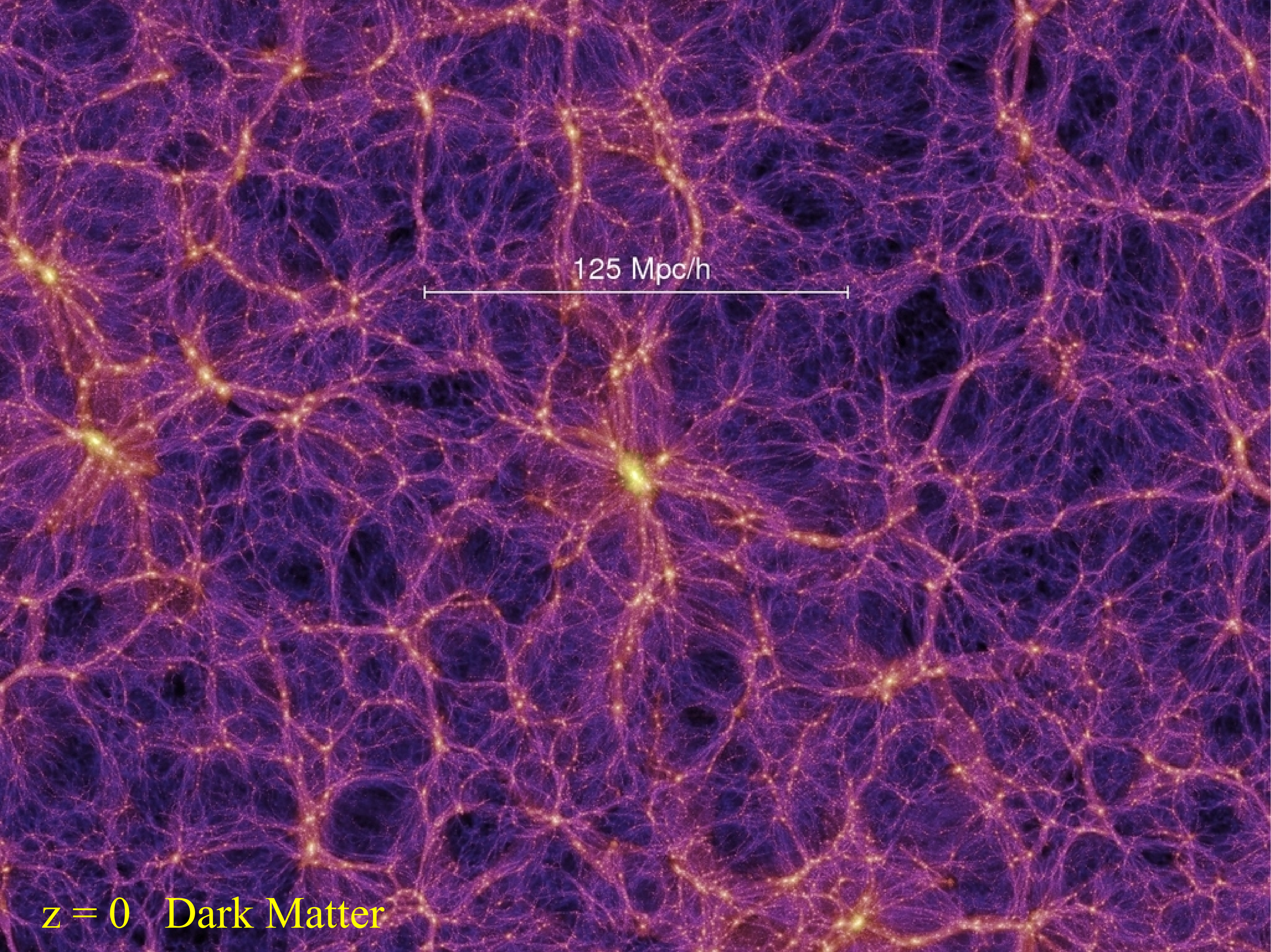
April 2006

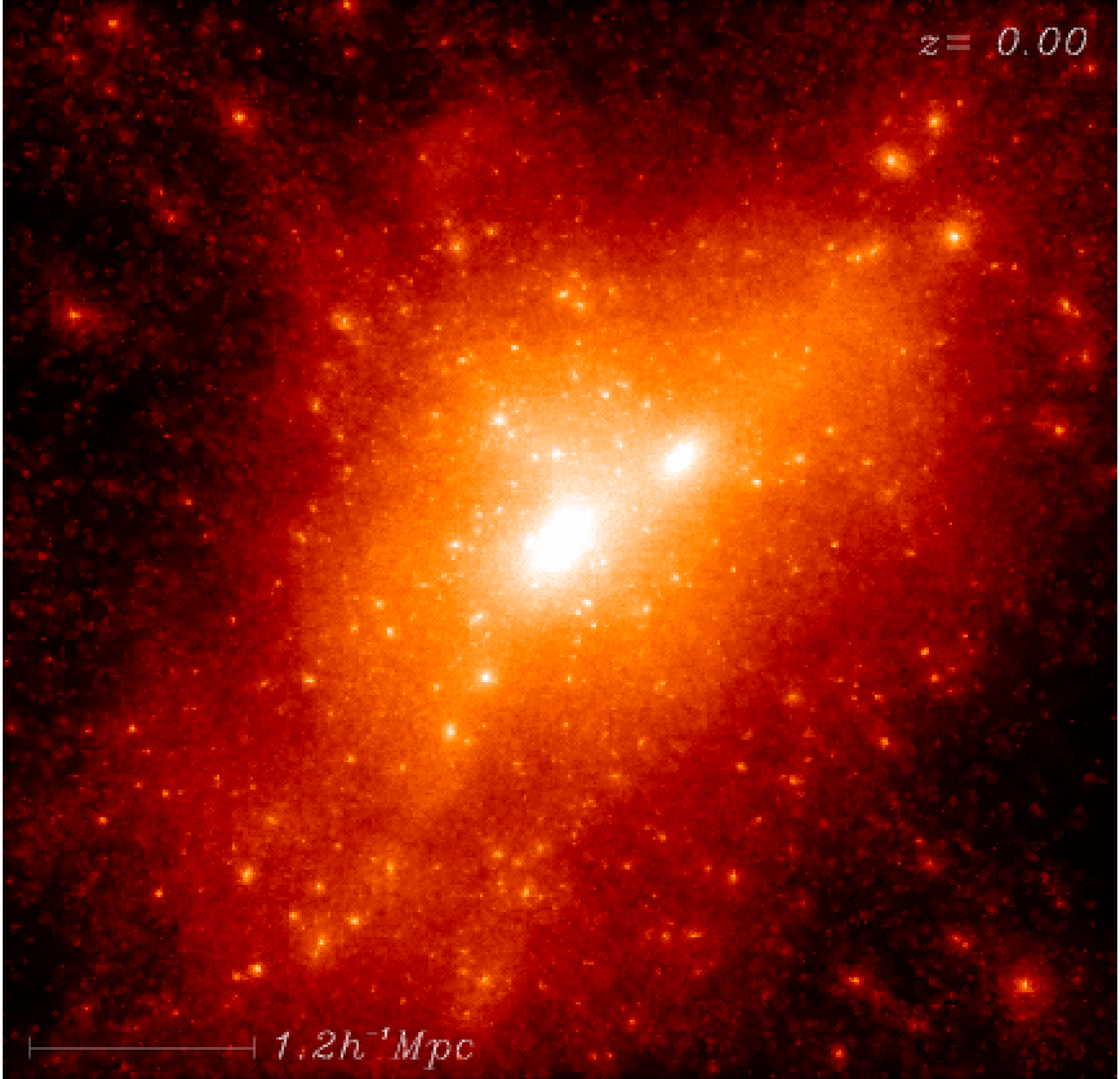
The Iguaçu Lectures

Nonlinear Structure Formation: The growth of galaxies and larger scale structures

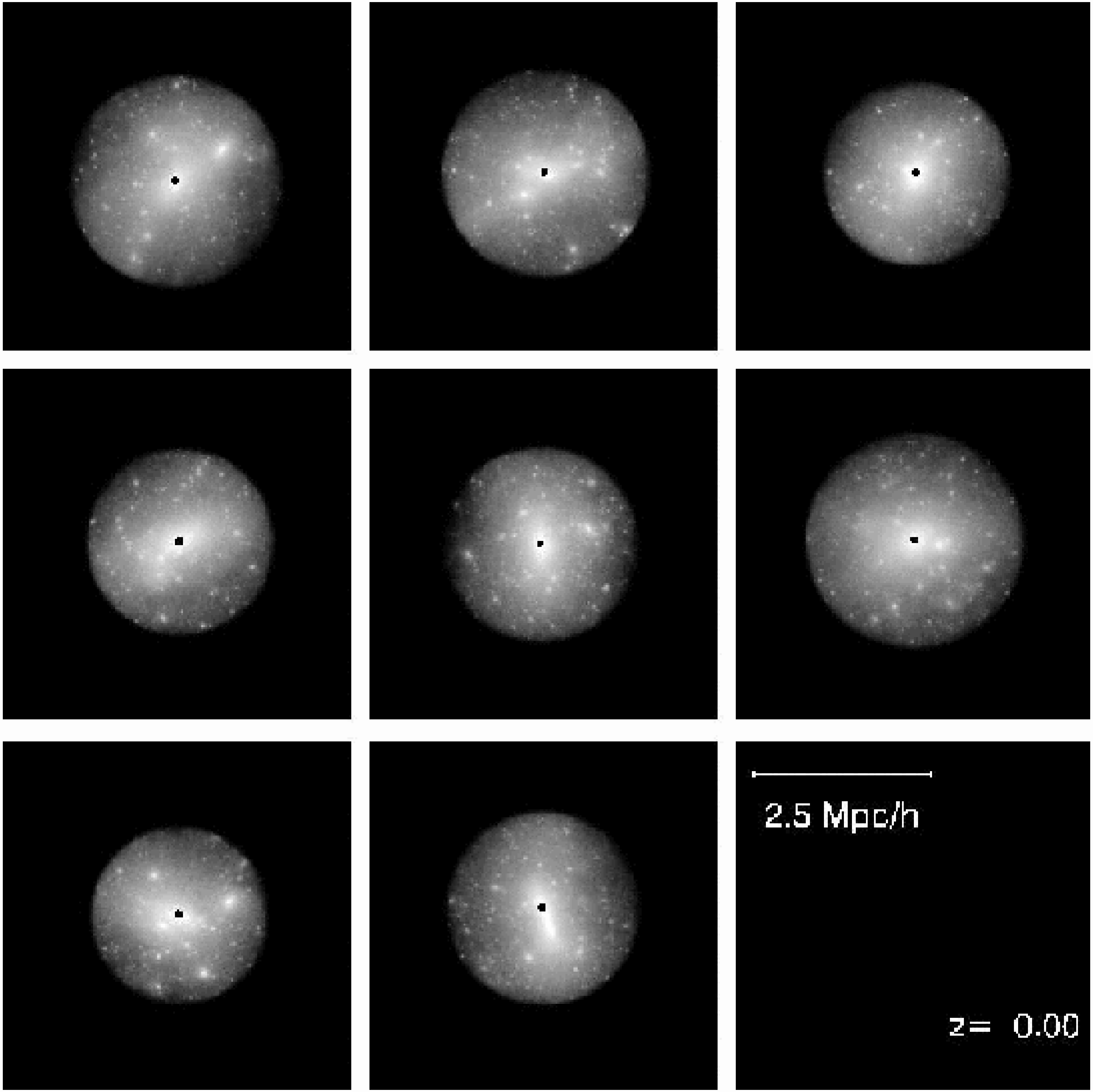
Simon White
Max Planck Institute for Astrophysics


125 Mpc/h
z = 0 Dark Matter

ROT



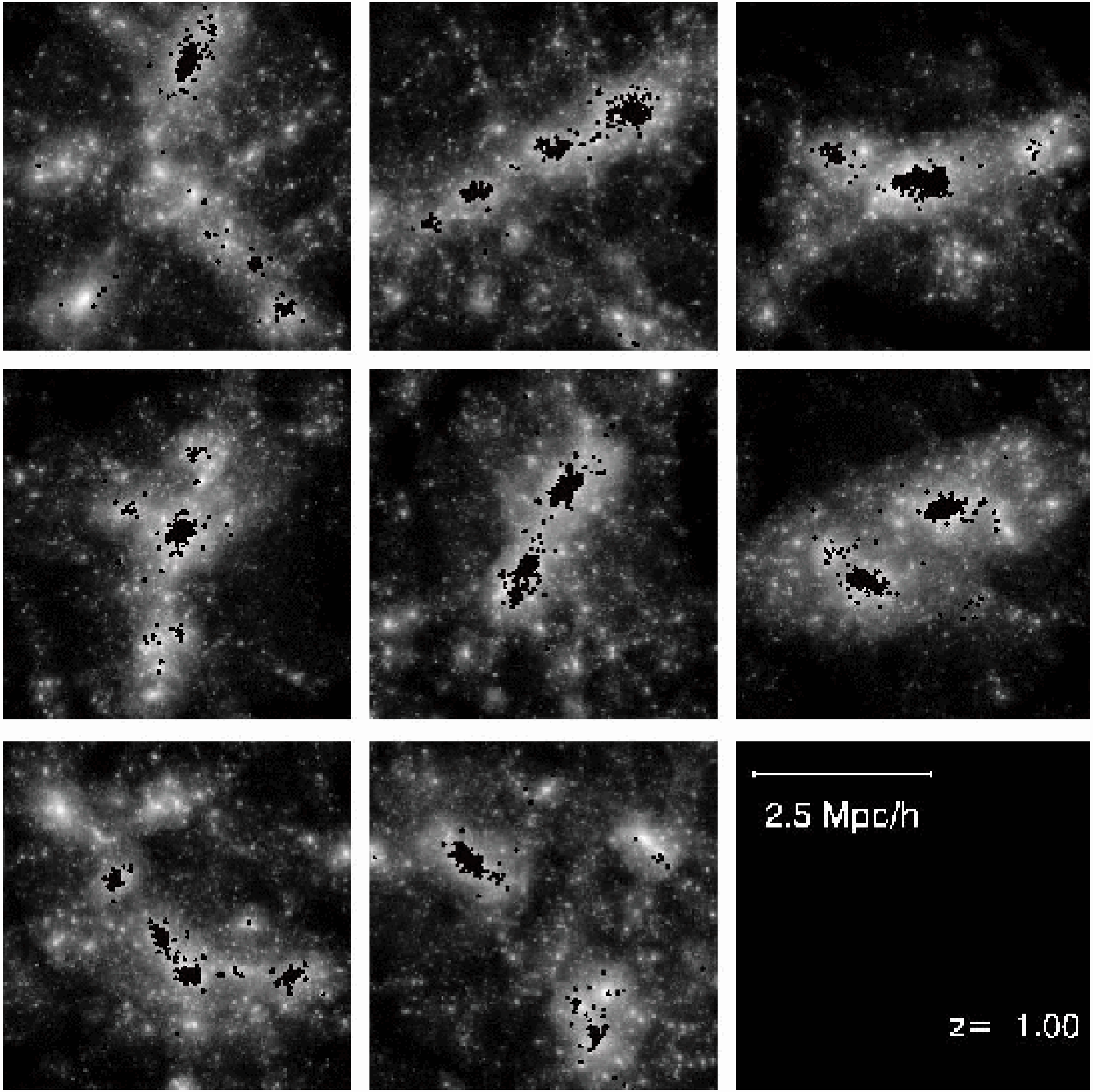
EVOL



Cluster structure in ΛCDM

- 'Concordance' cosmology
- Final cluster mass $\sim 10^{15} M_\odot$
- DM within 20 kpc at $z = 0$ is shown black

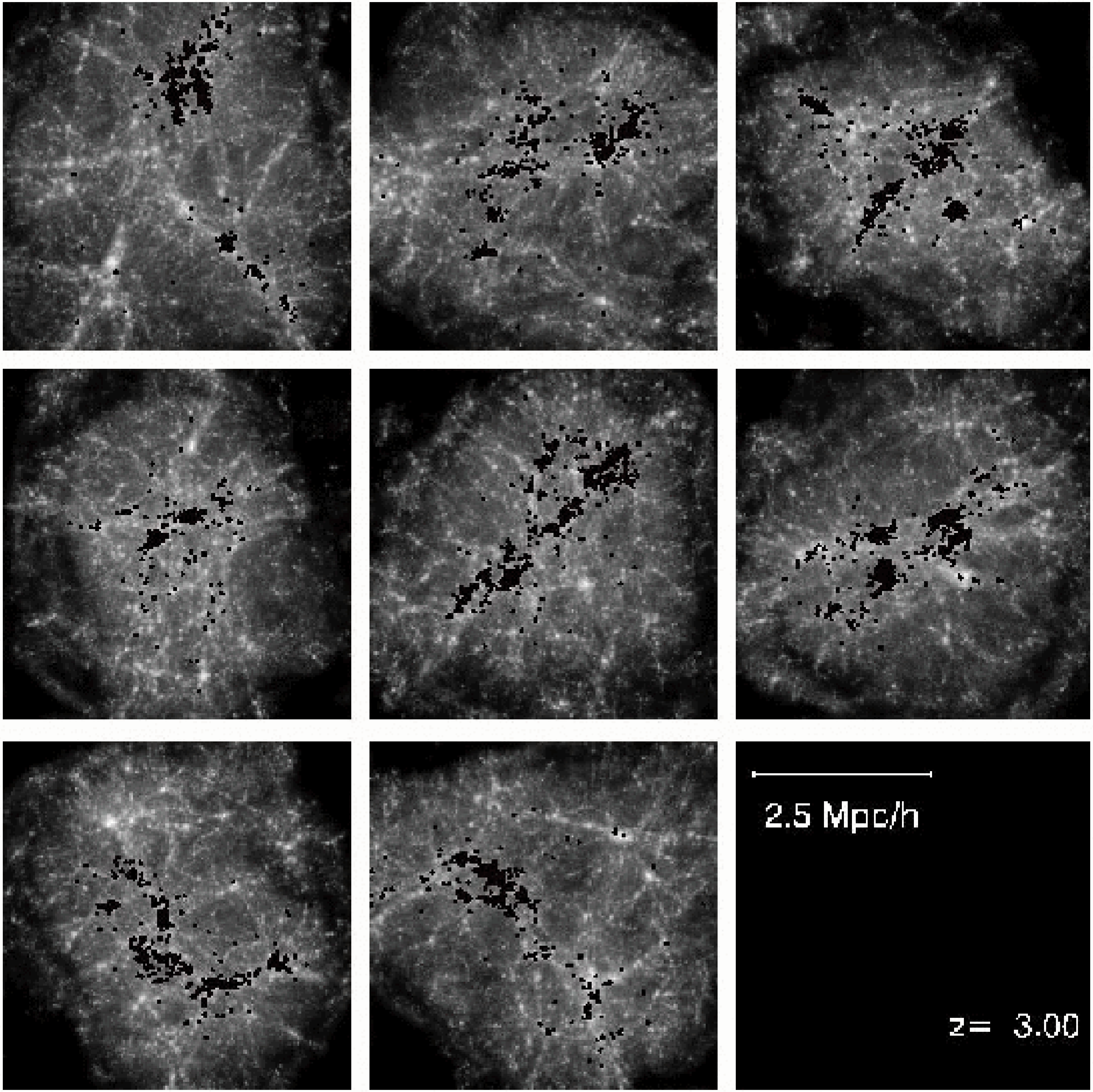
Gao et al 2004a



Cluster structure in ΛCDM

- 'Concordance' cosmology
- Final cluster mass $\sim 10^{15} M_\odot$
- DM within 20 kpc at $z = 0$ is shown black

Gao et al 2004a



Cluster structure in ΛCDM

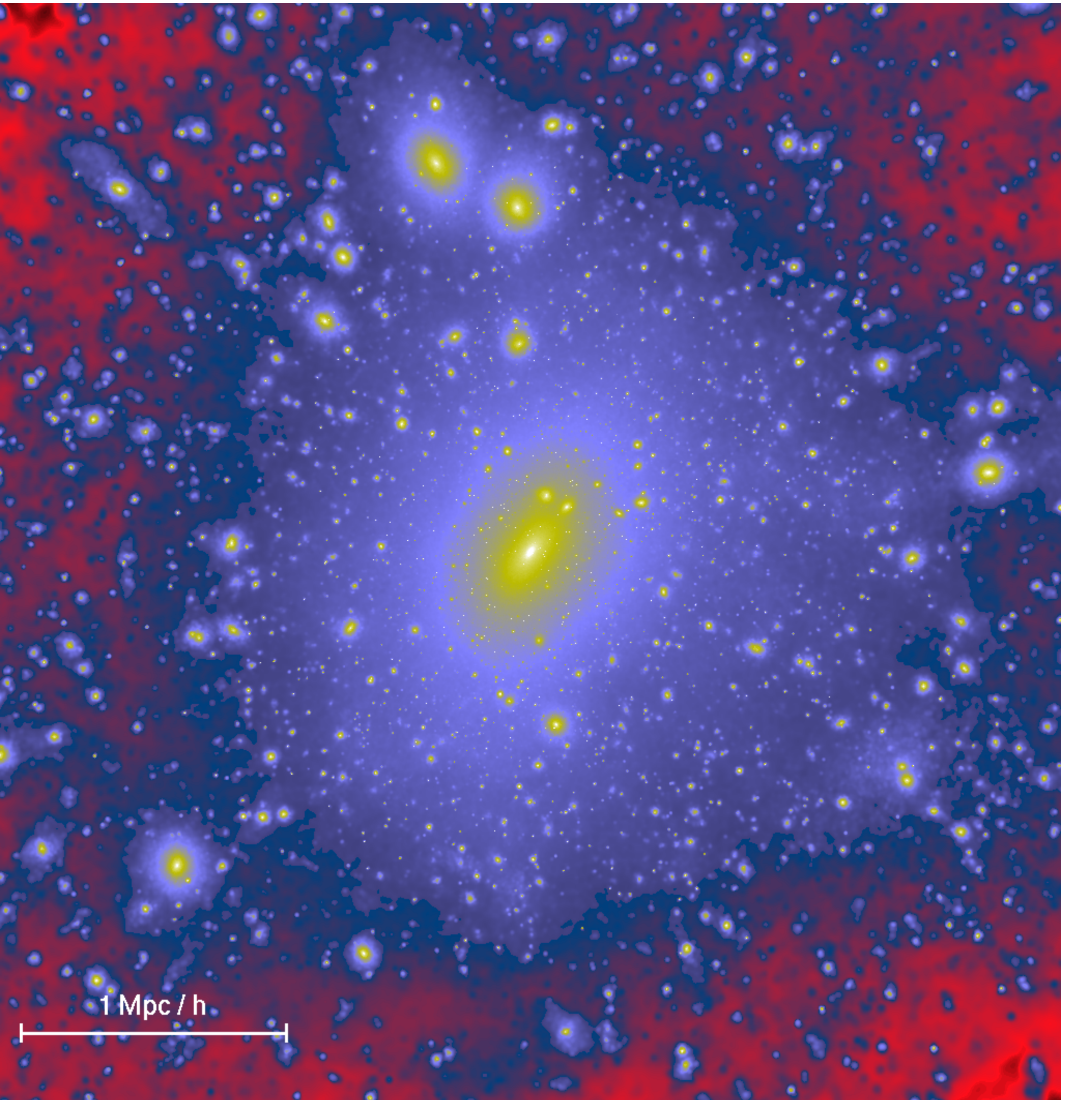
- 'Concordance' cosmology
- Final cluster mass ~10^{15} $M_\odot$
- DM within 20 kpc at $z = 0$ is shown black

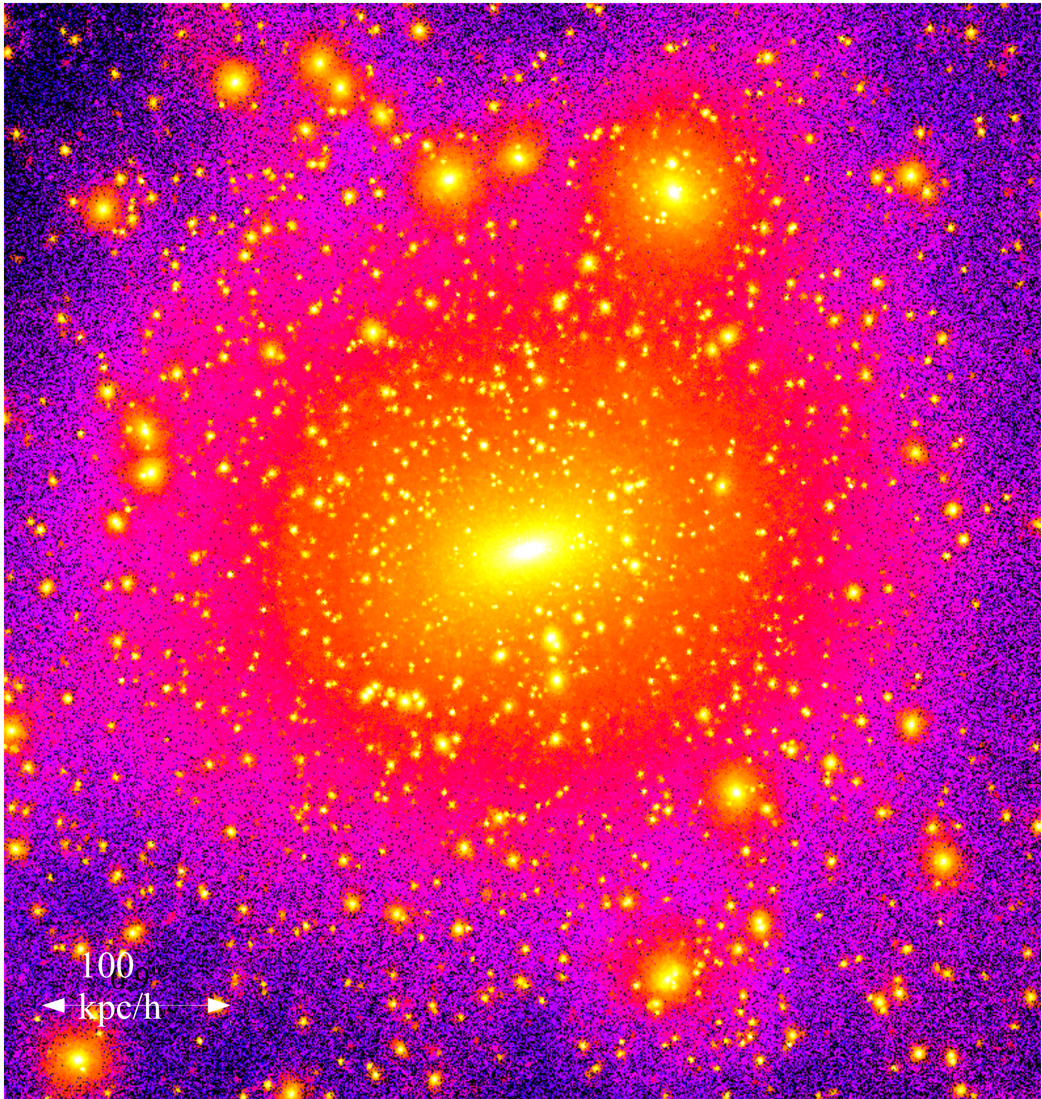
Gao et al 2004a

Small-scale structure in ΛCDM halos

A rich galaxy cluster halo
Springel et al 2001

A 'Milky Way' halo
Power et al 2002



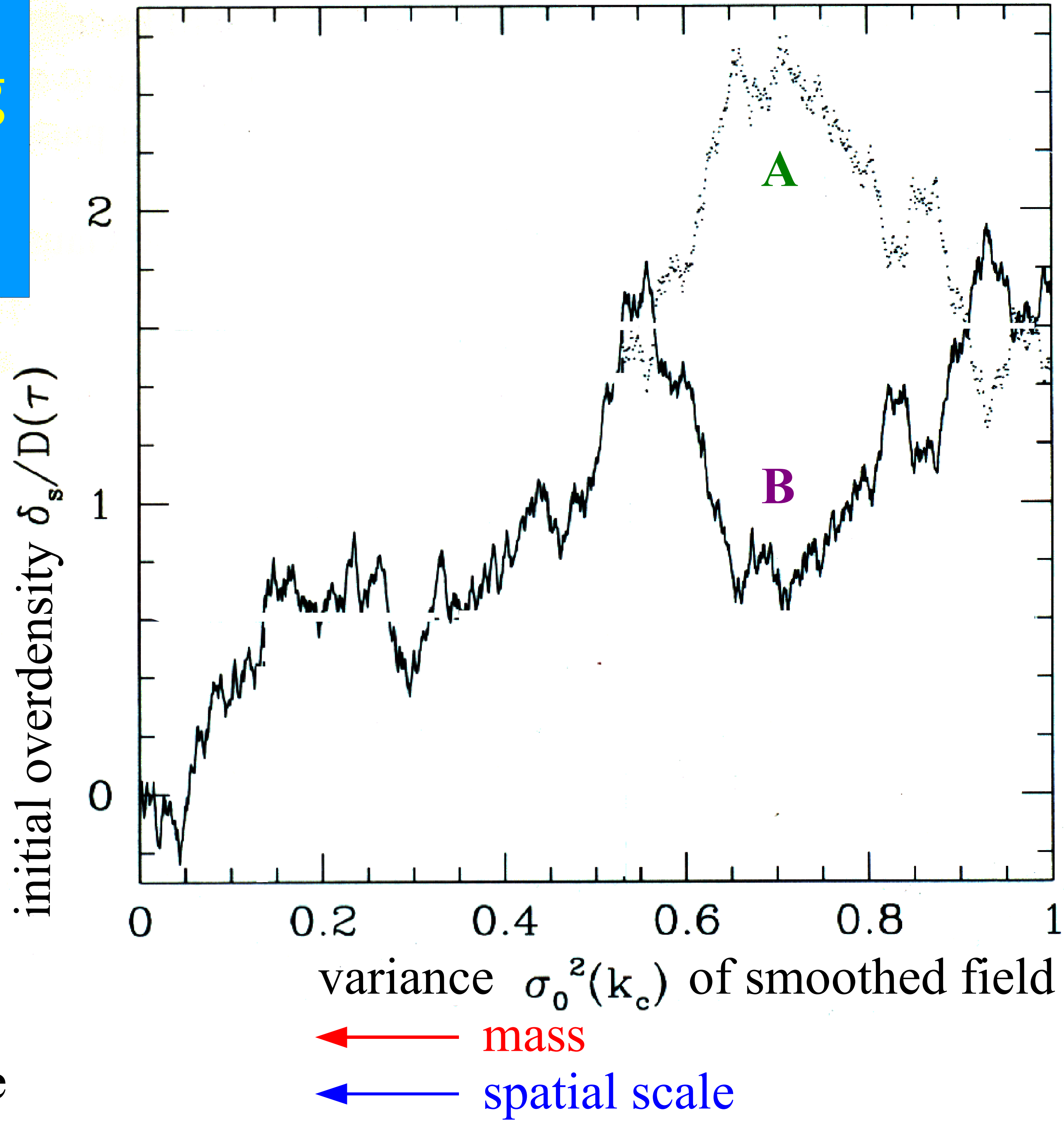


Overdensity vs smoothing at a given position

If the density field is smoothed using a sharp filter in k-space, then each step in the random walk is independent of all earlier steps

A Markov process

The walks shown at positions **A** and **B** are equally probable

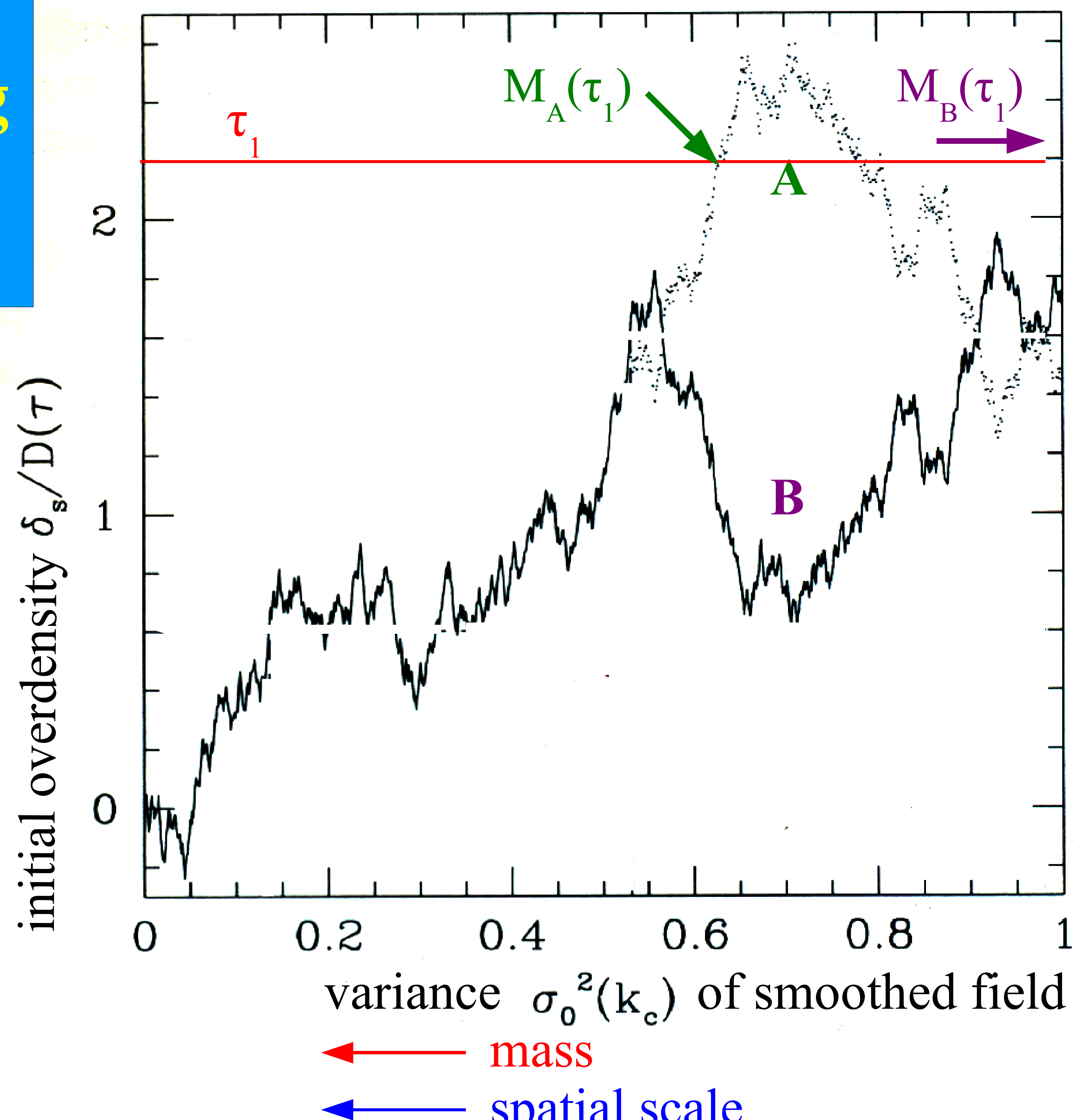


Overdensity vs smoothing at a given position

At an early time τ_1

A is part of a quite massive object

B is part of a very low mass object

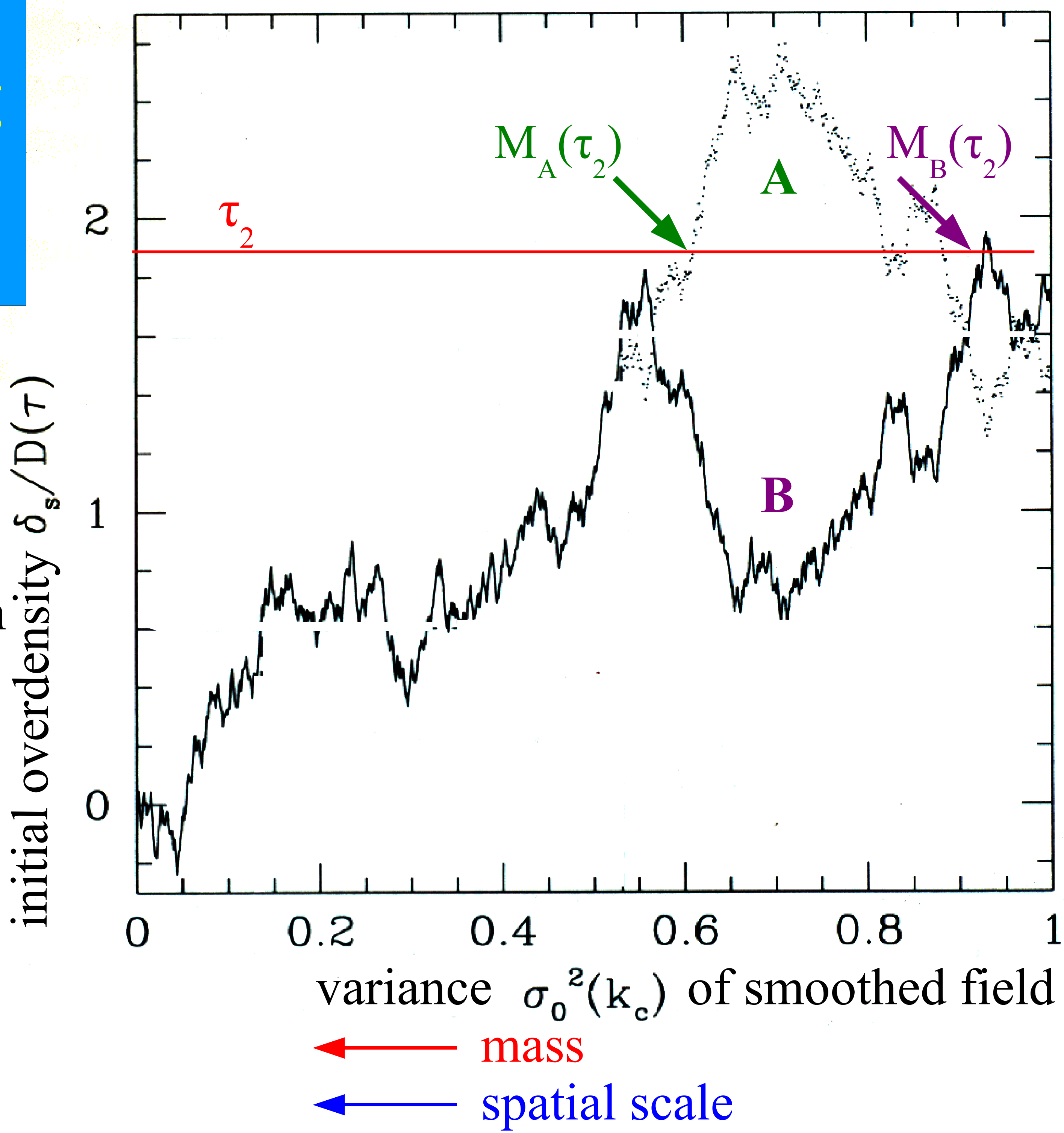


Overdensity vs smoothing at a given position

Later, at time τ_2

A's object has grown slightly by accretion

B's object has merged into a more massive system

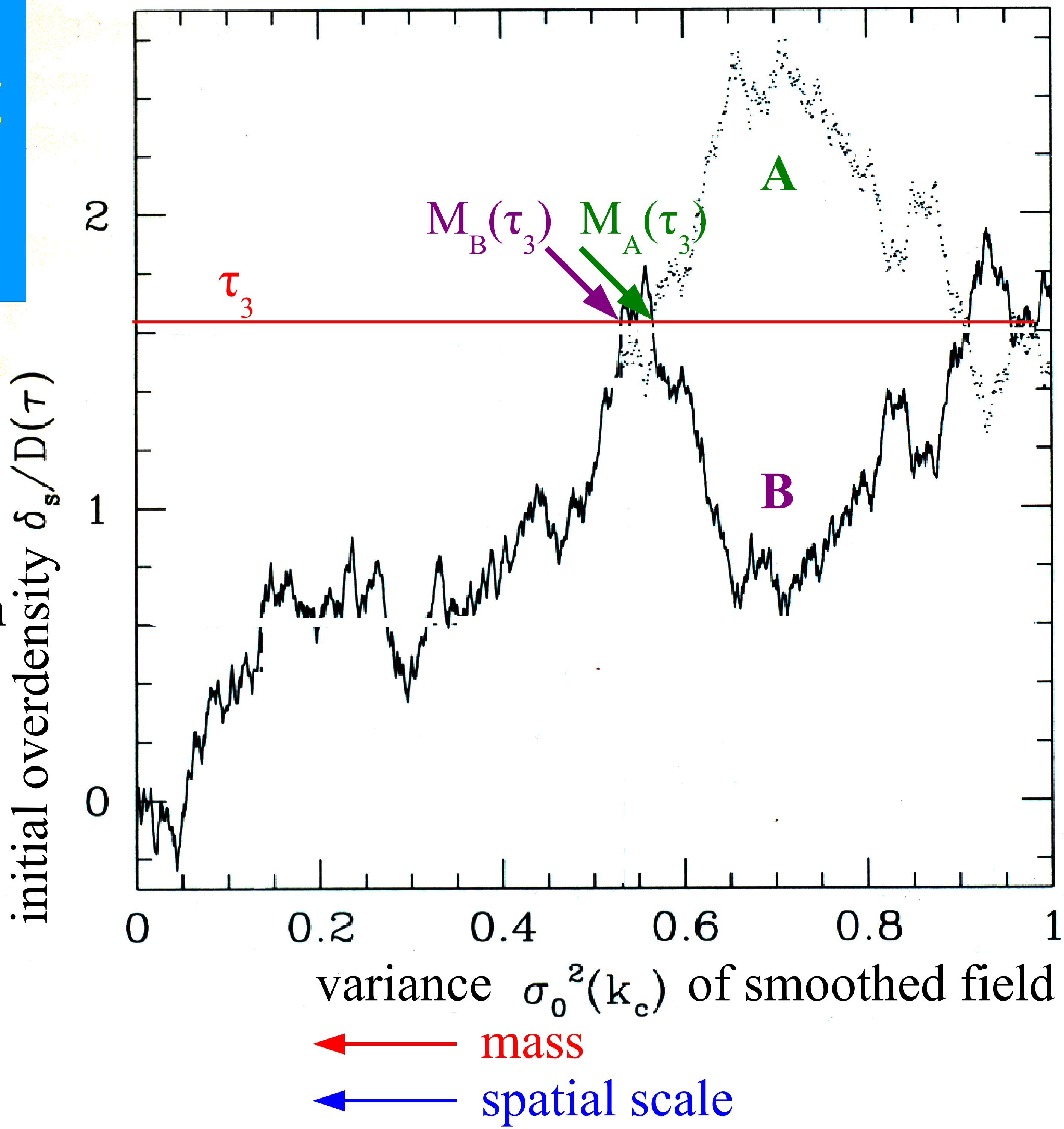


Overdensity vs smoothing at a given position

A bit later, time τ_3

A's object has grown further by accretion

B's object has merged again and is now more massive than **A**'s object

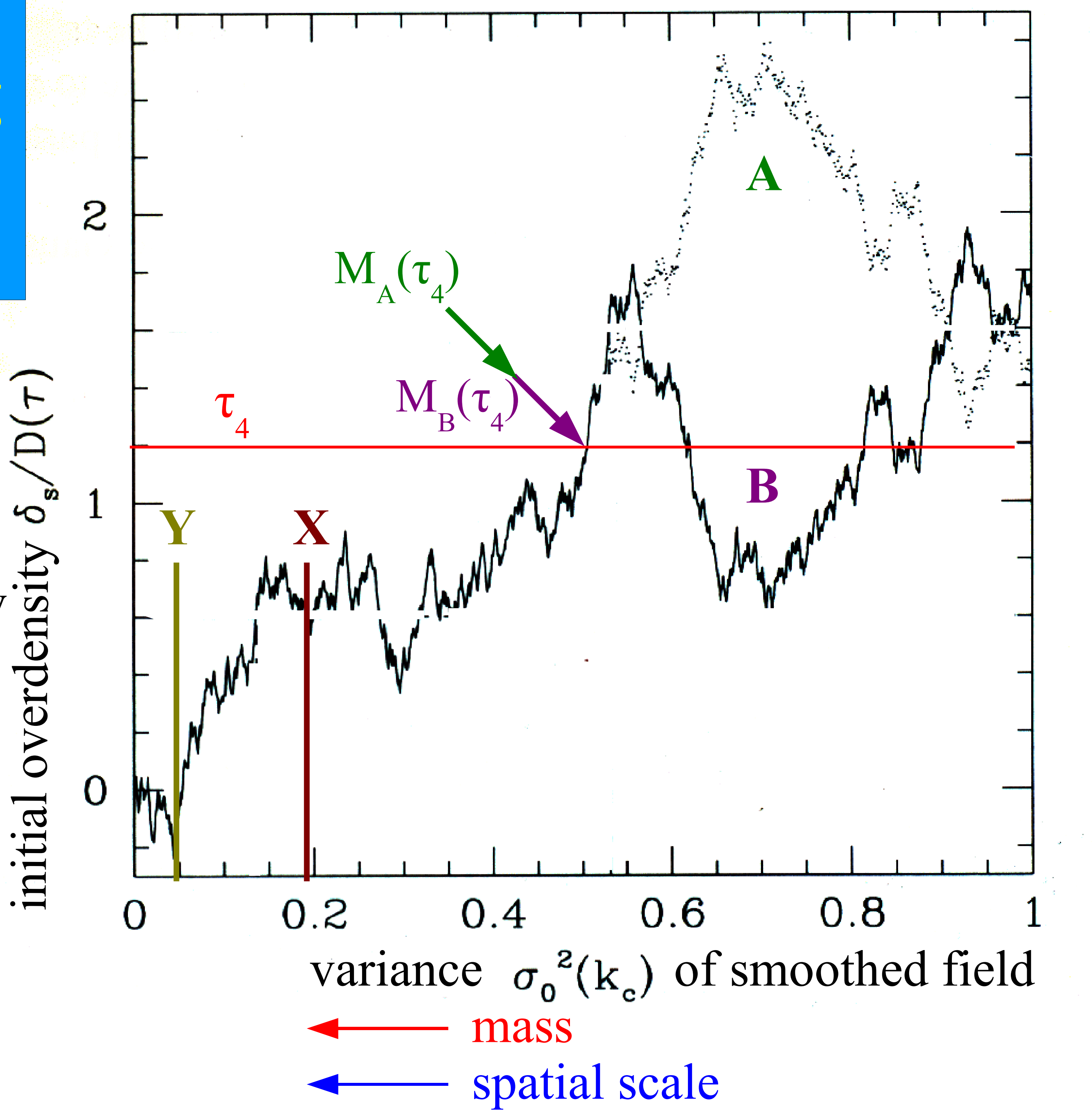


Overdensity vs smoothing at a given position

Still later, e.g. τ_4

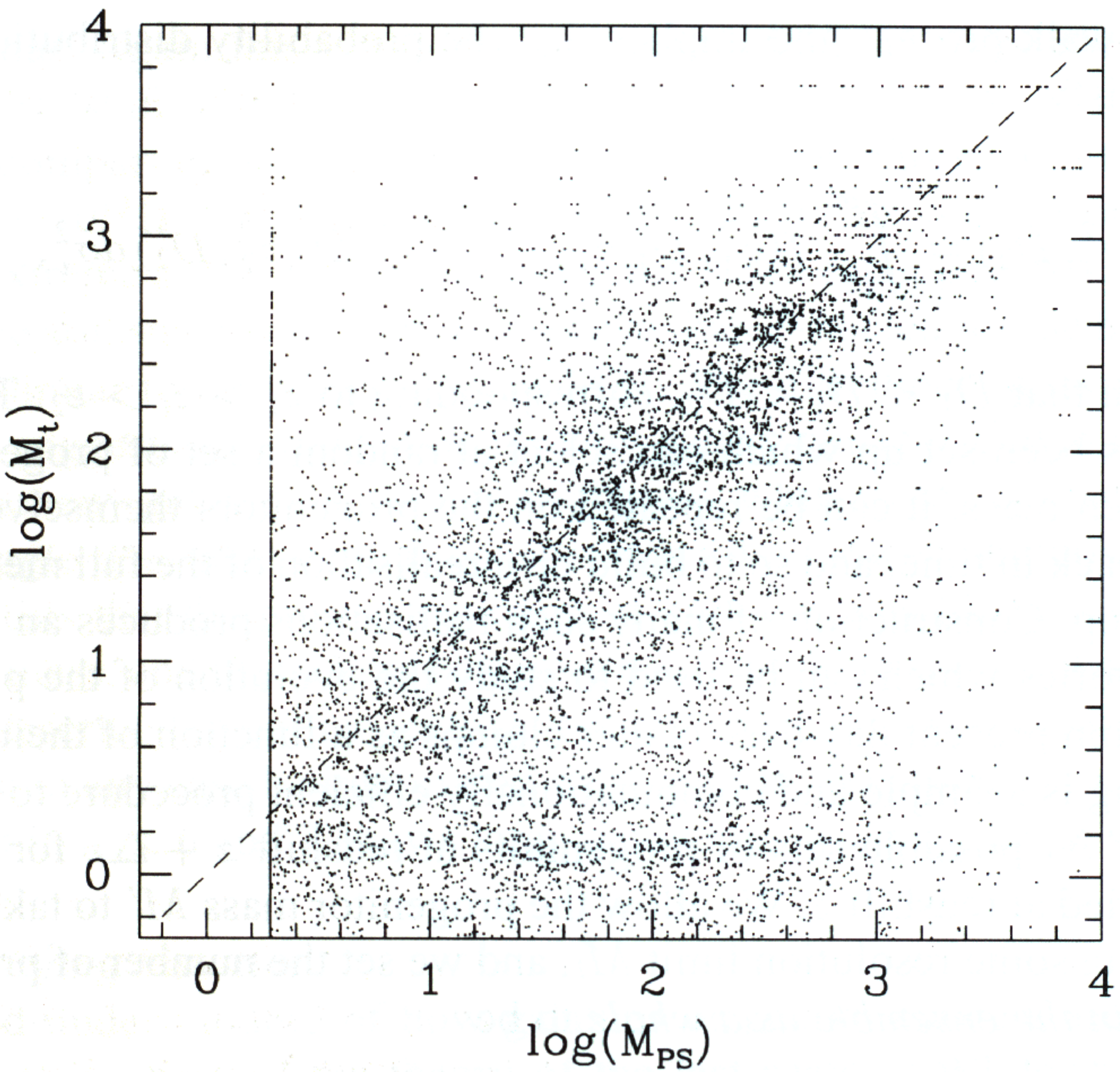
A and **B** are part of objects which follow identical merging/ accretion histories

On scale **X** they are embedded in a high density region.
On larger scale **Y** in a low density region



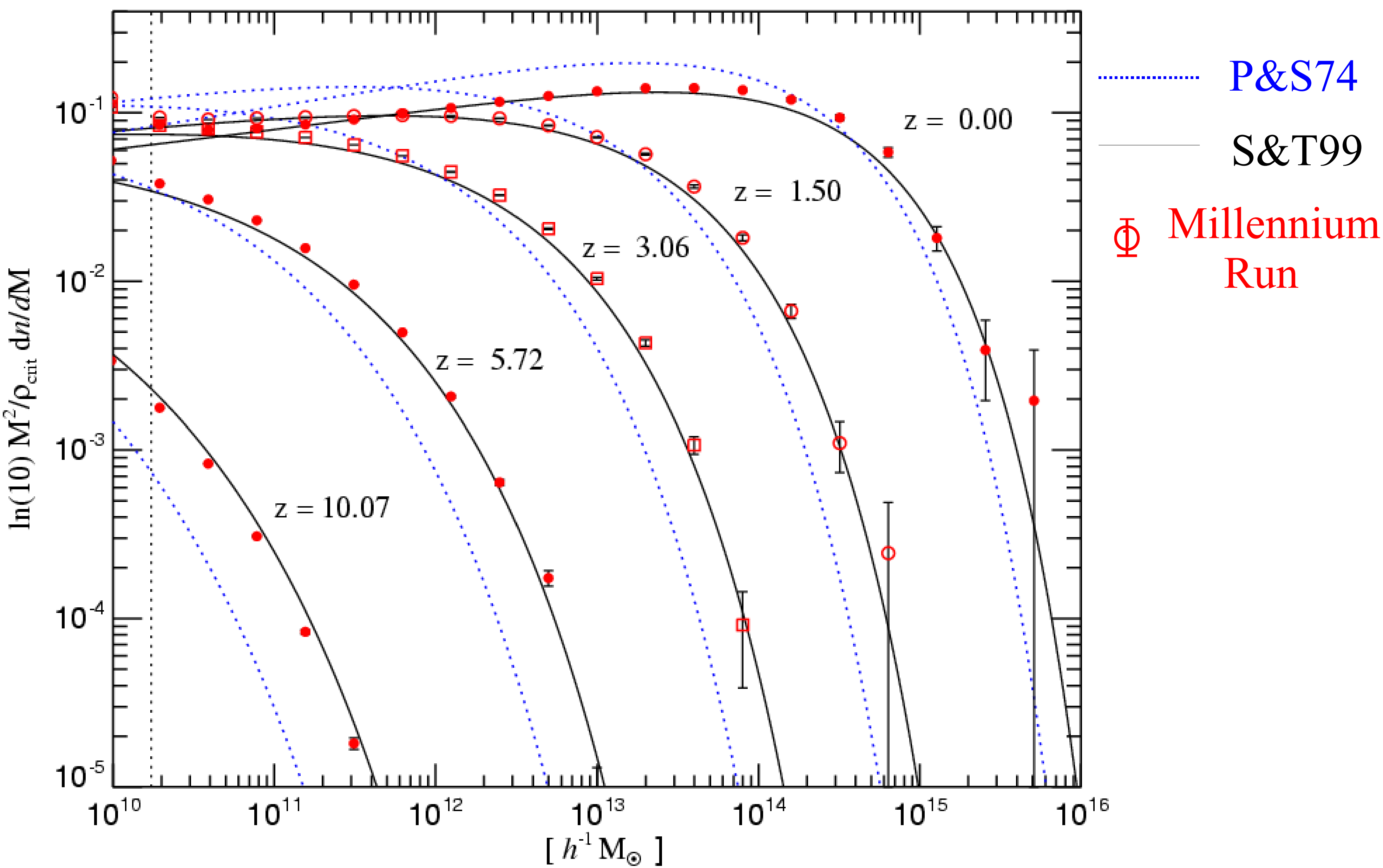
Does it work point by point?

Mass of the halo in which the particle is actually found



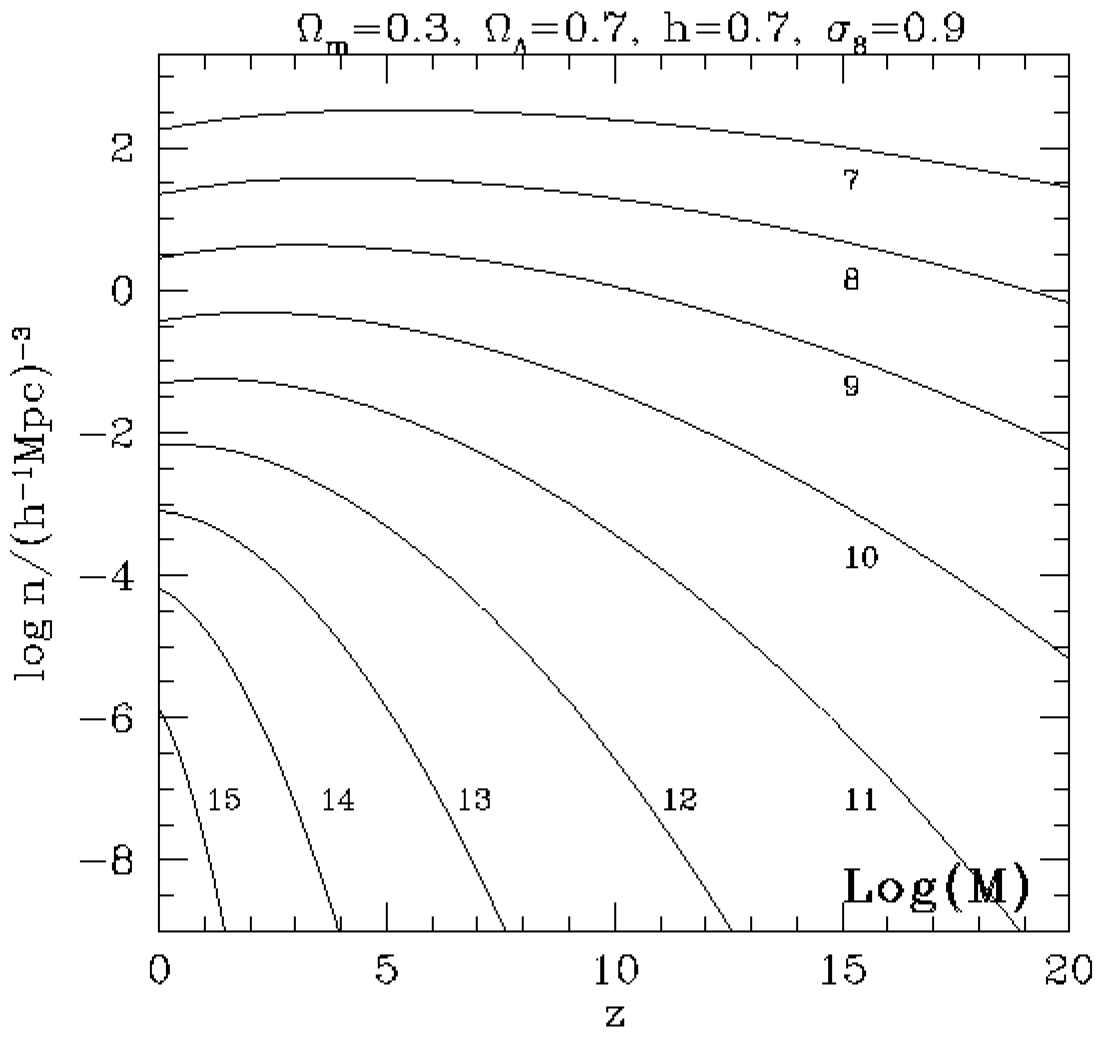
Halo mass predicted for each particle by its own sharp k-space random walk

Does it work statistically?



Evolution of halo abundance in ΛCDM

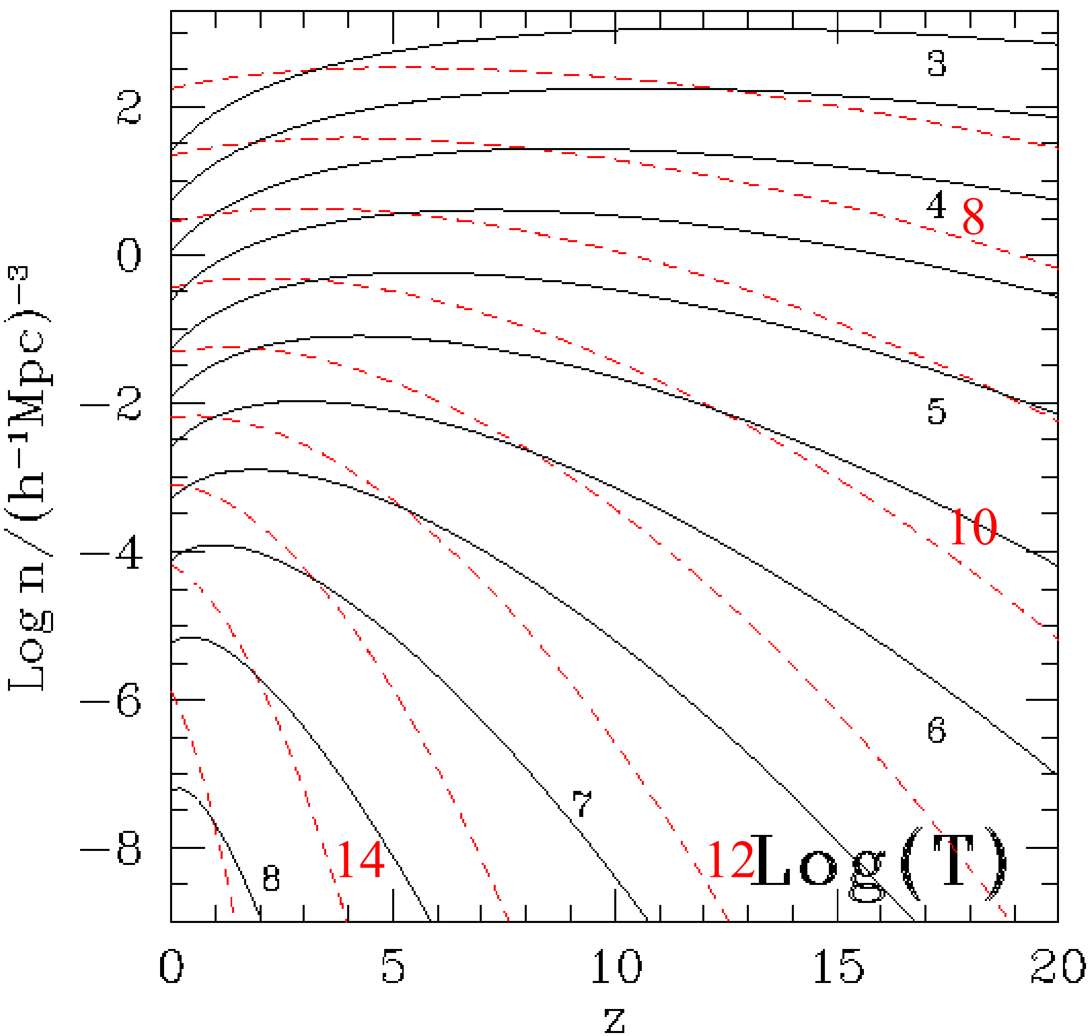
Mo & White 2002



- Abundance of rich cluster halos drops rapidly with z
- Abundance of Milky Way mass halos drops by less than a factor of 10 to z=5
- $10^9 M_\odot$ halos are almost as common at z=10 as at z=0

Evolution of halo abundance in ΛCDM

Mo & White 2002



- Temperature increases with both mass and redshift

  $T \propto M^{2/3}(1+z)$

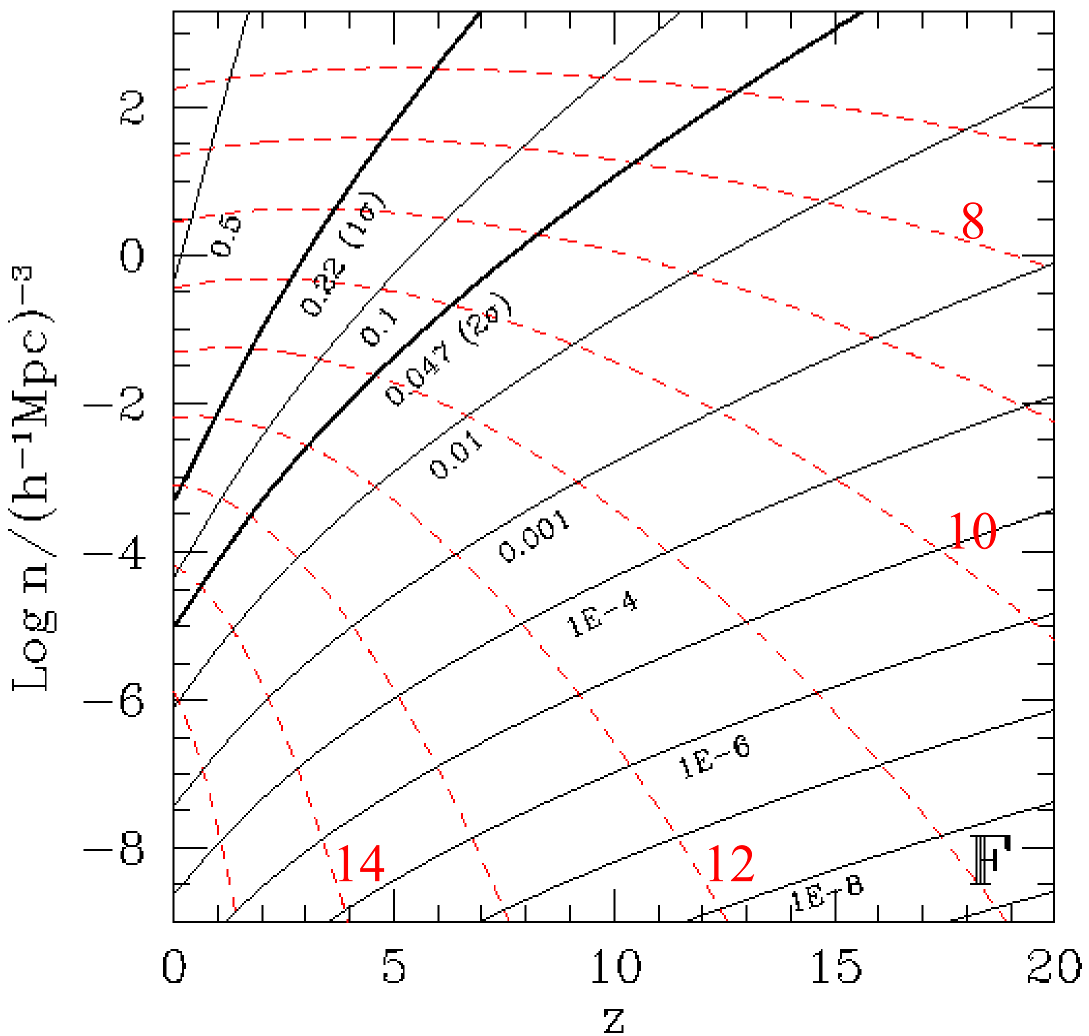
- Halos with virial temperature $T = 10^7$ K are as abundant at $z = 2$ as at $z=0$

- Halos with virial temperature $T = 10^6$ K are as abundant at $z = 8$ as at $z=0$

- Halos of mass $>10^{7.5} M_\odot$ have $T > 10^4$ K at $z=20$ and so can cool by H line emission

Evolution of halo abundance in ΛCDM

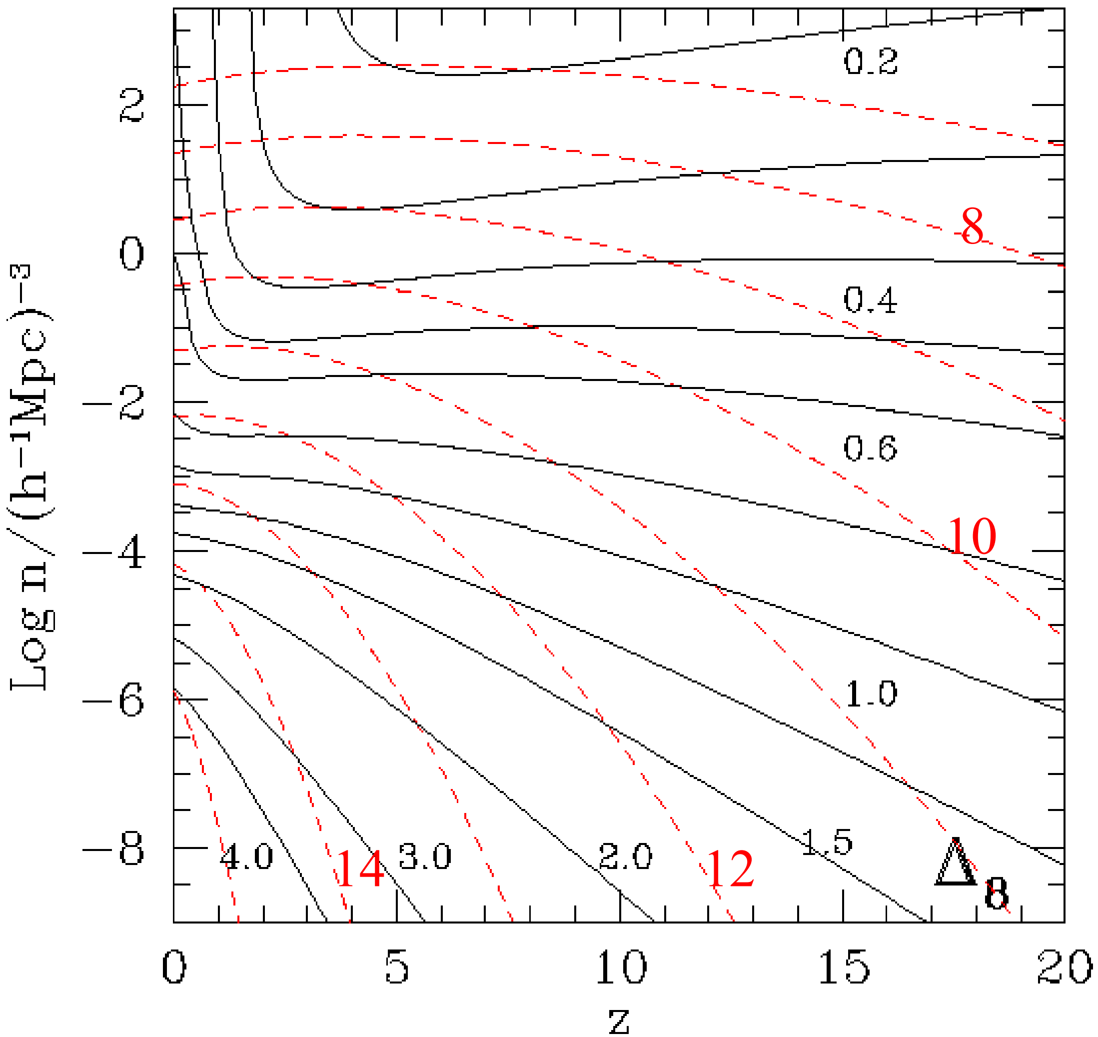
Mo & White 2002



- Half of all mass is in halos more massive than $10^{10} M_\odot$ at z=0, but only 10% at z=5, 1% at z=9 and 10^{-6} at z=20
- 1% of all mass is in halos more massive than $10^{15} M_\odot$ at z=0
- 40% of all mass at z=0 is in halos which cannot confine photoionised gas
- 1% of all mass at z=15 is in halos hot enough to cool by H line emission

Evolution of halo abundance in ΛCDM

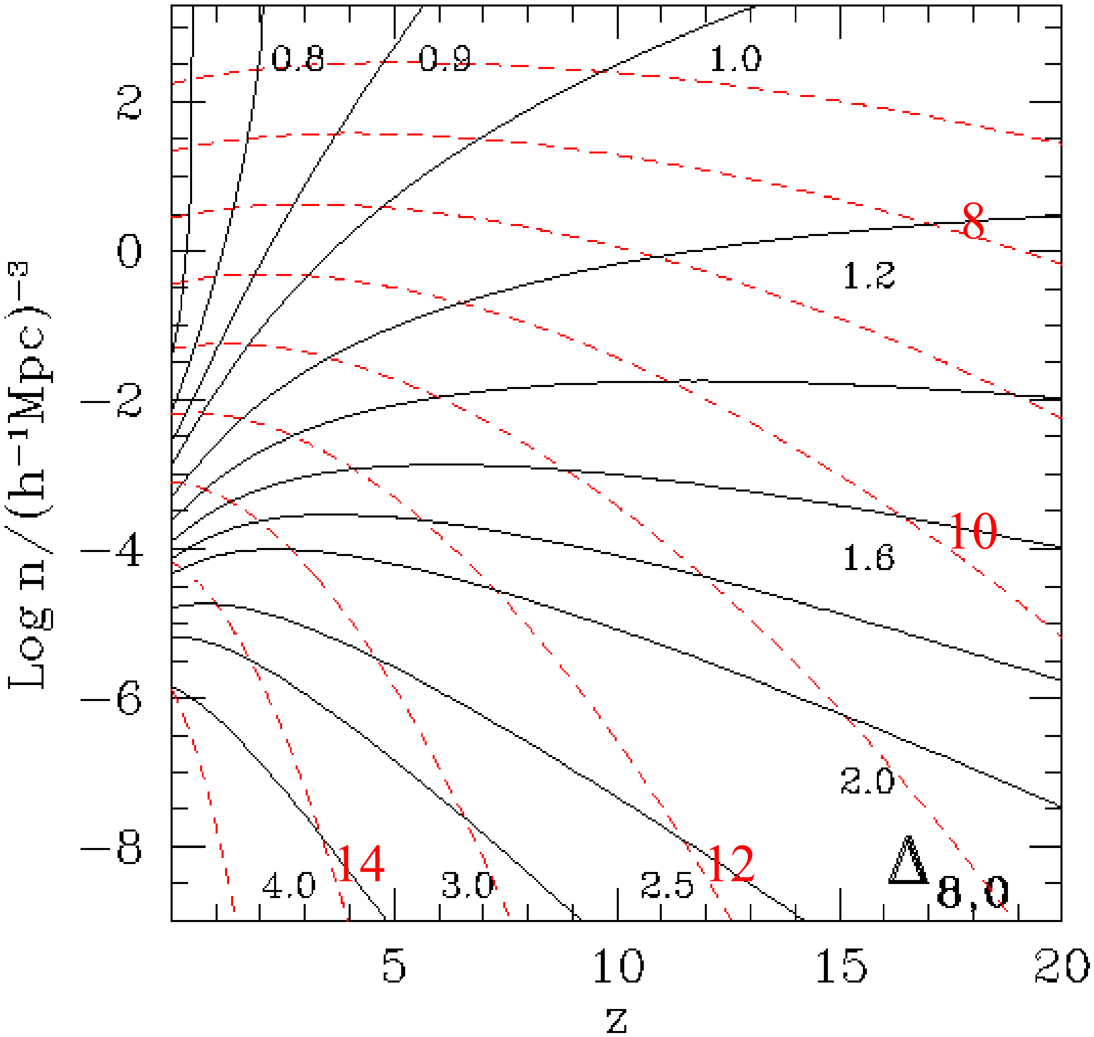
Mo & White 2002



- Halos with the abundance of L_* galaxies at z=0 are equally strongly clustered at all z < 20
- Halos of given mass or virial temperature are more clustered at *higher* z

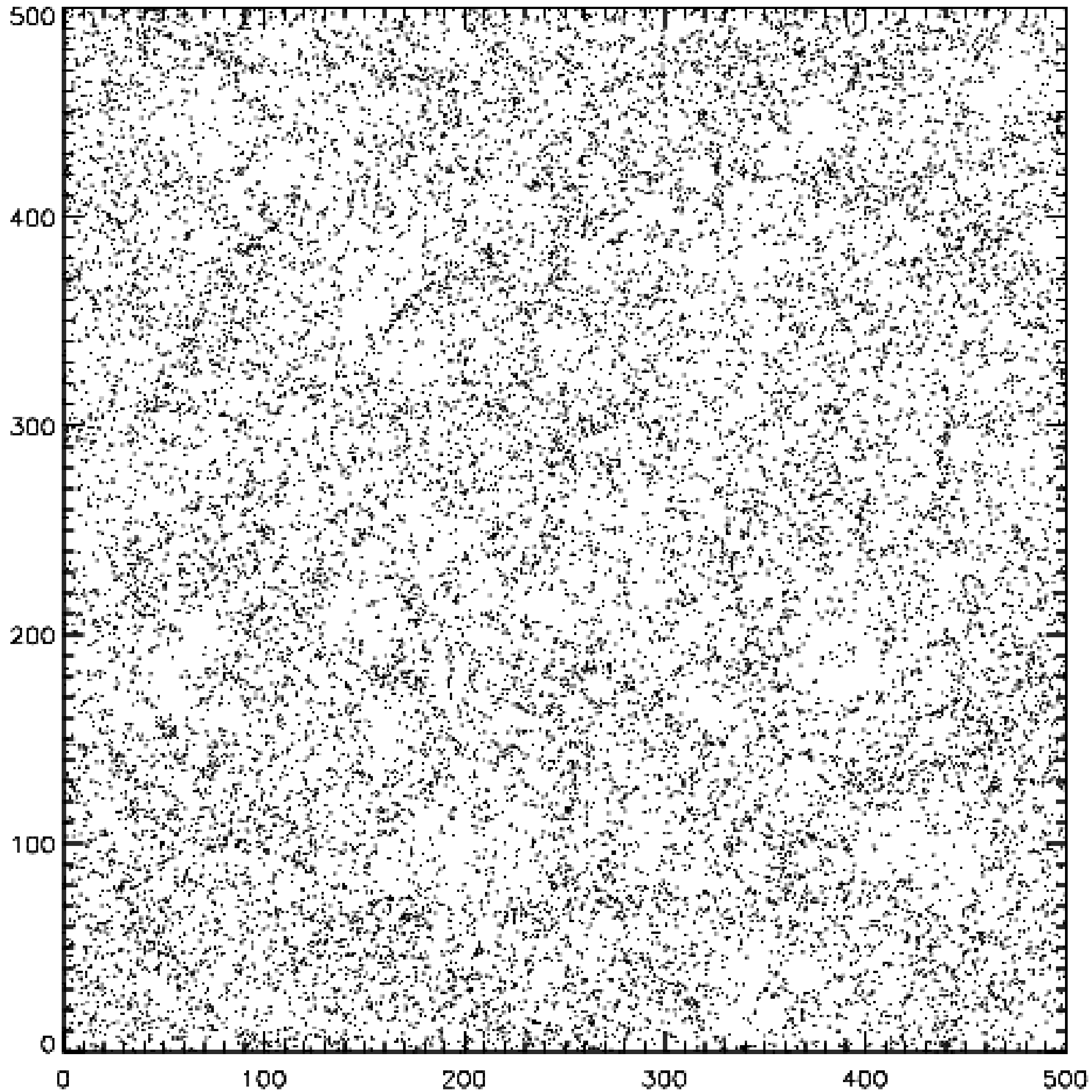
Evolution of halo abundance in ΛCDM

Mo & White 2002



- The remnants (stars and heavy elements) from all star-forming systems at z>6 are today more clustered than L_* galaxies
- The remnants of objects which at any z > 2 had an abundance similar to that of present-day L_* galaxies are today more clustered than L_* galaxies

Does halo clustering depend on formation history?

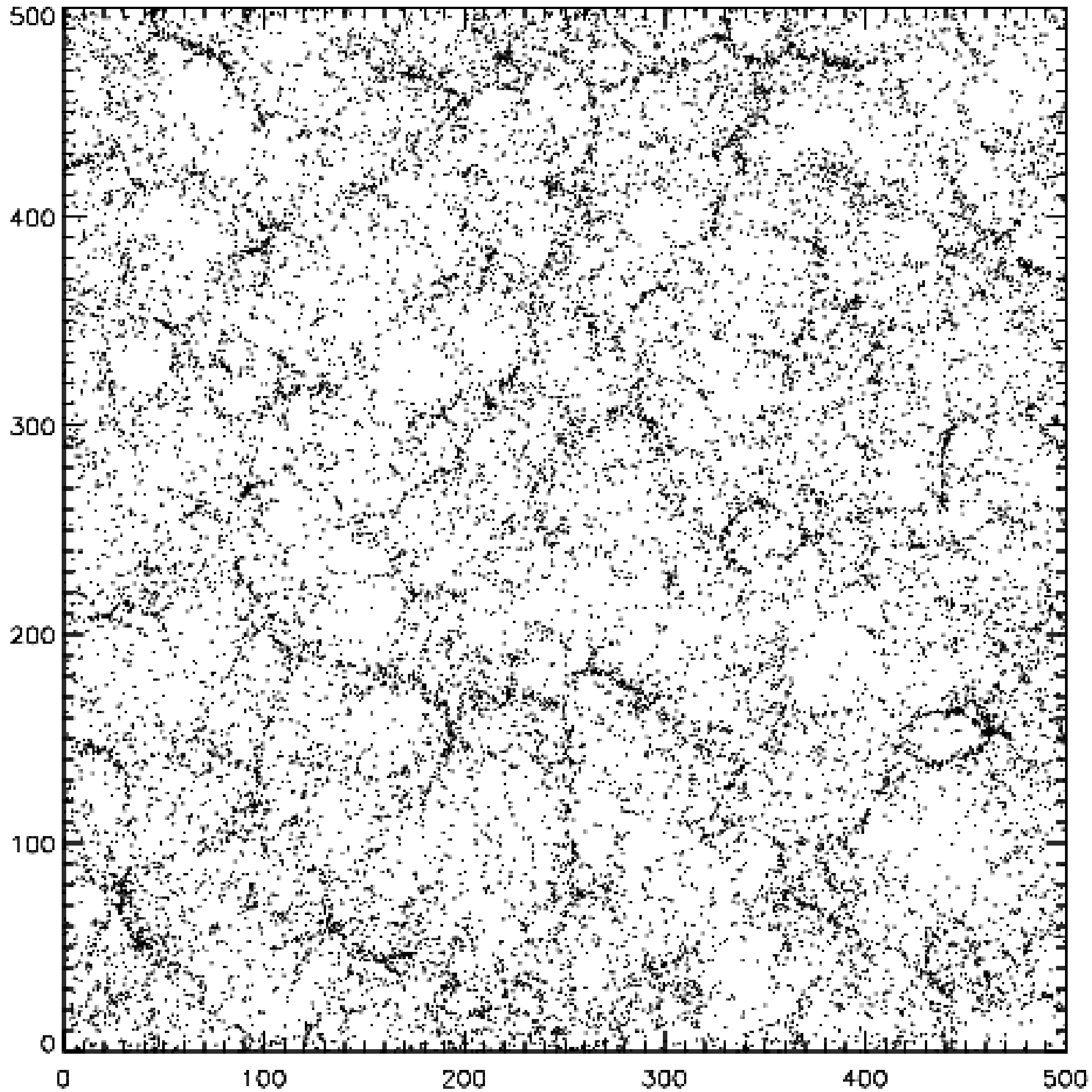


Gao, Springel & White 2005

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

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

Does halo clustering depend on formation history?



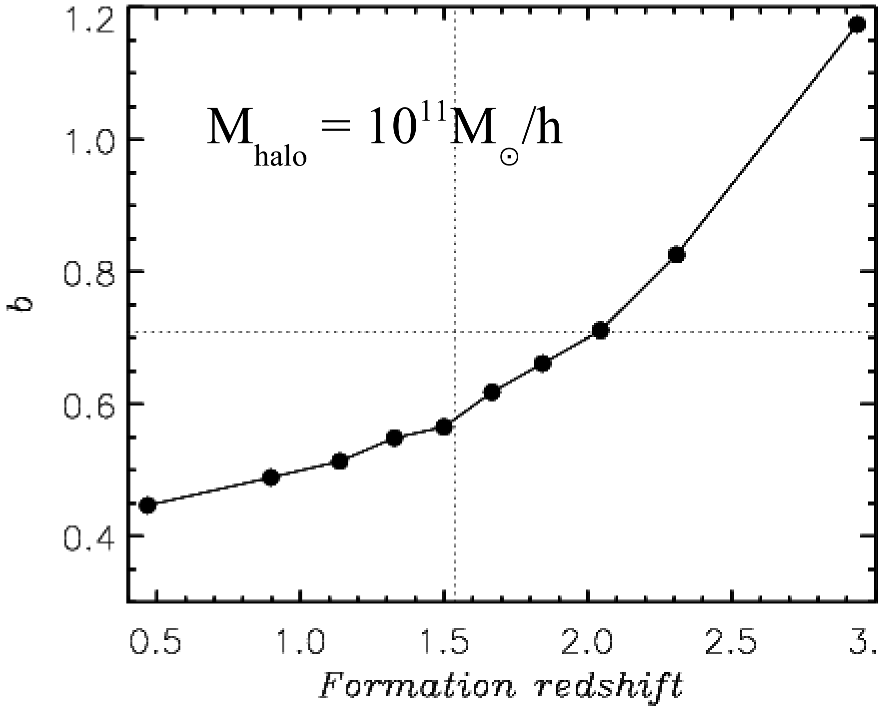
Gao, Springel & White 2005

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

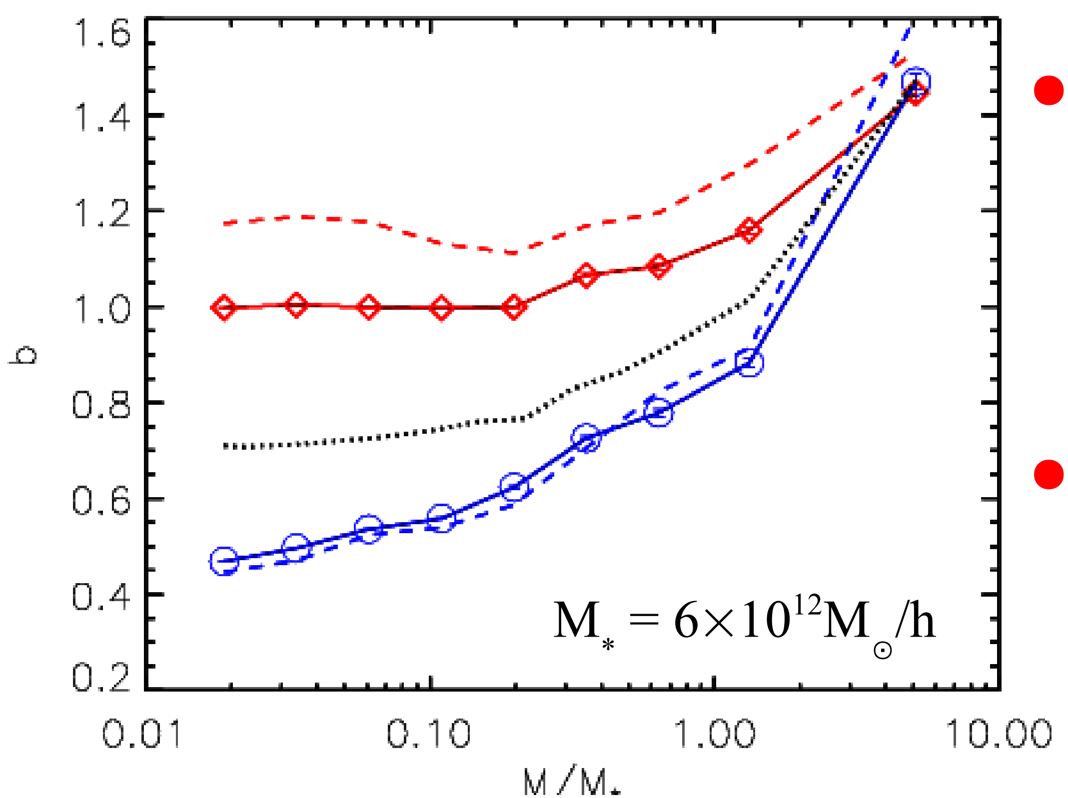
$$M_{halo} \sim 10^{11} M_{\odot}$$

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

Goals for simulating galaxy/AGN populations

- Explore the physics of galaxy formation
- Understand the links between galaxy and SMBH formation
- Clarify why galaxy properties are related to clustering
- Determine how environment stimulates galaxy activity
- Interpret new multi-wavelength surveys of galaxies
- Check if such surveys can provide precision tests of and parameter estimates for the standard ΛCDM paradigm

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?)

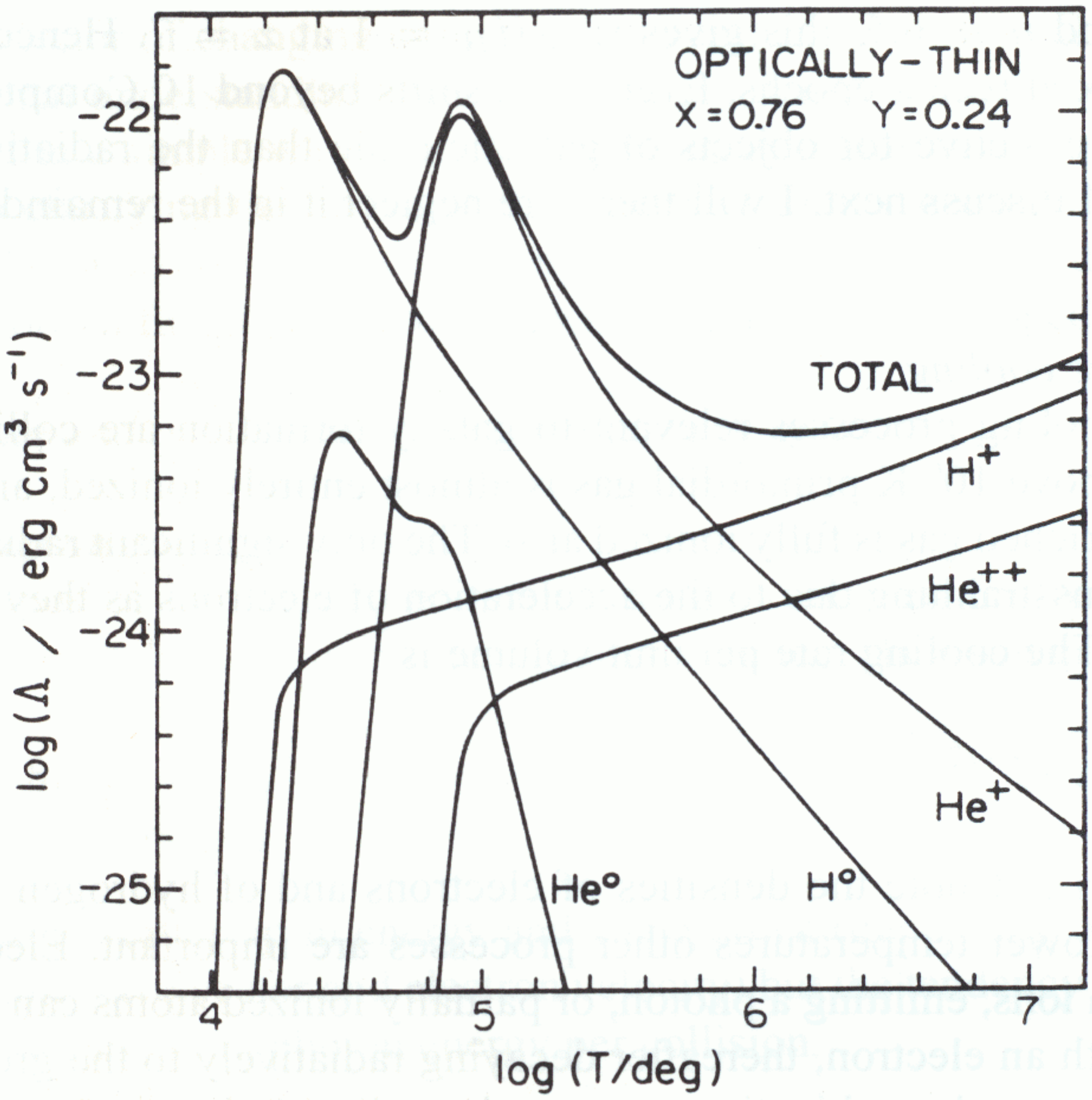
AGN physics

Black hole formation, feeding, AGN phenomenology, feedback

Environment interactions

Galaxy mergers, tidal effects, ram pressure effects

Cooling curve for metal-free, optically thin gas in collisional ionisation equ.



Luminosity/unit volume is

$$\mathcal{L} = n_e^2 \Lambda(T)$$

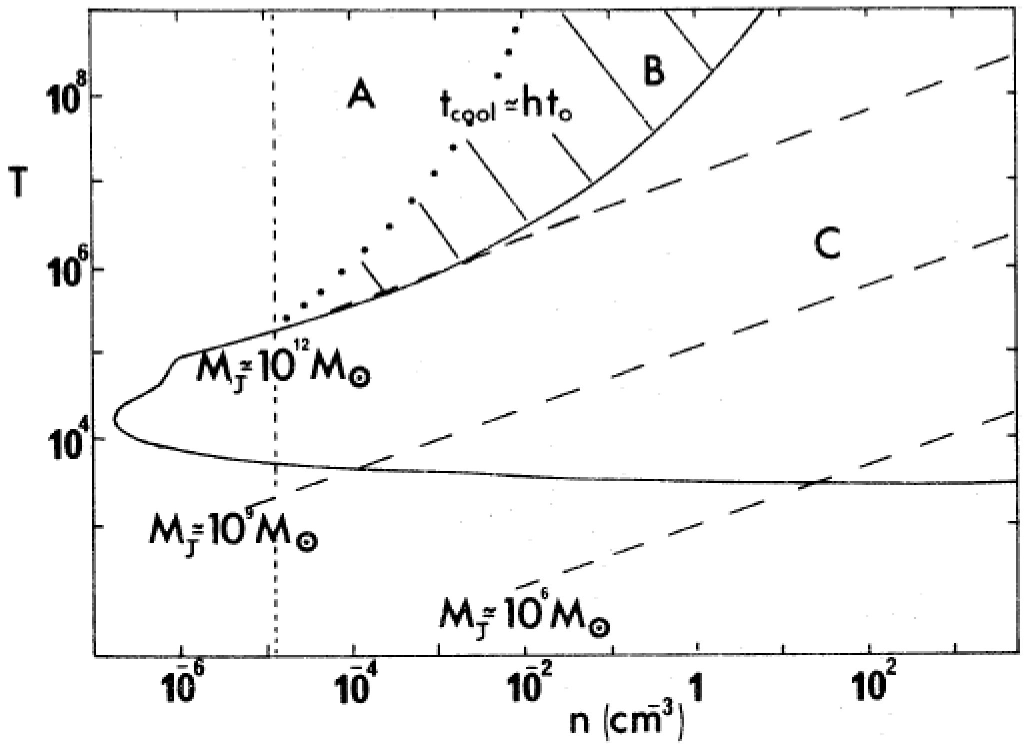
No cooling occurs below 10^4K unless H_2 can form

Addition of heavy elements increases cooling in the range 10^5K to 10^7K

Optically thin cooling time $t_{cool} \propto n_e T / \mathcal{L} \propto T / n_e \Lambda(T)$

c.f. gravitational collapse time $t_{dyn} \propto (G \rho)^{-1/2} \propto n_e^{-1/2}$

Radiative processes in galaxy formation



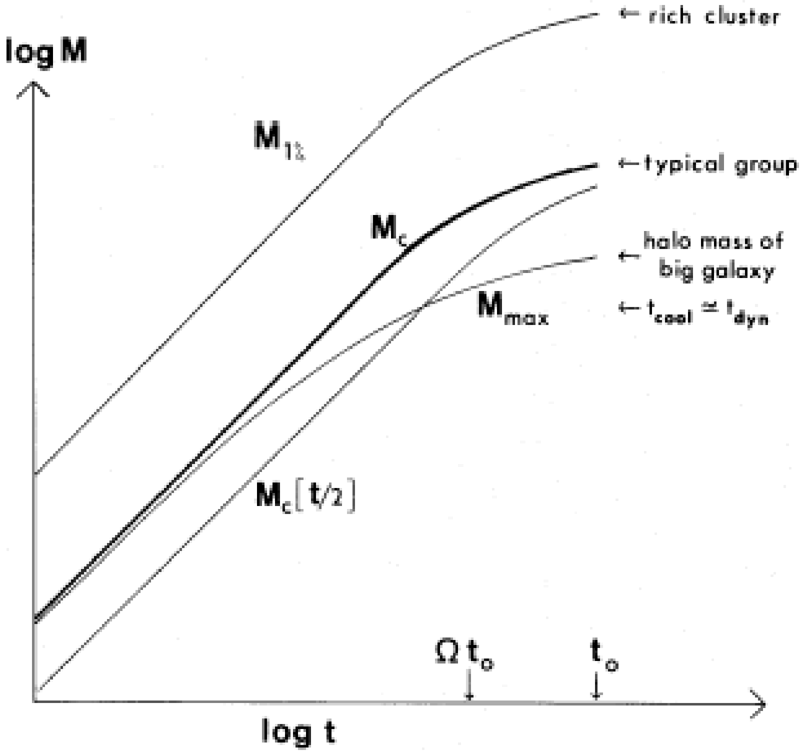
Rees & Ostriker 1977
Silk 1977
Binney 1977

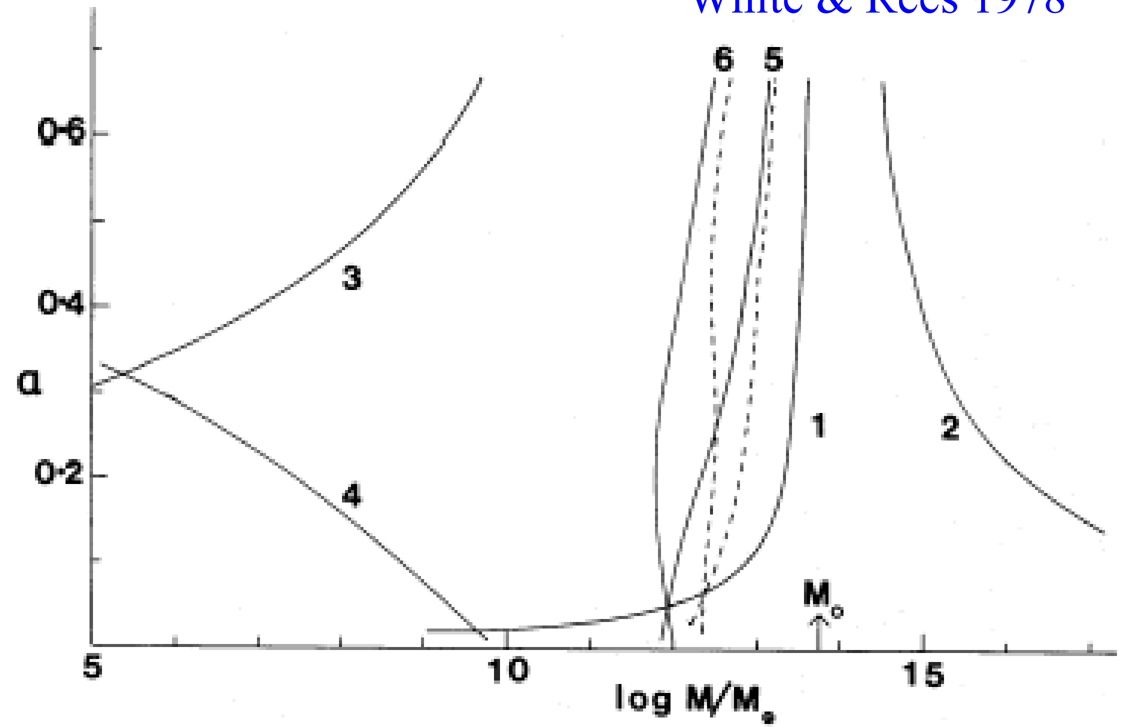
NO DARK MATTER!

- When gas clouds of galactic mass collapse:
  (i) shocks are radiative and collapse unimpeded, when $t_{cool} < t_{dyn}$ C
  (ii) shocks are non-radiative and collapse arrested, when $t_{cool} > t_{dyn}$ A,B
  where quantities are estimated at virial equilibrium
- Galaxies form in case (i) since fragmentation is possible
- Primordial cooling curve → characteristic mass $10^{12} M_\odot$

Towards a "modern" theory

White & Rees 1978

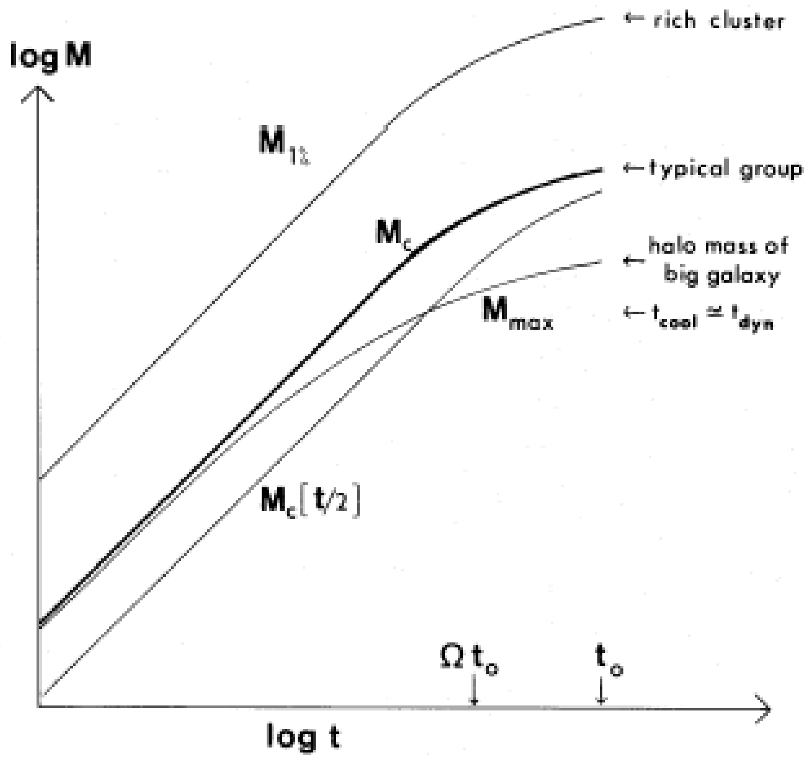


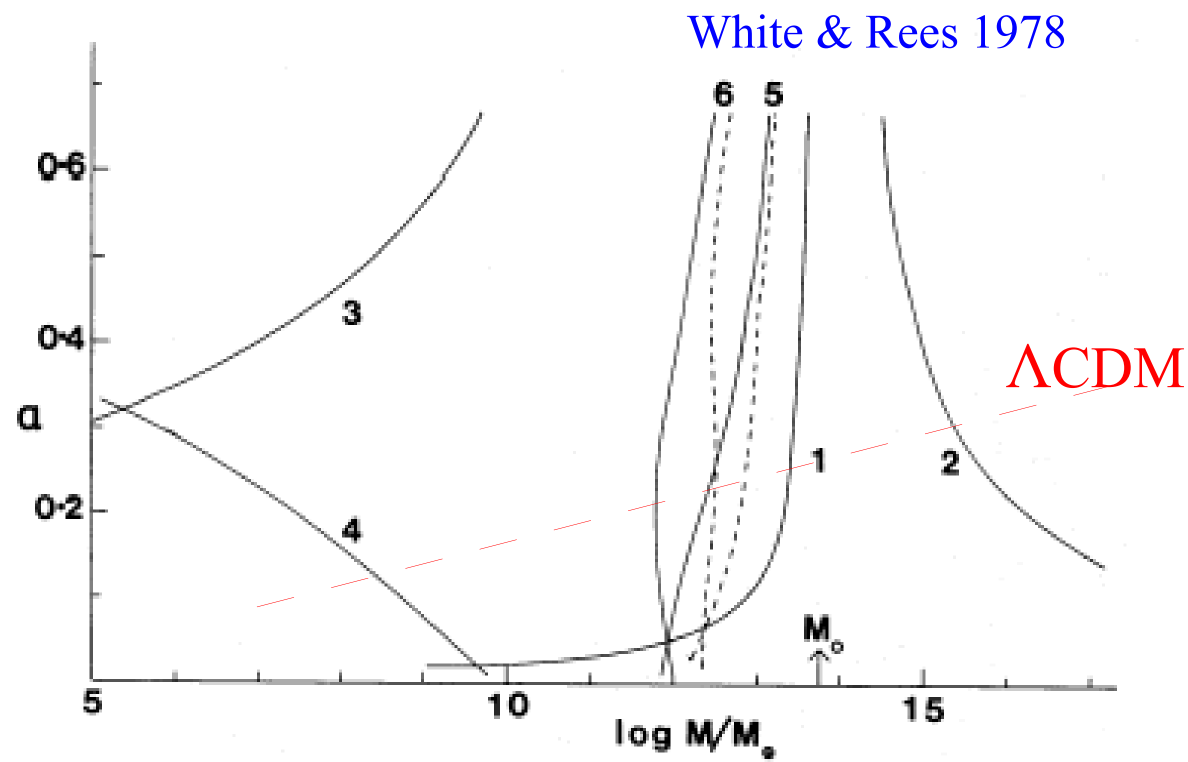


- Adding : (i) dark matter, (ii) hierarchical clustering, (iii) feedback
  - -- cooling always rapid for small masses and early times
  - -- only biggest galaxies sit in cooling flows
  - -- feedback *à la* Larson (1974) needed to suppress small galaxies

- A good model had: $\Omega_m = 0.20$, $\Omega_{gas} / \Omega_{DM} = 0.20$, $\alpha = 1/3$ (n = -1)

Towards a "modern" theory

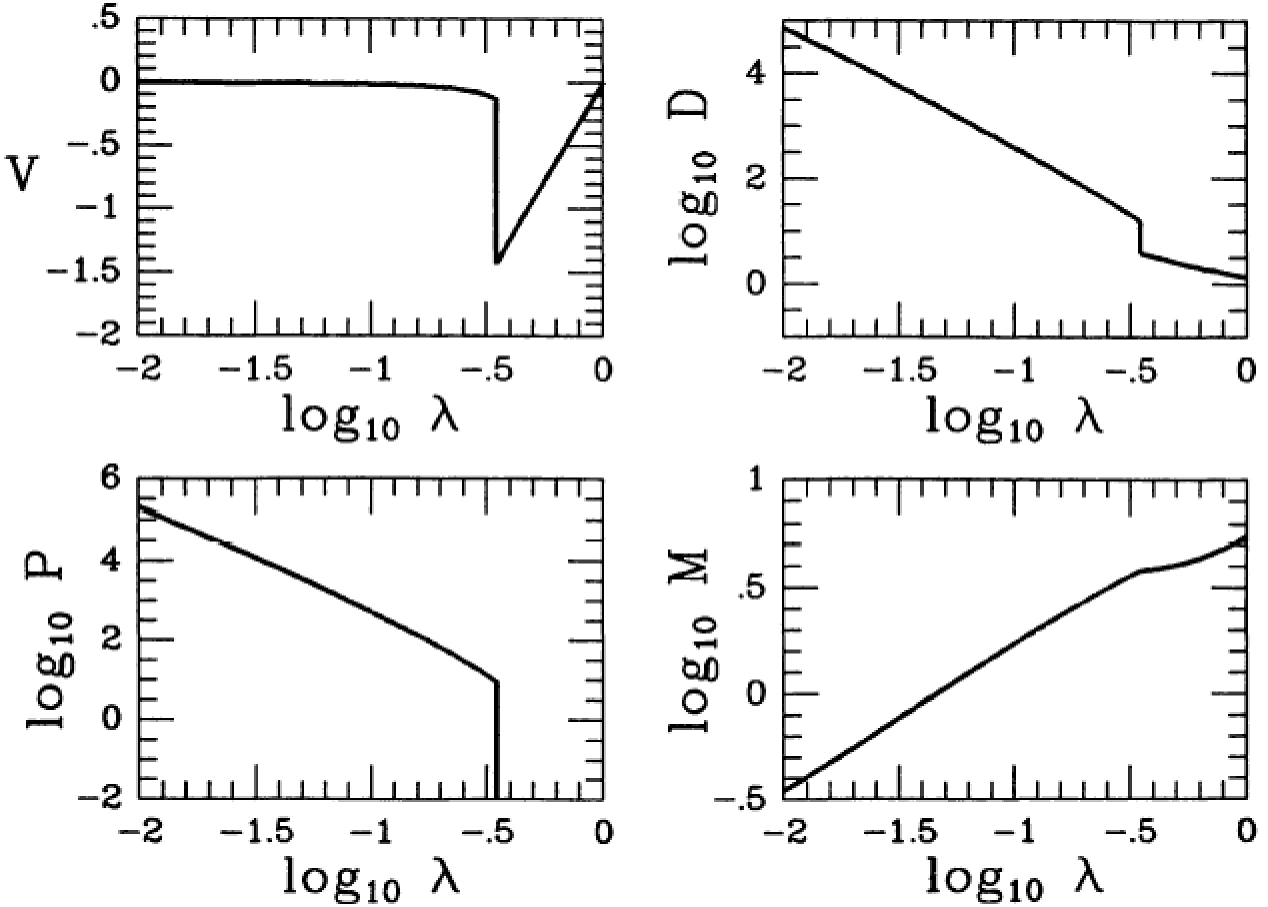




- Adding : (i) dark matter, (ii) hierarchical clustering, (iii) feedback
  - -- cooling always rapid for small masses and early times
  - -- only biggest galaxies sit in cooling flows
  - -- feedback *à la* Larson (1974) needed to suppress small galaxies

- A good model had: $\Omega_m = 0.20$, $\Omega_{gas} / \Omega_{DM} = 0.20$, $\alpha = 1/3$ (n = -1)

Spherical similarity solutions for infall

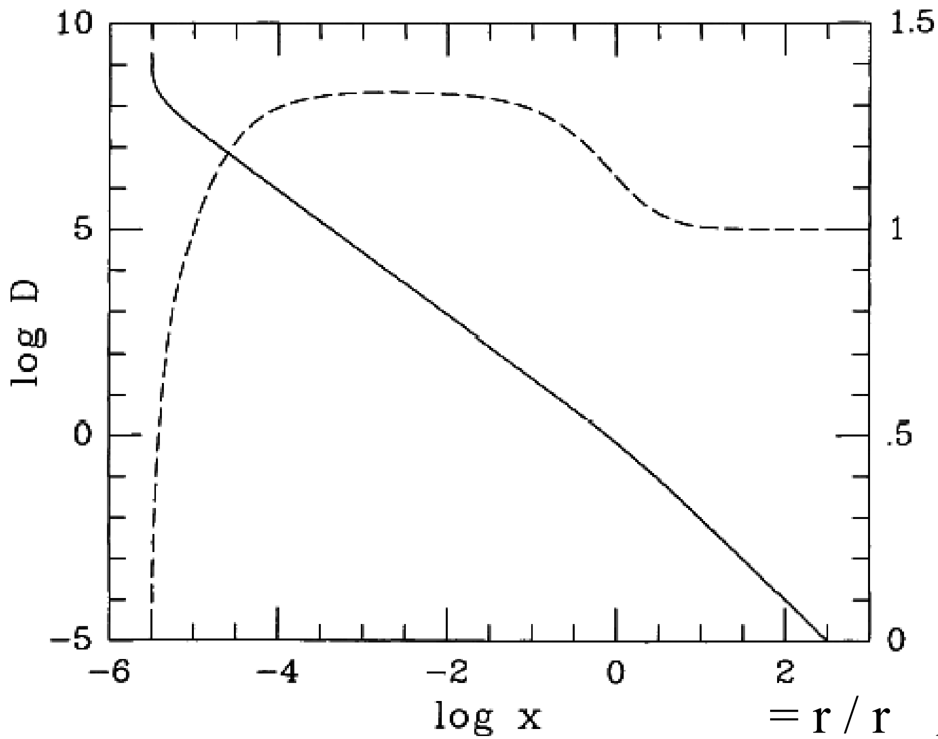


Bertschinger 1985

- Infall of DM + $\gamma = 5/3$ gas onto a point mass in an EdS universe
  - -- accretion shock at ~1/3 of turn-round radius
  - -- gas almost static inside shock
  - -- pre-shock gas has density about 4 times the cosmic mean
  - -- $kT(r) / \mu \sim GM(r) / r = V_c^2$; $R \sim V_c t$, $M \sim V_c^3 \, t / G$

Spherical similarity solutions for cooling

density



$= r / r_{cool}$

temperature

Bertschinger 1989

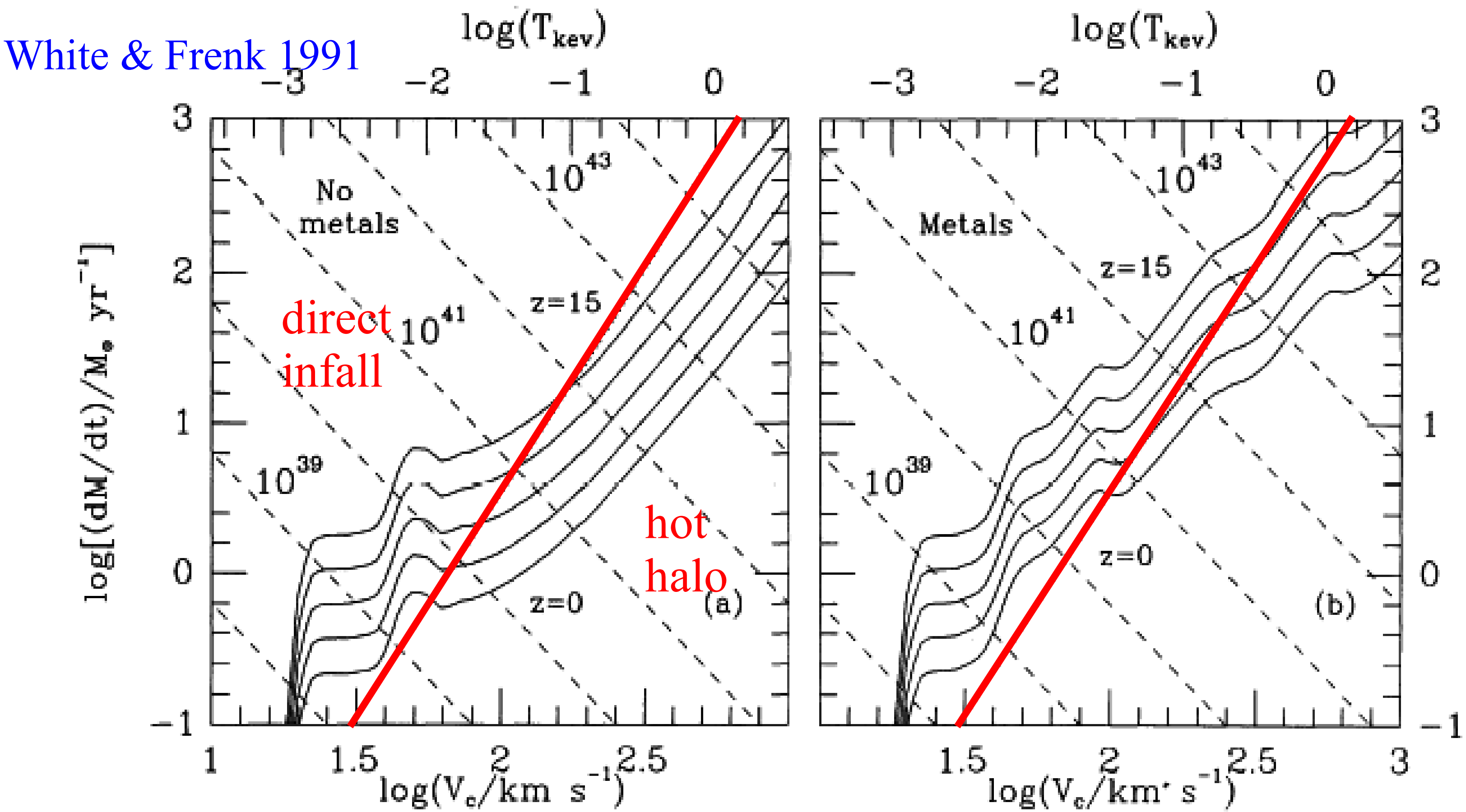
$V_c^2 \propto T \propto \text{const.}$

$M = r V_c^2 / G \propto r$

$\rho \propto r^{-2}$

- Cooling wave in equilibrium gas in an isothermal DM potential
  - -- $\rho \propto r^{-2}$ at large radius $r > r_{cool}$ where $t_{cool}(r_{cool}) = t$
  - -- $\rho \propto r^{-1.5}$ and $T = 1.33\, T_\infty$ at $r_{sonic} < r < r_{cool}$
  - -- $\rho \propto r^{-1.5}$, flow is supersonic free-fall, and $T \rightarrow 0$ at $r < r_{sonic}$
- Inflow rate $\propto t^{-1/2}$, cooling radius and cold mass $\propto t^{+1/2}$
- $r_{sonic} \sim r_{cool} \sim r_{shock}$ in protogalaxies ⟶ no static atmosphere?

Putting it together in a sCDM universe

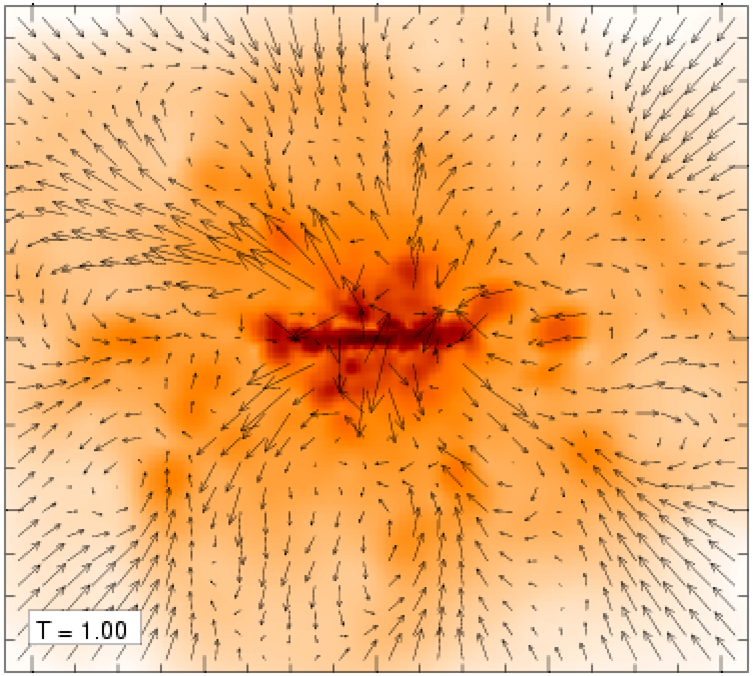


- *Assuming* $r_{cool} < r_{shock}$ for a hot atmosphere and taking $f_{baryon} = 0.1$

→ direct infall (i.e. no hot atmosphere) for $V_{circ} < 80$ km/s at z=3 when there is no chemical mixing, and for $V_{circ} < 250$ km/s at z=3 when efficient mixing is assumed

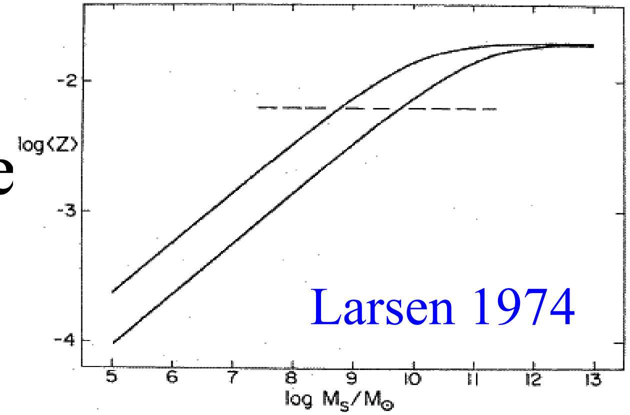
Feedback/galactic wind issues

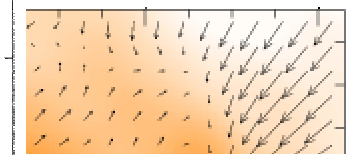
- Can supernova feedback drive galactic winds?
- Can these reproduce the mass-element abundance relation?
- Can they enrich intergalactic gas with heavy elements?
- Can these enhance formation of disks over bulges?
- What about feedback from Active Galactic Nuclei?

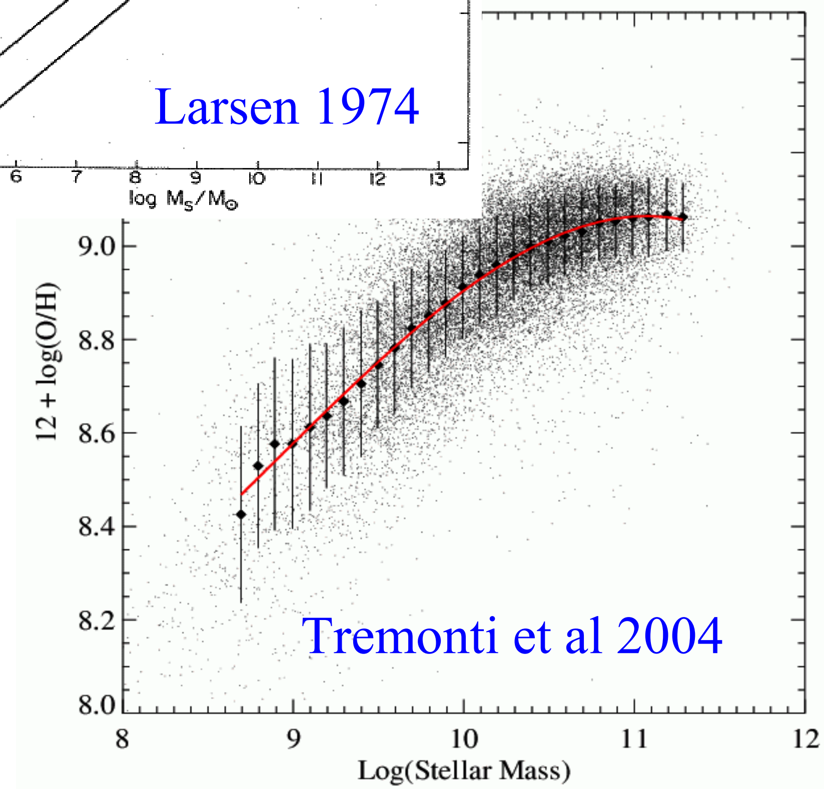


Feedback/galactic wind issues

- Can supernova feedback drive galactic winds?
- Can these reproduce the mass-element abundance relation?
- Can they enrich intergalactic gas with heavy elements?
- Can these enhance formation of disks over bulges?
- What about feedback from Active Galactic Nuclei?



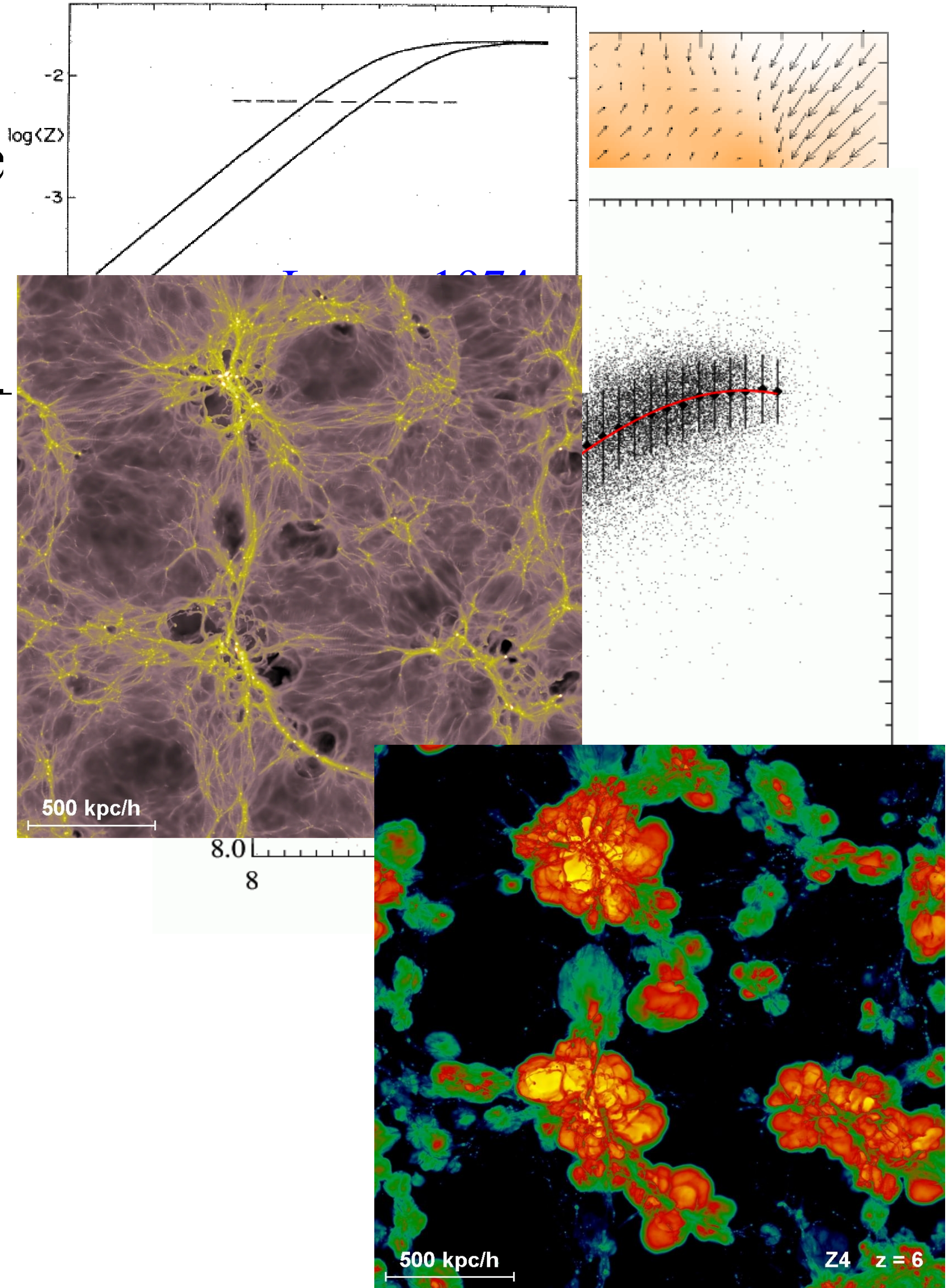


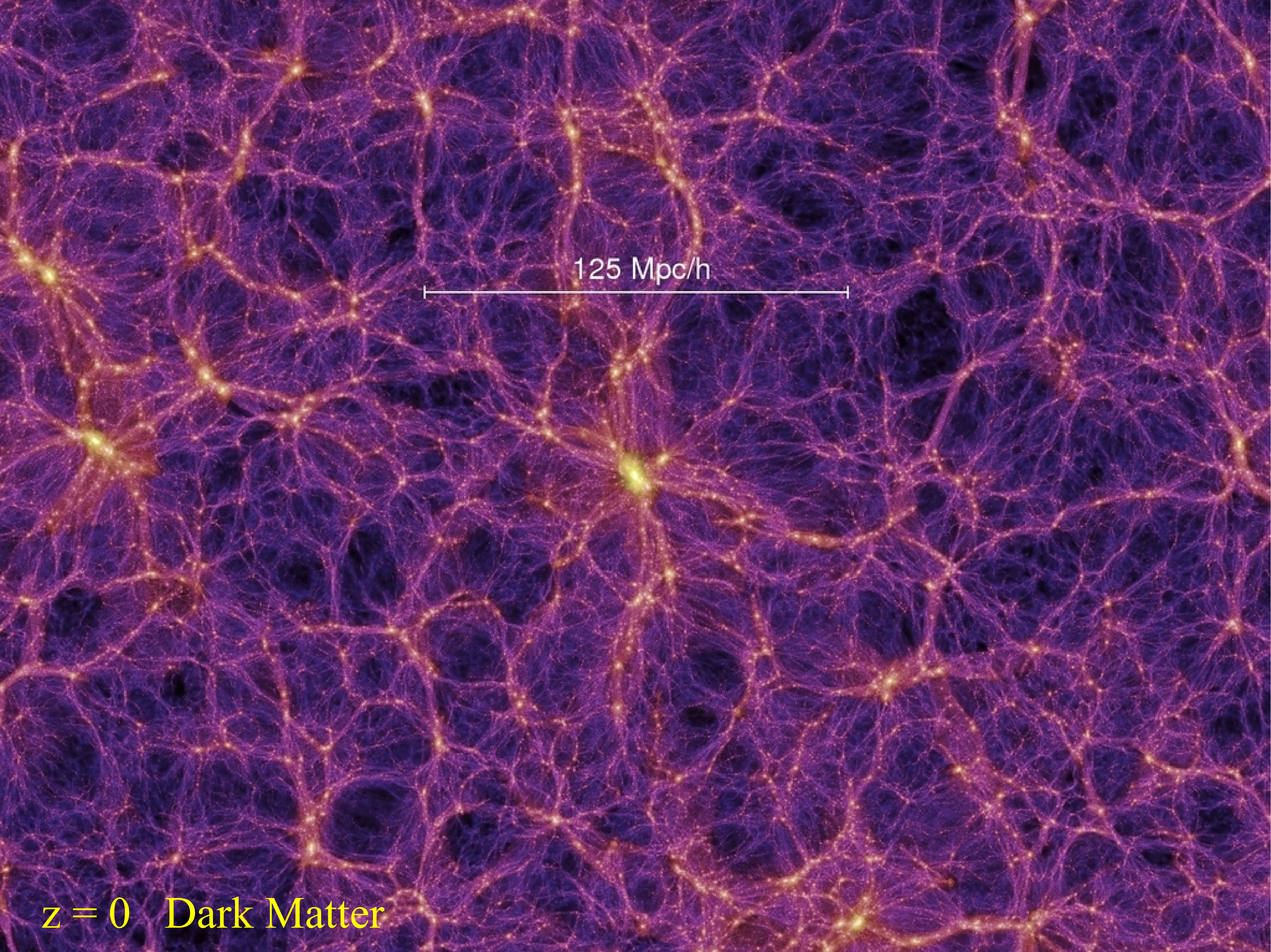


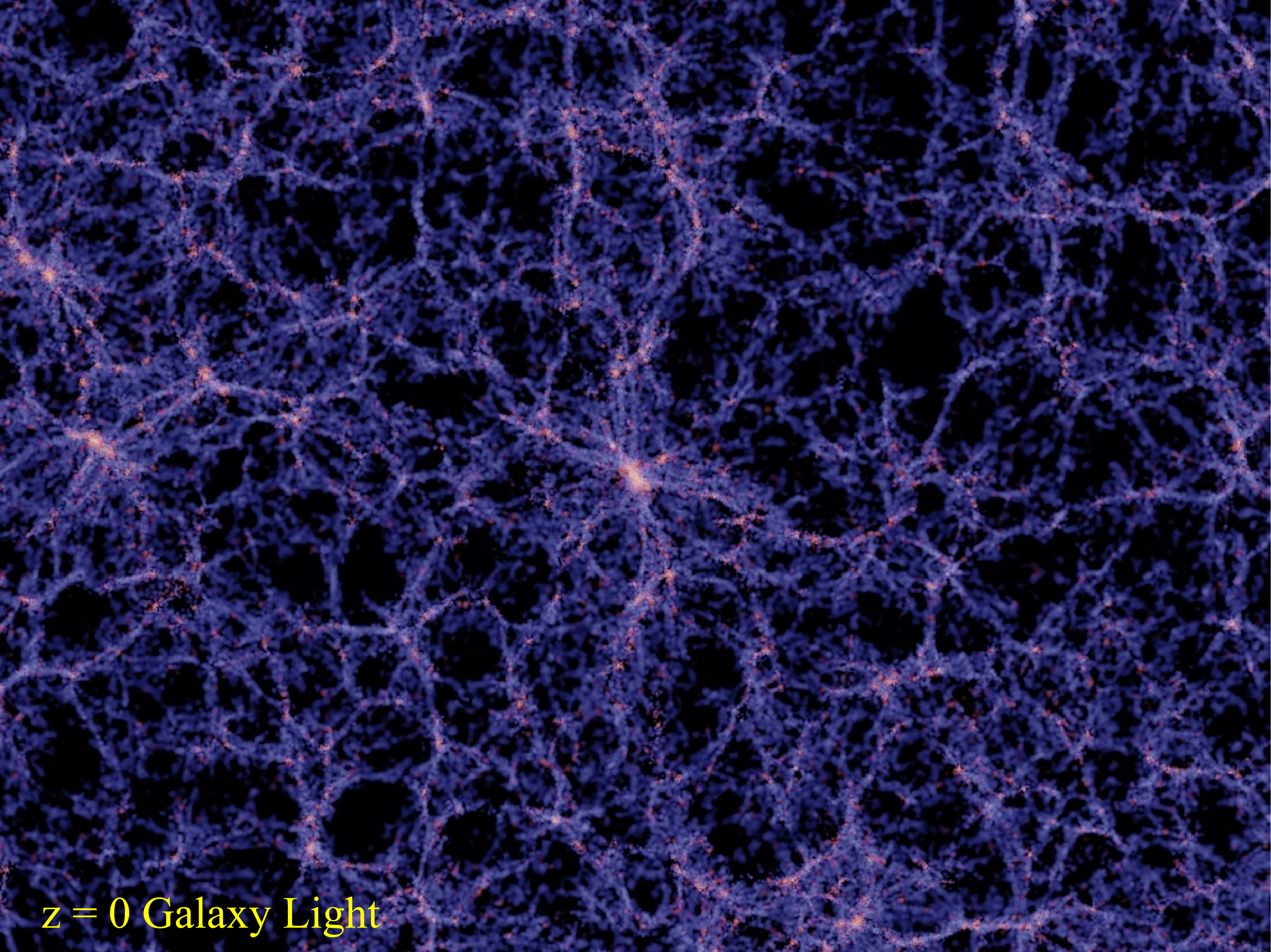
$$\dot{M}_{wind} \propto \dot{E}_{SN} / V_{esc}^{2}$$
$$\propto \dot{M}_{*} / V_{c}^{2}$$

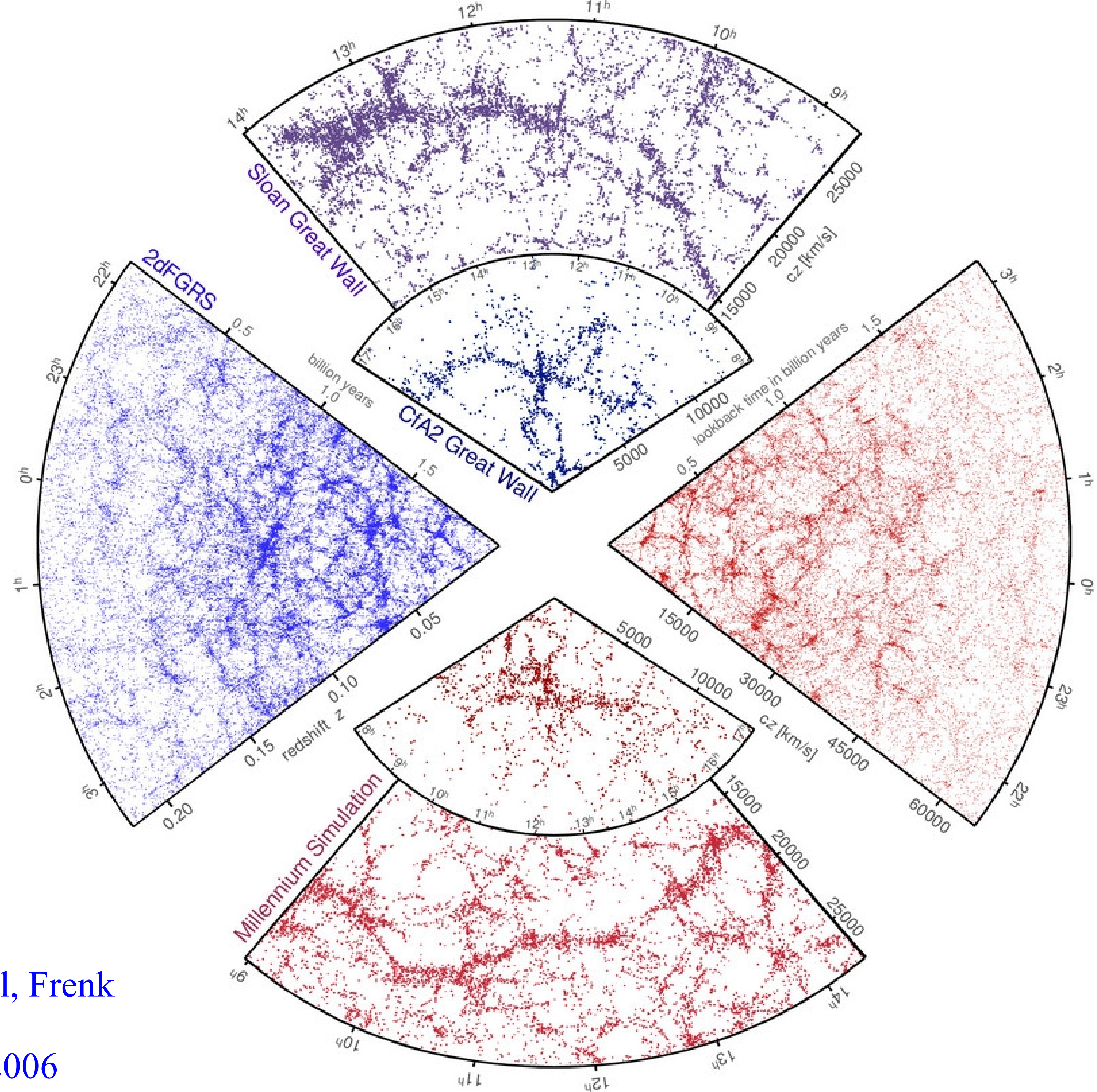
Feedback/galactic wind issues

- Can supernova feedback drive galactic winds?
- Can these reproduce the mass-element abundance relation?
- Can they enrich intergalactic gas with heavy elements?
- Can these enhance formation of disks over bulges?
- What about feedback from Active Galactic Nuclei?



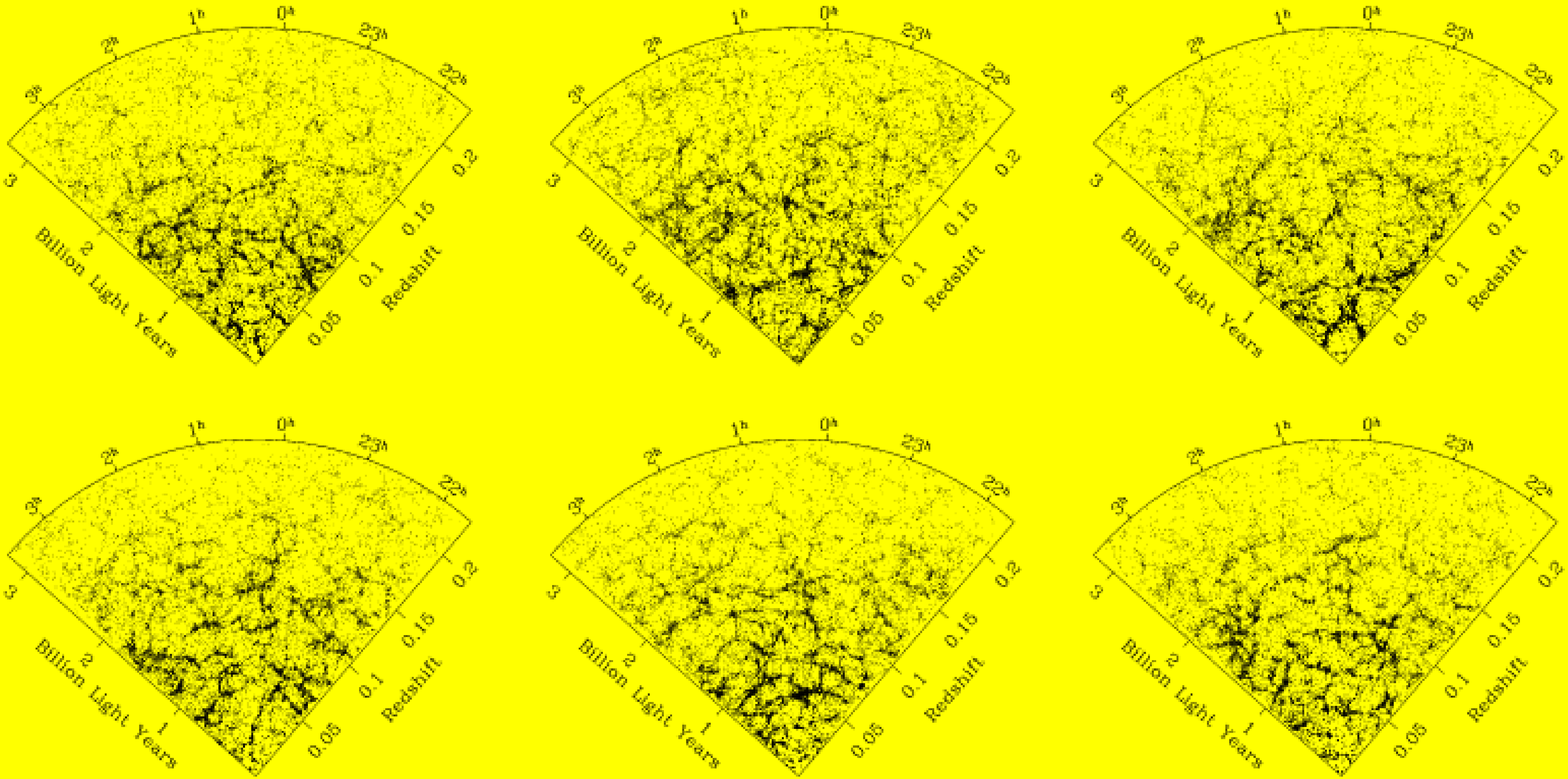

125 Mpc/h
z = 0 Dark Matter


z = 0 Galaxy Light



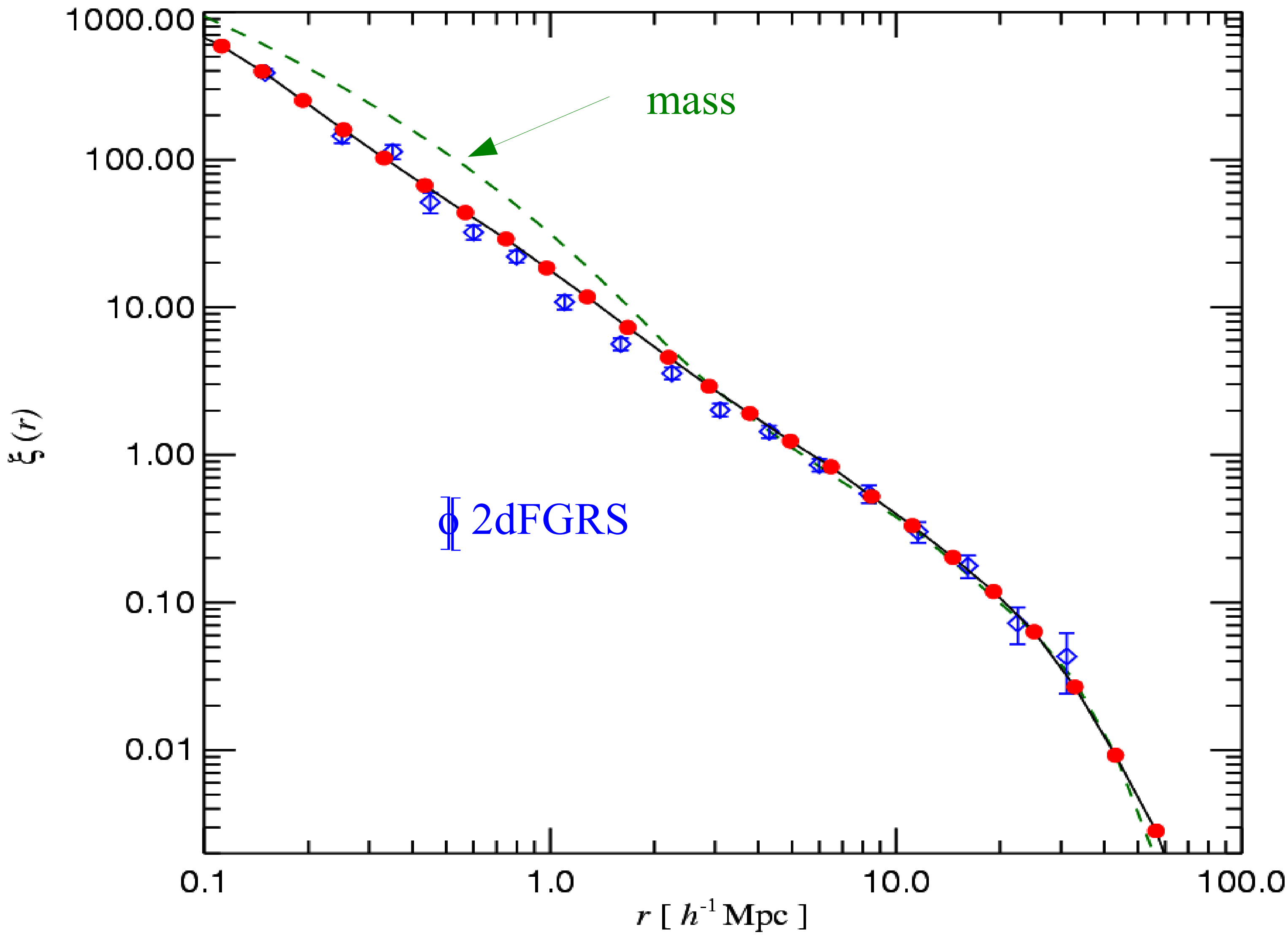
Springel, Frenk
&
White 2006

VIRTUAL vs REAL UNIVERSES



Galaxy autocorrelation function

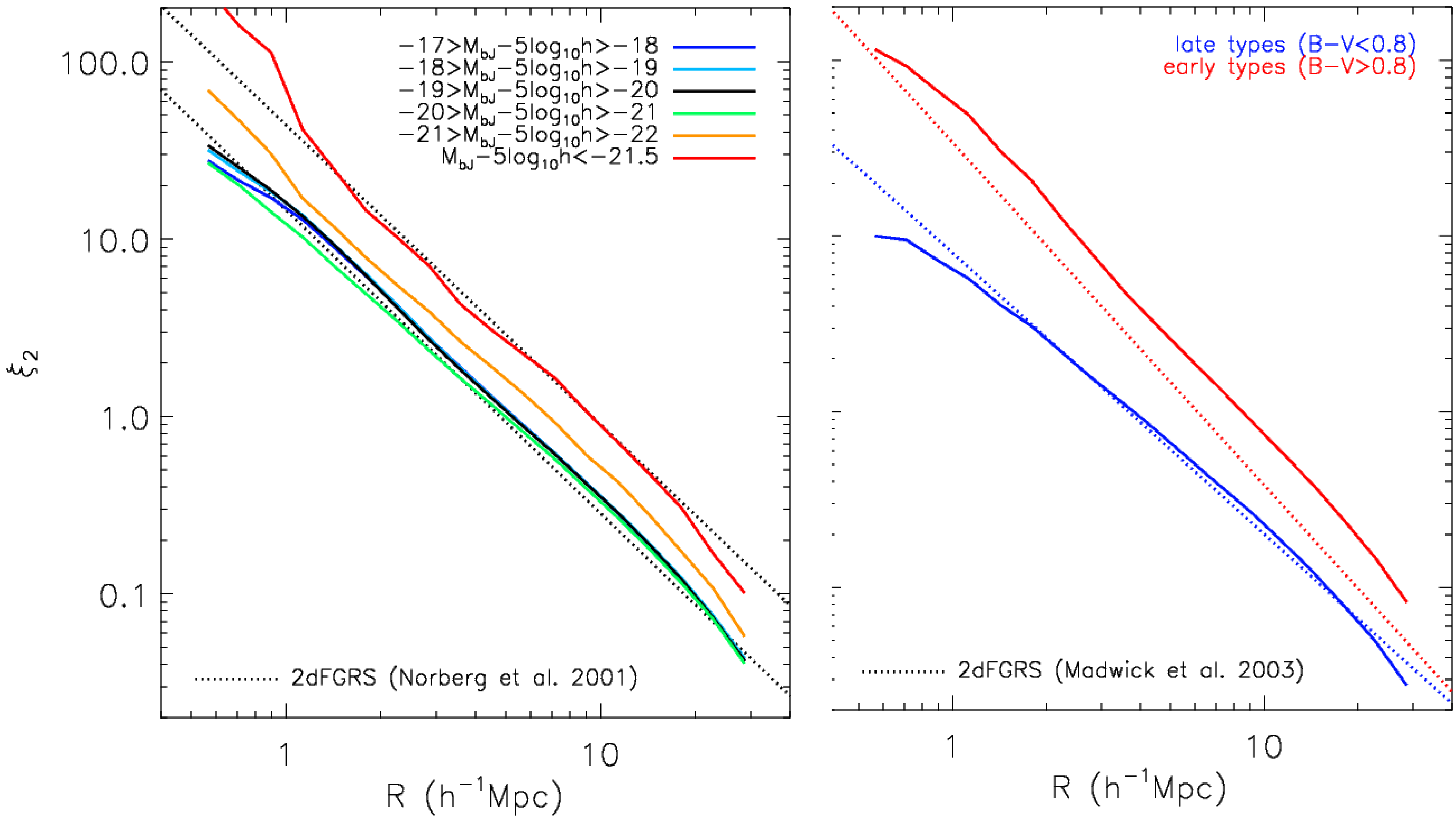
Springel et al 2005



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

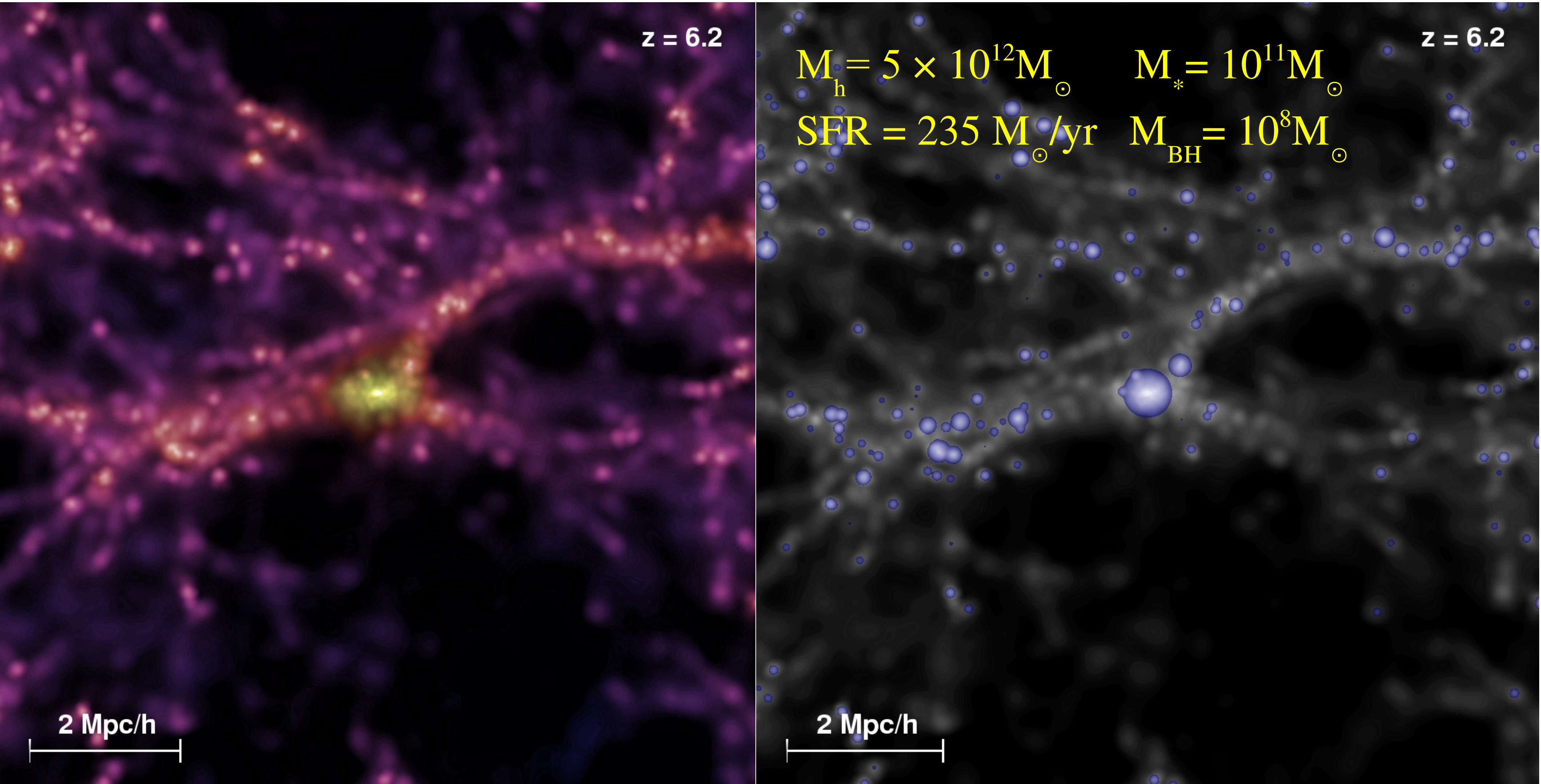
Correlation functions depend on L and colour

Croton et al 2005



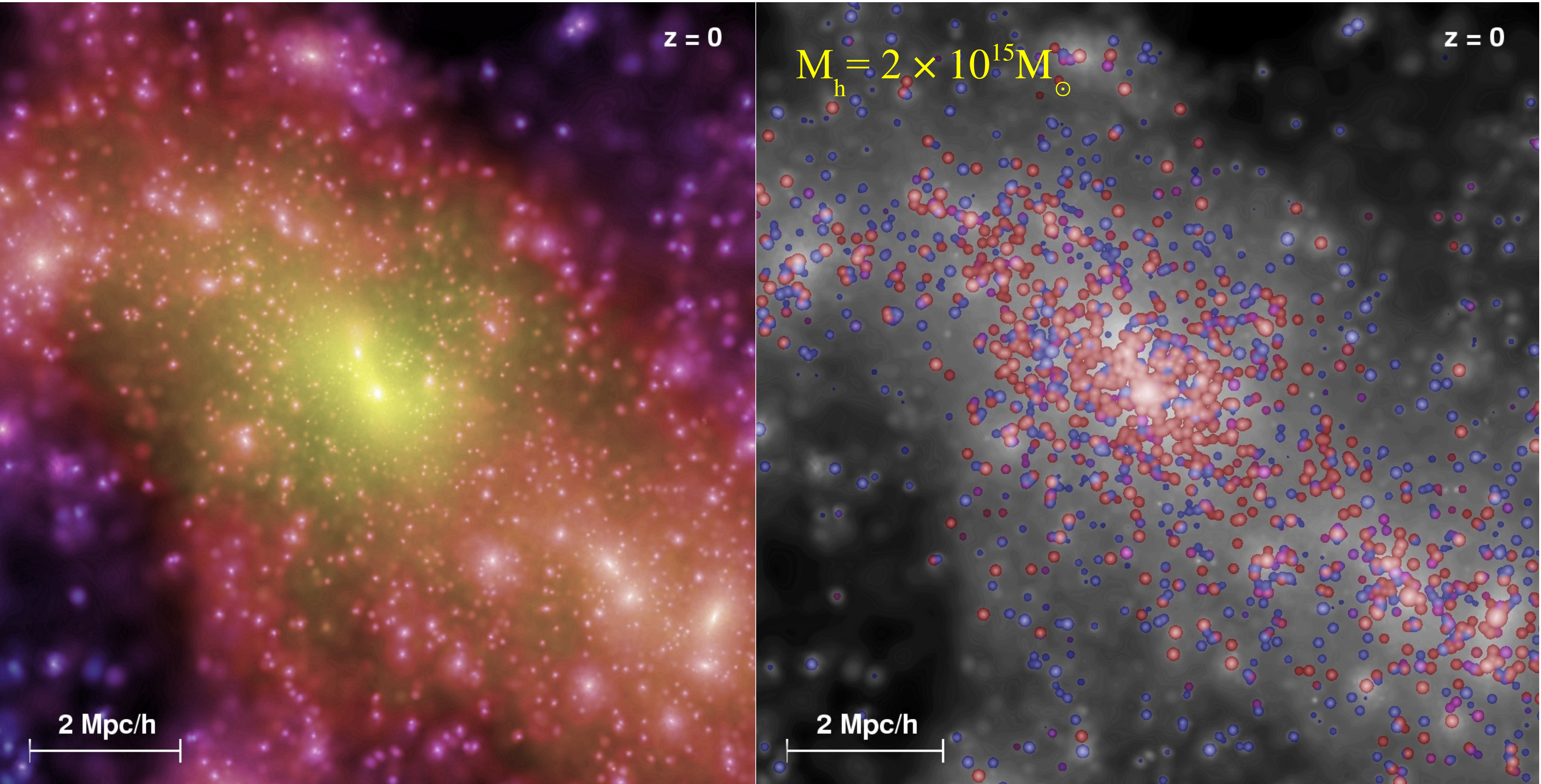
A bright quasar and its surroundings at 1 billion years

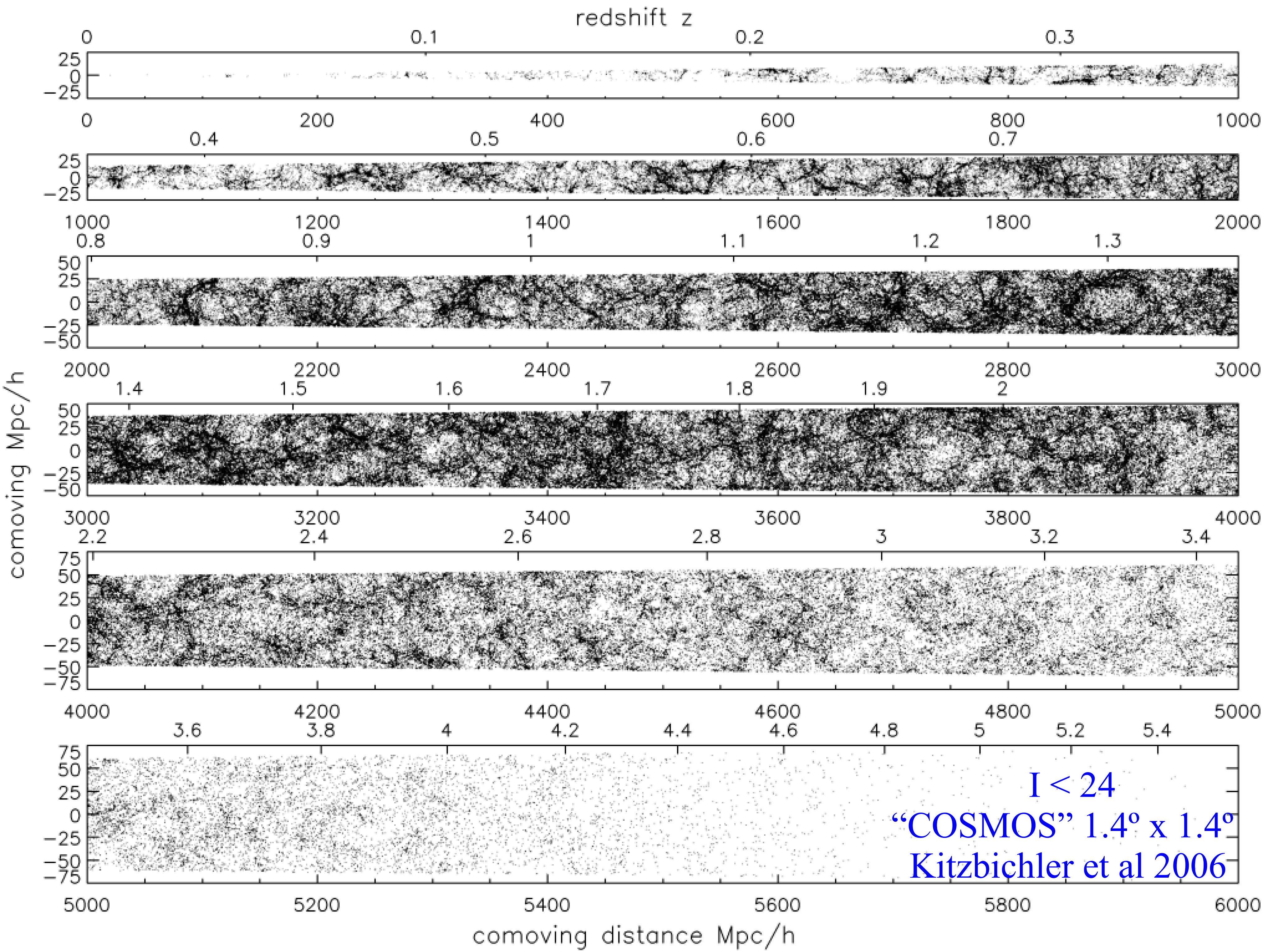
One of the most massive dark matter clumps, containing one of the most massive galaxies and most massive black holes.



The quasar's descendant and its surroundings today, at t = 13.7 billion years

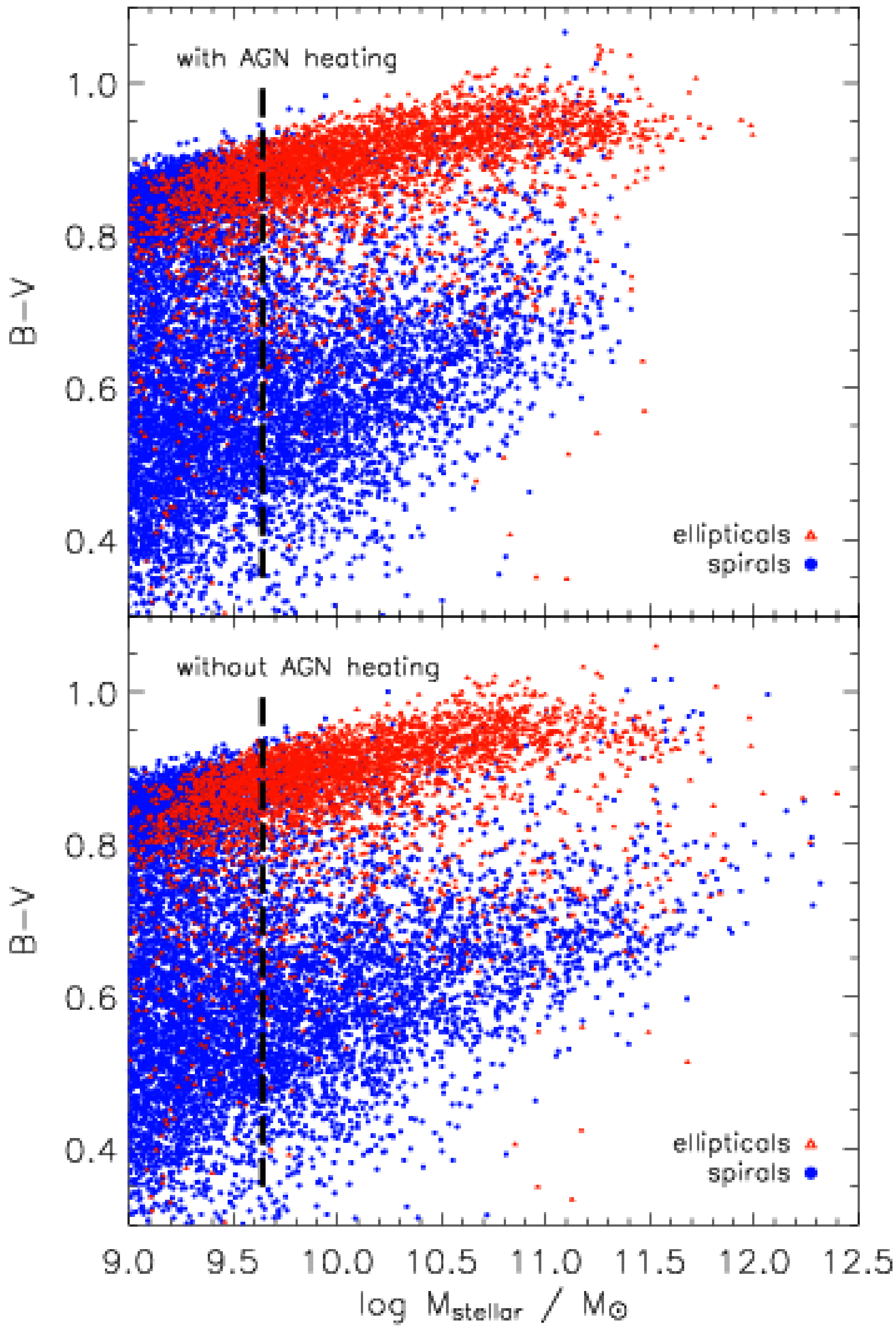
One of the most massive galaxy clusters. The quasar's descendant is part of the central massive galaxy of the cluster.




redshift z
comoving Mpc/h
comoving distance Mpc/h
I < 24
"COSMOS" 1.4º x 1.4º
Kitzbichler et al 2006

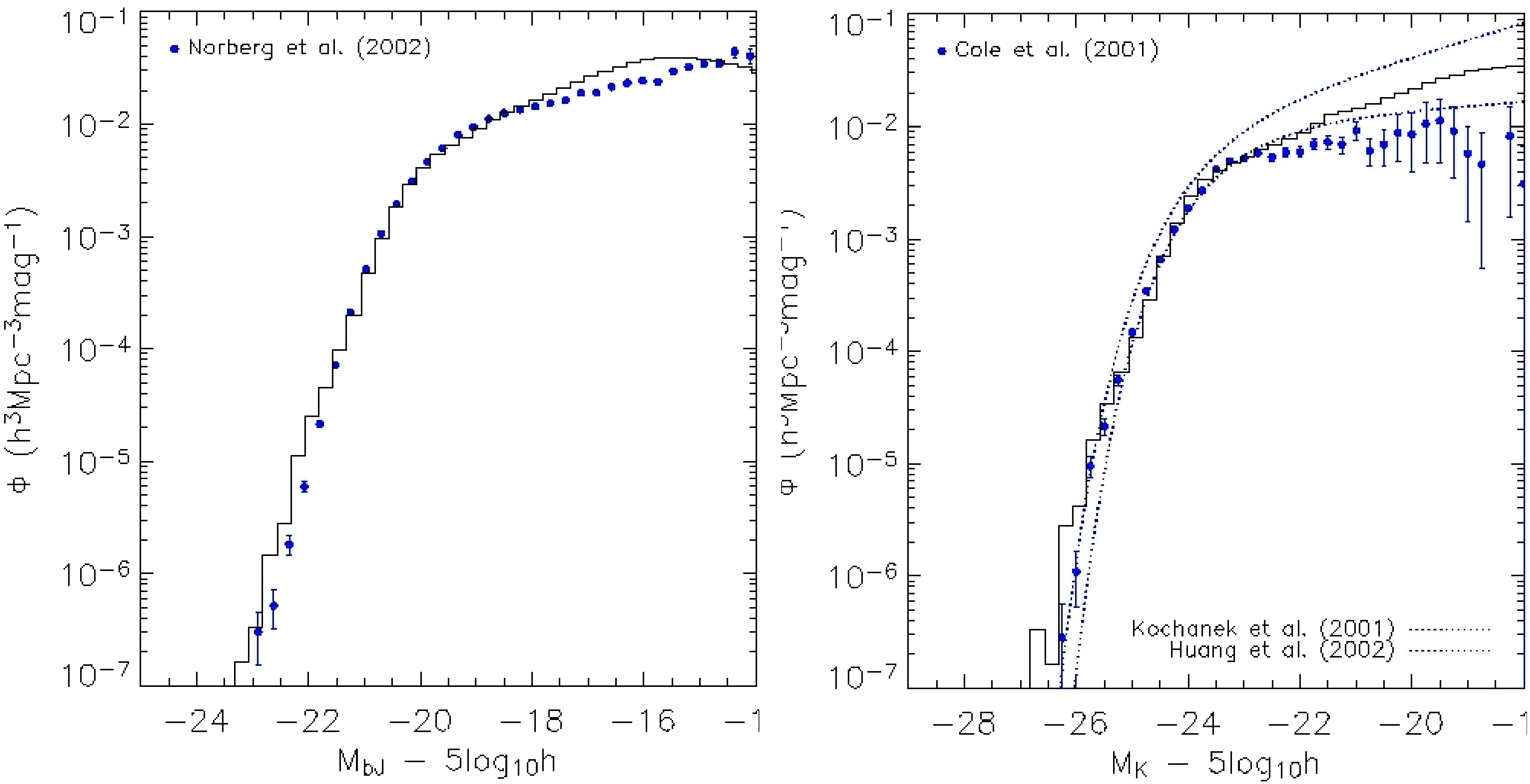
The effects of “radio mode” feedback on z=0 galaxies

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

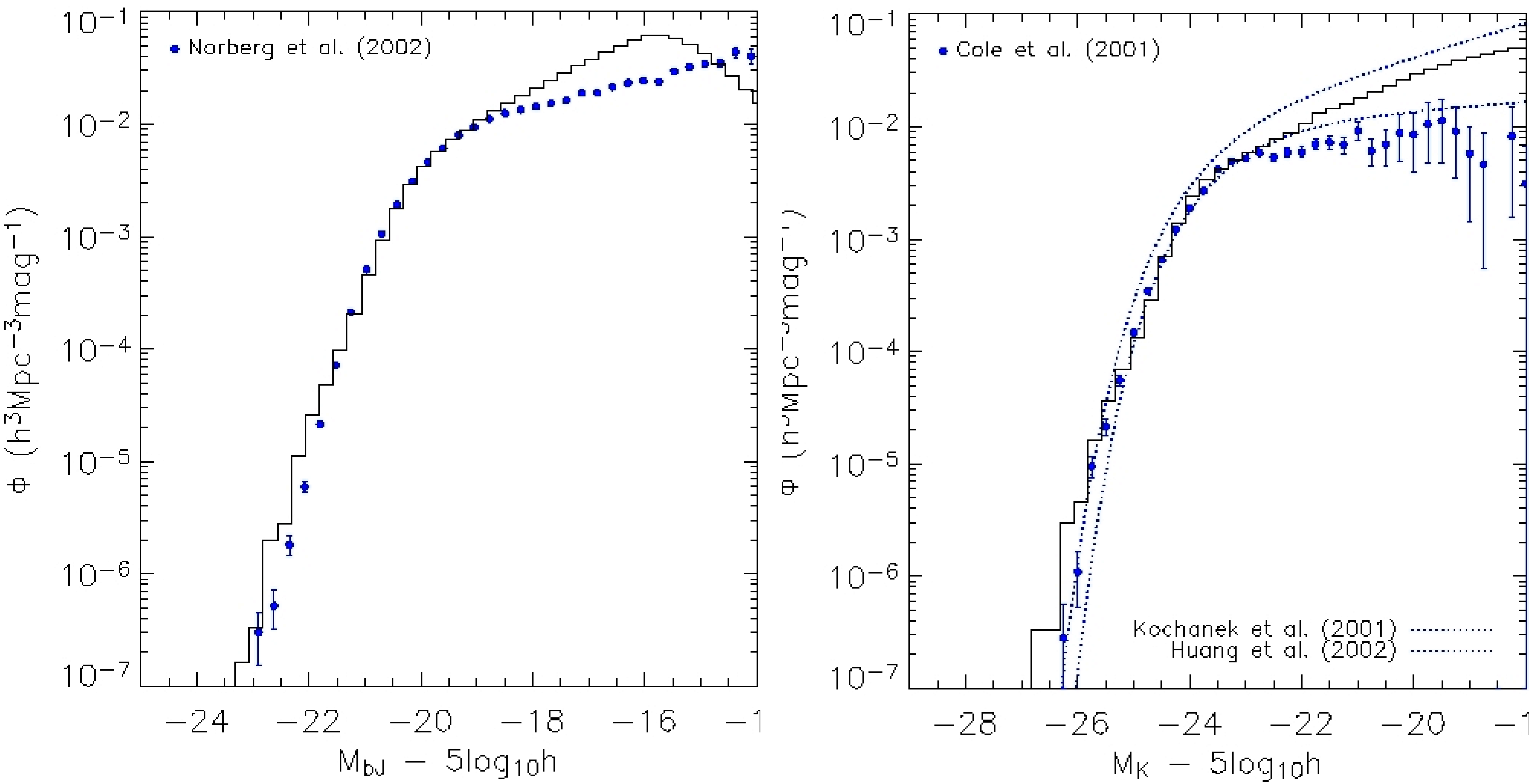
Effect of feedback on the Luminosity Function



Full model with reionisation, AGN and SN feedback

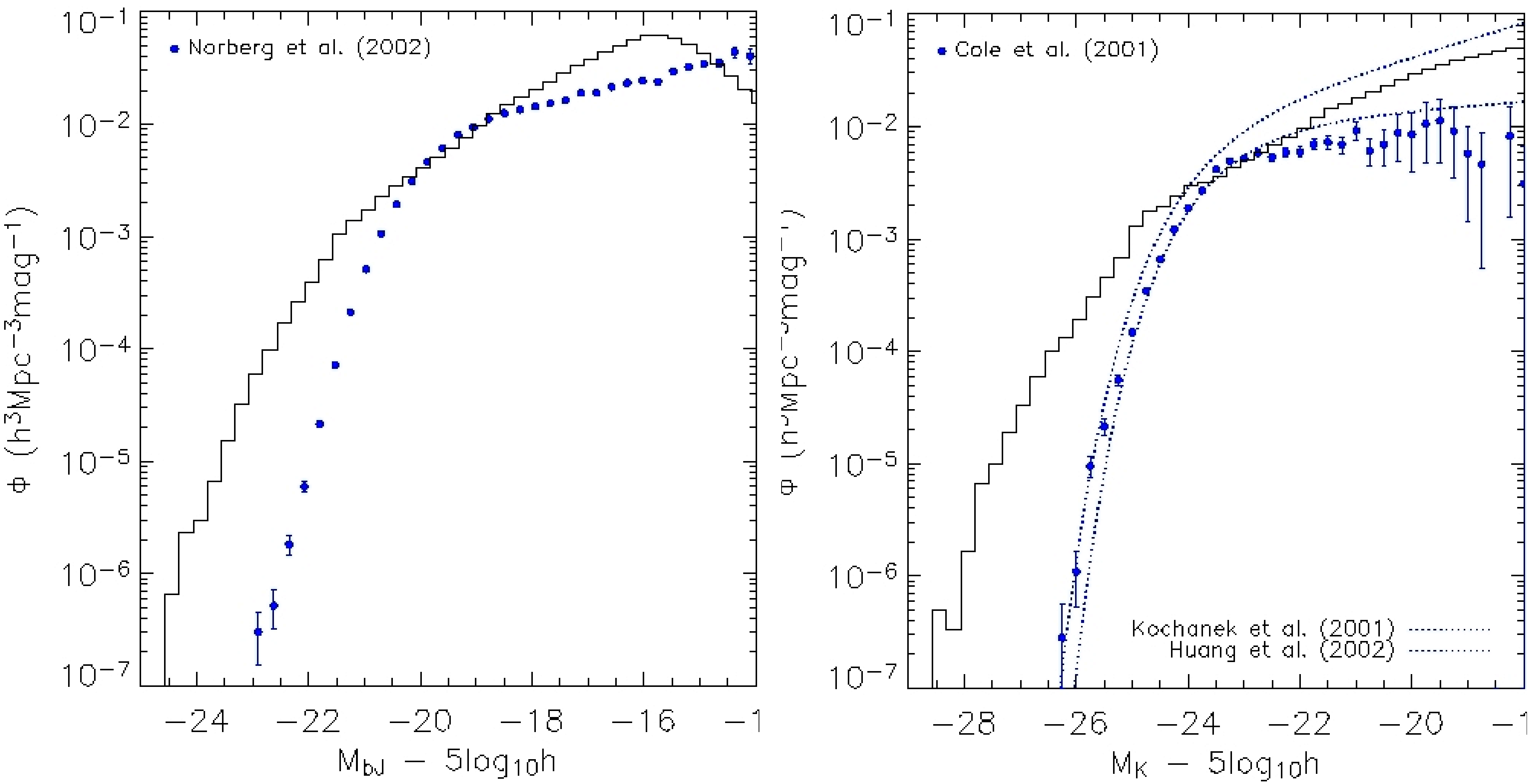
Croton et al 2006

Effect of feedback on the Luminosity Function



Full model with ~~reionisation~~, AGN and SN feedback   Croton et al 2006

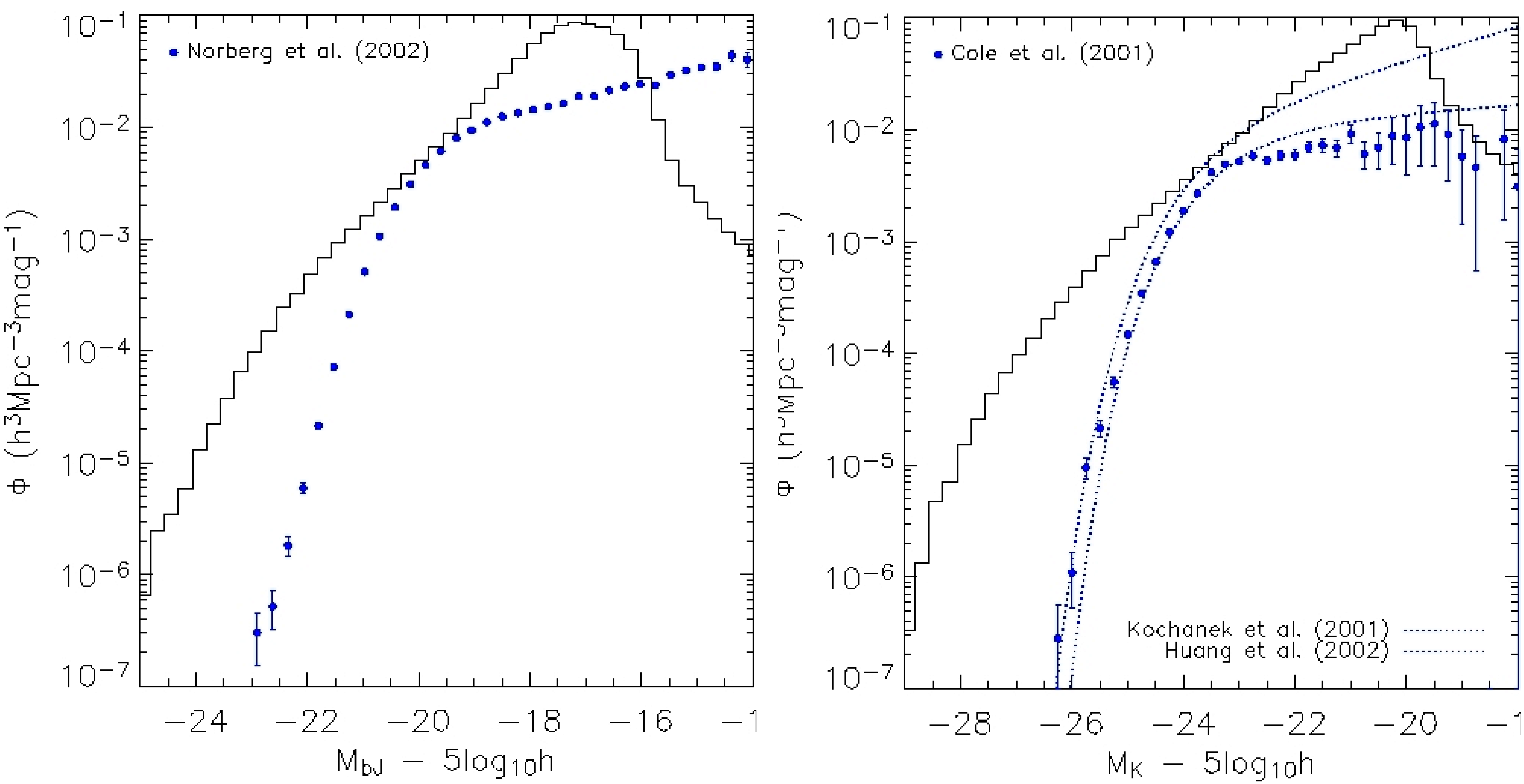
Effect of feedback on the Luminosity Function



Full model with reionisation, AGN and SN feedback

Croton et al 2006

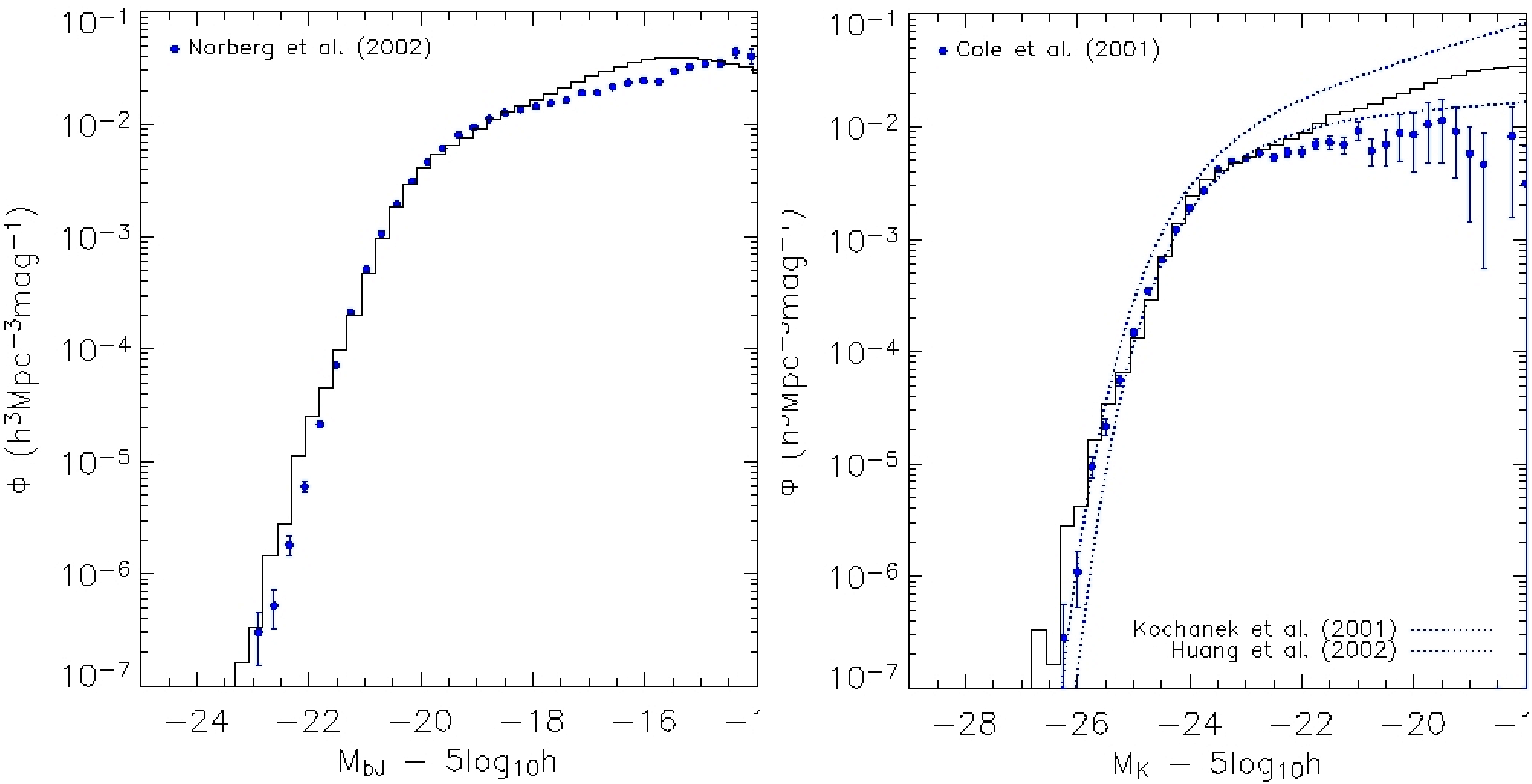
Effect of feedback on the Luminosity Function



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

Croton et al 2006

Effect of feedback on the Luminosity Function



Full model with reionisation, AGN and SN feedback Croton et al 2006

GERMAN ASTROPHYSICAL GAVO VIRTUAL OBSERVATORY

Exploring the milli-Millennium simulation with a relational database

http://www.g-vo.org/mpasims

Documentation


```
select D.I_HALO,
       D.SNAPNUM,
       D.N_P as D_NP,
       P1.N_P as P1_NP,
       P2.N_P as P2_NP
  from HALO P1,
       HALO P2,
       HALO D
 where P1.SNAPNUM=P2.SNAPNUM
   and P1.I_HALO < P2.I_HALO
   and P1.I_DESCENDANT = D.I_HALO
   and P2.I_DESCENDANT = D.I_HALO
   and P1.N_P >= .2*D.N_P
   and P2.N_P >= .2*D.N_P
   and D.N_P > 1000
```

Execute Query

Clear all

Help

Maximum number of rows to return to the query form: 10

Previous queries :

Halo 1 | Galaxy 1 — Find halos/galaxies at a given redshift (SNAPNUM) within a certain part of the simulation volume (X,Y,Z).

Halo 2 — Find the whole progenitor tree, in depth-first order, of a halo identified by its id (I_HALO)

Halo 3 — Find the progenitors at a given redshift (SNAPNUM) of all halos of mass (N_P) greater than 4000 at a later redshift (SNAPNUM). The progenitors are limited to have mass >= 100.

Halo 4 — Find all the halos of mass (N_P) >= 1000 that have just had a major merger, defined by having at least two progenitors of mass >= 0.2*descendant mass.

Halo 5 | Galaxy 5 — Find the mass/luminosity function of halos/galaxies at z=0 using logarithmic intervals.

Galaxy 6 — Find the Tully-Fisher relation, Mag_b/v/i/k vs V_vir for galaxies with bulge/total mass ratio < 0.1. Subsample by about 1% (RANDOM between 20000 and 30000).

Reformat CSV

Plot (VOPlot) — This button wil attempt to start up VOPlot within an applet, so that the current result can be explored graphically. This clearly requires that the browser has been configured for viewing applets.
DISCLAIMER This functionality has been partially tested only. Any problems are our responsibility, not VOPlot's.
It seems that the applet does not work properly with Konqueror.

Query time (in millisec) = 15623
Number of rows retrieved from database = 12 (Maximum # = 10000)

i_halo	snapnum	d_np	p1_np	p2_np
2576	60	1079	924	222