Nearly Normal Galaxies II
U.C. Santa Cruz, August 2005

Large-scale simulation of the galaxy/AGN population

Simon White
Max Planck Institute for Astrophysics

Millennium Run Statistics

Springel et al 2005

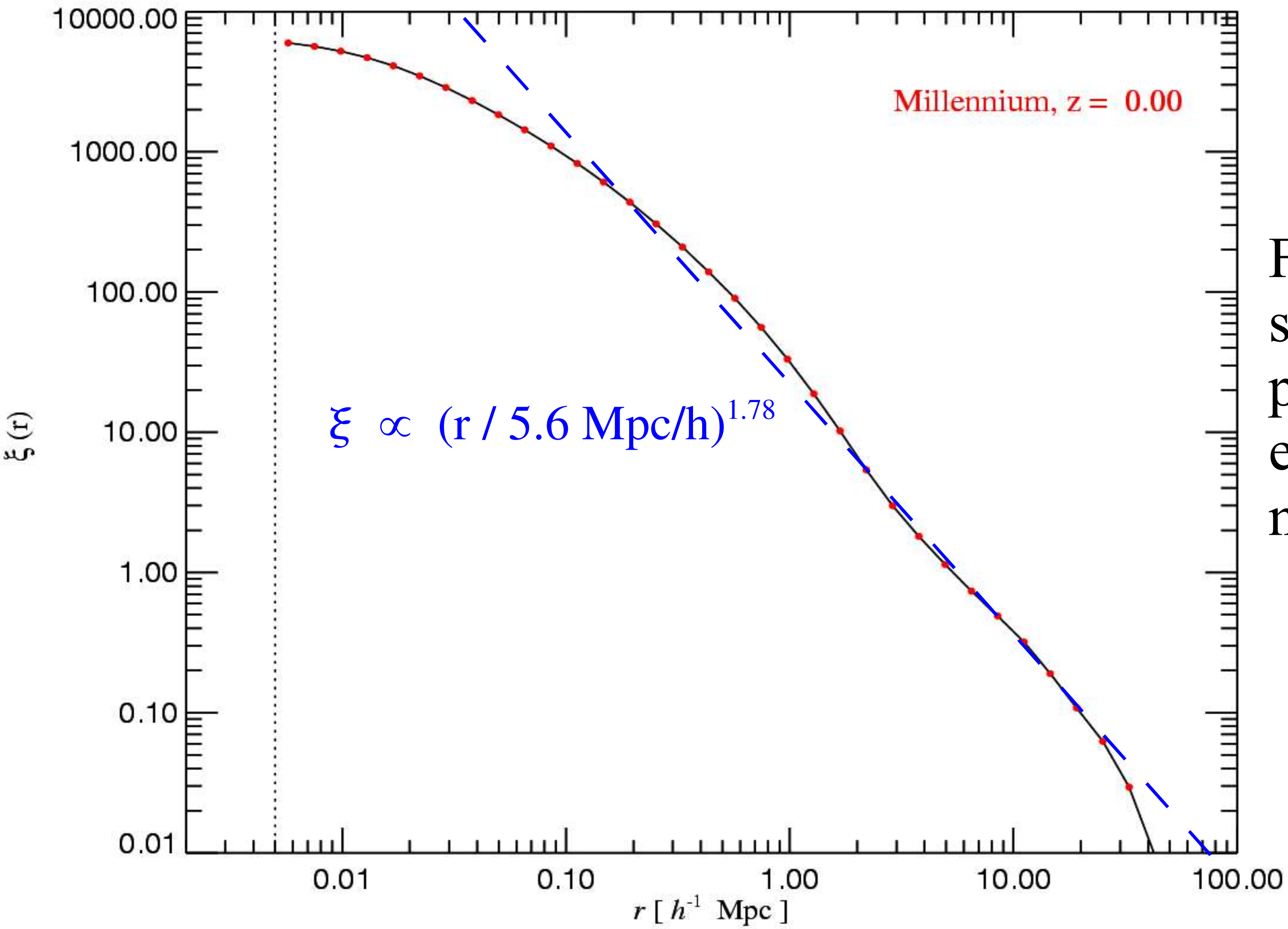
- Particle number: $N = 2160^3 = 10{,}077{,}696{,}000 \approx 10^{10}$
- Box size: $L = 500$ Mpc/h, softening: $\epsilon = 5$ kpc/h $\longrightarrow L/\epsilon = 10^5$
- Initial redshift: $z_{init} = 127$
- Cosmology: $\Omega_{tot}=1$, $\Omega_m=0.25$, $\Omega_b=0.045$, $h=0.73$, $n=1$, $\sigma_8=0.9$
- 343,000 processor-hours on 512 nodes of an IBM Regatta
  (28 machine days @ 0.2 Tflops using 1 Tbyte RAM)
- Full raw and reduced data stored at 64 redshifts

$\longrightarrow$ **27 Tbytes of stored data**

A testbed for studying galaxy formation models

Mass autocorrelation function

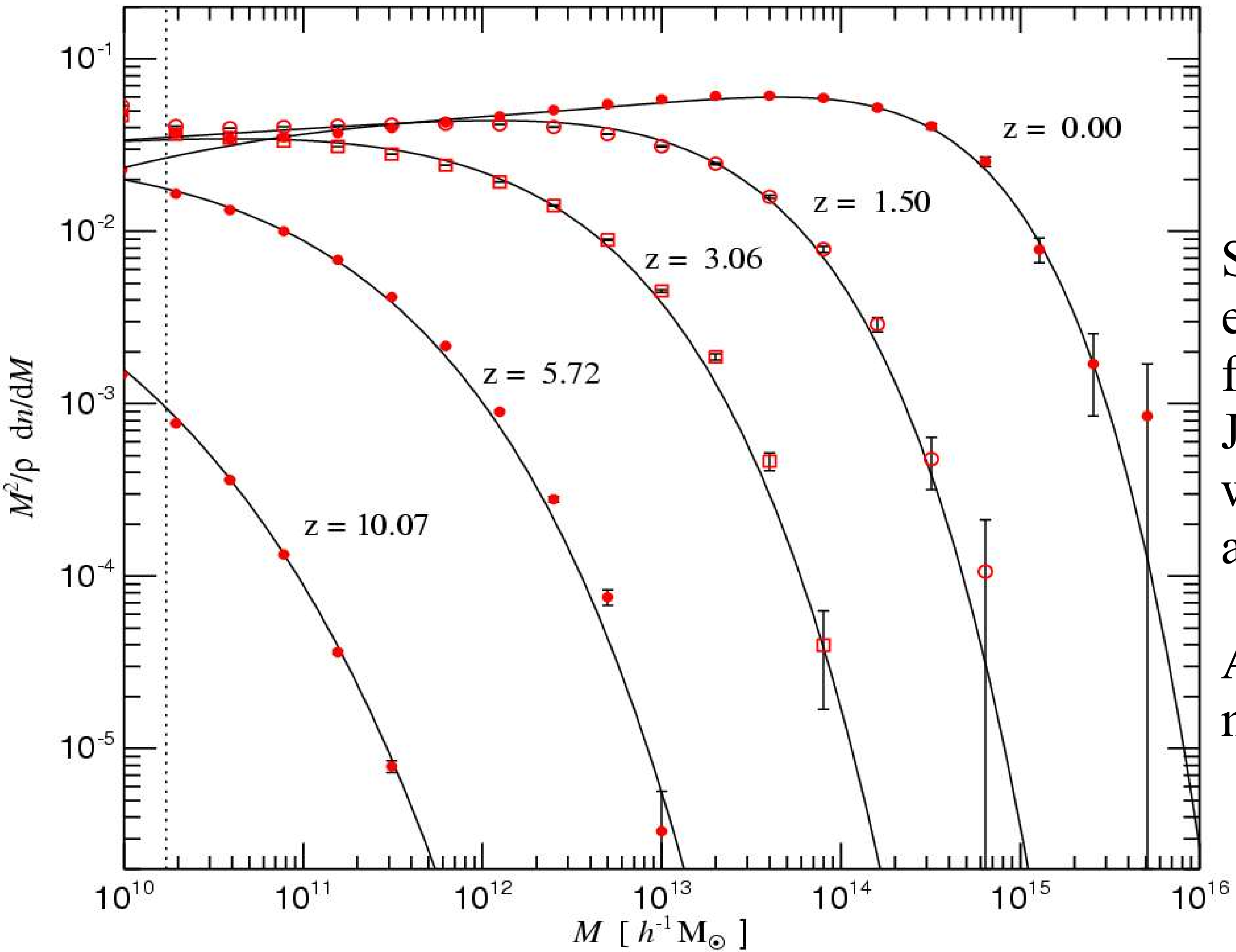
Springel et al 2005



For such a large simulation the purely statistical error bars are negligible on ξ

Halo Mass Functions in the MS

Springel et al 2005

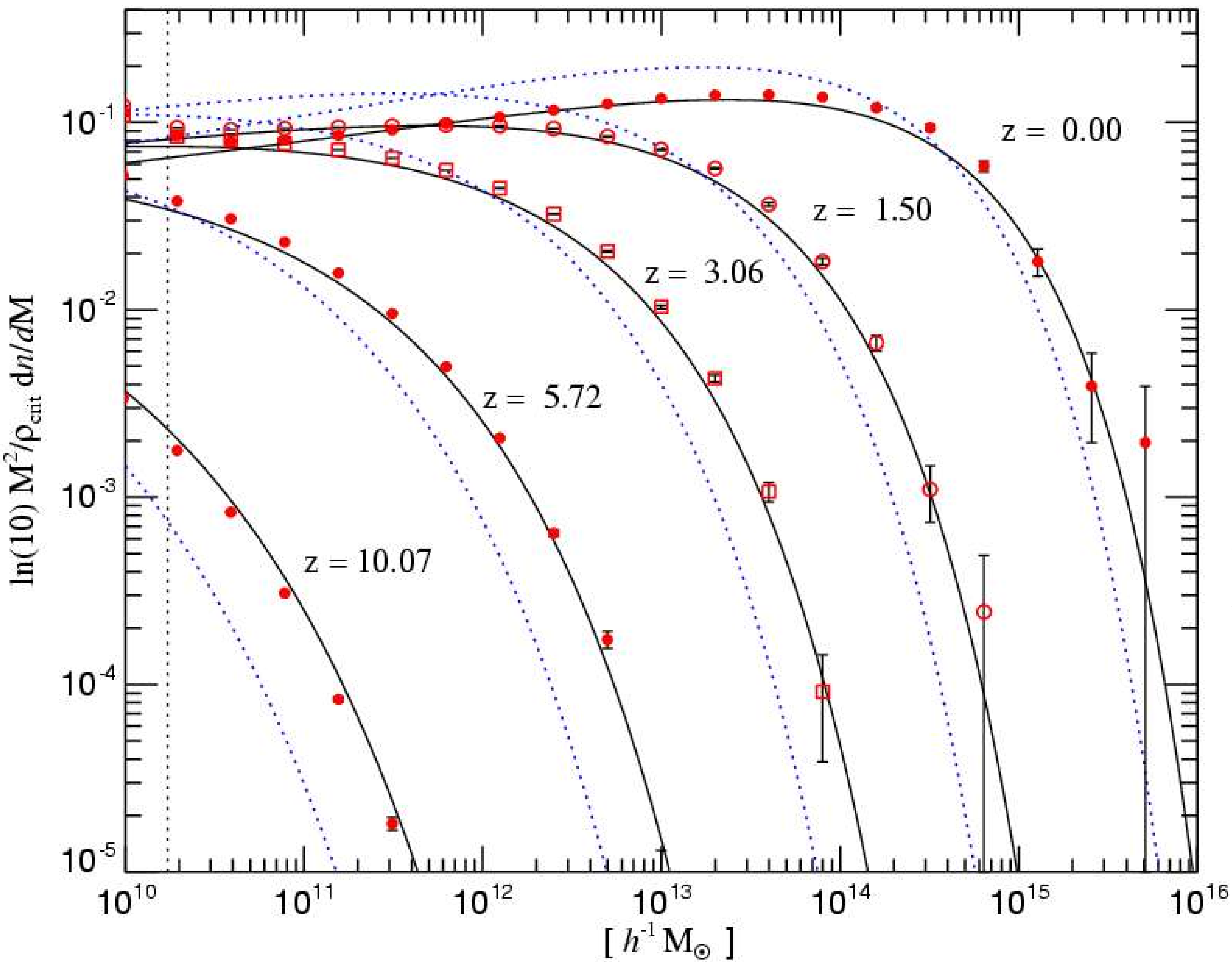


Solid curves are the empirical fitting formula from Jenkins et al 2001 with no parameters adjusted

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

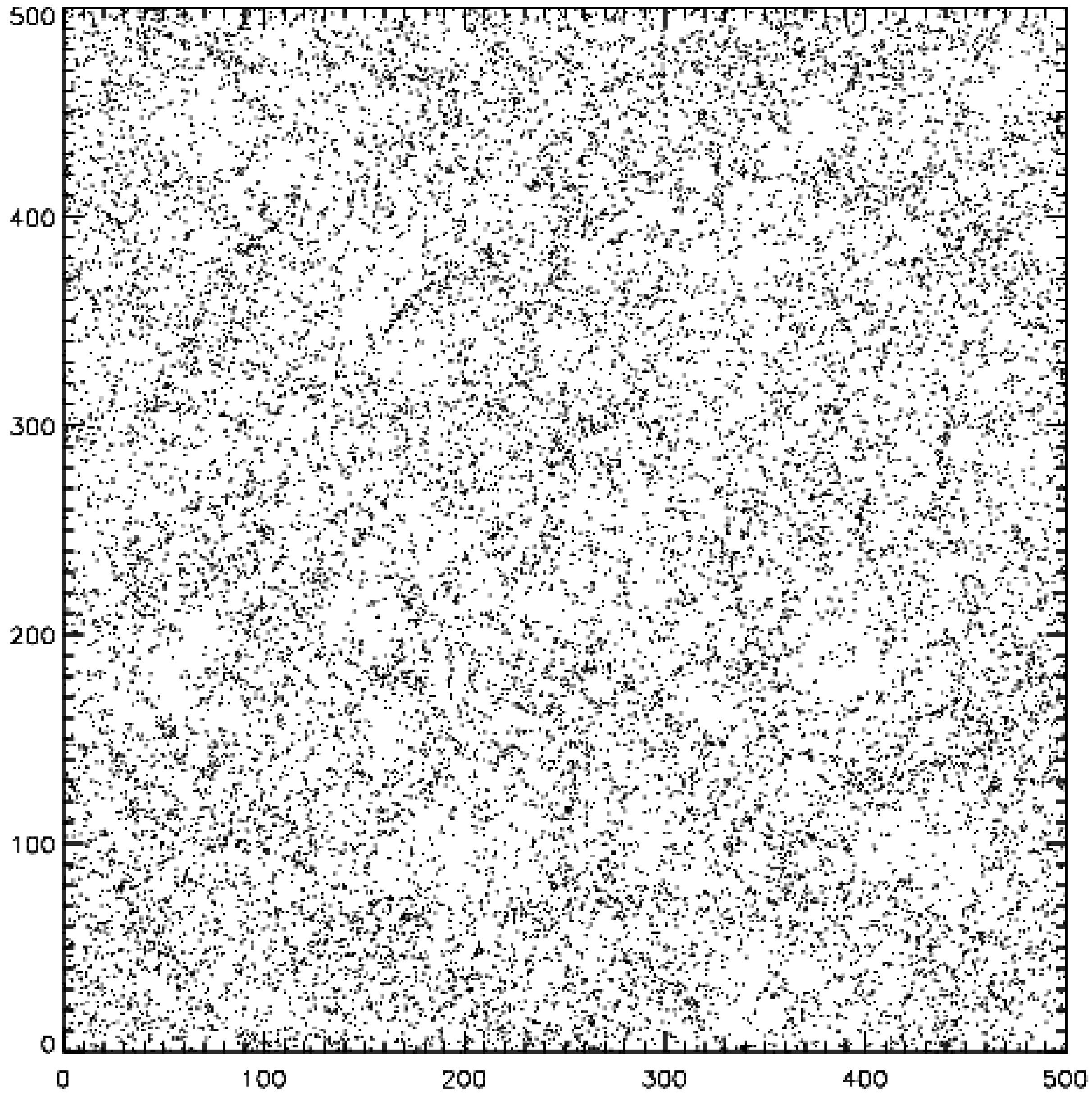
Halo Mass Functions in the MS

Springel et al 2005



Sheth-Tormen fits almost as well (solid lines) but Press & Schechter fails badly at high masses and early times (dotted lines)

Does formation history depend on environment?

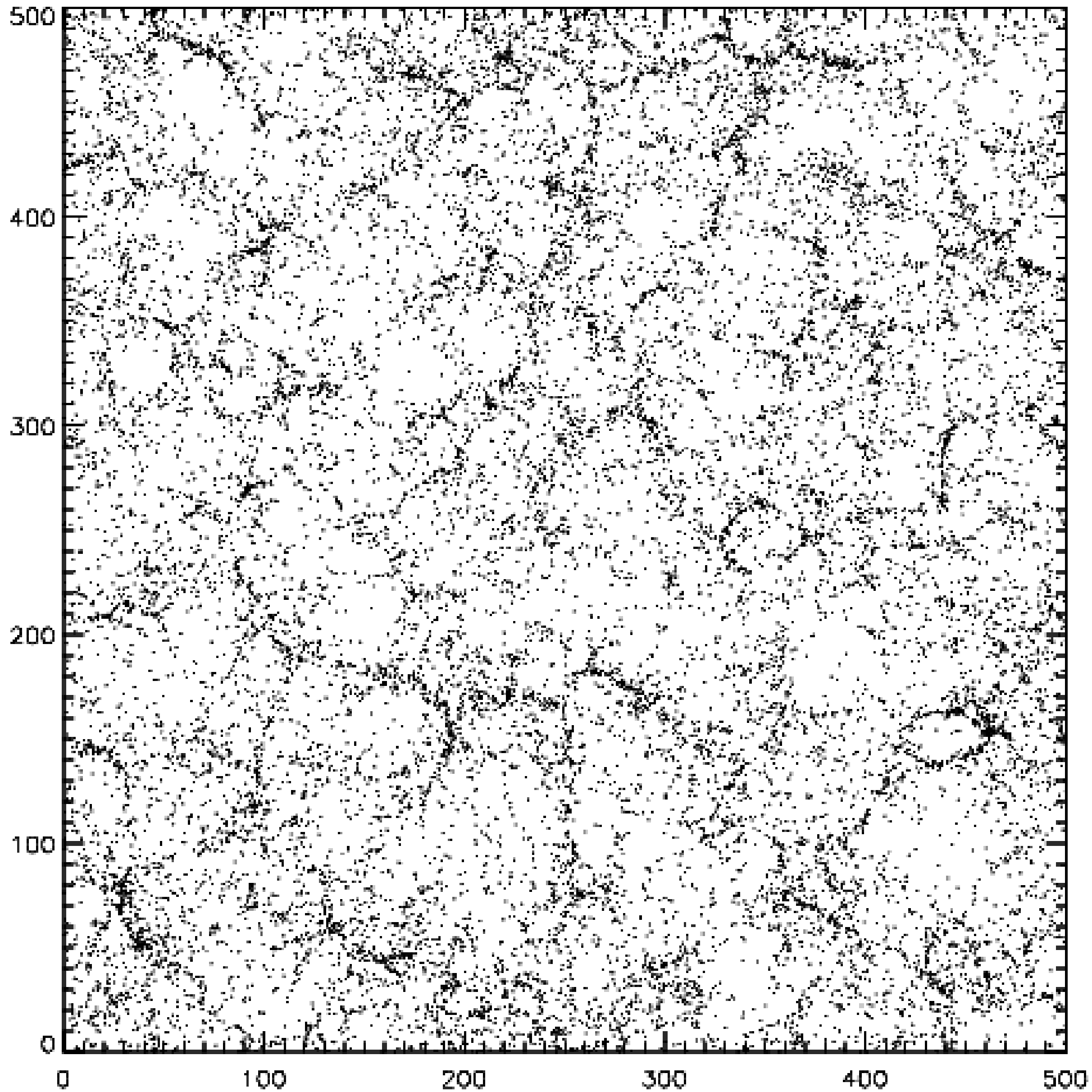


Gao, Springel & White 2005

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

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

Does formation history depend on environment?

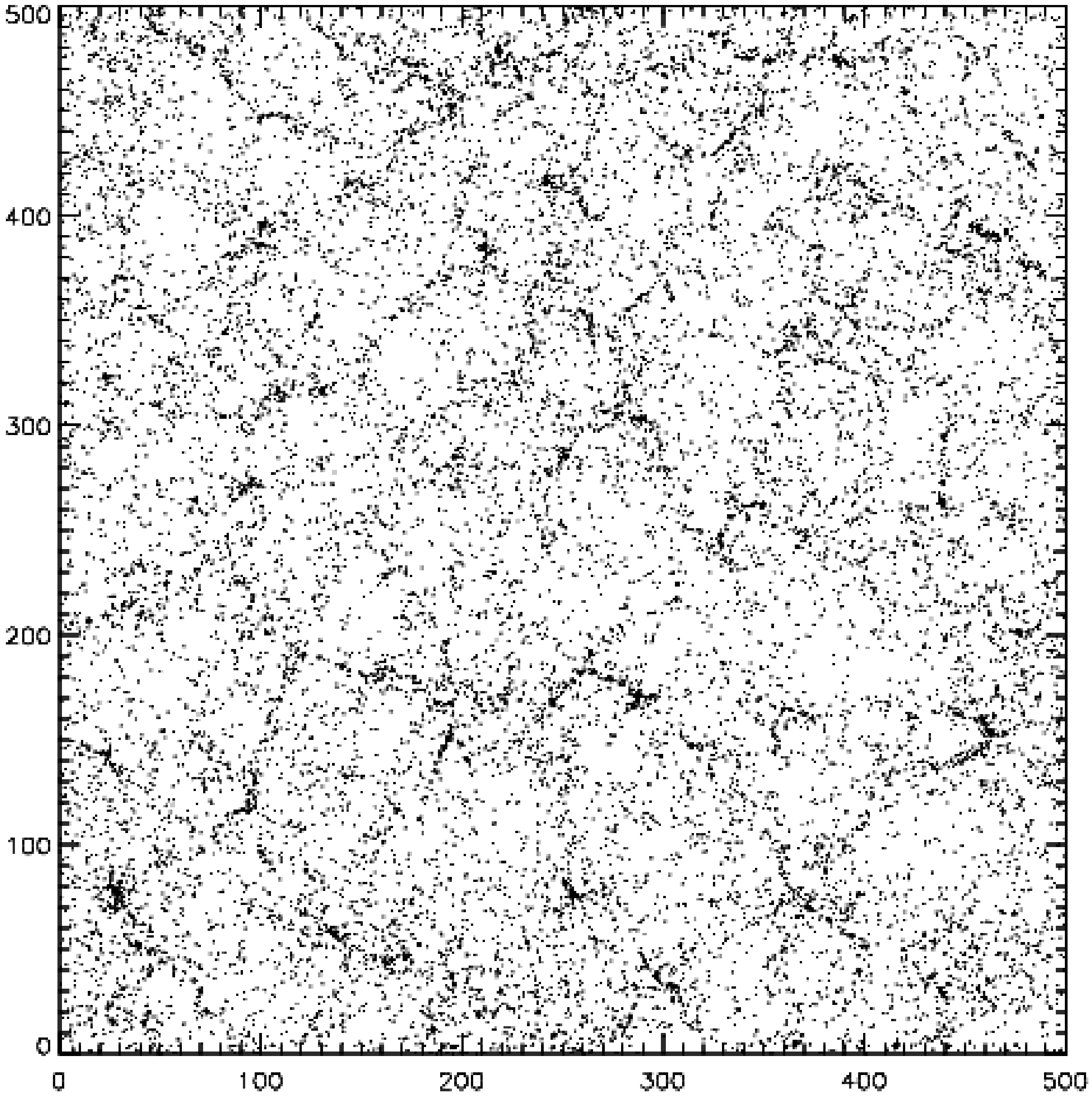


Gao, Springel & White 2005

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?

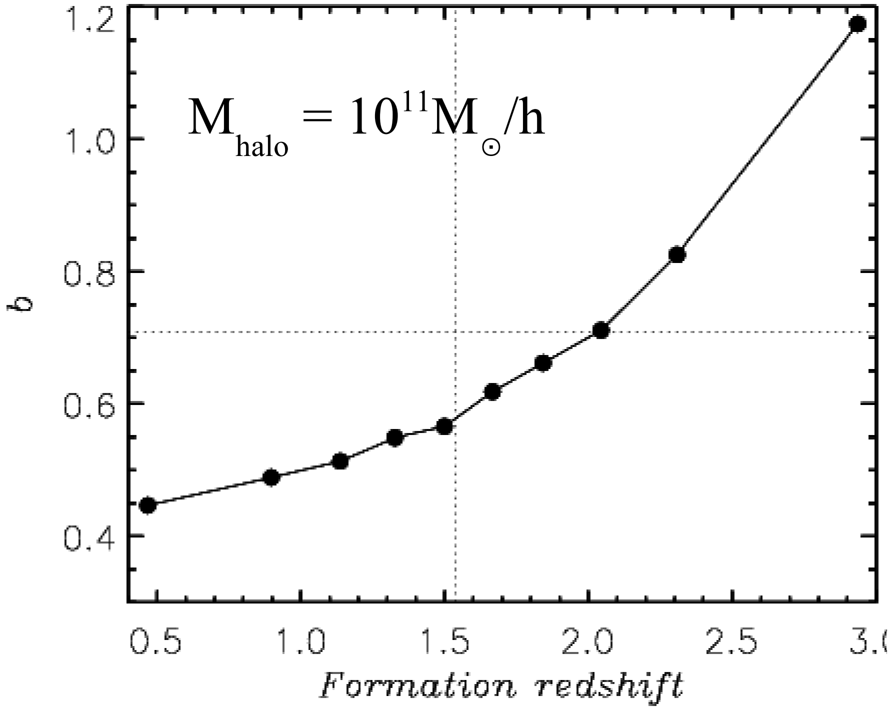


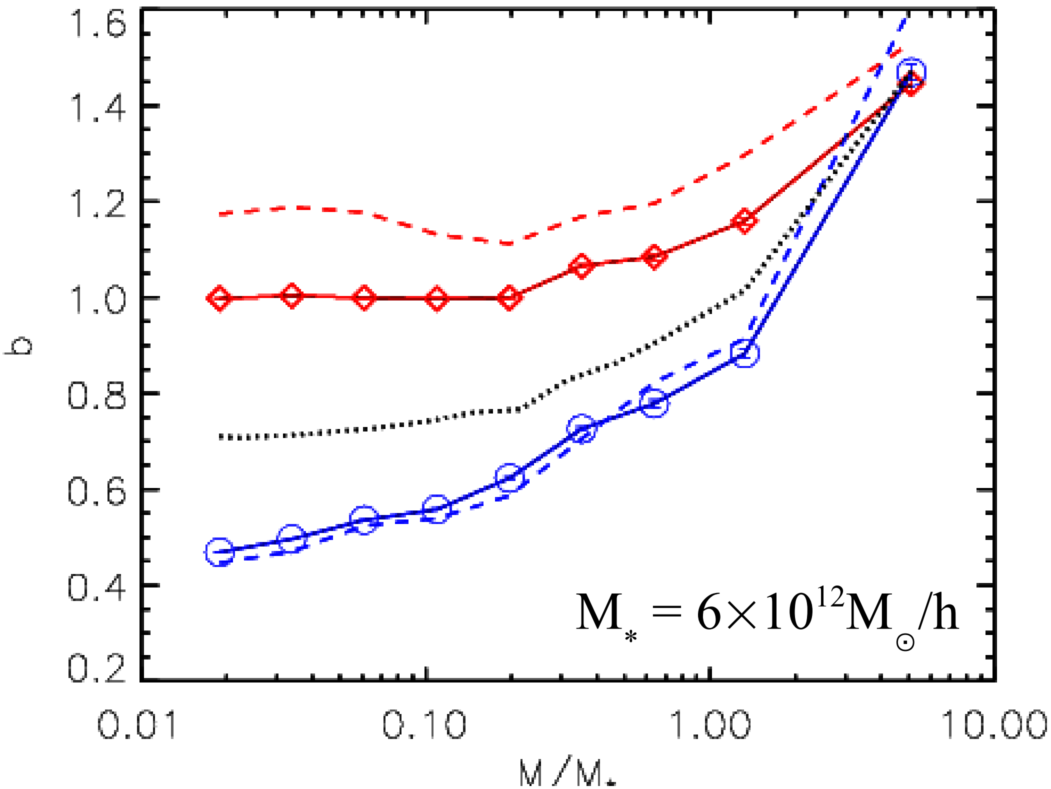
Gao, Springel & White 2005

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

Putting galaxies and AGN into the Millennium Run

Springel et al 2005; Croton et al 2005

- Build and store merger trees which encode the detailed assembly history of every z=0 halo and of the substructure within it

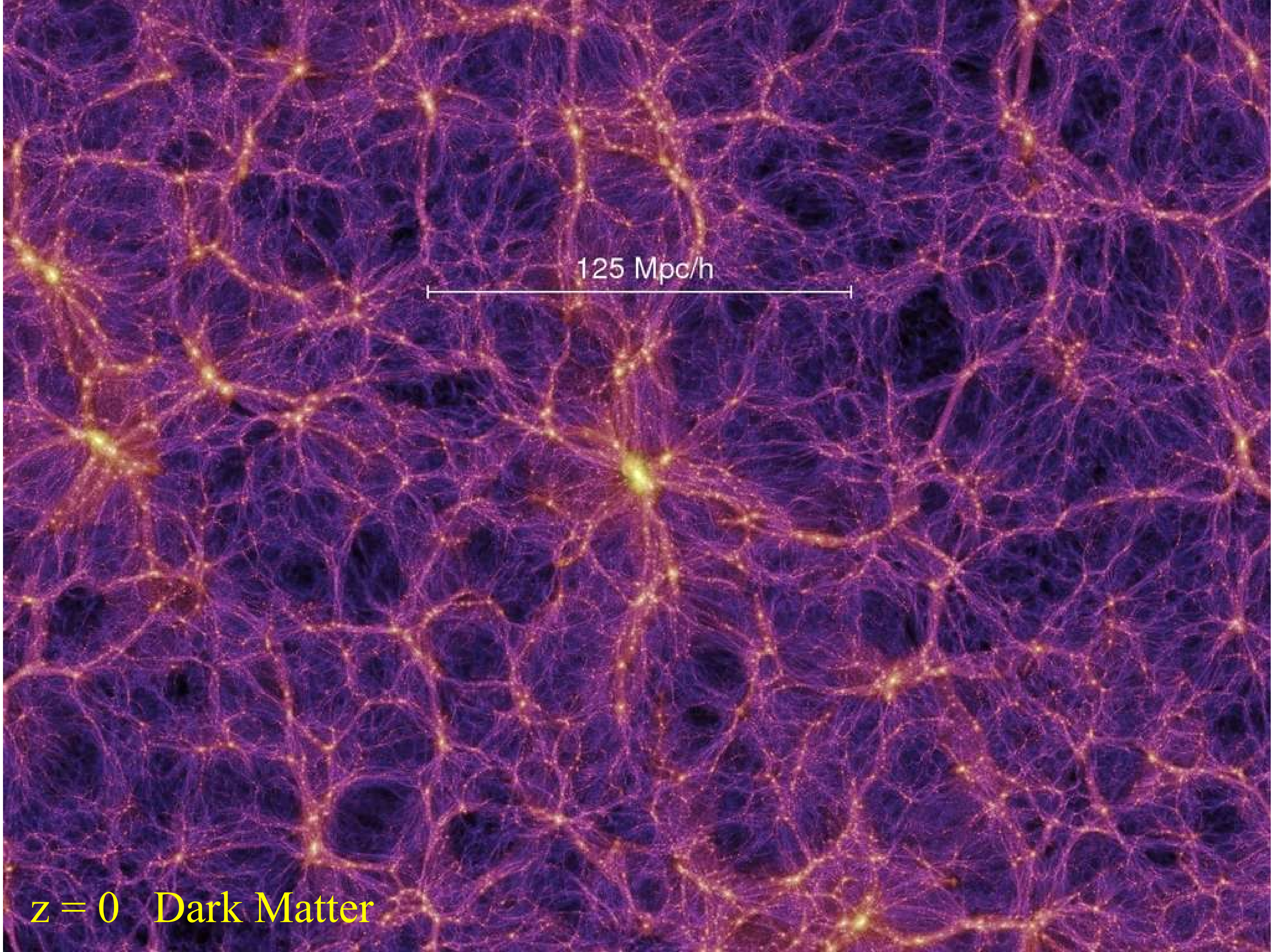
- Implement models for the formation/evolution of galaxies to follow
  - -- accretion, shock-heating and cooling of diffuse gas into disks
  - -- star formation from the ISM in disks
  - -- stellar evolution
  - -- SN feedback and stellar winds
  - -- chemical enrichment/dust formation
  - -- galaxy merging/morphological transformation

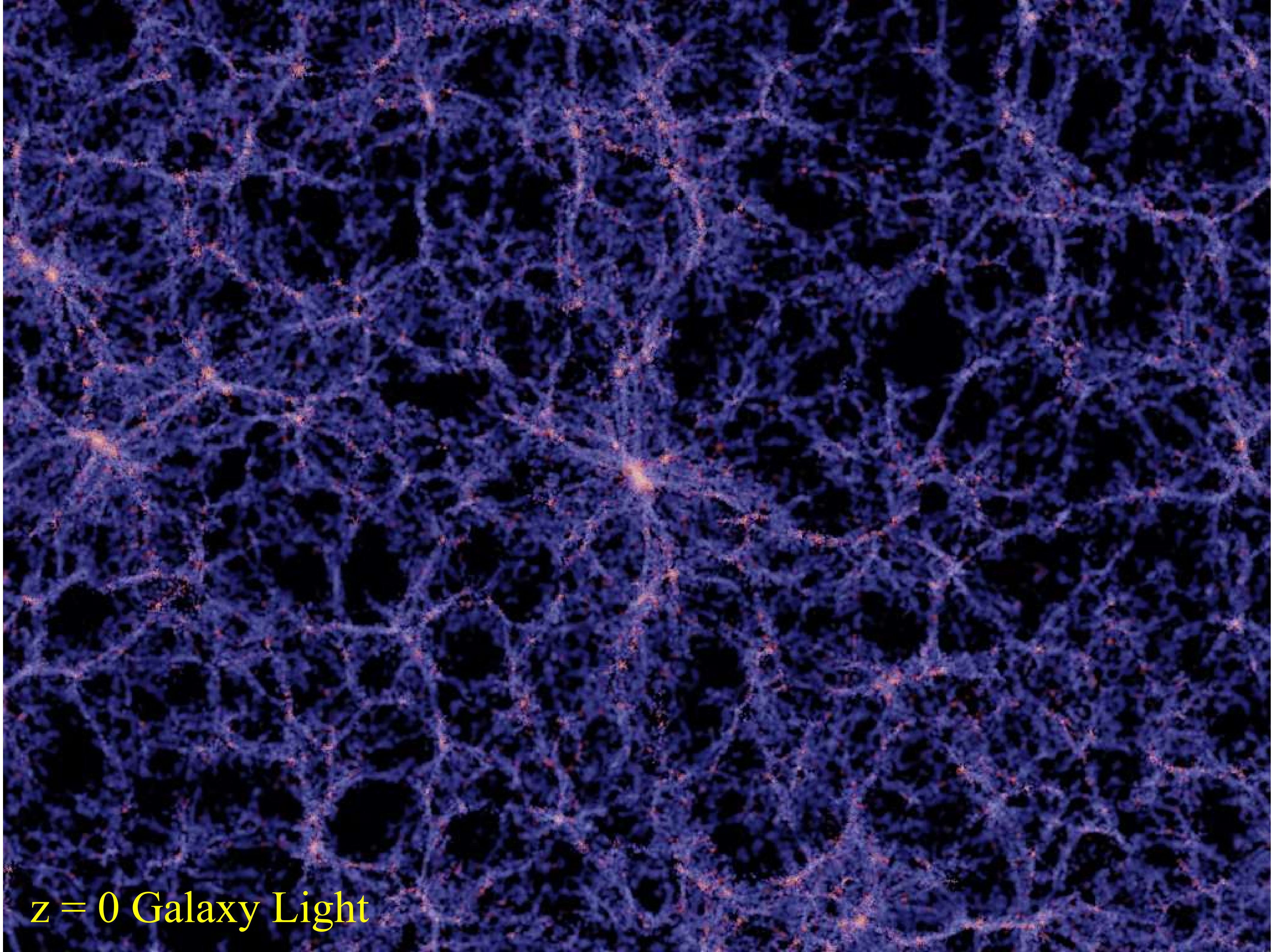
[After Springel et al (2001) and De Lucia et al (2004)]

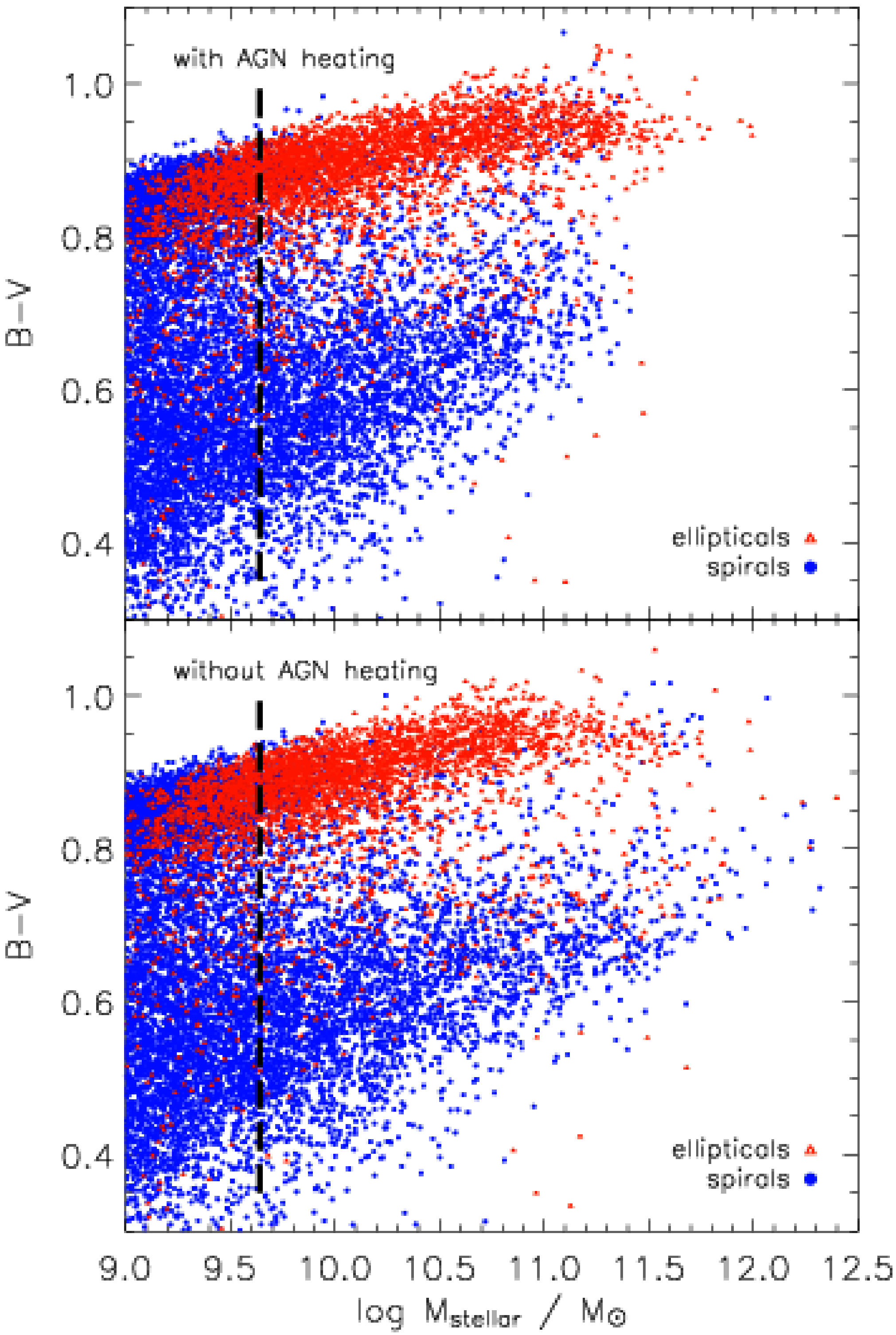
- Implement models for the growth of central black holes to follow
  - -- formation and growth from ISM gas during mergers
  - -- black hole mergers following galaxy mergers

[After Kauffmann & Haehnelt (2000)]

- Include "radio mode" feedback from BH at cooling flow centres
  - -- energy feedback from BH in the central dominant galaxy depends on BH mass, gas temperature and gas mass fraction $\propto f_{gas}\, m_{BH}\, T^{1.5}$


125 Mpc/h
z = 0   Dark Matter


z = 0 Galaxy Light

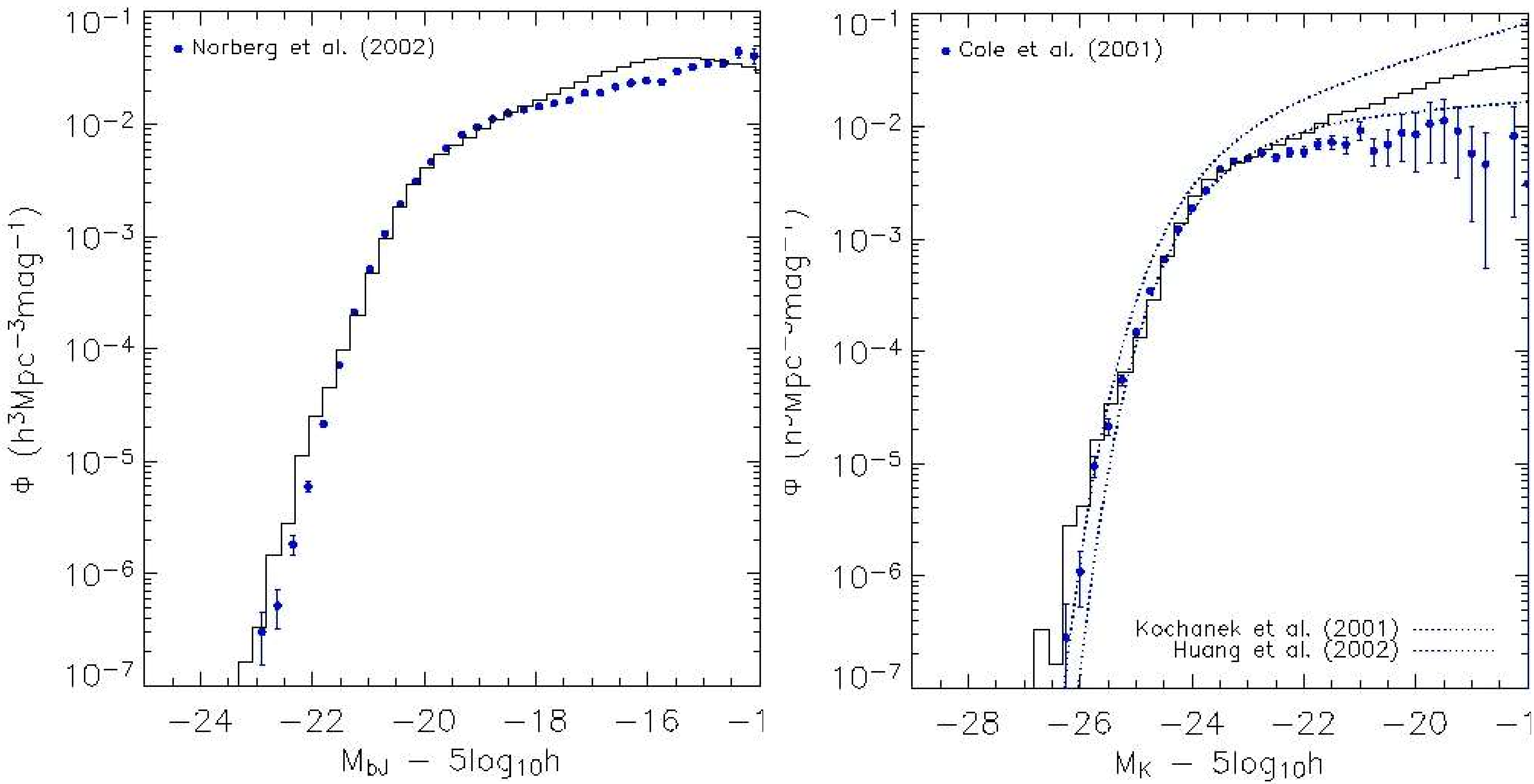


The effects of "radio mode" feedback on z=0 galaxies

Croton et al 2005

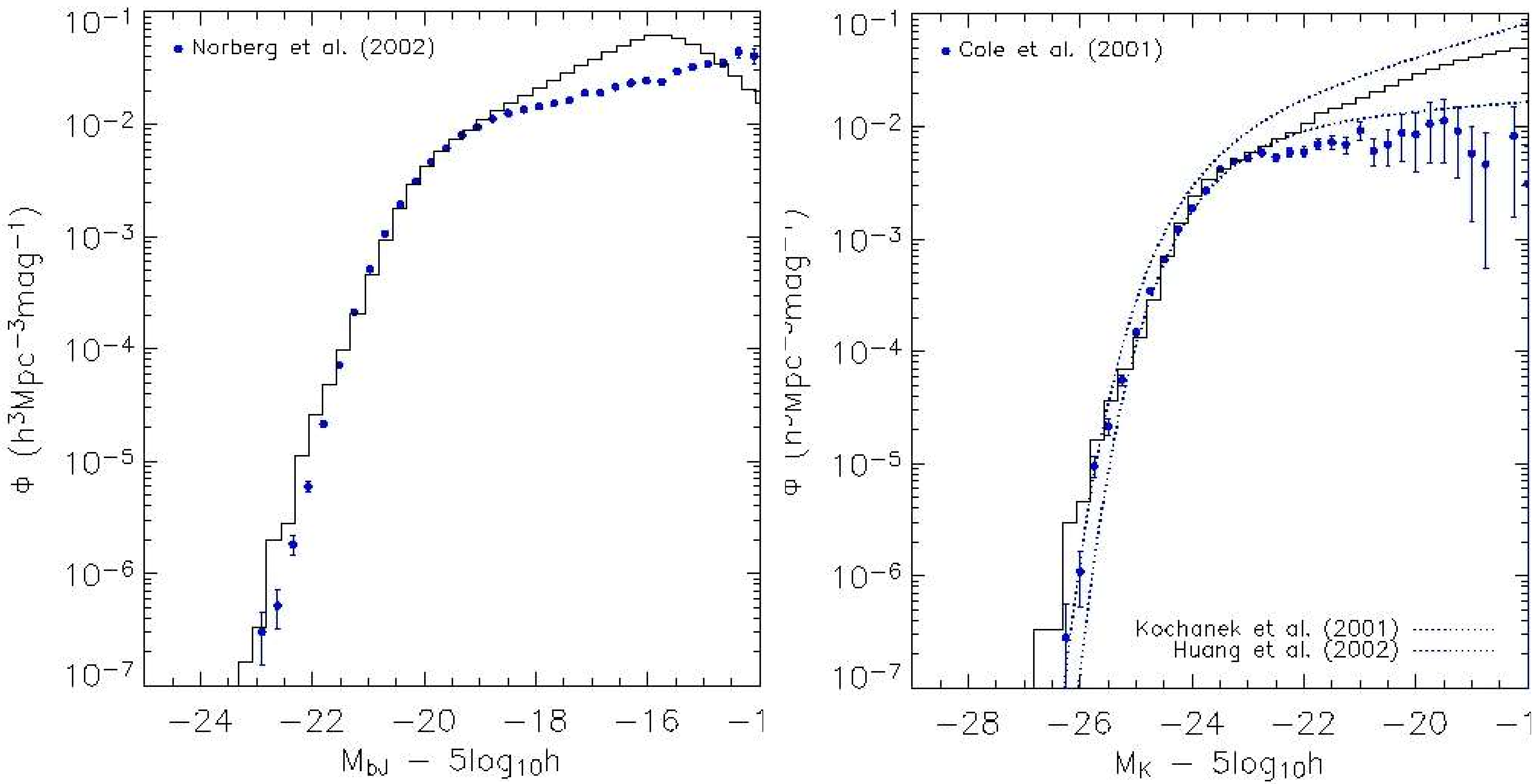
- In the absence of a "cure" for the cooling flow problem, the most massive galaxies are:
  - too bright
  - too blue
  - disk-dominated
- With cooling flows suppressed by "radio AGN" these galaxies are
  - less massive
  - red
  - elliptical

Effect of feedback on the Luminosity Function



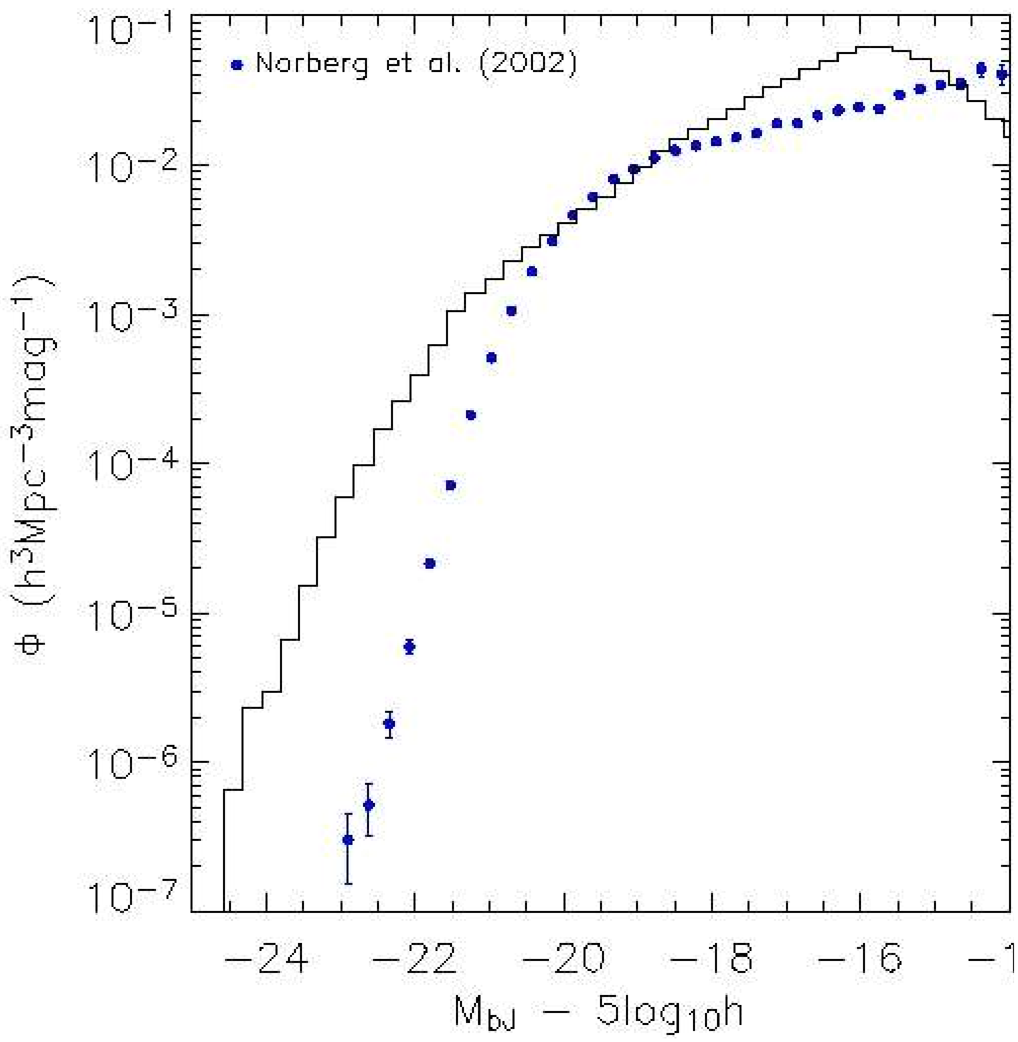
Full model with reionisation, AGN and SN feedback Croton et al 2005

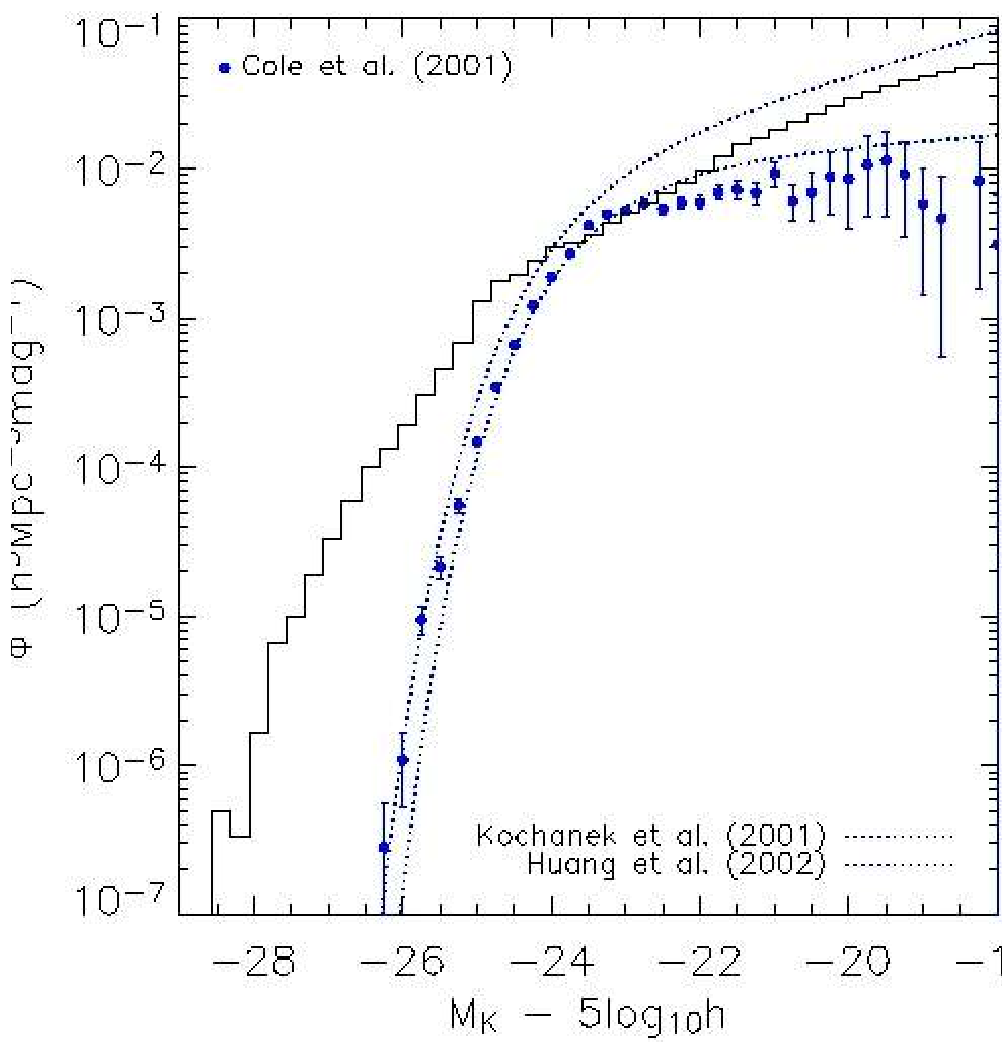
Effect of feedback on the Luminosity Function



Full model with ~~reionisation,~~ AGN and SN feedback Croton et al 2005

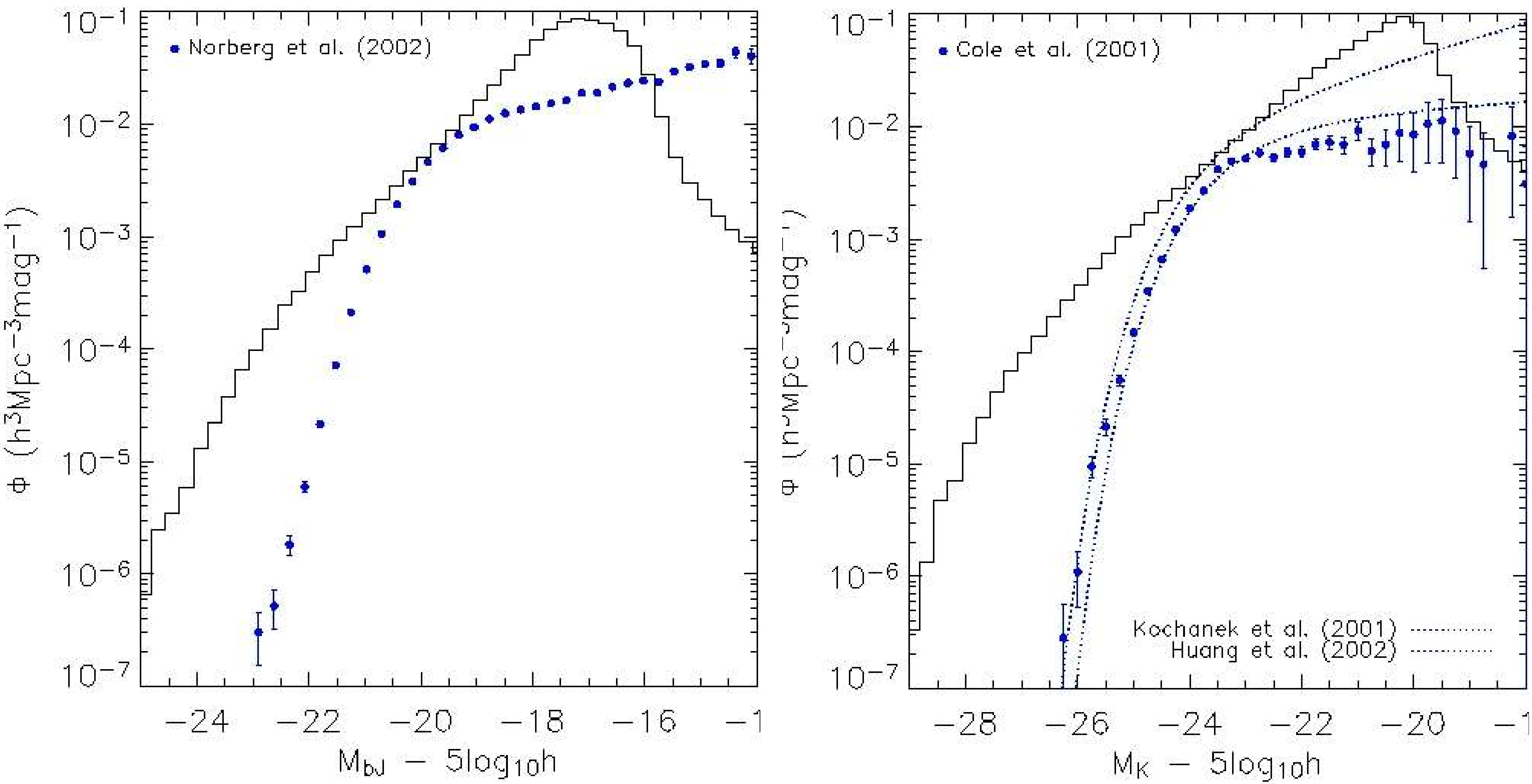
Effect of feedback on the Luminosity Function





Full model with ~~reionisation~~, ~~AGN~~ and SN feedback   Croton et al 2005

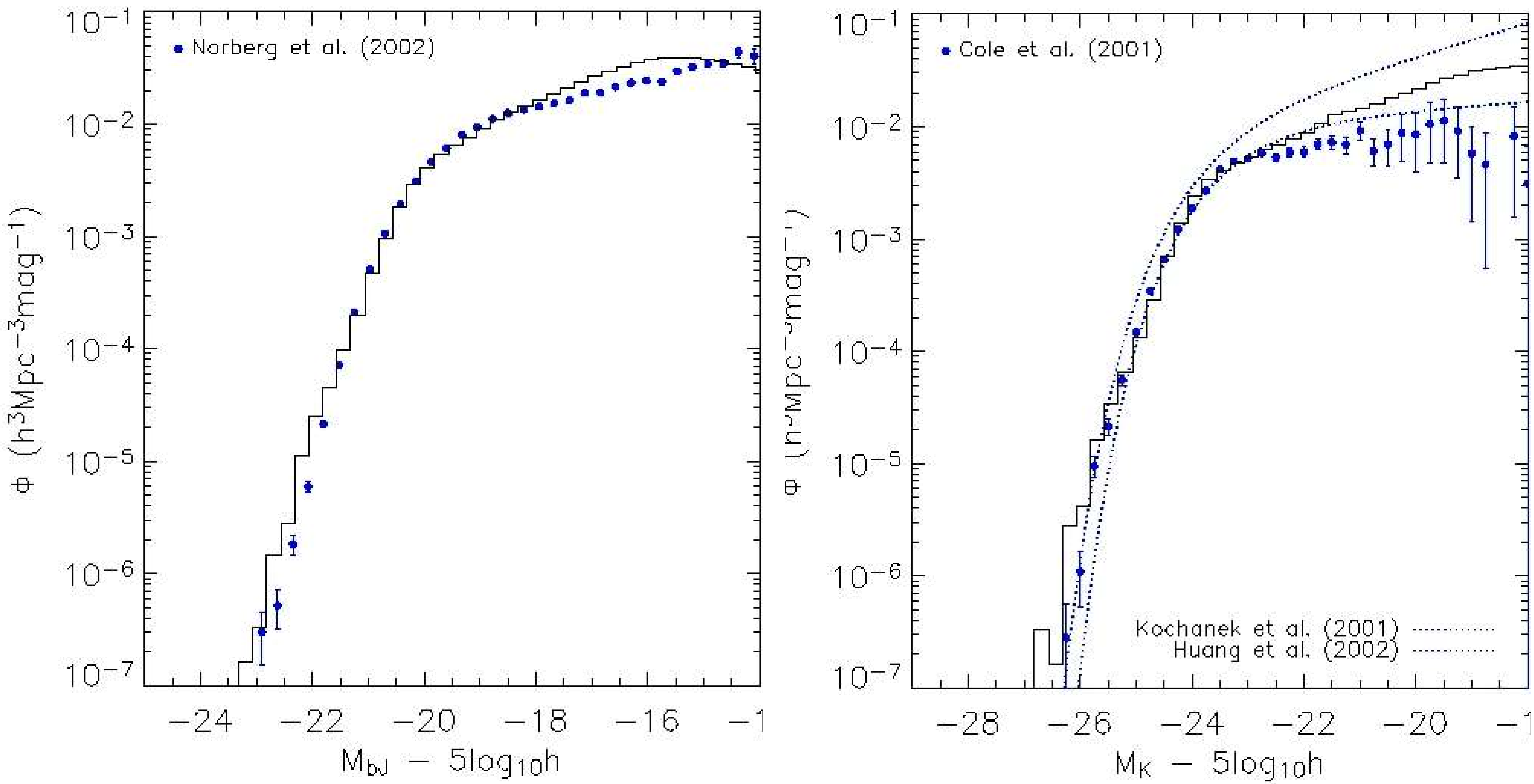
Effect of feedback on the Luminosity Function



Full model with ~~reionisation~~, ~~AGN~~ and ~~SN~~ feedback

Croton et al 2005

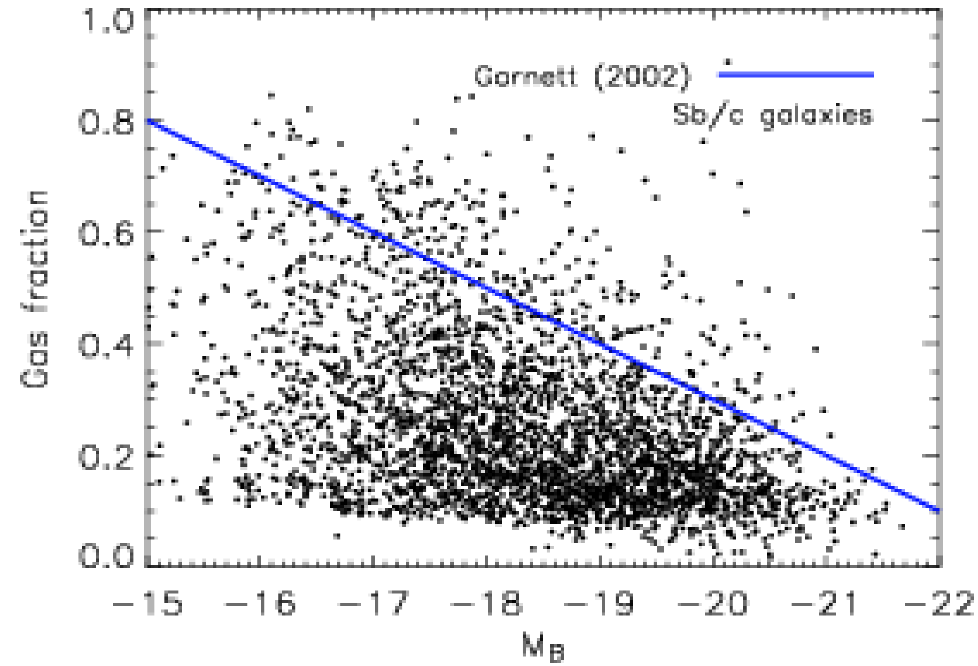
Effect of feedback on the Luminosity Function

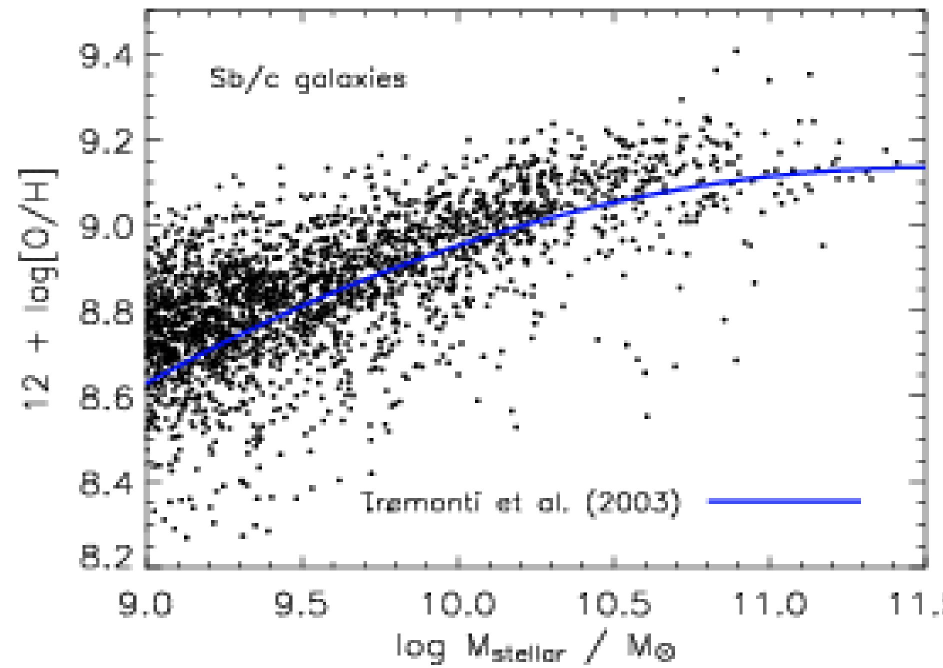


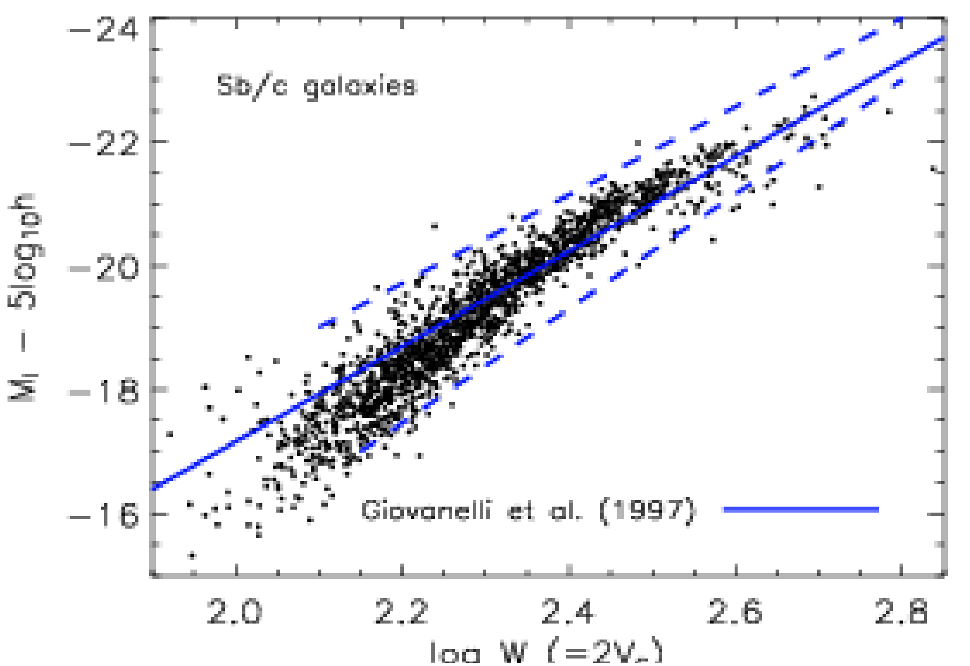
Full model with reionisation, AGN and SN feedback Croton et al 2005

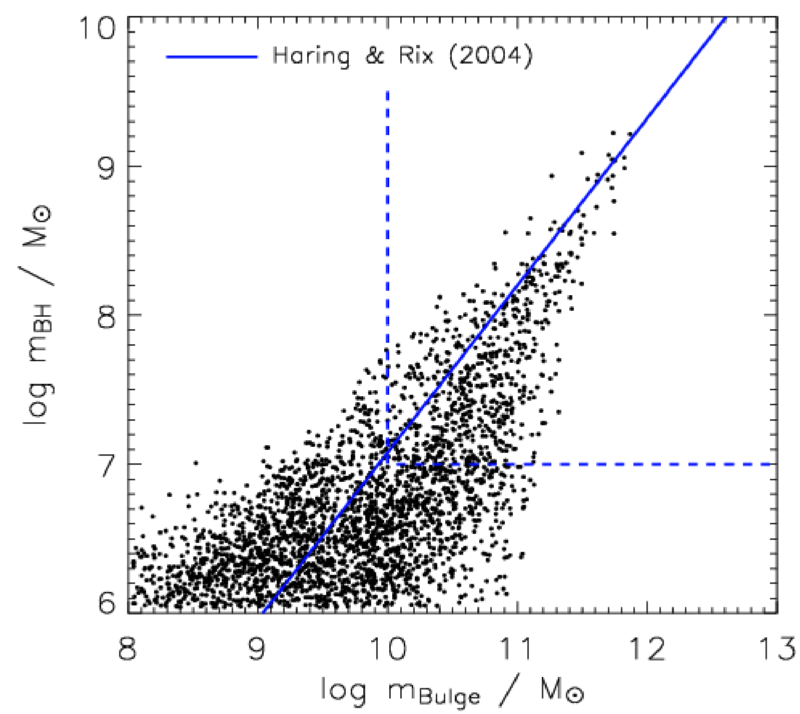
Other galaxy properties at z=0

Croton et al 2005



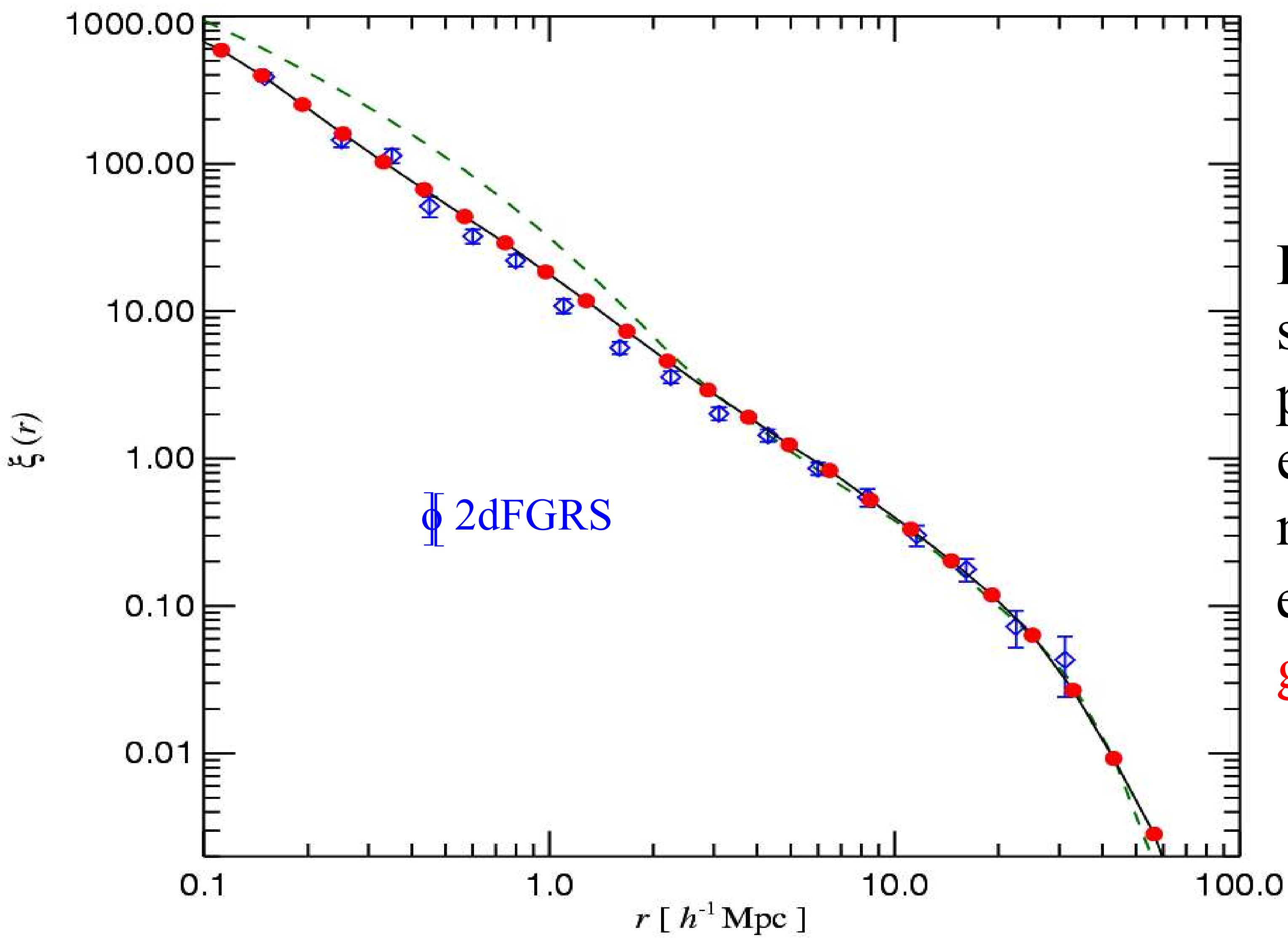






Galaxy autocorrelation function

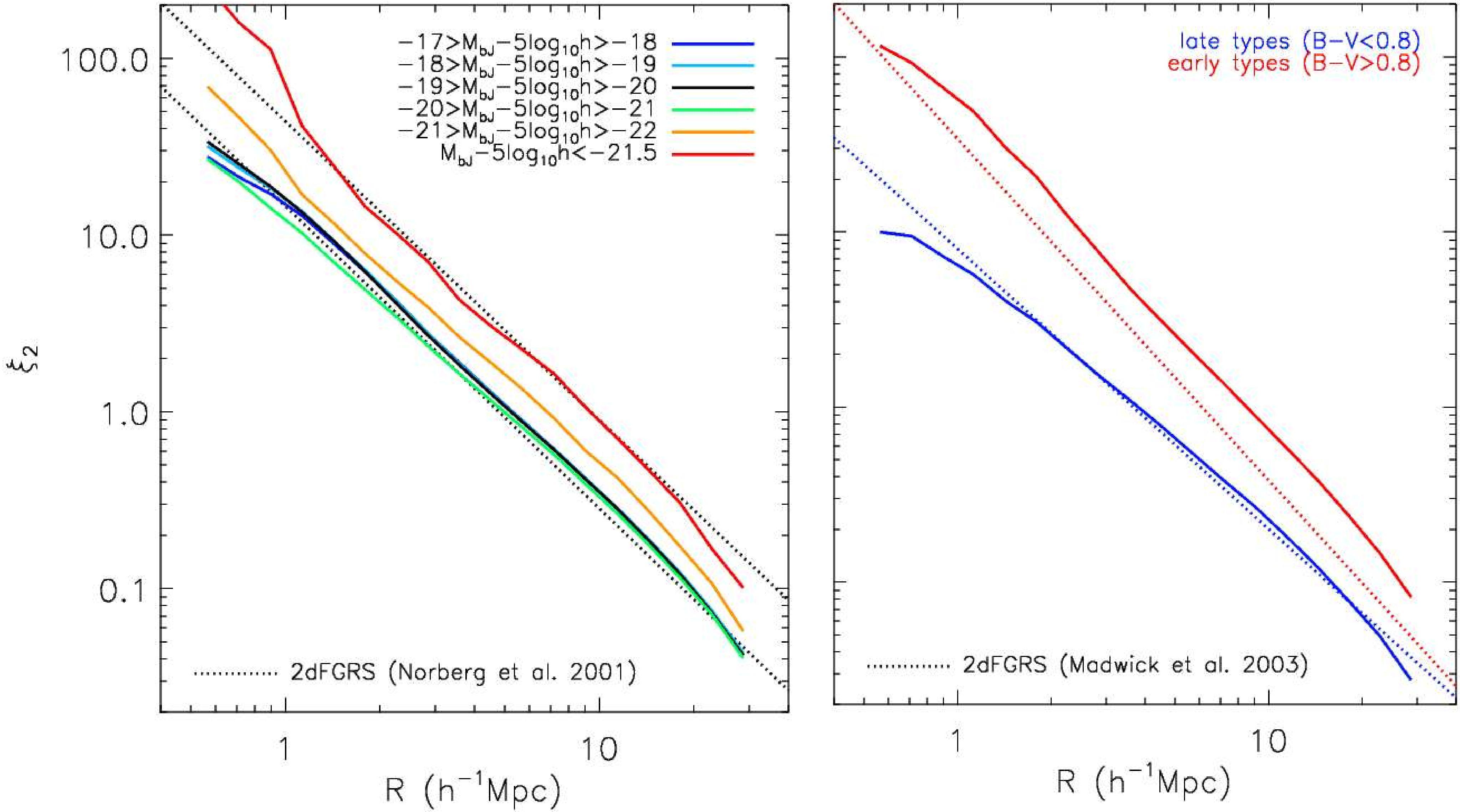
Springel et al 2005



For such a large simulation the purely statistical error bars are negligible on ξ even for the galaxies

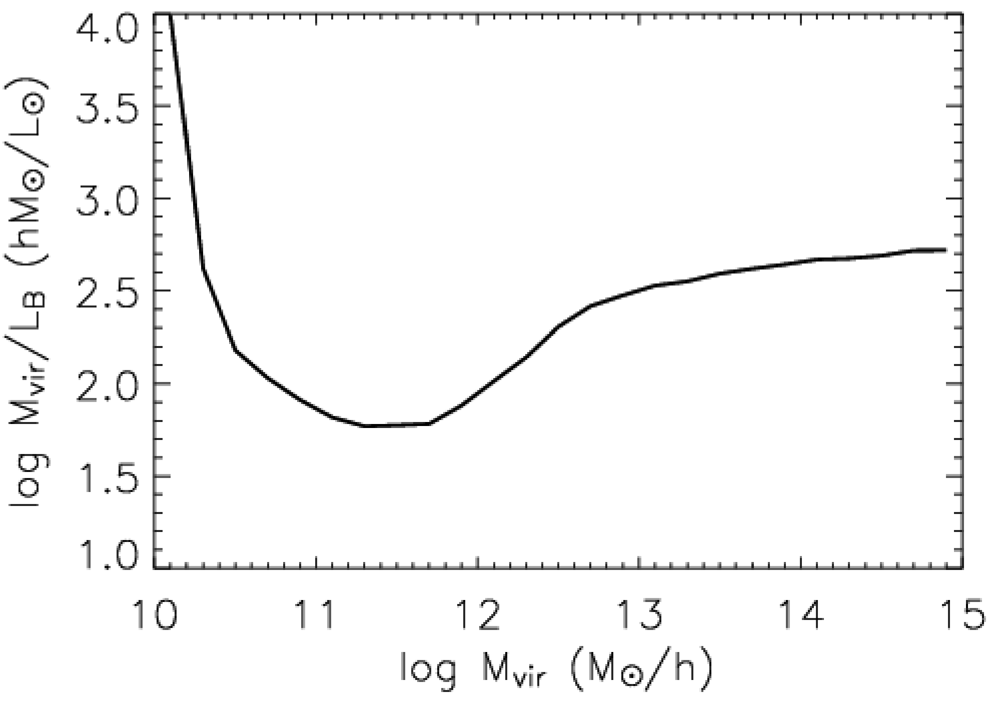
Galaxy autocorrelation function

Croton et al 2005



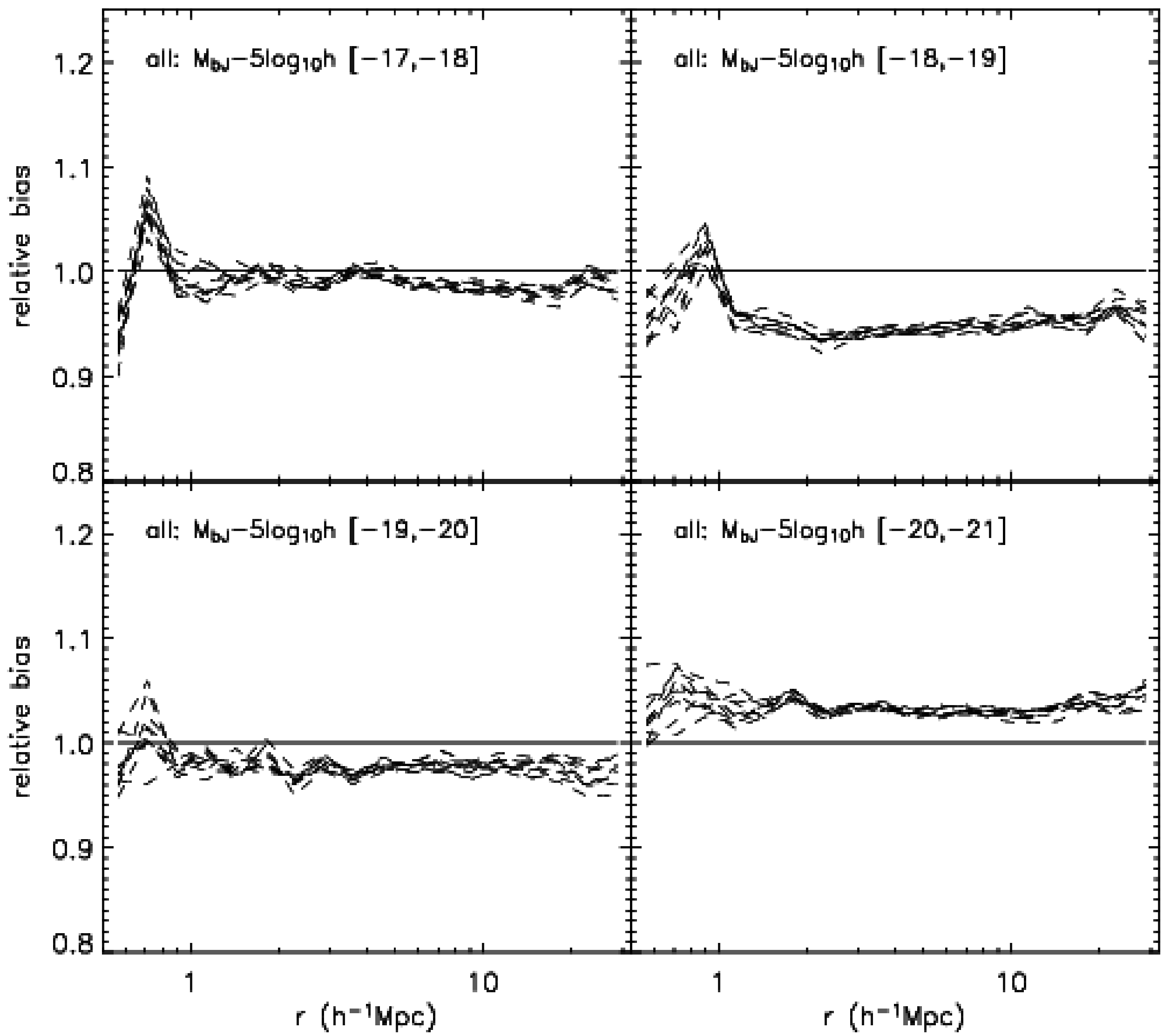
Mass-to-light ratios of z=0 halos

Croton et al 2005



- M/L is minimum for Milky Way mass halos
- We find consistent LF's, ξ's and M/L ratios for clusters in the concordance model with $\sigma_8 = 0.9$ (c.f. van den Bosch HOD results)

A test of the HOD model

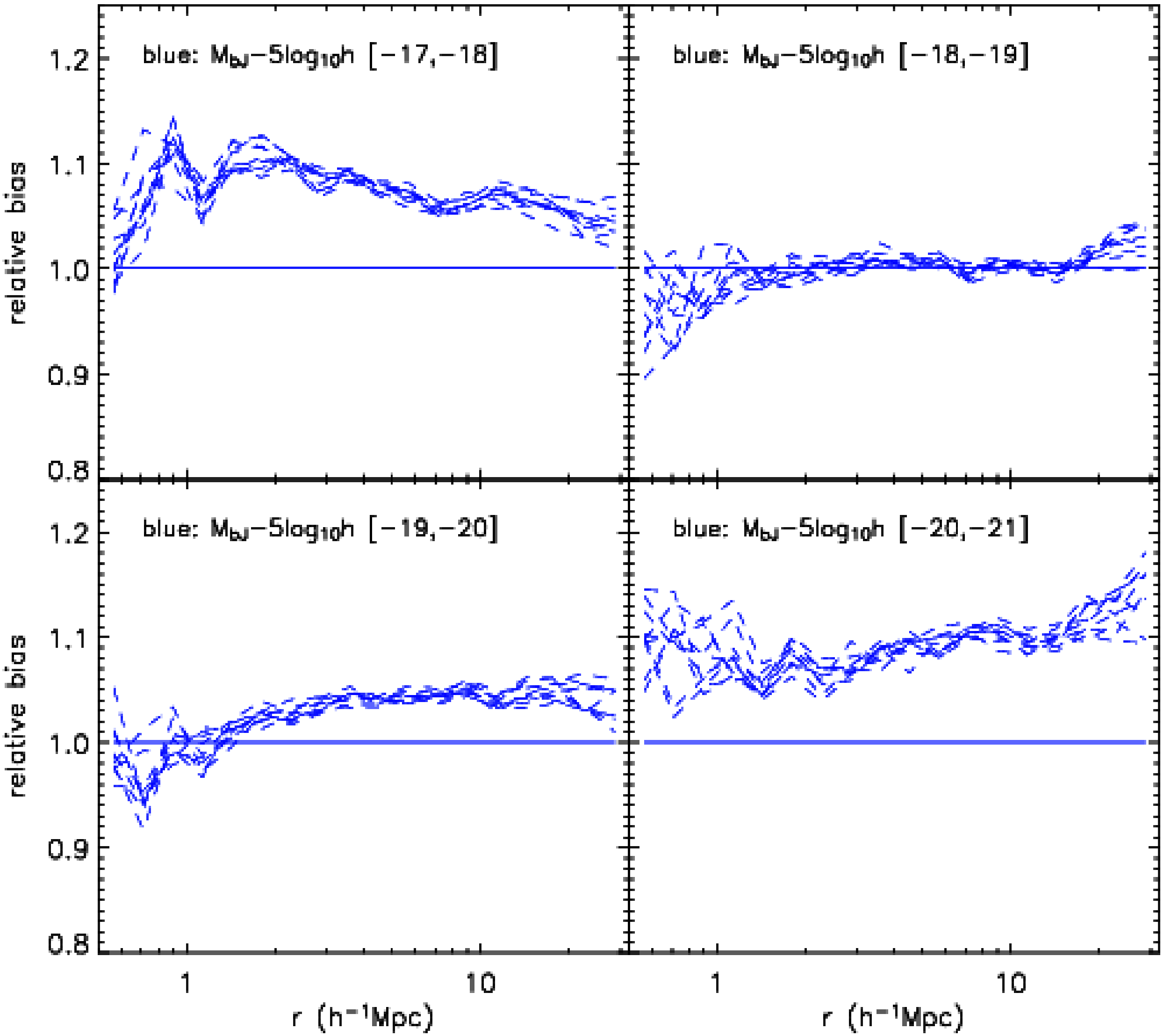


All galaxies

Galaxy autocorrelations are compared between two models
(a) a full simulation of galaxy formation
(b) the same simulation but with galaxy populations shuffled among halos of fixed mass

The bias plotted is the square root of the ratio of the correlation func's

A test of the HOD model

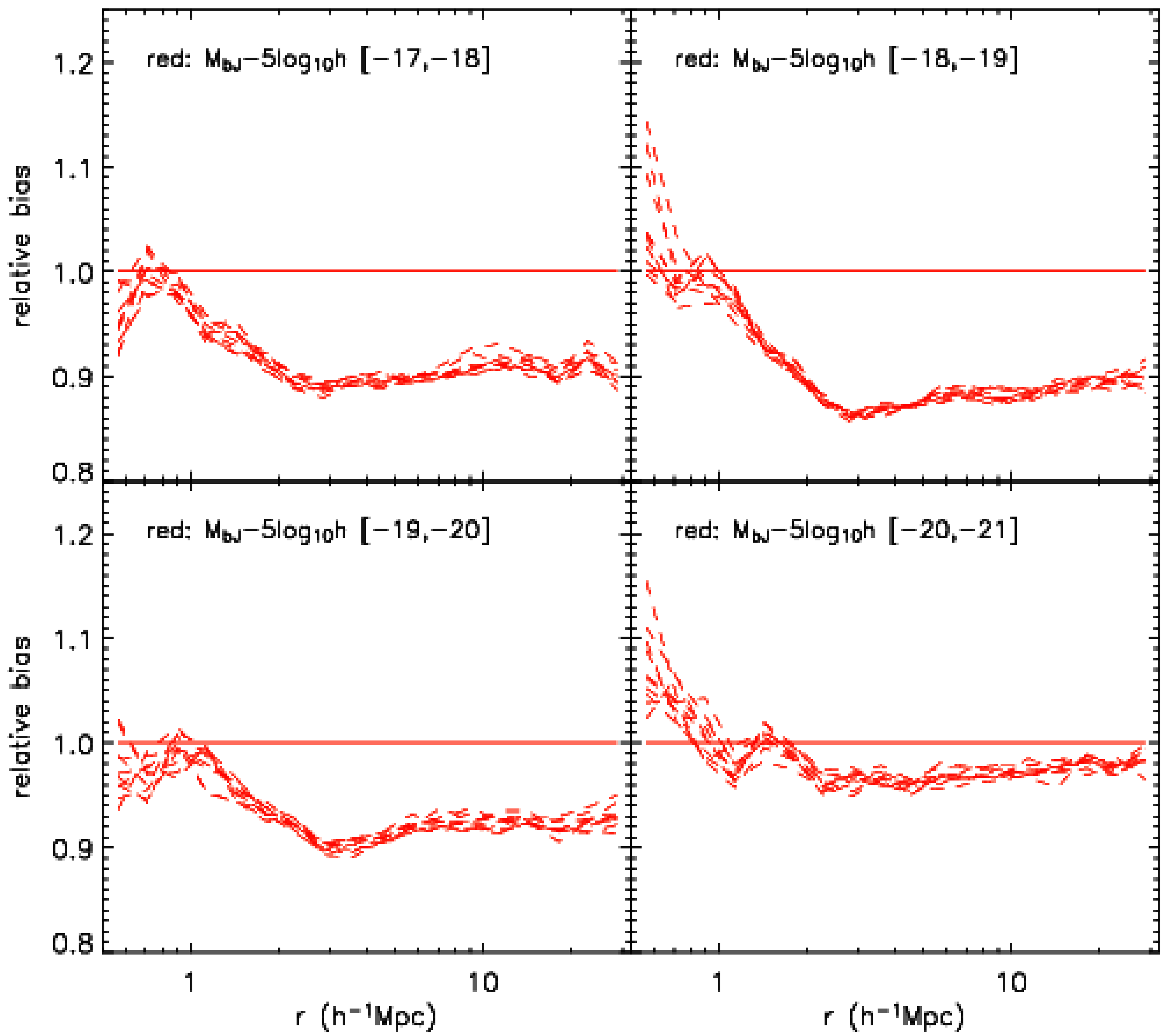


Blue galaxies

Galaxy autocorrelations are compared between two models
(a) a full simulation of galaxy formation
(b) the same simulation but with galaxy populations shuffled among halos of fixed mass

The bias plotted is the square root of the ratio of the correlation func's

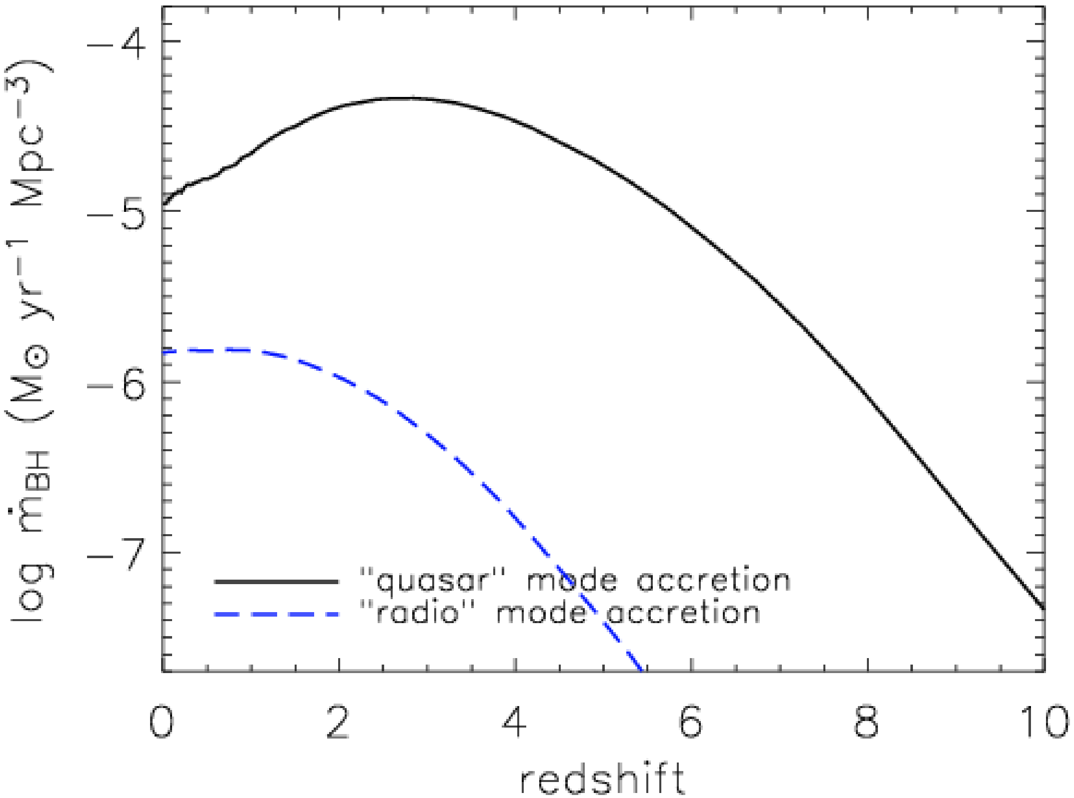
A test of the HOD model



Red galaxies

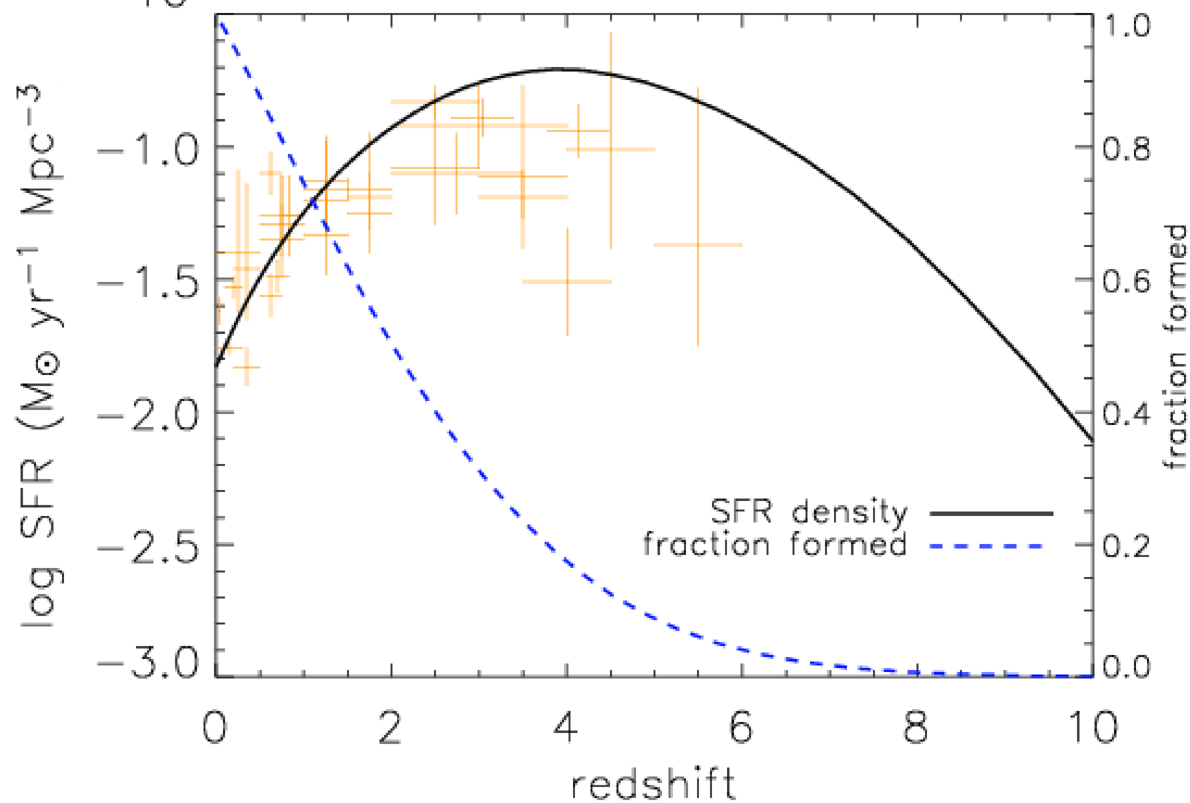
Galaxy autocorrelations are compared between two models
(a) a full simulation of galaxy formation
(b) the same simulation but with galaxy populations shuffled among halos of fixed mass

The bias plotted is the square root of the ratio of the correlation func's



Evolution of feedback sources

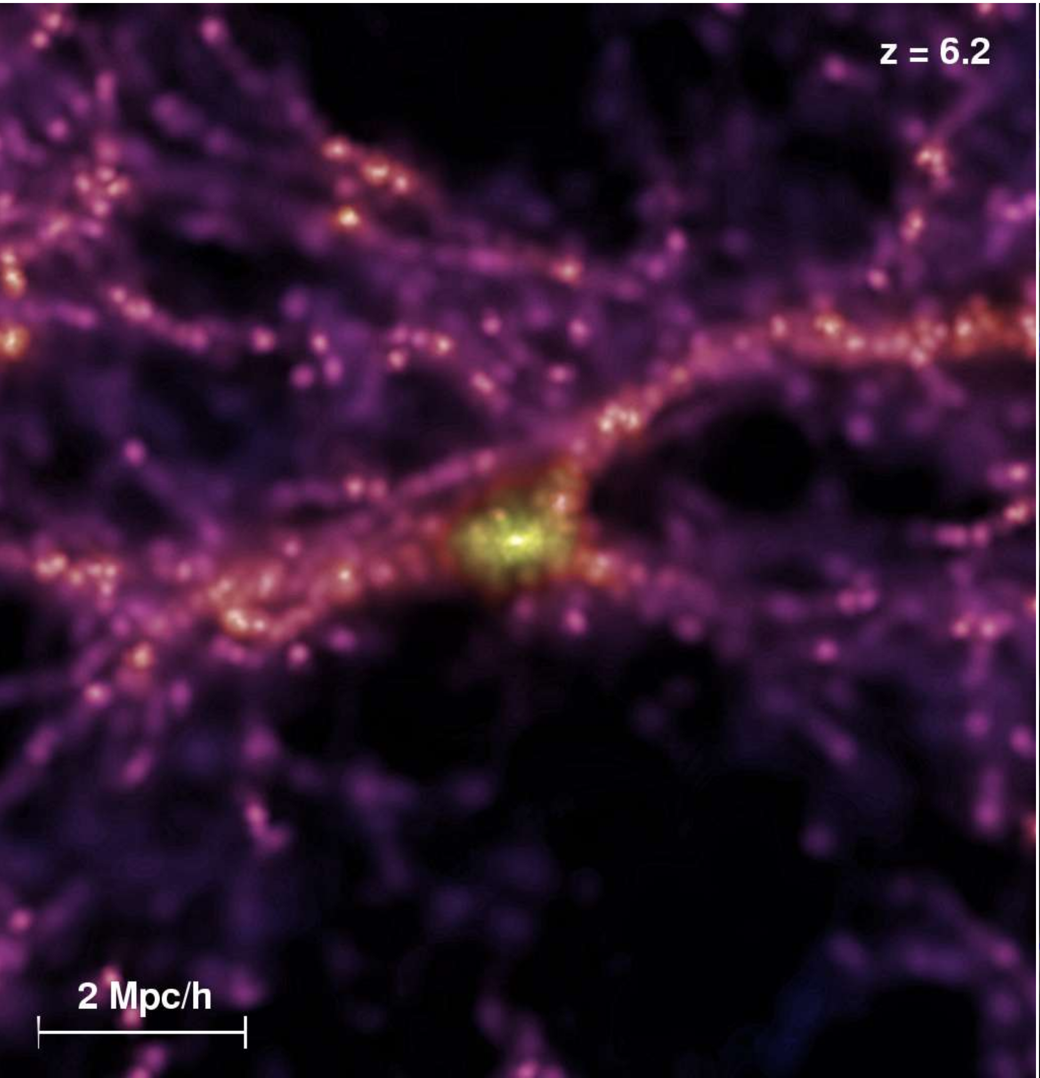
Croton et al 2005

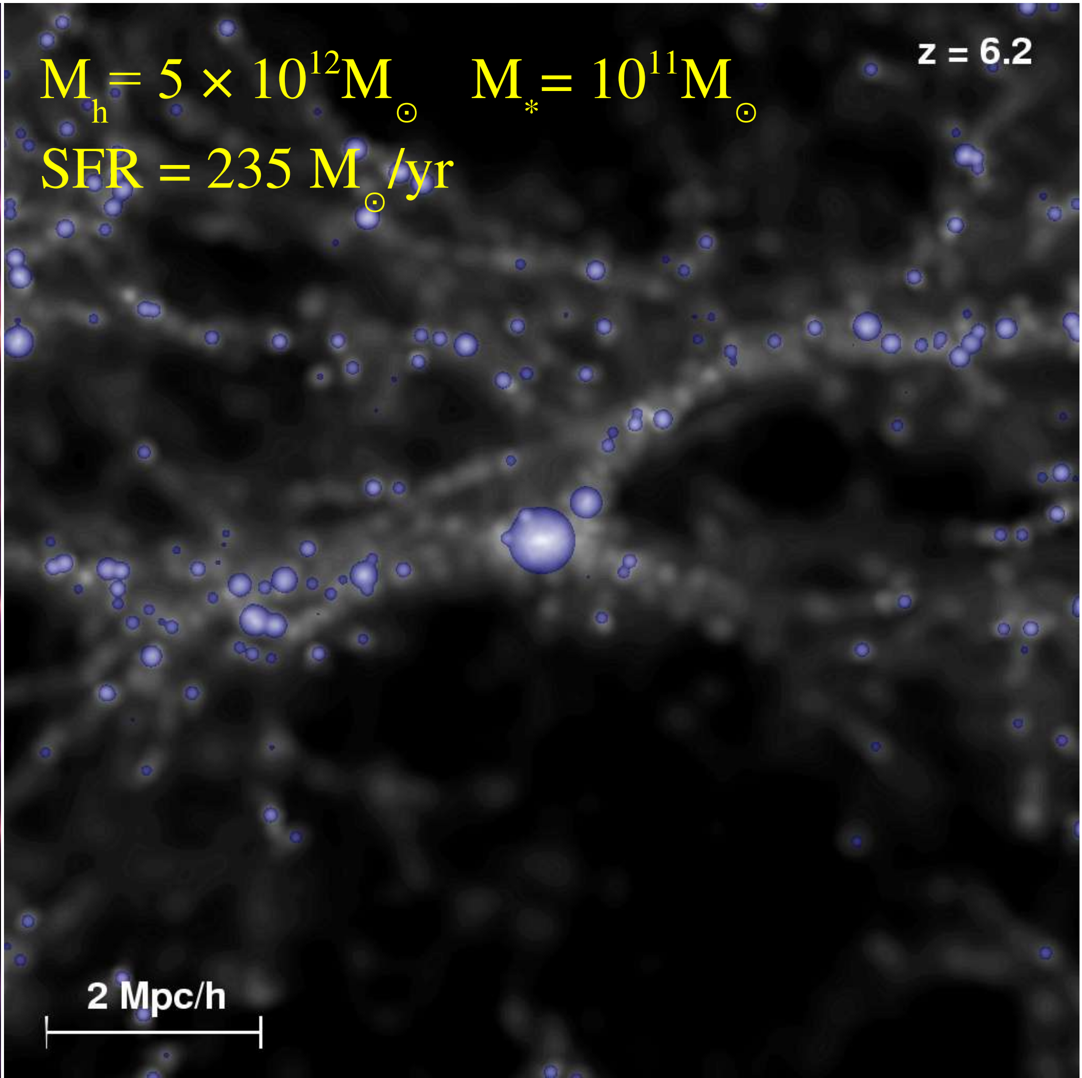


“SDSS Quasar” Host at z=6.2

Springel et al 2005

One of the most massive halos, containing one of the most massive galaxies with one of the highest SFR's and most massive BH's

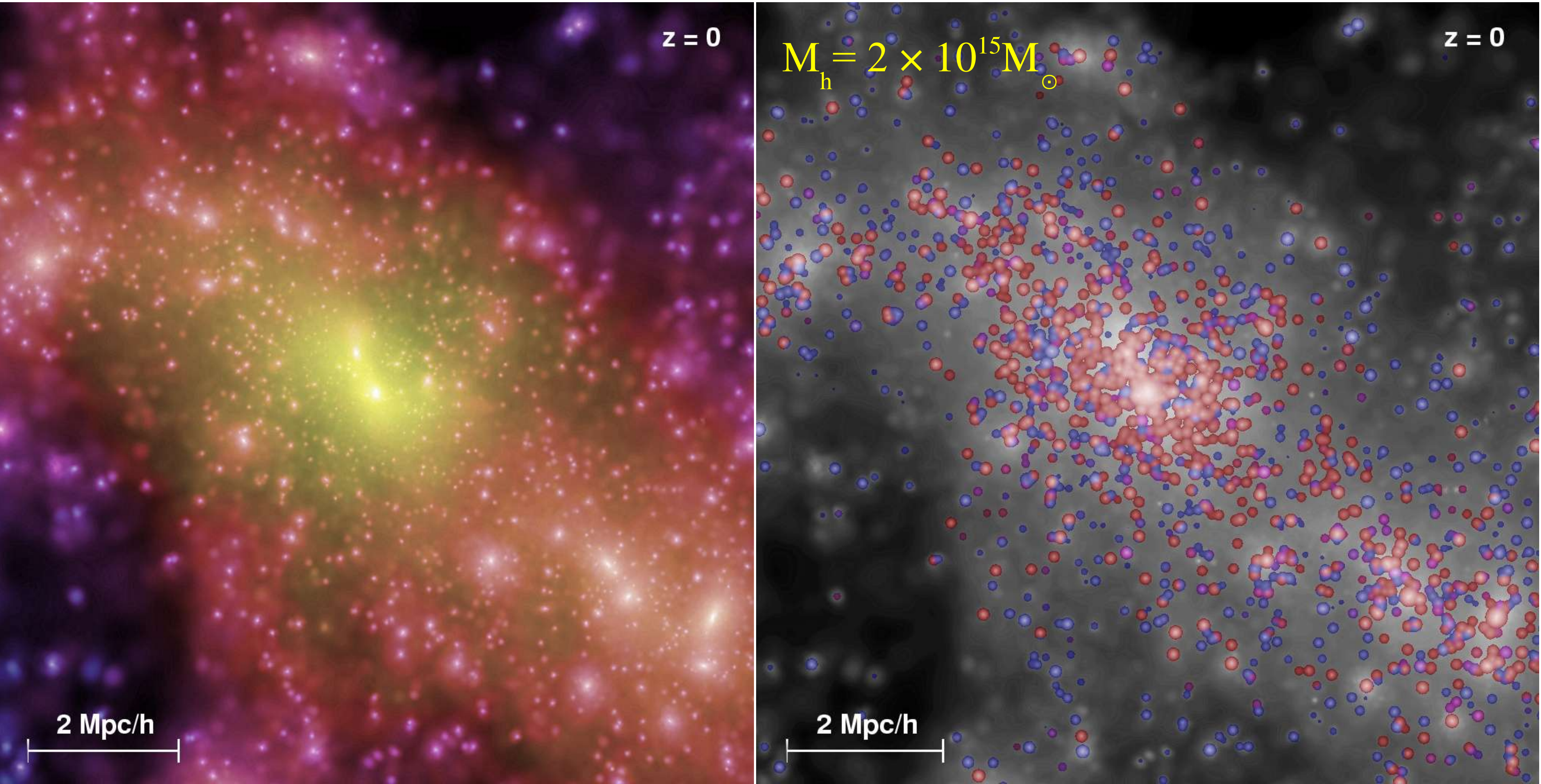




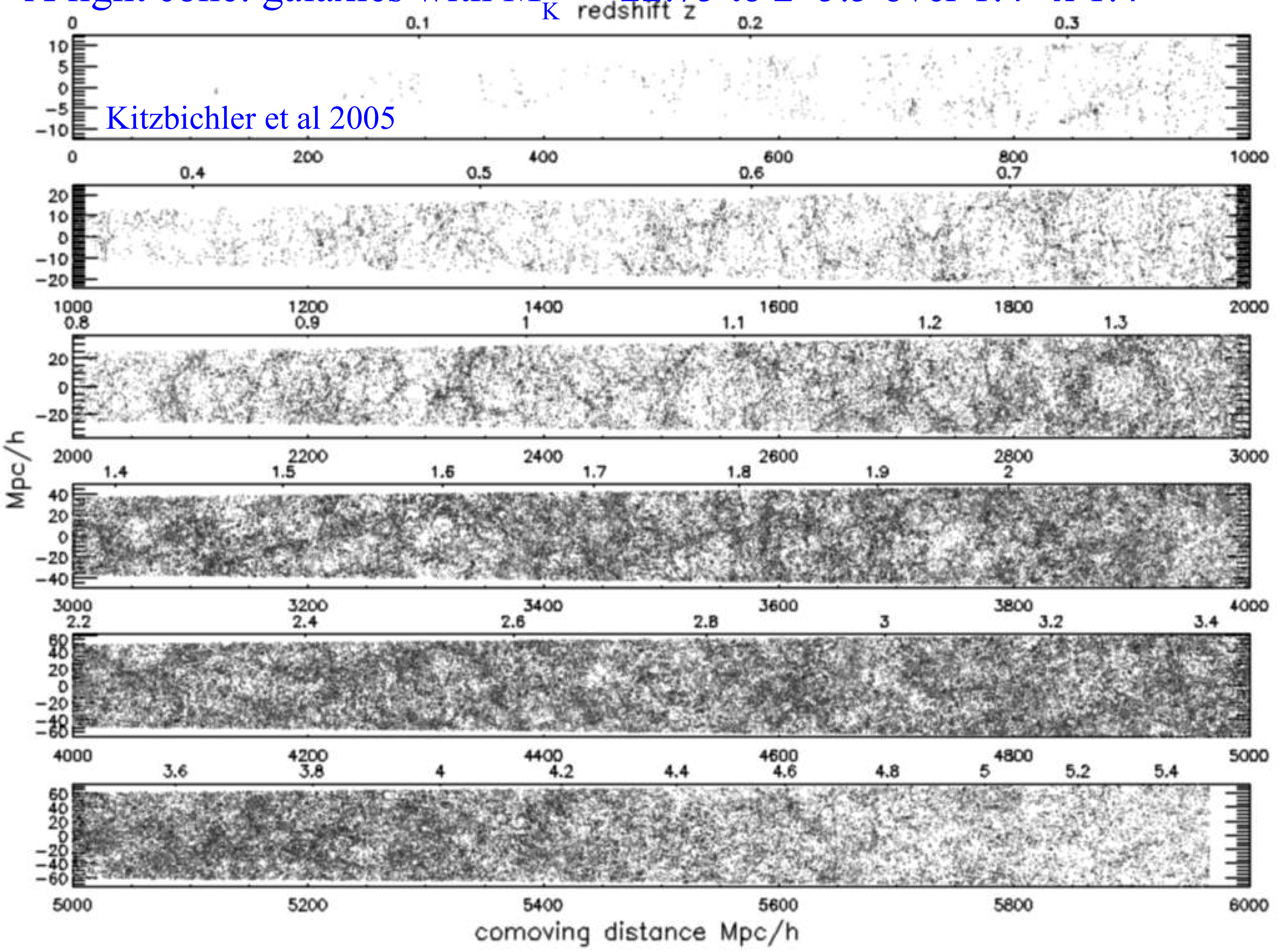
“SDSS Quasar” Descendant at z=0

Springel et al 2005

One of the most massive clusters. The quasar descendant is in the central cD galaxy. Its progenitor had $M_h \sim 2.5 \times 10^{10} M_\odot$ at $z = 17$

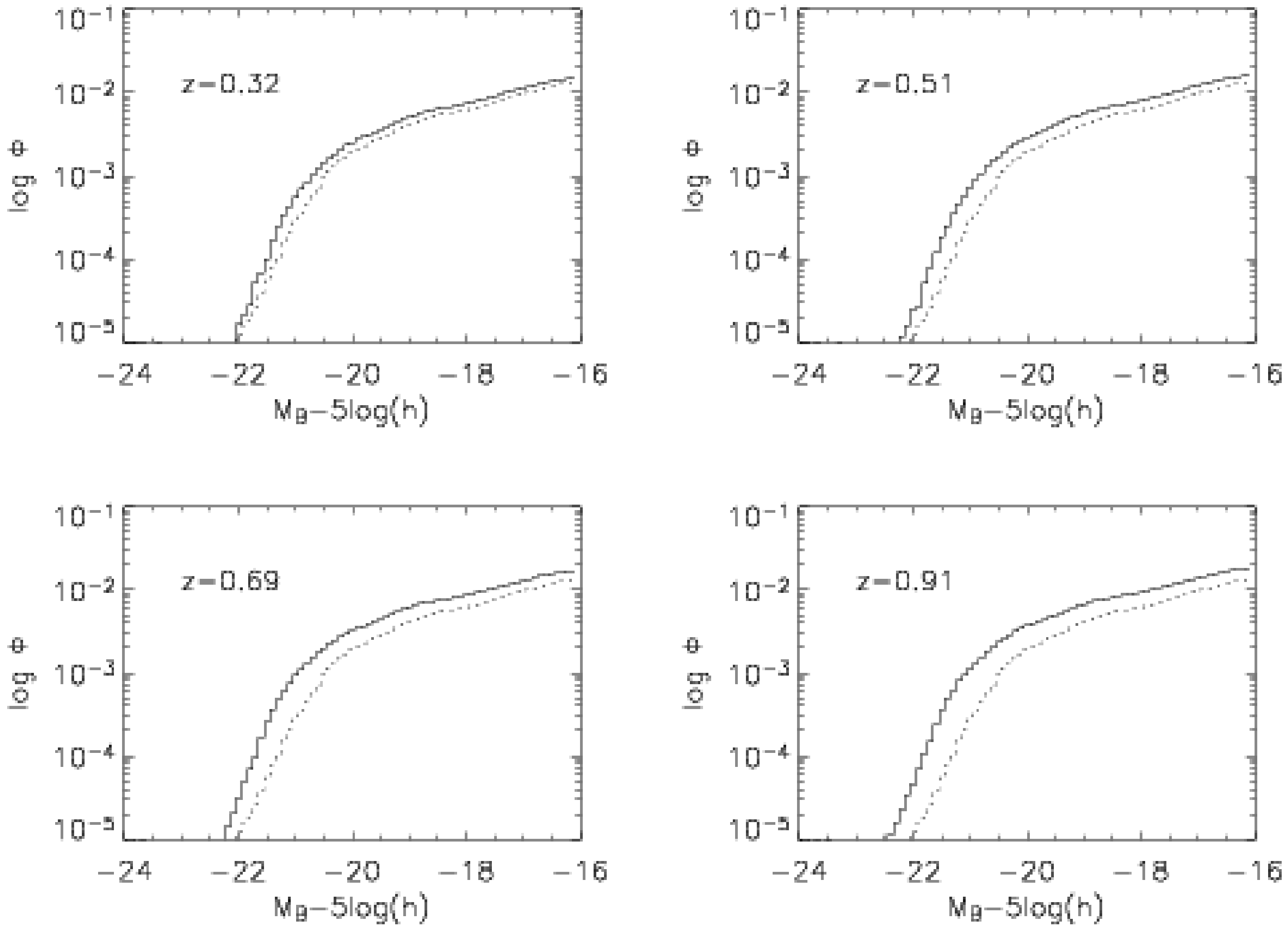


A light cone: galaxies with $M_K < -22.75$ to z=5.5 over 1.4° x 1.4°



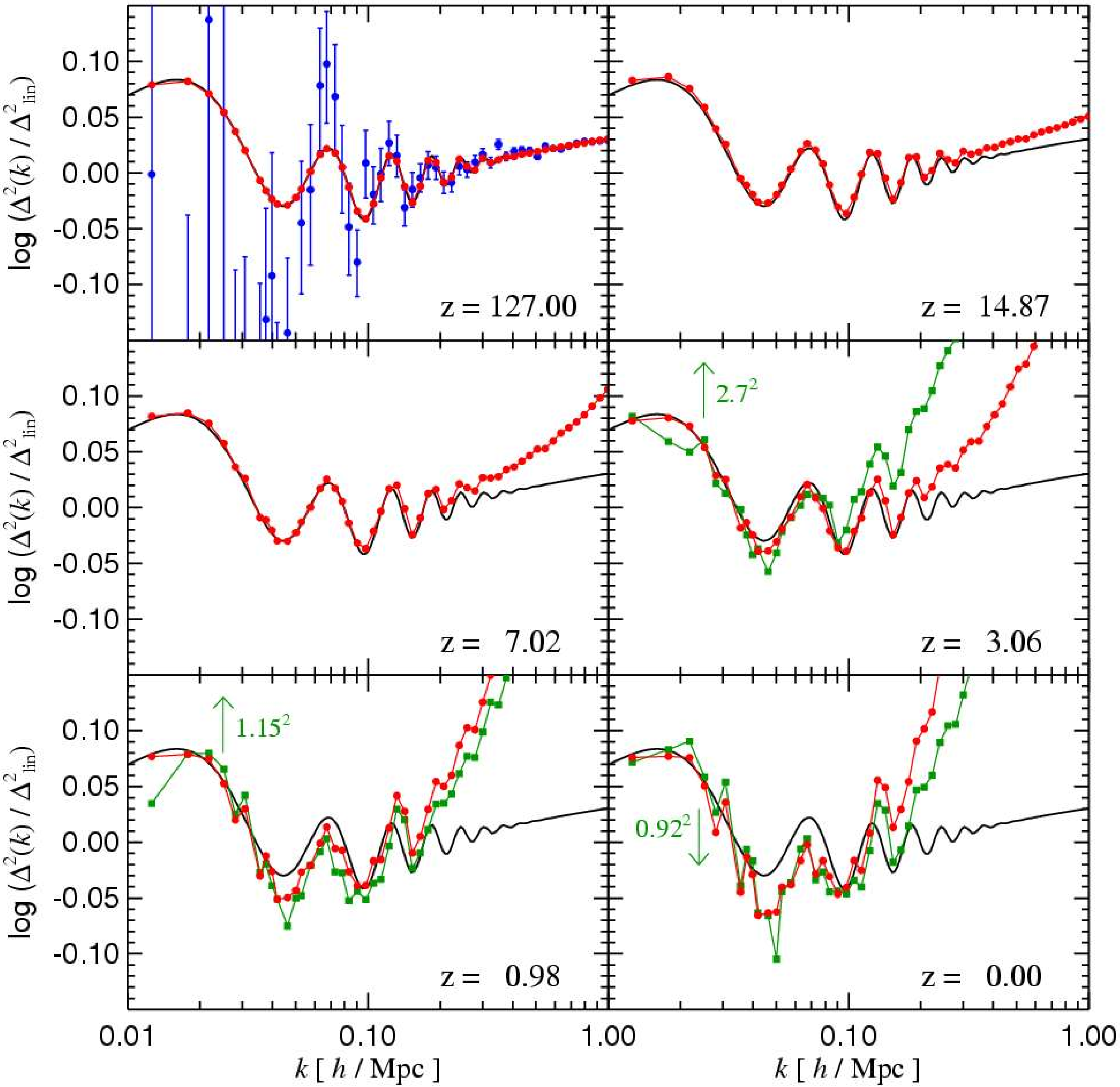
Evolution of the B-band luminosity function

Kitzbichler et al 2005



Baryon wiggles in the *galaxy* distribution

Springel et al 2005



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

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

CONCLUSIONS

- Halo formation history depends on present environment

  HOD models describe clustering at best approximately

- Cooling flow suppression is needed to cut off the LF and to produce bright galaxies which are red, dead and elliptical

  Observation suggests due to radio activity in central galaxies
  Strongly sub-Eddington accretion is sufficient

- Standard assumptions can produce "SDSS" quasars at $z = 6$

  Black hole mass growth cannot be Eddington limited
  Progenitors in place by $z \sim 16$; descendents in cluster cD's

- Baryon "wiggles" are present but *distorted* in the distribution of *galaxies*

  Once calibrated $\longrightarrow$ yardstick to constrain Dark Energy
  Distortions appear to depend on baryonic physics