Halo velocity and concentration functions in the standard LCDM cosmology

Francisco Prada

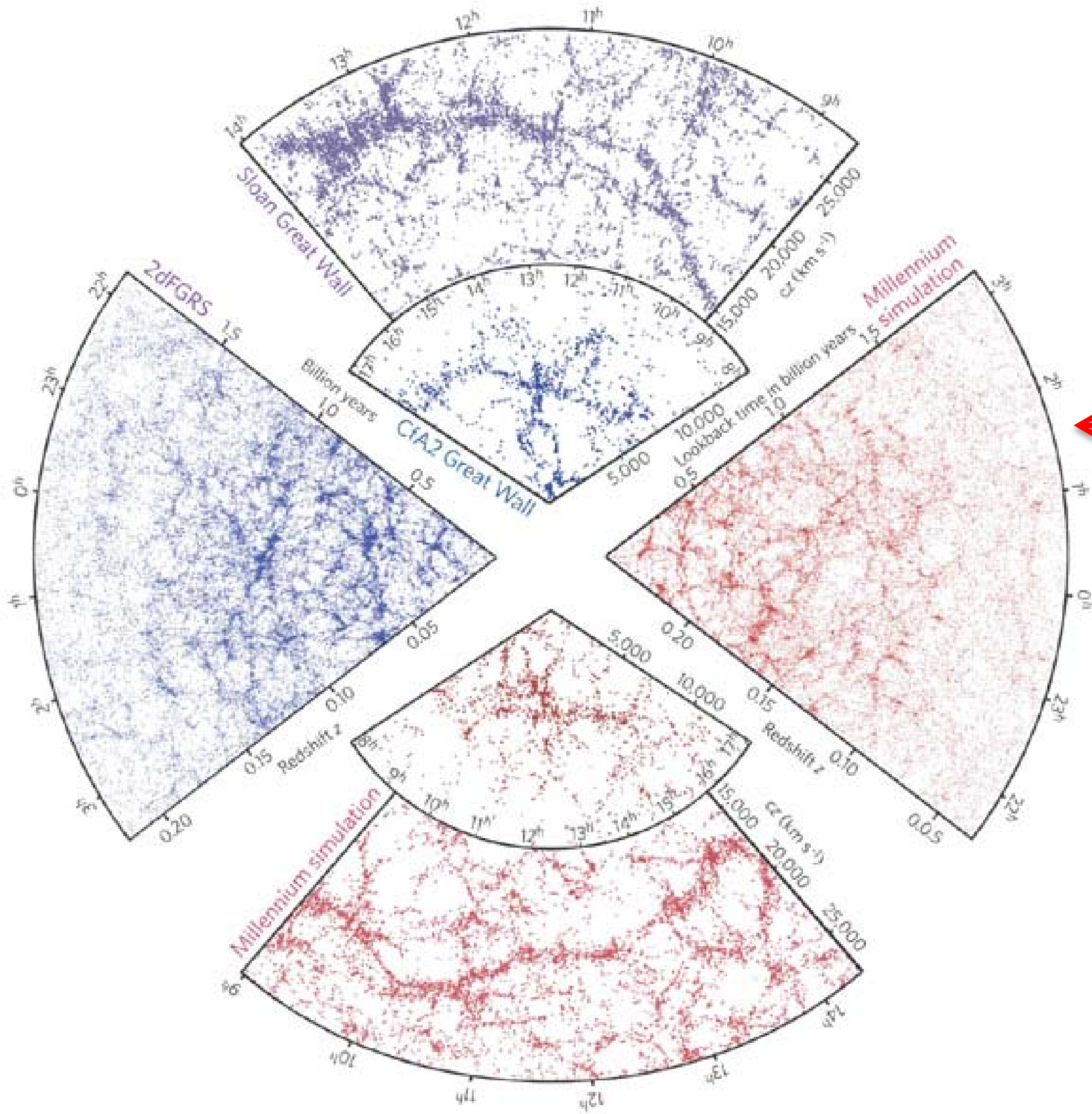
IAA-CSIC, Granada, Spain

Results from a paper in prep., *Prada, Klypin* et al. 2011

Caltech, Feb. 18th, 2011

Galaxy-Halo connection

Data



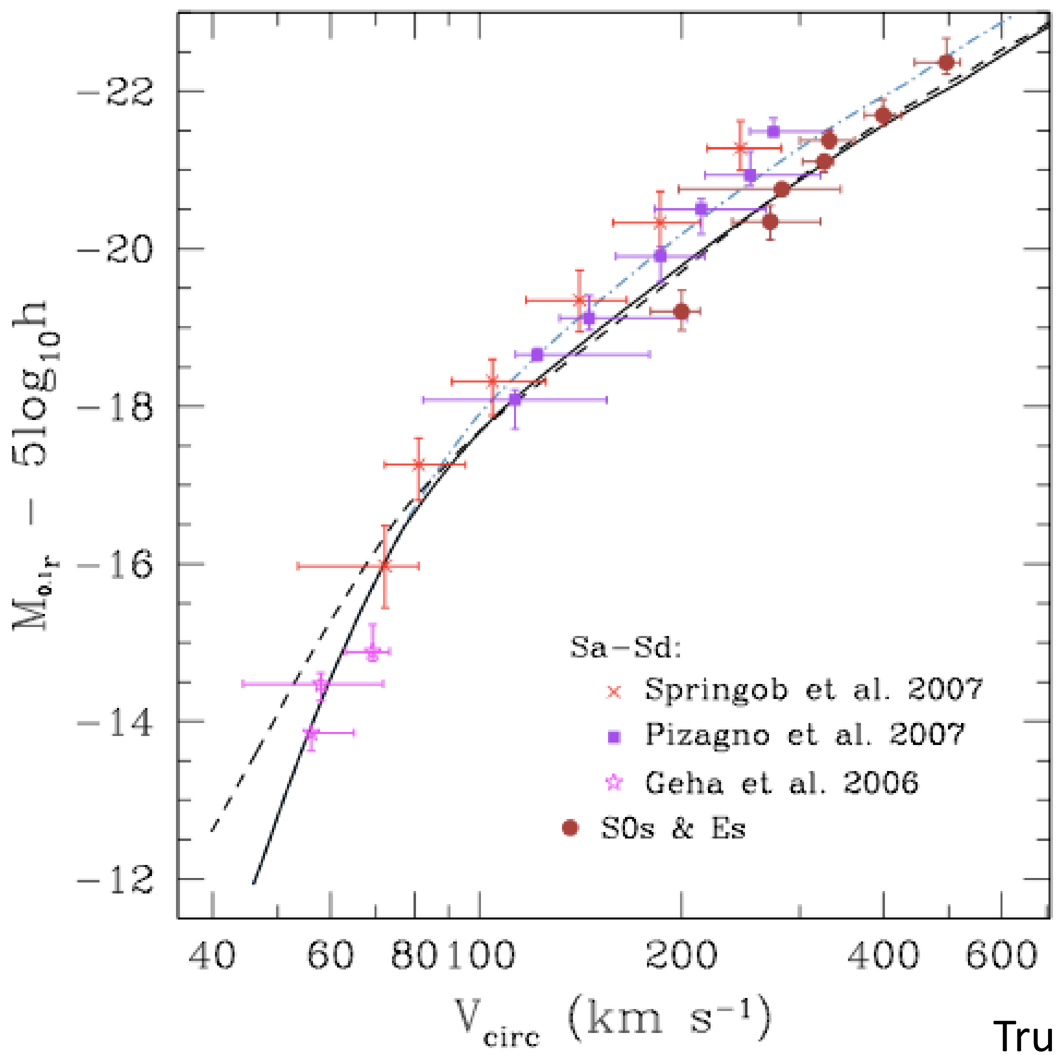
Simulations

I. Velocity functions

The maximum of the halo circular velocity profile

$$V^2_{max}=max[GM(<r)/r]$$

is a measure of the depth of the dark matter halo potential well and it is expected to correlate well with the baryonic component of galaxies such as the luminosity or stellar mass as followed from the Tully-Fisher relation. The maximum circular velocity at present, for dominant halos, and at the time of accretion, in the case of subhalos, gives a better match to model the observed luminosity dependence and evolution of galaxy clustering from high-z to the present (e.g. Conroy et al. 2006). Another example is the recent work by Trujillo-Gomez et al. 2010 where they provide LCDM predictions for basic statistics of galaxies: Luminosity-- and Baryonic Mass--Velocity Relations, and Velocity Functions.



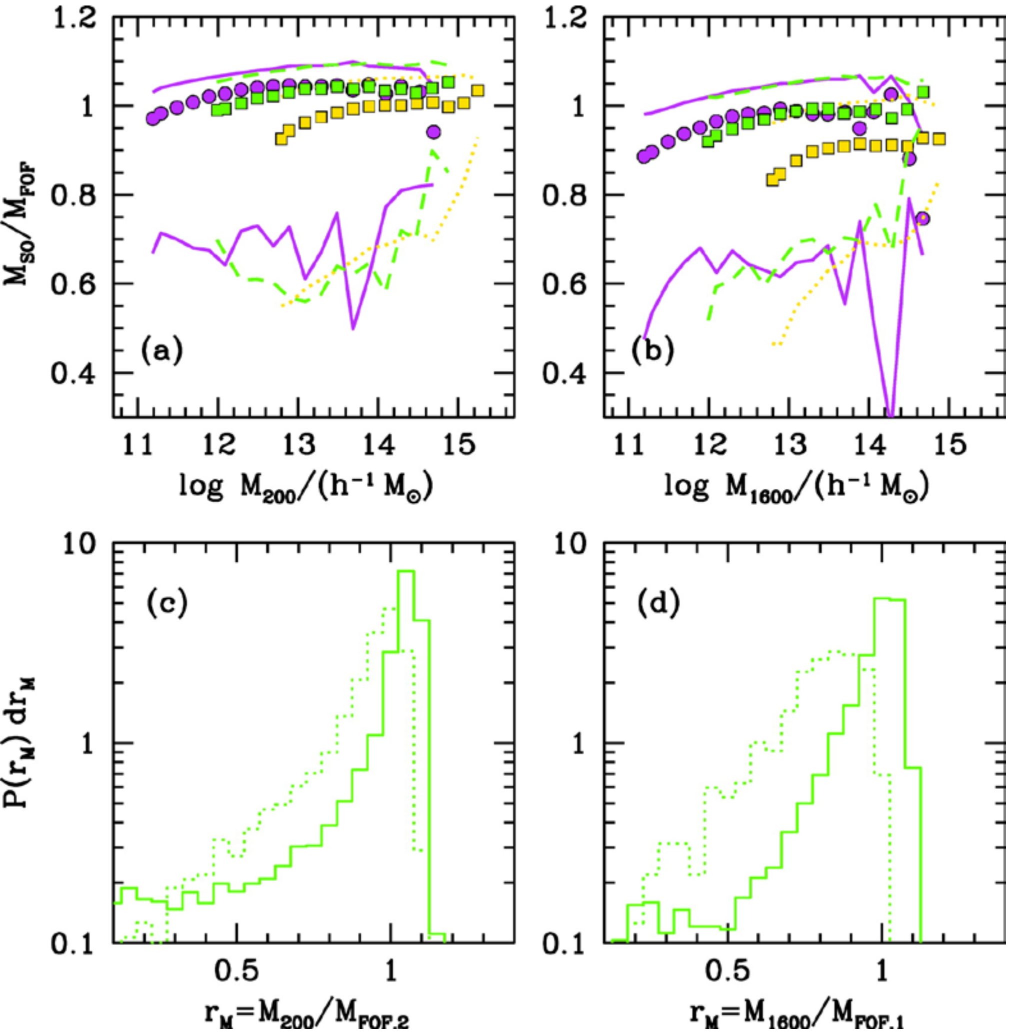
Trujillo-Gomez et al. 2010

Fig. 4.— Comparison of the observed LuminosityVelocity 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. 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. The dashed curve show results for a steeper ($\alpha = -1.34$) slope of the LF. The dot-dashed curve shows predictions after adding the baryon mass but without adiabatic contraction. Points show representative observational samples.

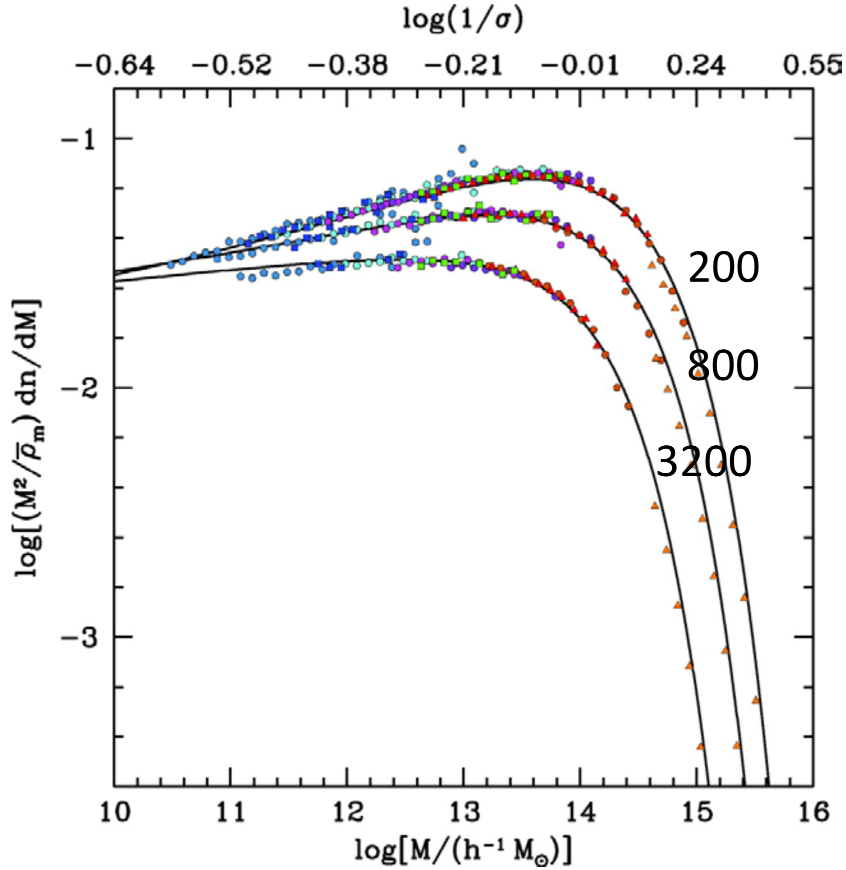
Comparison between spherical overdensity masses and friends-of-friends masses for the same sample of halos

SO 200, FOF ll0.2

SO 1600, FOF ll0.1



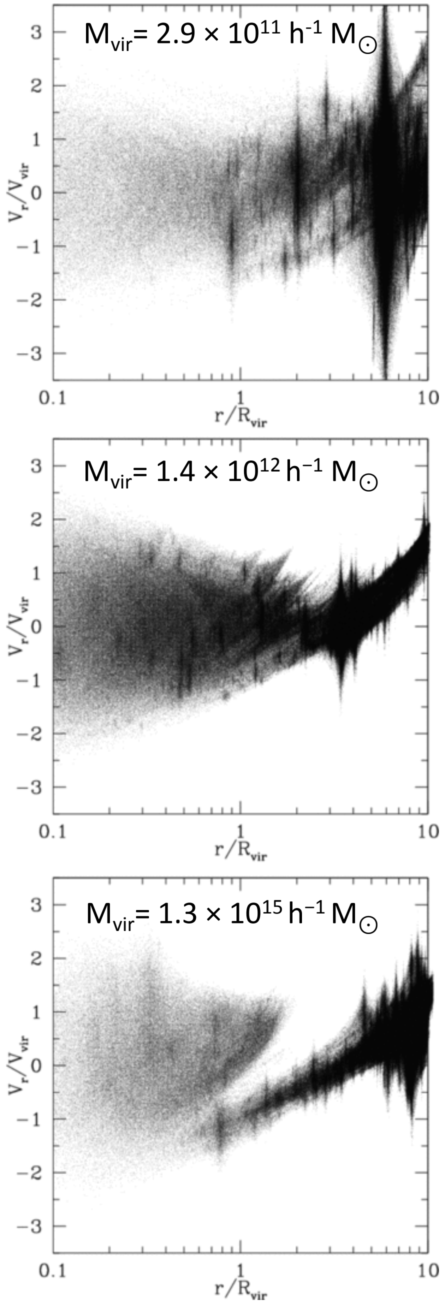
Mass functions for different SO



Tinker et al. 2008

Motivation

Prada et al. 2006, Cuesta et al. 2008



Phase space diagram for the particles in dark matter halos.

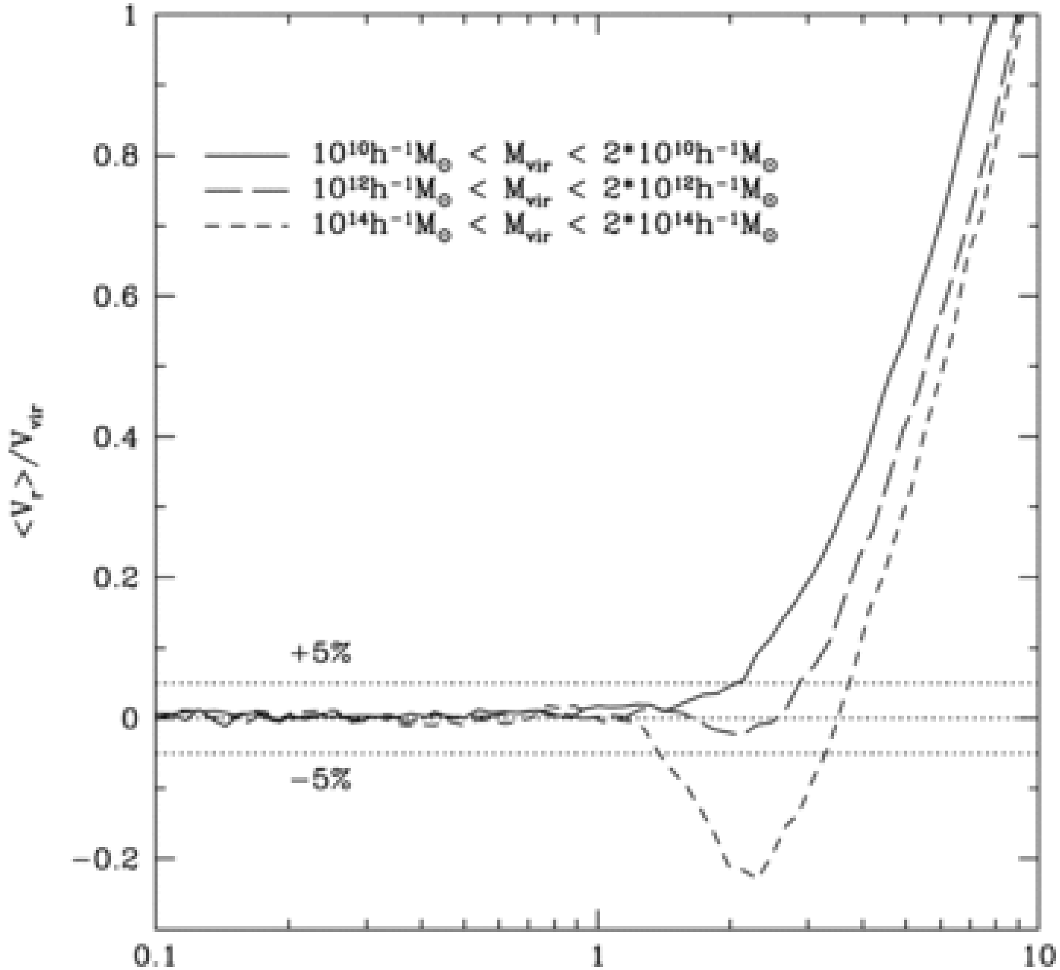


Figure 4. Mean radial velocity for three different mass bins. The profiles were obtained by averaging over hundreds of distinct haloes on each mass bin. In dotted lines is shown the selected threshold delimiting the static region (5 per cent of the virial velocity). Cluster-sized haloes display a region with strong infall (dashed line). In contrast, low-mass haloes (solid line) and galactic haloes (long-dashed line) do not show infall at all but a small outflow preceding the Hubble flow.

Table 1. Basic parameters of the cosmological simulations used in this work. L_{box} is the side length of the simulation box, N_p is the number of simulation particles, ϵ is the force resolution in comoving coordinates, M_p refers to the mass of each simulation particle, and Ω_m, Ω_Λ , Ω_b, n_s (the spectral index of the primordial power spectrum), h (the Hubble constant at present in units of 100 $km/sMpc^{-1}$) and σ_8 (the rms amplitude of linear mass fluctuations in spheres of 8 $h^{-1}Mpc$ comoving radius at redshift zero) are the ΛCDM cosmological parameters used for each simulation (see text).

Name	L_{box} $h^{-1}Mpc$	N_p	ϵ $h^{-1}kpc$	M_p $h^{-1}M_\odot$	Ω_m	Ω_Λ	Ω_b	n_s	h	σ_8	reference
Millennium	500	2160^3	5.0	$8.61\,10^8$	0.25	0.75	0.0450	1.00	0.73	0.90	Springel et al. 2005
Millennium-II	100	2160^3	1.0	$6.89\,10^6$	0.25	0.75	0.0450	1.00	0.73	0.90	Boylan-Kolchin et al. 2009
Bolshoi	250	2048^3	1.0	$1.35\,10^8$	0.27	0.73	0.0469	0.95	0.70	0.82	Klypin et al. 2010
MultiDark	1000	2048^3	4.0	$8.63\,10^9$	0.27	0.73	0.0469	0.95	0.70	0.82	this work

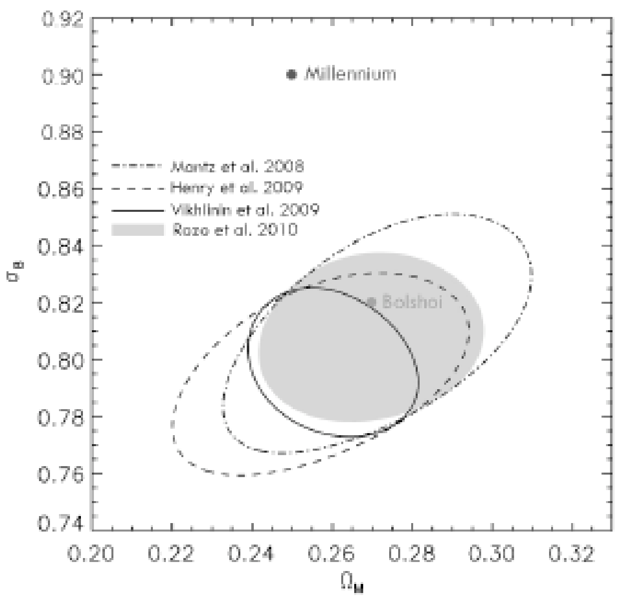
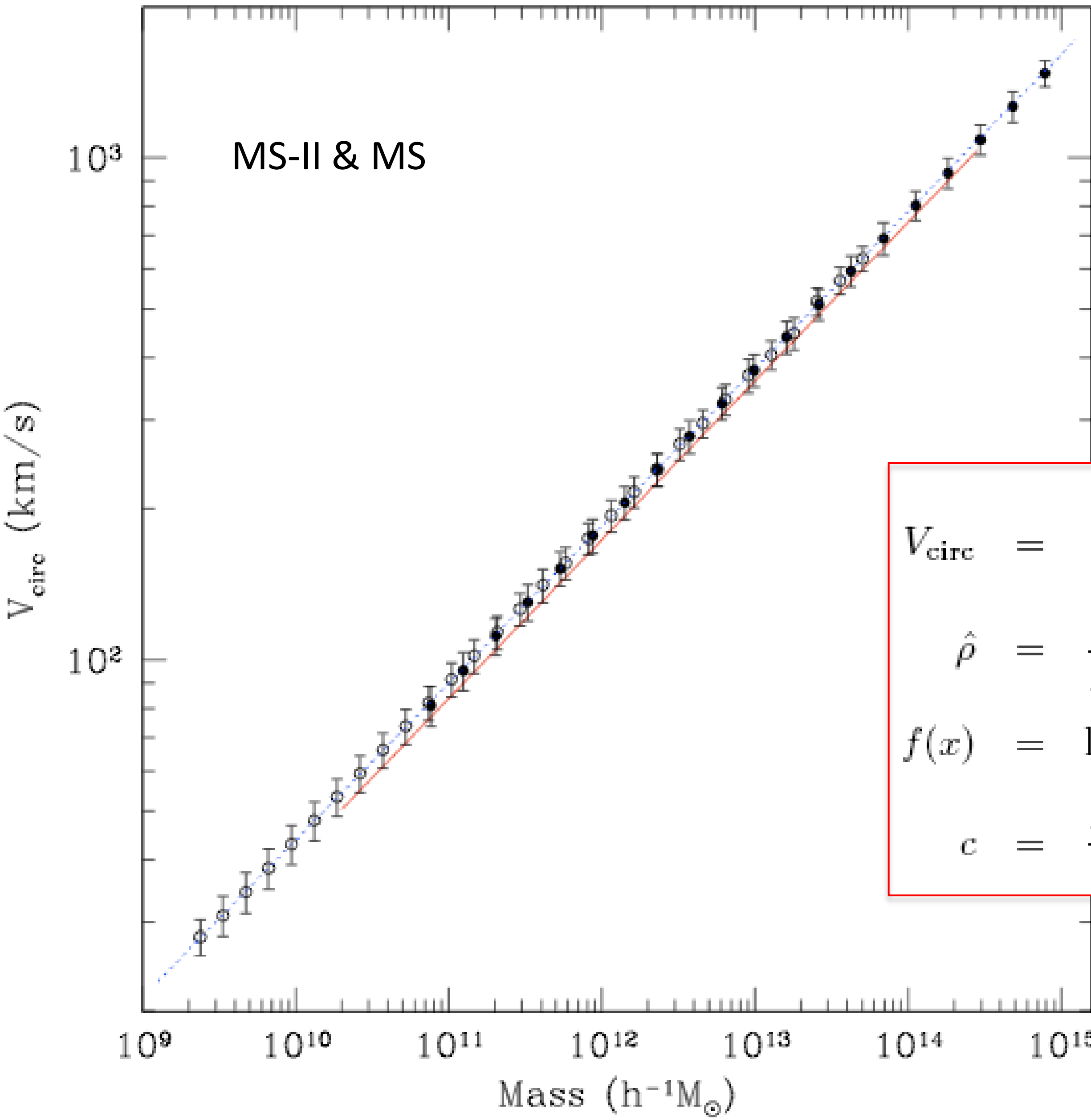


Fig. 1.— Optical and X-ray cluster abundance plus WMAP constraints on σ_8 and Ω_M. Contours show 68% confidence regions for a joint WMAP5 and cluster abundance analysis assuming a flat ΛCDM cosmology. The shaded region is SDSS optical maxBCG cluster abundance + WMAP5 analysis from Rozo et al. (2009) (which is also the source of this figure). The X-ray + WMAP5 constraints are from several sources: the low-redshift cluster luminosity function (Mantz et al. 2008), cluster temperature function (Henry et al. 2009), and cluster mass function (Vikhlinin et al. 2009). All four recent studies are in excellent agreement with each other and with the Bolshoi cosmological parameters. The Millennium I and II cosmological parameters are far outside these constraints.

Klypin et al. 2010



90% of the halos have their V_{max} within 8% the median value.

$$V_{\rm circ} = \left[G\frac{f(x_{\rm max})}{f(c)}\frac{c}{x_{\rm max}}\hat{\rho}^{1/3}\right]^{1/2} M_{\rm vir}{}^{1/3}$$

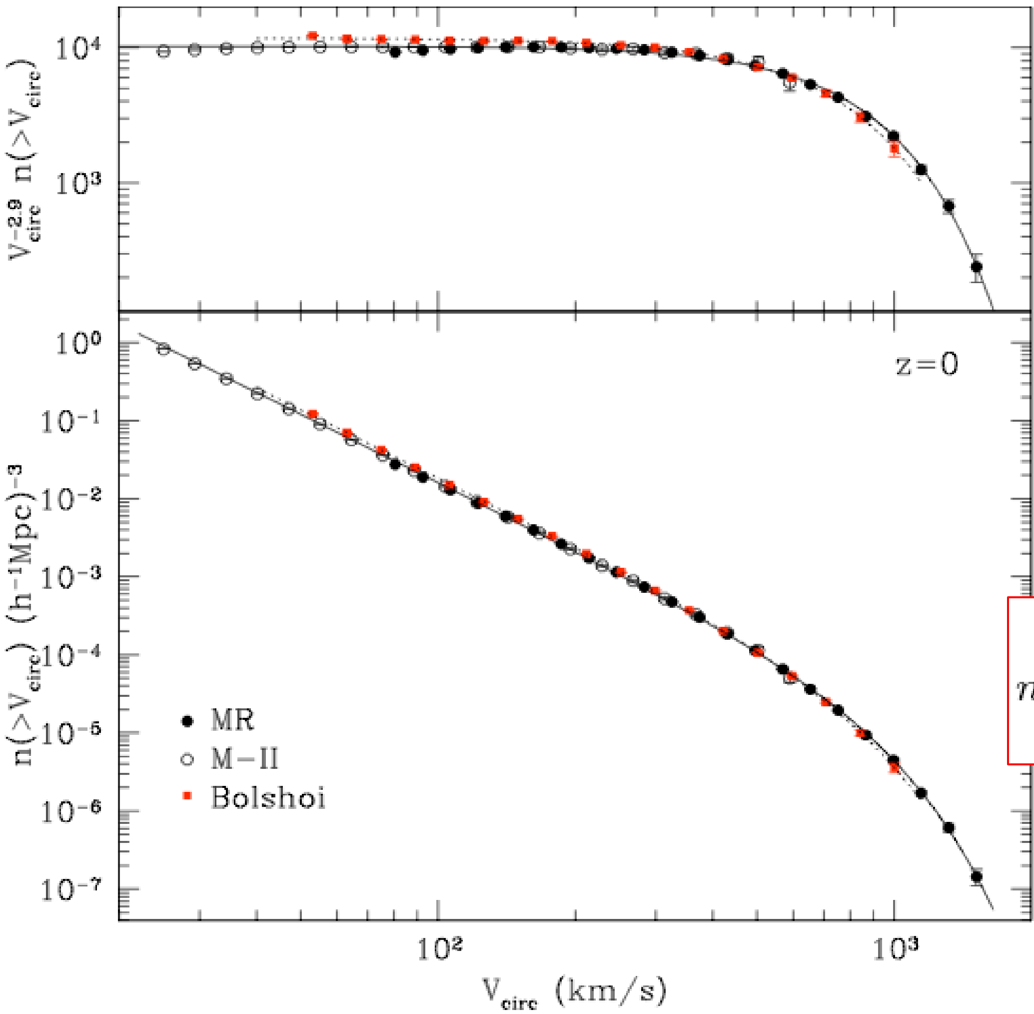
$$\hat{\rho} = \frac{M_{\rm vir}}{R_{\rm vir}{}^3} = \frac{4\pi}{3}\Delta_{\rm vir}\rho_{cr}\Omega_{\rm M},$$

$$f(x) = \ln(1+x) - \frac{x}{1+x},$$

$$c = \frac{R_{\rm vir}}{r_s}, \quad x = \frac{R}{r_s}, \quad x_{\rm max} = 2.15.$$

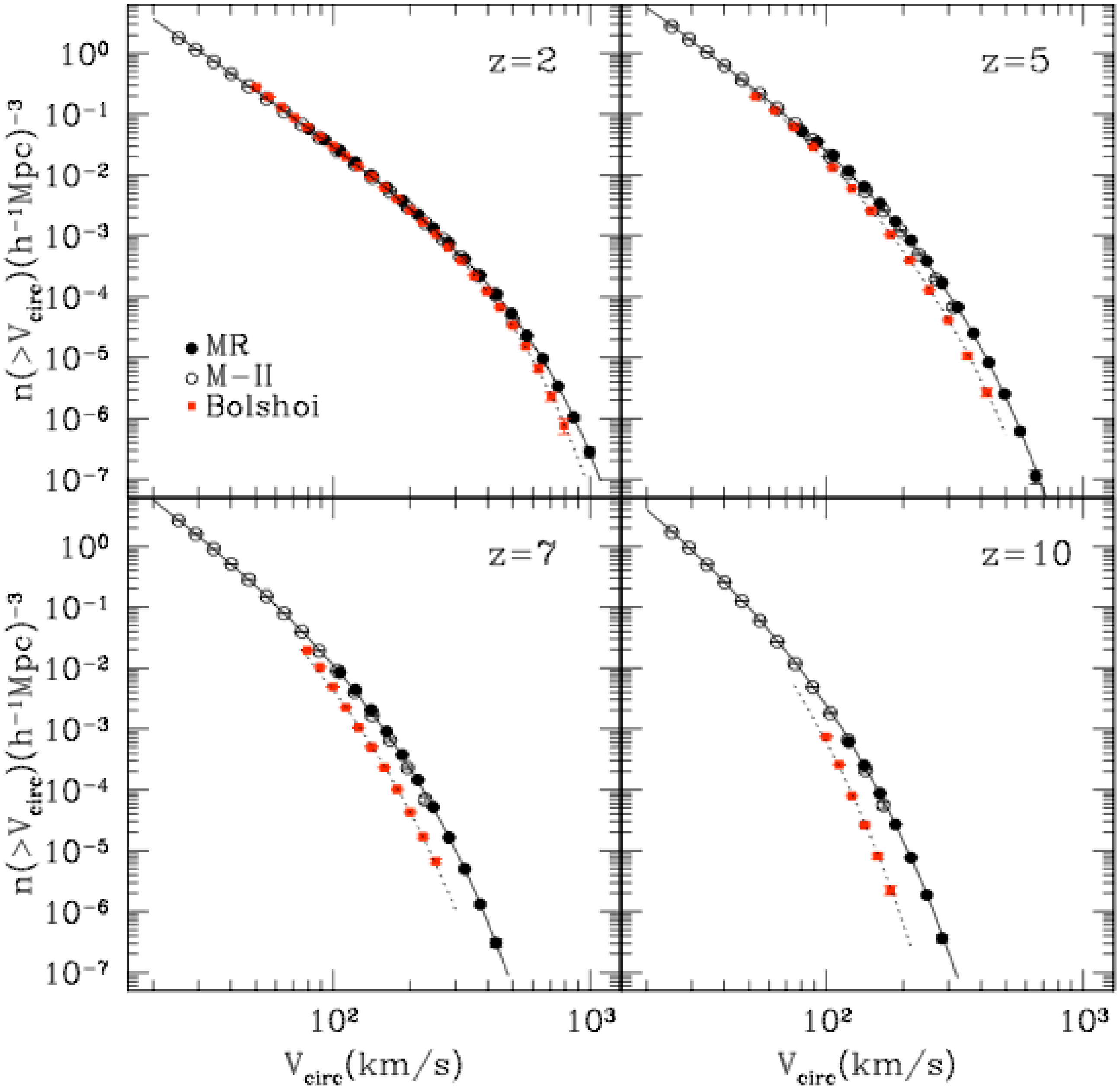
Dependence of maximum circular velocity on halo mass for distinct halos at z=0.

Cumulative velocity function for distinct halos



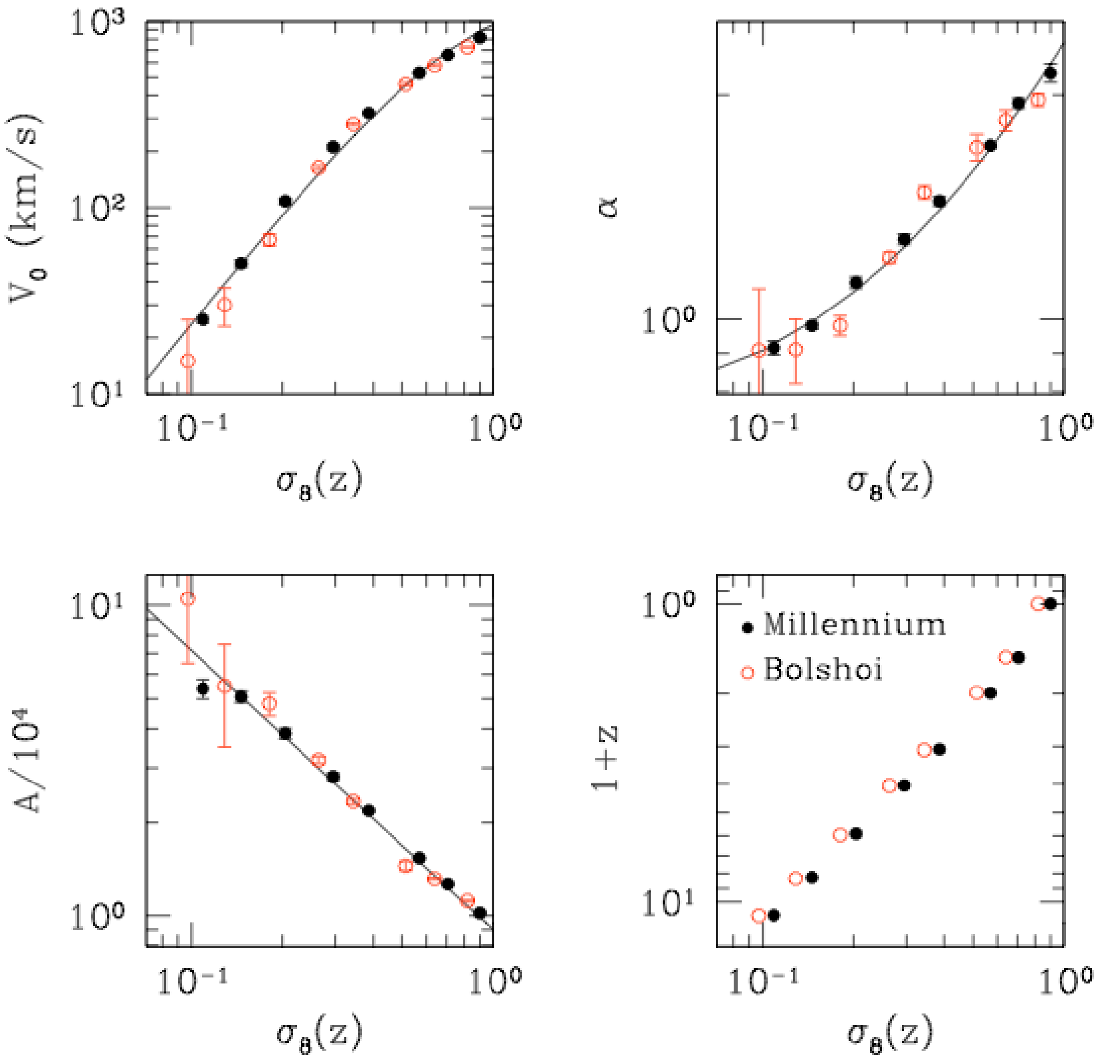
$$n(>V_{max}) = AV_{max}^{-2.9} \exp\left(-\left[\frac{V_{max}}{V_0}\right]^{\alpha}\right)$$

Bottom: Cumulative velocity function at z=0 for distinct halos in the Bolshoi (filled squares) and Millennium simulations, MS (filled circles) and MS-II (open circles), in units of h^3 Mpc^{-3}.
Top: Product $V_{max}^{-2.9}$ $n(>V_{max})$ of the maximum circular velocity and the cumulative vel. function.



Cumulative velocity function for distinct halos in the Bolshoi (filled squares) and Millennium, MS (filled circle) and MS-II (open circle) simulations at several redshifts

Halo velocity function in the LCDM cosmology



Prada et al. 2011, in prep.

$$n(>V_{max}) = AV_{max}^{-2.9}\exp\left(-\left[\frac{V_{max}}{V_0}\right]^{\alpha}\right)$$

(Eq. 1)

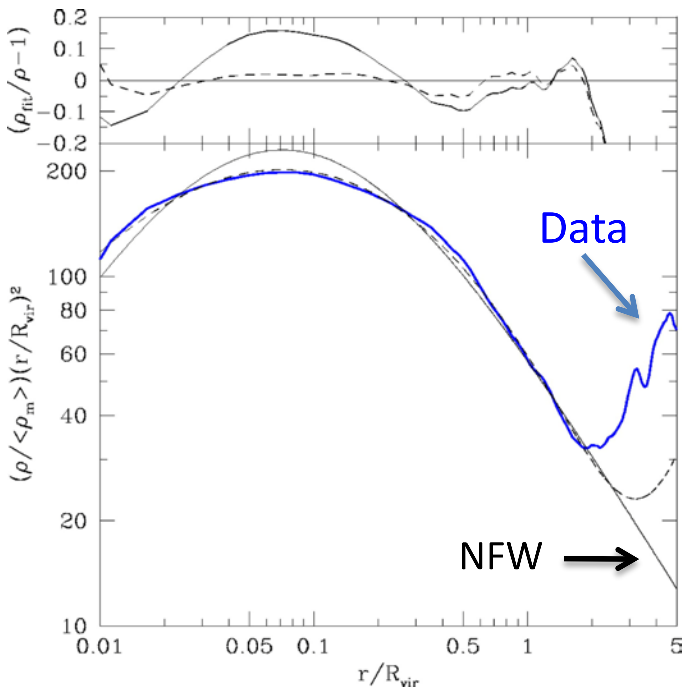
$$\begin{aligned} A &= 0.90\times 10^4\sigma_8^{-0.9}(z)(h^{-1}\mathrm{Mpc/km\ s^{-1}})^{-3}, \\ V_0 &= 2400\frac{\sigma_8^2(z)}{1+1.5\sigma_8^2(z)}\mathrm{km\ s^{-1}}, \\ \alpha &= 0.7+1.65\sigma_8^{0.9}(z). \end{aligned}$$

Parameters of the LCDM velocity function for distinct halos as a function of ♦$_8$(z). Filled circles show the parameters found by fitting Eq. 1 to the cumulative velocity function from the Millennium simulations at different redshifts. Open circles correspond to the Bolshoi velocity function fits. The bottom right panel shows the evolution of ♦$_8$ with redshift, as predicted by the linear perturbation theory of structure growth

II. Concentration functions

Two ways of measuring concentration:

- Fits to density profiles, e.g. NFW



$c = R_{vir}/r_s$

- V_{max}/V_{200} is directly related to halo concentration; assuming NFW density profile:

$$\frac{V_{\rm max}}{V_{200}} = \left(\frac{0.216\,c}{\ln(1+c) - c/(1+c)}\right)^{1/2}$$

$$V_{200} = \left(\frac{GM_{200}}{R_{200}}\right)^{1/2}$$

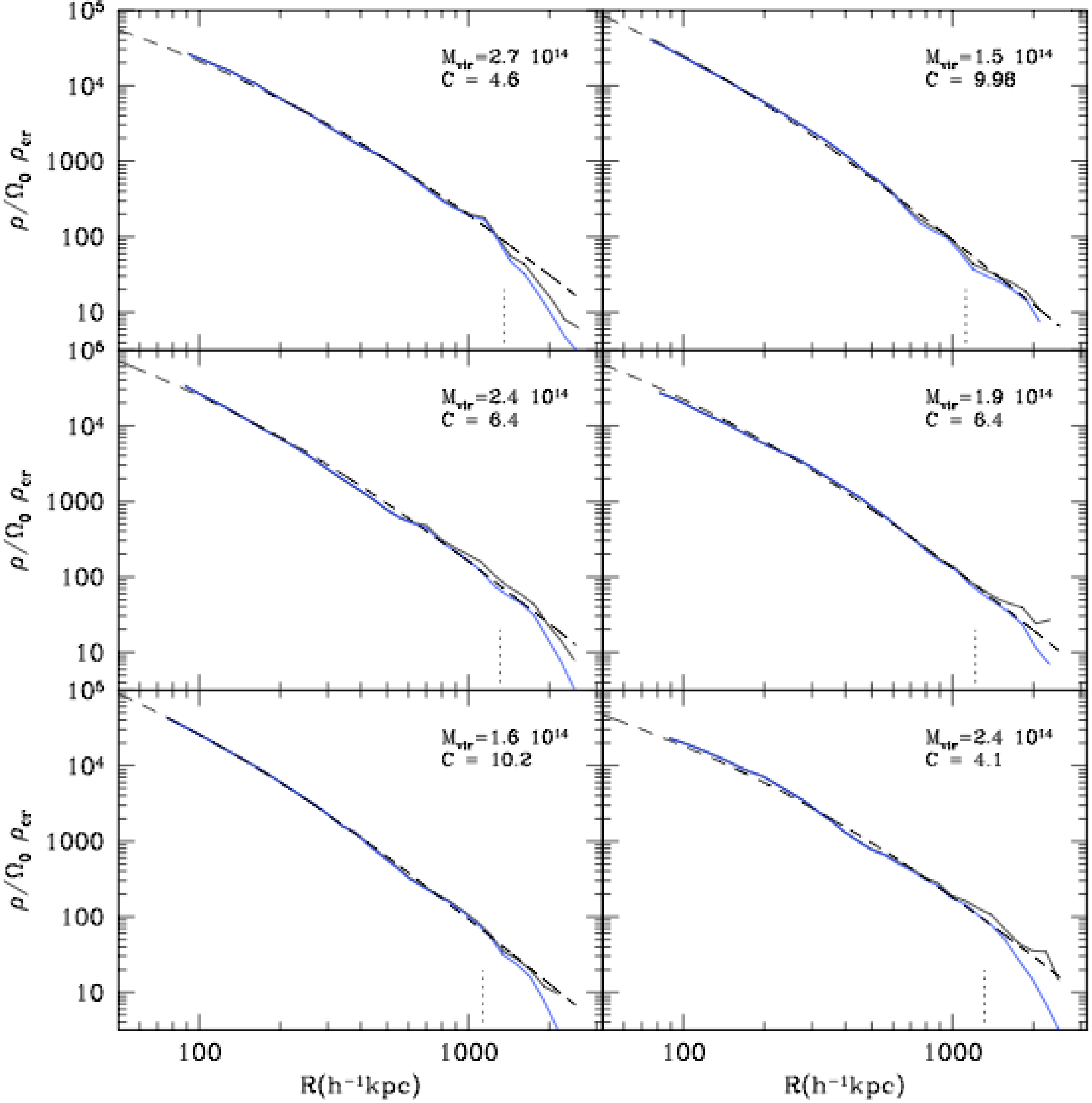
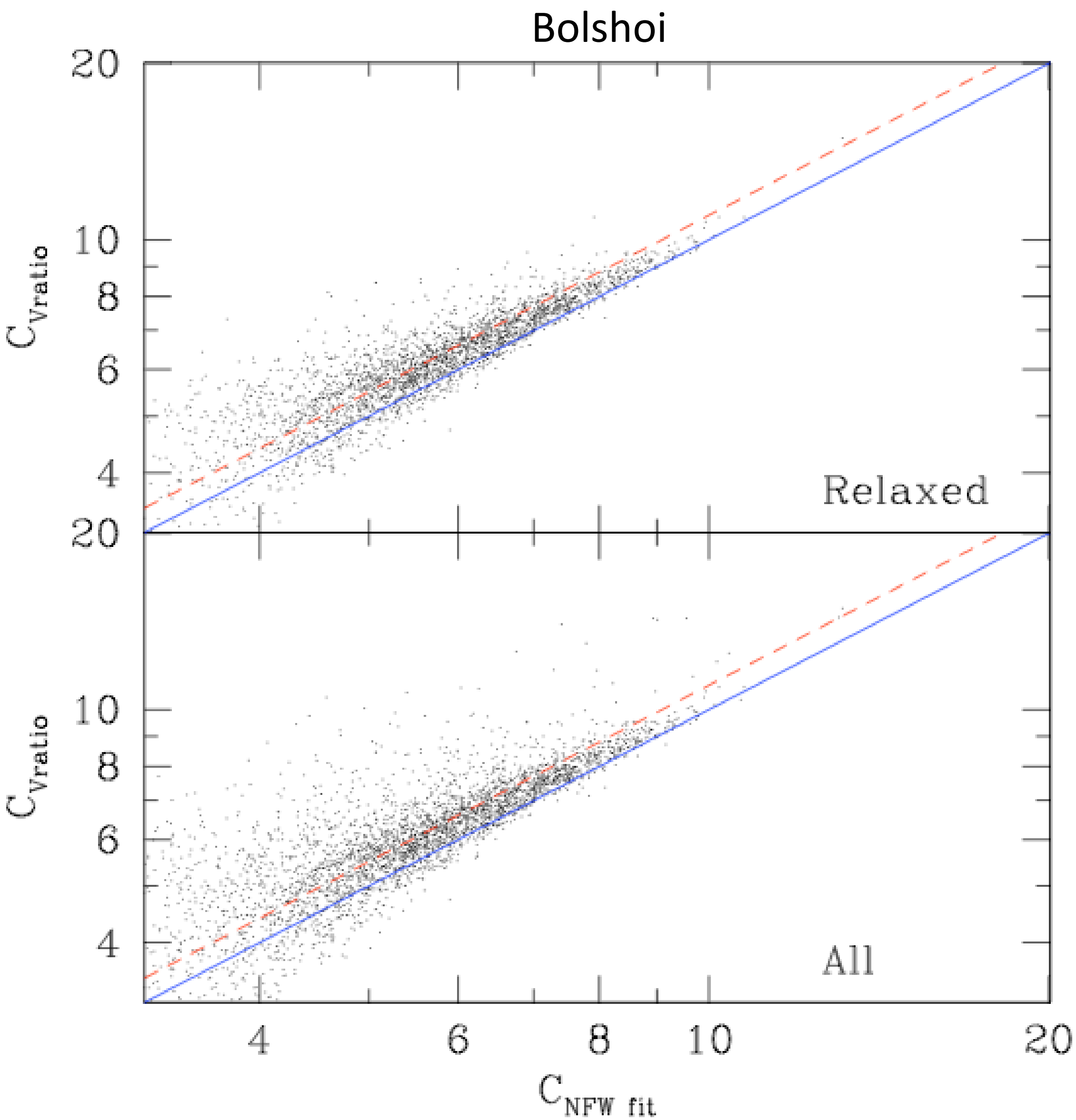


Figure 1. Examples of halo profiles and fitting them using concentrations obtained with the ratios of the maximum circular velocity $V_{\rm max}$ to the halo velocity V_{200}. Each panel shows two full curves: the density profile of all particles (upper curve) and only bound particles (lower curve). The dashed curves are the approximations. Typically the highly concentrated and relaxed halos are well fit by the approximations (two bottom panels). Low concentrated halos and halos with large perturbations (two top panels) show large deviations between the data and approximations. Fitting those unrelaxed profiles with standard minimization technique does not improve the accuracy of the fits as indicated by dot-dashed curve in the top-right panel.



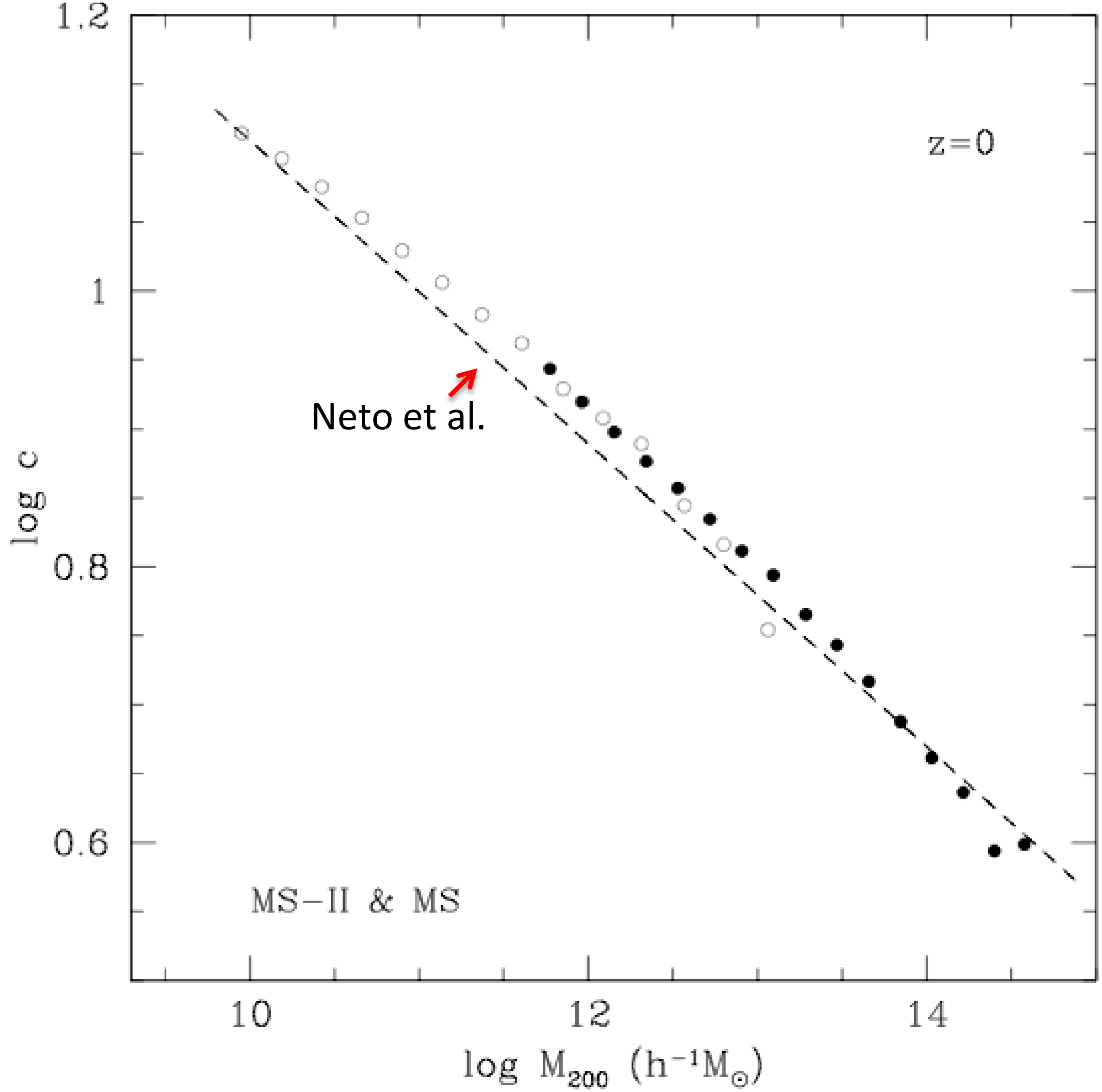
There is a tight relation between the two estimates of concentration. On average there is a small 5-10% offset between C_{vratio} and $C_{NFW\ fit}$

C_{vratio} ←

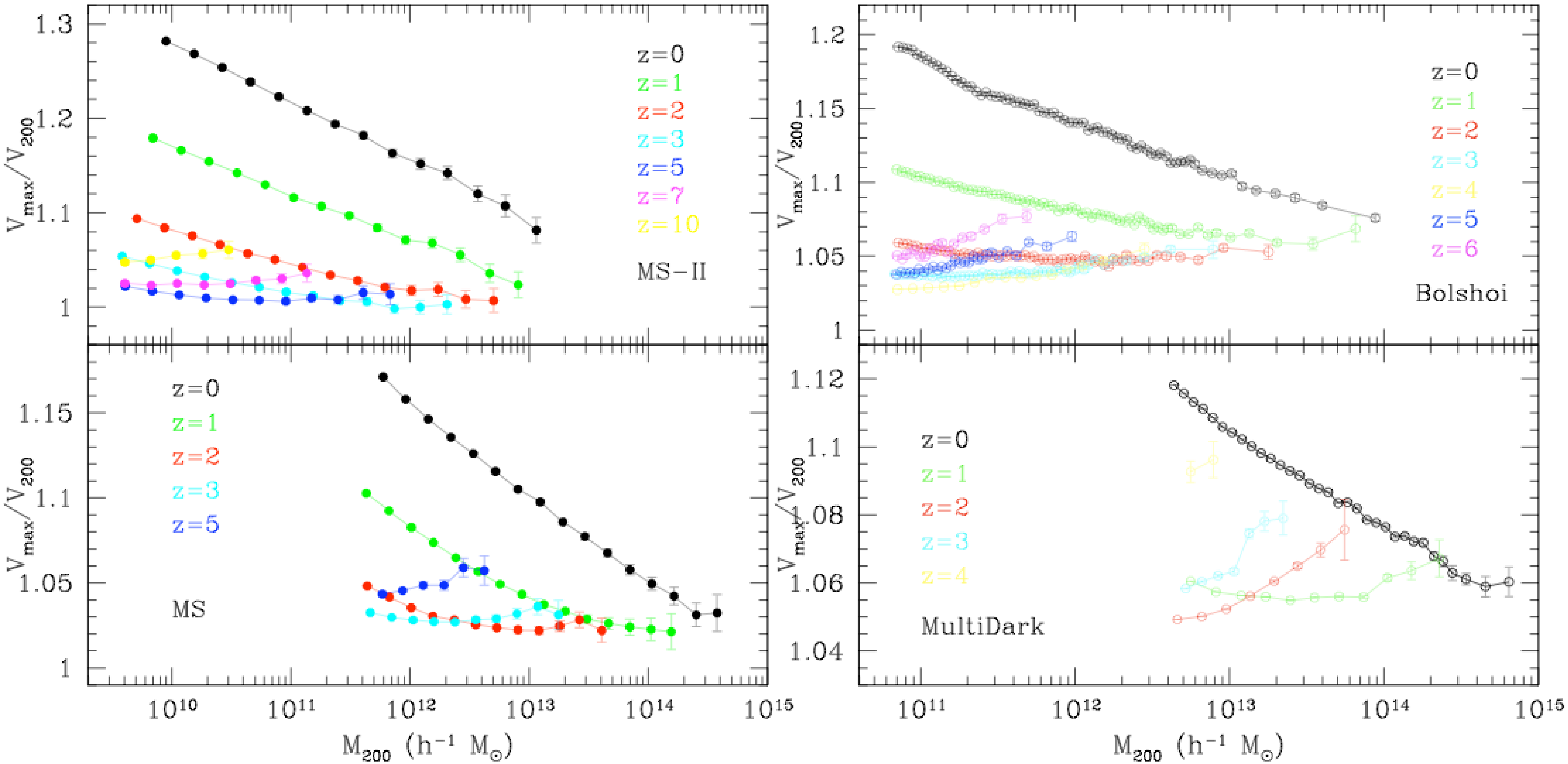
$$\frac{V_{max}}{V_{200}} = \left(\frac{0.216\,c}{\ln(1+c) - c/(1+c)}\right)^{1/2}$$

For NFW density profile

MS-II & MS



Evolution with redshift of the halo concentrations



The ratio V_{max}/V_{200} of the maximum circular velocity to the virial velocity as a function of mass M_{200} for distinct halos at different redshifts.
Left: MS-II and MS simulations. Right: Bolshoi and the new MultiDark simulation

Concentration – Mass relation

Fig. 5.— Evolution of concentration of distinct halos with redshift. The full curves and symbols show results of simulations. Analytical approximations are shown as dashed curves. All the fits have the same functional form of eq. (12) with two free parameters. At low redshifts the halo concentration decreases with increasing mass. However, the trend changes at high redshifts when the concentration is nearly flat and even has a tendency to slightly increase with mass.

Klypin et al. 2010

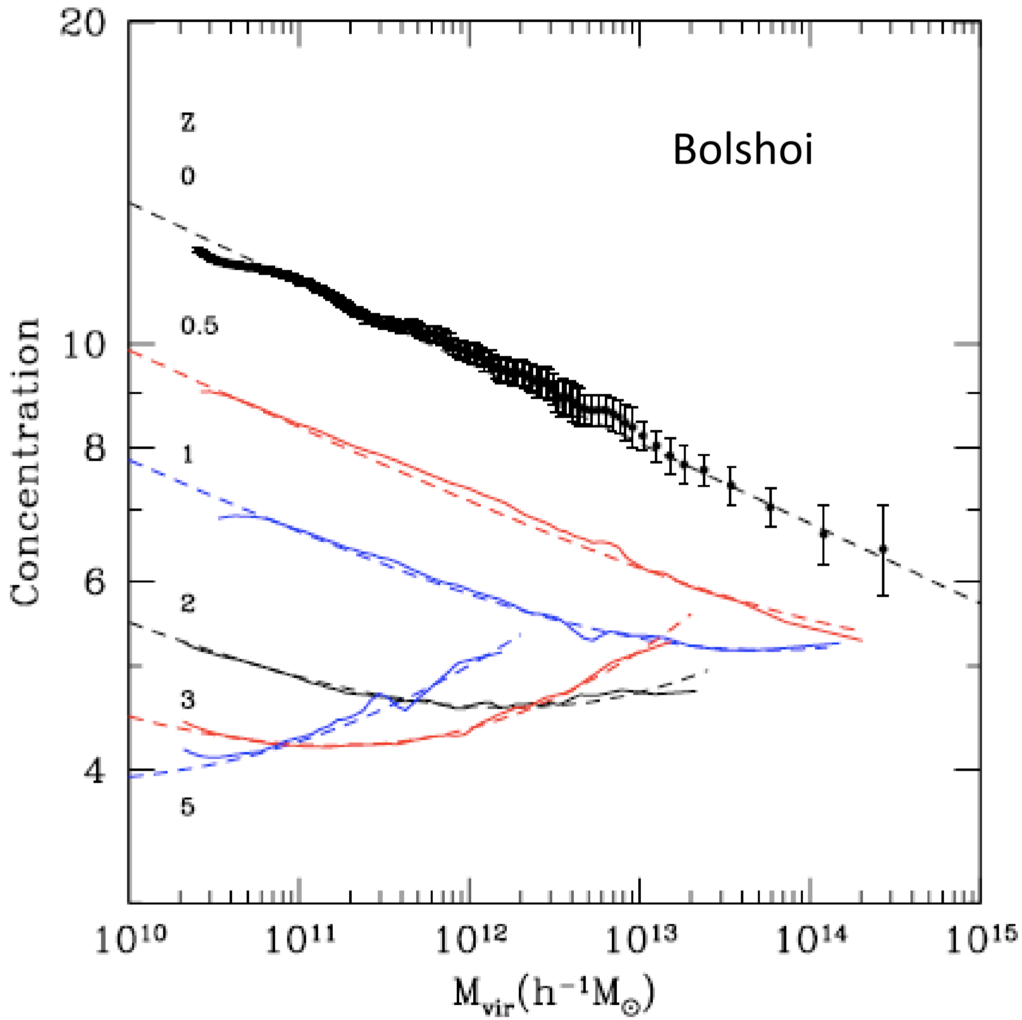
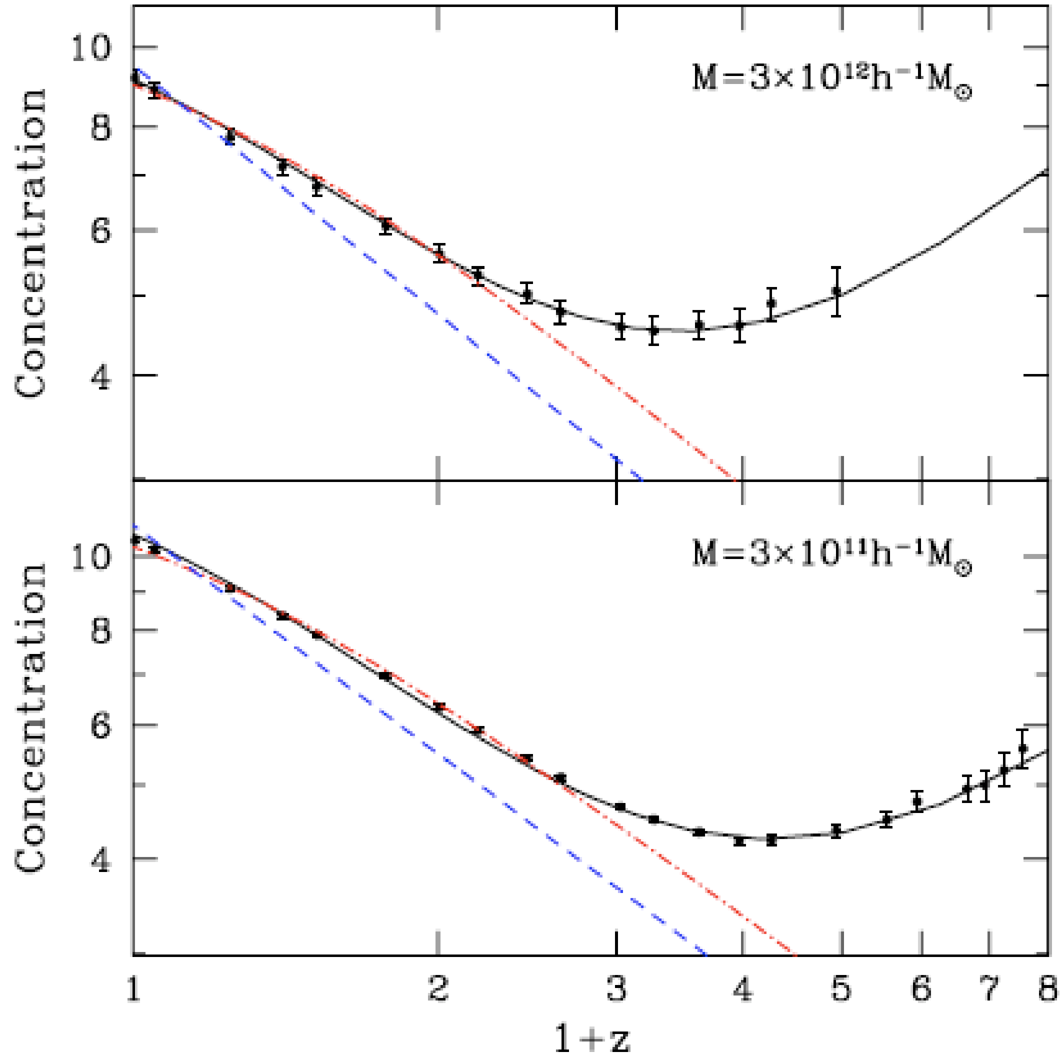
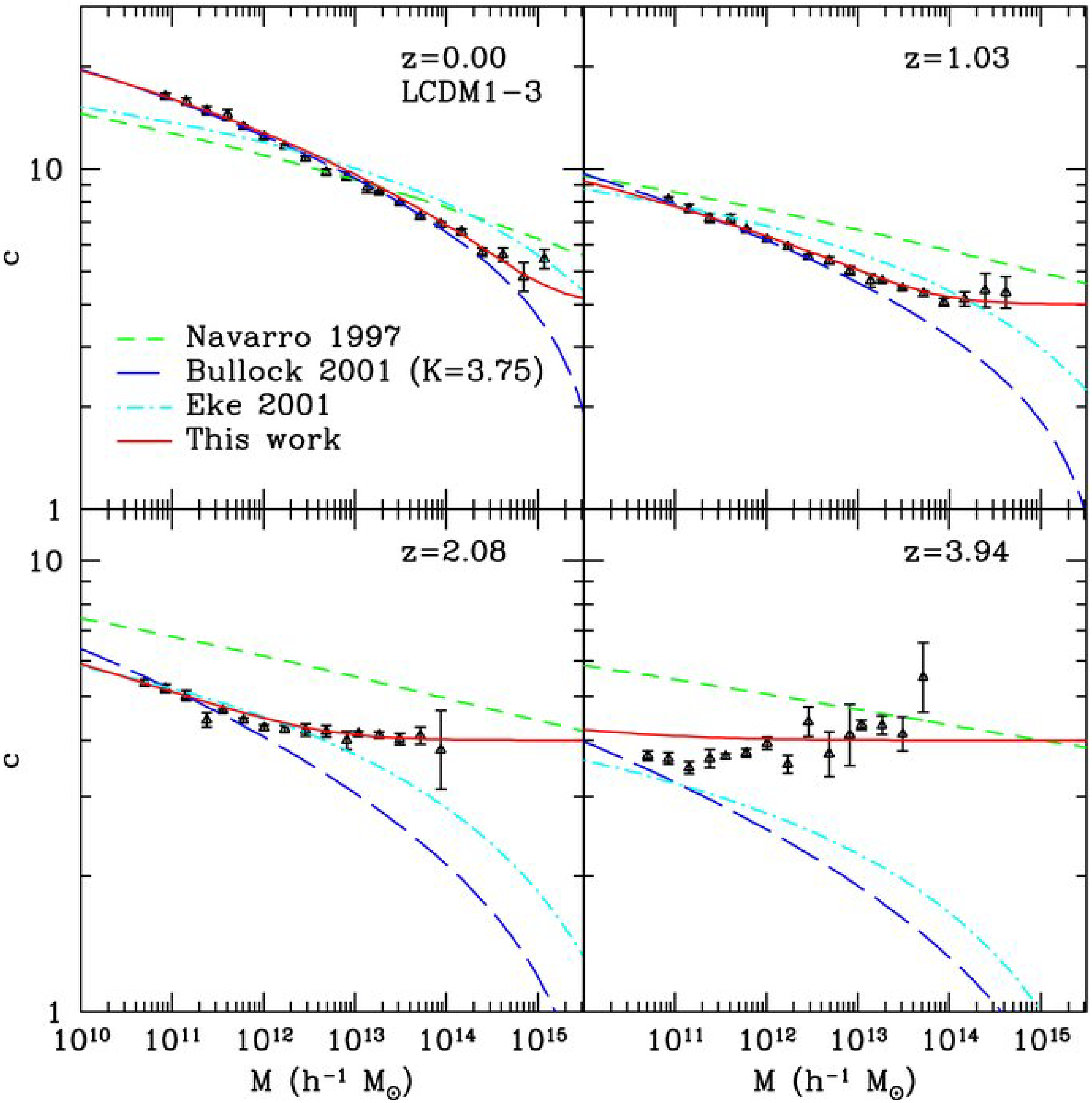


Fig. 6.— Evolution of halo concentration for halos with two masses indicated on the plot. The dots show results of simulations. For the reference the dashed lines show a power-law decline $c \propto (1+z)^{-1}$. Concentrations do not change as fast as the law predicts. At low redshifts $z < 2$ the decline in concentration is $c \propto \delta$ (dot-dashed curves), where δ is the linear growth factor. At high redshifts the concentration flattens and then slightly increases with mass. For both masses the concentration reaches a minimum of $c_{\min} \approx 4-4.5$, but the minimum happens at different redshifts for different masses. The full curves are analytical fits with the functional form of eq. (13).

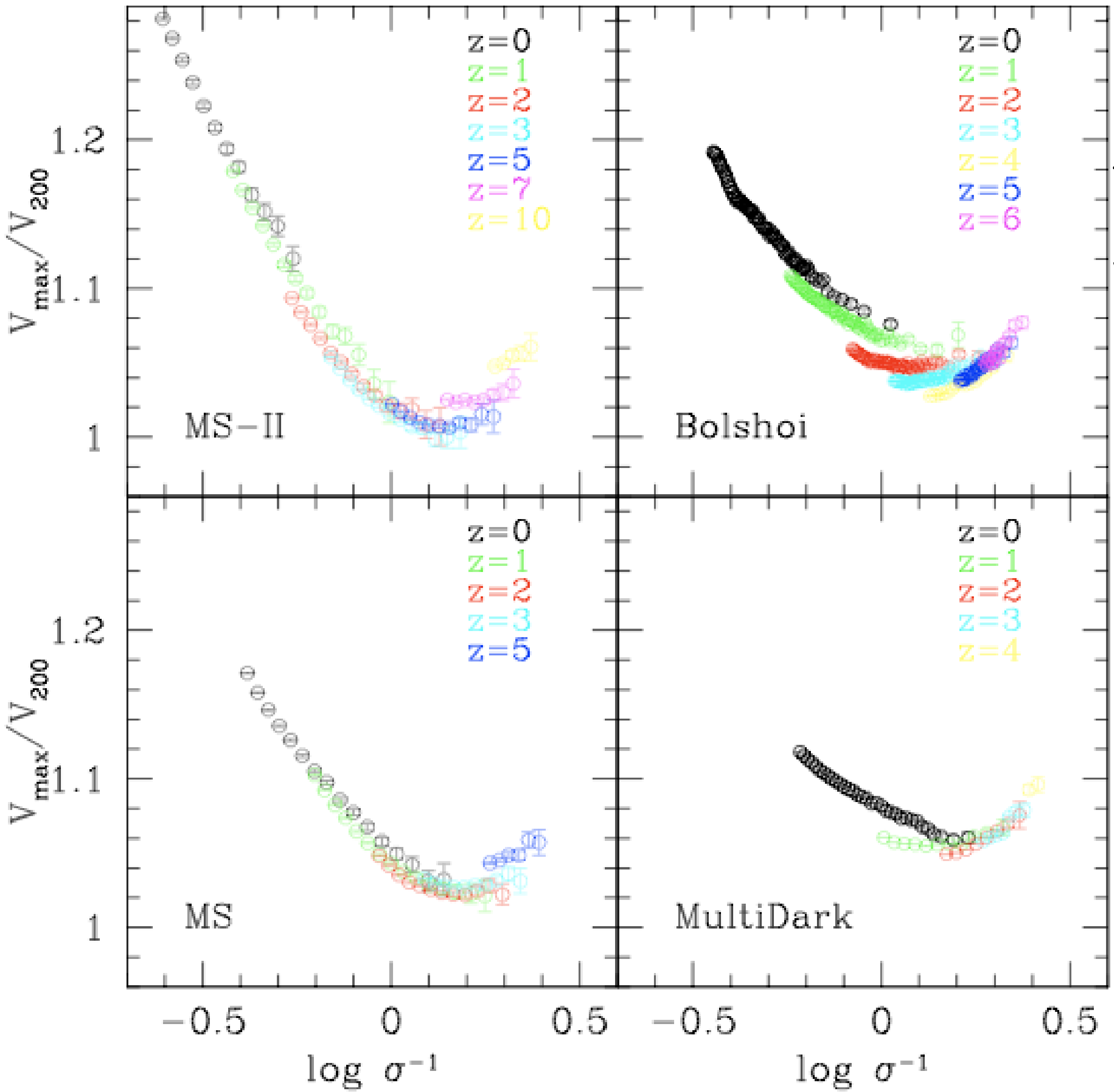
Klypin et al. 2010





Zhao et al. 2009

THE $C - \sigma(M)$ RELATION



V_{max}/V_{200} velocity ratio as a function of log ♦$^{-1}$

Halo concentration, when expressed in terms of the variable log ♦$^{-1}$, is a well behave function with an U-shaped trend which decreases with log ♦$^{-1}$ up to a well defined scale, in which it begin to increase

♦◘♦☎💣📄🗀🗀📪a✆◘

$$\frac{\delta^2(a)}{2\pi^2}\int_0^\infty k^2 P(k) W^2(k,M)dk$$

The c – ♦ relation: a new empirical model for the halo mass -- concentration relation

Similar to the mass function, we find that concentration is not universal and has some dependence on redshift. We attribute this residual redshift dependence of c(♦🖭a) mostly to the change in the growth rate of fluctuation D(a) related to the change of ⌖$_m$(a). D(a) depends only on one parameter:

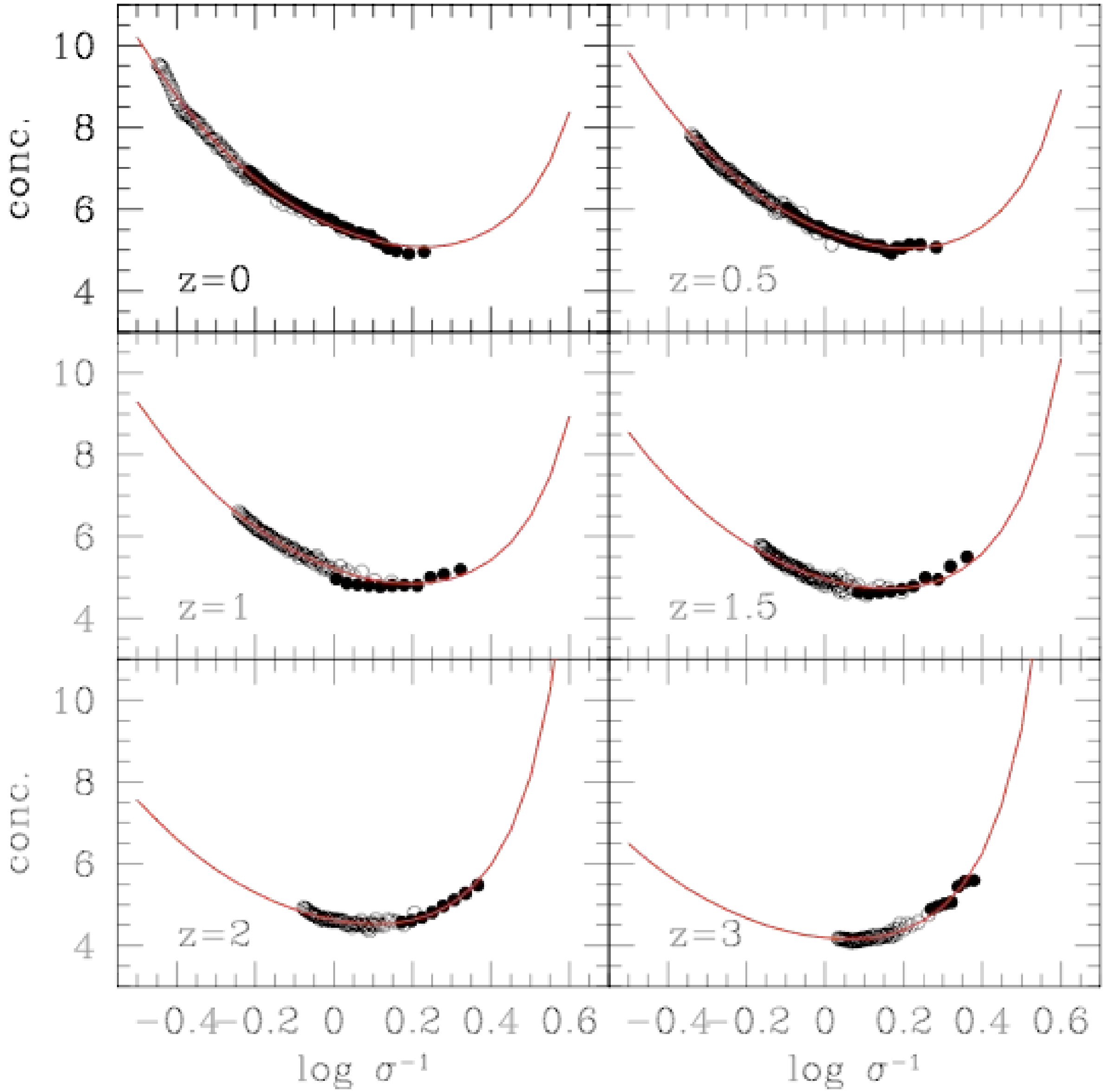
$$x \equiv \left(\frac{\Omega_{\Lambda,0}}{\Omega_{\mathrm{m},0}} \right)^{1/3} a$$

Because all our approximations use only ♦ and x, we *expect* that they are applicable for different redshifts and different cosmological parameters. Fitting all the available data from Bolshoi and MultiDark simulations gives the following approximation for halo concentration:

$$\begin{aligned} c(\sigma, x) &= B_0(x)\,\mathcal{C}(\sigma'), \\ \sigma' &= B_1(x)\,\sigma(M_{200}, x), \\ \mathcal{C}(\sigma') &= A\left[\left(\frac{\sigma'}{b}\right)^c + 1\right] \exp\left(\frac{d}{\sigma'^2}\right), \\ A &= 3.055,\ b = 1.361,\ c = 0.997,\ d = 0.0565. \end{aligned}$$

$B_0(x)$ and $B_1(x)$ are defined in such a way that they are equal to unity at z=0 for the WMAP-5 parameters of the Bolshoi and MultiDark simulations.

Bolshoi & MultiDark

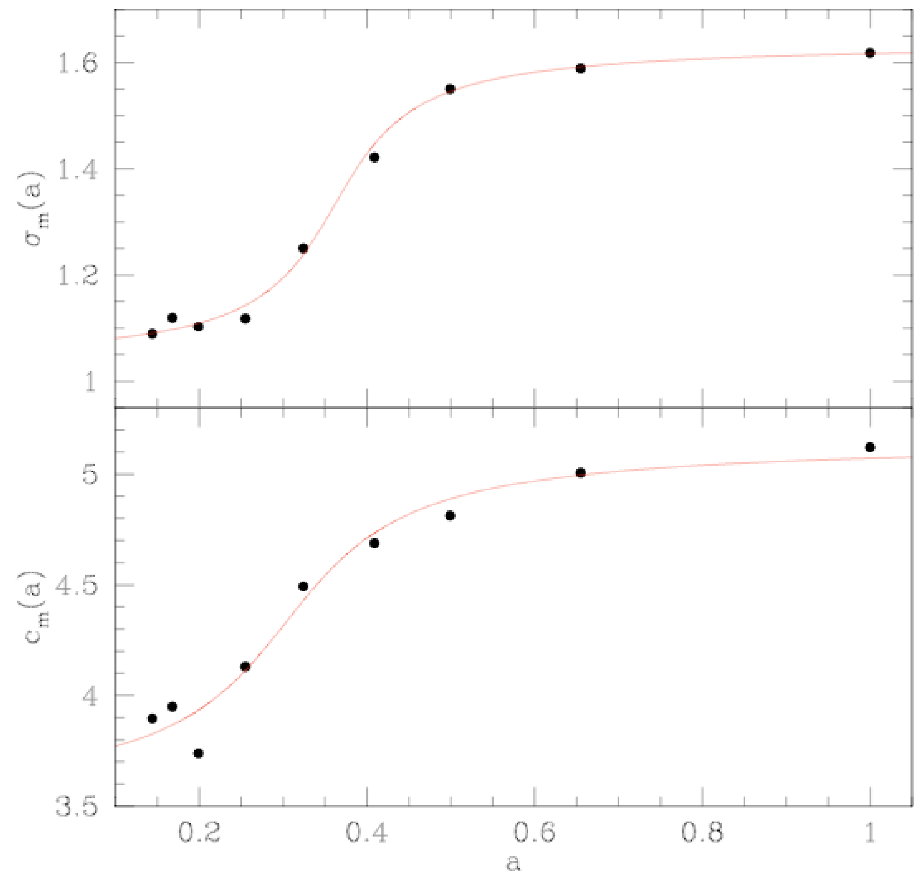


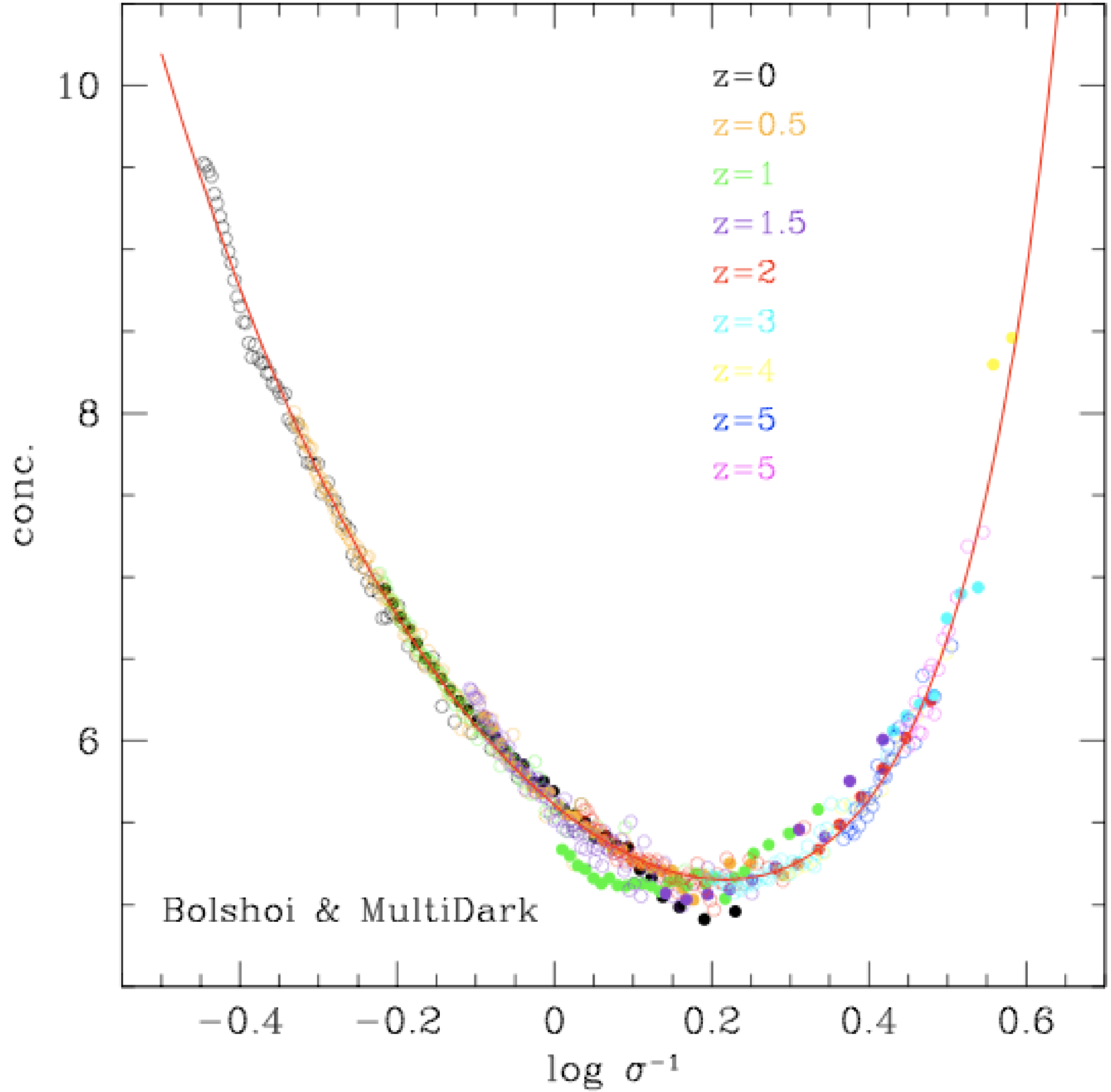
Concentration – ♦(M_{200}) median relation for distinct halos in the Bolshoi (open symbols) and MultiDark (filled symbols) simulations for different redshifts. Solid lines are fits from our empirical model.

$$B_0(x) = c_{\min}(x)/c_{\min}(1.393)$$
$$B_1(x) = \sigma_{\min}(x)/\sigma_{\min}(1.393),$$

where $c_{\min}$ and $\sigma_{\min}$ define the minimum of the halo concentrations and the value of σ at the minimum:

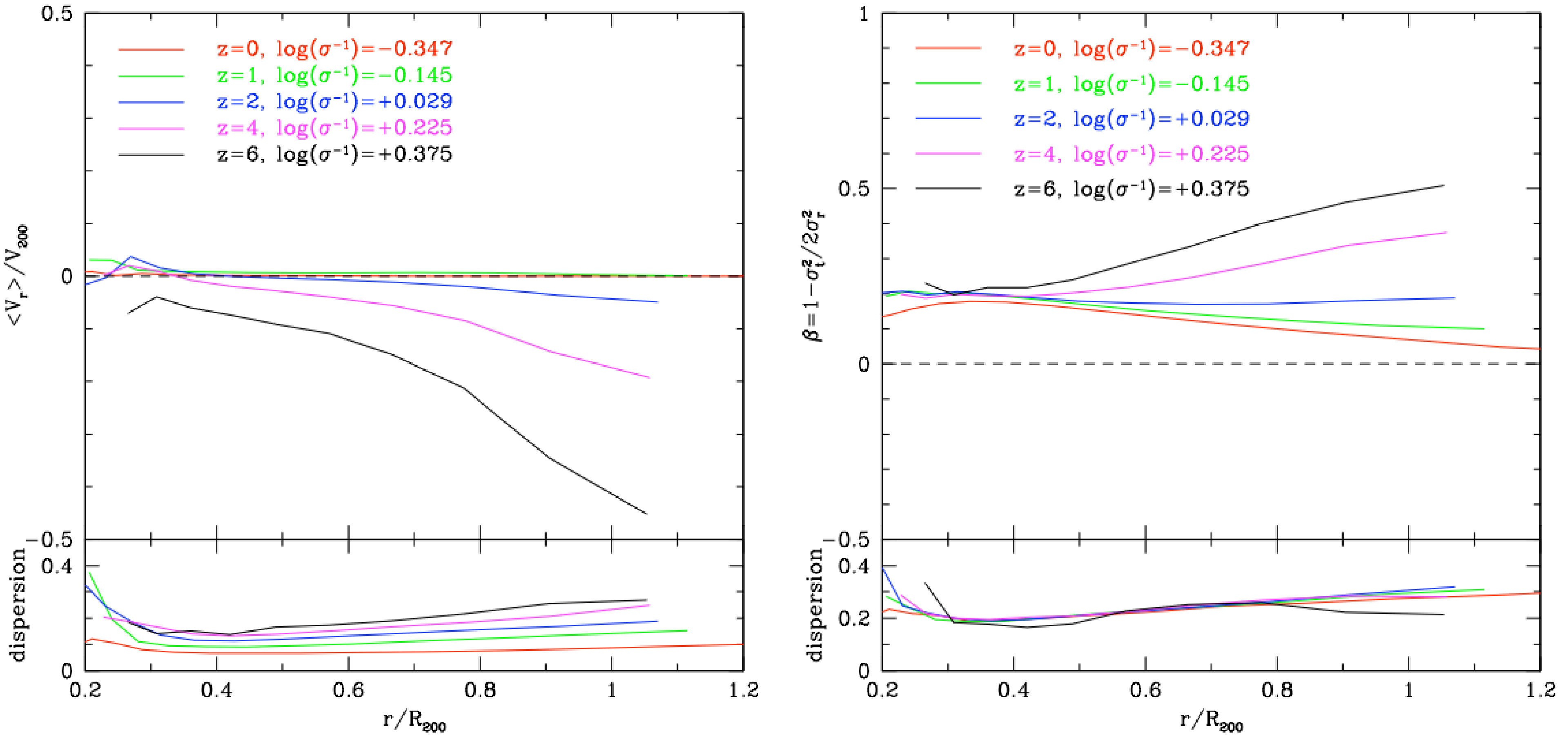
$$c_{\min}(x) = c_0 + (c_1 - c_0)\left[\frac{1}{\pi}\arctan\left[\alpha(x - x_0)\right] + \frac{1}{2}\right]$$
$$\frac{1}{\sigma_{\min}(x)} = \frac{1}{\sigma_0} + (\frac{1}{\sigma_1} - \frac{1}{\sigma_0})\left[\frac{1}{\pi}\arctan\left[\beta(x - x_1)\right] + \frac{1}{2}\right]$$
$$c_0 = 3.342,\ c_1 = 5.195,\ \alpha = 4.807,\ x_0 = 0.401,$$
$$\sigma_0 = 0.976,\ \sigma_1 = 0.6086,\ \beta = 9.309,\ x_1 = 0.263$$





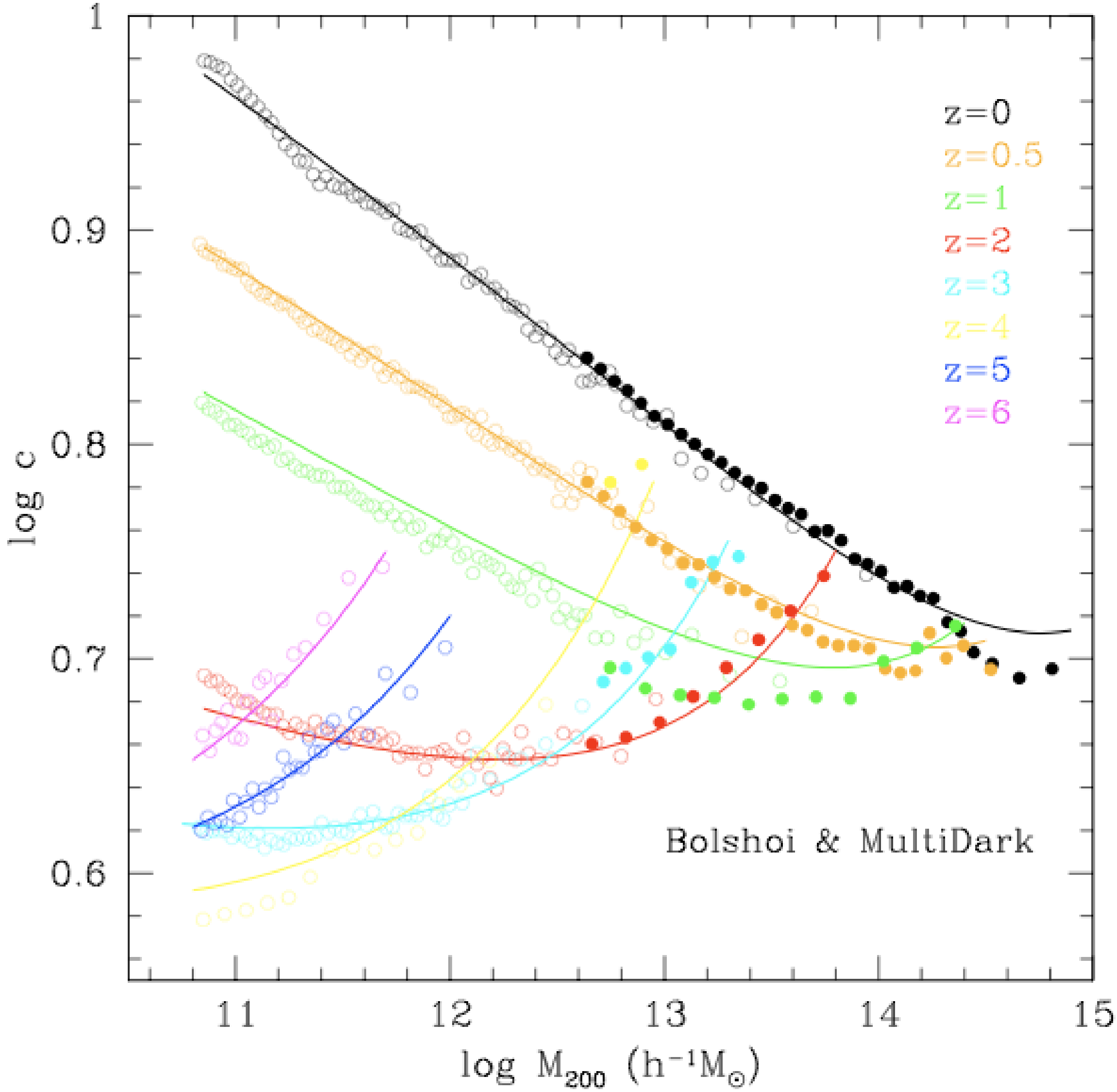
Prada et al. 2011

Concentration as a function of log ♦$^{-1}$, but now c-♦ data at each epoch have been scaled by its corresponding value of ♦$_{min}$(a) and c_{min}(a). Solid line is our parameterization.



At large redshifts, the halos that show the upturn are very rare: their mass is much larger than the characteristic mass M_* of halos existing at that time. Most of them likely experience a very fast growth. The also represent very high-♦ peaks of the density field.

II. Halo mass-concentration relation in the LCDM cosmology

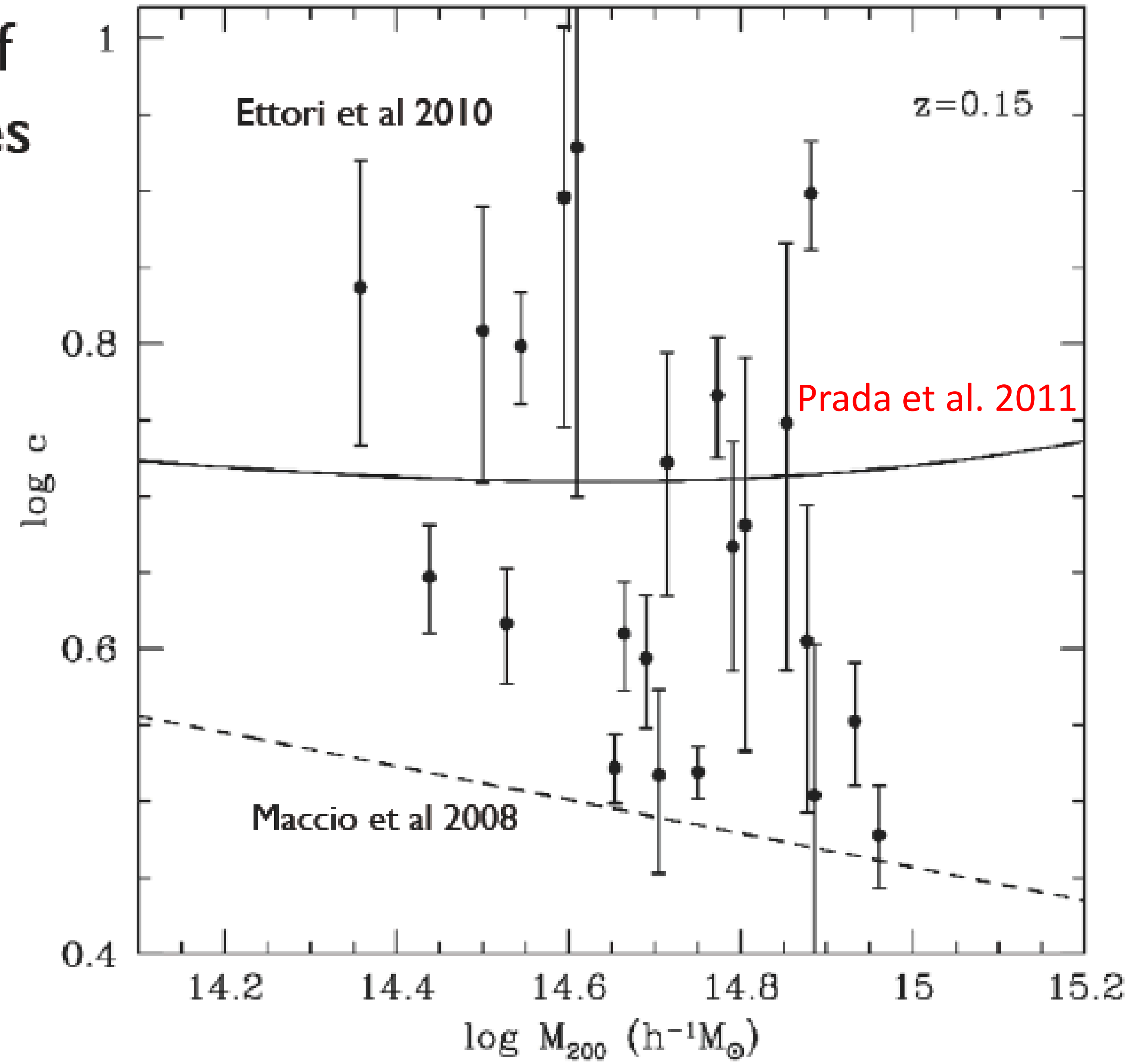


Prada et al. 2011, in prep.

Halo mass-concentration of distinct halos in the Bolshoi (open symbols) and MultiDark (filled symbols) simulations. Sold lines correspond to our empirical model.

Concentration of clusters of galaxies

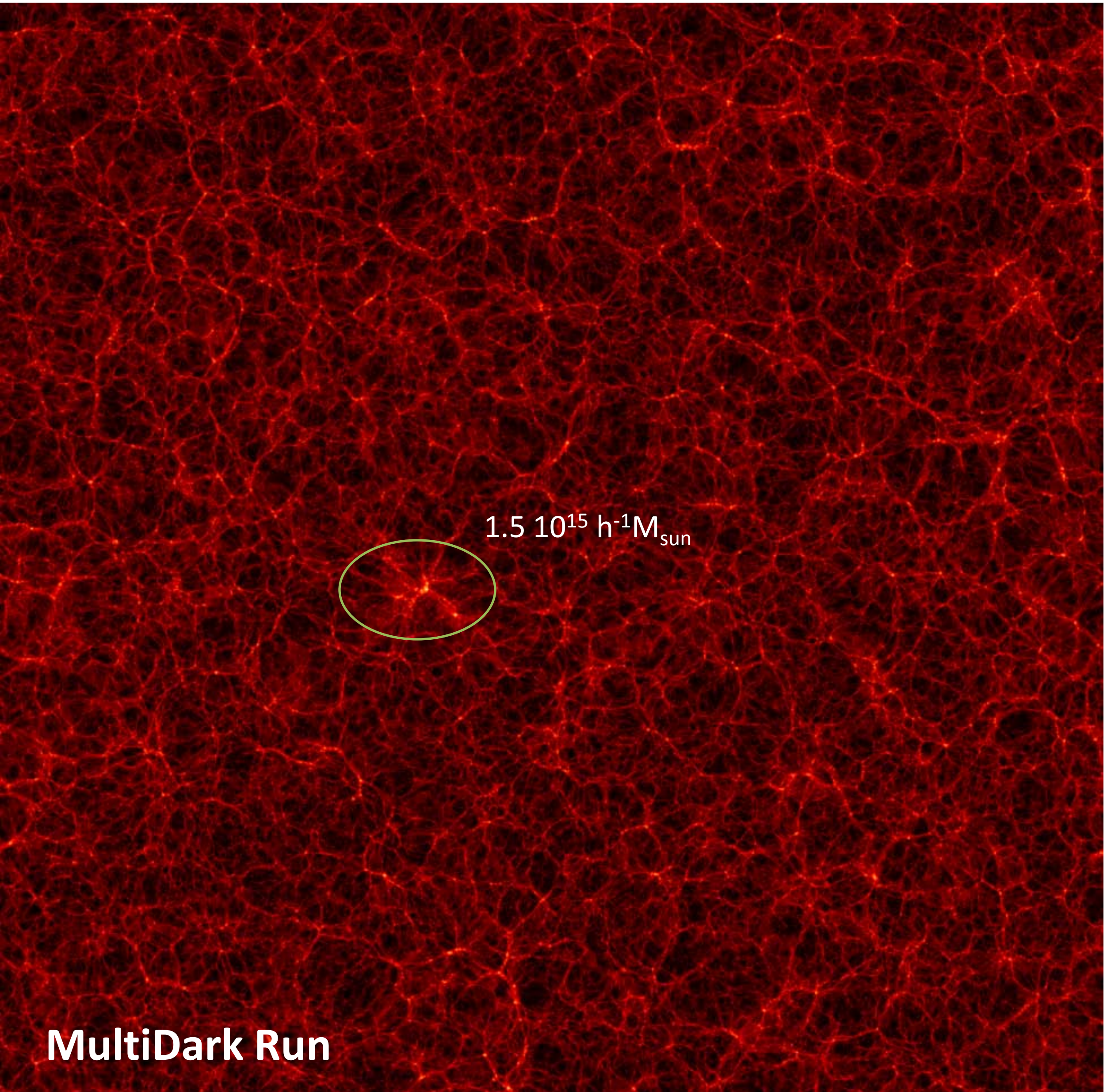
WMAP-7, sigma8 =0.82

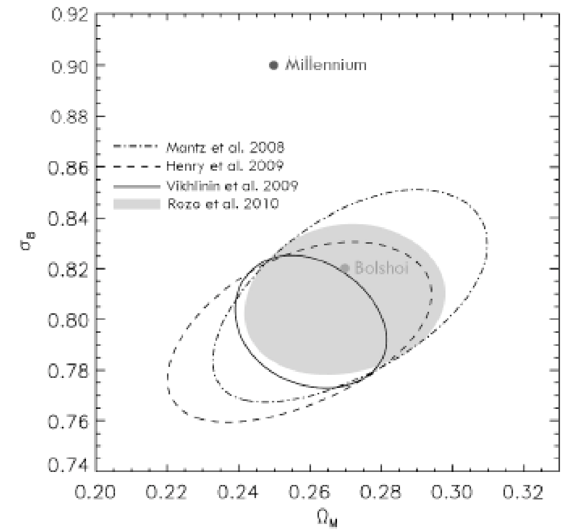


MultiDark
Multimessenger Approach for Dark Matter Detection

MULTIDARK suite of simulations for BOSS studies

F. Prada, A. Klypin, & S. Gotlloeber





Run with ART code by A. Klypin

1Gpc/h

L_{box}= 1000 h^{-1} Mpc

N_{part}= 2048^3

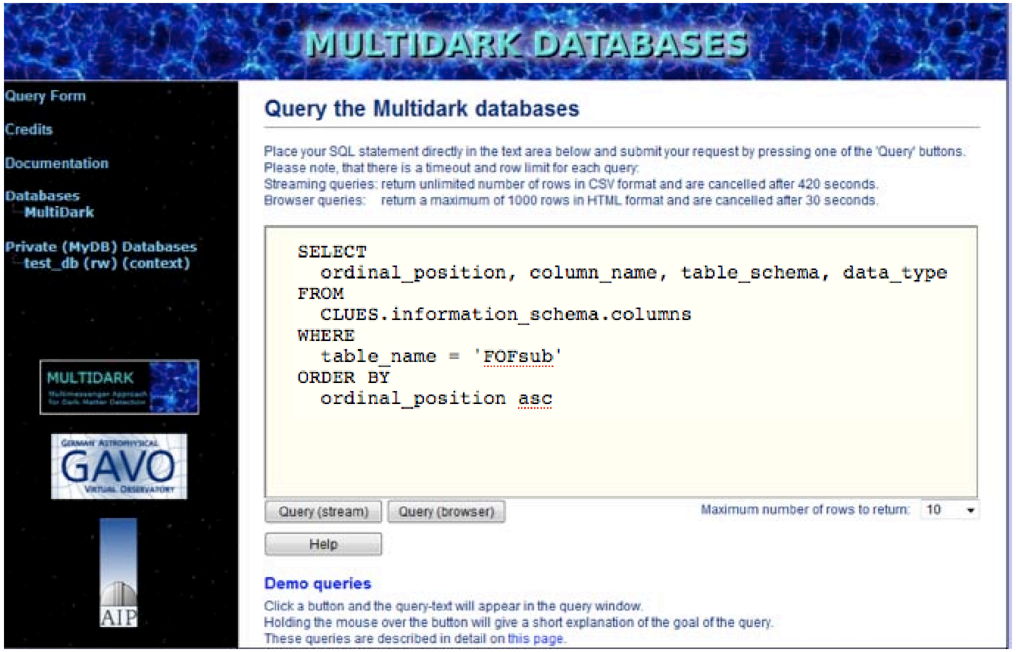
Force res.= 4kpc comov.

M_{part}=8.77 10^9 h^{-1} M_{sun}

MultiDark Database

- collaboration with Astrophysical Institute Potsdam (AIP), supported by GAVO
- Database for MULTIDARK simulations will include:
  - halo + galaxy catalogues (positions, velocities, properties)
  - kinematic and density profiles
  - snapshots of simulations (particle selection)
- design similar to Millennium Simulation DB
- compliant to international VO (virtual observatory) standards
- Web interface:
  - direct access via SQL queries
  - store results of queries in own database (registered users)
  - history of previous queries
  - on-line documentation

www.multidark.org



MultiDark Database

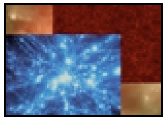
Welcome to the MultiDark Database

***** All data provided here are currently only in a pre-release state and MUST NOT (yet) be used for SCIENTIFIC purposes! *****
The MultiDark database provides results from cosmological simulations performed within the MultiDark project. This database can be queried by entering SQL statements directly into the Query Form. The access to that form and thus access to the public & private databases is password protected - if you haven't done so, please register first.
More information on the simulations, the database, its design and the possibilities to access the data are described in the Documentation, where we also provide a little tutorial on SQL (SQL Step-by-Step) and some Frequently Asked Questions.

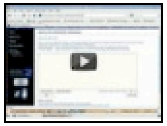
Registration
Access to the Query Form is password-protected - if you don't want to register, use the **public user**:
username: multidark_public
password: [none]
For gaining full access to all data in the database, registration via the Registration Form, also linked at the Registration page of the Documentation, is required.

Contact
For any comments, suggestions, help requests, bug reports etc., please don't hesitate to contact us by filling out our Contact Form.

Status
The current status of the database and the web application is reported in the section Status. This is the place to look for any news related to the simulations and the database.



Images & Movies
We have collected some images (and now also the first movies!) related to the MultiDark simulations at Images & Movies. Feel free to use them for talks, posters or just enjoy them!
You have created a nice movie yourself and want to share it with other people? Excellent! Just fill out the Contact Form and send us a short description, where to find the movie/picture, what it shows and which data and code was used to produce it. We will then consider adding it to this web page.



Demo Video
For an easy start we created a little video on YouTube for you which demonstrates the basic usage of the web interface for accessing the MultiDark Database. Have a look at our section Demos&Tutorials or watch it directly on YouTube.

MultiDark
Multimessenger Approach for Dark Matter Detection

GERMAN ASTROPHYSICAL GAVO VIRTUAL OBSERVATORY

AIP

www.multidark.org

MultiDark Database

- Home
- Query Form
- Credits
- Documentation

Databases
- Bolshoi
- MDR1
- miniMDR1
- Spatial3D_db

Private (MyDB) Databases
- mdark_db (rw) (context)

MultiDark
Multimessenger Approach for Dark Matter Detection

German Astrophysical GAVO Virtual Observatory

AIP

Query the MultiDark Database

Welcome Multi Dark test user!

Admin Pages

***** All data provided here are currently only in a pre-release state and MUST NOT (yet) be used for SCIENTIFIC purposes. *****

Place your SQL statement directly in the text area below and submit your request by pressing one of the 'Query' buttons.
Please note, that there is a timeout and row limit for each query:
Streaming queries: return unlimited number of rows in CSV format and are cancelled after 420 seconds.
Browser queries: return a maximum of 1000 rows in HTML format and are cancelled after 30 seconds.

```
select top 10 * from miniMDR1..FOF where snapnum = 85 order by np desc
```

Query (stream) | Query (browser) | Maximum number of rows to return: 10

Help | Clear Text

Previous queries

Show all previous queries for current user (max. 1000) with additional information in a new window:

Advanced query history

Demo queries

www.multidark.org

MultiDark Database

- Home
- Query Form
- Credits
- Documentation
- 1: Introduction
- 2: Databases
- 3: Database Access
- 4: Demos & Tutorials
- 5: Frequently Asked Questions

MultiDark
Multimessenger Approach for Dark Matter Detection

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Thank you!