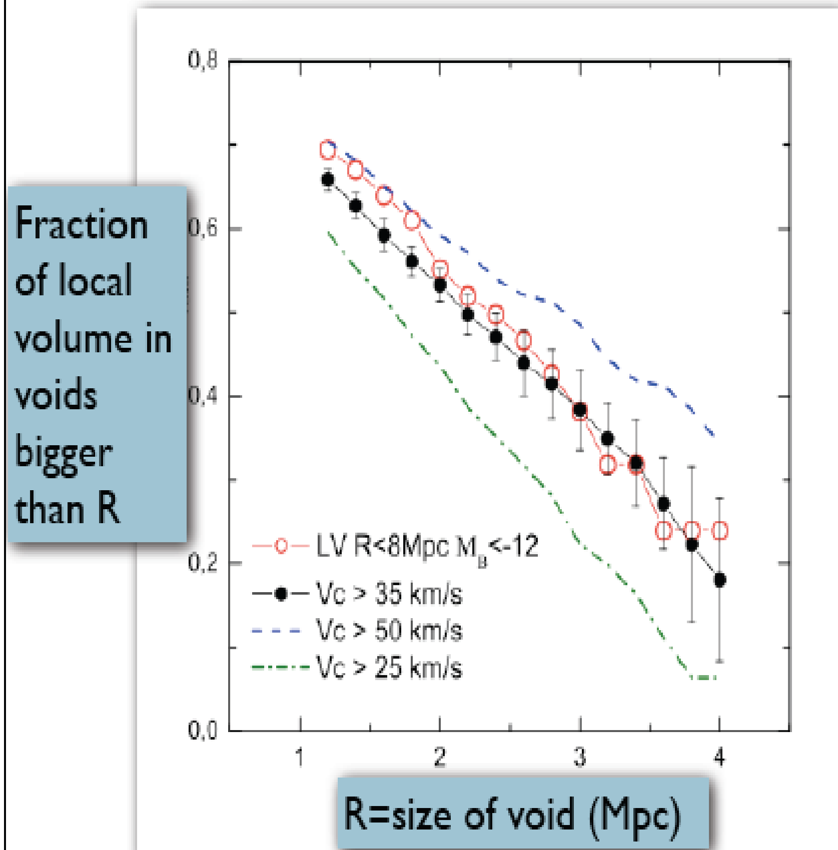
LCDM-model faces the same overabundance problem, which it had with the number of satellites in the LG: the theory predicts a factor of 10 more halos as compared with the observed number of dwarf galaxies.





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

Anton V. Tikhonov[1]* and Anatoly Klypin[2]†
[1] Universitetsky prospect, 28, Department of Mathematics and Mechanics, St.Petersburg State University, Saint-Petersburg, 198504, Russian Federation
[2] Department of Astronomy, New Mexico State University, Las Cruces, New Mexico 88003-8001, USA



~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

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**.

$$V(r) = (GM(r)/r)^{1/2}$$
$$V_c = 20 km/s \ – \ M_{vir} \sim 10^9 M_o$$
$$V_c = 50 km/s \ – \ M_{vir} \sim 10^{10} M_o$$

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 galaxy sample

The first compilation of a Local volume (LV) sample of galaxies within 10Mpc - Kraan-Korteweg & Tammann (1979) - the 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) of the Local Void which looks practically free from galaxies.

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 NIR surveys of the zone of avoidance, ‘‘blind’’ sky surveys in the 21 sm line, HIPASS and HIJASS.

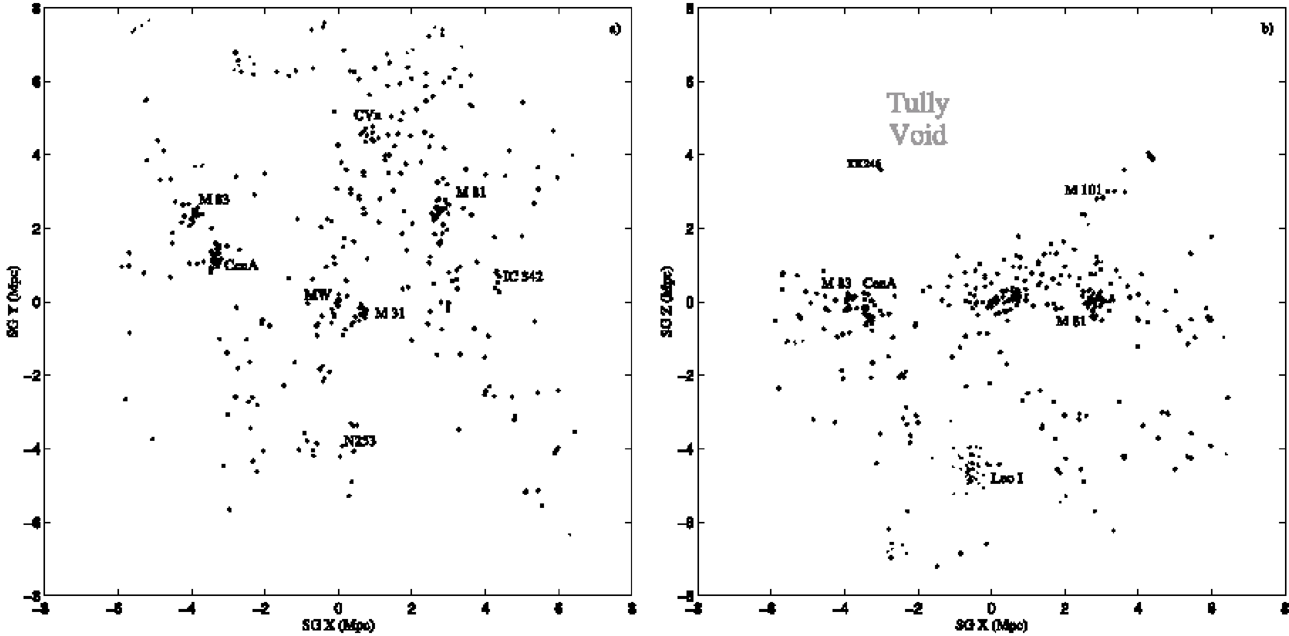
At the present time, the sample of galaxies with distances less than 10 Mpc numbers about 550 galaxies. For half of them the distances have been measured to an accuracy as high as 8-10% (**Karachentsev et al., 2004=Catalog of Neighboring Galaxies**). Over the last 5 years, snapshot surveys with Hubble Space Telescope (HST) have provided us with the TRGB distances for many nearby galaxies.

(**!!**) The distances are not measured using the redshifts – instead we have “real” 3D galaxy distribution with peculiar velocity field in the Local Volume .

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

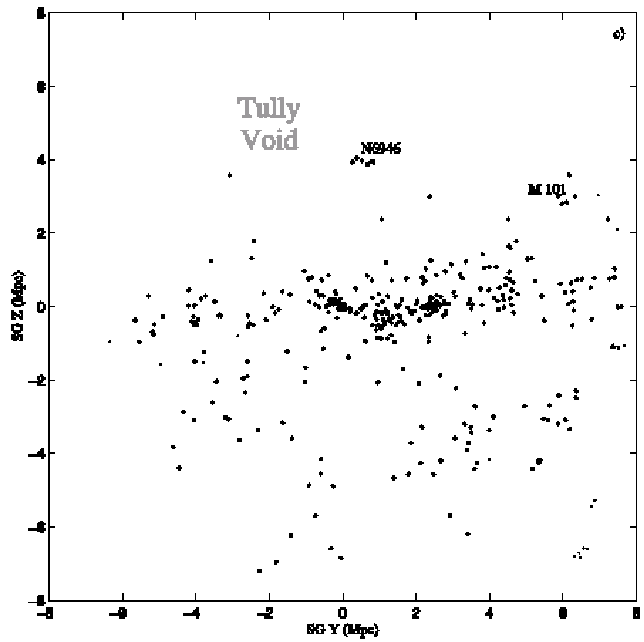


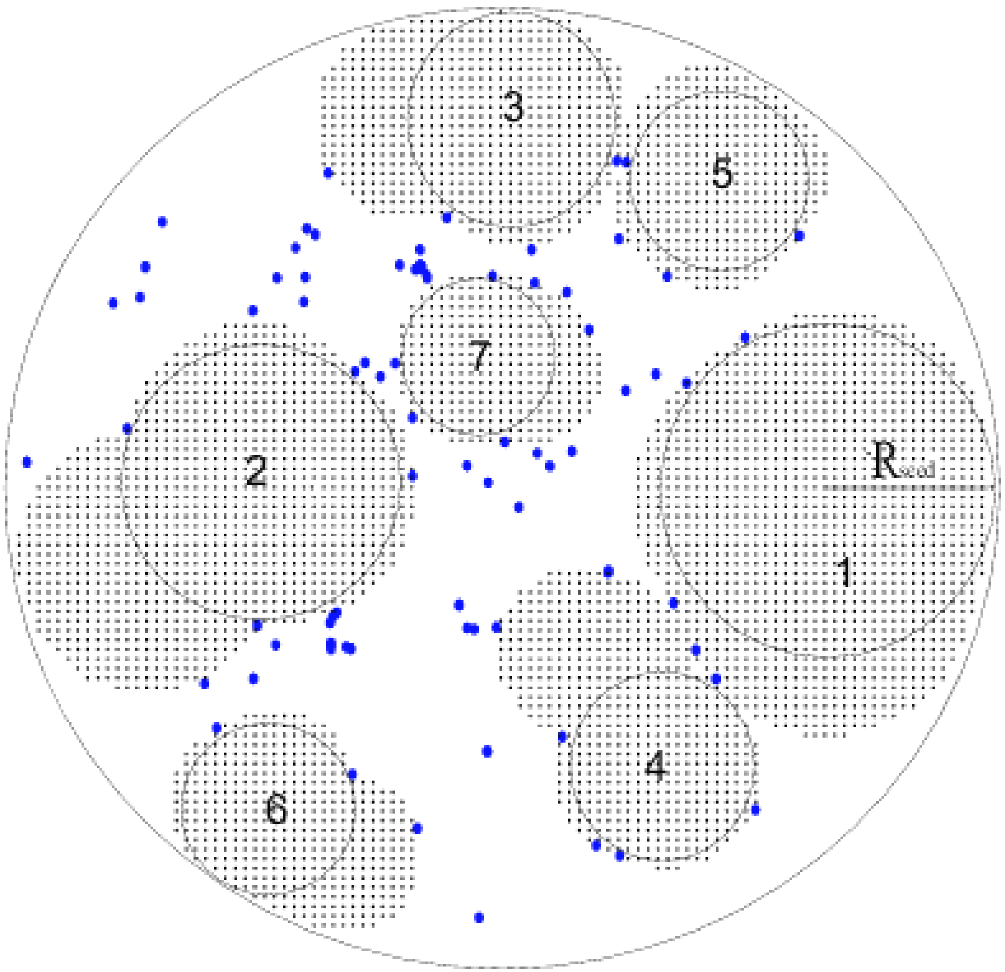
FIG. 5.—Panorama of the LV within a radius of 8 Mpc in Cartesian supergalactic coordinates. Galaxies from Table 1 with $D > 8$ Mpc are shown as small circl
(*a*) SGX-SGY, galaxies projected onto the plane of the Local Supercluster; (*b*) SGX-SGZ, the distribution in Z (perpendicular to the plane of the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

Void detection algorithm

- **3D grid**.
- **Empty seed sphere** of largest possible radius $\mathbf{R_{seed}}$ is identified.
- **Expansion of seed spheres** by spheres with radius $\mathbf{R_{sph} > 0.9\ R_{seed}}$ 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

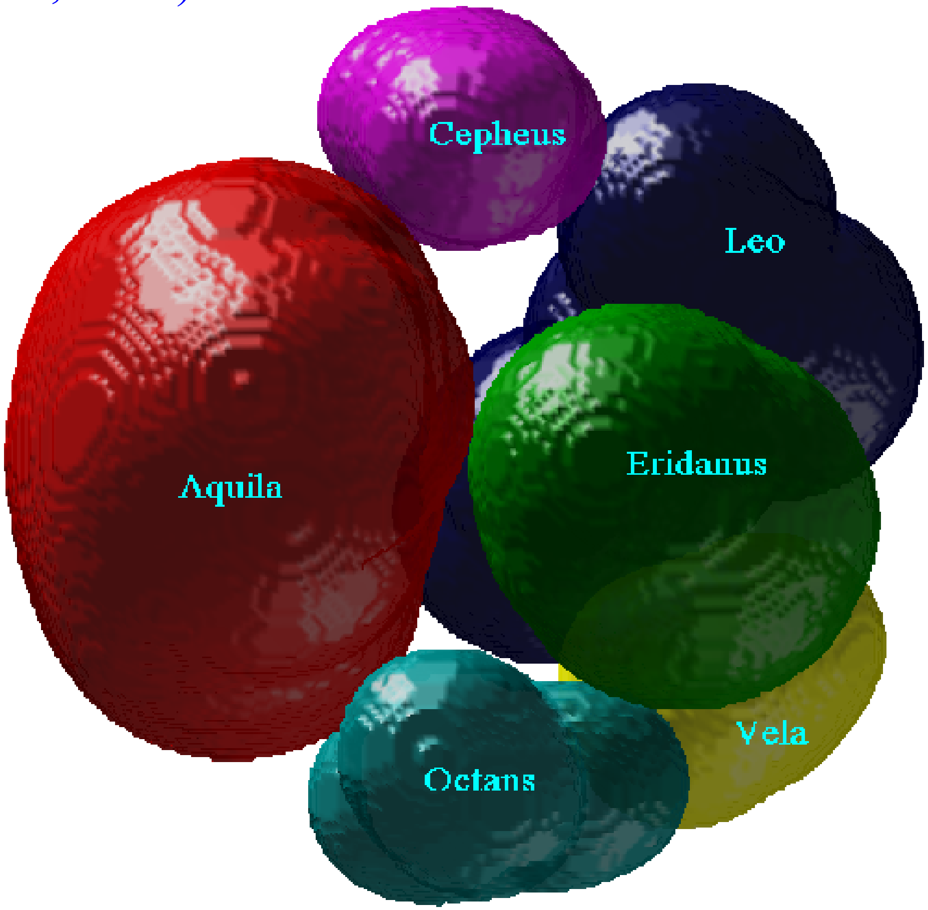
Cumulative void function ΔV/V(>Rvoid)



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.

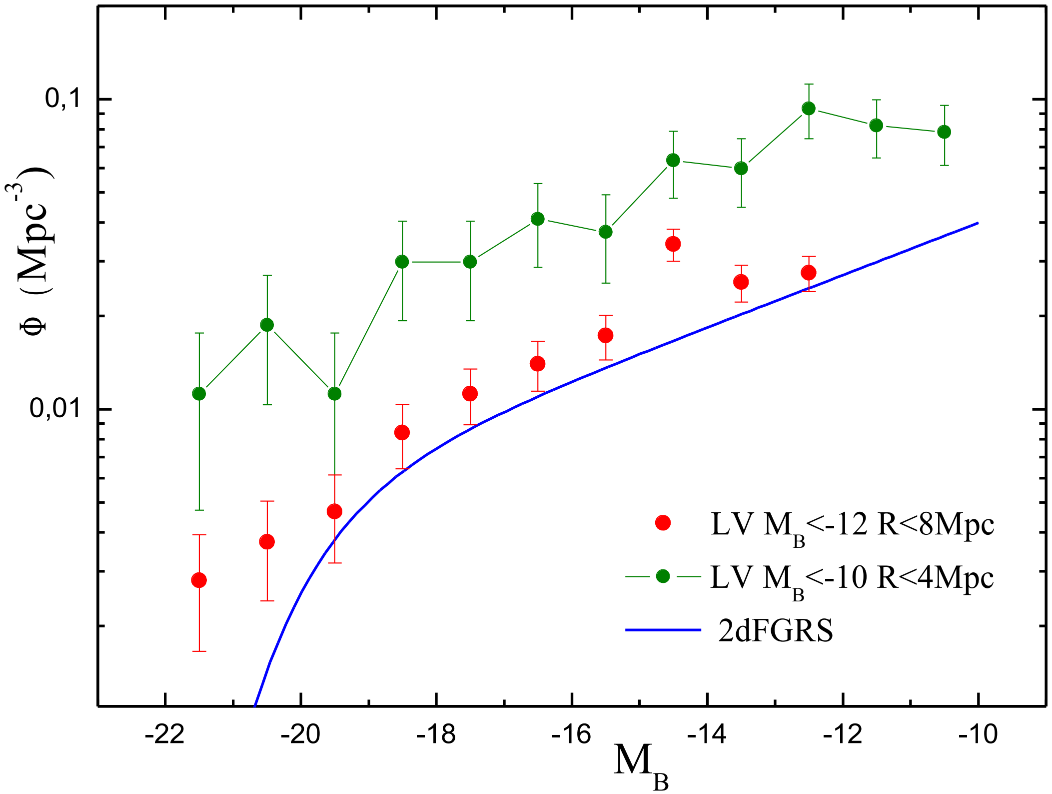
¼ of the Local Volume is occupied by Void in Aquila - front part of the Local (Tully) Void (Tikhonov & Karachentsev, 2006)



Luminosity functions of LV galaxies

2 volume limited samples in LV

1) M_B **< -12** within **8Mpc** 2) M_B **< -10** within **4Mpc**.

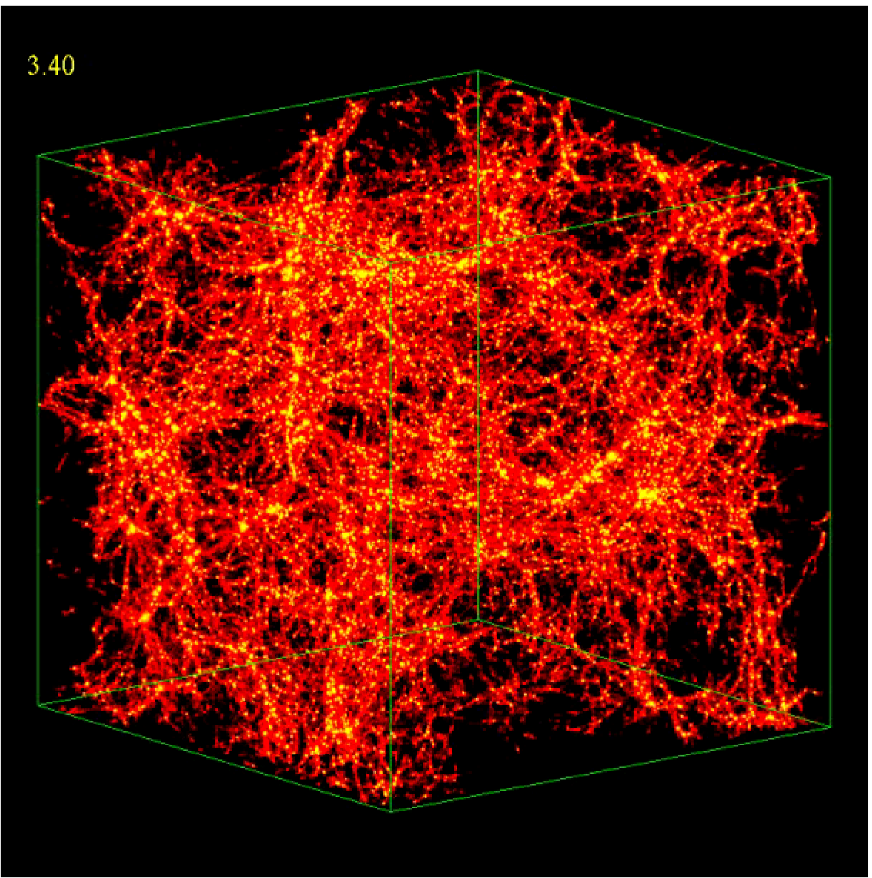


α ~ 1.2

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

Simulation S_3: (1) no haloes with Mass$> 2 \times 10^{13} M_\odot$ inside a 8 Mpc sphere; (2) The number density of haloes found inside 8Mpc sphere with $V_c > 100$ km/s exceeds the mean value in the whole box by factor in the range $1.5 - 1.7$; (3) There are no haloes more massive than $1.0 \times 10^{12} M_\odot$ with distances in the range 1-3 Mpc. (4) Central haloes of different LG-candidates are located at distance more then 5Mpc one from the other. There are 14 samples with above criteria in the simulation S_3.

RMS Peculiar Velocity – deviations from the HUBBLE FLOW - σ_H

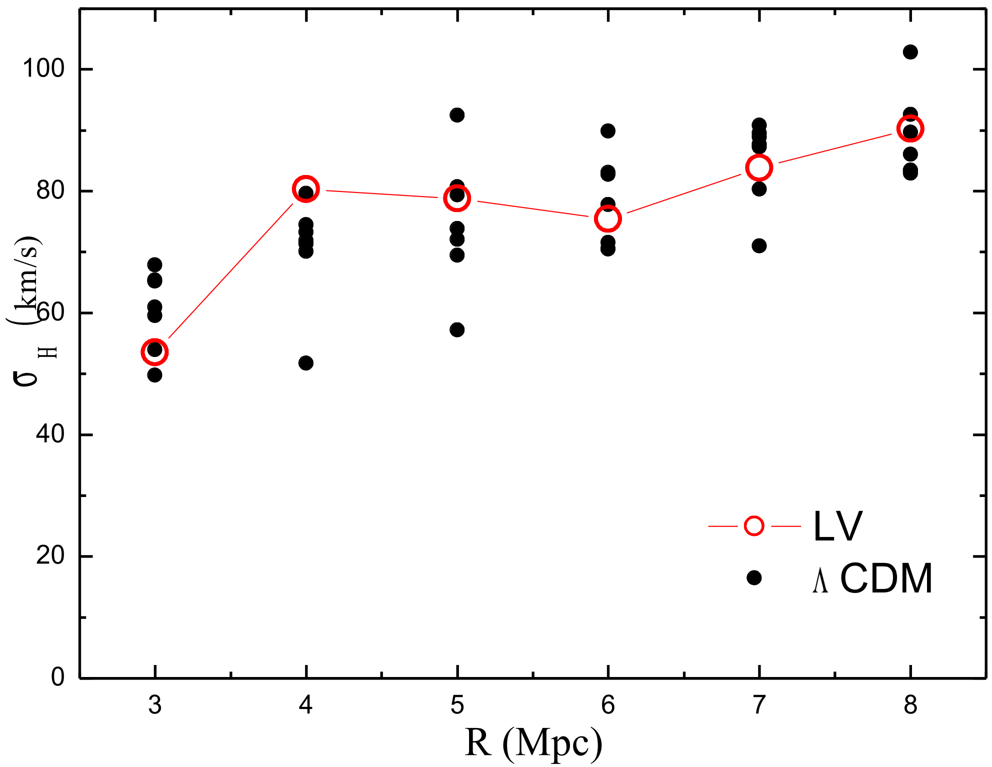


Figure 2. σ_H^{true} with apex and error correction for LV in the volume from 1 Mpc up to R Mpc with σ_H in corresponding volume for 7 model LV-candidates from Box160CR

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

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

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

Local Volume

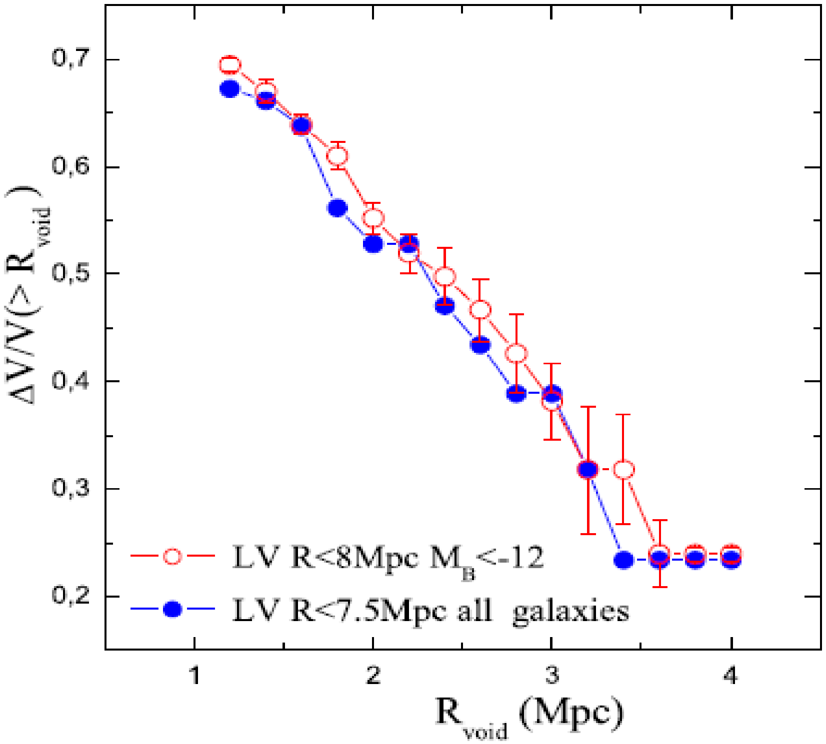


Figure 4. the void function for two observational samples. The full curve with open circles are for a complete volume limited sample with $M_B < -12$ and $R < 8\,\mathrm{Mpc}$. 1σ errors obtained by Monte Carlo resampling distances from catalog by means of additon gaussian distributed characteristic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

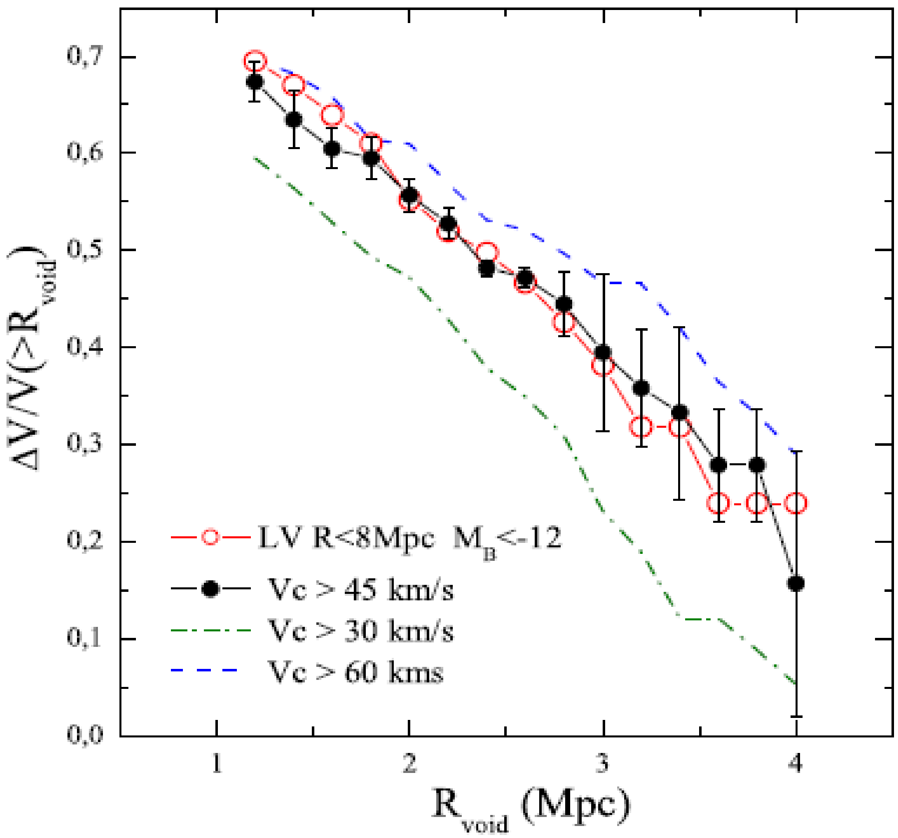


Figure 3. Observational data (the complete sample, circles) are compared with the distribution of voids in samples of halos with different limits on halo circular velocity. VF for $V_c = 45\,\mathrm{km/s}$ provides a remarkably good fit to observations. Note that the LCDM model predicts very large empty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

Box64CR $\sigma_8 = 0.75$

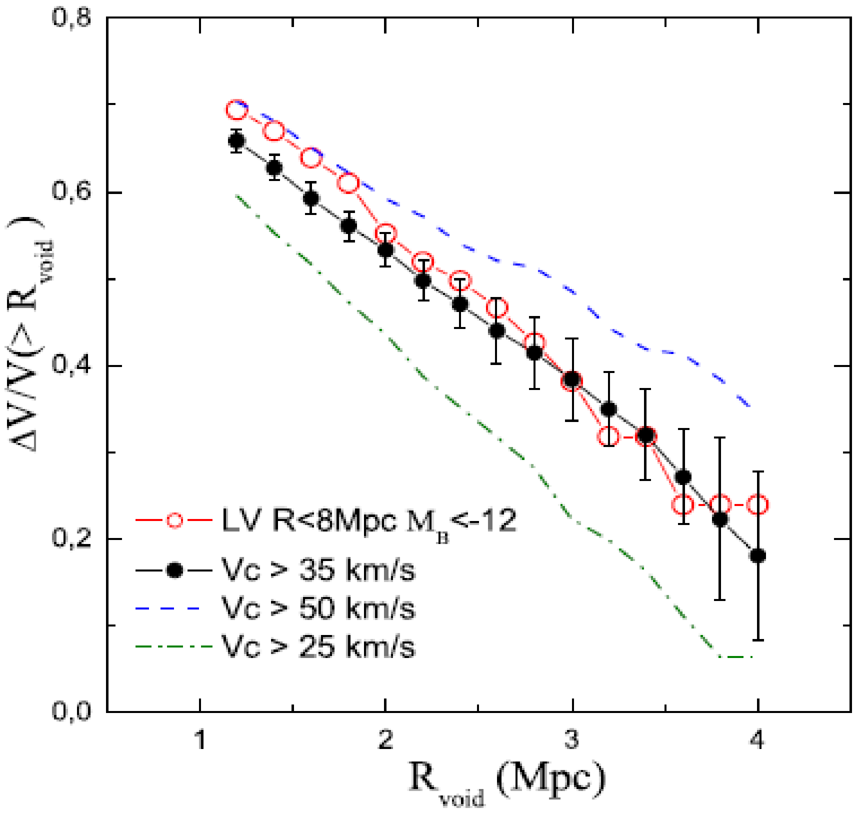


Figure 5. Observational data (the complete sample $M_B < -12$) are compared with the distribution of voids in 14 samples from Box64CR of halos with different limits on halo circular velocity. In this case VF for $V_c = 35\,\mathrm{km/s}$ (shown with 1σ scatter) provides a better fit to observations.

Box160CR $\sigma_8 = 0.75$

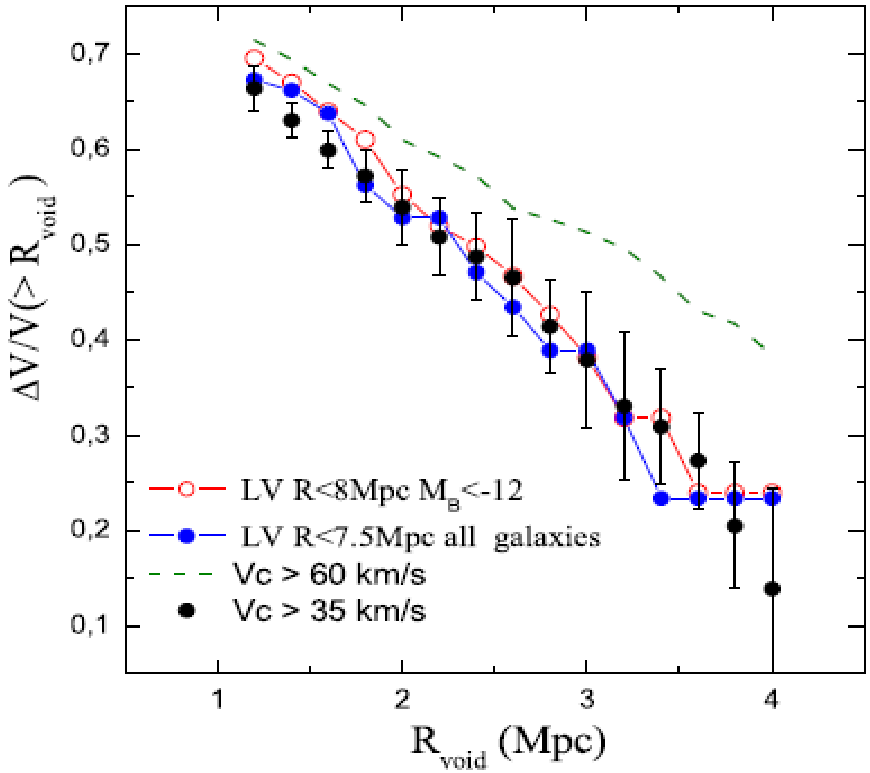
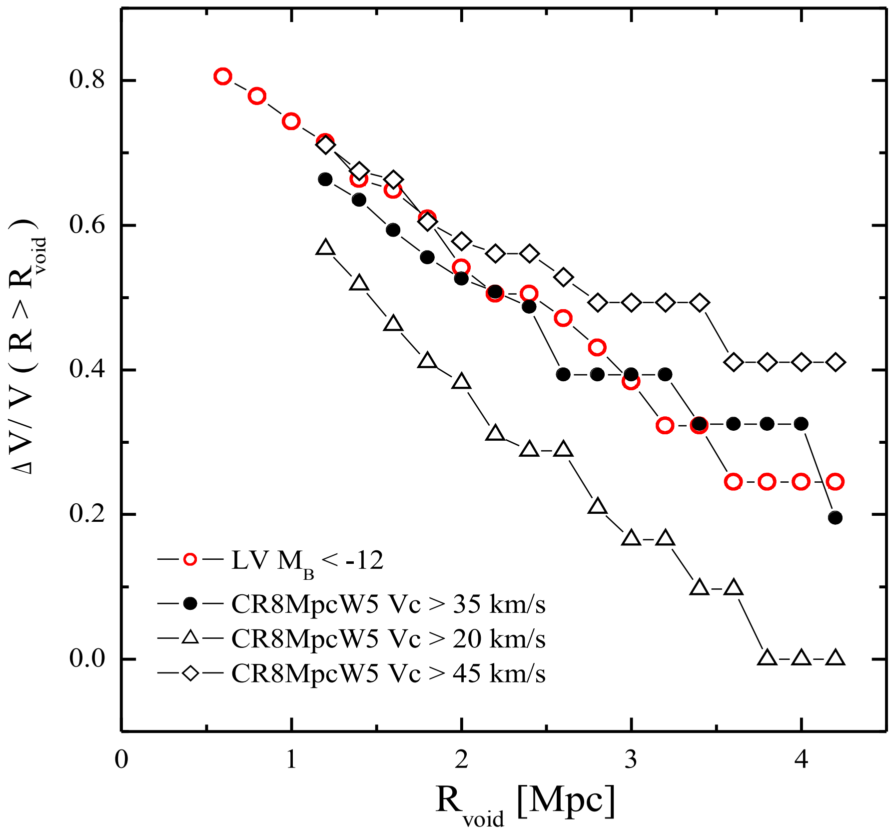


Figure 6. Observational data (the complete sample $M_B < -12$) are compared with the distribution of voids in 7 samples from Box160CR of halos with different limits on halo circular velocity. CVF for $V_c = 35\,\mathrm{km/s}$ (shown with 1σ scatter) provides a remarkably good fit to observations. Because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

New CR WMAP5 simulation, 2009

S. Gottloeber, G. Yepes, Y.Hoffman



Density profiles of “dark” halos inside voids

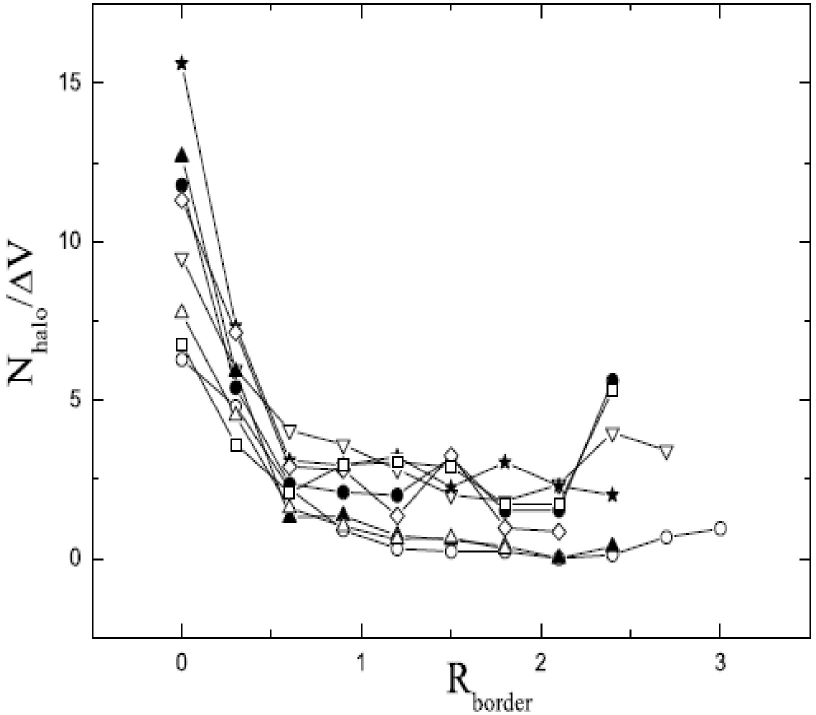
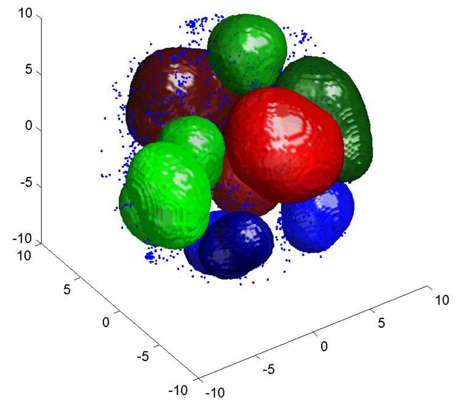
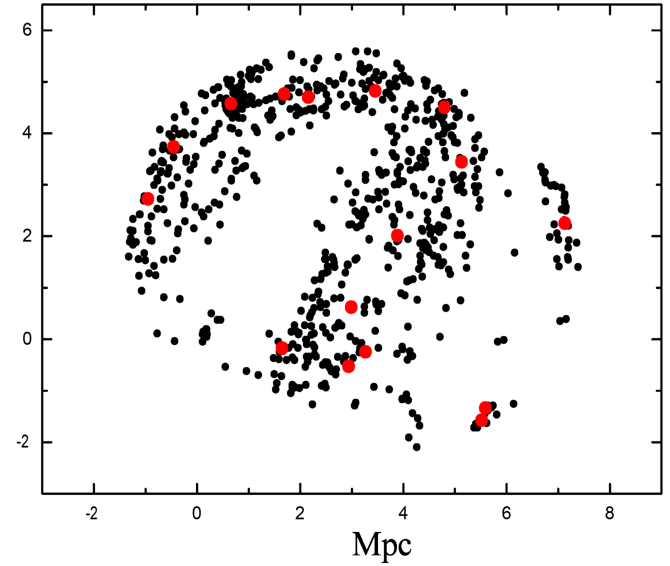


Figure 7. Density profiles in 8 largest voids found in 10 Mpc spherical region from Box80S defined by haloes with $V_c > 45$ km/s. $N/\Delta V$ – halo ($V_c < 45$ km/s) number density in shells 0.3 Mpc thick inside voids that located on the constant distances from the void borders. D_{border} – distance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





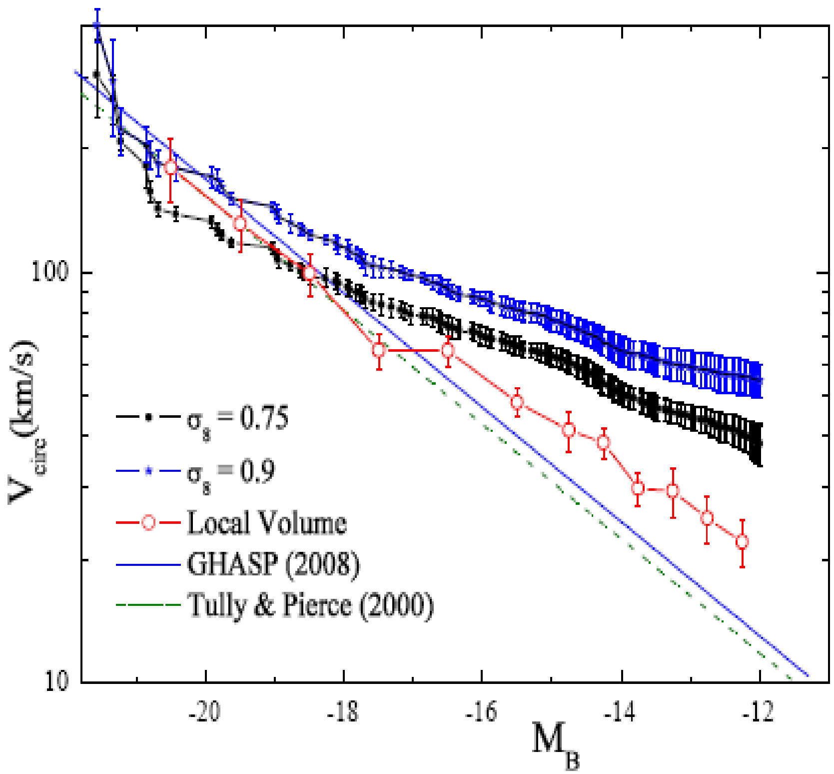
LCDM- Overabandance

Isolated dIrr $V_{\rm rot} = W_{50}/2\sqrt{1-(b/a)^2}$

In terms of TF-relation
LV Spirals + Irregulars

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

Name	M_B	axial ratio	W_{50}	$V_{\rm rot}$	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

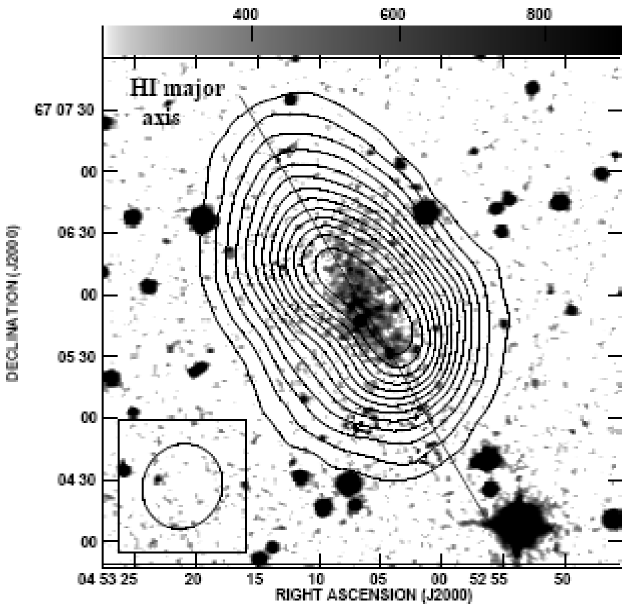


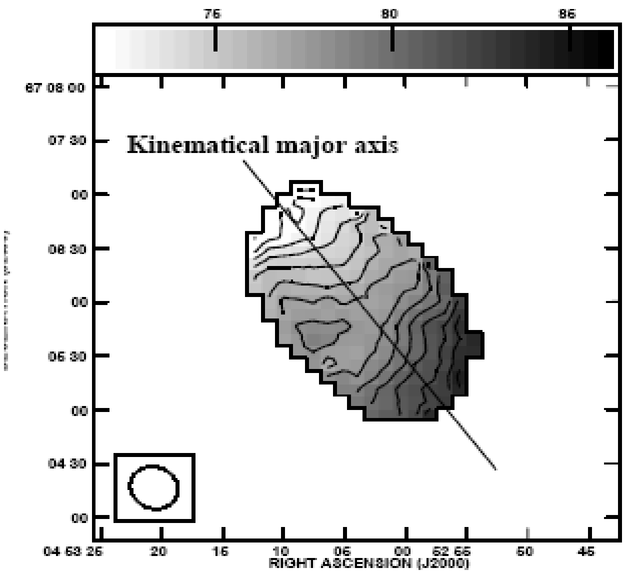
We would like to emphasize that the disagreement with the theory is staggering. The observed spectrum of void sizes disagrees at many sigma level from the theoretical void spectrum if haloes with $V_c > 20\,\mathrm{km/s}$ host galaxies brighter than $M_B = -12$. We can look at the situation from a different angle. In the LCDM model with $\sigma_8 = 0.9$ there are ~ 320 haloes with $V_c > 45\,\mathrm{km/s}$ – the same number as the number of galaxies in the Local Volume with the $M_B = -12$ limit. In the same volume in the LCDM model there are ~ 3500 haloes with $V_c > 20\,\mathrm{km/s}$. If all these haloes host galaxies brighter than $M_B = -12$, the theory predicts a factor of ten more haloes as compared with the observations.

Dwarf Galaxies

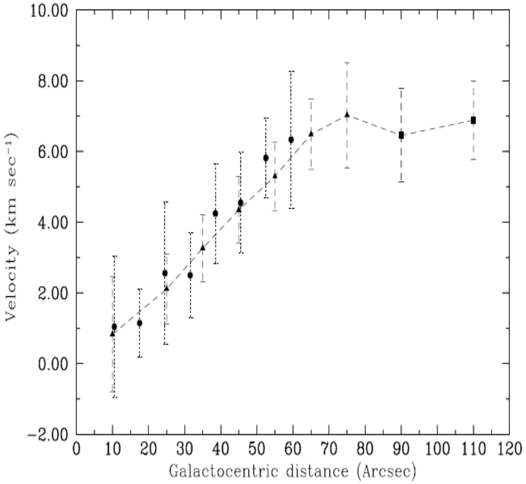
dIrr Camelopardalis B; D=2.2Mpc;
$M_B = -10.9$

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





J.Chengalur and A.Begum
GMRT



dIrr CGCG 269-049 $M_B = -12.46$ D=3.4Mpc

$V_{rot} \sin(i) \le 8$ km s^{-1}

J.Chengalur and A.Begum

GMRT

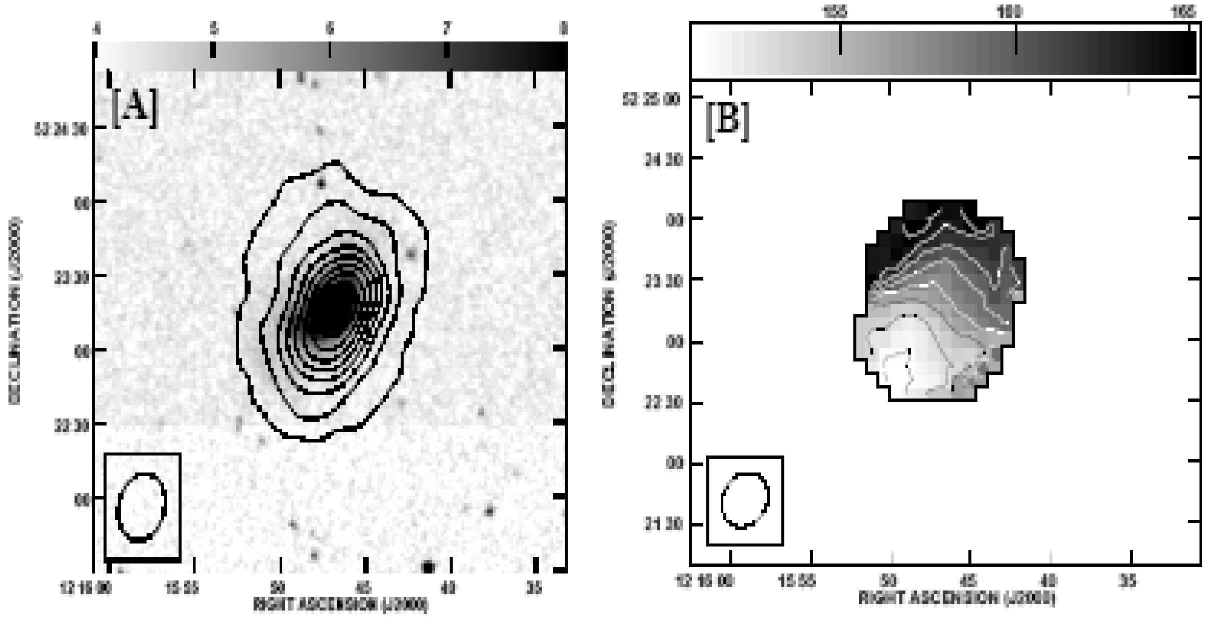
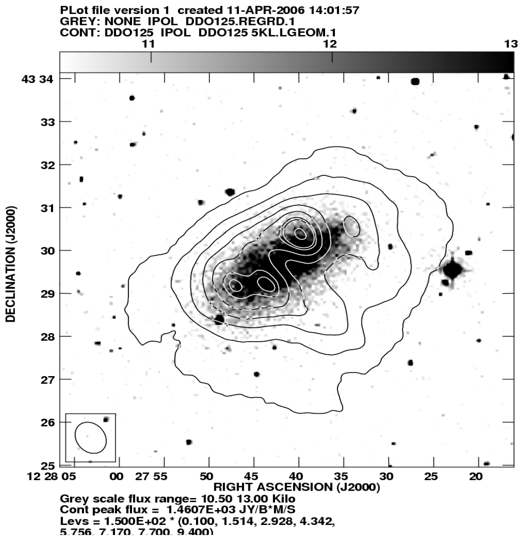
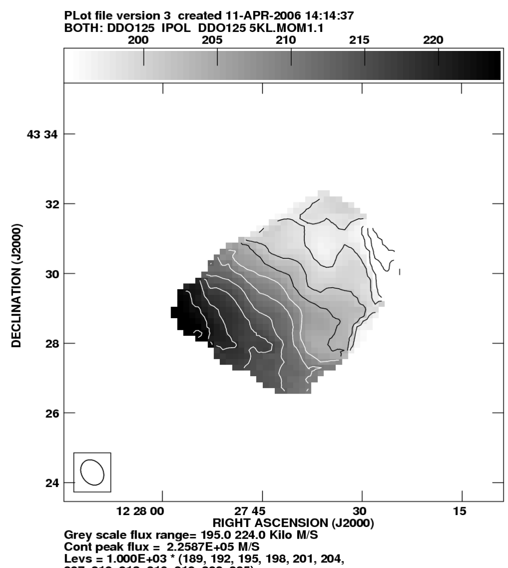


Figure 5. [A] The B band optical DSS image of CGCG 269-049 (greyscales) with the GMRT $28'' \times 24''$ resolution integrated HI emission map (contours) overlayed. The contour levels are 0.08, 1.12, 2.18, 3.23, 4.28, 5.33, 6.39, 7.44, 8.49 and 9.55 $\times 10^{20}$ atoms cm^{-2}. [B] The HI velocity field for galaxy at $28'' \times 24''$ resolution. The contours are in the steps of 2.0 km s^{-1} and range from 151.0 km s^{-1} to 165.0 km s^{-1}.

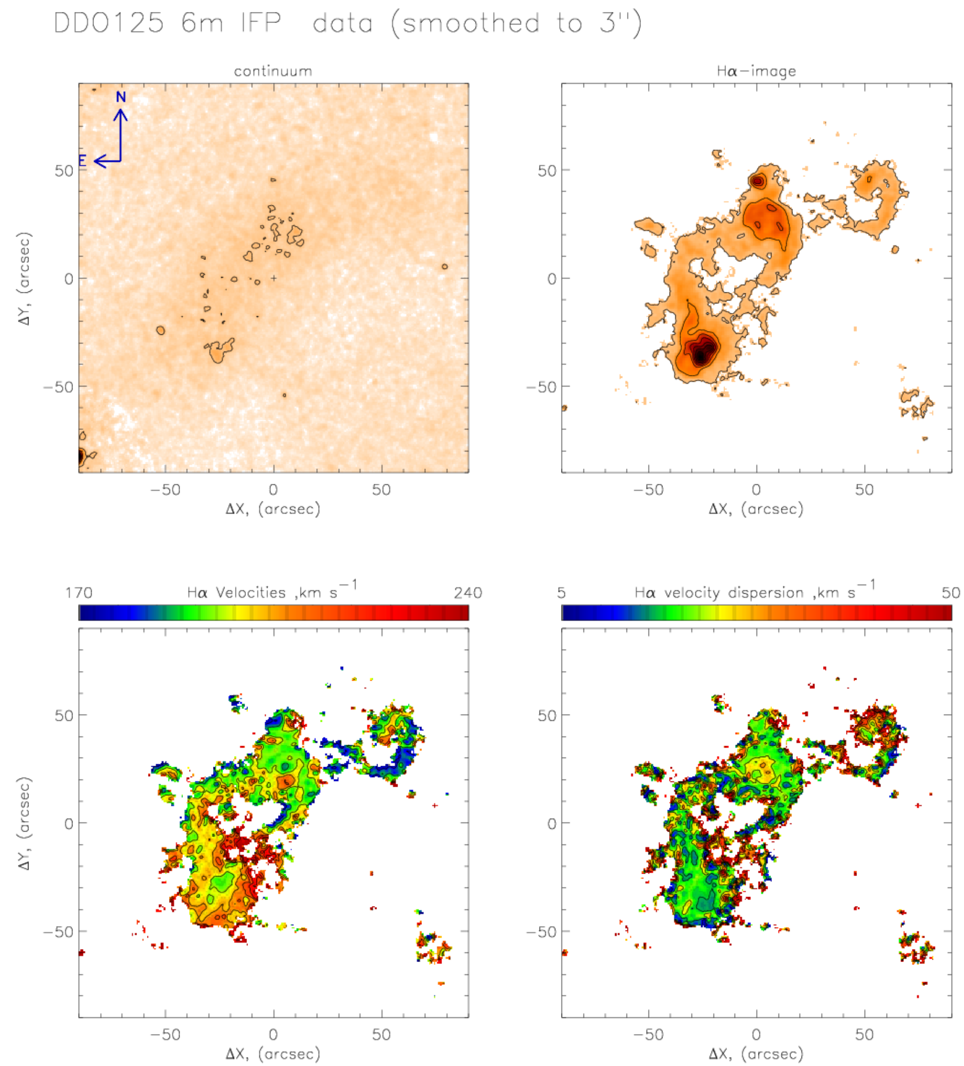
J. Chengalur and A. Begum
GMRT





dIrr DDO125 D=2.54Mpc M_B=-14.16

$V_{rot} \sim 20$ km/s



A.Moiseev, 6m Russian telescope

Conclusions

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

Possible Solutions:

1. Thousand of **dSph**s 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. **LWDM**-models (P(k) - truncation) $m_X \sim 1keV$

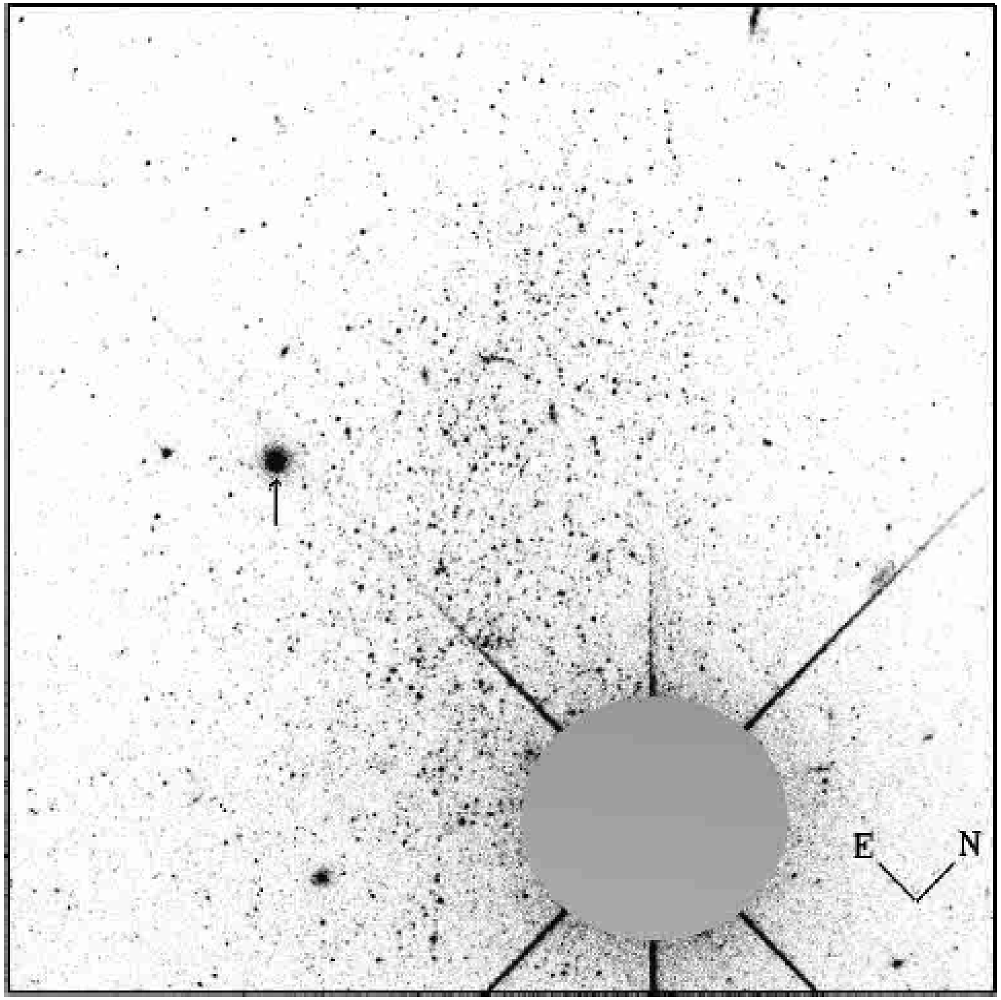
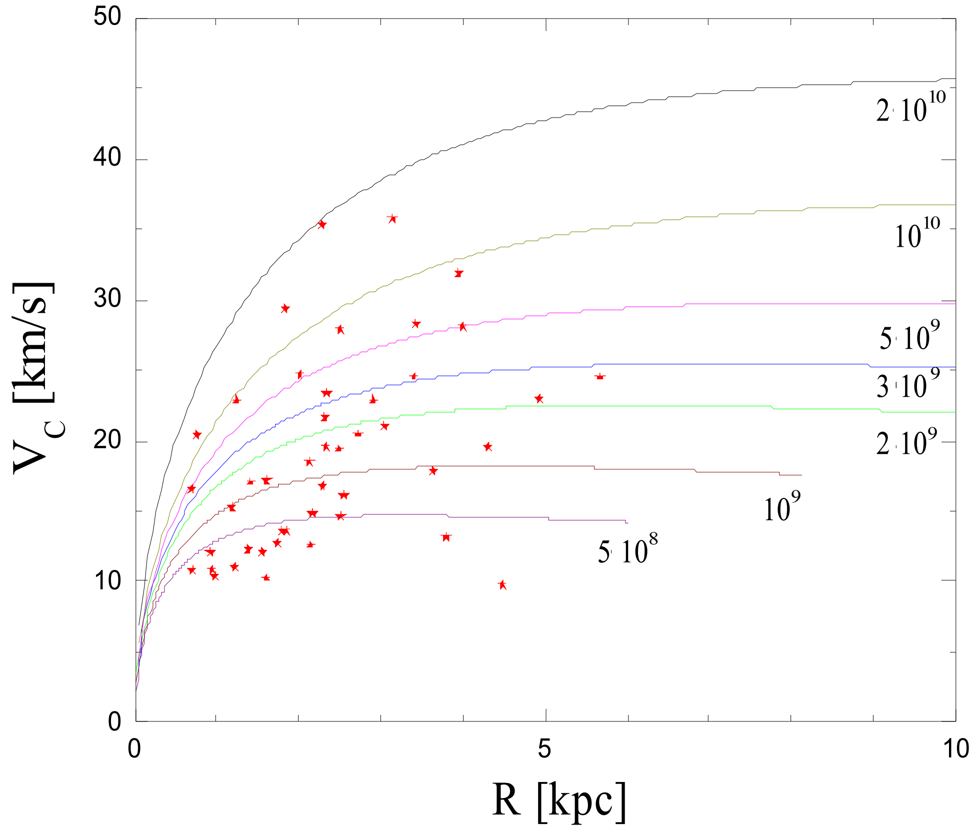


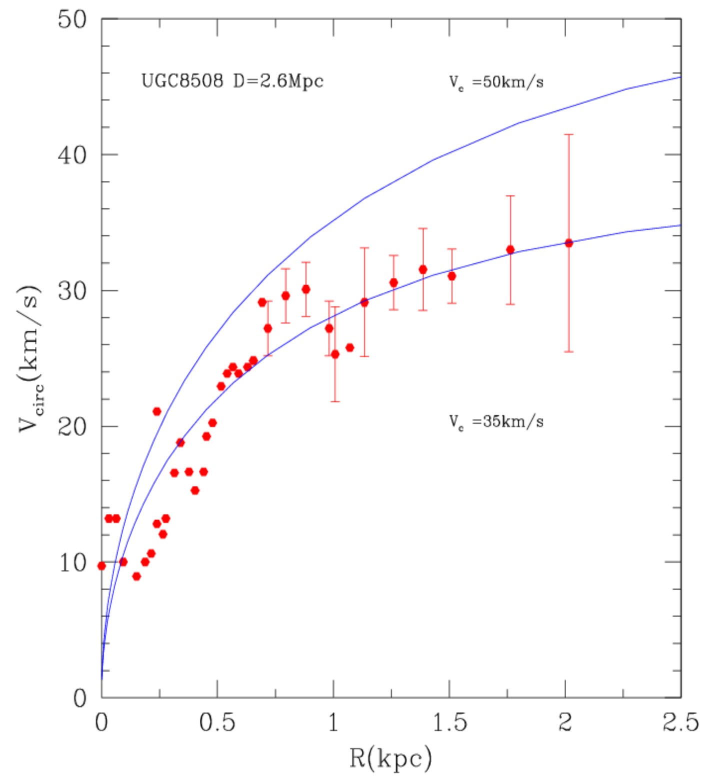
Fig. 2. WF3 image of KKR 25 produced by combining the two 600 s exposures taken through the F606W and F814W filters. A globular cluster candidate is indicated by the arrow.

KKR25
dSph in the field

M_B = -9.94
D = 1.86 Mpc (TRGB)
Central SB, Σ_V =24^m/□"

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





NFW circular velocity profiles for DM haloes with masses Between 5e8 and 2e10/h Msun. Red stars: observed *V*rot versus HI radii taken from the **FIGGS** LV galaxy sample

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

We cannot place the galaxy into a large halo.

One can clearly see that most of the observational points are located on the flattening parts of the NFW velocity profiles with circular velocities below 30 km/s. Since dwarf galaxies are expected to be DM dominated, the association of the observed rotational velocities at the HI radius with the maximum circular velocity of DM haloes is in our opinion a valid approximation

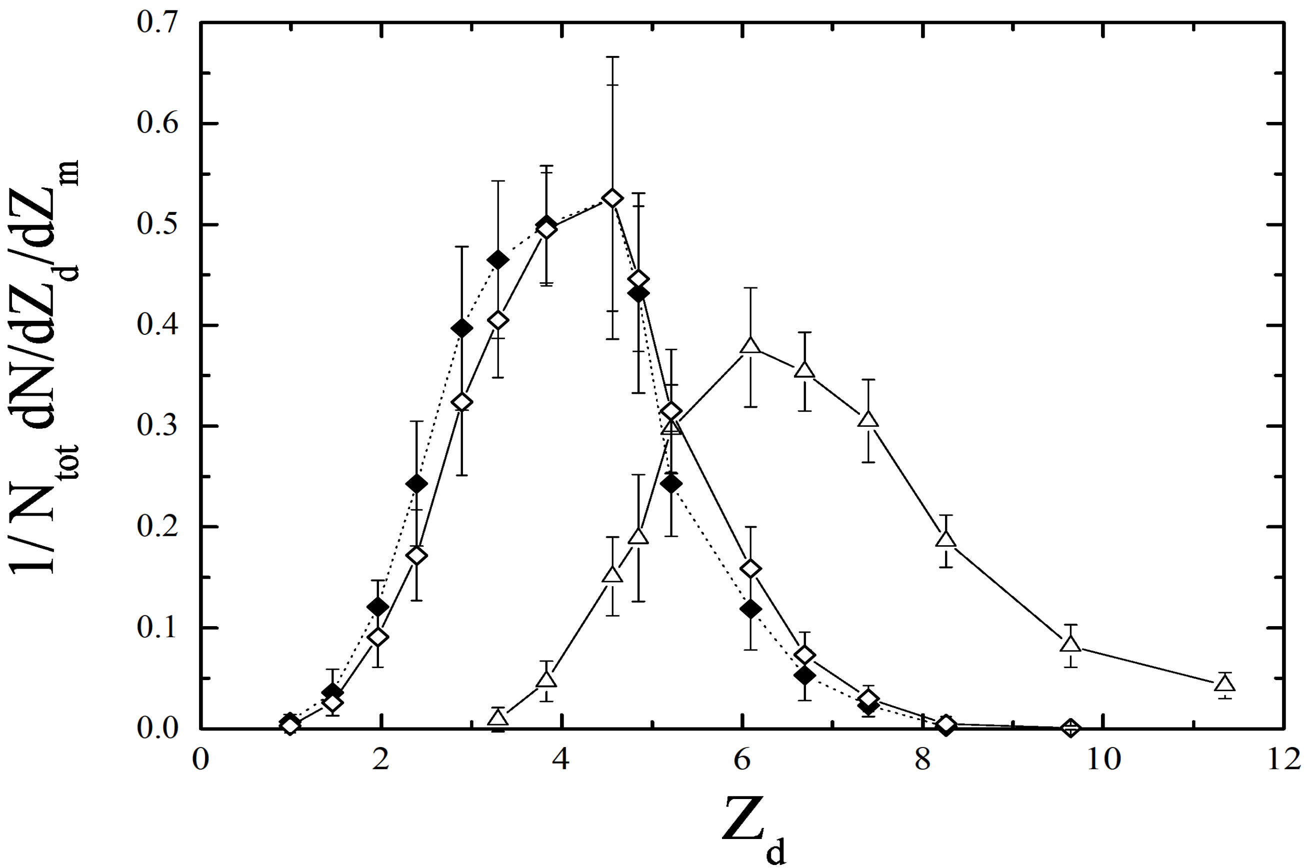
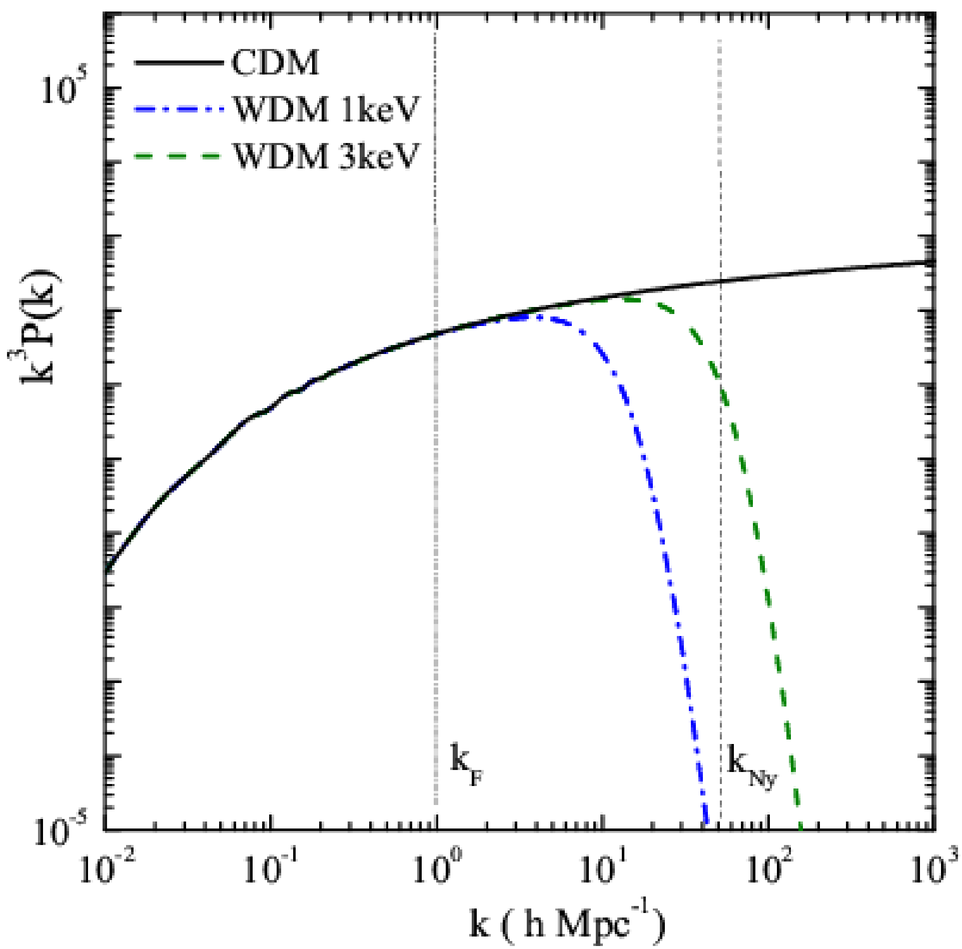


Figure 10. The differential number fraction of progenitors of haloes which became more massive than 3e8/h at redshift **Z**d.
Filled diamonds: haloes with **Vc** < 35 km/s at $z = 0$ inside minivoids; open diamonds: haloes with **Vc** < 35 km/s outside minivoids; triangles: haloes with **Vc**> 35 km/ s. Error bars are 1σ deviations

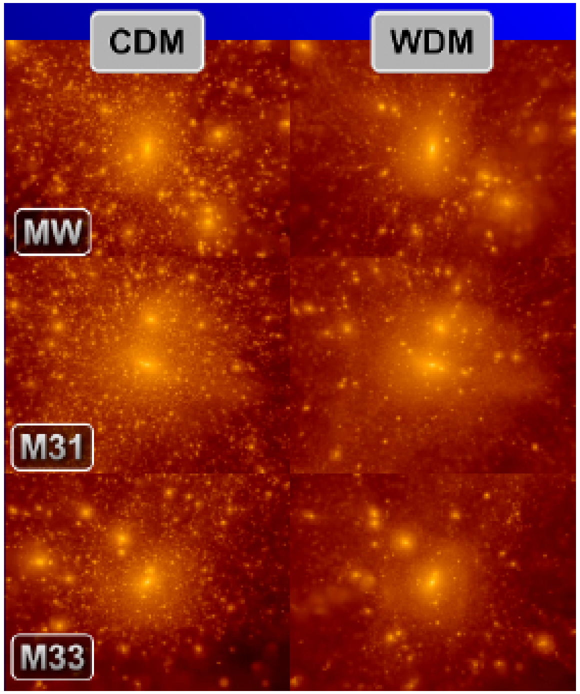
WDM-paradigm $m_X = 1keV$

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

Initial conditions

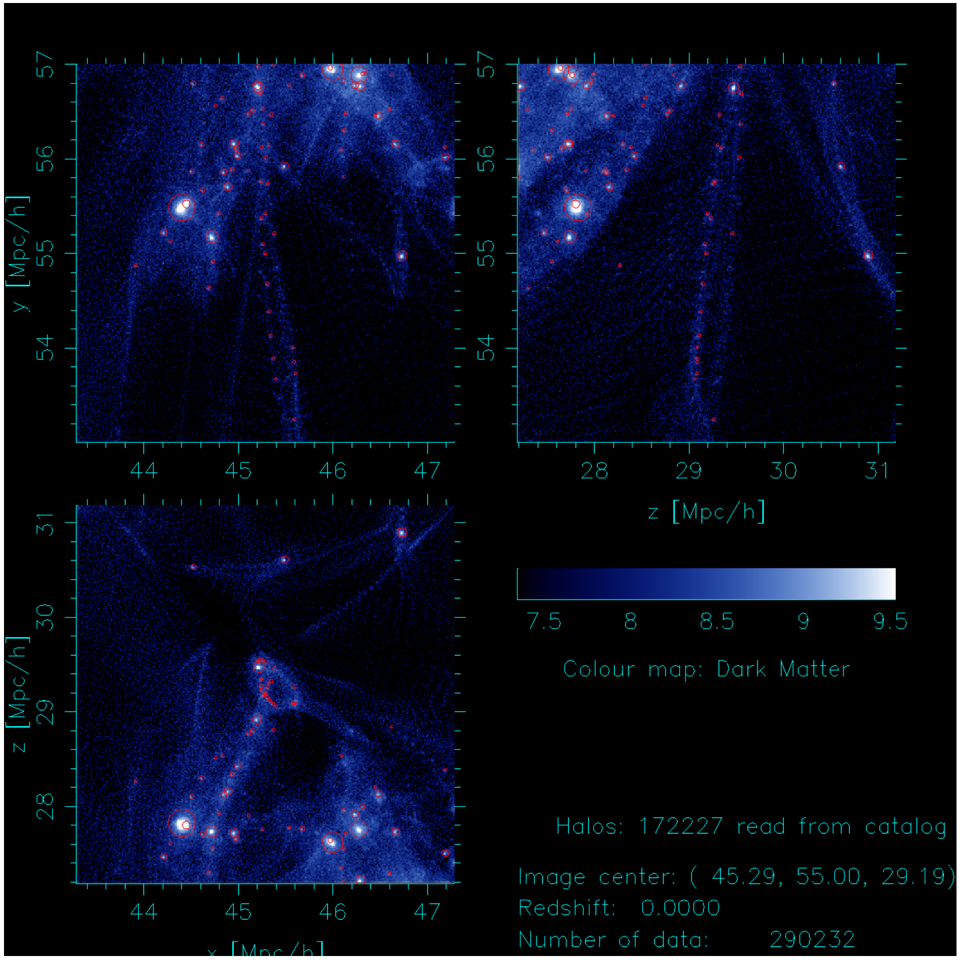


Resulting haloes

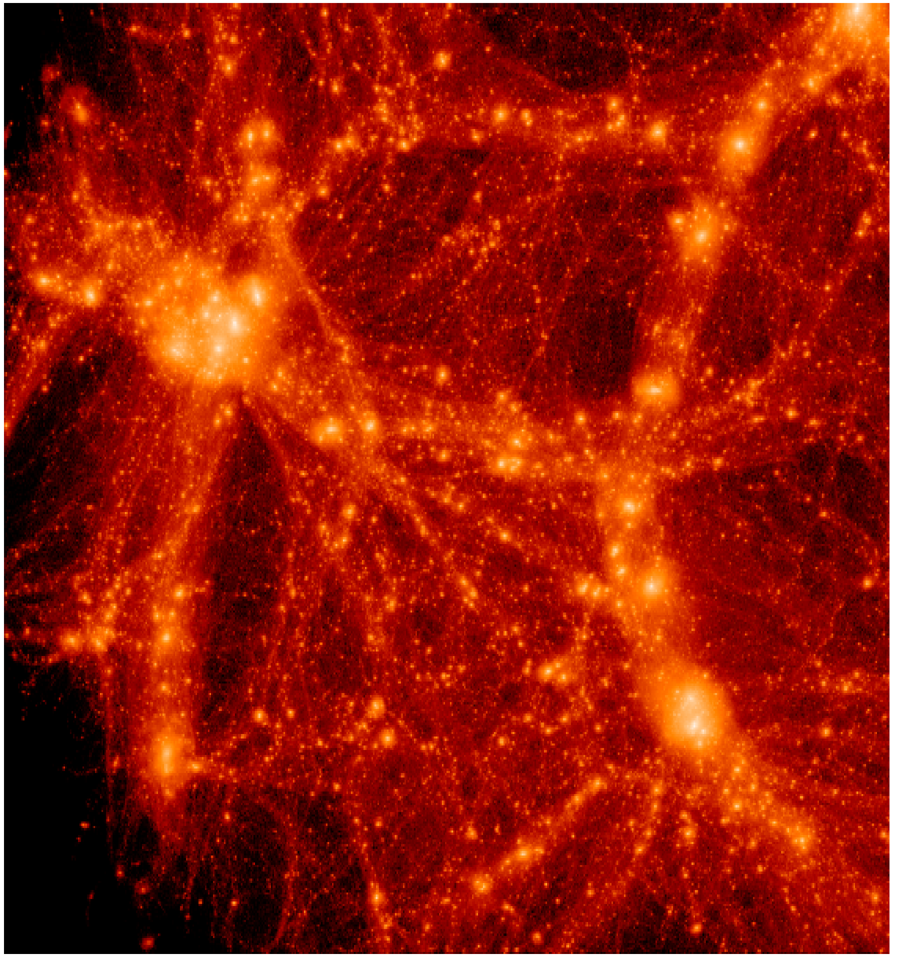


Arman Khalatyan

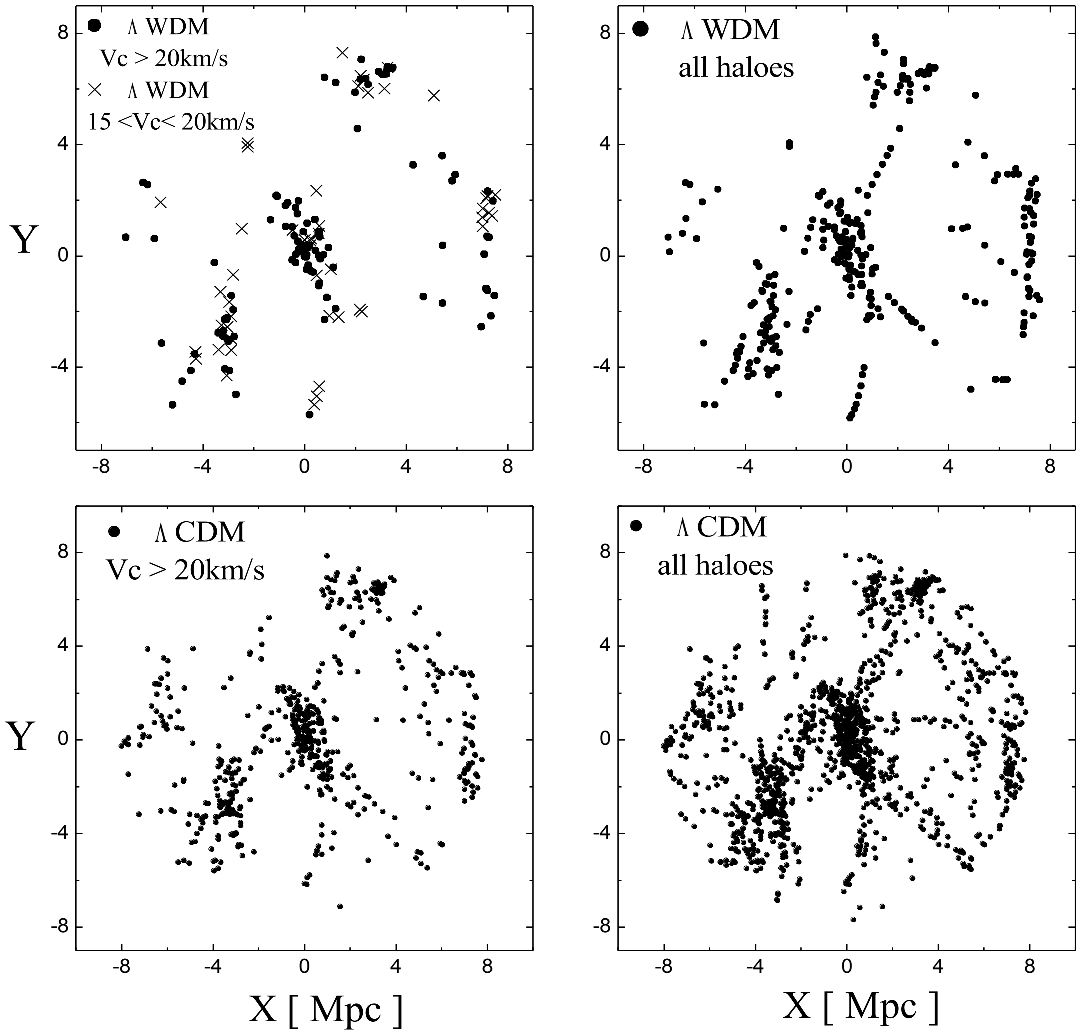
WDM



CDM



WDM-like simlations (with P(k)-truncation suffer by fake-haloes:
Appeared via spurious fragmentation of filaments
Wang&White, 2007; Klypin, 2008

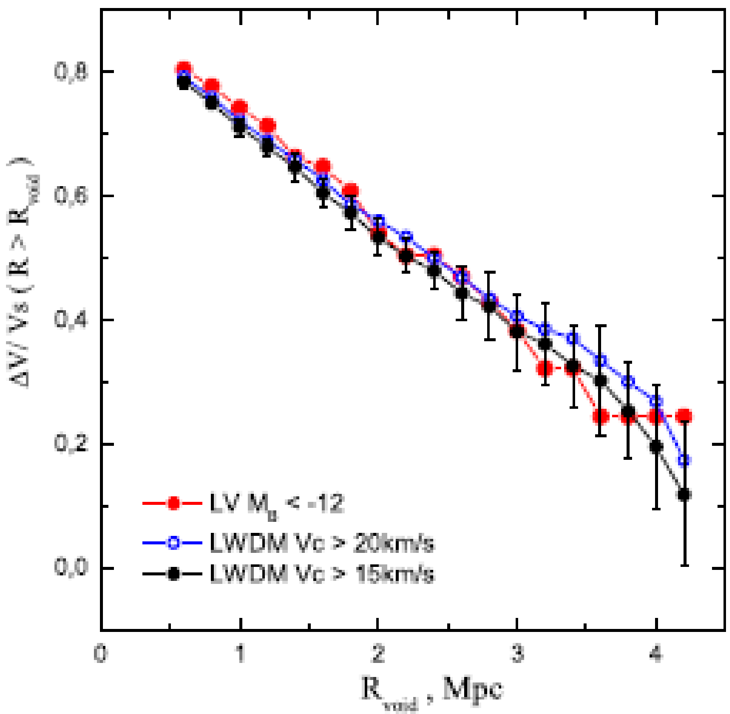


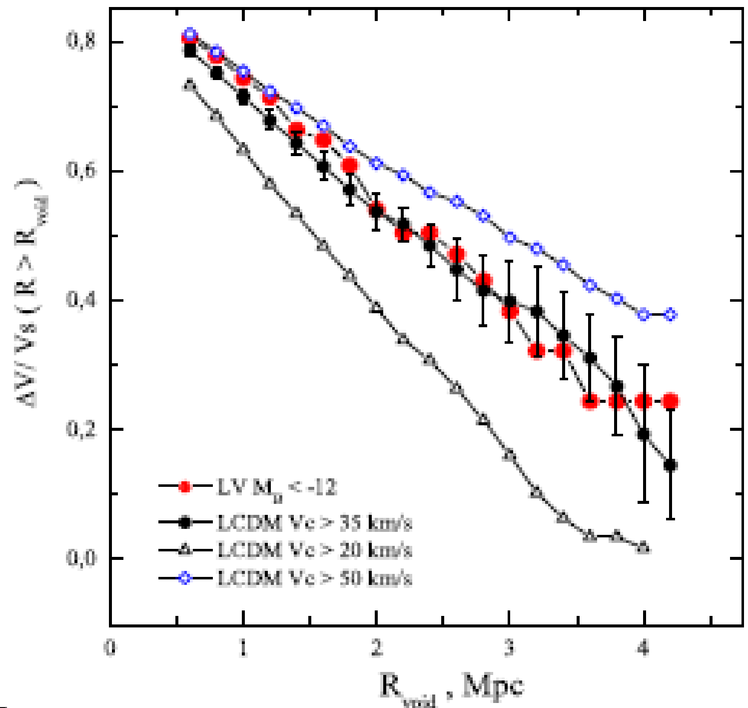
Λ WDM
Vc > 20km/s
Λ WDM
15 <Vc< 20km/s
Λ WDM
all haloes
Λ CDM
Vc > 20km/s
Λ CDM
all haloes
Y
X [Mpc]

Void-functions

WDM

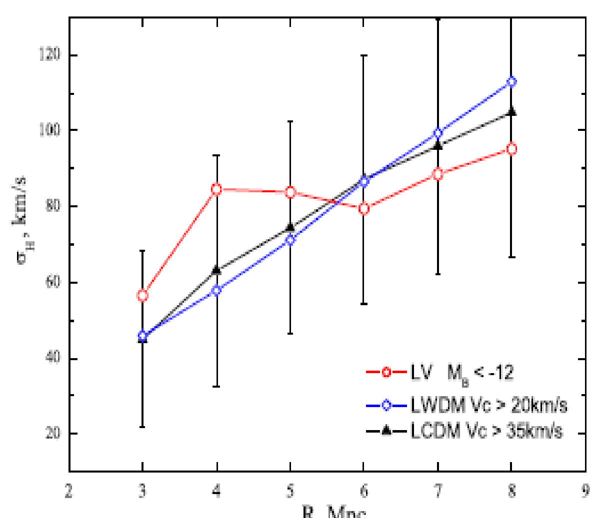
CDM





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

σ_H



V^{lim} = 35 km/s