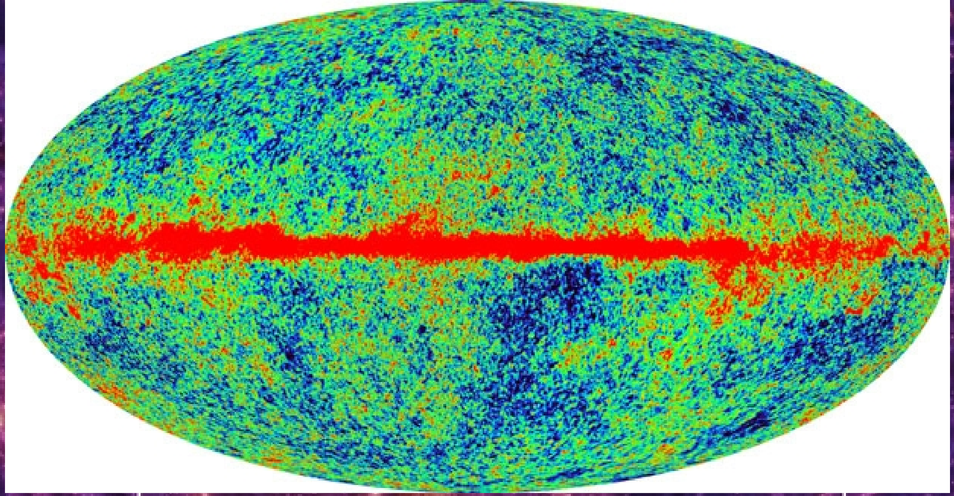
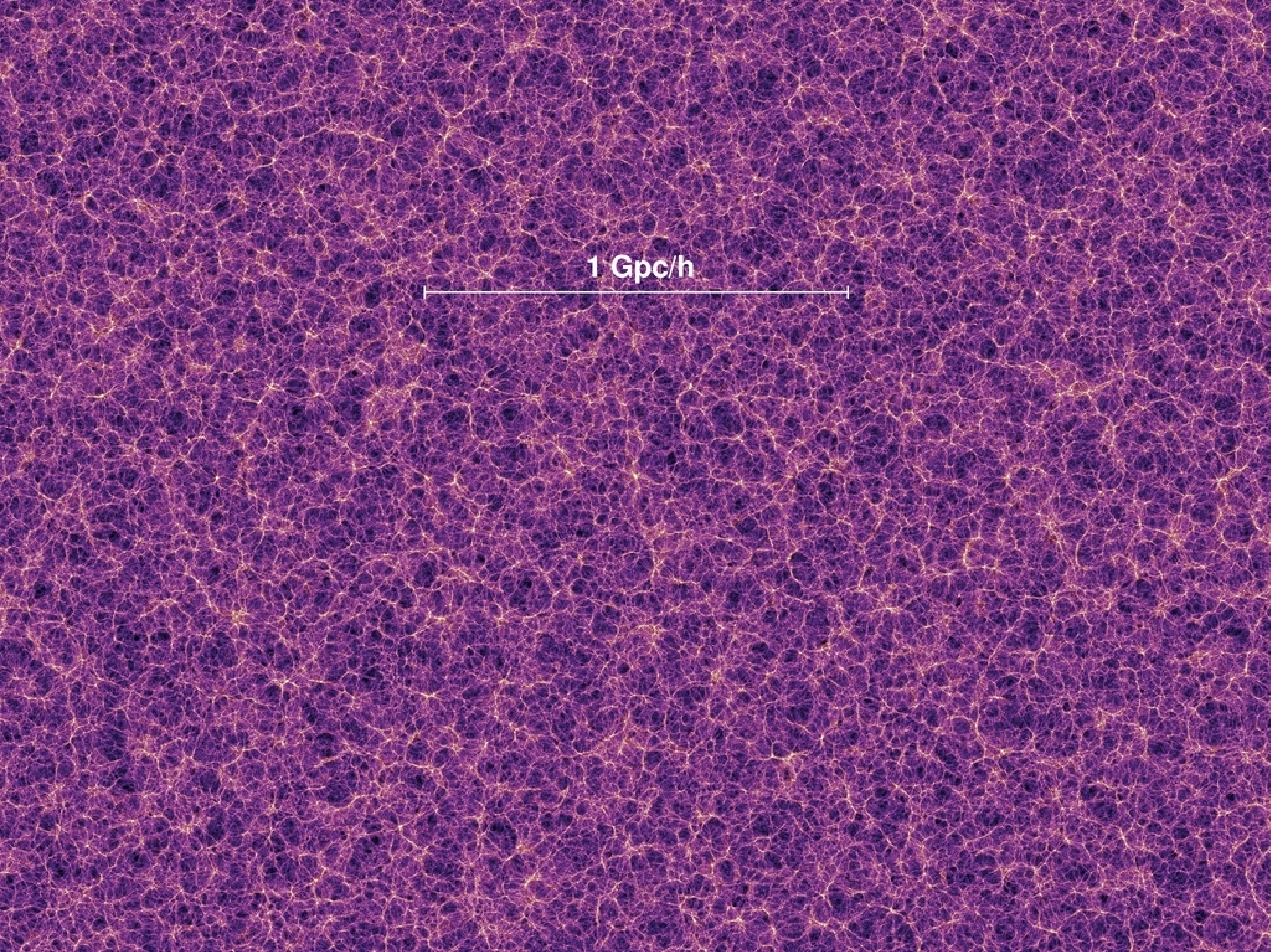
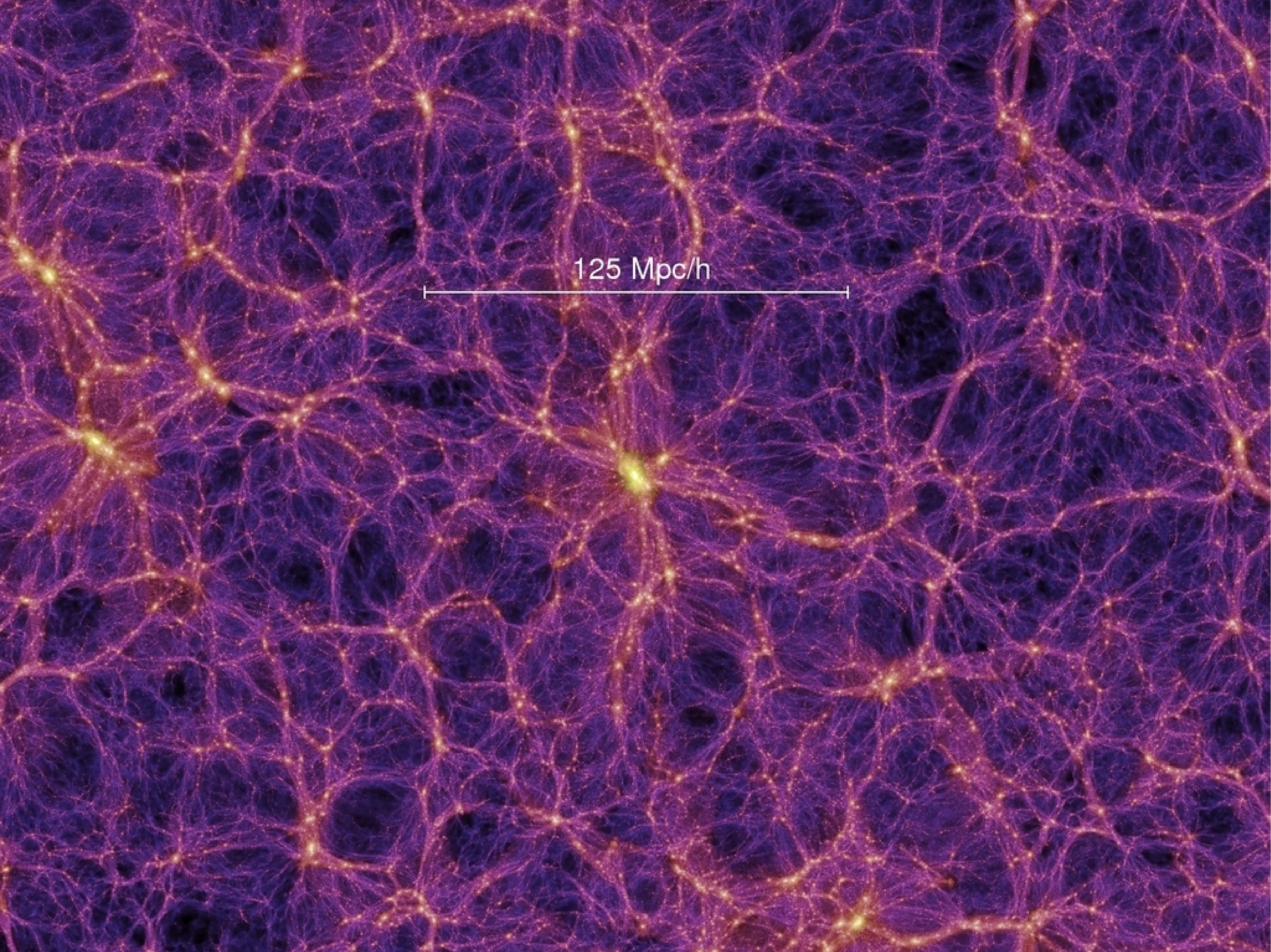


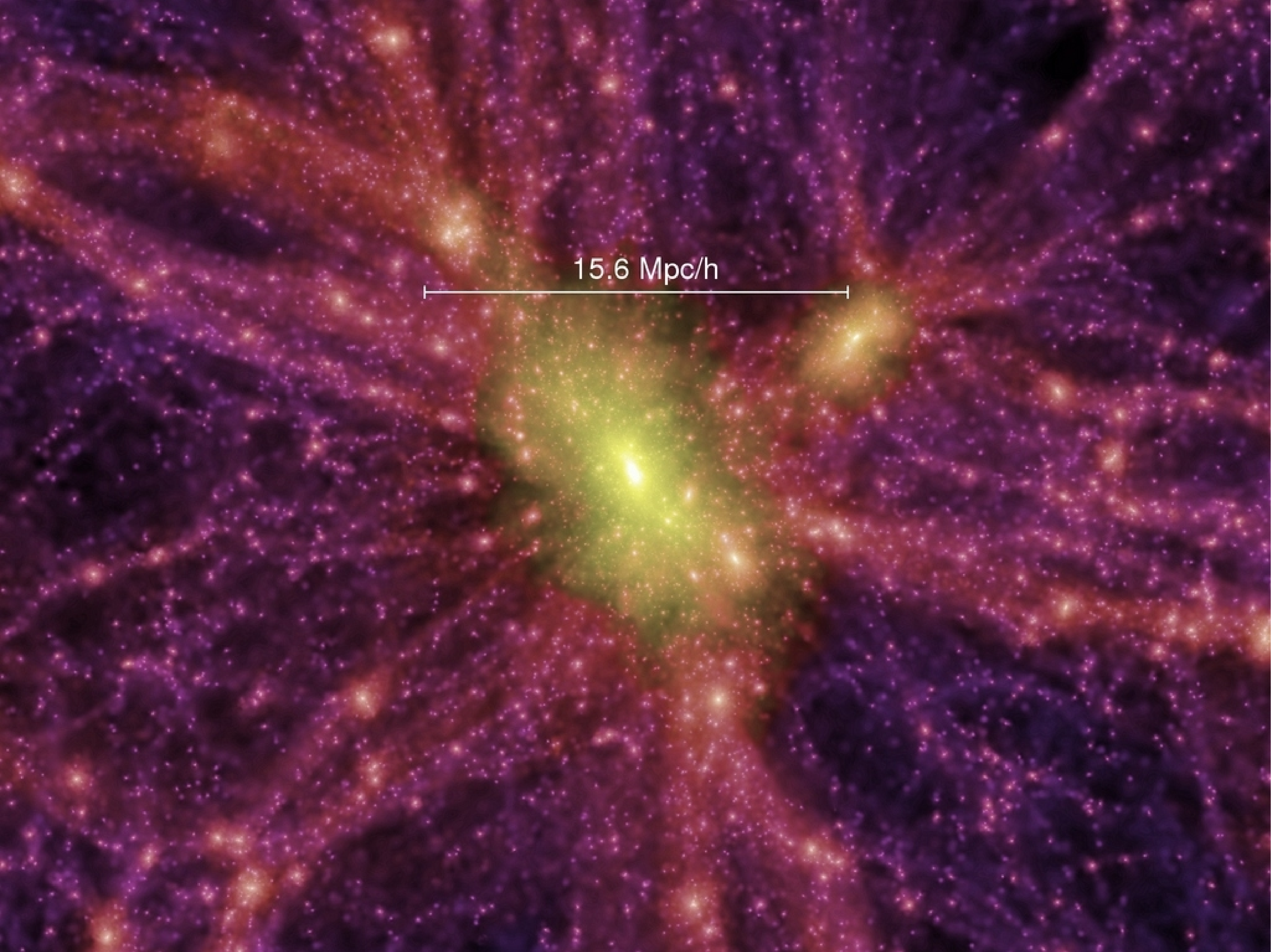
Heating and Cooling in Galaxies and Clusters
Garching
August 2006

Feedback and Galaxy Formation

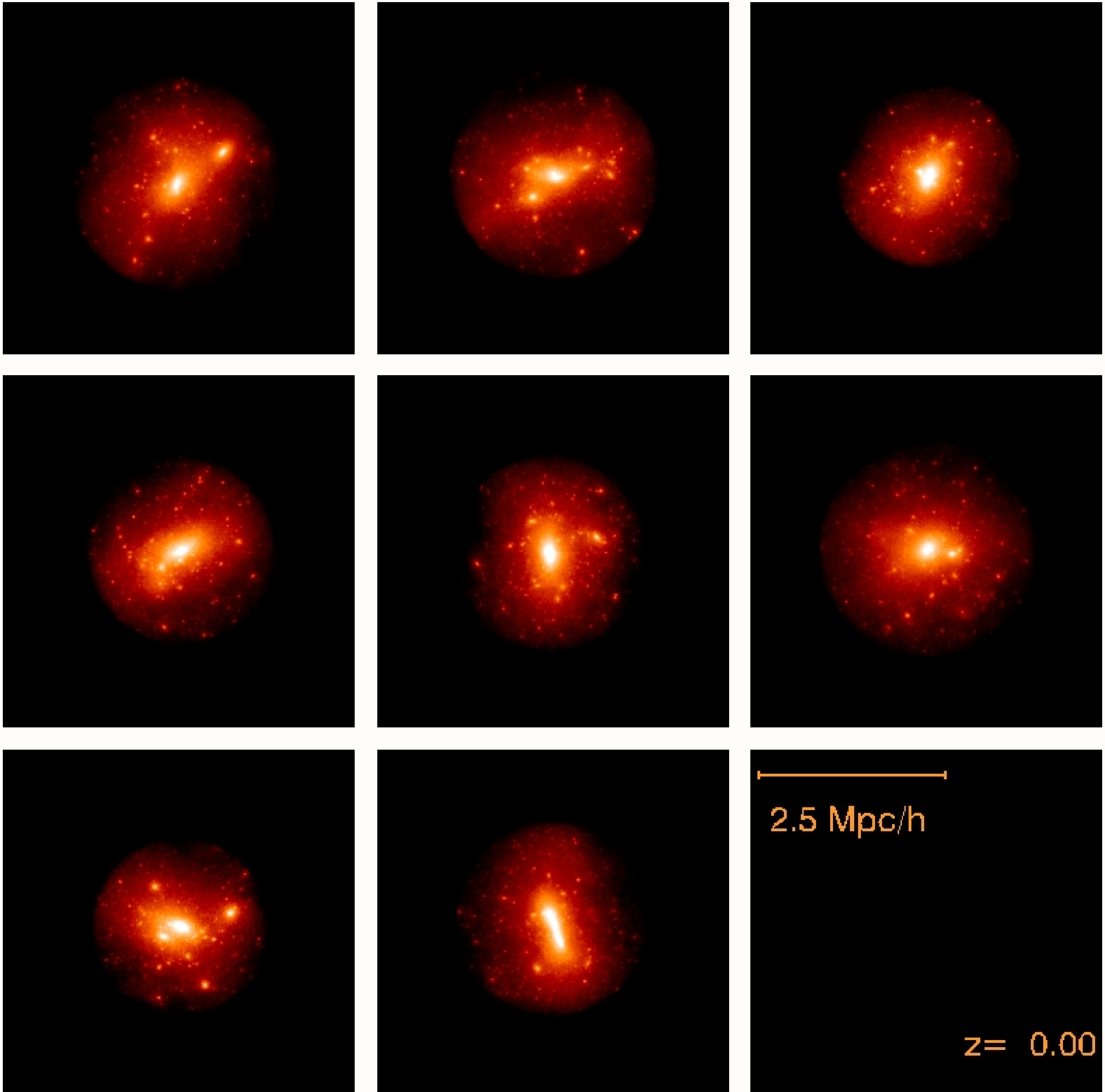
Simon White
Max Planck Institute for Astrophysics


1 Gpc/h


125 Mpc/h


15.6 Mpc/h

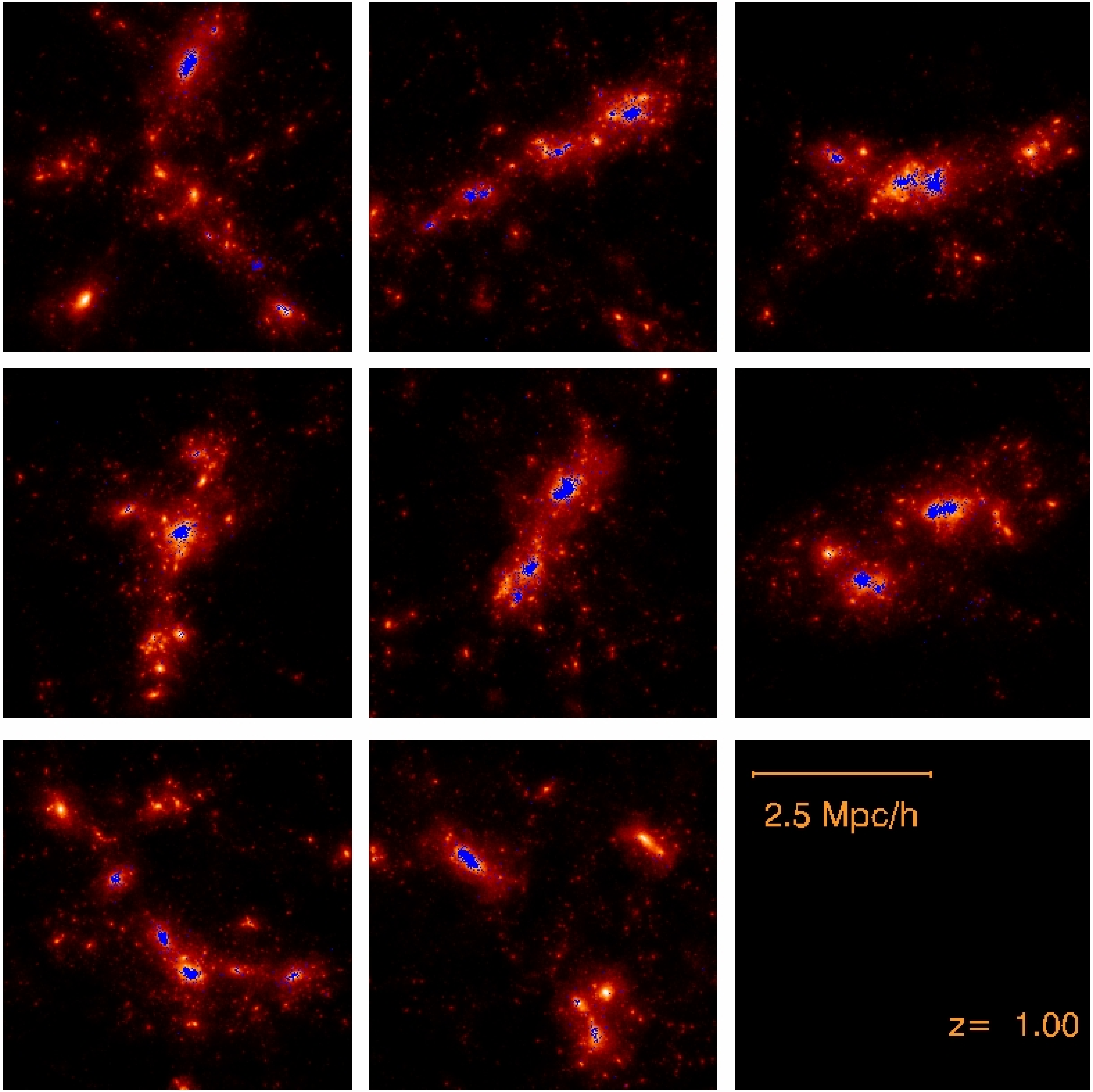

3.9 Mpc/h



Cluster assembly in ΛCDM

Gao et al 2004

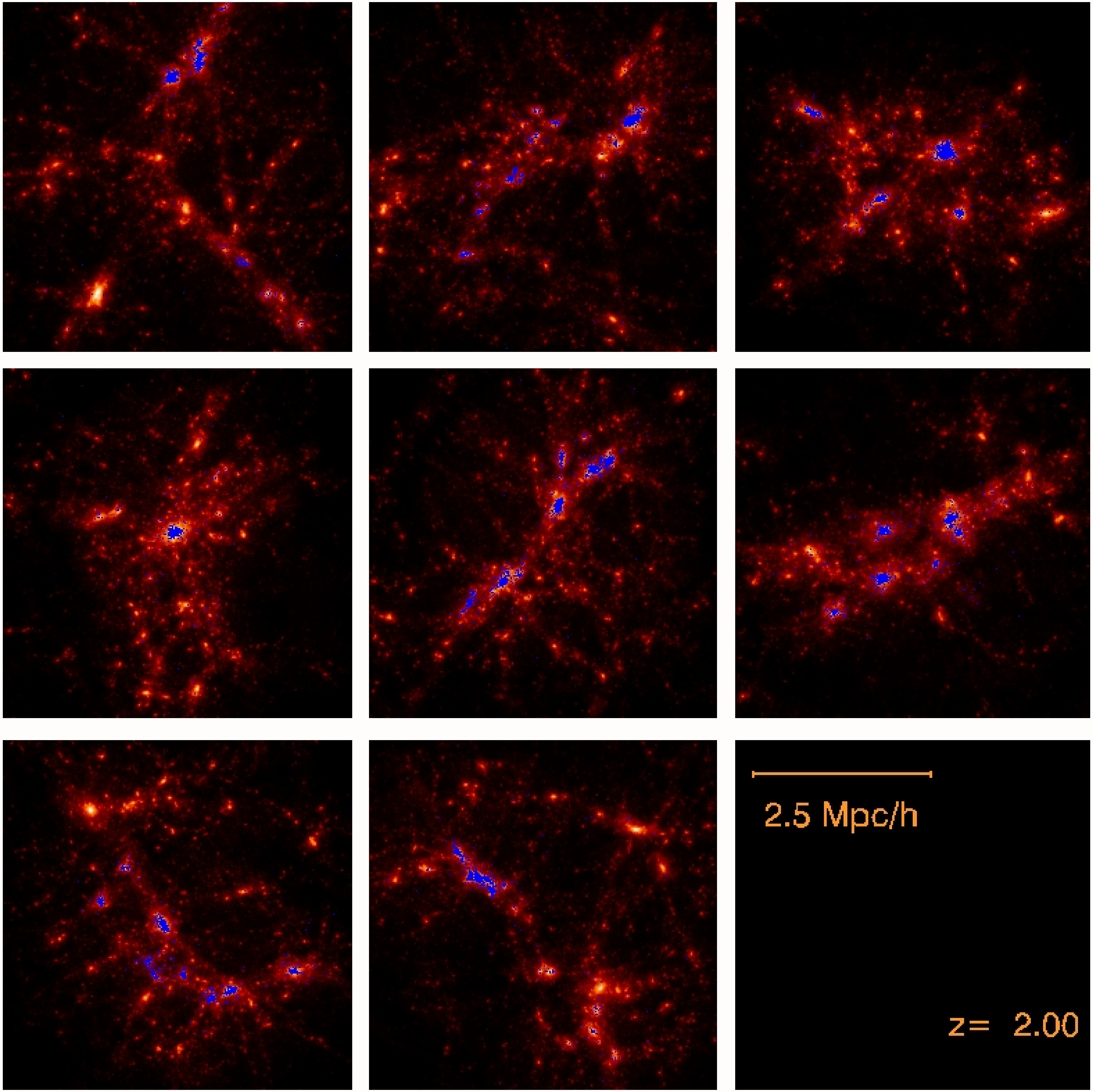
- 'Concordance' cosmology
- Final cluster mass ~10^{15} $M_\odot$
- Only DM within R_{200} at $z = 0$ is shown



Cluster assembly in ΛCDM

Gao et al 2004

- 'Concordance' cosmology
- Final cluster mass $\sim 10^{15} M_\odot$
- Only DM within R_{200} at $z = 0$ is shown
- DM within 20 kpc at $z = 0$ is shown blue



Cluster assembly in ΛCDM

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- Final cluster mass ~10^{15} $M_\odot$
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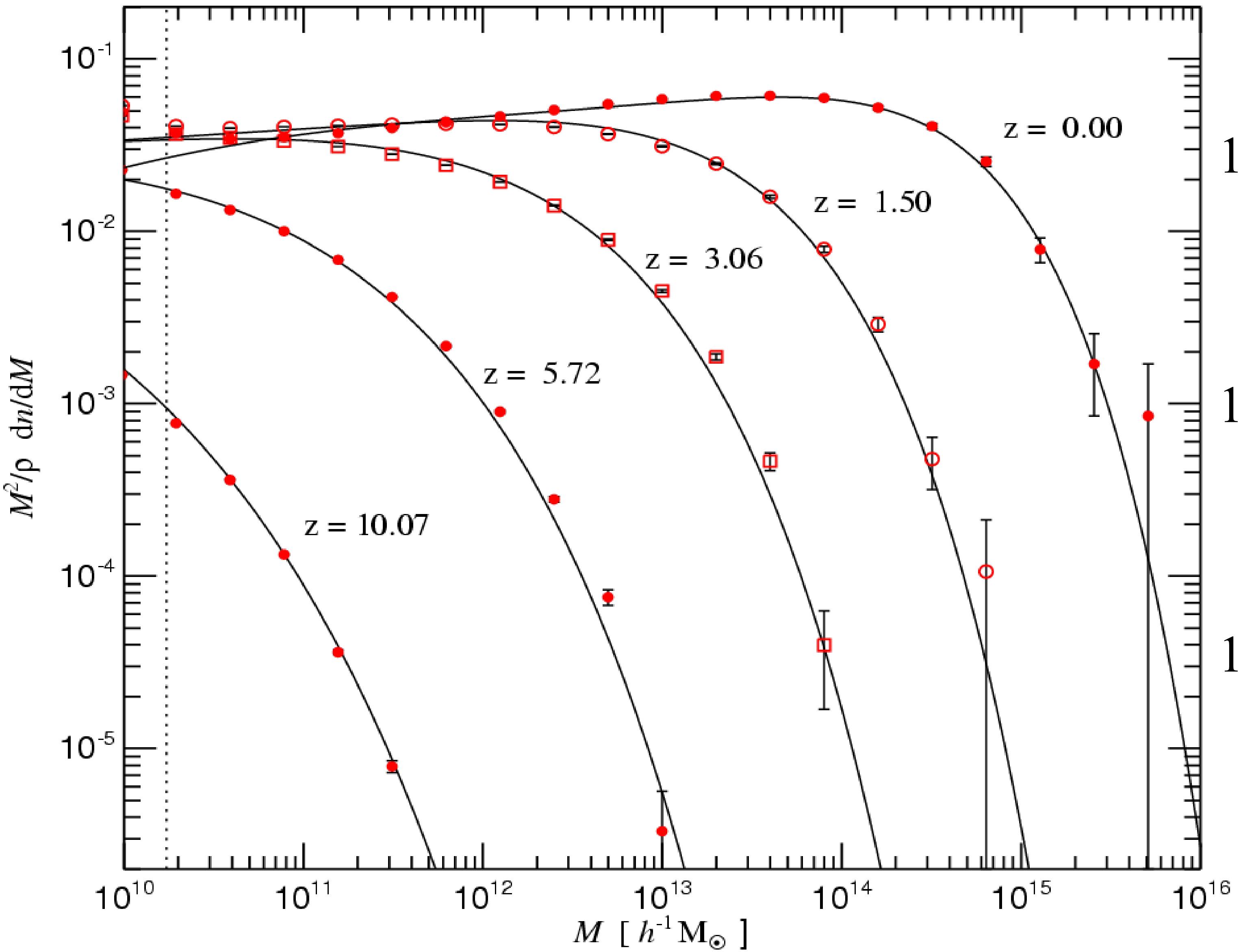
Halo Mass Functions in the MS

Springel et al 2005, Mo & White 2002



At z = 0

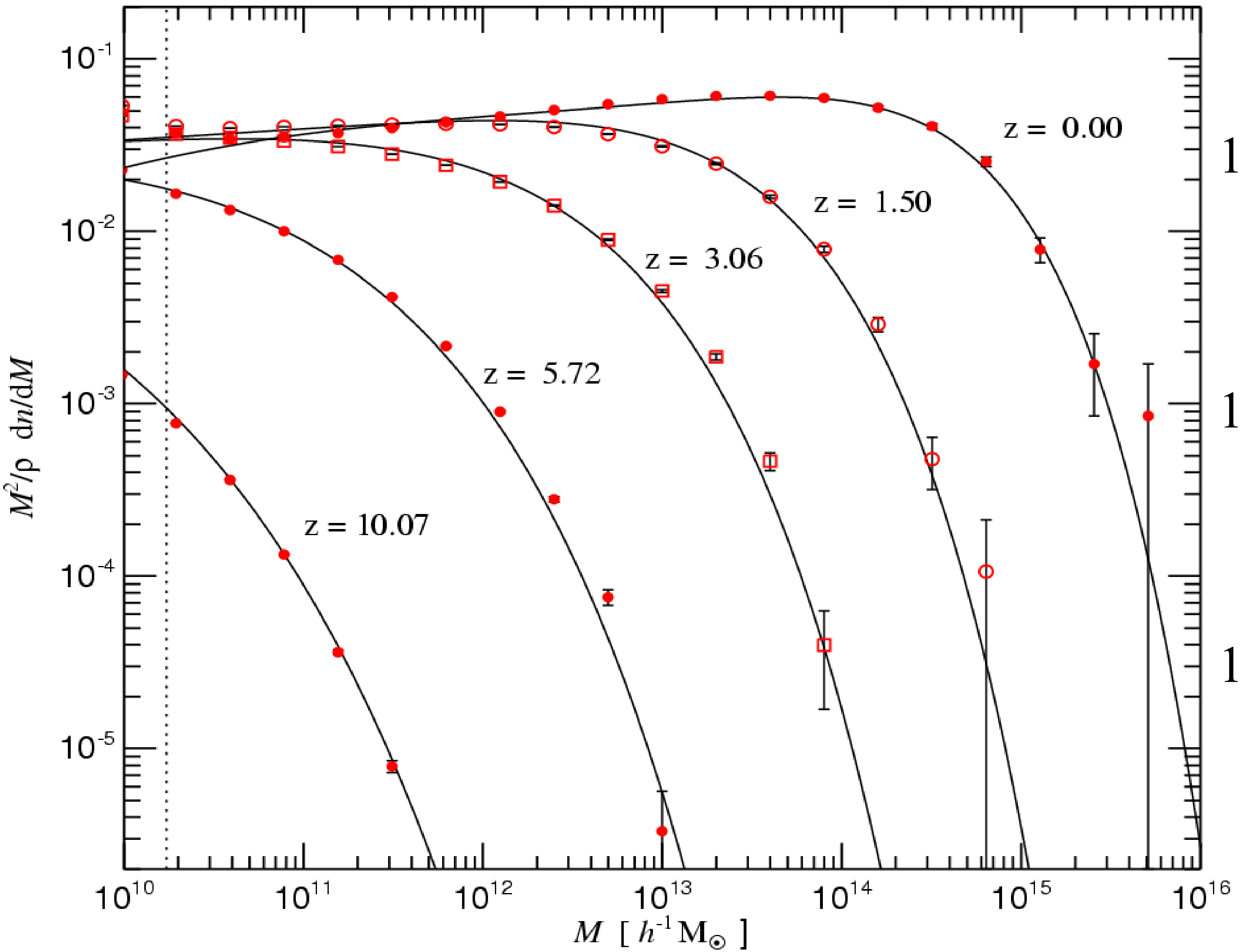
1/2 of DM in halos
$M > 2 \times 10^{10} M_\odot$
T > 30,000 K

10% in halos
$M > 10^{14} M_\odot$
T > 1 keV

1% in halos
$M > 10^{15} M_\odot$
T > 5 keV

Halo Mass Functions in the MS

Springel et al 2005, Mo & White 2002



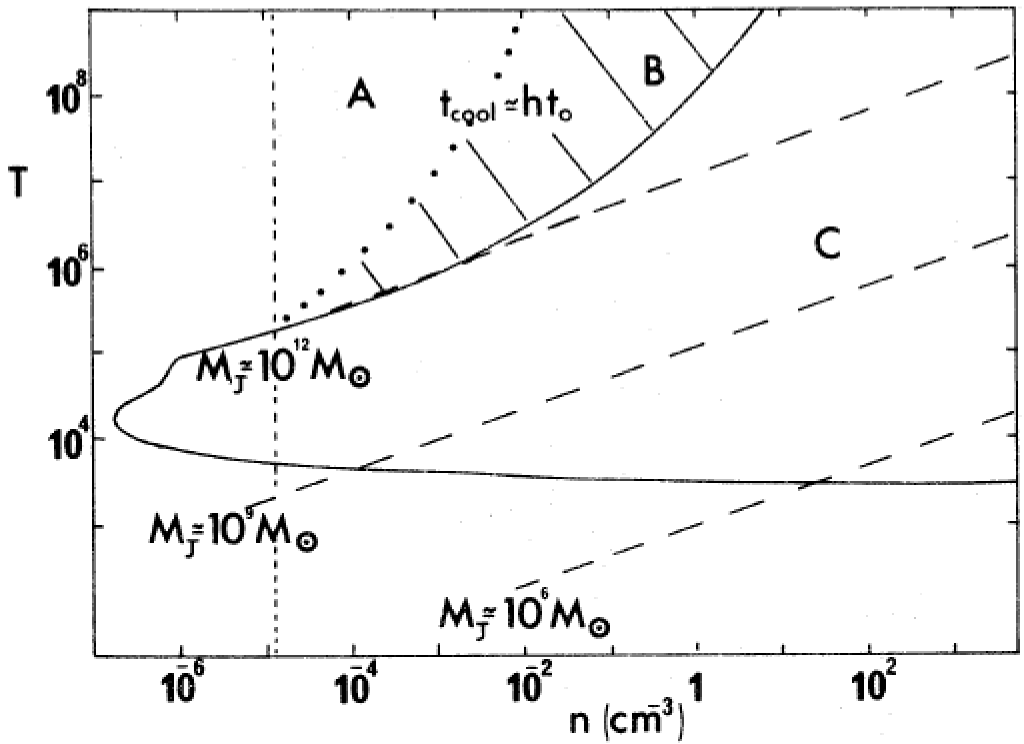
At z = 1.5

1/2 of DM in halos
$M > 10^7 M_\odot$
$T > 700$ K

10% in halos
$M > 10^{13} M_\odot$
$T > 0.4$ keV

1% in halos
$M > 10^{14} M_\odot$
$T > 2$ keV

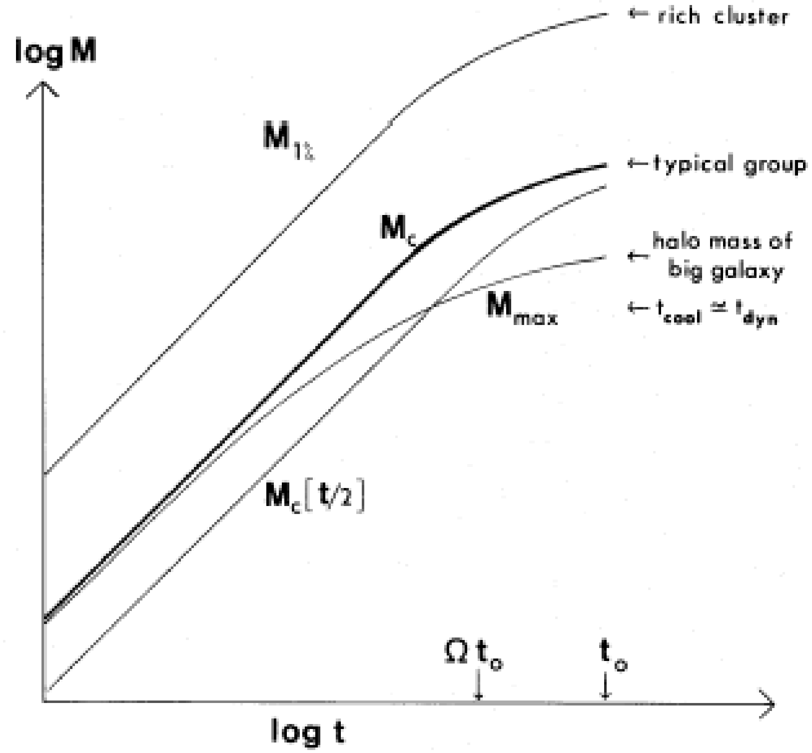
Radiative processes in galaxy formation



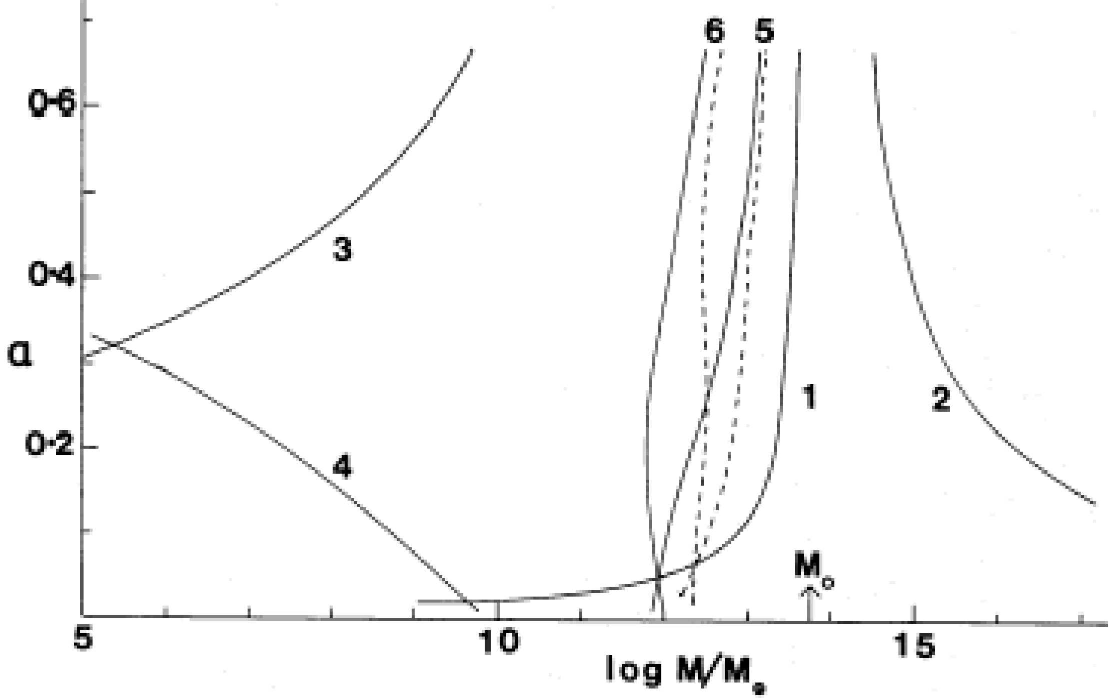
Rees & Ostriker 1977
Silk 1977
Binney 1977

- 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 (ii) since fragmentation is possible
- Primordial cooling curve → characteristic mass $10^{12} M_\odot$

Towards a "modern" theory



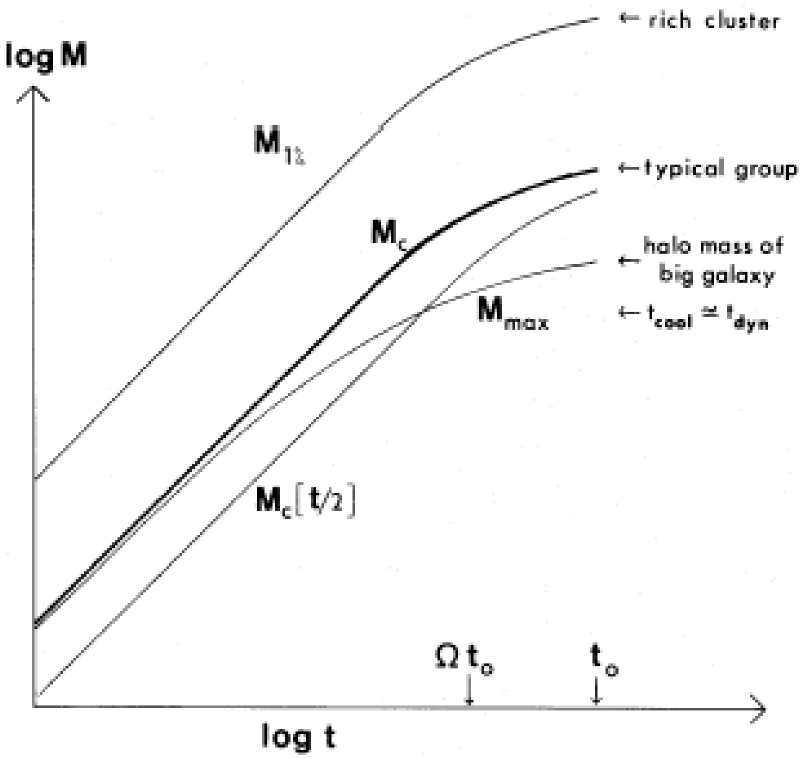
White & Rees 1978



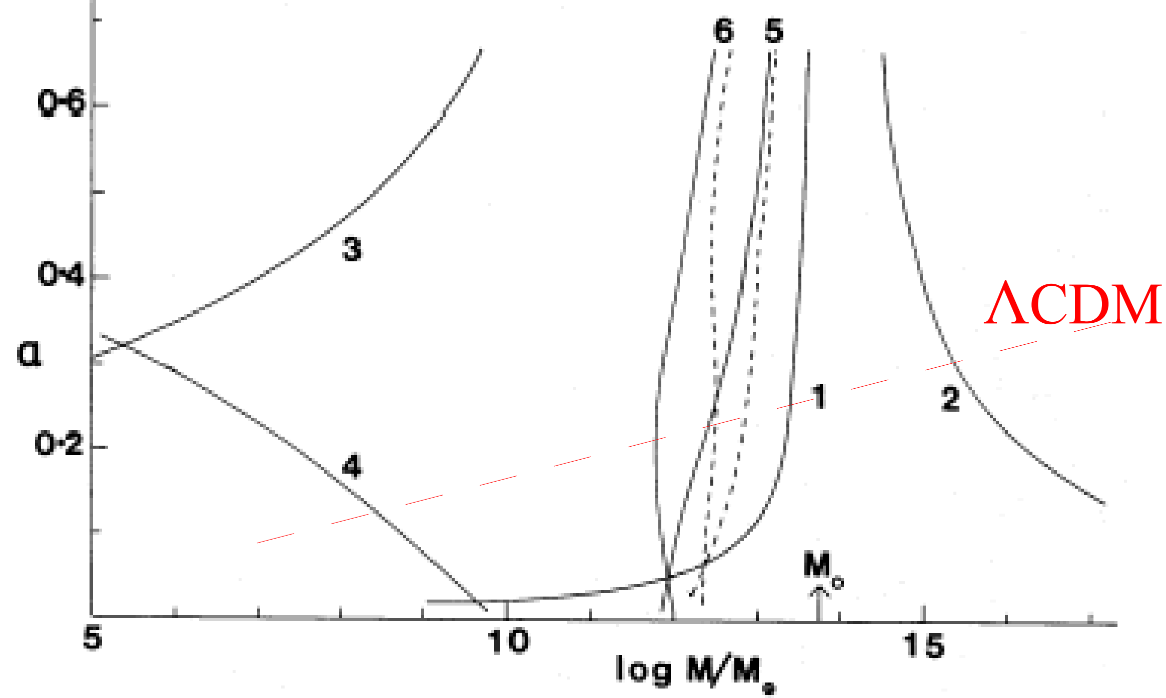
- Adding : (i) dark matter, (ii) hierarchical clustering, (iii) feedback
  - -- cooling always rapid for small masses and early times
  - -- only biggest galaxies sit in cooling flows
  - -- feedback *à la* Larson (1974) needed to suppress small galaxies

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

Towards a “modern” theory



White & Rees 1978



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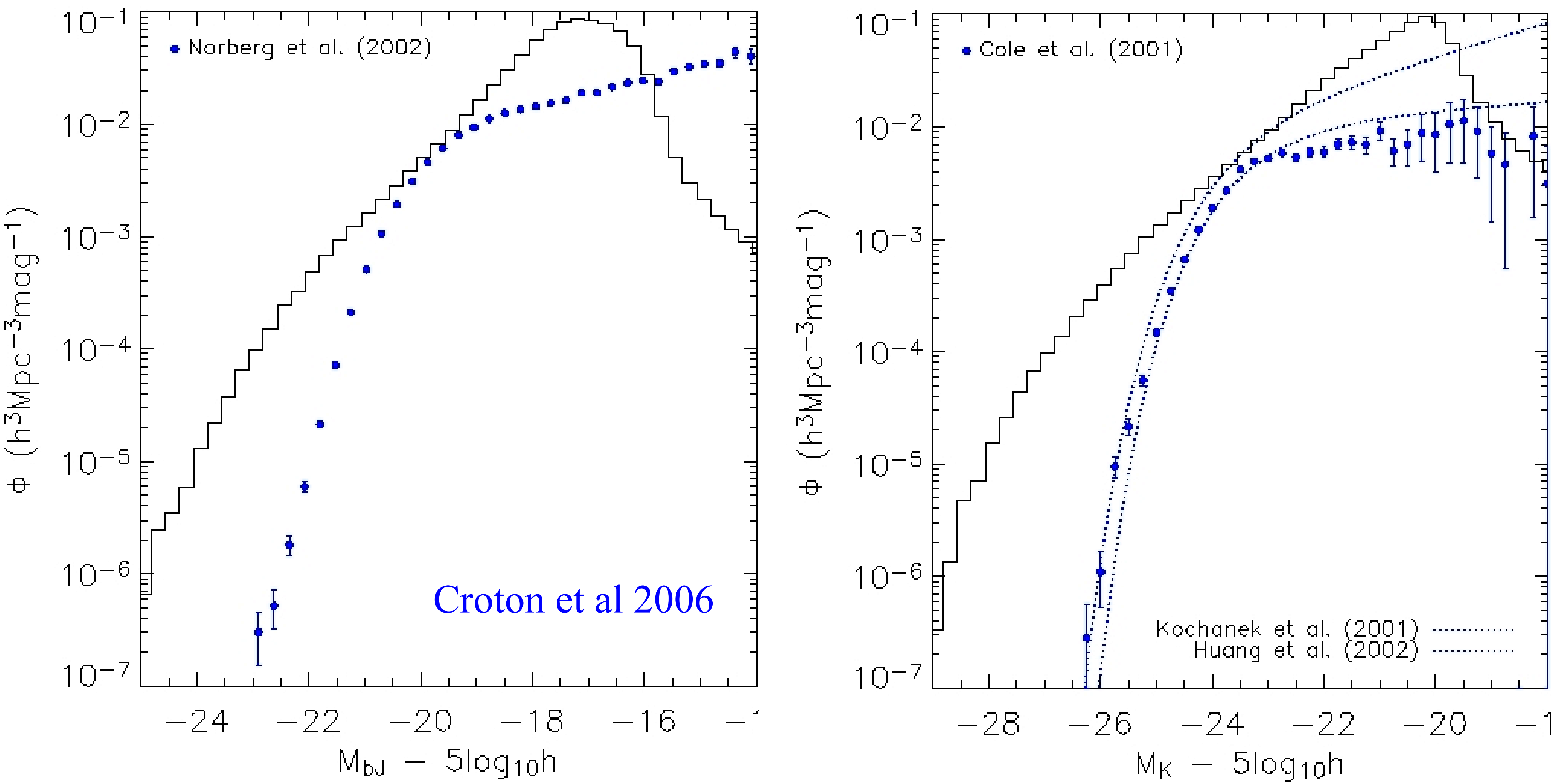
Luminosity Function in a ΛCDM model w/o Feedback



Concordance model with cooling and star formation but no feedback

--- too many stars --- wrong shape --- cD's too massive

Types of Feedback

- Radiative Feedback
  - -- UV/X-rays from young stars, AGN, Population III ?
    - -- dissociate H_2 in early structures?
    - -- heat and reionise the IGM
    - -- suppress dwarf galaxy formation?
- Hydrodynamic Energy Input
  - -- flows driven by SN, stellar winds, AGN?
    - -- regulate star formation in galaxies
    - -- drive galactic fountains, winds?
    - -- suppress cooling flows in galaxy clusters
- Material Feedback
  - -- injection of metals/ISM/relativistic plasma into IGM
    - -- enriches the IGM?
    - -- creates bubbles in IGM → gaps in the Ly α forest?

Feedback Epochs

- Pre-reionisation
  -- H_2 destruction by Pop III truncates early formation?
- Reionisation
  -- UV radiation from first galaxies and AGN creates overlapping HII regions, ionising and heating the IGM
  -- UV/X-rays heat HI causing 21cm emission
- Galaxy formation
  -- feedback controls efficiency of star formation in protogalaxies
  -- winds enrich the IGM
  -- AGN ionise HeII
- Low redshift Universe
  -- radio source input to cluster atmospheres
  -- suppression of star formation in massive galaxies?

Feedback Effects on Galaxy Formation

- Reionisation/radiative feedback

  radiative heating produces large effective Jeans mass and suppresses gas fraction in halos with less than the *filter* mass

  $f(M, z) = f_0 / (1 + 0.26\, M_F(z) / M)^3$ Gnedin 2000; Kravtsov et al 2004

- Supernova feedback

  Reheats ISM $\Delta M_{reheat} = \varepsilon_{reheat}\, \Delta M_*$ Martin 1999

  Heats halo gas $\Delta E_{halo} = \varepsilon_{halo}\, \tfrac{1}{2}\, \Delta M_*\, V_{SN}^2$ White & Frenk 1991

  Ejects gas $\Delta M_{eject} = \Delta E_{halo} / \tfrac{1}{2} V_{vir}^2 - \Delta M_{reheat}$ Kauffmann et al 1999

- AGN feedback

  "Radio" mode $\Delta M'_{cool} = \Delta M_{cool} - \eta\, f_{gas}\, M_{BH}\, T_{clus}^3$ Croton 2006

  "Quasar" mode builds up BH masses

  --establishing $M_{bh} - \sigma$ relation Kauffmann & Haehnelt 2000

  --truncating star formation? Hopkins, Hernquist, Di Matteo, Springel et al

Feedback Effects on Galaxy Formation

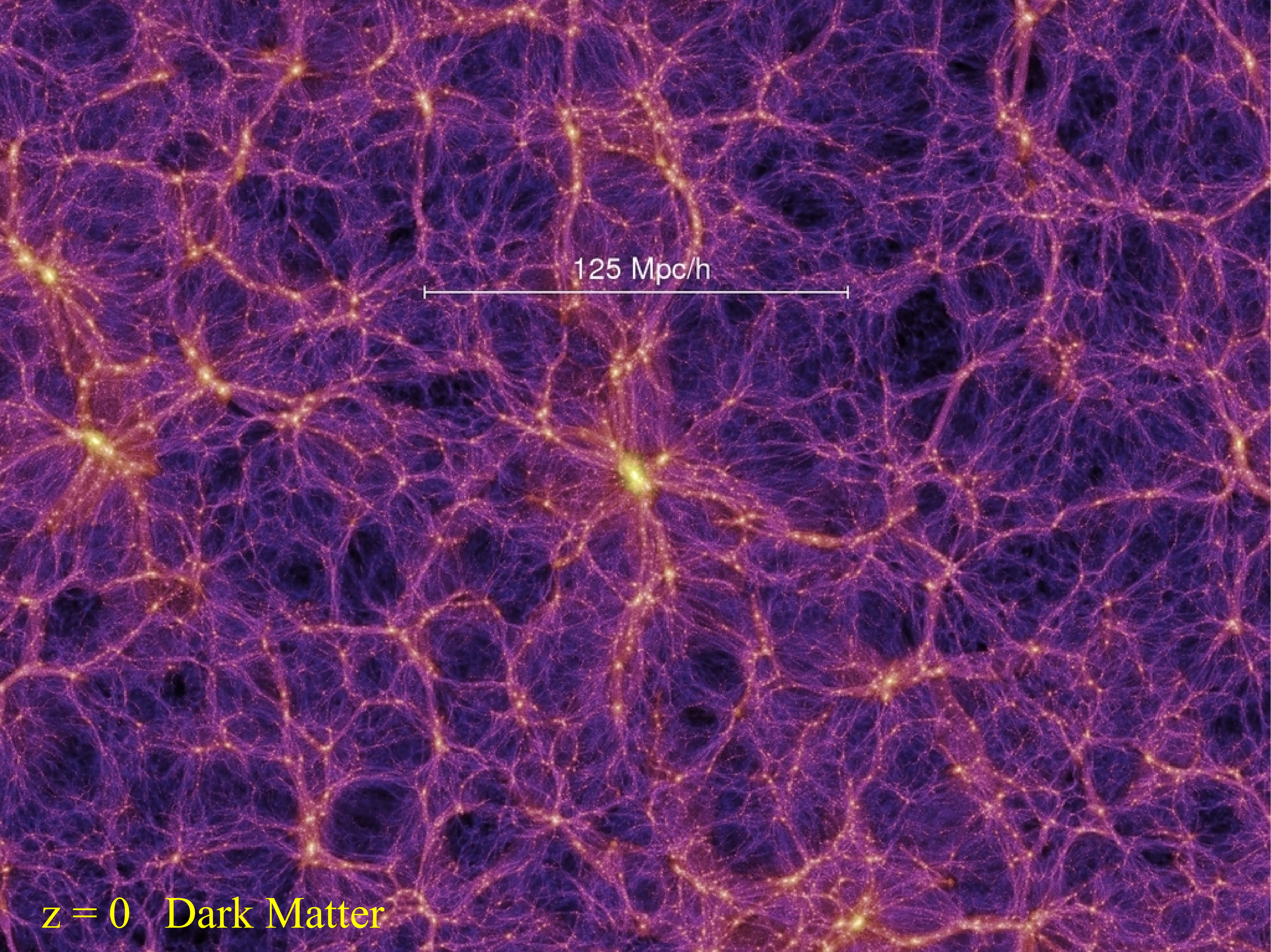
To study the influence of these processes on the properties of the observed galaxy population we need...

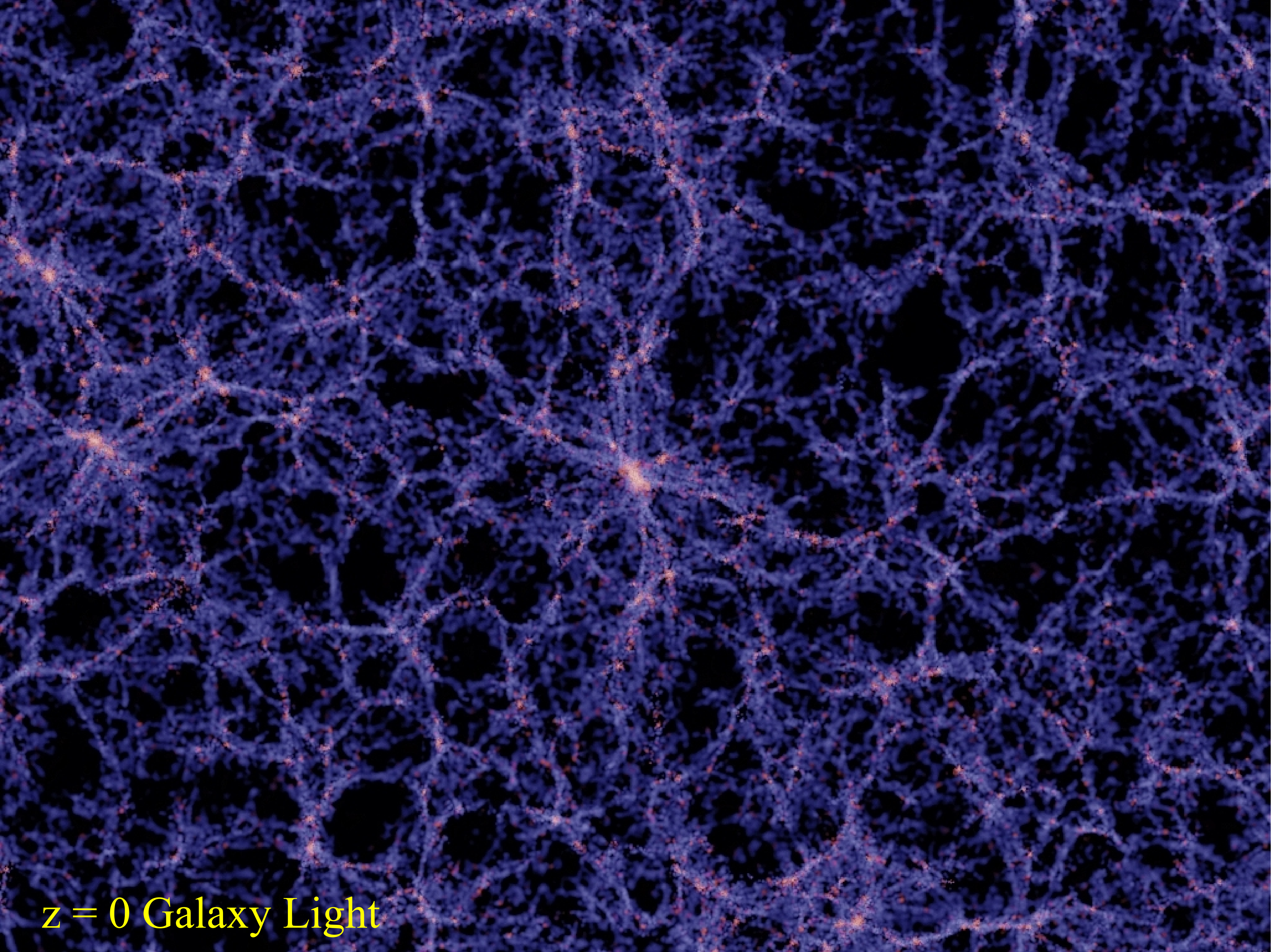
(a) Techniques to include them in cosmological simulations (Kauffmann & Haehnelt 2000; Springel et al 2001, 2005; Croton et al 2006)

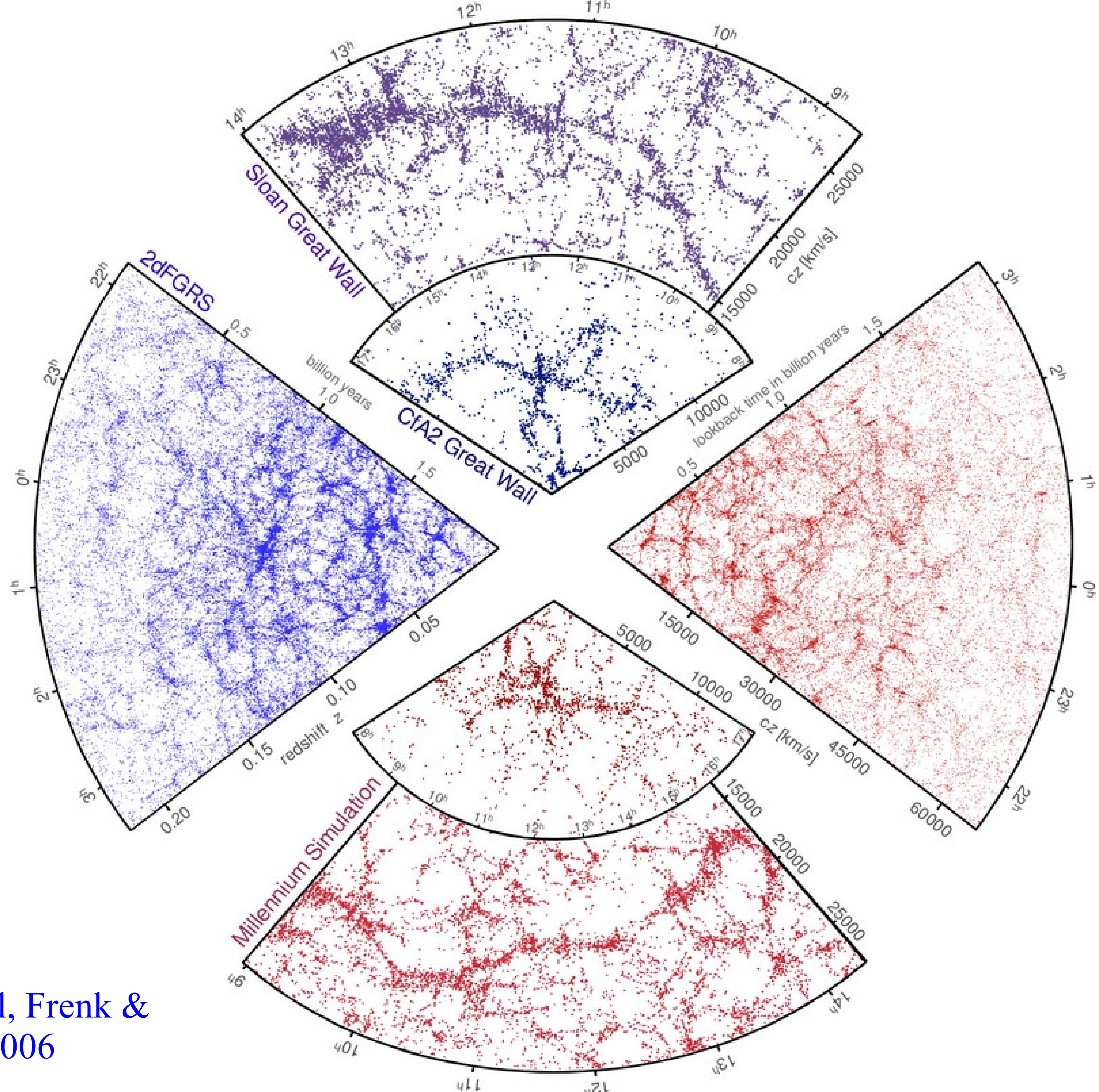
(b) Simulations of high enough resolution to follow the assembly of small galaxies

(c) Simulations of large enough volume to represent bright galaxies, galaxy clusters, quasar hosts...

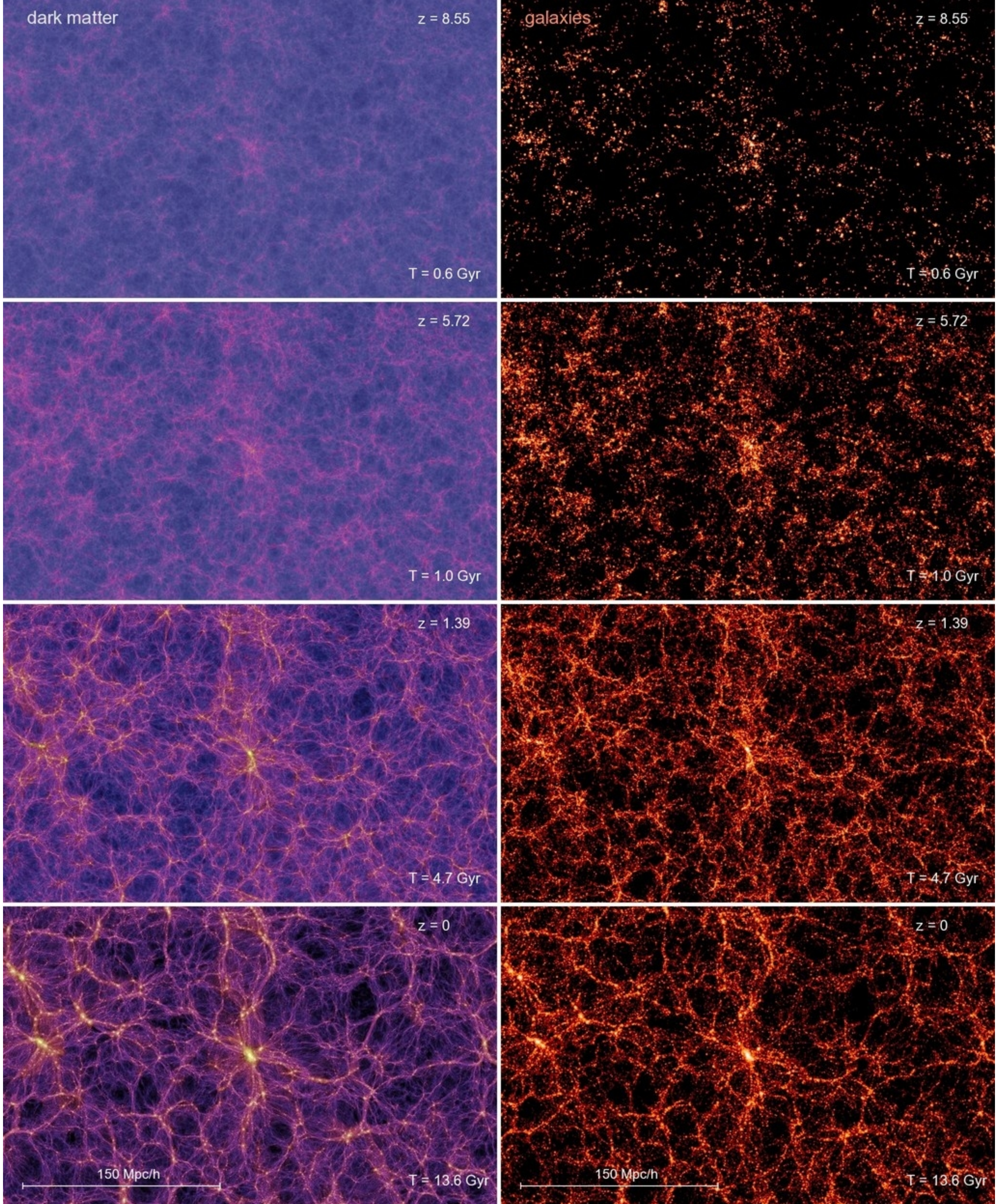
This requires simulations with a LARGE number of particles


125 Mpc/h
z = 0 Dark Matter


z = 0 Galaxy Light



Springel, Frenk &
White 2006



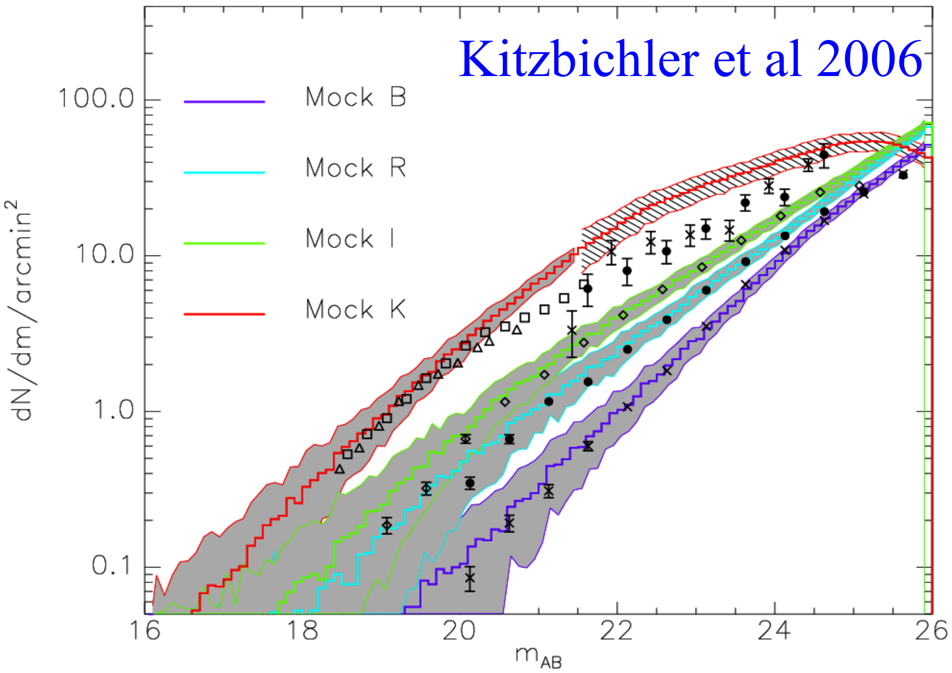
Large-scale structure at high redshift

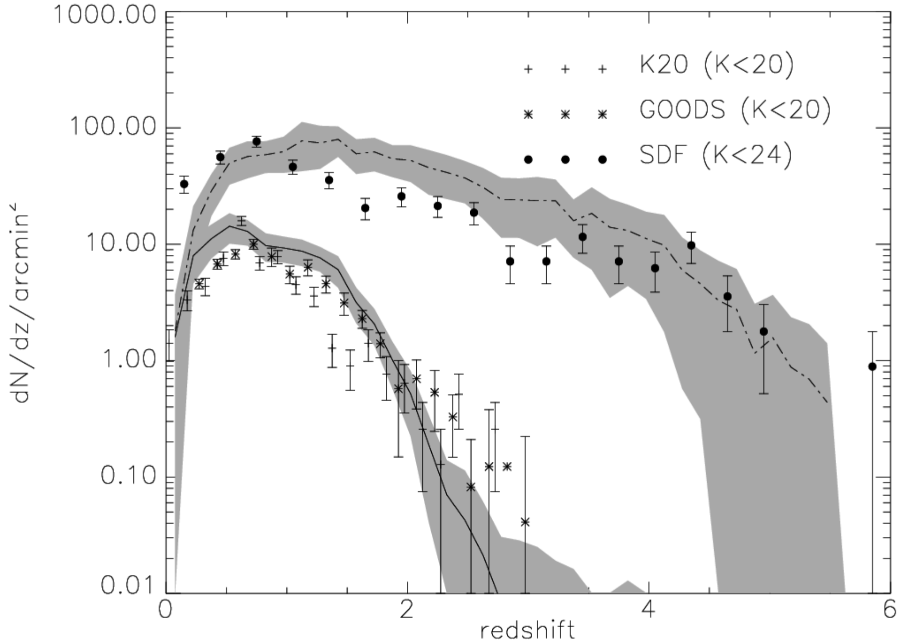
Springel, Frenk & White 2006

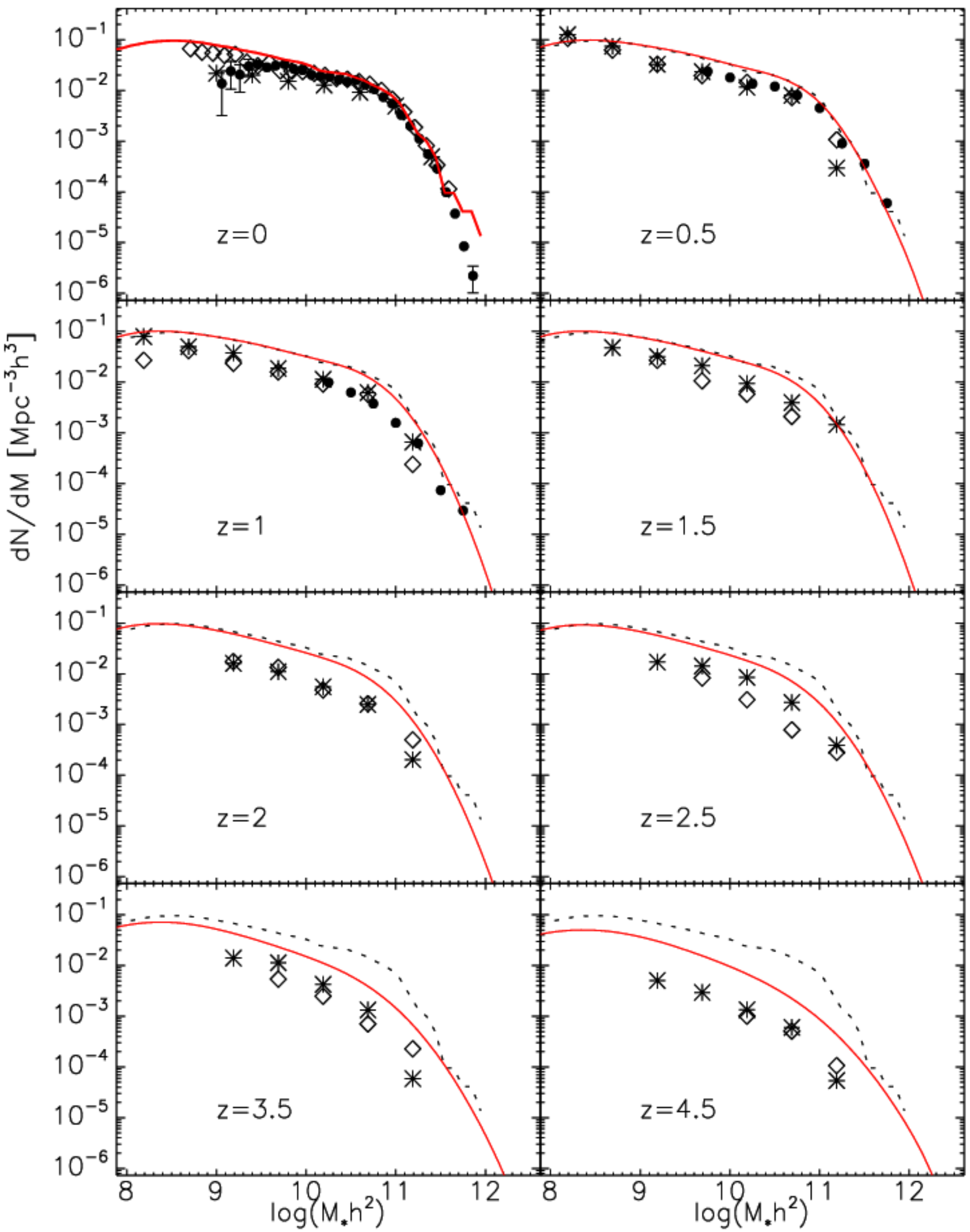
Large-scale structure in the galaxy distribution evolves very little with redshift

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

Model comparison at high redshift

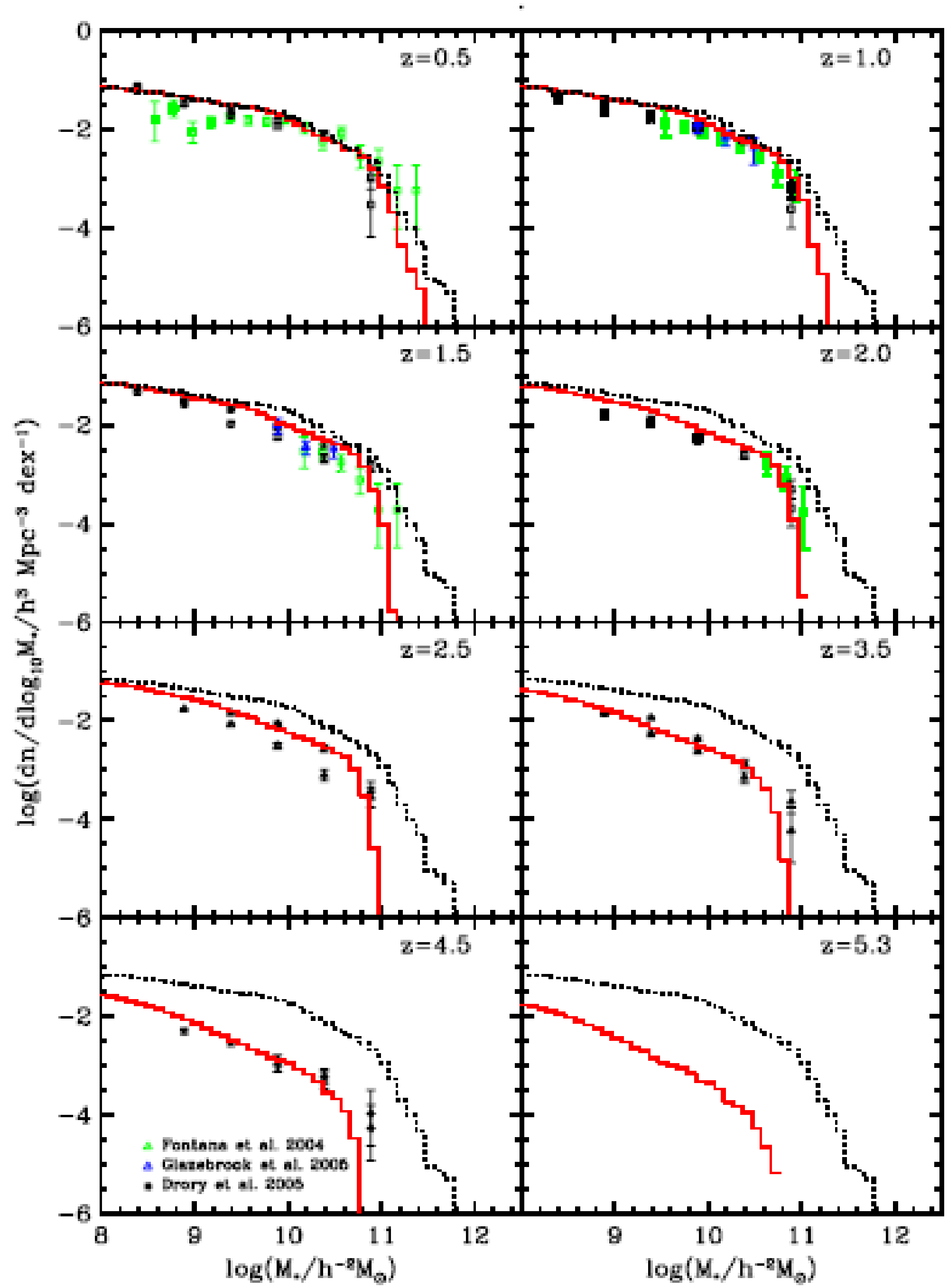






- Too many massive galaxies at high z

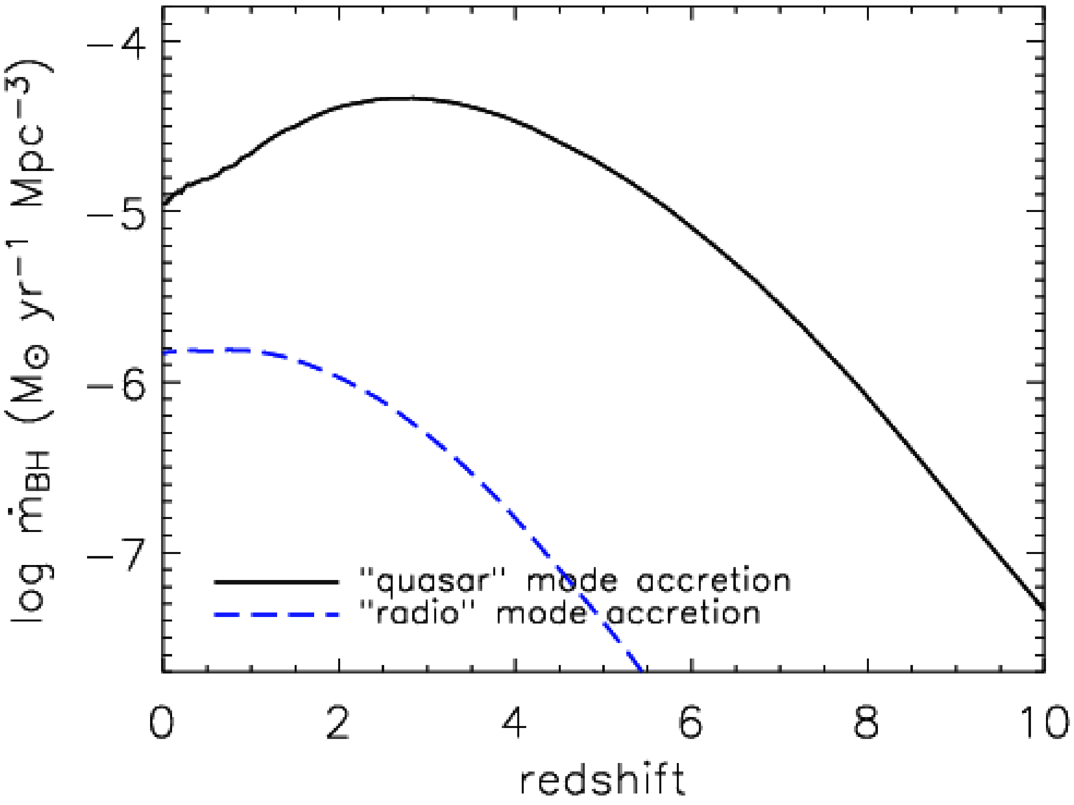
Details in the treatment of AGN growth and feedback can fix the differences at high redshift

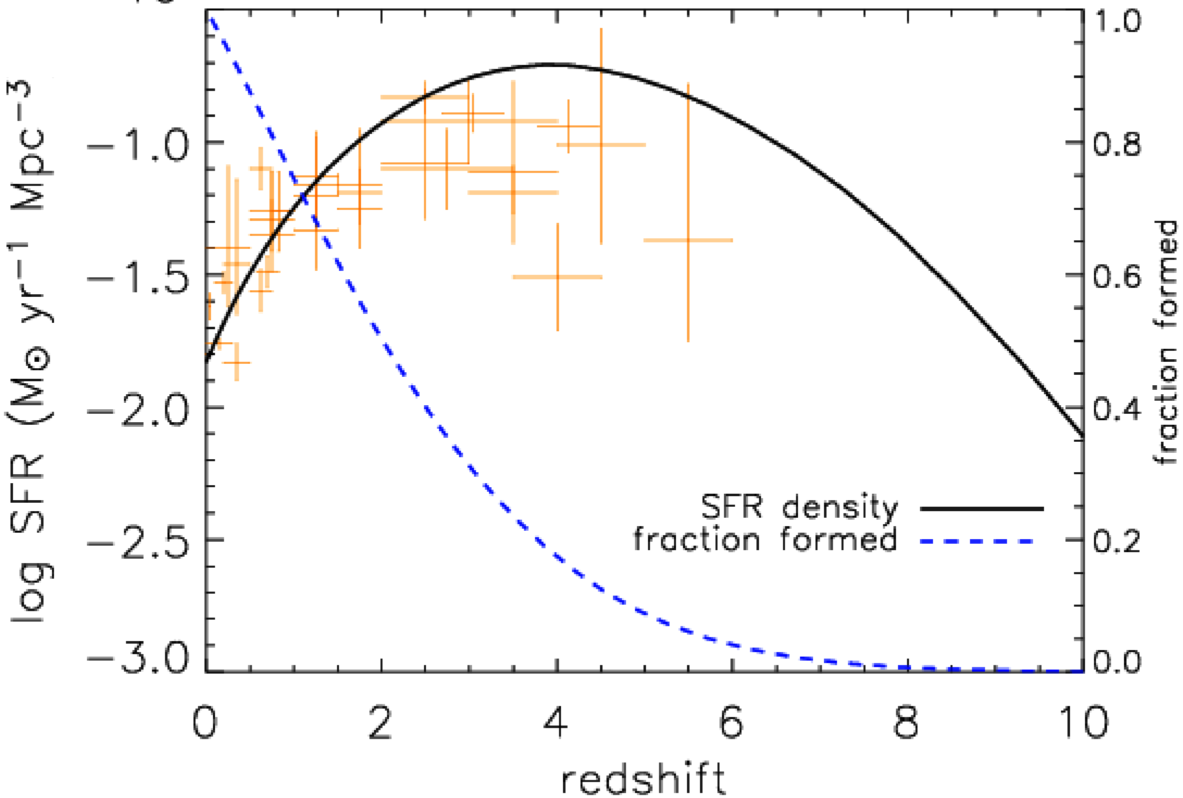


Bower et al 2006

Evolution of feedback sources

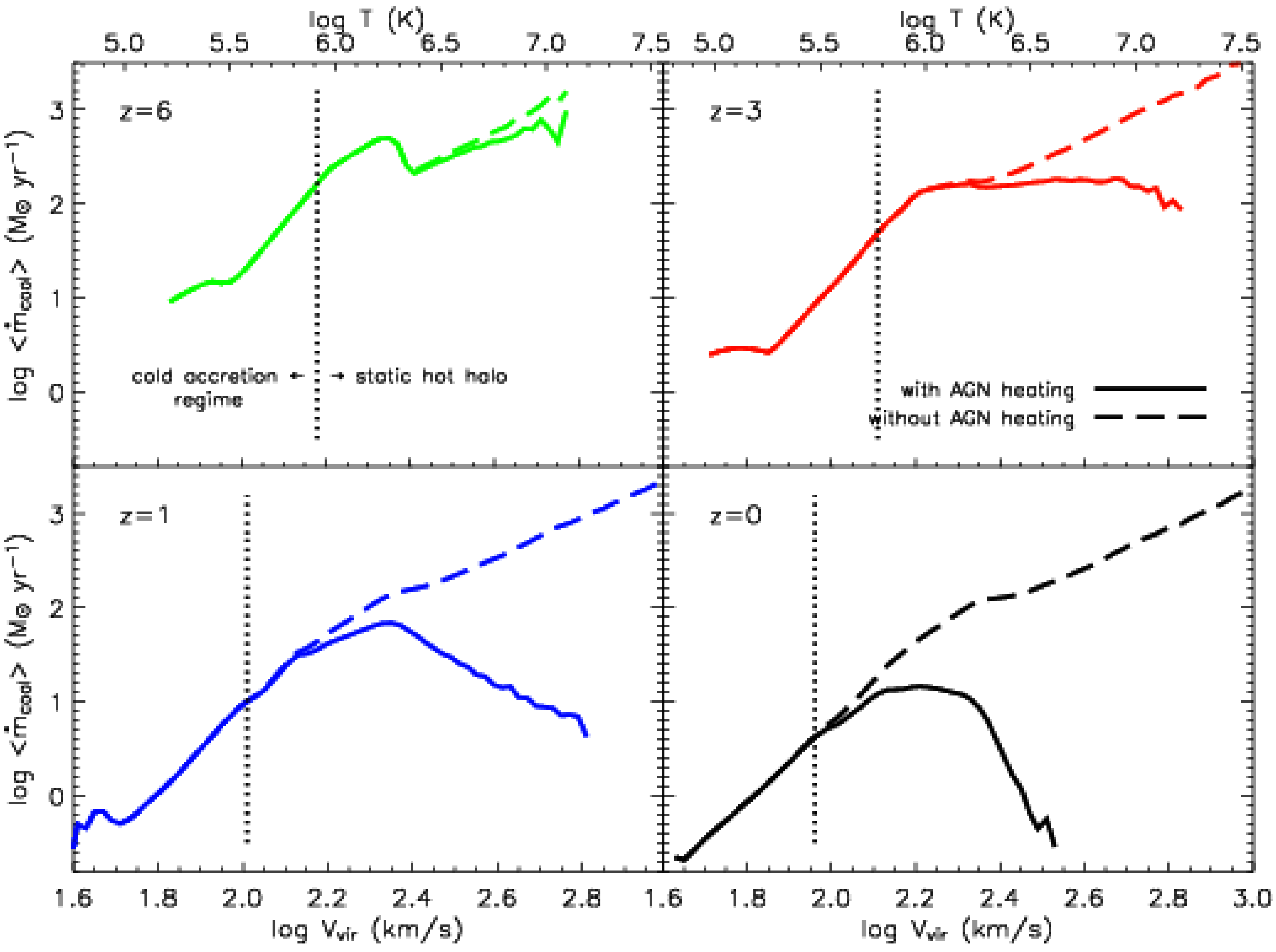
Croton et al 2006



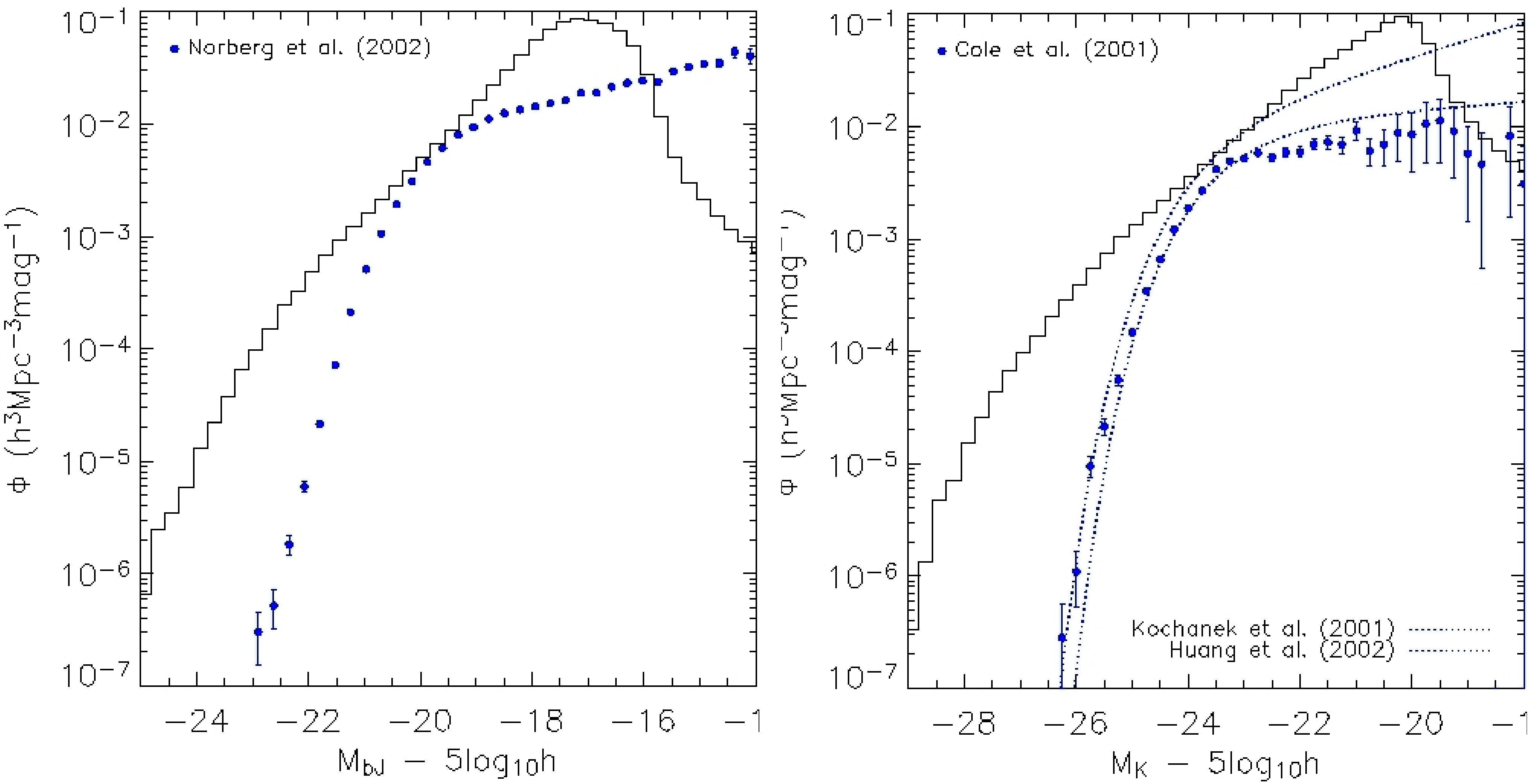


Effects of "radio mode" feedback on cooling rates

Croton et al 2006



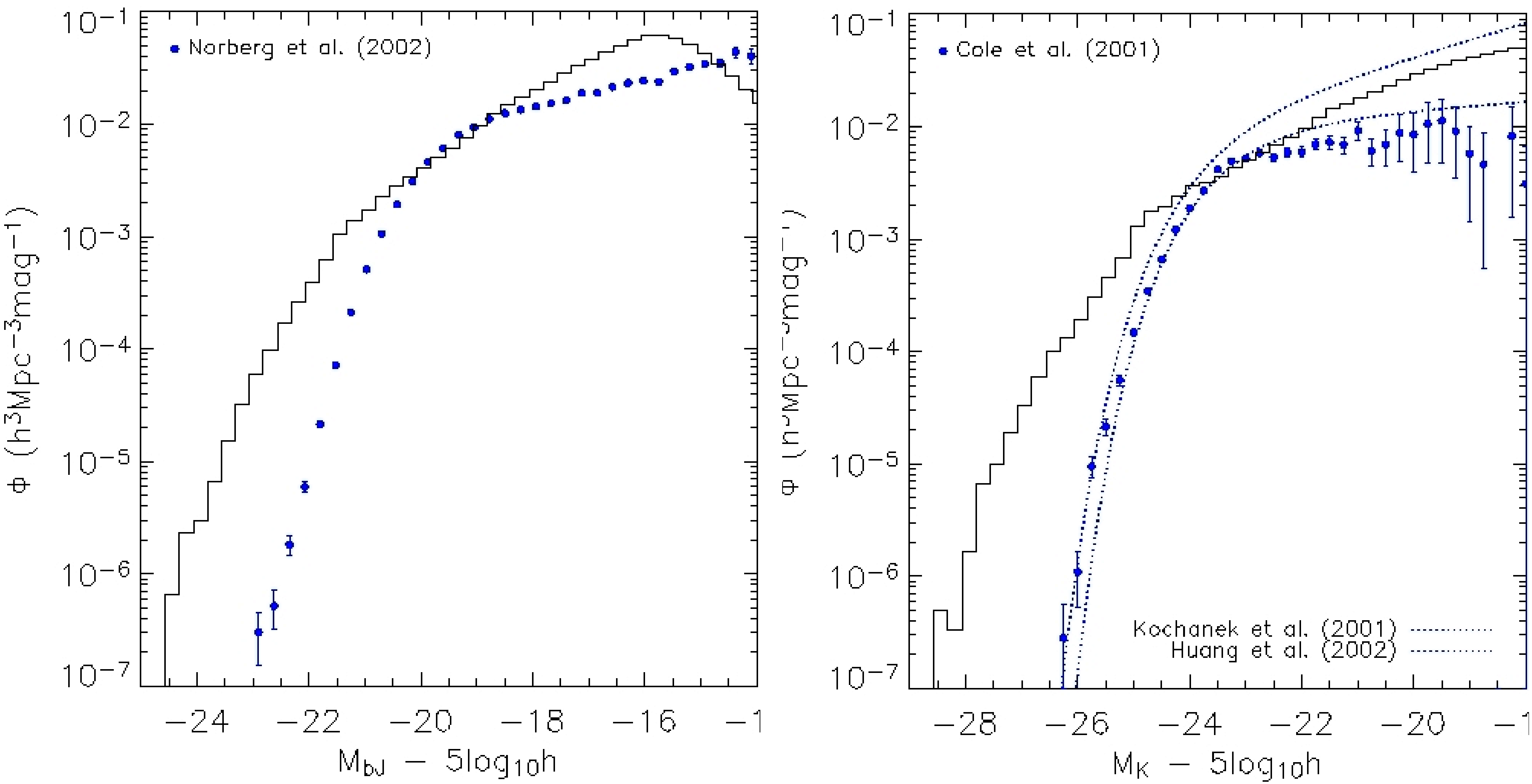
Effect of feedback on the Luminosity Function



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

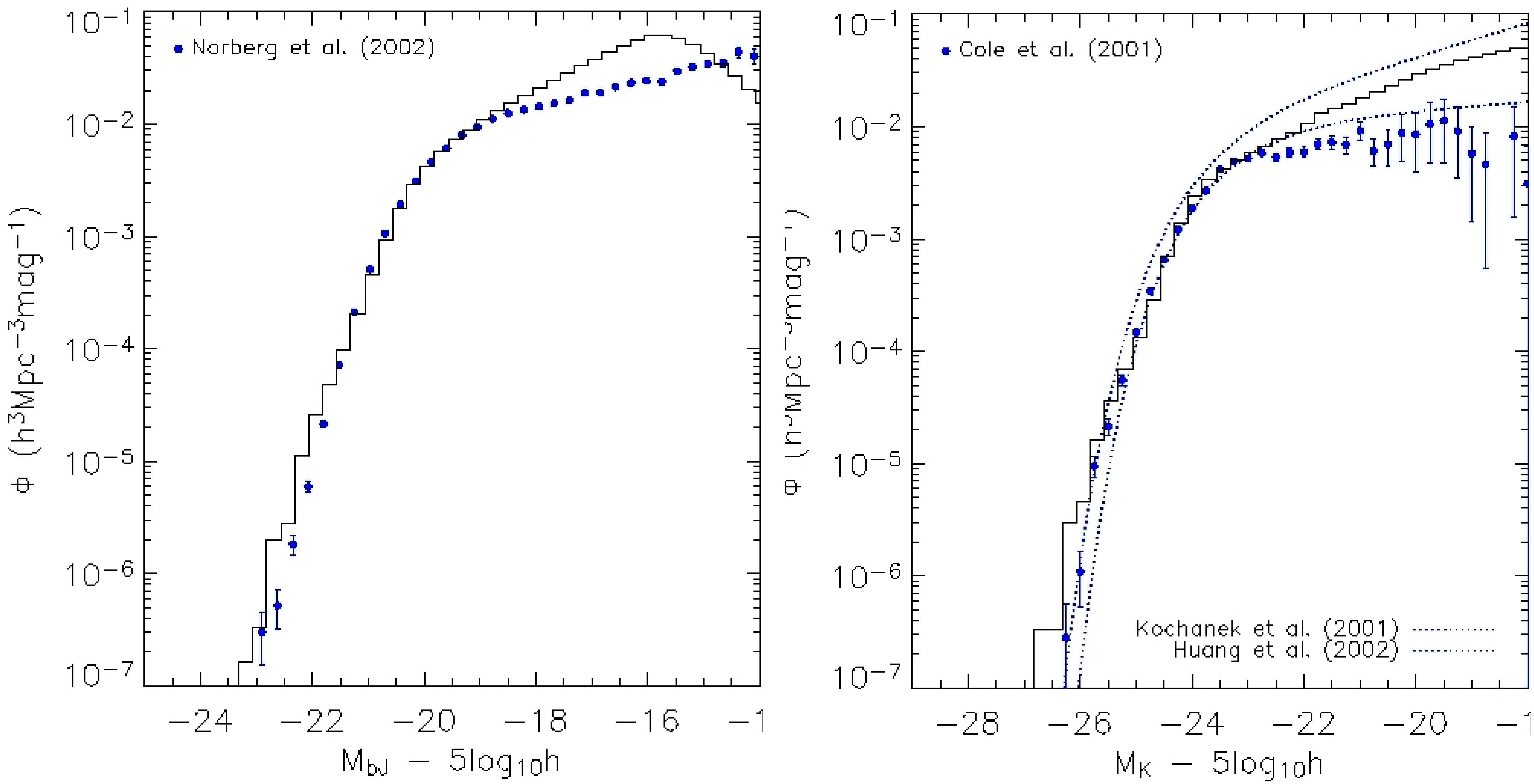
Croton et al 2006

Effect of feedback on the Luminosity Function



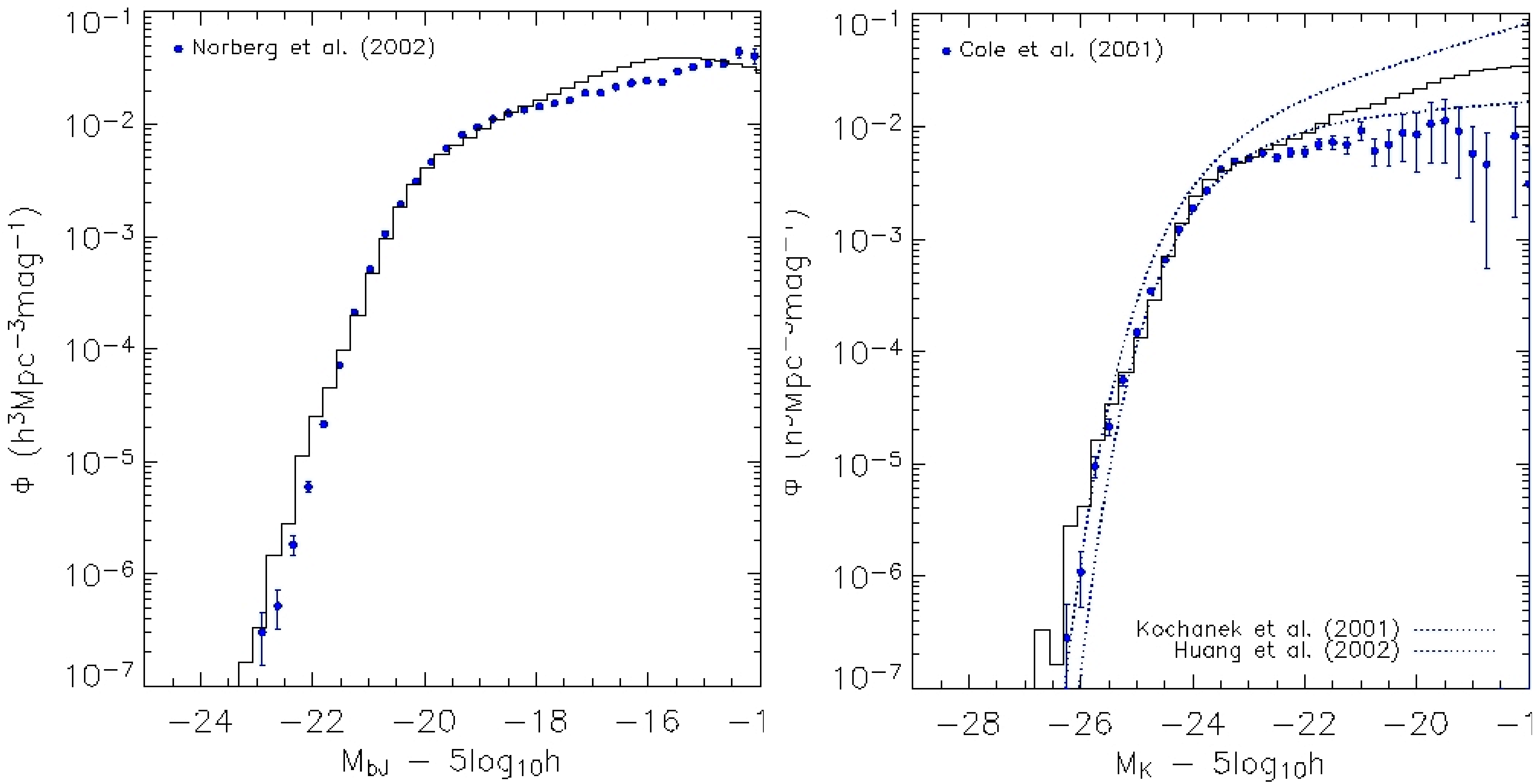
Full model with ~~reionisation~~, ~~AGN~~ and SN feedback   Croton et al 2006

Effect of feedback on the Luminosity Function



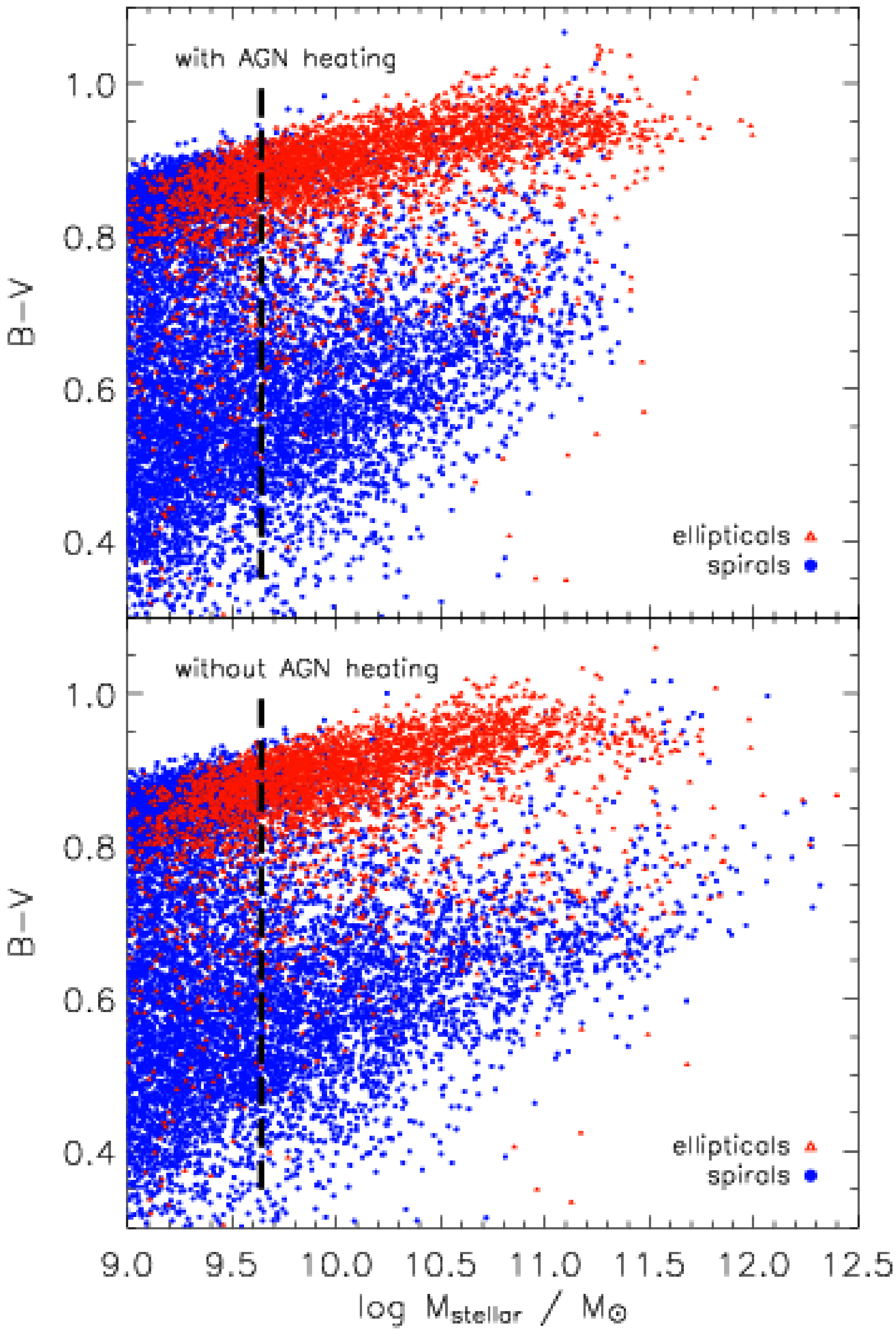
Full model with ~~reionisation~~, AGN and SN feedback   Croton et al 2006

Effect of feedback on the Luminosity Function



Full model with reionisation, AGN and SN feedback

Croton et al 2006



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

Croton et al 2006

- 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

Which aspects of feedback are critical?

- Reionisation filtering has little effect on any but the faintest galaxies. May be relevant for faint Local Group dwarfs? At late times radiative effects are weak because of poor coupling.
- SN feedback can progressively reduce the star formation efficiency in galaxies fainter than L* and so flatten the faint end slope of the LF. Hard to get a strong enough effect. Insufficient energy to suppress massive galaxy formation.
- An additional mechanism is needed (radio AGN?) to suppress star formation in massive "cooling flow" systems. It should not involve star formation since the most massive galaxies are red. It must become effective at *high* mass and at *late* times

Indications from Observations

- Radio AGN (rather than SN or optical AGN) appear to be linked closely to low redshift cool cores.

- Radio and optical AGN activity appear to be independent phenomena at low redshift (and low luminosity?)

- It is optical (and X-ray) AGN activity which appears to be linked to the *growth* of black hole mass (Sołtan argument) and to the *formation* of bulge stars (SDSS data)

- Little evidence for strong, large-scale outflows from optical/ X-ray AGN

→ suppressing inflow is a radio phenomenon? ←

GERMAN ASTROPHYSICAL GAVO VIRTUAL OBSERVATORY

Exploring the milli-Millennium simulation with a relational database

Documentation

1. Introduction
    1.1 Simulation
    1.2 Semi-analytical galaxy formation
    1.3 Science questions
    1.4 Storing merger trees
    1.5 Peano-Hilbert spatial indexing
    1.6 Links
2. Relational databases and SQL
3. Tables
    3.1 HALO
    3.2 FOF
    3.3 SAGFUNIT
    3.4 SNAPSHOTS
    3.5 GALAXY
4. Views
5. Functions
6. Demo queries
    Halo 1
    Galaxy 1
    Halo 2
    Halo 3
    Halo 4
    Halo 5
    Galaxy 5
    Galaxy 6


```
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)

http://www.mpa-garching.mpg.de/Millennium

i_halo	snapnum	d_np	p1_np	p2_np
2576	60	1079	924	222