The LCDM paradigm: successes and challenges on scales of galaxies

Anatoly Klypin (NMSU)

LCDM: Good news and Bad news

- DM profiles and concentrations
- Velocity and Mass Function
- Satellites: abundance, number-density profiles
- Adiabatic contraction
- Galaxies and Dark Matter: abundance matching

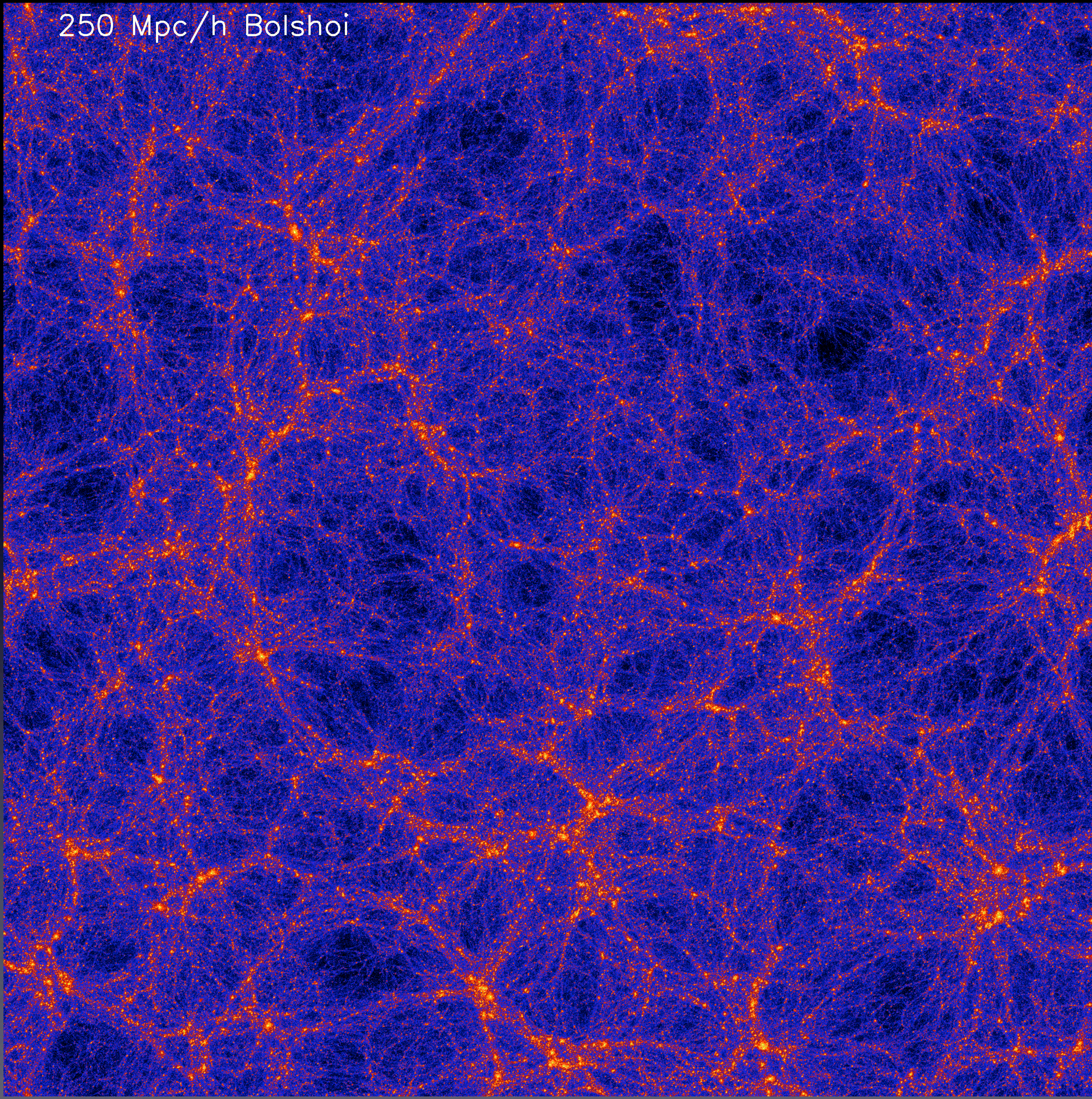
- *Abundance of dwarf galaxies: not satellites*
- *Mass function at z=10*

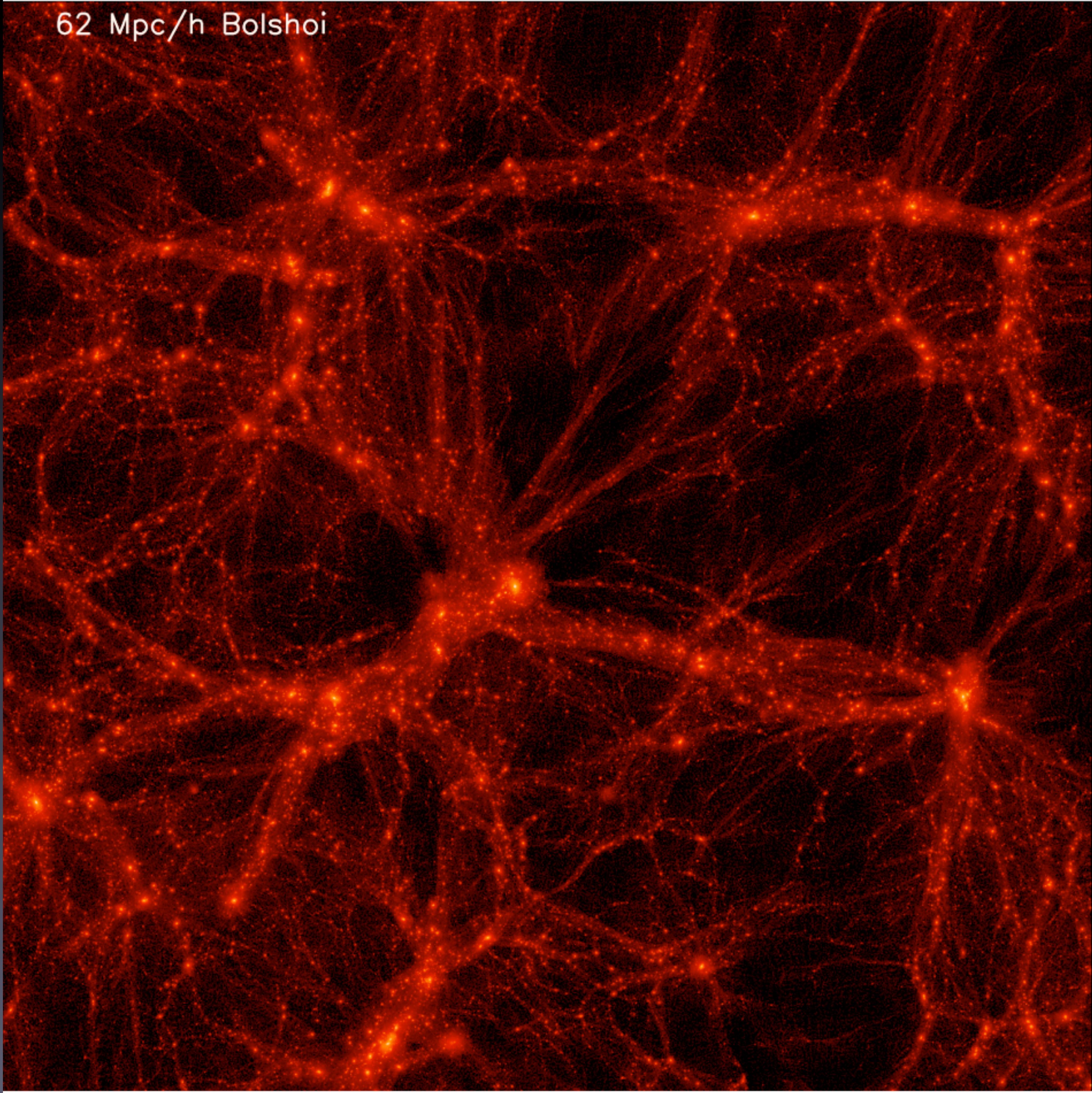
The Bolshoi simulation ART code

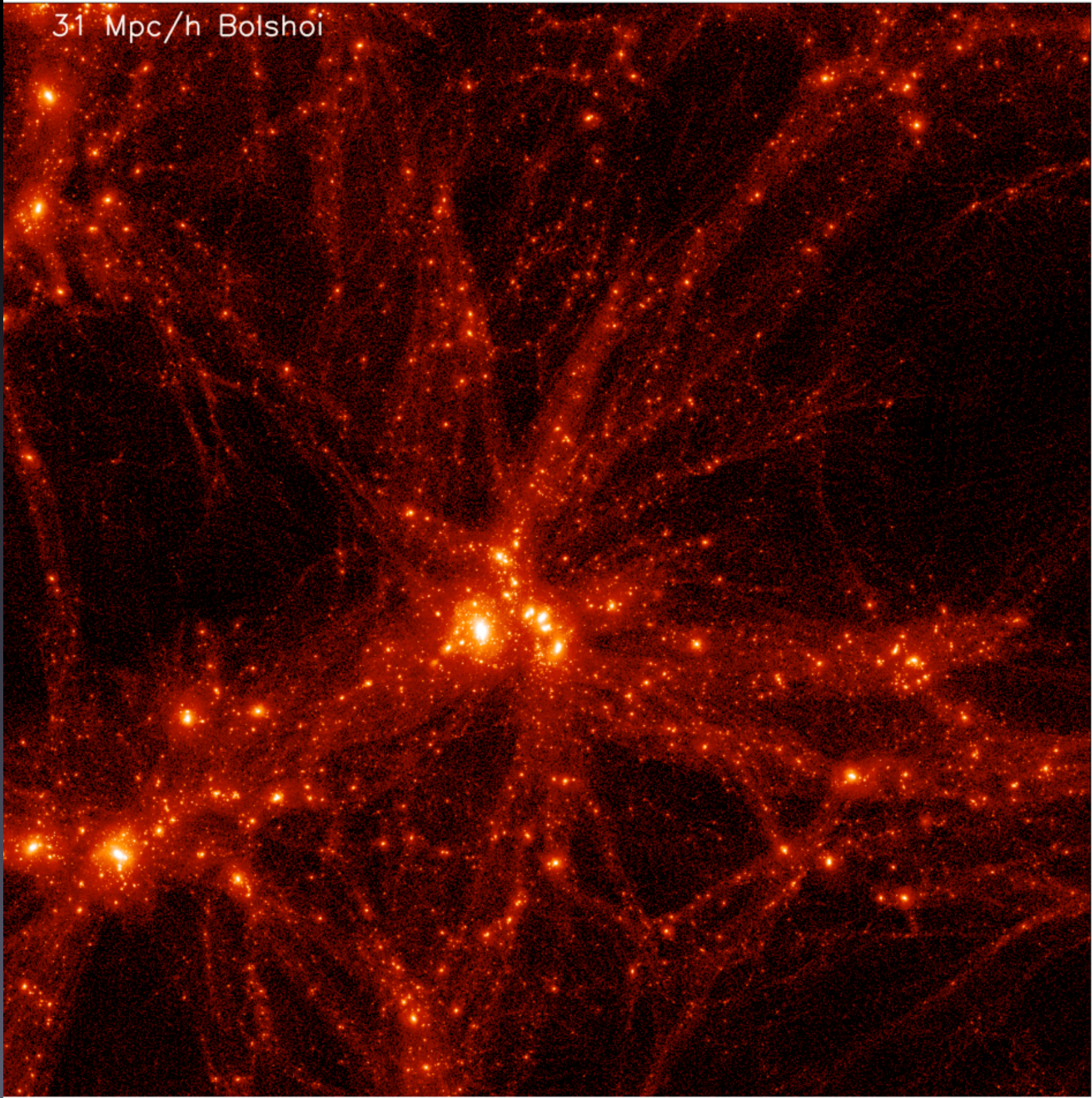
250Mpc/h Box
LCDM
s8 = 0.82
h = 0.70
8G particles
1kpc/h force resolution
1e8 Msun/h mass res

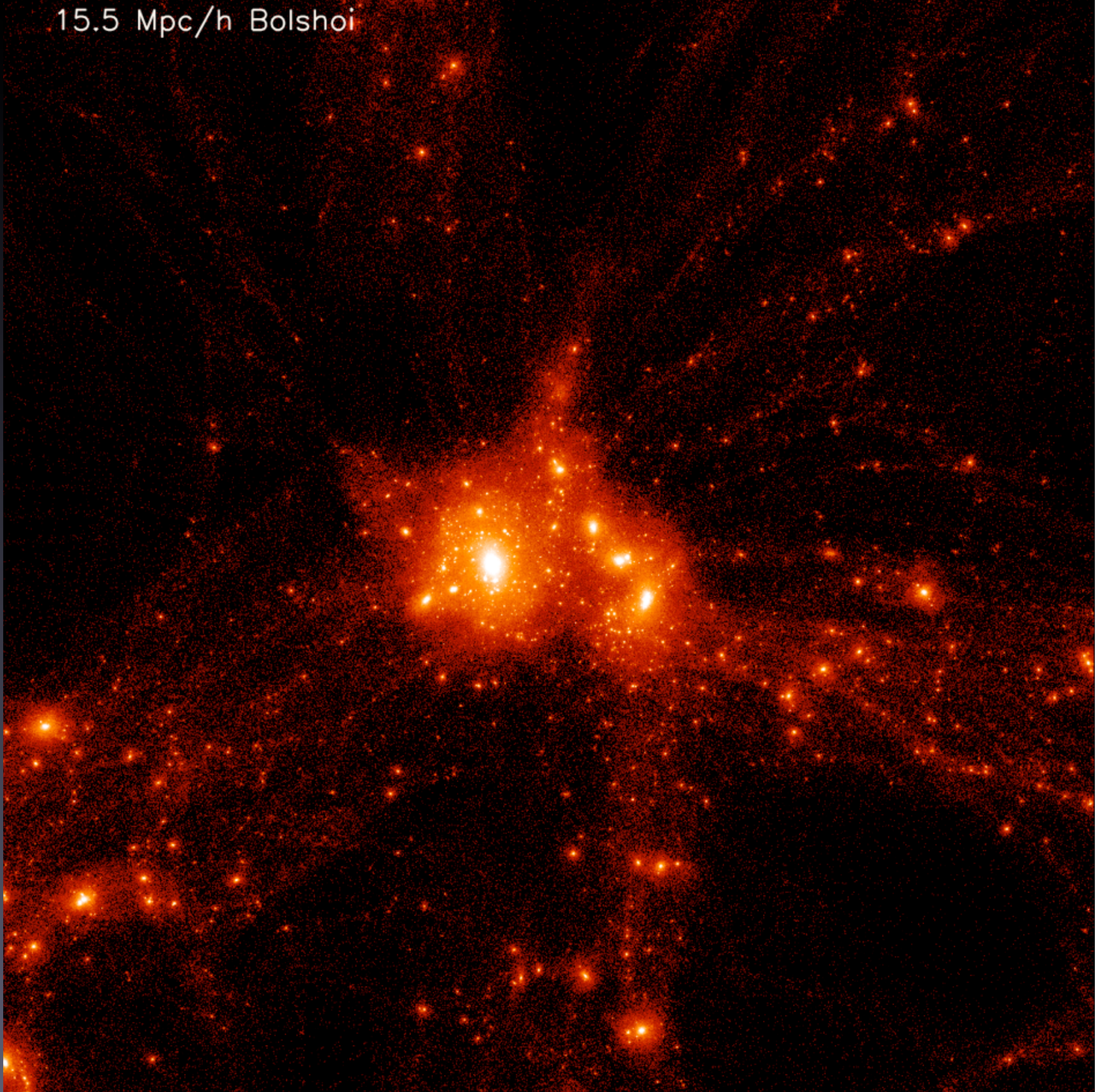
dynamical range 262,000
time-steps = 400,000

NASA AMES
supercomputing center
Pleiades computer
13824 cores
12TB RAM
75TB disk storage
6M cpu hrs
18 days wall-clock time

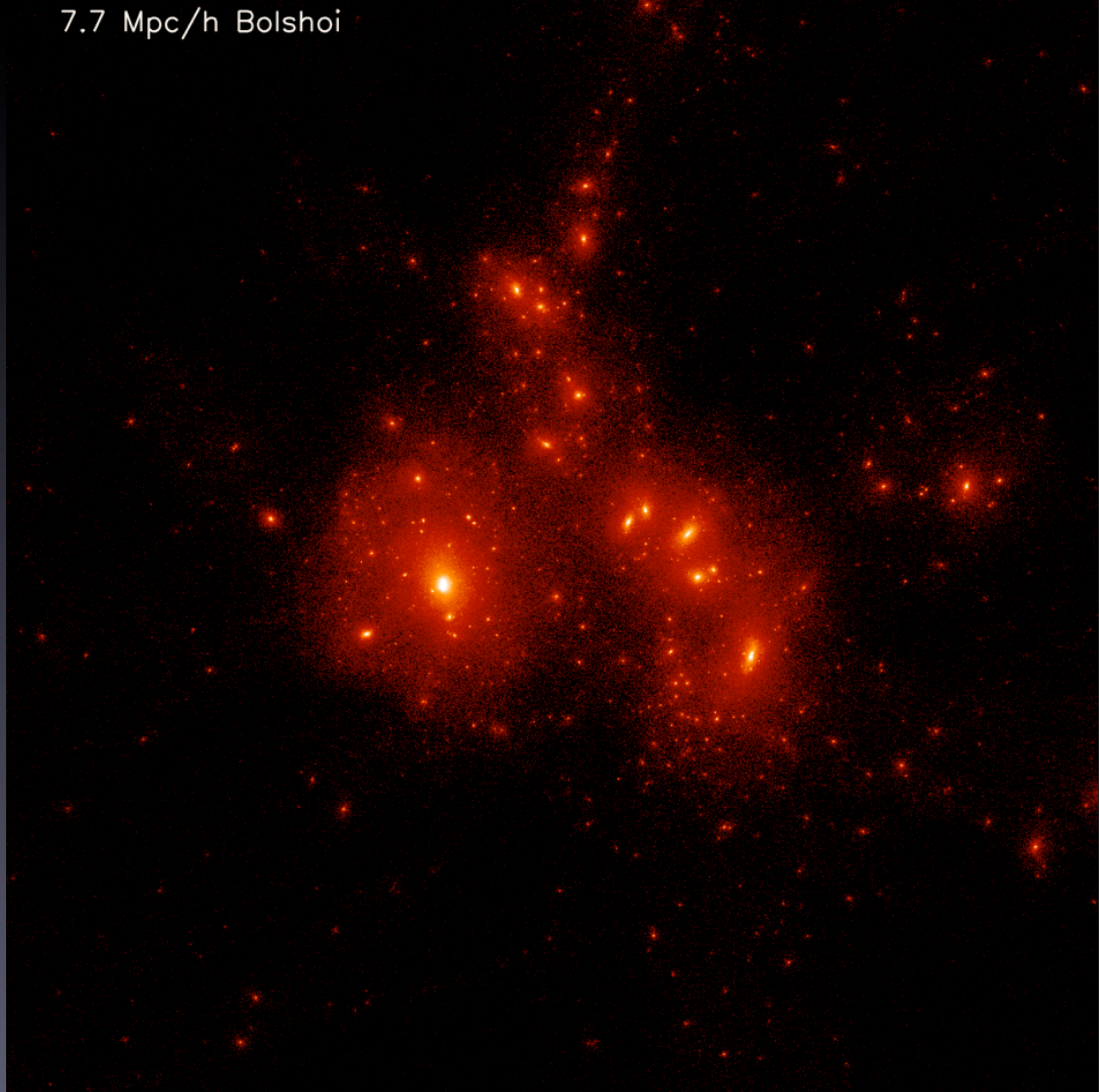



62 Mpc/h Bolshoi


31 Mpc/h Bolshoi

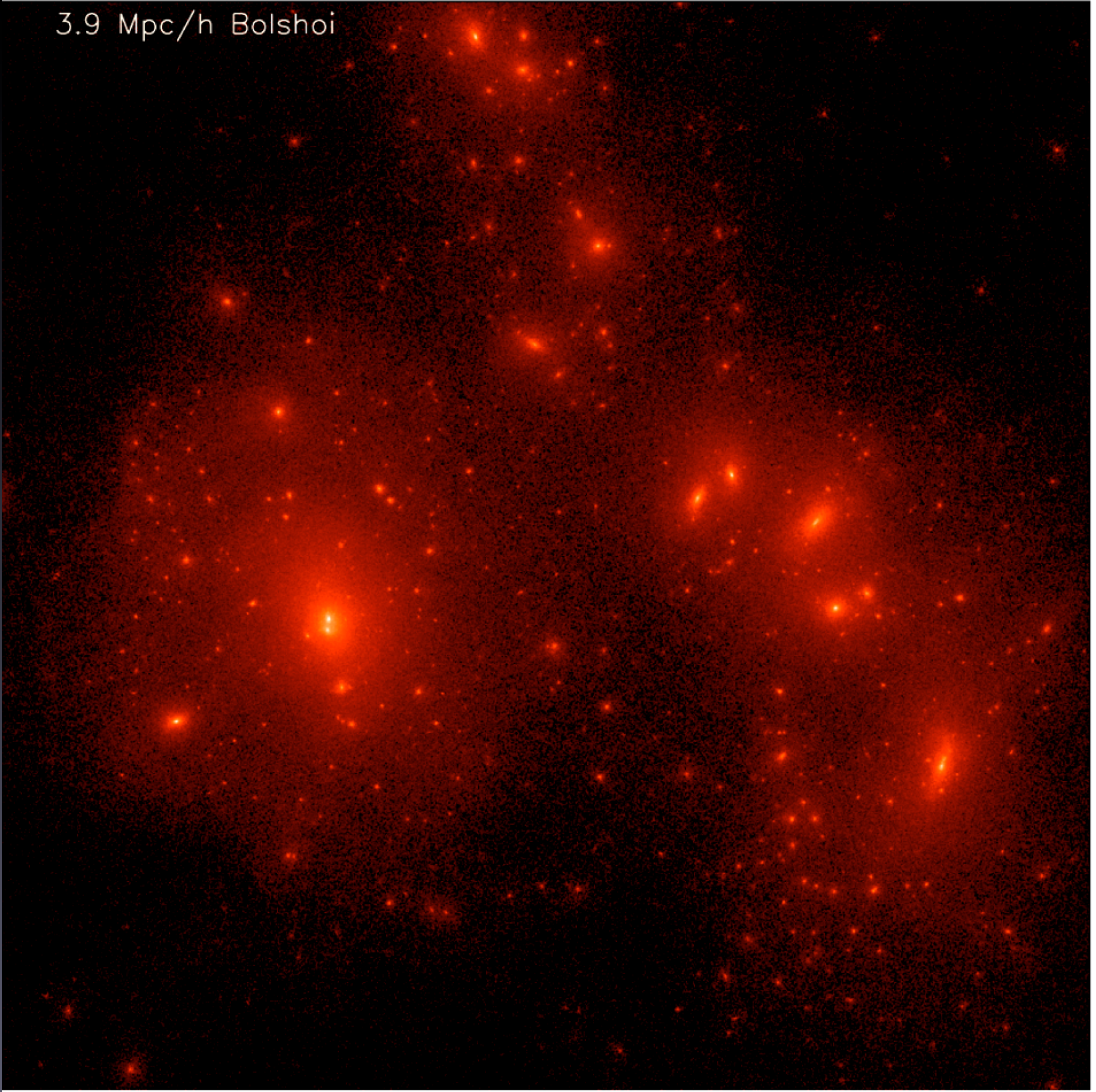

15.5 Mpc/h Bolshoi

Small Galaxy Group

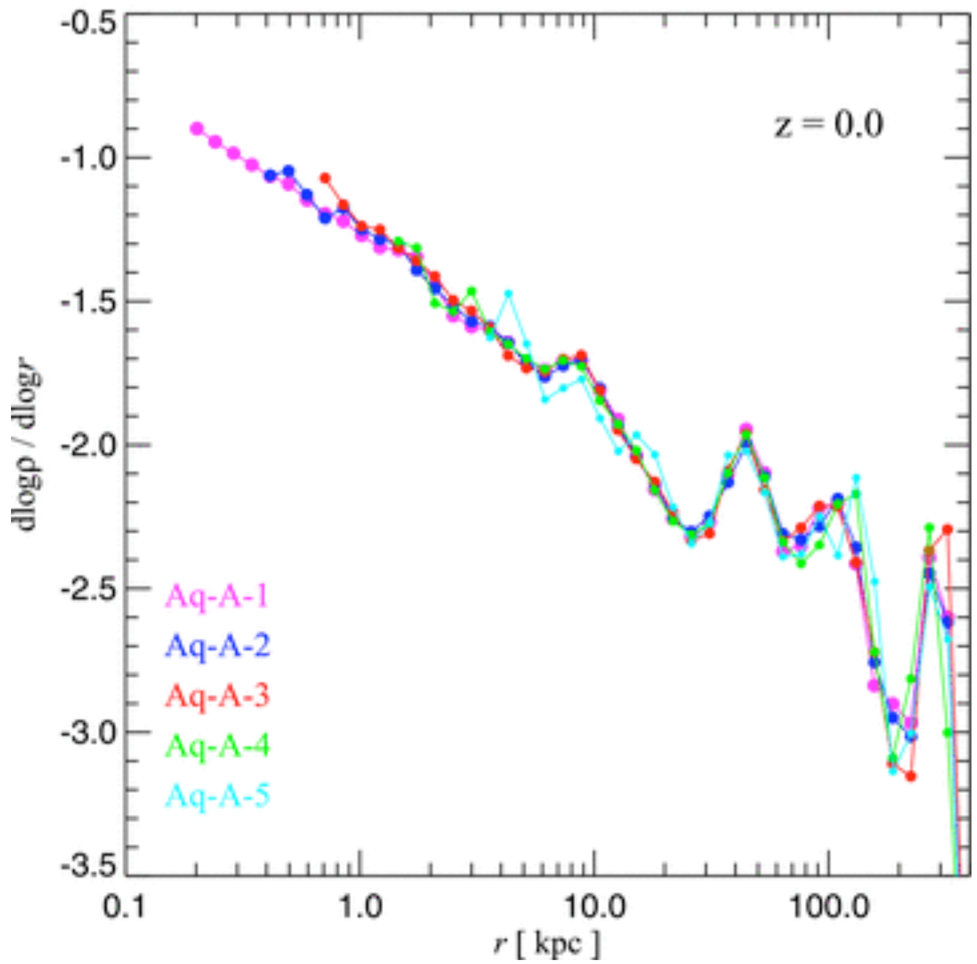


Small Galaxy Group

Central Region



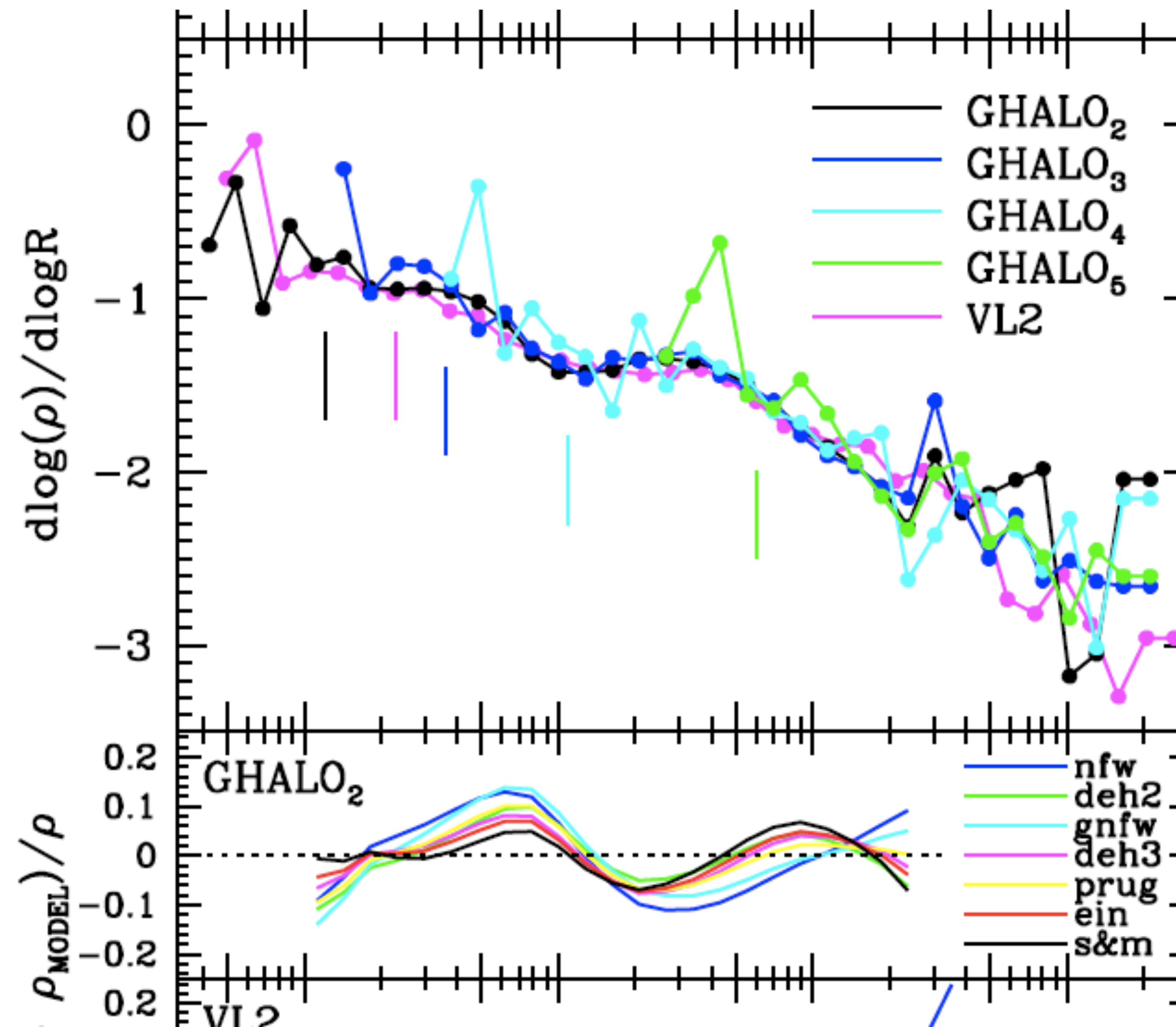
Dark matter profiles



Aquarius simulation. Springel et al 2008. WMAP-1

Central slope is very close to -1

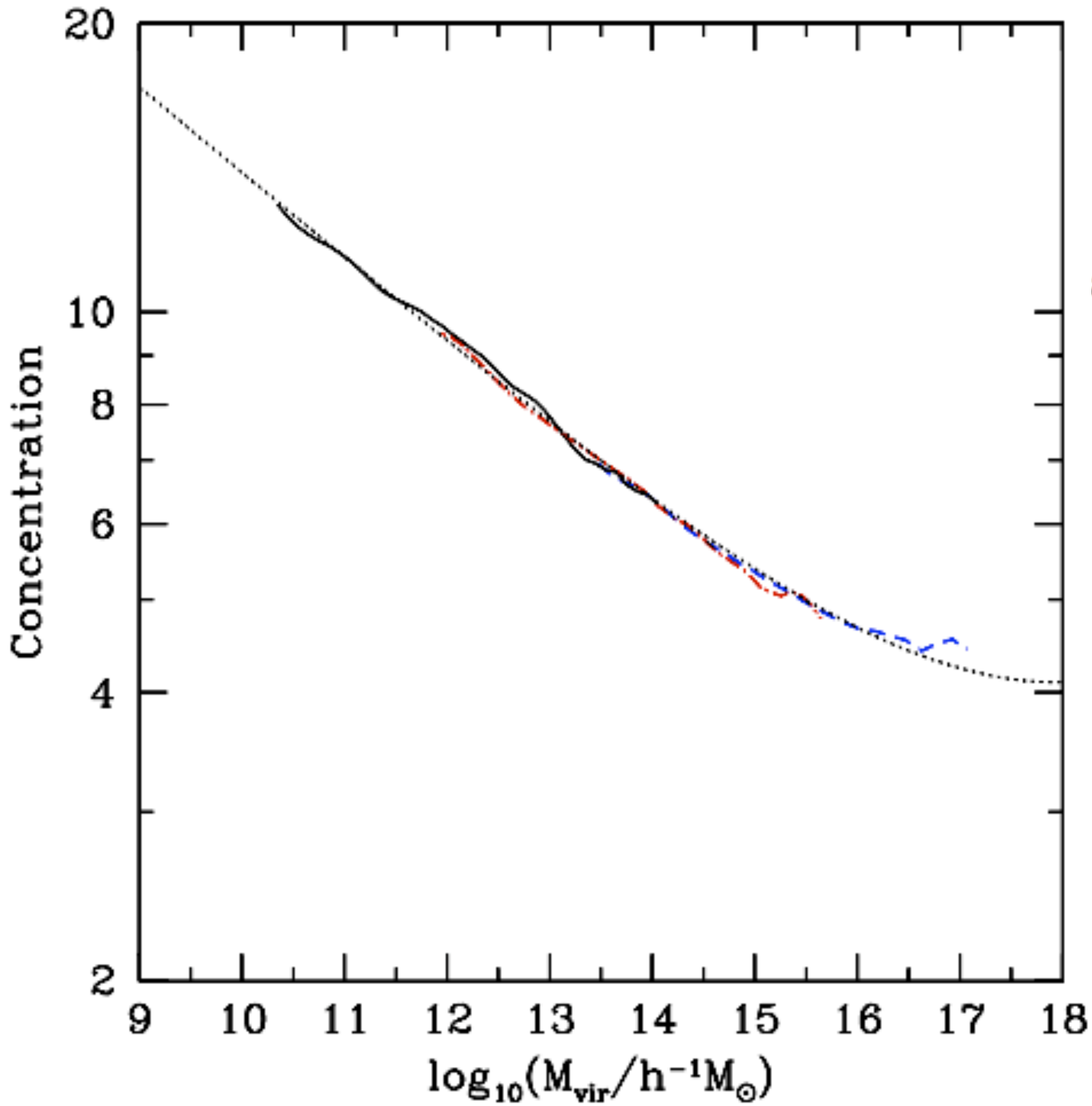
For normal galaxies it does not matter: baryons dominate



Stadel etal 2009

Halo Concentration: $C = R_{vir}/R_s$

Klypin et al 2010



$$c(M_{\rm vir}) = 9.35 \left(\frac{M_{\rm vir}}{10^{12}h^{-1}M_\odot} \right)^{-0.09}$$

and for subhalos:

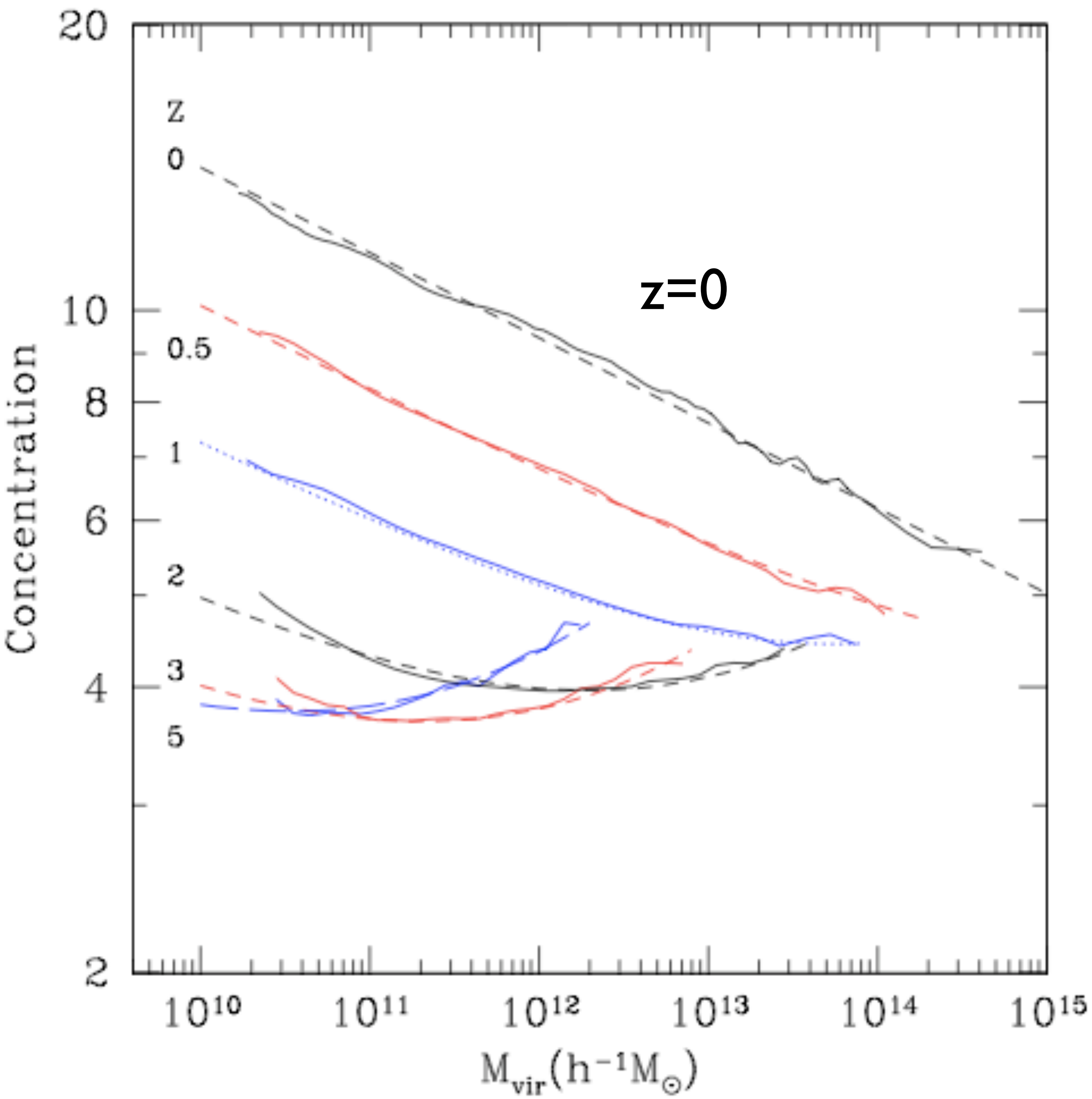
$$c(M_{\rm sub}) = 12 \left(\frac{M_{\rm sub}}{10^{12}h^{-1}M_\odot} \right)^{-0.12} .$$

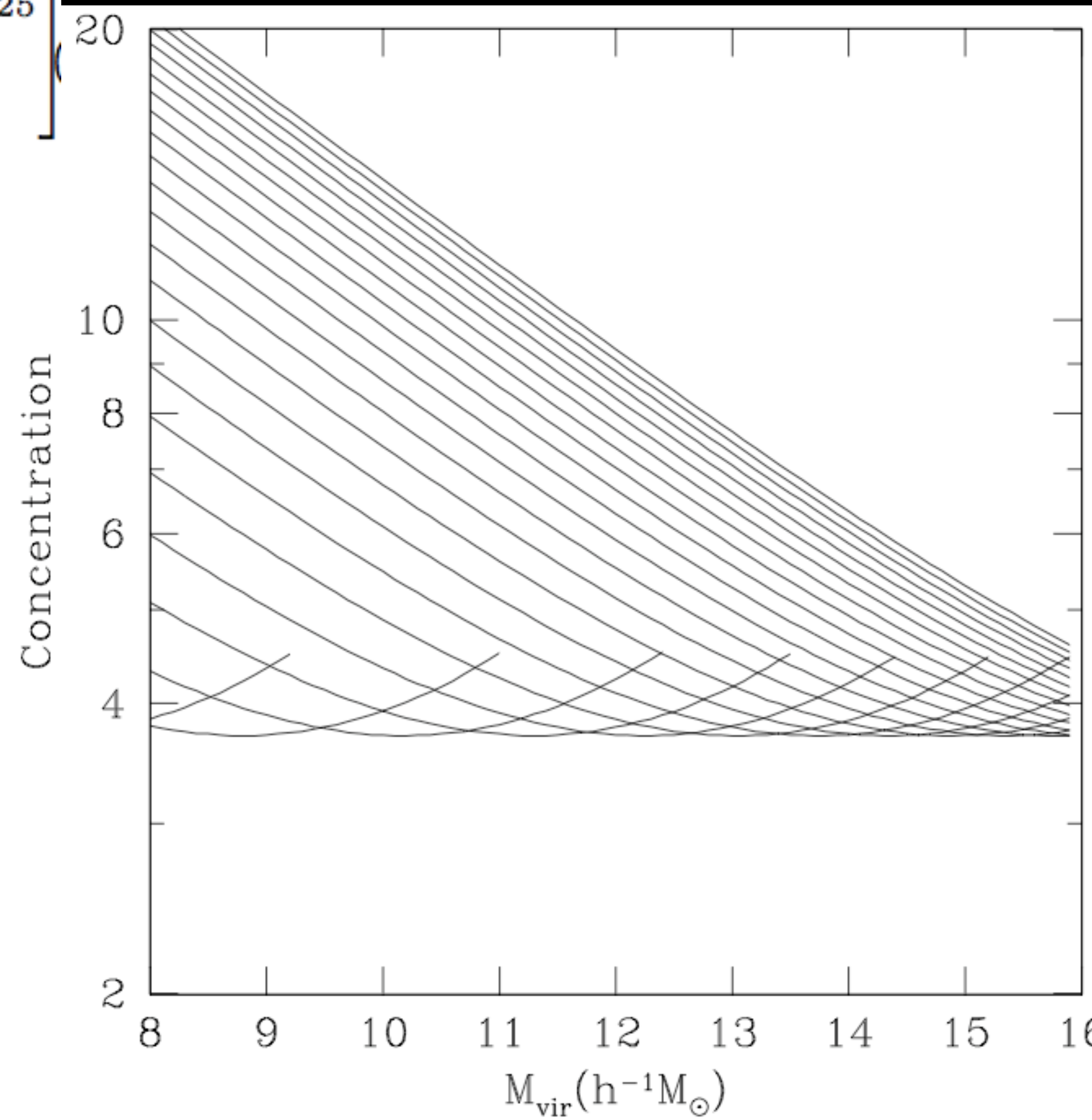
Concentration at z=0 for σ_8=0.82

Bullock etal99 is our paper, but, please do not use it

$$c(M_{\rm vir}, z) = 9.2\delta^{1.3}(z)\left(\frac{M_{\rm vir}}{10^{12}h^{-1}M_\odot}\right)^{-0.09} \times \left[1 + 0.013\left(\frac{M_{\rm vir}}{10^{12}h^{-1}M_\odot}\delta(z)^{-\frac{1.3}{0.09}}\right)^{0.25}\right]$$

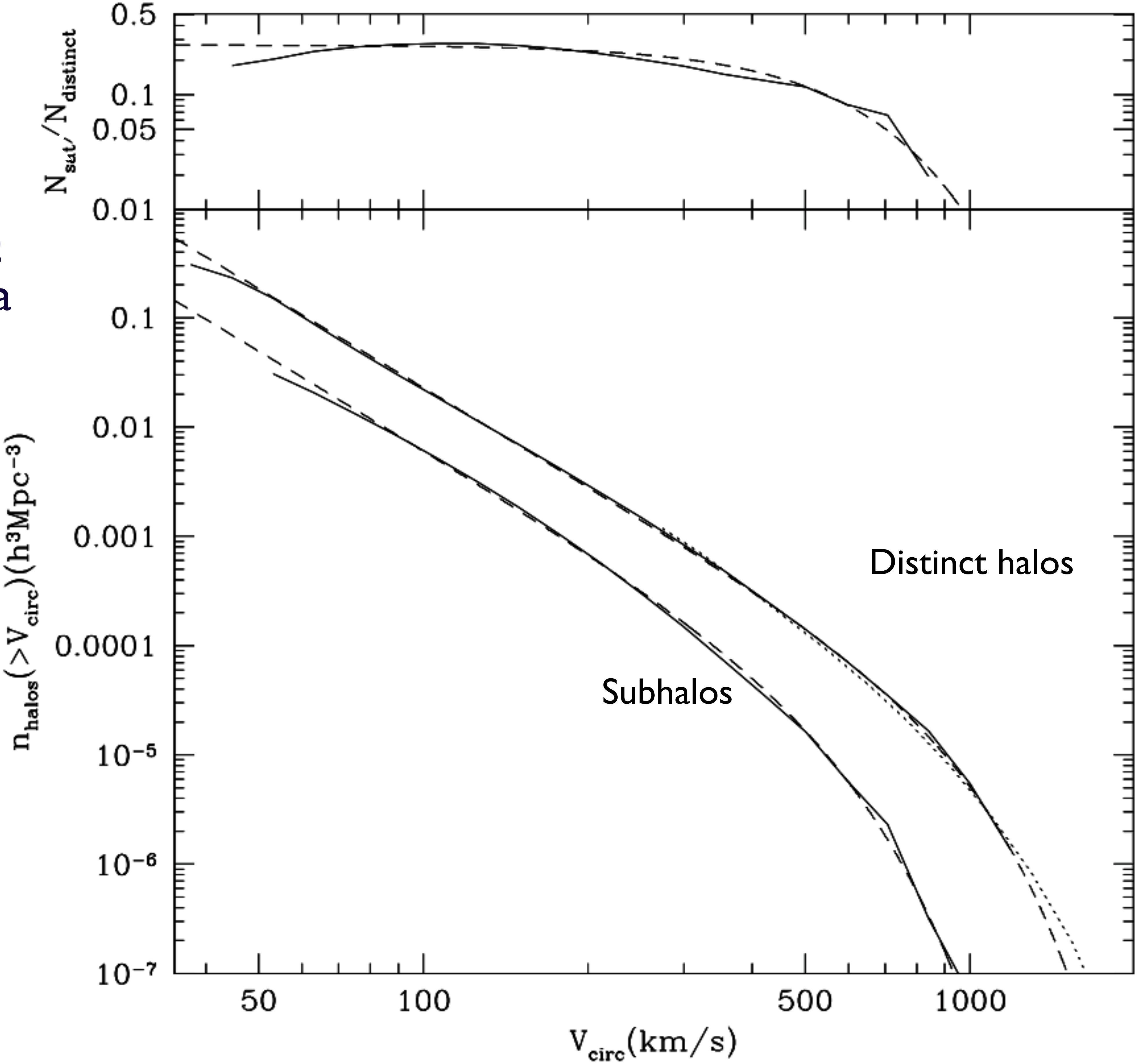
Halo Concentration





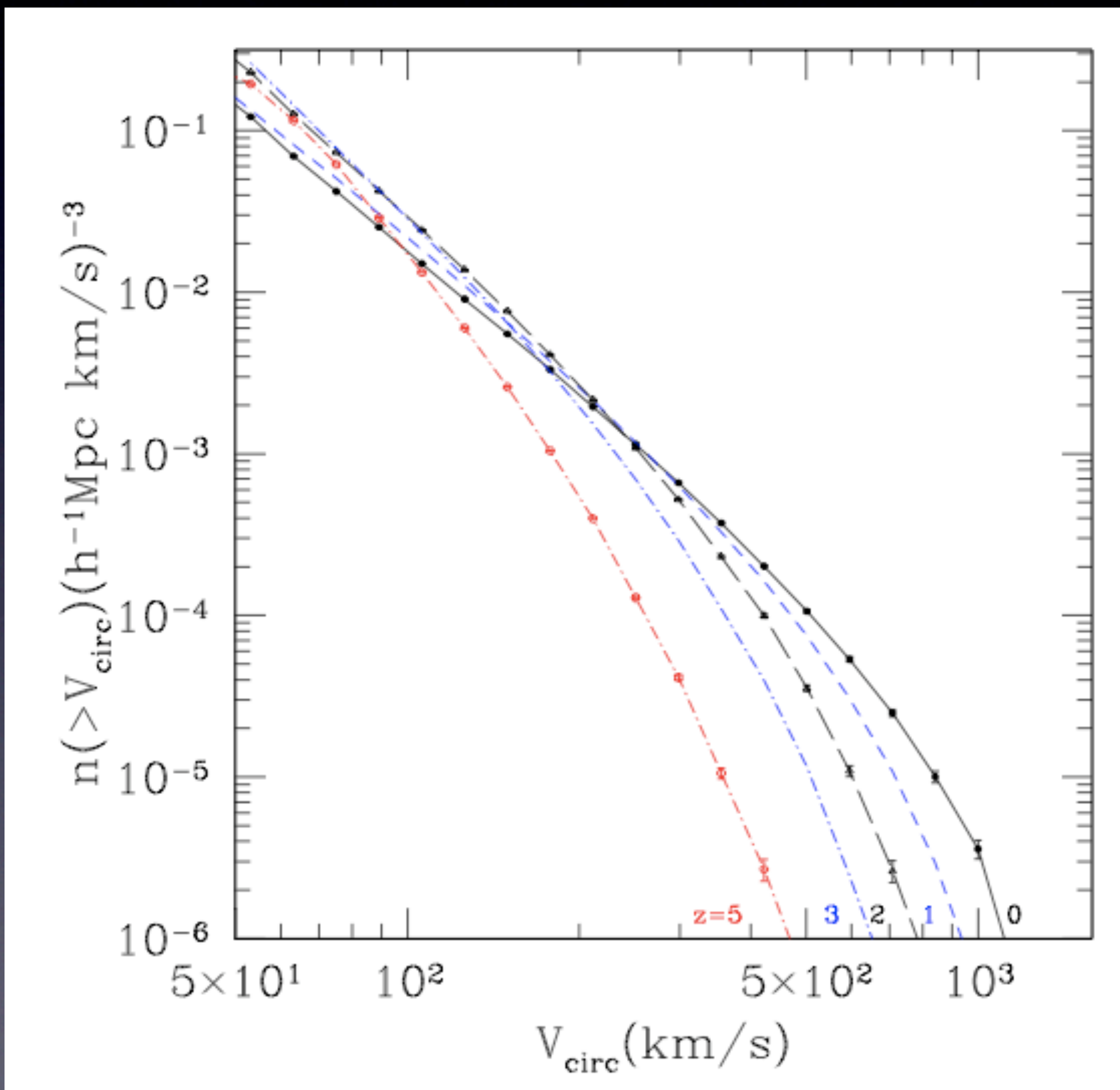
Velocity Functions

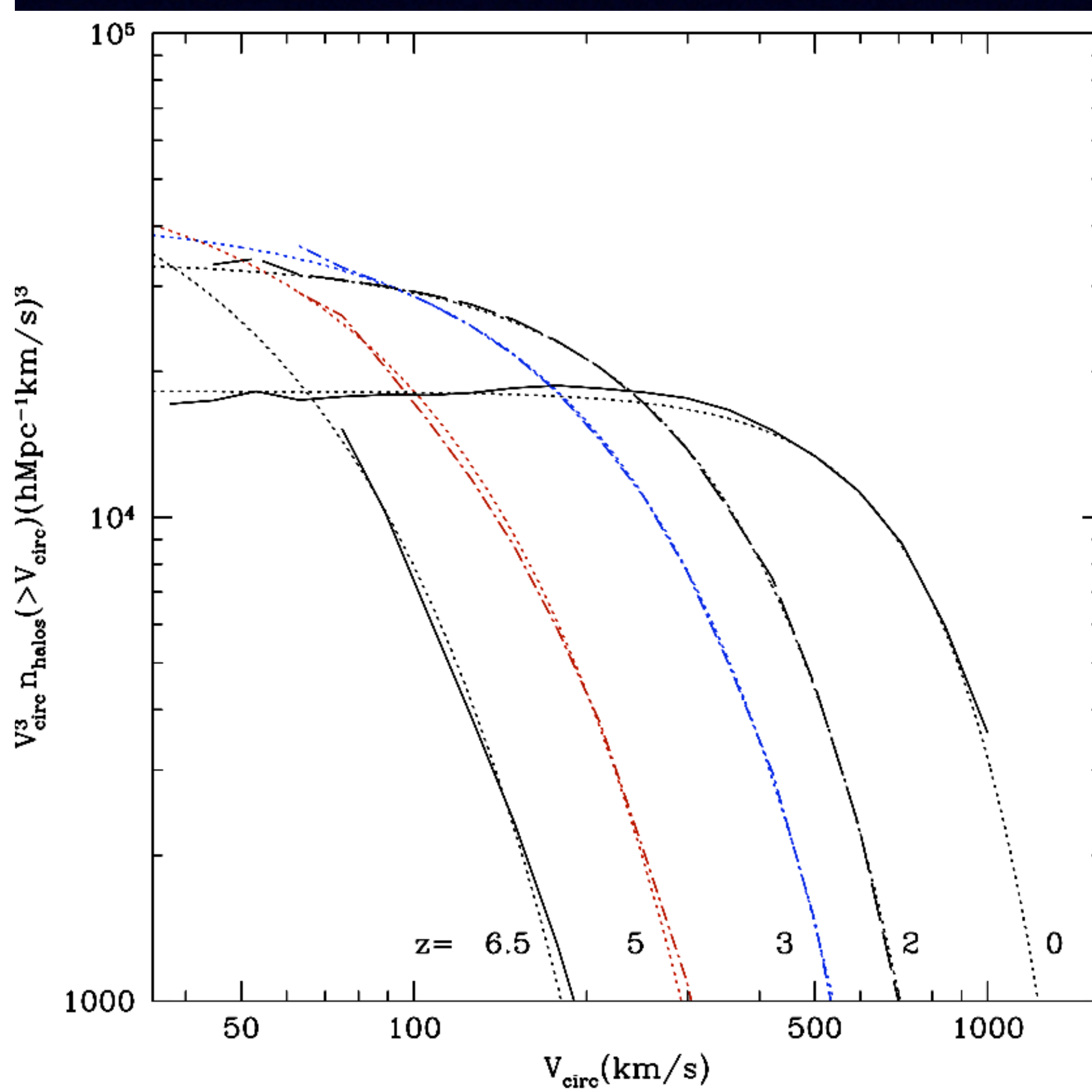
From Magellanic Clouds to Coma Cluster

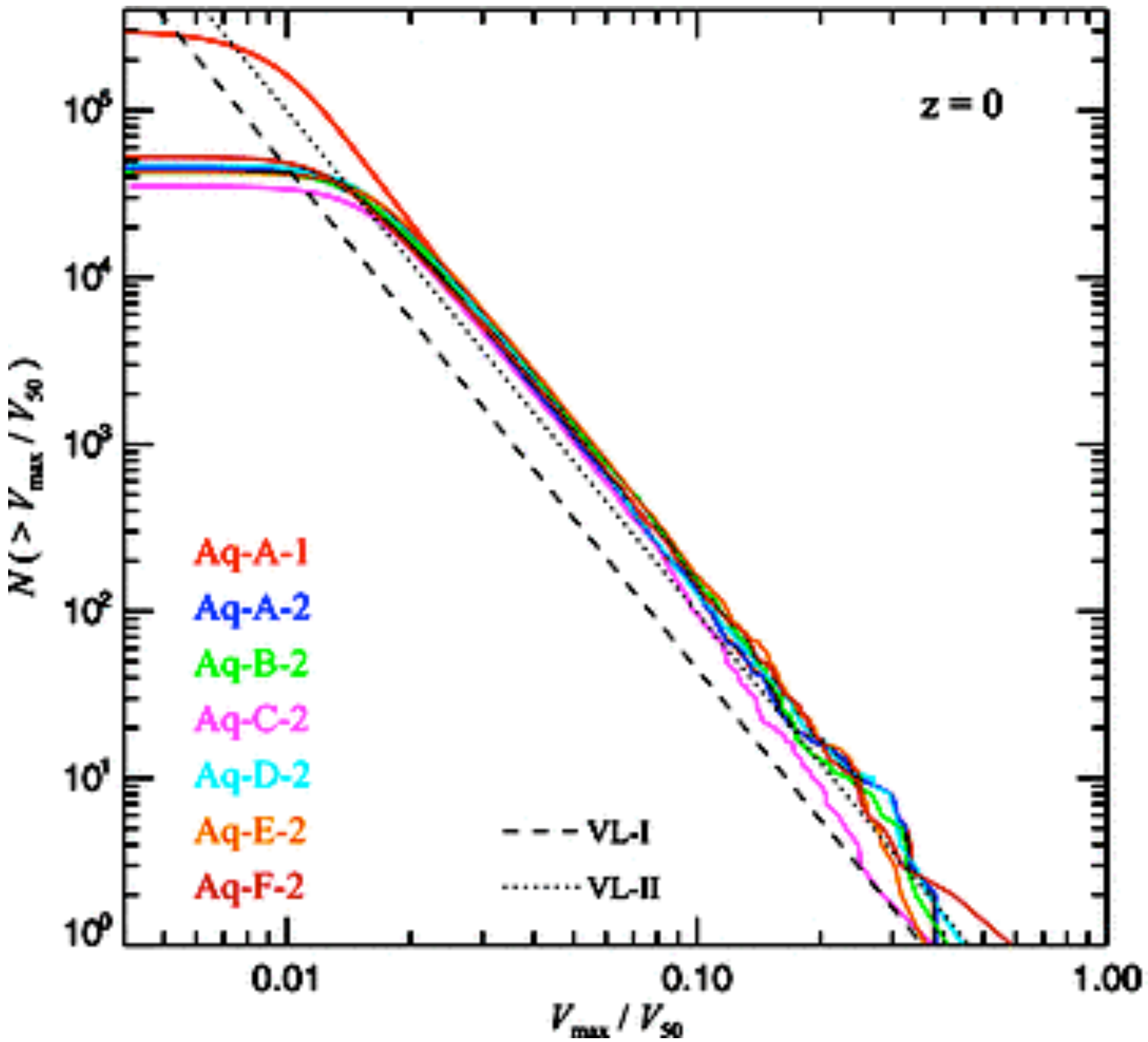


250Mpc/h
8G particles
1kpc resolution

Accurate predictions for Velocity function of distinct halos







Aquarius simulation. Springel et al 2008. WMAP-1

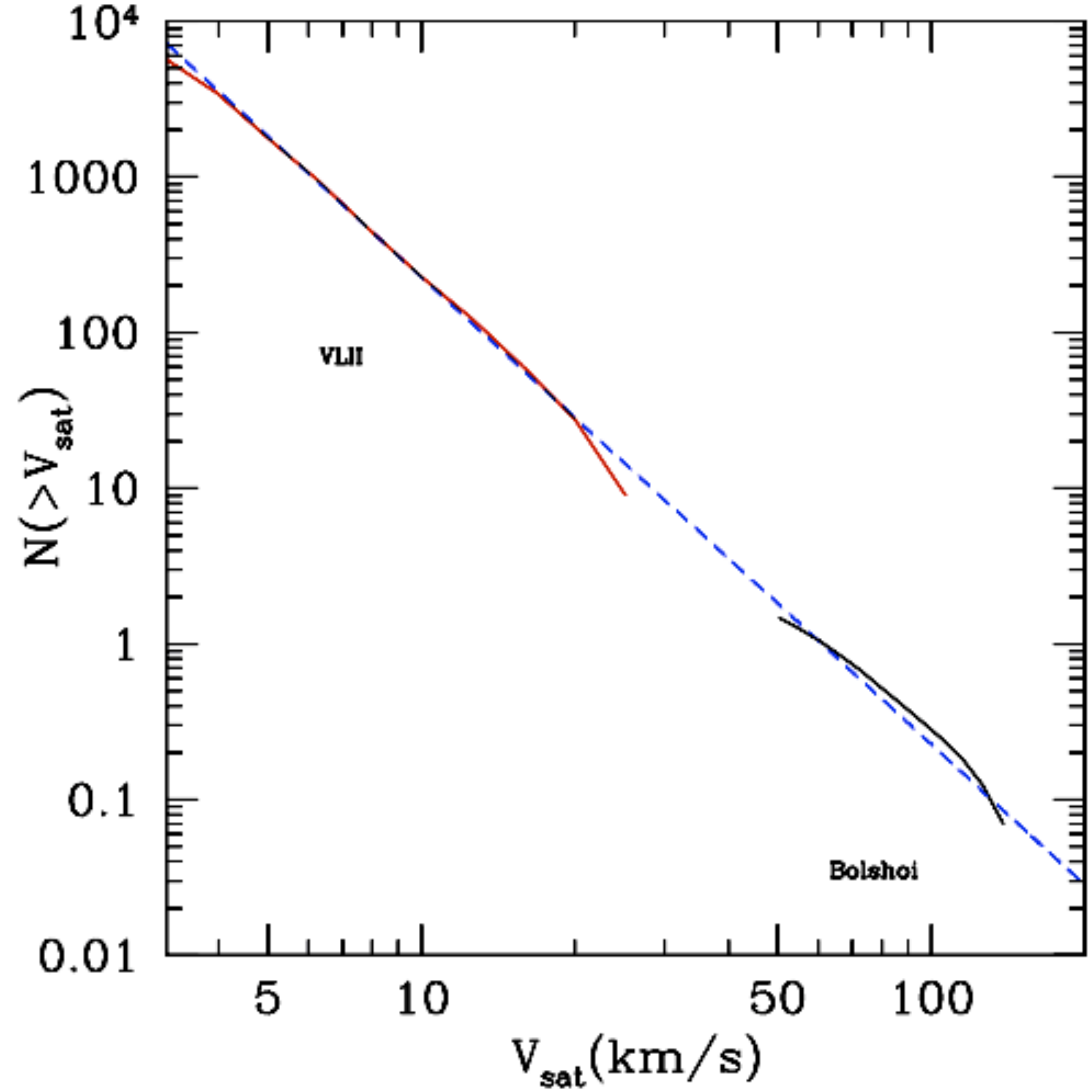
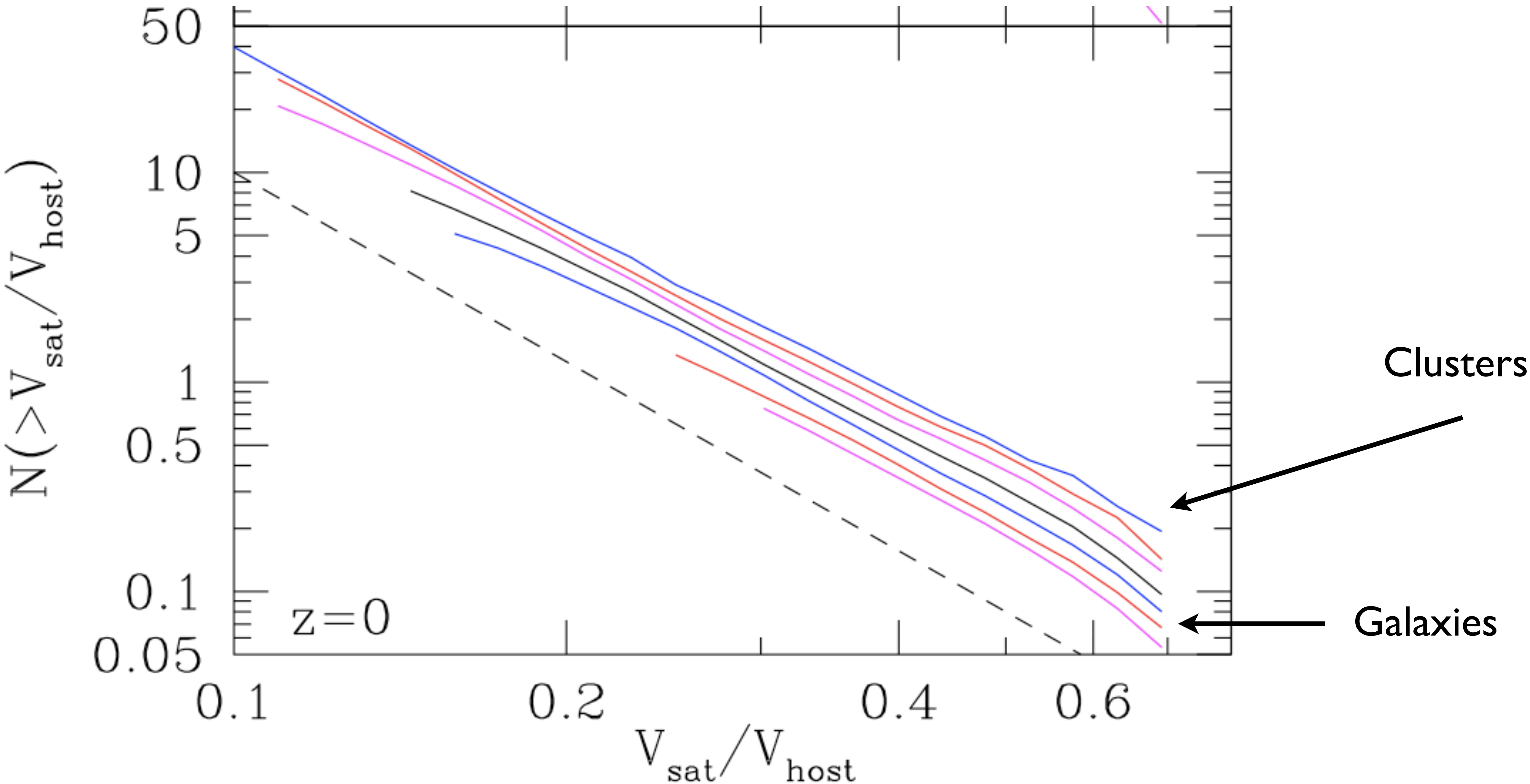


Fig. 18.— Comparison of satellite velocity functions in Via Lactea II and Bolshoi simulations for halos with V_{circ} = 200 kms/s and $M_{vir} \approx 1.3 \times 10^{12} h^{-1} M_\odot$. The dashed line is a power law with the slope −3, which provides excellent fit to

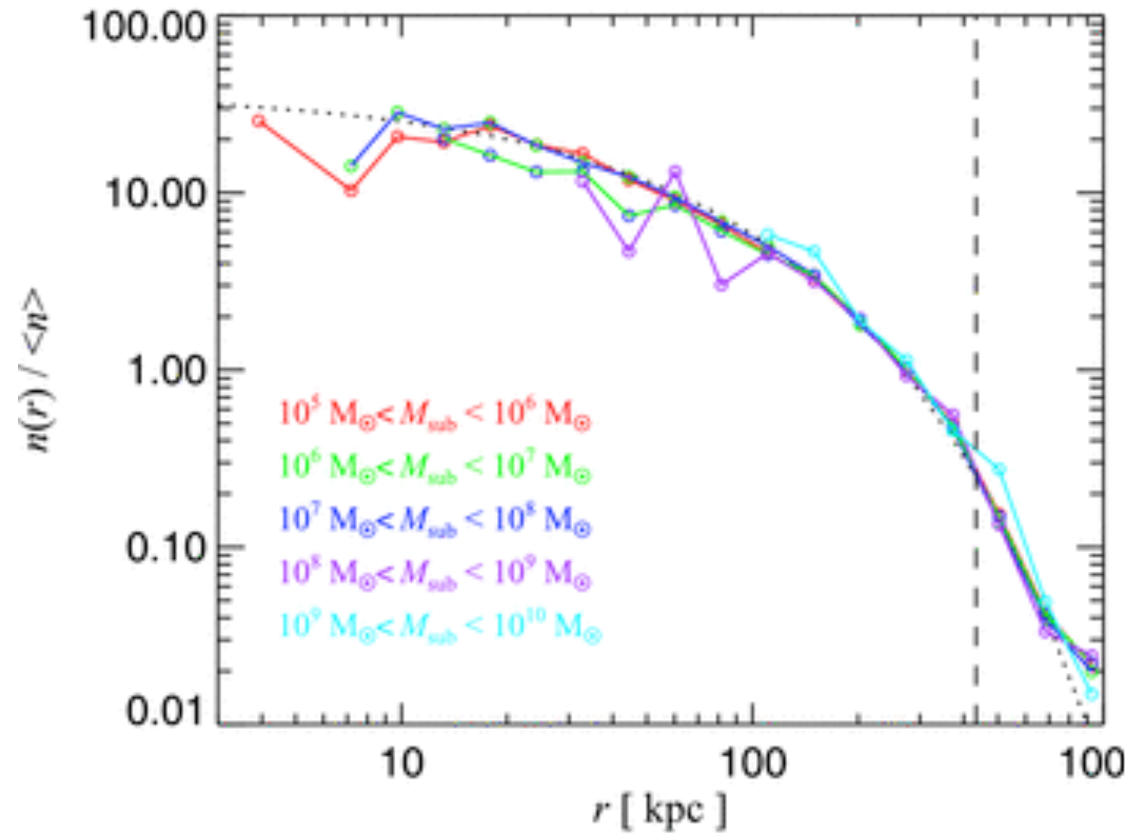
Bolshoi and ViaLactea II. Klypin et al 2010. WMAP-7

$$n(>V) = AV^{-3}$$

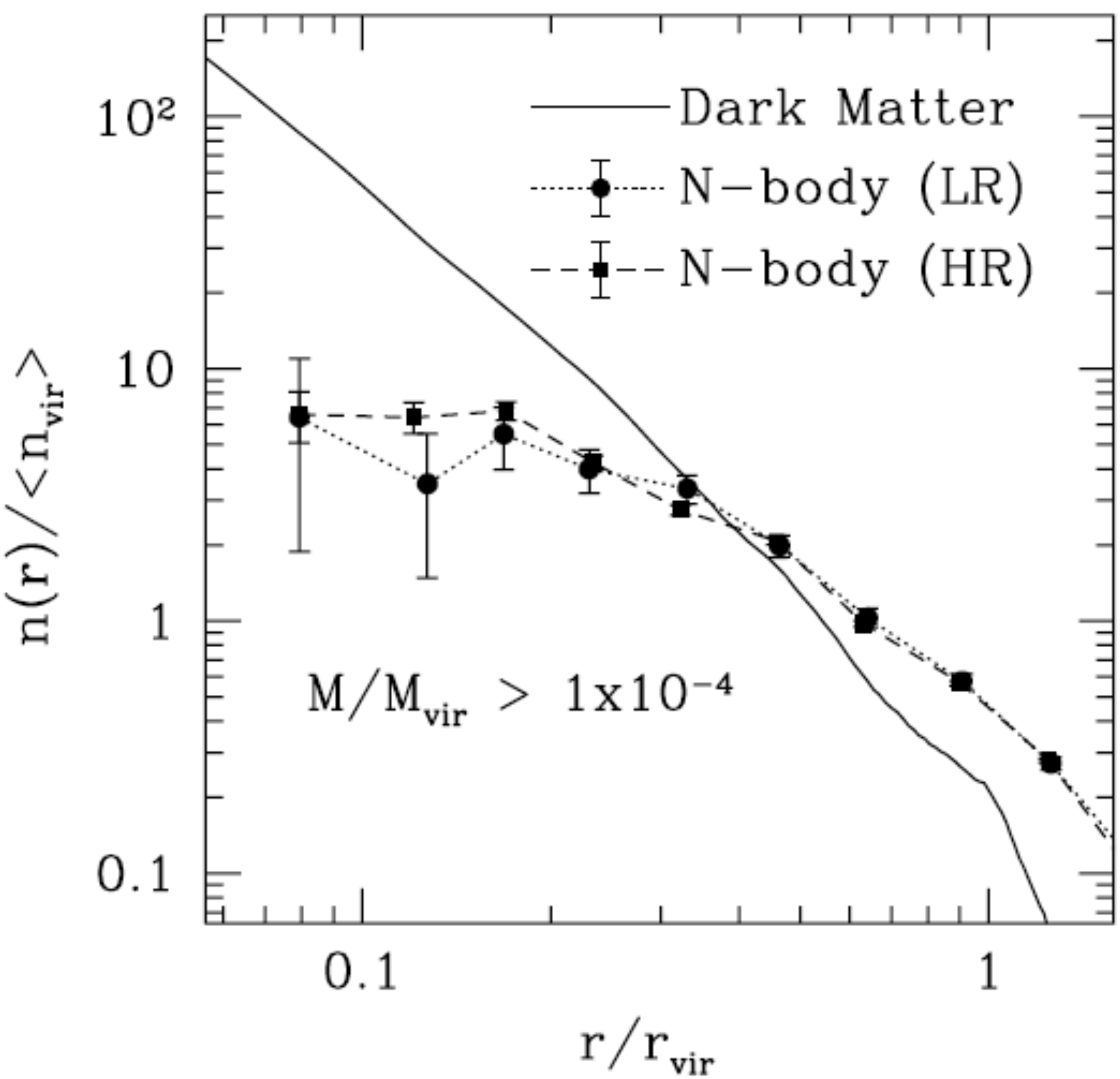


Number of satellites increases with the mass of parent halo

Gao etal 2004, Klypin et al 2010. WMAP-7



Aquarius simulation. Springel et al 2008.
WMAP-1
Subhalos are selected by mass. This gives an impression of a very large core



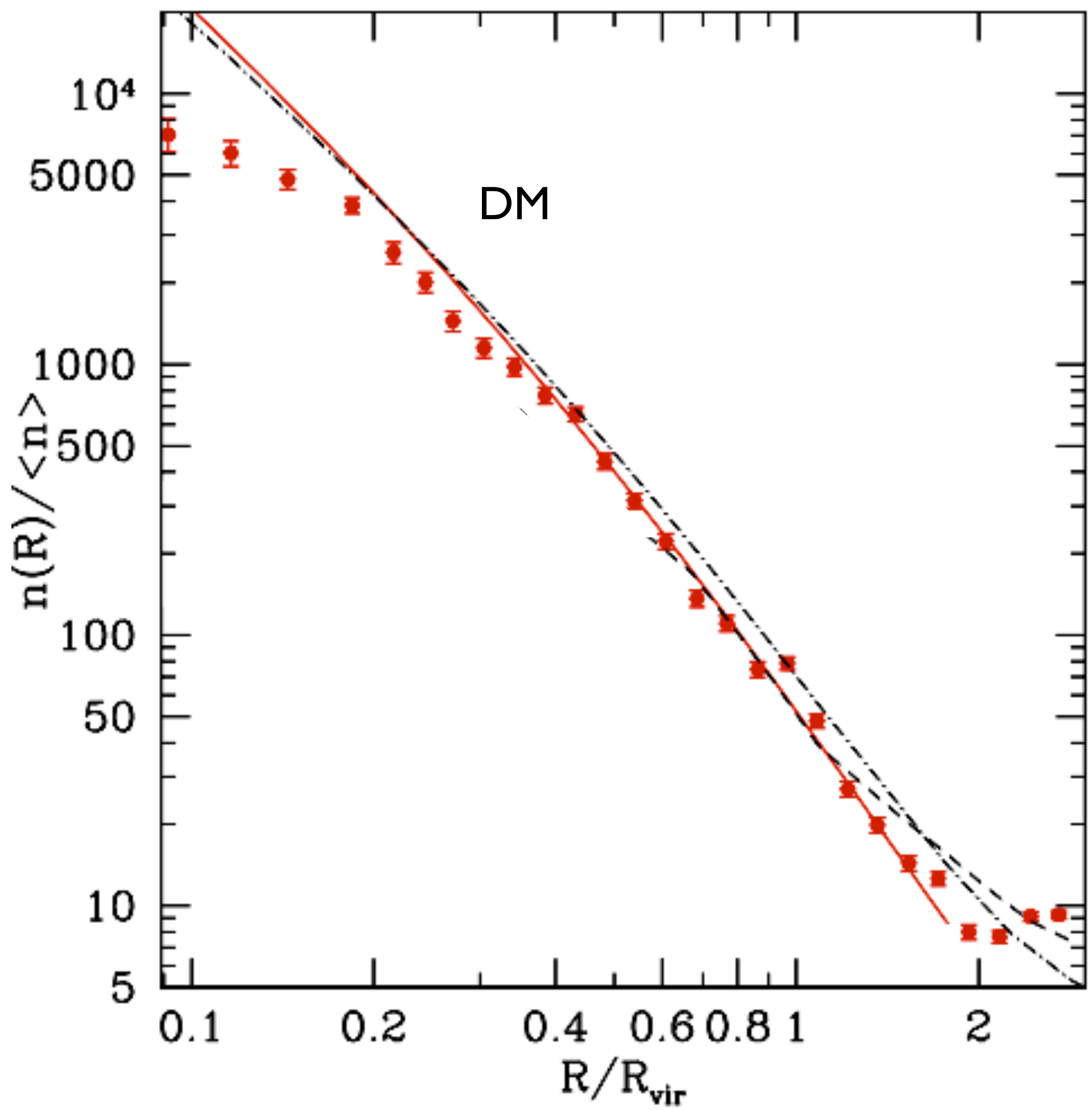
Nagai & Kravtsov 2005

Symbols are satellites in Via Lactea II simulation (1G particle, one halo with Vcirc =200km/s) normalized using Bolshoi

Curves are n(r) DM density profile

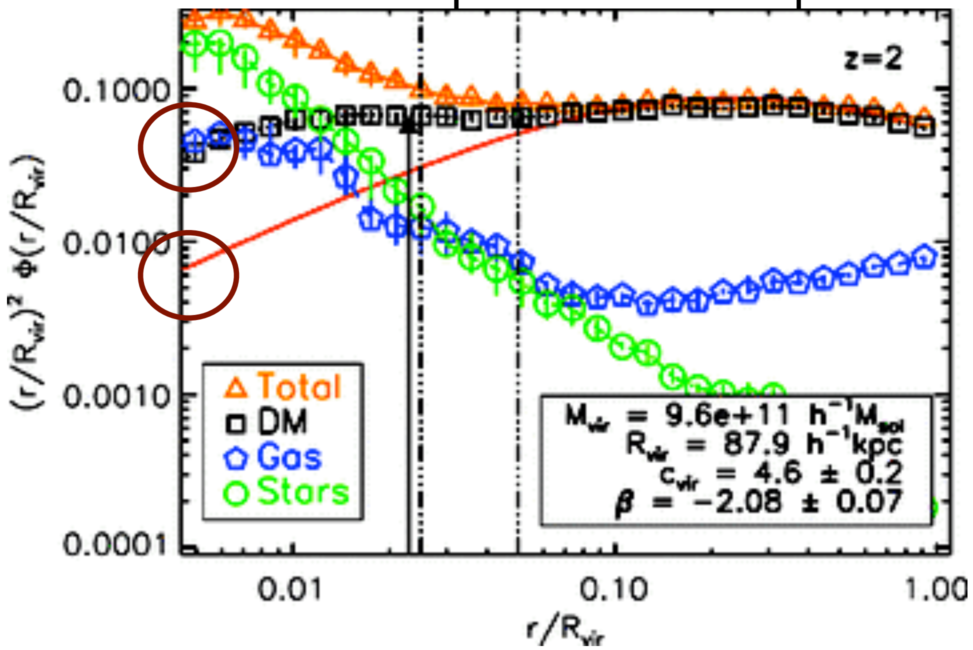
Dash - satellites in Bolshoi

Satellites tightly follow DM at r > 0.2Rvir: they are NOT 'flatter' distributed in the outer regions of halos.



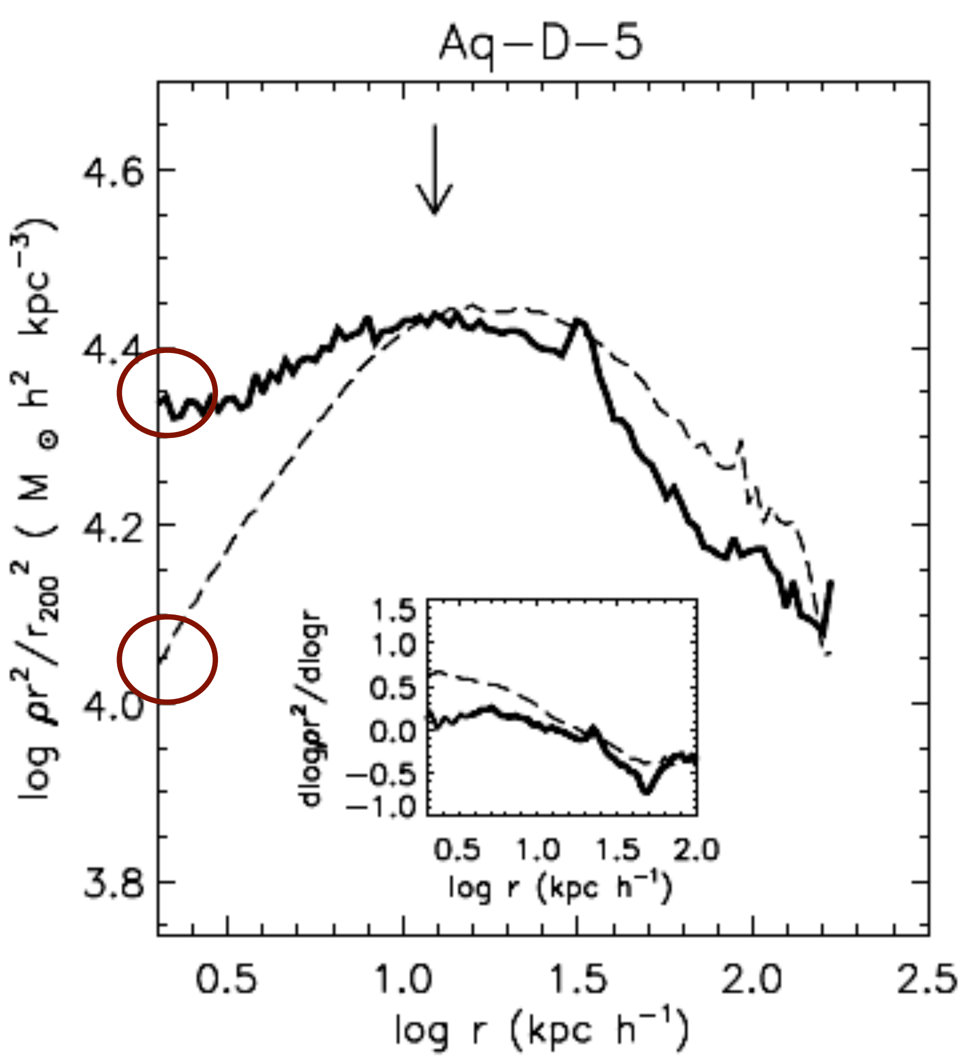
Bolshoi and ViaLactea II. Klypin et al 2010. WMAP-7
Subhalos are selected by circular velocity.
Satellites follow Dark matter for R= 0.2-2Rvir

Red line NFW - compare with black squares. Duffy et al 2010

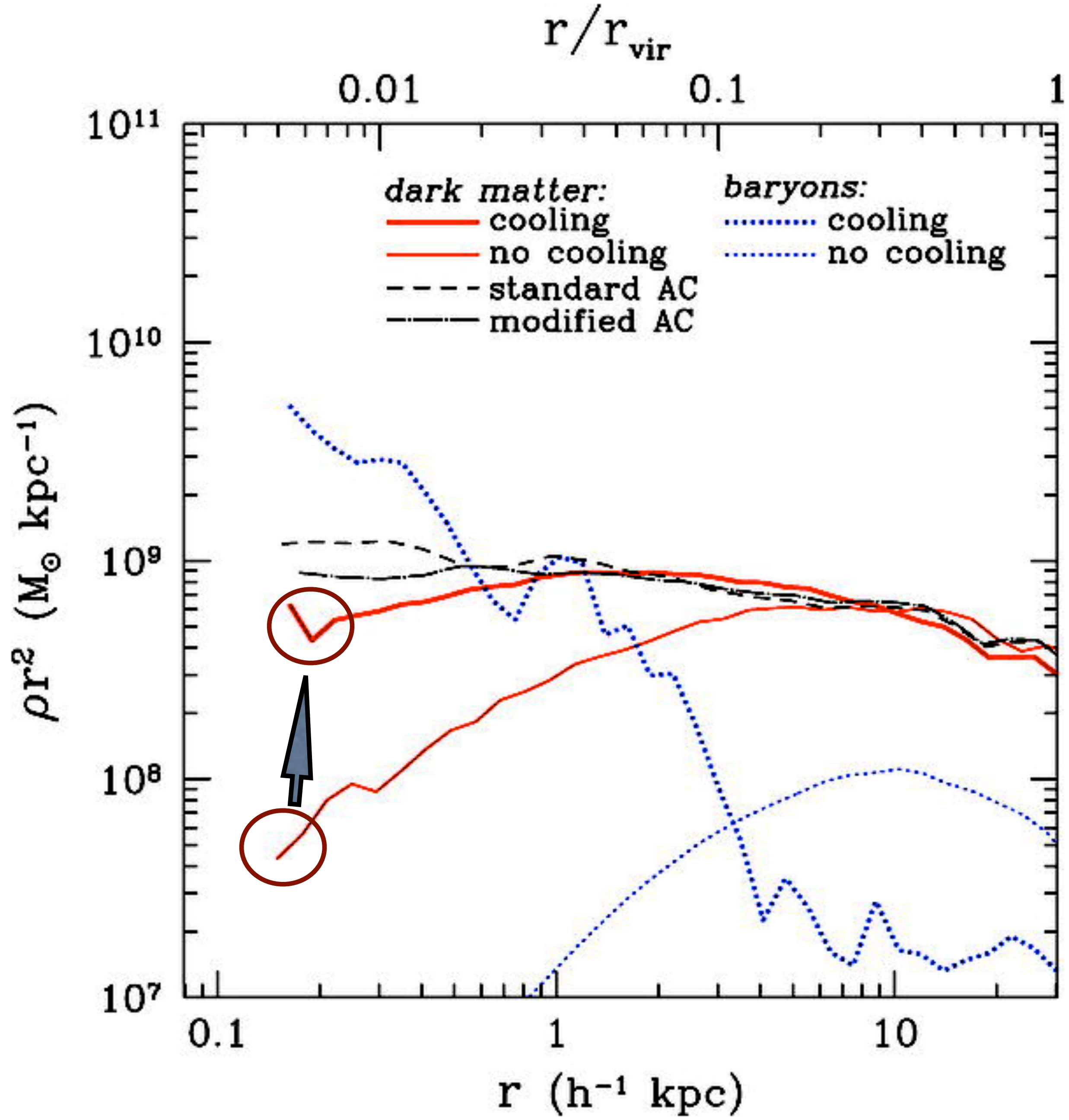


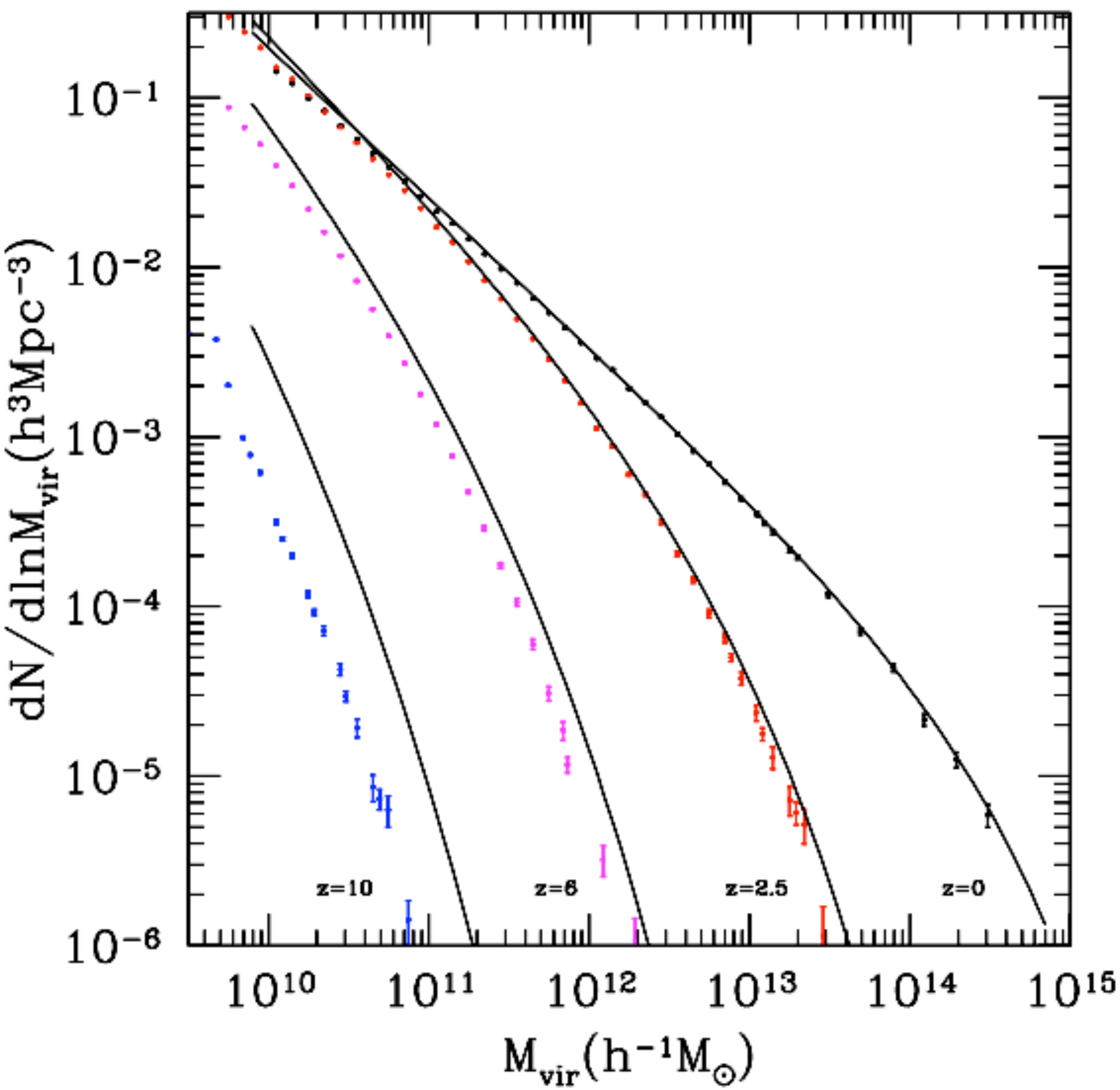
Adiabatic compression is always present. Do not forget to use it.

DM profiles - [dash: no baryions] .Tissera et al 2009



compare red lines. Gnedin et al 2004





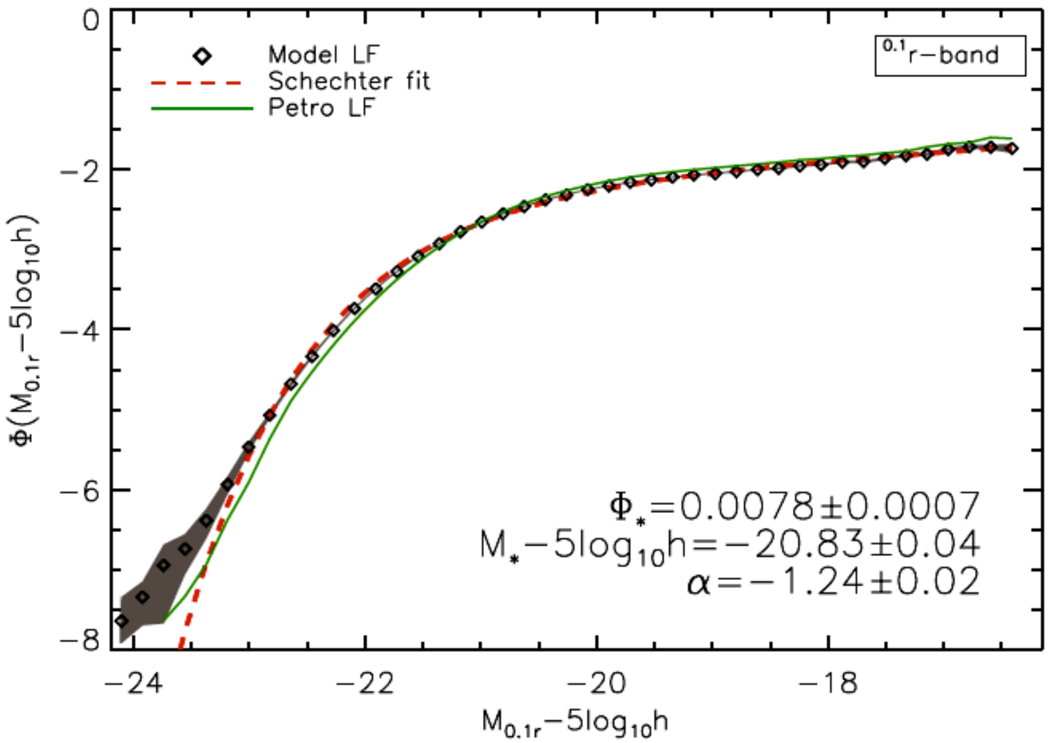
Full: Sheth&Tormen
Symbols: N-body Bolshoi,
Spherical overdensity

Correction factor for Sheth&Tormen:

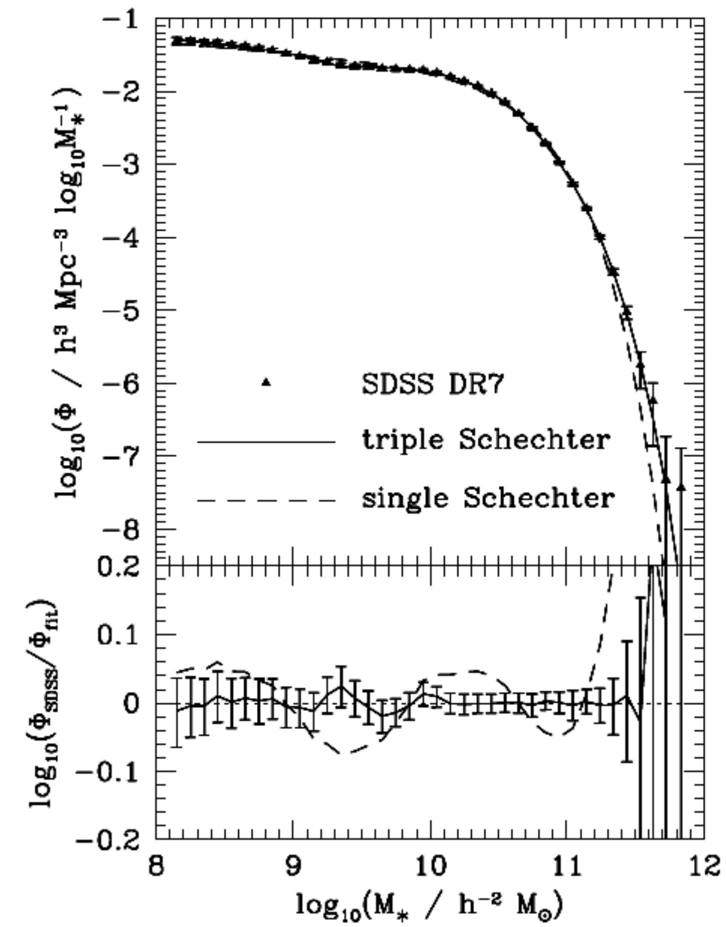
$$F(\delta) = \frac{(5.501\delta)^4}{1 + (5.500\delta)^4}$$

Bolshoi: Klypin et al 2010
Tinker 2008: z=0-2.5

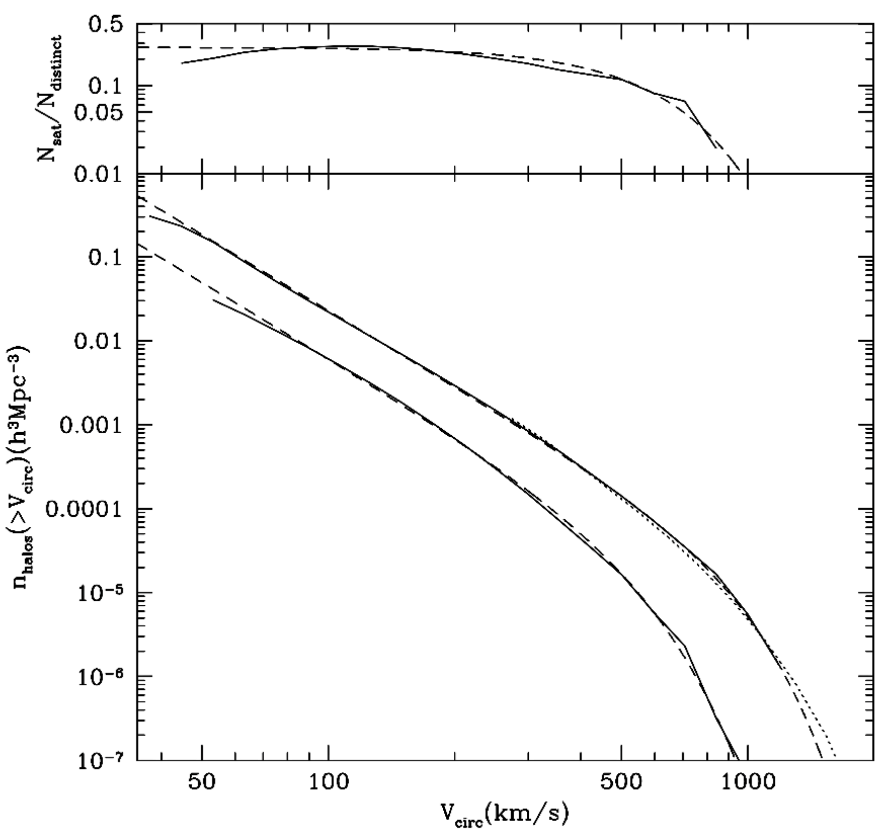
Luminosity function of galaxies



Stellar mass function of galaxies + fraction in gas



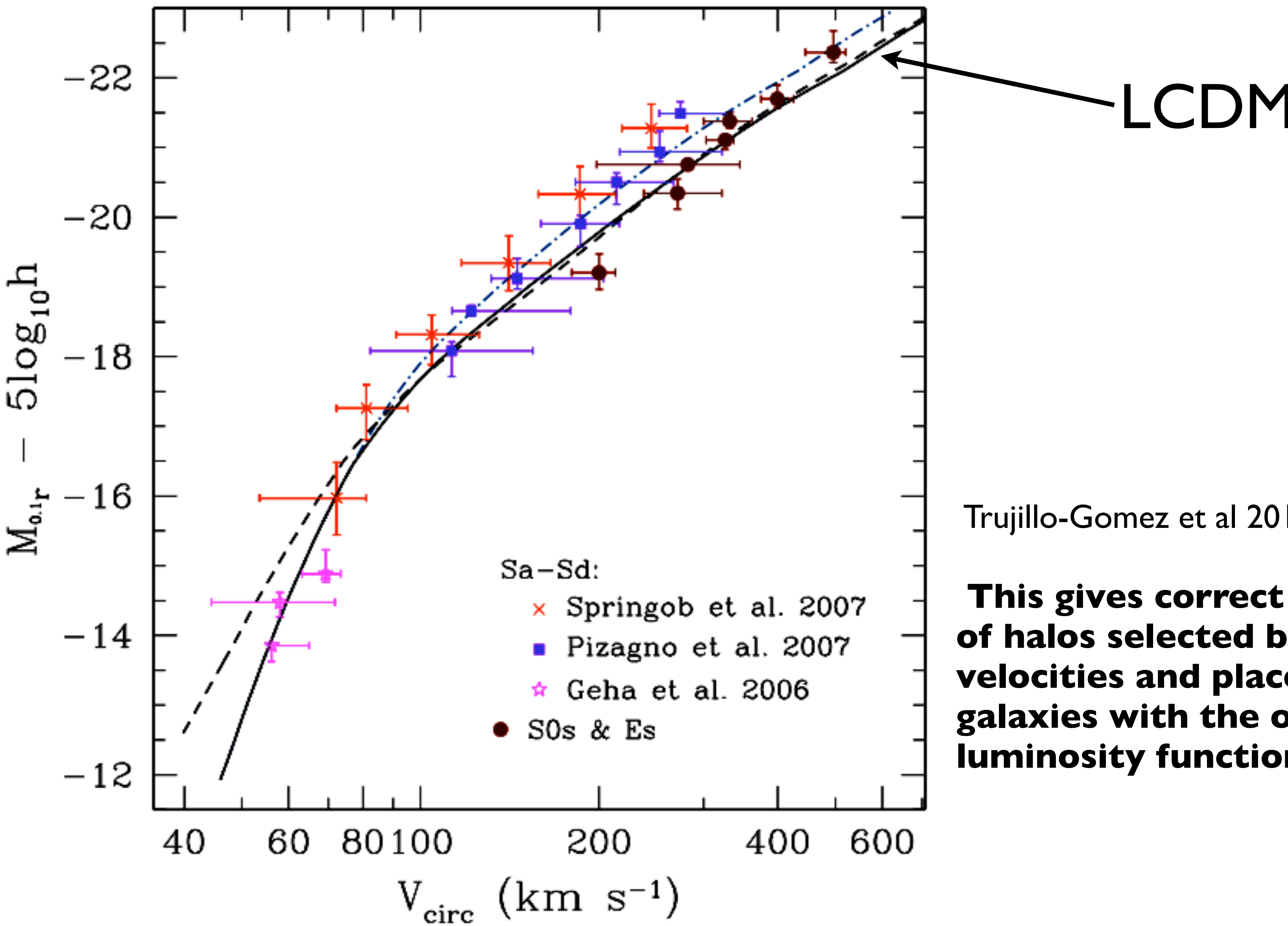
Velocity function of halos



Matching three functions gives: Luminosities and stellar masses of galaxies hosted by dark matter halos

Kravtsov etal 2004, Tasitsiomi etal 2004, Conroy etal 2006, Guo etal 2009, Klypin etal 2010

LV relation: Luminosity vs circular velocity at 10kpc



Trujillo-Gomez et al 2010. Guo etal 2009

This gives correct abundance of halos selected by circular velocities and places them in galaxies with the observed luminosity function

Amount of baryons is important

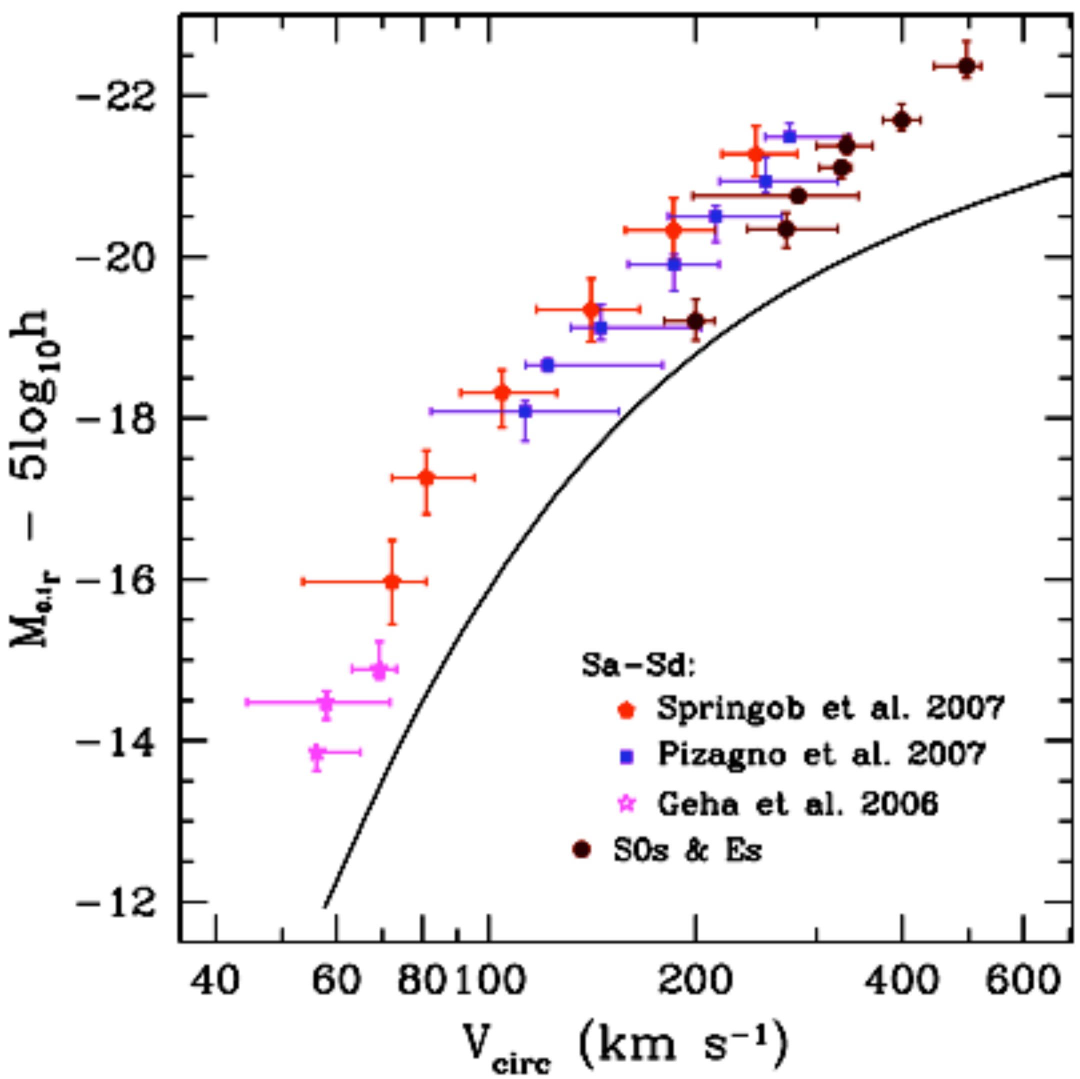


Fig. 8.— Effect of excessive mass of baryons. We assume that *half* of the universal baryon fraction within each halo forms its galaxy. Median values

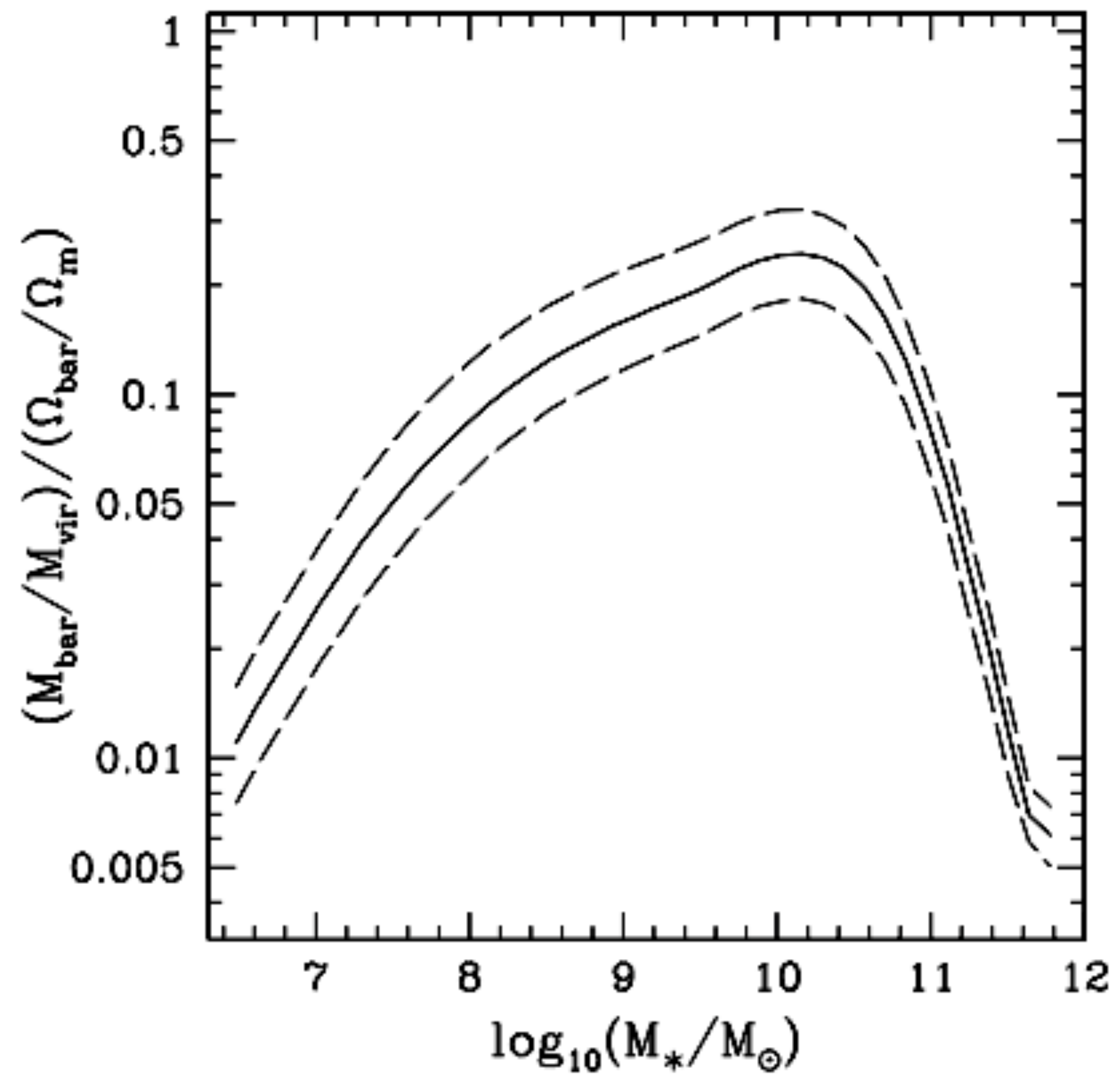
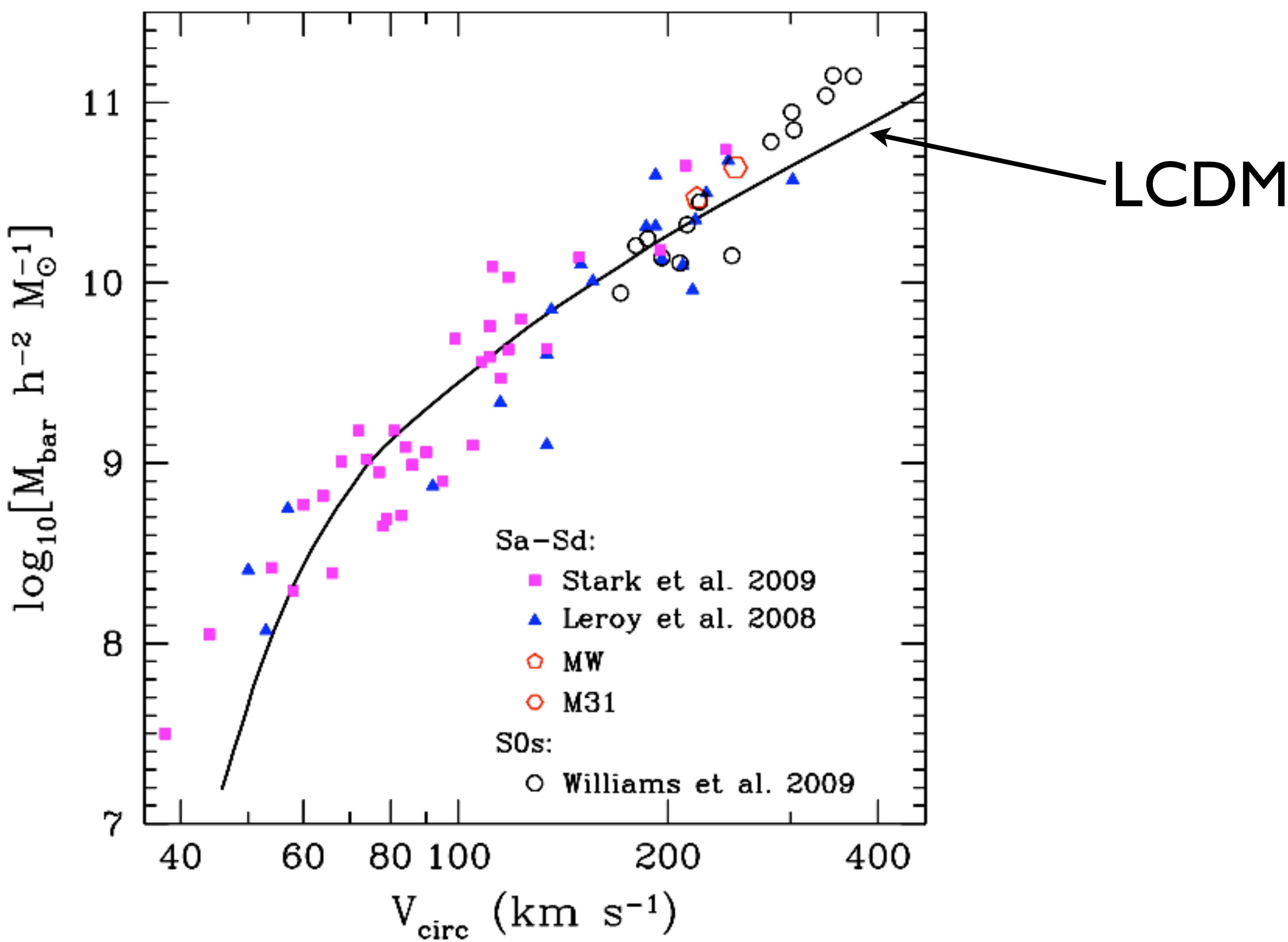
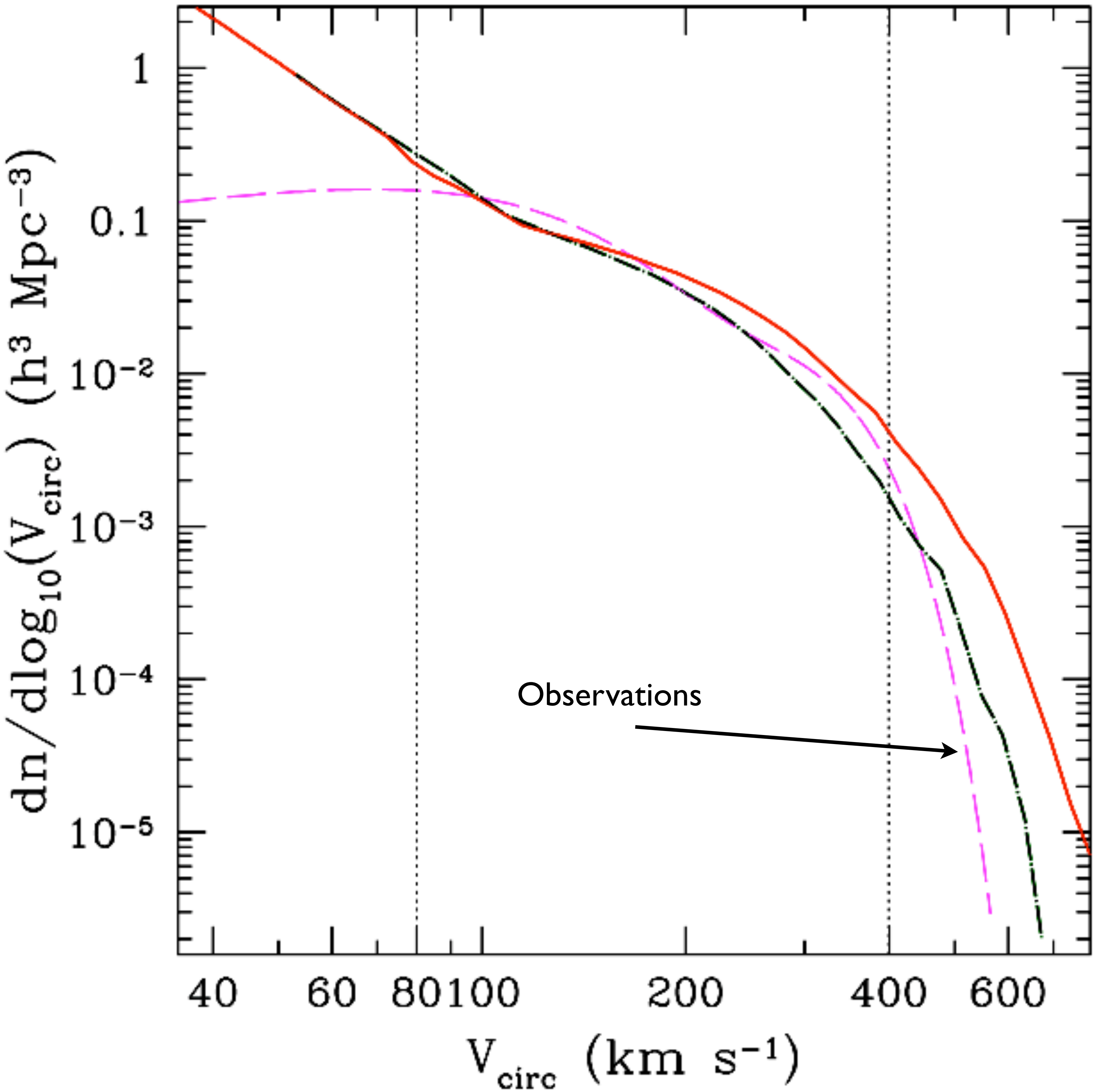


Fig. 9.— Baryon fraction relative to the universal value as a function of stellar mass for the ΛCDM model using the abundance-matching procedure. The solid lines show the median and 1-σ scatter of the distribution, which is due to the scatter in halo concentrations.

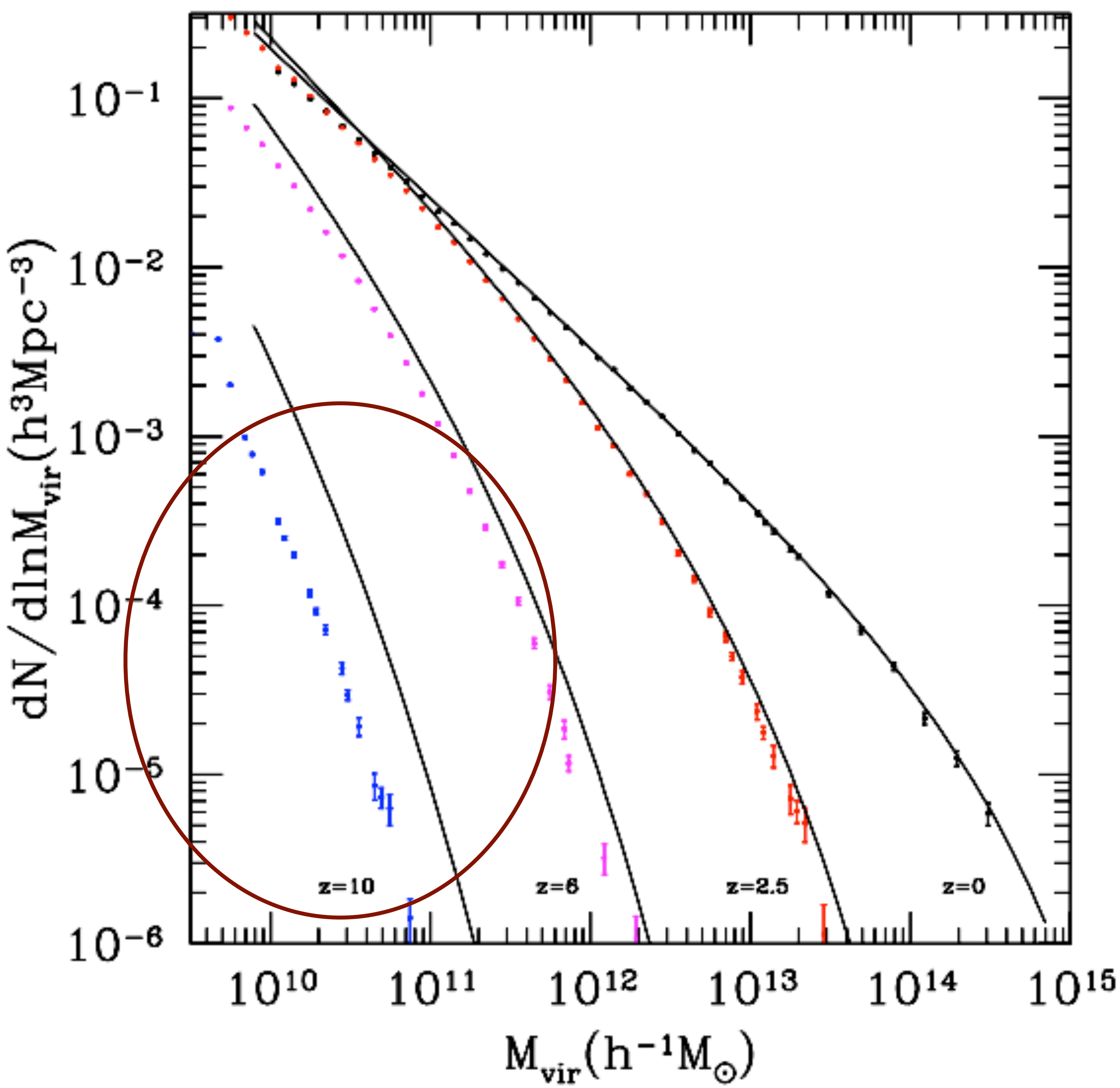
Mass of baryons in galaxies: observations vs LCDM



Number of galaxies with Vcirc: observations vs LCDM

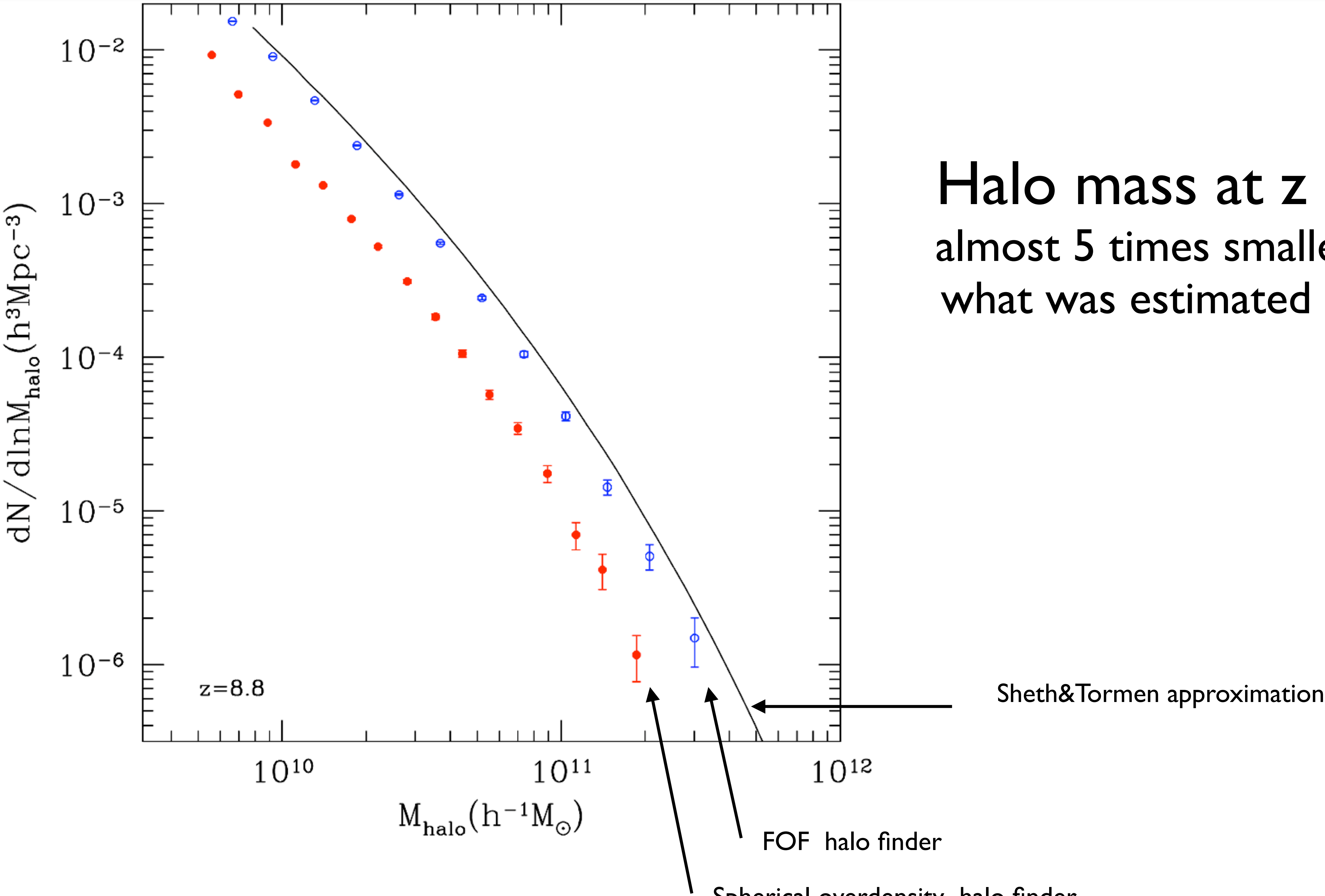


For galaxies with velocities 80-400 km/s LCDM predicts the same abundance as observed in the Universe



Mass function of halos at z=6-10:
too low for models of re-ionization

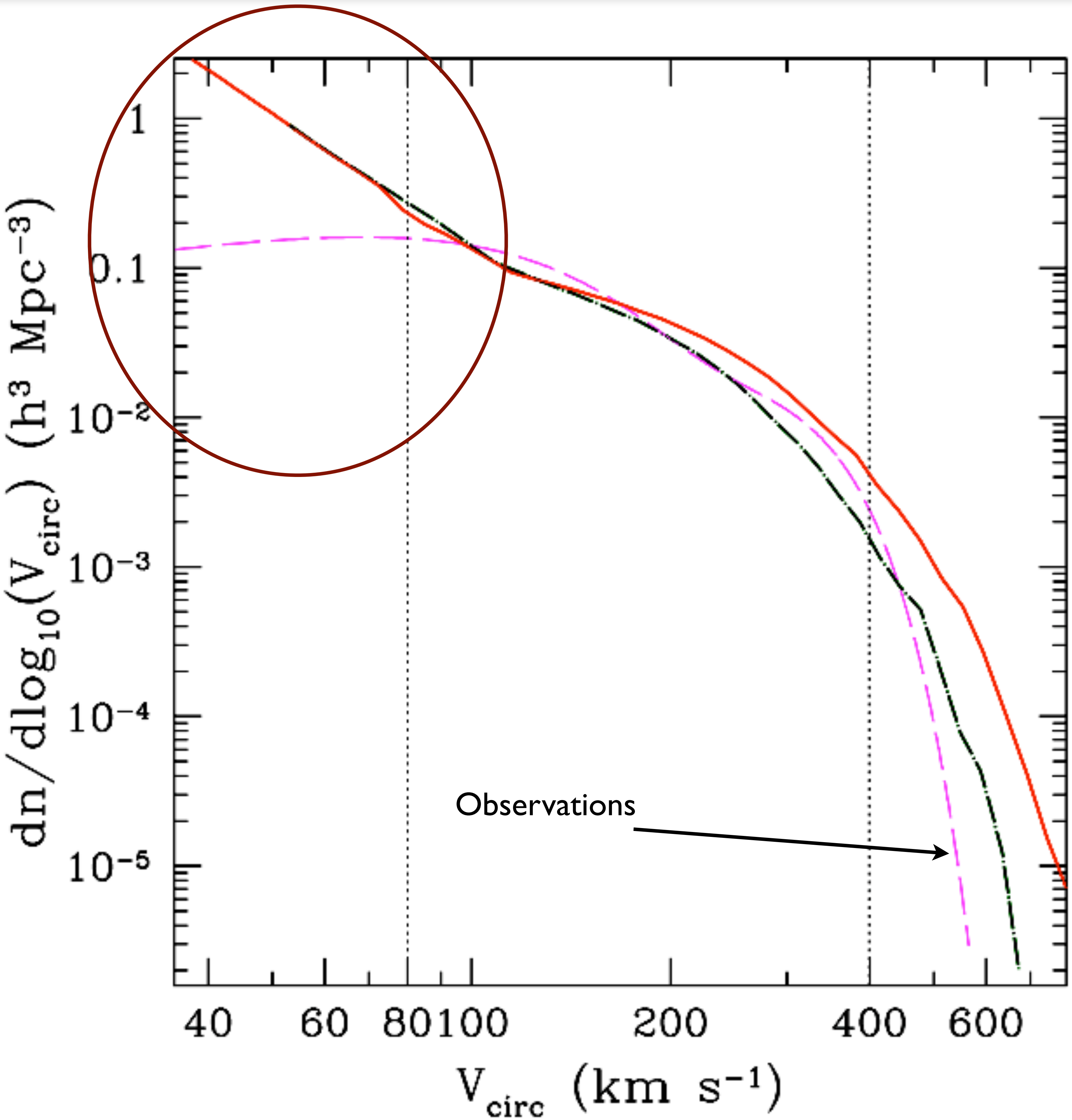
Full: Sheth&Tormen
Symbols: N-body Bolshoi, Spherical overdensity



Halo mass at z =8.8:

almost 5 times smaller than what was estimated before

Number of galaxies with Vcirc: observations vs LCDM



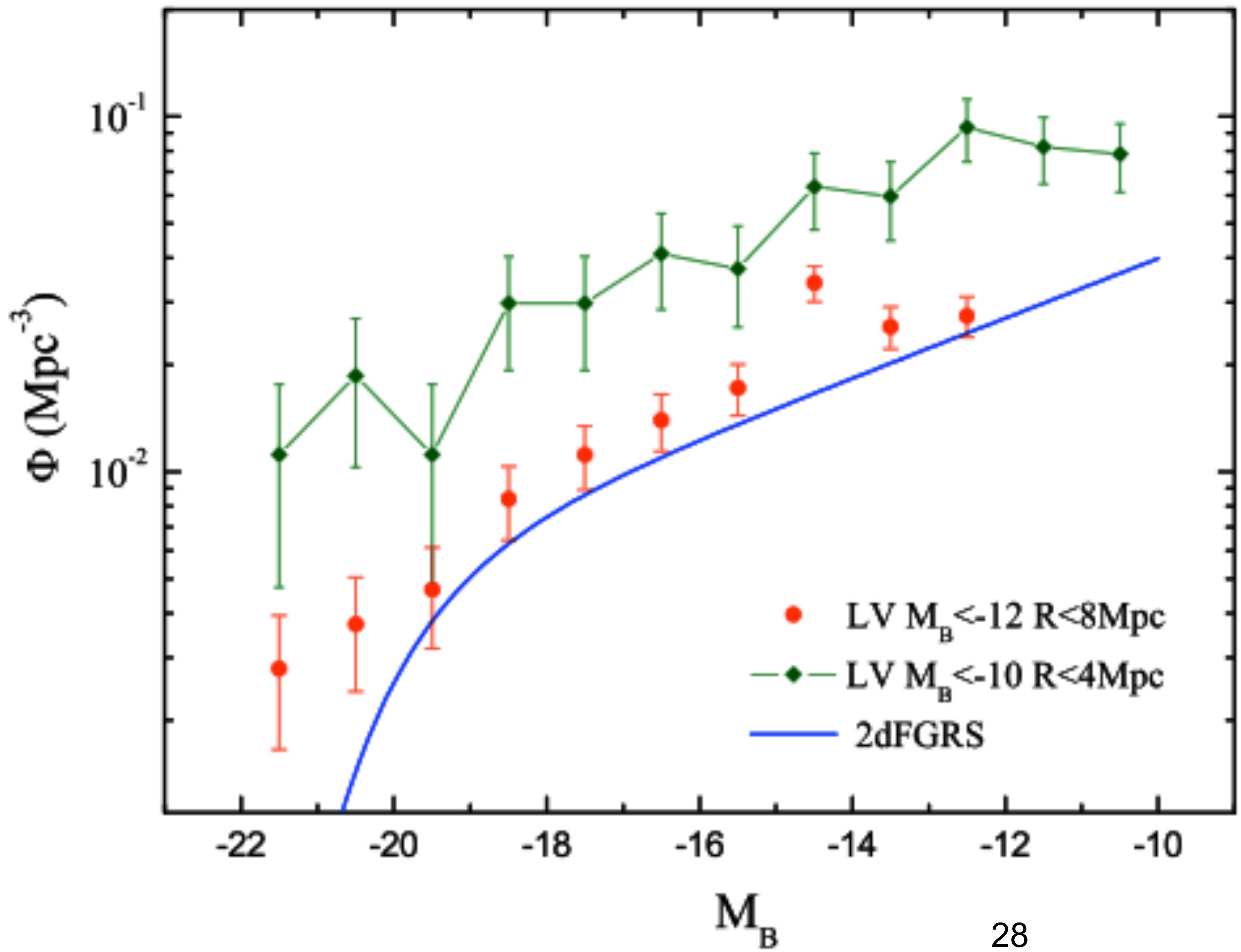
Overabundance of dwarf galaxies with Vcirc =50km/s

This is a different and much worse problem as compared with the 'satellites' overabundance.

Galaxies in the Local Volume:

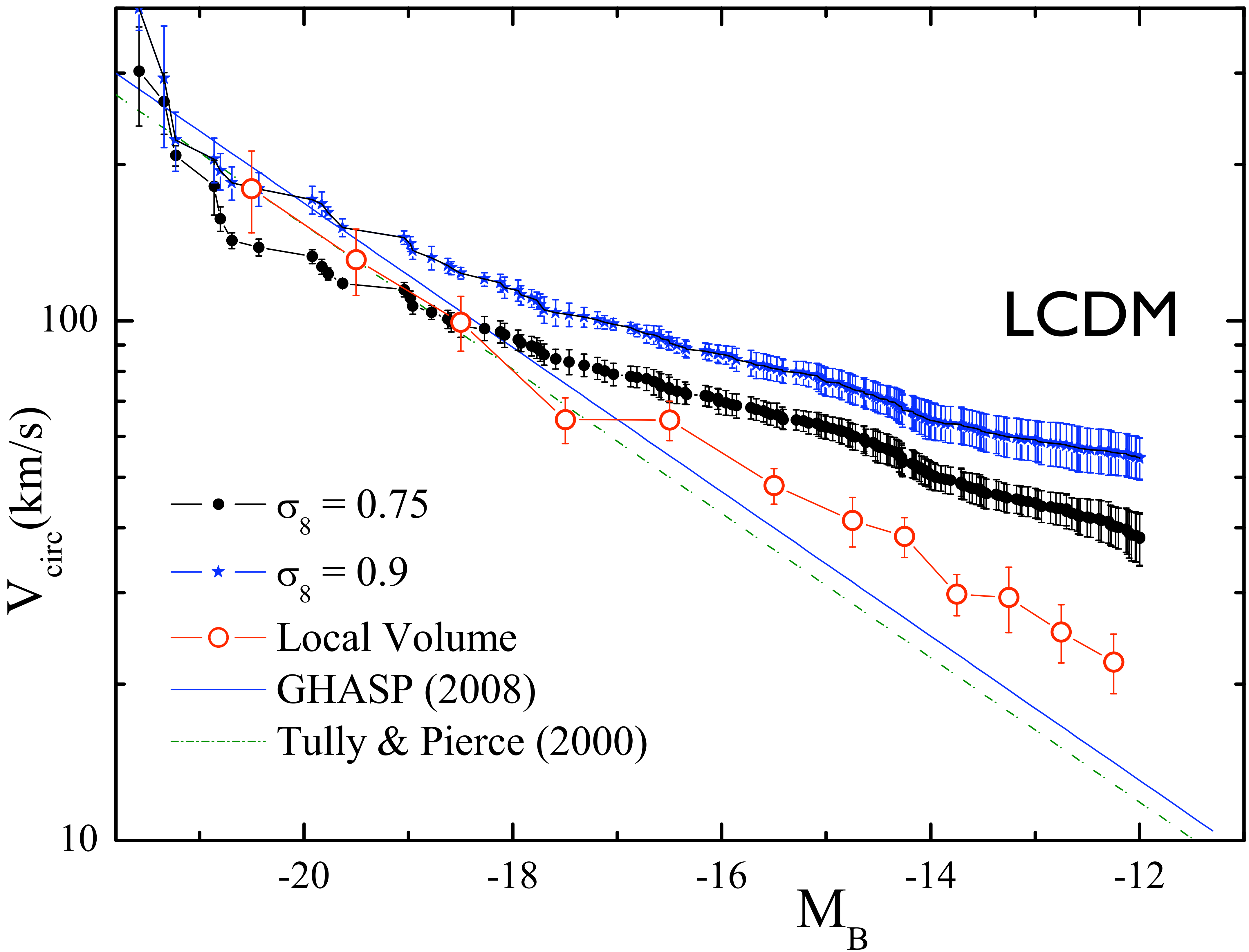
- distances less than 10 Mpc
- 550 galaxies: Complete to M=-12
- Count voids: regions without galaxies

Tikhonov& Klypin 2008



Data: Karachentsev & Co

Map luminosity to circular velocity

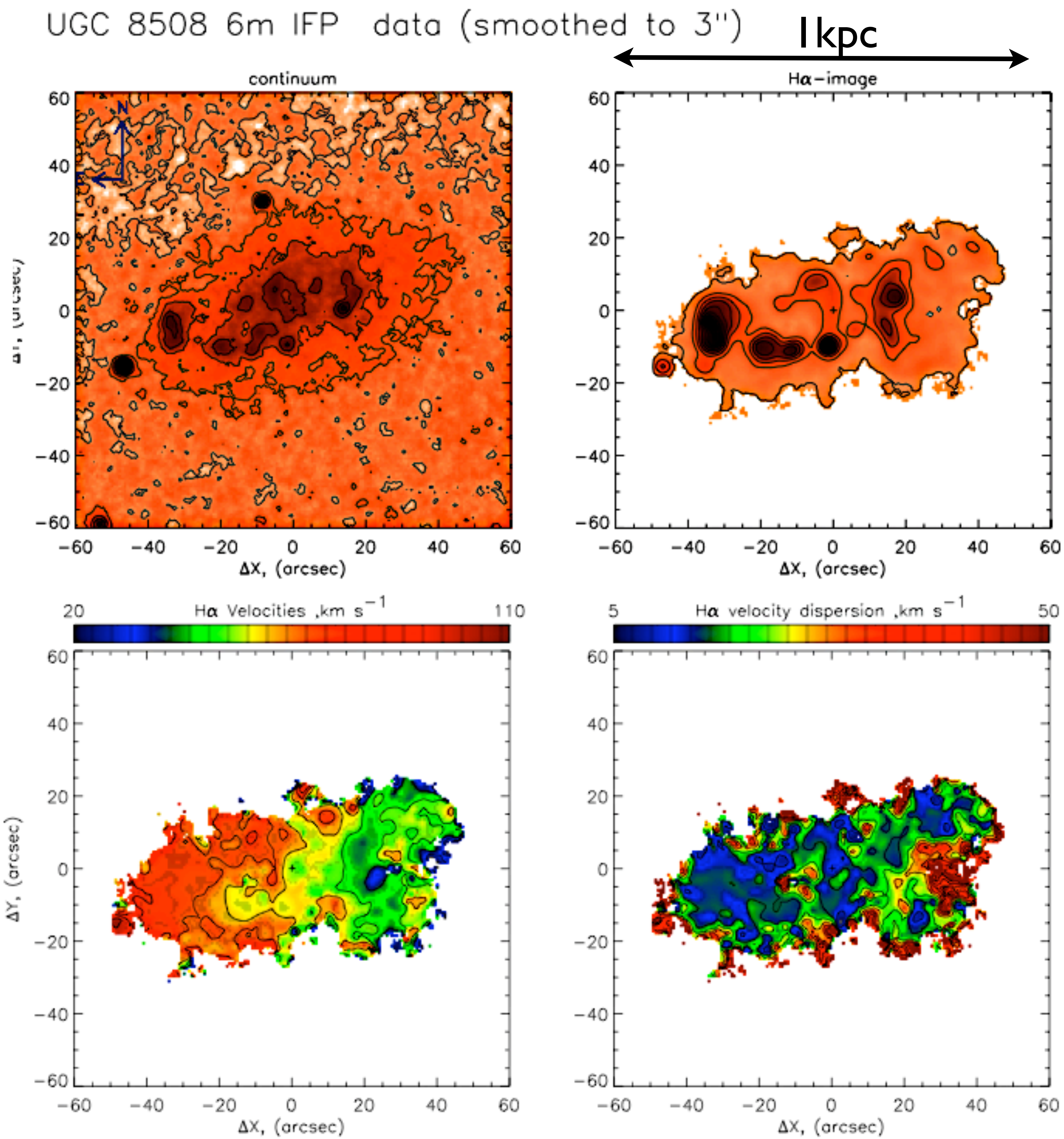


Example: UGC8508

Distance 2.5 Mpc

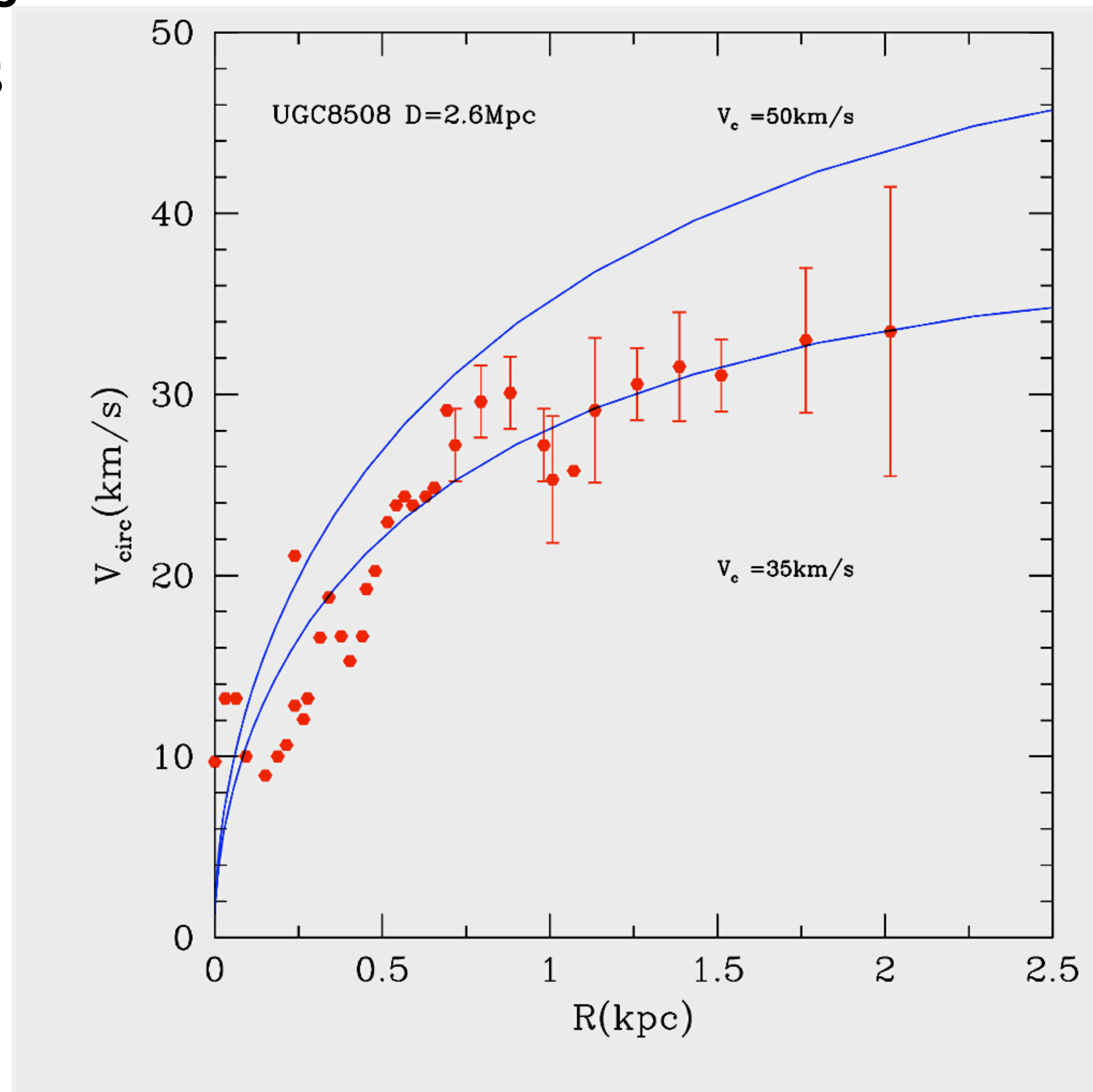
M_B =-12.9

Russian 6m telescope



Velocity of rotation:
Observed: 25-30 km/s
Theory: 40-50 km/s

Theory predicts too large circular velocity



What is the Problem? Put it in different way

Observational Facts	Theory
There are ~500 galaxies in the Local Volume.	In LV-analogs in LCDM model ~500 largest halos have the same spatial distribution as observed dwarf galaxies. Great!
Observed dwarfs have small circular velocities (~20km/s)	DM halos are big (40-50 km/s)
There are dwarfs (~10km/s) that form stars NOW	Current explanation for overabundance of MW satellites (eg Koposov et al 2009) requires significant suppression of galaxies below 30km/s. Galaxies with Vc<30km/s should not form stars after re-ionization (z=11)

Standard explanation for overabundance of dwarf DM halos does not work: no tidal stripping for field dwarfs.

Conclusions

- LCDM predicts correct abundance and structure of galaxies with circular velocities from 50 km/s to 300 km/s

- Little room for environmental effects: Circular velocity defines most of the properties of galaxies

- Not enough halos at z=10 for re-ionization?

- *Big problems* with dwarfs: too many are predicted with Vcirc =30-50 km/s.