Granada, November 2004

Large-scale simulation of the galaxy distribution

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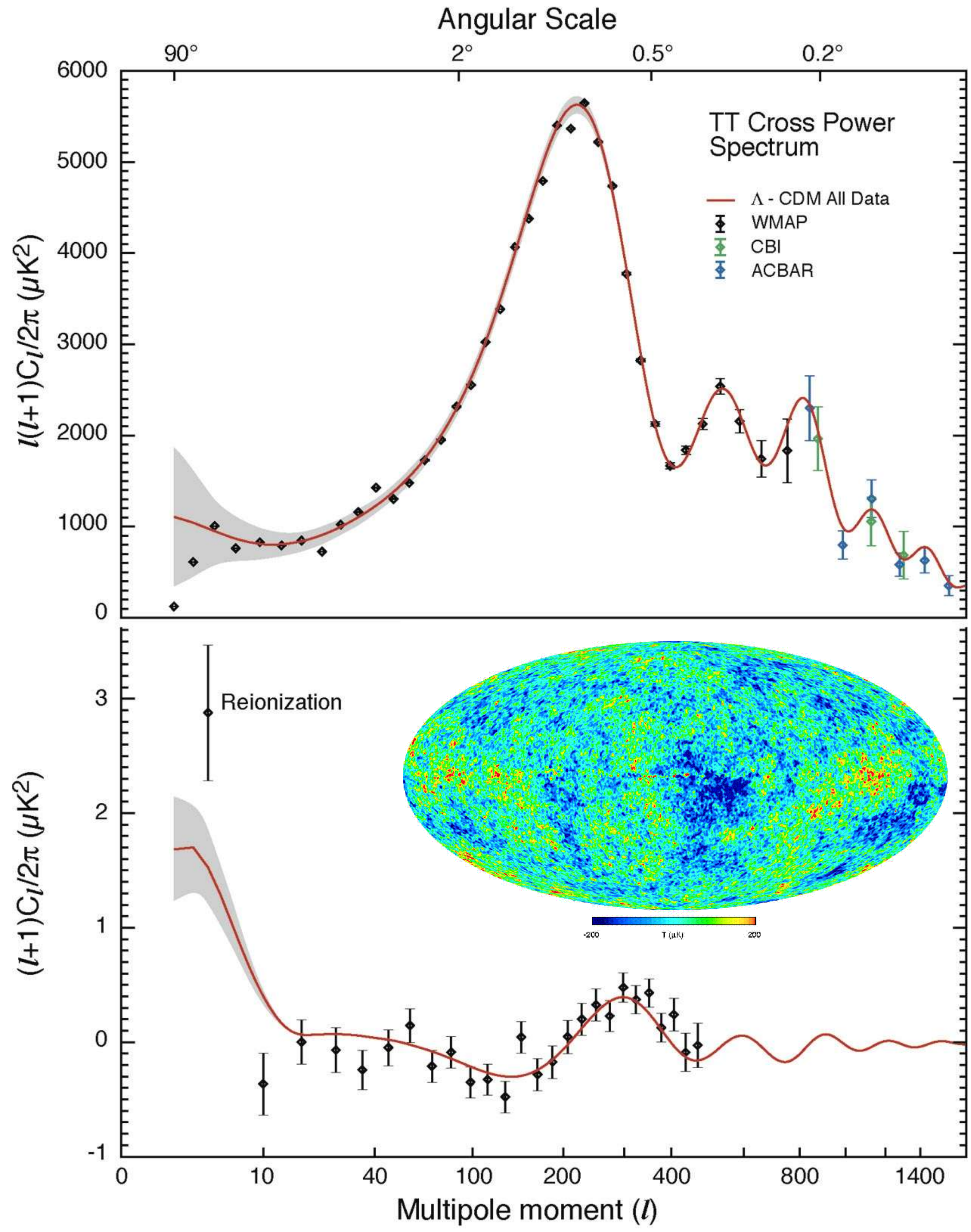


The Emergence of the Cosmic Initial Conditions

- Temperature-temperature and temperature-E-polariz'n power spectra for *WMAP* and interferometers
- Best flat ΛCDM model has:

  (Bennett et al 2003)

  $t_o = 13.7 \pm 0.2$ Gyr

  $h = 0.71 \pm 0.03$ $\quad$ $\sigma_8 = 0.84 \pm 0.04$

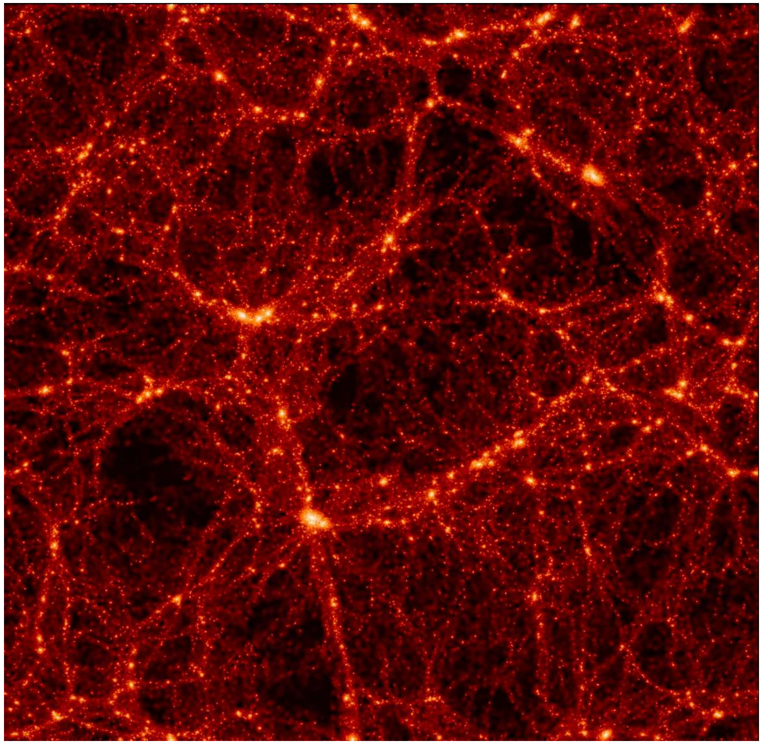
  $\Omega_t = 1.02 \pm 0.02$ $\quad$ $\Omega_m = 0.27 \pm 0.04$

  $\Omega_b = 0.044 \pm 0.004$

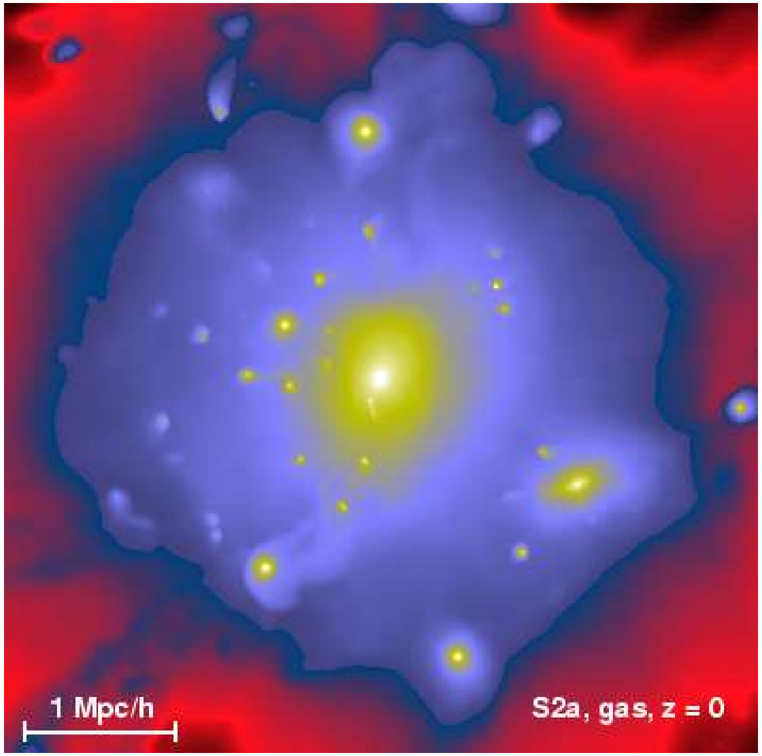
  $\tau_e = 0.17 \pm 0.07$
- Parameters in excellent agreement with other data

Structure evolution in the standard paradigm

...can be simulated reliably for the dark matter



...and also in the baryons when cooling is neglected...



...but not including cooling, star formation and related processes.

Goals for a Model of the Galaxy Population

Predict the joint distribution of luminosity, colour, size, gas content, characteristic velocity, morphology and nuclear activity as a function of redshift and of spatial clustering

-- Luminosity function: split by colour, morphology, AGN...

-- B/T, disk size, bulge size, gas content as functions of L...

-- Tully-Fisher, Faber-Jackson, Fundamental Plane....

-- Morphology-density relations, correlation functions, cluster M/L, galaxy content, abundance...

-- Evolution of SF and AGN activity, “Madau” plots, LBG's, DLA's, SCUBA sources, SDSS quasars.....

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

AGN physics

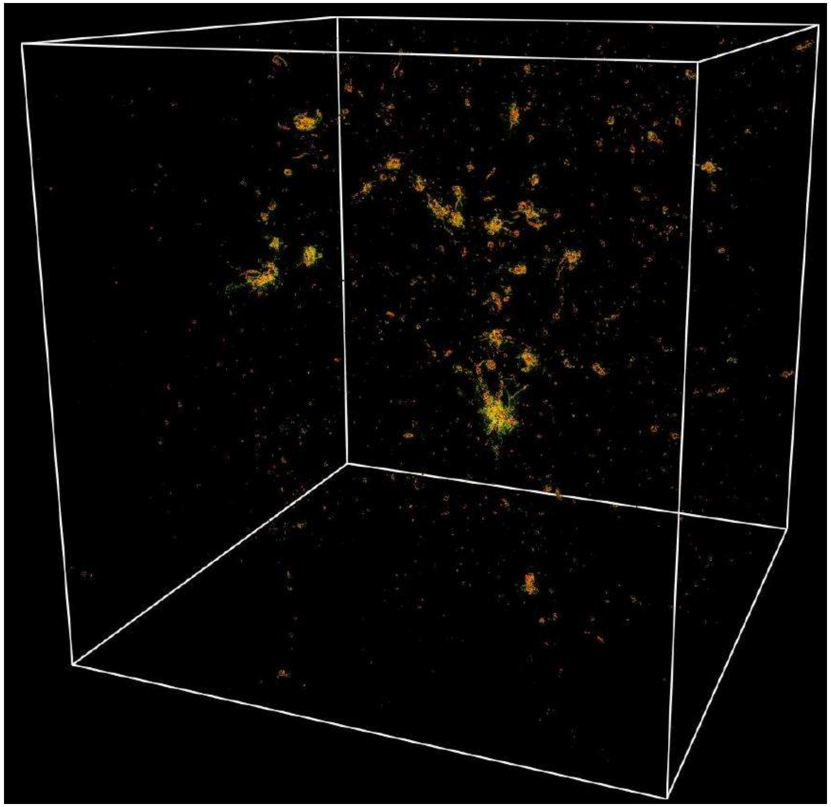
BH formation, feeding, AGN phenomenology, feedback

Environment interactions

Galaxy mergers, tidal effects, ram pressure effects

Modelling the galaxy population I

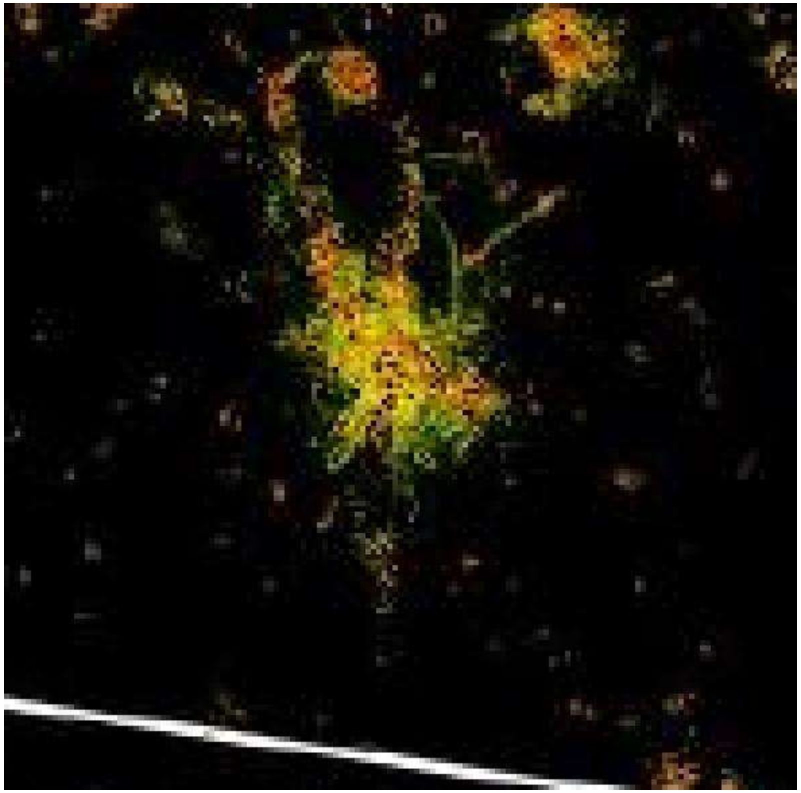
25 Mpc/h



Z=0

Cen et al (2001)

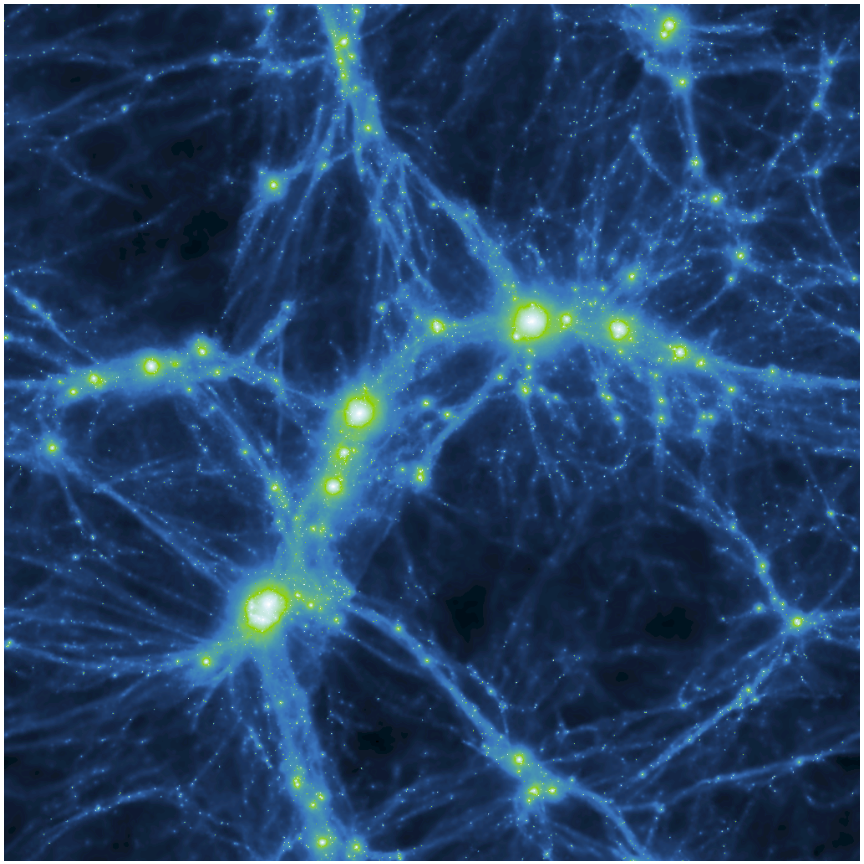
5 Mpc/h



Large Eulerian grid code 768 x 768 x 768 cells

Modelling the galaxy population II

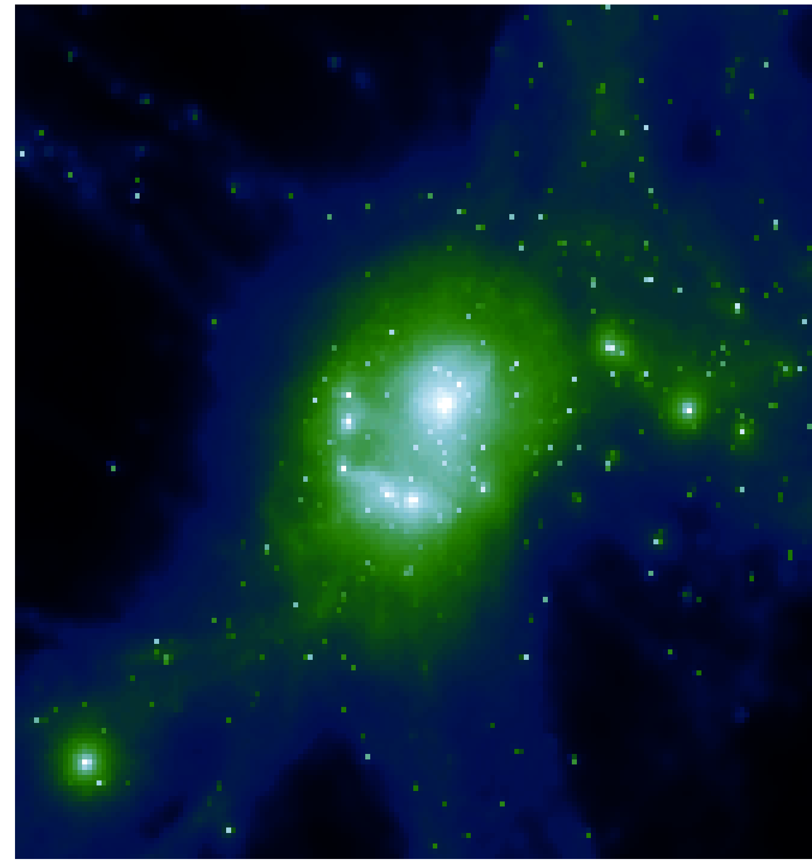
33.5 Mpc/h



Z=0

Springel Hernquist & White (2001)

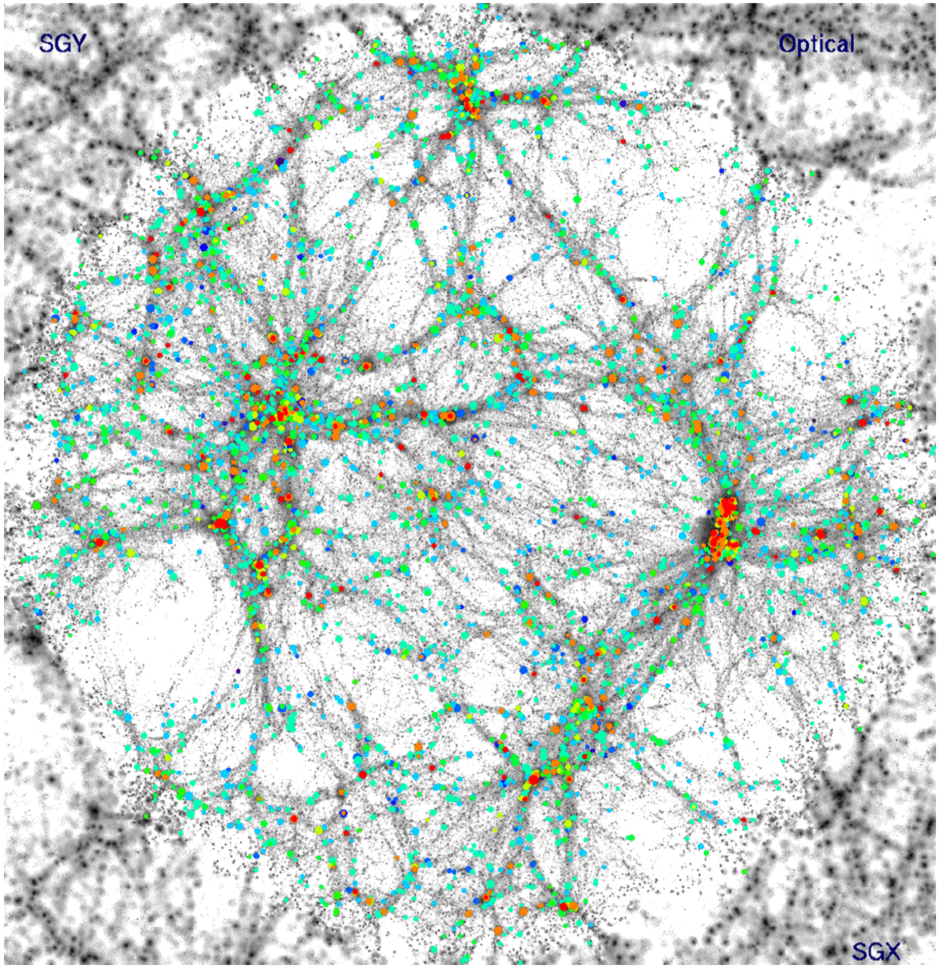
5 Mpc/h



2 x 300^3 particle N-body + SPH simulation including star formation

Modelling the galaxy population III

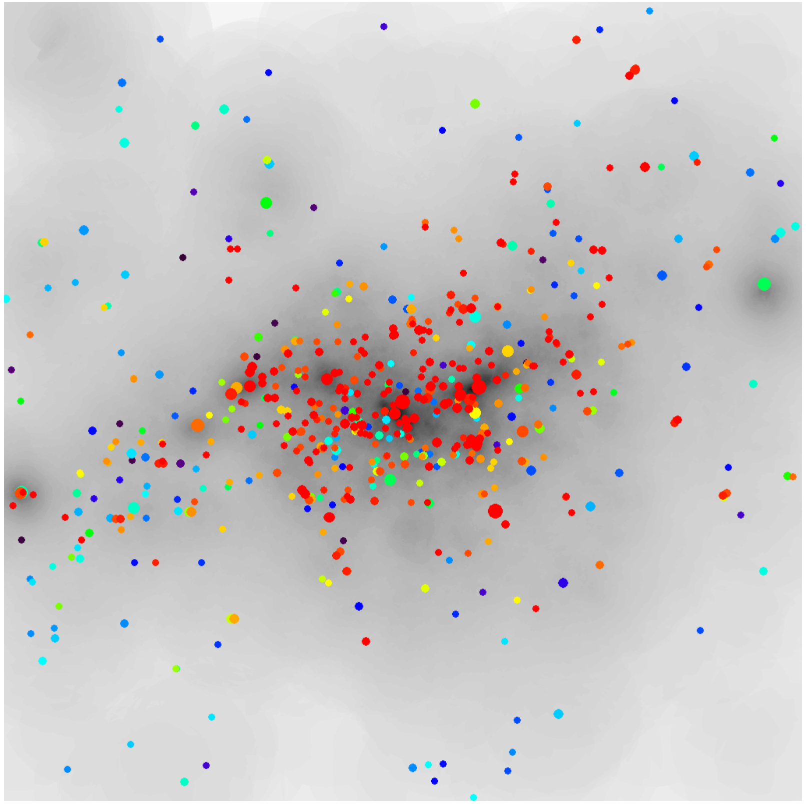
160 Mpc/h



Z=0

Mathis et al (2001)

5 Mpc/h



"Virgo" $M_B < -17.0$

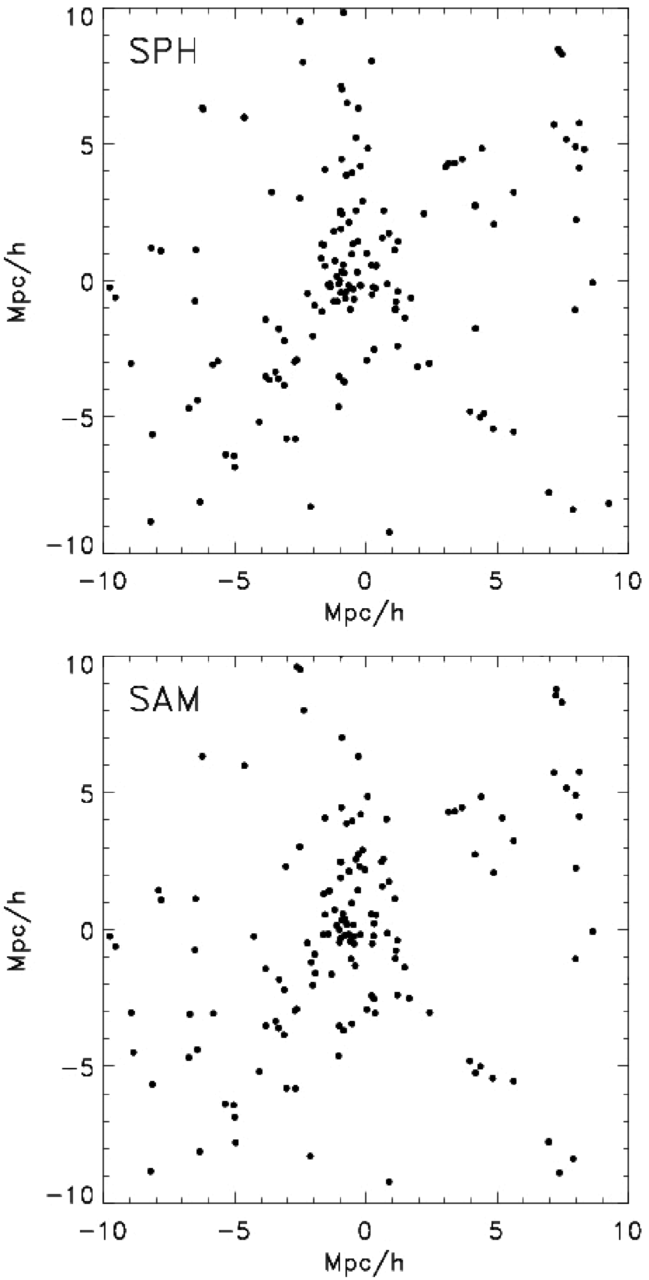
70 million DM-particle simulation with phenomenological baryonic physics

- a ΛCDM model *constrained* to match the local Universe -

Modelling Gas Cooling and Condensation

- In nonlinear structures (halos) infalling gas heats to the virial temperature $T \sim 35\,(V_{circ}/\,\mathrm{km\ s^{-1}})^2$
- In massive objects and at late times a quasi-statistic hot gas atmosphere builds up, otherwise gas cools quickly
- Cold gas builds up in a central, baryon dominated object where it forms stars or settles into a rotation-supported disk
- Cooling times are strongly metal-dependent at the temperatures characteristic of bright galaxies → issues of mixing from winds
- The cooling process at the centres of present-day groups and clusters appears to be suppressed – the "cooling flow problem"

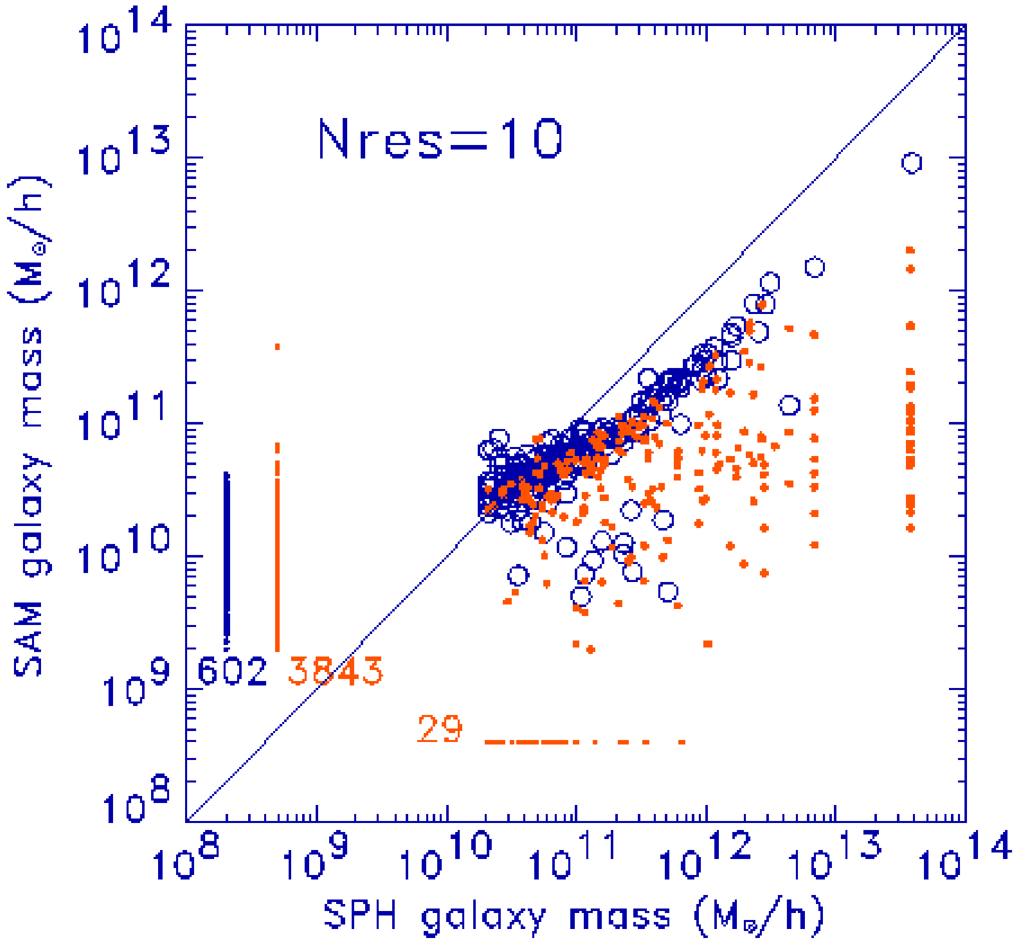
SPH vs SA galaxy formation in a cluster simulation



- Simulation of a 7 x 10^{14} h^{-1}Mpc cluster in a ΛCDM universe
- 2 x 10^5 dark matter particles in the high resolution region
- 2 x 10^5 gas particles in the SPH simulation
- Cooling only included in both simulations
- SPH `galaxies' contain >9 cold particles
- SA `galaxies' form in >9 particle halos
- Images show `galaxies' with mass above 6 x 10^{10} h^{-1} M_{sun} in both cases

Yoshida, Stöhr, Springel, White (2001)

Object by object comparison of SPH and SA 'galaxies'



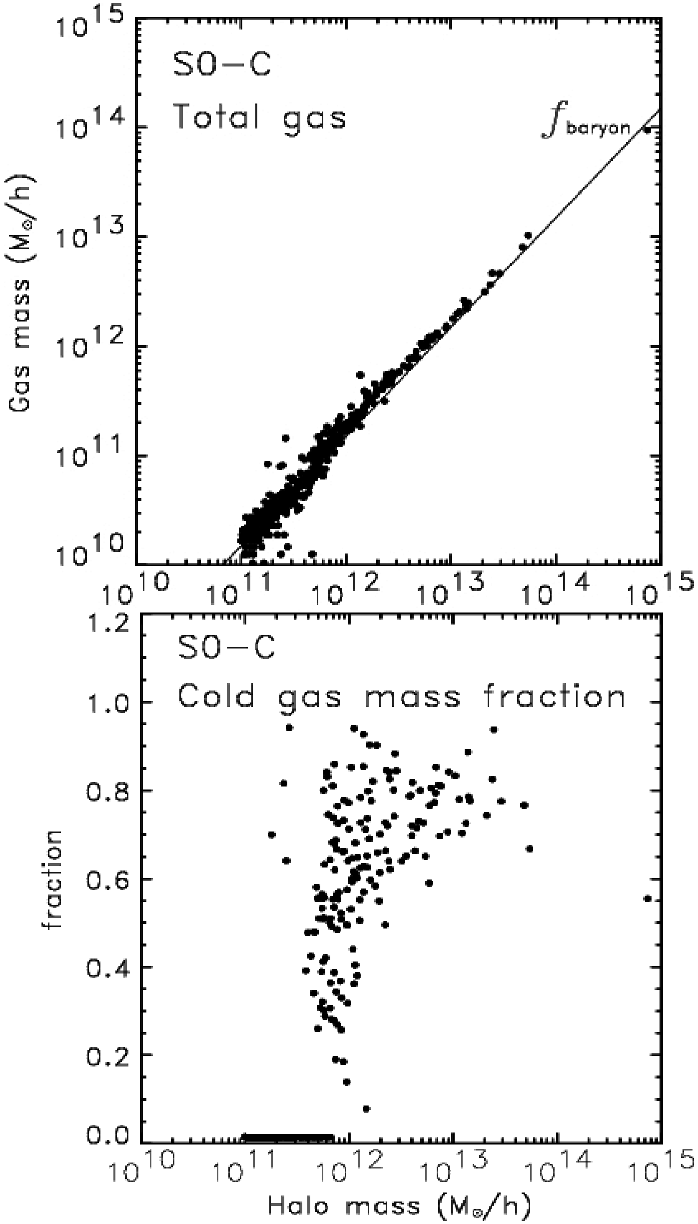
- To the respective resolution limits there are 359 SPH and 4775 SA `galaxies' (when SA merging switched off)
- Almost all SPH galaxies have a SA counterpart

  → SPH galaxies form only at the centres of dark halos

- Most low mass SA galaxies have no SPH counterpart

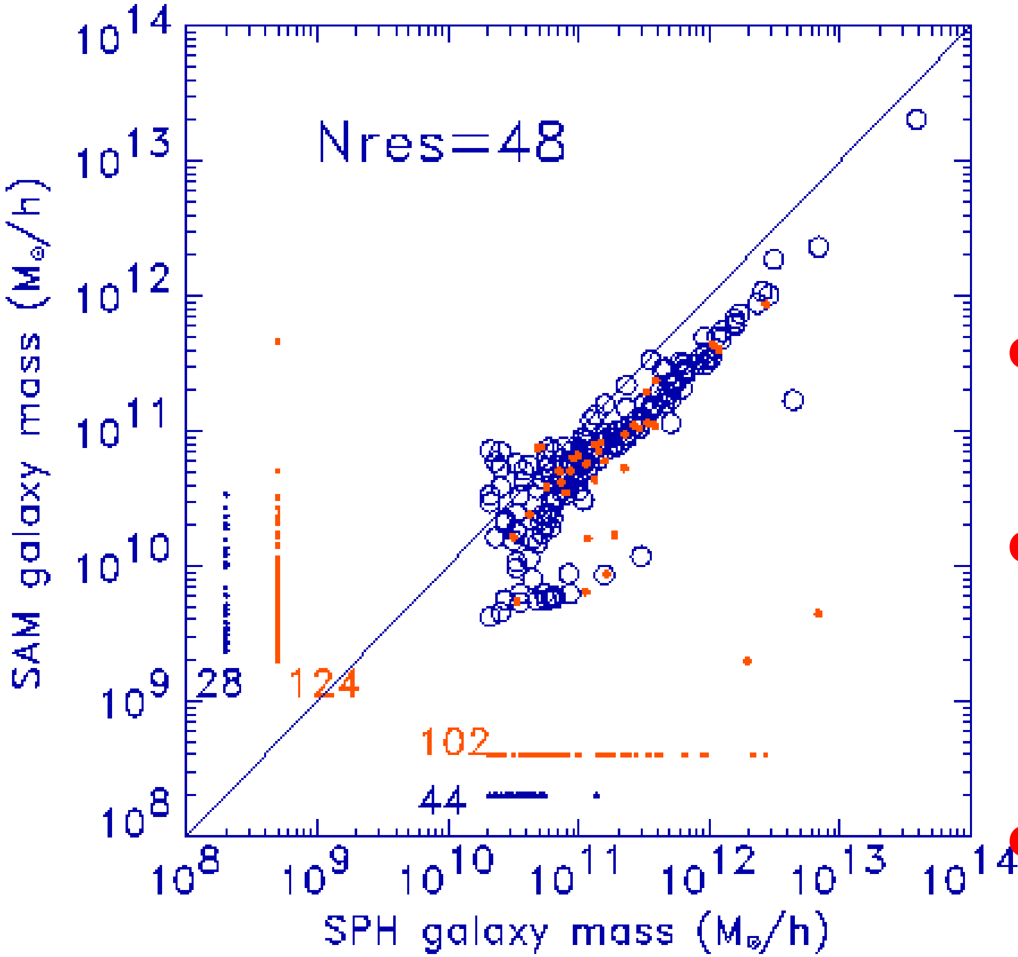
  → Effective SPH resolution is lower than SA resolution

SPH gas accumulation and cooling in halos



- Gas content of all halos is very close to $f_{baryon} M_{halo}$
- Most gas cools by z=0 in big halos
- Gas cooling is suppressed in halos with mass less than about 50 particles

Merging and cooling in SPH vs SA `galaxies'



- Stopping all SA galaxy formation in halos with < 48 particles (and allowing SA merging)

  $N_{gal}(SPH) = N_{gal}(SA)$

- Except near the mass limit there is an excellent correspondance
- The masses are tightly related with

  $M_{gal}(SPH) = 2.5\ M_{gal}(SA)$

  (this is a problem with the <u>SPH)</u>
- The main cluster contains the same number of SPH and SA galaxies

SPH vs SA for treating cooling

- Above the resolution limit of both techniques there is excellent object-by-object agreement
- The resolution limit of SPH is at a 5 times larger dark matter mass than that of SA
- Merging rates in the approaches agree
- Cooling rates are too high in SPH because of kernel smoothing problems near phase boundaries
- Cooling rates may be too low in SA because of an incorrect coefficient in the cooling flow model
- For equivalent resulting galaxy populations SA needs 2 to 3 orders of magnitude less CPU time than SPH

Treating star formation

- There is no *a priori* theory for star formation, only observational relations such as the Kennicutt "laws"

- Both simulations and SA models assume simple physically based prescriptions for the star formation rate, e.g.

$$\rho_g > \rho_{thresh}; \ \nabla\bullet\rho_g \mathbf{u} < 0; \ m_{Jeans} < m_{part}; \ d\rho_* / dt = \varepsilon \, \rho_g / t_{dyn} \quad \text{(SPH)}$$

$$\sigma_g > \sigma_{thresh}; \ d\sigma_* / dt = \varepsilon \, (\sigma_g - \sigma_{thresh}) / t_{dyn} \quad \text{(SA)}$$

- Form and parameters of the SF laws are *chosen* to reproduce the observations

- Observations of SF to high redshift can check assumptions

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

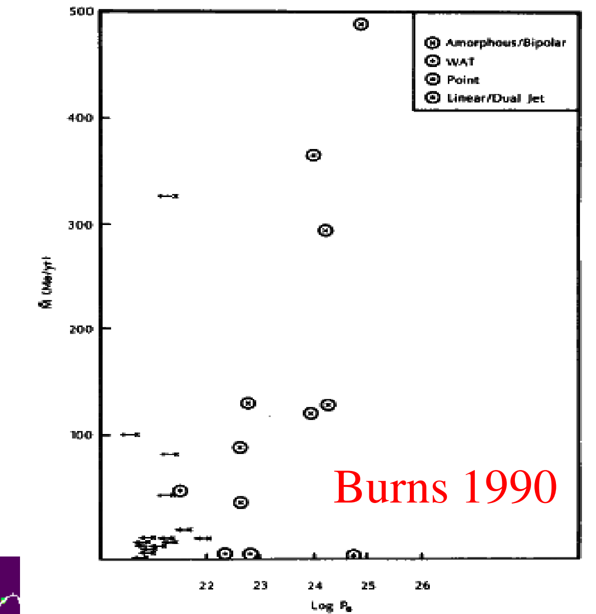
- AGN feedback

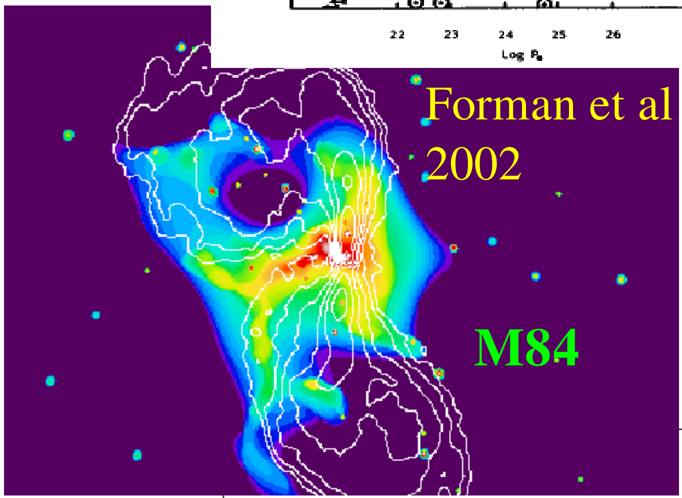
  "Radio" mode $\Delta M'_{cool} = \Delta M_{cool} - \eta\ M_{BH}^{\alpha}\ T_{clus}^{\beta}$ Croton 2004

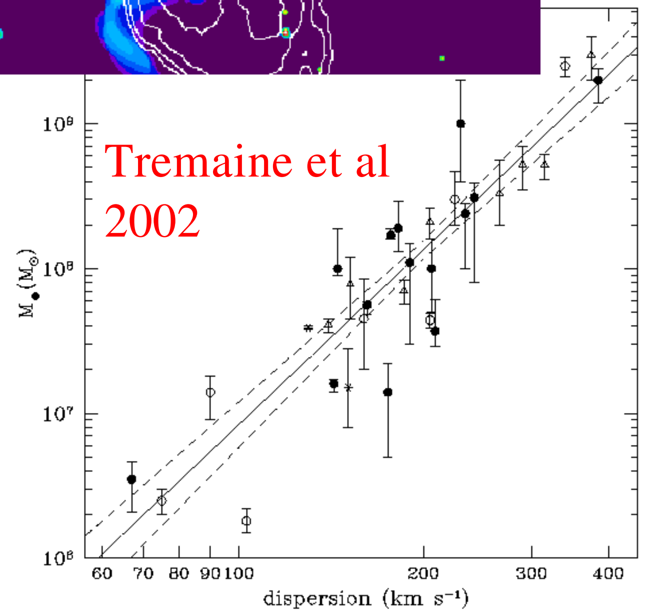
  "Quasar" mode builds up BH masses, establishes Magorrian relation, feedback included in SN? Kauffmann & Haehnelt 2000

Feedback from Radio Galaxies

- 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 rAGN
- The central AGN are *observed* to influence the gas strongly *without* sig. star formation
  → rAGN affect cooling flows
- BH masses correlate strongly with global properties for *all* spheroids
  → spheroid and BH formation are closely intertwined for all galaxies -- HOW?







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

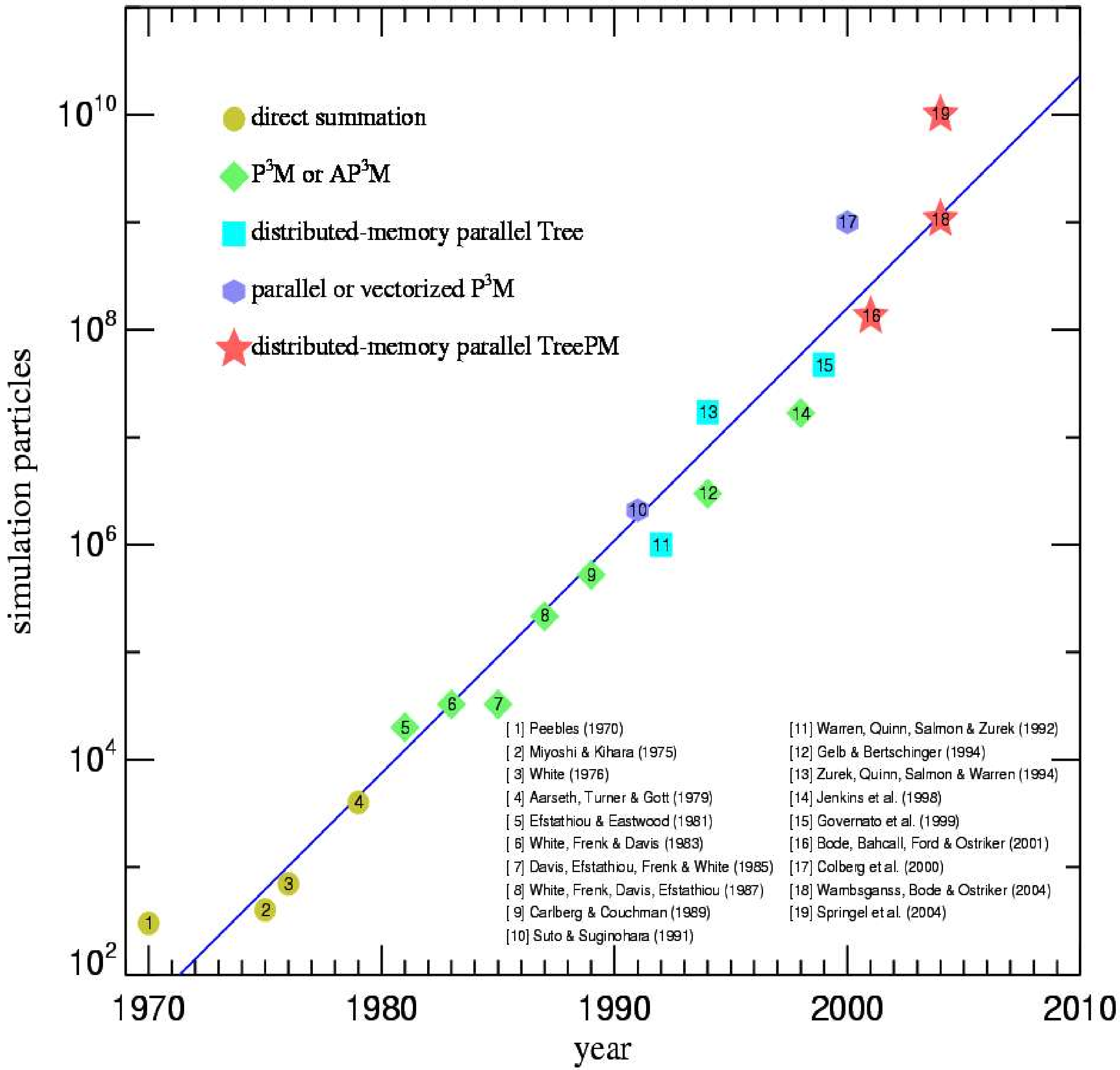
(c) Simulations of large enough volume to represent bright galaxies, galaxy clusters, quasar hosts...

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**

A <u>testbed</u> for studying galaxy formation models

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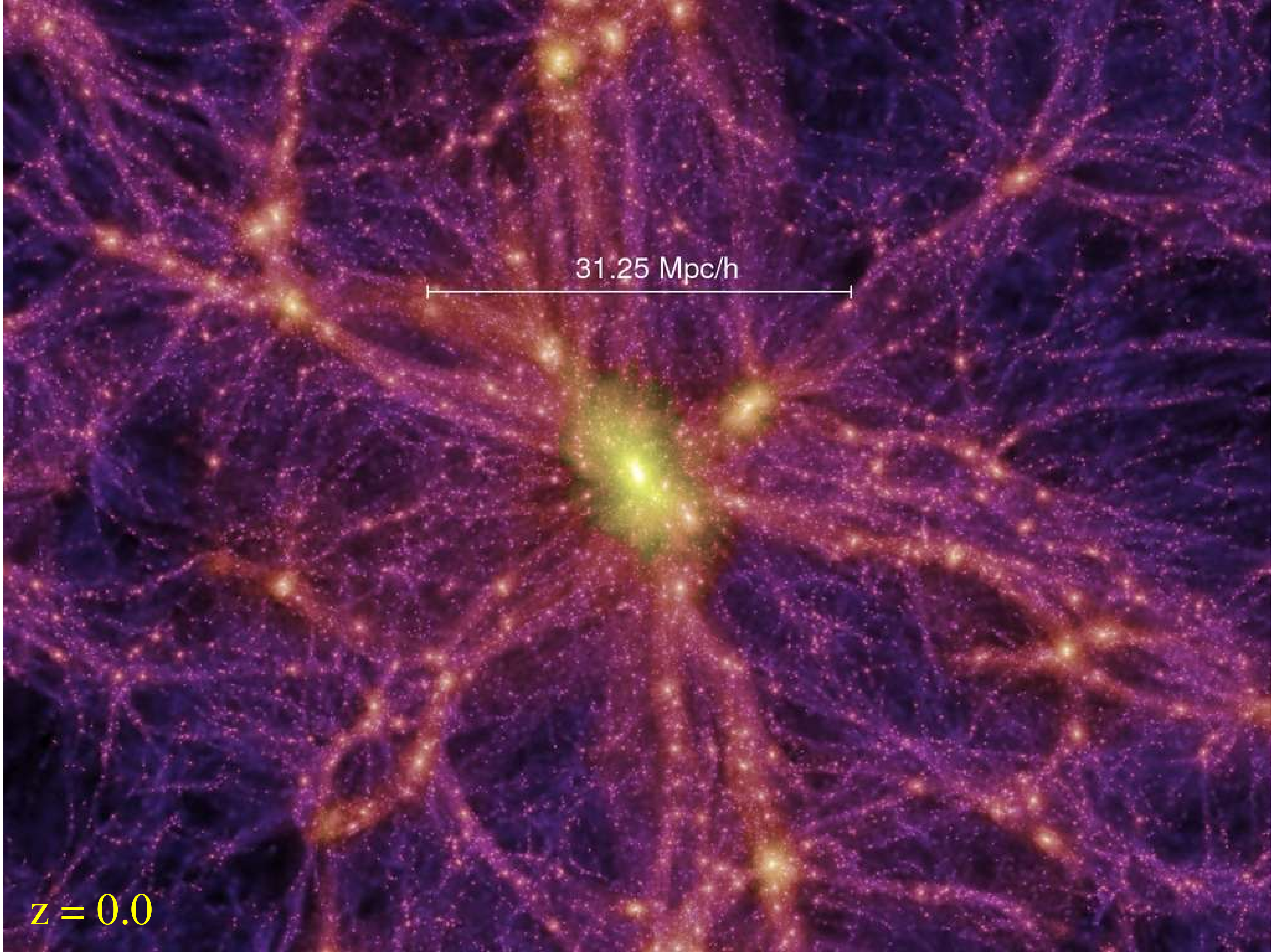
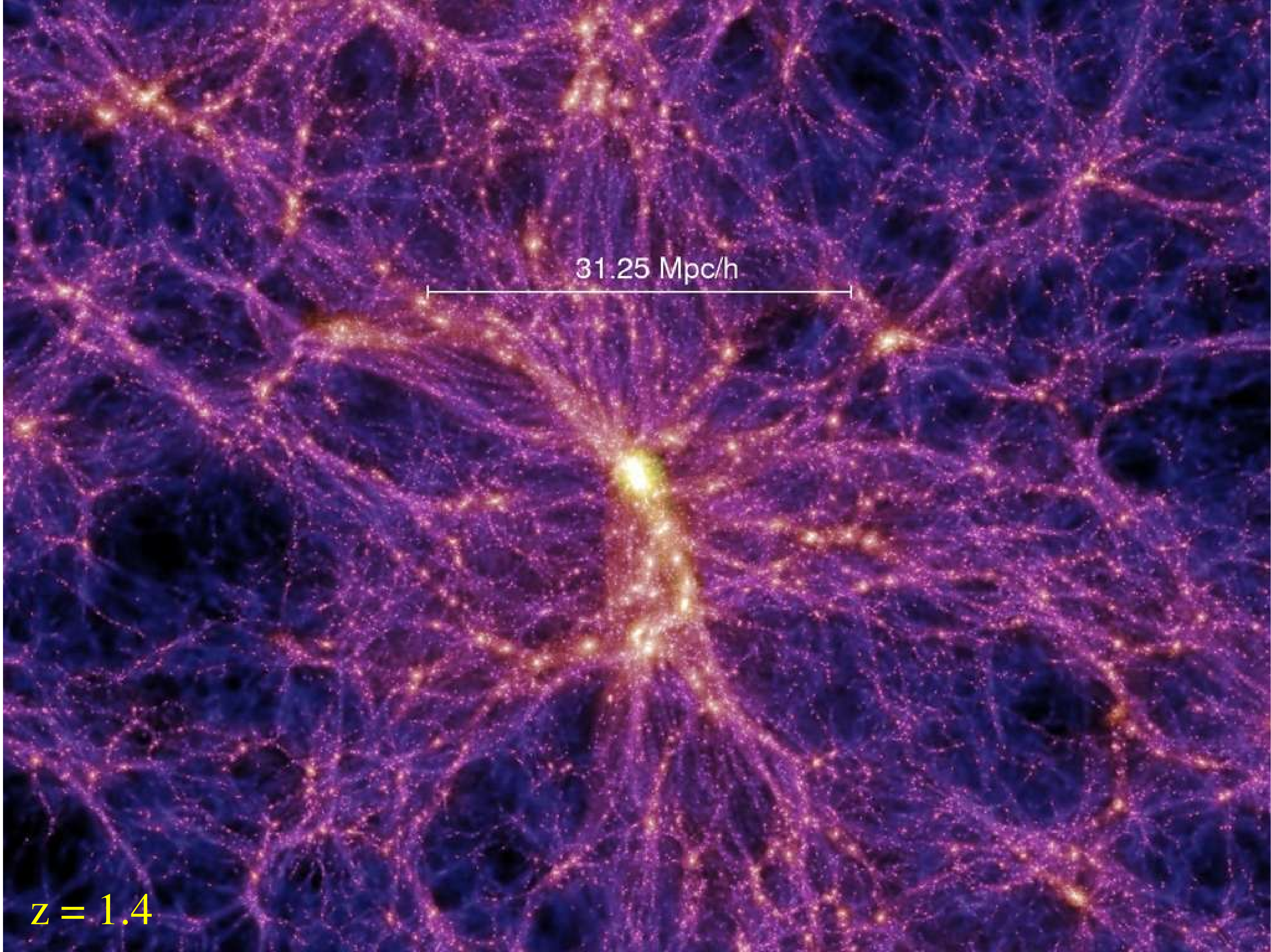
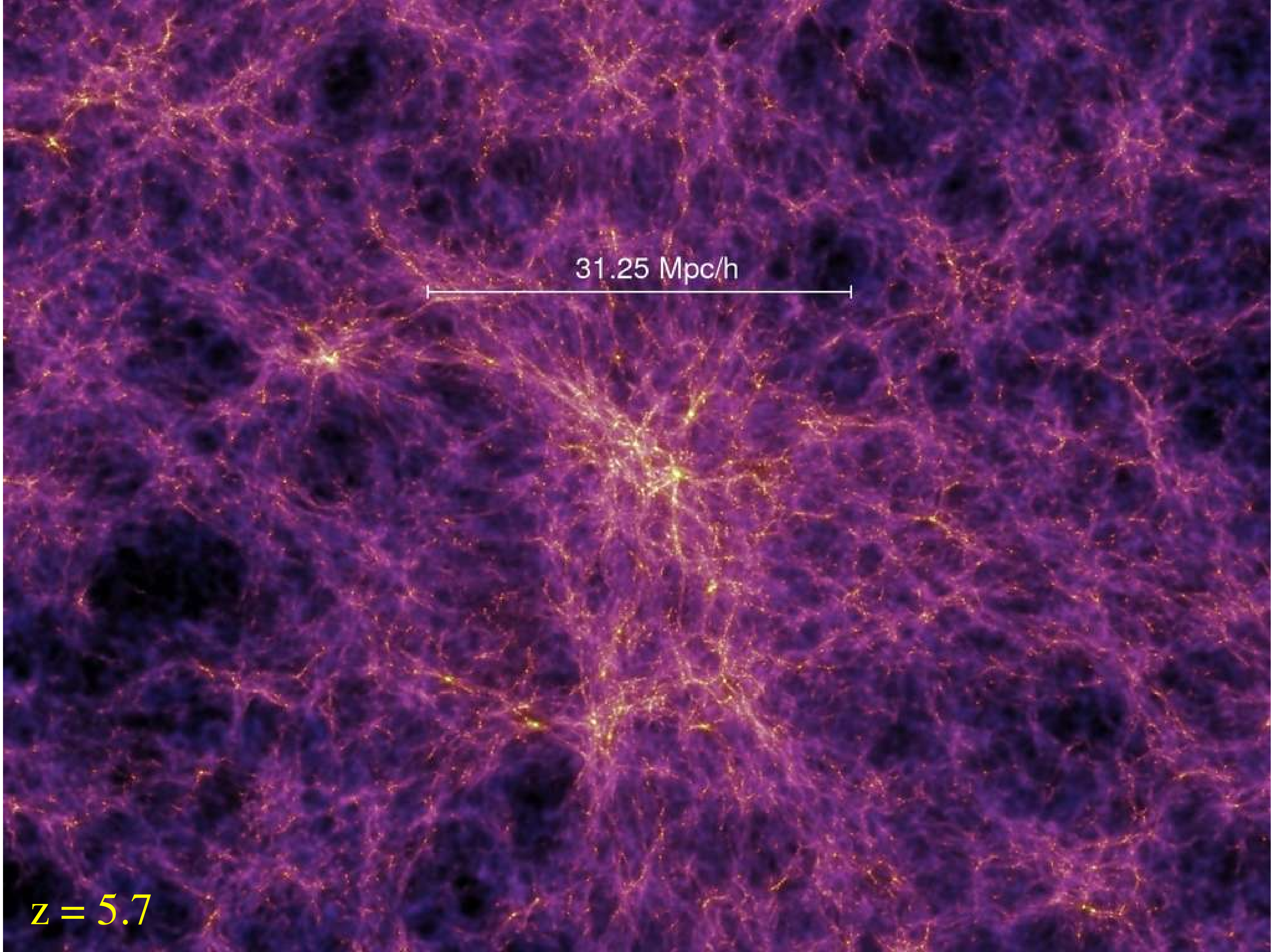
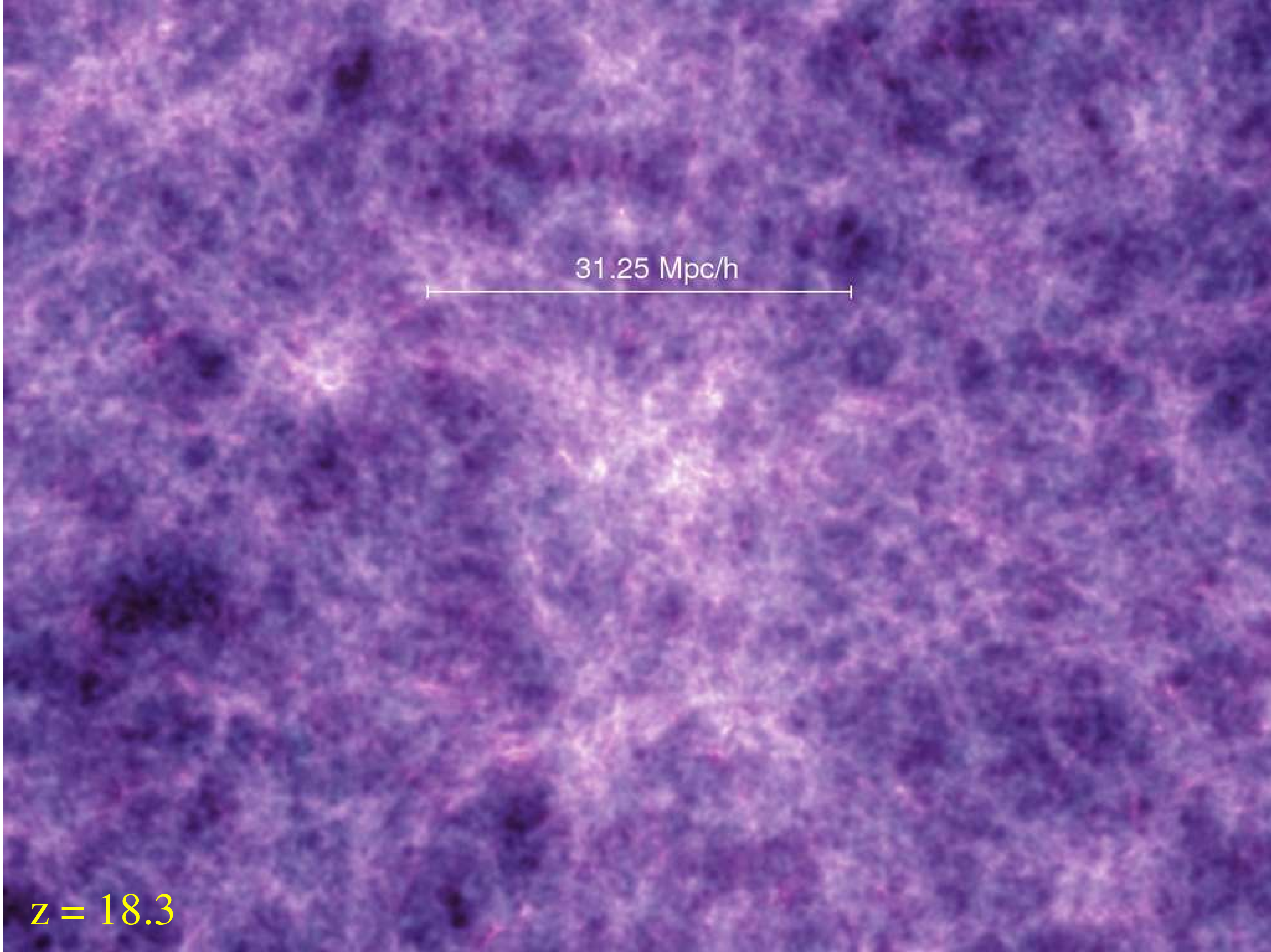
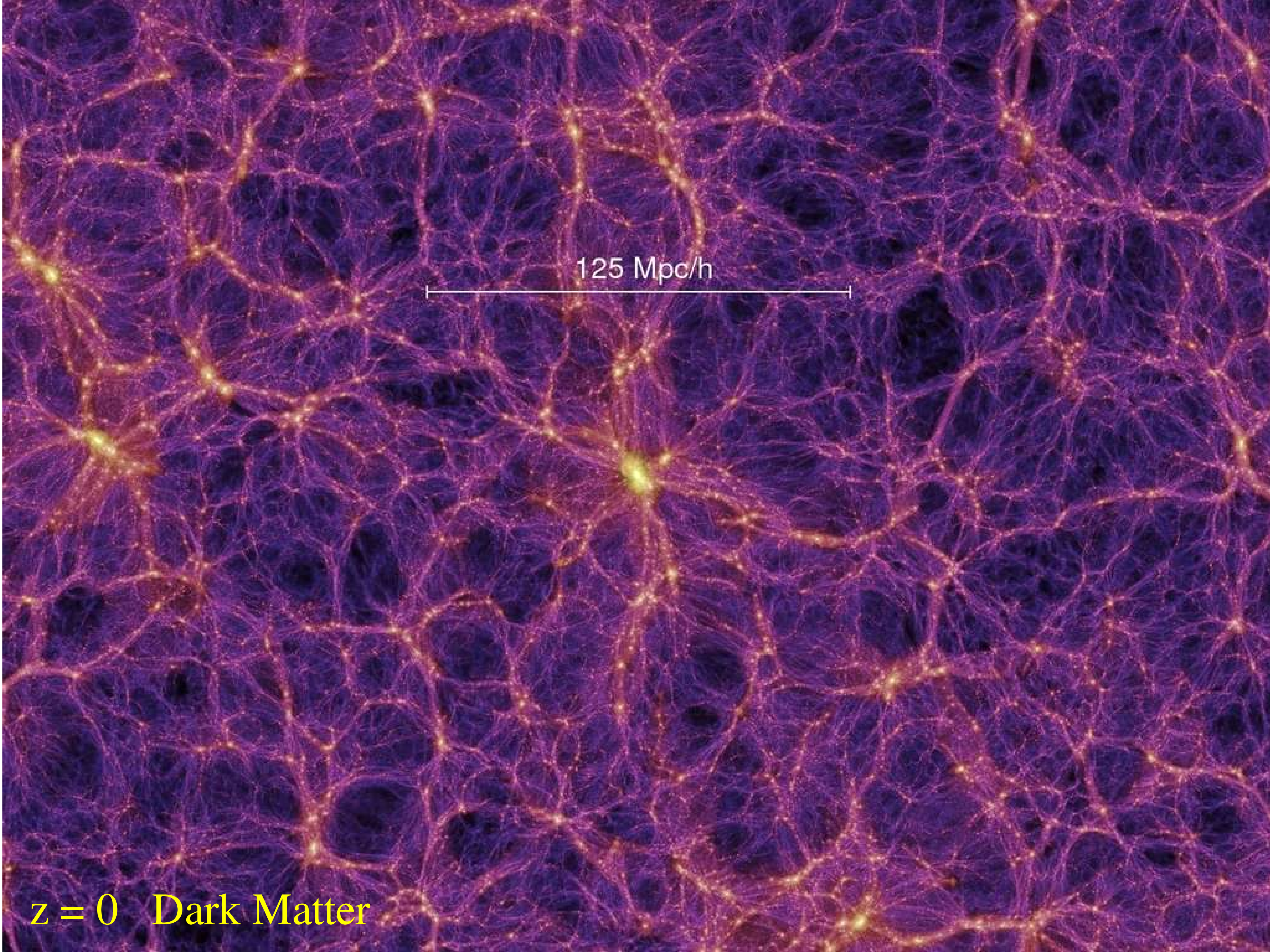
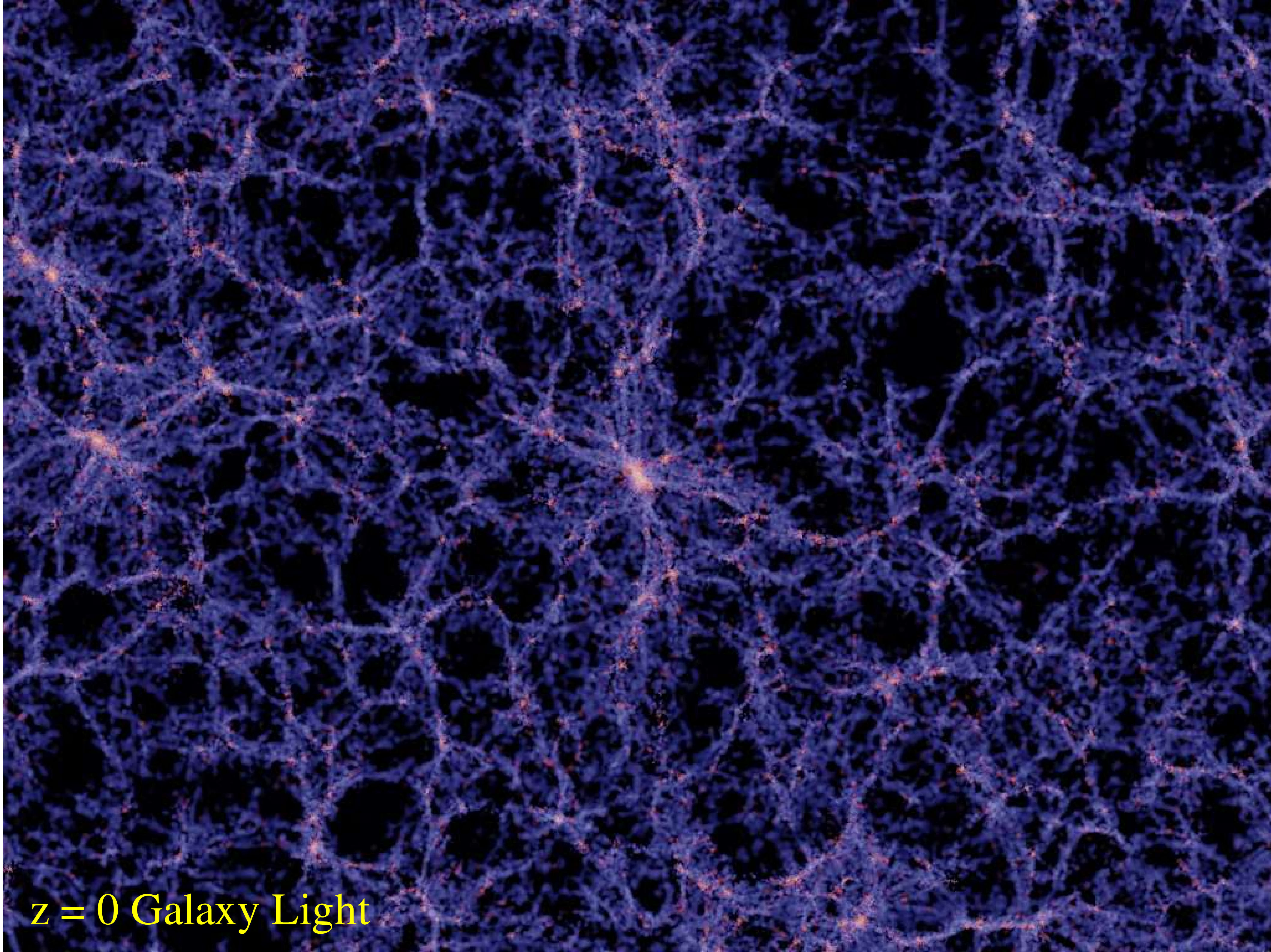

31.25 Mpc/h
z = 0.0


31.25 Mpc/h
z = 1.4


31.25 Mpc/h
z = 5.7


31.25 Mpc/h
z = 18.3

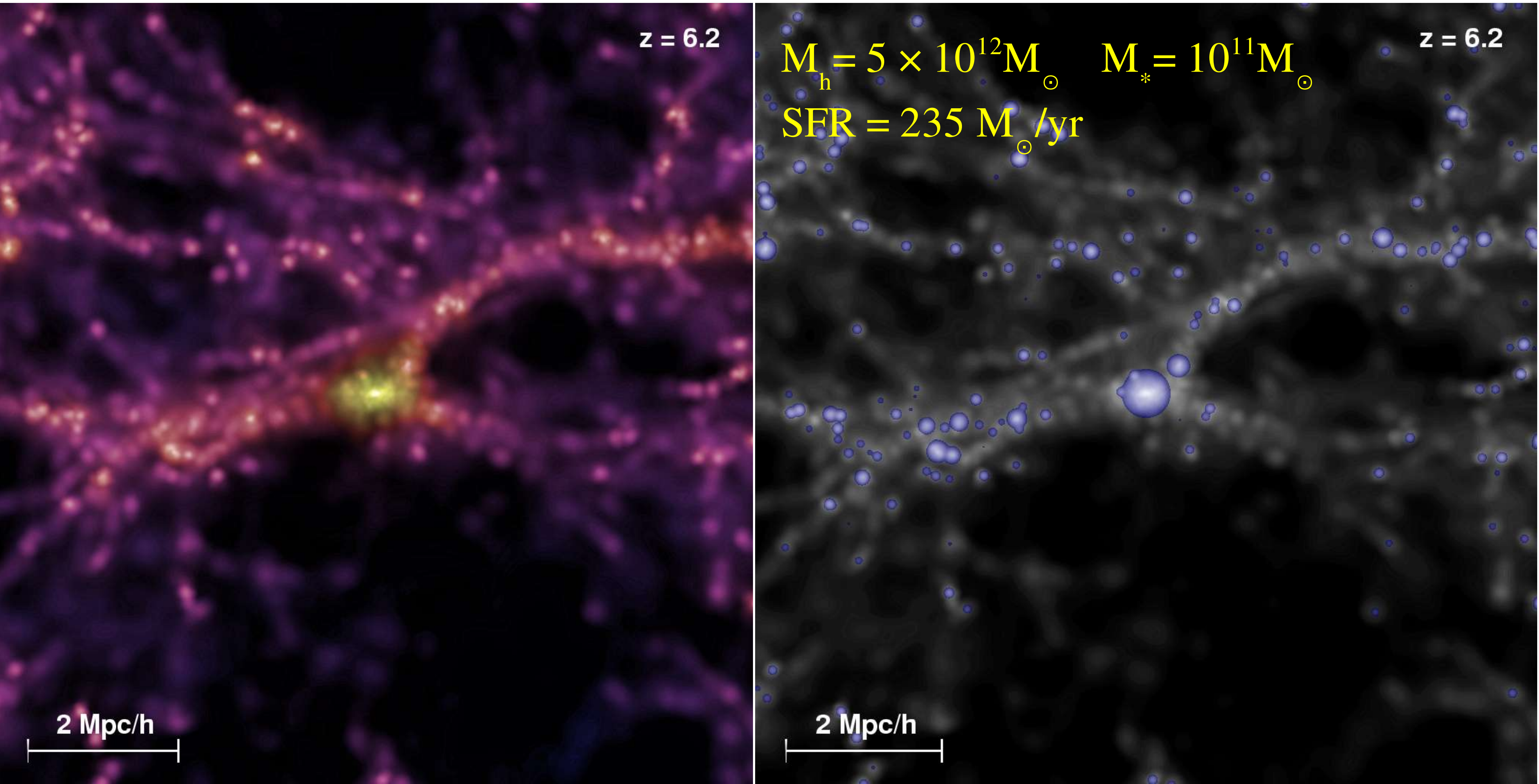

125 Mpc/h
z = 0 Dark Matter


z = 0 Galaxy Light

"SDSS Quasar" Host at z=6.2

Springel et al 2004

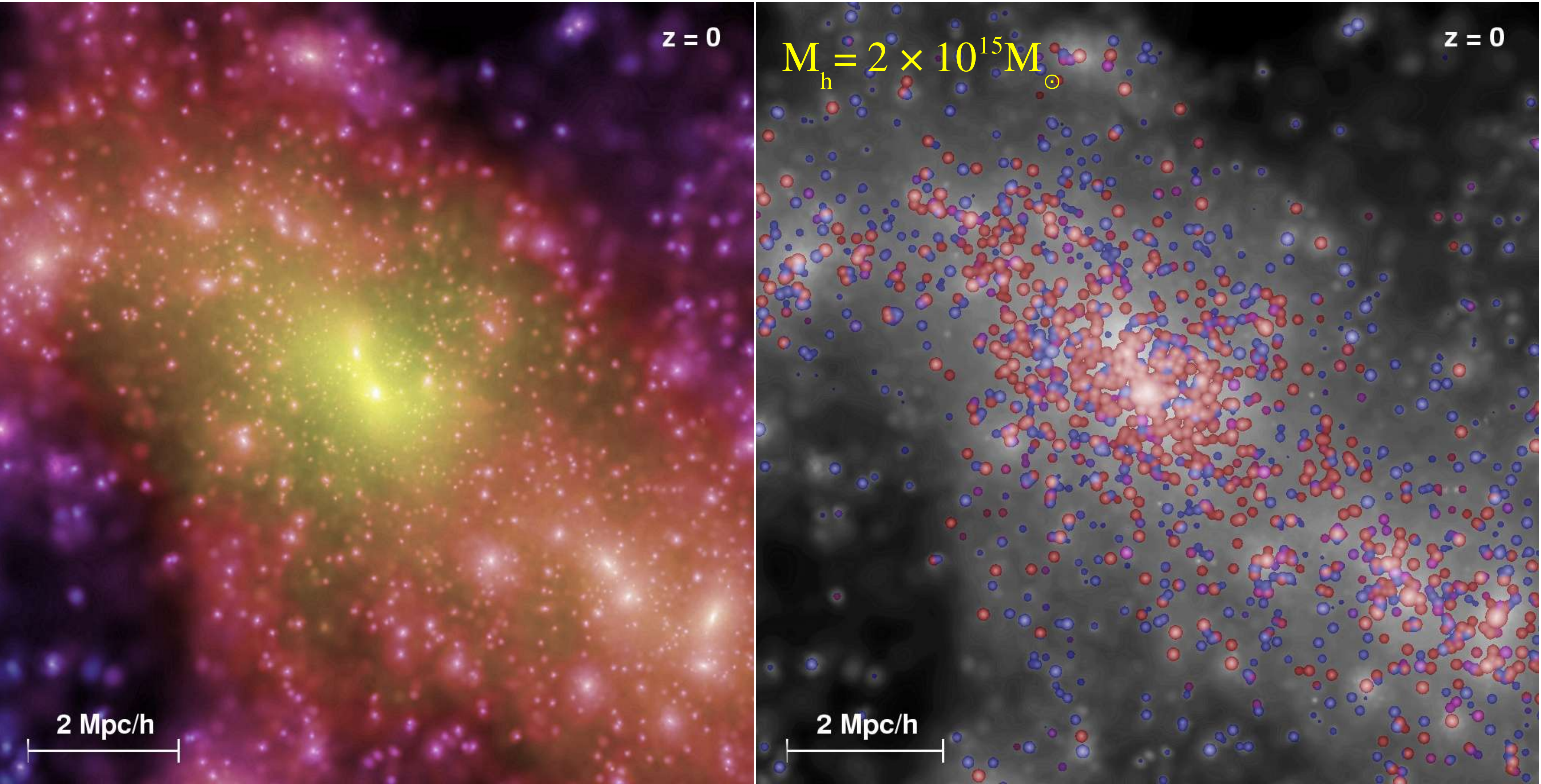
One of the most massive halos, containing one of the most massive galaxies with one of the highest SFR's and most massive BH's



"SDSS Quasar" Descendant at z=0

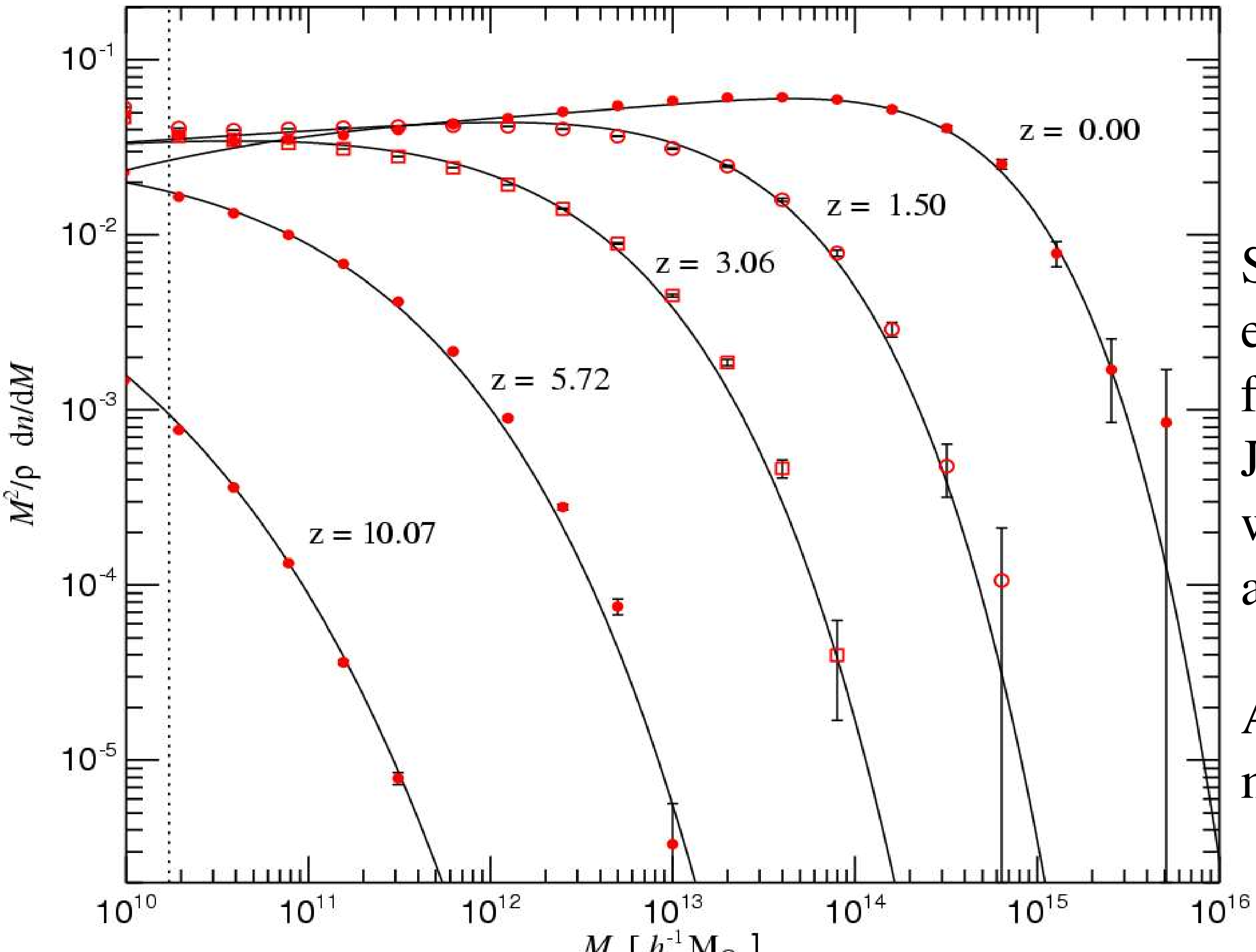
Springel et al 2004

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

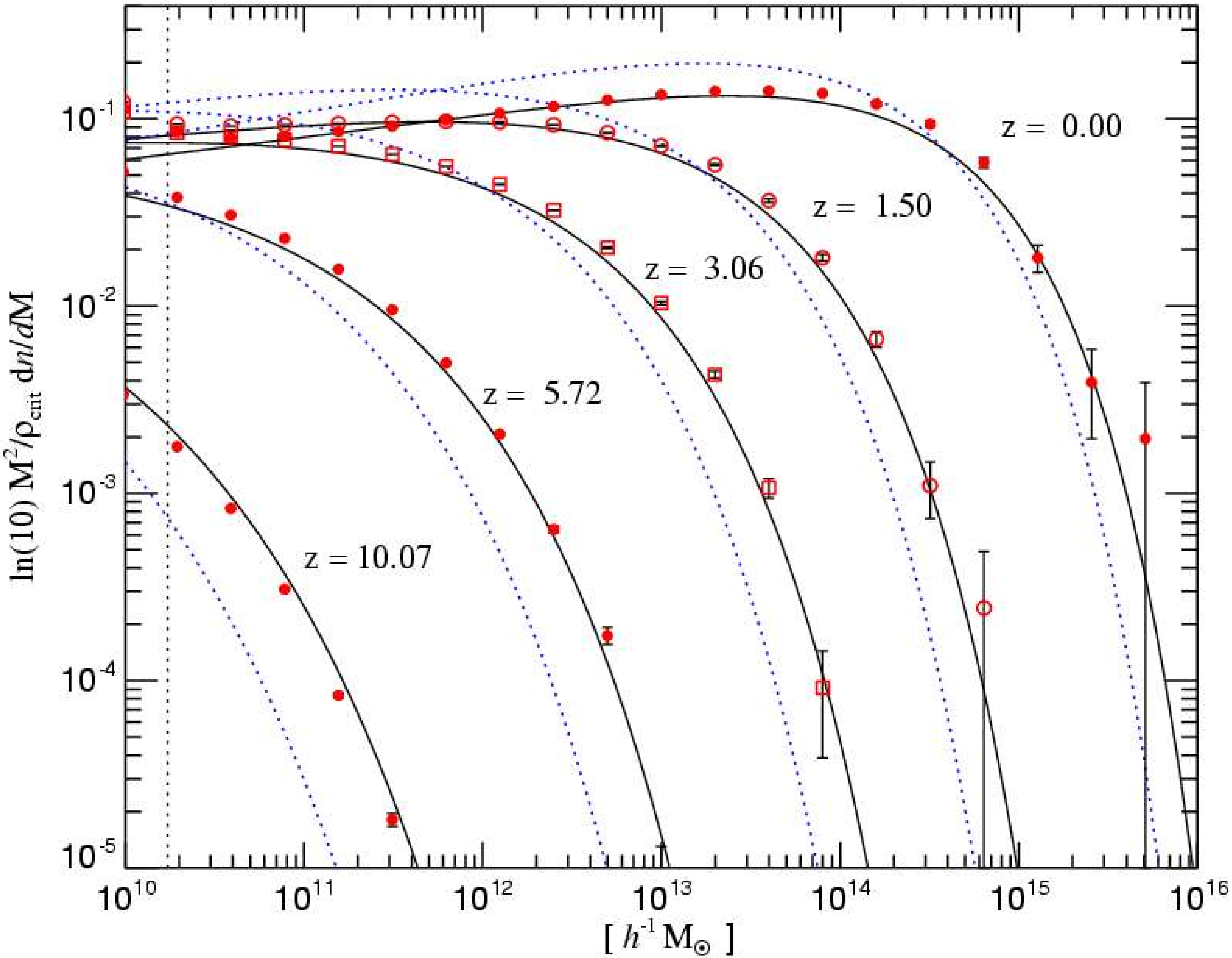


Solid curves are the empirical fitting formula from Jenkins et al 2001 with no parameters adjusted

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

Halo Mass Functions in the MS

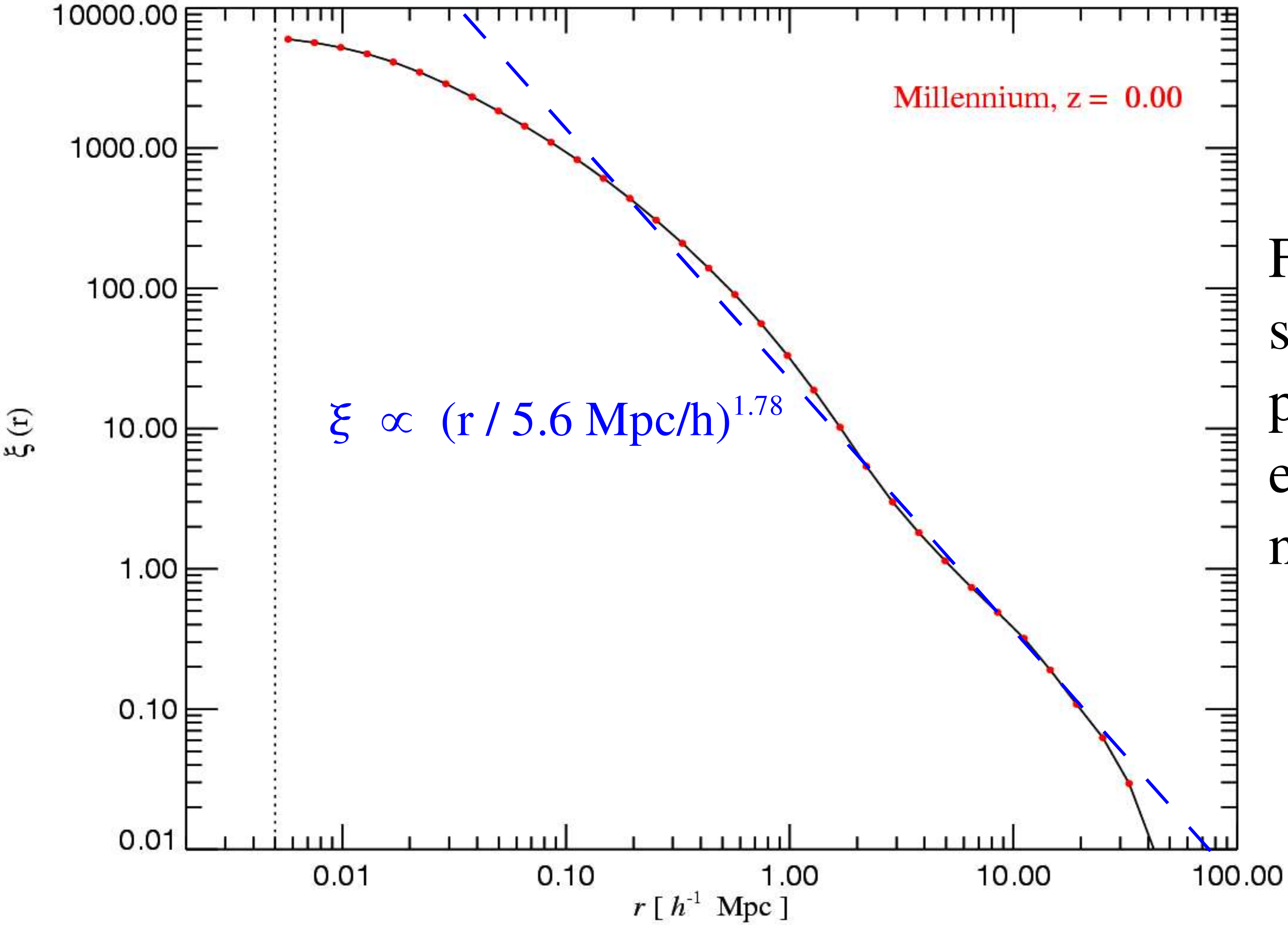
Springel et al 2004



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

Mass autocorrelation function

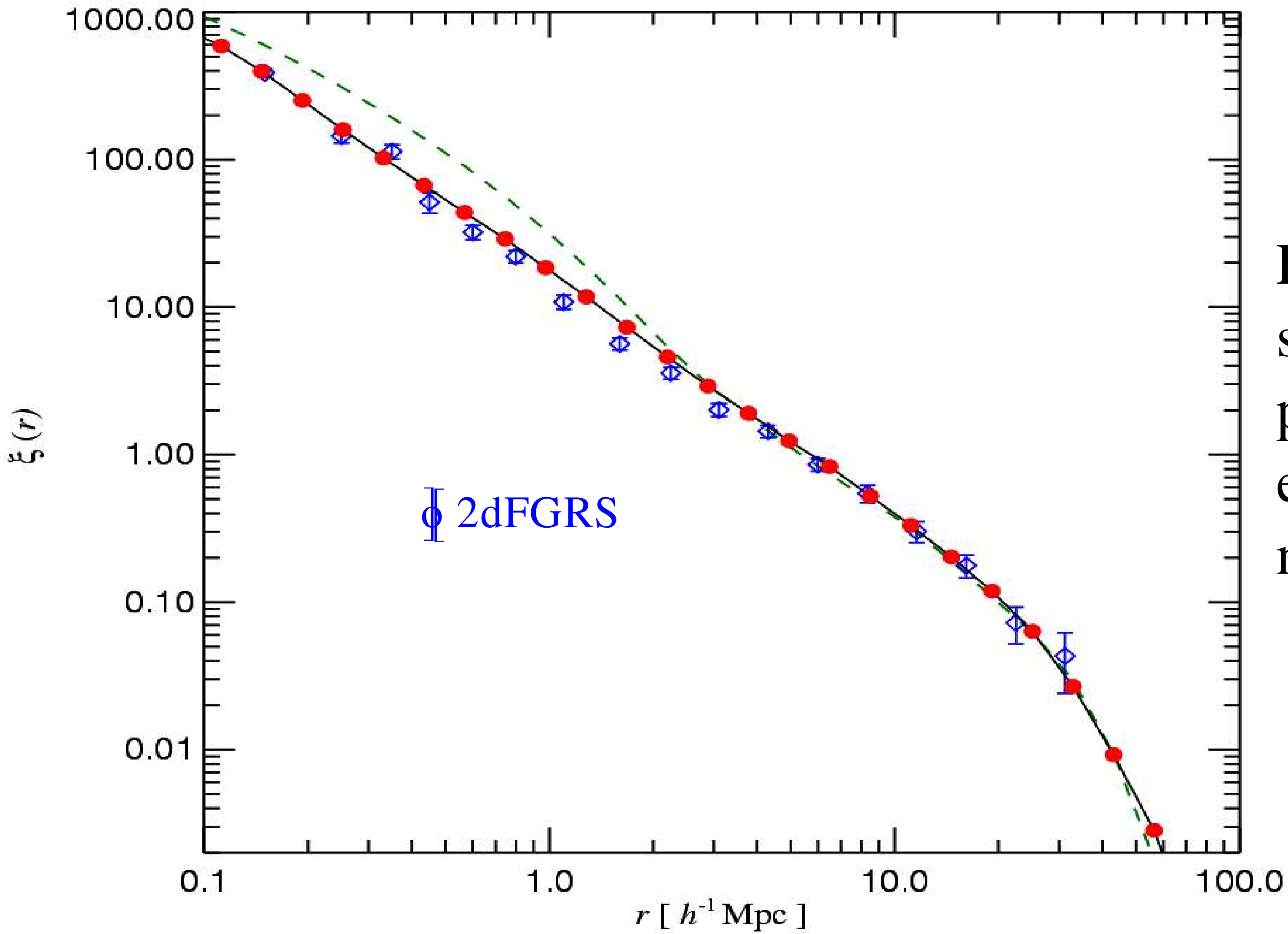
Springel et al 2004



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

Galaxy autocorrelation function

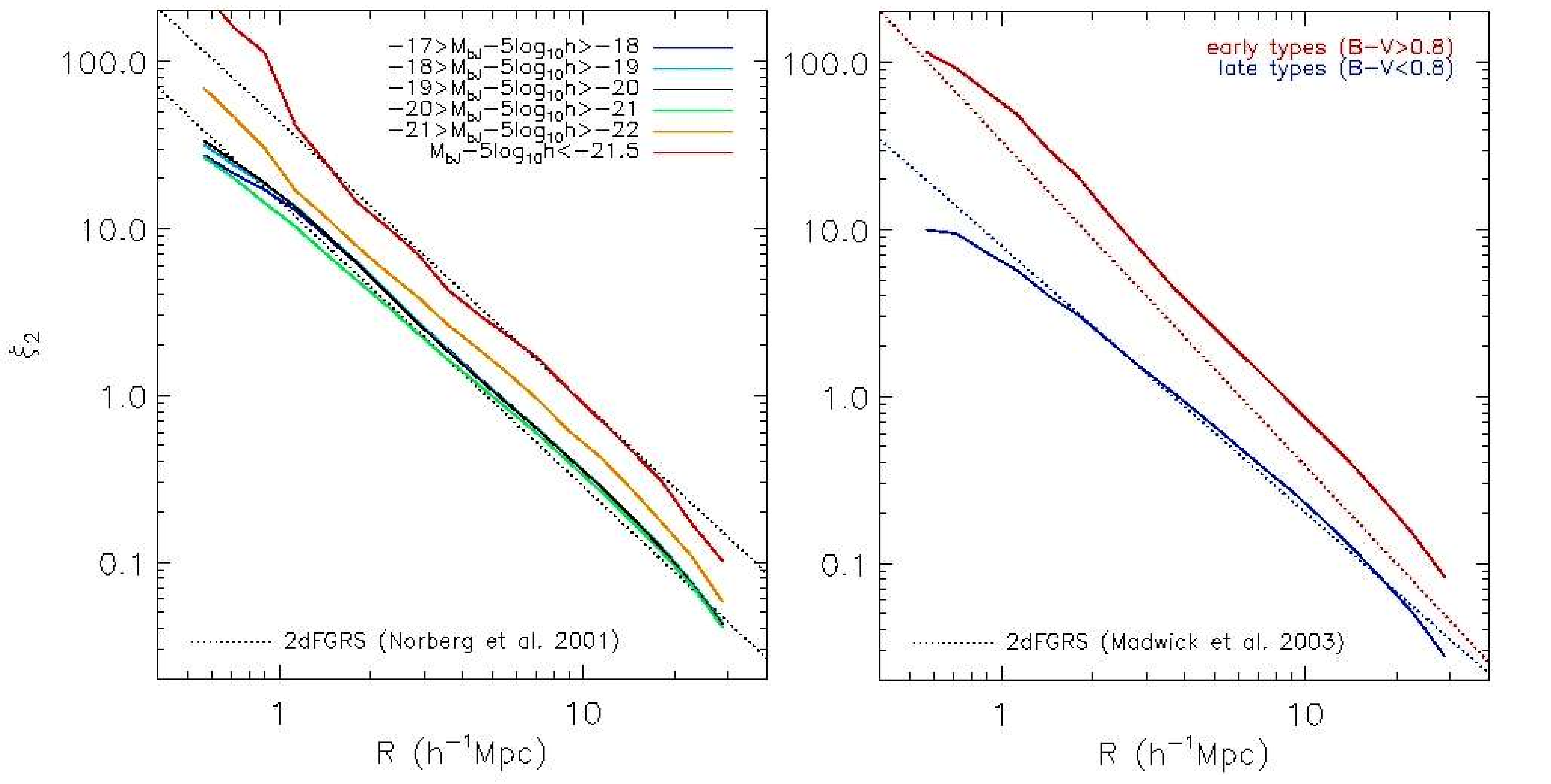
Springel et al 2004

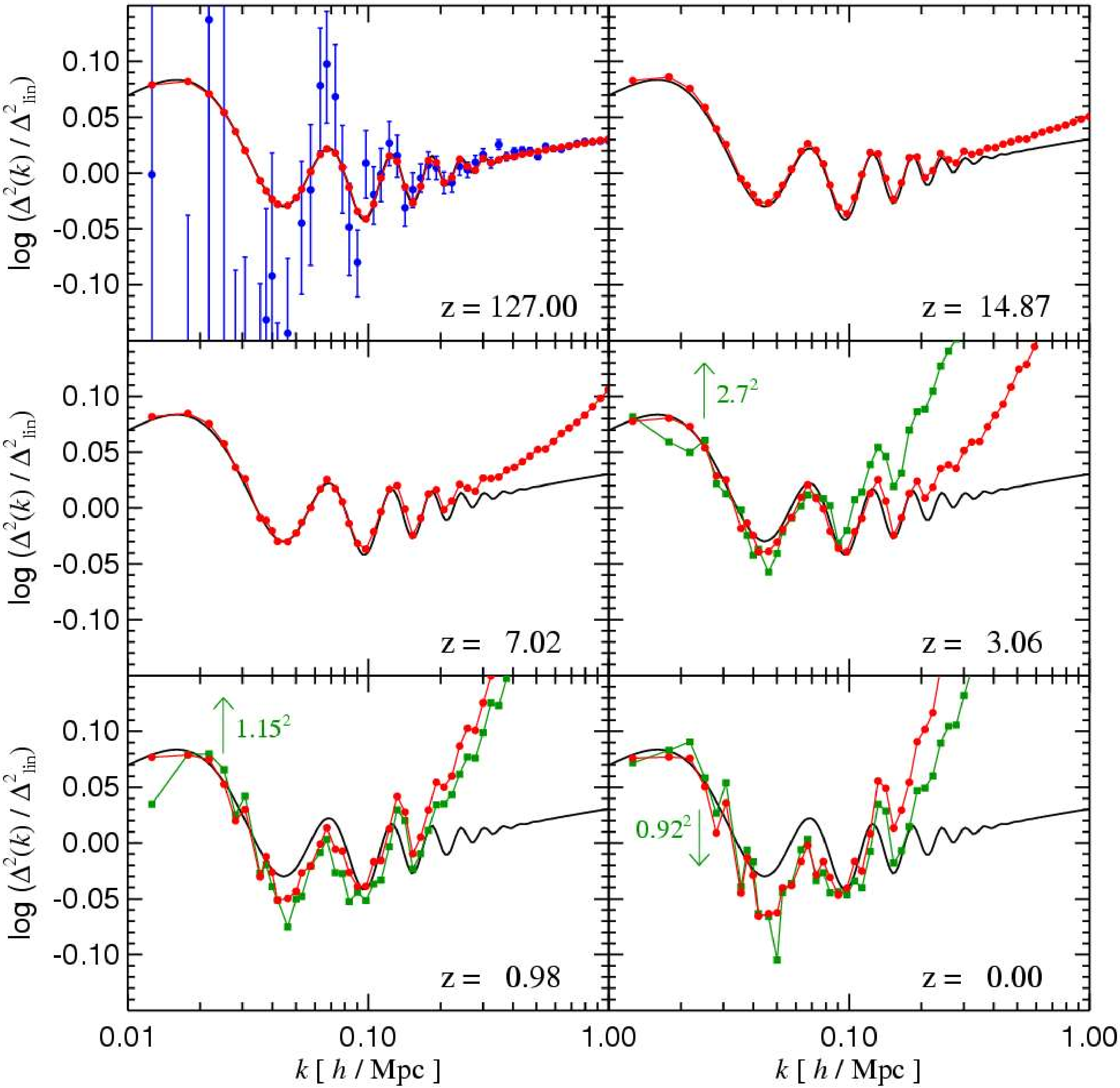


For such a large simulation the purely statistical error bars are negligible on ξ even for the galaxies

Galaxy autocorrelation function

Croton et al 2004





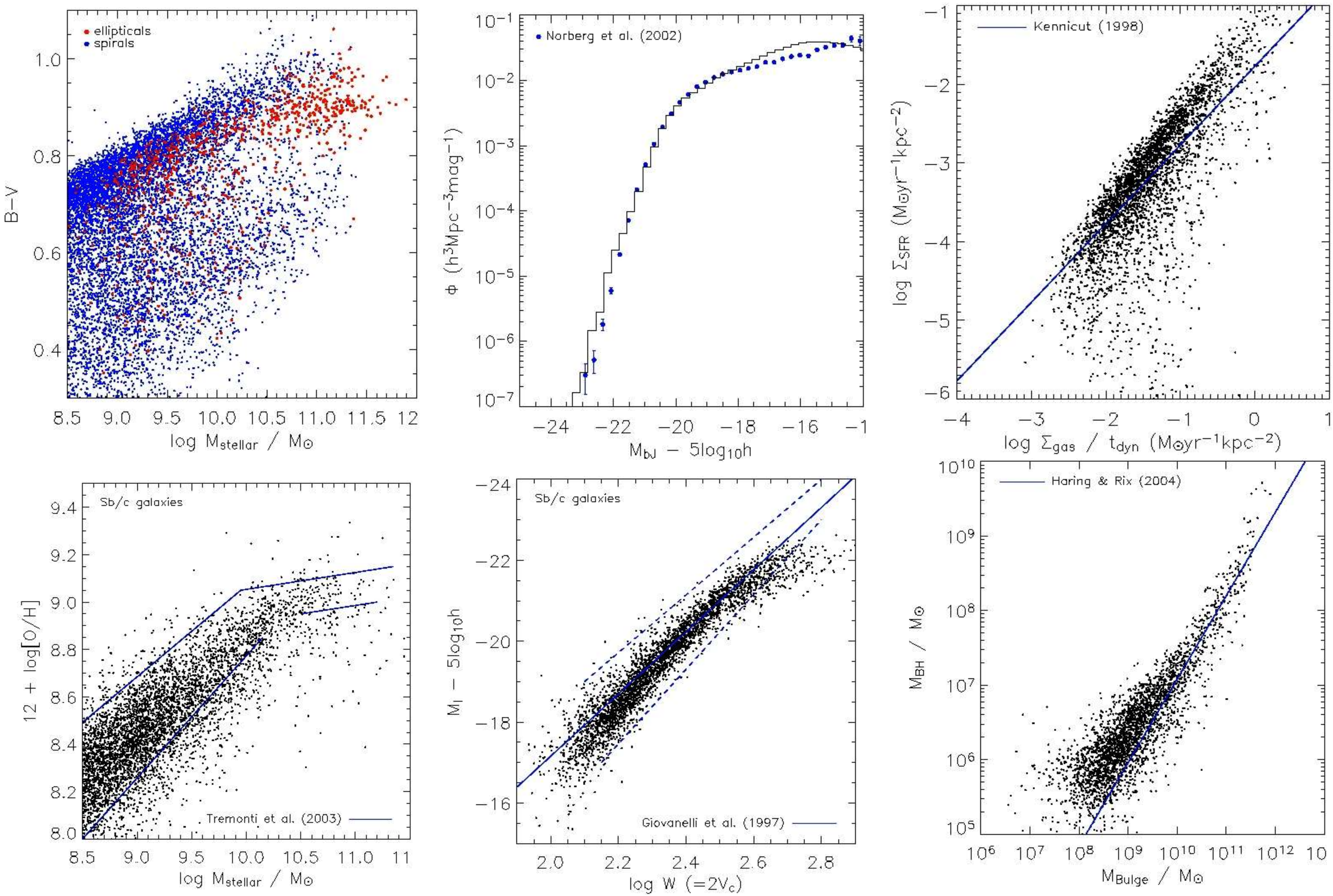
Baryon wiggles in the *galaxy* distribution

Springel et al 2004

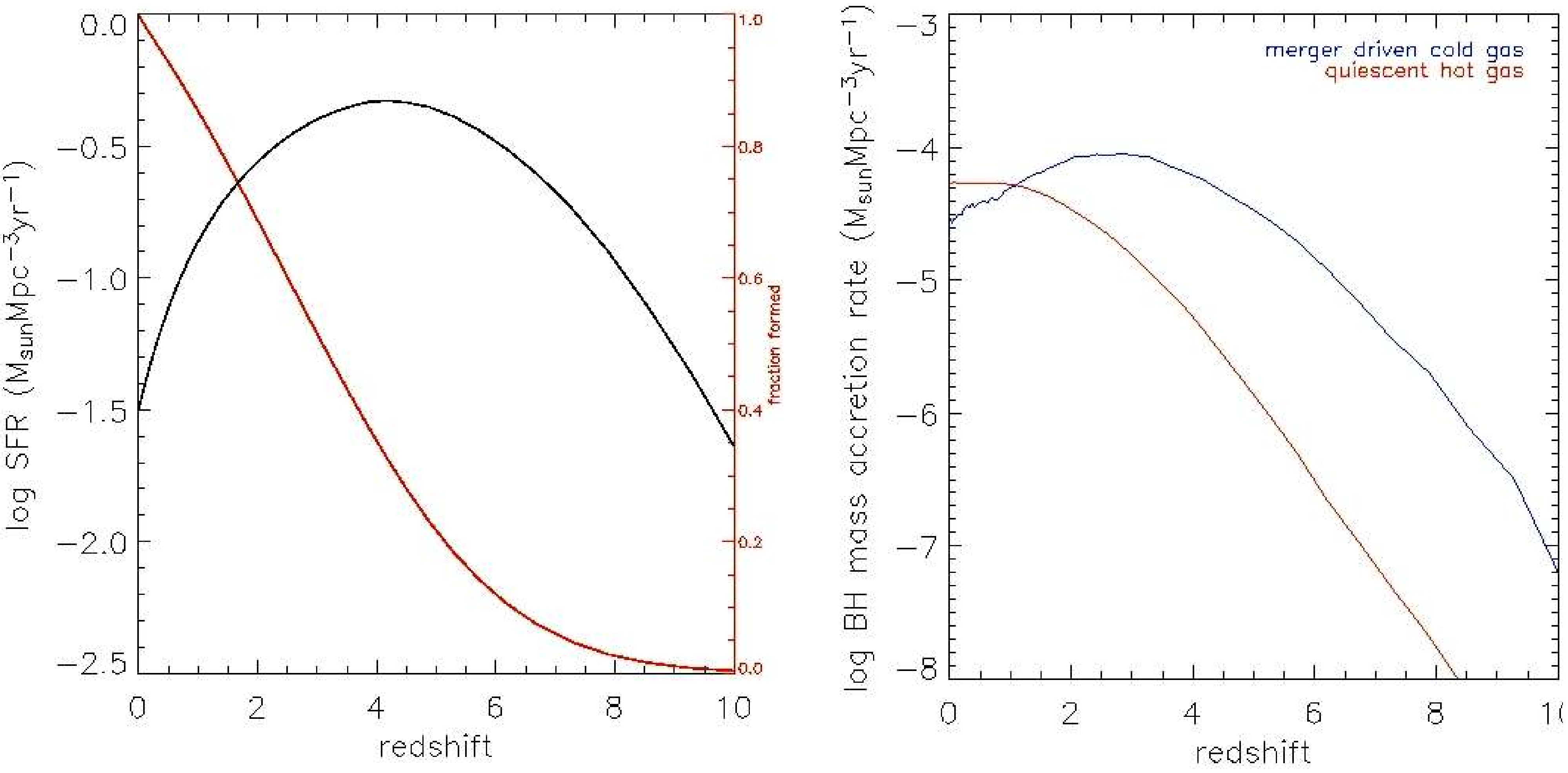
Power spectra from the Millennium run divided by a baryon-free ΛCDM spectrum

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

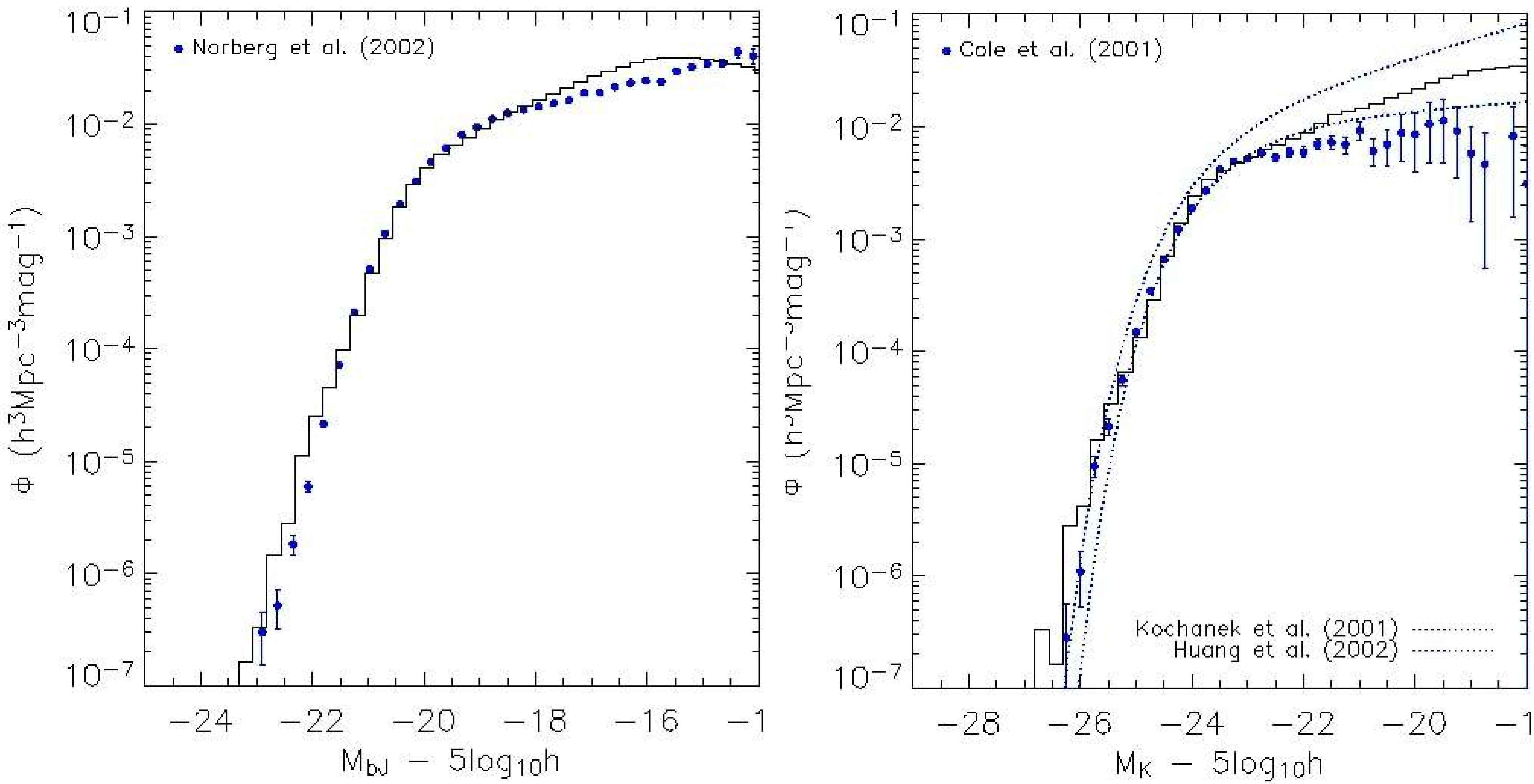
Various galaxy properties at z=0



Evolution of feedback sources

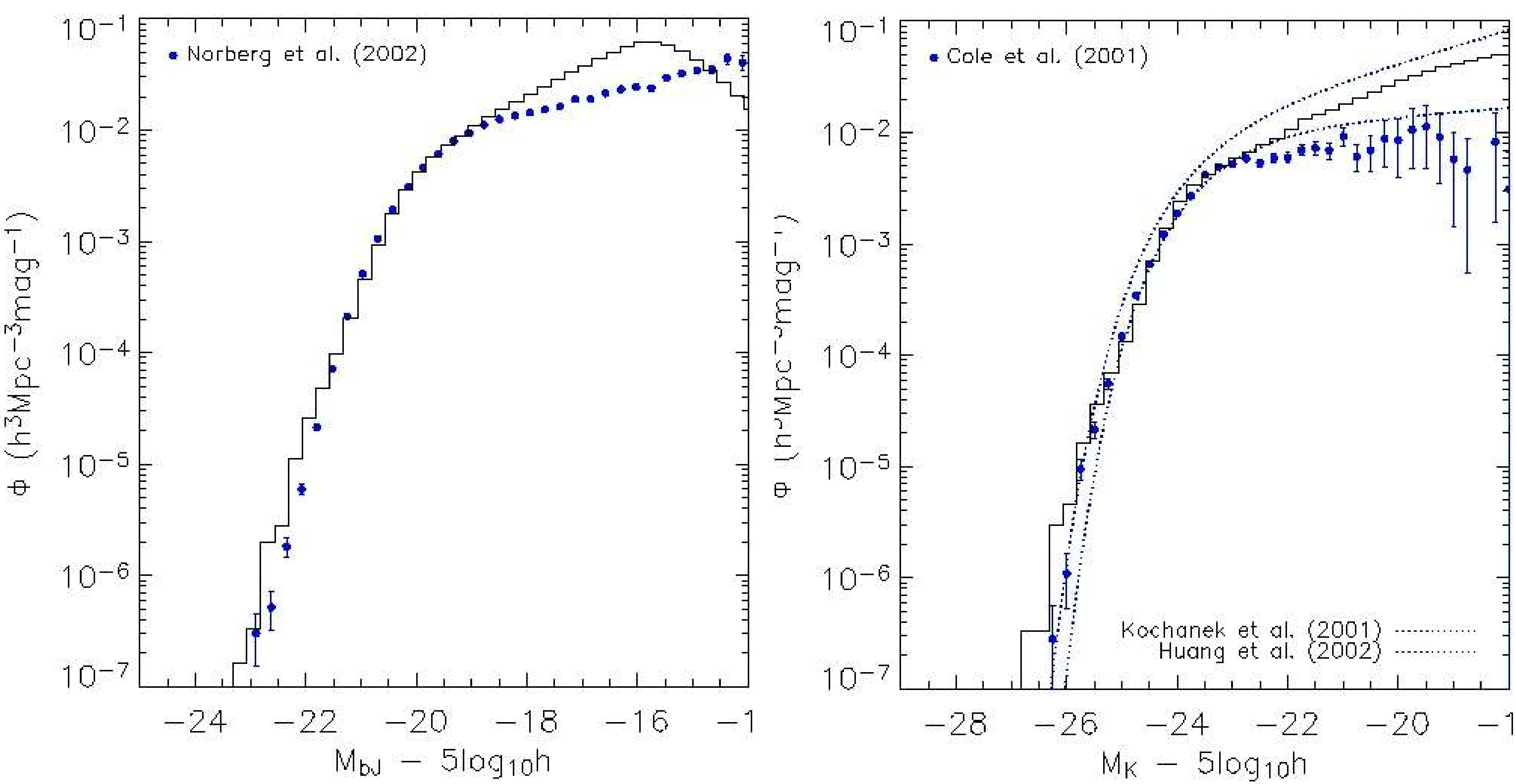


Effect of feedback on the Luminosity Function



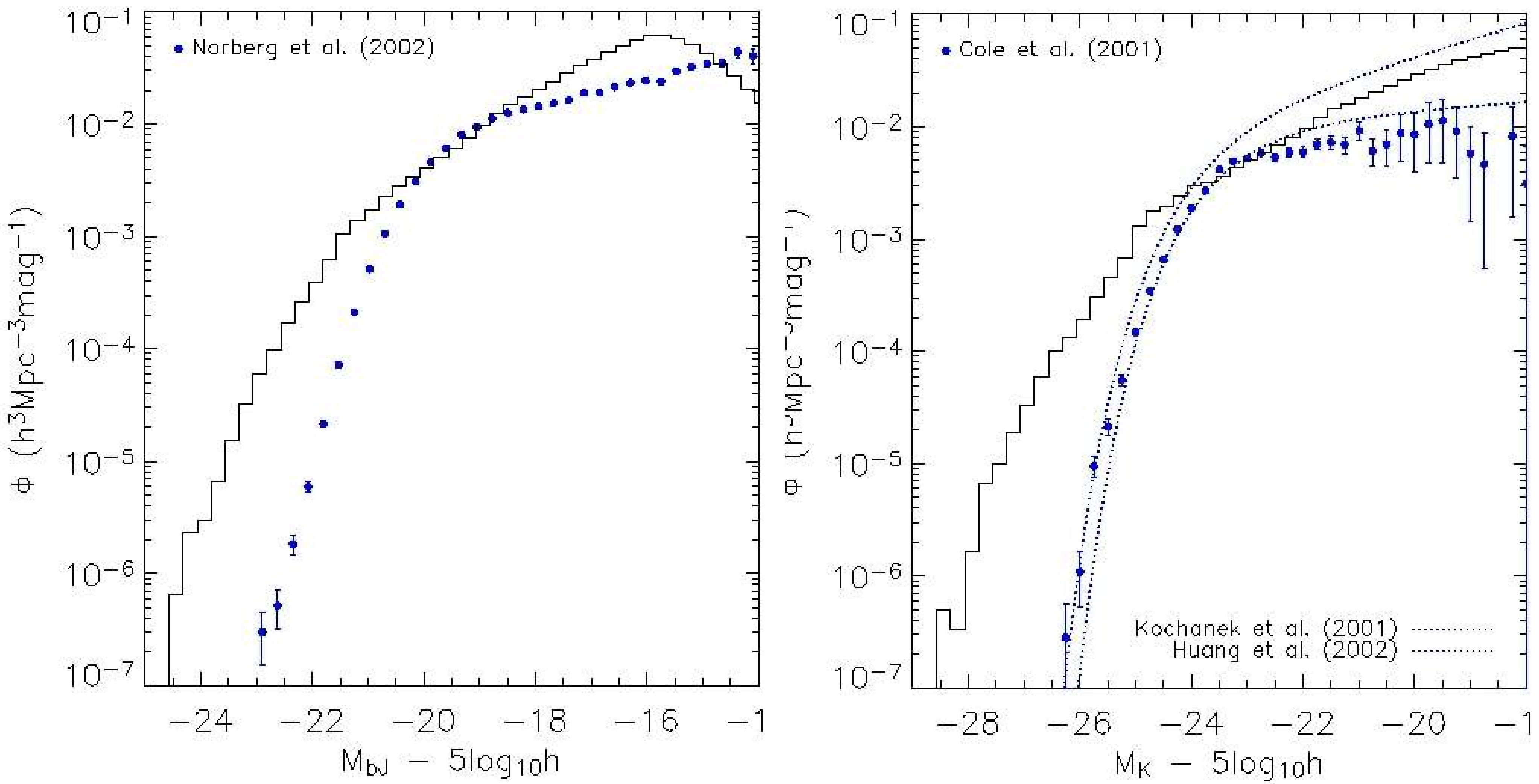
Full model with reionisation, AGN and SN feedback Croton et al 2004

Effect of feedback on the Luminosity Function



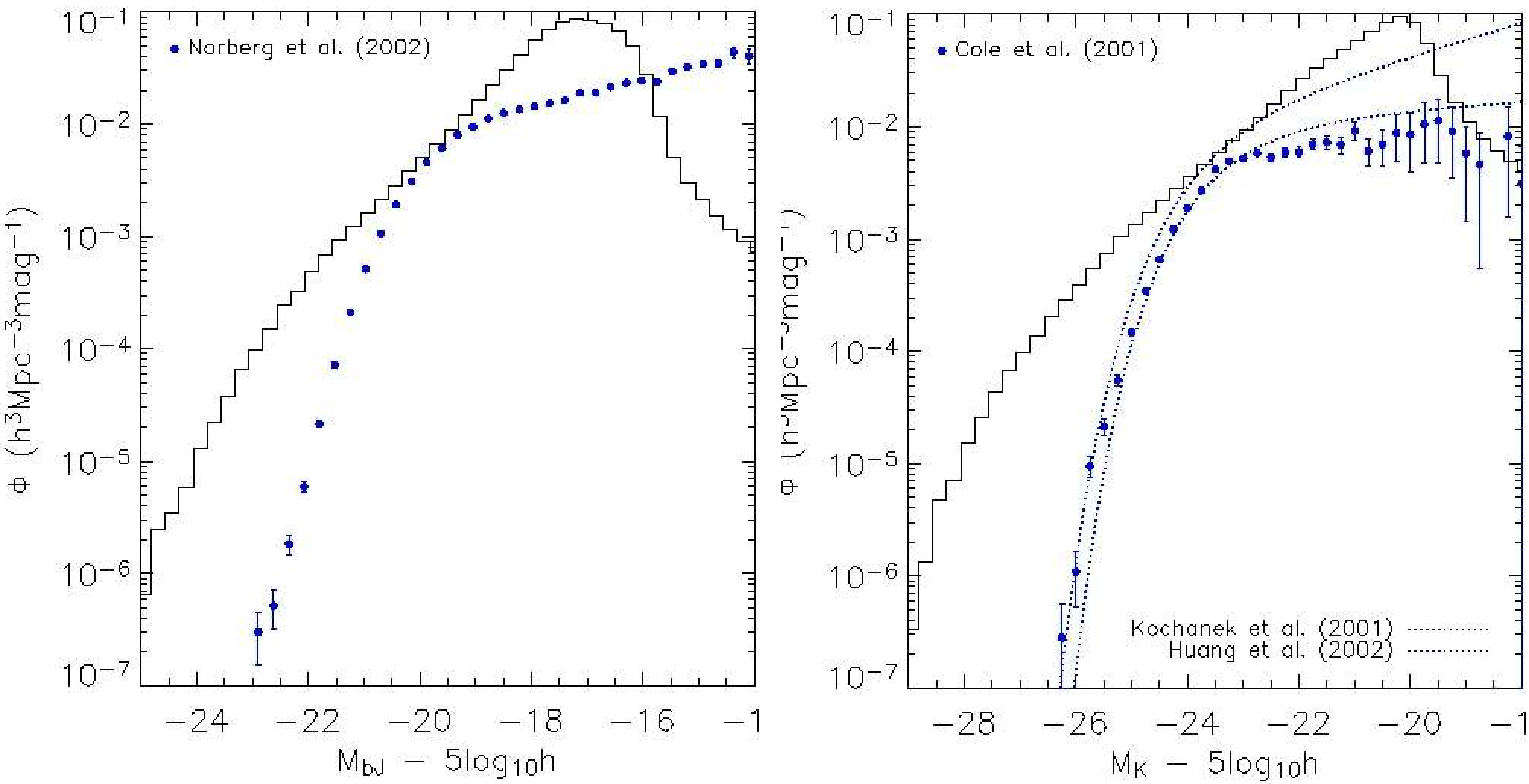
Full model with ~~reionisation~~, AGN and SN feedback   Croton et al 2004

Effect of feedback on the Luminosity Function



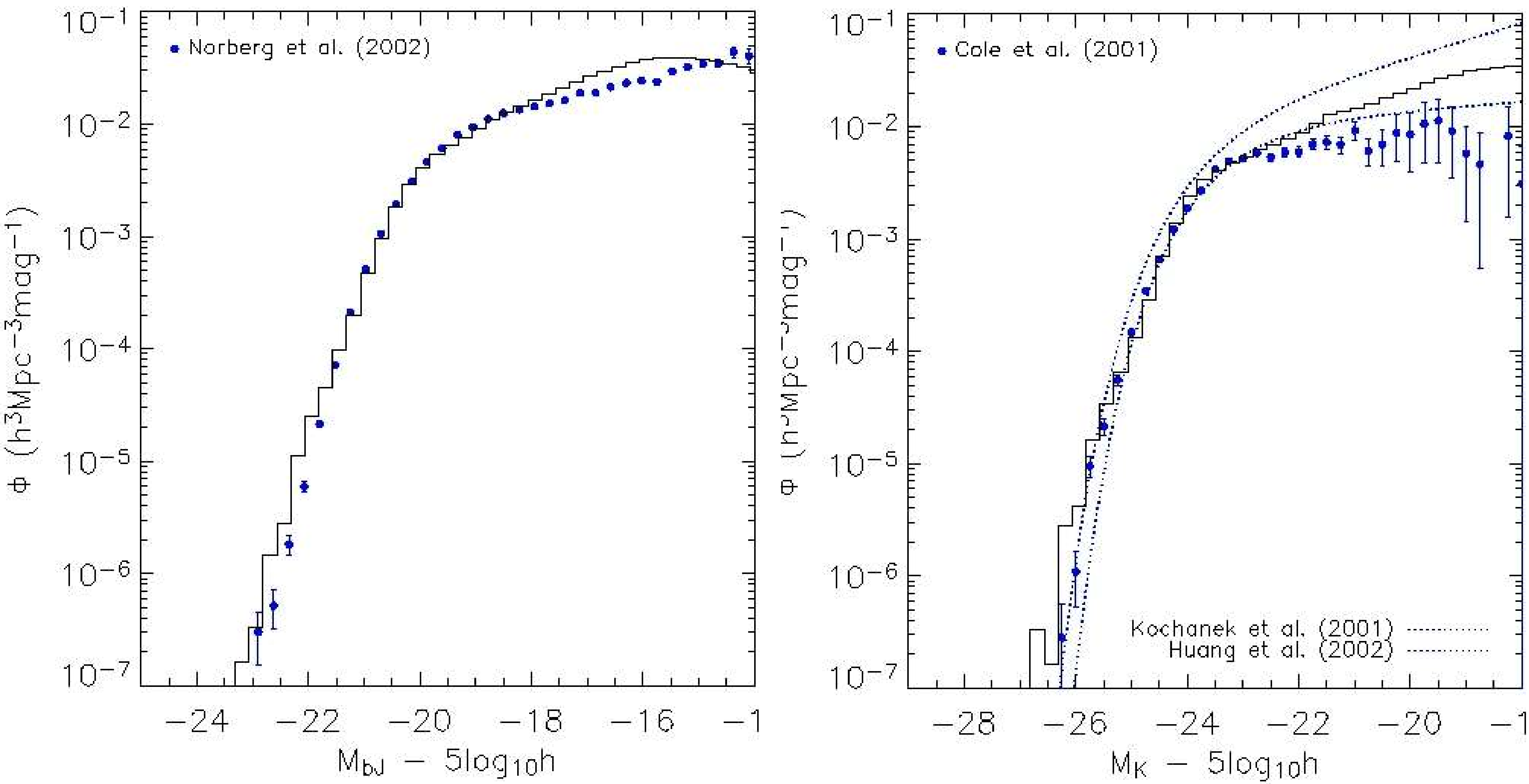
Full model with ~~reionisation~~, ~~AGN~~ and SN feedback Croton et al 2004

Effect of feedback on the Luminosity Function



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

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.

Conclusion

Within the standard ΛCDM paradigm physical models for the many processes affecting galaxy formation can be tested against the observed galaxy population by inserting them *post hoc* in a large simulation like the Millennium Run

The observed luminosity function of galaxies requires at least *two* independent feedback mechanisms:

— One (supernovae?) is most effective in *low* mass galaxies and results in ejection of matter

— The other (radio AGN?) is most effective in *high* mass galaxies and suppresses accretion and further star formation