Structure Formation: Dark Matter Halos

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- Formation of non-linear structures: simulations
- Halo mass function
- Halo Velocity function
- Density profiles
- Halo concentration
- Subhalos
- Abundance matching: connecting halos with galaxies
- Small scales: dwarfs, satellites
- Warm dark matter

Evolution of Perturbations

- *Inflation*: fluctuations in metric carried over the horizon by the fast expansion
- During Big Bang fluctuations grow
- Recombination: fluctuations in radiation start to move freely. Baryons are catching up the dark matter.
- z=20: first stars
- z=10 first galaxies, QSO, black holes
- ....

Cosmological n-body simulations

Codes:

- TREE
- AMR

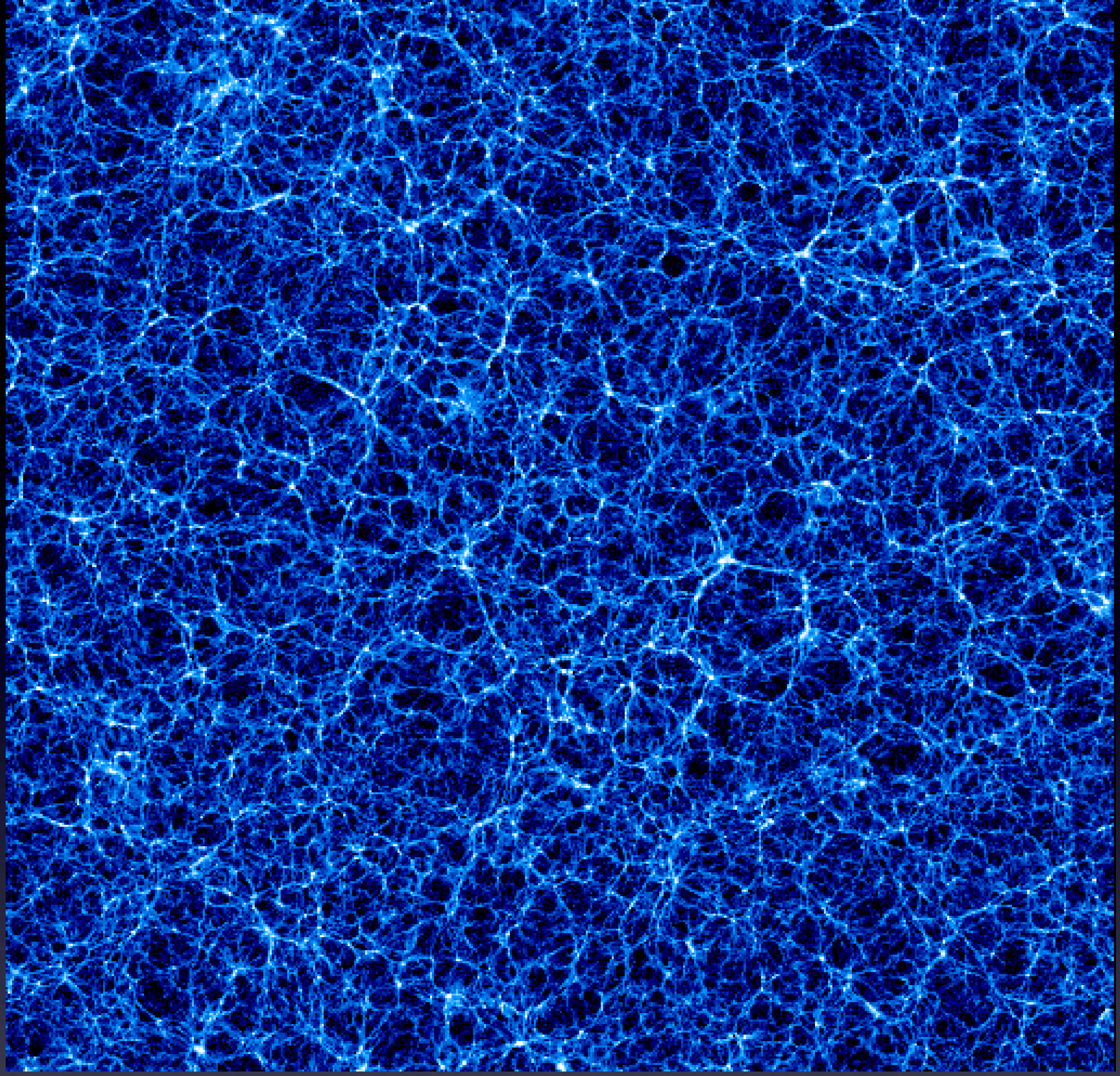
Advantages:

- Fast. Typical simulation has 1 billion particles
- Parallel, when used for large volumes. Hundreds of processors.

Challenges:

- Very high accuracy is required for large-scale problems (eg DE, cluster mass function)
- Inefficient parallelization for individual objects with many millions of particles: only few processors.
- Too much data: analysis is difficult

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.



500 Mpc

Yepes et al

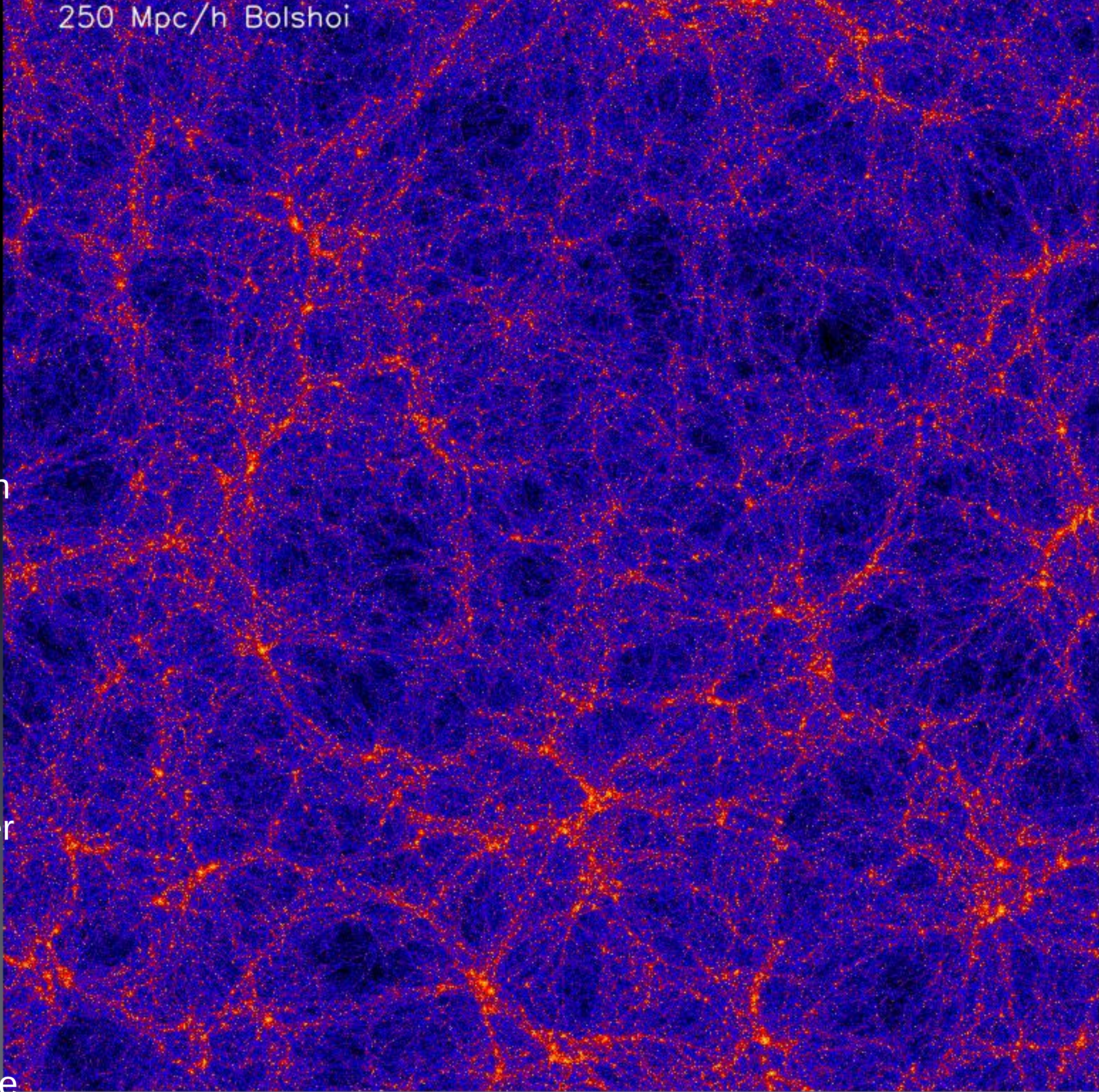
1G+1G n-body + gas simulation

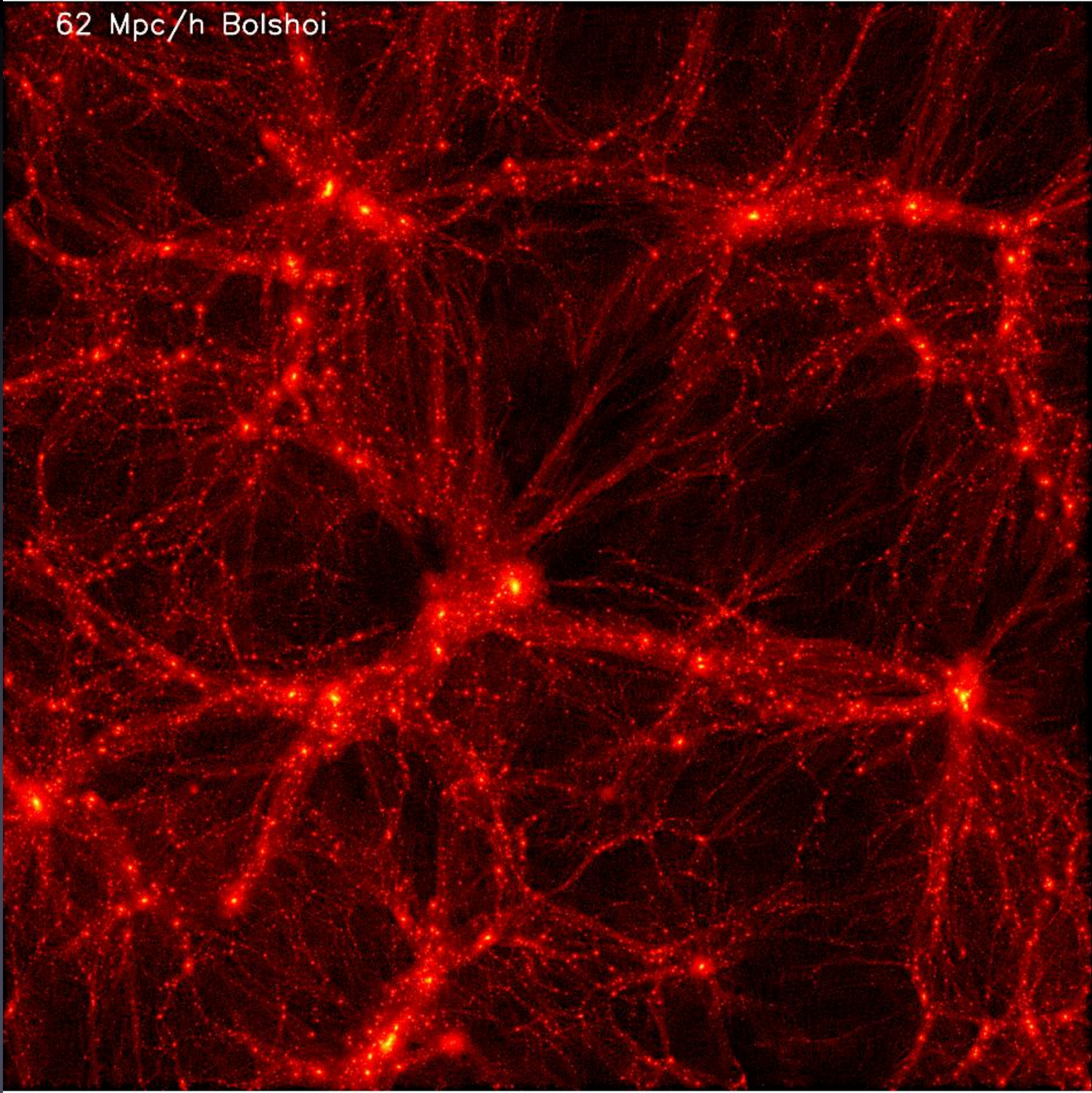
The Bolshoi simulation ART code

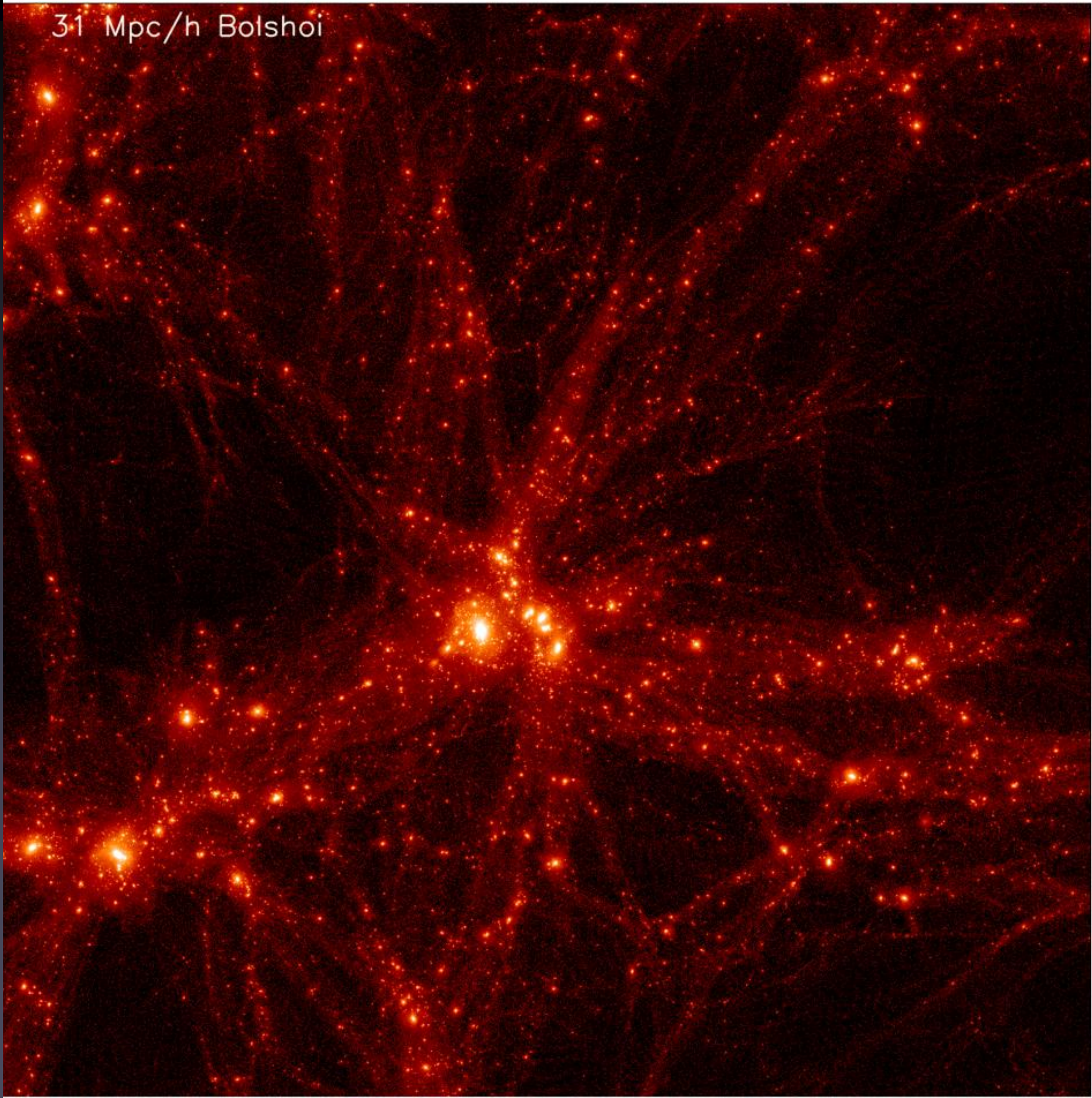
250Mpc/h Box
LCDM
s8 = 0.83
h = 0.73
8G particles
1kpc/h force resolution
1e8 Msun/h mass res

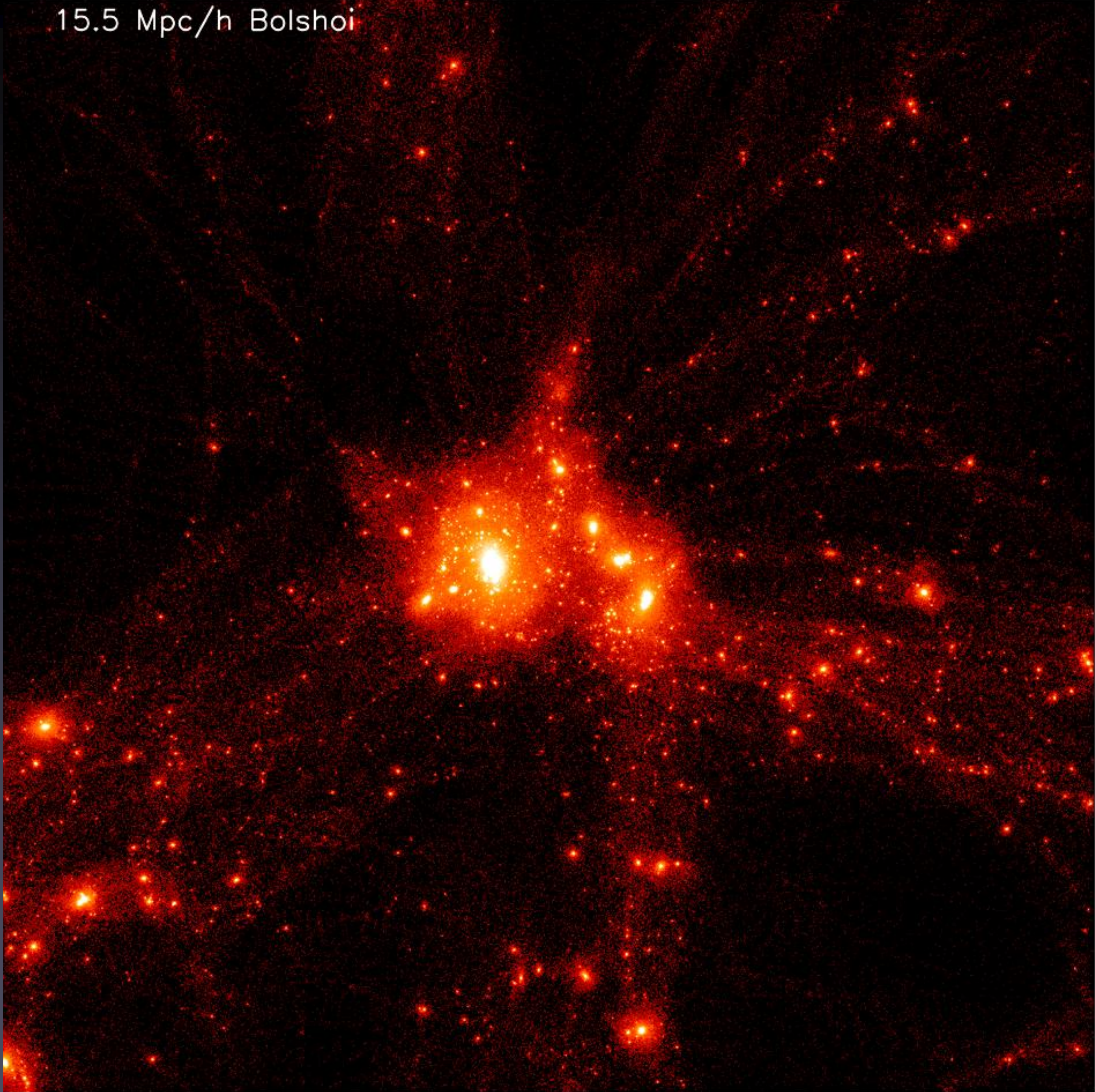
dynamical range
262,000
time-steps = 400,000

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

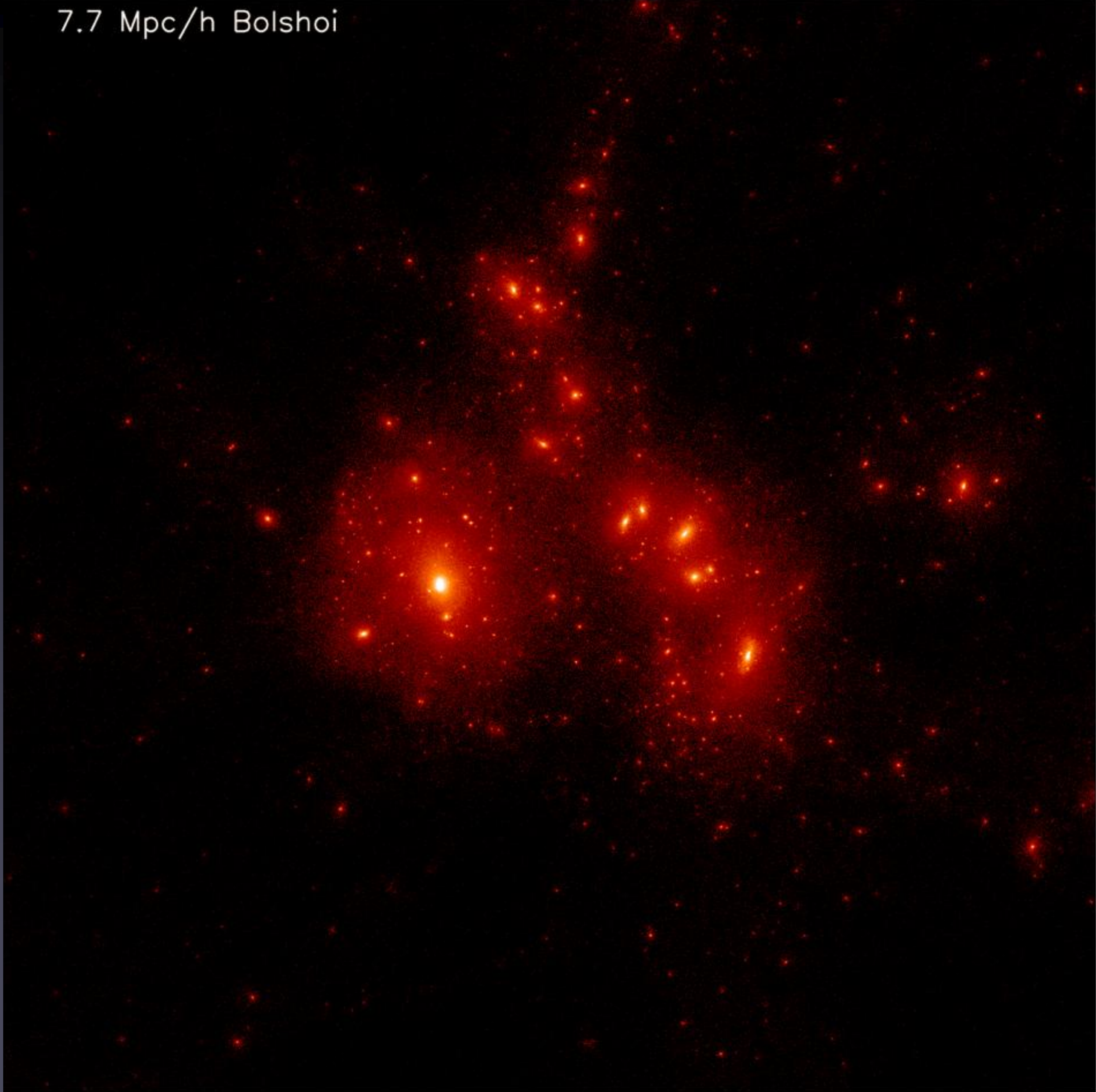



62 Mpc/h Bolshoi


31 Mpc/h Bolshoi

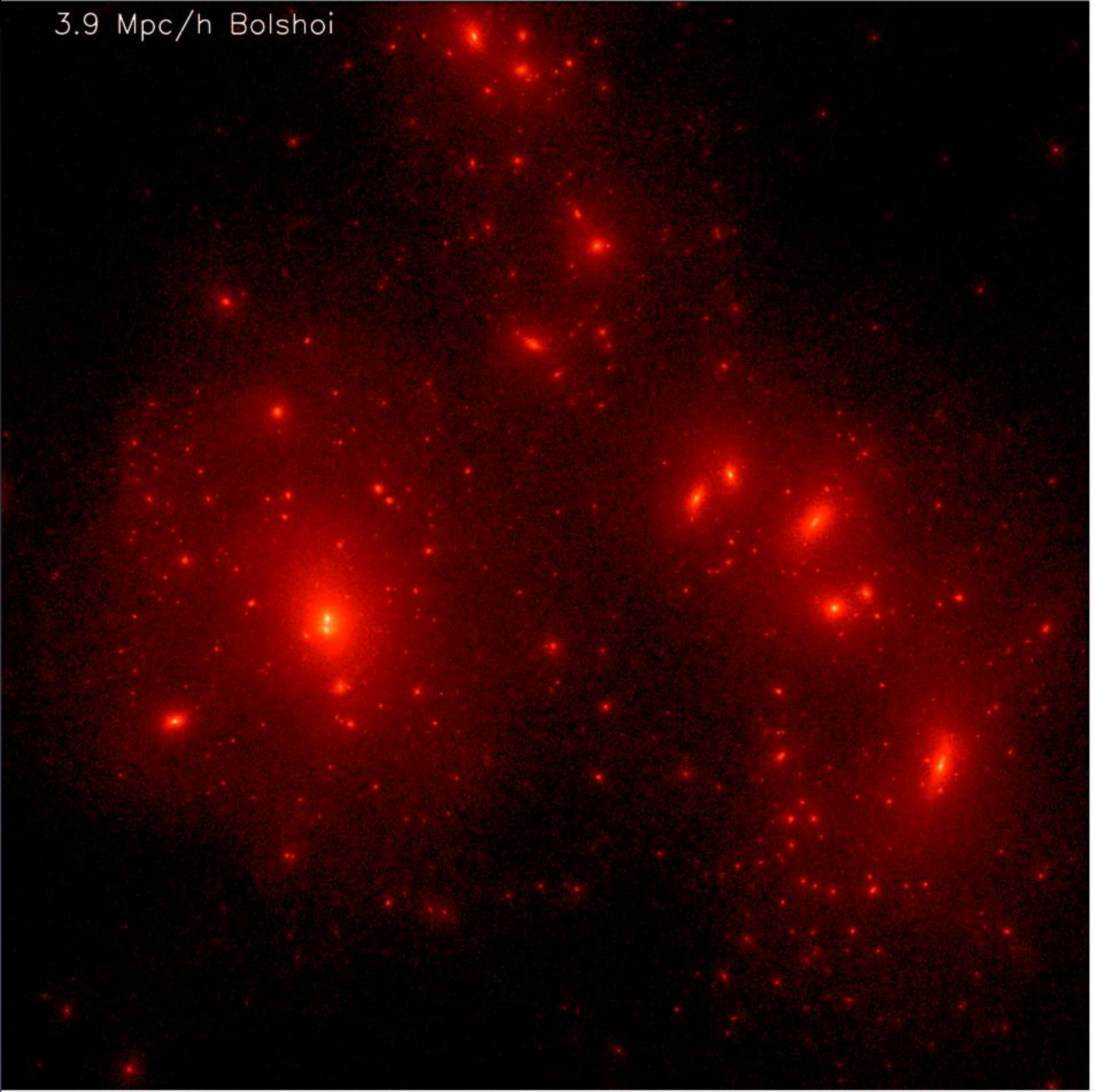

15.5 Mpc/h Bolshoi

Small Galaxy Group



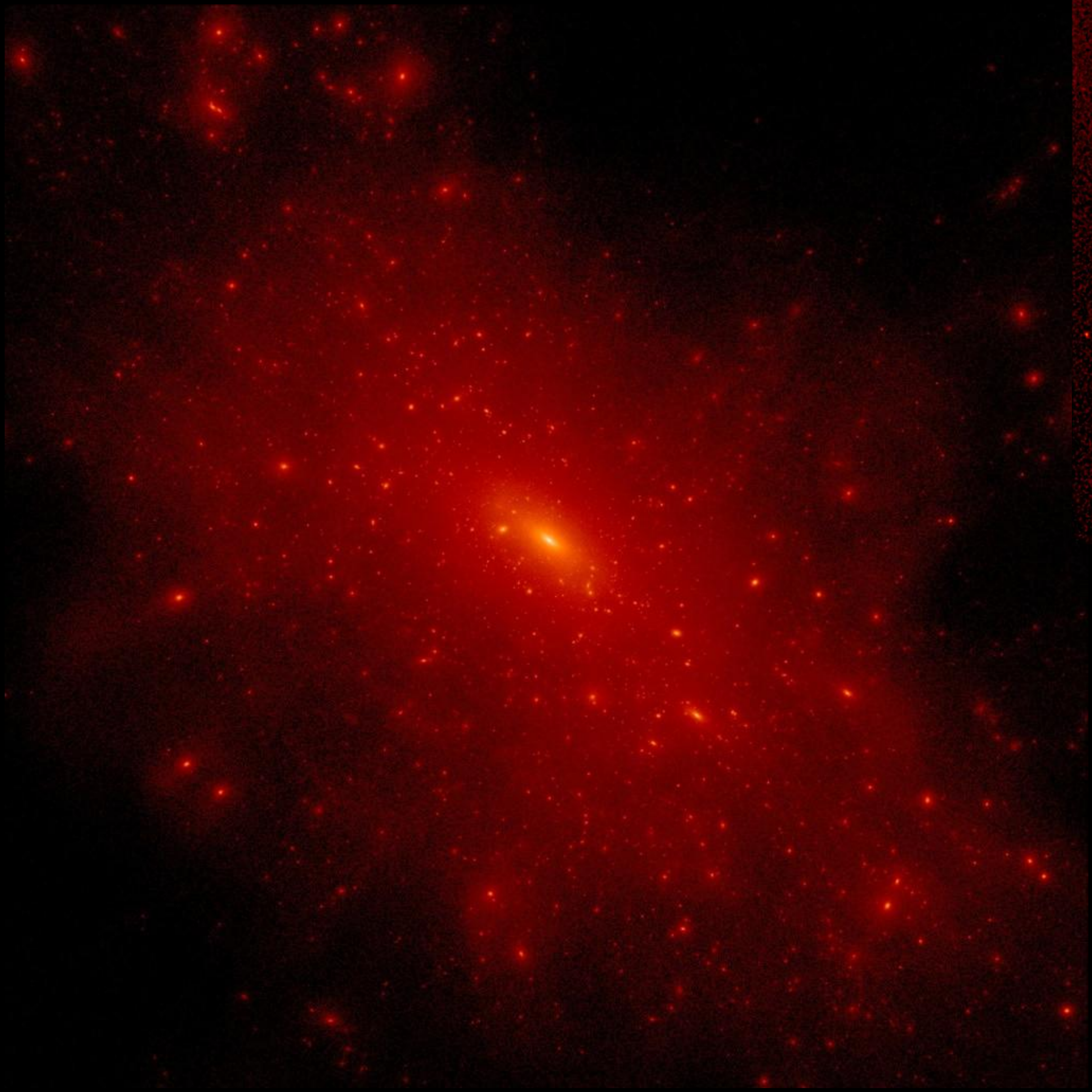
Small Galaxy Group

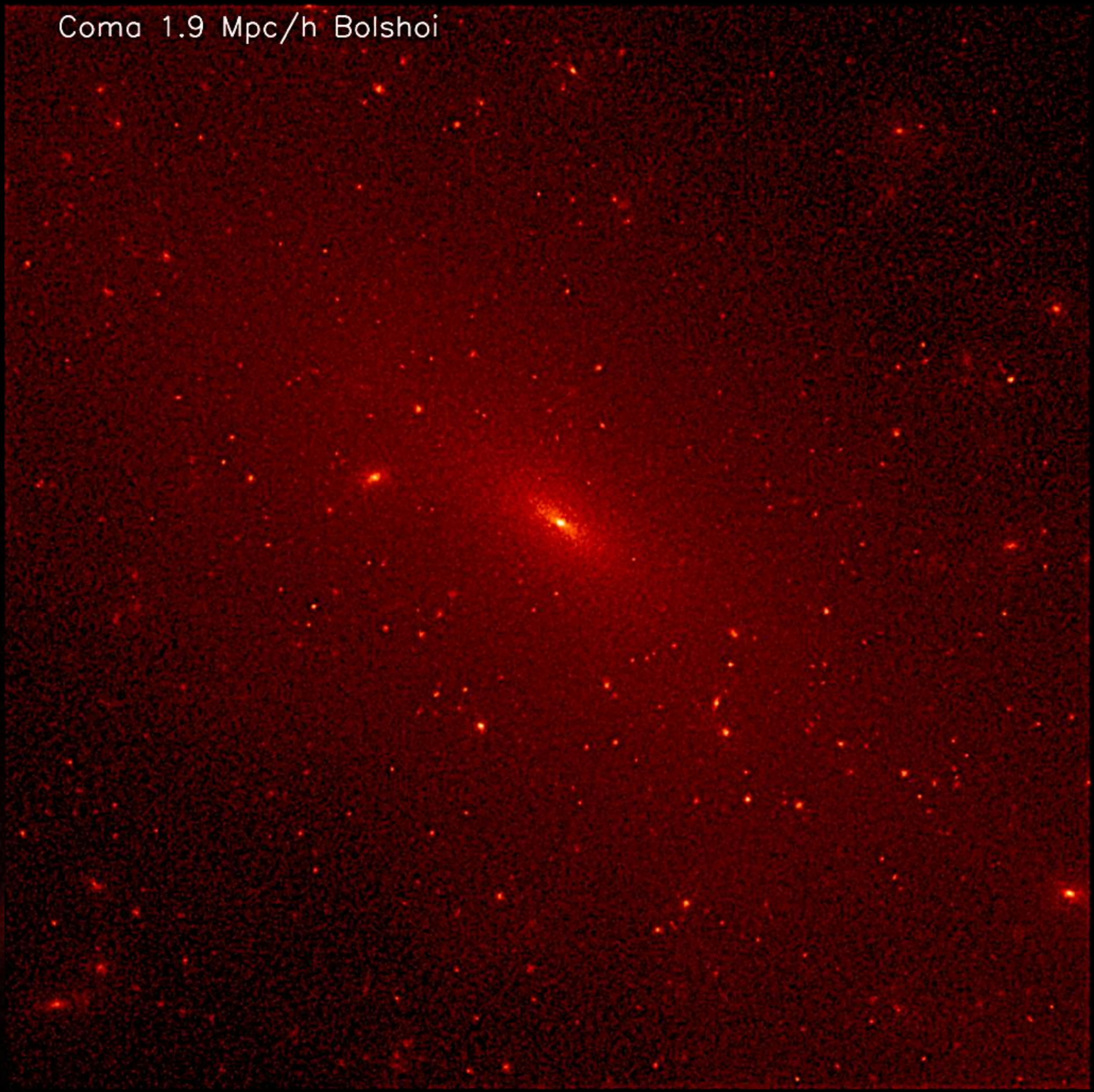
Central Region



"Coma" cluster of galaxies

7.7Mpc





1.9Mpc

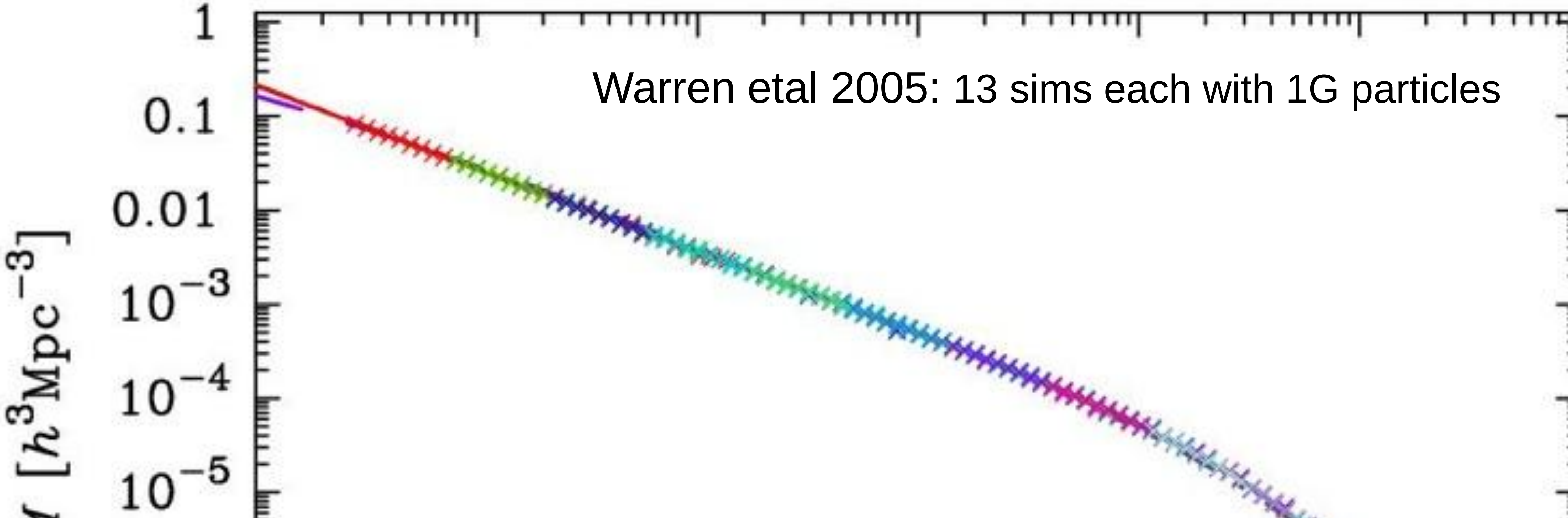
Formation of a MW-size halo

0.5Mpc

ART

Klypin, Kravtsov

Mass function of distinct halos



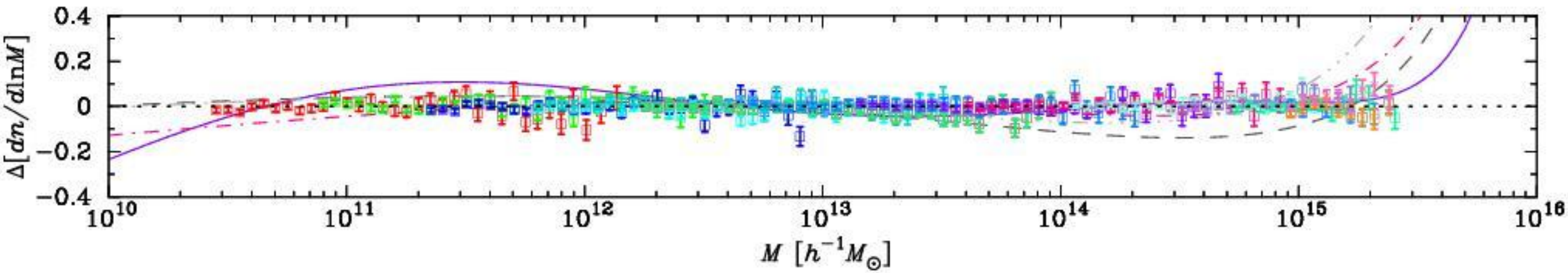
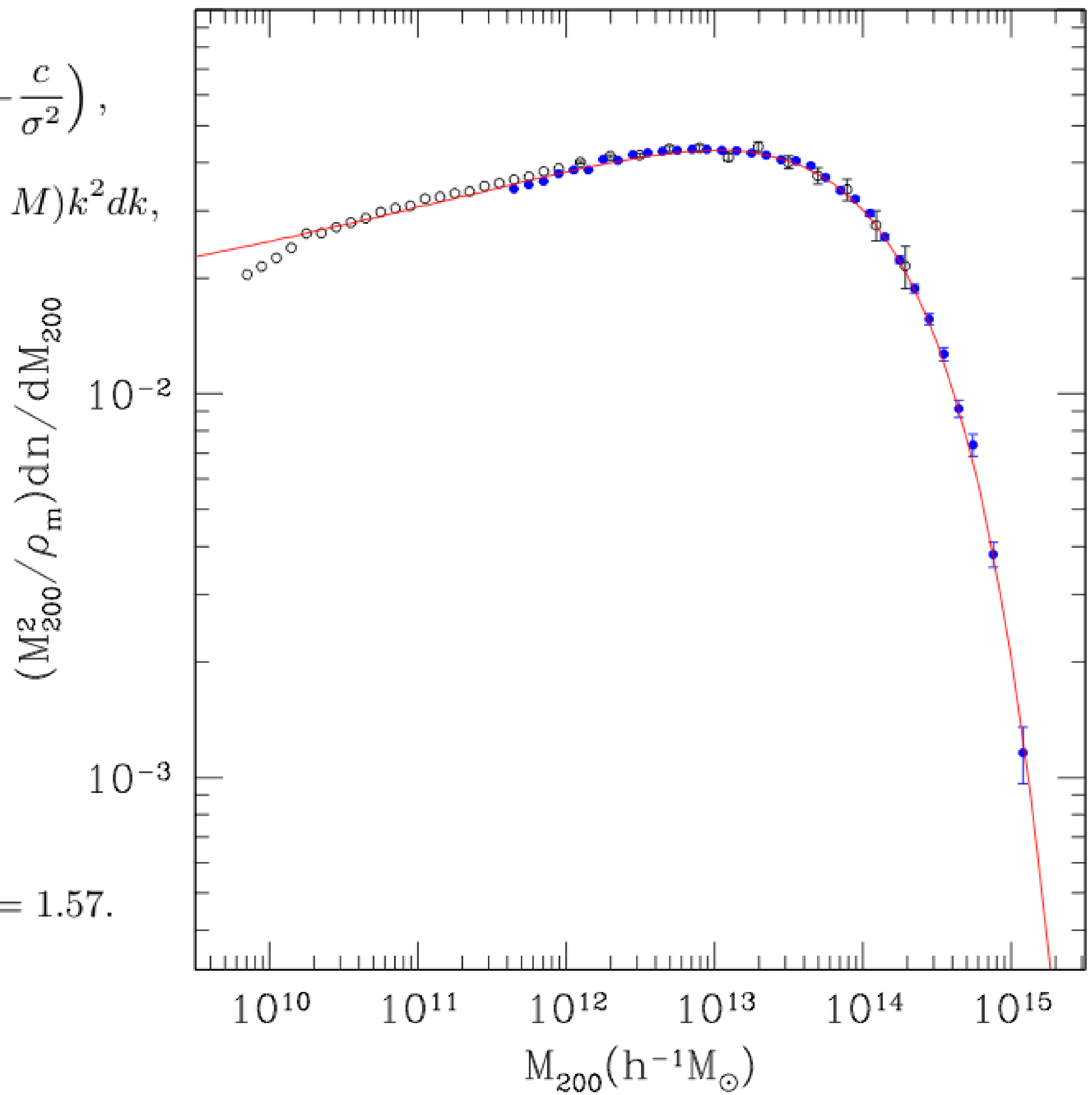


FIG. 2.— Shown are the residuals from the binned simulation data to the fit presented in this work as square data points of different colors per simulation. The Jenkins fit is the solid (purple) line, ST original fit the dashed (dark gray) line, the ST fit with parameters A, a, p free with dot-dashed line (red), and the ST fit with a, p free and amplitude A set to require all dark matter in halos as a triple-dot-dashed line (light gray). The binned mass function from the Virgo Hubble Volume simulation are the asterisk points with errors (pink).

Mass function of distinct halos

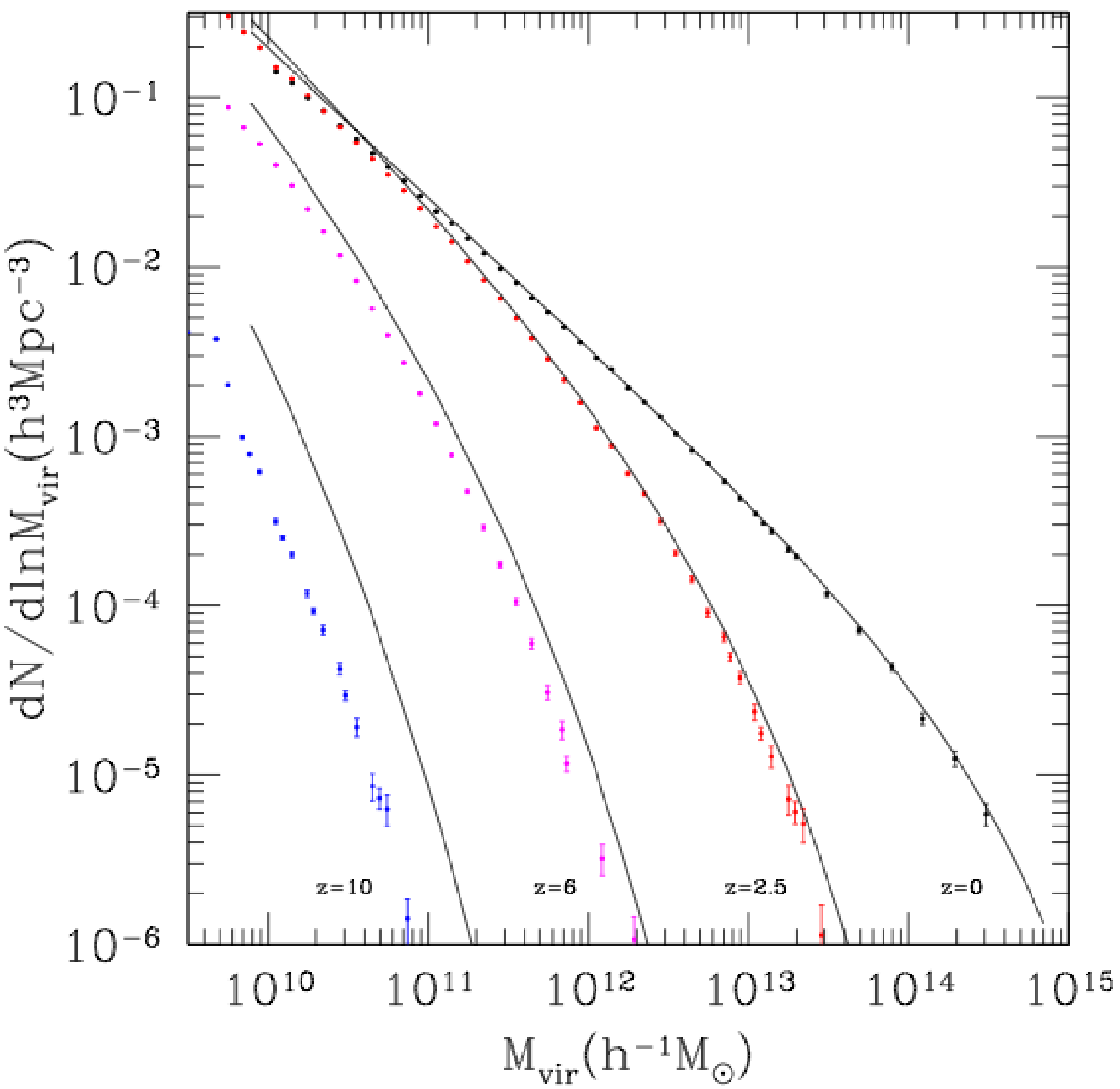
$$\frac{dn}{dM} = f(\sigma)\frac{\rho_m}{M}\frac{d\log\sigma^{-1}}{dM},$$
$$f(\sigma) = A\left[1+\left(\frac{\sigma}{b}\right)^{-a}\right]\exp\left(-\frac{c}{\sigma^2}\right),$$
$$\sigma^2(M,z) = \frac{1}{2\pi^2}\int_0^\infty P(k,z)W^2(k,M)k^2dk,$$



$A = 0.213,\ a = 1.80,\ b = 1.85,$ and $c = 1.57.$

Prada et al 2011

Halo Mass function



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

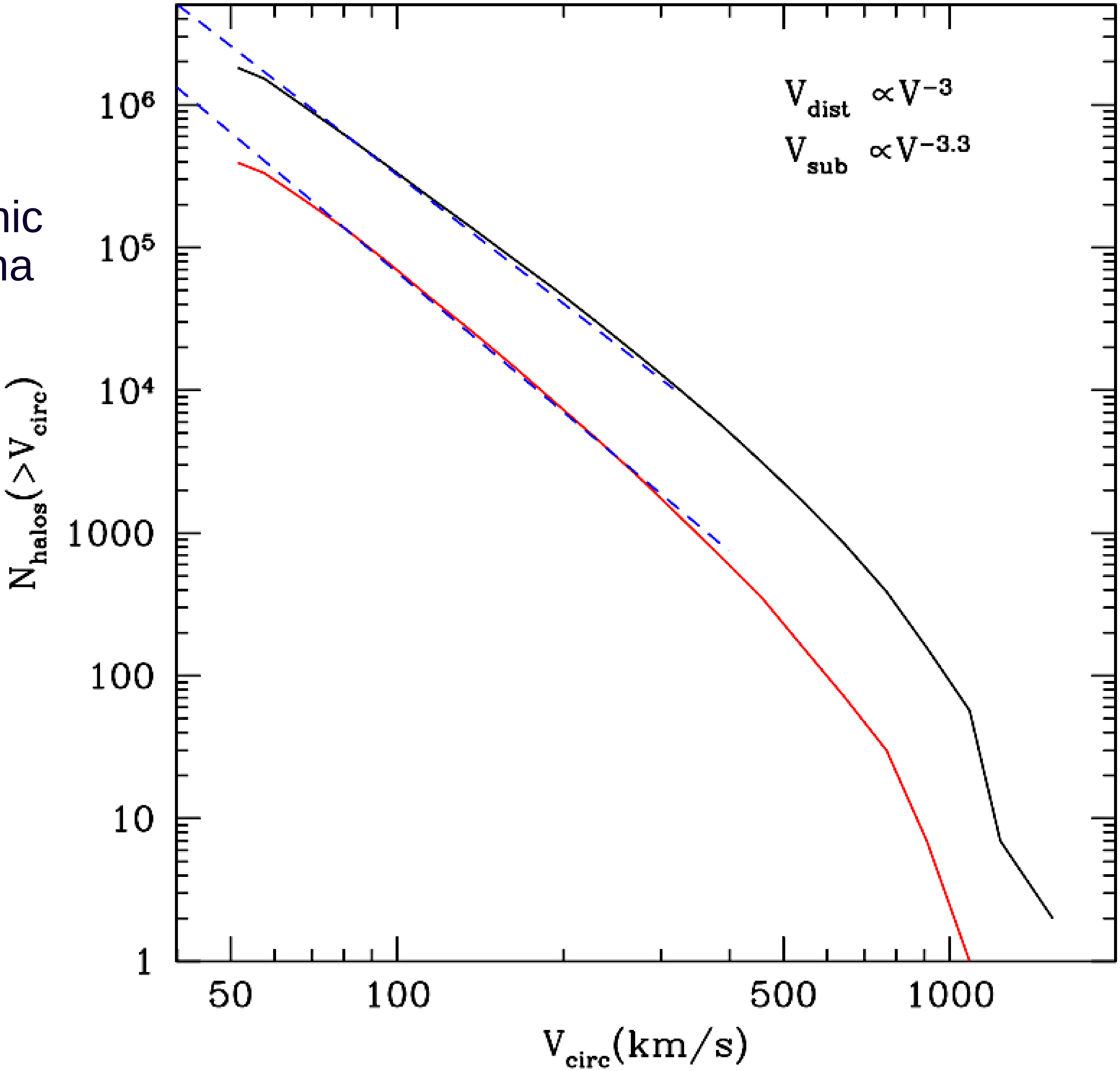
Correction factor for Sheth&Tormen:

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

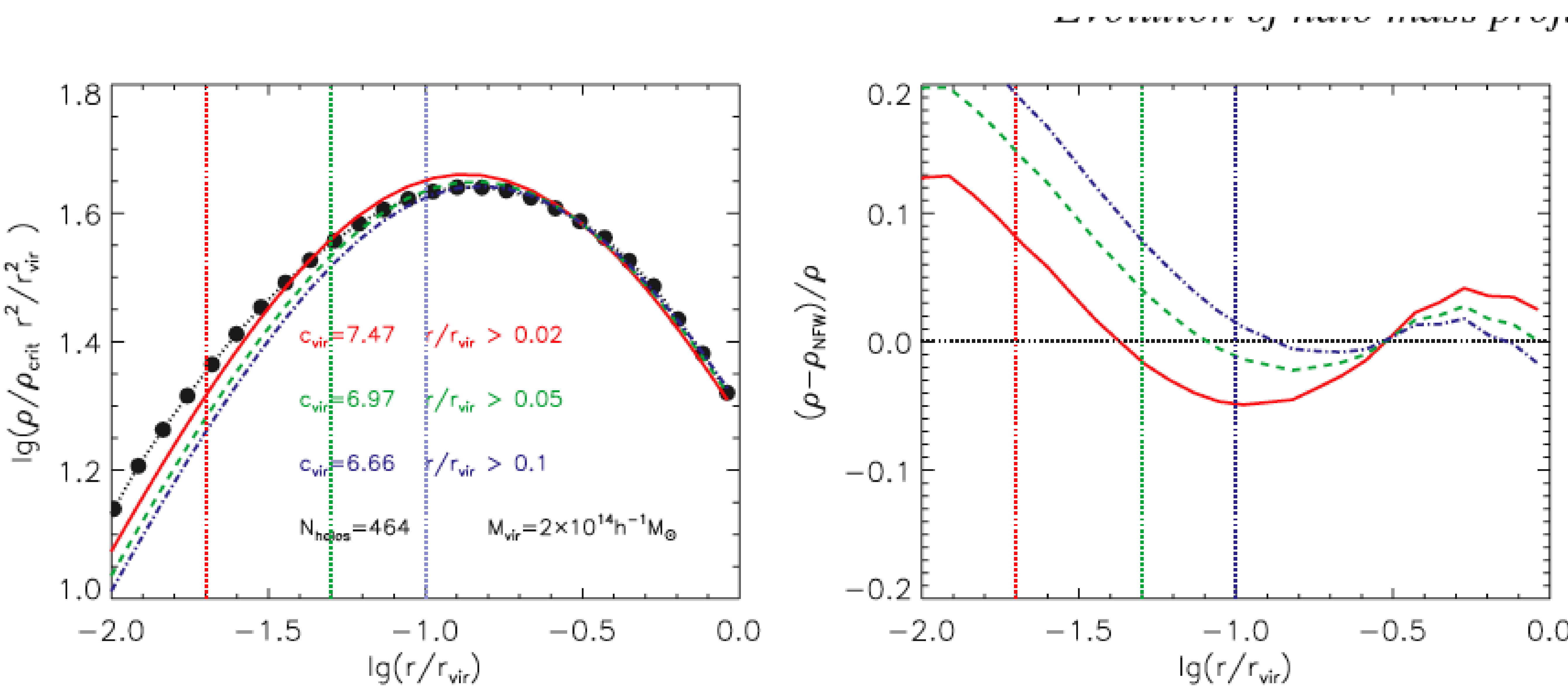
Bolshoi: Klypin et al 2010
Tinker 2008: z=0-2.5

Velocity Functions

From Magellanic Clouds to Coma Cluster



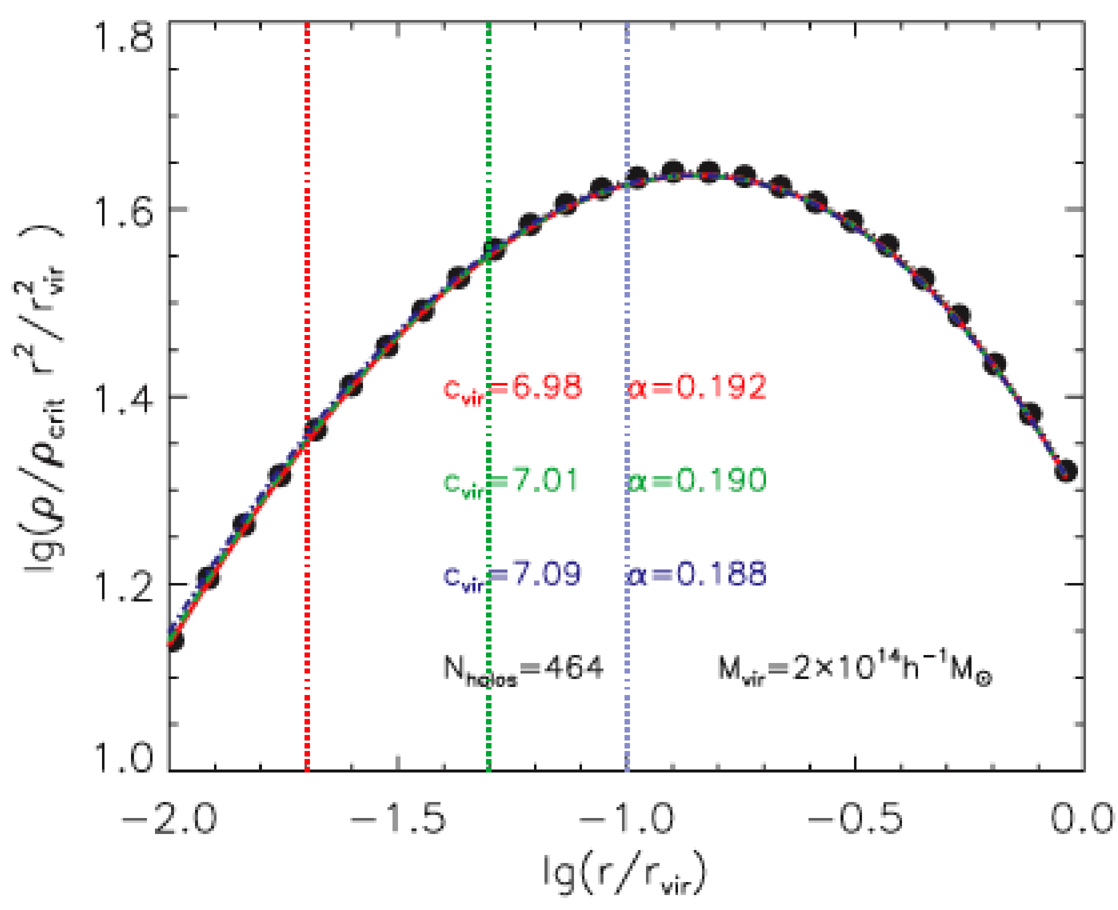
Halo Profiles

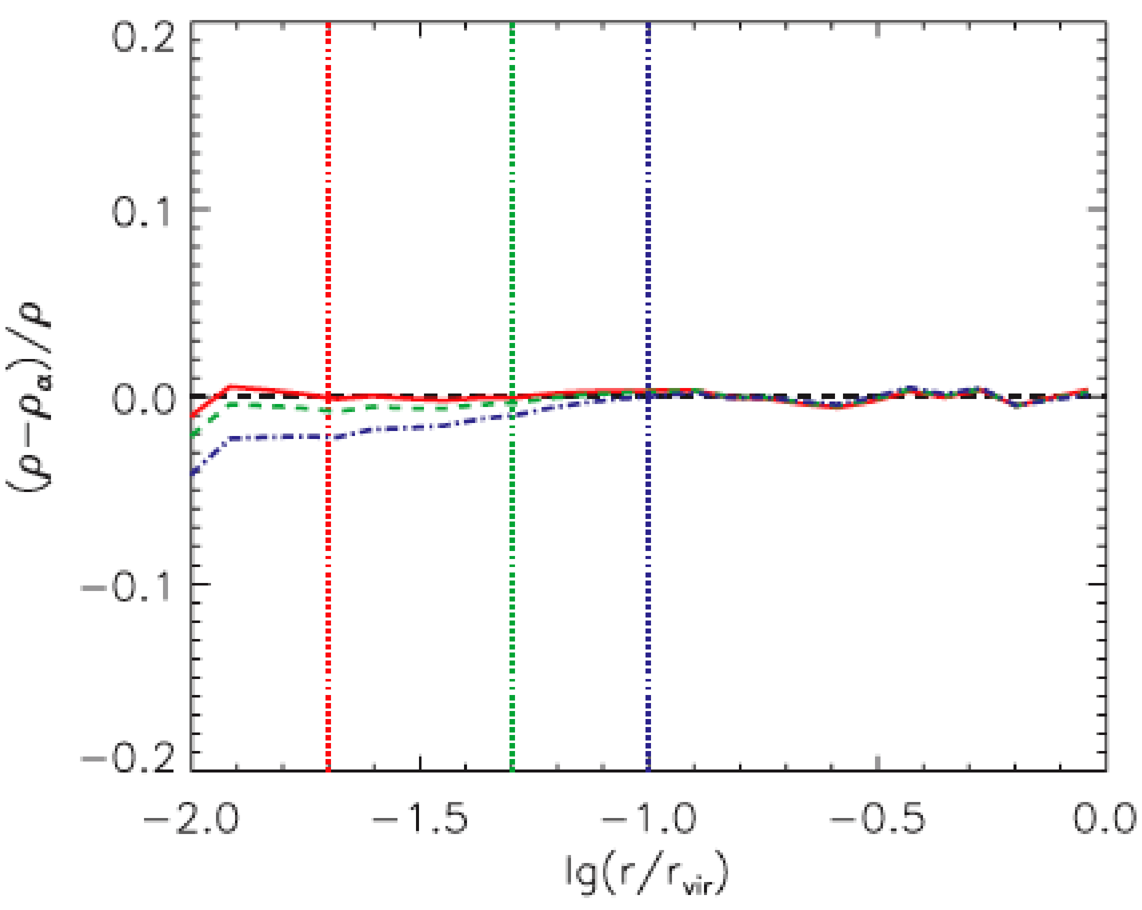


NFW profile:

$$\frac{\rho(r)}{\rho_{\rm crit}} = \frac{\delta_{\rm c}}{(r/r_{\rm s})(1+r/r_{\rm s})^2},$$

where $\rho_{\rm crit} = 3H^2/8\pi G$ is the critical density

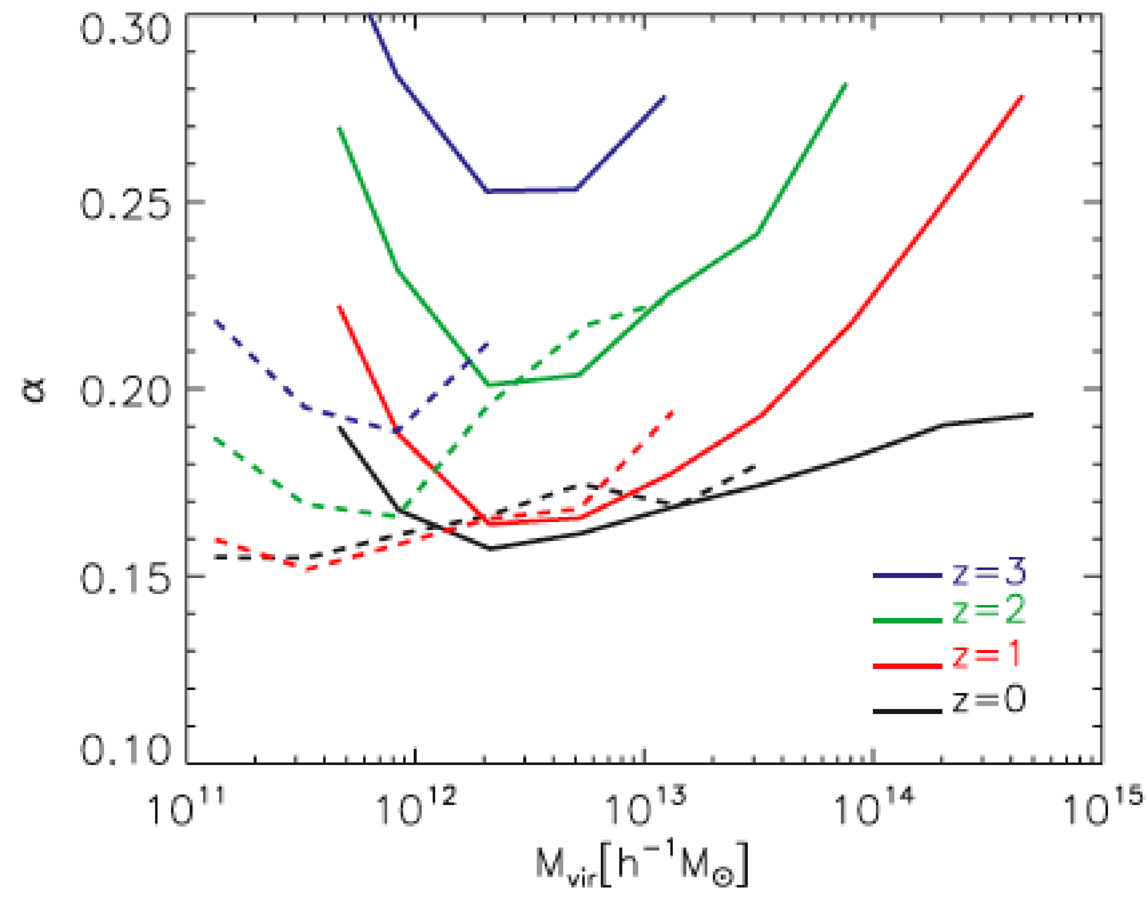




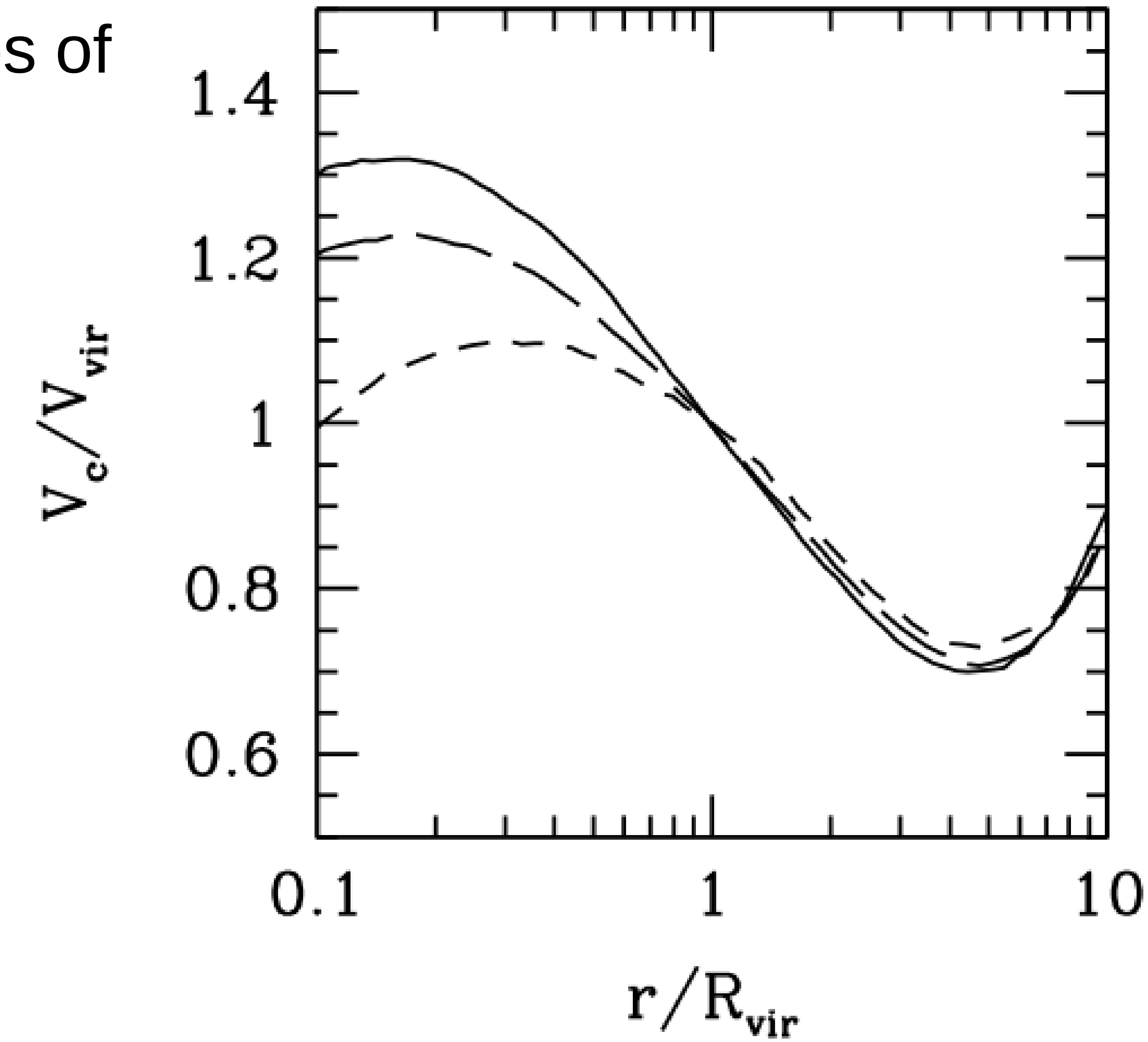
Einasto profile: better approximation with three parameters

$$\ln\left(\frac{\rho}{\rho_{-2}}\right) = -\left(\frac{2}{\alpha}\right)\left[\left(\frac{r}{r_{-2}}\right)^{\alpha} - 1\right]$$

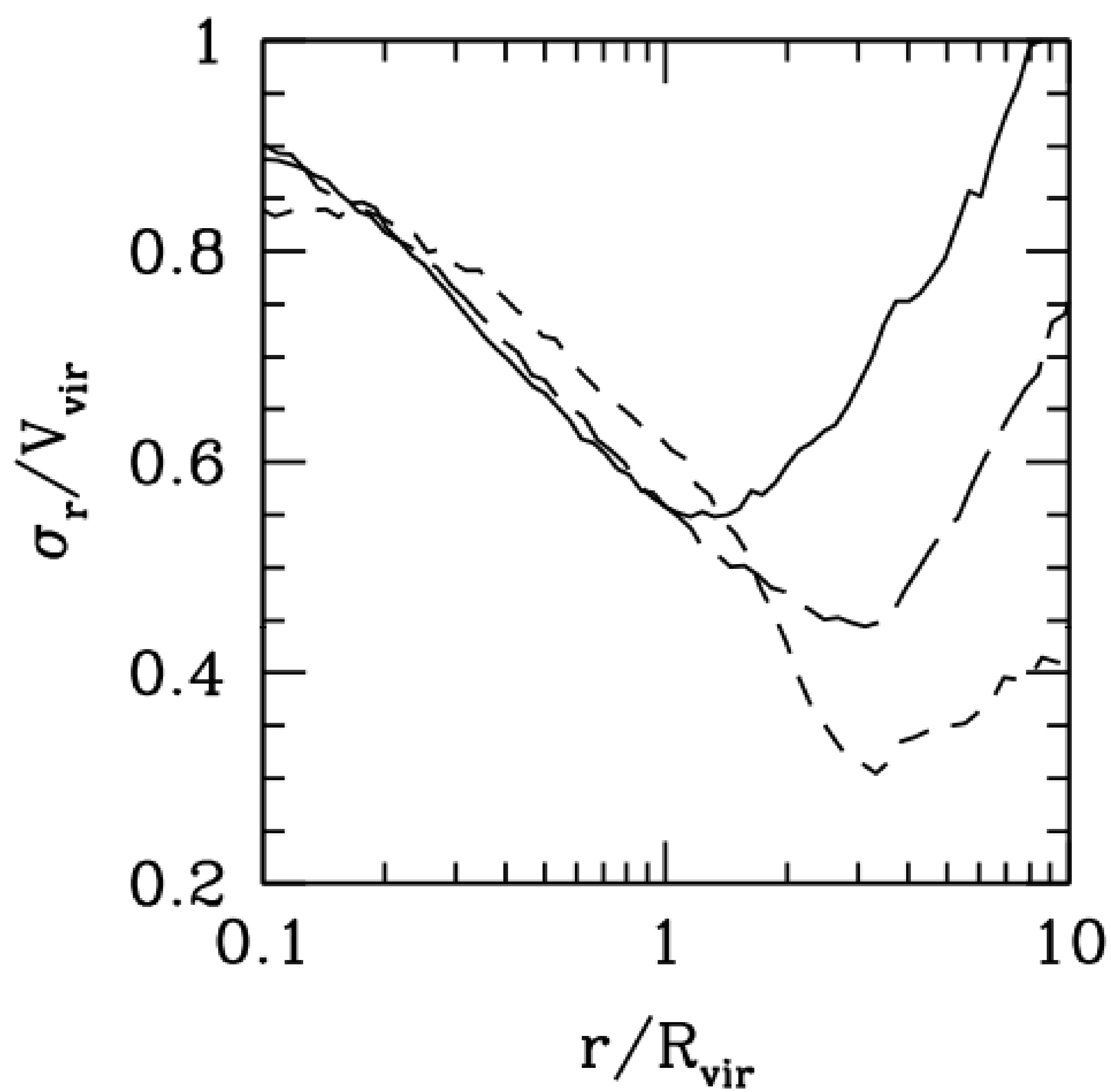
$$\frac{\mathrm{d}\log\rho}{\mathrm{d}\log r} = -2\left(\frac{r}{r_{-2}}\right)^{\alpha}$$



Circular velocity profiles for halos of different mass



Cuesta et al 2008



Dispersion velocity profiles for halos of different mass

Are halos in equilibrium?

$$\frac{r}{\rho}\frac{d(\rho v_r)}{dt} + \sigma_r^2\left[\frac{d\ln(\rho\sigma_r^2)}{d\ln r} + 2\beta\right] = v_c^2(r), \qquad (3)$$

where v_r is the radial velocity and $v_c^2(r) = GM(< r)/r$.

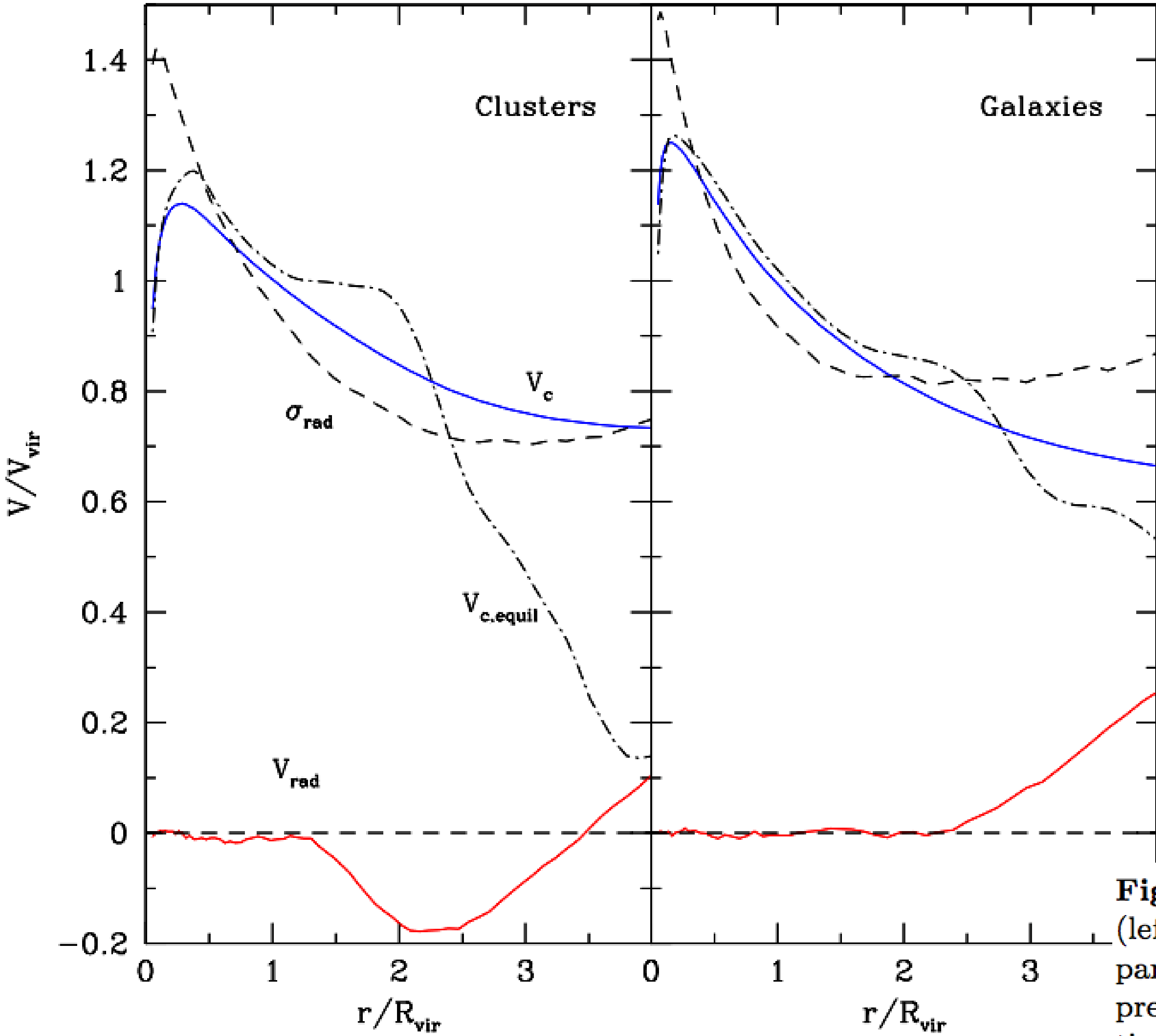


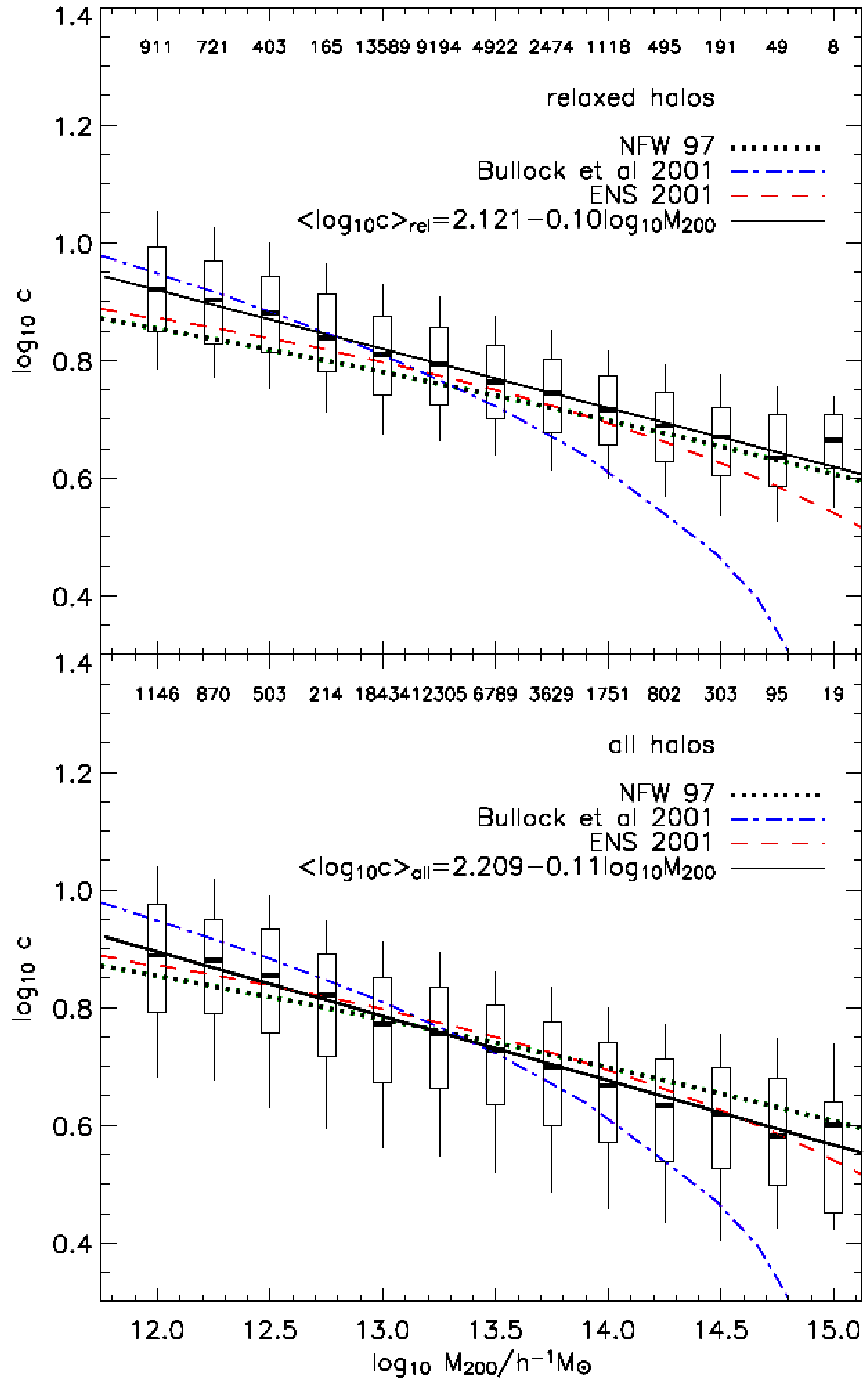
Figure 8. Different velocity components for cluster-size haloes (left panel $M_{\rm vir} \approx 2\times10^{14}h^{-1}{\rm M}_\odot$) and galaxy-size haloes (right panel $M_{\rm vir} \approx 10^{12}h^{-1}{\rm M}_\odot$). The dot-dashed curves shows the predictions $v_{c,equil}$ of stationary Jeans equation (4). The stationary solution closely follows the real circular velocity up to $(2-2.5)R_{\rm vir}$ for galaxy-size haloes. It falls below v_c at larger distances indicating significant non-stationary effects. The situation with clusters is different: the central virialized region is surrounded by a shell where virialization is happening ($v_{c,equil} > v_c$) followed by the region where $v_{c,equil} < v_c$. See text for details.

Halo Concentration as function of halo mass.

Halo concentration c = Rvir/Rs

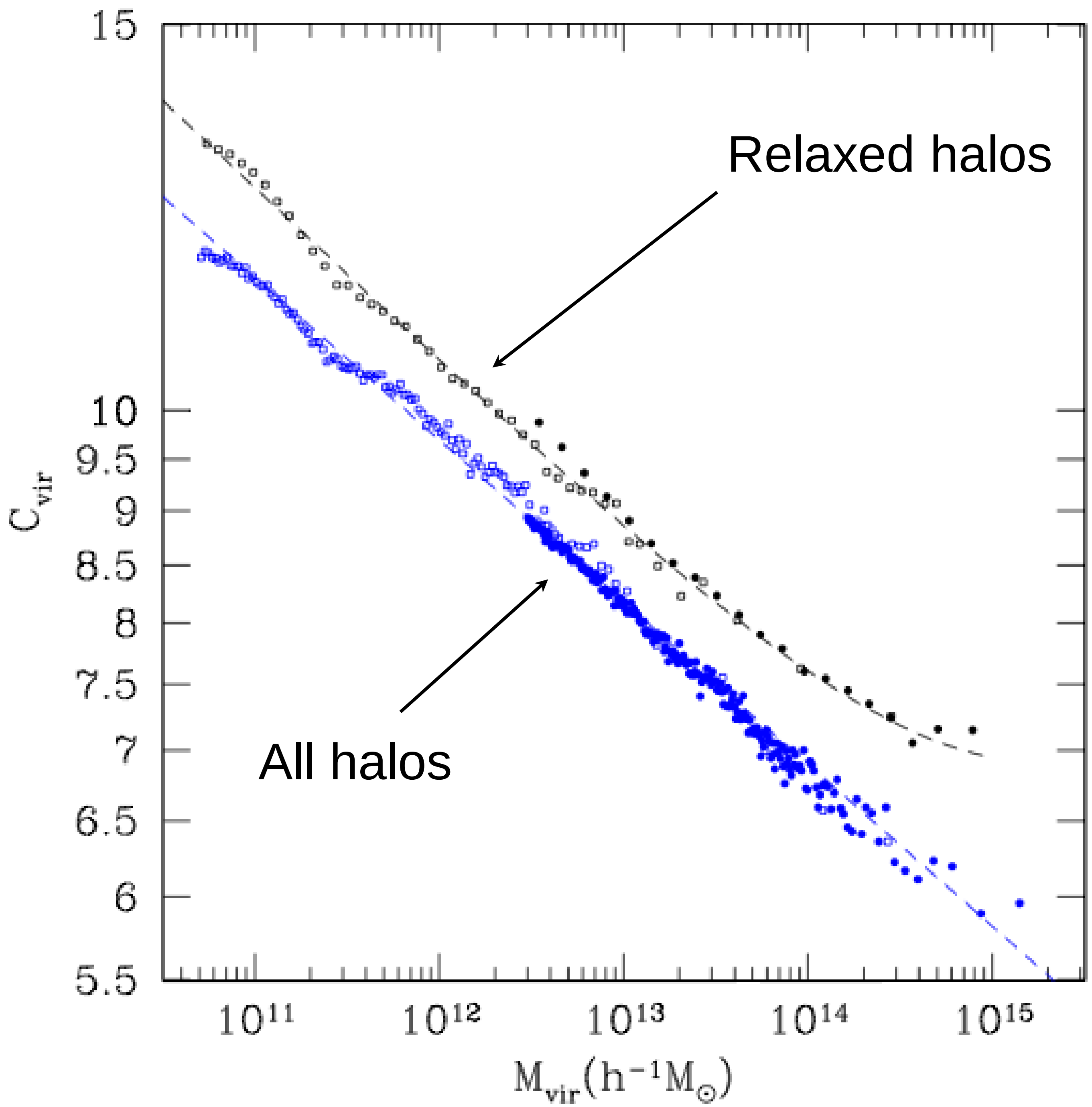
Spread in concentration Δlog(c)=0.1

Neto et al 2007. Millennium simulation



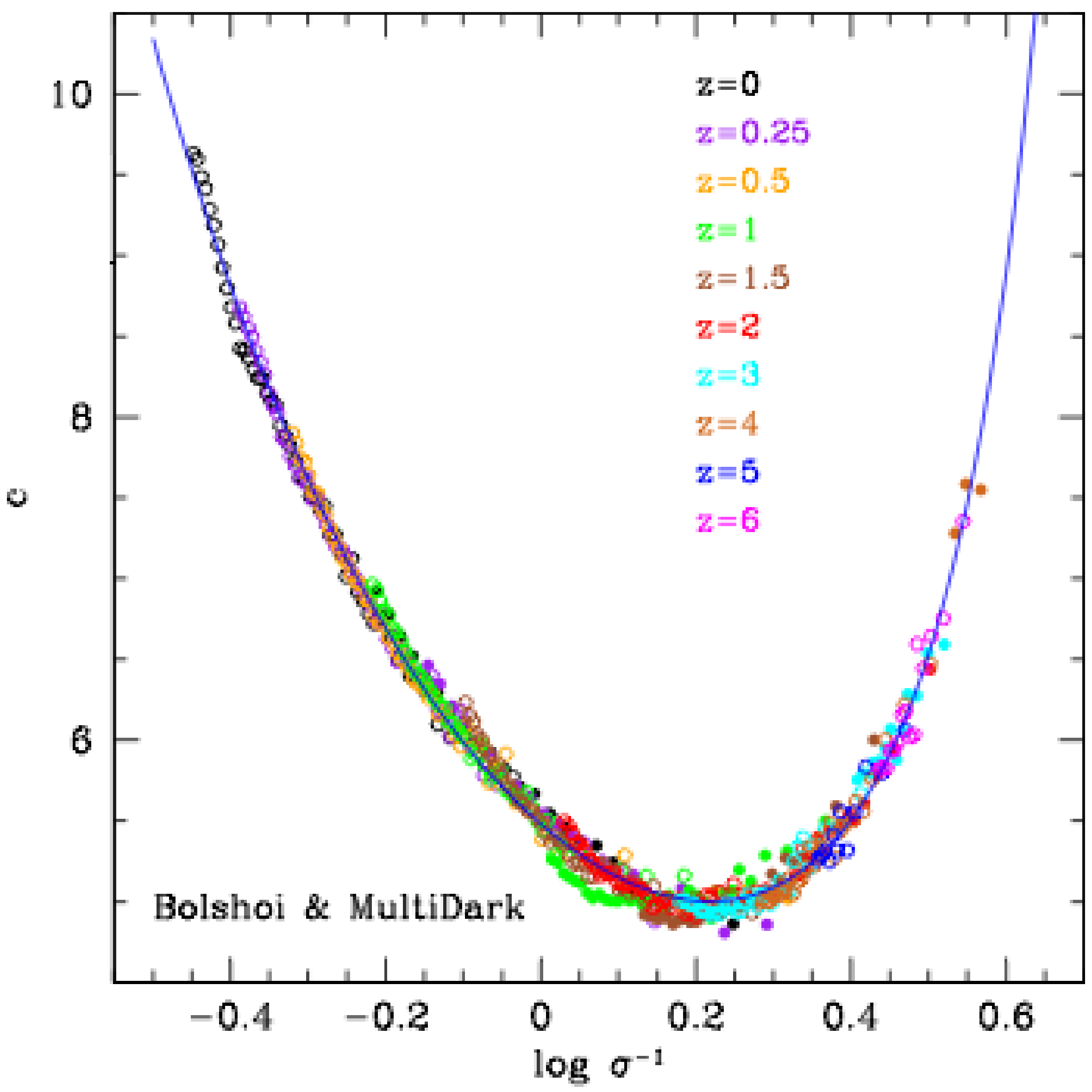
Halo Concentration as function of halo mass.

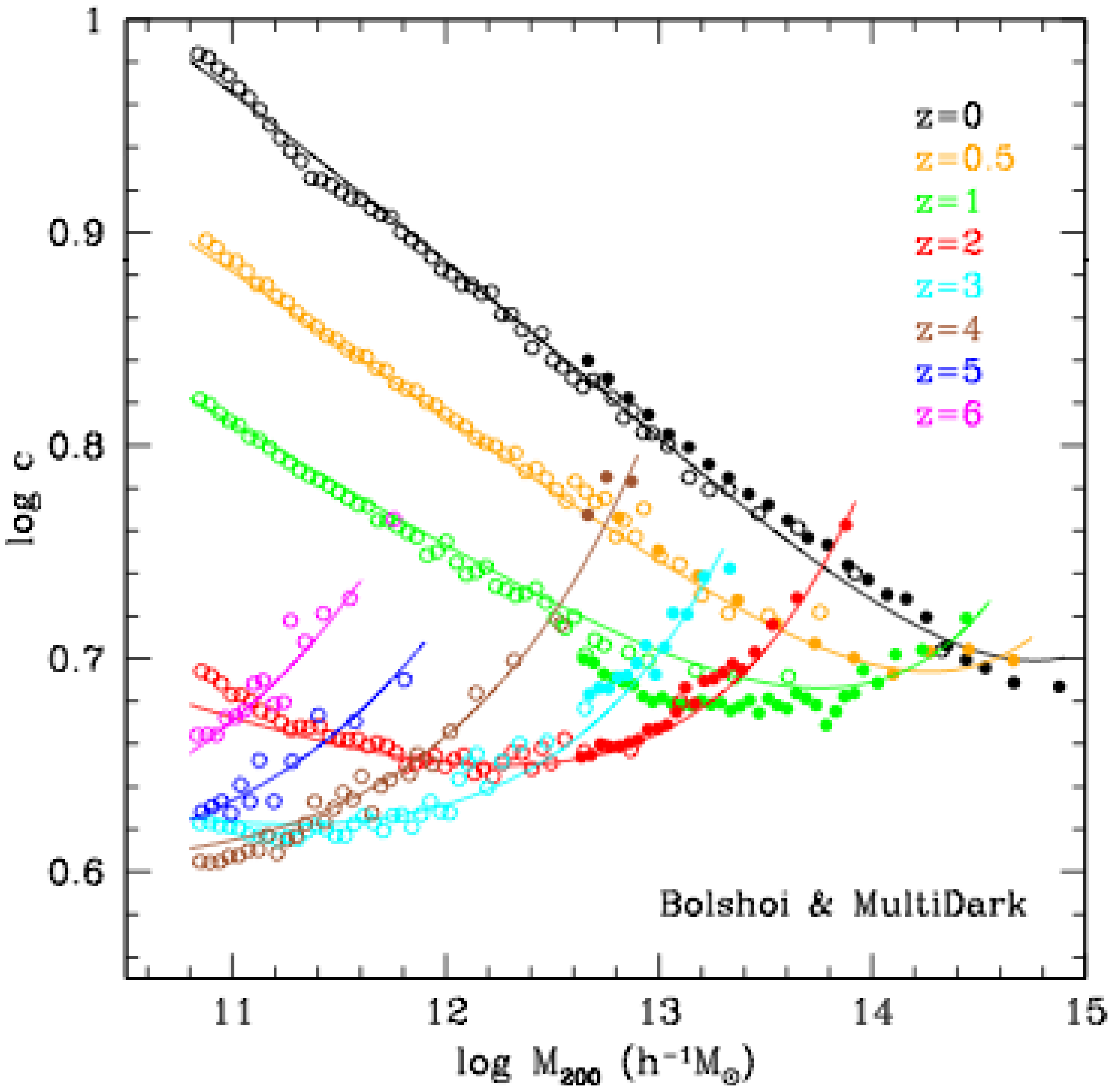
Effects of selection of halos



Prada et al 2011

Evolution of concentration with time





Subhalo mass function

Gao et al 2004

Halos are not self-similar:
Large halos have more substructure.
Yet the effect is very weak.

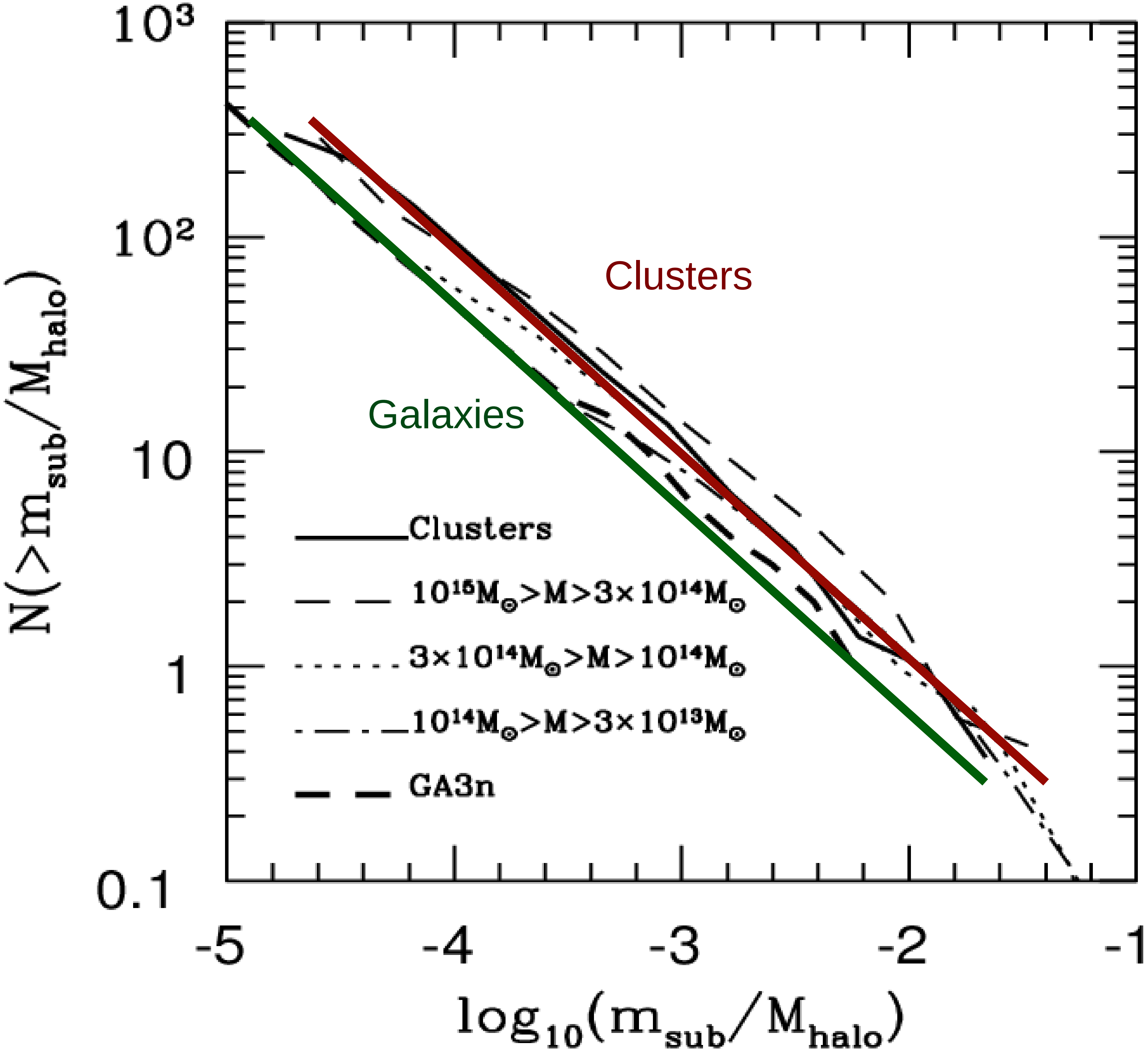
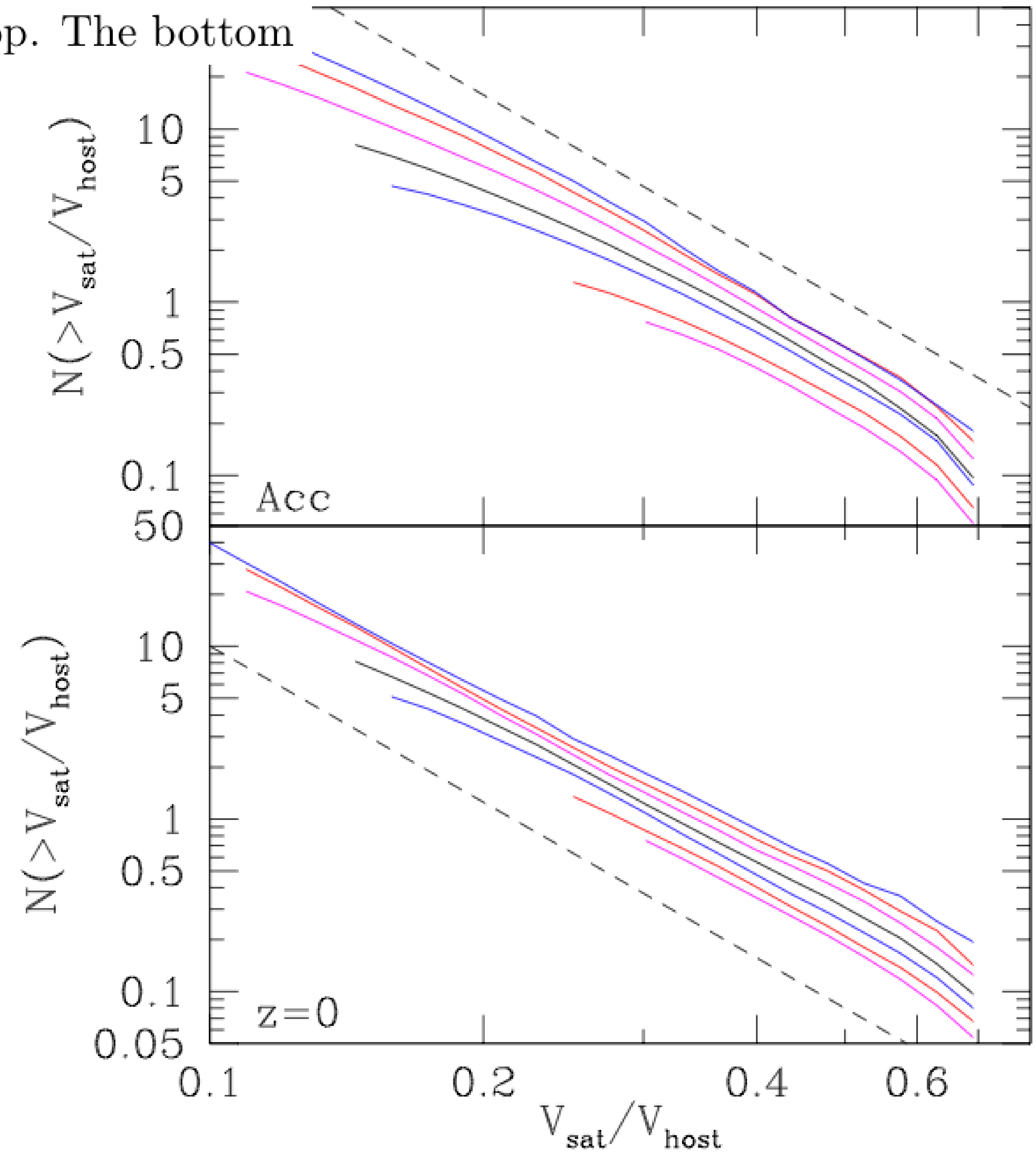


Fig. 11.— The cumulative velocity function of satellites for host halos with different maximum circular velocities ranging from ≈ 150 km s^{-1} to ≈ 1000 km s^{-1} from bottom to top. The bottom

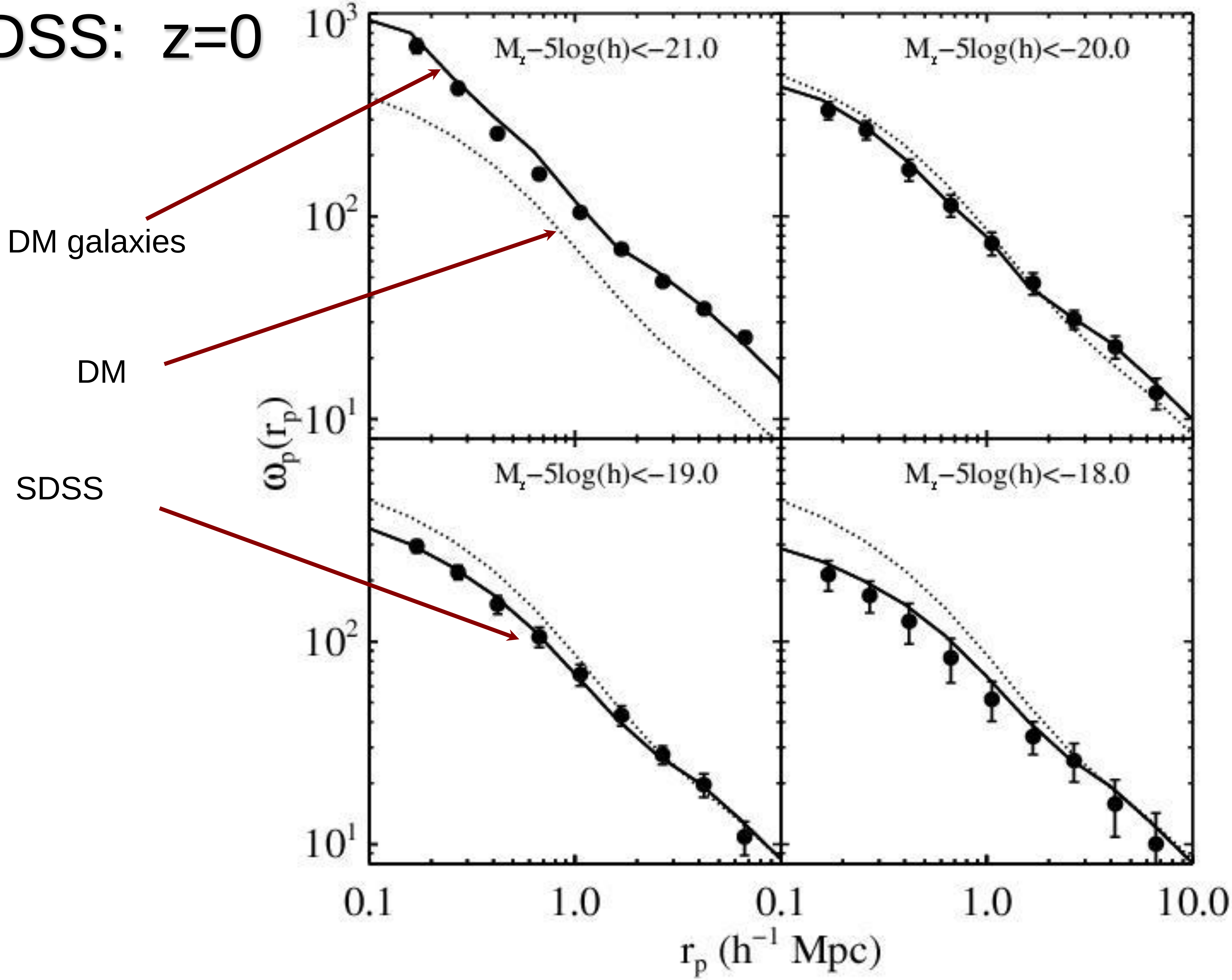


HAM: halo abundance matching

- Conroy, Wechsler, Kravtsov (2005): **N-body only**
  - Get all halos from high-res N-body simulation
  - Use maximum circular velocity (NOT mass)
  - For subhalos use V_{max} before they became subhalos
  - Every halo (or subhalo) is a galaxy
  - Every halo has luminosity: **LF is as in SDSS**
  - No cooling or major mergers and such. Only DM halos

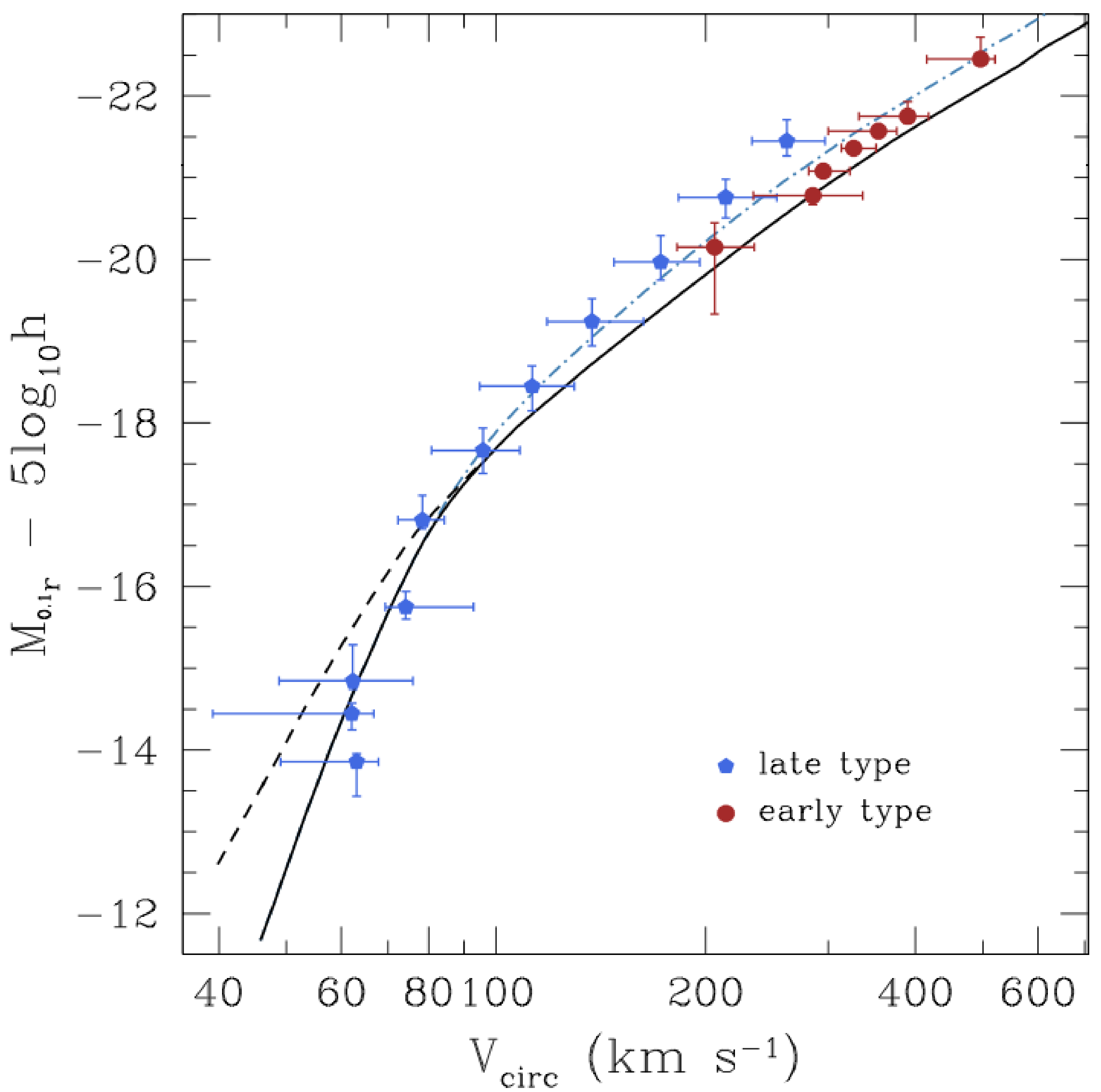
- **Reproduces most of observational properties of galaxies**

SDSS: z=0



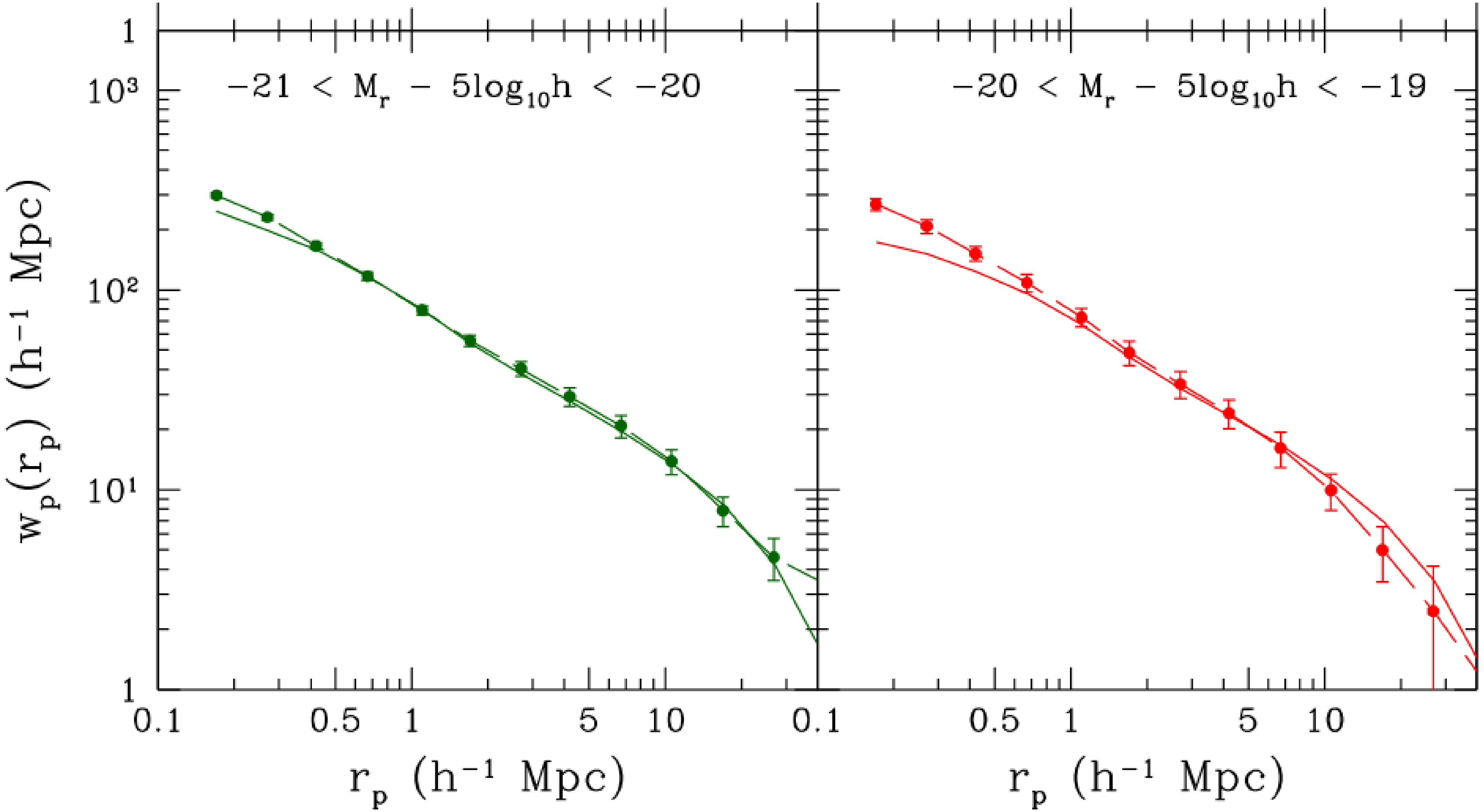
DM galaxies
DM
SDSS
$M_r-5\log(h)<-21.0$
$M_r-5\log(h)<-20.0$
$M_r-5\log(h)<-19.0$
$M_r-5\log(h)<-18.0$
10^3
10^2
10^1
10^2
10^1
$\omega_p(r_p)$
0.1
1.0
0.1
1.0
10.0
r_p (h^{-1} Mpc)

Abundance matching: placing galaxies in halos

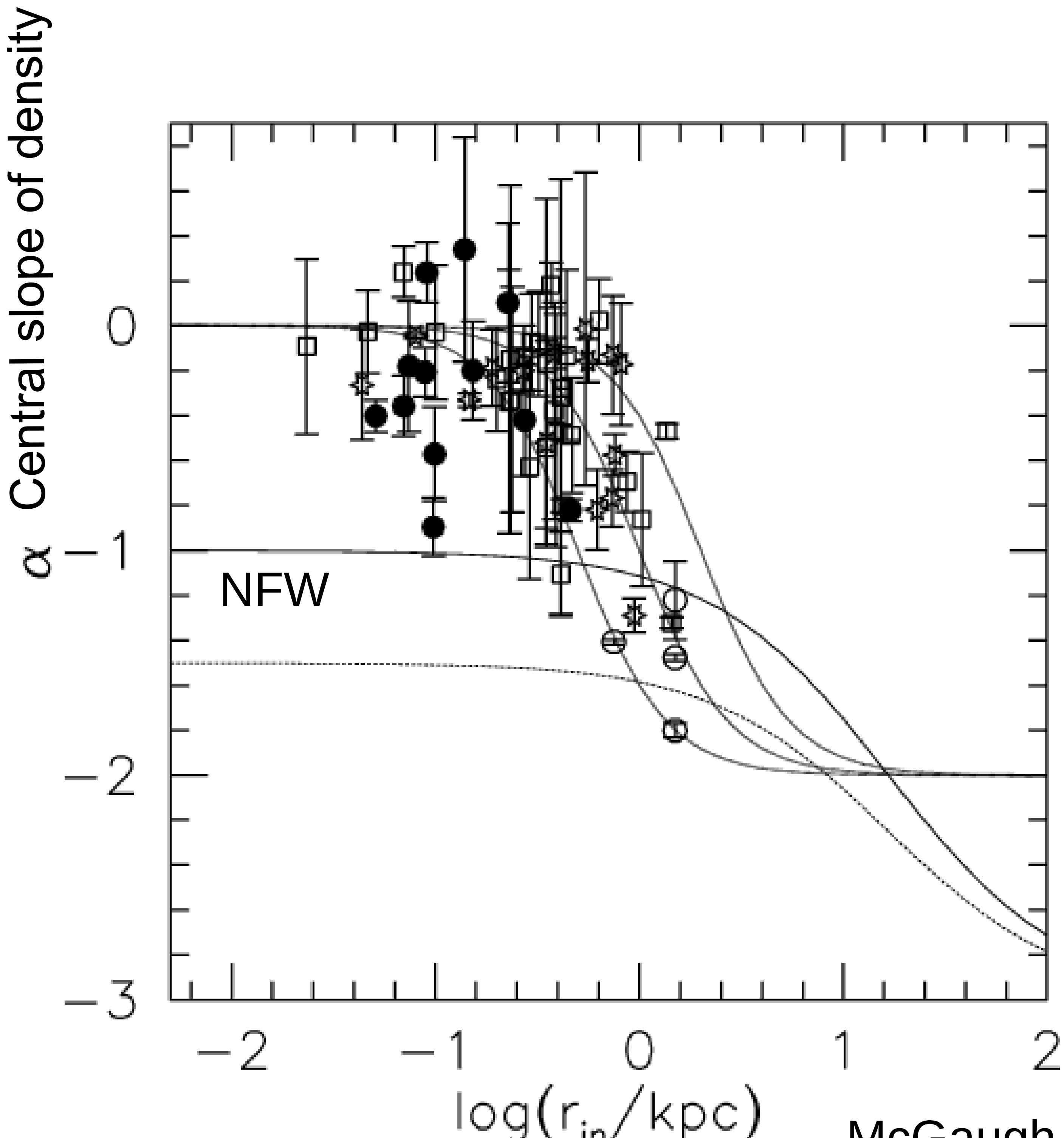


Trujillo-Gomez et al 2010

Abundance matching: correlation function of galaxies



Very small scales: cusps and cores



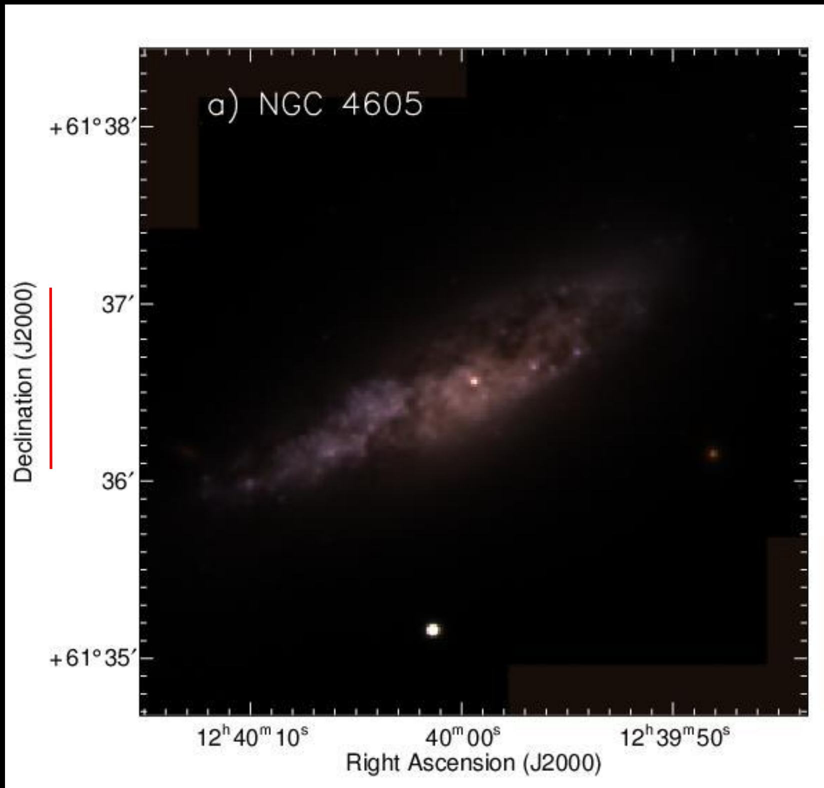
McGaugh et al 2002

- Cusps and rotation curves:
- too much of DM in central parts of galaxies?

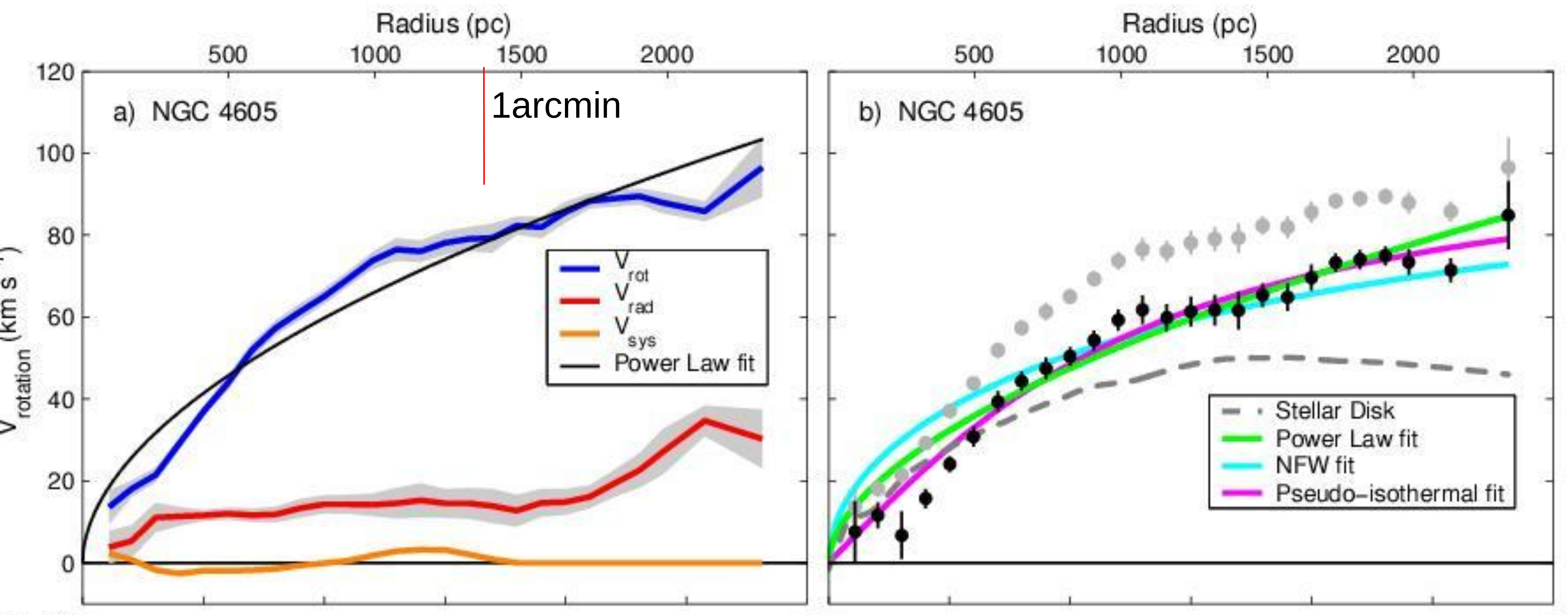
Simon etal 04 NGC 4605 Vmax =100km/s

-- Usual problems with NFW.

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



Simon et al.

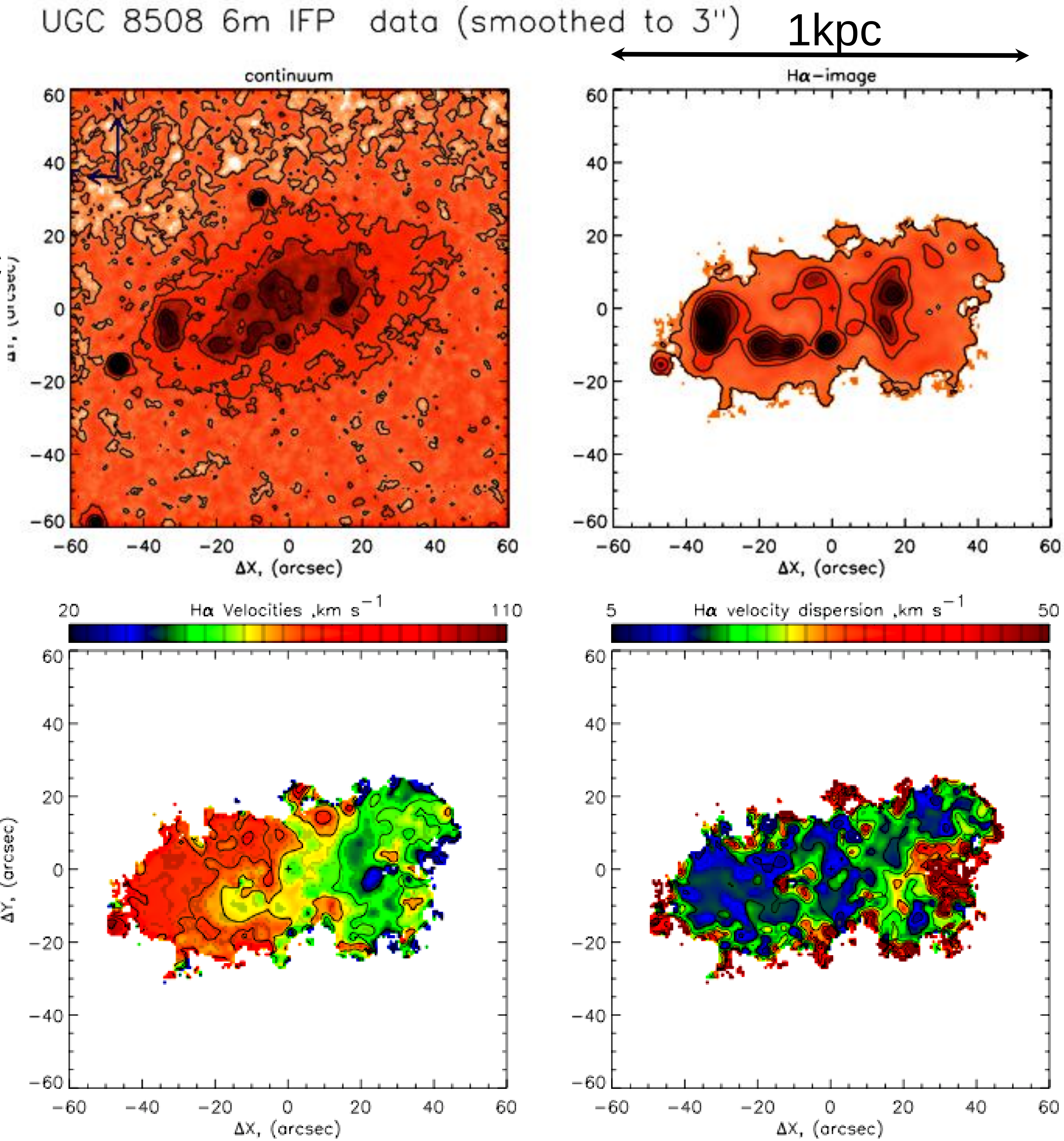


Example: UGC8508

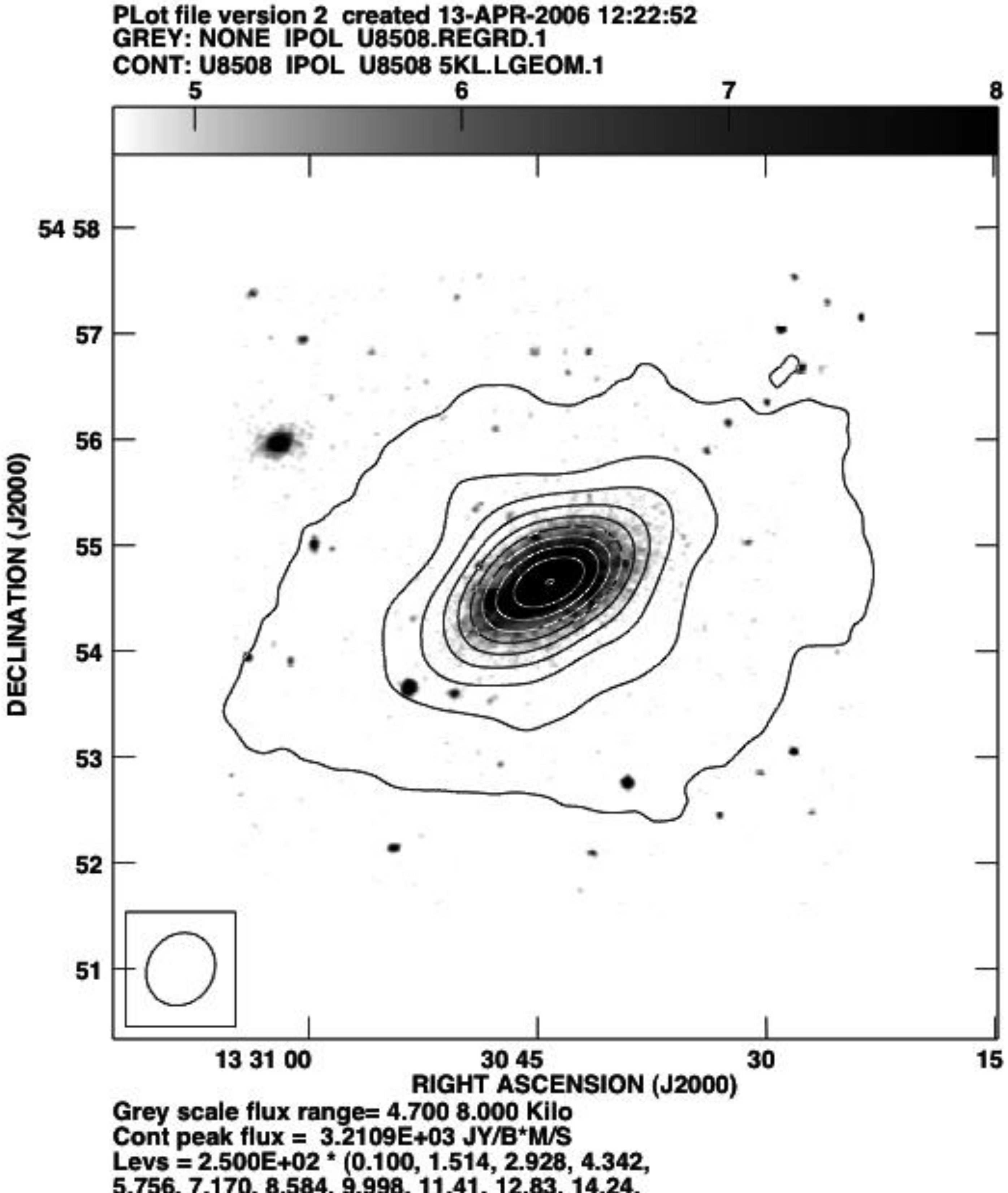
Distance 2.5 Mpc

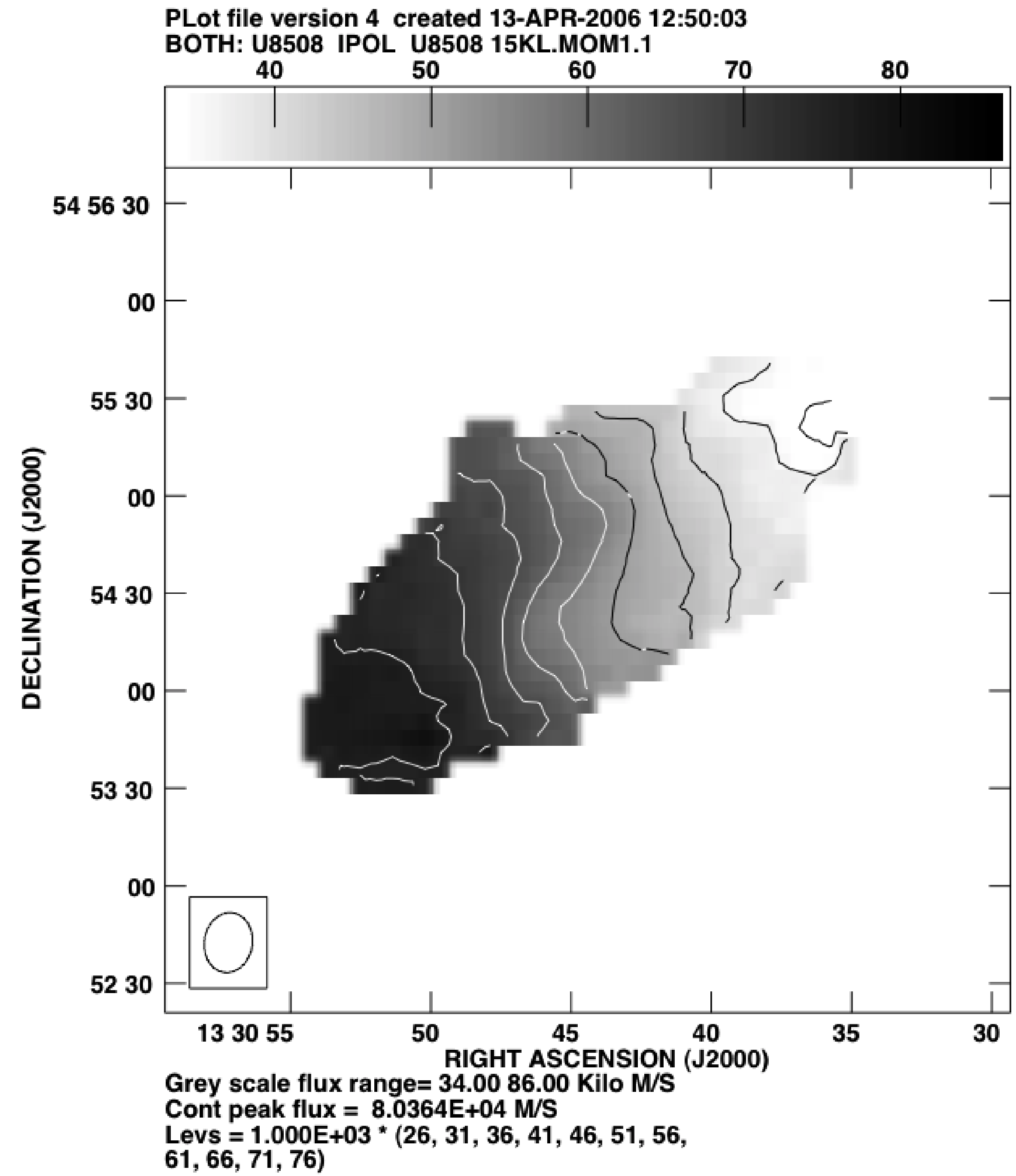
$M_B = -12.9$

Russian 6m telescope



HI data

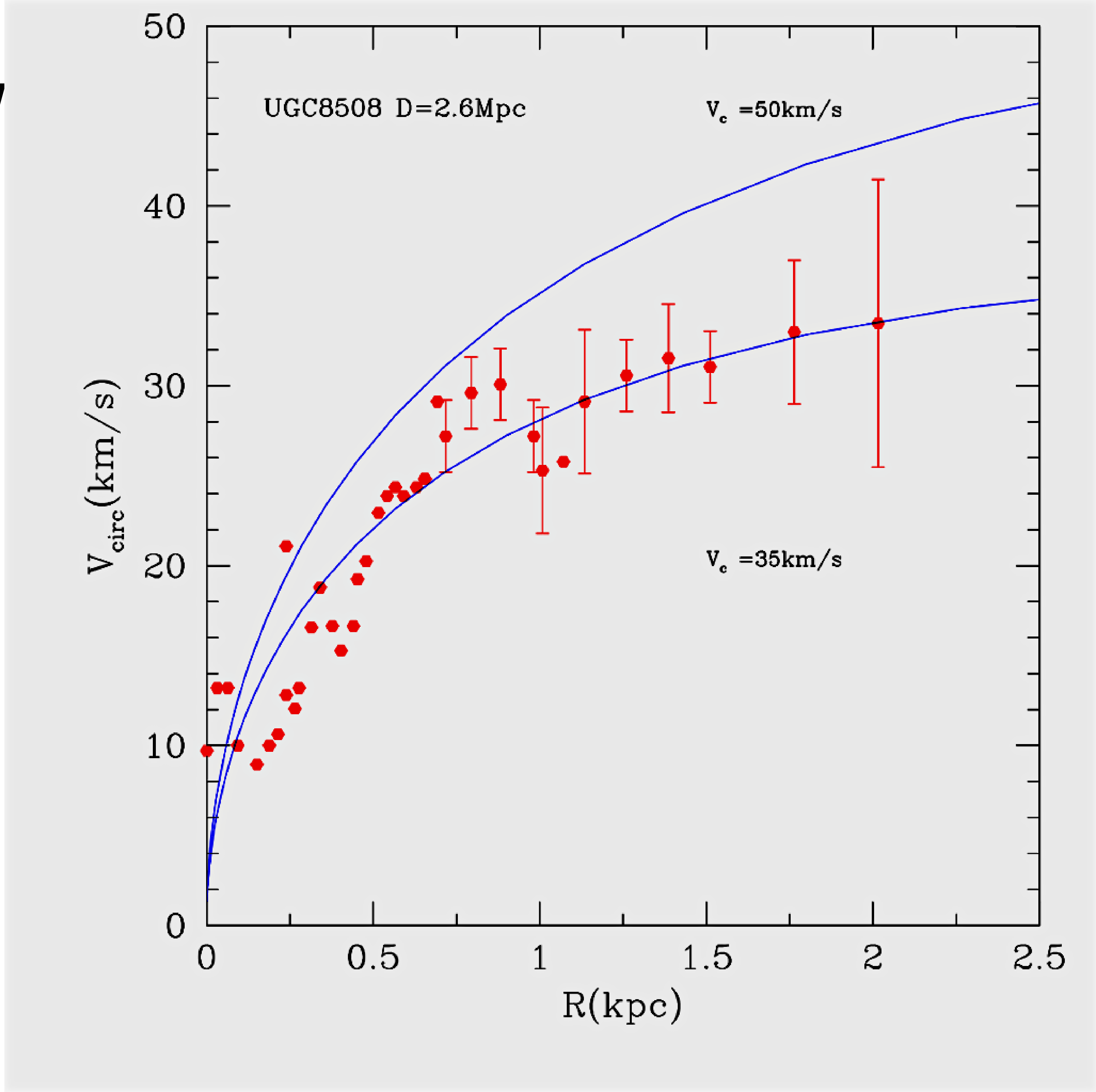




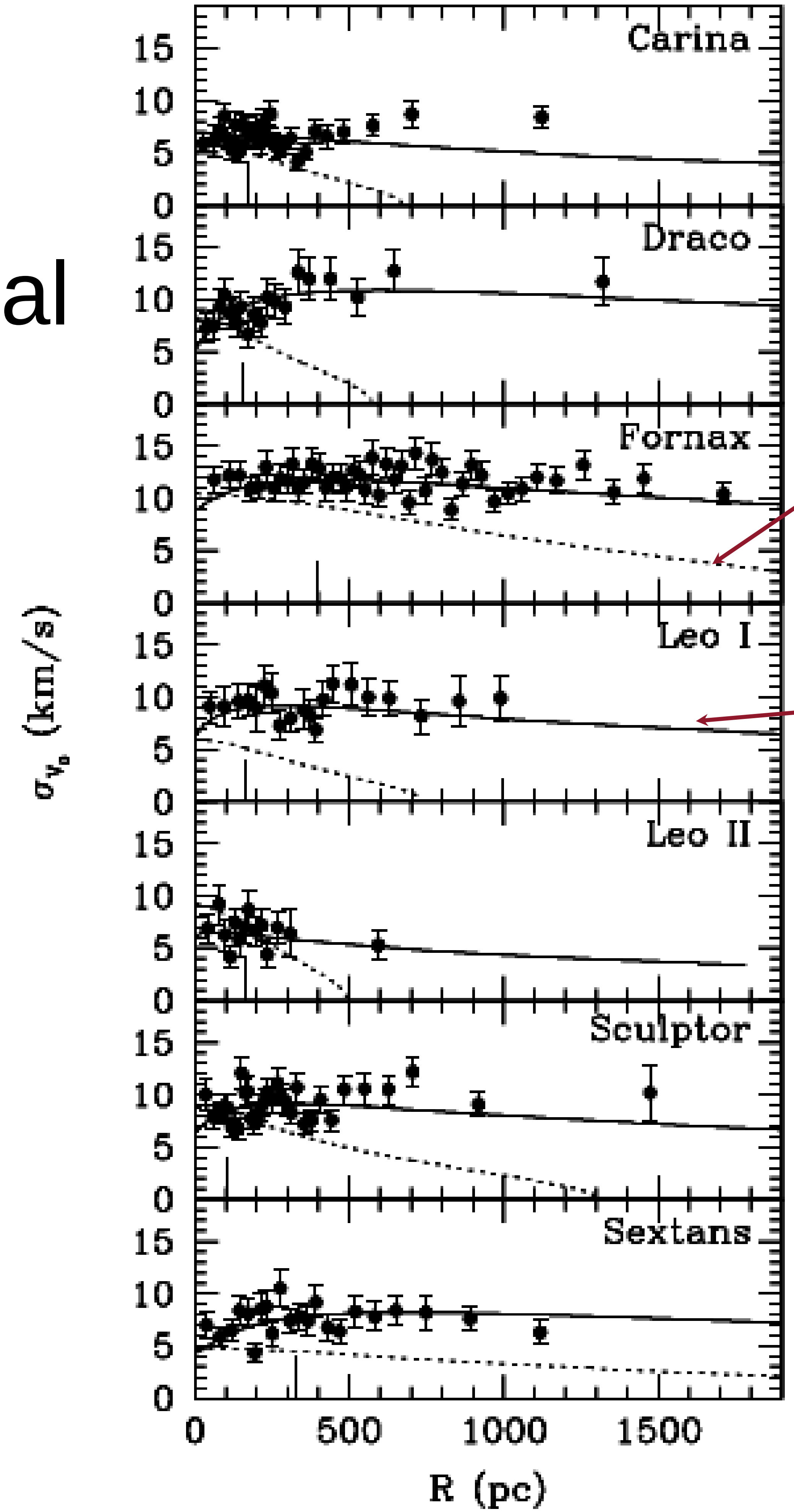
GMRT: India

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

Theory predicts too large circular velocity



Dwarf Spheroidal Galaxies



Light traces mass

Cosmological predictions: DM+baryons

Walker et al 2006:

thousands of stars with accurate velocities

Klypin et al 1999

Moore et al 1999

Early explanation for the discrepancy was photoionization. Now it is mostly tidal stripping: luminous satellites were much larger in the past. The small halos were photo evaporated.

Kravtsov, Gnedin, Klypin 2004

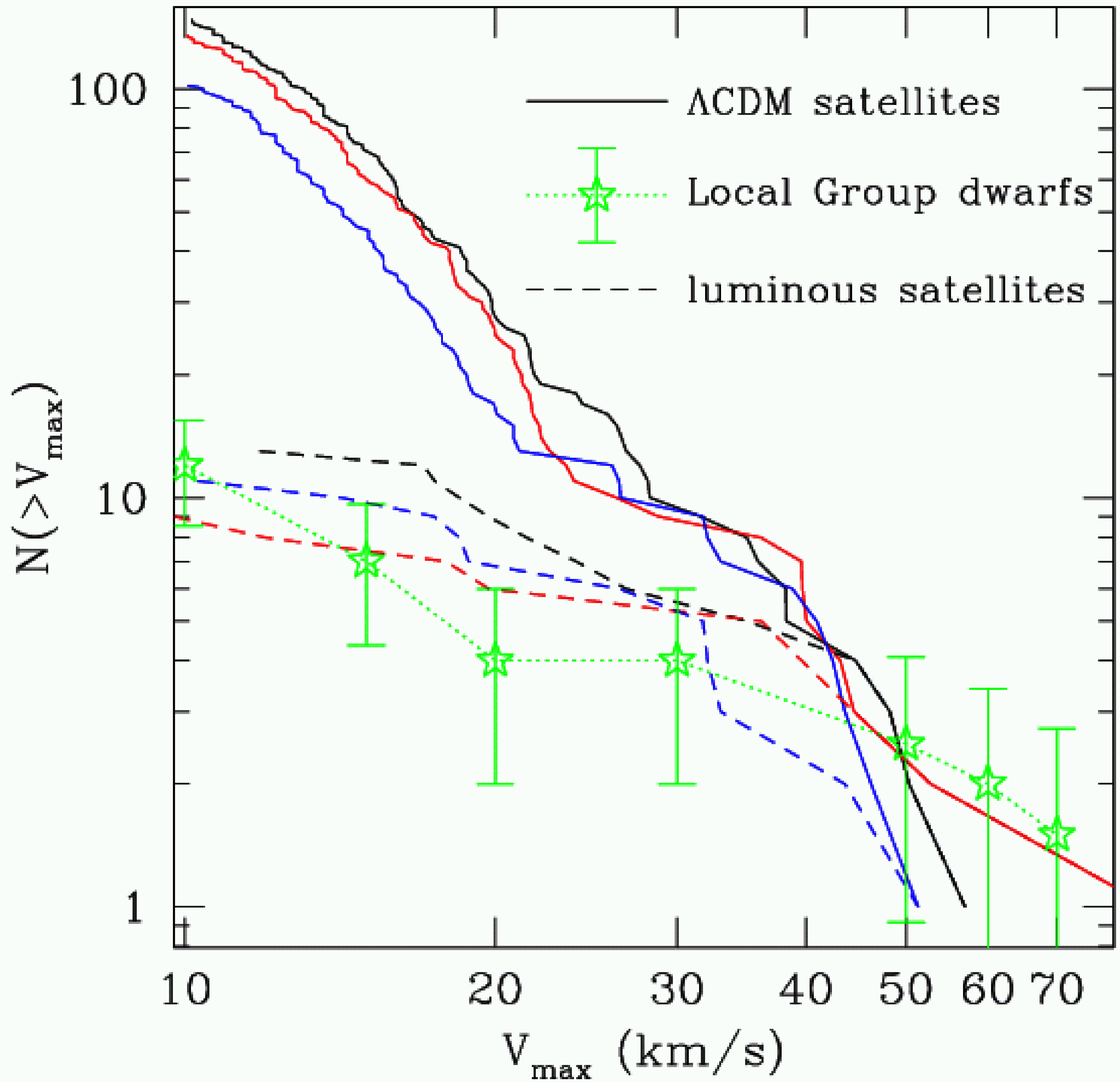


FIG. 7.— The cumulative velocity function of the dark matter satellites in the three galactic halos (*solid lines* compared to the average cumulative velocity function of dwarf galaxies around the Milky Way and Andromeda galaxies (*stars*). For the objects in simulations V_{circ} is the maximum circular 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

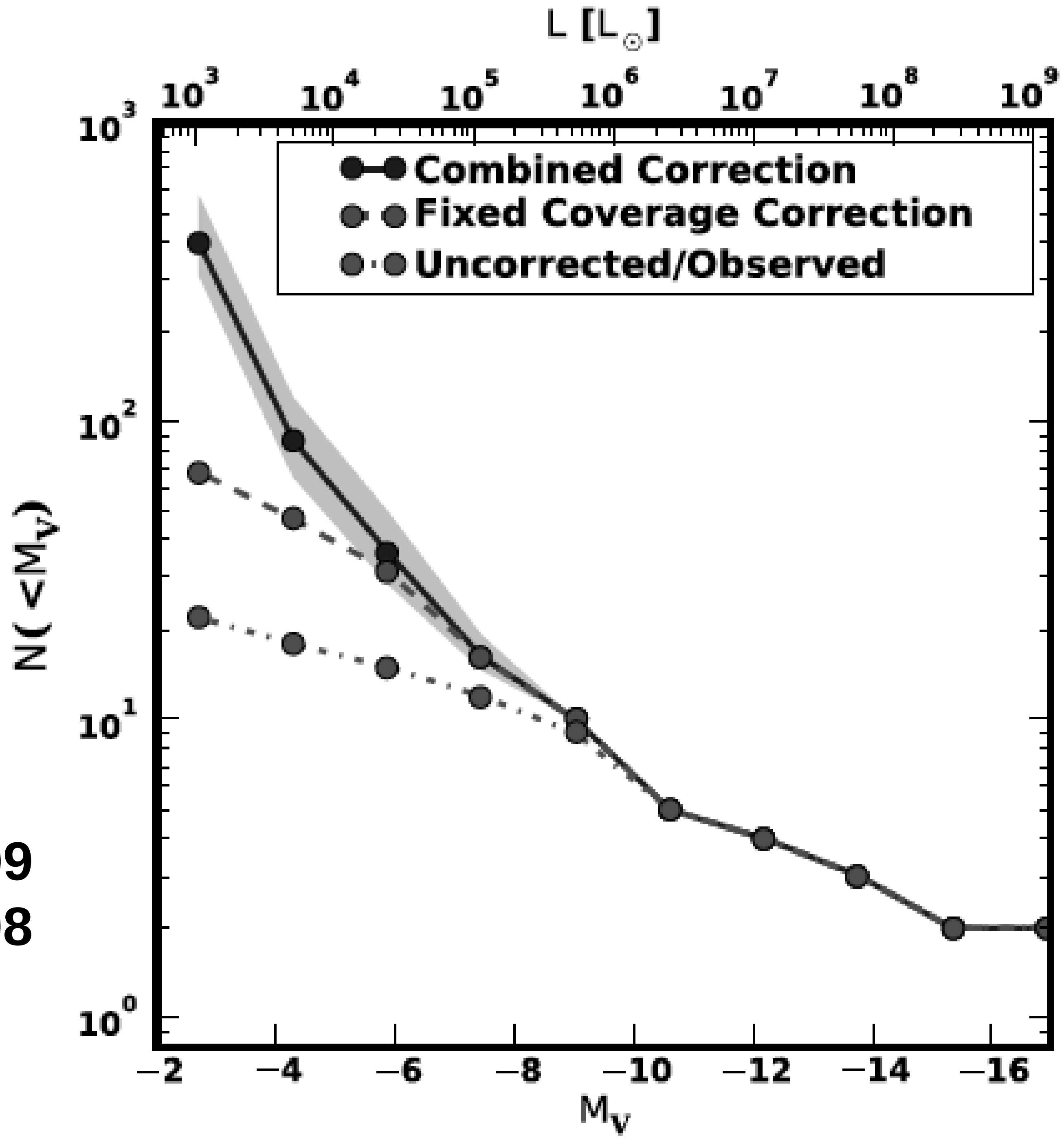
SDSS: new satellites

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?

MW satellites “explained”

Koposov et al (2009): “A quantitative explanation of the observed population of Milky Way satellite galaxies”

(a) EPS and HOD models (a la Zentner etal 2005)
(b) phenomenological model, which gives Mstars(z,Vcirc)
(c) Dwarf galaxies below Vcrit =25-30km/s do not form stars after re-ionization

V_{crit} should be a strong function of z, if we believe simulations

Satellites of the Milky Way:

- Lots of data. Very small halos can only be found close to us.

- *Big mess:* our MW substantially affects the dwarfs:
- tidal stripping
  - we end up not knowing how big was the satellite before it fell to MW
- morphological changes
  - dSph in the inner region, dIrr outside

Warm DM: Motivation

- Nature of dark matter: sterile neutrino as wdm
- Solve problems of cosmology

Effects:

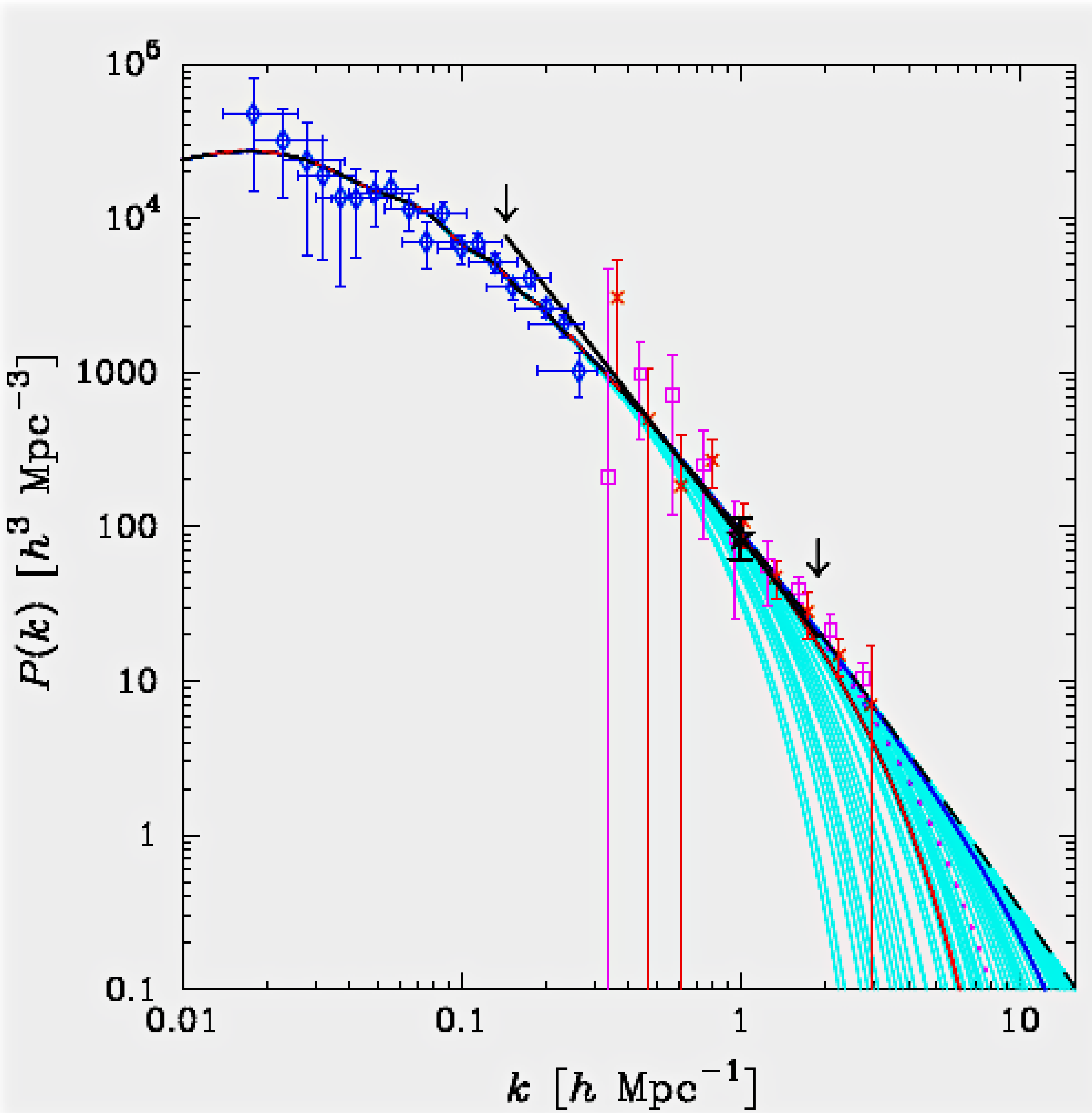
- free streaming wipes out fluctuations on small scales: changes in P(k): low limits on wdm mass
- phase-space density constraints. For KeV-scale wdm, this gives 100pc cores (Strigari 06)
- Radiative decay: upper limits on wdm mass

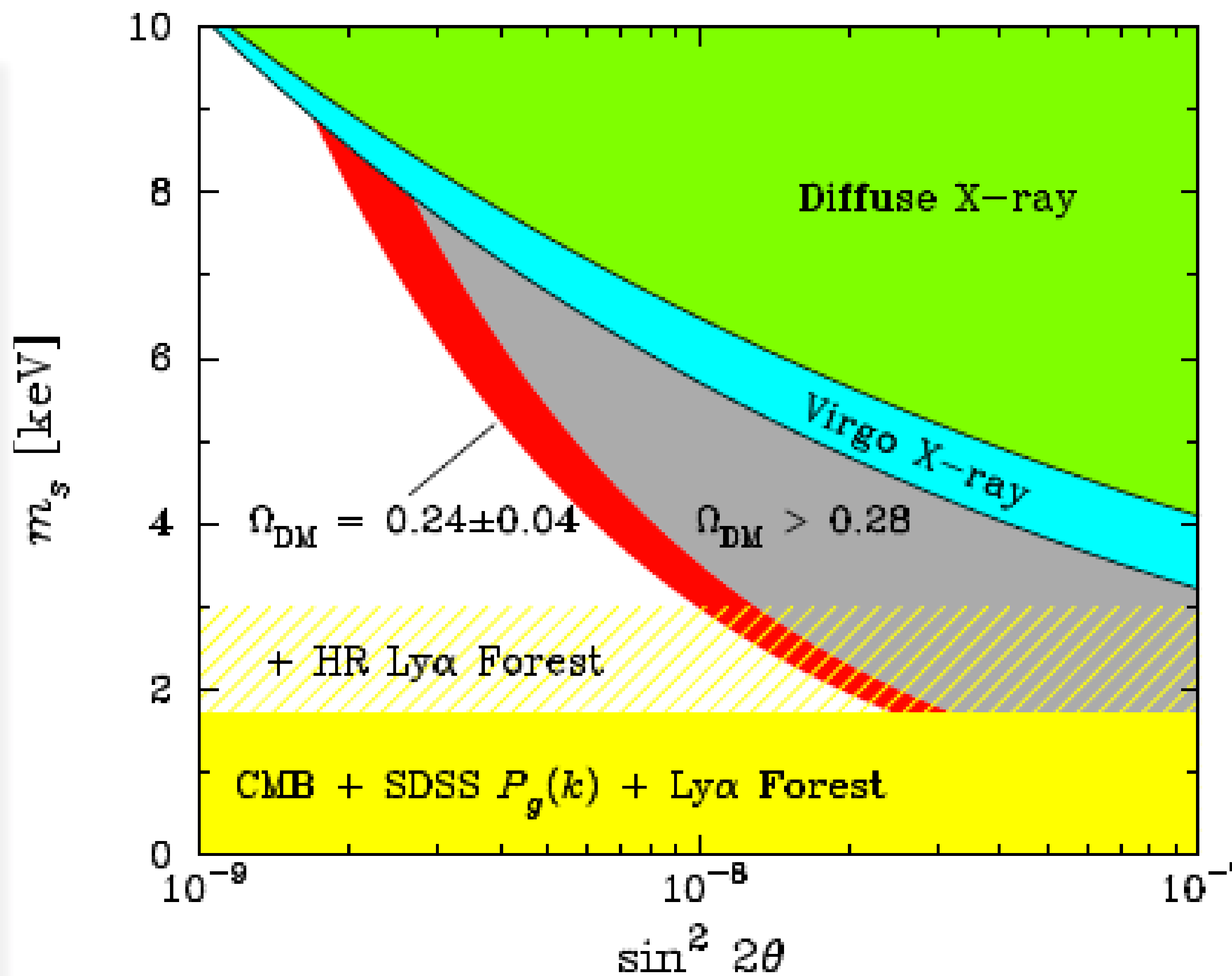
Cosmological problems:

- core/cusp problem: can wdm remove cusps?
- subhalos: reduce the number of subhalos

Power spectrum

Abazajian 2006



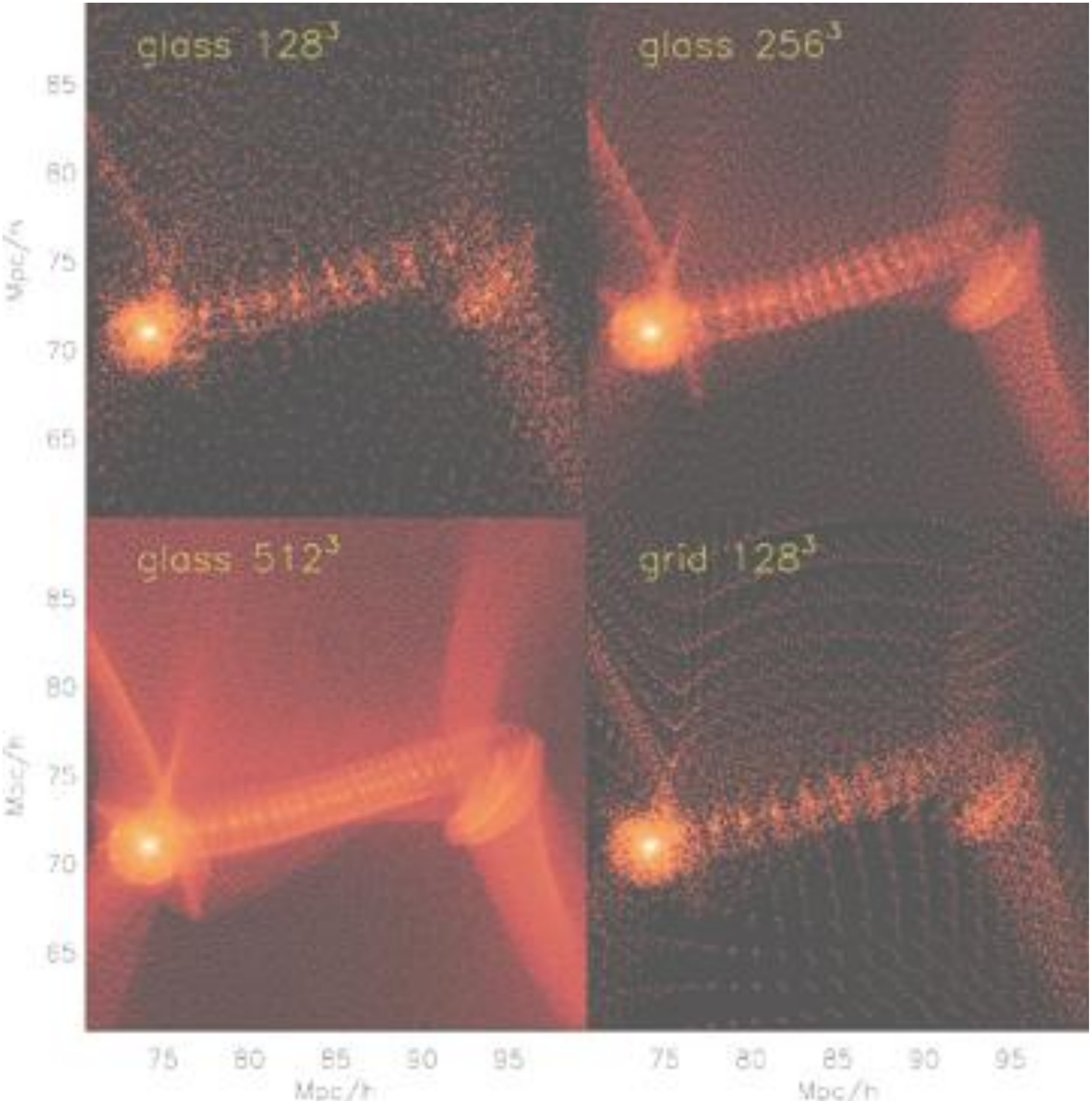


1.7 keV $< m_s < 8.2$ keV.

FIG. 1: Shown are the resulting linear matter power spectra $P(k)$ for a standard flat cosmological model $\Omega_{DM} = 0.26$, $\sigma_8 = 0.9$, $\Omega_b = 0.04$, and $h = 0.7$ at $z = 0$, and with sterile neutrino warm to cold dark matter in the mass range 0.3 keV $< m_s < 140$ keV (gray/cyan). The corresponding CDM case is dashed (black). Small-scale clustering data used here are the SDSS 3D power-spectrum of galaxies (diamonds), the inferred slope and amplitude of the matter power spectrum from SDSS Lyα forest observations (star point and slope between arrows), the inferred matter power spectrum from Lyα forest observations from Croft et al. [32] (cross points) and the LUQAS (square points), as interpreted by VHS [33]. Lyα forest measures are evolved to $z = 0$ by the appropriate growth function. The solid (blue) line at high-k is $P(k)$ for upper limit $m_s = 8.2$ keV from observations of Virgo [49], the solid (red) line at low-k is that for the lower limit from the SDSS Lyα forest in this

Wang & White 2007.
Even with 512 particles the filament is highly fragmented.

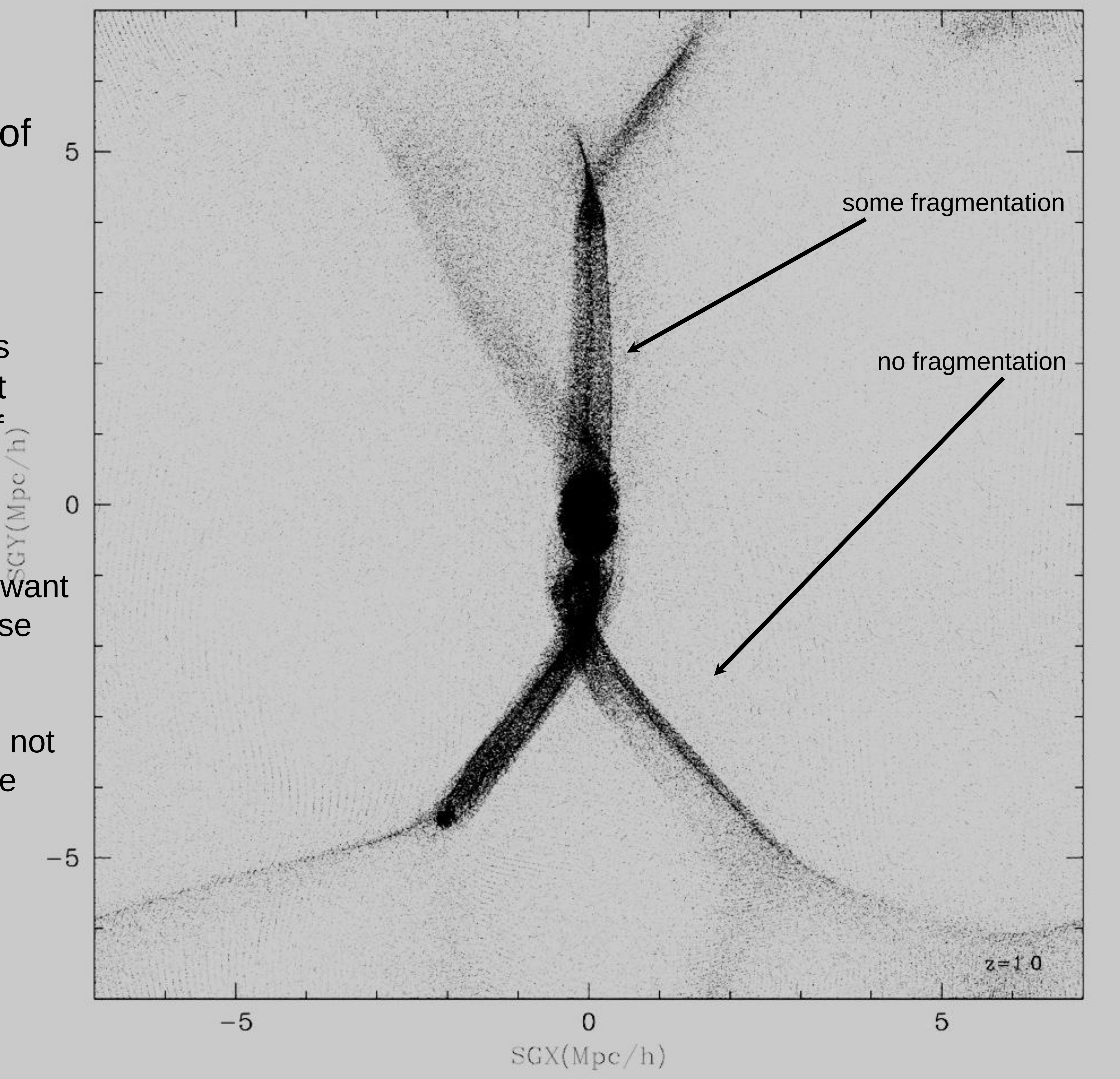
The 256 and 128 configurations were plain horrible



Slice: 2Mpc 1/10 of particles

Note numerous caustics and folders
Large halos form at brunching points of caustics

Important issue is fragmentation of long filaments. We do not want this to happen because this would indicate significant numerical defects. So far we do not see large defects. The filaments are mostly smooth.

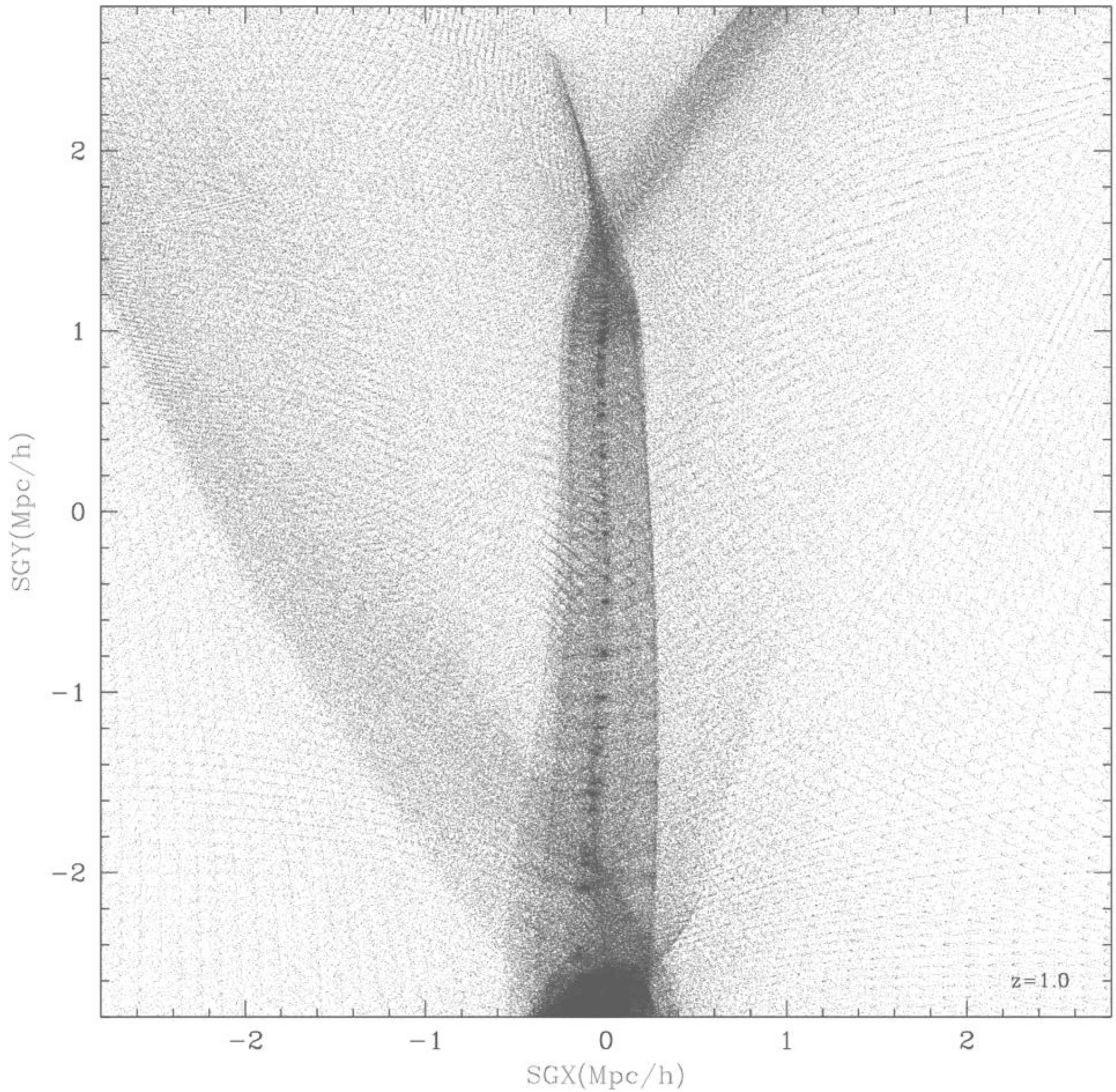


Our results

Numerical fragmentation is diminished by placing particles on a **grid** and reducing resolution so that the shot noise is suppressed by force softening

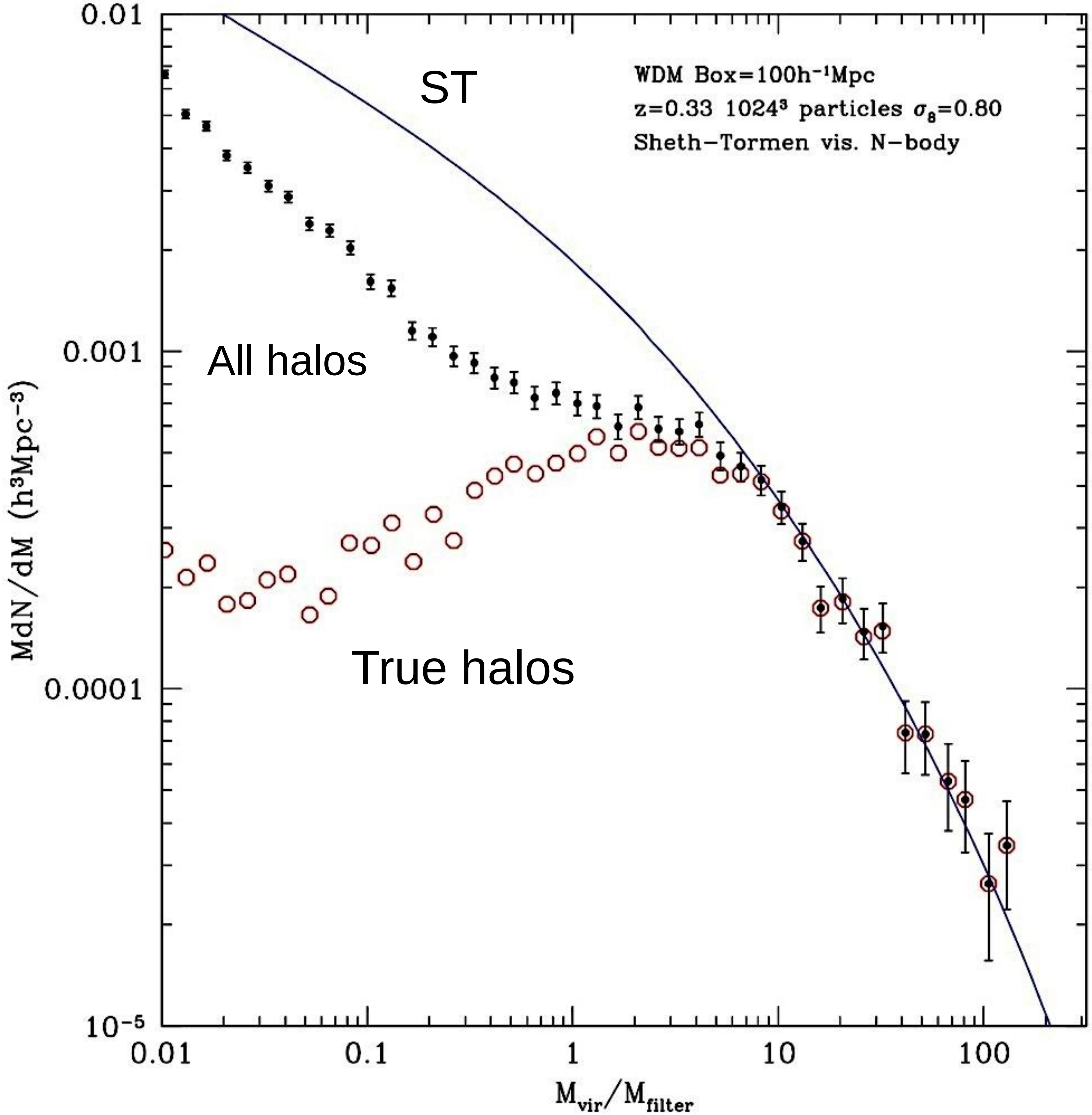
Instabilities can be suppressed, but they cannot go away

There are only two real halos in this picture



Mass function

- Analytics fails for small halos: orders of magnitude off
- For M>10Mvir ST is good discription
- Mass function declines at small masses. There is no increase predicted by W&W

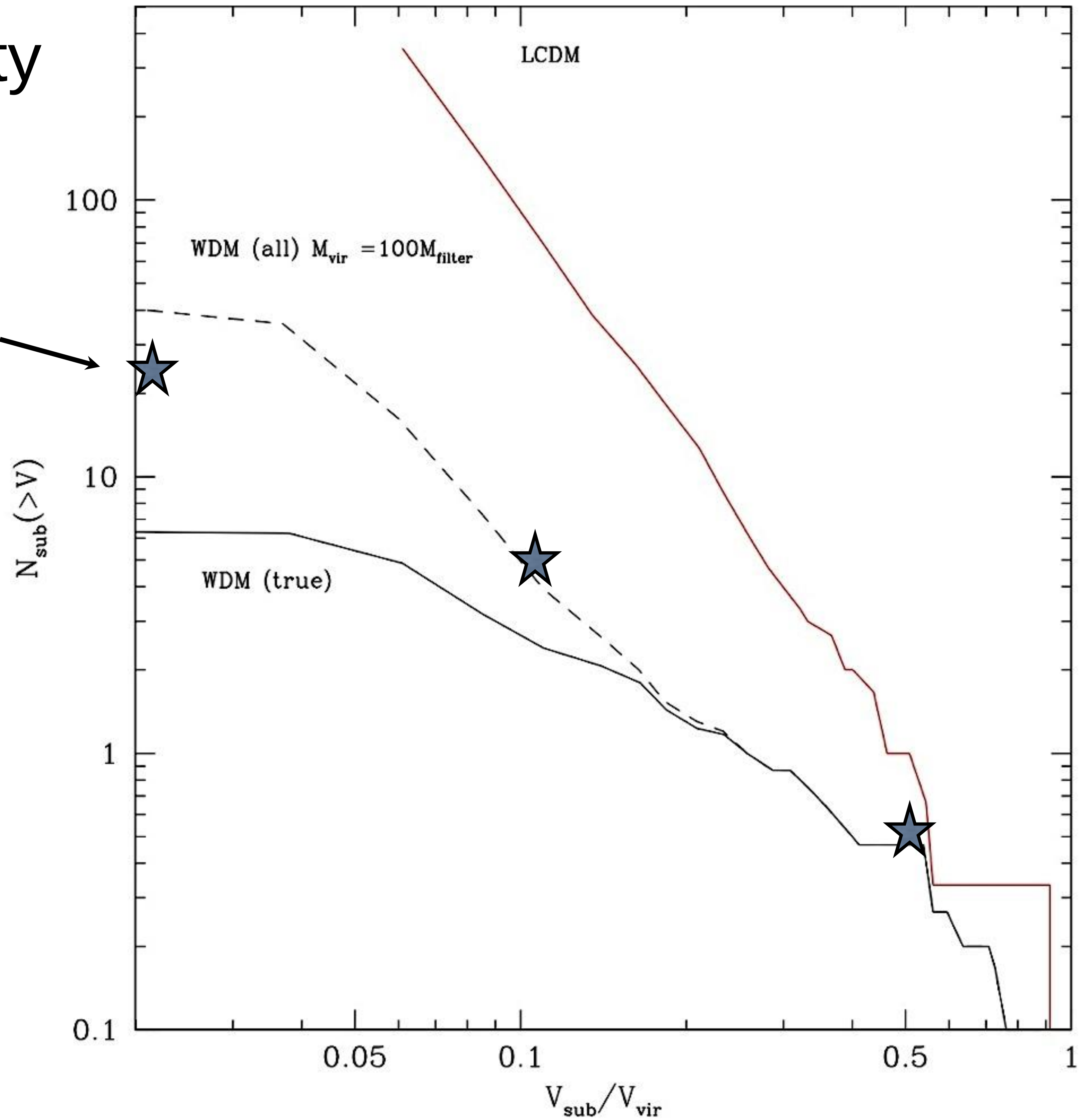


Subhalo velocity function

MW

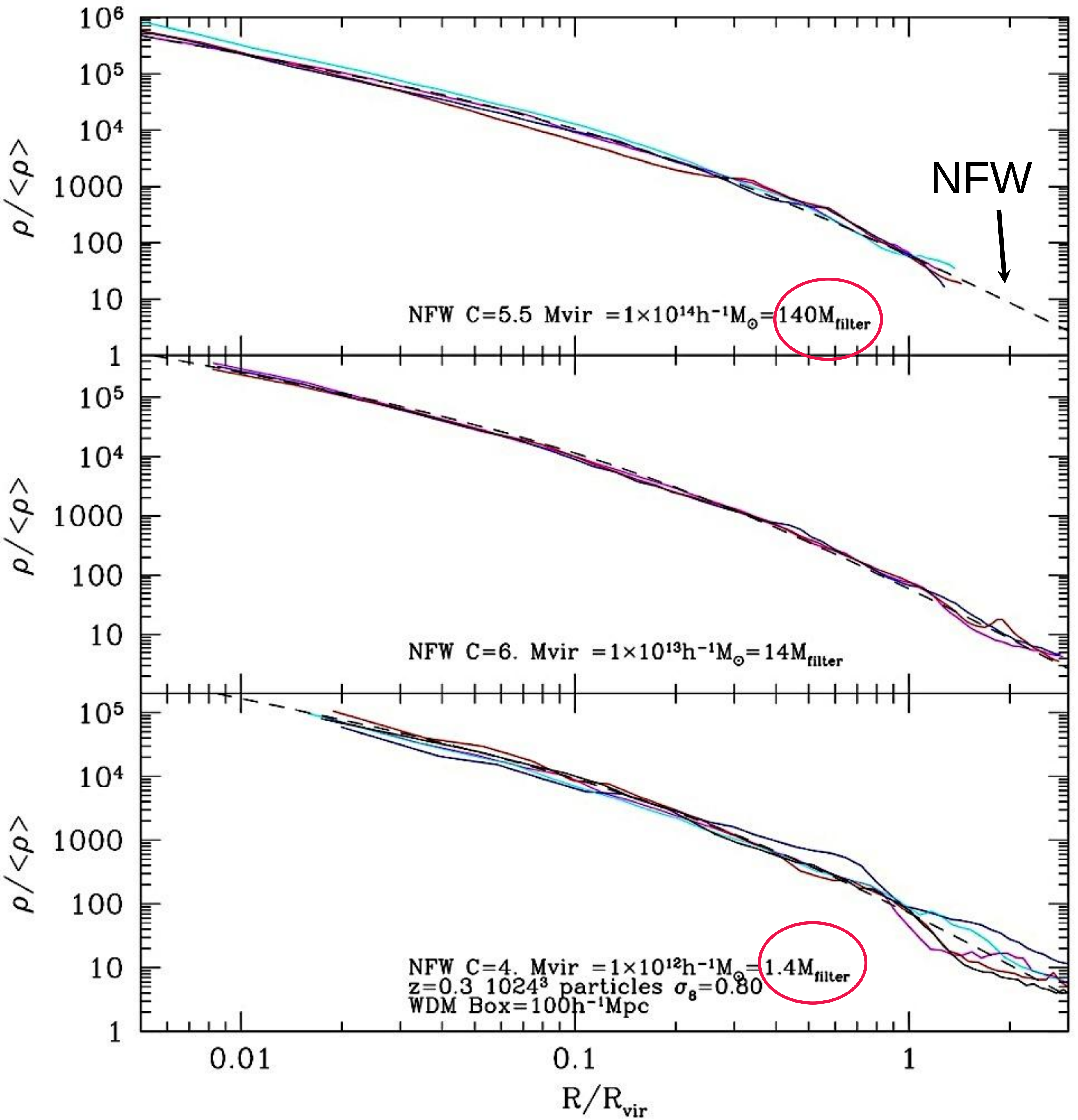
In order to have enough (20-30) satellites for MW, we need Mmw =200Mfilter This gives Mfilter =5e9Msun

m_S= 3KeV



Density Profiles

Normal concentration for masses >> Mfilter



Low concentration for halos of this mass

Conclusions

- Two regimes of growth of fluctuations for WDM:
    - M<Mfilter: fast non-hierarchical collapse. Low concentration halos. No real subhalos. Lots of quickly dispersed caustics
    - M >> Mfilter: hierarchical growth. Surprisingly little memory of previous stage of evolution (american style). Mass function is well approximated by ST; normal halo profiles and concentrations
- m_s > 3 KeV Based on abundance of substructure
- WDM does not solve any problems of cosmology
- Numerical fragmentation is the curse of the field. There are ways of handling it, but so far most of the results should be mummified and put to rest in the King’s Valley

Conclusions

- Significant progress in dark matter-only simulations. More accurate simulations are needed for large-scale effects in order to constrain Dark Energy models.

- Evolution of the Large Scale Structure is mostly the evolution of filaments.