TR33: kick-off meeting
Heidelberg, Nov. 2006

Simulating the Dark Universe

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Simulation Input to Precision Cosmology

- Precision Large-Scale Structure: Cosmic Shear
  -- $P(k, z)$, $N_{halo}(M, z)$, $S_3(z)$, $S_4(z)$, Ω_m, Ω_Λ, $w(z)$...
- Halo Core Structure and Ellipticity: Arc Abundances
  -- Cross-sections for tangential/radial arcs
  -- Implications for nature of DM, assembly history of galaxies
- Substructure Abundances:
  -- Detection of 'invisible' subhaloes (e.g. multiply imaged QSO)
  -- Test of CDM power spectrum and nature of DM
- Relation of Halo to Galaxy/ICM/IGM Properties
  -- Structure in the Ly α forest
  -- Luminosity/stellar mass/L_x /T_x halo mass relations
  -- Halo truncation in clusters -- nature of DM
  -- Evolution of bias, BAO to measure $w(z)$

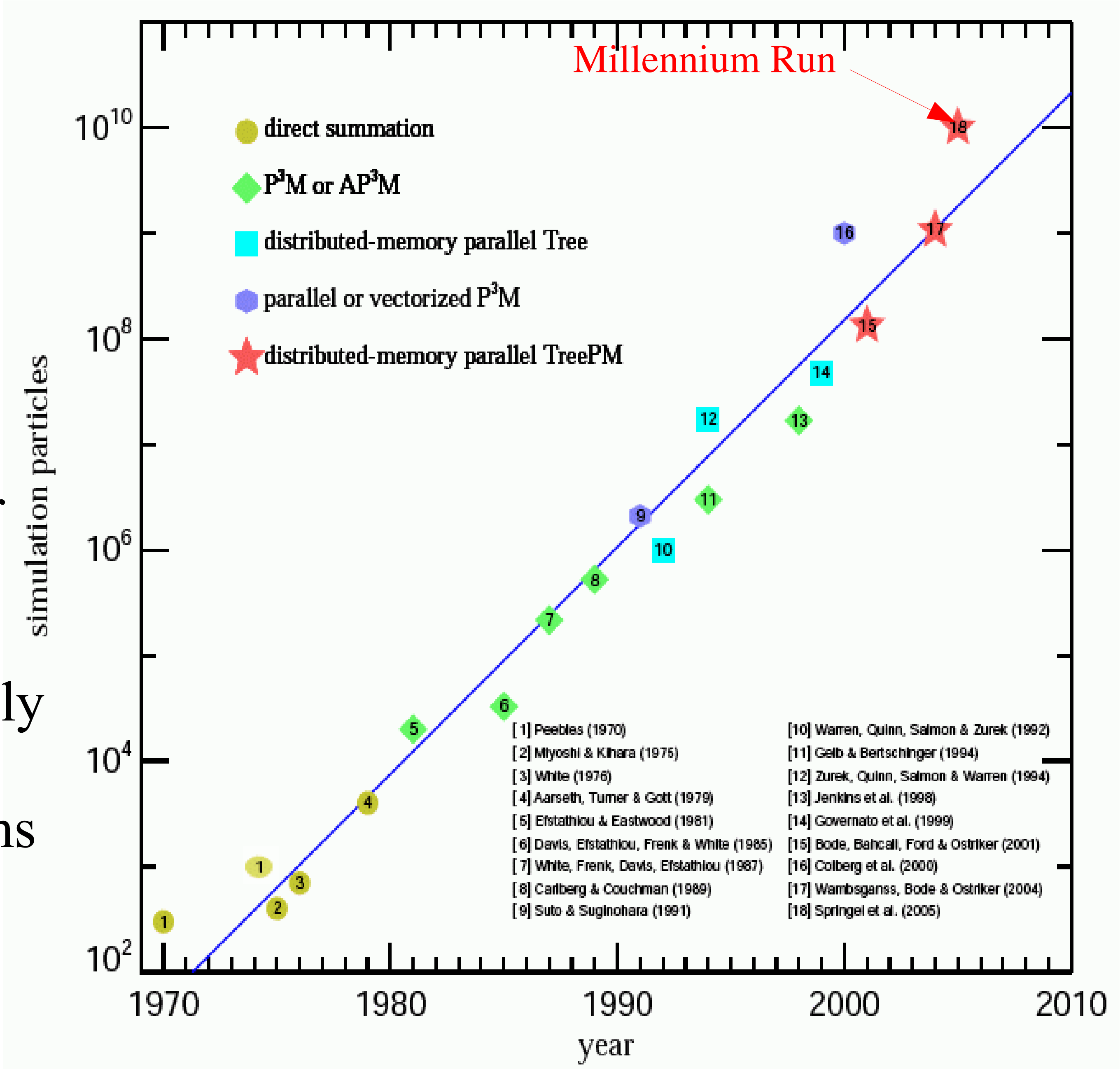
Requirements for a Precision Simulation

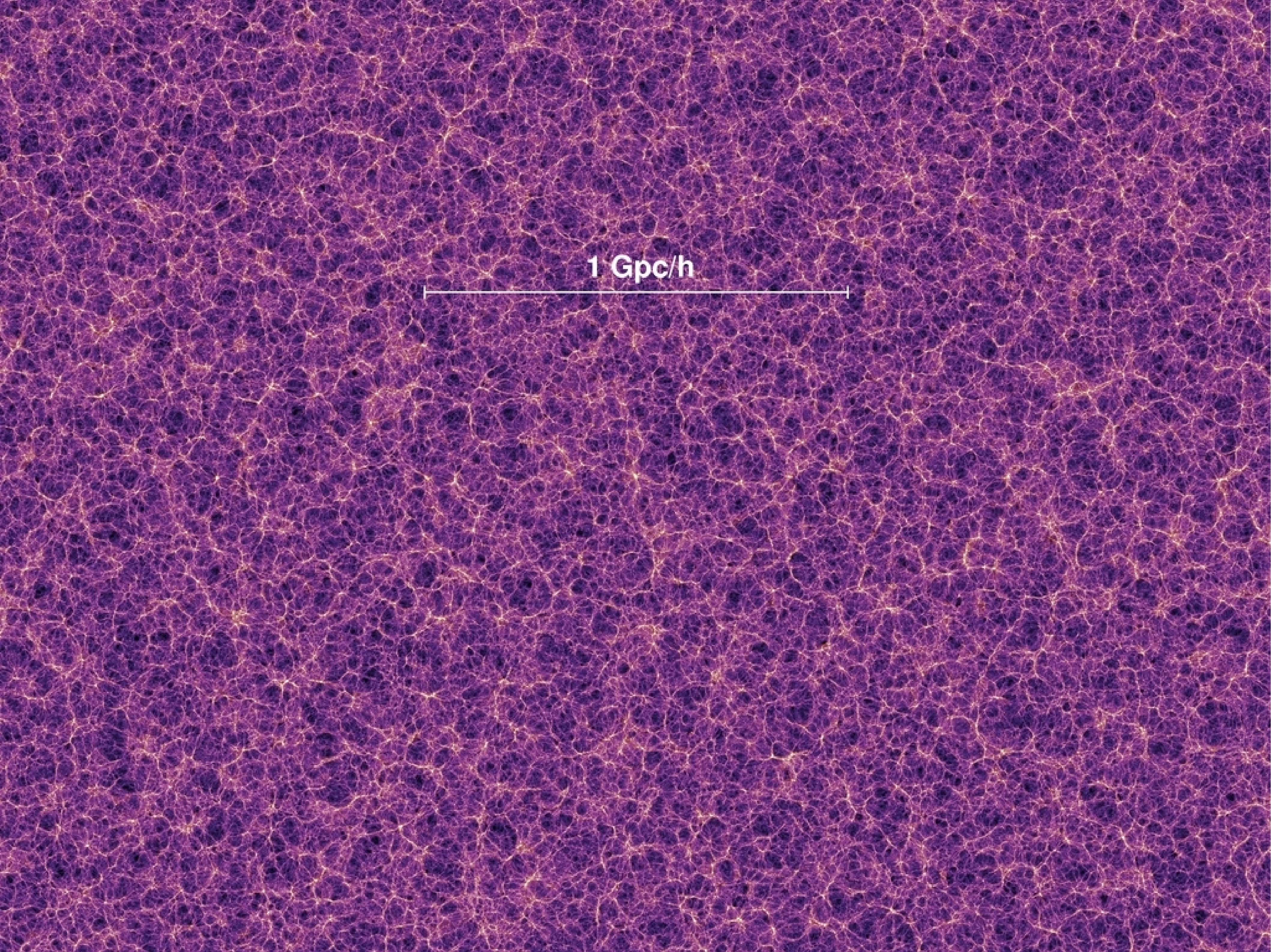
- Large volume to reduce cosmic variance
- Small particle mass to suppress shot-noise/2-body effects
- Proper representation of ΛCDM initial conditions
- Accurate forces in near uniform and highly non-uniform regimes
- Accurate time integration, even at high density
- Adequate treatment of baryonic physics
- Proper representation of observational procedures

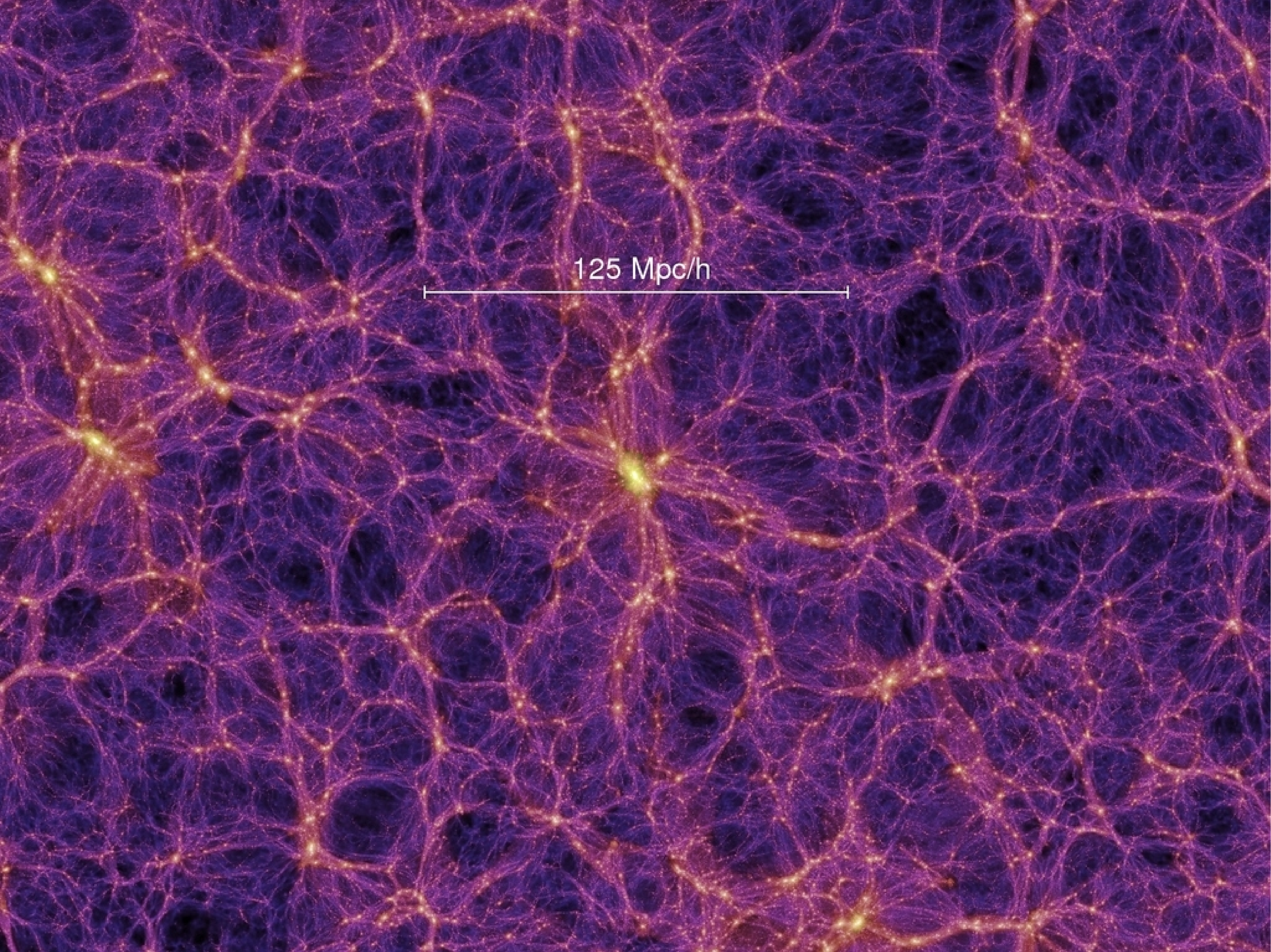
Moore's Law for Cosmological N-body Simulations

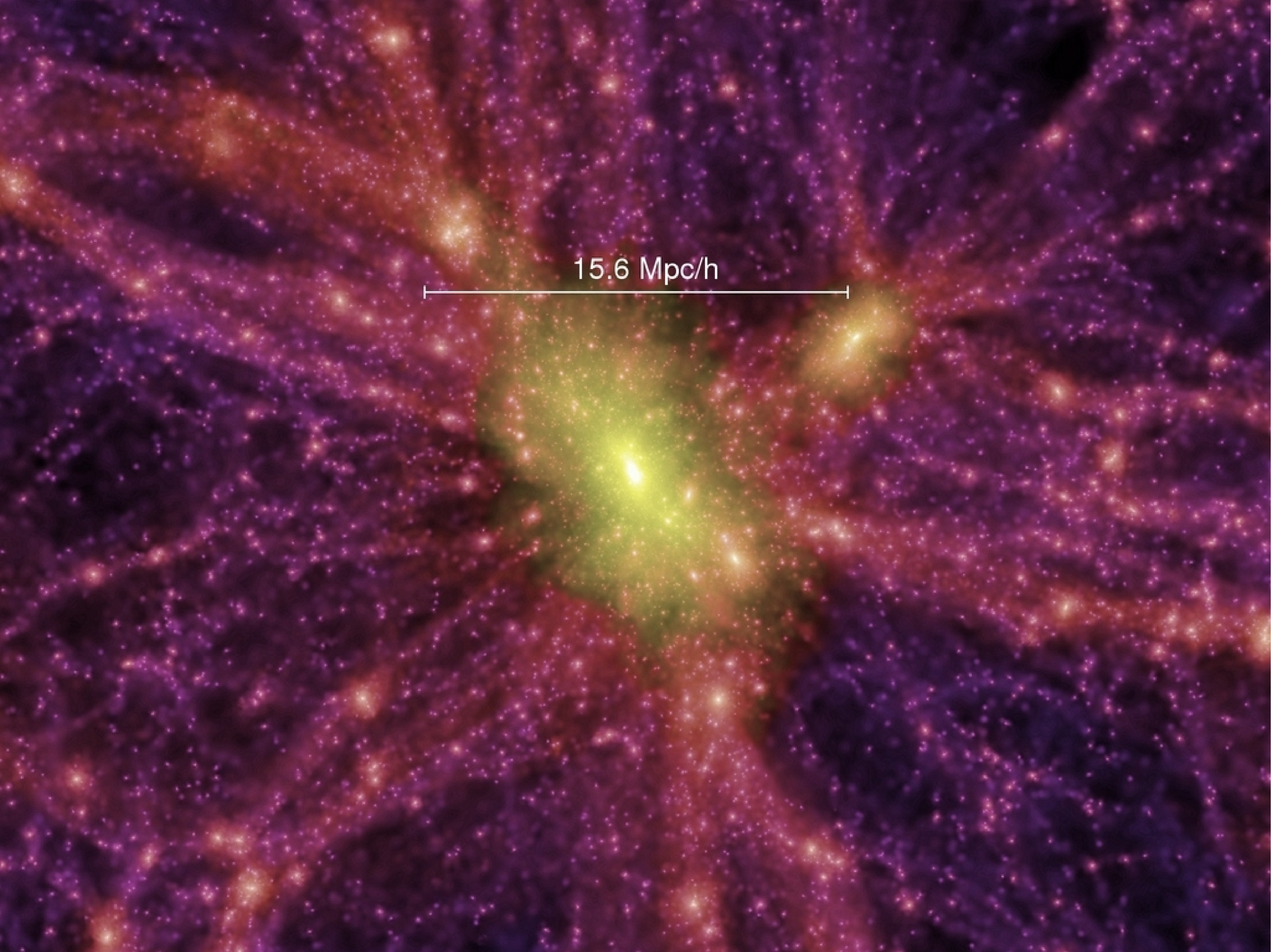
Springel et al 2005

- Computers double their speed every 18 months
- A naive N-body force calculation needs N^2 op's
- Simulations double their size every 16.5 months
- Progress has been roughly equally due to hardware and to improved algorithms




1 Gpc/h

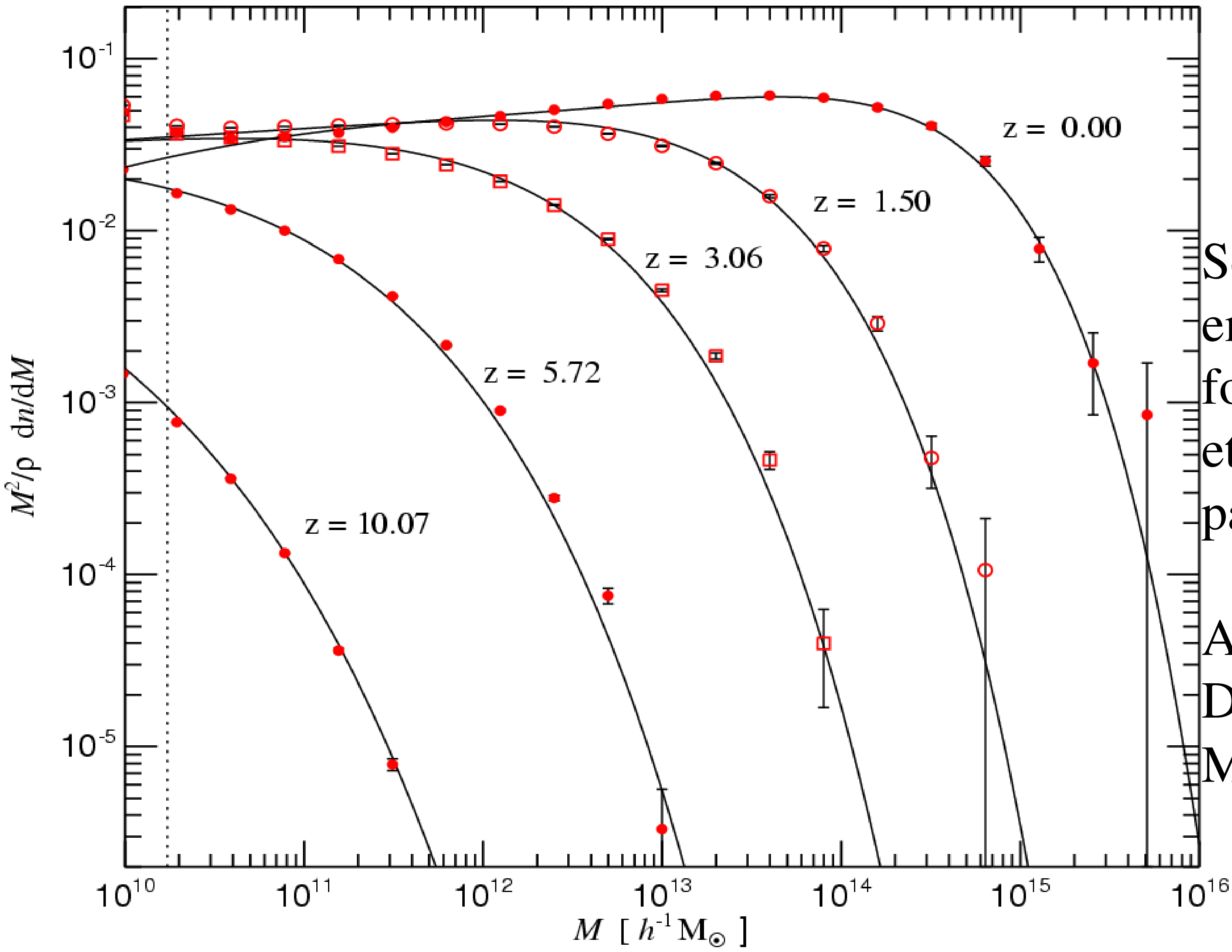

125 Mpc/h


15.6 Mpc/h


3.9 Mpc/h

Halo Mass Functions in the MS

Springel et al 2005

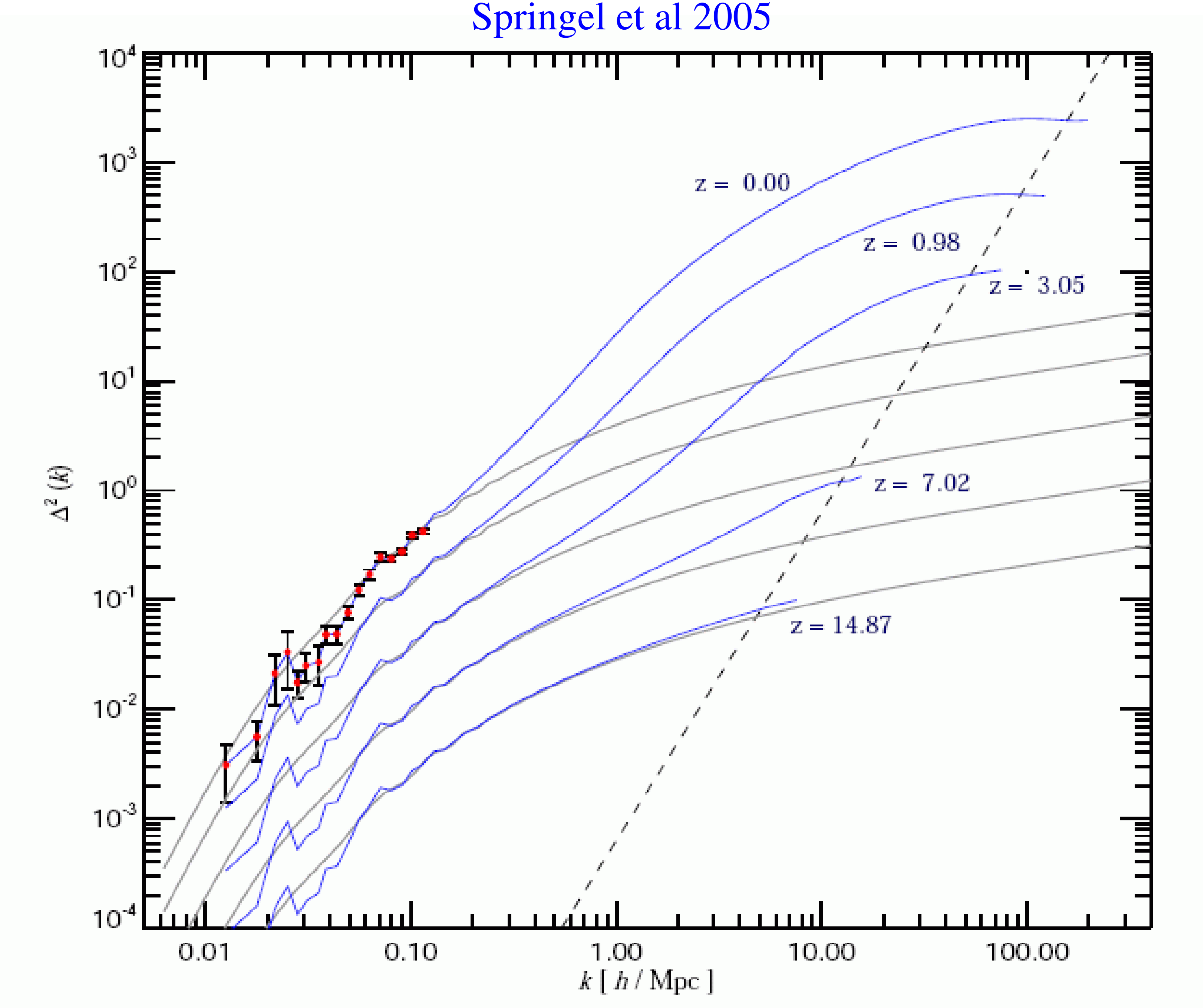


Solid curves are the empirical fitting formula from Jenkins et al 2001 with no parameters adjusted

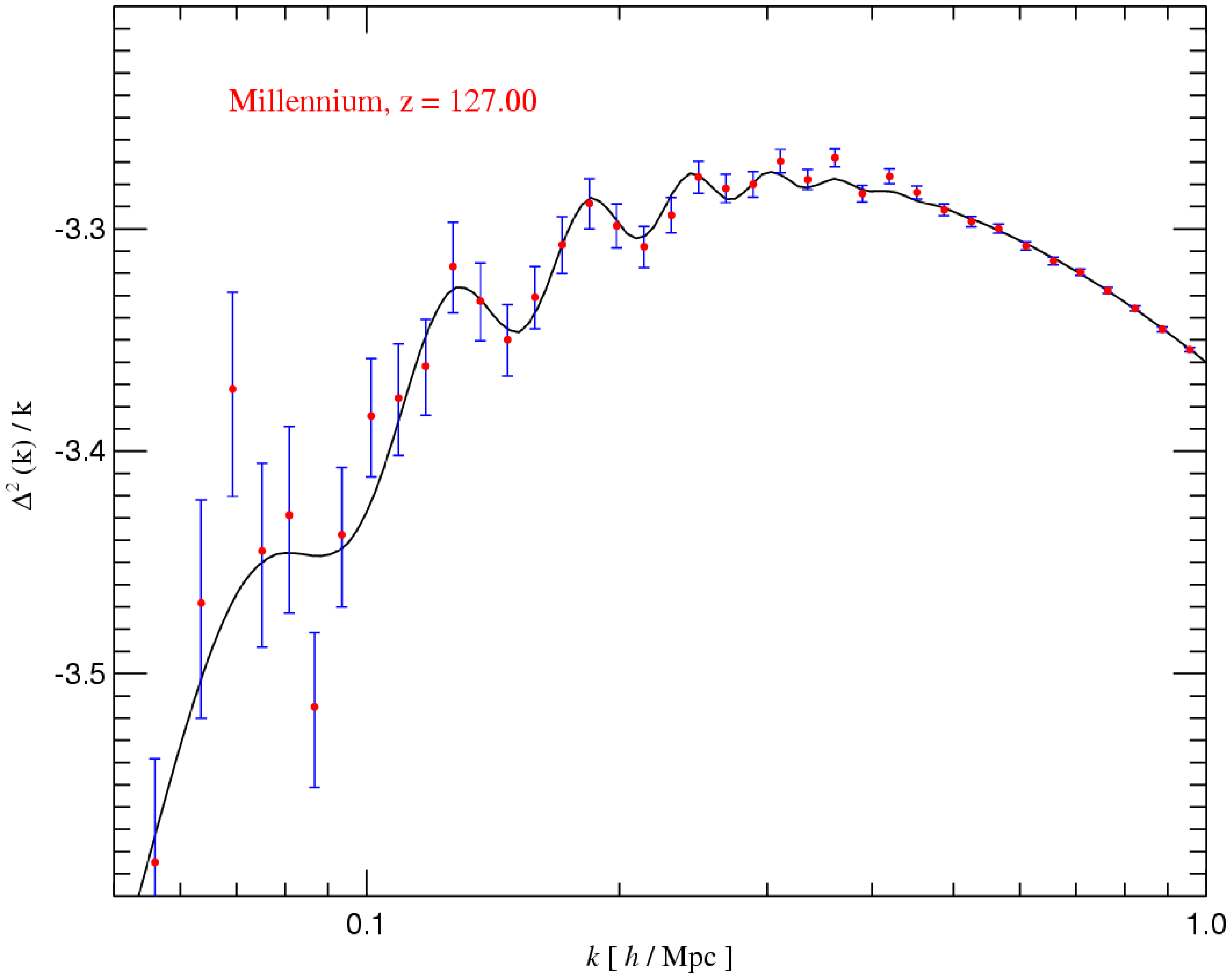
At z = 0 half of all DM is in lumps of $M > 2 \times 10^{10} M_\odot$

Mass Power Spectra in the MS

Springel et al 2005



The Evolution of the Baryonic 'Wiggles'



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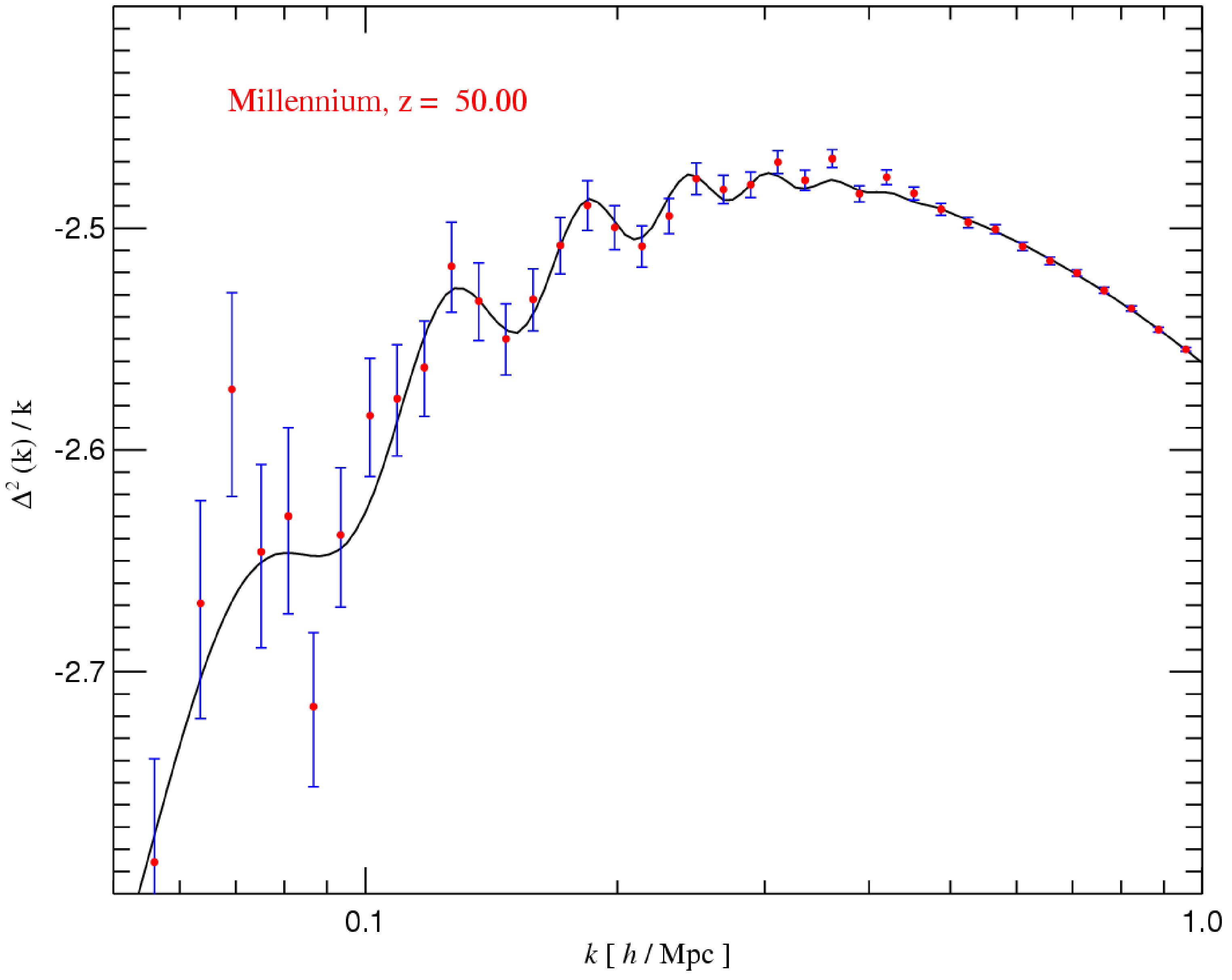

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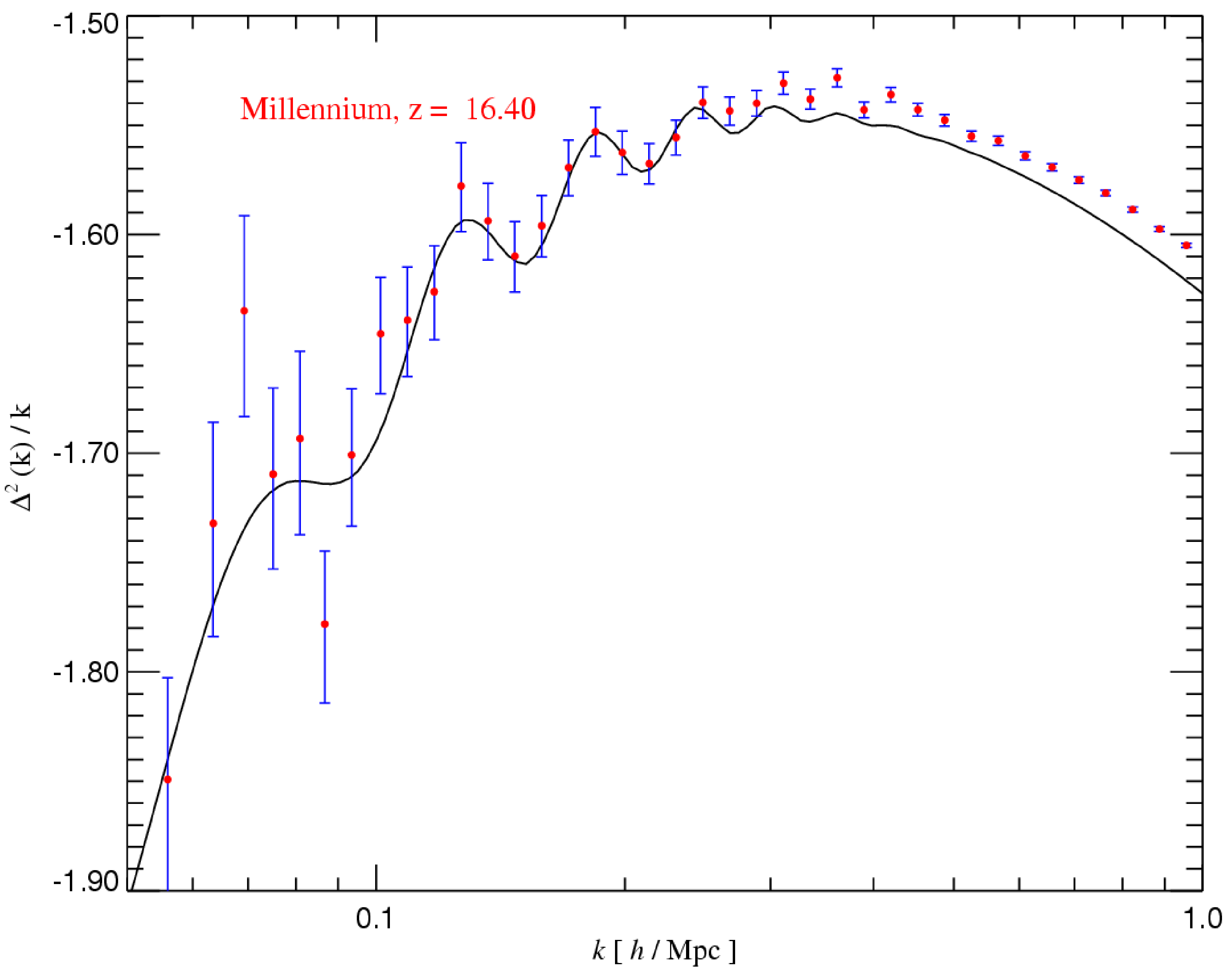

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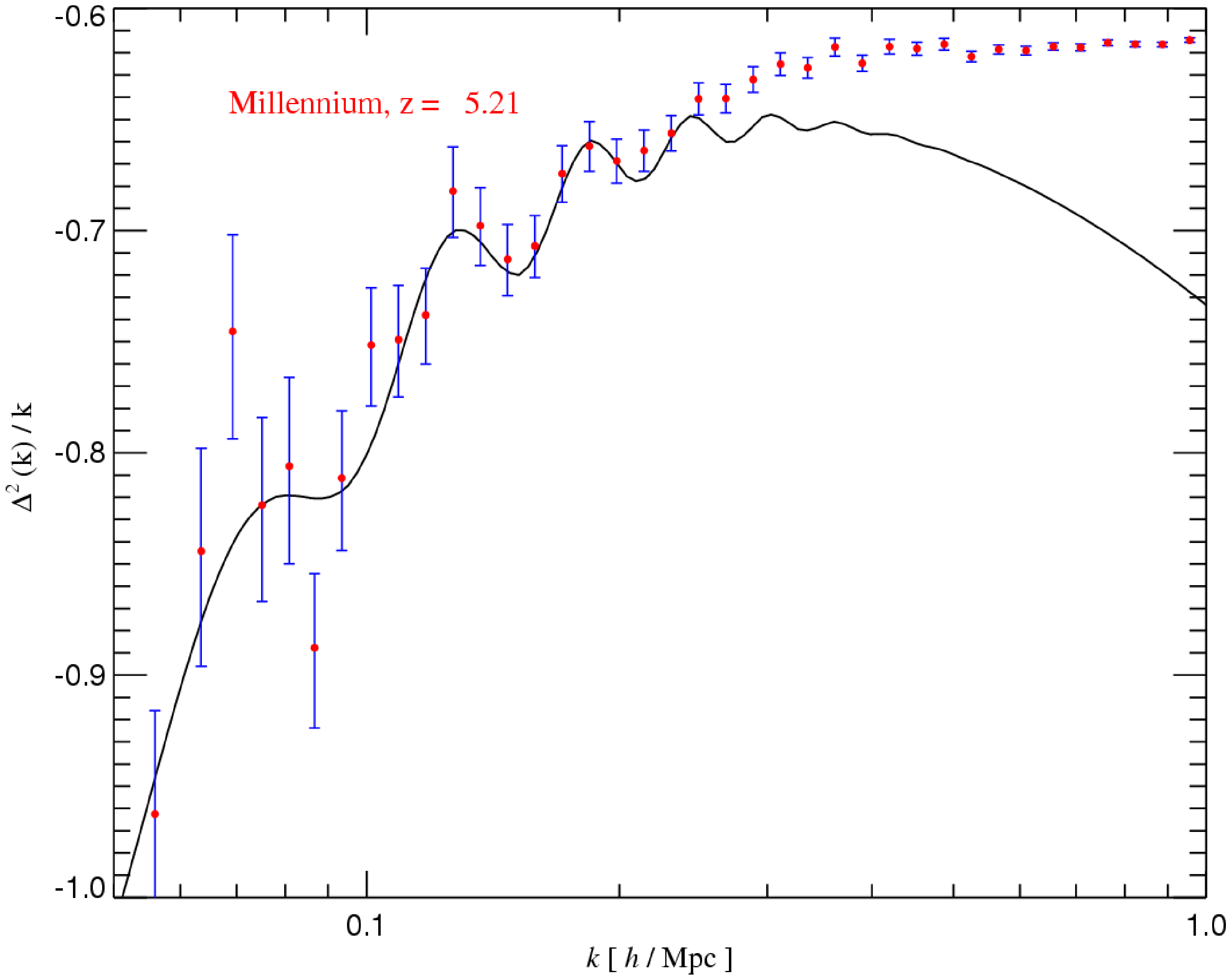

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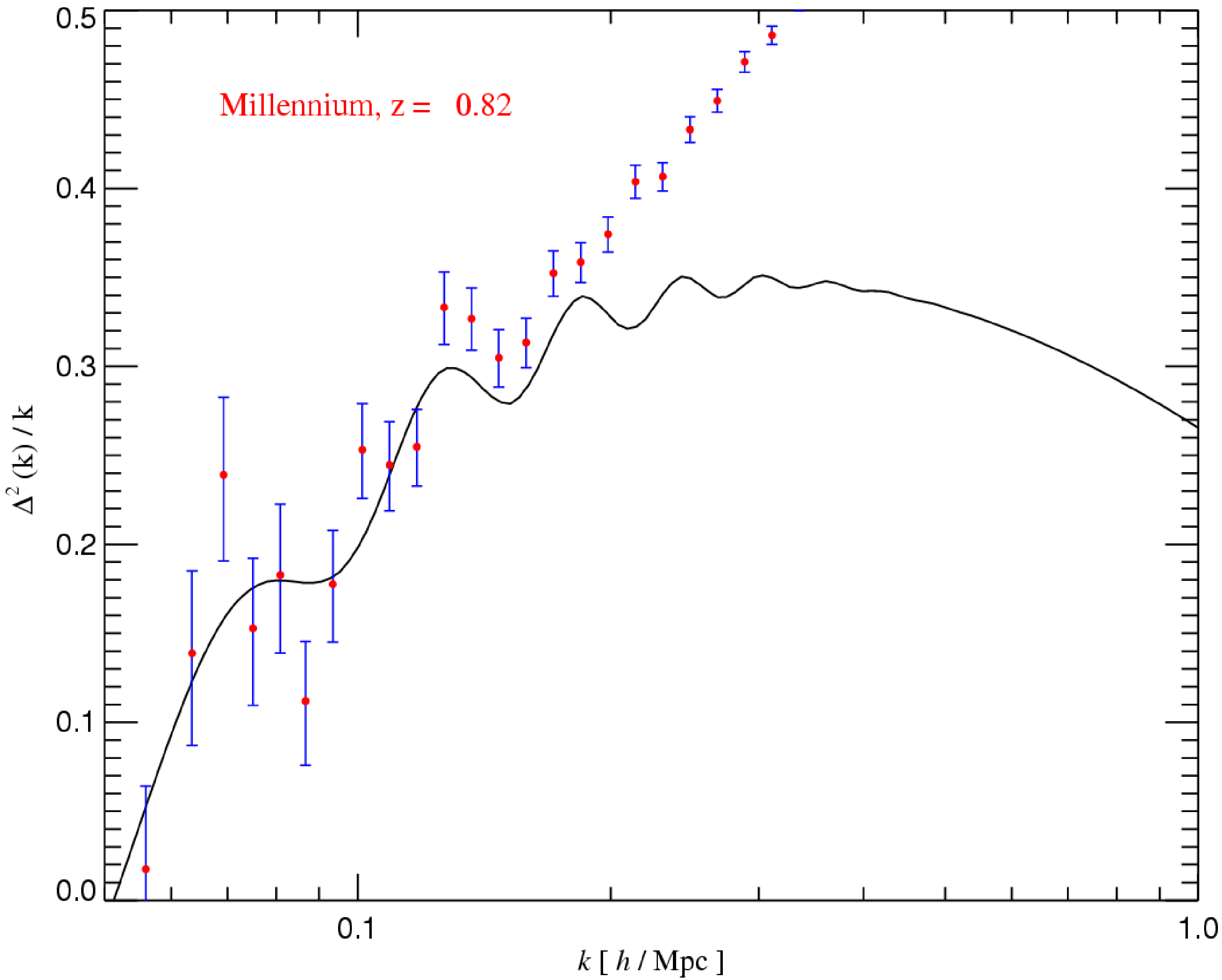

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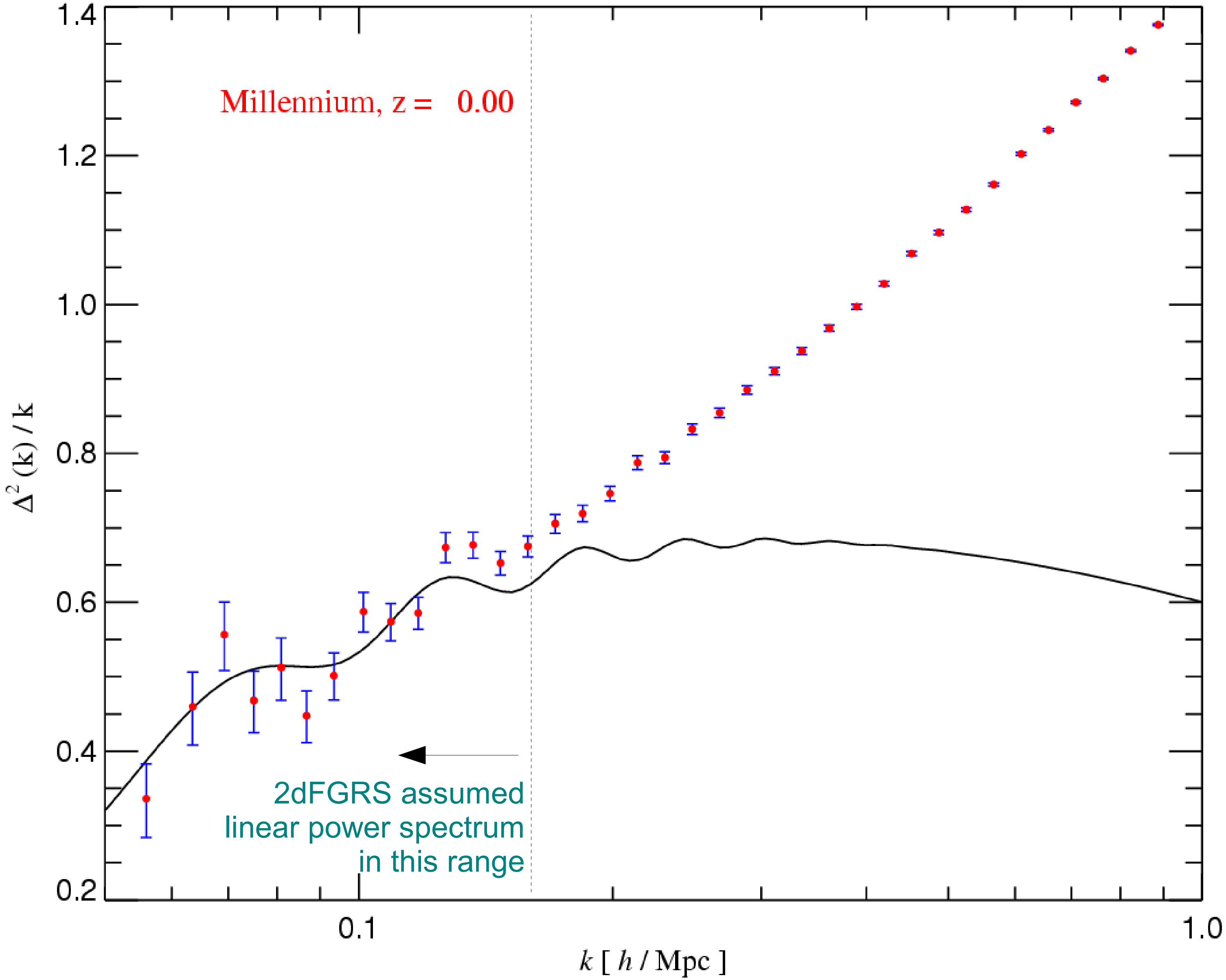
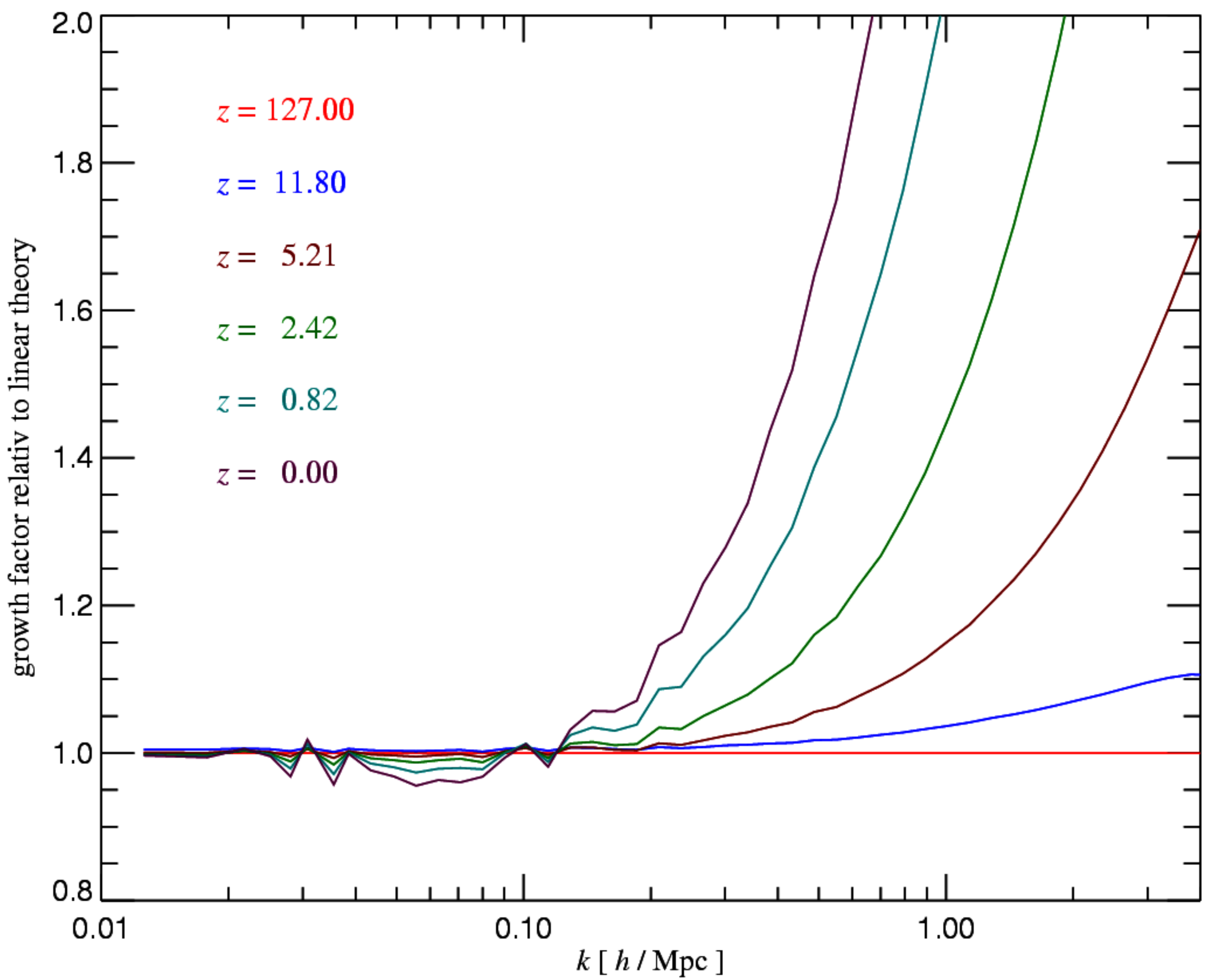
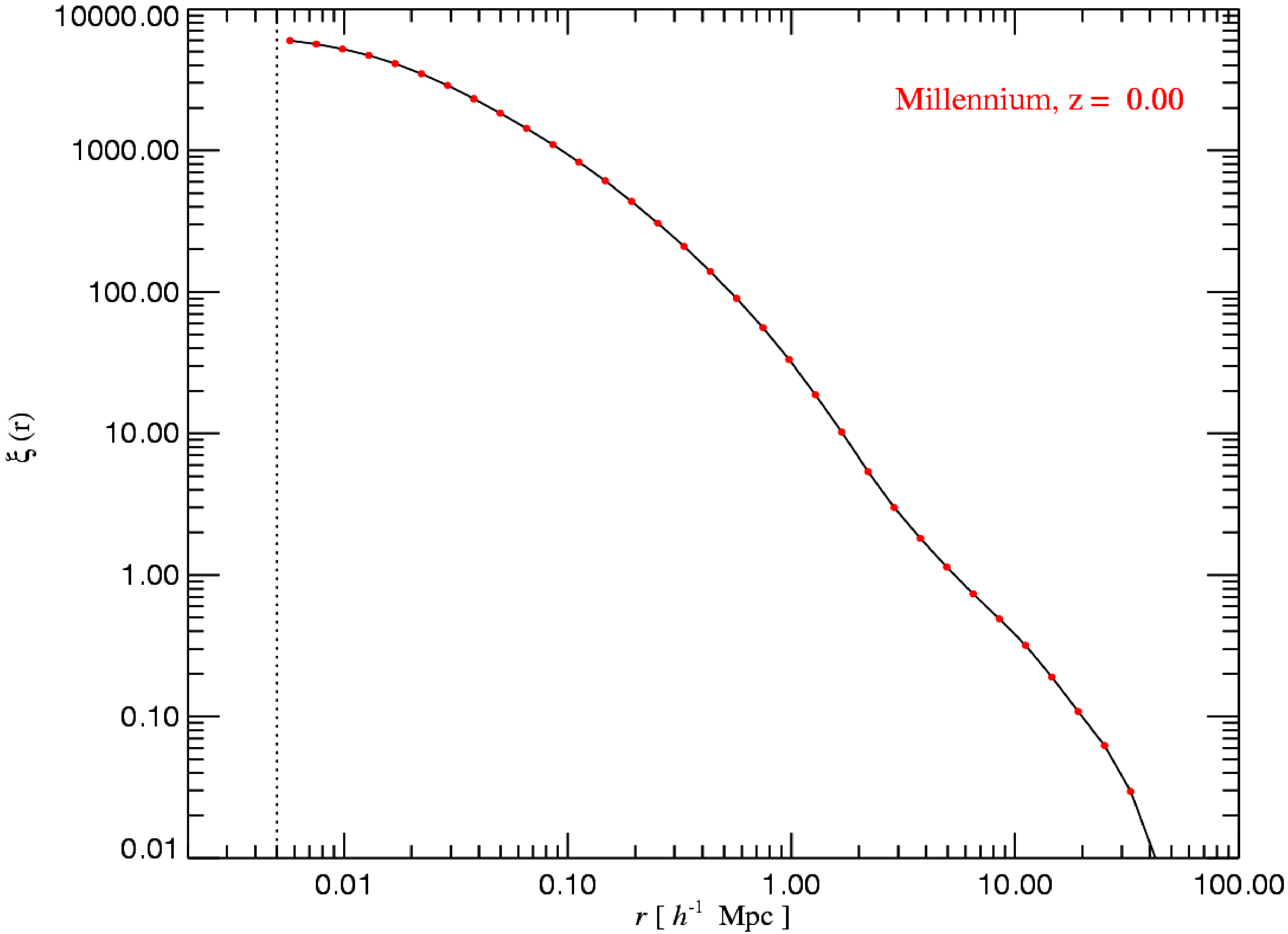


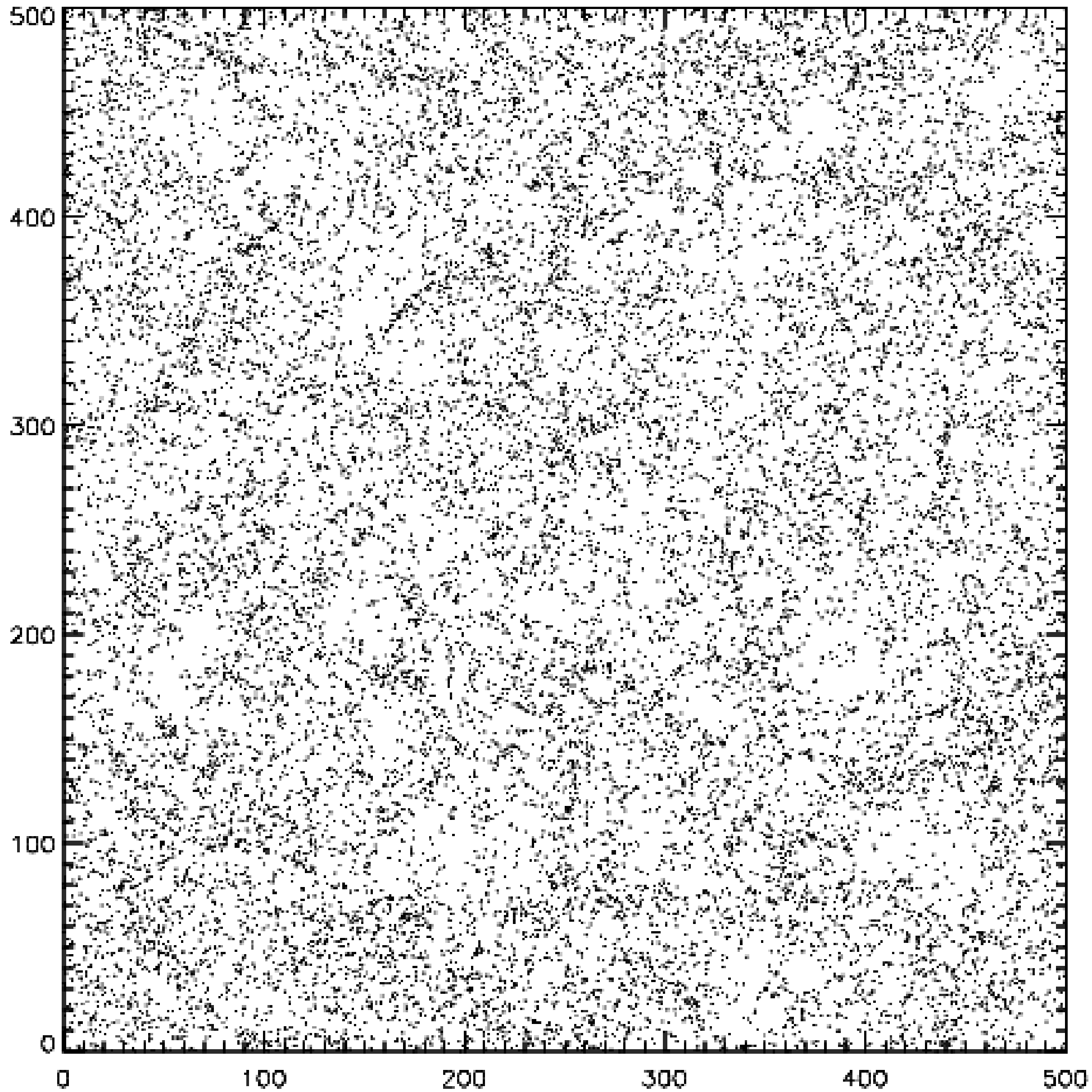
Growth relative to linear as a function of scale



Mass autocorrelation function



Does halo clustering depend on formation history?



Gao, Springel & White 2005

The 20% of halos with the *lowest* formation redshifts in a 30 Mpc/h thick slice

$M_{halo} \sim 10^{11} M_{\odot}$

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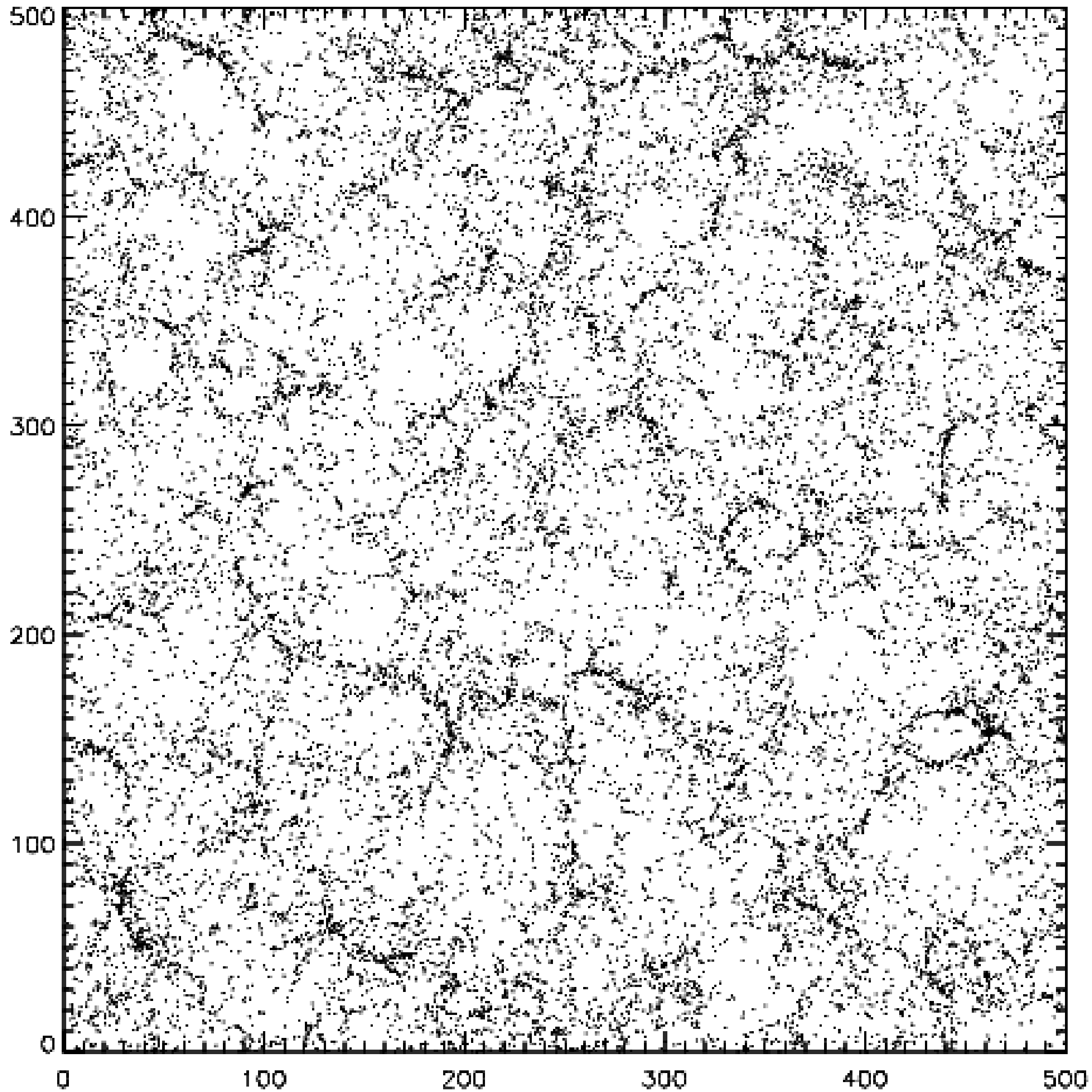
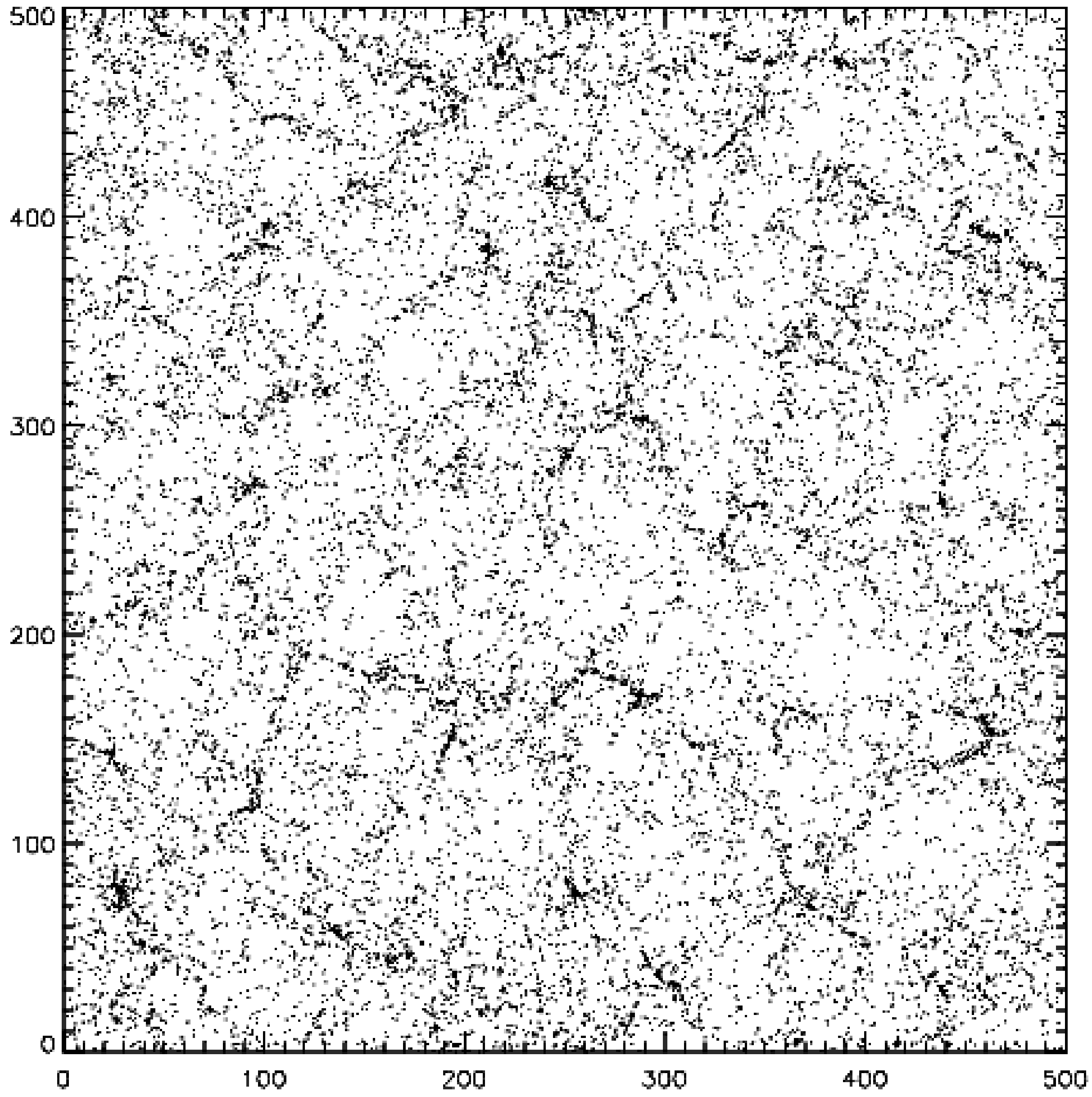


Gao, Springel & White 2005

The 20% of halos with the ***highest*** formation redshifts in a 30 Mpc/h thick slice

$$M_{halo} \sim 10^{11} M_{\odot}$$

Does formation history depend on environment?

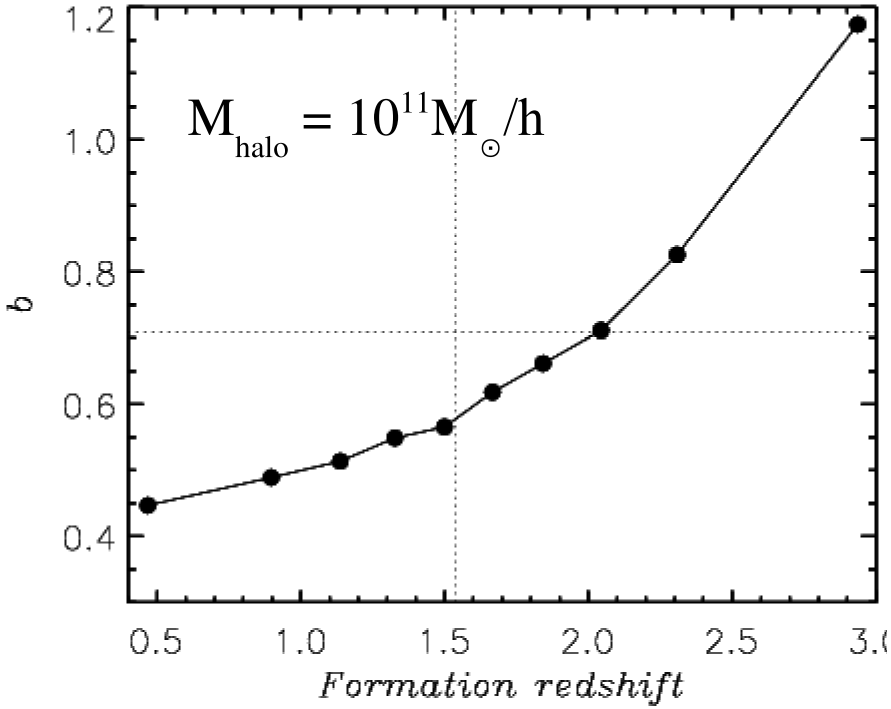


Gao, Springel & White 2005

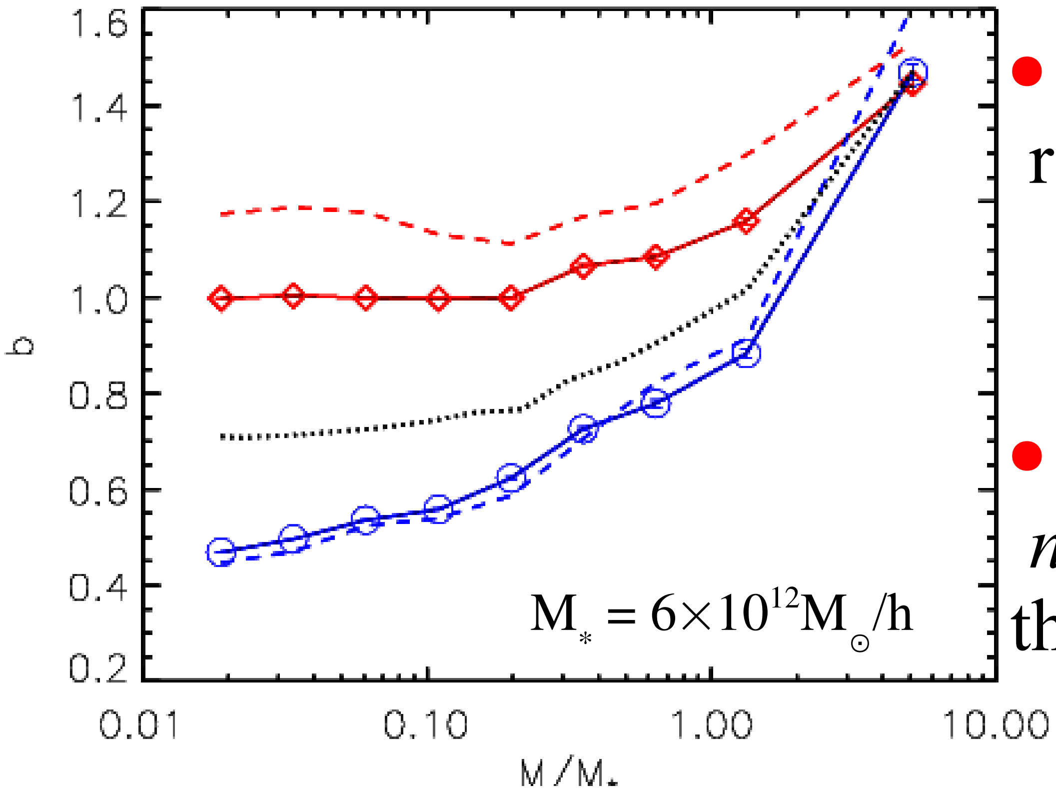
An equal number of randomly chosen DM particles

Halo bias as a function of mass and formation time

Gao, Springel & White 2005



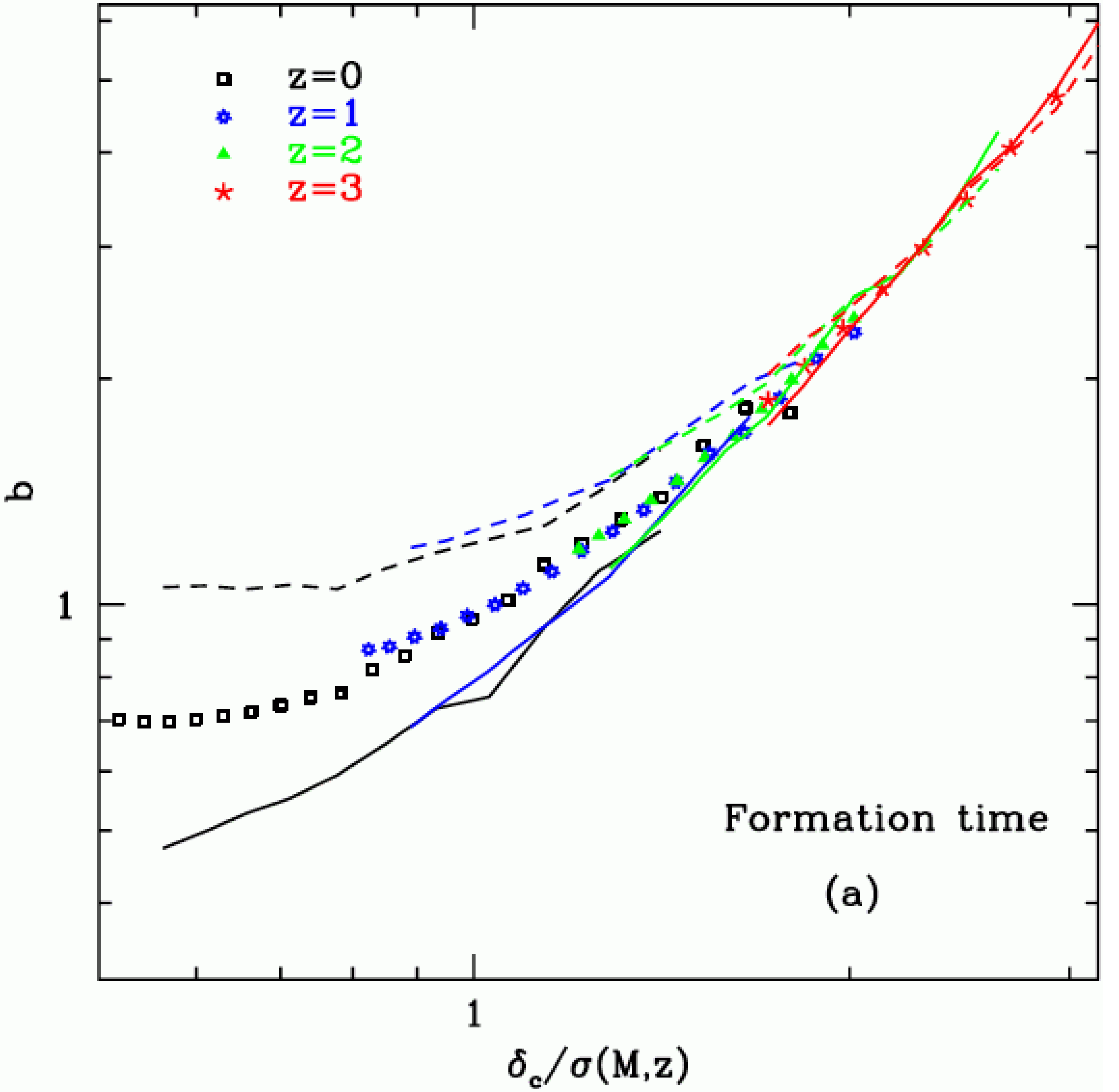
- Bias increases smoothly with formation redshift



- The dependence on formation redshift is strongest at low mass
- This dependence is consistent *neither* with excursion set theory *nor* with HOD models

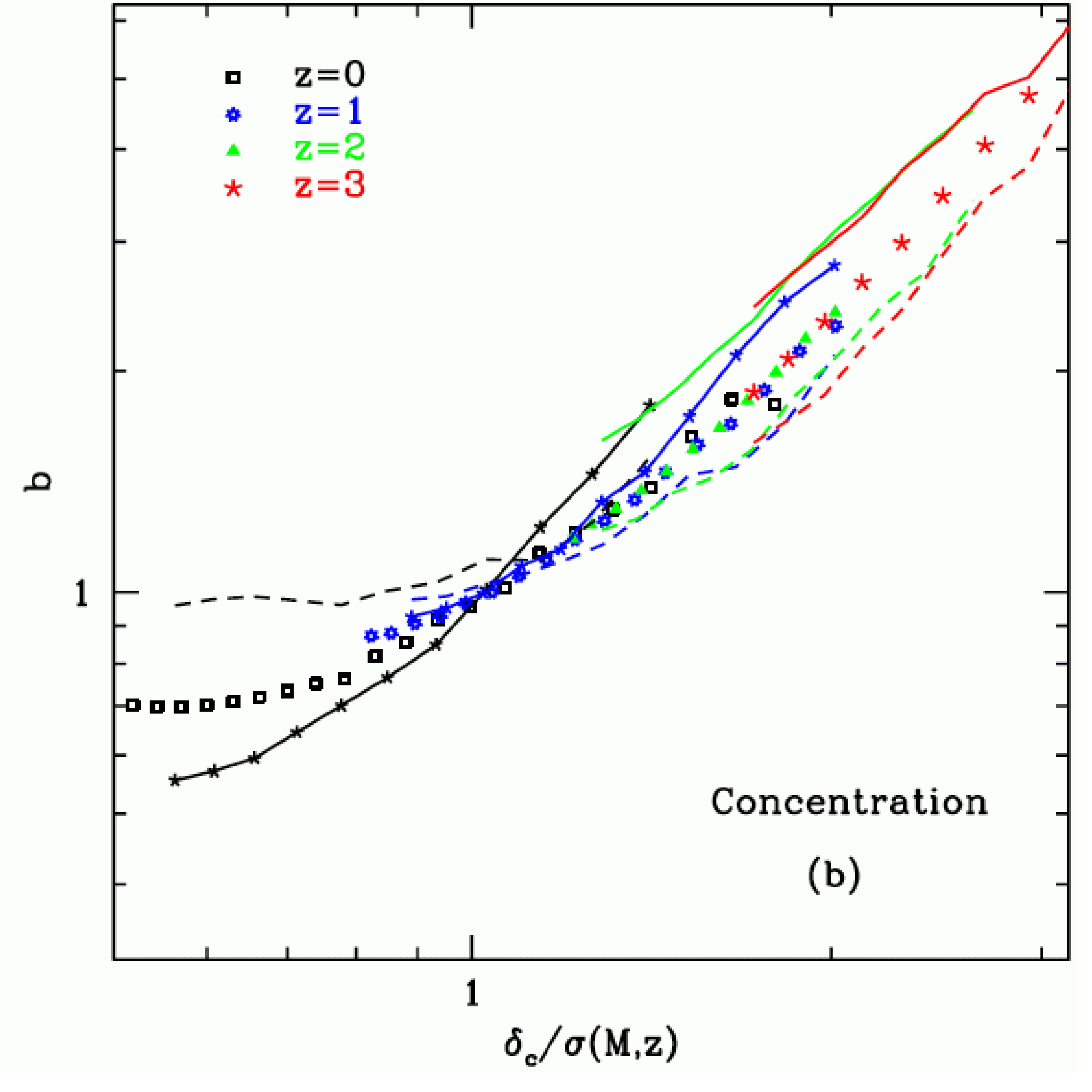
Halo bias as a function of mass and formation time

Gao & White 2006



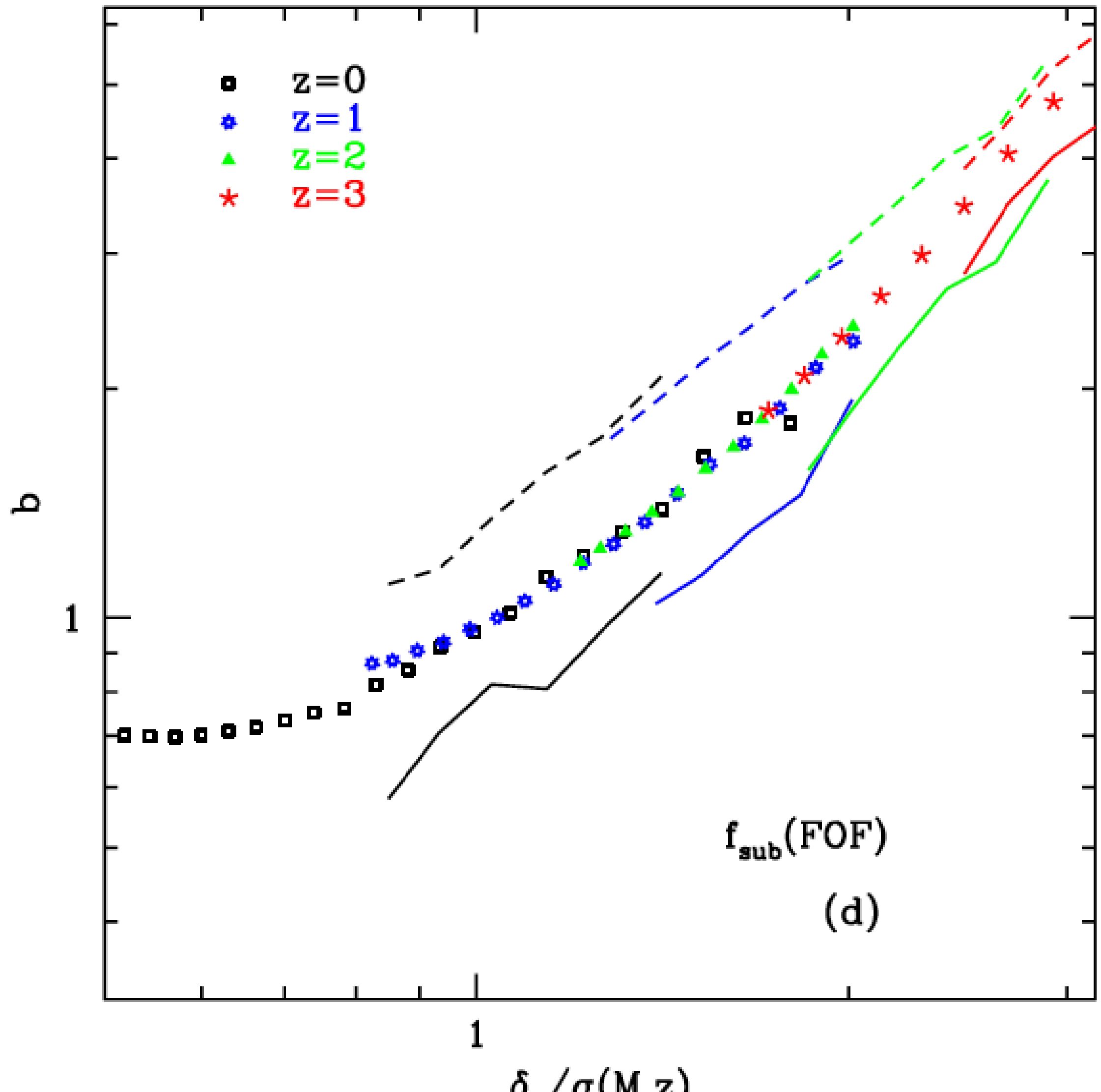
Halo bias as a function of mass and concentration

Gao & White 2006



Halo bias as a function of mass and substructure

Gao & White 2006



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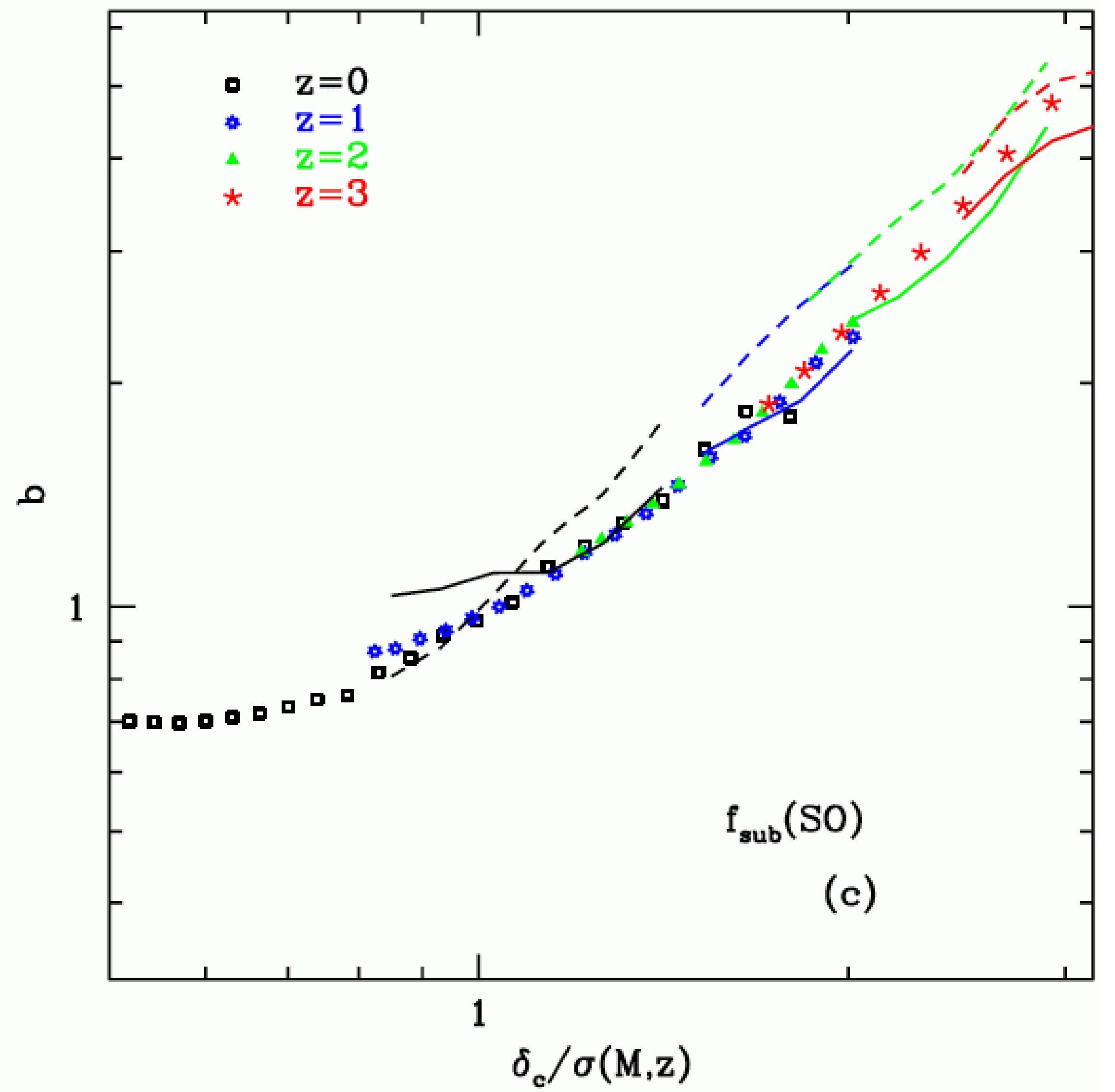
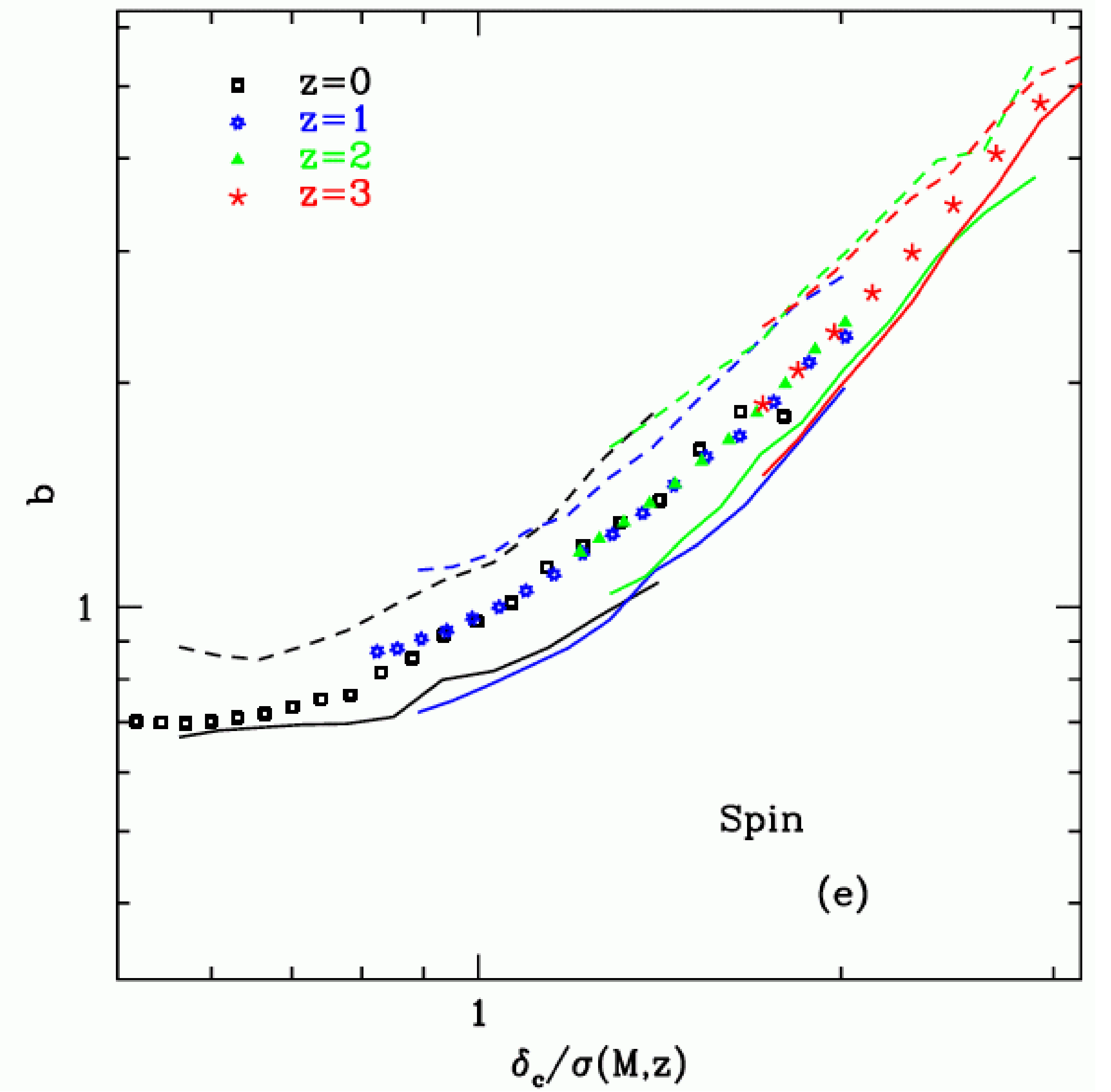
Gao & White 2006



Halo bias as a function of mass and spin

Gao & White 2006



Physics for Galaxy Formation Modelling

Gas Cooling and Condensation

Sensitive to metal content, phase structure, UV background...

Star Formation

No *a priori* understanding -- efficiency? IMF?

Stellar Feedback

SF regulation, metal enrichment, galactic winds

Stellar Aging

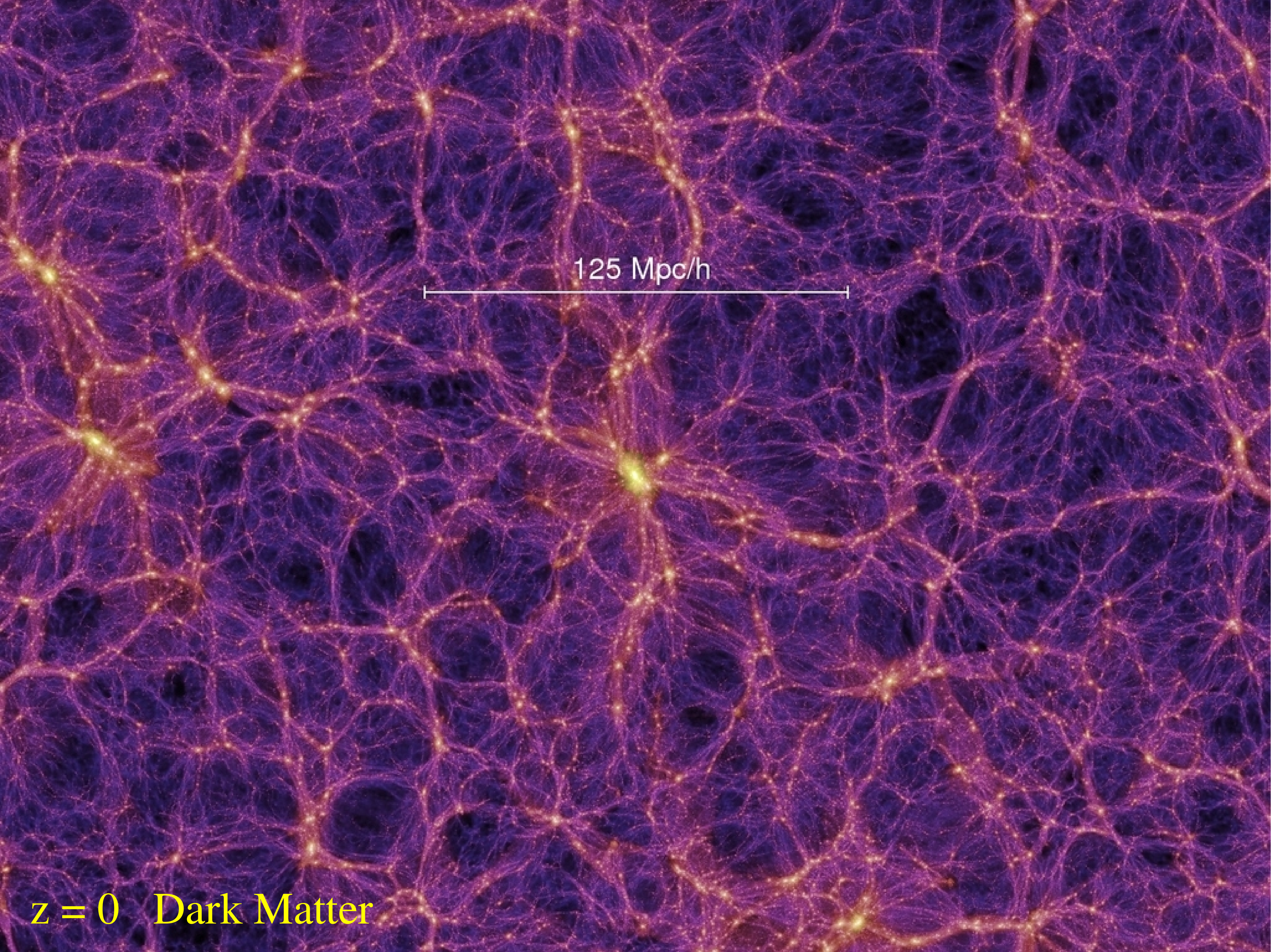
Population synthesis → luminosities, colours, spectra, (dust?)

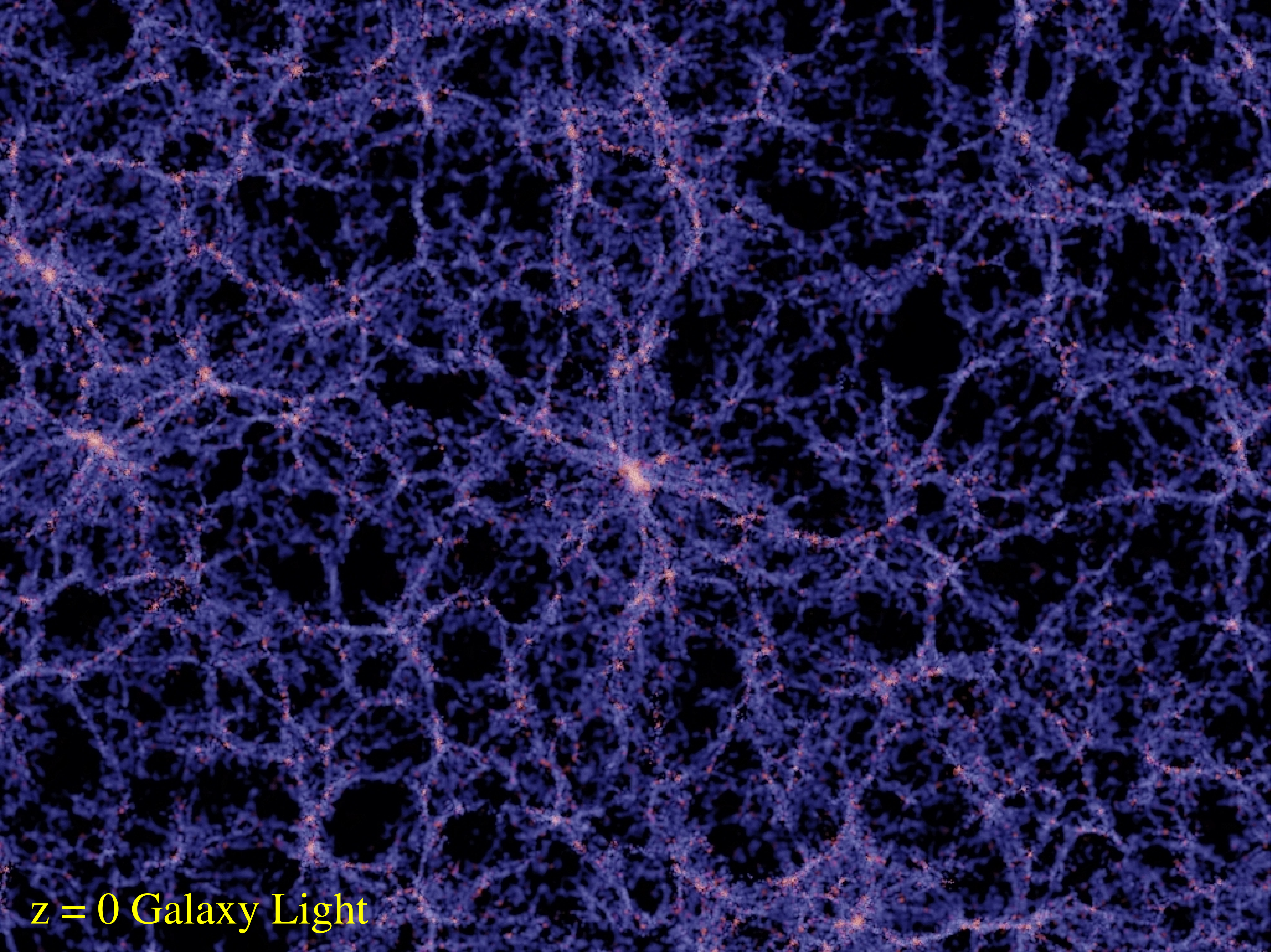
AGN physics

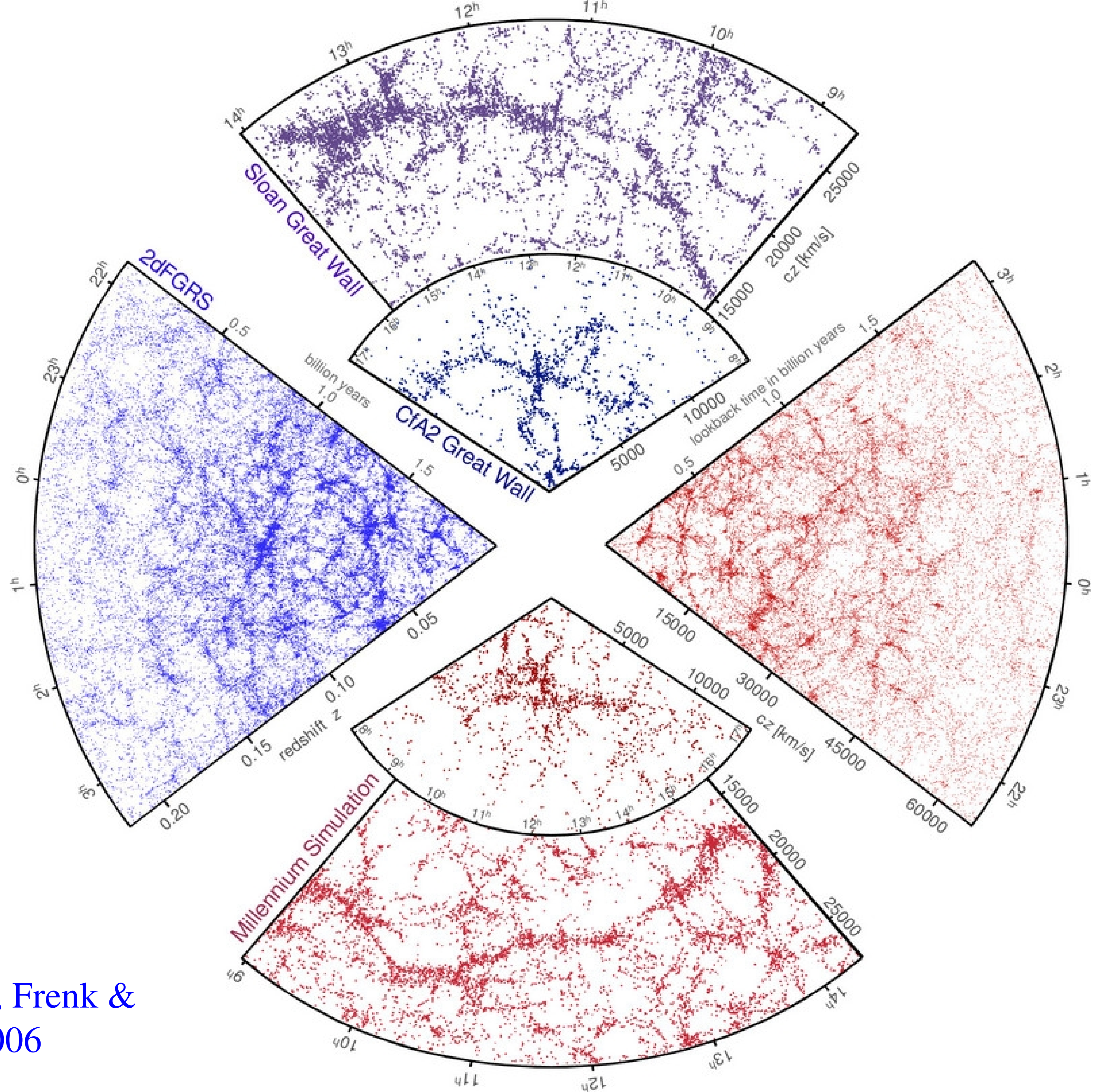
Black hole formation, feeding, AGN phenomenology, feedback

Environment interactions

Galaxy mergers, tidal effects, ram pressure effects


125 Mpc/h
z = 0 Dark Matter

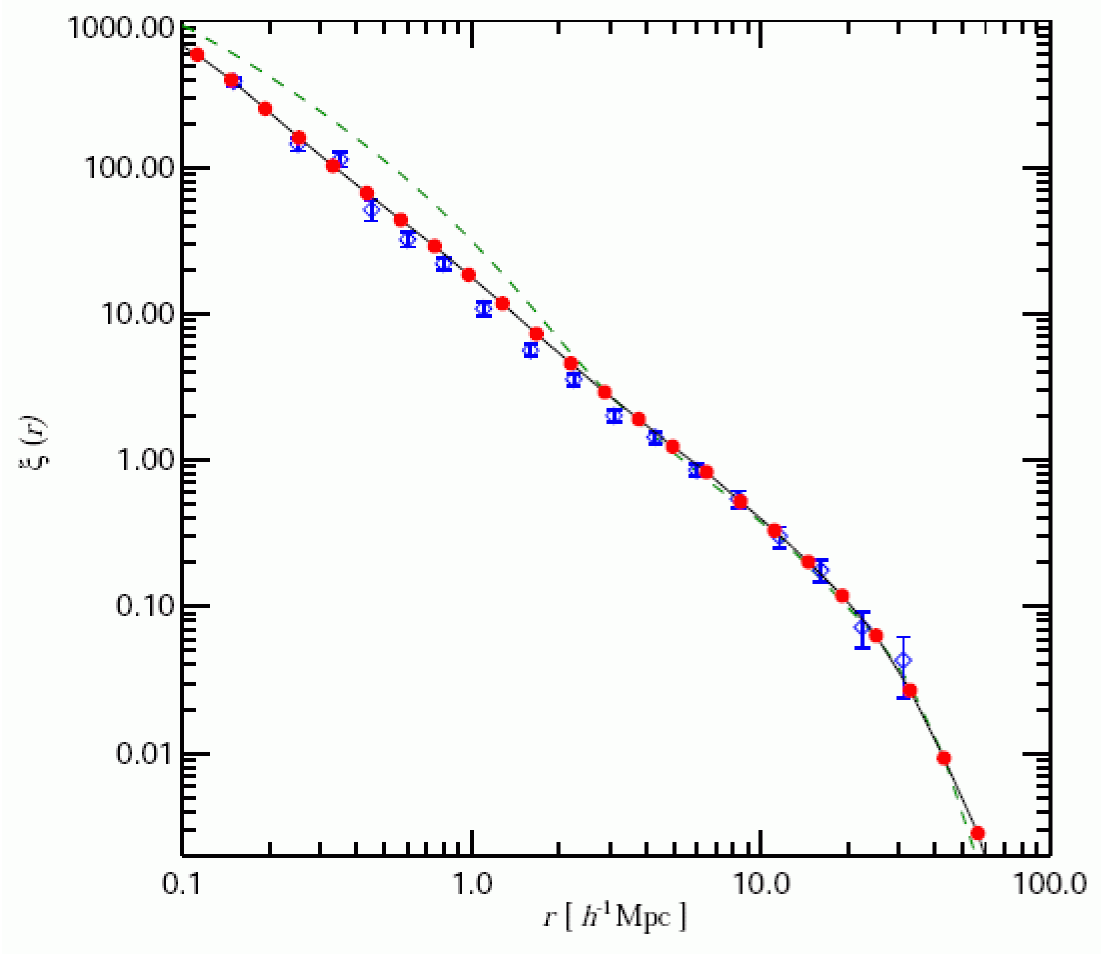

z = 0 Galaxy Light

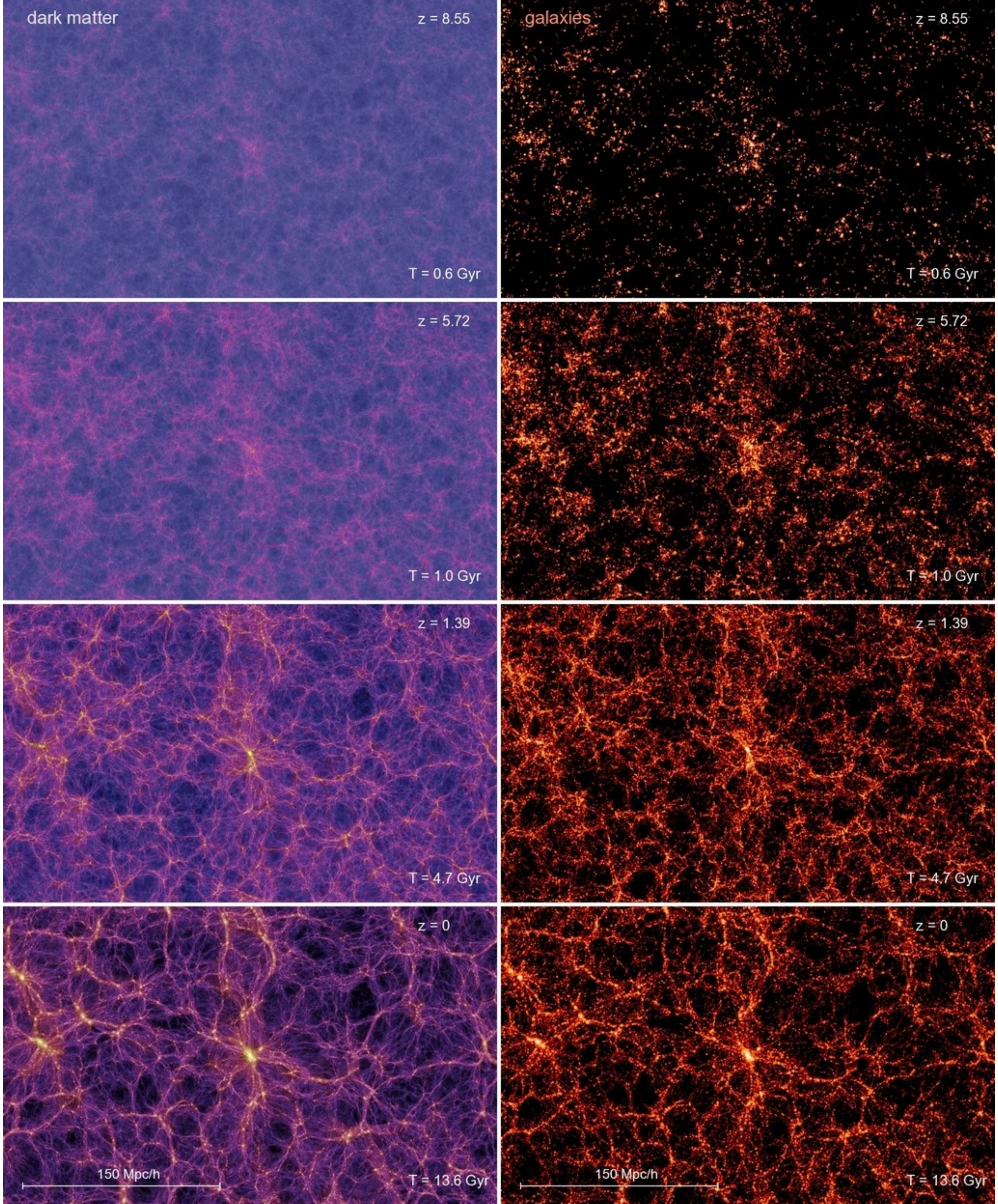


Springel, Frenk & White 2006

Mass/galaxy autocorrelations in the MS

Springel et al 2005





Large-scale structure at high redshift

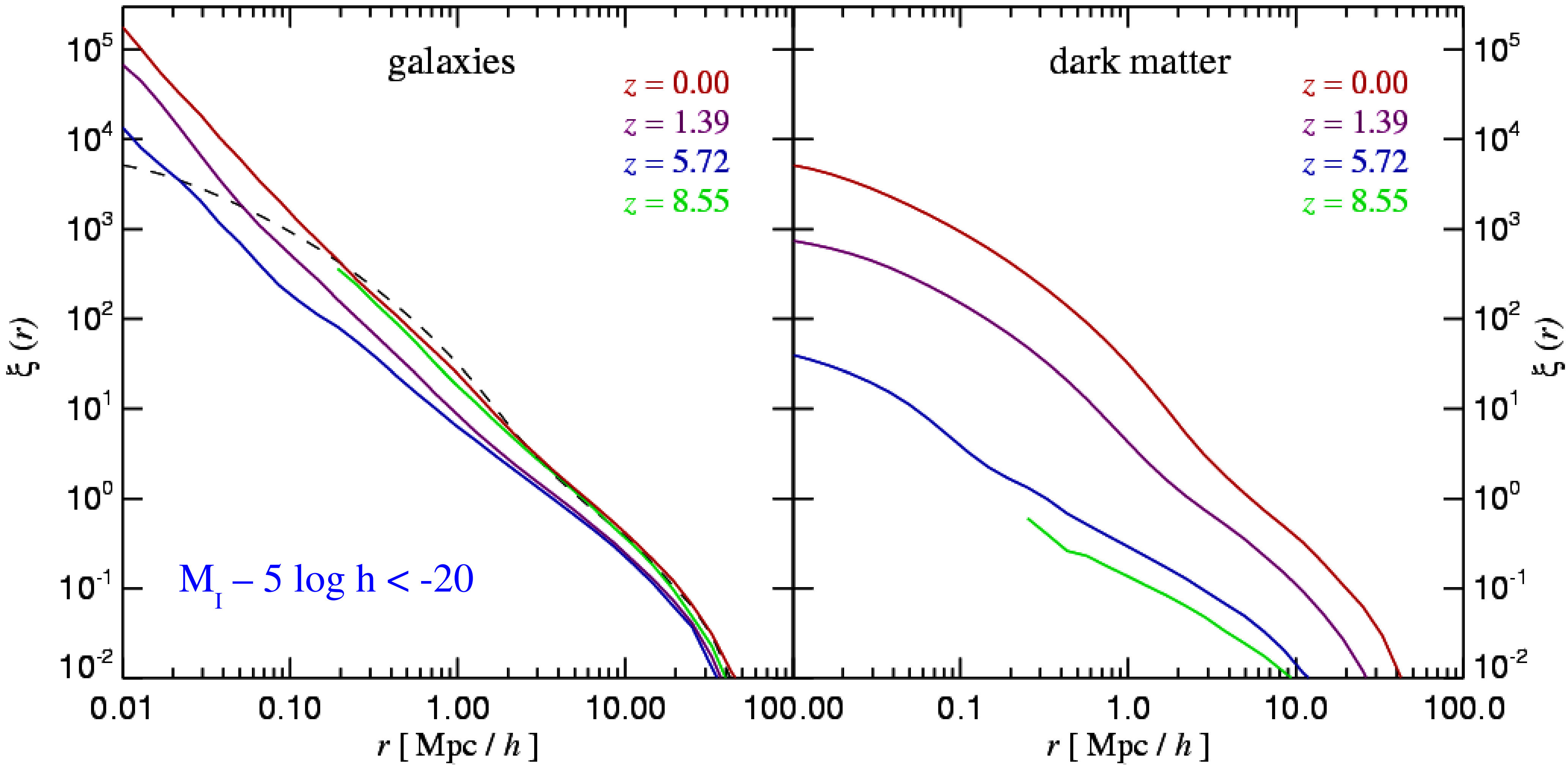
Springel, Frenk & White 2006

Large-scale structure in the galaxy distribution evolves very little with redshift

It is as strong at z=8.5 as at z=0

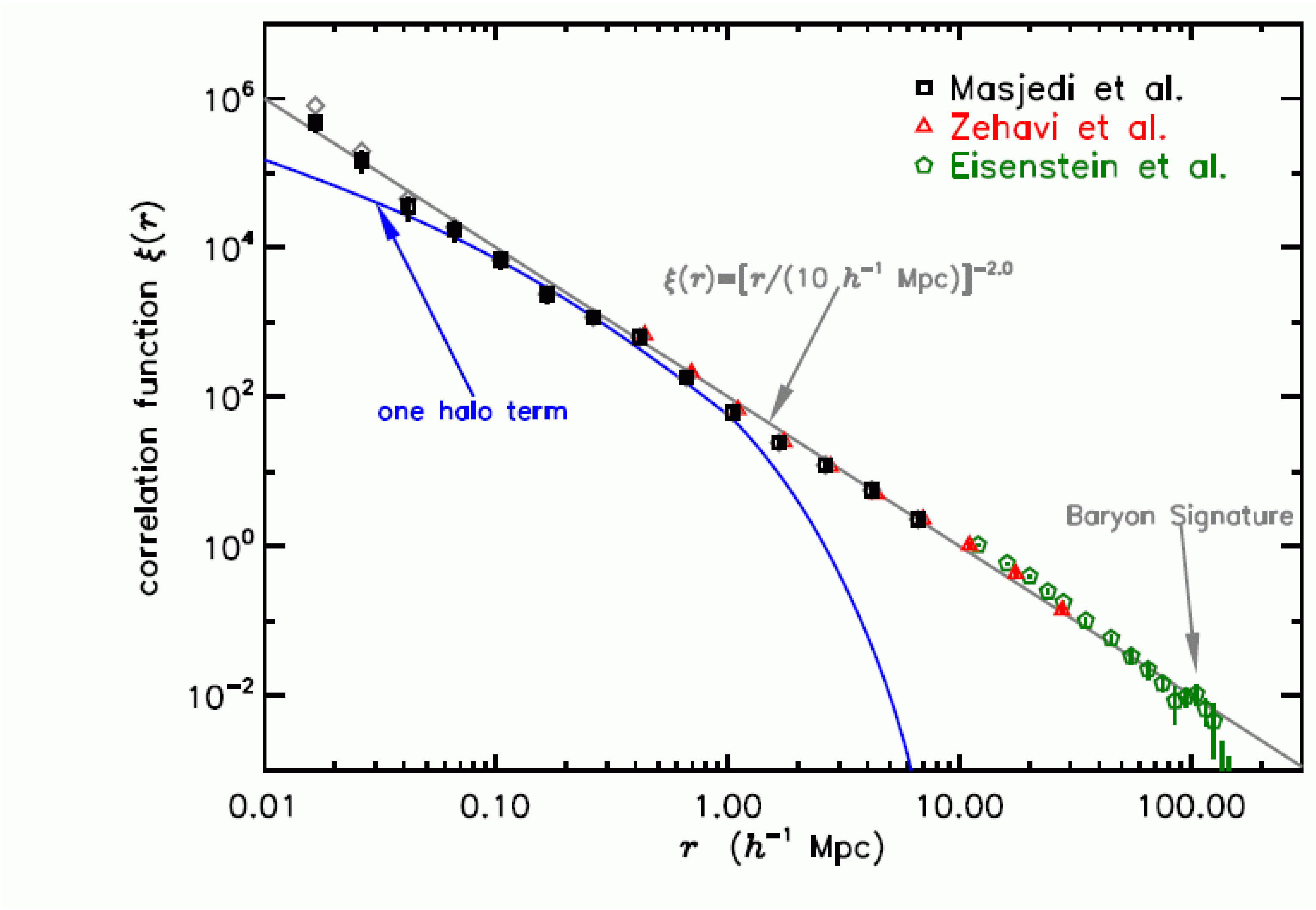
Evolution of mass and galaxy correlations

Springel, Frenk & White 2006



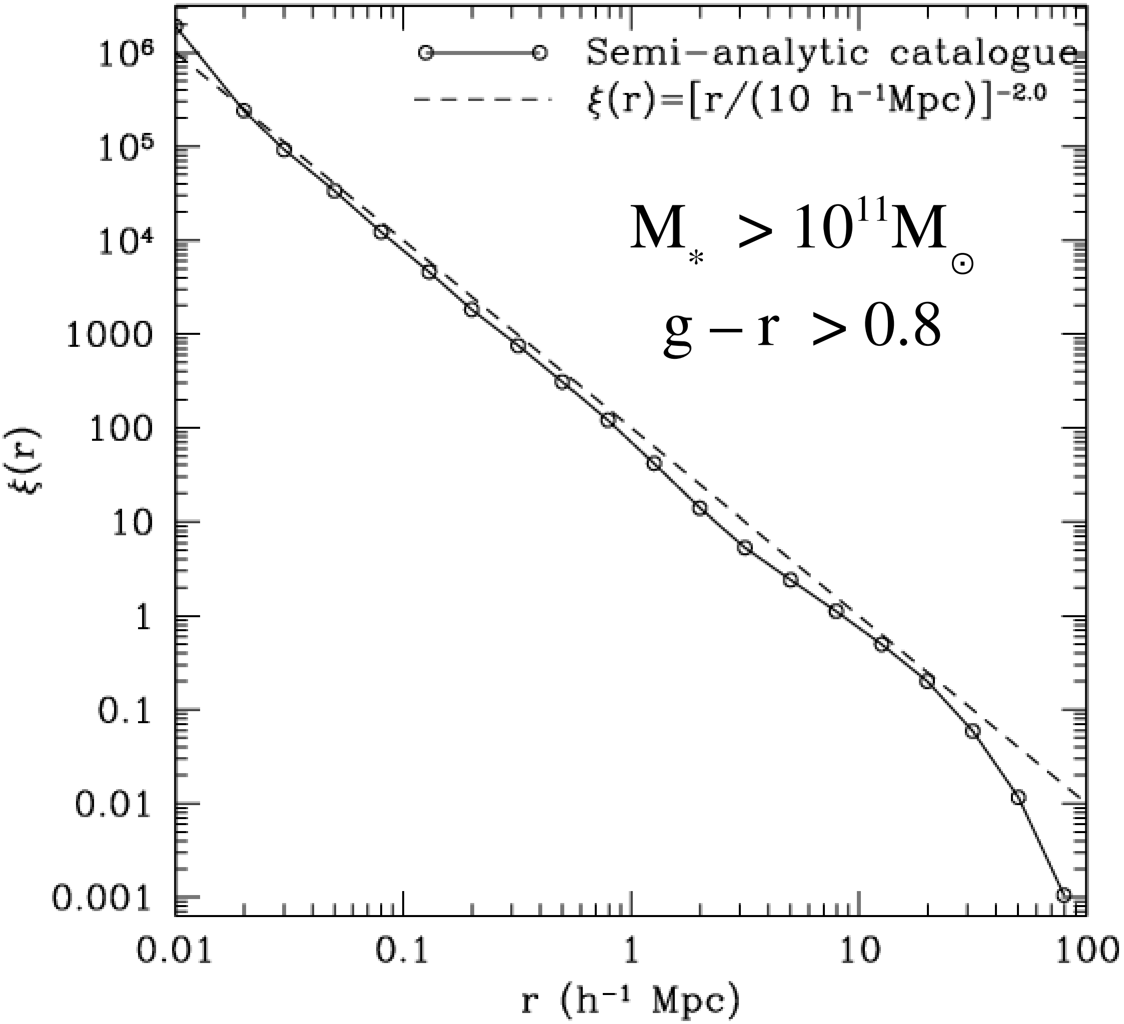
Precise estimates of autocorrelation functions Luminous red galaxies in the SDSS

Masjedi et al 2005



Precise estimates of autocorrelation functions
Luminous red galaxies in the M.S.

From public Millennium Simulation data archive



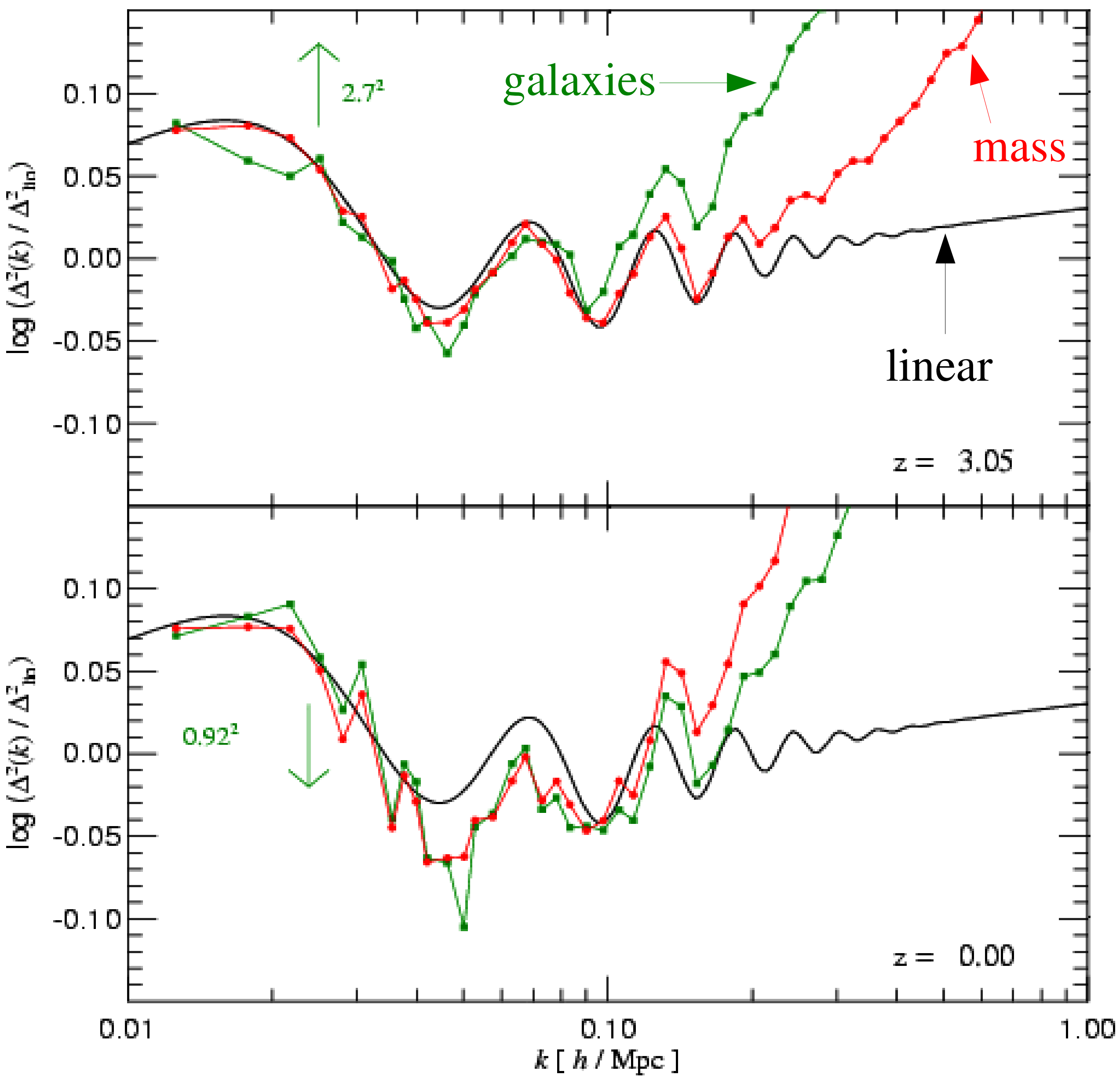
- Matching the observed correlations on scales below ~ 200kpc requires a radial distribution of satellites differing

(i) from the mass distr'n

(ii) from the simulated subhalo distribution

Baryon wiggles in the *galaxy* distribution

Springel et al 2005

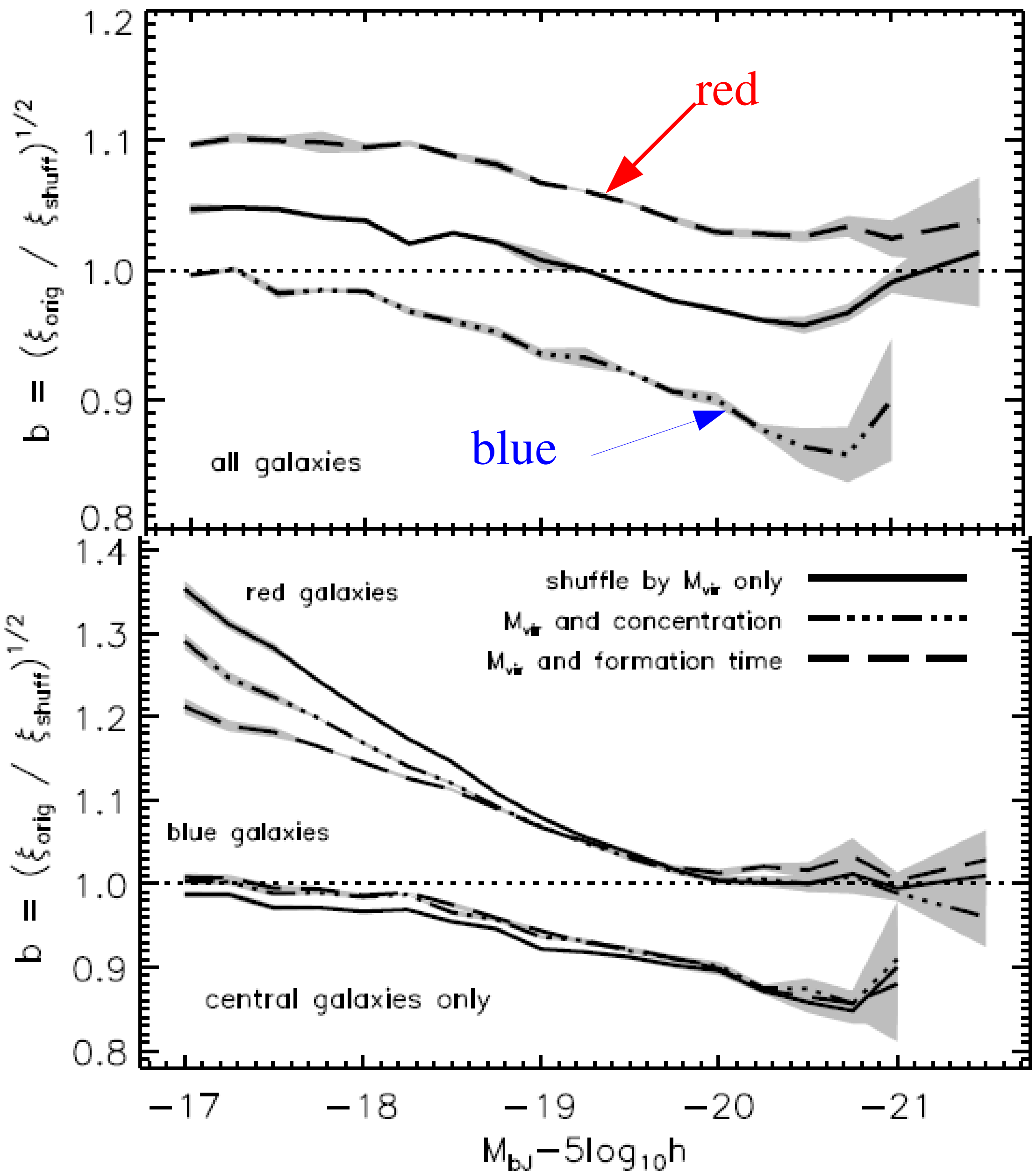


Power spectra from the Millennium run divided by a baryon- free Λ CDM spectrum

Galaxy samples are matched to plausible large observational surveys at given z

Assembly bias in simulated galaxy catalogues

Croton, Gao & White 2006



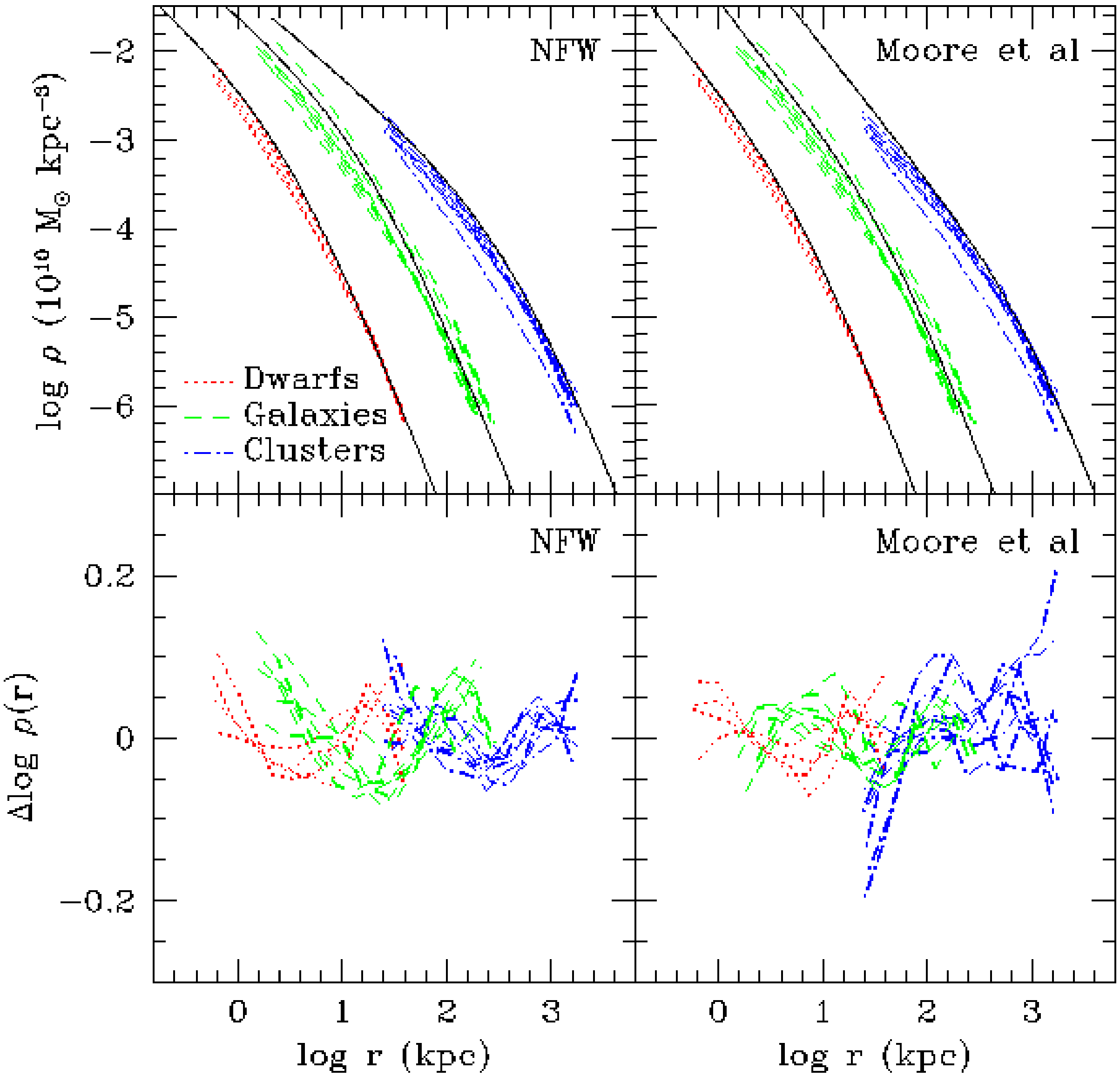
- Take a *simulation* of galaxy formation (Croton et al 2006)
- Calculate galaxy correlations for absolute magnitude limited galaxy samples
- Shuffle galaxy populations among halos of *identical* mass
- Calculate galaxy correlations for the same galaxy samples
- Compare relative bias on large scales as function of mag. limit

Science from halo (cluster/galaxy) profiles

- Initial velocities of DM (cold, warm, hot...)
- Interactions of DM (with DM, DE or baryons -- annihilation)
- Small scale power in the initial power spectrum (tilt, break...)
- Baryon accumulation effects (assembly sequence...)
- Relation of cluster X-ray properties (T, L) to mass and z (for Dark Energy studies from cluster abundance evolution)

Profiles from high-resolution simulations

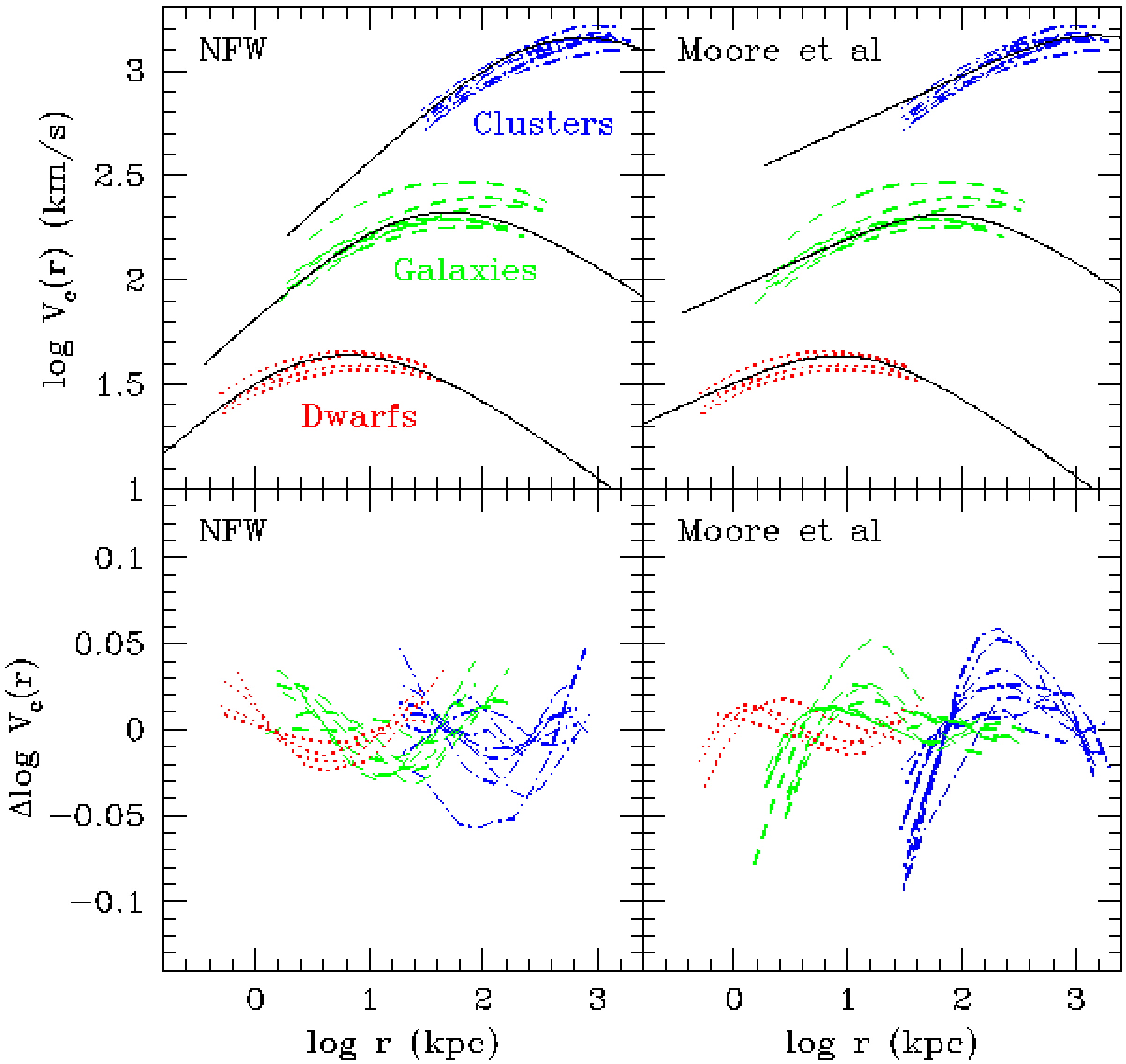
Navarro et al 2004



- ΛCDM halos simulated individually with high resolution -- $N_{200} > 10^6$
- Least square fit to NFW and Moore profiles
- Systematic deviations in inner regions in both cases, particularly for clusters

Profiles from high-resolution simulations

Navarro et al 2004



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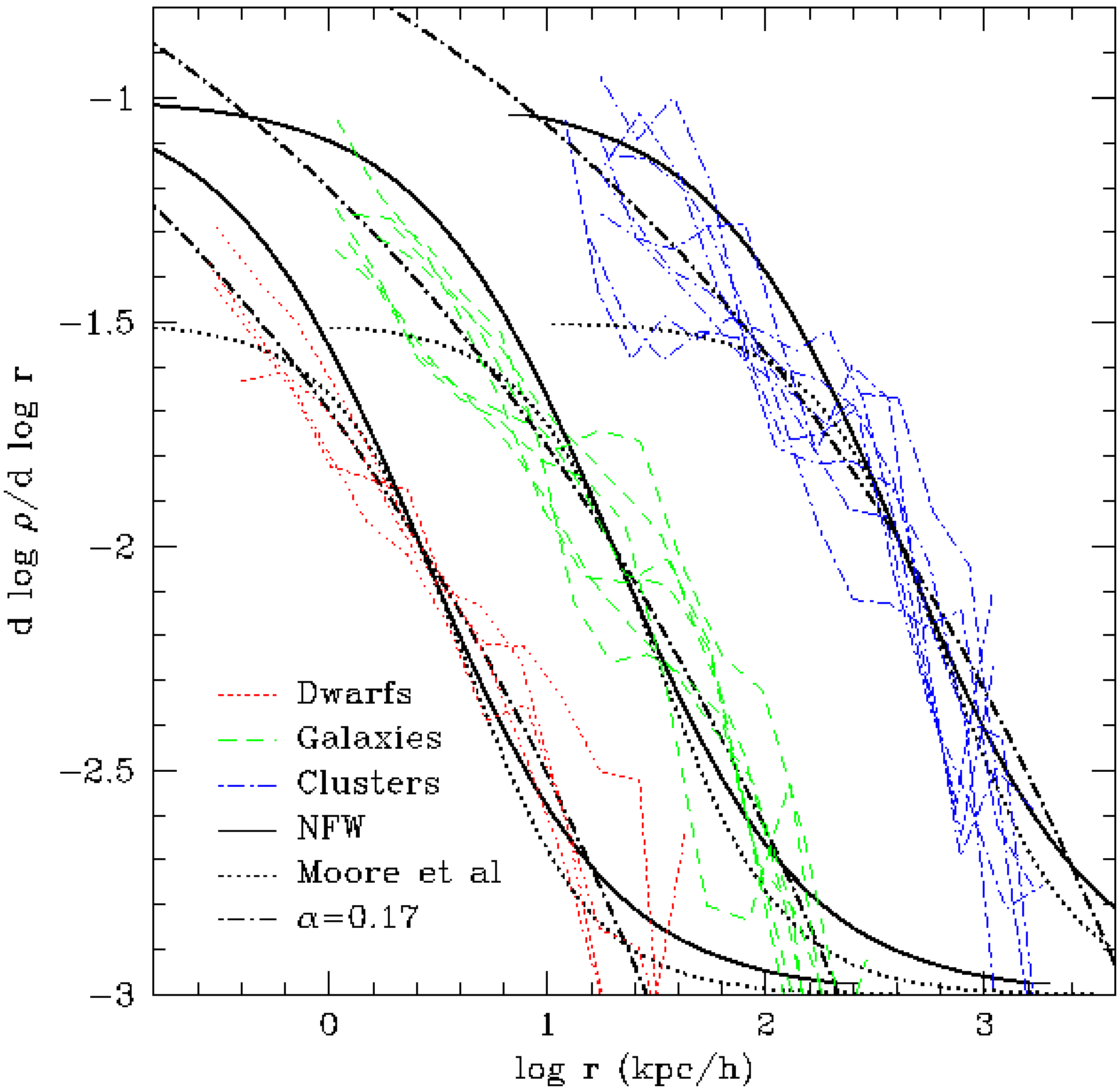
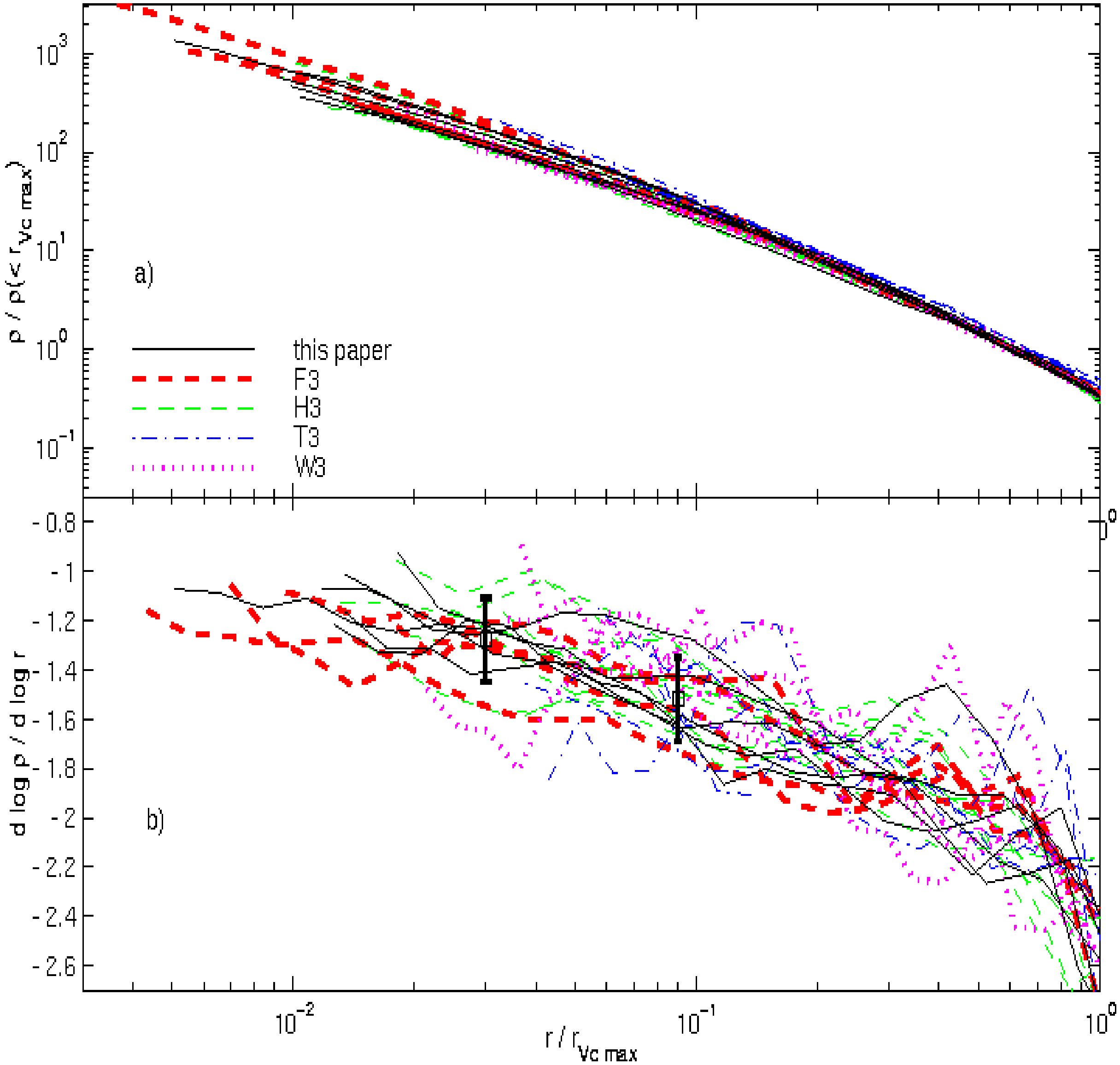


- ΛCDM halos simulated individually with high resolution -- $N_{200} > 10^6$
- Density profile slopes vary more gradually than Moore or NFW profiles
- No sign of converging to *any* asymptotic inner slope

Profiles from high-resolution simulations

Diemand, Moore & Stadel 2004



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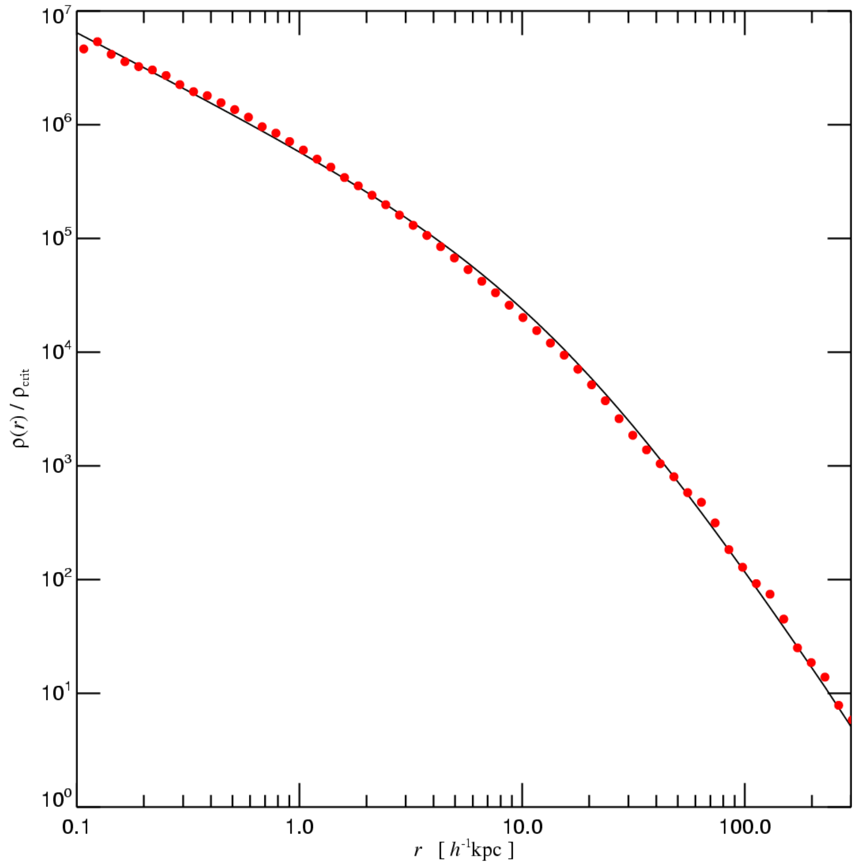
A high-resolution Milky Way halo

600 kpc

Navarro et al 2006

$$N_{200} \sim 3 \times 10^7$$

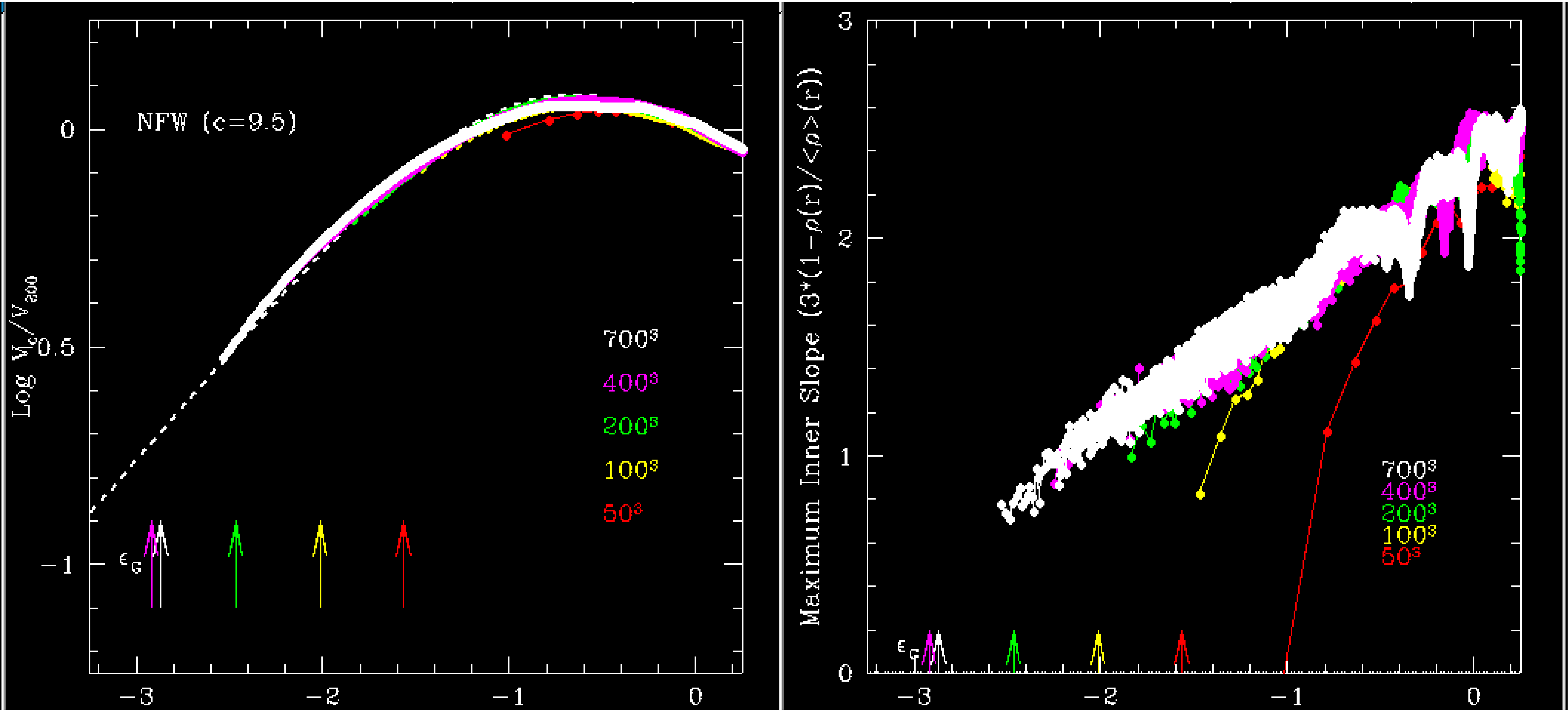


Convergence tests on density profile shape

Navarro et al 2006

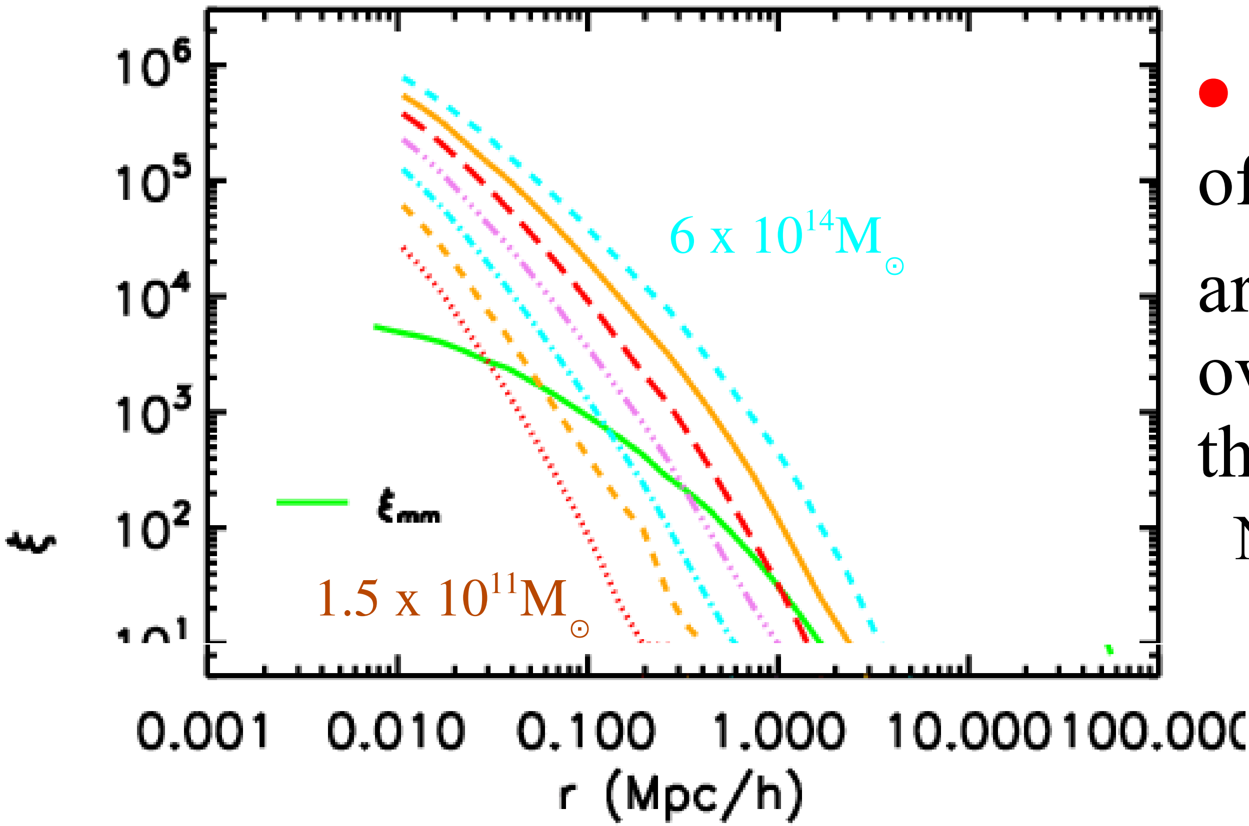
DM profiles are converged to a few hundred parsecs

The inner asymptotic slope must be shallower than – 0.9



Density profile shapes at large radii

Hayashi et al 2006



- Mean density profiles of halos of given M_{200} are well fit down to overdensities of 10 by the fitting formula of Navarro et al (2004)

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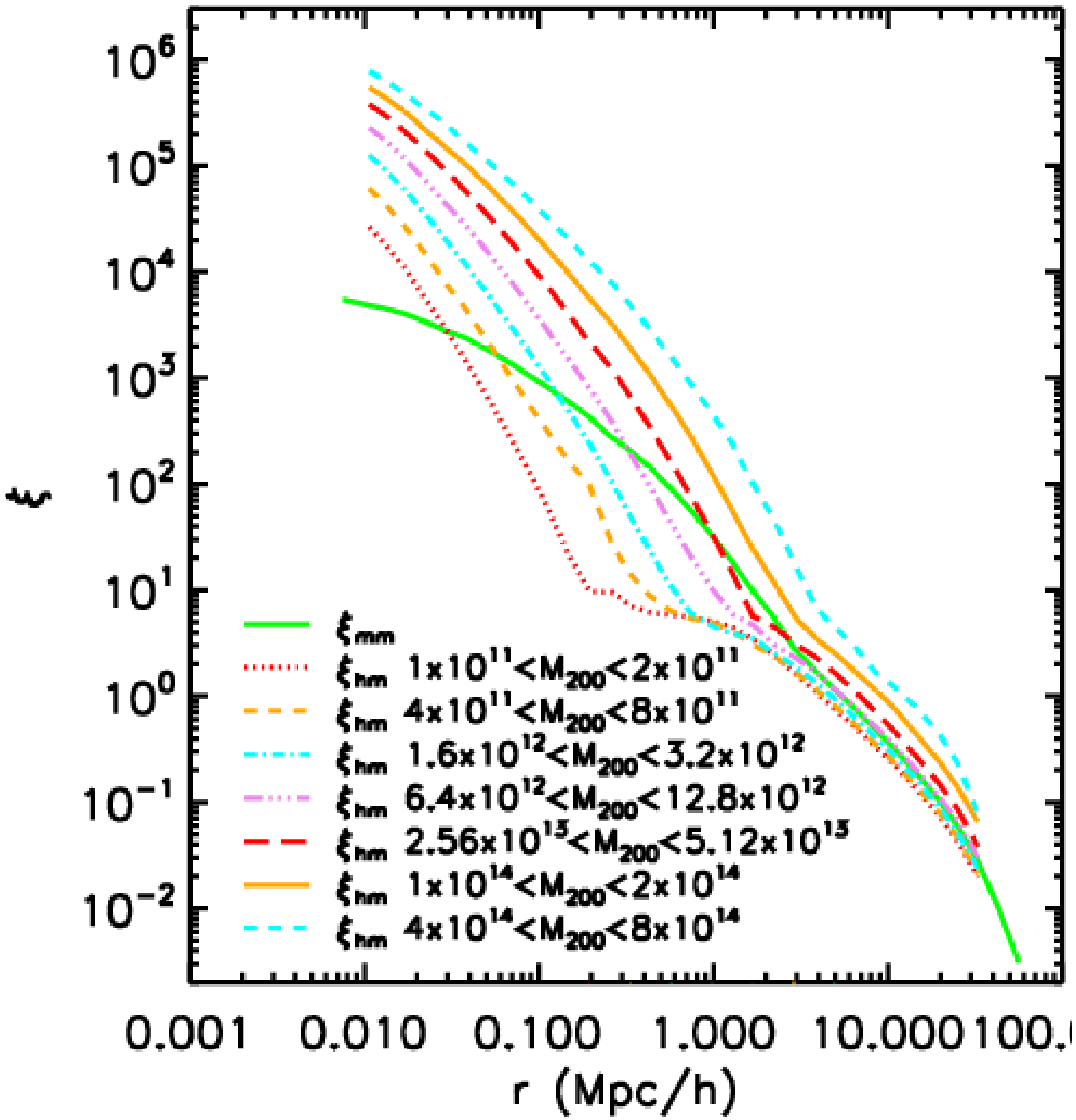

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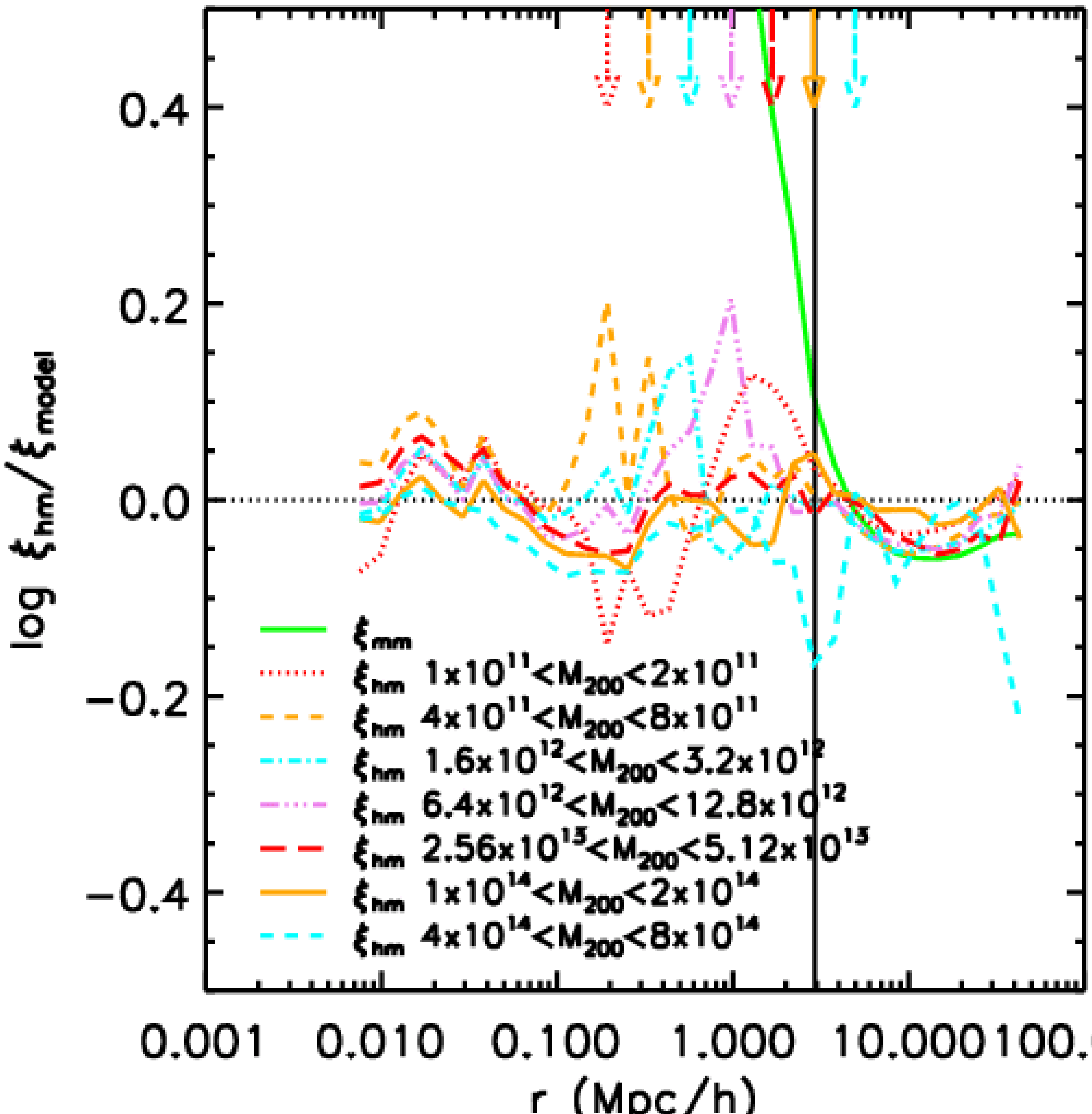

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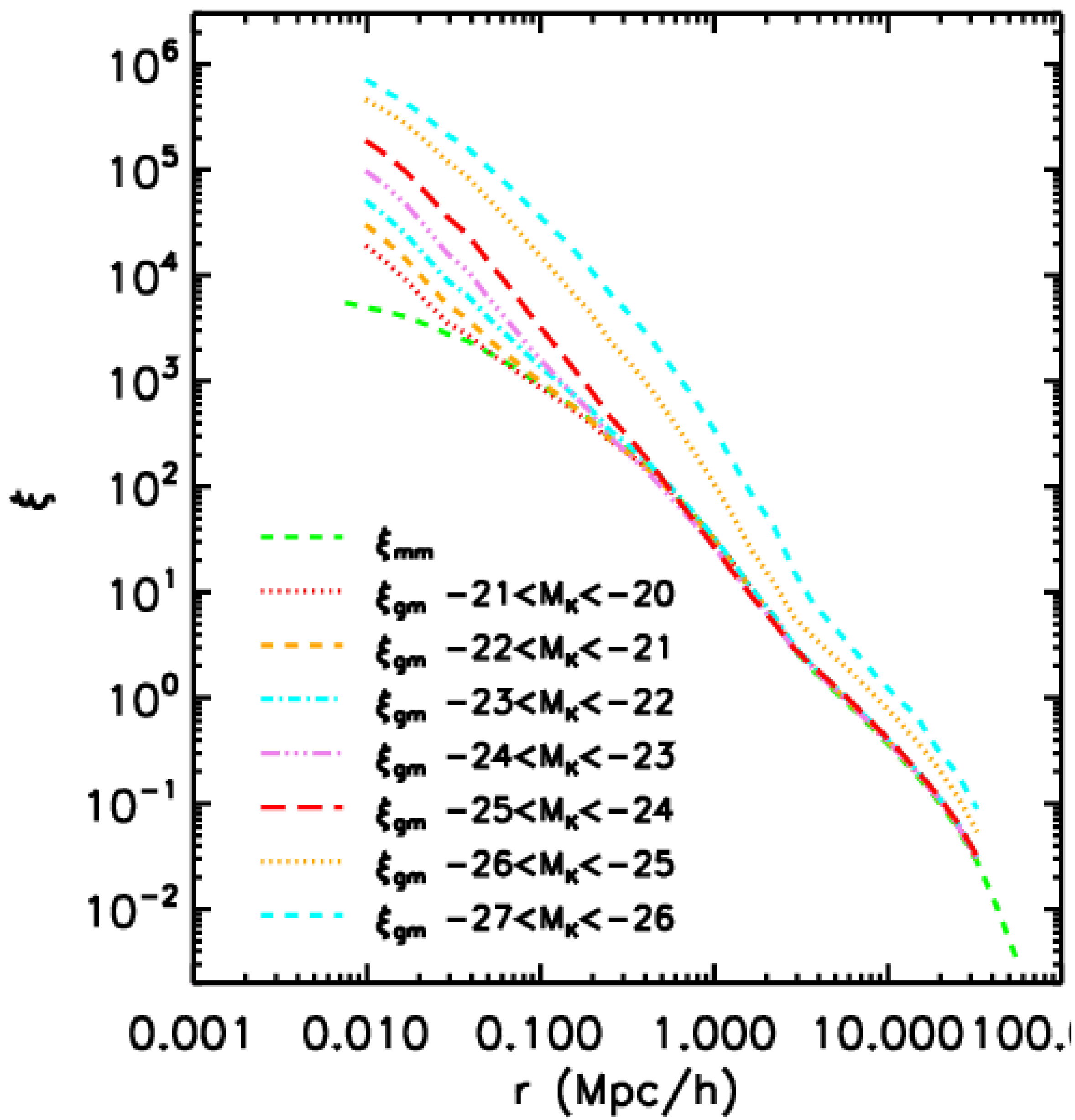
Galaxy-mass cross-correlations to large radii

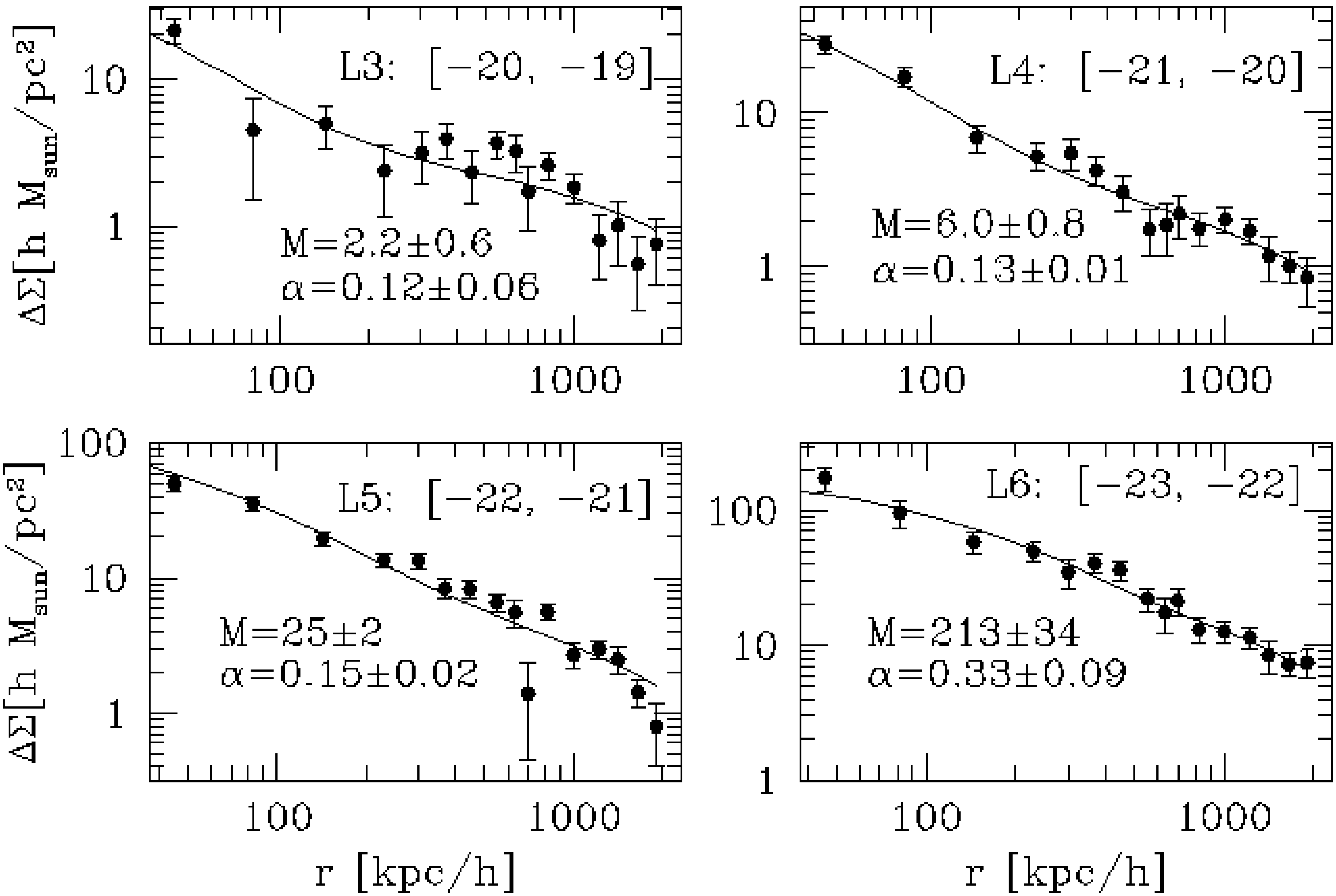
Hayashi et al 2006



- Galaxy mass cross-correlations are directly measurable through galaxy-galaxy lensing
- They can be predicted from an HOD model and mean halo mass profiles
- Here they are predicted with the Croton et al gal. formation simulation
- On large scale they follow the *nonlinear* ξ_{mm}

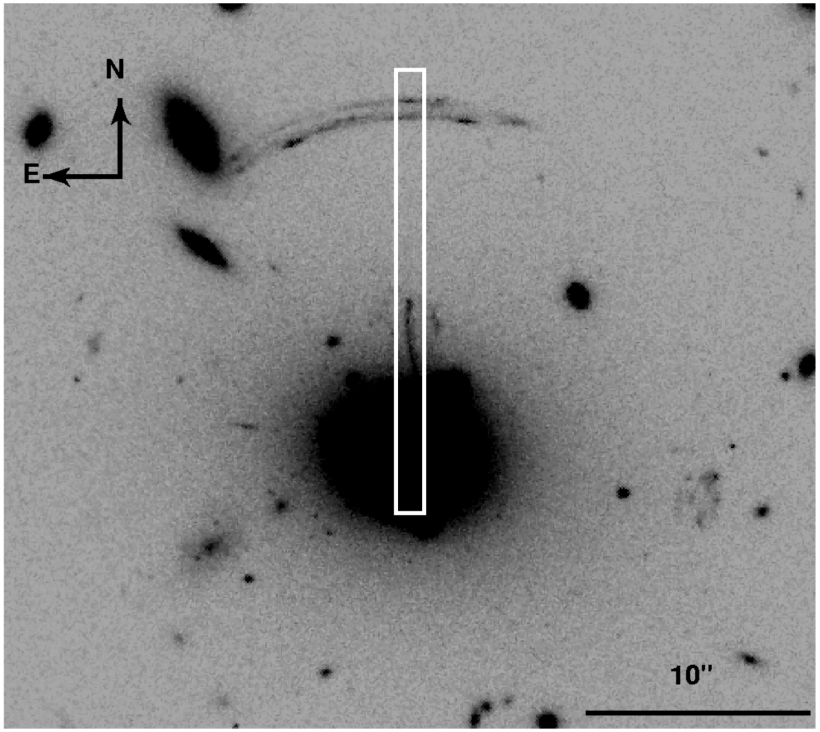
Weak lensing measures of halo mass profiles

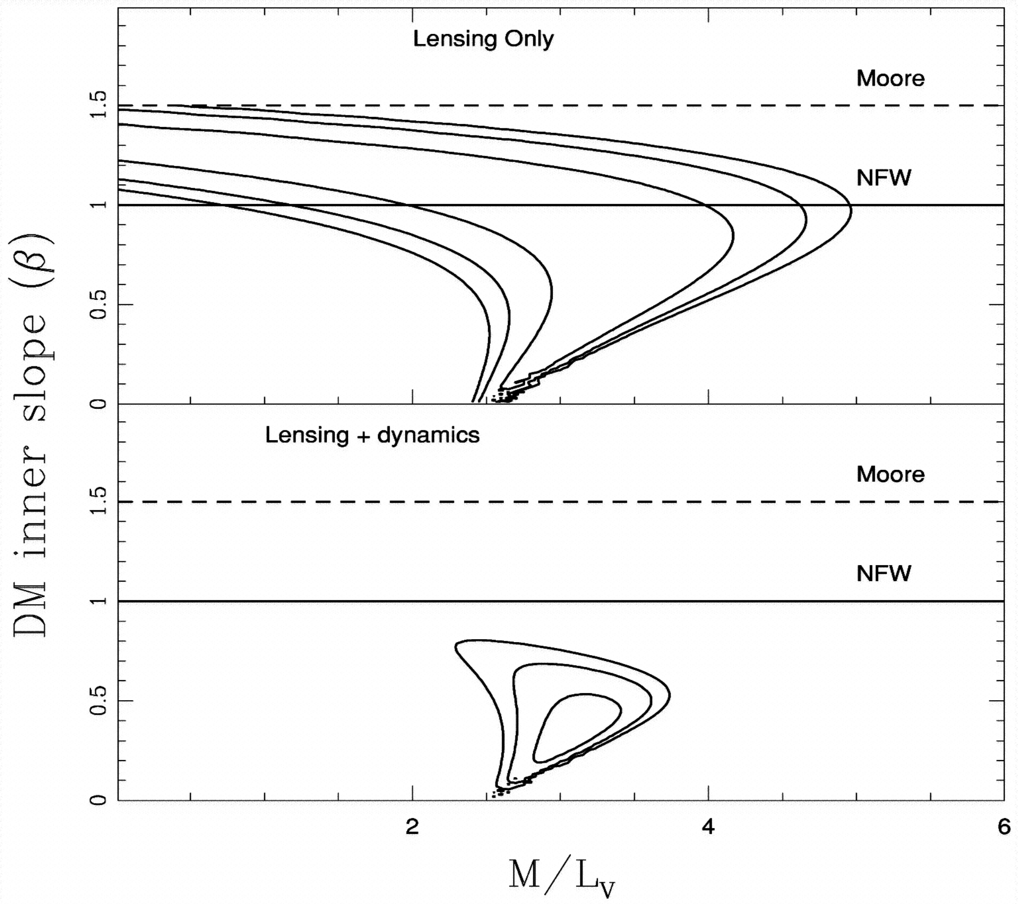
Seljak et al 2004: from SDSS



Constraining DM properties with strong lensing ?

Sand, Treu & Ellis 2002



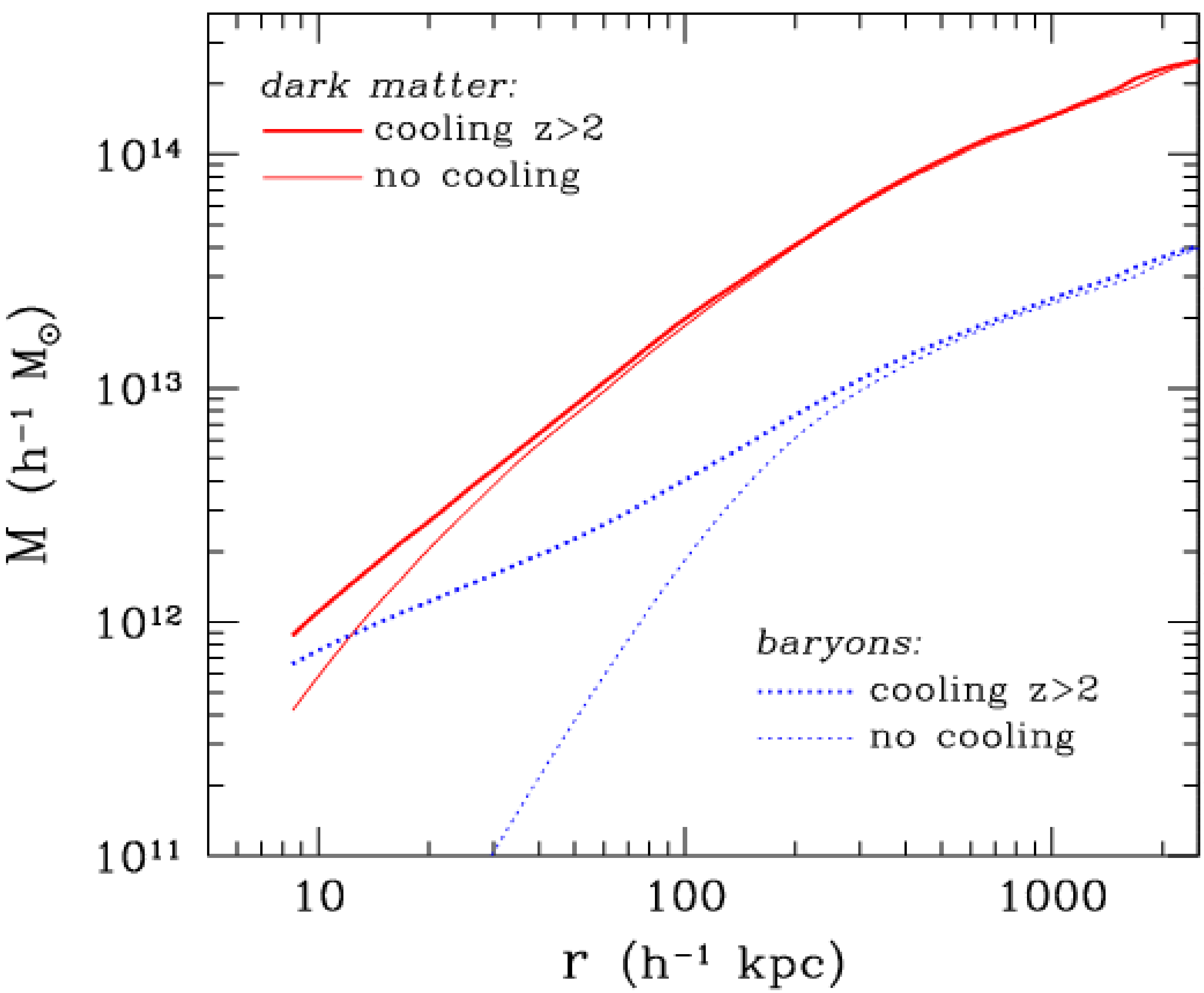


- Model potential as power law DM + galaxy with constant M/L
- Consistency with radial arc, tangential arc & velocity dispersion profile

  → inner slope of DM profile shallower than NFW
- Constraint is substantially weakened if the inner DM distribution can be significantly flattened (Bartelmann & Meneghetti 2004, Dalal & Keaton 2004)

Does the *total* mass profile converge to NFW?

Gnedin, Kravtsov, Klypin & Nagai 2004

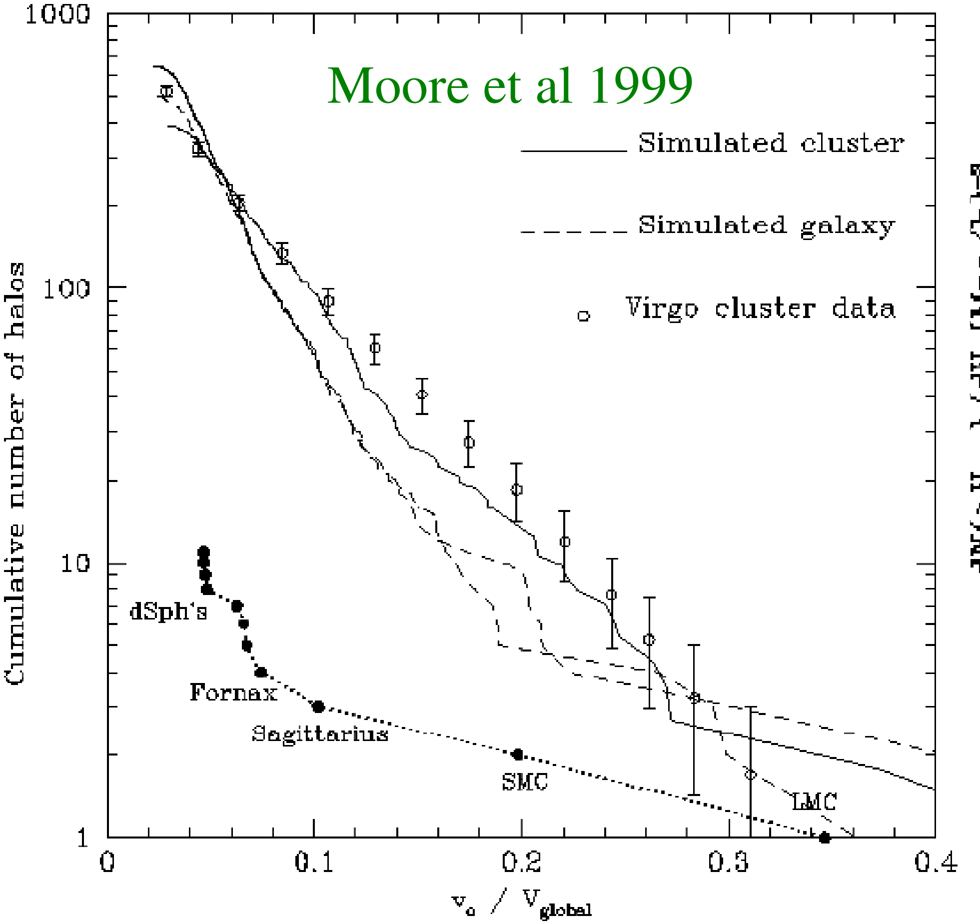


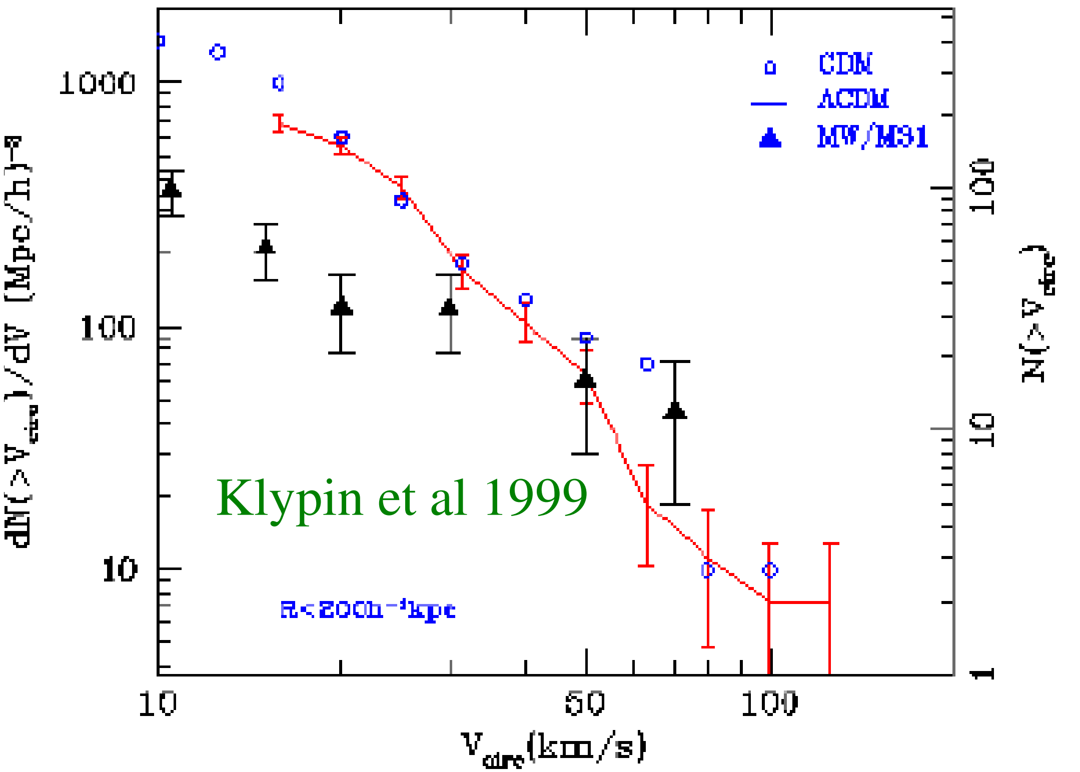
- Two simulations of the formation of a cluster including gas and with identical initial cond'ns
- No cooling in one: cooling/star-formation at z > 2 in the other
- Several mergers occur in the core at z < 2
- The DM distribution is still more concentrated in the model with stars

Science from halo substructures

- Initial velocities of DM (cold, warm, hot...)
- Interactions of DM (self-interacting, interactions with baryons)
- Small scale power in the initial power spectrum (tilt, break...)
- Baryon accumulation effects (assembly sequence...)
- Tidal effects as a function of environment history

Is the kinematics of the Milky Way's satellites inconsistent with ΛCDM substructure?

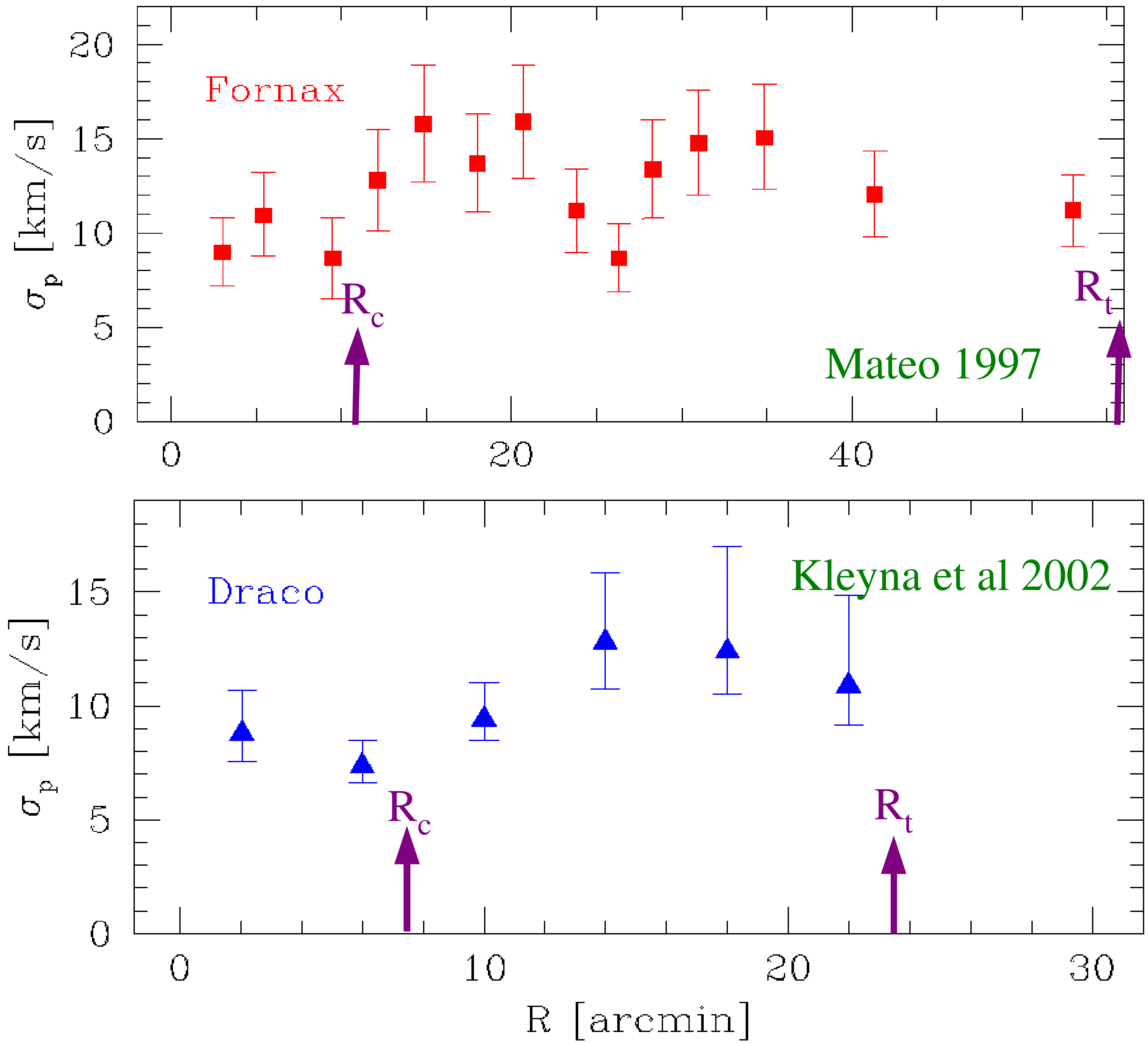




- Number of observed satellites was ***claimed*** to be ~1/10 the number of ΛCDM satellites with the same max. circular velocity $V_c = (GM/r)^{1/2}$
- But the MW data are plotted at the ***incorrect*** values of V_c for this test!

Stoehr et al 2002

Dark Matter within Satellites



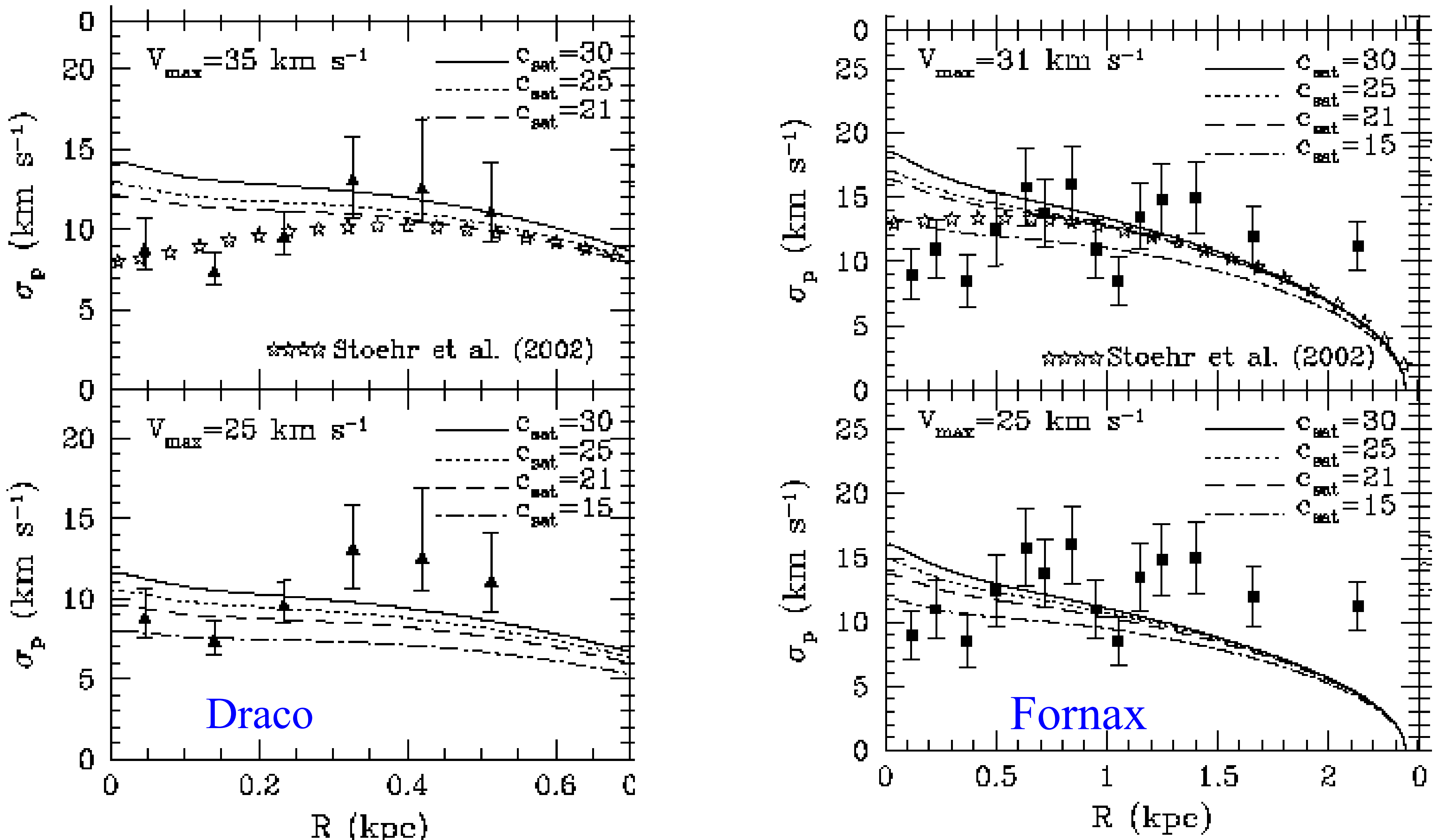
- Flat stellar velocity dispersion out to the tidal radius
  → *rising* V_c curve
- Extended DM halos?
- High DM phase density? ~~*WDM*~~ ?
- $V_{c,max} \gtrsim$ 25 km/s ?
- Critical observation: extratidal stars?

DENSITY PROFILES OF COLD DARK MATTER SUBSTRUCTURE: IMPLICATIONS FOR THE MISSING-SATELLITES PROBLEM

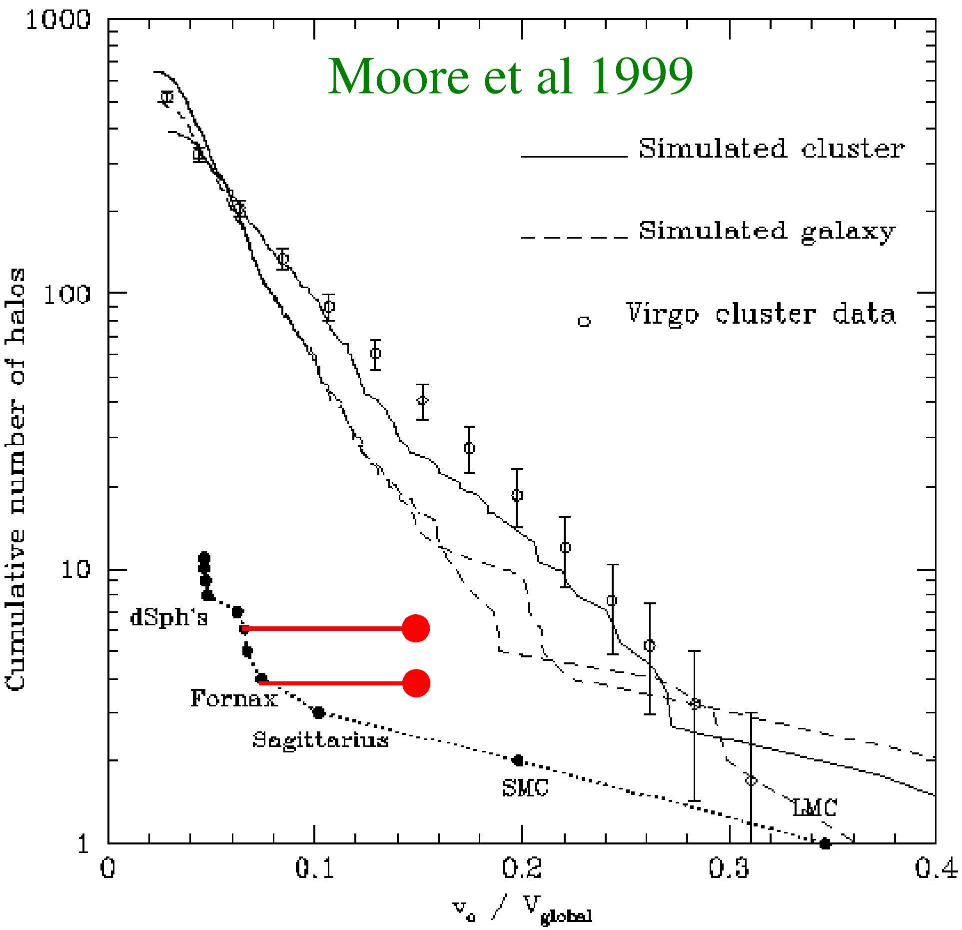
2004 (ApJ)

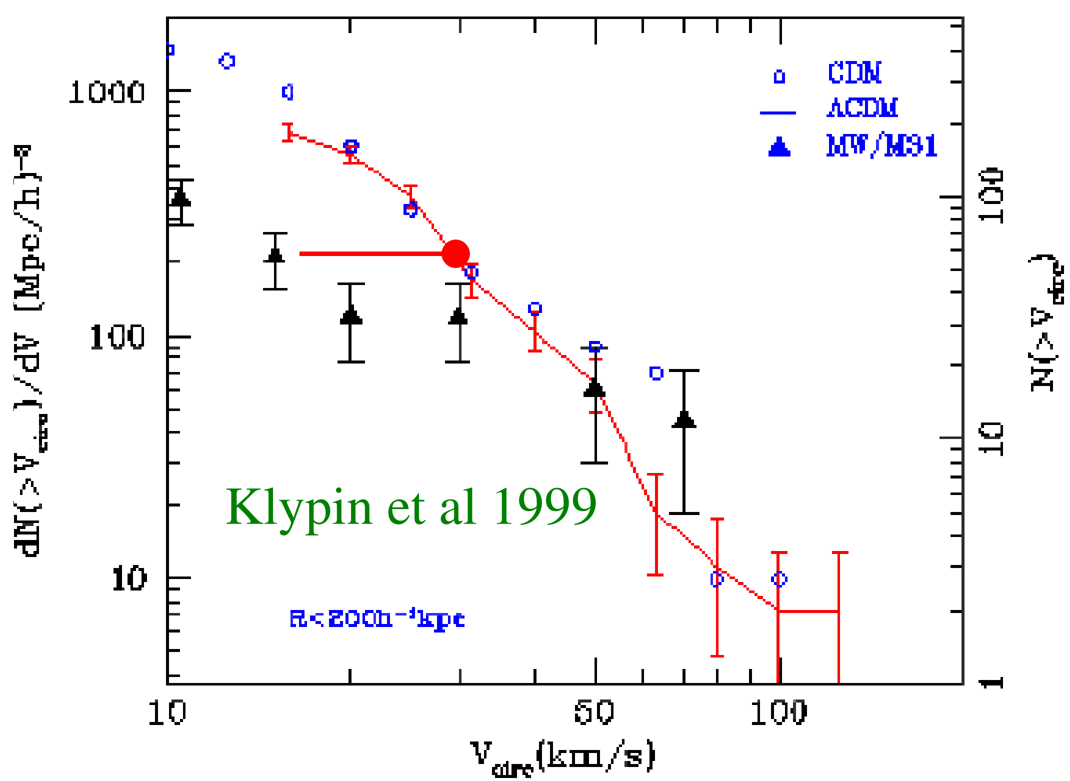
Stelios Kazantzidis[1], Lucio Mayer, Chiara Mastropietro, Jürg Diemand, Joachim Stadel, and Ben Moore

Motivated by the structure of our stripped satellites, we compare the predicted velocity dispersion profiles of Fornax and Draco to observations, assuming that they are embedded in CDM halos. We demonstrate that models with isotropic and tangentially anisotropic velocity distributions for the stellar component fit the data only if the surrounding dark matter halos have maximum circular velocities in the range $20 - 35\ \mathrm{km s^{-1}}$.



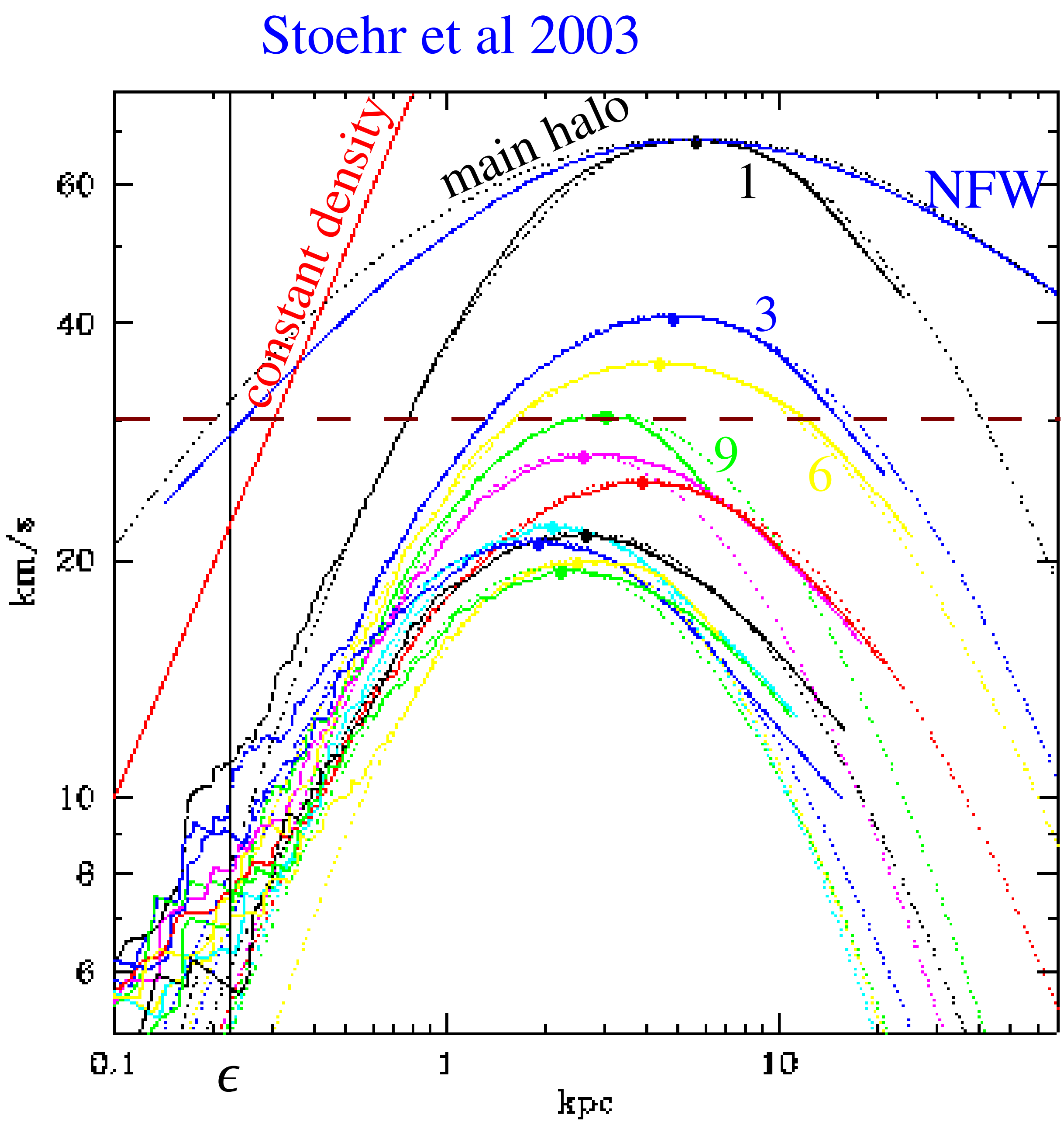
Inconsistency with observed satellite kinematics?





- Inconsistency is much less dramatic when one uses the *limiting* circular velocity inferred from the velocity dispersion profiles
- The *maximum* of the DM circular velocity profile may be outside the visible galaxy and still larger (plots show shift to V_{max} = 30 km/s)

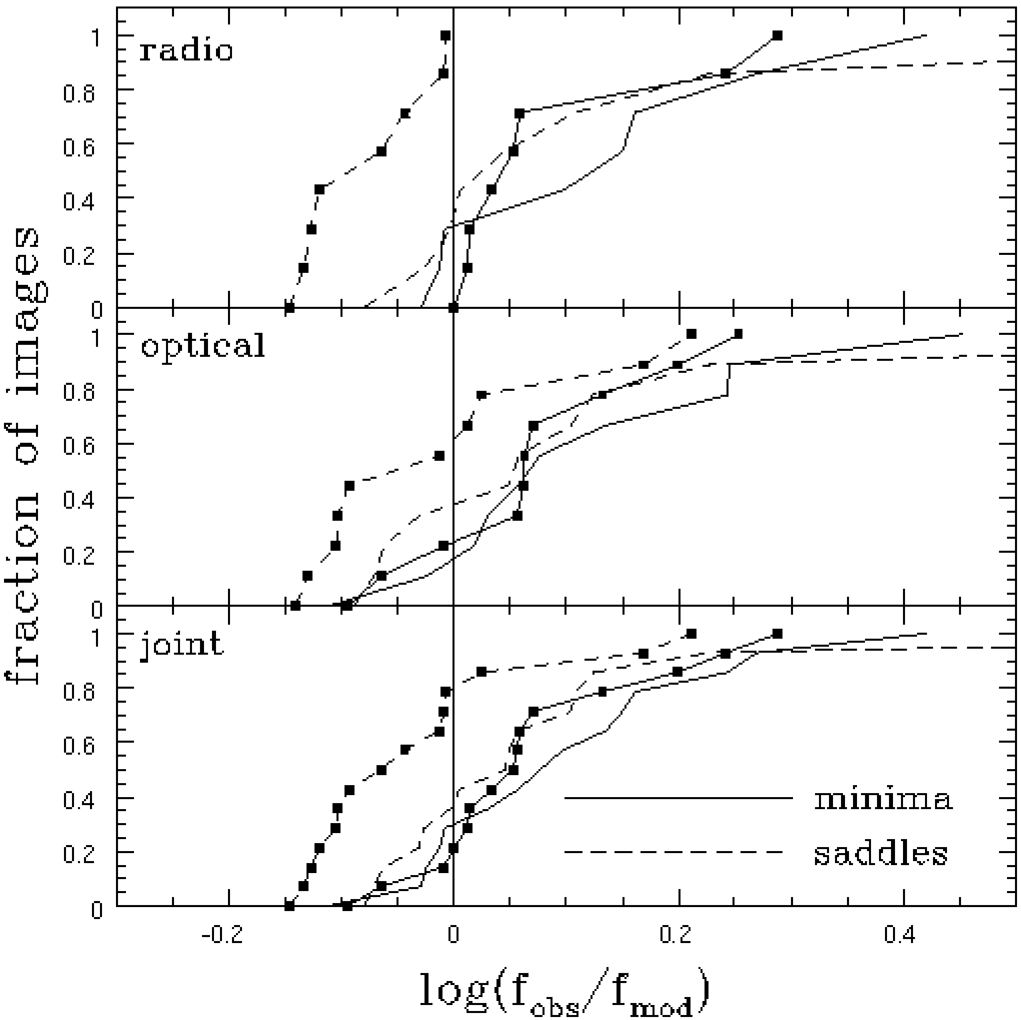
Satellite circular velocity curves



- Circular velocity curves for 11 of the 30 most massive subhalos in a 10^7 particle 'Milky Way' halo
- The NFW and 'main halo' curves are scaled to the (r_m, V_m) of largest subhalo
- All curves are narrower than NFW or 'main halo'
- The maximum circular velocities are at radii well outside observed satellites
- ***The MOST MASSIVE of these potentials <u>could</u> host the observed satellites***

Detection of ΛCDM substructure?

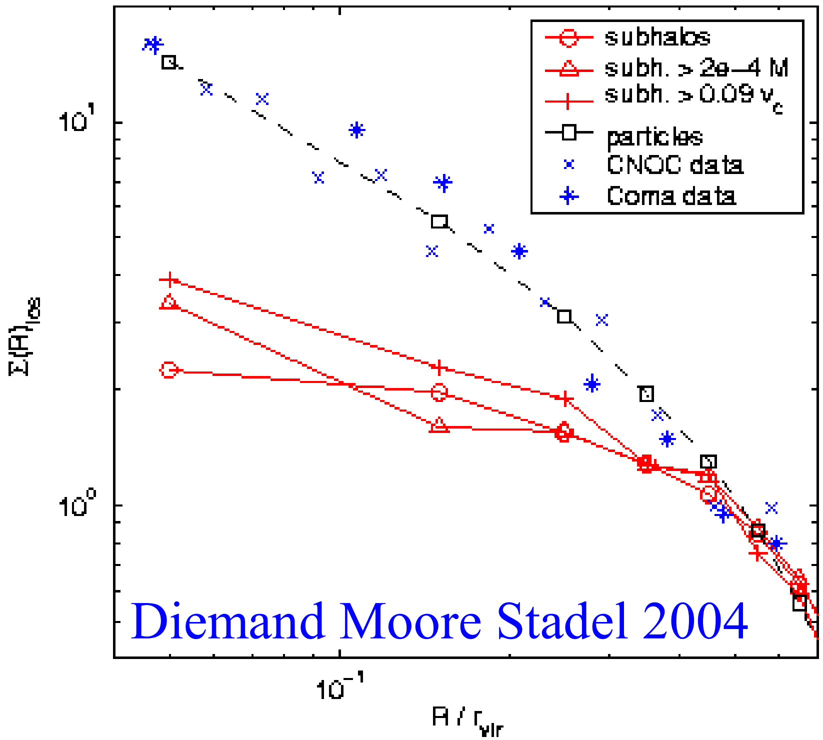
Dalal & Kochanek 2002



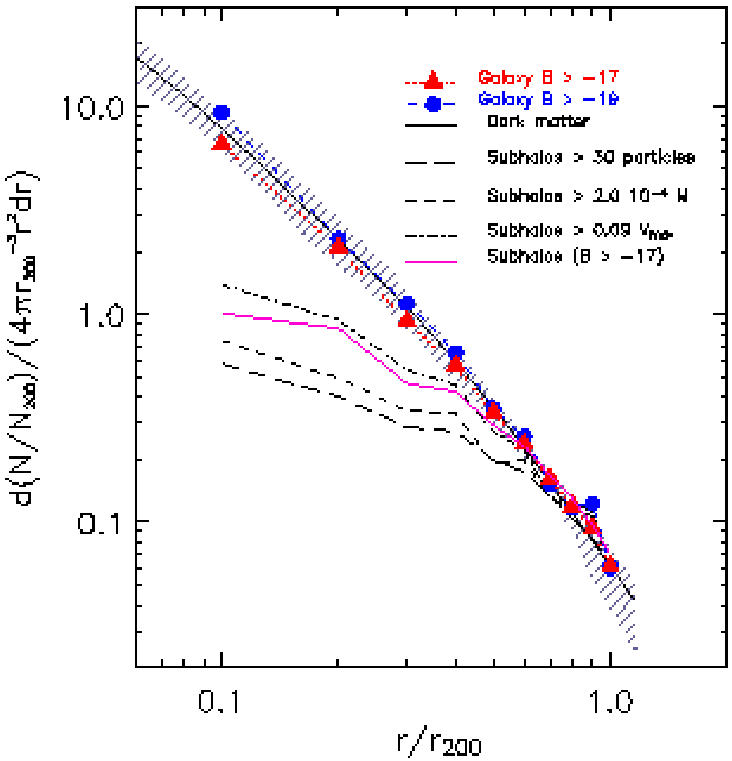
- In 4-image lensed quasars, the image *geometry* allows image classification into minima/saddles and brighter/fainter of each type
- Smooth lens models which fit the image positions usually *fail* to fit their relative brightness
- The brightest saddle image is preferentially dimmed, as expected for perturbation by fine structure
- This *cannot* be due to propagation effects, e.g. in the ISM of the lens
- It *cannot* be due to microlensing as radio images are too big
- 5 - 10% of lens mass must be in substructure but it might be just *projected* on the lens (Metcalf 2004)

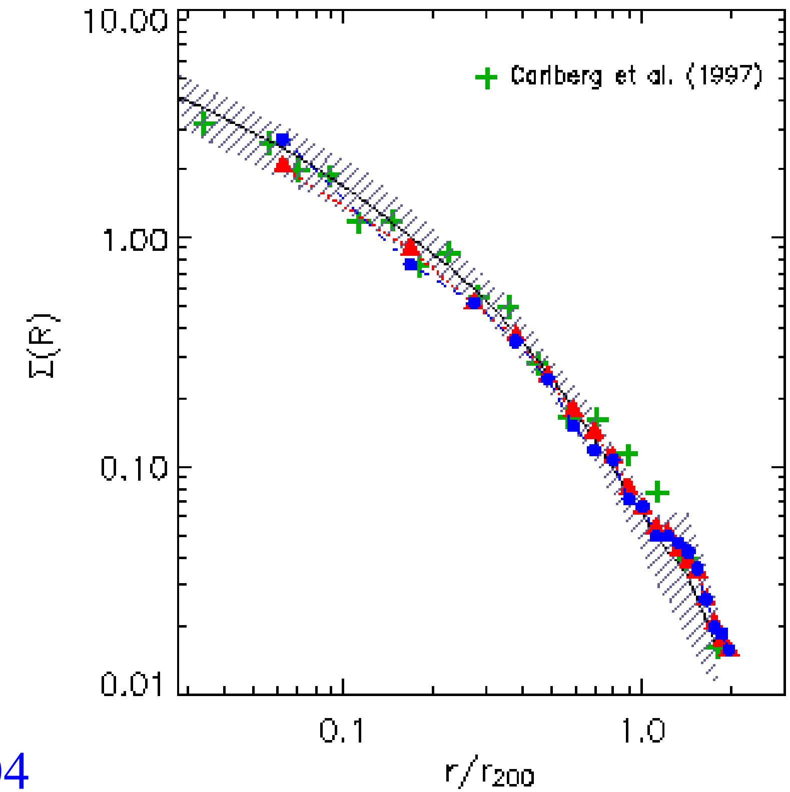
ΛCDM may have too little substructure?

- Radial density profile of substructure is much less concentrated than that of the DM as a whole
  → too little substructure projected on the centre to produce anomalies? or to produce cluster galaxy profiles?



Diemand Moore Stadel 2004

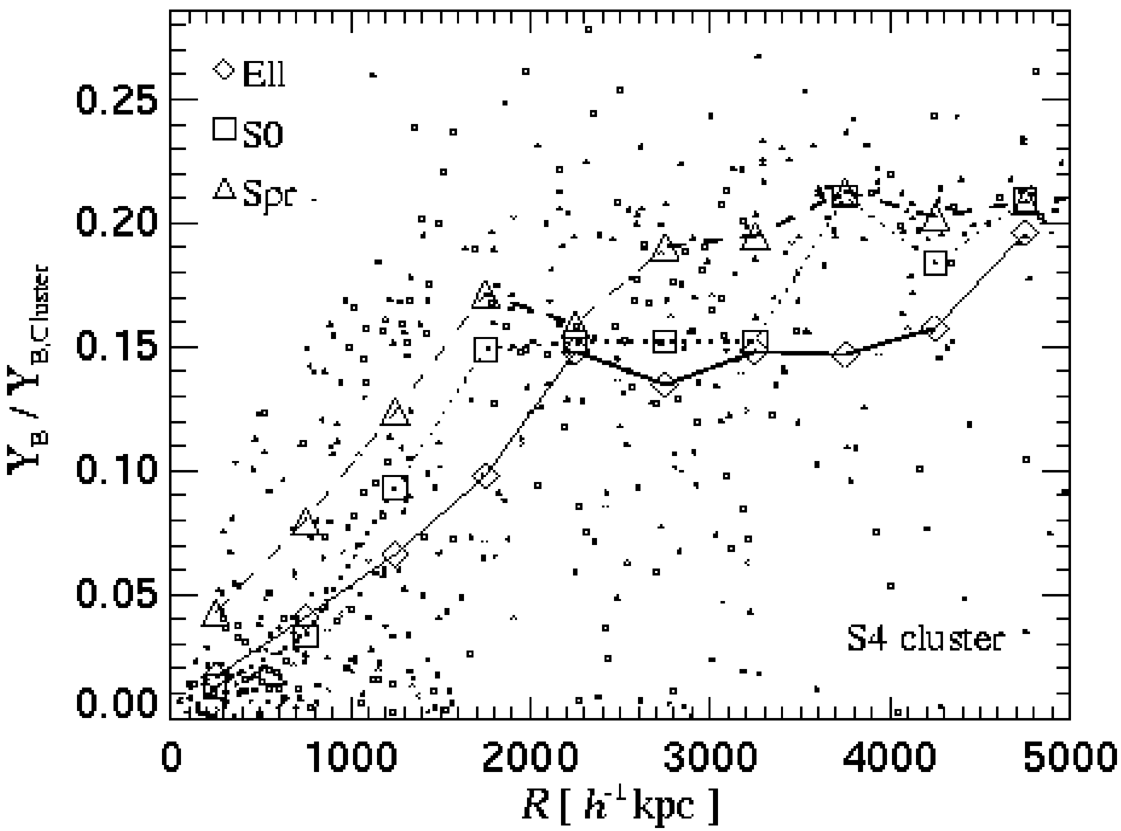




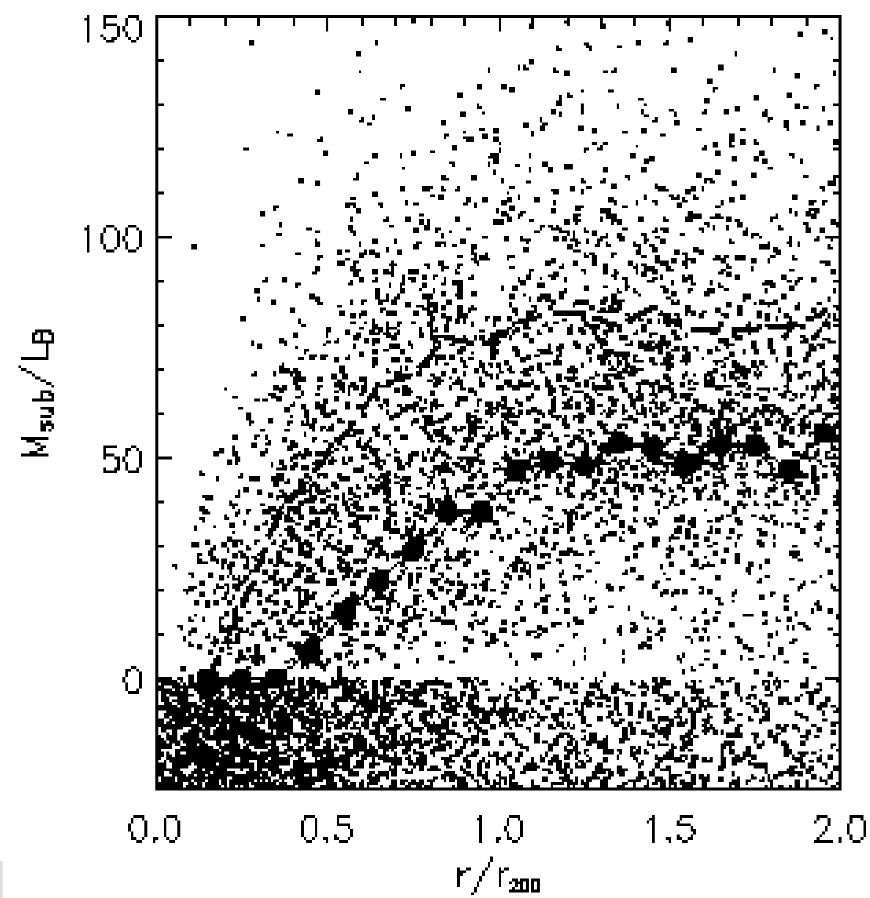
Gao et al 2004

Halos of galaxies in clusters

- The halos of cluster galaxies are less massive at smaller radii
- E's have smaller halo masses than disk galaxies of the same L
- Many galaxies have almost all their halo (and some stars?) stripped



Springel et al (2001) All resolved subhaloes



Gao et al (2004) All galaxies M < -17

Questions/topics for simulations

- Shape and profiles of halos – relation to DM/DE physics
- Relation of large-scale structure in mass/galaxies/IGM
- Mass, galaxy and X-ray/SZ properties of clusters
- Relation of halo properties to assembly/clustering/cosmology
- Truncation of halos within larger structures
- Line-of-sight effects along cosmological light-cones (Sachs-Wolfe, CMB-lensing/galaxy distribution cross-correlations, higher-order shear and shear-galaxy correlations)

Precision cosmology will require precise simulations!