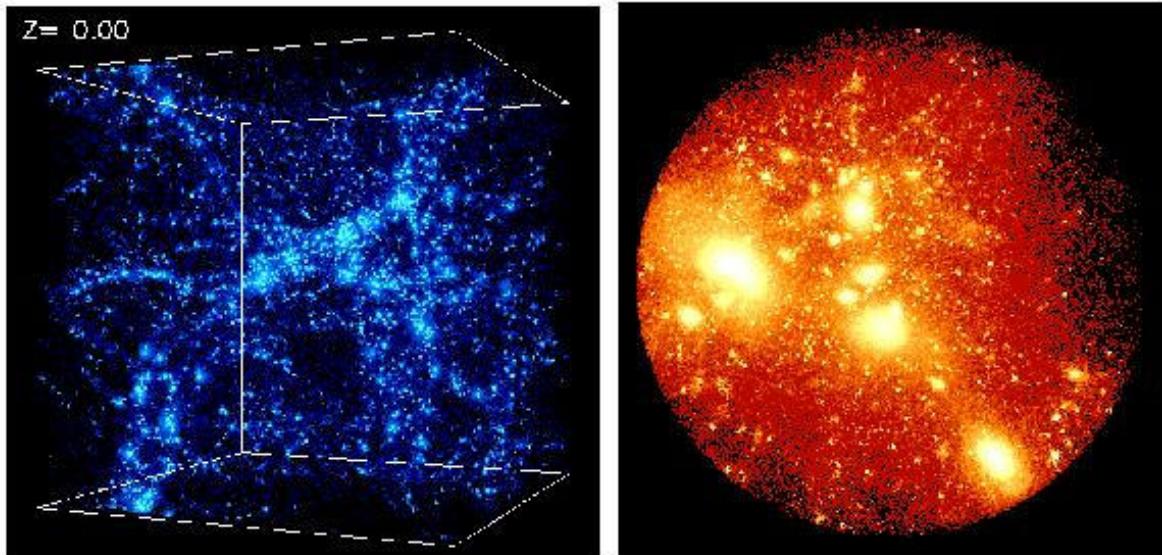


Cold Dark Matter models of structure formation: remarkable success or spectacular failure?

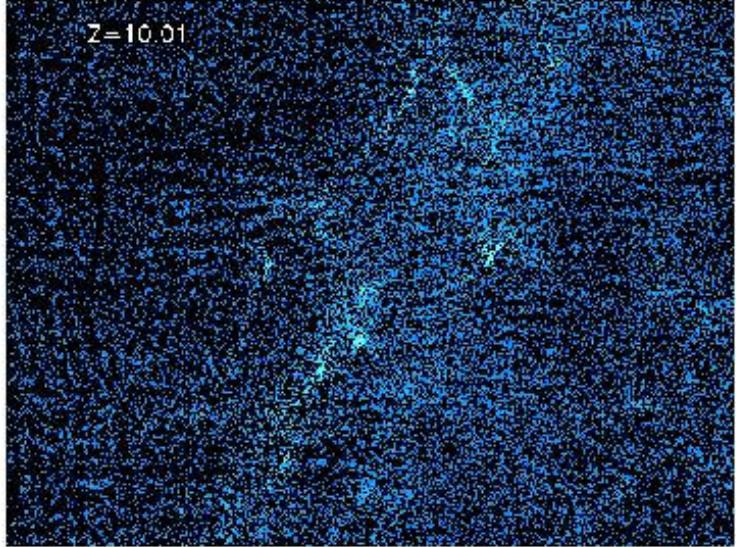


Andrey Kravtsov

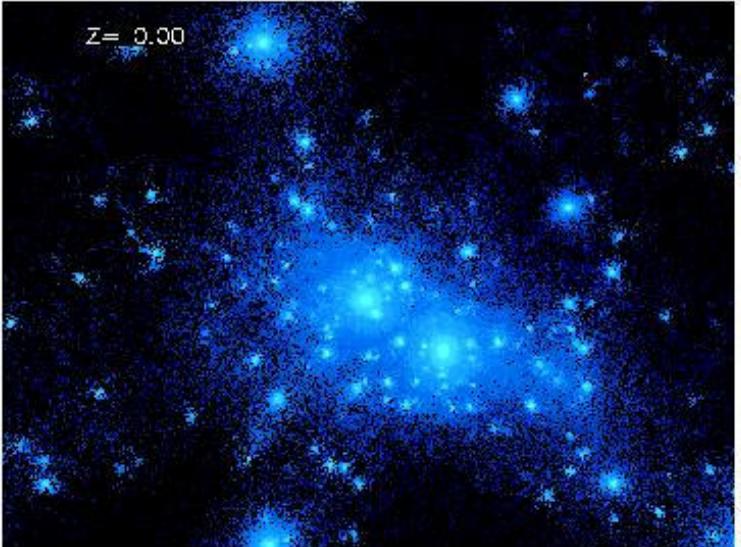
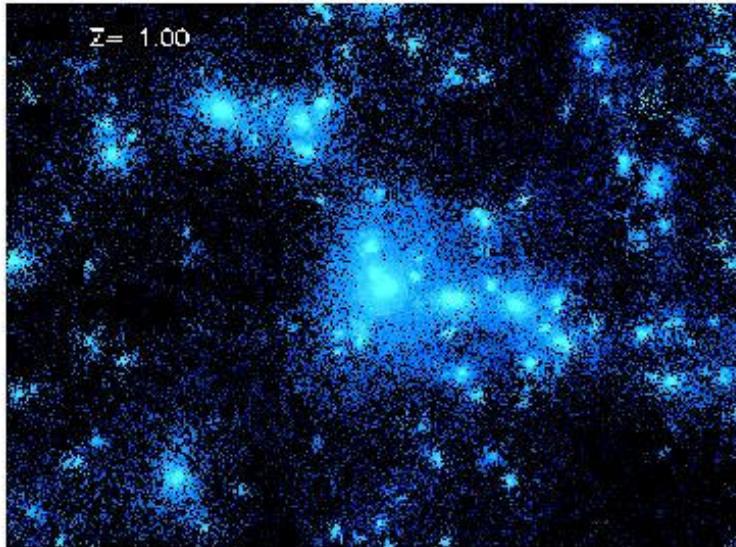
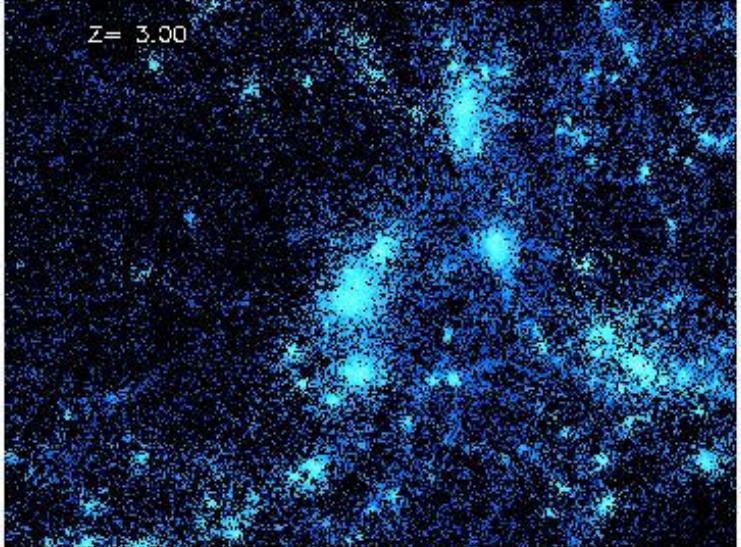
*Department of Astronomy & Astrophysics
Center for Cosmological Physics, University of Chicago*

<http://astro.uchicago.edu/~andrey>

← → $3/h$ Mpc

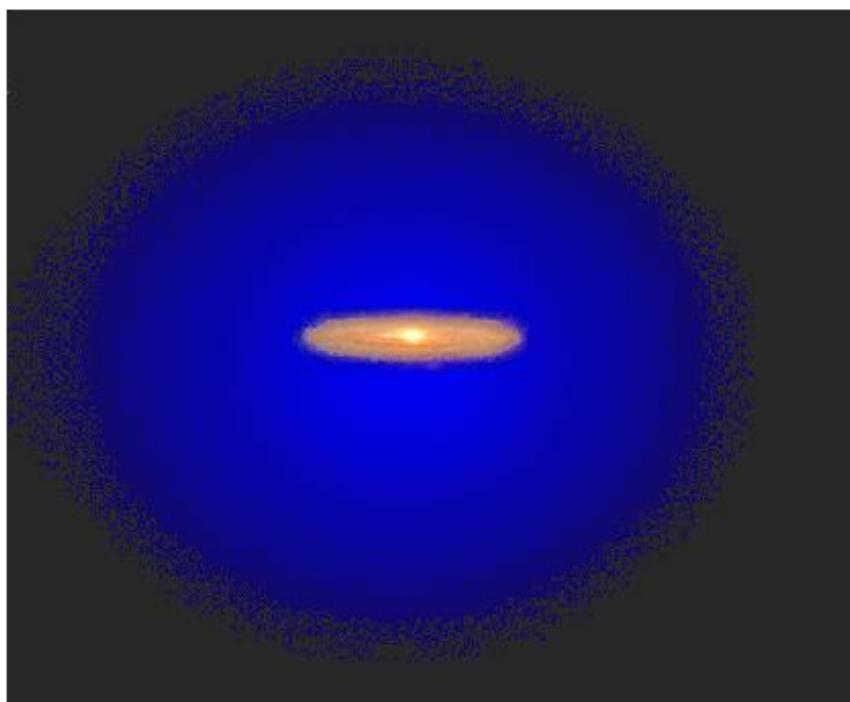


Λ CDM

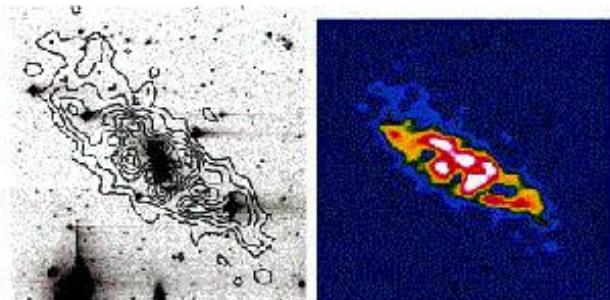


Galaxies in CDM models form in massive extended DM halos

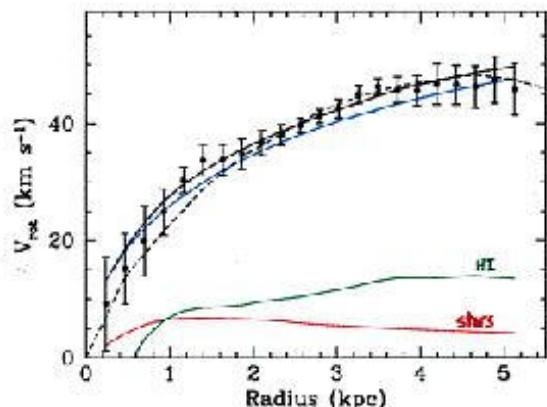
Galaxy formation in CDM models is driven by the collapse of dark matter halos.



DDO 154



(Original HI data from Carignan & Purton, 1999)



Cold Dark Matter models are roughly two decades old but a lot of progress very recently...

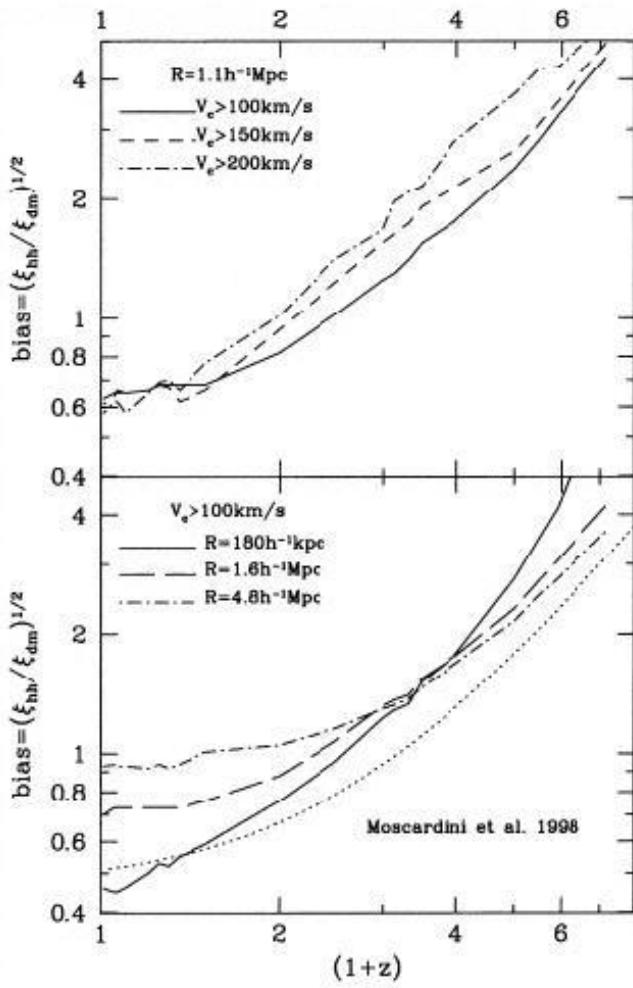
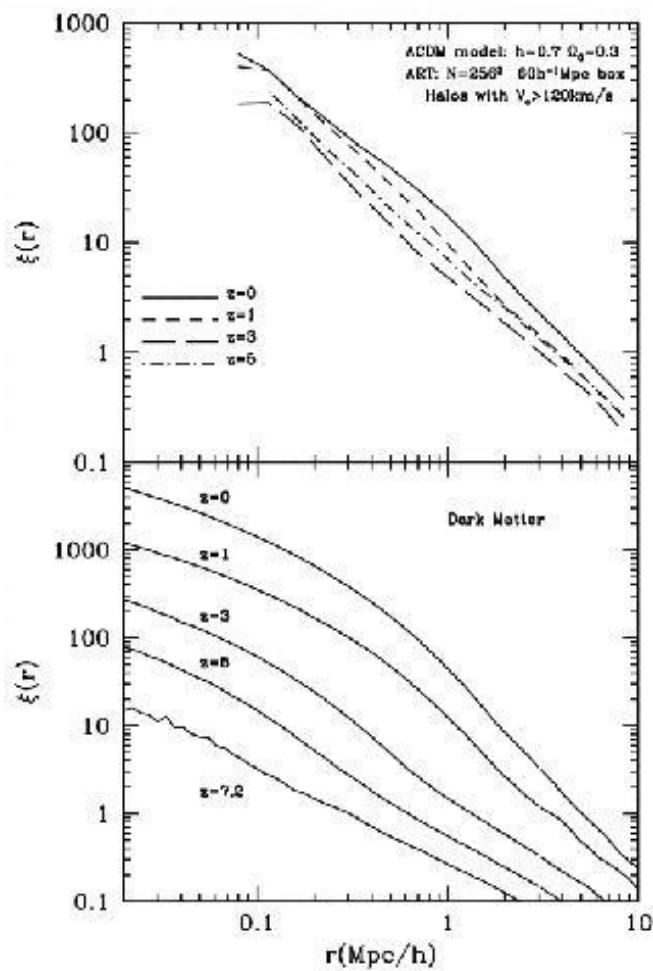
Accurate and detailed predictions allow thorough model testing.

This highlighted several remarkable successes and potentially fatal problems of the CDM models...

I will focus on:

- ▷ Predictions on clustering and velocity field of galactic halos
- ▷ Mass function of halos
- ▷ Predictions on the abundance, spatial distribution, and orbital parameters of substructure in dark matter halos (i.e., halos within halos)
- ▷ Density and angular momentum structure of DM halos
- ▷ Some of the problems that CDM faces and several proposed modifications to the model

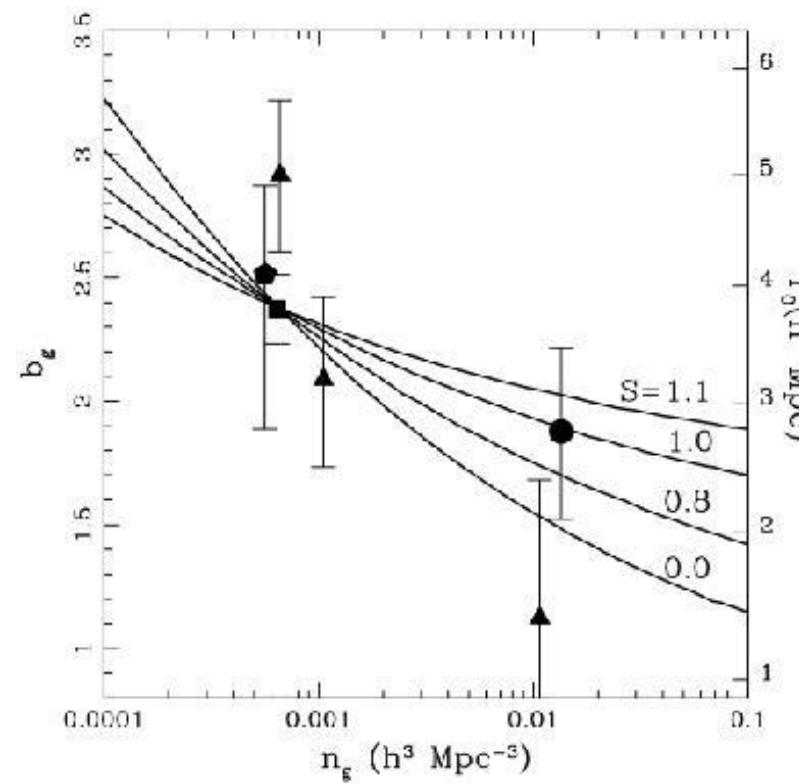
2-point correlation function of dark matter halos and bias



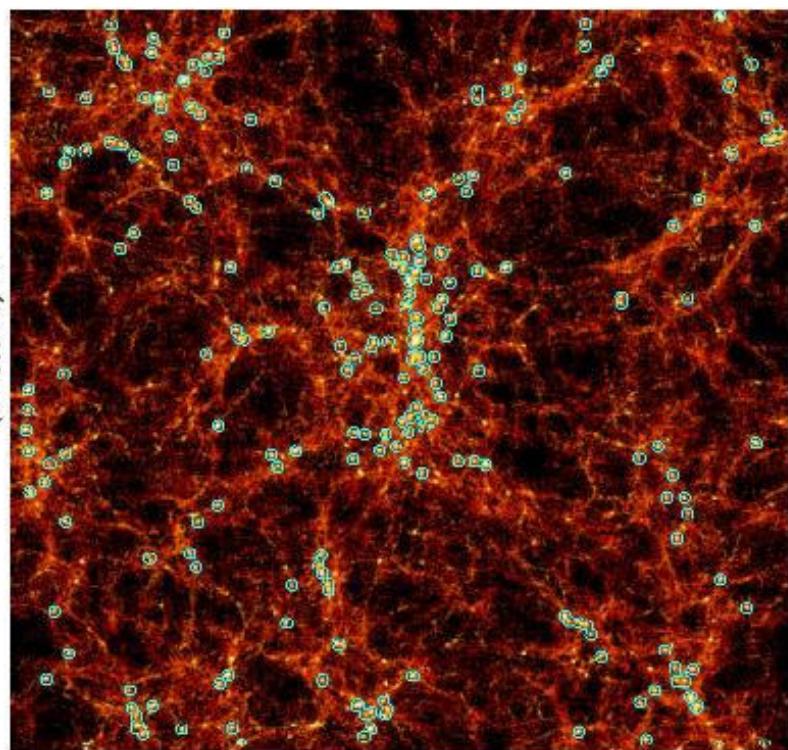
Brainerd & Villumsen 1992-94; Couchman 1994; Colin et al. 1997; Bagla 1998;
Colin, Klypin & Kravtsov 1999; Kravtsov & Klypin 1999; Jenkins et al. 2000; Benson et al. 2000

High - redshift galaxies are strongly biased

Adelberger et al. 1998; Giavalisco et al. 1998; Steidel et al. 1999; Adelberger 2000;
Giavalisco & Dickinson 2001; Porciani & Giavalisco 2001

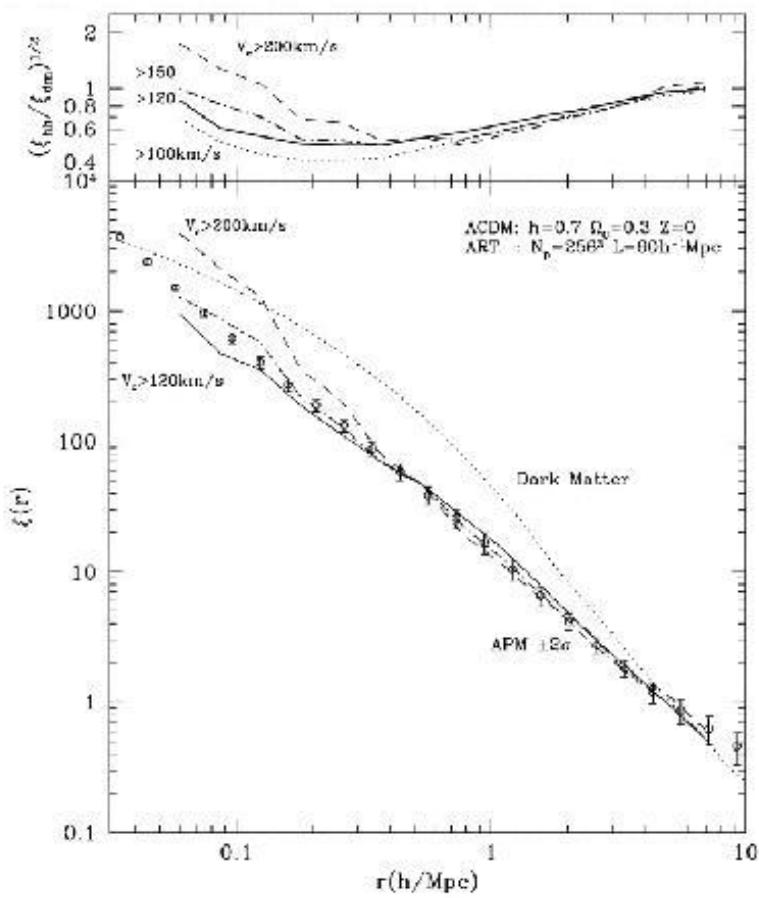


Bullock et al. 2002

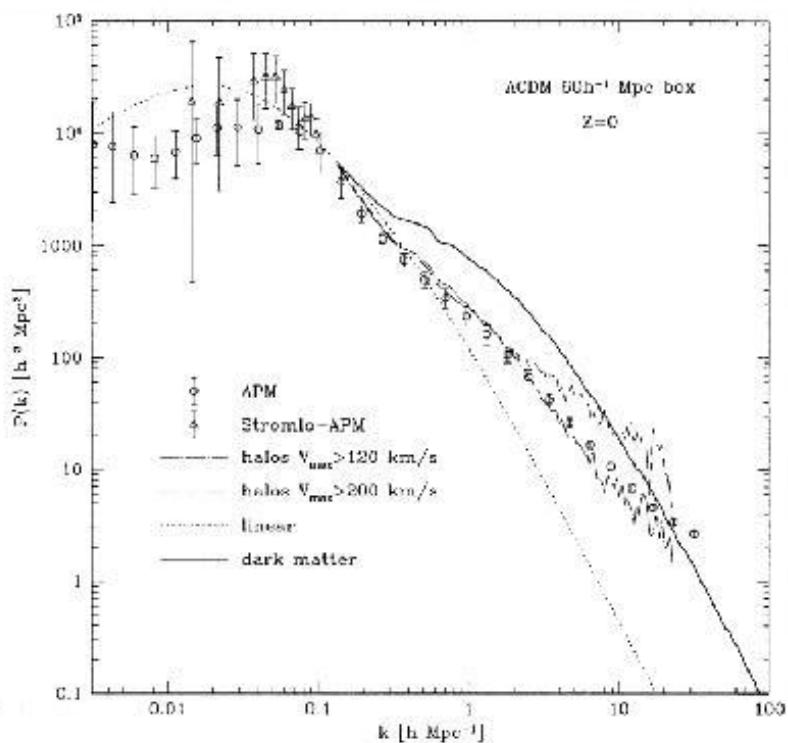


Governato et al. 1998

2-point correlation function: LCDM vs. observations

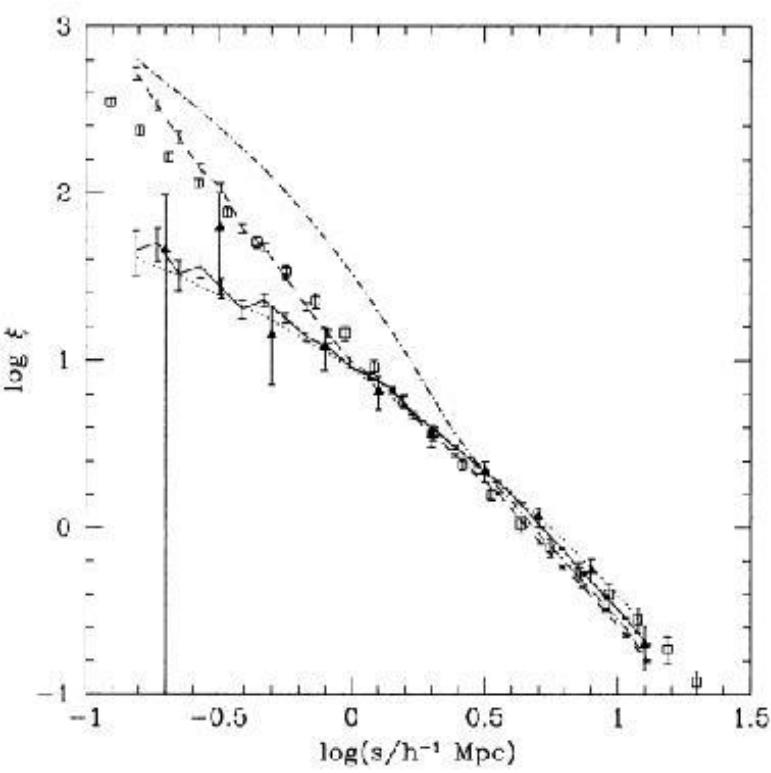


Colin, Klypin, Kravtsov 1999

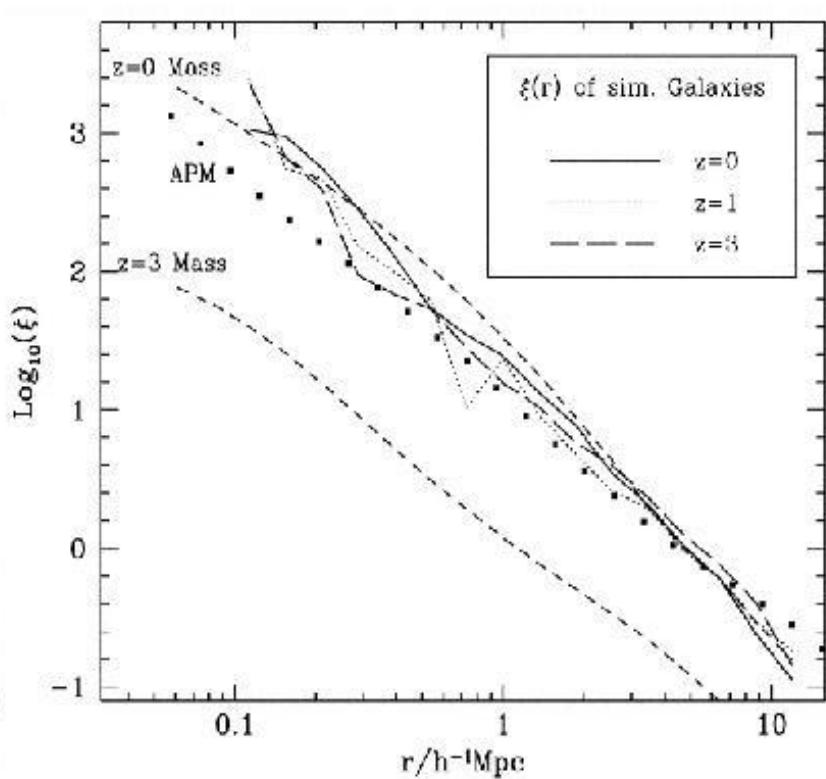


Kravtsov & Klypin 1999

2-point correlation function: excellent agreement between different methods



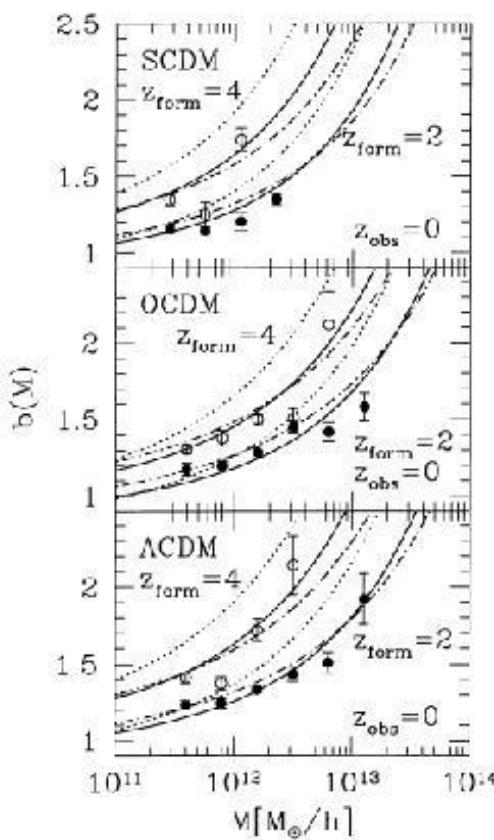
N-body + SAM modelling
Benson et al. 2000



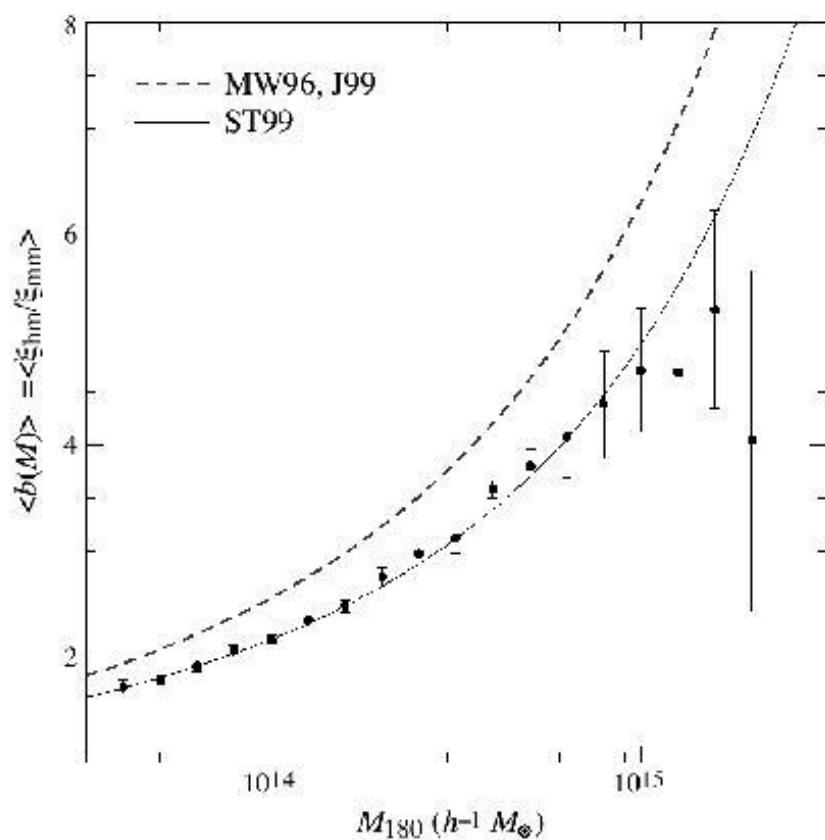
Gas clumps in gasdynamics simulations
Pearce et al. 2000

Mass dependence of halo bias

Brainerd & Villumsen 92- 94; Bagla 1998; Jing 1999; Sheth & Tormen 1999



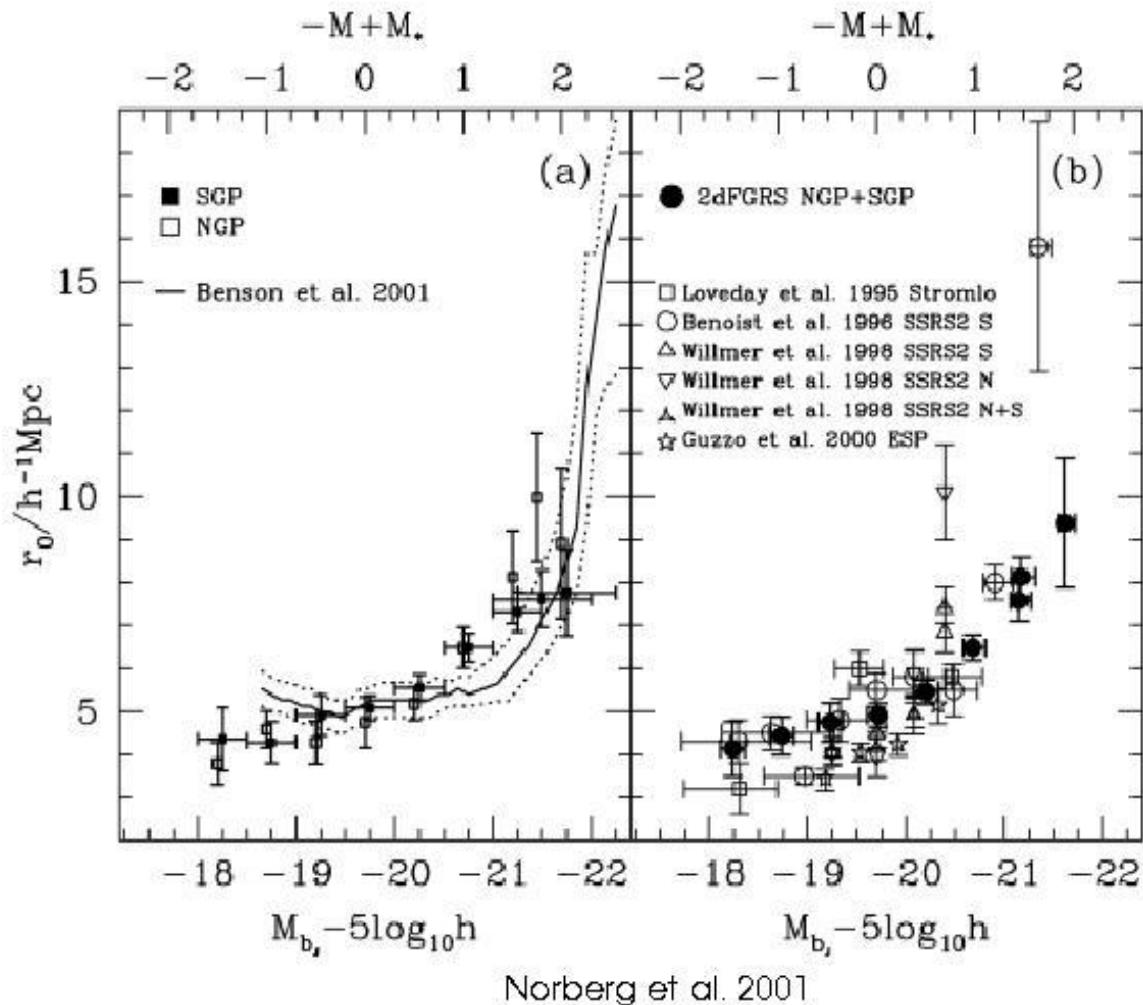
Sheth & Tormen 1999



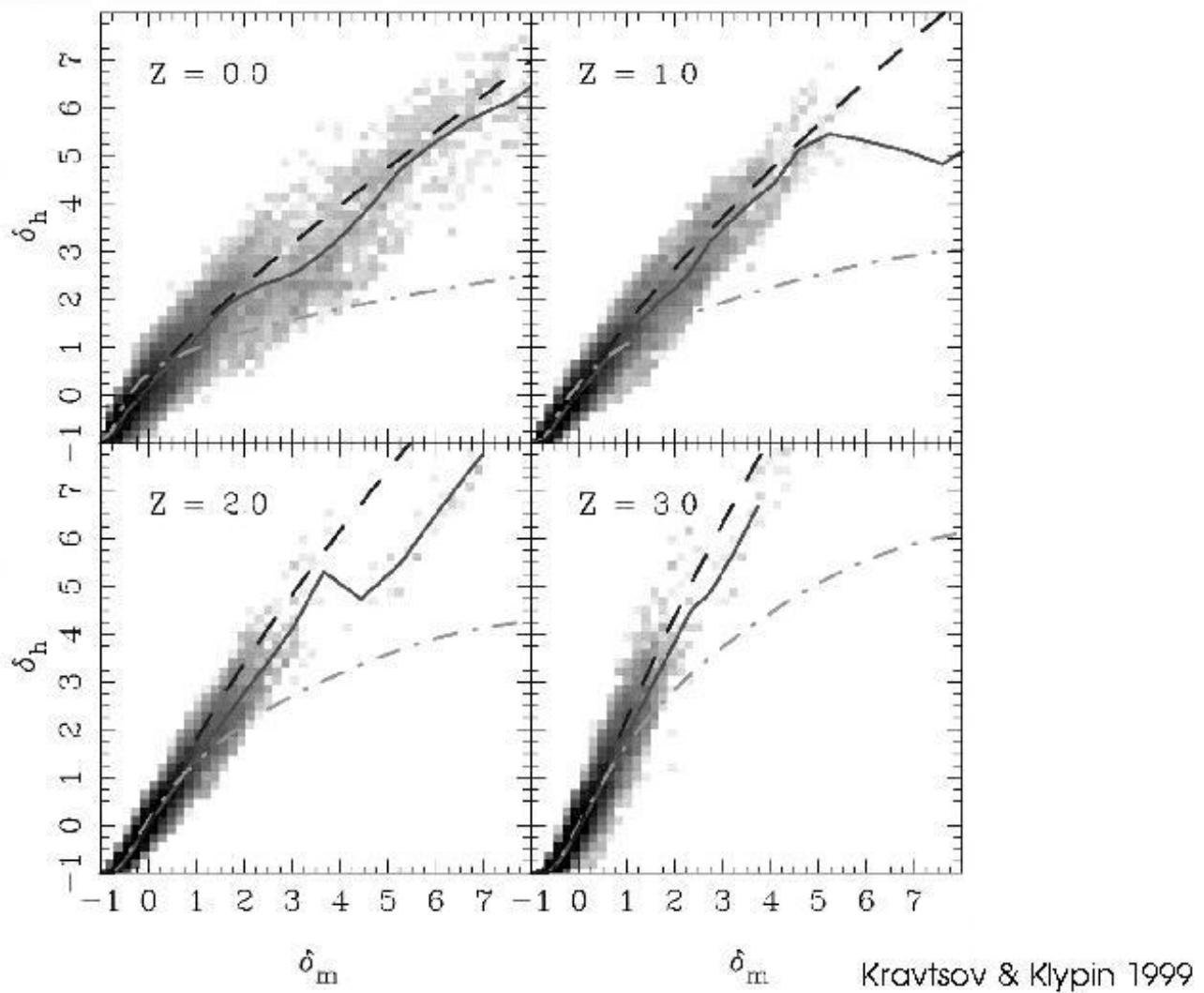
Hu & Kravtsov 2002

Luminosity dependence of galaxy clustering

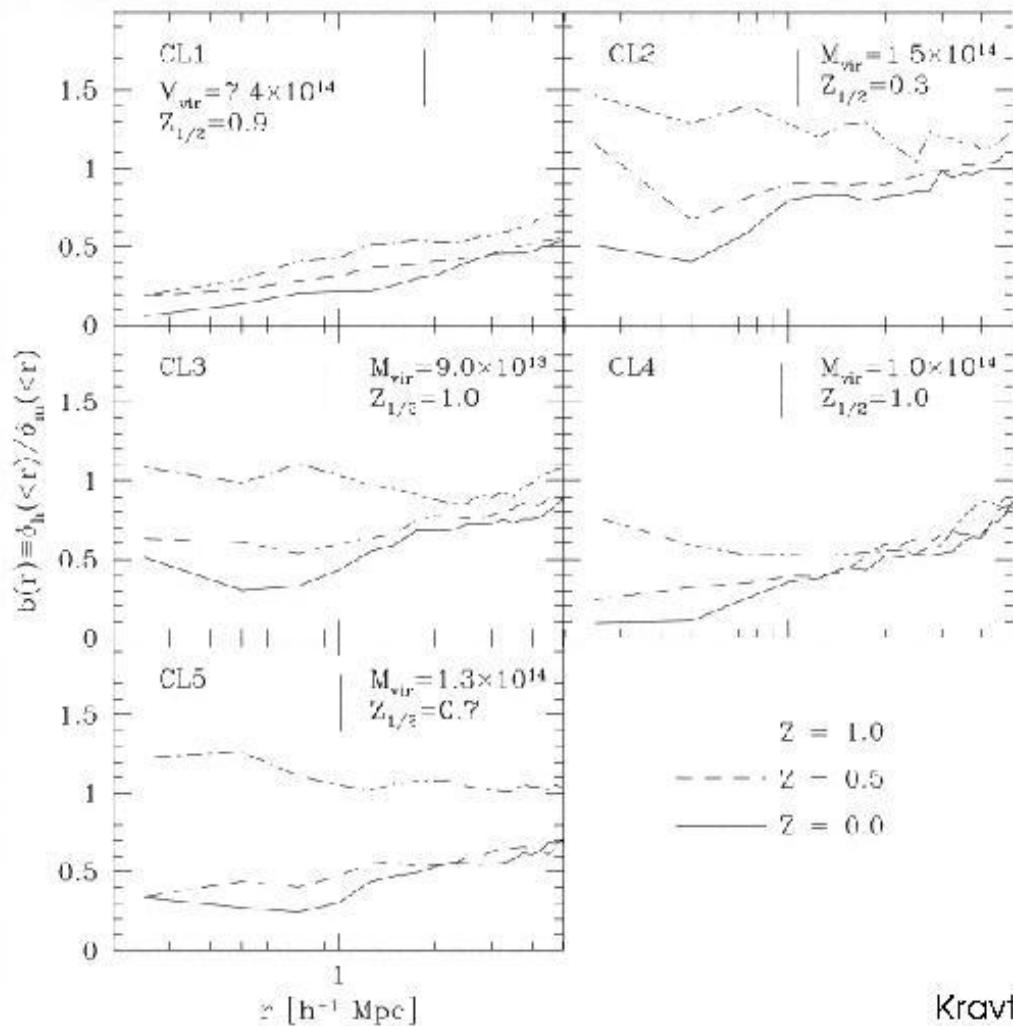
Norberg et al (2dF team) 2001, 2002; Zehavi et al. (SDSS team) 2002



The origin of small - scale antibias

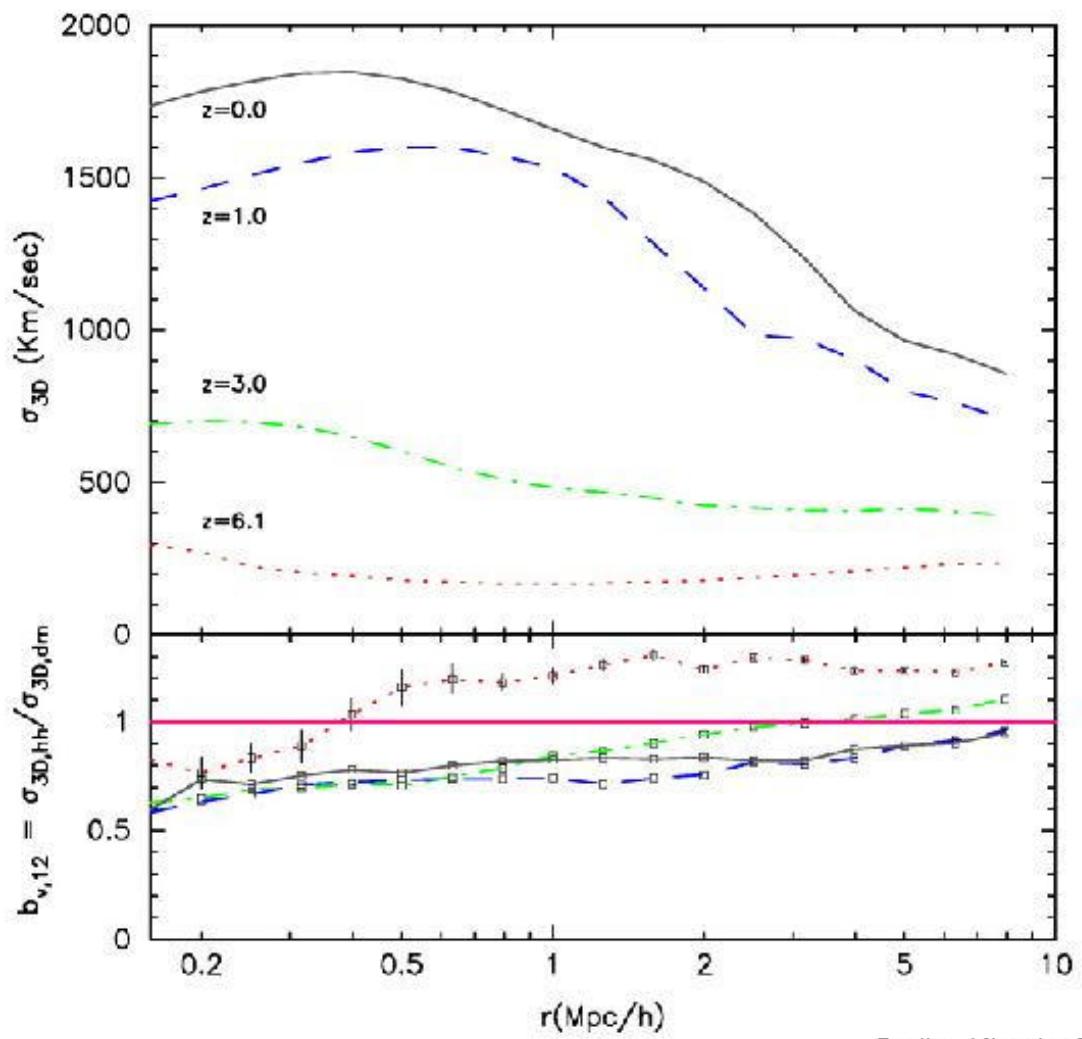


The origin of small - scale antibias



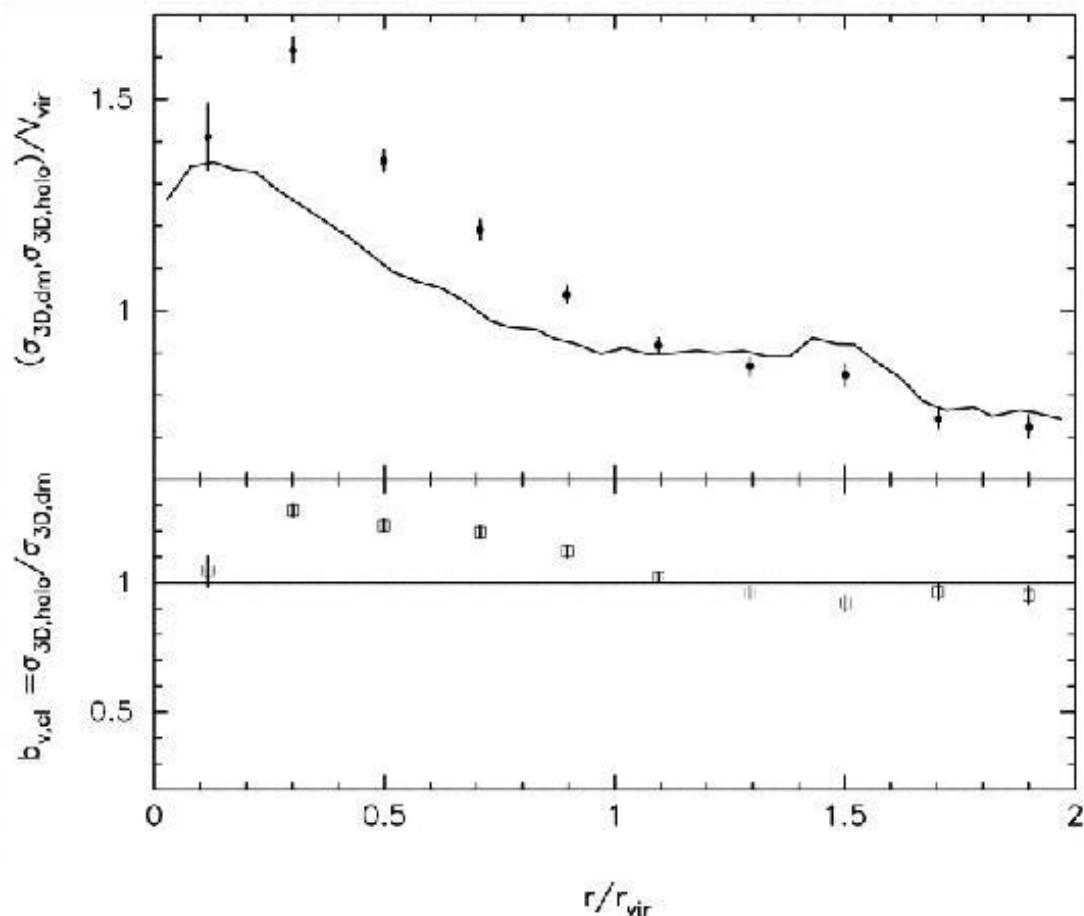
Kravtsov & Klypin 1999

Peculiar velocities of dark matter halos



Colin, Klypin & Kravtsov 2000

Do halos trace the peculiar velocity field of matter? 3D velocity dispersion profiles of CDM clusters



Colin, Klypin & Kravtsov 2000

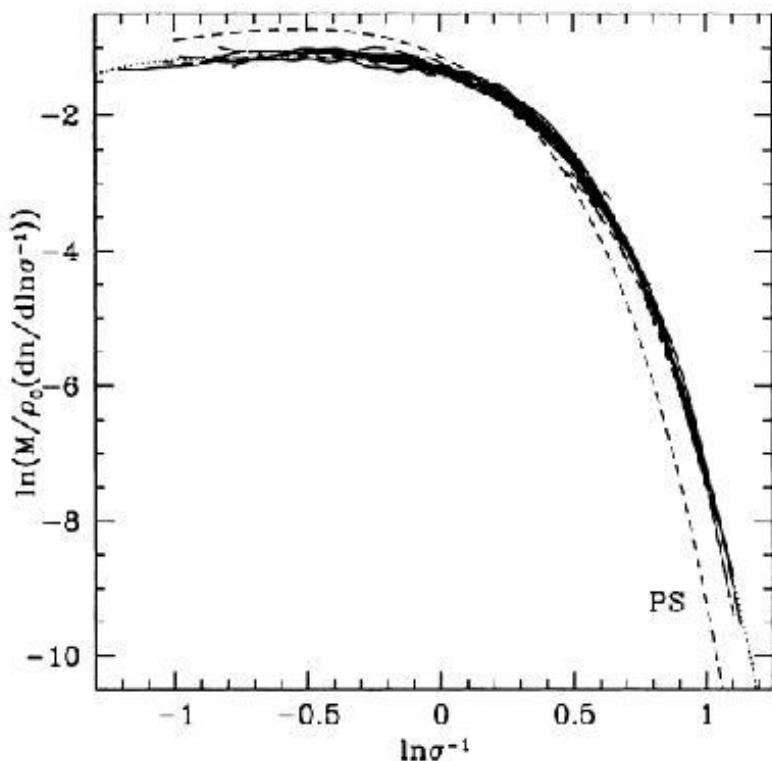
Galaxy clustering and bias: summary

- Correlation function of matter is not a power- law on small scales and does not match galaxy clustering at $r < 5 \text{ Mpc}$
- Halo/galaxy bias is linear (scale - independent) on large scales and is scale- dependent on small ($r < 5 \text{ Mpc}$) scales. There are non- linear bias models that match simulation results extremely well
- Predicted correlation function of galaxies is power- law over three decades in scale and matches the observed correlation function
- Bias is a strong function of time. High- z objects are expected to be very strongly biased.
- Bias is a function of halo mass, current models reproduce luminosity and color dependence of galaxy clustering
- Pairwise velocity dispersion of galactic halos is significantly lower than that of DM at $z=0$, and matches the observed velocity dispersion of galaxies

Halo mass function

Sheth & Tormen 1999; Jenkins et al. 2001

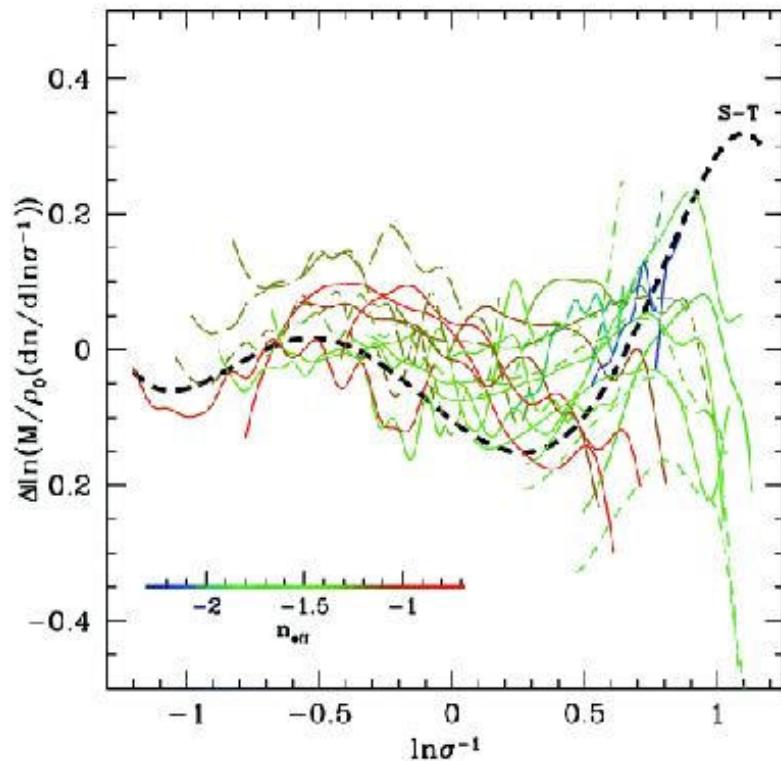
Evrard et al. 2001; Hu & Kravtsov 2002; Zheng et al. 2002; White 2002



Sheth & Tormen 1999:

$$\nu f(\nu) \equiv m^2 \frac{n(m, z)}{\bar{\rho}} \frac{d \log m}{d \log \nu}$$

$$\nu f(\nu) = A \left(1 + \frac{1}{\nu^p}\right) \left(\frac{\nu t}{2}\right)^{1/2} \frac{e^{-\nu t/2}}{\sqrt{\pi}},$$



Jenkins et al. 2001:

$$f(\ln\sigma^{-1}) \equiv \frac{M}{\bar{\rho}_m(z)} \frac{dn(< M, z)}{d\ln\sigma^{-1}},$$

$$f(\ln\sigma^{-1}) = A \exp(-|\ln\sigma^{-1} + B|^\epsilon),$$

Halo mass function

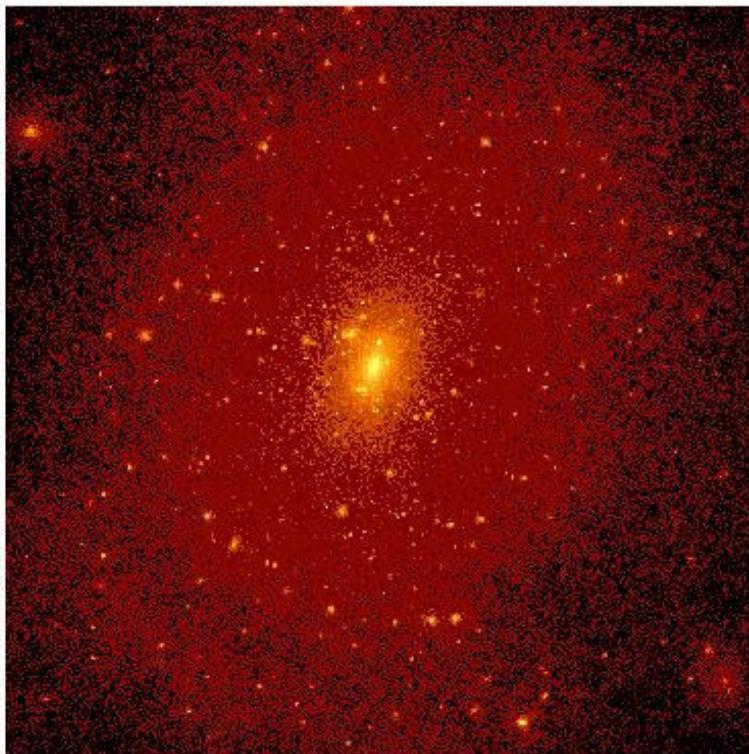
Can be expressed in universal form which works for different cosmologies and redshifts *if (and only if) the halo mass is defined as the mass within a radius of a fixed overdensity with respect to the mean density of the universe.*

Commonly used overdensity is 180 or 200. See White (2002) for comparisons of mass functions for different mass definitions

Other mass definitions can always be easily converted to the above definition because we know the density structure of dark matter halos (see Hu & Kravtsov 2002 for useful mass conversion fitting formulae)

Substructure in CDM halos

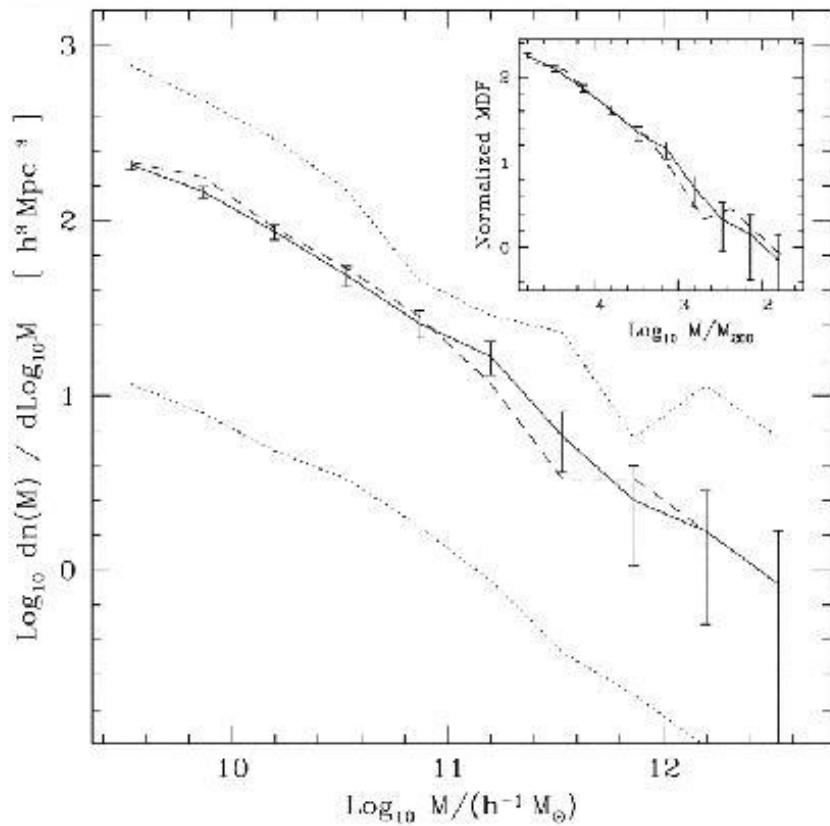
Discussion topics



- Are there too many/few subhalos predicted by CDM models?
- Is spatial distribution of subhalos in galactic halos too extended?
- how about cluster halos (e.g., Virgo, Fornax)?
- can discrepancies be explained by ordinary physical processes (e.g., suppression of starformation in the presence of UV background)?
- can high-velocity clouds (HVCs) be the CDM substructure?
- how substructure can be used to put constraints on CDM, WDM, SIDM, etc. models?

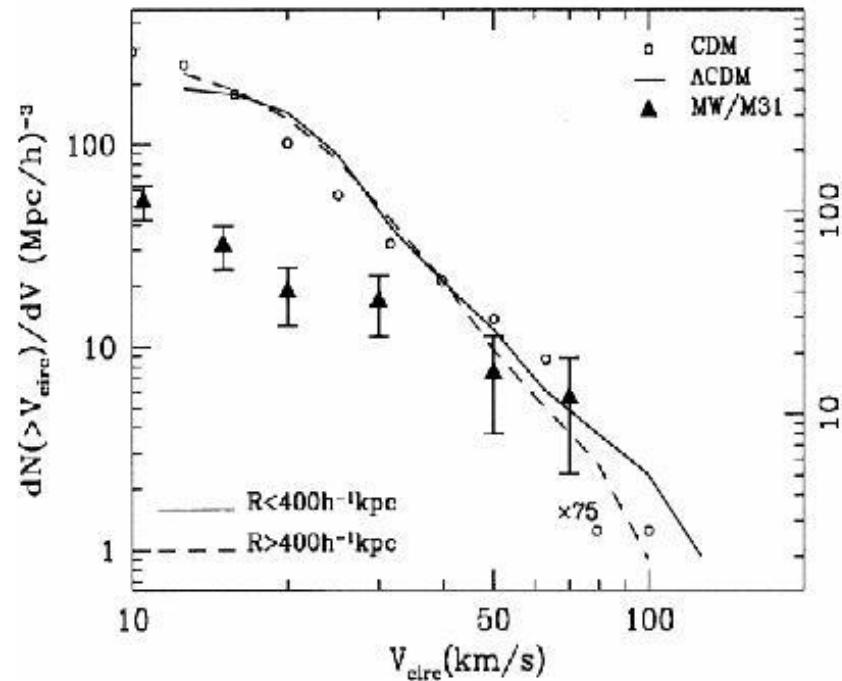
Mass function of subhalos

Klypin et al. 1999; Moore et al. 1999; Ghigna et al. 2000

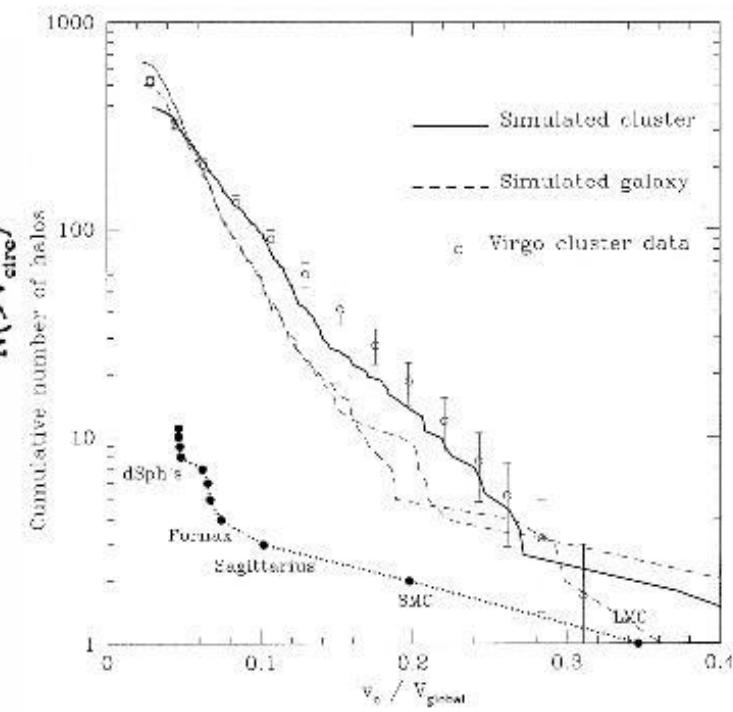


Ghigna et al. 2000

Velocity function of subhalos: overprediction of galactic satellite abundance

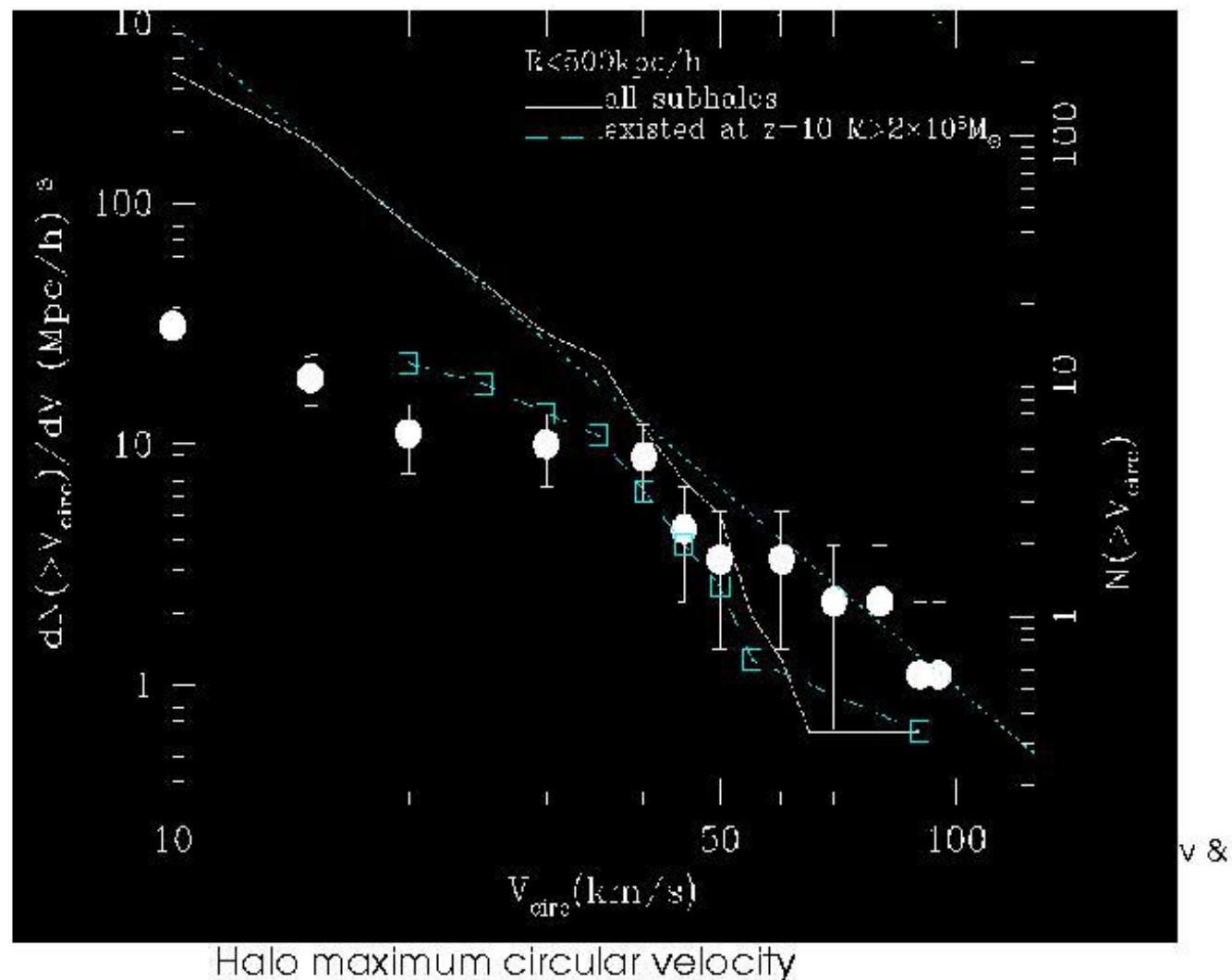


Klypin et al. 1999

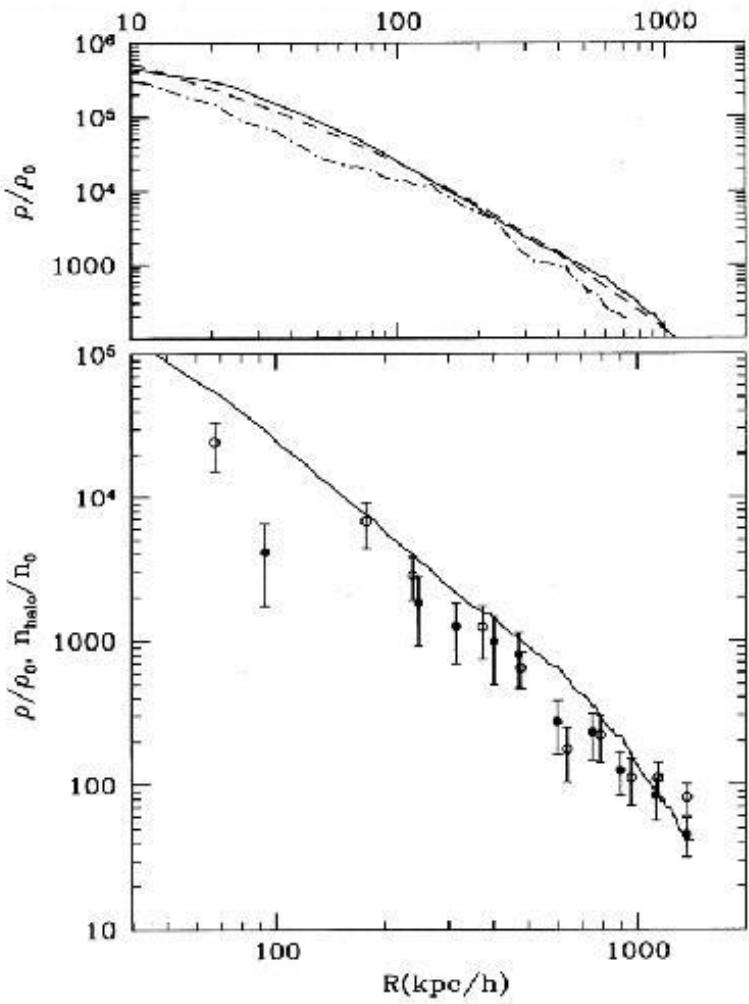


Moore et al. 1999

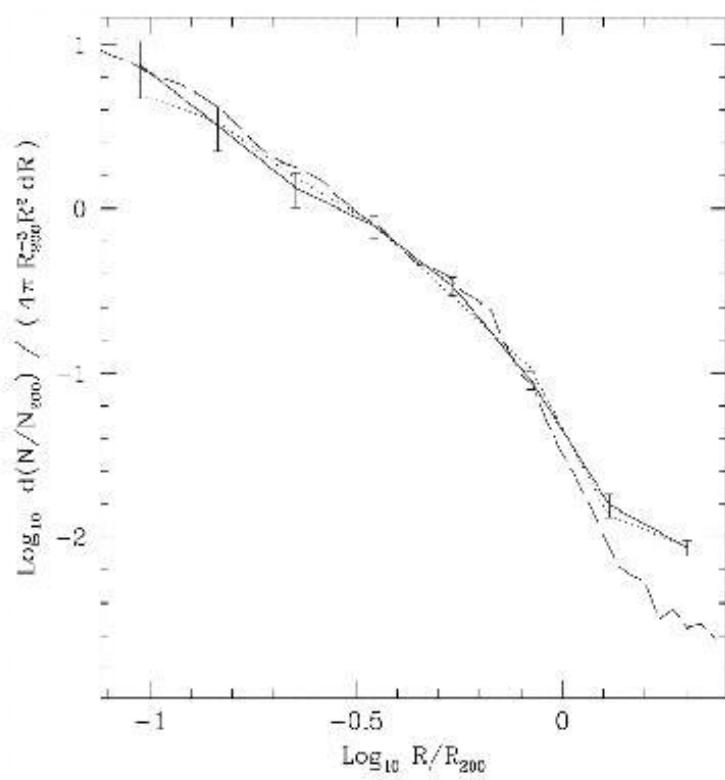
VF of subhalos collapsed at $z > z_{\text{re}}$



Radial distribution (number density profile) of subhalos



Colin, Klypin, Kravtsov 1999



Ghigna et al. 2000

Median galactocentric distance for satellites

	$V_{\text{circ}} > 20 \text{ km/s}$	$V_{\text{circ}} > 15 \text{ km/s}$	$V_{\text{circ}} > 10 \text{ km/s}$
<u>MW/M31</u>			
$R < 200/h \text{ kpc}$	$43 \pm 20/h \text{ kpc}$	$57 \pm 16/h \text{ kpc}$	$70 \pm 13/h \text{ kpc}$
<u>LCDM</u>	118/h kpc for $R < 200$; 178/h kpc for $R < 500/h \text{ kpc}$		
<u>Reionization</u>	102/h kpc for $R < 200$; 143/h kpc for $R < 500/h \text{ kpc}$		
<u>WDM</u>	139/h kpc for $R < 200$; 217/h kpc for $R < 500/h \text{ kpc}$		

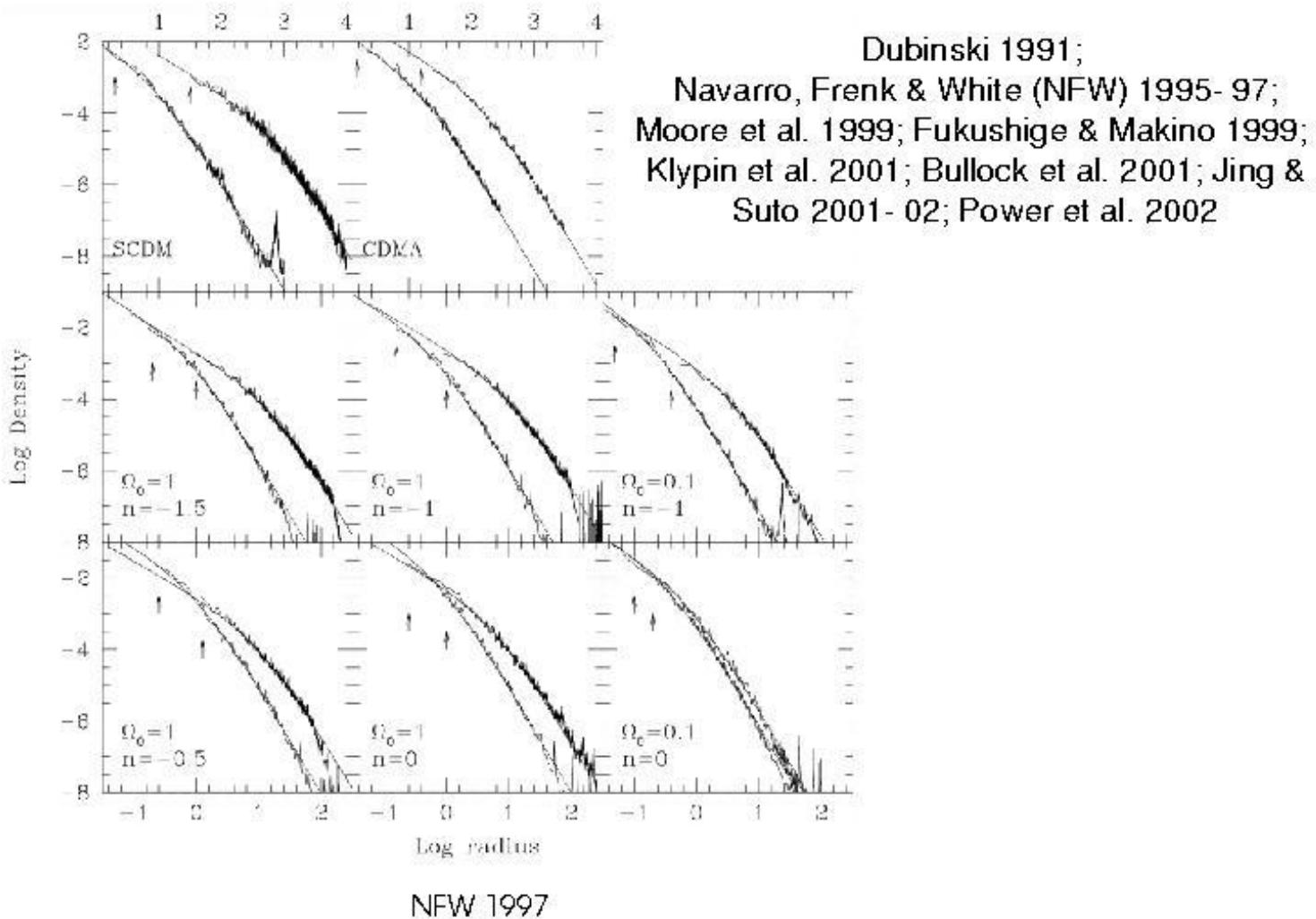
Conclusion: if this is a serious discrepancy (currently, we have only one system, our Local Group to work with) SIDM, WDM, and other modifications to CDM *will not help (they will probably make this particular discrepancy worse)*.

Reionization model *may work*

Halo mass function: summary

- Halo mass function is currently calibrated with accuracy $< 10\%$ in amplitude for CDM cosmologies.
- The mass function can be expressed in a universal (cosmology and redshift independent form) if mass is defined in a specific way.
- Mass function of subclumps is similar in shape to that of isolated halos, but is different in normalization.
- The predicted abundance of subclumps in galactic halos greatly exceeds the observed abundance of satellites around galaxies

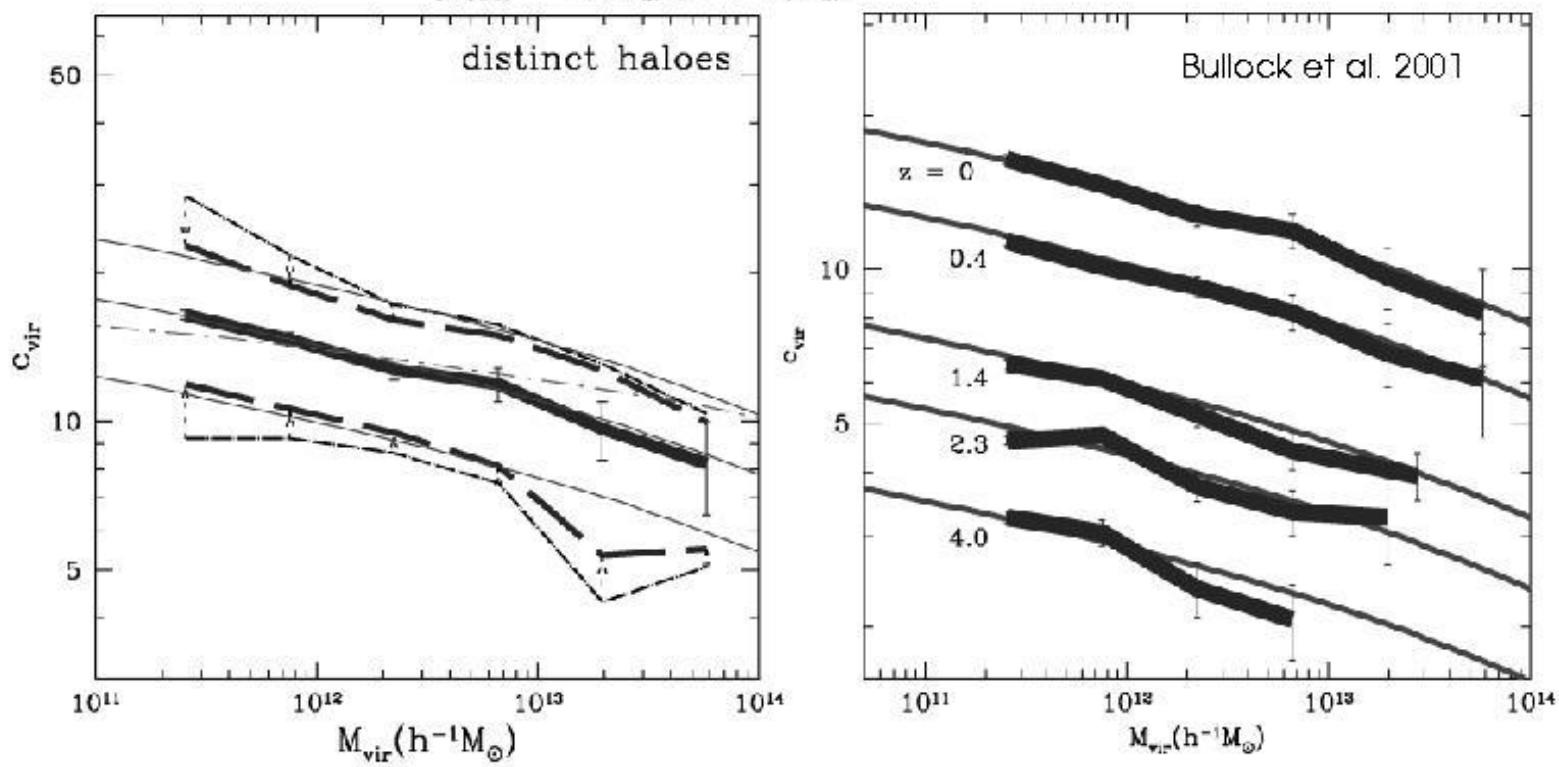
Density profiles of DM halos



Halo concentrations

NFW96,97; Jing 2000; Bullock et al. 2001

$$\frac{\rho(r)}{\rho_{\text{crit}}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}, \quad \text{Concentration:} \\ C = r_{\text{vir}}/r_s$$

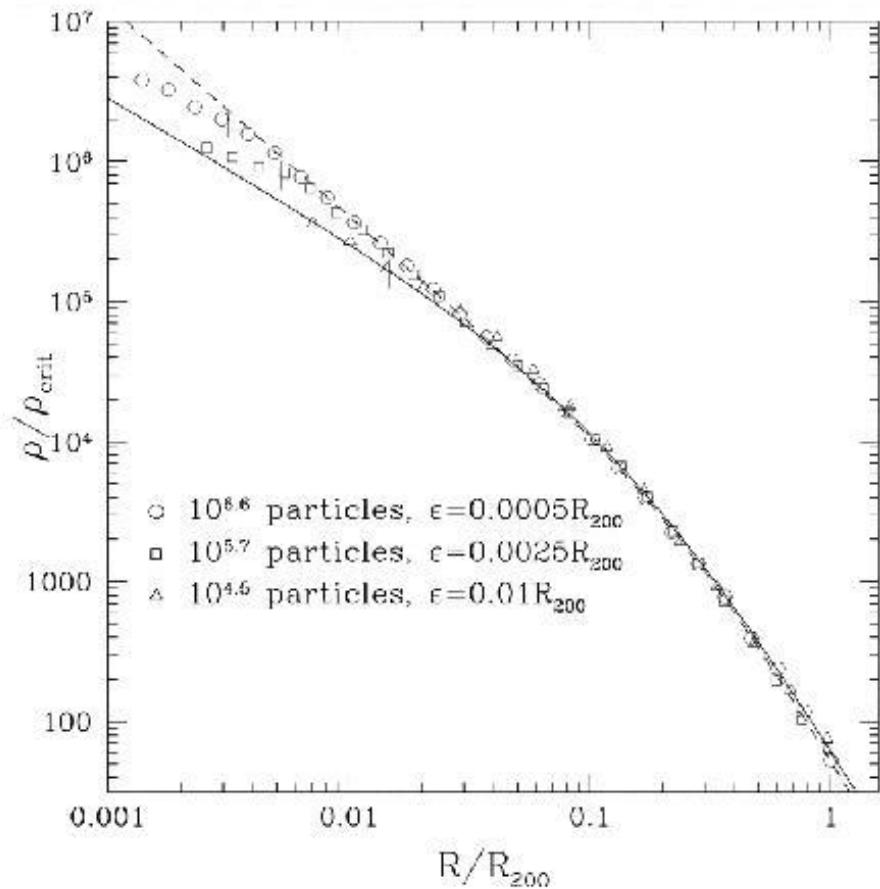


$$p(c)dc = \frac{1}{\sqrt{2\pi\sigma_{\ln c}^2}} \exp\left[-\frac{(\ln c - \ln \bar{c})^2}{2\sigma_{\ln c}^2}\right] d\ln c,$$

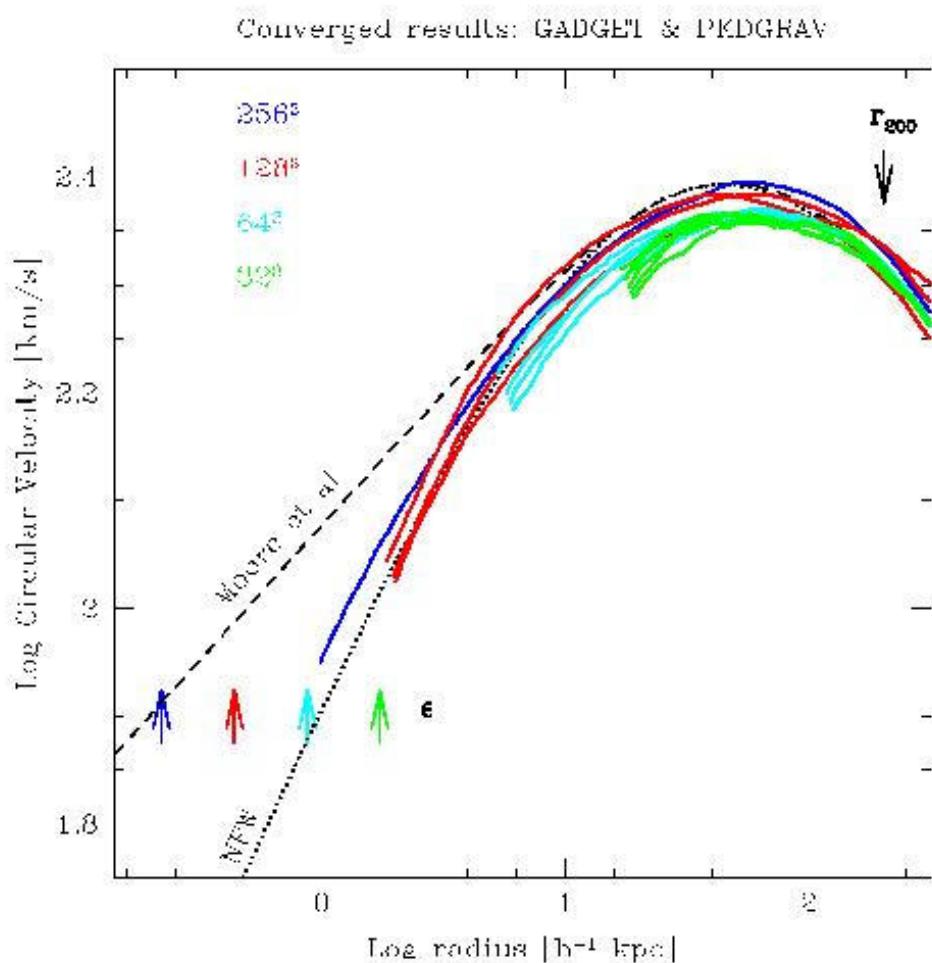
$$\bar{c}(M, z) = 9(1+z)^{-1} \left[\frac{M}{M_*(z)} \right]^{-0.13}, \\ \sigma_{\ln c} = 0.2,$$

The inner slope controversy

Fukushige & Makino 1999; Moore et al. 1999;
Jing & Suto 2001; Klypin et al. 2001; Power et al. 2002



The jury is still out ...



Power et al. 2002

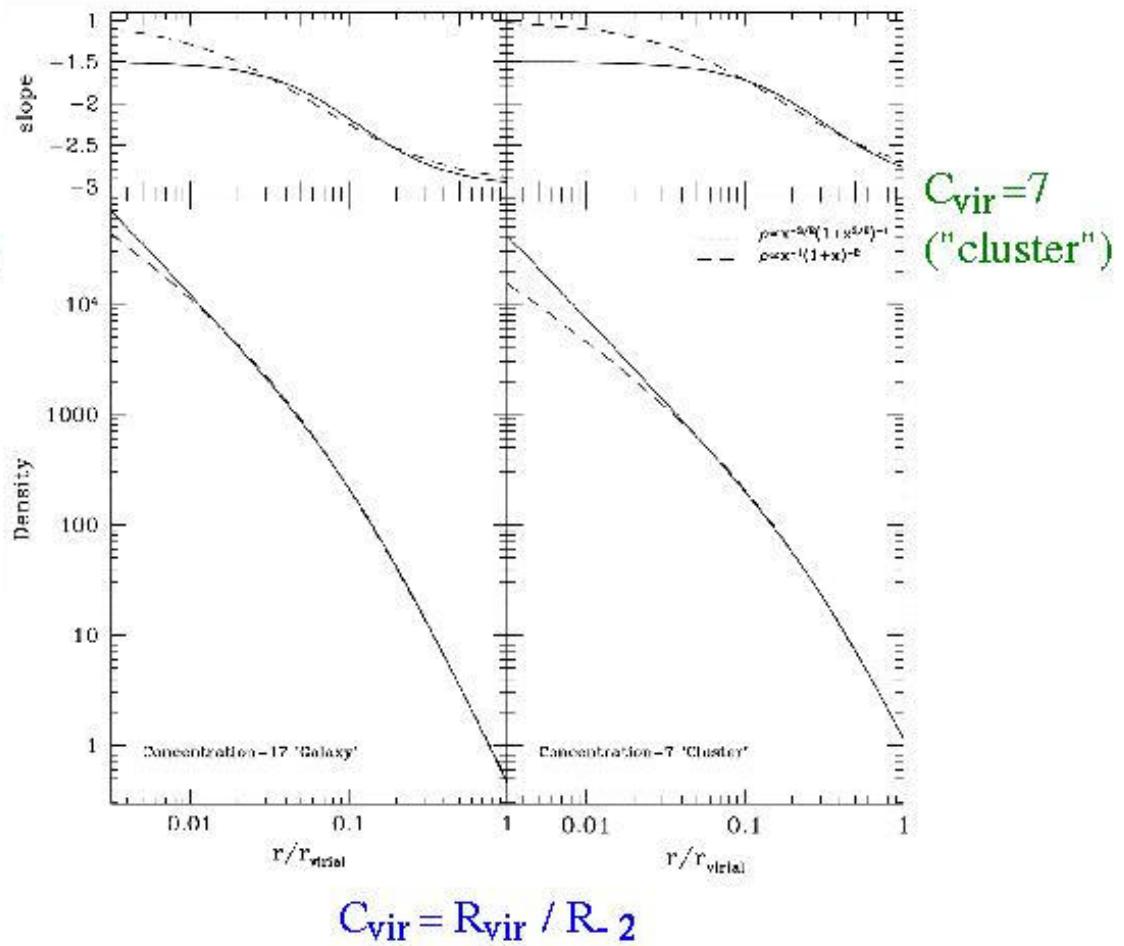
NFW vs. Moore et al. profile

Log.
slope

$C_{\text{vir}} = 17$
("galaxy")

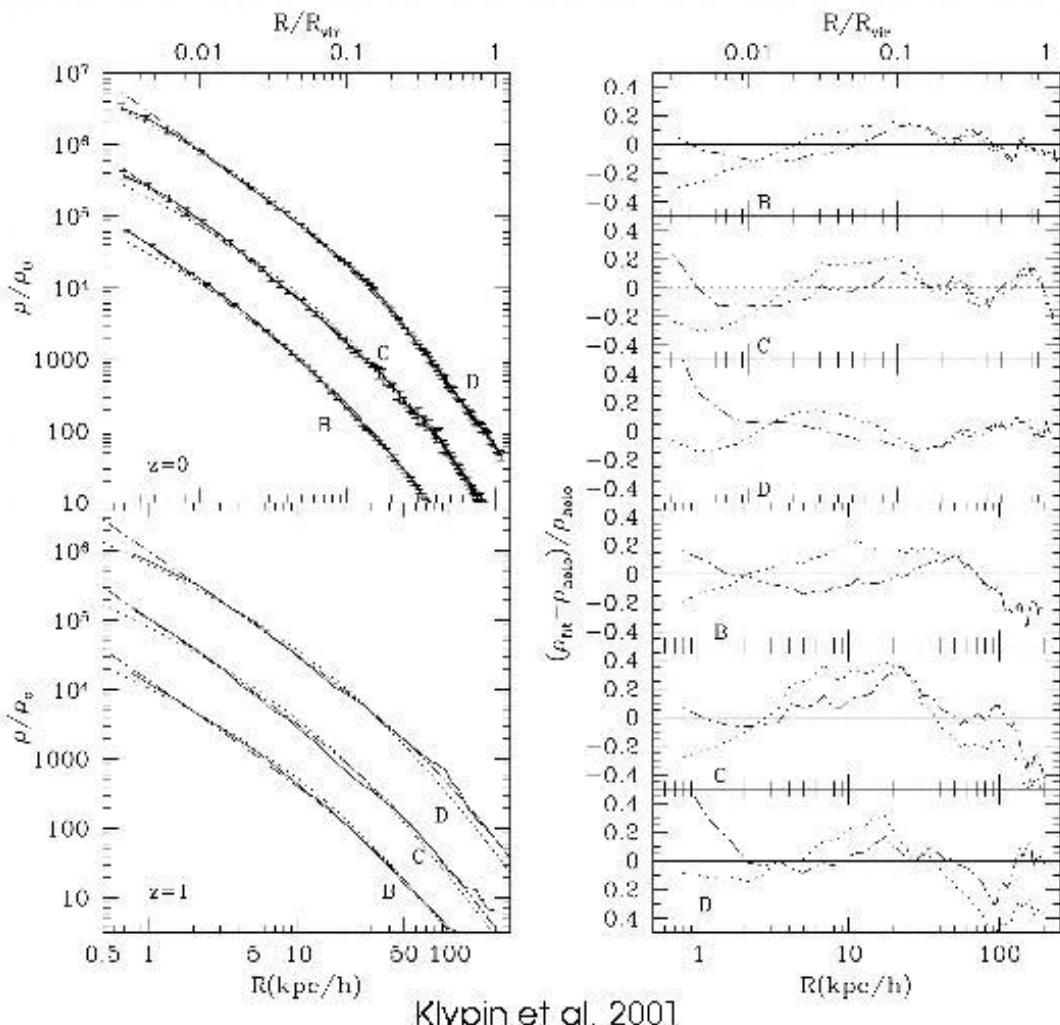
$C_{\text{vir}} = 7$
("cluster")

Overdensity



$$C_{\text{vir}} = R_{\text{vir}} / R_2$$

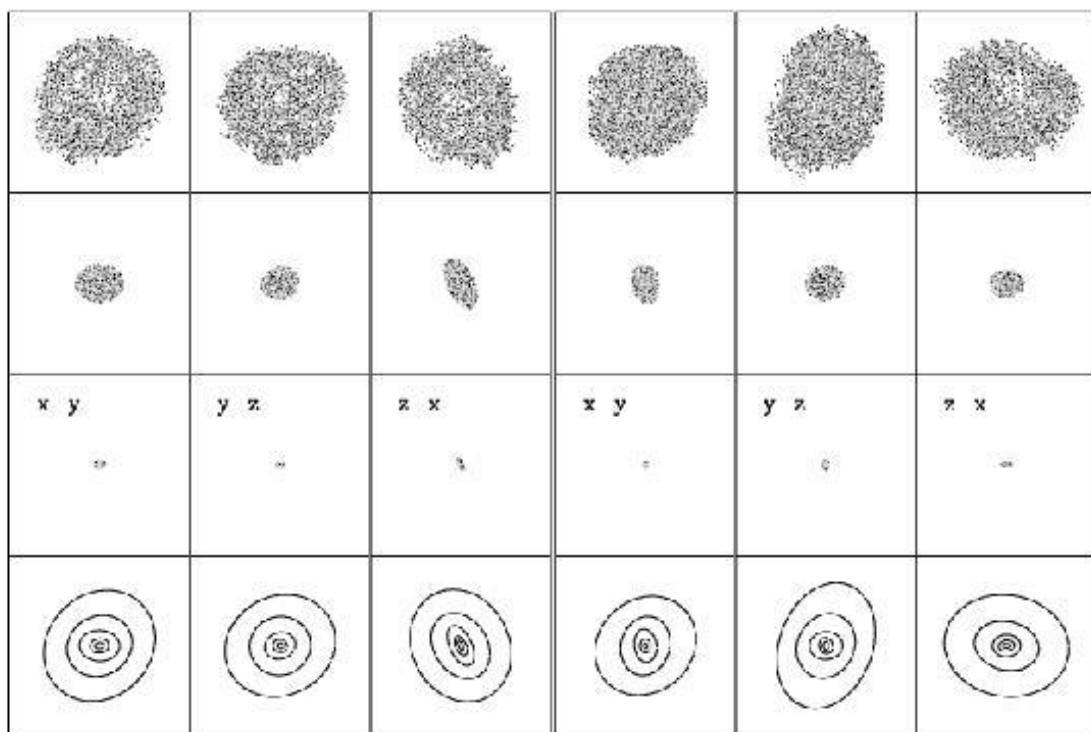
It is possible that there is scatter in central slopes,
just like there is scatter in halo concentrations



Klypin et al. 2001

Triaxiality of dark matter halos

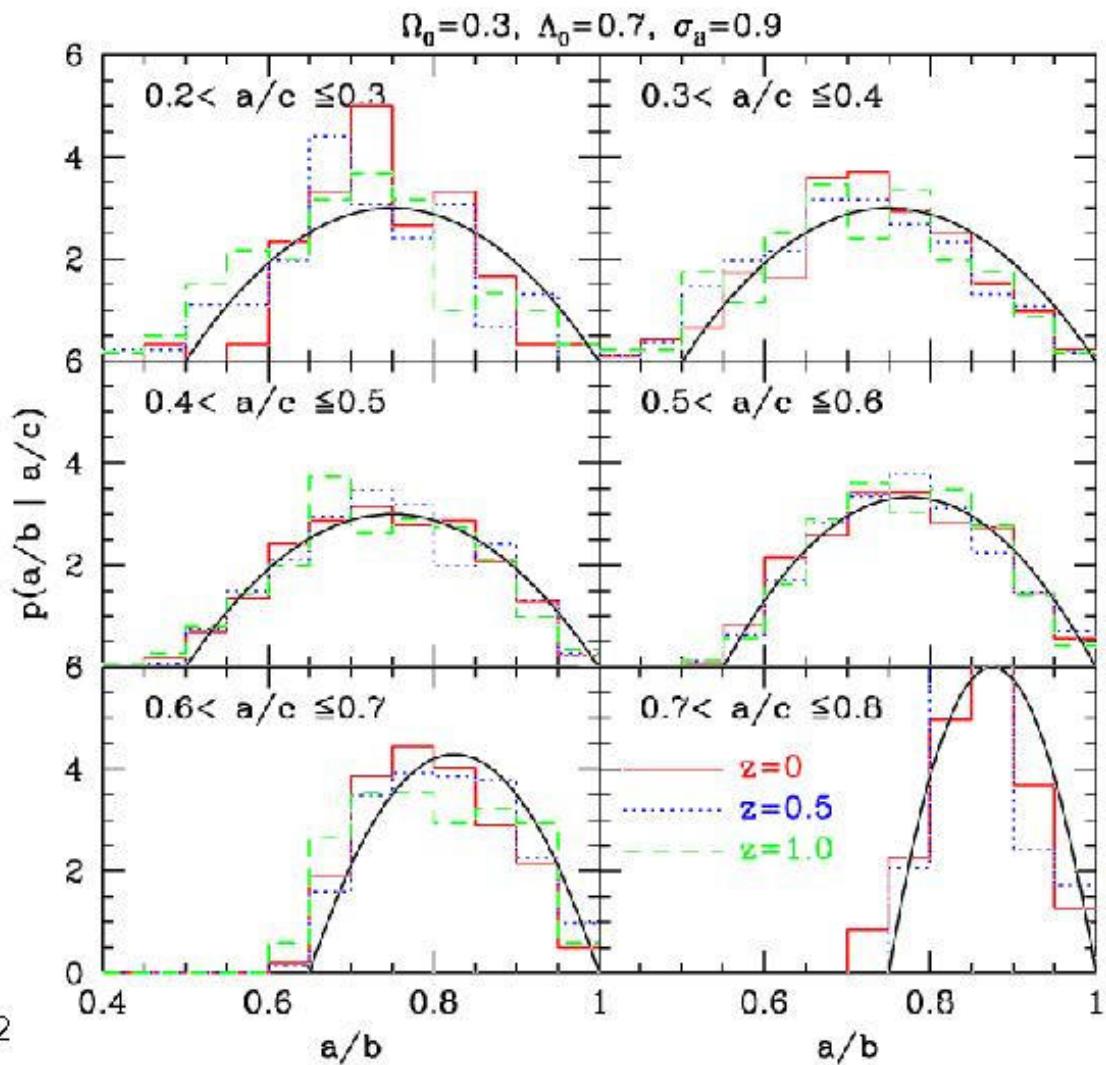
Bullock et al. 2001; Jing & Suto 2002



Jing & Suto 2002

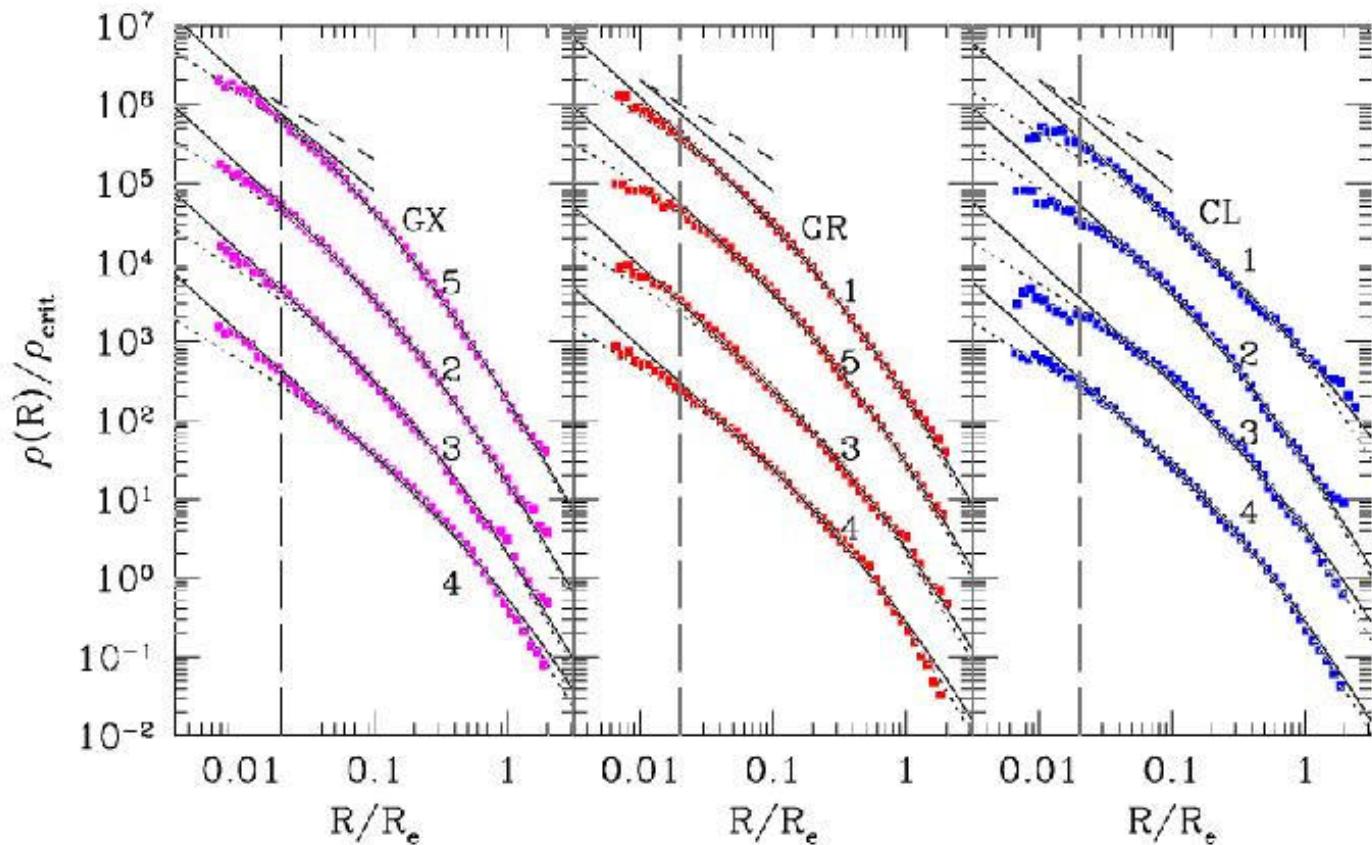
Distribution of axis ratios

Warren et al. 1992; Bullock et al. 2001; Jing & Suto 2002



Triaxial density profiles

Jing & Suto 2002



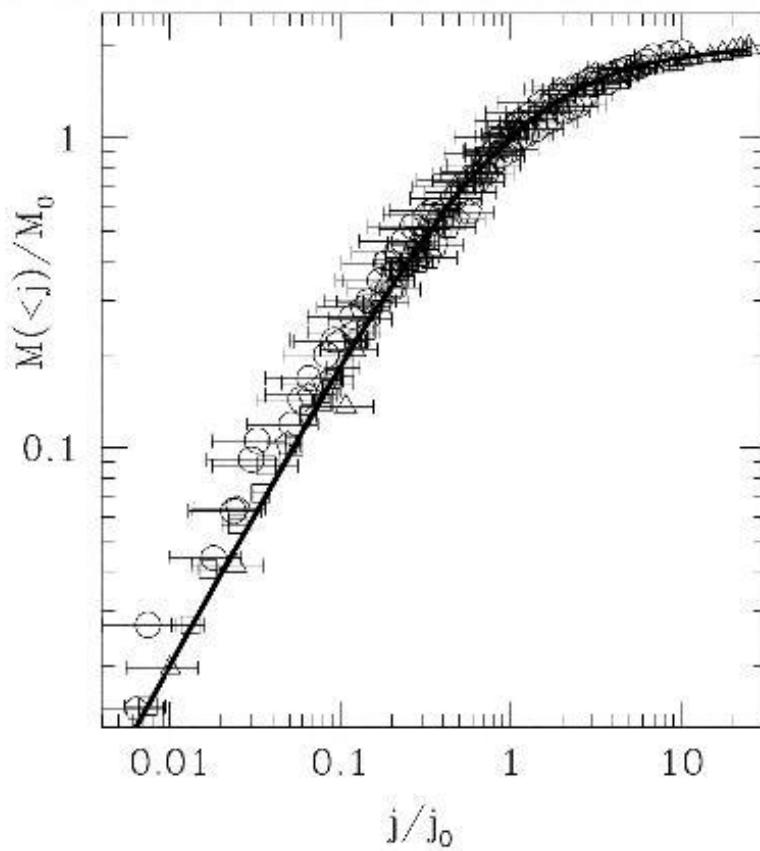
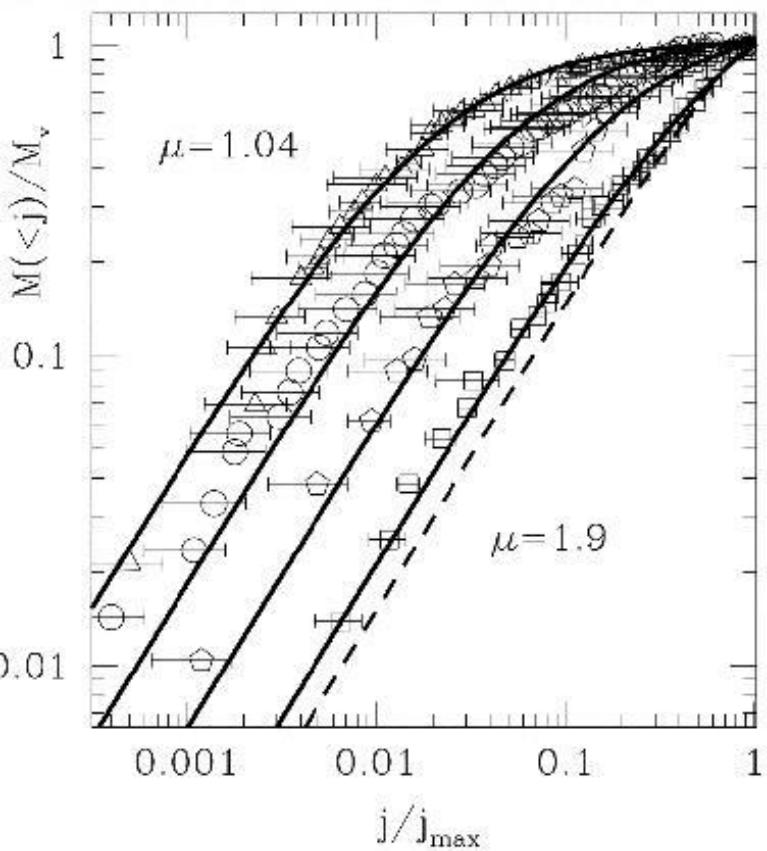
$$R^2(\rho_s) = \frac{X^2}{a^2(\rho_s)} + \frac{Y^2}{b^2(\rho_s)} + \frac{Z^2}{c^2(\rho_s)}.$$

Specific angular momentum distribution of DM halos

Bullock et al. 2001

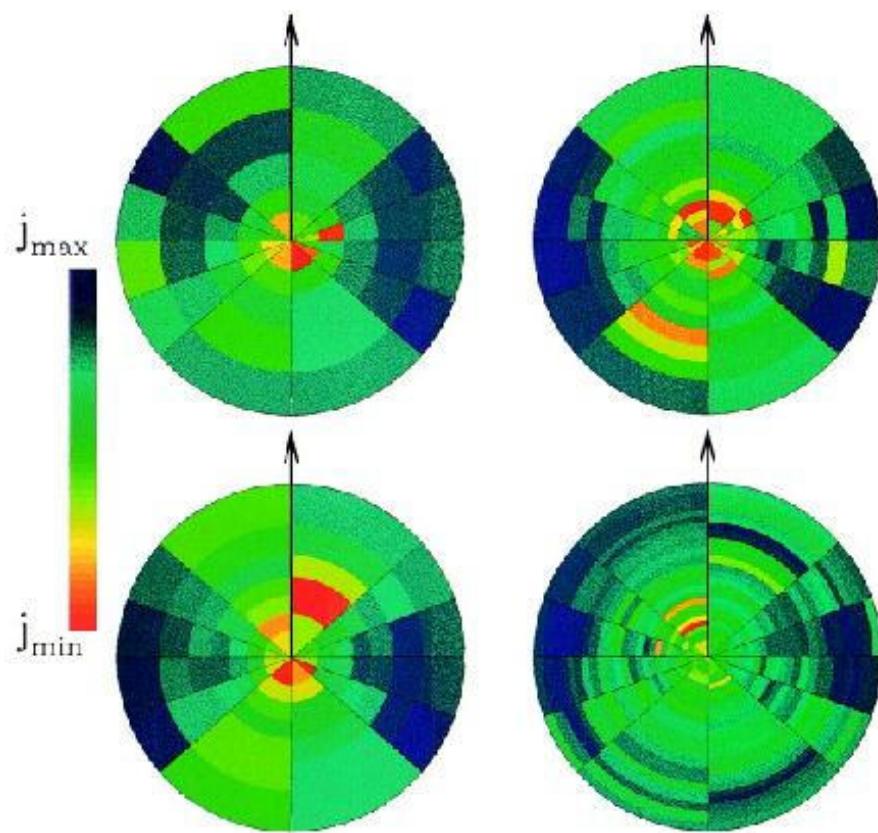
see also Bullock, Kravtsov & Colin 2002; van den Bosch et al. 2002; Chen & Jing 2002

$$M(<j) = M_{\text{tot}}[1 - (1 - j/j_{\max})^{3/2}],$$
$$M(<j) = M_v \frac{\mu j}{j_0 + j}, \quad \mu > 1.$$



Specific angular momentum: spatial structure

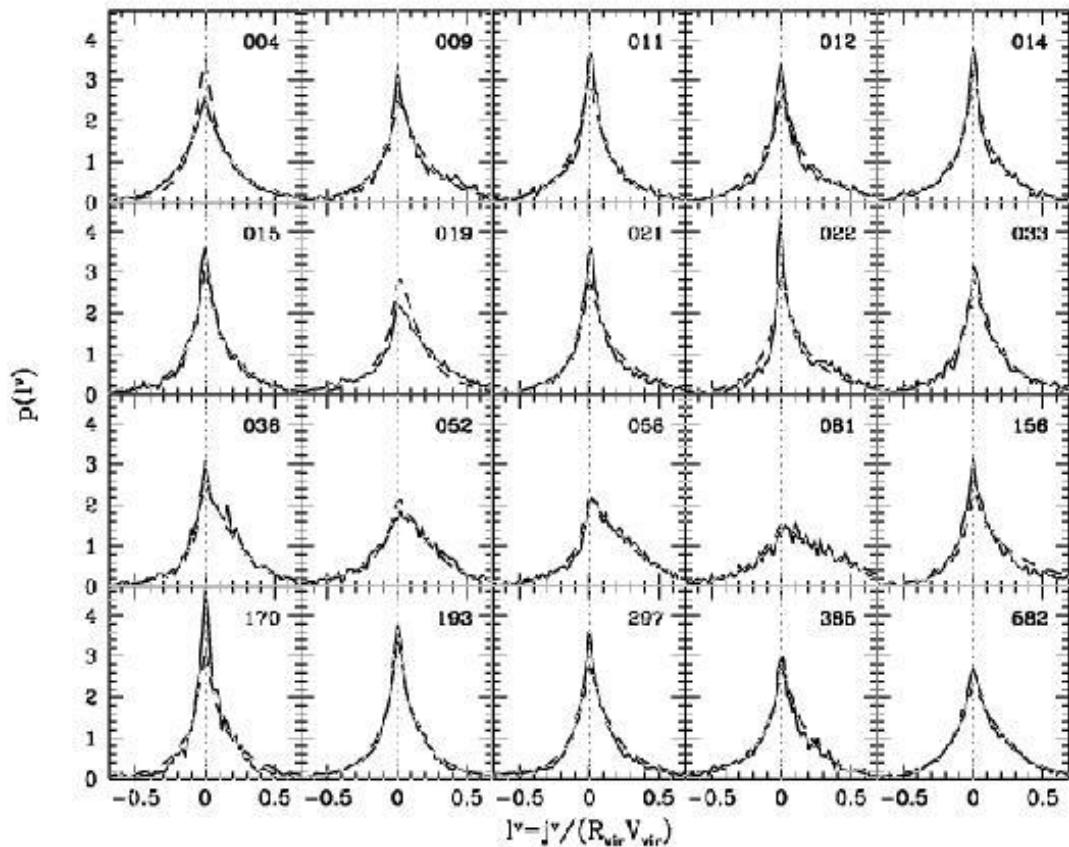
Bullock et al. 2001



$$M(< j) = M_{\text{tot}} [1 - (1 - j/j_{\max})^{3/2}] ,$$
$$M(< j) = M_v \frac{\mu j}{j_0 + j} , \quad \mu > 1 .$$

Distribution of specific angular momentum: dark matter - gas connection

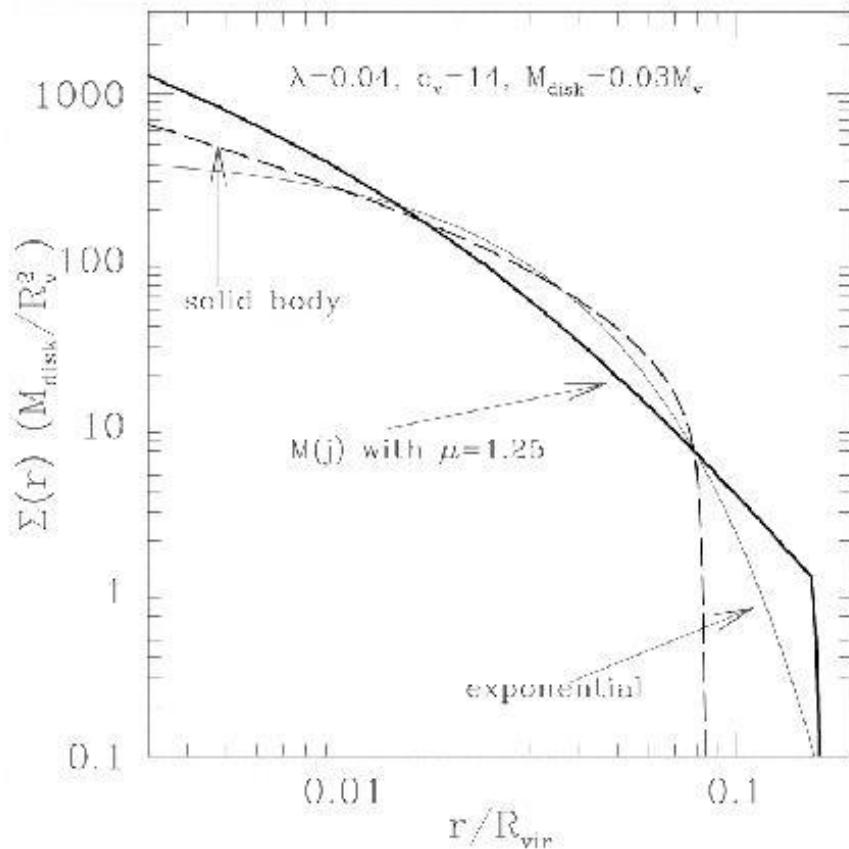
van den Bosch et al. 2002



Specific angular momentum: halo- disk connection

Bullock et al. 2001

van den Bosch et al. 2001

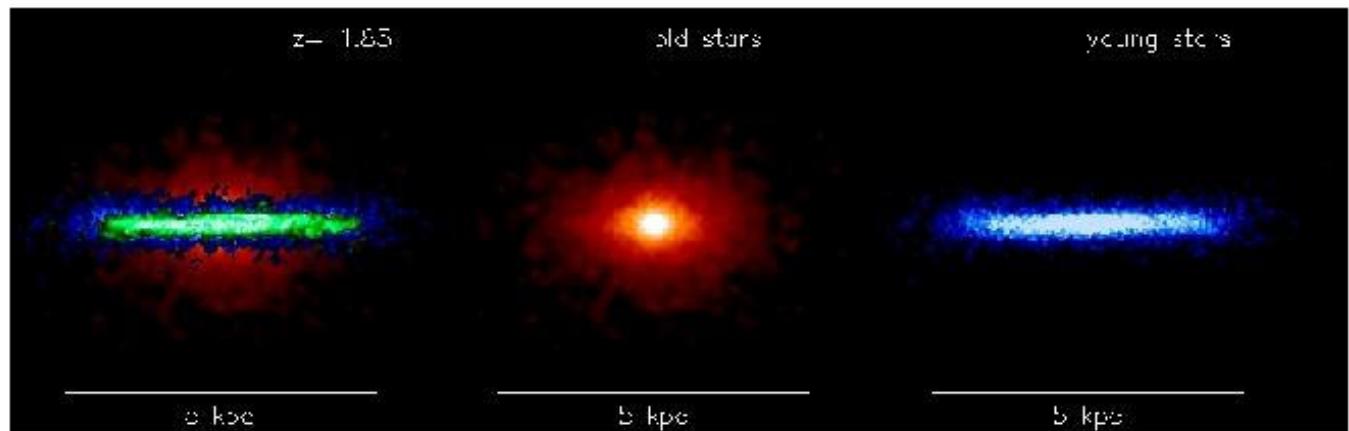


$$M(< j) = M_{\text{tot}} [1 - (1 - j/j_{\max})^{3/2}] ,$$

$$M(< j) = M_v \frac{\mu j}{j_0 + j} , \quad \mu > 1 .$$

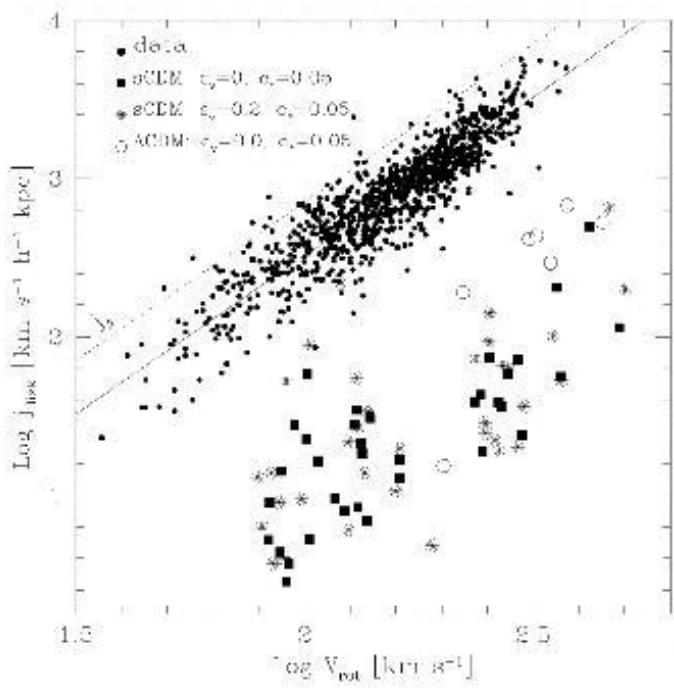
Formation of galactic disks in CDM halos

Simulations qualitatively reproduce general morphology of disk galaxies

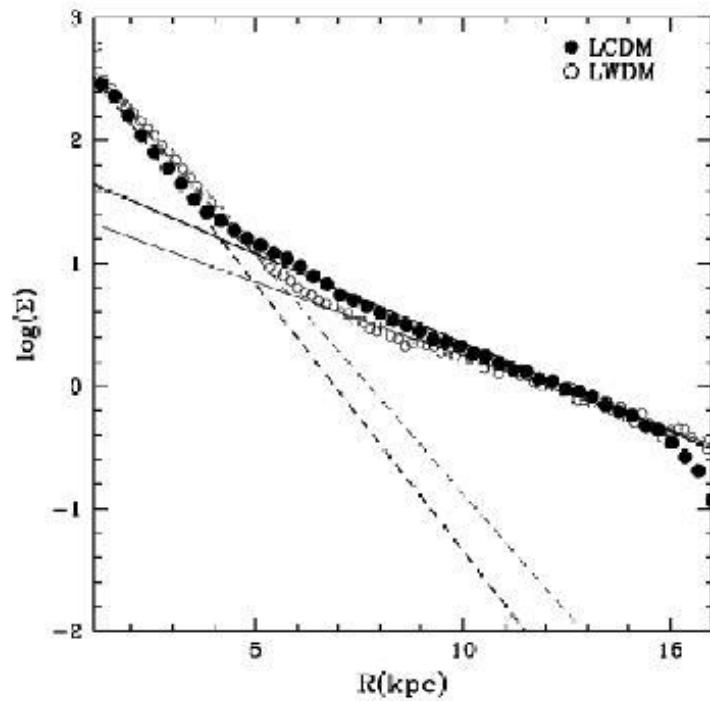


Navarro & Steinmetz 2002

Formation of galactic disks in CDM halos: angular momentum problem



Navarro & Steinmetz 1997- 2000

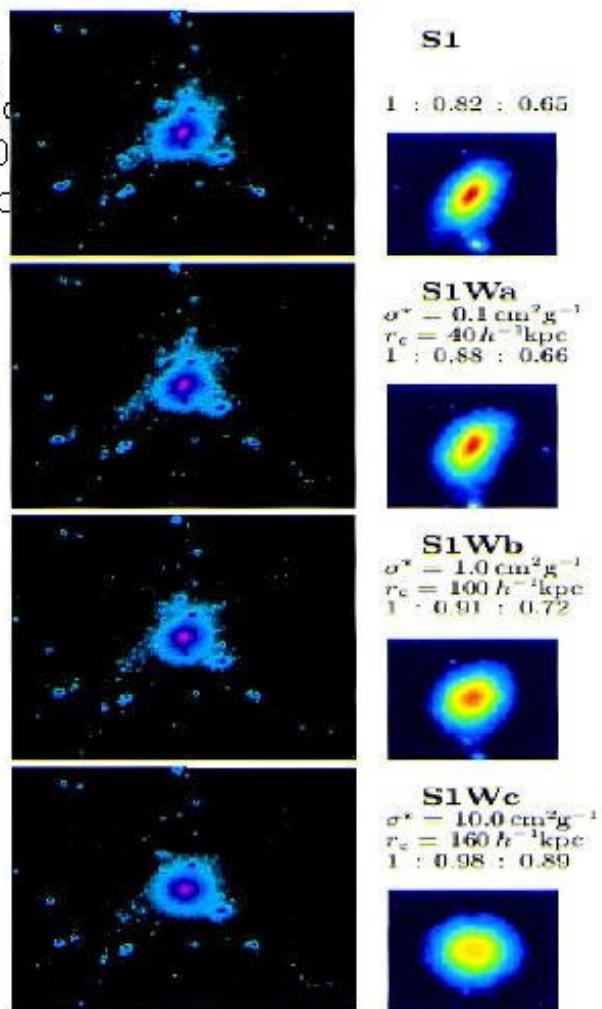


Governato et al. 2002

Modifications to CDM

- Self-interacting DM (SIDM)

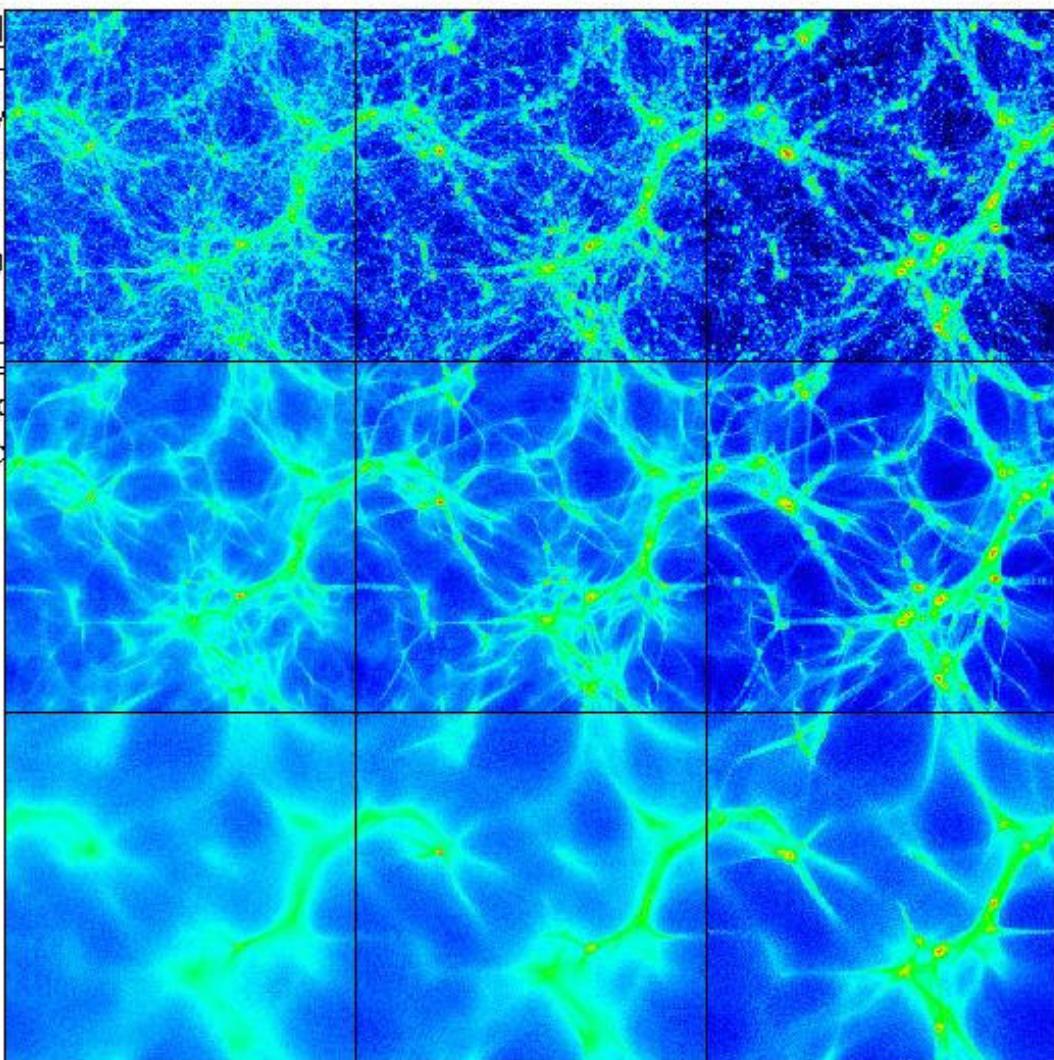
Spiegel & Steinhardt (1999); and followup by Hannestad (1999); Miralda- Escude (2000); Moore Hogan & Dalcanton (2000); Yoshida et al. (2000); Firmani et al. (2000); Mo & Mao (2000); Kochanek & Colin et al (2000- 02)



Modifications to CDM

- Self-interacting DM (SI)

Spergel & Steinhardt
Hannestad (1999); M
Hogan & Dalcanton
Firmani et al. (2000);
Colin et al (2000- 02)



- Warm dark matter (WDM)

Sommer- Larsen & Do
Kamionkowski & Liddle
Knebe et al. (2001)

Modifications to CDM

- Self-interacting DM (SIDM)

Spiegel & Steinhardt (1999); and followup by Ostriker(1999);
Hannestad (1999); Miralda- Escude (2000); Moore et al. (2000);
Hogan & Dalcanton (2000); Yoshida et al. (2000a,b); Burkert (2000);
Firmani et al. (2000); Mo & Mao (2000); Kochanek & White (2000);
Colin et al (2000- 02)

- Warm dark matter (WDM)

Sommer- Larsen & Dolgov (1999); Hogan (1999);
Kamionkowski & Liddle (1999); Colin et al. (1999); Bode et al.(2000);
Knebe et al. (2001)

- A combination of the above

Hannestad & Scherrer (2000)

- Repulsive DM Goodman (2000)

- Annihilating DM Medvedev (2000)

- Non- CDM solutions (e.g., MOND)

- Titled power spectra (Zentner & Bullock 2002)

CDM scorecard

✓	Clustering/velocity field of galactic halos	Excellent agreement
✓	Halo mass function	Consistent with current data
✓	Abundance of satellites around galaxies	discrepancy, but could be explained
✓	Abundance of galaxies in clusters	agreement
✓	Density structure of galaxy clusters	consistent at large radii at small radii, data are inconclusive
✗	Density structure of galactic cores	appears to be inconsistent, but debate about data and possible solutions rages on
✓	Concentrations and scatter	Not clear, scatter in concentrations just barely consistent with scatter in TF relation
✓	AM distribution of DM and gas	Not clear, but AM distribution has to be modified to produce exponential disks
✗	AM of galactic disks	Inconsistent with current numerical predictions, but recent simulations produce disks that are much more similar to observed disks (i.e., it may be solved)
✓	Triaxiality of DM halos	Not clear, but this is a generic prediction -> we need observational tests

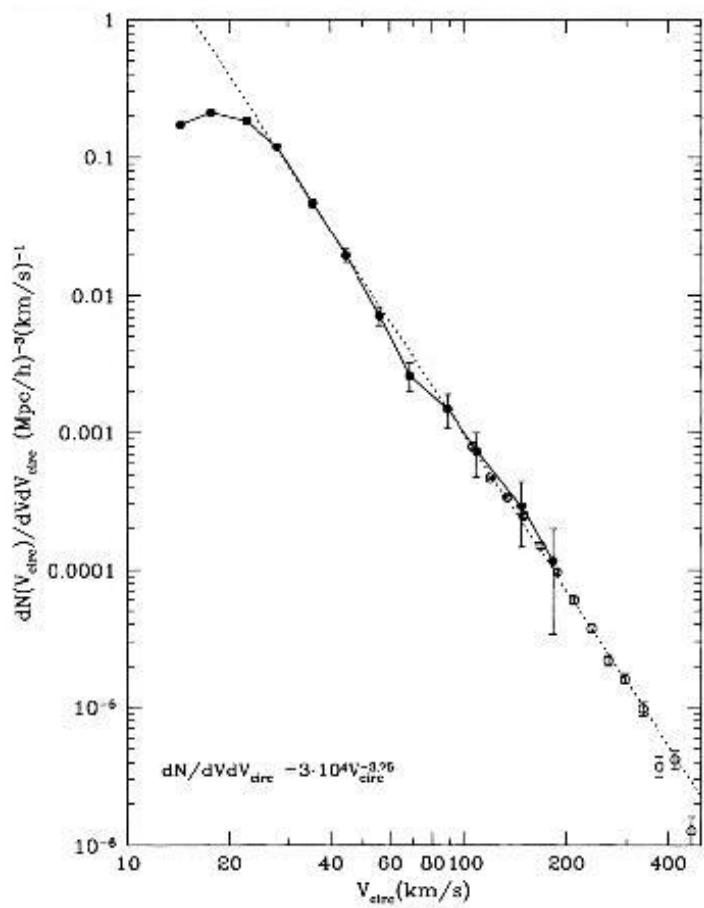


CDM is still a champion but its supremacy is challenged

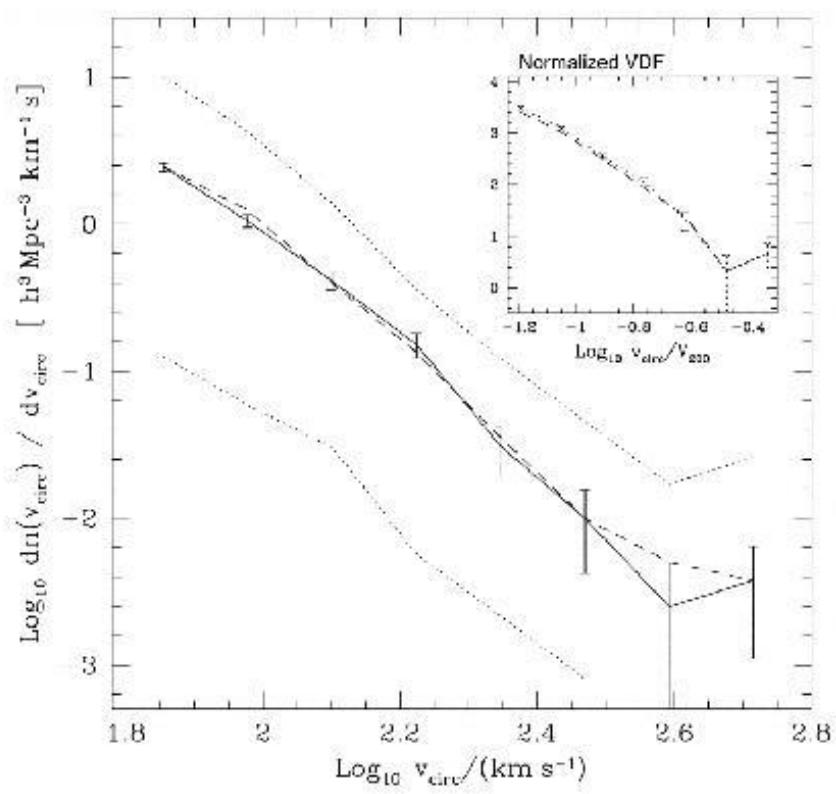
as more and more detailed predictions are becoming available, we need more innovative observational constraints such as precession of satellite orbits, lensing constraints on halo density profiles and substructure, etc.

some of the new tests will be discussed at the upcoming CfCP workshop
"CDM predictions on small - scales: current and future tests" in Chicago
July 31 - Aug 2, 2002
<http://cfcp.uchicago.edu/workshops/cdm2002/index.html>

Velocity function of subhalos

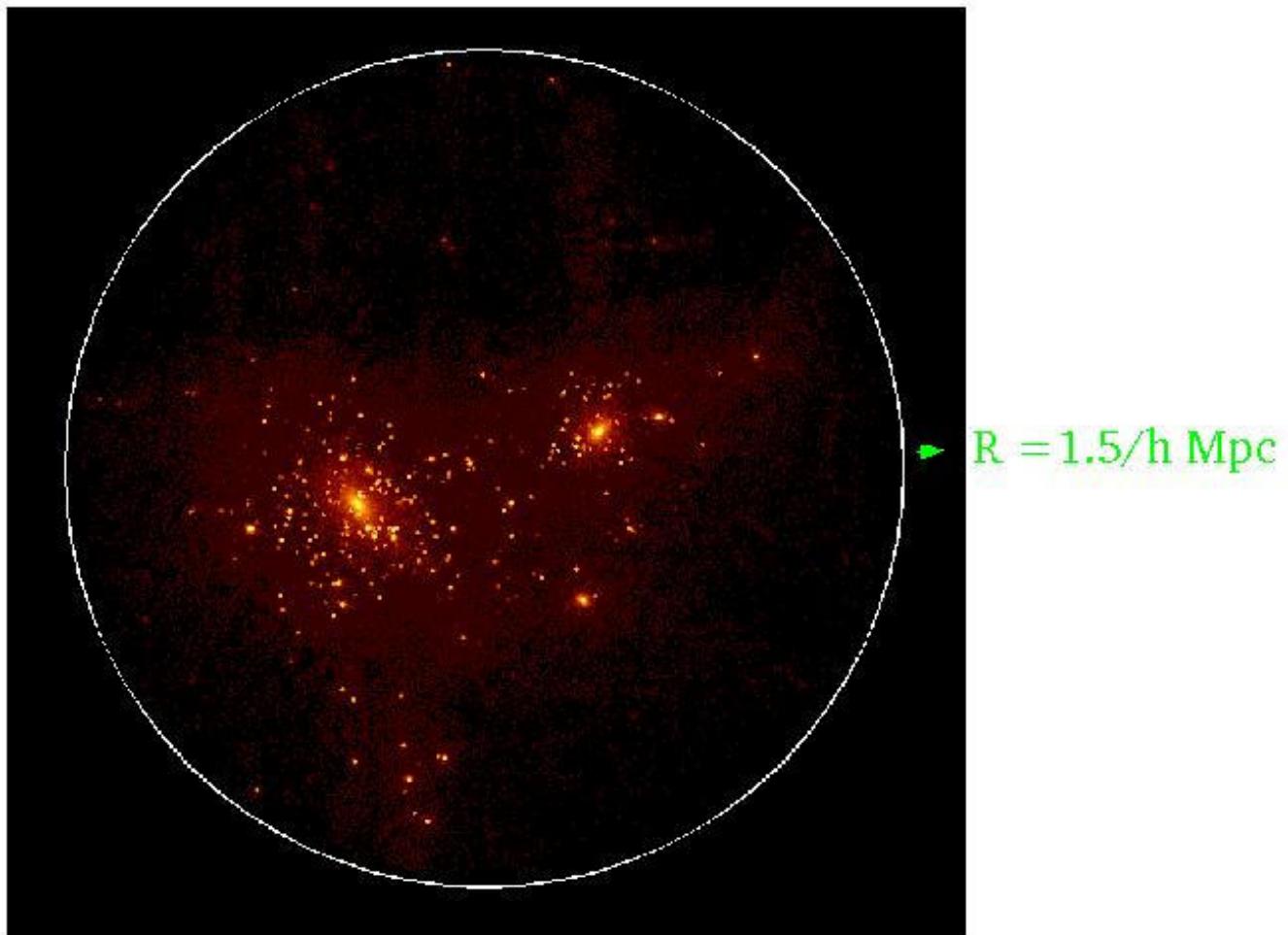


Klypin et al. 1999



Ghigna et al. 2000

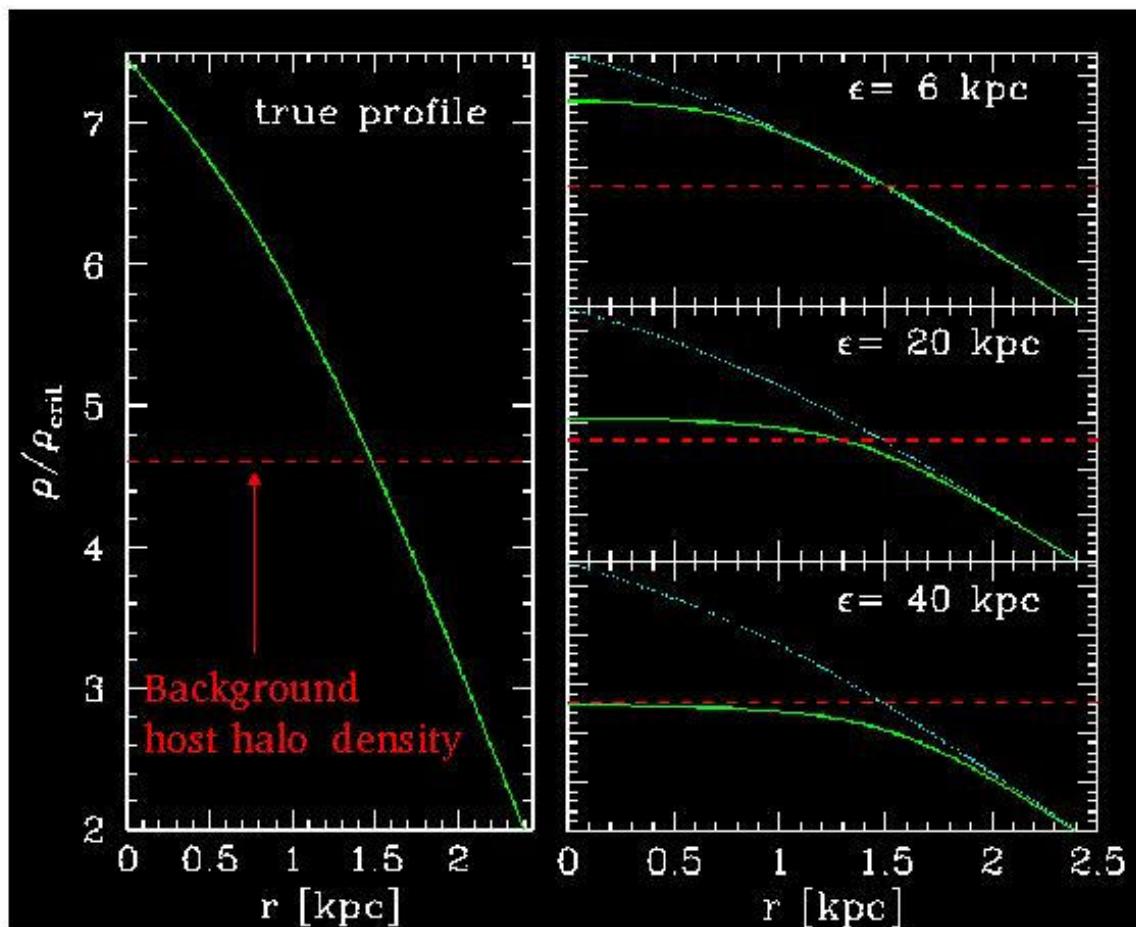
HALOS IN THE SCDM SIMULATION



Klypin, Kravtsov, Valenzuela & Prada 1999

CAUSES OF OVERMERGING

premature tidal disruption of subhalos

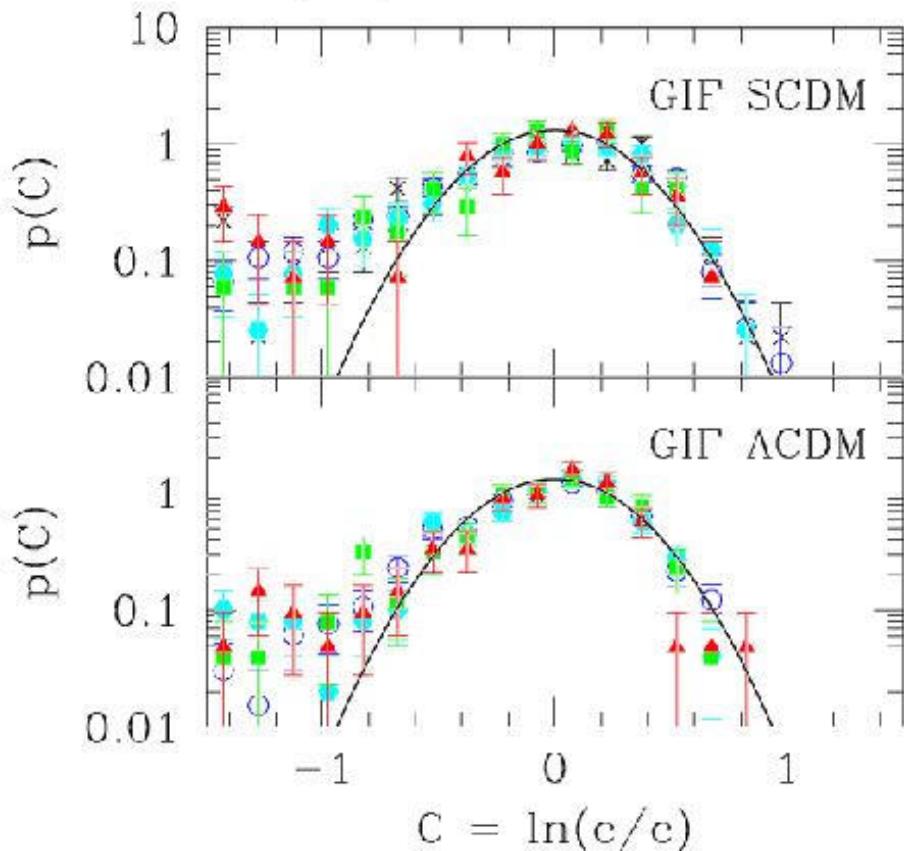


Intrinsic scatter in concentrations

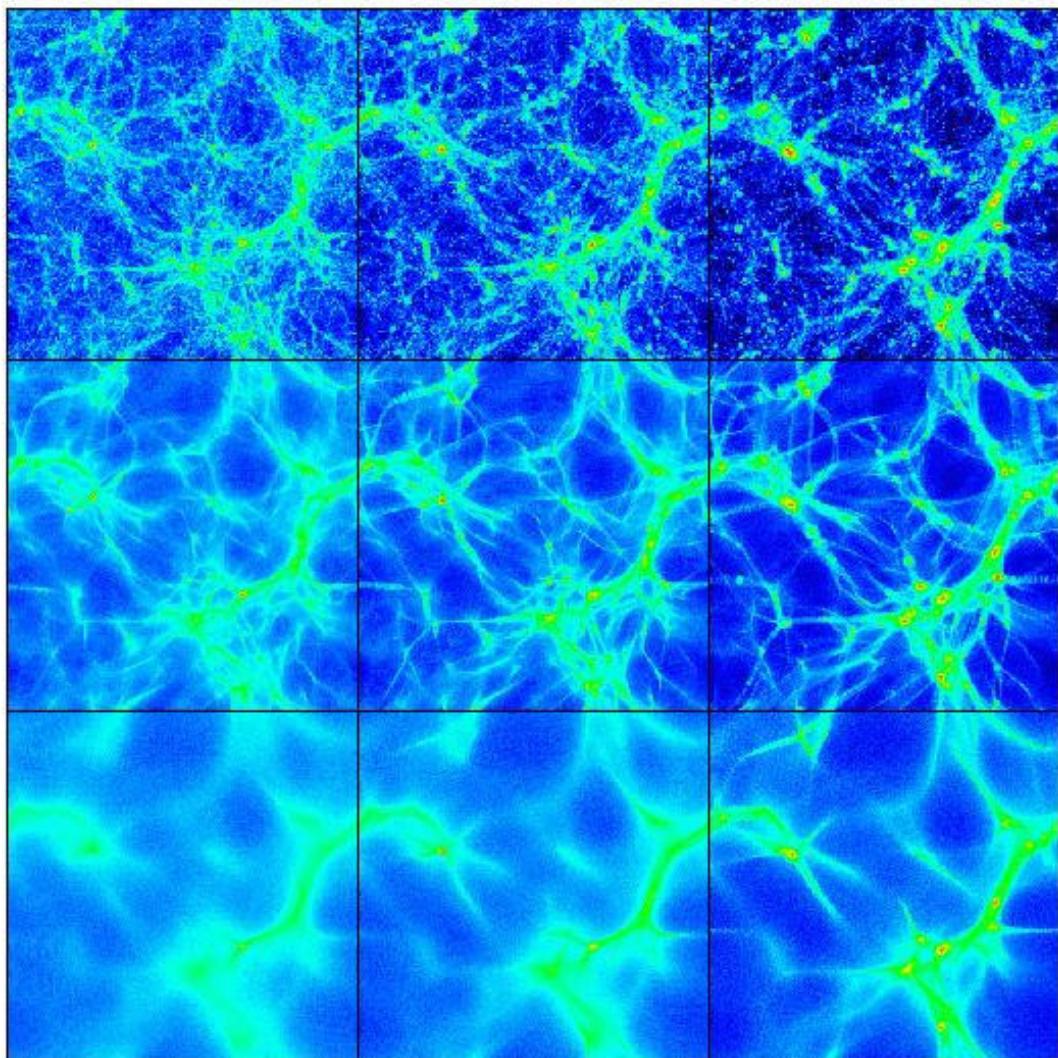
Jing 2000; Bullock et al. 2001

$$\frac{d\bar{n}}{dM dc} = \left(\frac{dn}{dM} \right)_{\text{PS}} p(c), \quad (25)$$

$$p(c)dc = \frac{1}{\sqrt{2\pi\sigma_c^2}} \exp \left[-\frac{(\ln c - \ln \bar{c})^2}{2\sigma_{\ln c}^2} \right] d\ln c,$$



Warm Dark Matter

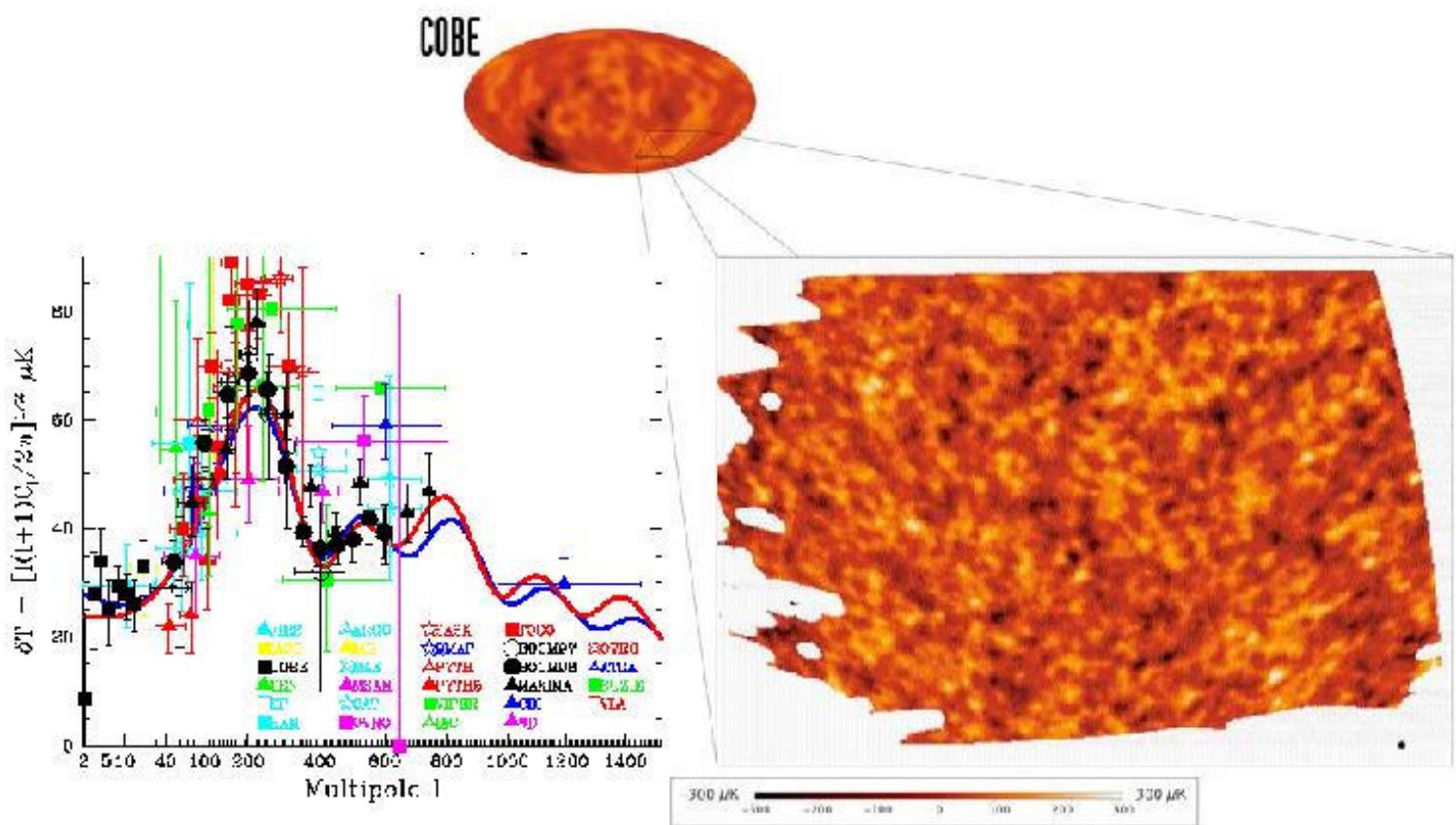


Bode, Ostriker
& Turok 2000

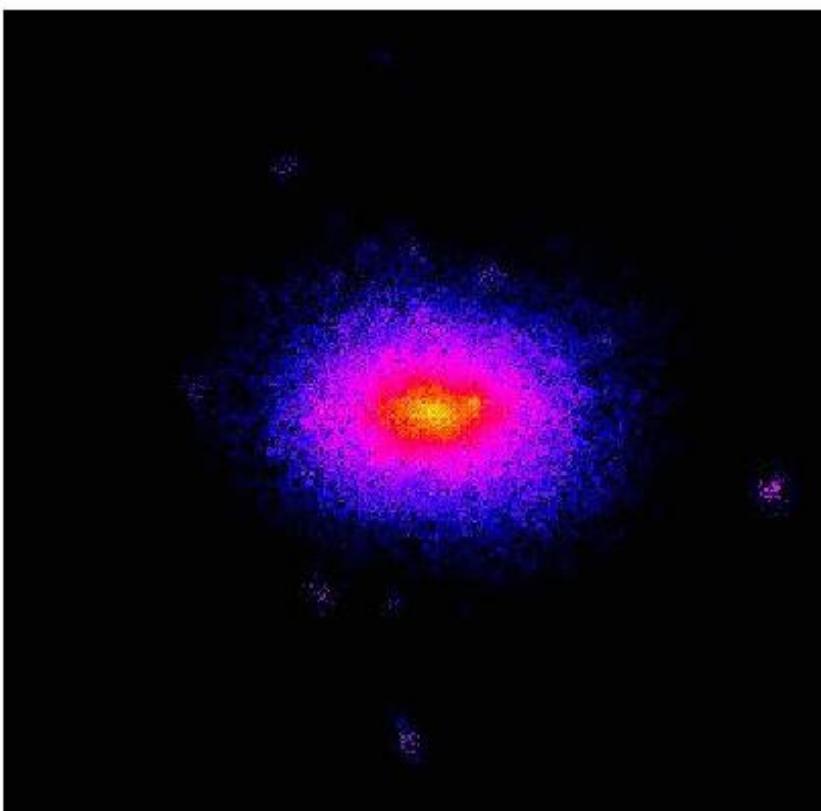
Internal structure of dark matter halos

- Spherically- averaged density profiles of DM halo population can be well described by a universal functional form, although individual profiles can significantly deviate from the average.
- Density profiles of CDM halos are concentrated (e.g., compared to SIS halos) and are cuspy in the inner region.
- CDM halos are triaxial with a well- defined distribution of axis ratios.
- DM halos are not solid body rotators. The internal distribution of specific angular momentum can be described by a 'universal' distribution but again distributions of individual halos may exhibit scatter.
- Baryons and dark matter have similar angular momentum distributions.
- We have promising models of angular momentum evolution and distribution of dark matter, but not for baryons.
- How angular momentum of gas disk forming inside a halo is related to the angular momentum of the host halo and what processes are responsible for any differences remains a mystery.

CMB FLUCTUATIONS AT $Z \sim 1000$



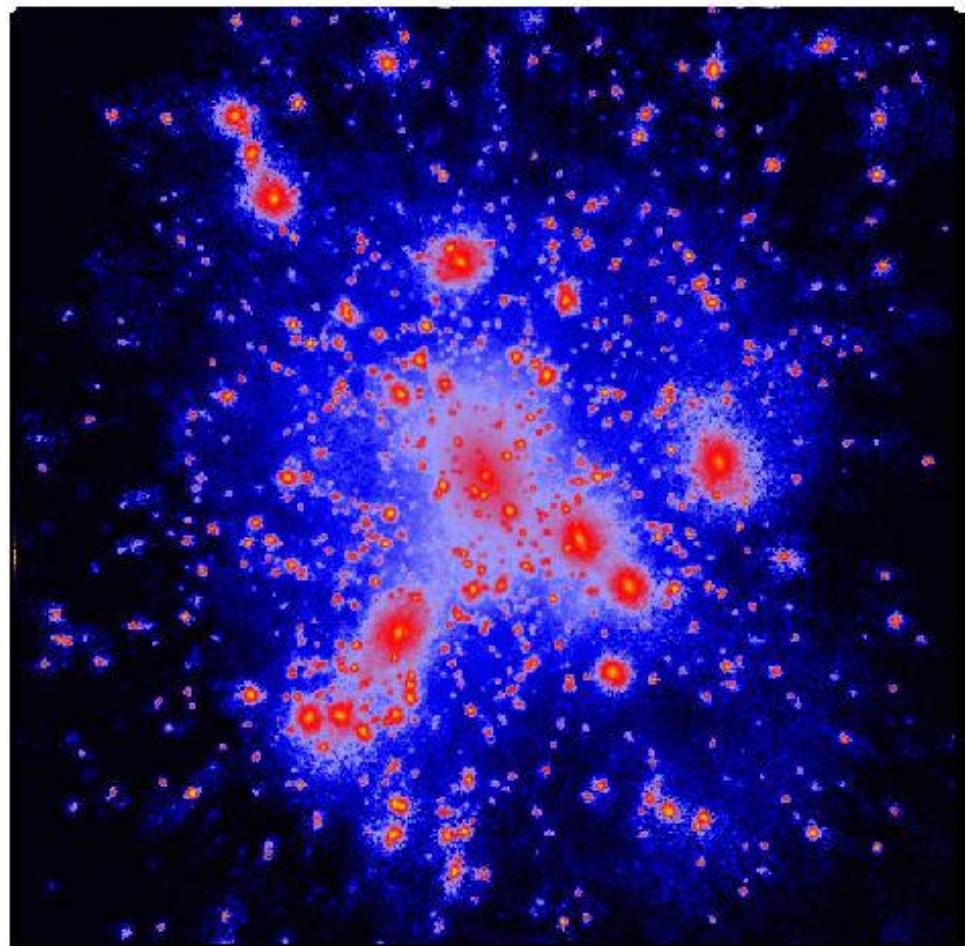
“OVERMERGING” PROBLEM



‘... by no stretch of the imagination does one form “galaxies” in the current cosmological simulations: the physical model and dynamic range are inadequate to follow any but the crudest details...’

Summers et al. 1995, ApJ 454, 1

“OVERMERGING” NO MORE



Credit: B. Moore (nbody.net)

Klypin, Kravtsov &
Gottloeber 1998

Ghigna et al. 1998

Tormen et al. 1998, 1999