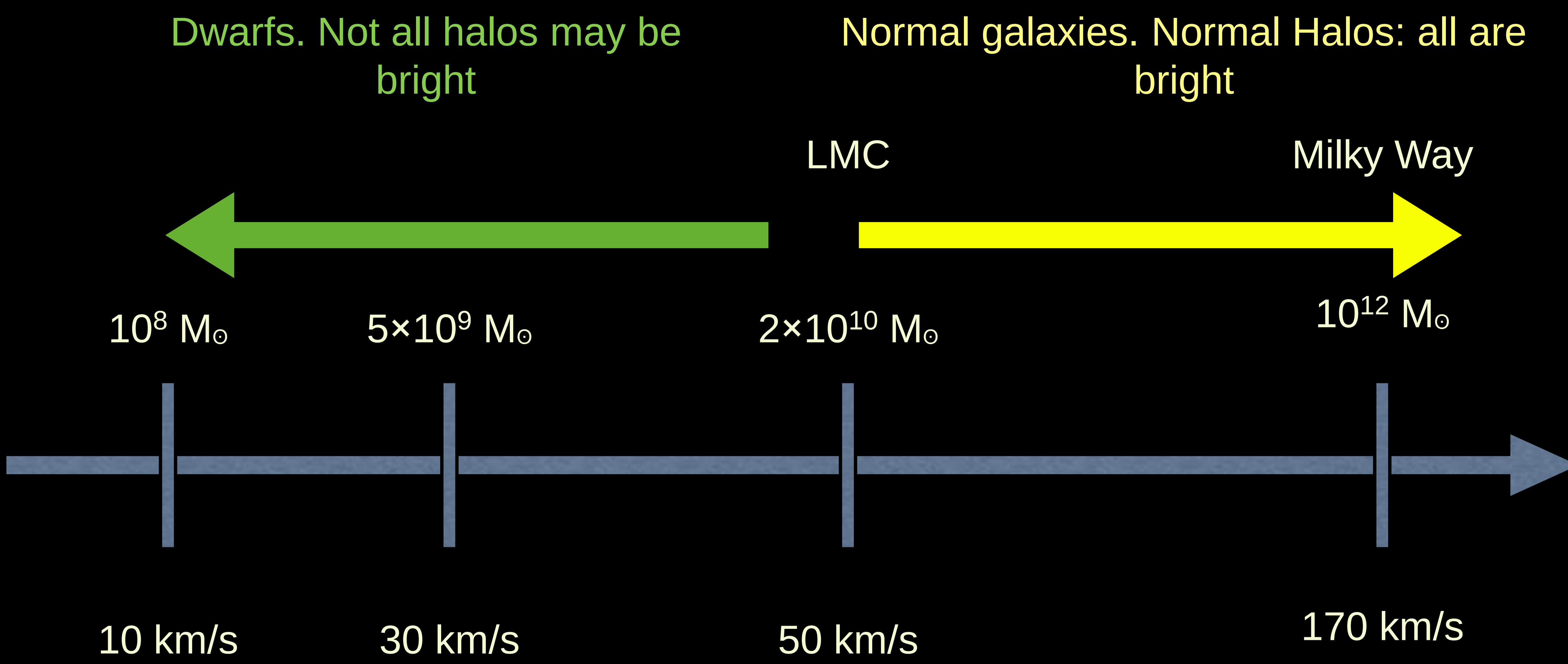
The LCDM paradigm: successes and challenges on scales of galaxies

Anatoly Klypin (NMSU)

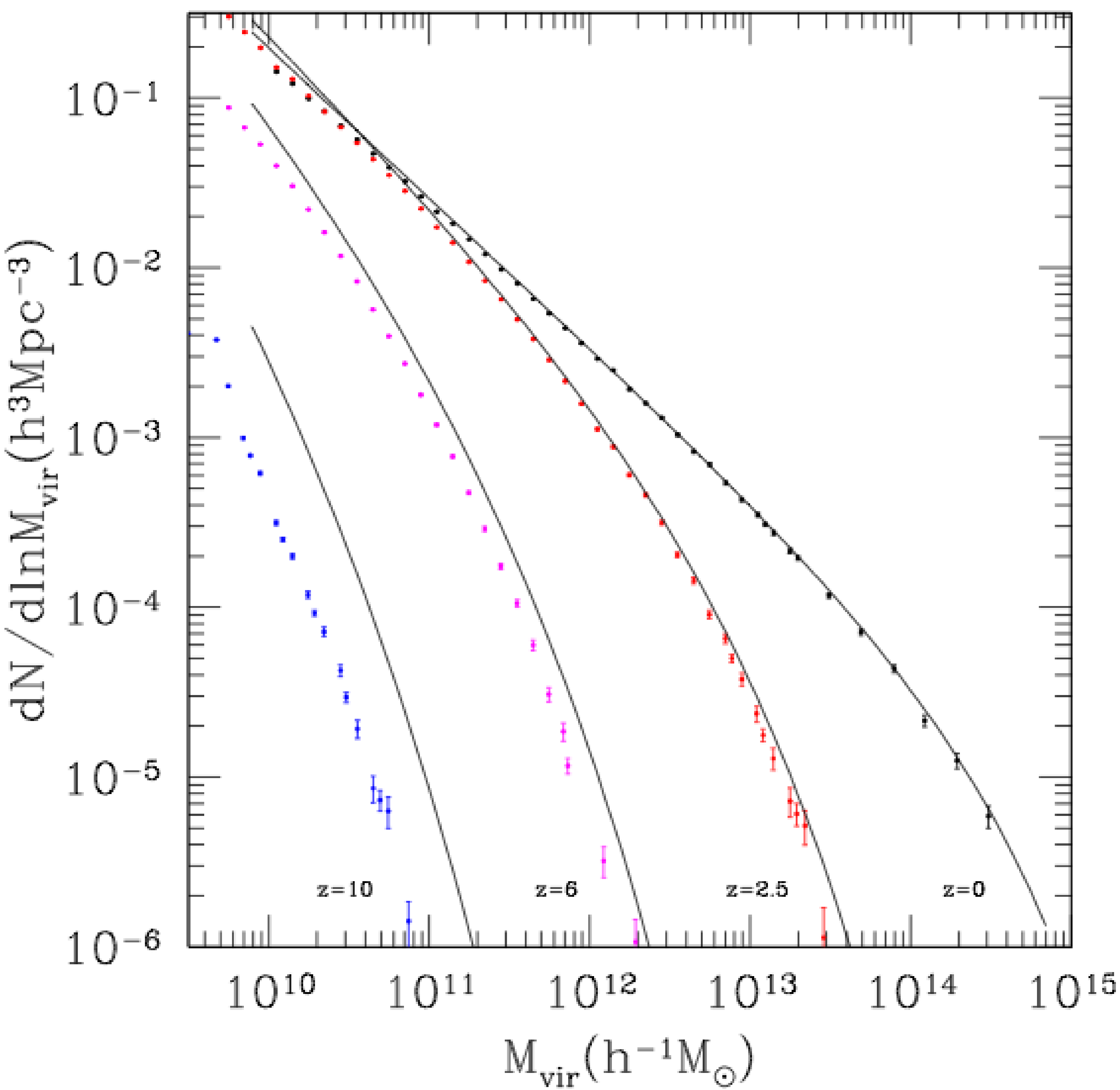
LCDM

- DM profiles, concentrations, ...
- Clustering of galaxies: P(k) and correlation functions
- Satellites: abundance, number-density profiles
- Galaxies and Dark Matter: abundances



Scales of galaxies

Lots of statistics can be now predicted with very high accuracy



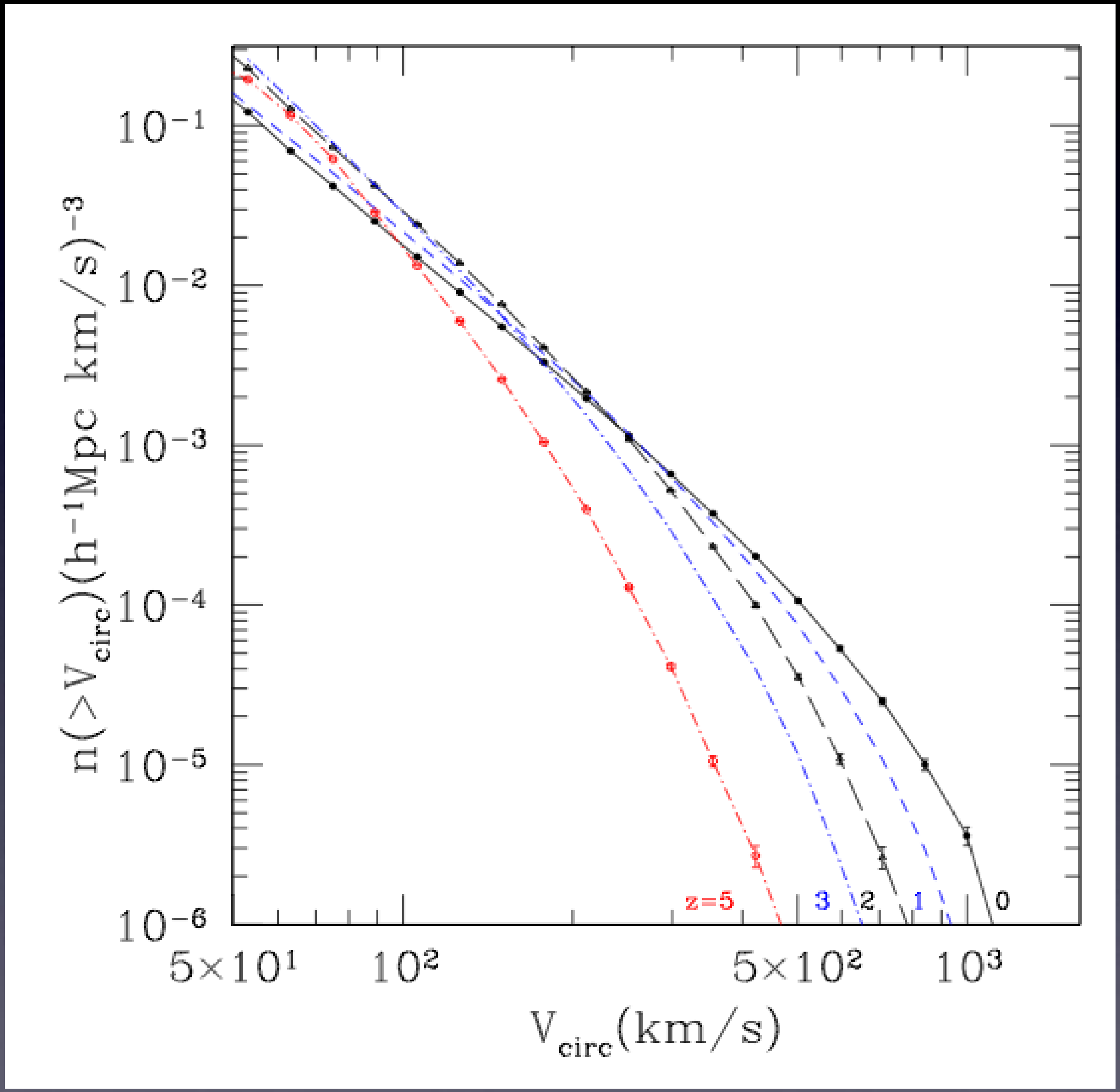
Full: Sheth&Tormen
Symbols: N-body Bolshoi,
Spherical overdensity

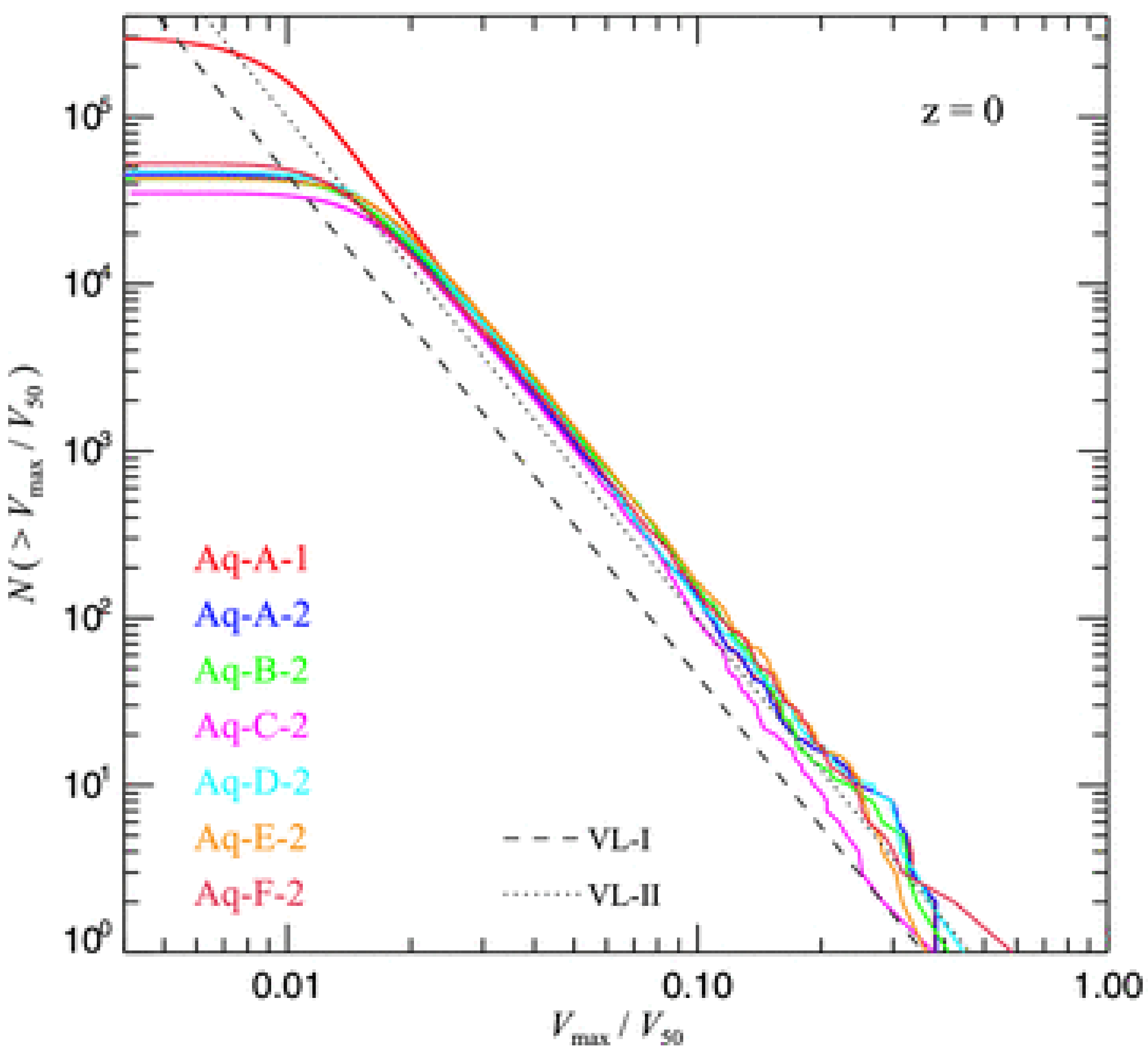
Correction factor for Sheth&Tormen:

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

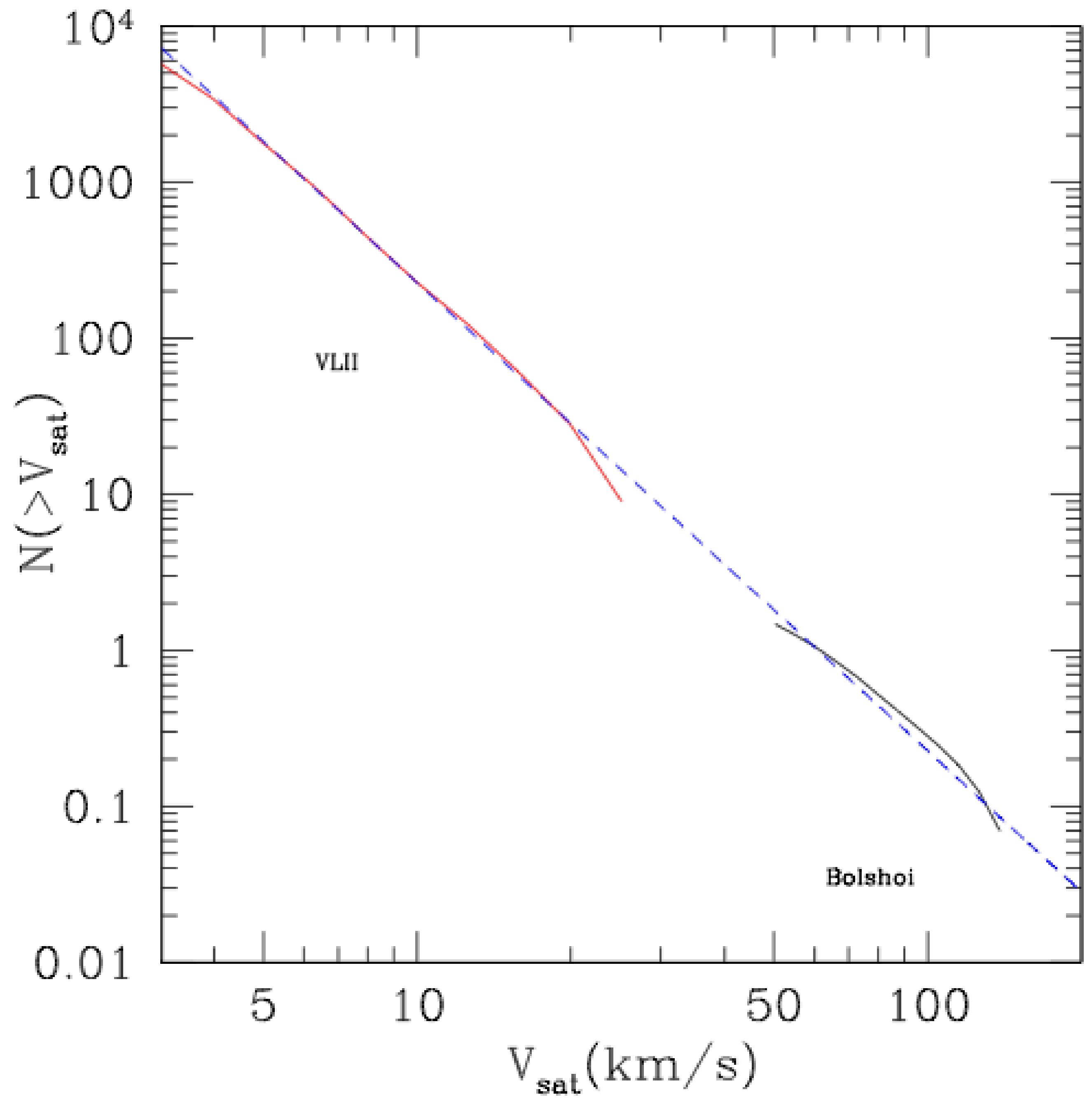
Bolshoi: Klypin et al 2010
Tinker 2008: z=0-2.5

Accurate predictions for Velocity function of distinct halos





Aquarius simulation. Springel et al 2008.
WMAP-1



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

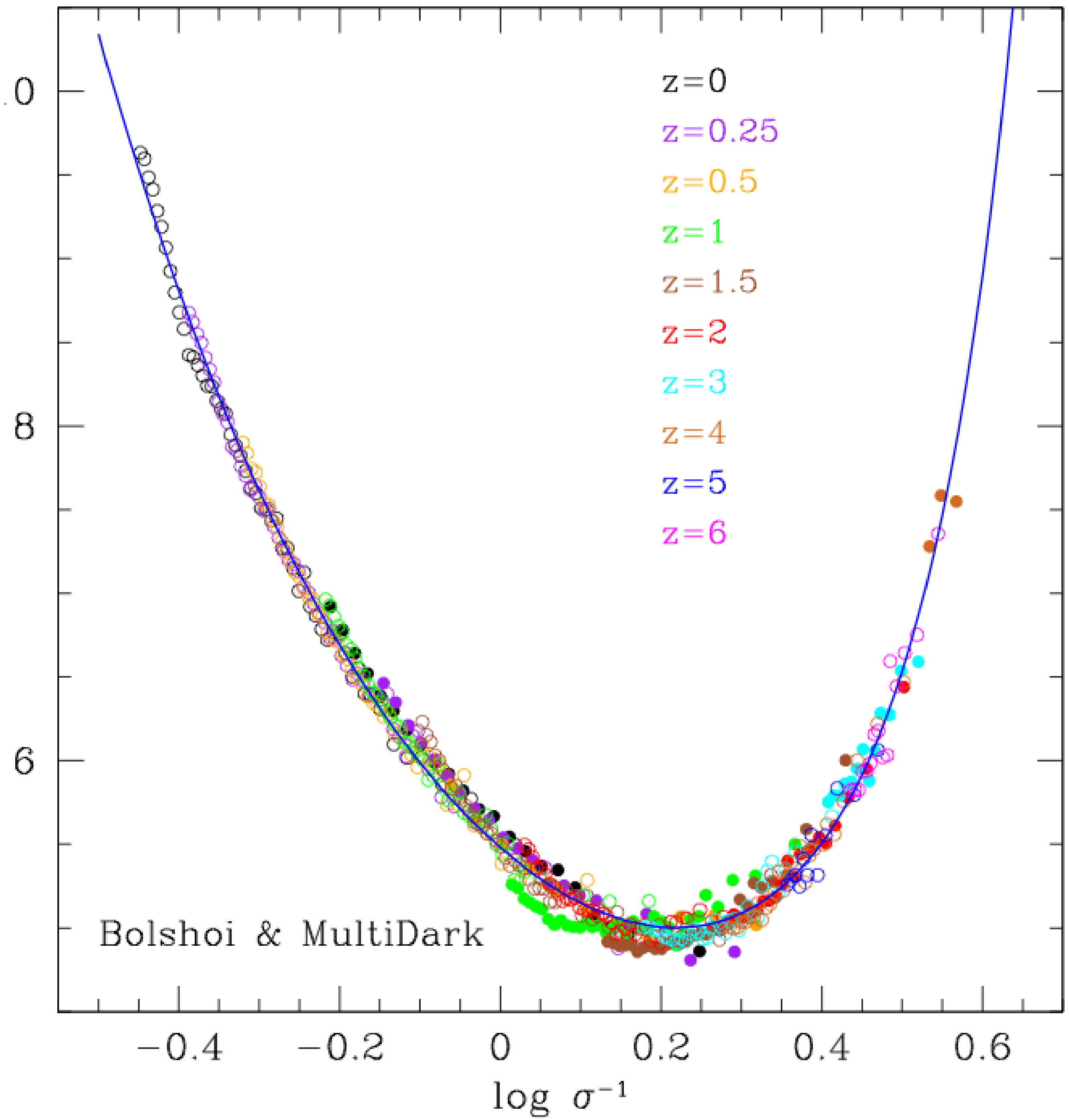
Fig. 18.— Comparison of satellite velocity functions in Via Lactea II and Bolshoi simulations for halos with $V_{circ} = 200$ kms/s and $M_{vir} \approx 1.3 \times 10^{12} h^{-1} M_{\odot}$. The dashed line is a power law with the slope -3, which provides excellent fit to

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

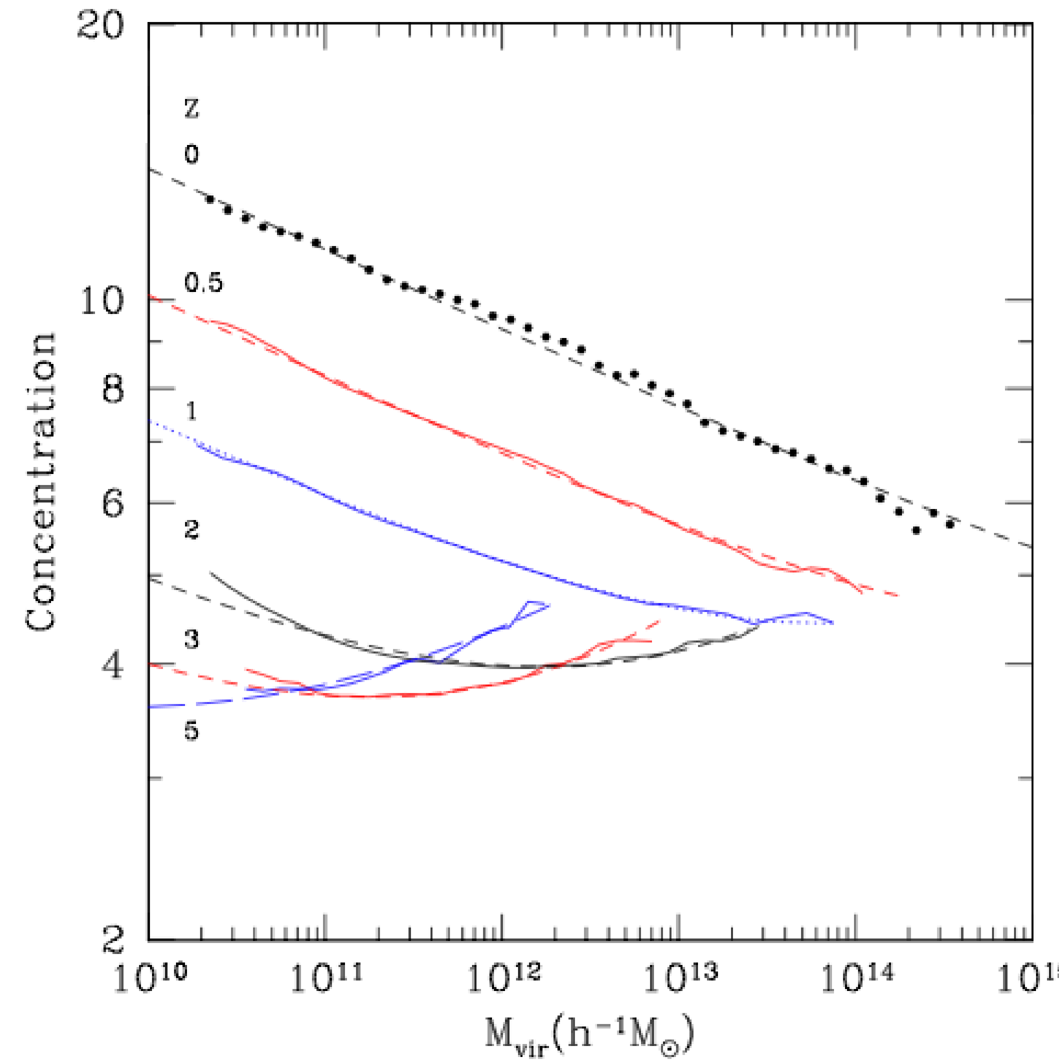
Small mass

Large mass

Concentration

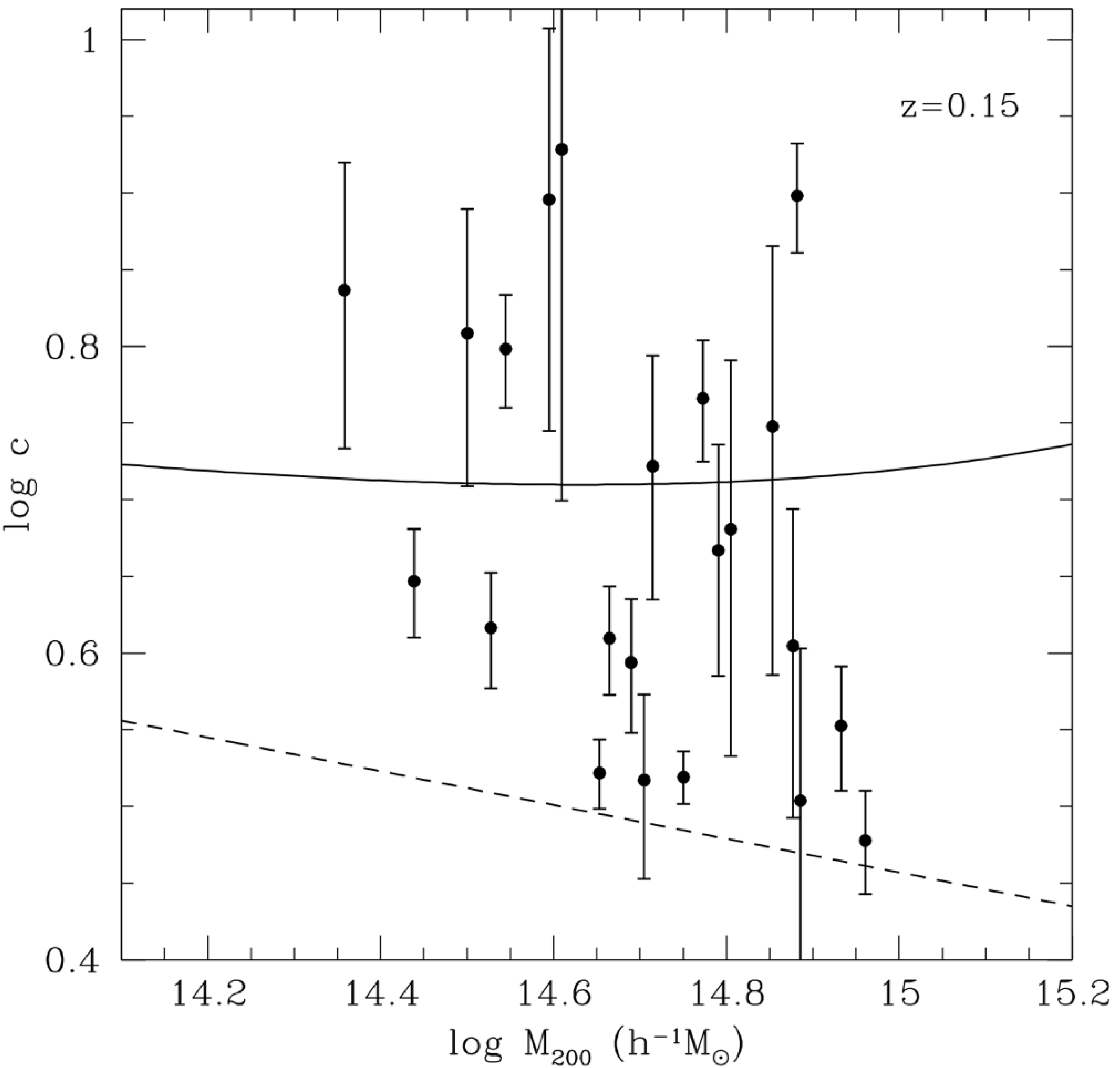


Prada et al 2011



Klypin et al 2010

Concentrations of Clusters of galaxies

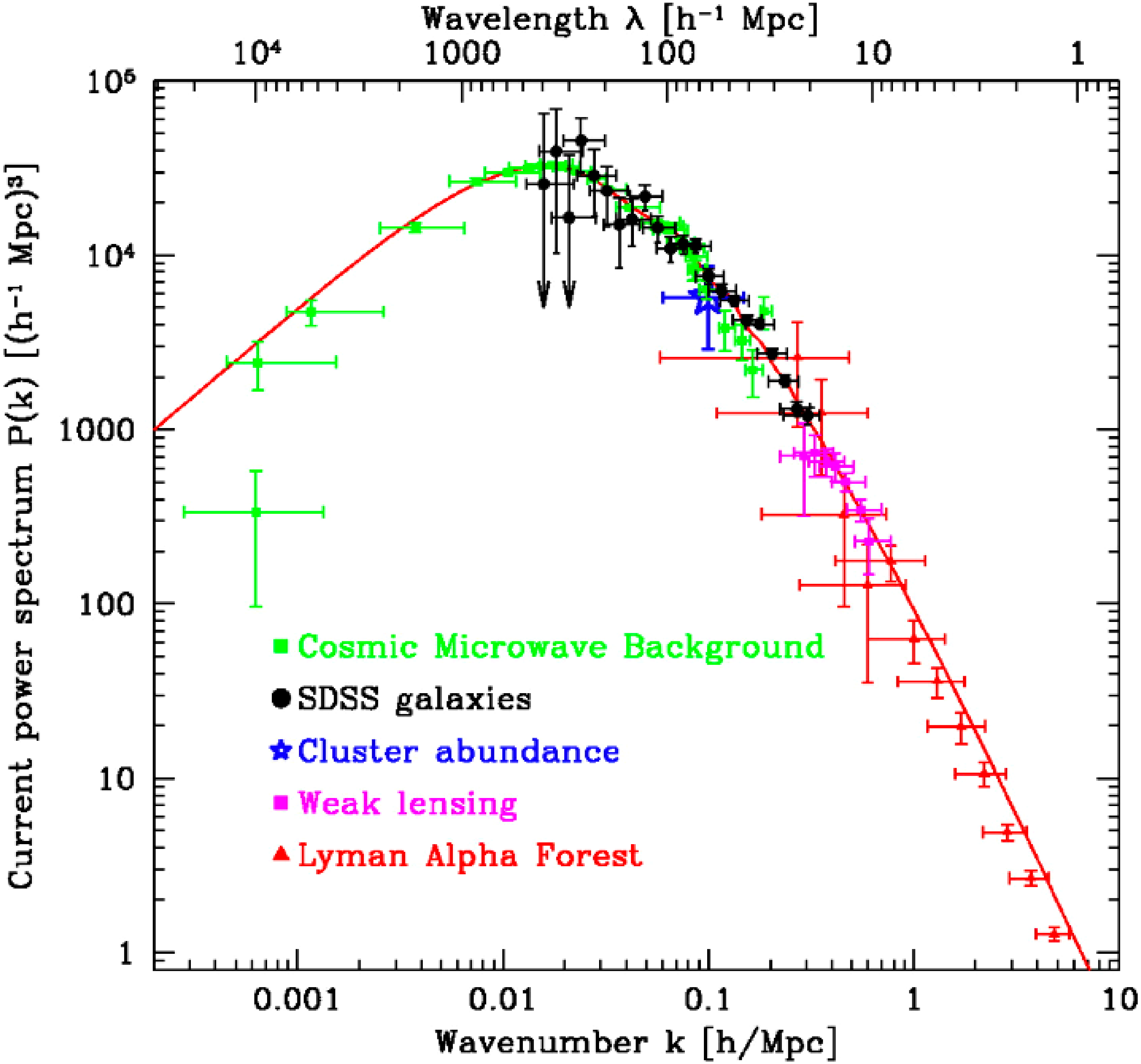


Prada et al 2011 Median Concentrations

Maccio et al 2008

Probing 100kpc scales

The Observed Power Spectrum



(Tegmark et al.)

Baryonic acoustic oscillations: Power spectrum

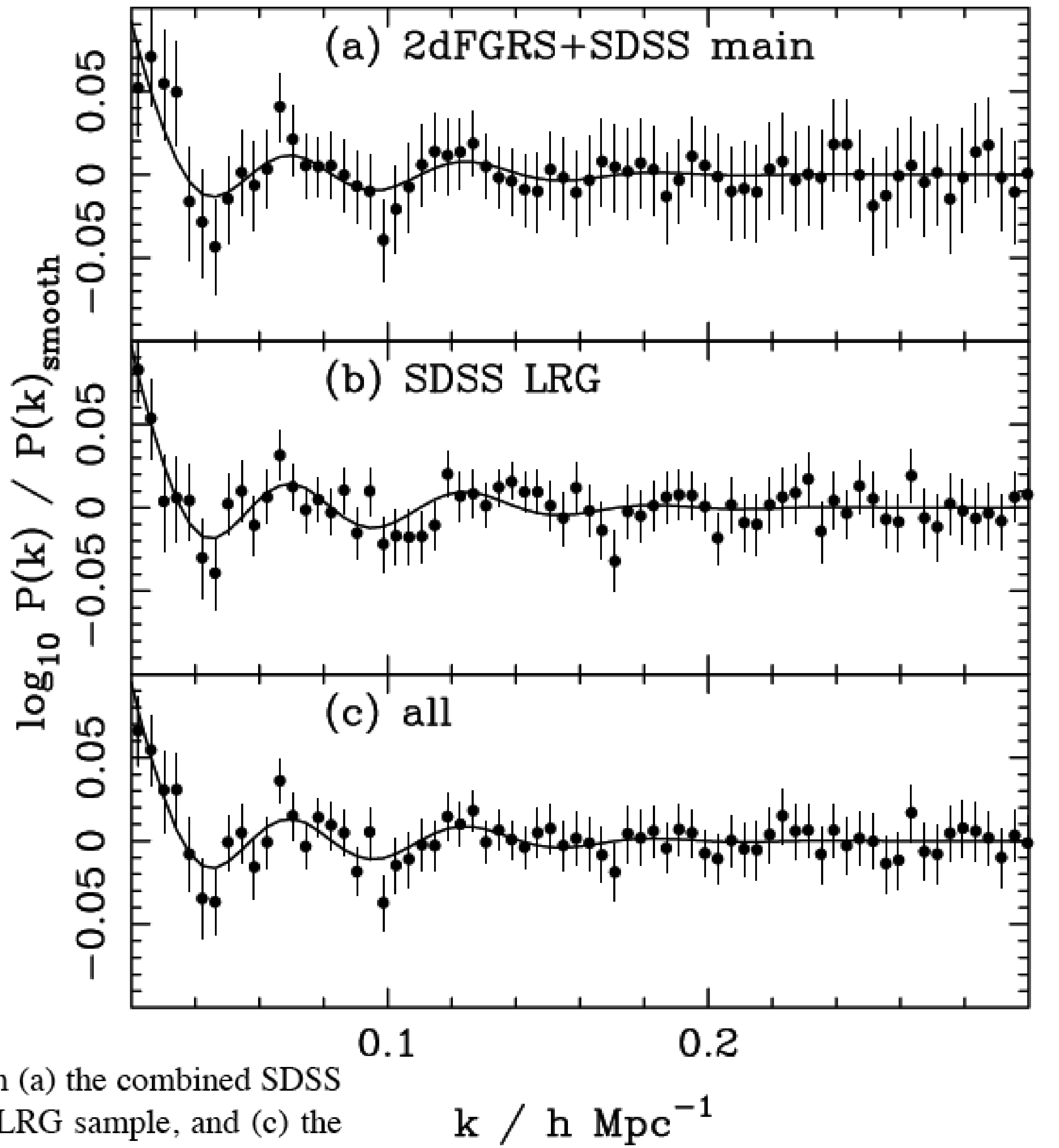
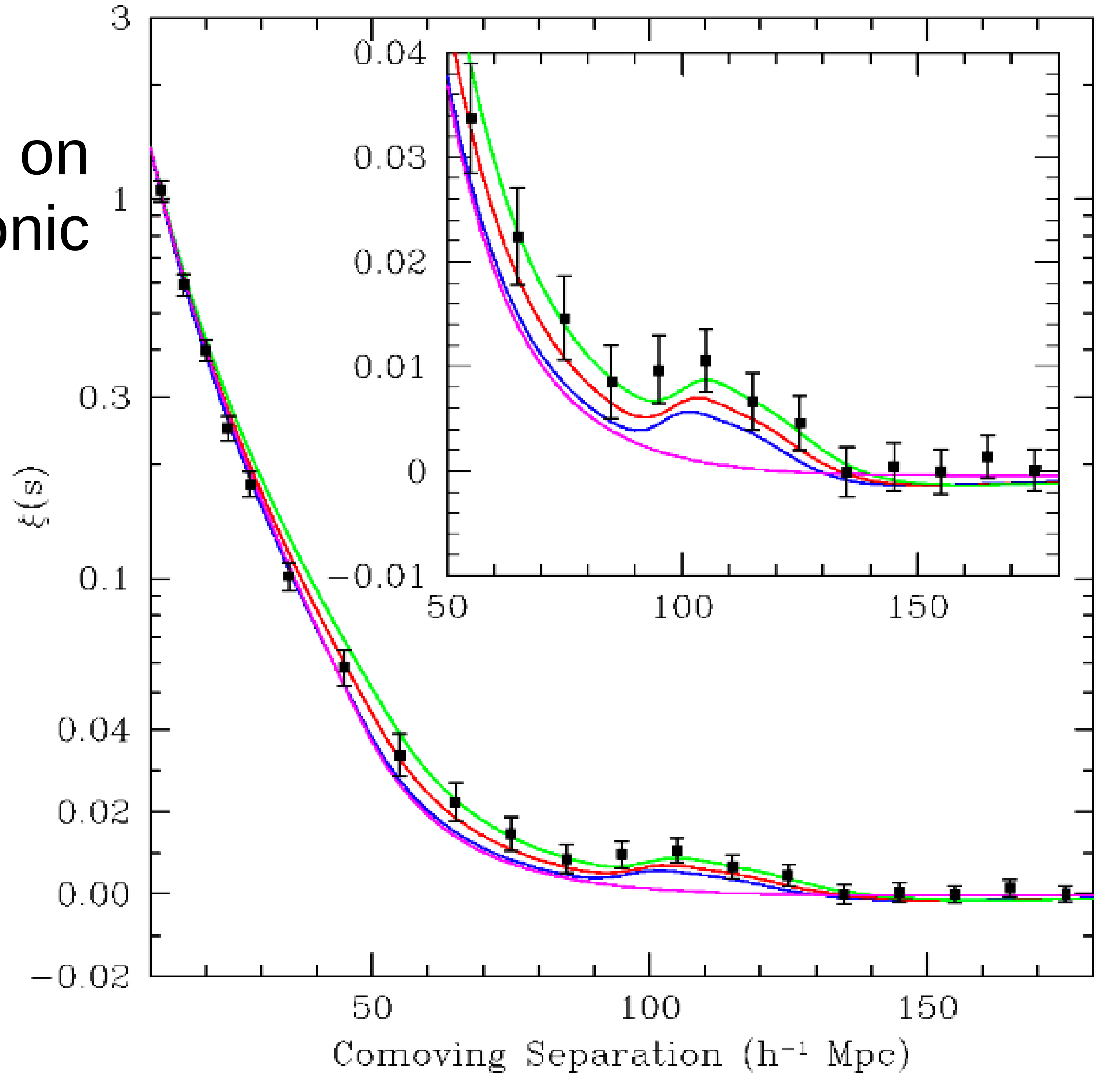


Figure 2. BAOs in power spectra calculated from (a) the combined SDSS and 2dFGRS main galaxies, (b) the SDSS DR5 LRG sample, and (c) the combination of these two samples (solid symbols with 1σ errors). The data are correlated and the errors are calculated from the diagonal terms in the co-variance matrix. A standard ΛCDM distance–redshift relation was assumed to calculate the power spectra with $\Omega_{\rm m} = 0.25$, $\Omega_\Lambda = 0.75$. The power spec-

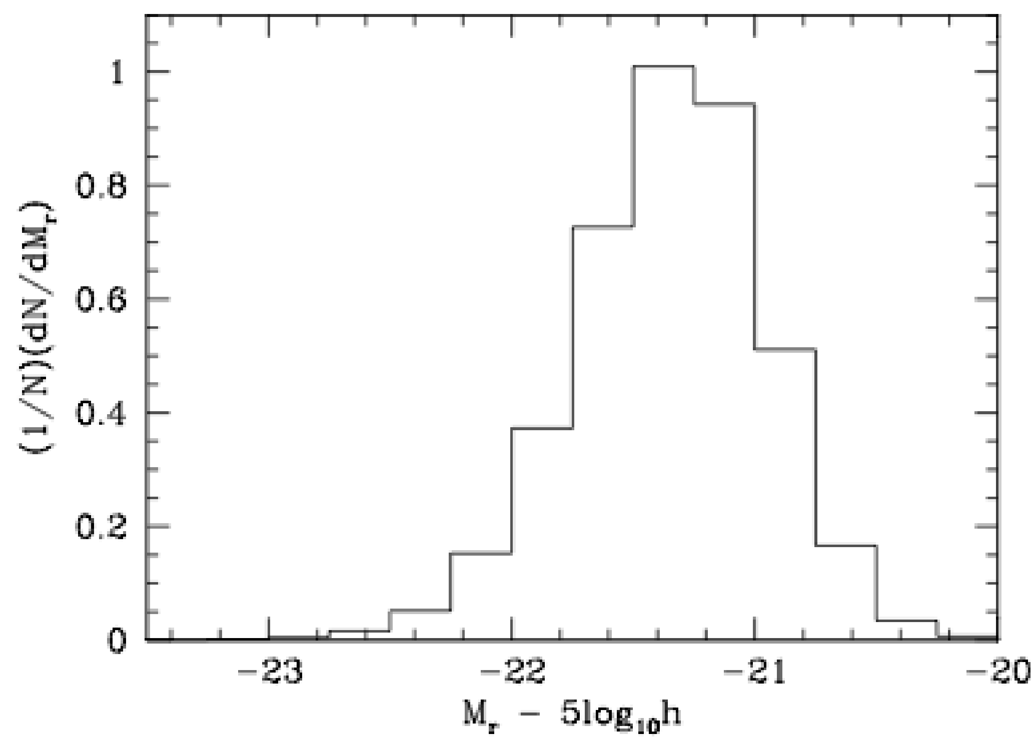
Percival etal 2007

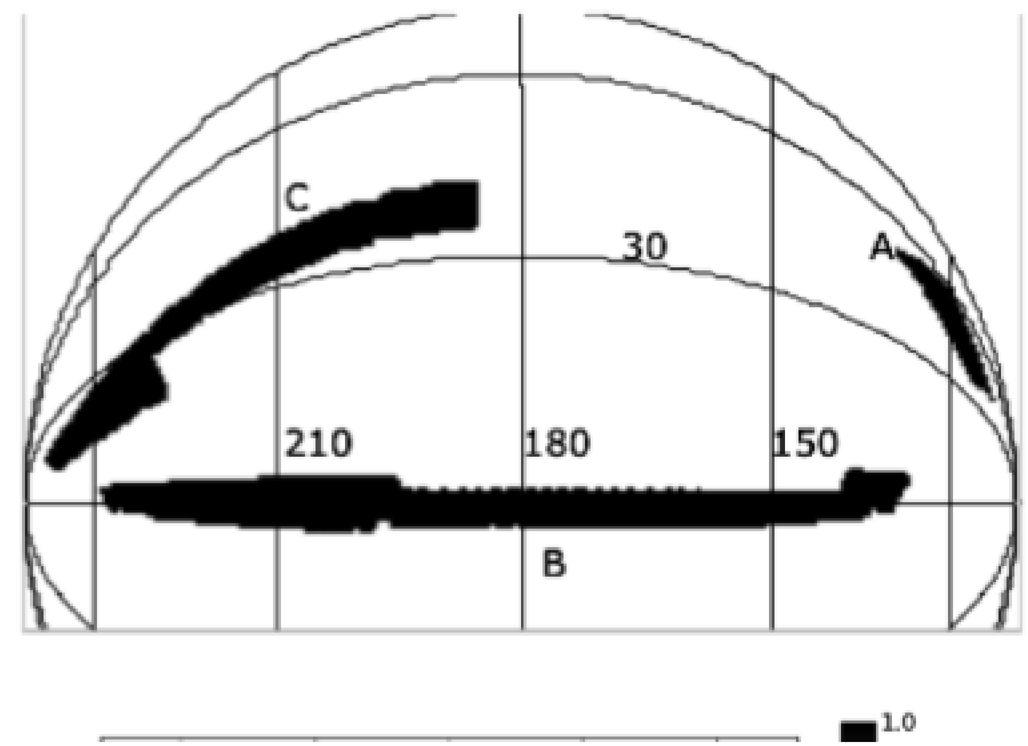
Correlation function on large scales: baryonic oscillations

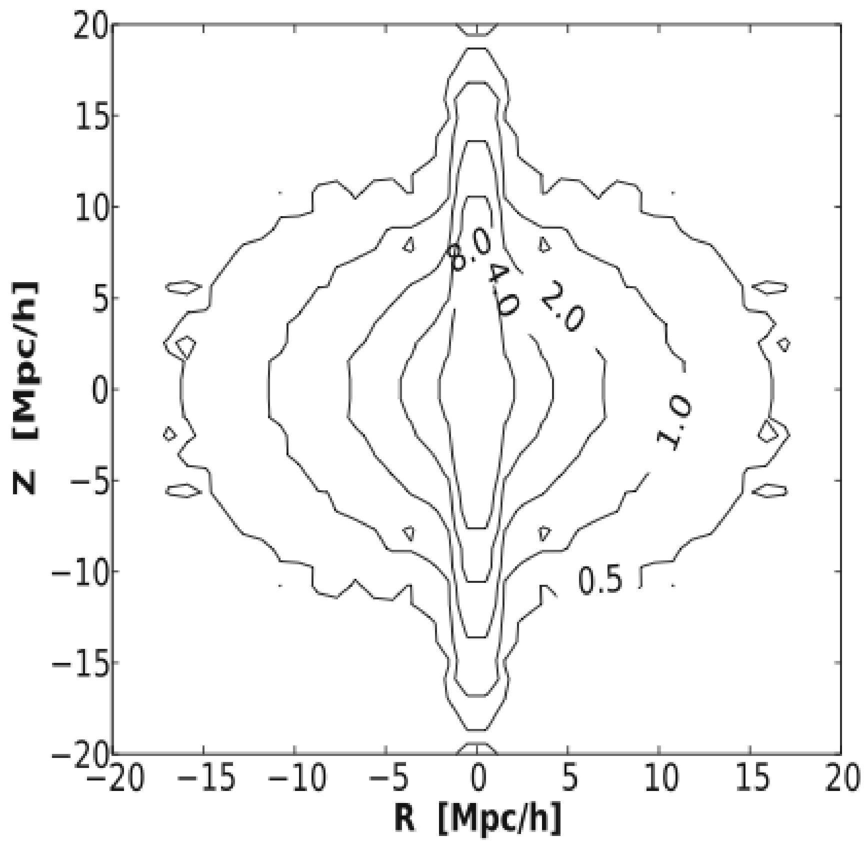


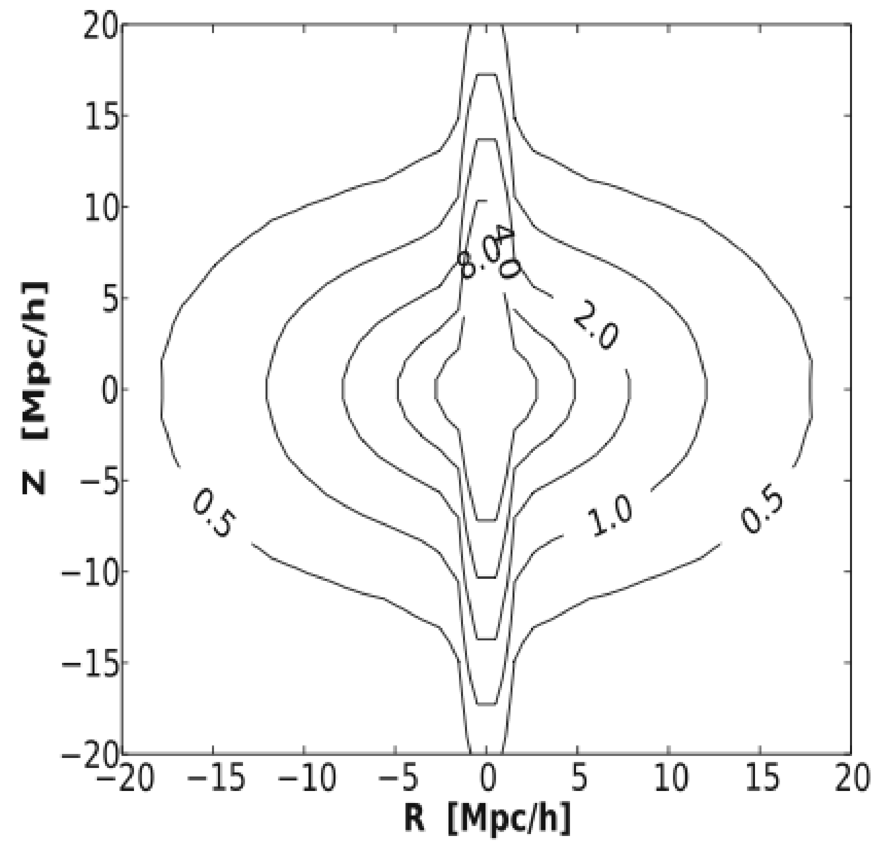
SDSS (Eisenstein et al.)

THE CLUSTERING OF MASSIVE GALAXIES AT z ~ 0.5 FROM THE FIRST SEMESTER OF BOSS DATA M.White et al 2010

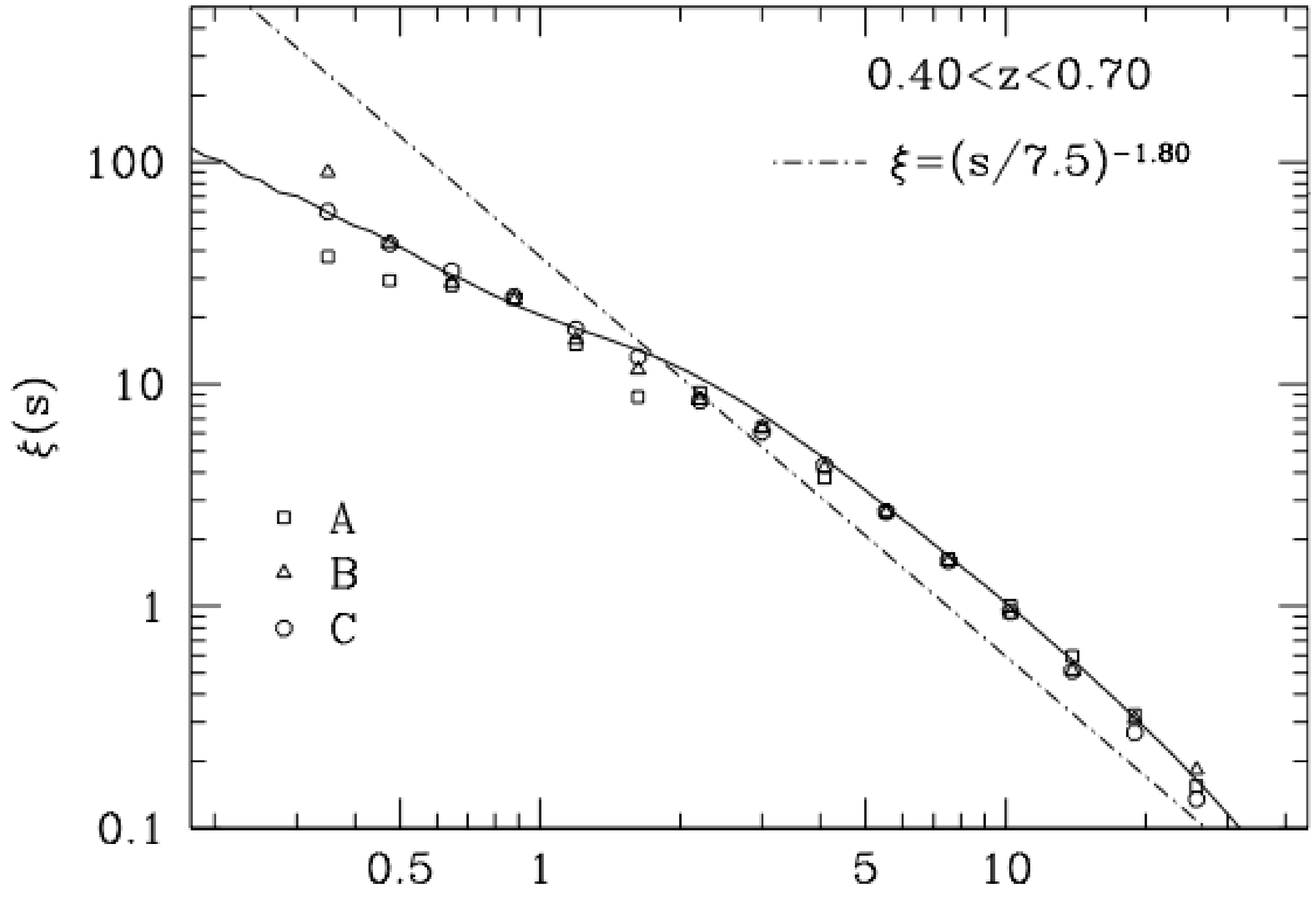




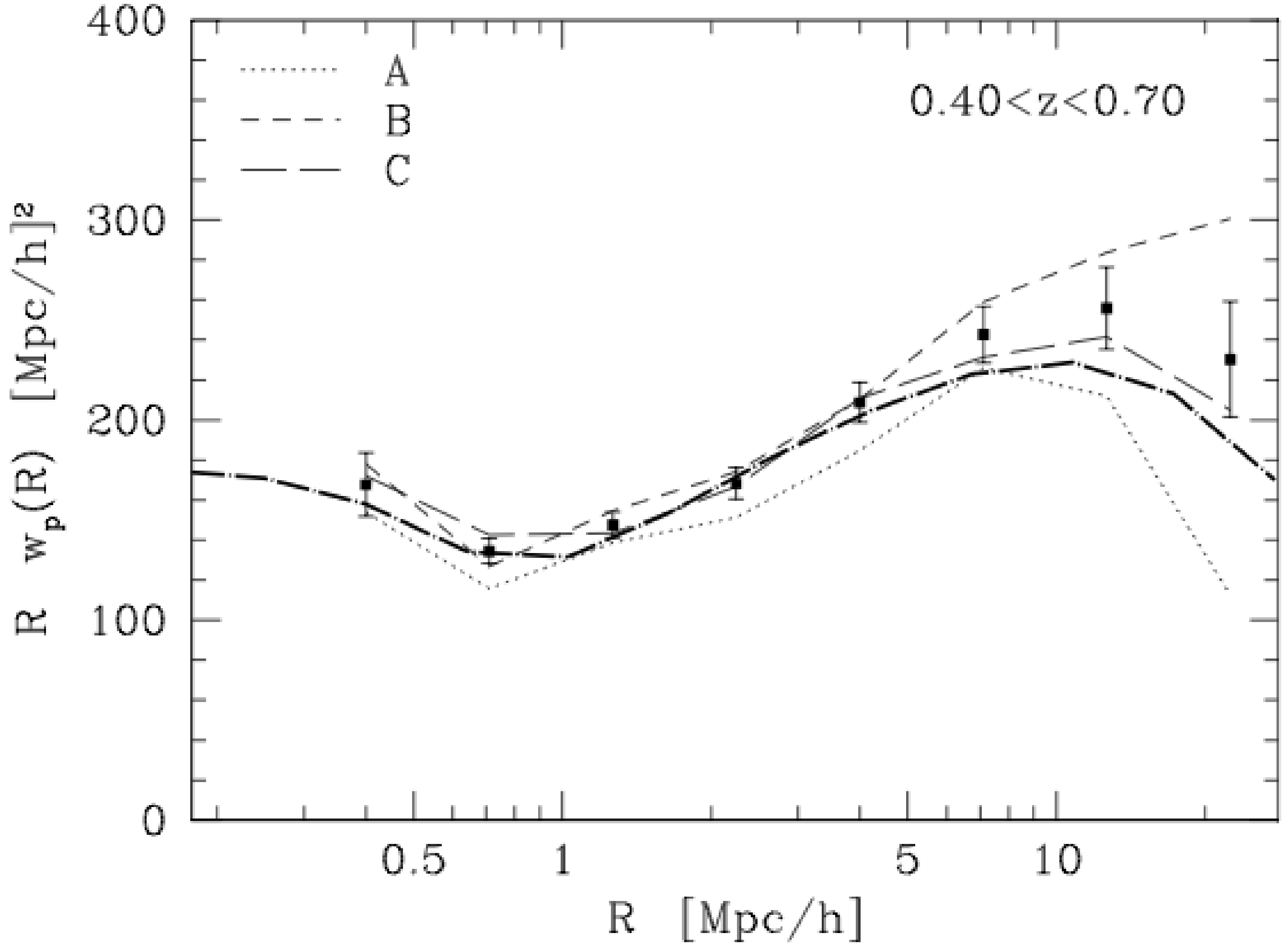




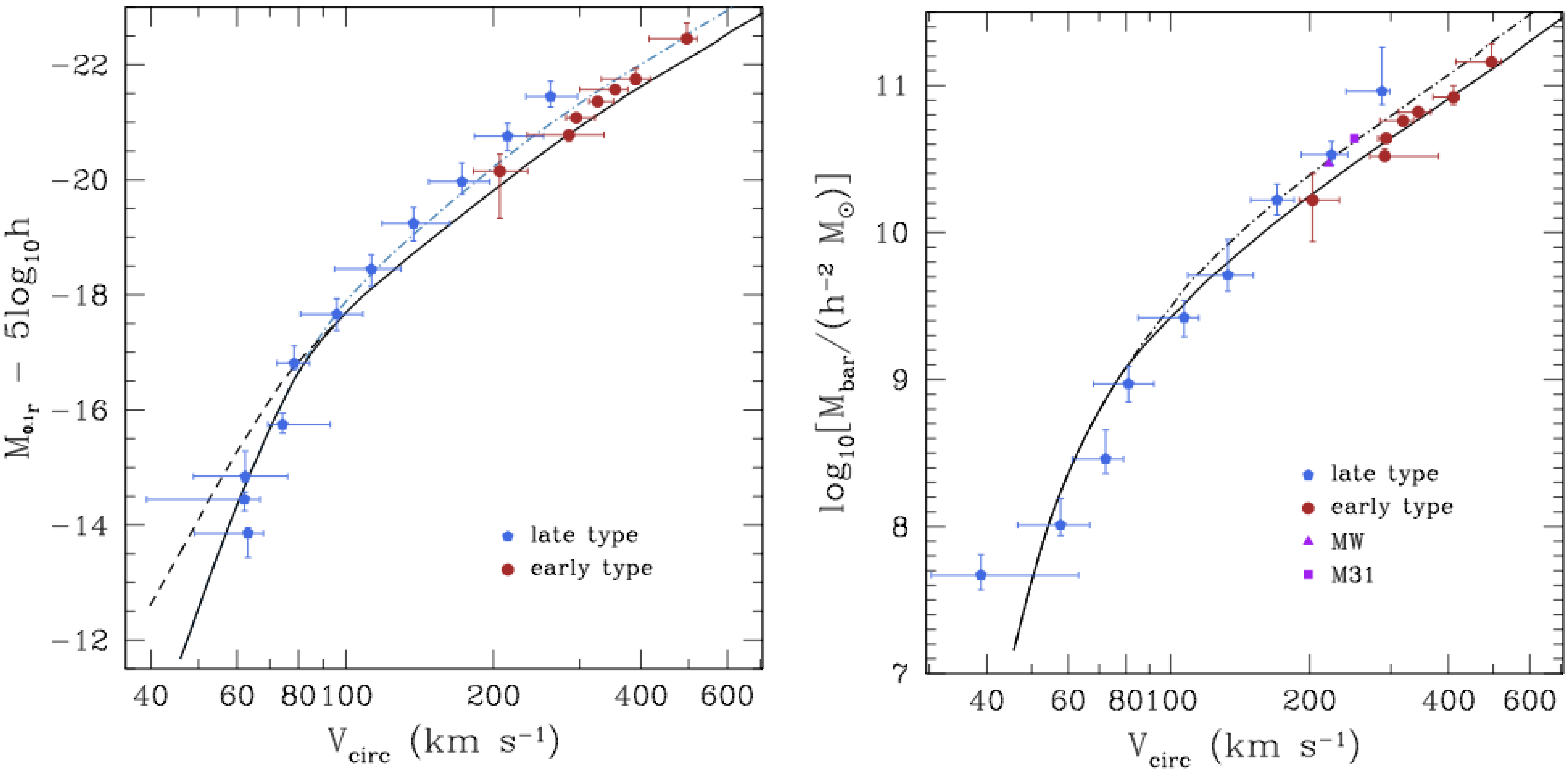
Redshift- space correlation function. Full = theory



Real space correlation function. Dot-dash = theory

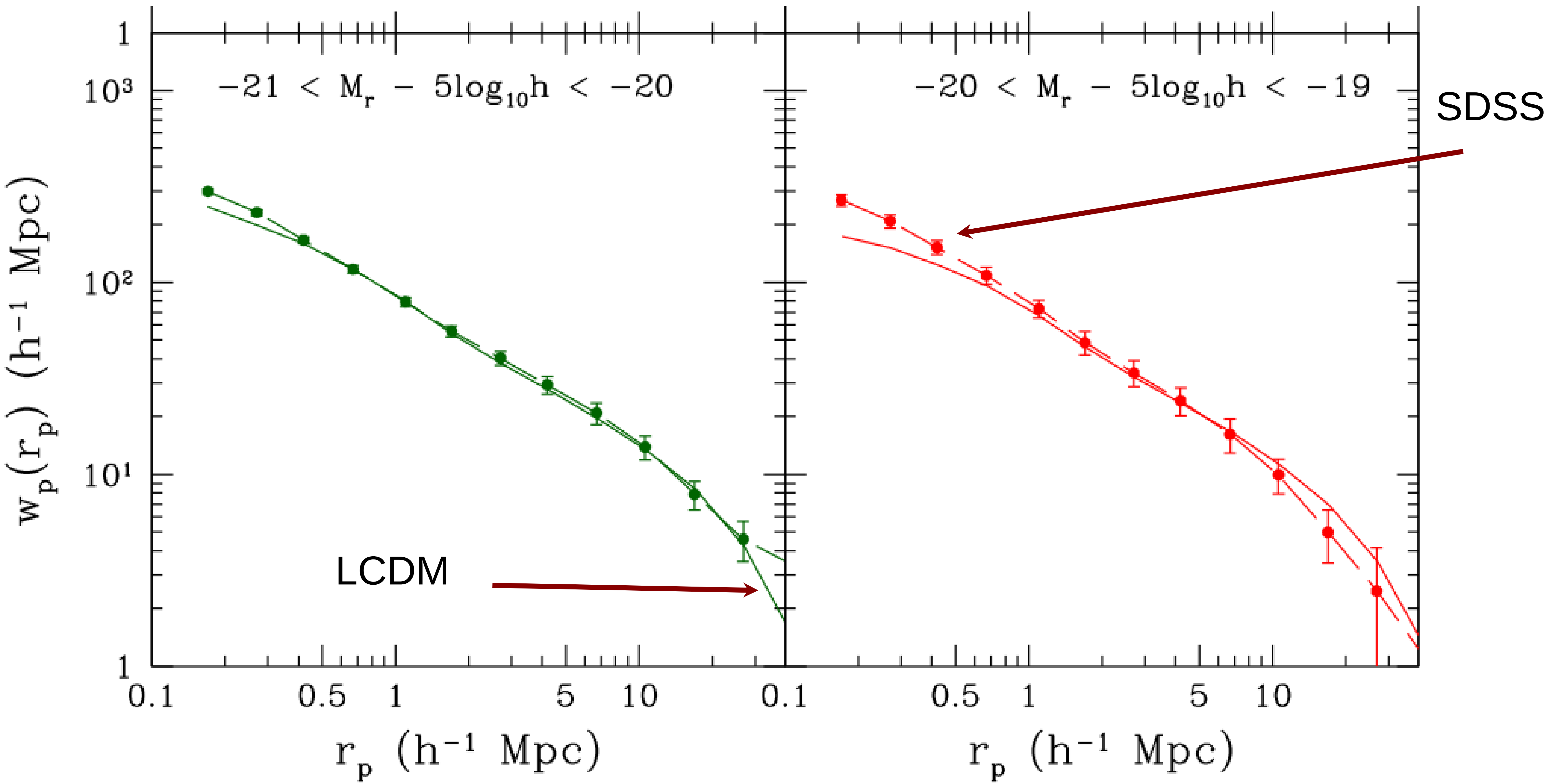


10-50 kpc scales: *Matching Galaxies with Dark Matter Halos*



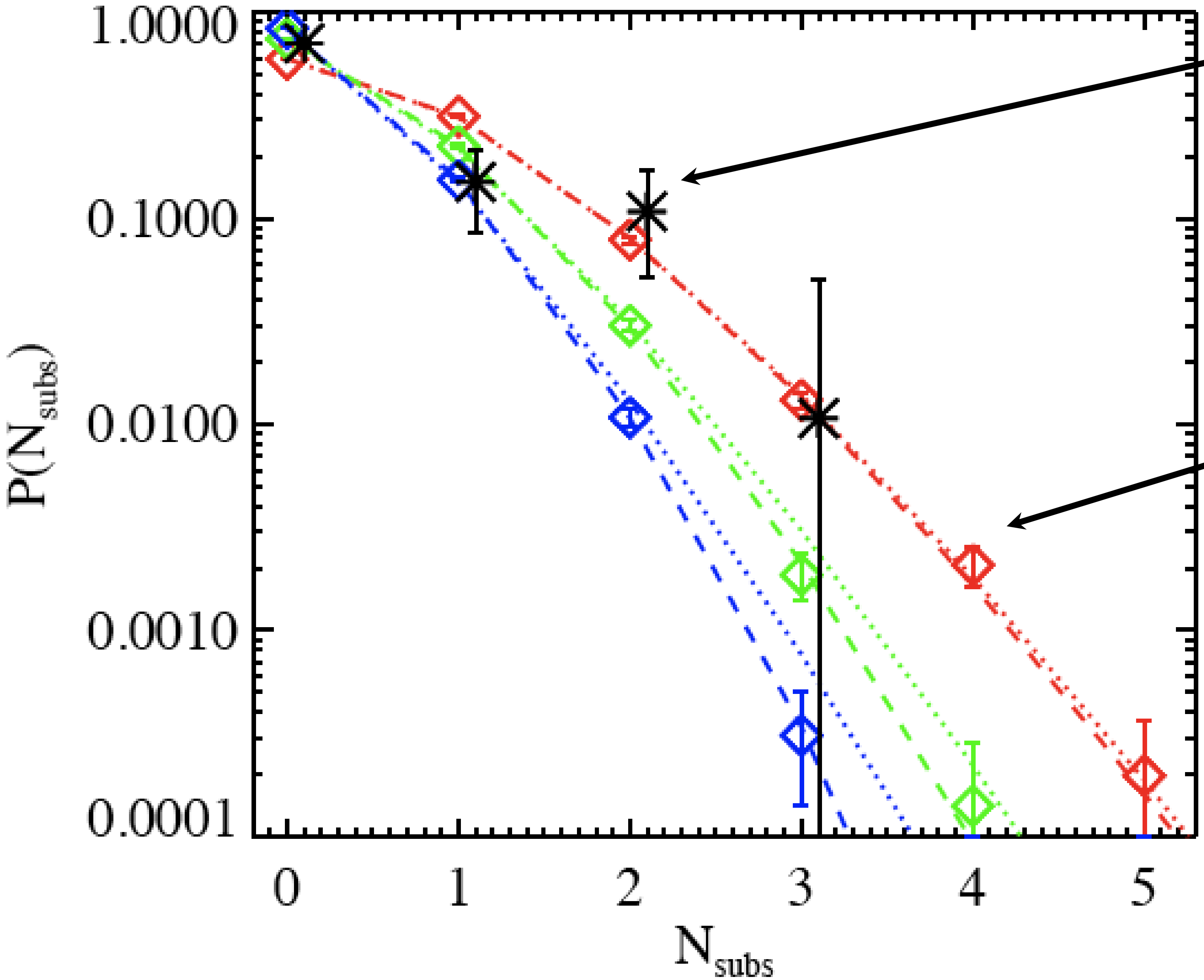
Trujillo-Gomez et al 2010

Abundance matching: correlation function of galaxies



Observations - LCDM: just enough Magellanic Clouds

The probability distribution for the abundance of **Magellanic Clouds**-like satellites around **Milky Way**-mass hosts in simulations (colored diamonds).



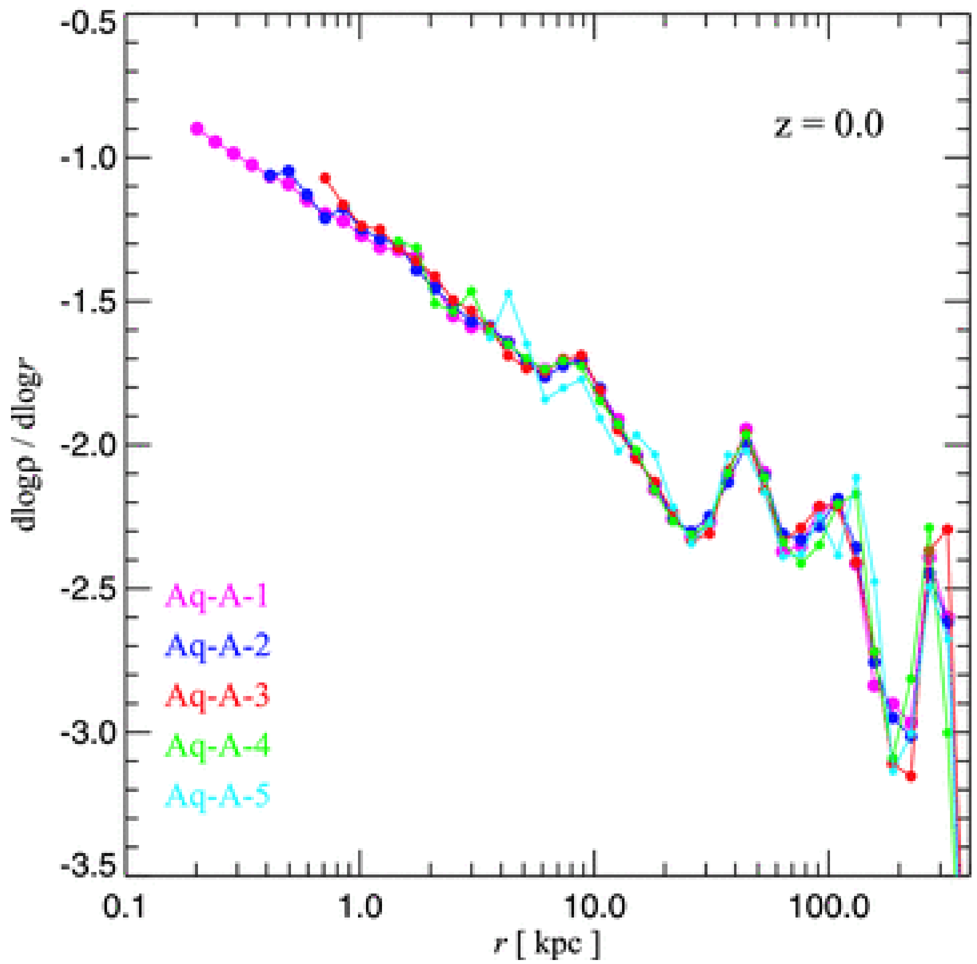
Observations

LCDM

Vmax > 50 km/s

Busha et al 2010

Dark matter profiles: standard LCDM

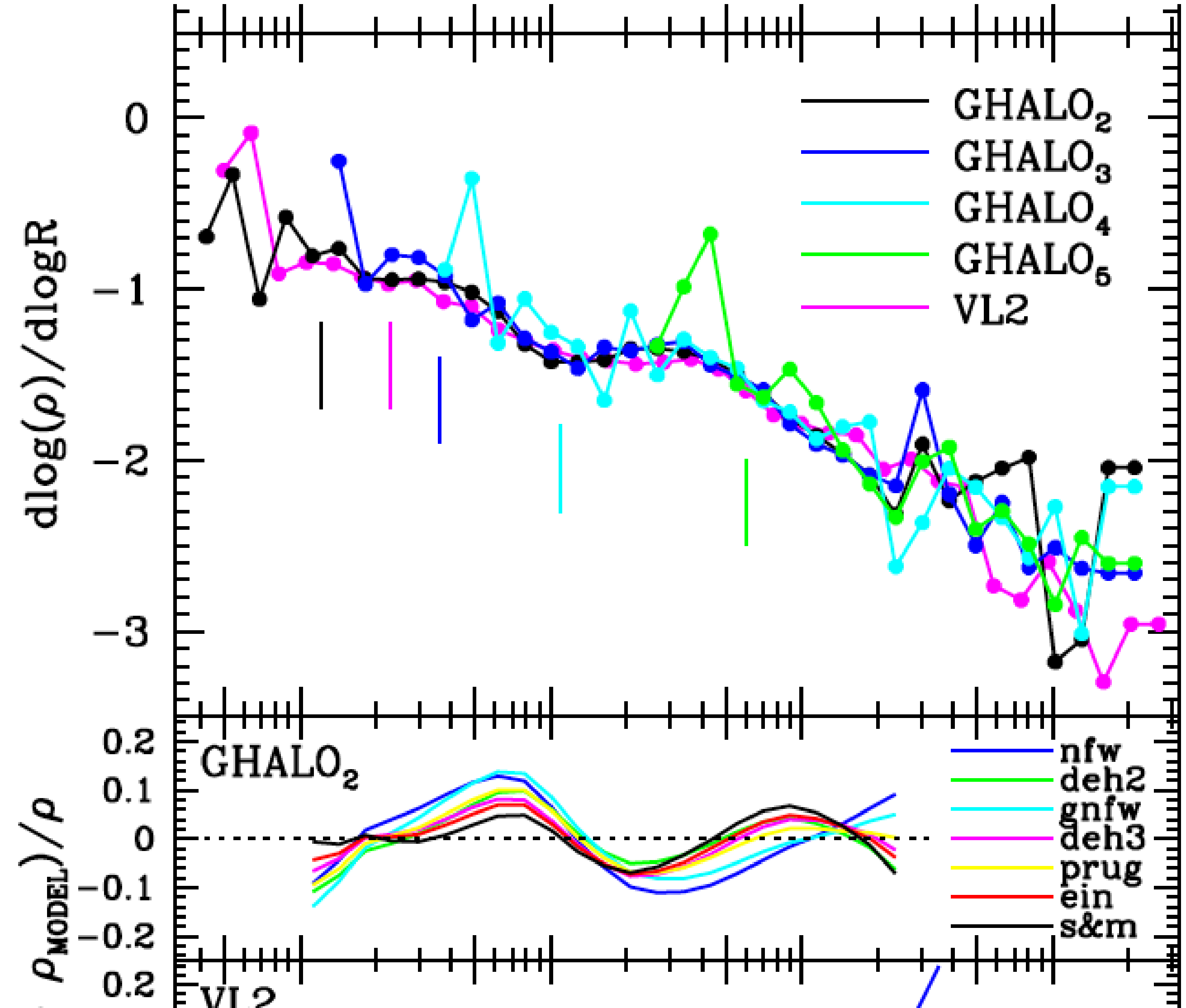


Aquarius simulation. Springel et al 2008. WMAP-1

Central slope is very close to -1

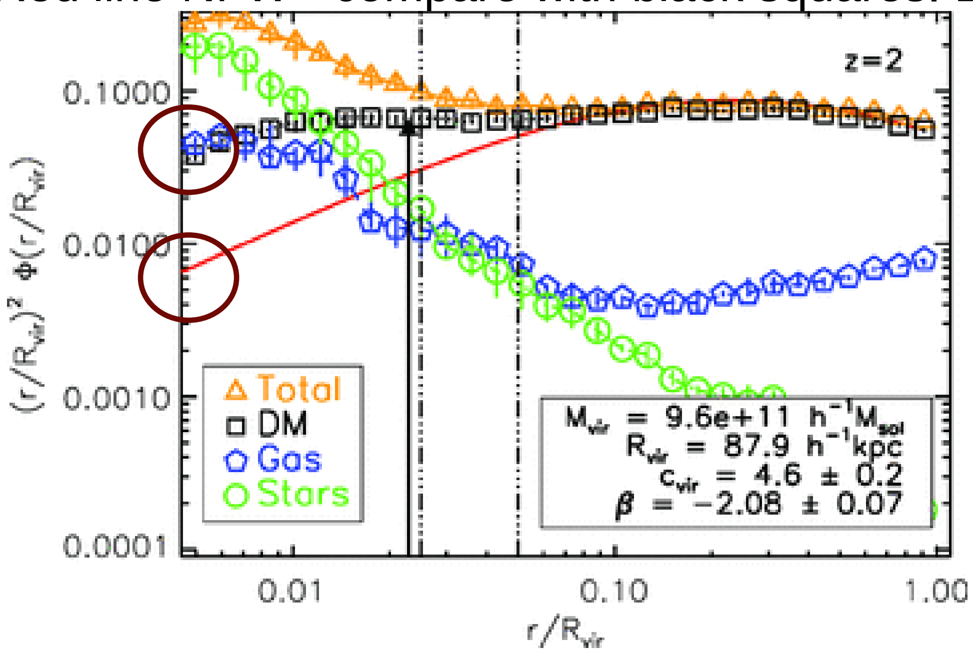
For normal galaxies it does not matter: baryons dominate

100pc



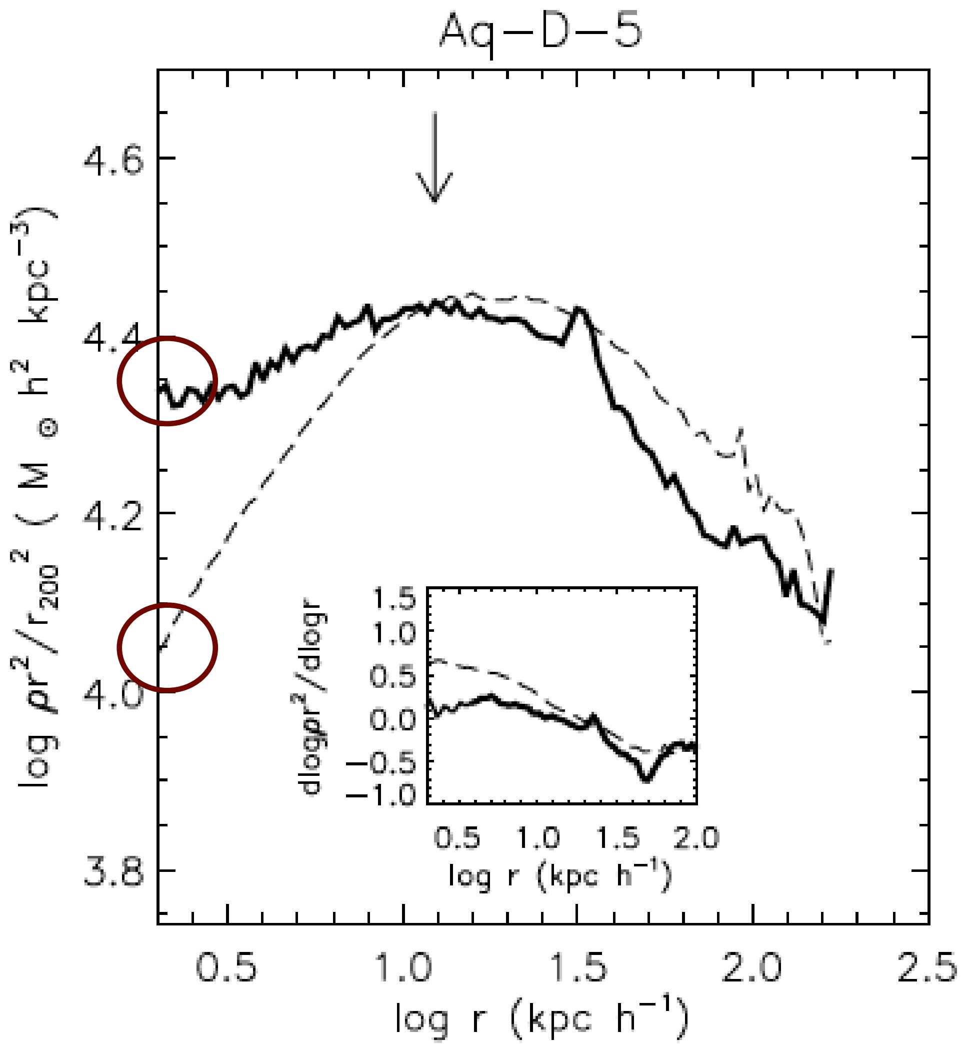
Stadel etal 2009

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

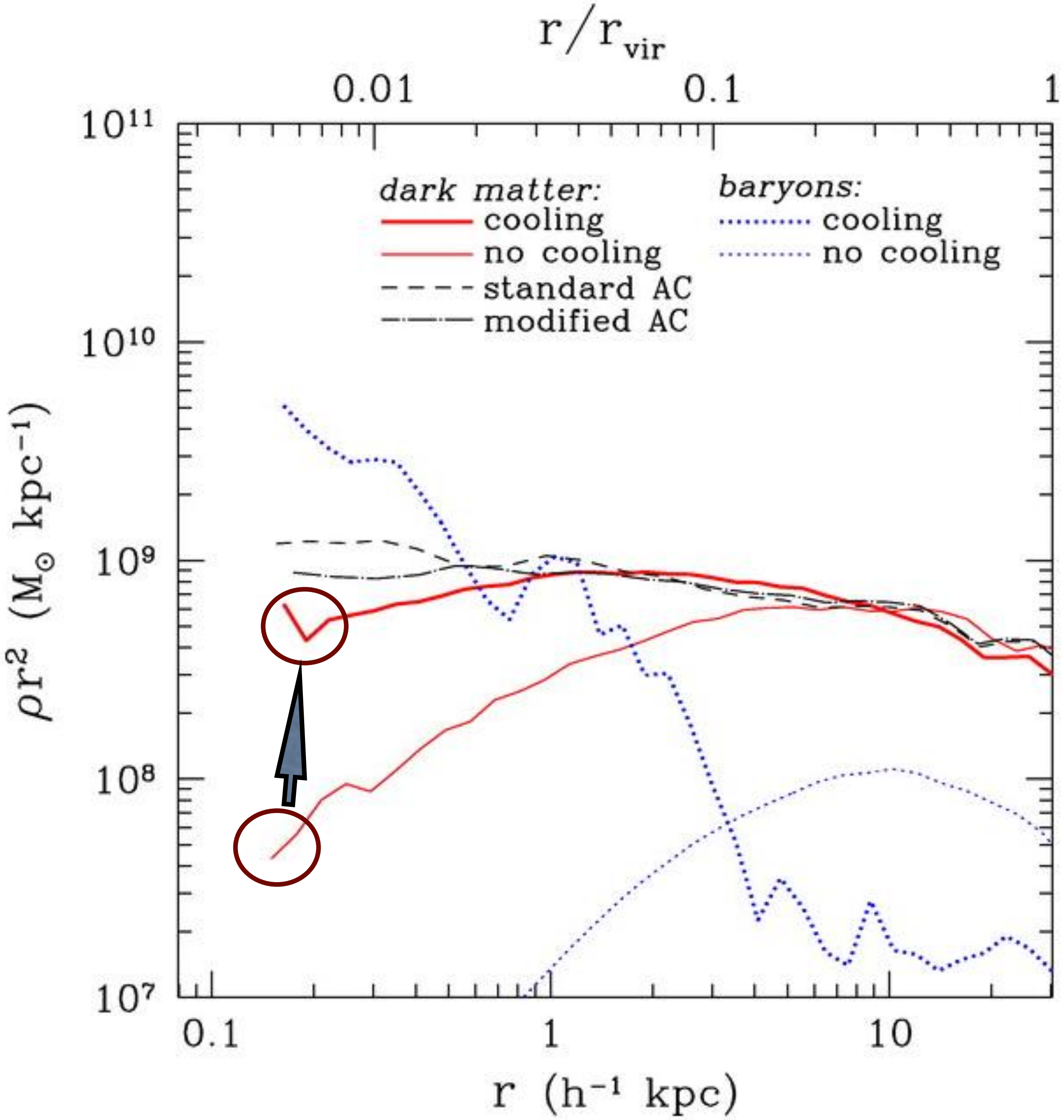


Adiabatic compression is always present. Do not forget to use it.

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



compare red lines. Gnedin et al 2004



Klypin et al 1999

Moore et al 1999

Early explanation for the discrepancy was photoionization.

Tidal stripping: luminous satellites were much larger in the past. The small halos were photo evaporated.

Kravtsov, Gnedin, Klypin 2004

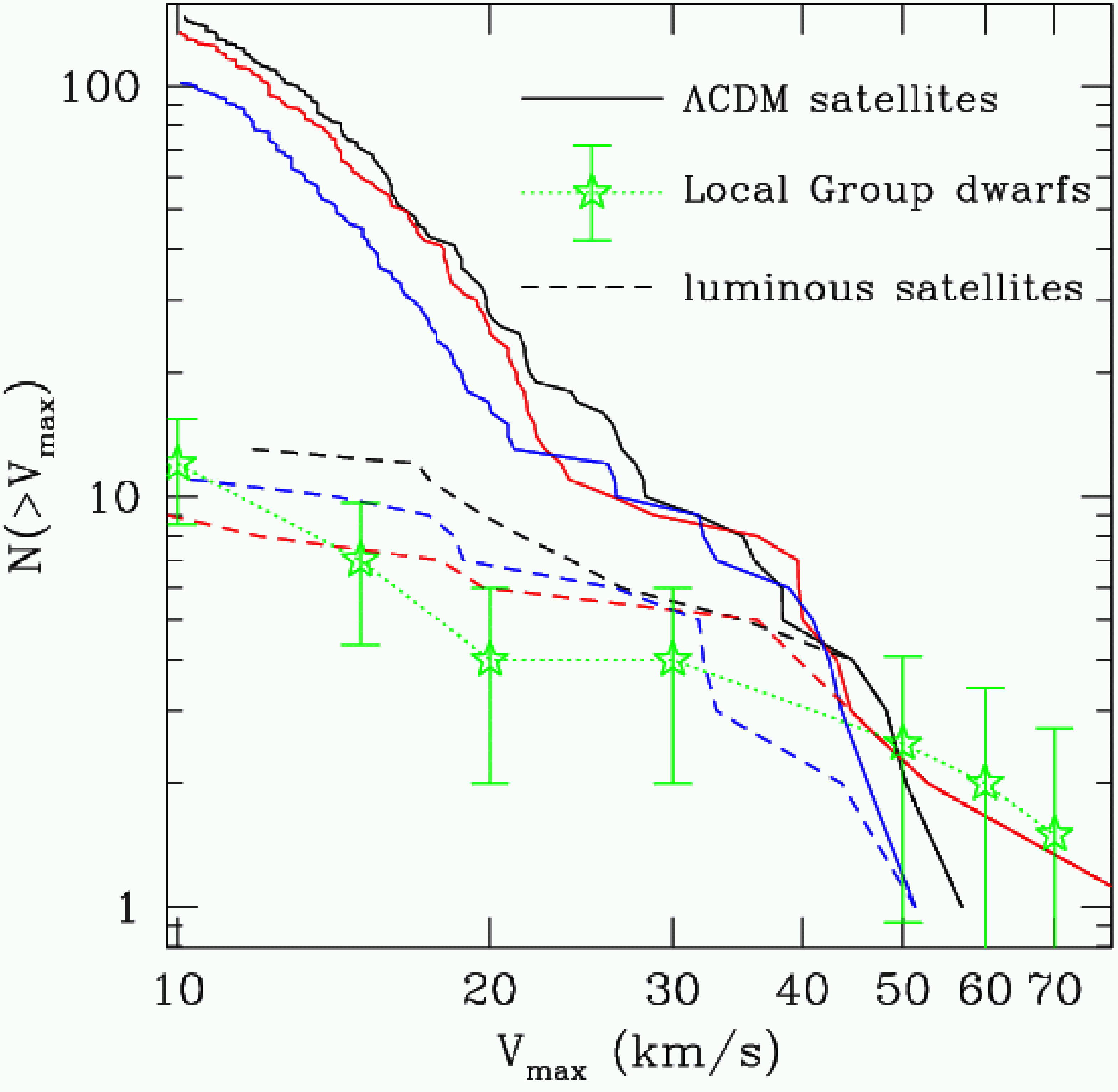


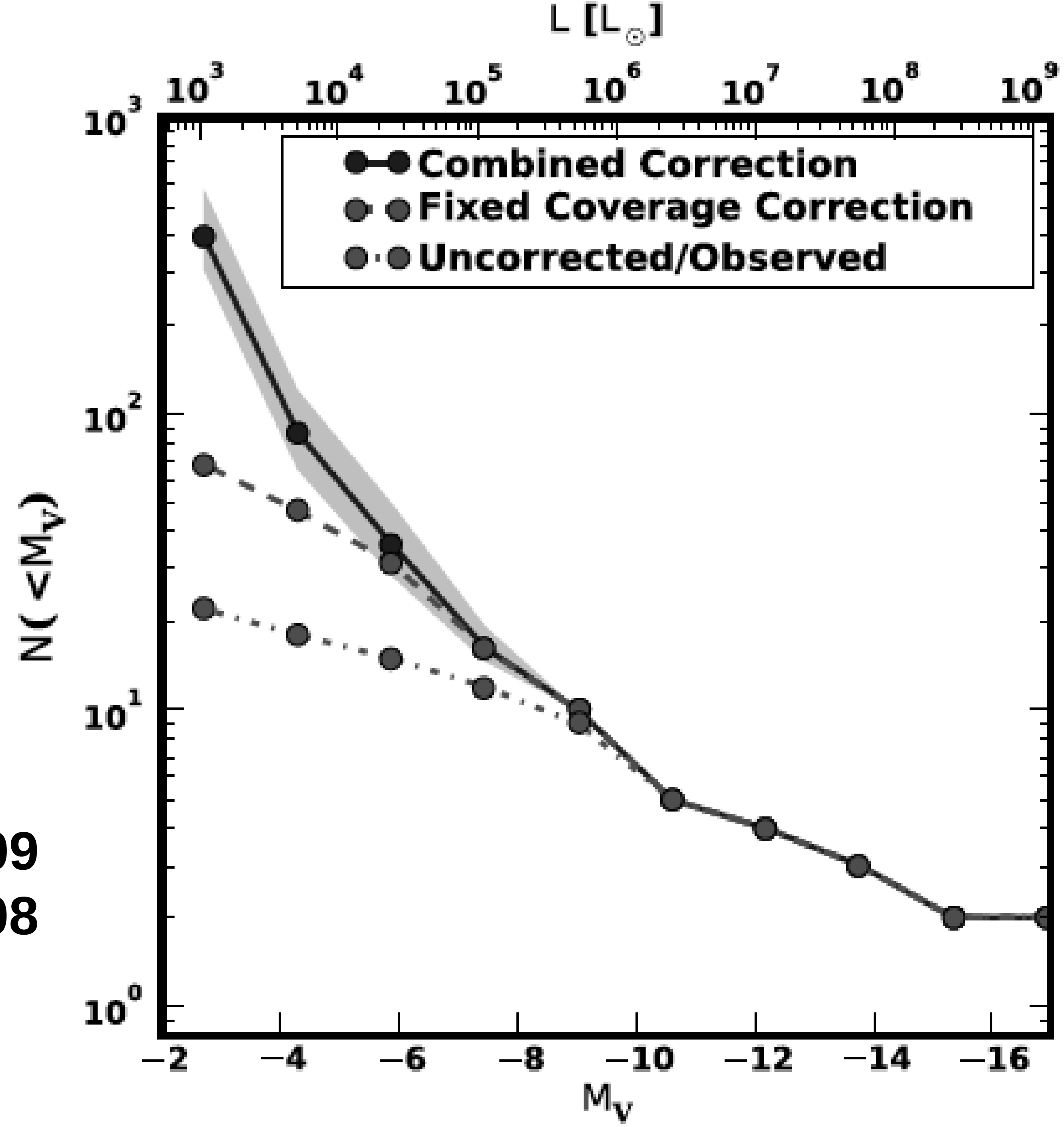
FIG. 7.— The cumulative velocity function of the dark matter satellites in the three galactic halos (*solid lines* compared to the average cumulative velocity function of dwarf galaxies around the Milky Way and Andromeda galaxies (*stars*). For the objects in simulations V_{circ} is the maximum circular velocity, while for the Local Group galaxies it is either the circular velocity measured from rotation curve or from the line-of-sight velocity dispersion assuming isotropic velocities. Both observed and simulated objects are

SDSS: new satellites

Classic satellites: about 10

SDSS: about **12** new satellites
only 20% of the sky

Correcting for sky coverage: **60**
Correcting for distance incompleteness: **300 -600**



Koposov etal 2009
Tollerud et al 2008

Newly discovered satellites are very small stellar rms velocities 5-10km/s

How to suppress formation of a galaxy

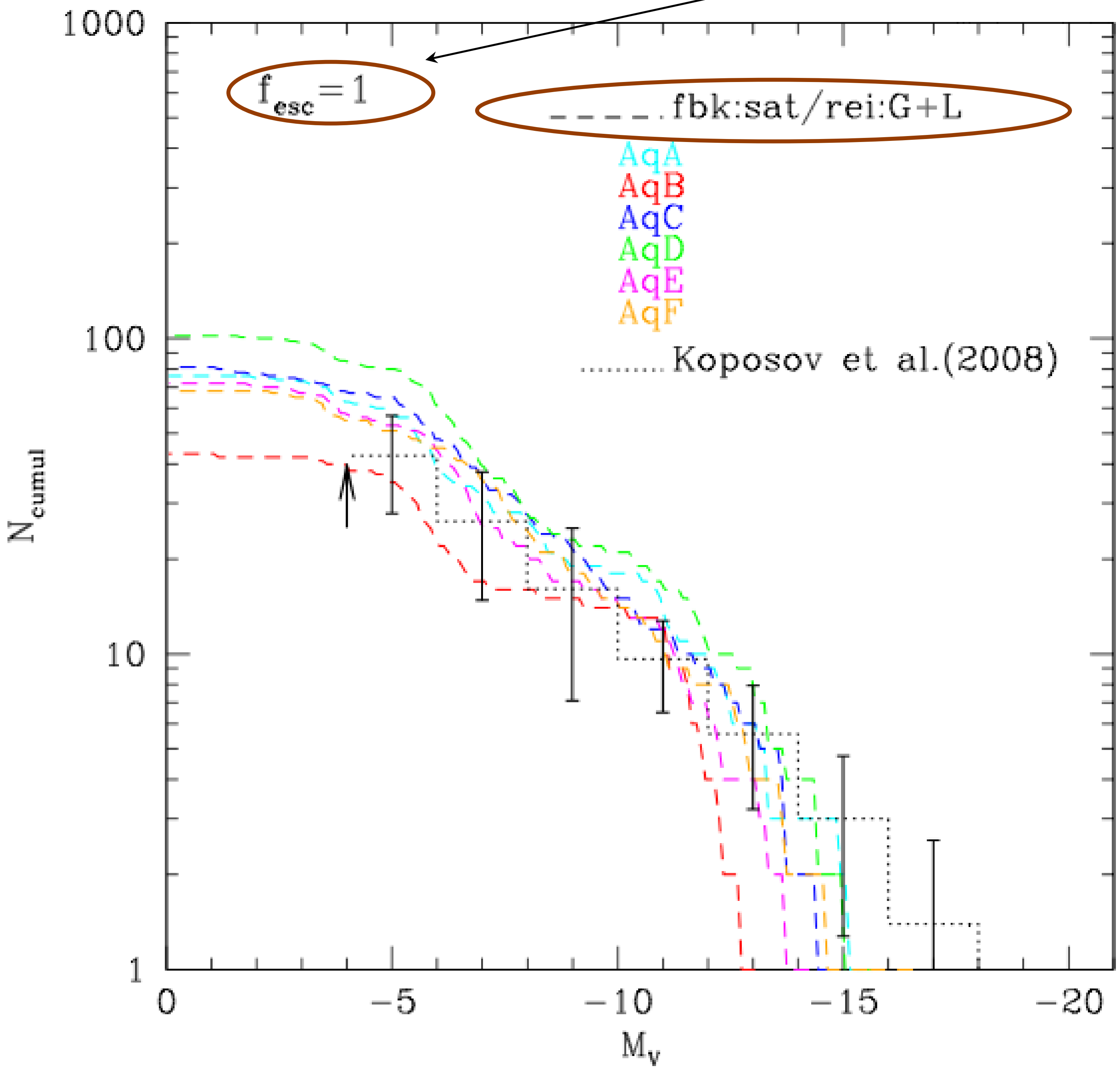
- Star-formation/Supernovae. Dekel & Silk (1985)
- Photoionization/heating (Bullock etal 2000)

How to kill of a galaxy

V_{crit} =30-40 km/s

Is there a limit on mass of galaxy?

Fraction of UV ionizing photons that leaks from galaxies and ionizes intergalactic medium



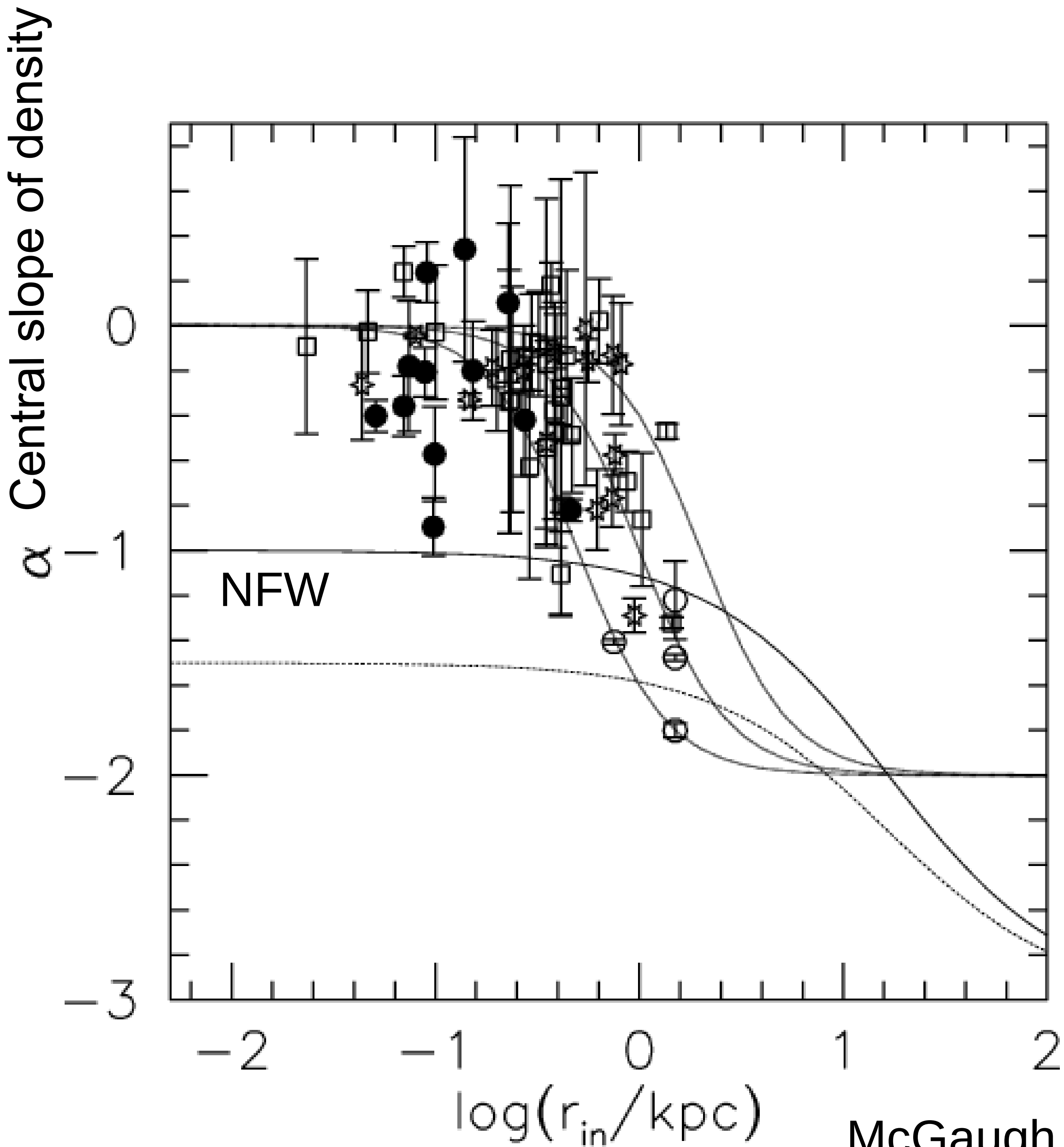
The model is constrained to match a wide range of properties of the present day galaxy population as a whole, but at high redshift it requires an escape fraction of UV photons near unity in order completely to reionize the universe by redshift z >8. In the most successful model the local sources photoionize the pre-galactic region completely by z ≃ 10.

In addition to the luminosity function of Milky Way satellites, the model matches their observed luminosity-metallicity relation, their radial distribution and the inferred values of the mass within 300 pc

Font et al 2011

Structure of dwarf galaxies

Very small scales: cusps and cores



McGaugh et al 2002

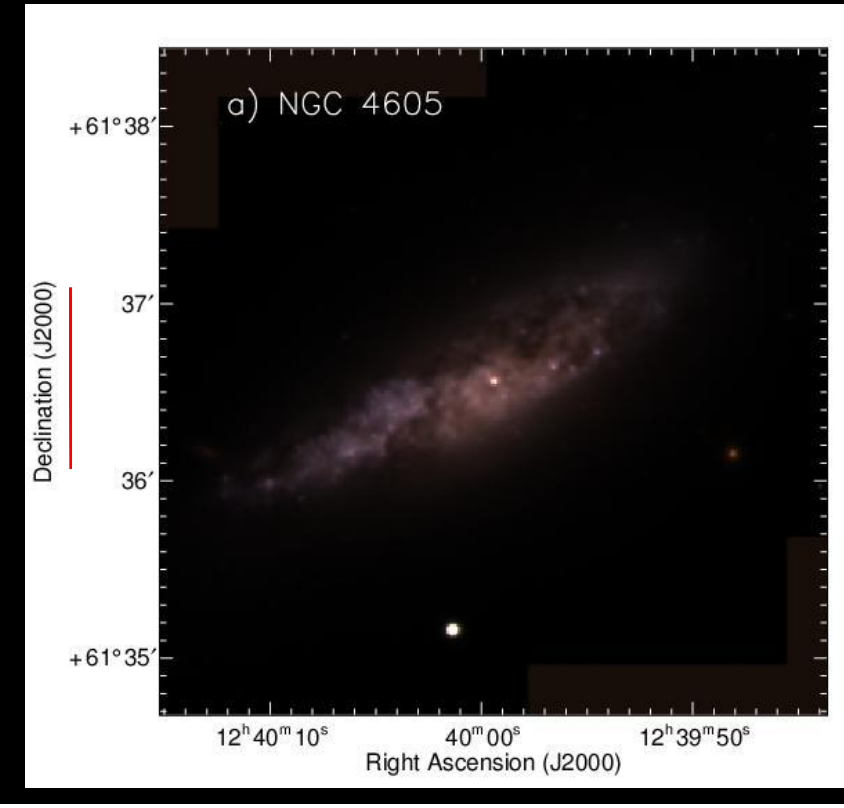
Cusps and rotation curves:

too much of DM in central parts of galaxies?

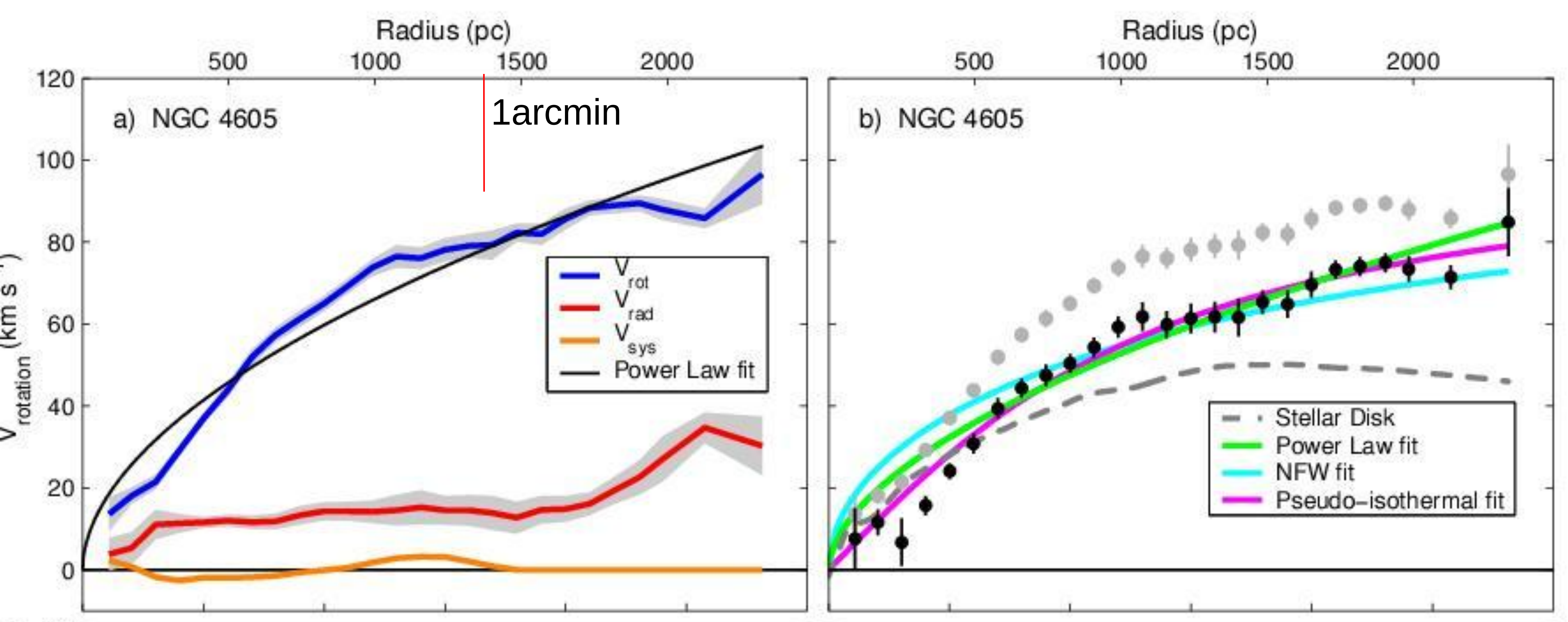
Simon etal 04   NGC 4605 Vmax =100km/s

-- Usual problems with NFW.

-- Disk is important: normal M/L_R=1 M/L_K= 0.5



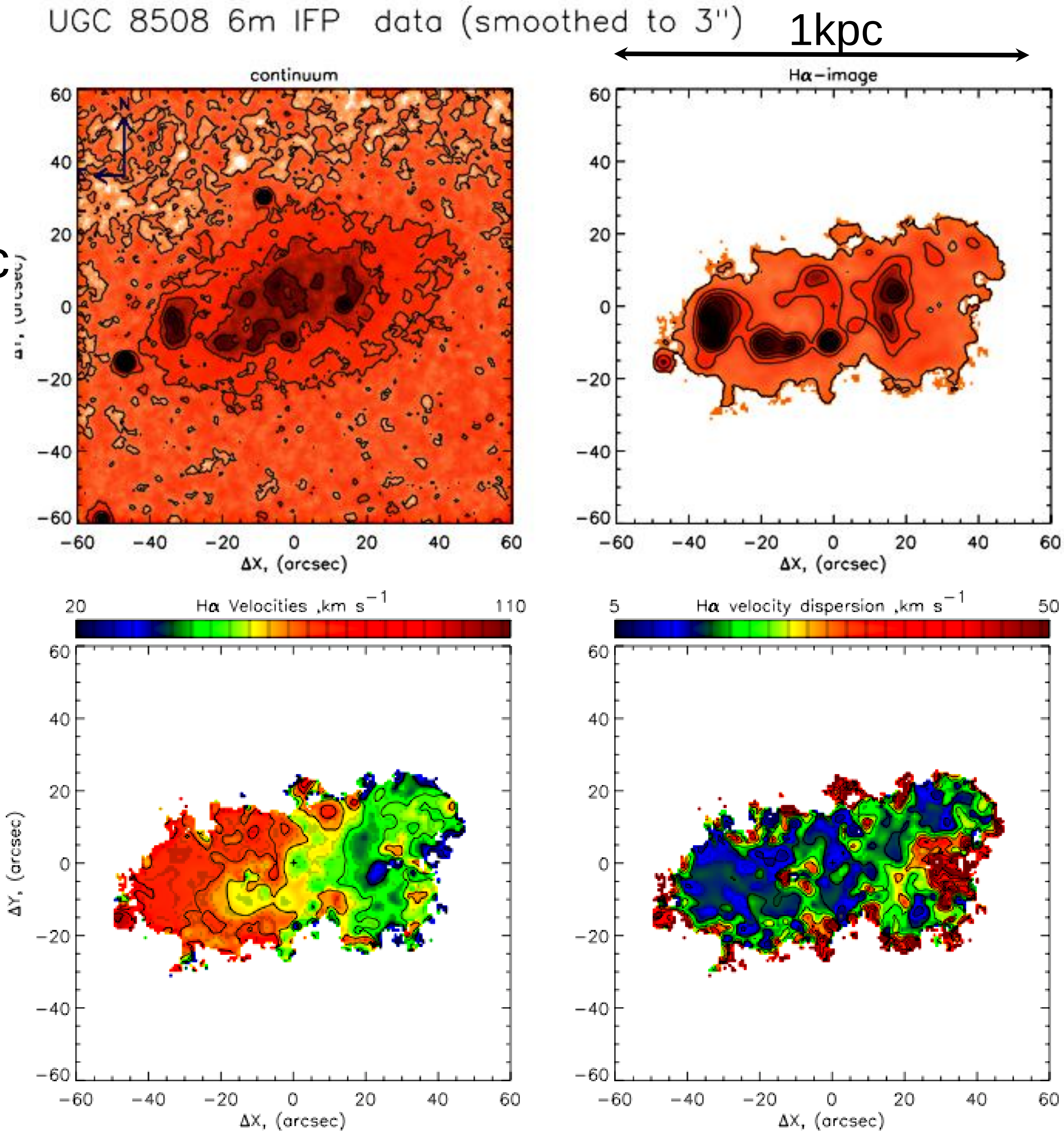
Simon et al.



Example: UGC8508

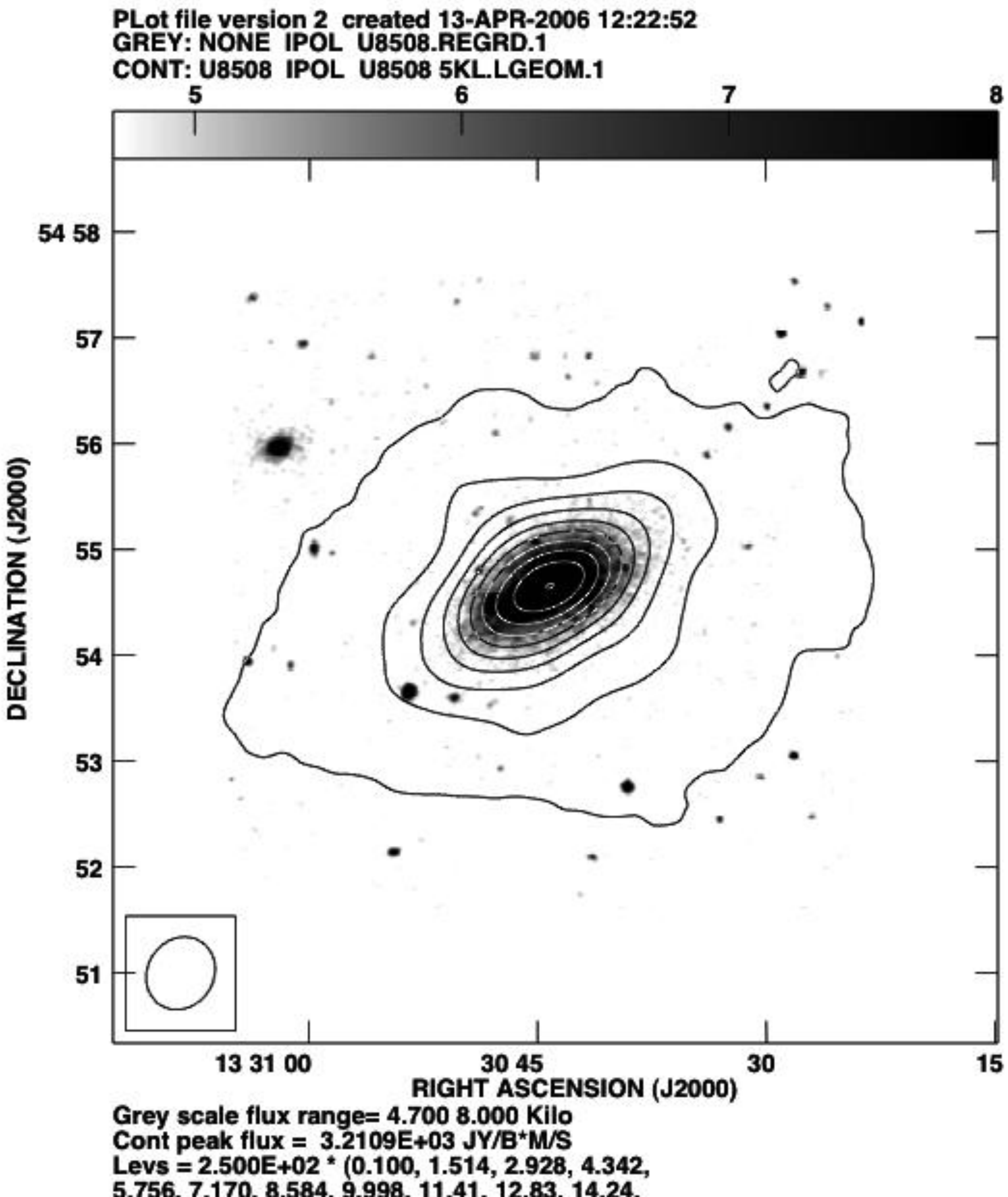
Distance 2.5 Mpc

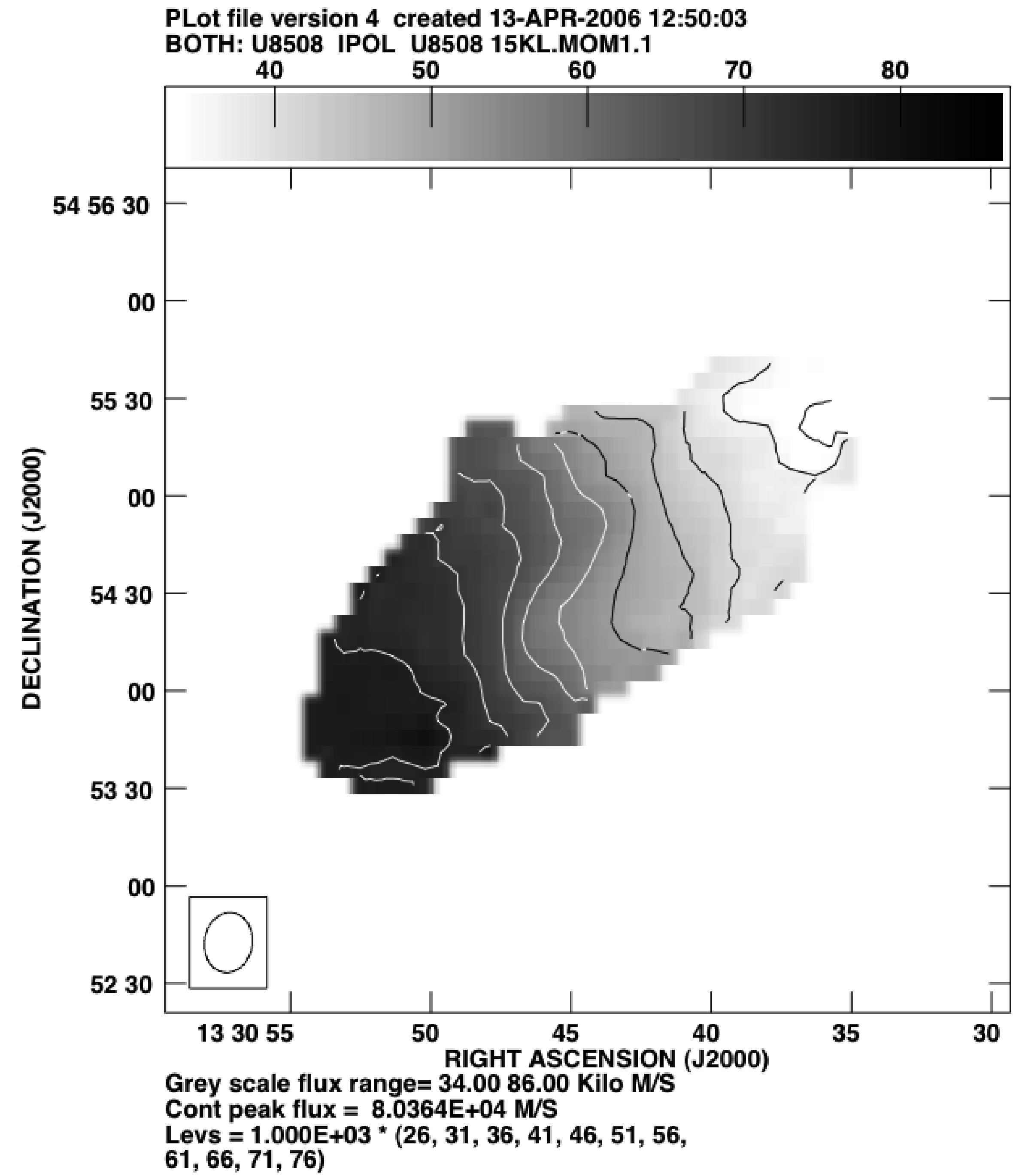
M_B =-12.9



Russian 6m telescope

HI data

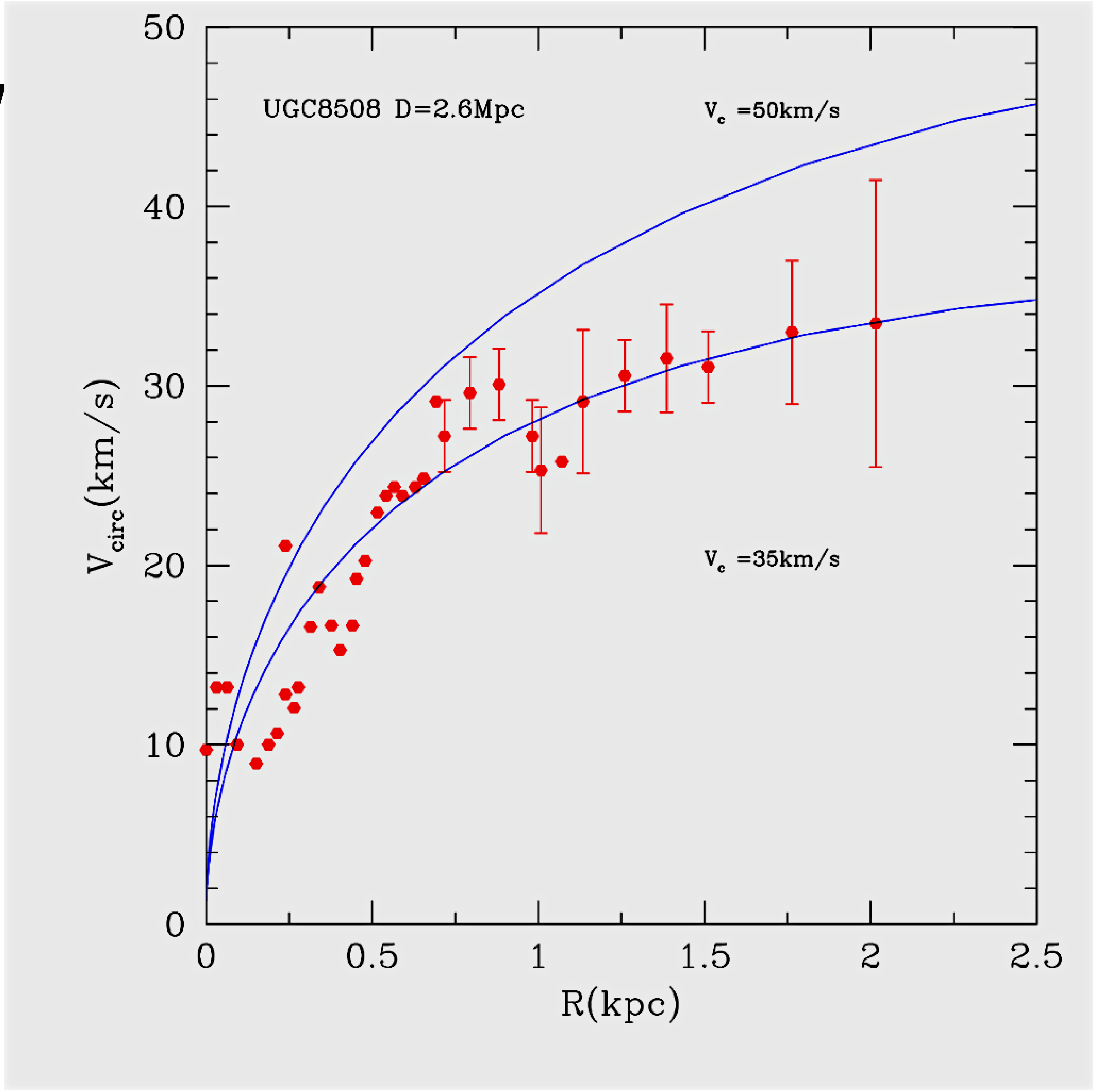




GMRT: India

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

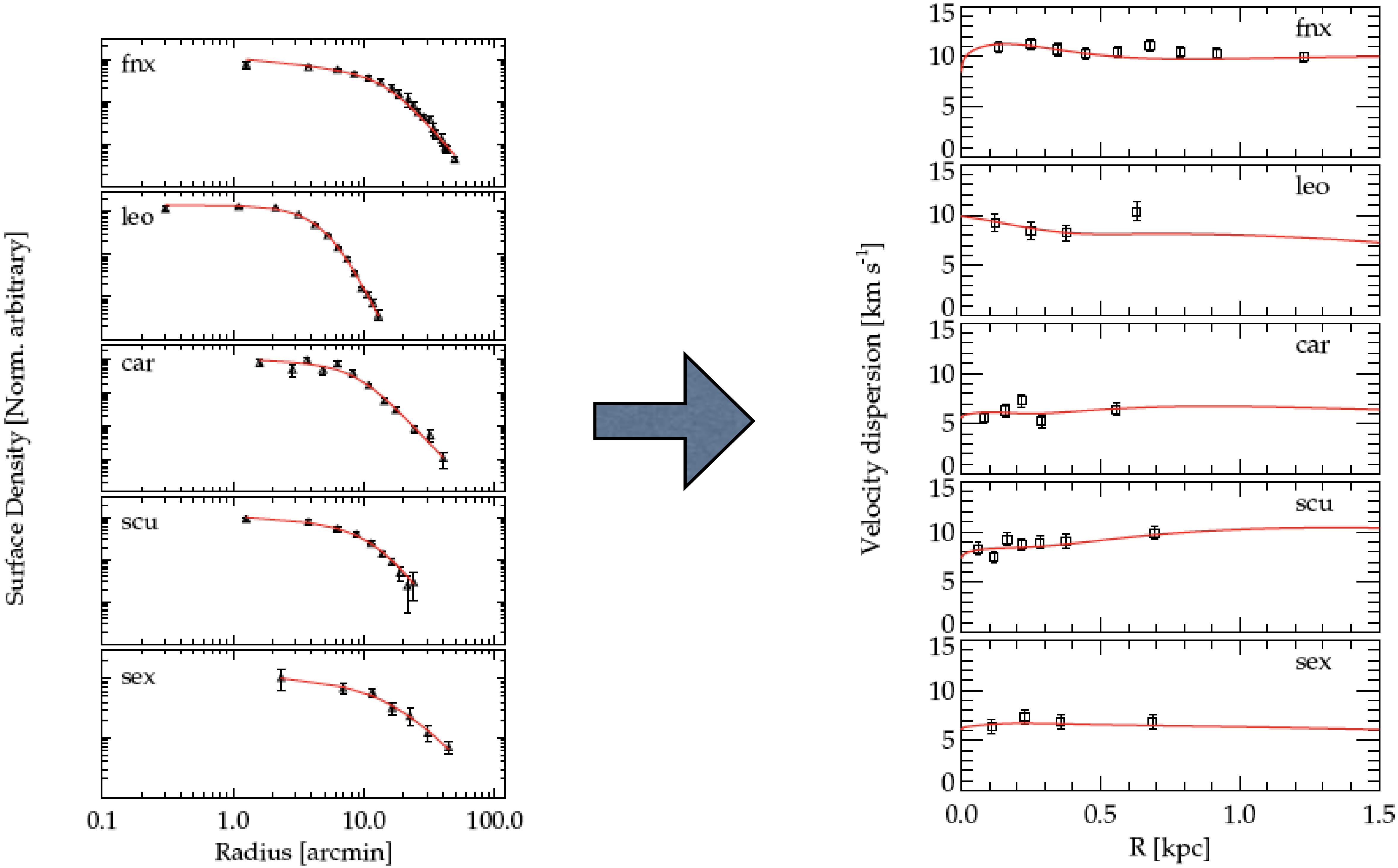
Theory predicts too large circular velocity



Kinematics of Milky Way Satellites in a Lambda Cold Dark Matter Universe

Louis E. Strigari[1], Carlos S. Frenk[2] and Simon D. M. White[3]

fully consistent with ΛCDM expectations and do not require cored dark matter distributions.



Too big to fail? The puzzling darkness of massive Milky Way subhalos

Michael Boylan-Kolchin*†, James S. Bullock, and Manoj Kaplinghat
Center for Cosmology, Department of Physics and Astronomy, 4129 Reines Hall, University of California, Irvine, CA 92697, USA

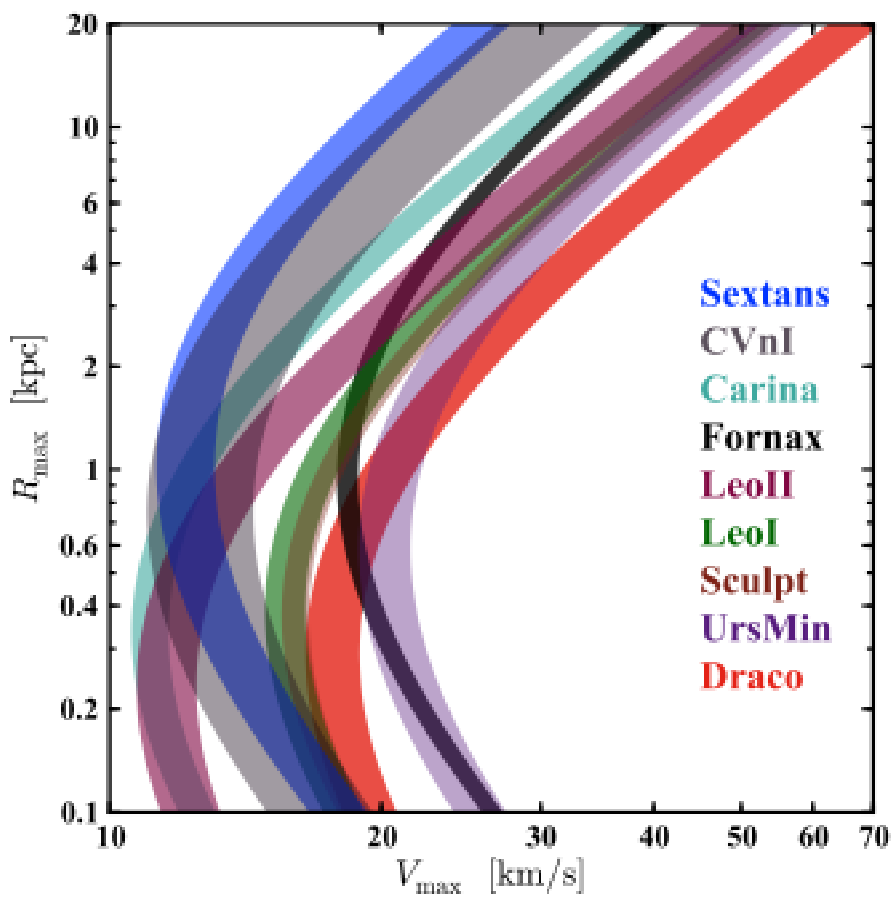


Figure 1. Constraints on the $V_{max} - R_{max}$ values (assuming NFW profiles) of the hosts of the nine bright ($L_V > 10^5\,L_\odot$) MW dwarf spheroidal galaxies. The colored bands show $1\,\sigma$ confidence

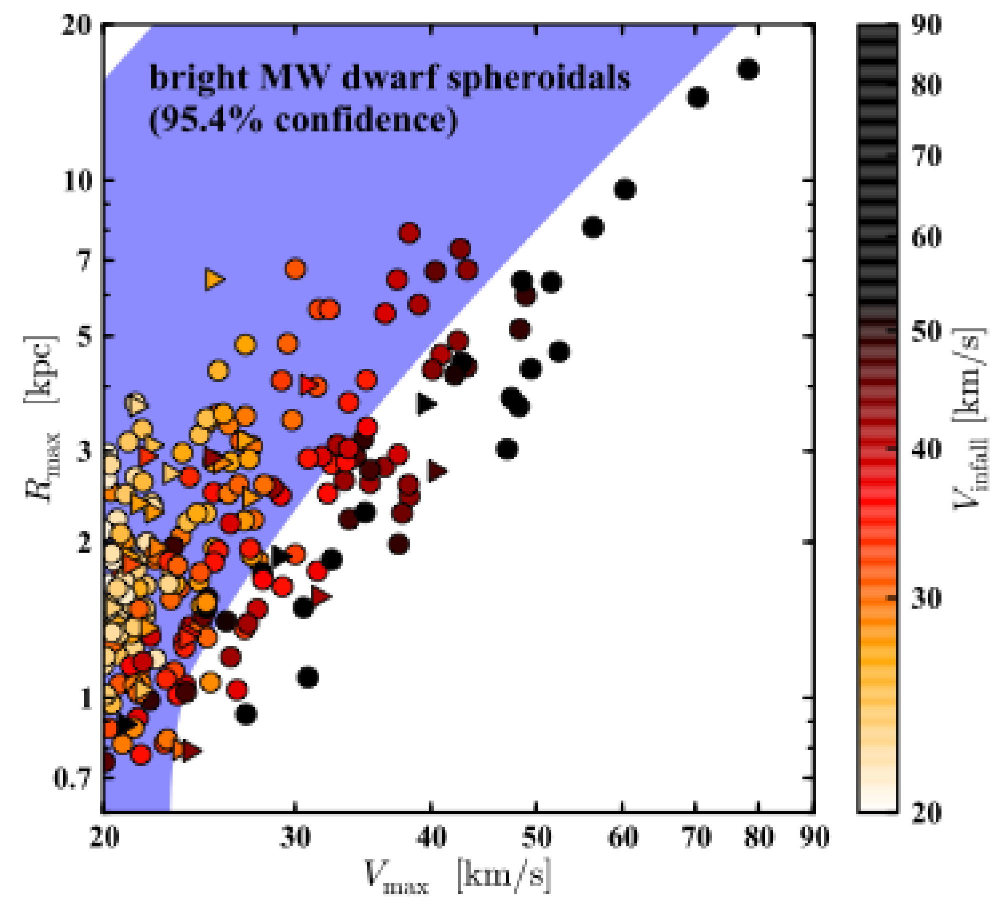
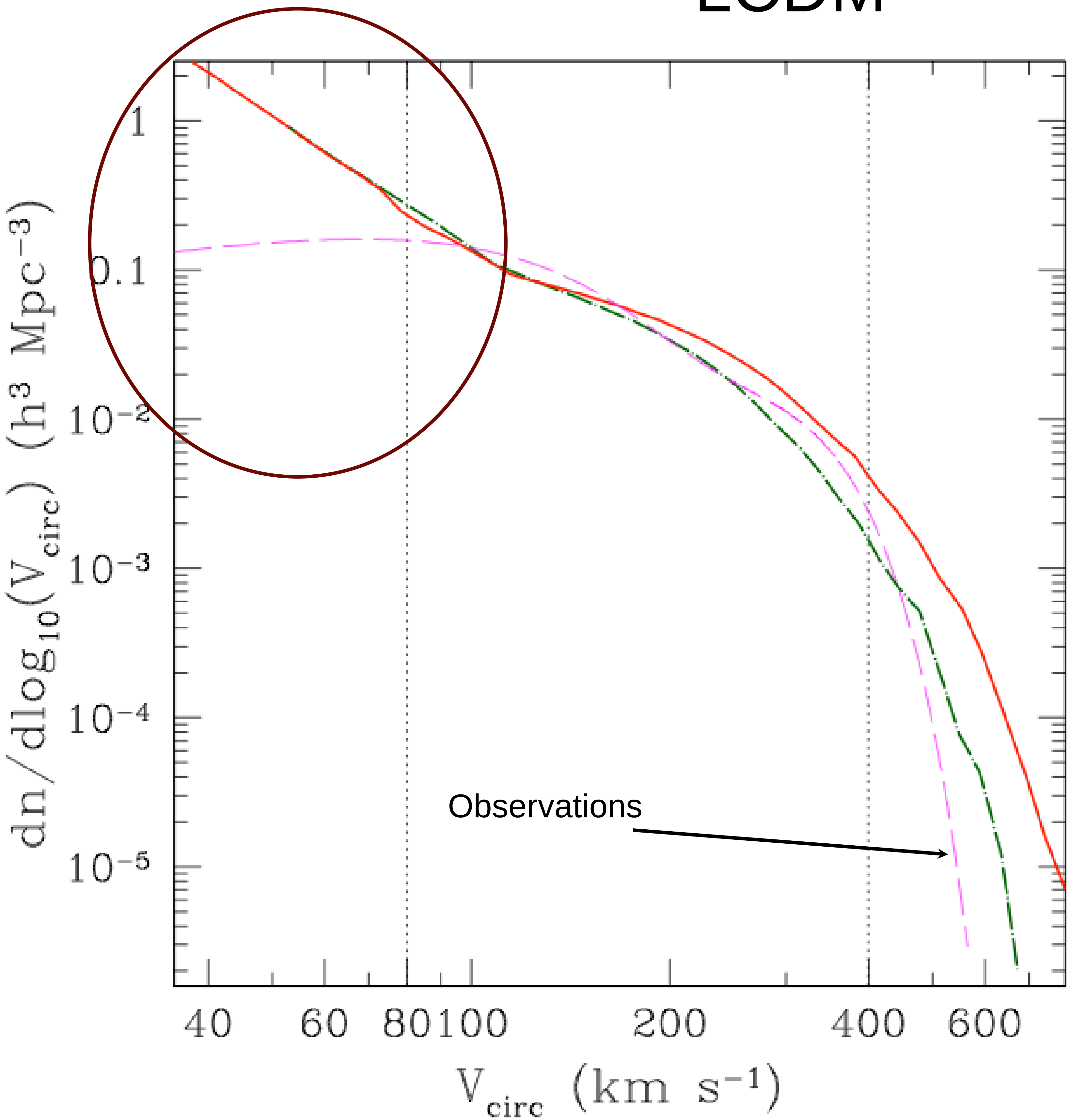


Figure 2. Subhalos from all six Aquarius simulations (circles) and Via Lactea II (triangles), color-coded according to V_{infall}. The

We show that dissipationless ΛCDM simulations predict that the majority of the most massive subhalos of the Milky Way are too dense to host any of its bright satellites ($L_V > 10^5\,L_\odot$). These dark subhalos have circular velocities at infall of

Abundance of galaxies

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.

Conclusions

- Very accurate estimates for numerous statistics
- Tests down to 10 kpc: LCDM is doing fine
- Not clear what happens on smaller scales