Galaxy-Intergalactic Medium Interactions
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Feedback Processes in Numerical Simulations

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Types of Feedback

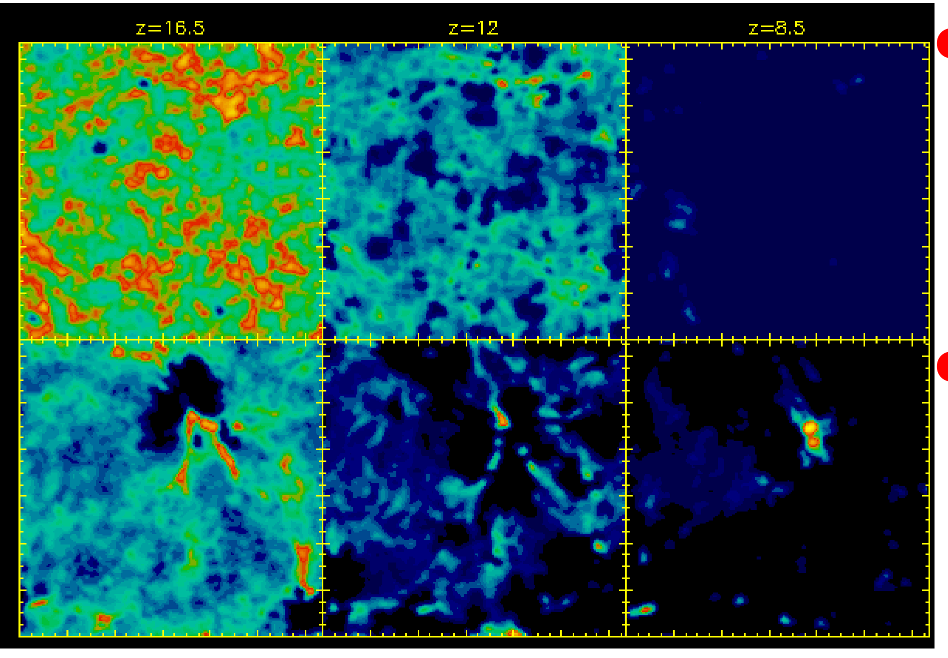
- Radiative Feedback
  - -- UV/X-rays from young stars, AGN, Population III ?
    - -- dissociate H_2 in early structures?
    - -- heat and reionise the IGM
    - -- suppress dwarf galaxy formation?
- Hydrodynamic Energy Input
  - -- flows driven by SN, stellar winds, AGN?
    - -- regulate star formation 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 $\longrightarrow$ 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
  - -- hydrodynamic effects control 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?

Numerical issues I

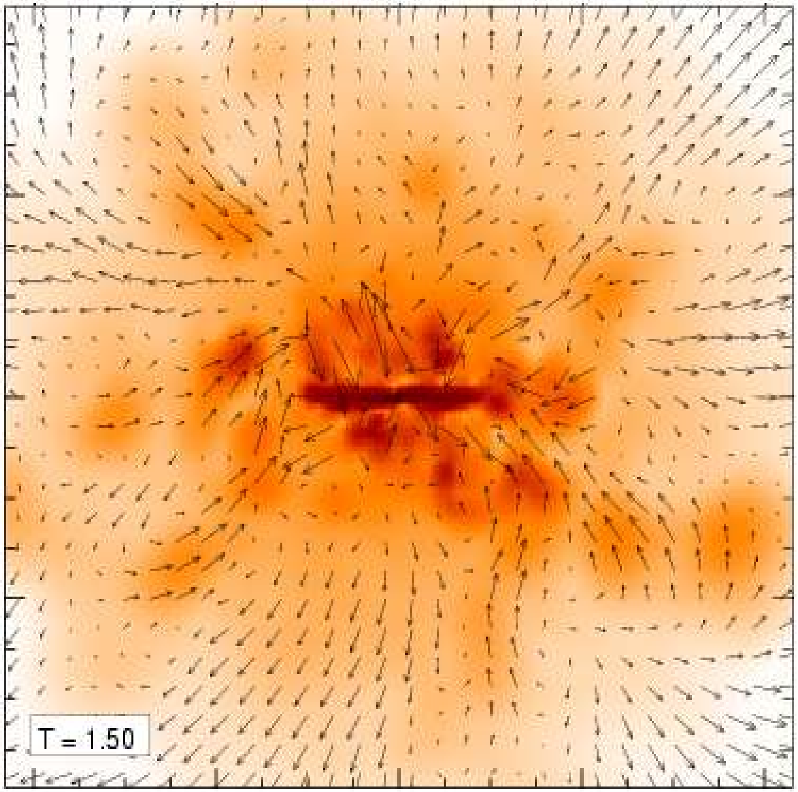
Ciardi et al 2002



- Radiative transfer technique
  - -- appropriate approximation
  - -- frequency dependence
- Source distribution
  - -- evolution, self-consistent?
  - -- escape fraction, anisotropy?
  - -- effective spectrum
- Dynamics
  - -- reaction of IGM to overpressure of HII regions
  - -- consistent integration of ionisation and motions
- Simulation size
  - -- dominant sources may be rare
  - -- photon mean free path becomes long
  - -- 'proto-' cluster and void regions have large scale

Numerical issues II

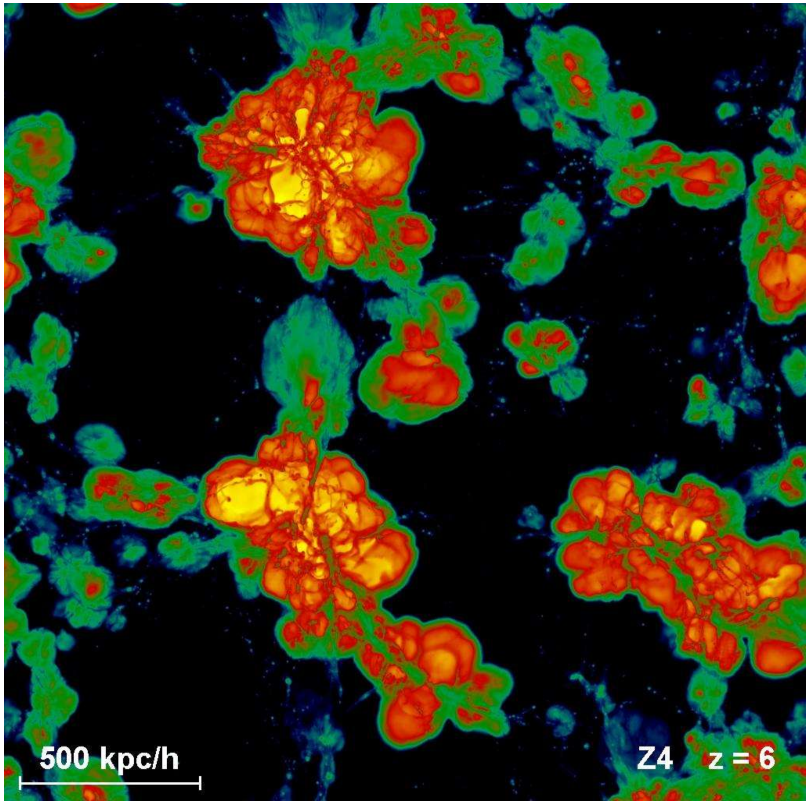
Springel & Hernquist 2002



- Structure of ISM
  - -- Multiphase medium
  - -- relation to star formation activity
  - -- heating/mixing by infalling gas
  - -- cosmic ray/B field component
- Sources energising the ISM
  - -- SN type I and II, stellar winds
  - -- AGN
  - -- entrainment
- Enrichment
  - -- mixing of heavy elements into various phases
  - -- effect on cooling rates and phase structure
- Structure of infalling IGM
  - -- from instabilities on wind/IGM interface
  - -- from inflow/outflow interaction

Numerical issues III

Springel & Hernquist 2002



- Structure of IGM
  - -- left over from reionisation
  - -- from previous winds
- Mixing on bubble boundary
  - -- cooling in boundary layer
  - -- mixing of metals into cool gas
- Gas in bubbles
  - -- evaporation of dense clouds
  - -- stimulated star formation
- Relativistic plasma
  - -- acceleration at shocks, advection in wind, radio AGN
  - -- effect on dynamics?
- Simulation Size
  - -- Large domains needed for proper IGM statistics

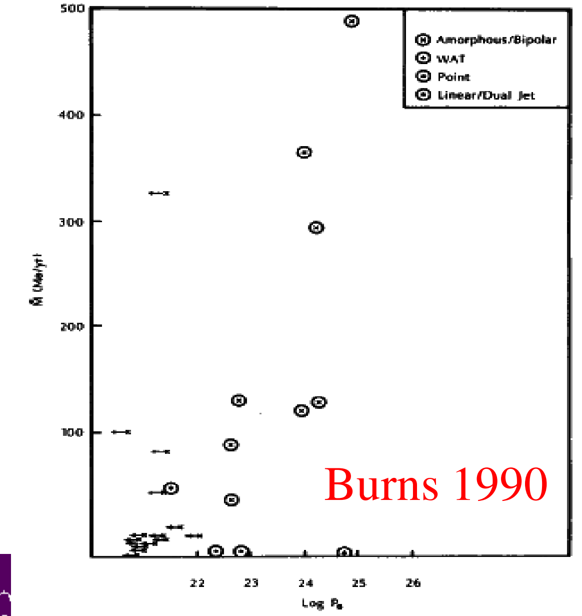
Some homework for MJR?

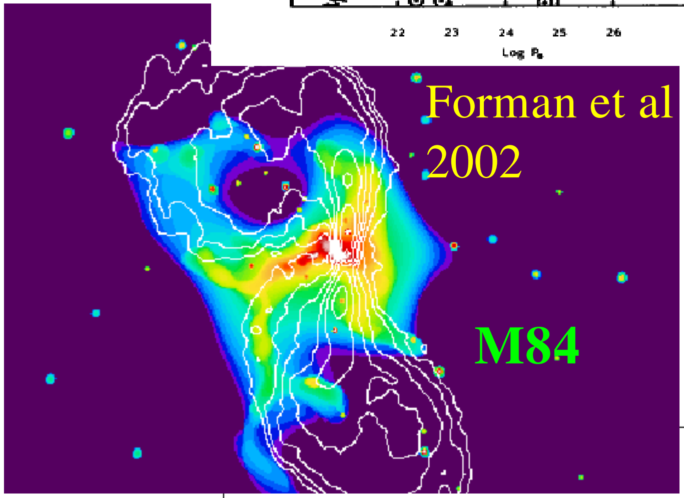
- Almost all "cooling flows" have central cD's, the most luminous spheroids known
  → cooling flows "grow" cD's

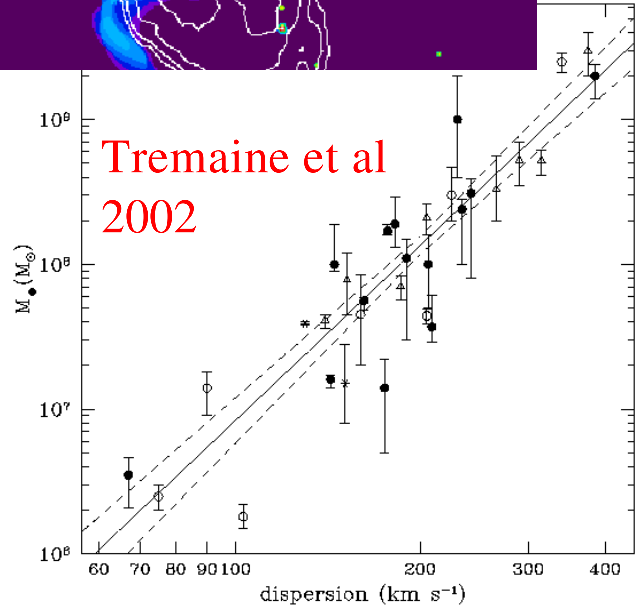
- Luminous radio sources are over-abundant and nearly ubiquitous in such "cD's"
  → cooling flows fuel AGN

- The central AGN are *observed* to influence the surrounding gas strongly
  → AGN affect cooling flows

- BH masses correlate strongly with global properties for *all* spheroids
  → spheroid and BH formation are closely intertwined for all galaxies -- HOW?

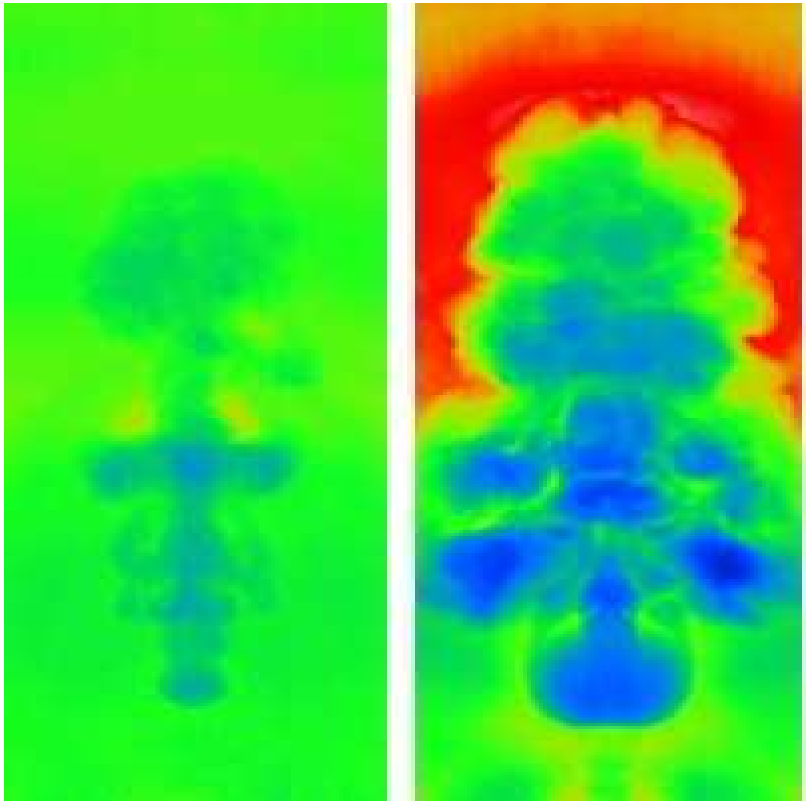






Numerical issues IV

Bruggen et al 2002



- Nature of source
  - -- nature of jet
  - -- duty cycle/profile of activity
  - -- feedback of activity on fueling
- Interaction with ICM
  - -- hot spot?
  - -- particle reacceleration?
- Bubble interface
  - -- Rayleigh-Taylor instabilities?
  - -- diffusion/mixing of components
- Thermodynamics of ICM
  - -- multiphase cooling structure?
  - -- dissipation of dynamical heating?
  - -- X-ray and CR heating?
- Relation to cluster-wide dynamics?

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

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

- AGN feedback

  "Radio" mode $\Delta M'_{cool} = \Delta M_{cool} - \eta\ M_{BH}^{\ \alpha}\ T_{clus}^{\ \beta}$ Croton 2004

  "Quasar" mode builds up BH masses, establishes Magorrian relation, feedback included in SN?   Kauffmann & Haehnelt 2000

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, Croton et al 2004)

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

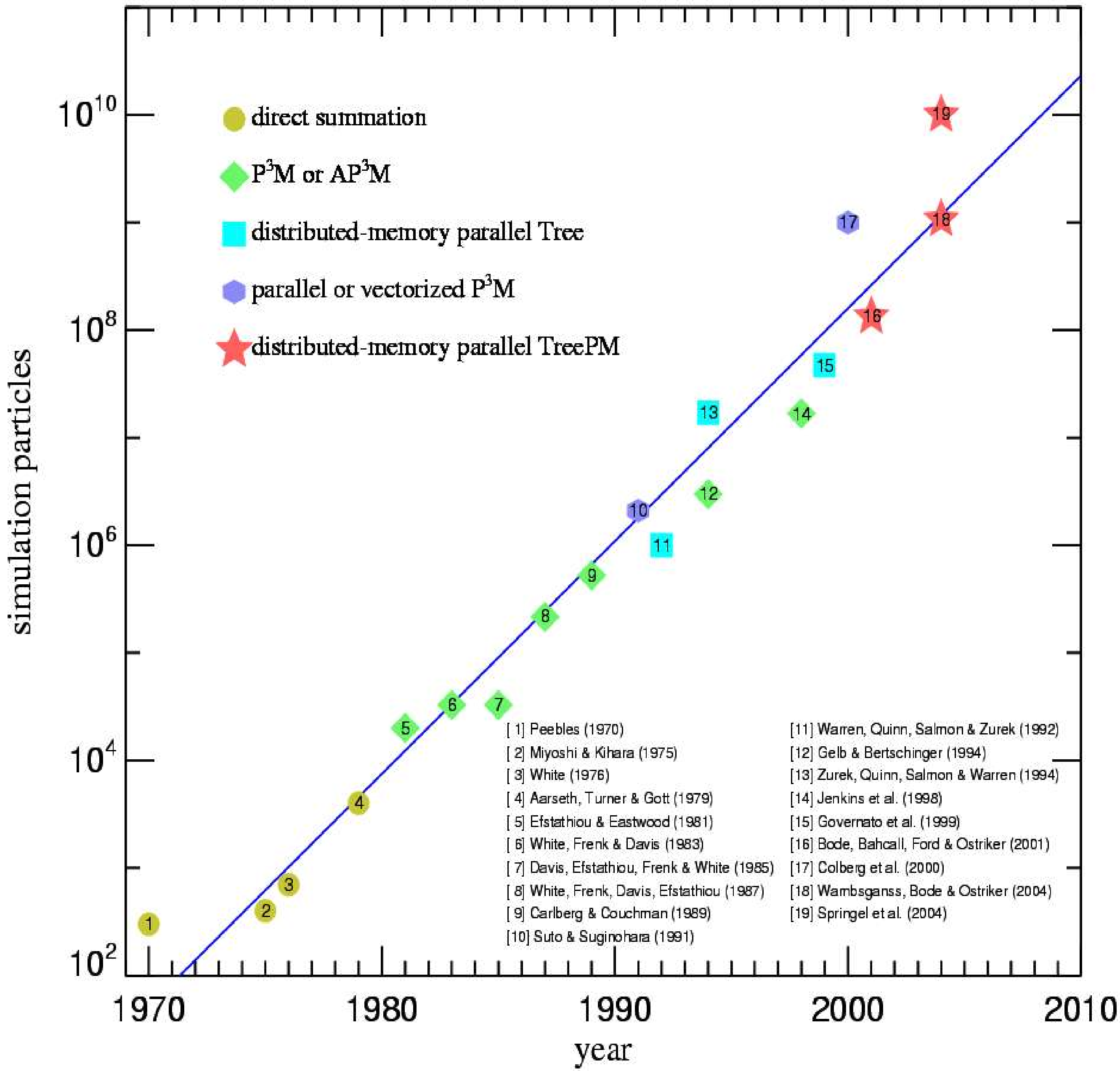
(c) Simulations of large enough volume to represent bright galaxies, galaxy clusters, quasar hosts...

This requires simulations with a LARGE number of particles

Moore's Law for Cosmological N-body Simulations

Springel et al 2004

- 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
- $N = 10^{10}$ should have been reached in 2008
- But it has already been completed...



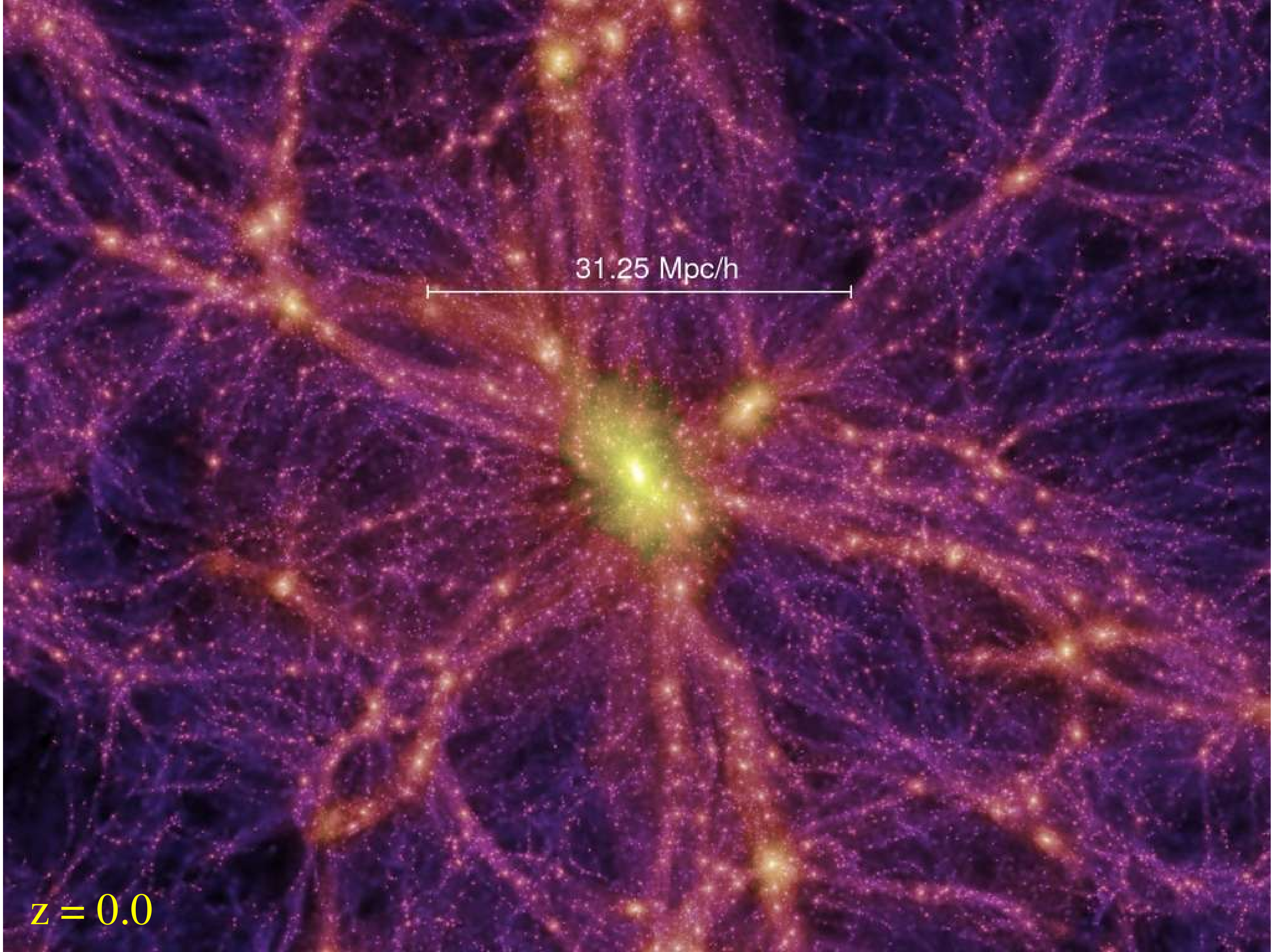
Millennium Run Statistics

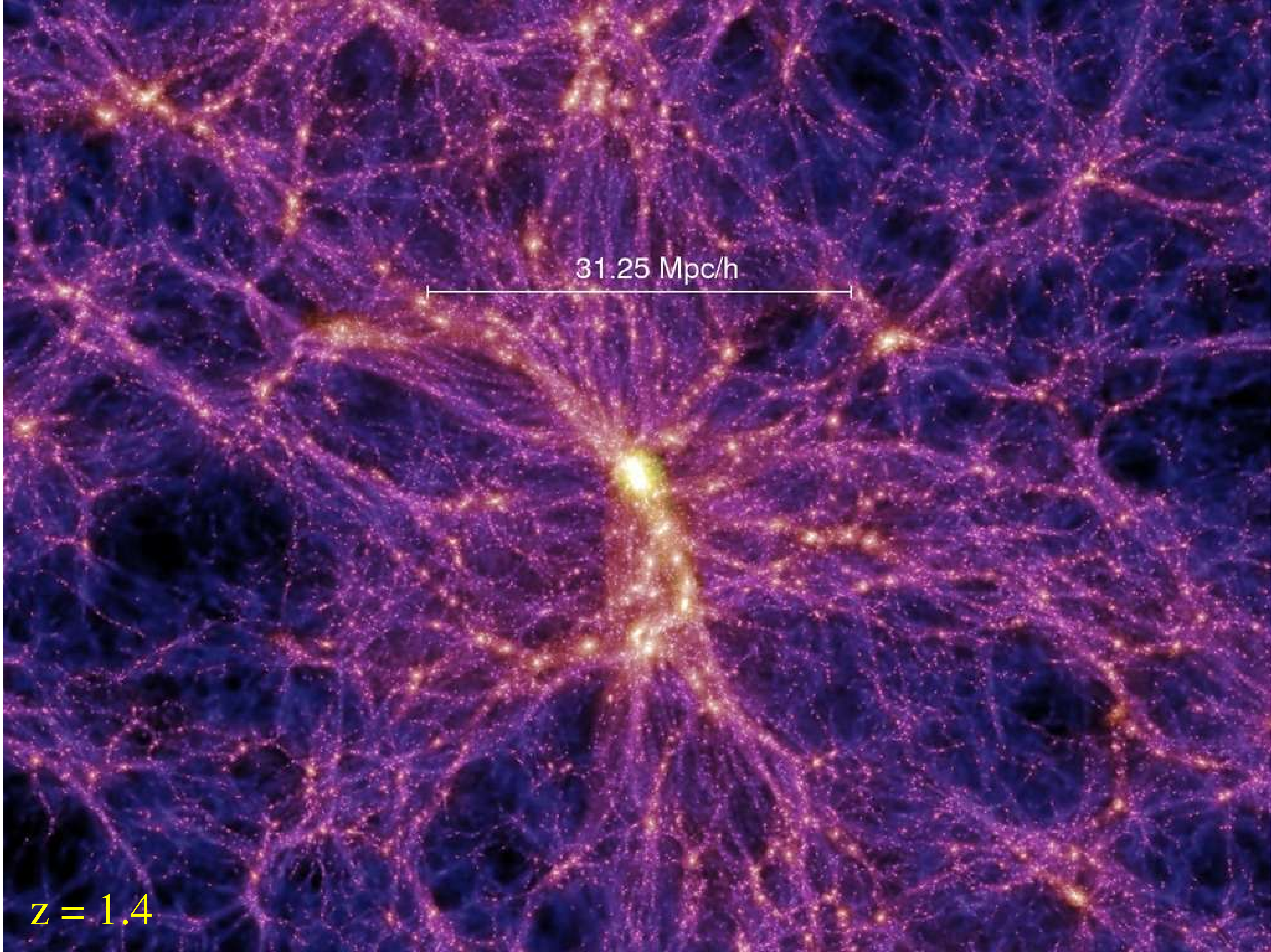
Volker Springel and the Virgo Consortium

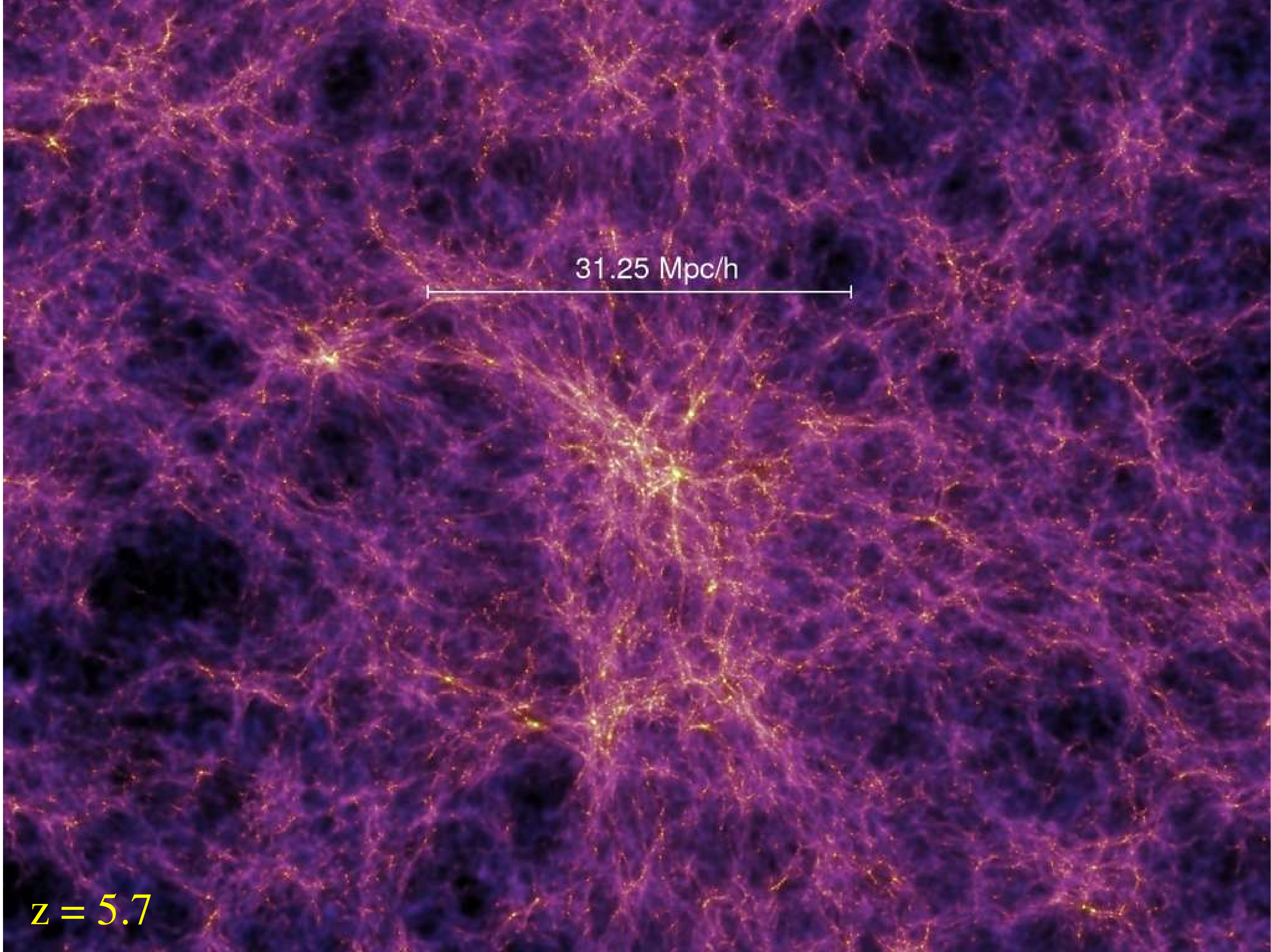
- Particle number: $N = 2160^3 = 10{,}077{,}696{,}000 \approx 10^{10}$
- Box size: $L = 500$ Mpc/h, Softening: $\epsilon = 5$ kpc/h $\longrightarrow$ $L/\epsilon = 10^5$
- Initial redshift: $z_{init} = 127$
- Cosmology: $\Omega_{tot}=1$, $\Omega_m=0.25$, $\Omega_b=0.045$, $h=0.73$, $n=1$, $\sigma_8=0.9$
- 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

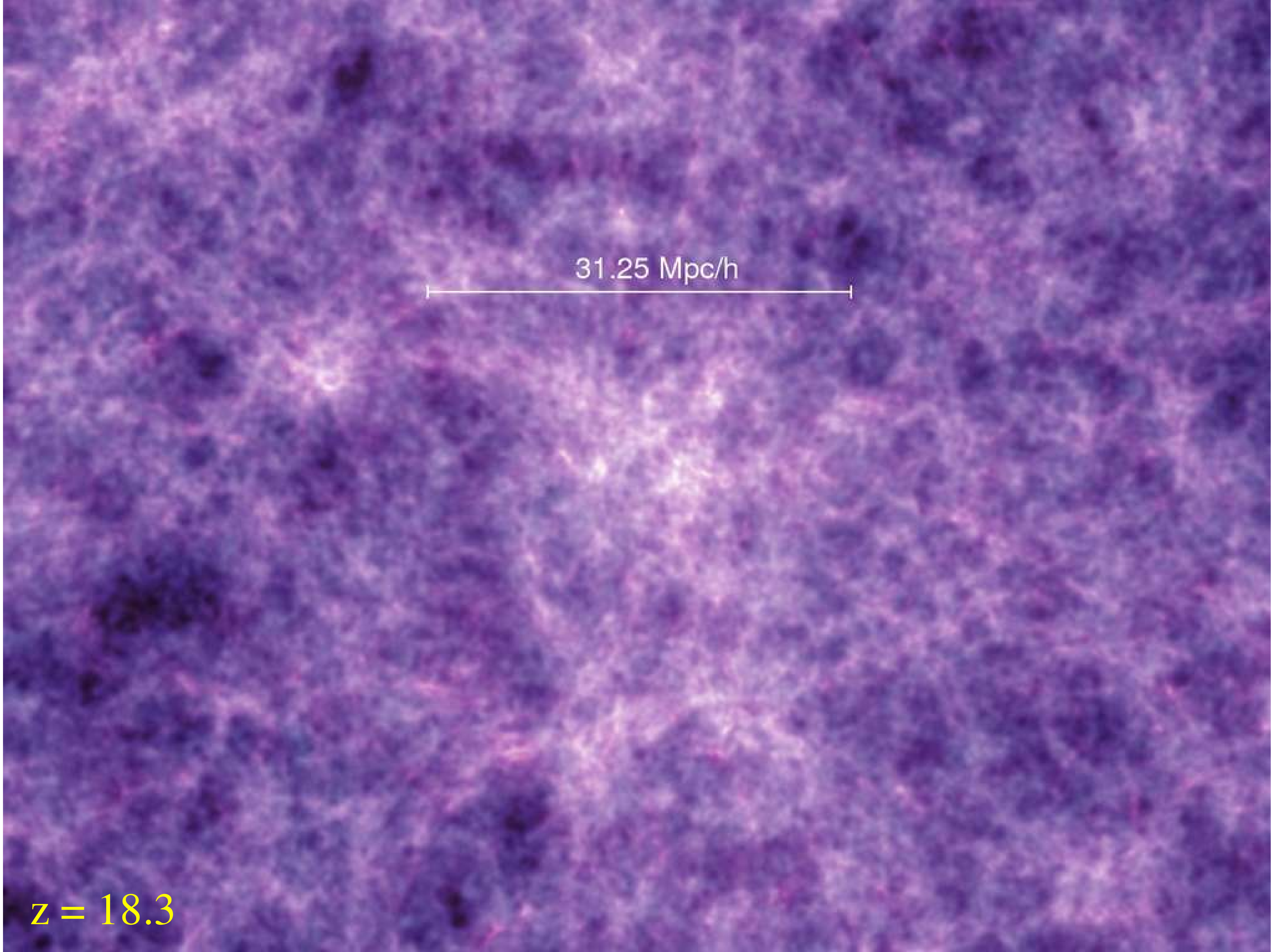
$\longrightarrow$ **27 Tbytes of stored data**

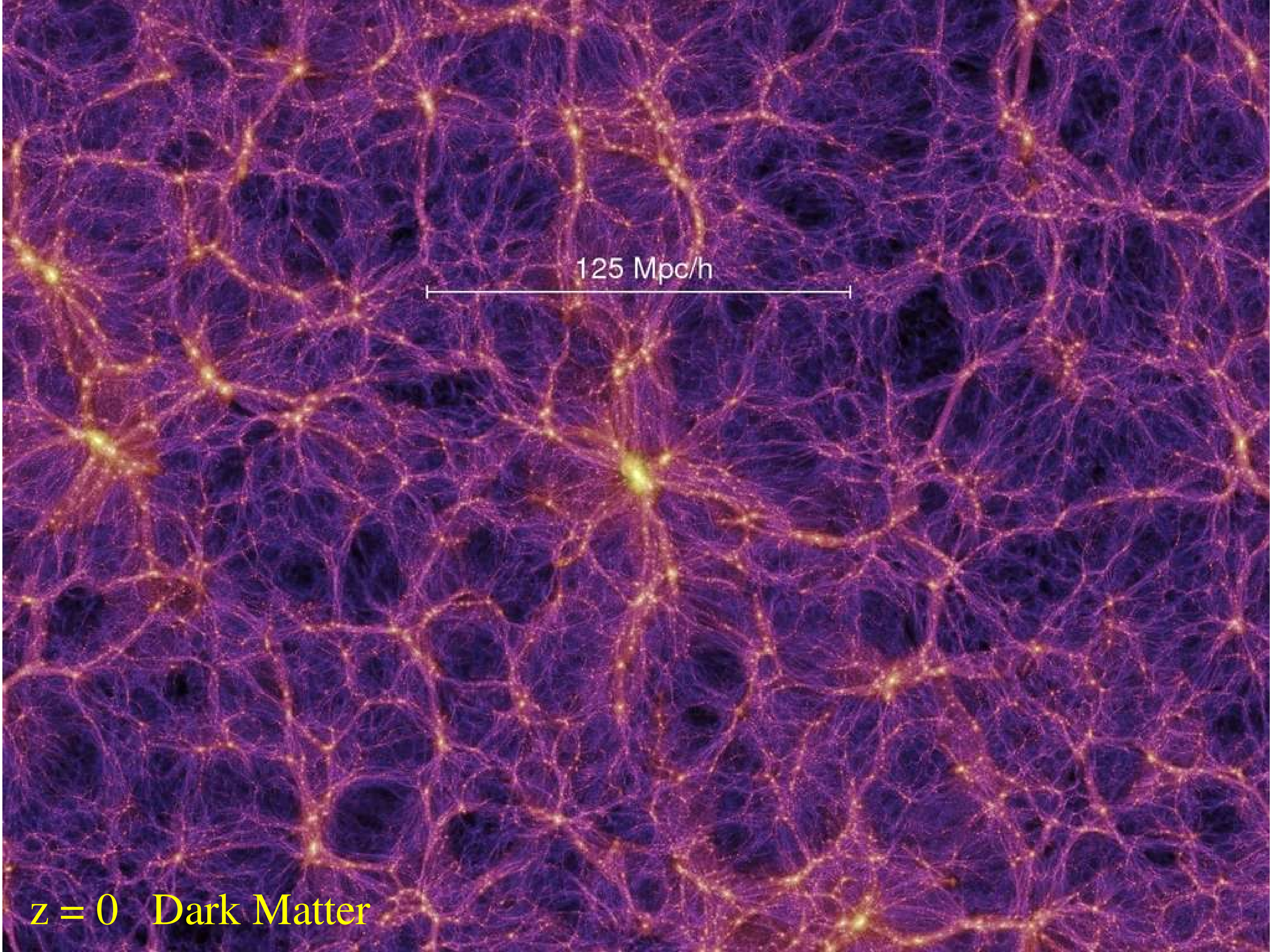
Archive for a Theoretical Virtual Observatory

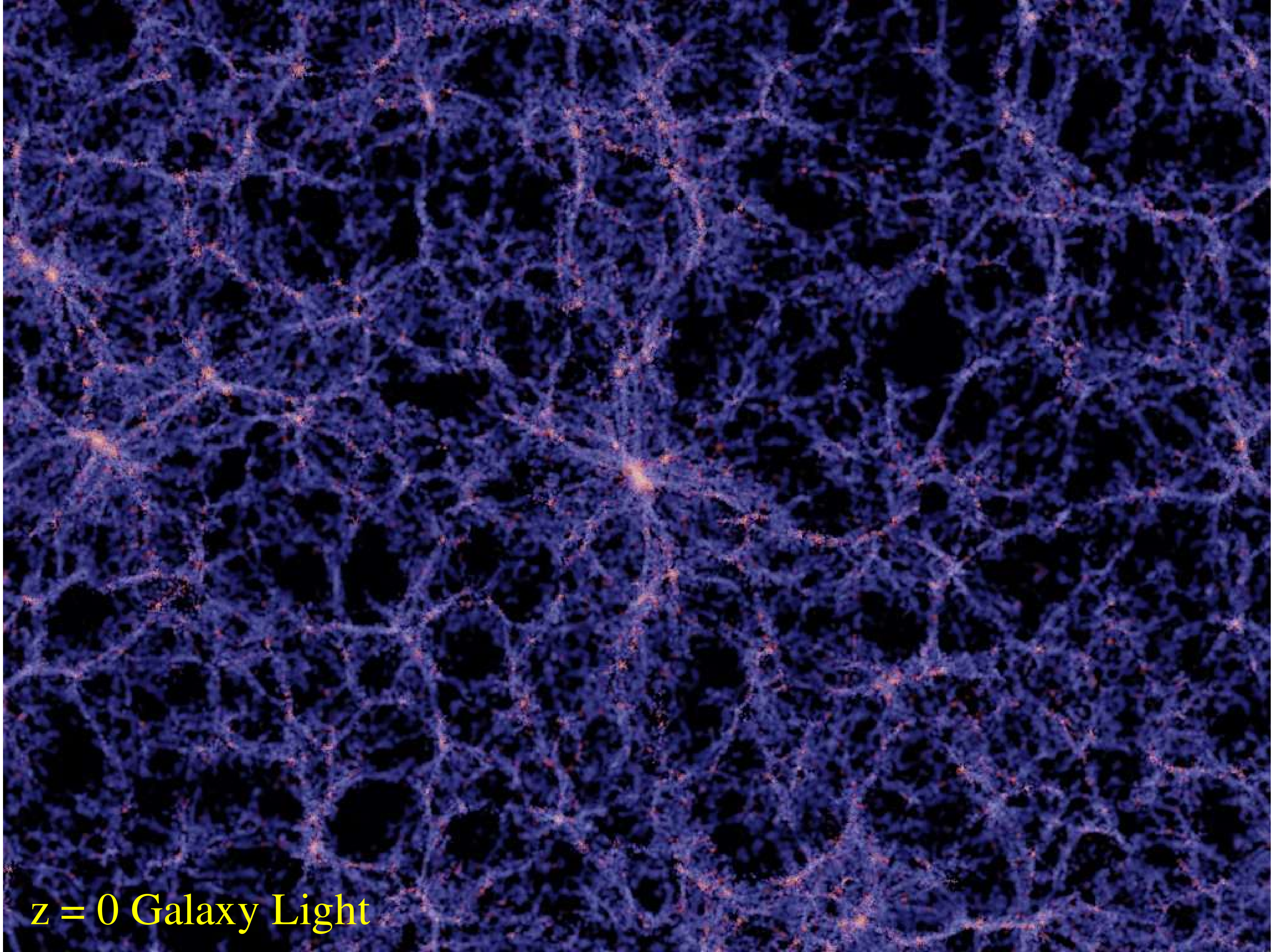

31.25 Mpc/h
z = 0.0


31.25 Mpc/h
z = 1.4


31.25 Mpc/h
z = 5.7


31.25 Mpc/h
z = 18.3

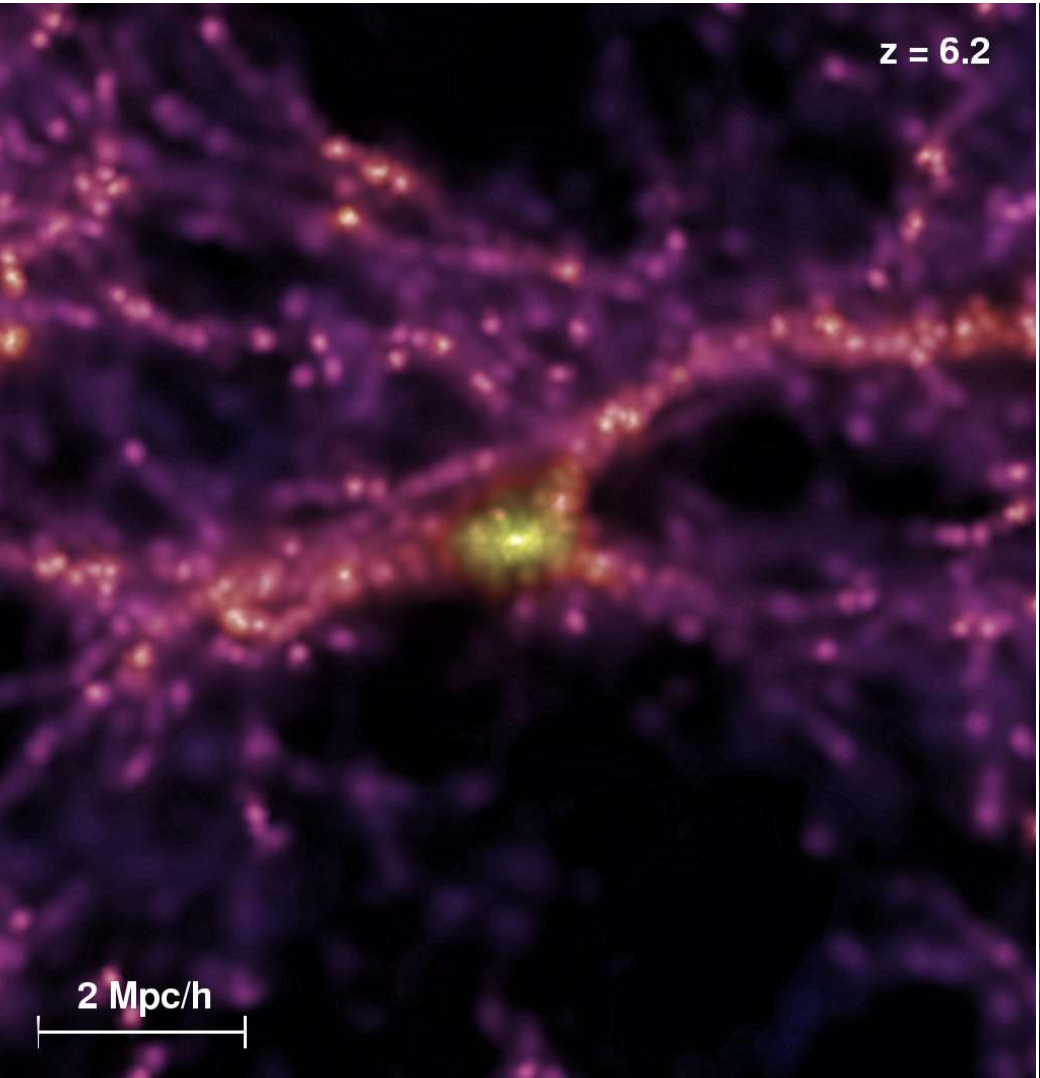

125 Mpc/h
z = 0 Dark Matter

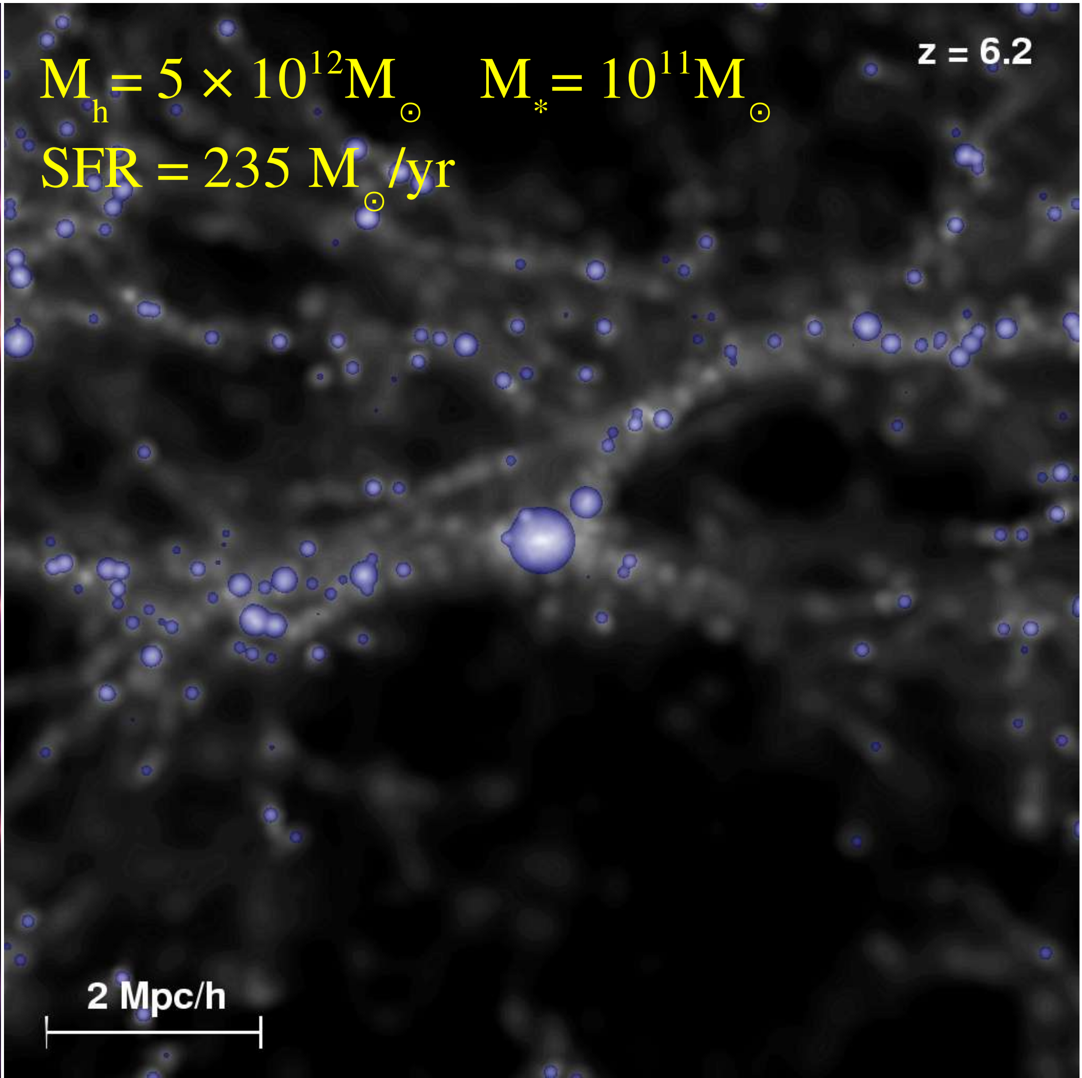

z = 0 Galaxy Light

“SDSS Quasar” Host at z=6.2

Springel et al 2004

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

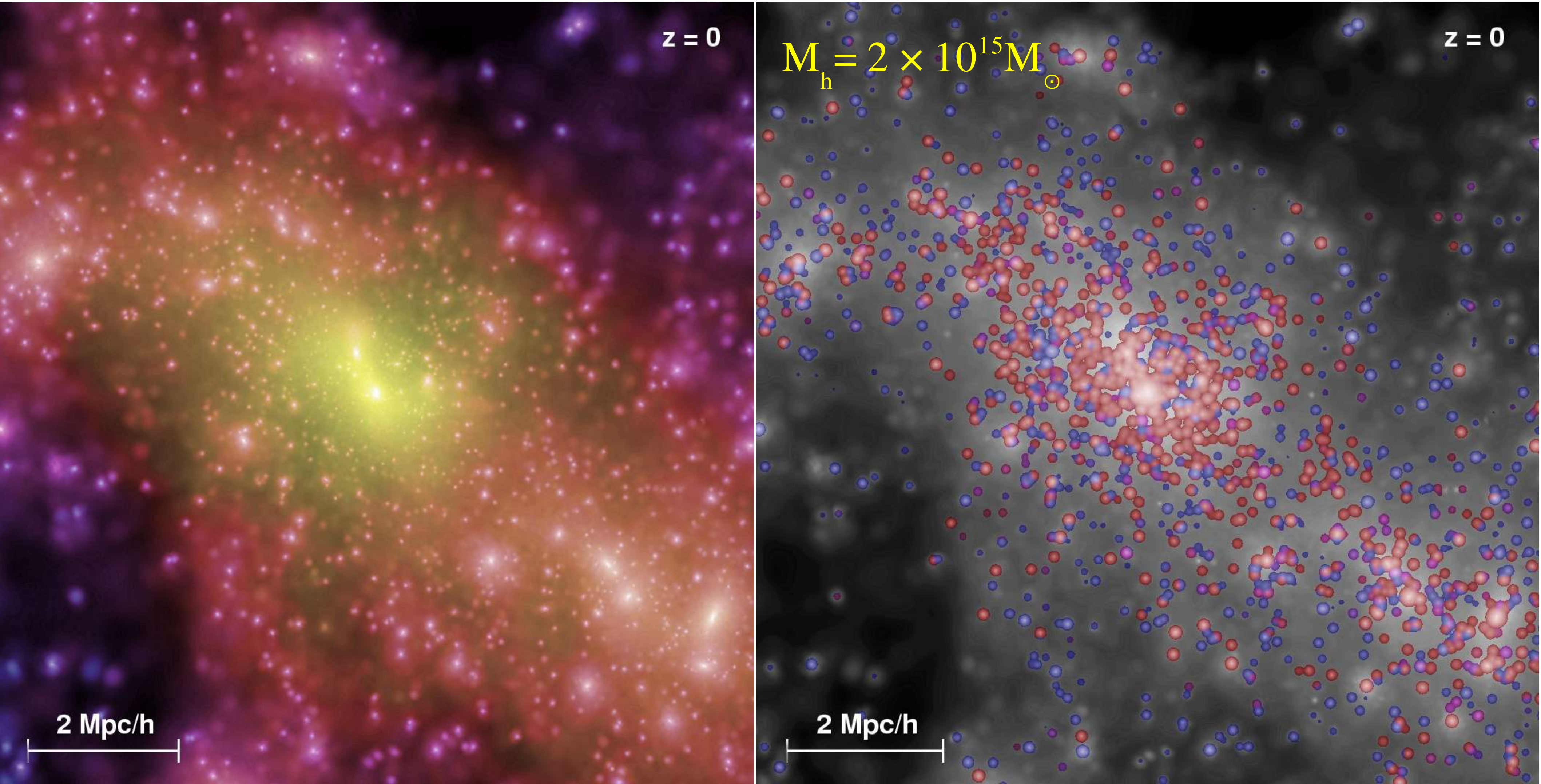




“SDSS Quasar” Descendant at z=0

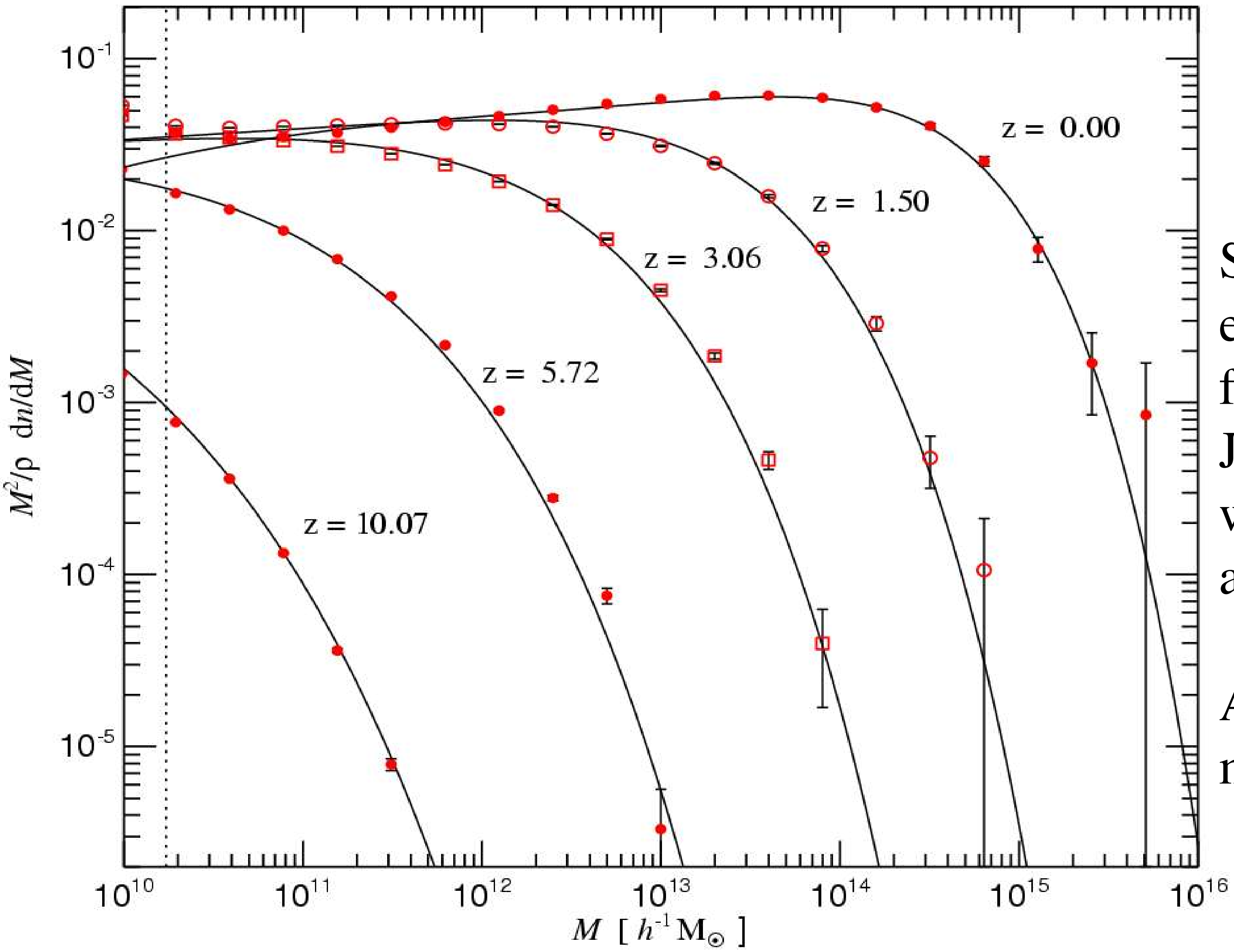
Springel et al 2004

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 $z = 17$



Halo Mass Functions in the MS

Springel et al 2004

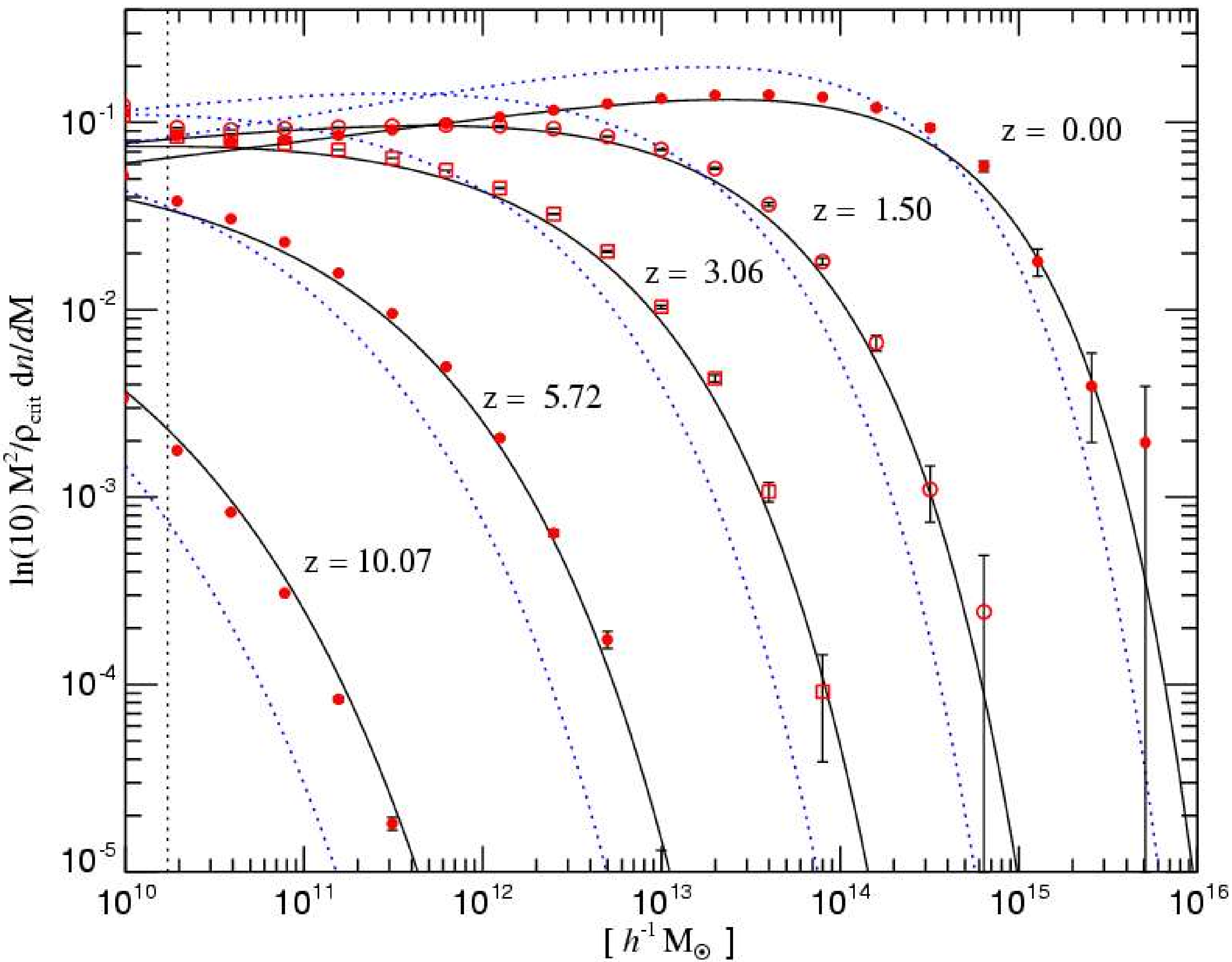


Solid curves are the empirical fitting formula from Jenkins et al 2001 with no parameters adjusted

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

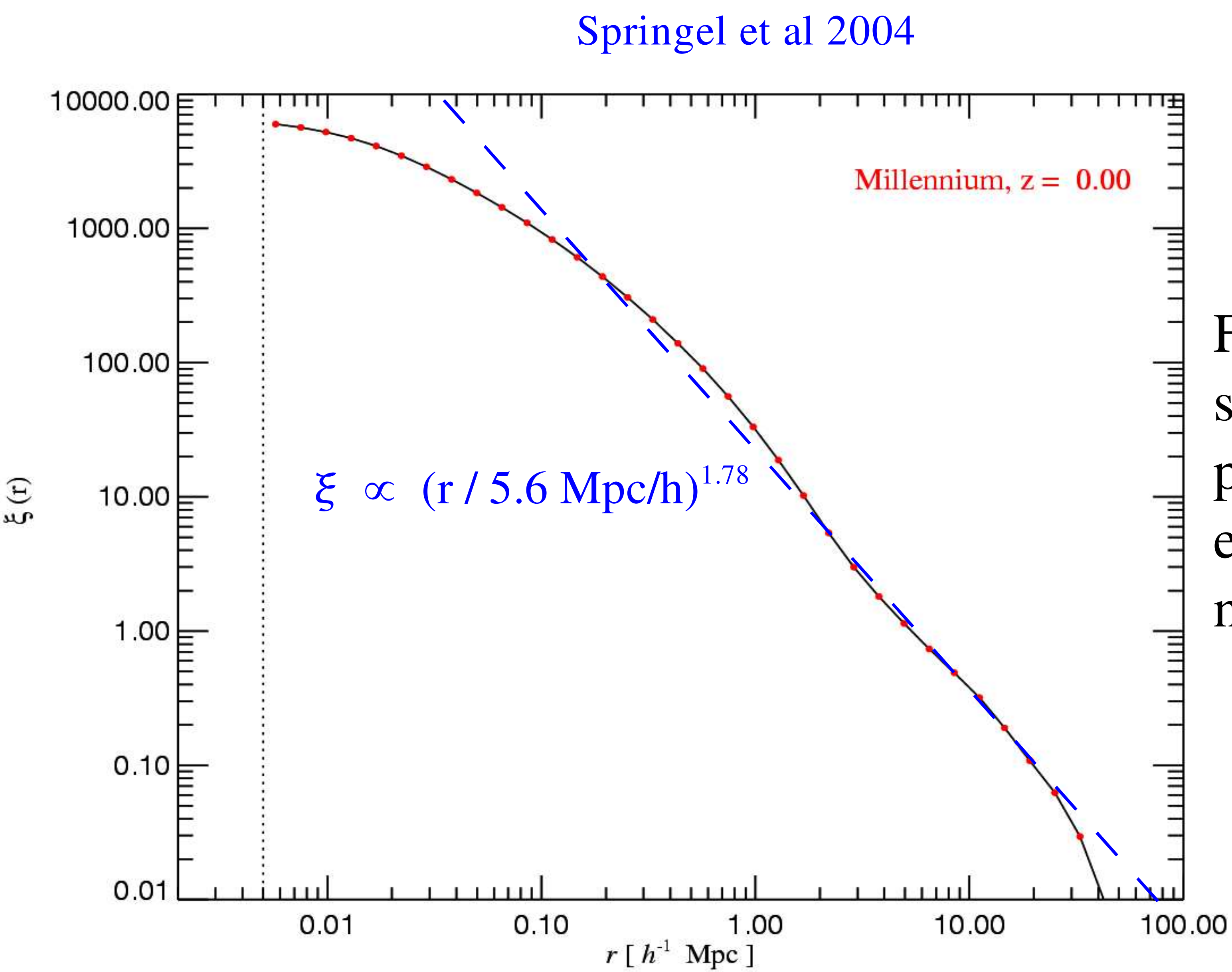
Halo Mass Functions in the MS

Springel et al 2004



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

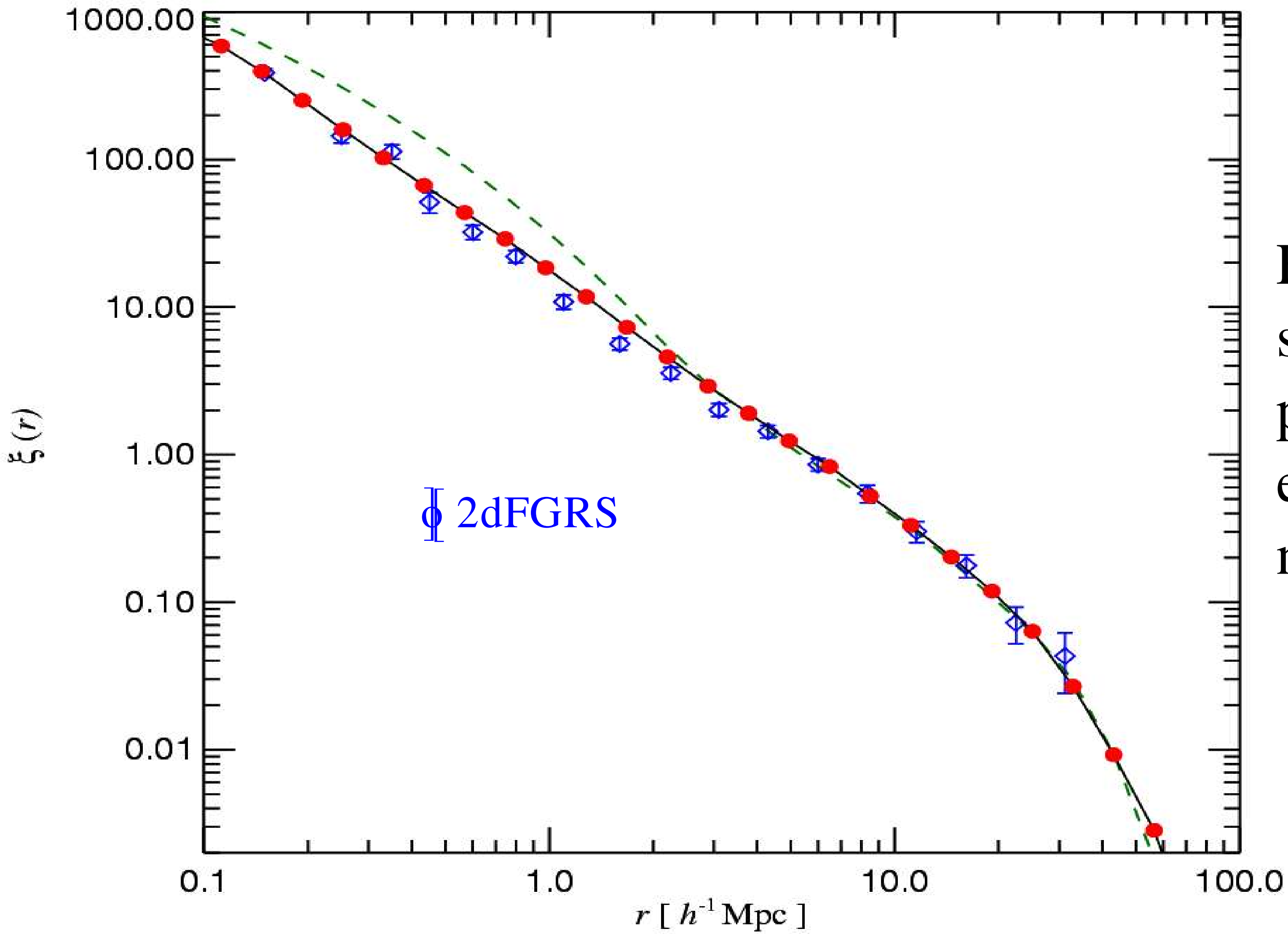
Mass autocorrelation function



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

Galaxy autocorrelation function

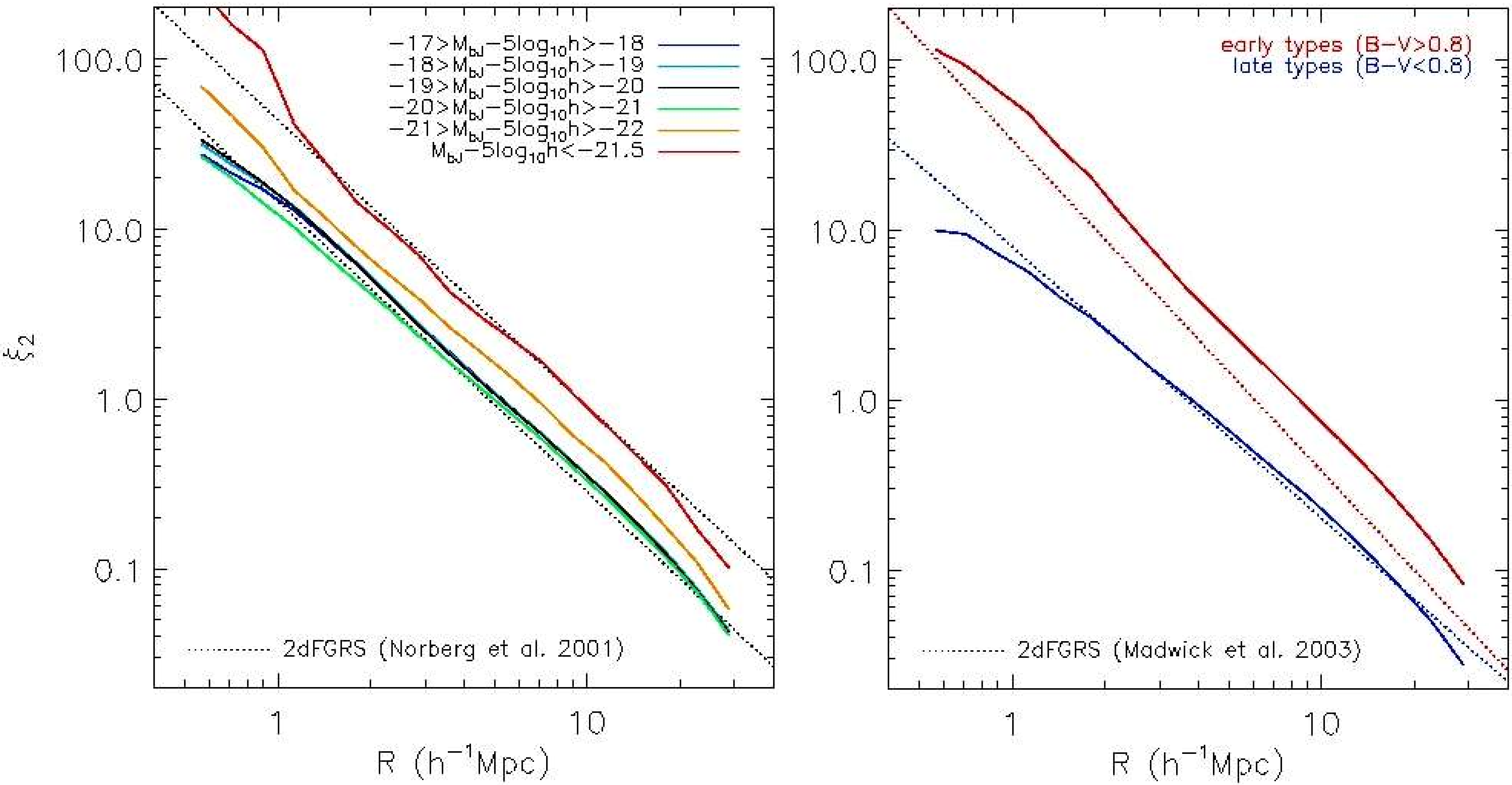
Springel et al 2004

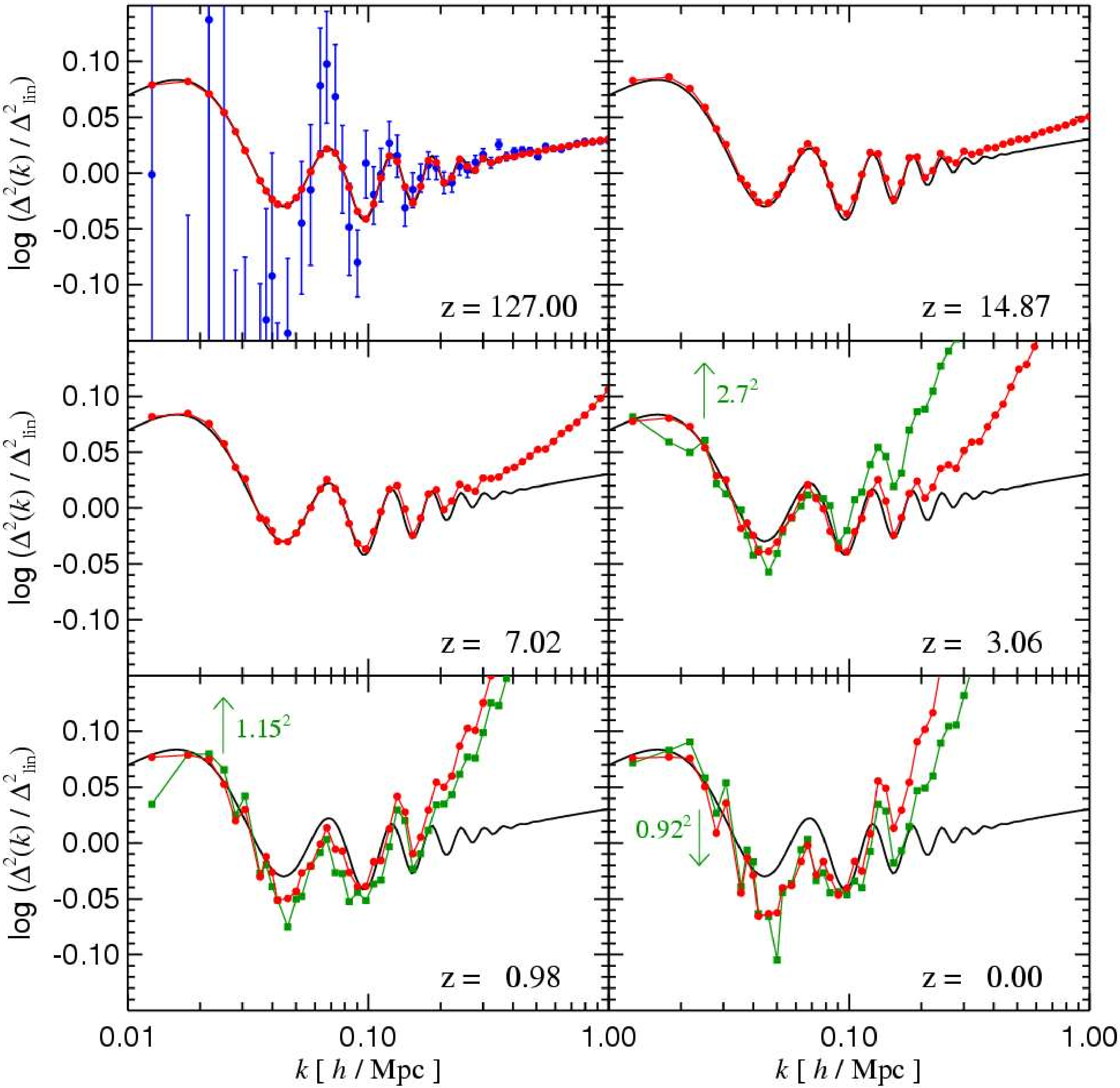


For such a large simulation the purely statistical error bars are negligible on ξ even for the galaxies

Galaxy autocorrelation function

Croton et al 2004





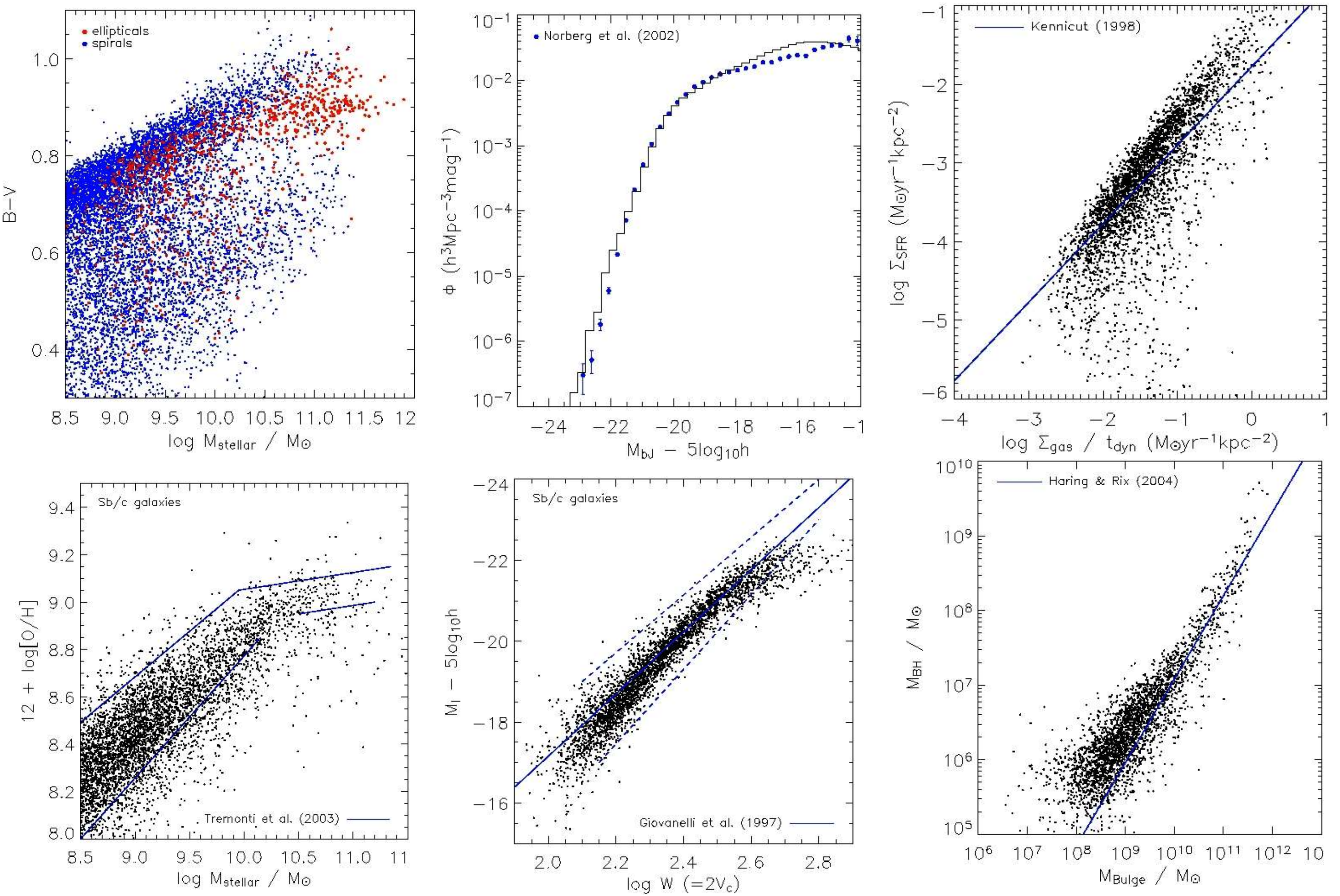
Baryon wiggles in the *galaxy* distribution

Springel et al 2004

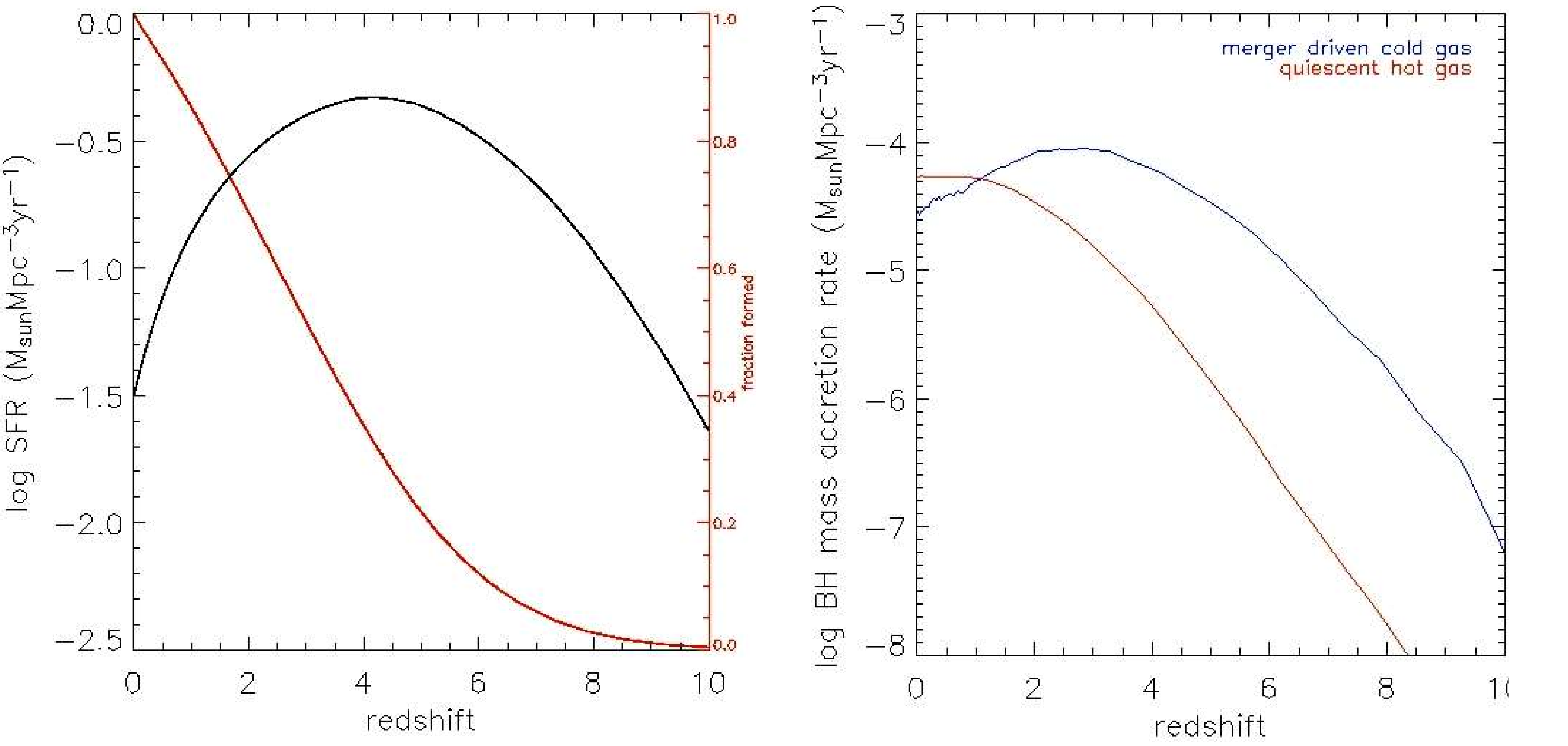
Power spectra from the Millennium run divided by a baryon-free ΛCDM spectrum

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

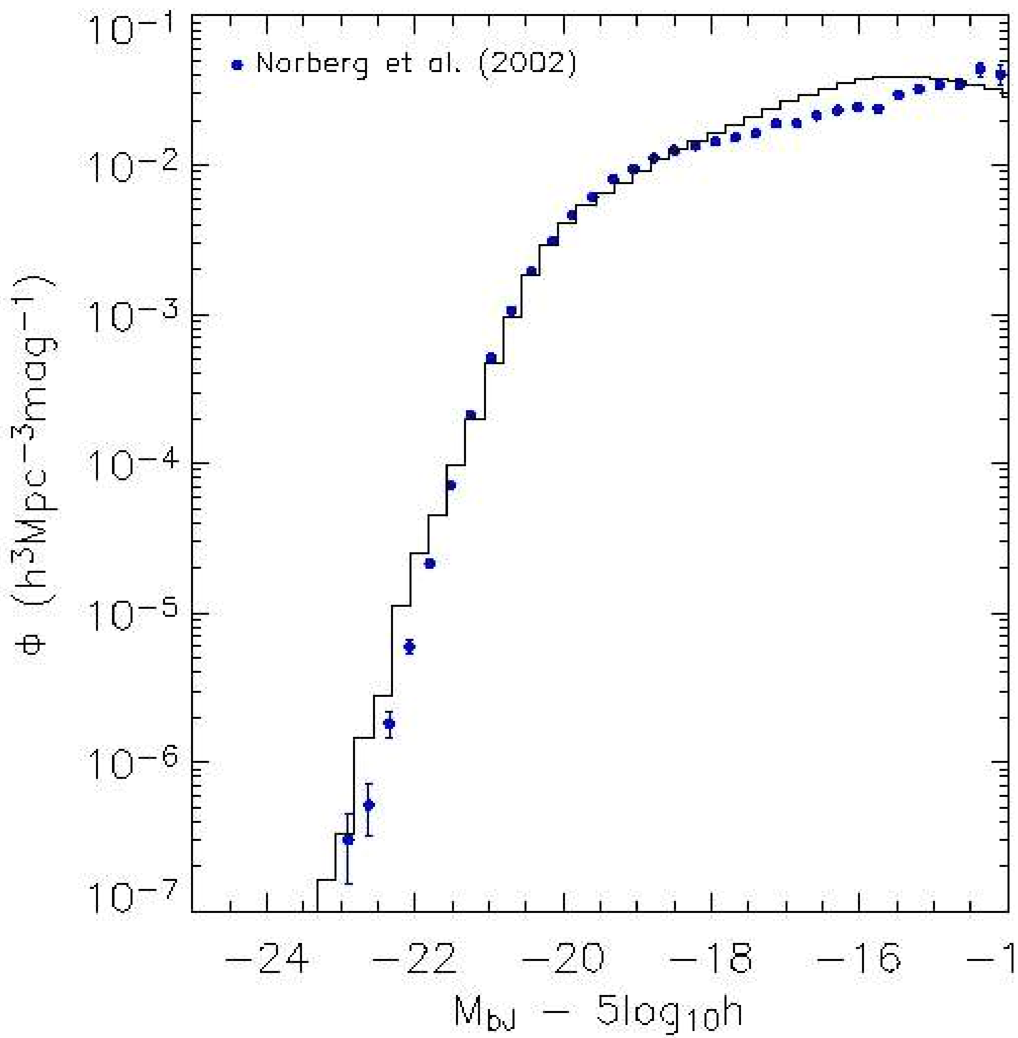
Various galaxy properties at z=0

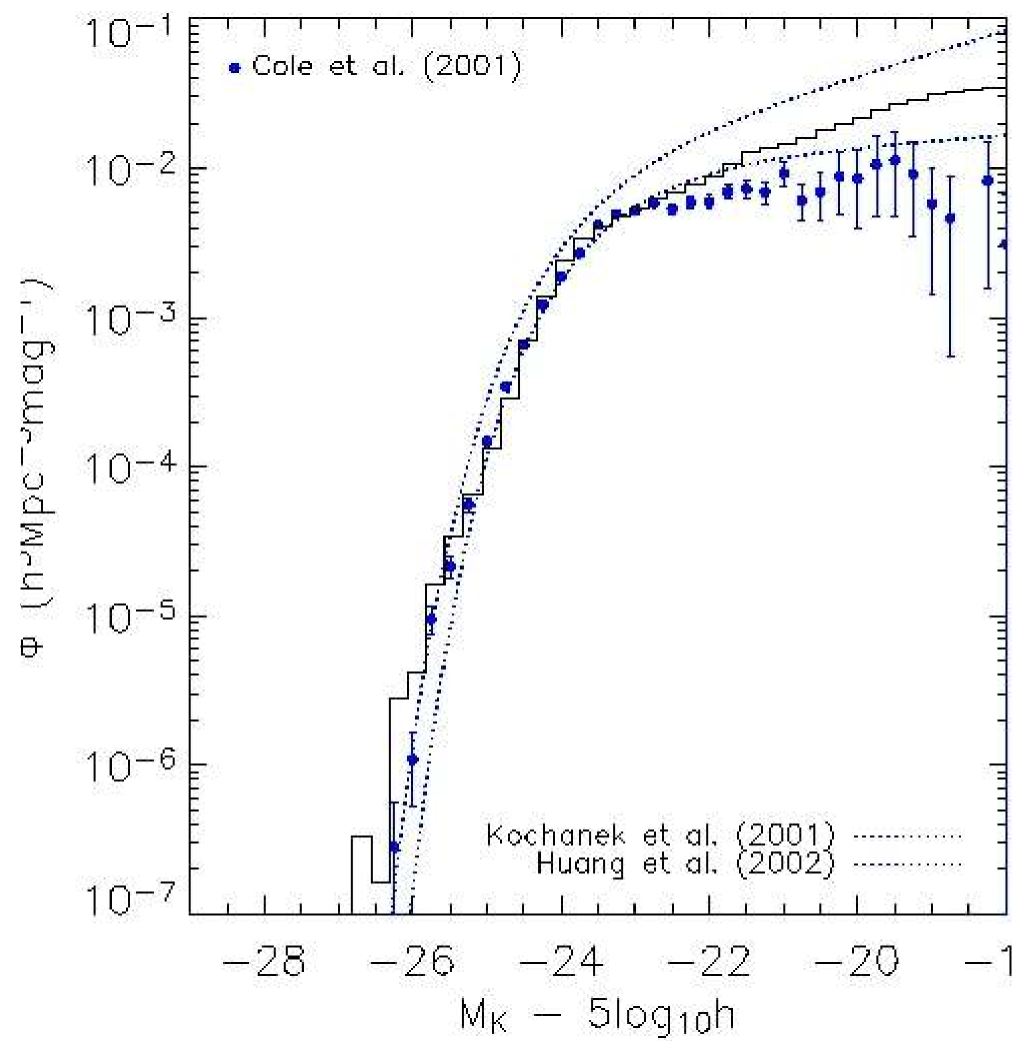


Evolution of feedback sources



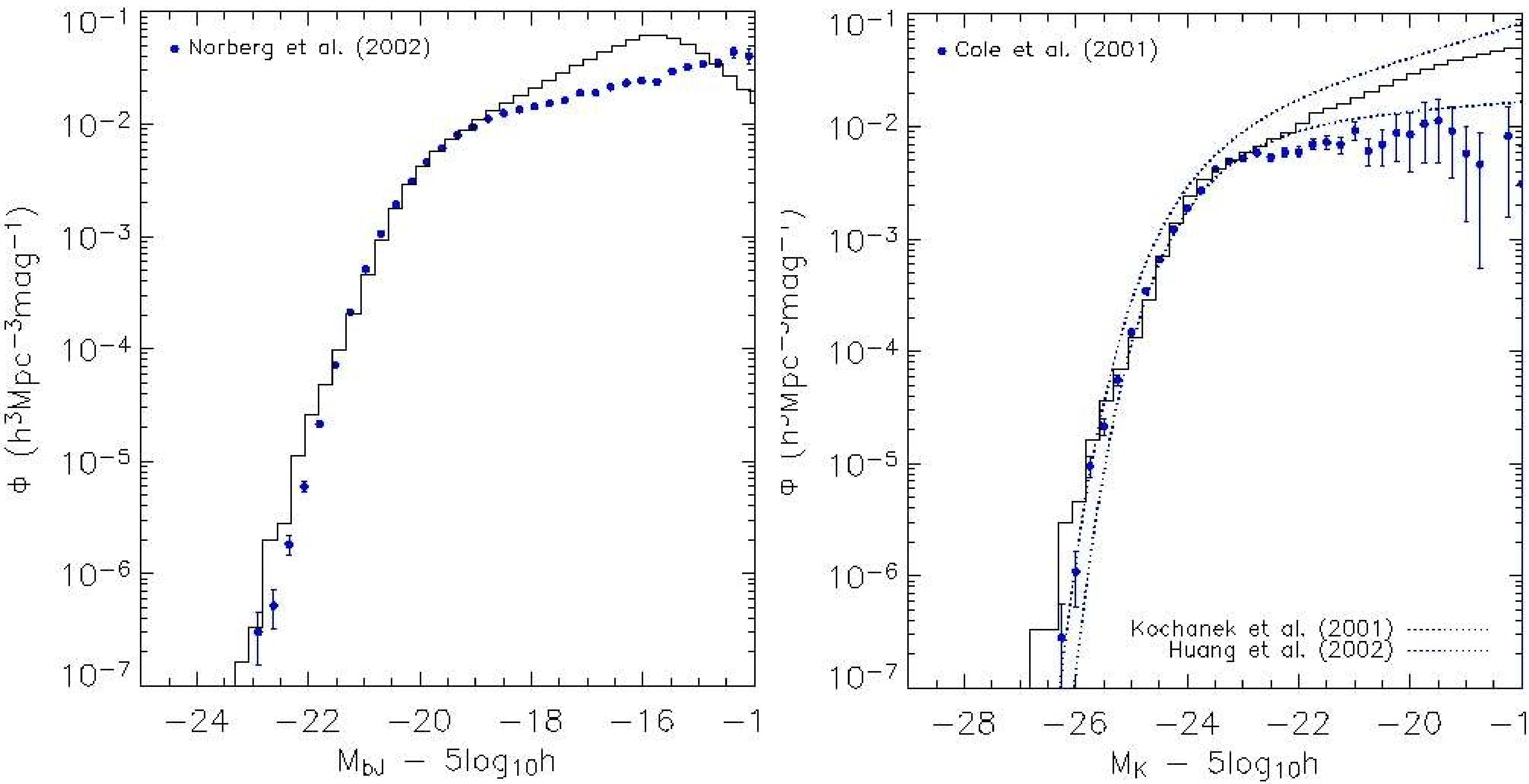
Effect of feedback on the Luminosity Function





Full model with reionisation, AGN and SN feedback Croton et al 2004

Effect of feedback on the Luminosity Function



Full model with ~~reionisation~~, AGN and SN feedback Croton et al 2004

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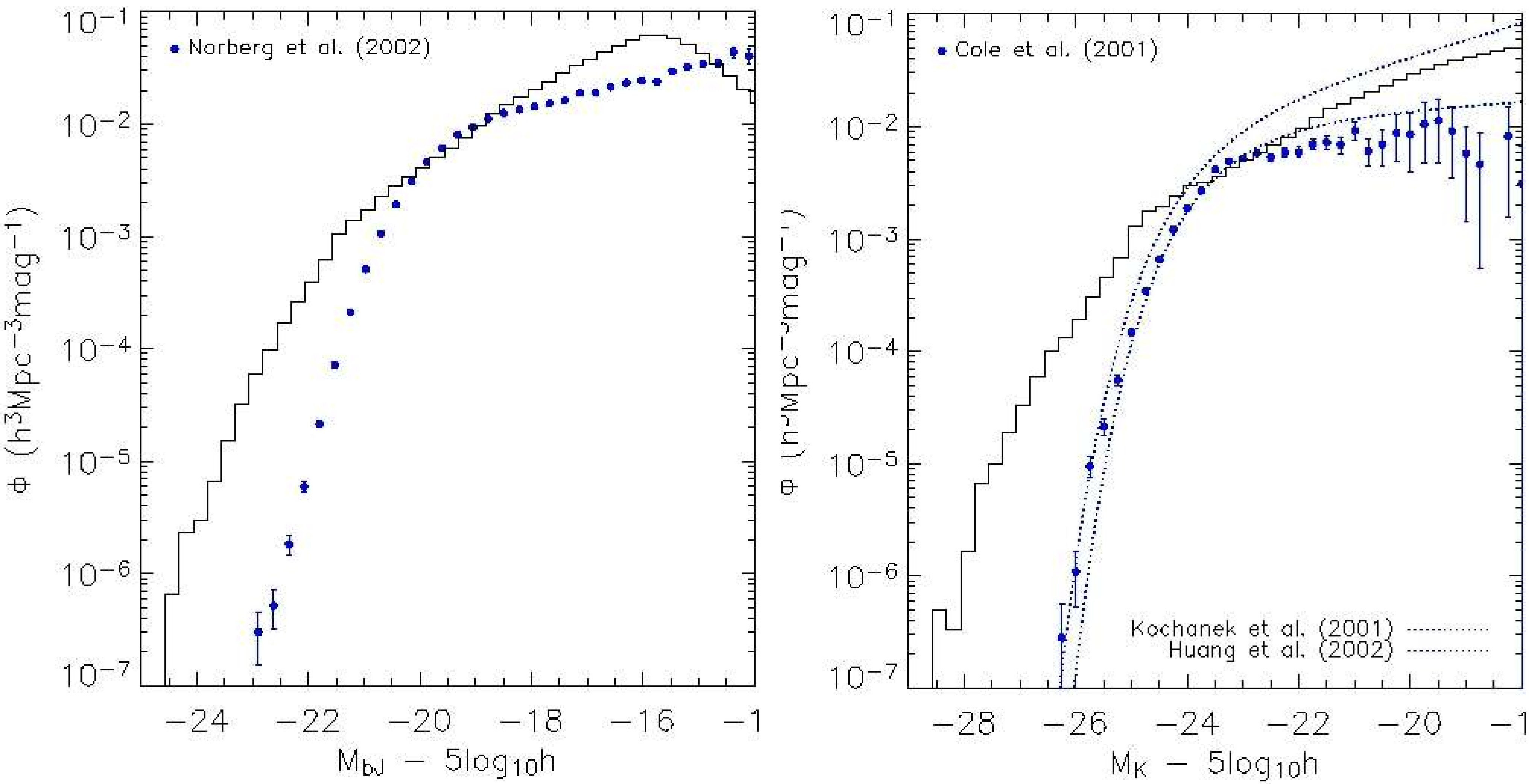
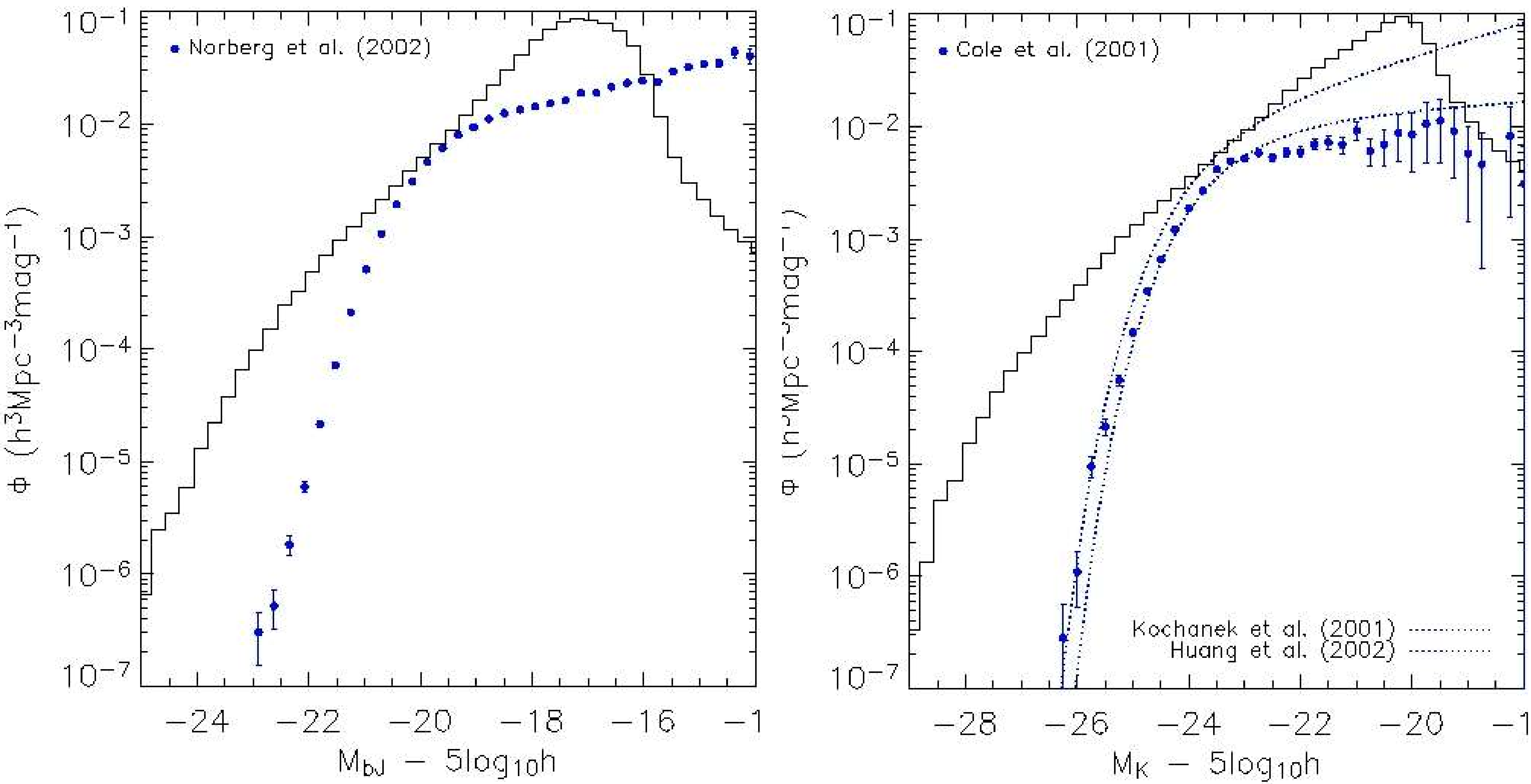


Full model with ~~reionisation~~, ~~AGN~~ and SN feedback   Croton et al 2004

Effect of feedback on the Luminosity Function



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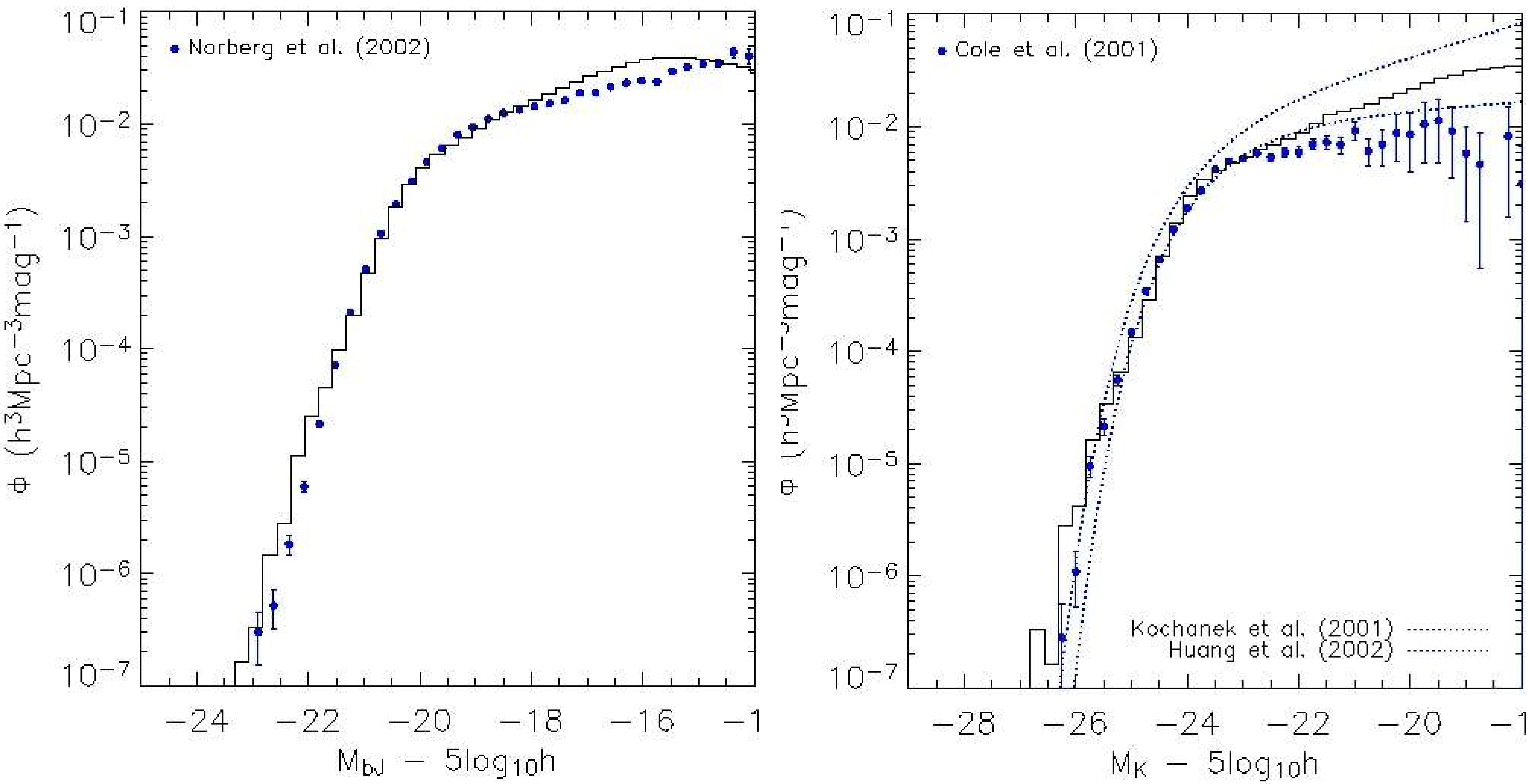
Effect of feedback on the Luminosity Function



Full model with reionisation, AGN and SN feedback Croton et al 2004

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?
- 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.
- An additional mechanism is needed (radio AGN?) to suppress star formation in massive "cooling flow" systems. It should not involve star formation since most massive galaxies are red

Conclusions

- Radiation, hydrodynamic and material feedback are all important at some time for the galaxy/IGM interaction
- Many aspects of feedback are too uncertain and too complex to be reliably simulated
- Insertion of simplified models into simulations or semi-analytic treatments remains the only way to gain intuition
- Star-formation related feedback (incl. “quasar-mode” AGN?) may be responsible for the faint-end slope of the LF
- Non-star-formation related feedback (“radio mode” AGN?) may be responsible for the exponential cut-off of the LF