Zurich, August 2003

Nature versus Nurture
the evolution of dense environments

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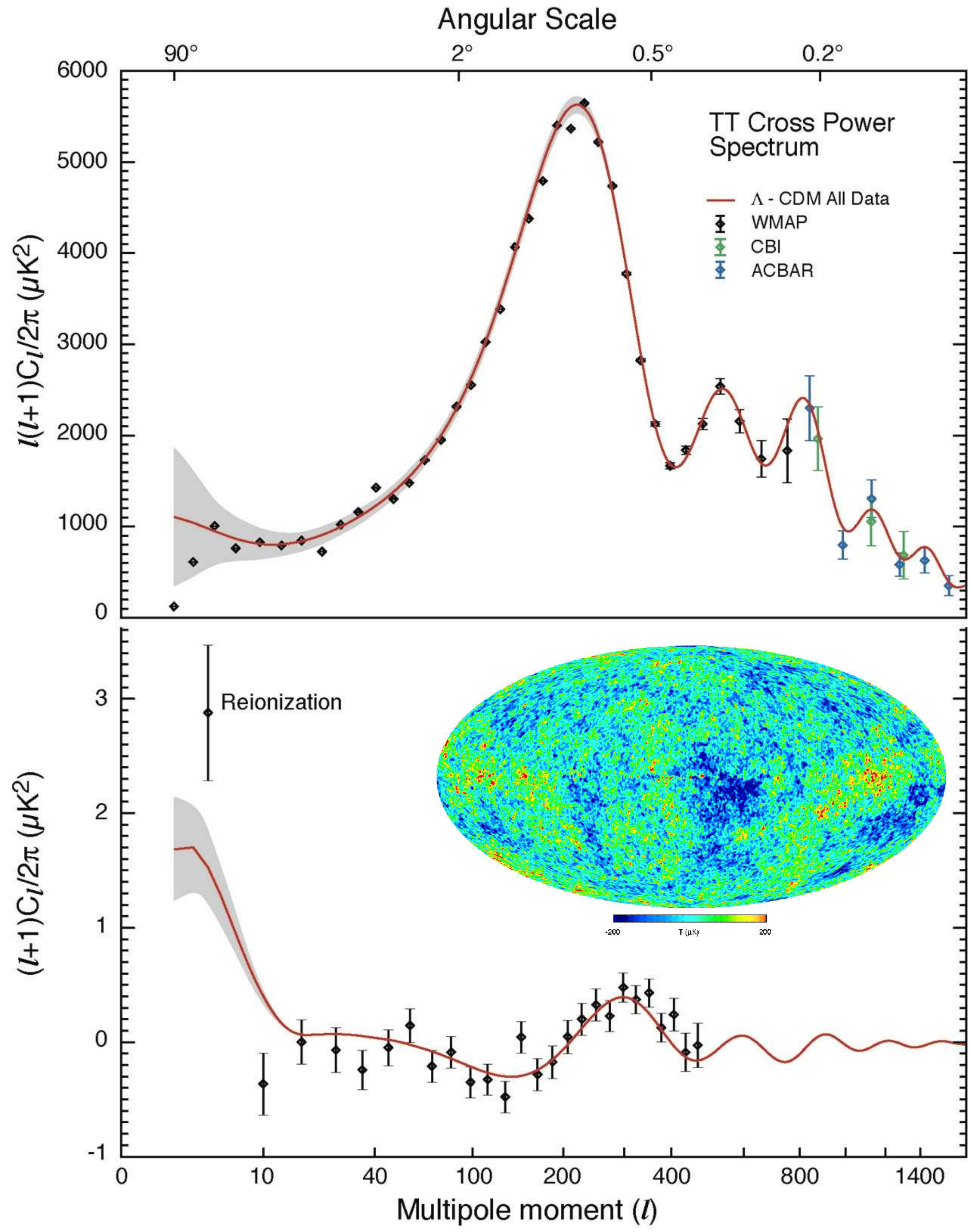


Emergence from the Cosmic Initial Conditions

- Best ΛCDM model has:

  (Bennett et al 2003)

  $t_o = 13.7 \pm 0.2$ Gyr

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

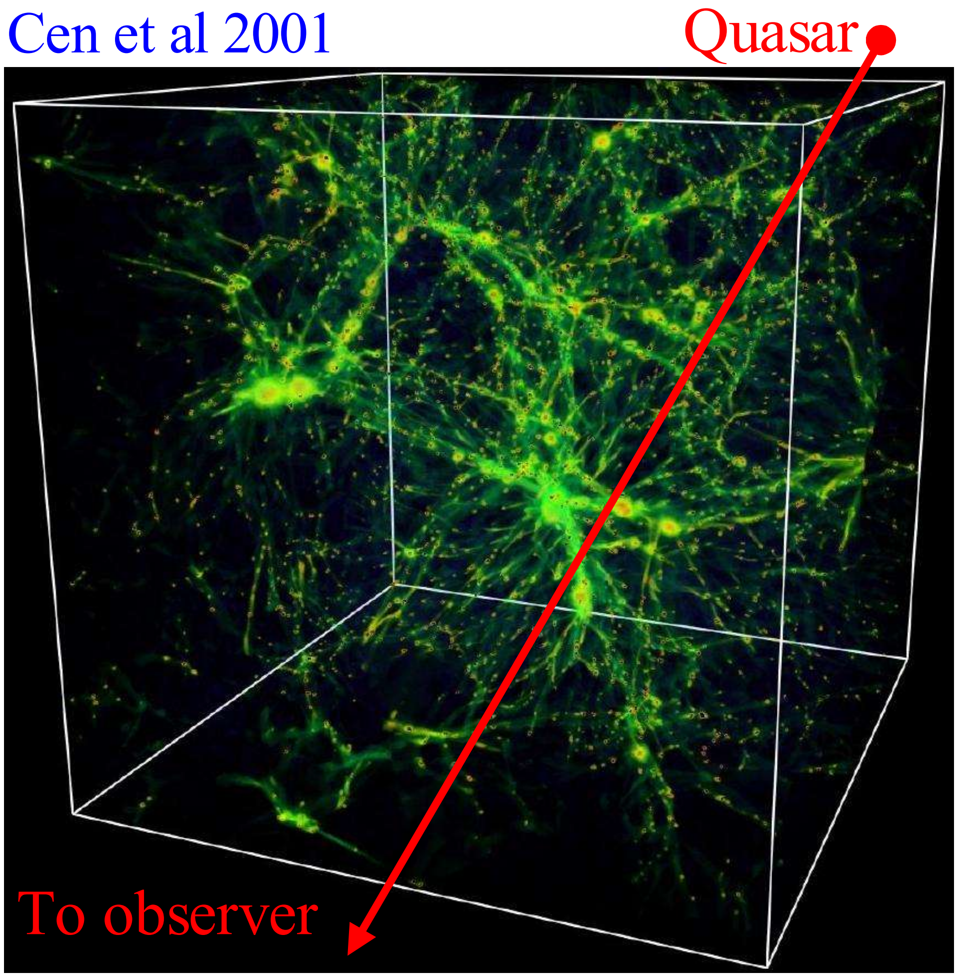
  $\Omega_t=1.02 \pm 0.02$ $\Omega_m=0.27 \pm 0.04$

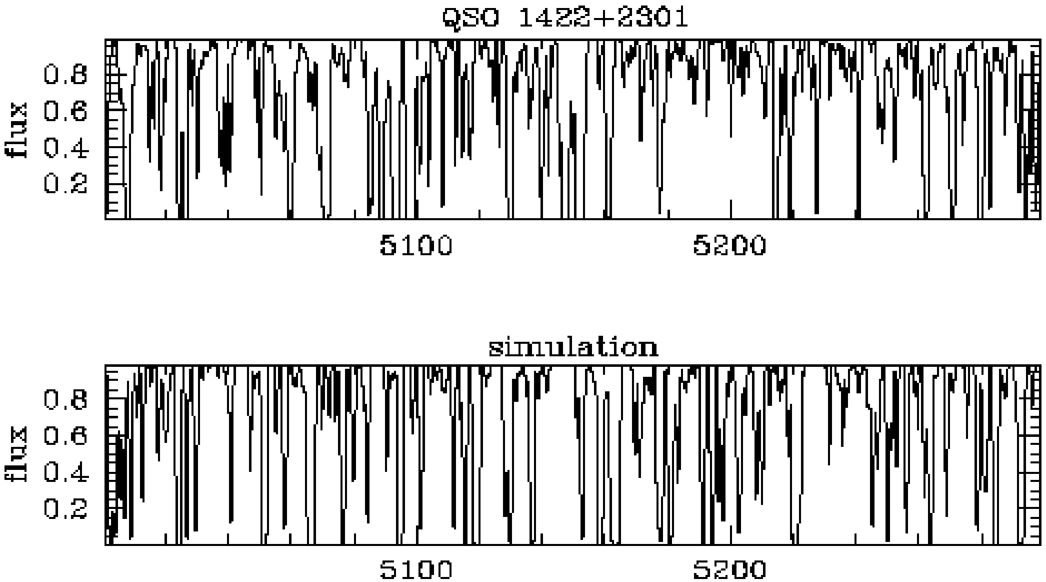
  $\Omega_b=0.044 \pm 0.004$

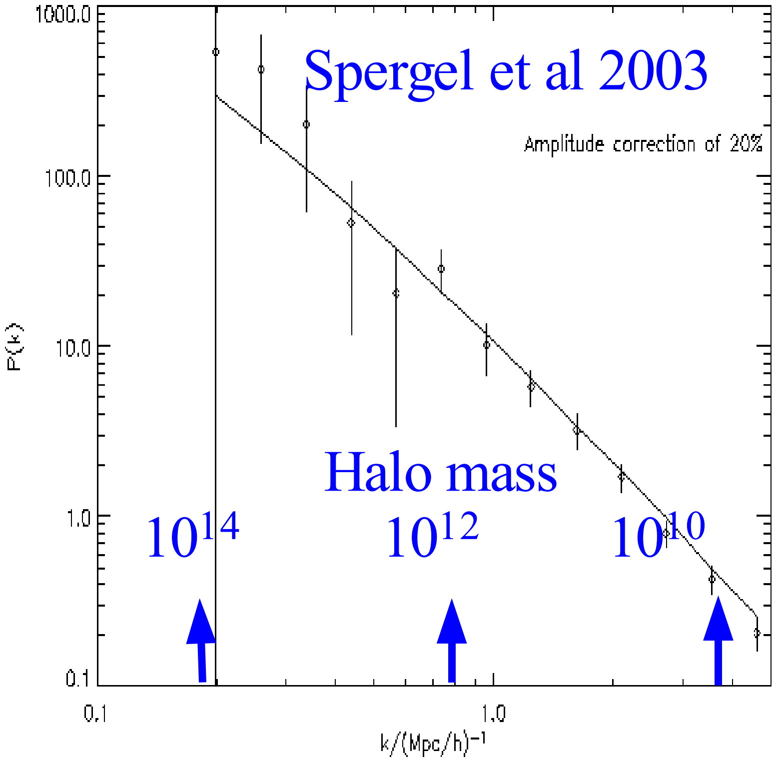
  $\tau_e=0.17 \pm 0.07$

- Parameters in excellent agreement with earlier data: only 'surprise' is the high τ_e
- The cosmological frame for galaxy/cluster formation is set -- the *astrophysics* is not

Structure in the intergalactic medium







- Structure in the Ly α forest appears to confirm the WMAP model down to the scales which build dwarf galaxies

The origin of environmental dependencies

Do galaxies in different environments differ

Because their formation histories are different

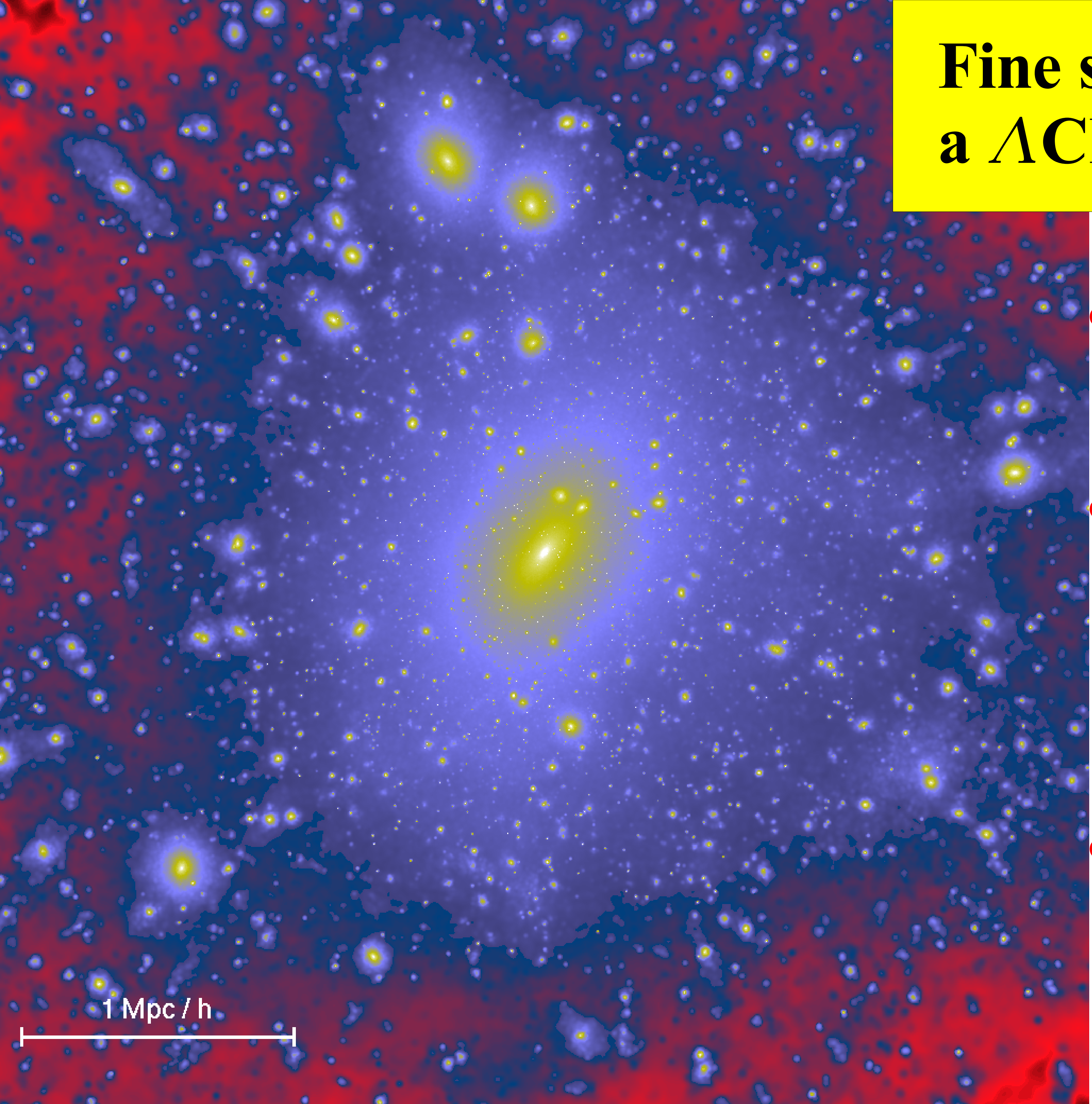
or

Because their later evolution was differently driven

In hierarchical gravitational clustering from gaussian IC's, the detailed assembly history of a halo of *given* mass is statistically *<u>independent</u>* of its larger scale environment

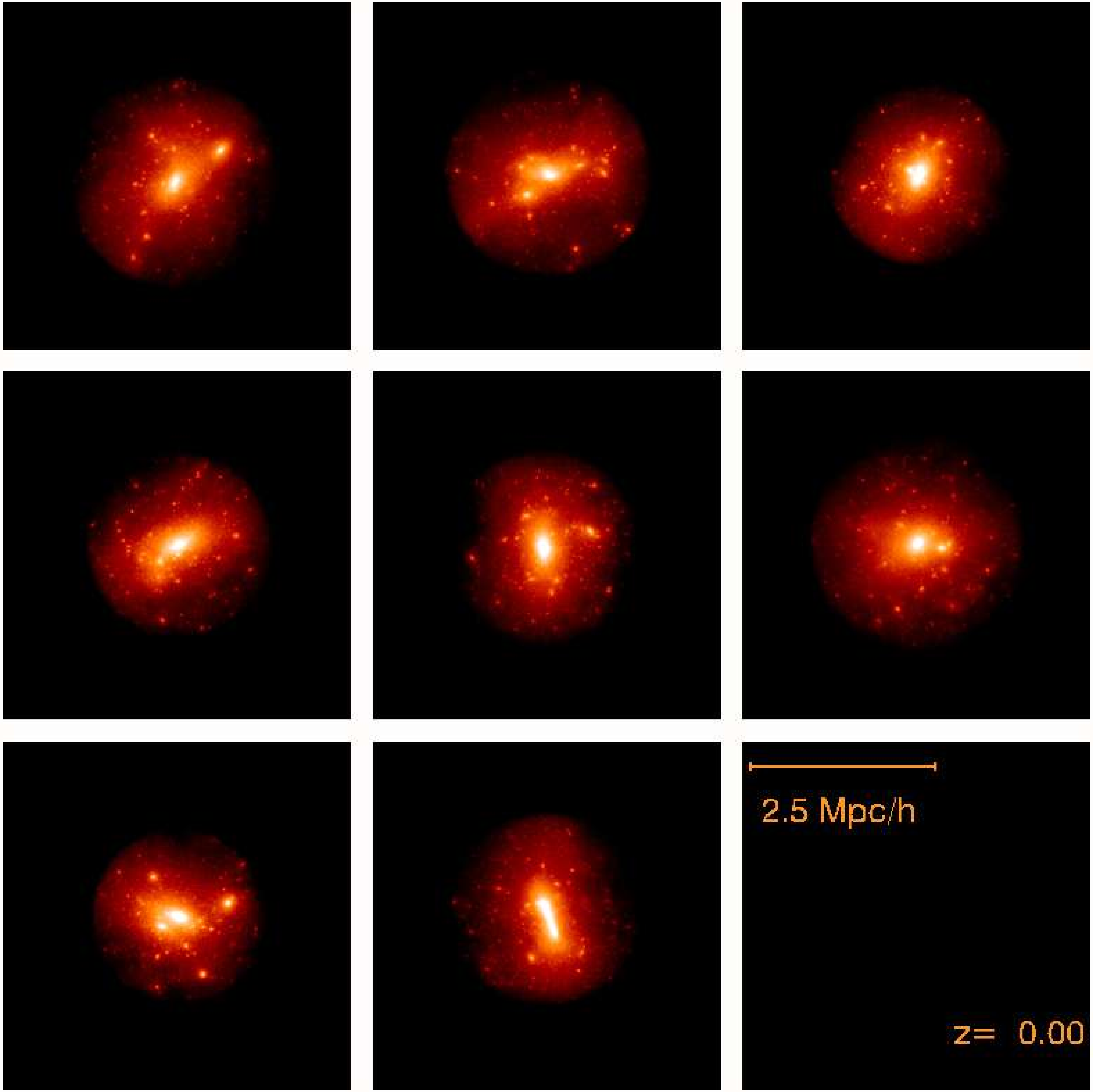
- Differences in galaxy population require non-local processes which vary with large-scale environment
- Galaxies of similar mass may differ systematically if they inhabit *halos* of different mass

Fine structure of a ΛCDM cluster



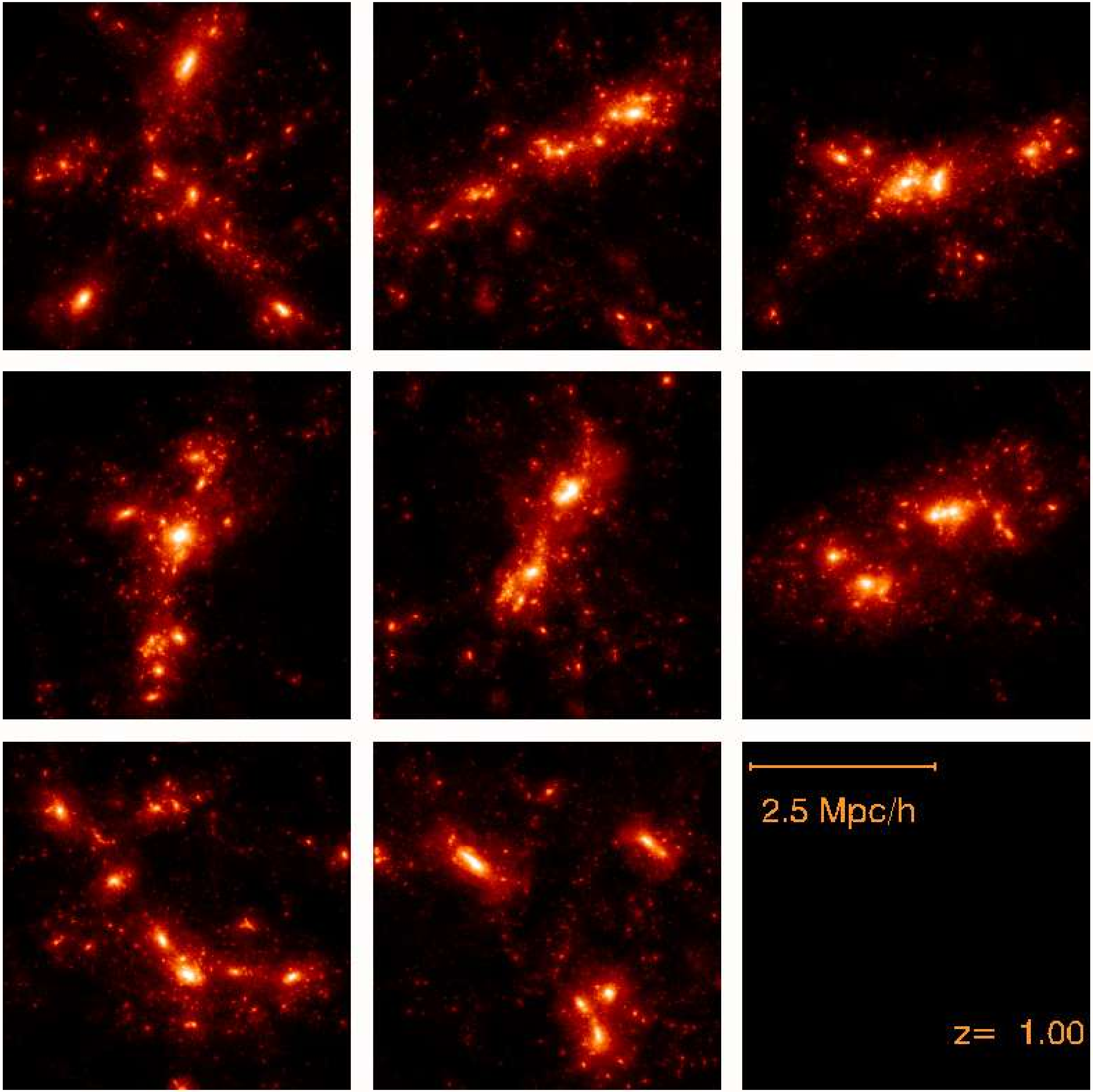
- Cluster has mass $\sim 10^{15}\,M_\odot$
- Substructures are the remnant cores of halos that have fallen into the forming cluster
- The substructures presumably mark galaxy sites

Springel et al 2001



Cluster structure in ΛCDM

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



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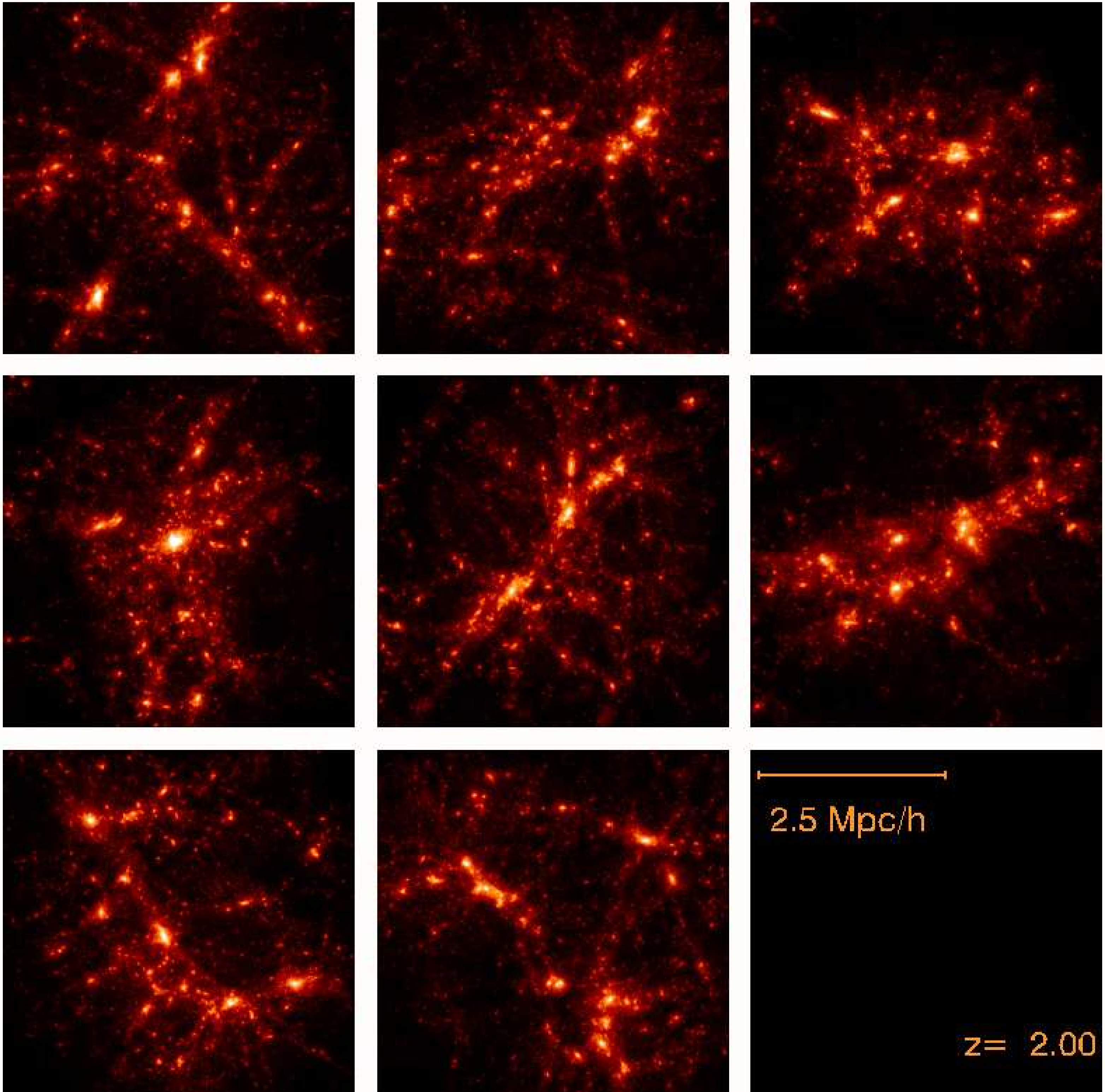
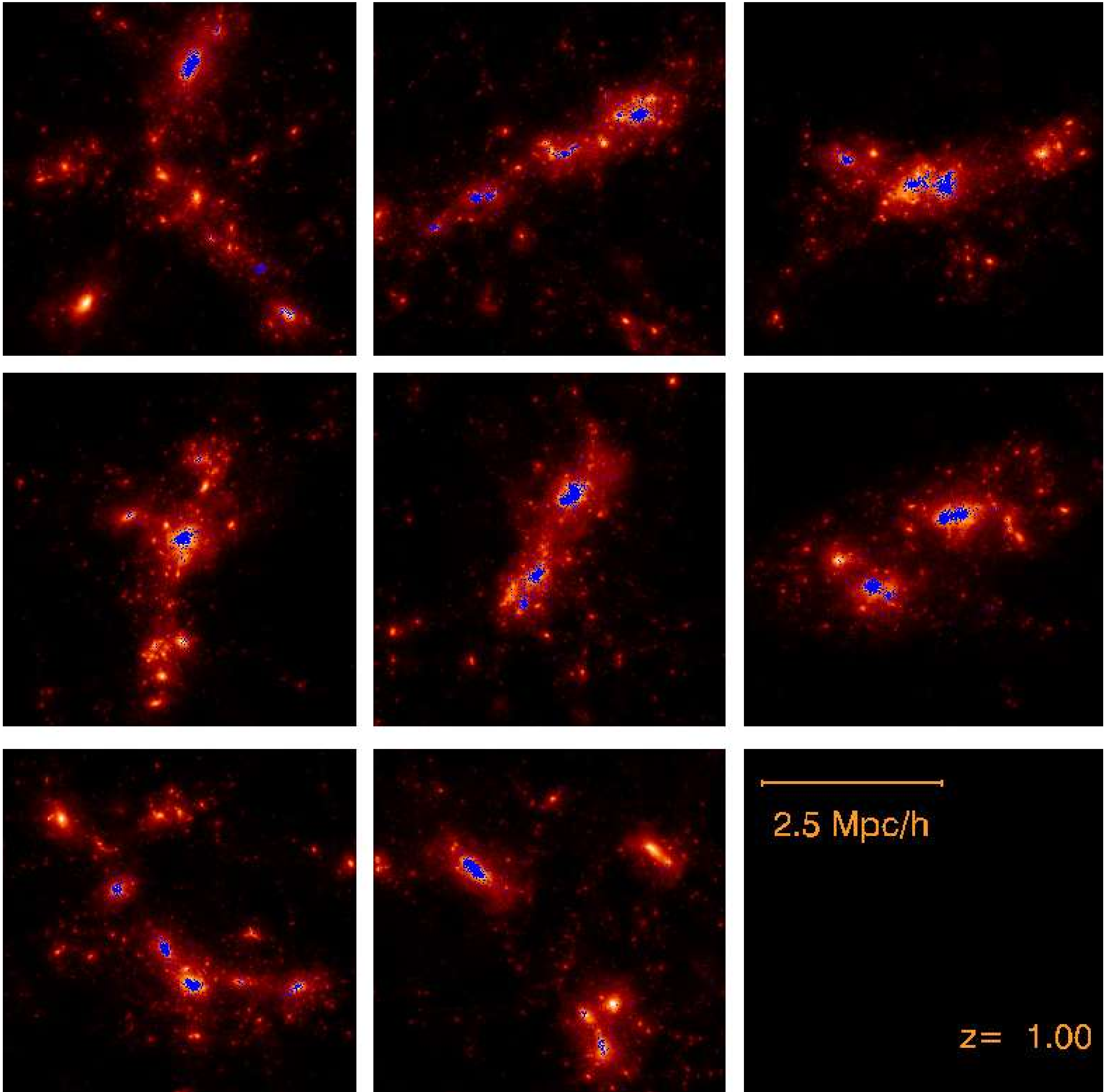


Cluster structure in ΛCDM

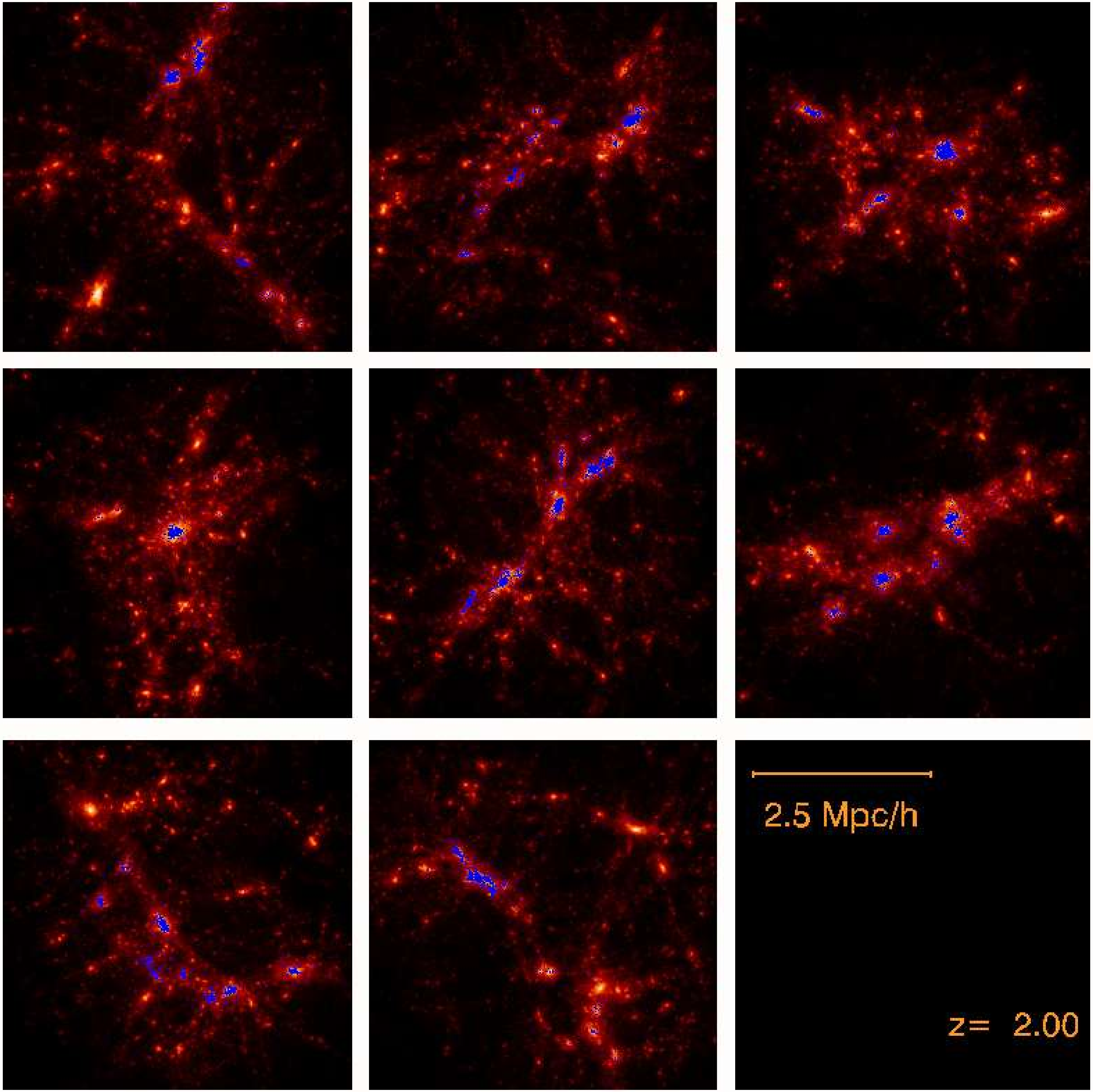
- Many z = 0 cluster members were not in a cluster at z = 2 or z = 1
- Low redshift clusters form from z = 1(or 2) superclusters

Growth of inner structure



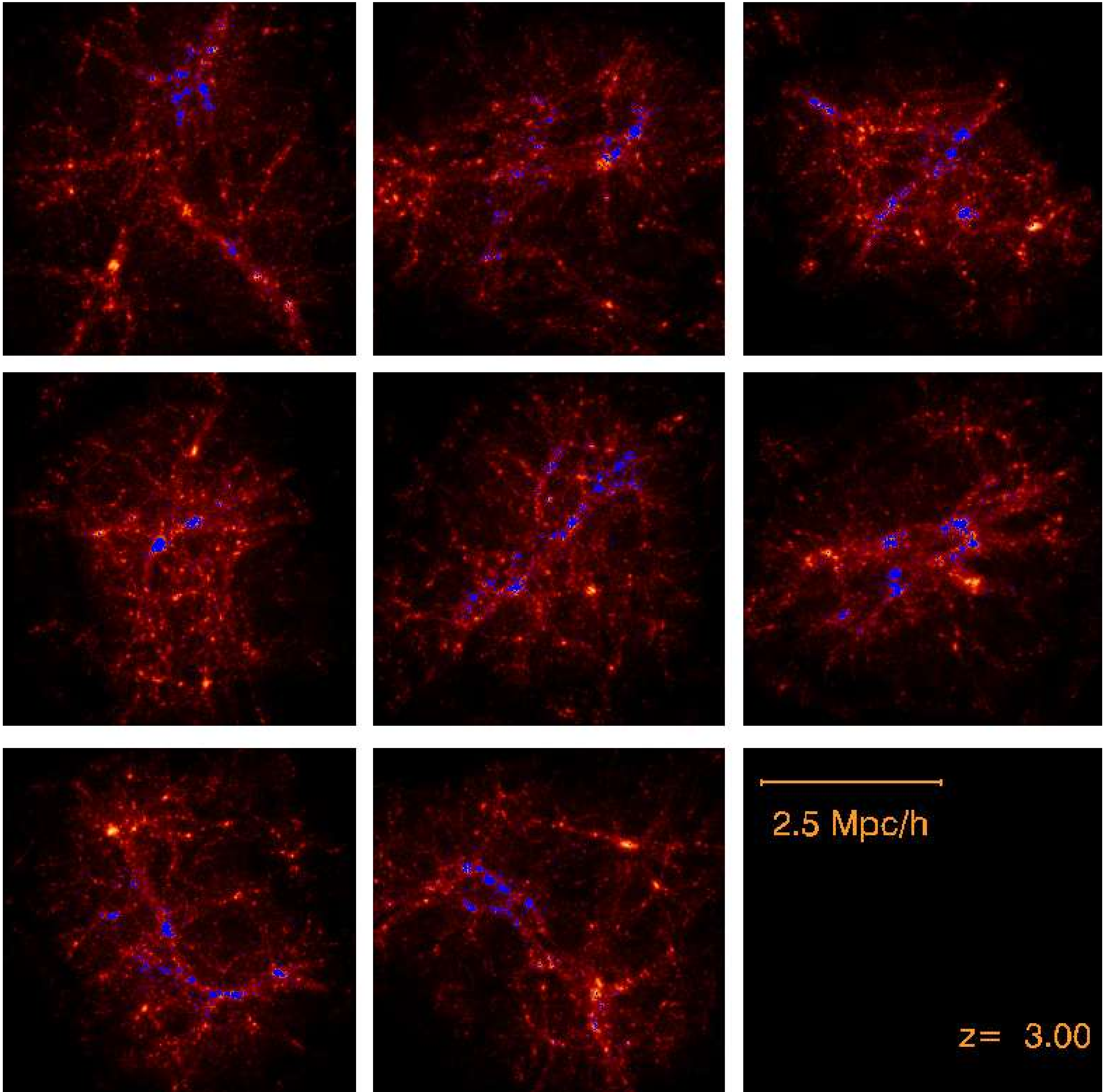
- DM particles within 20kpc at $z = 0$ are shown in blue
- In many cases they come from disjoint regions with Mpc separations at $z = 1$

Growth of inner structure



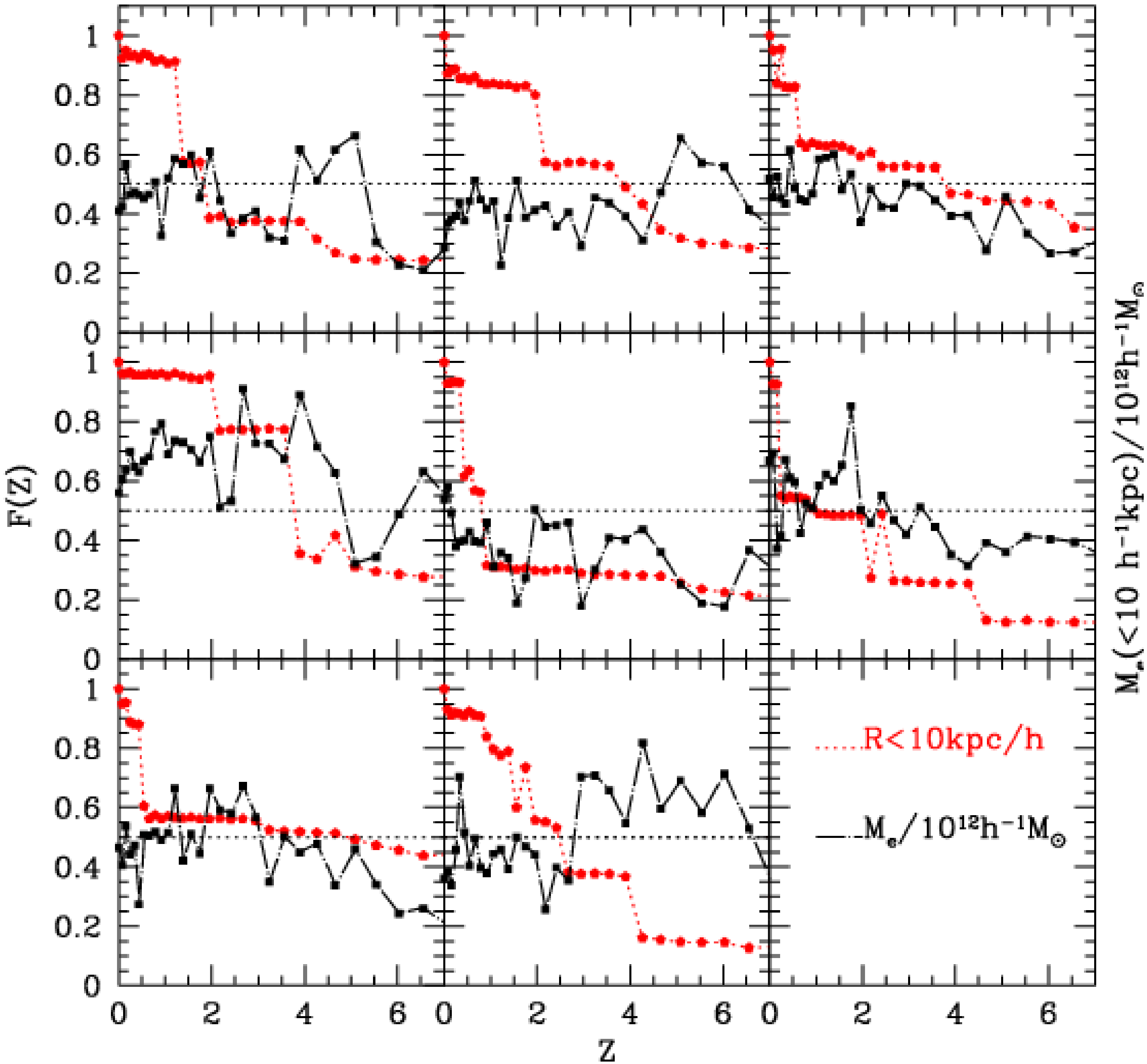
- DM particles within 20kpc at z = 0 are shown in blue
- In most cases they come from disjoint regions with Mpc separations at z = 2

Growth of inner structure



- DM particles within 20kpc at z = 0 are shown in blue
- In all cases they come from disjoint regions with Mpc separations at z = 3

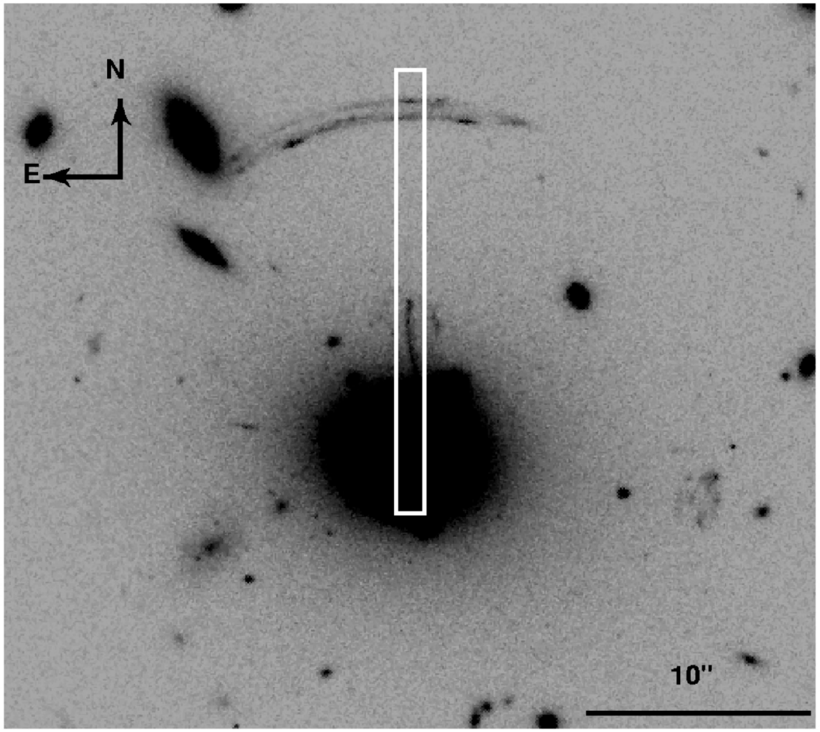
Gao, Loeb, Peebles, White, Jenkins 2003

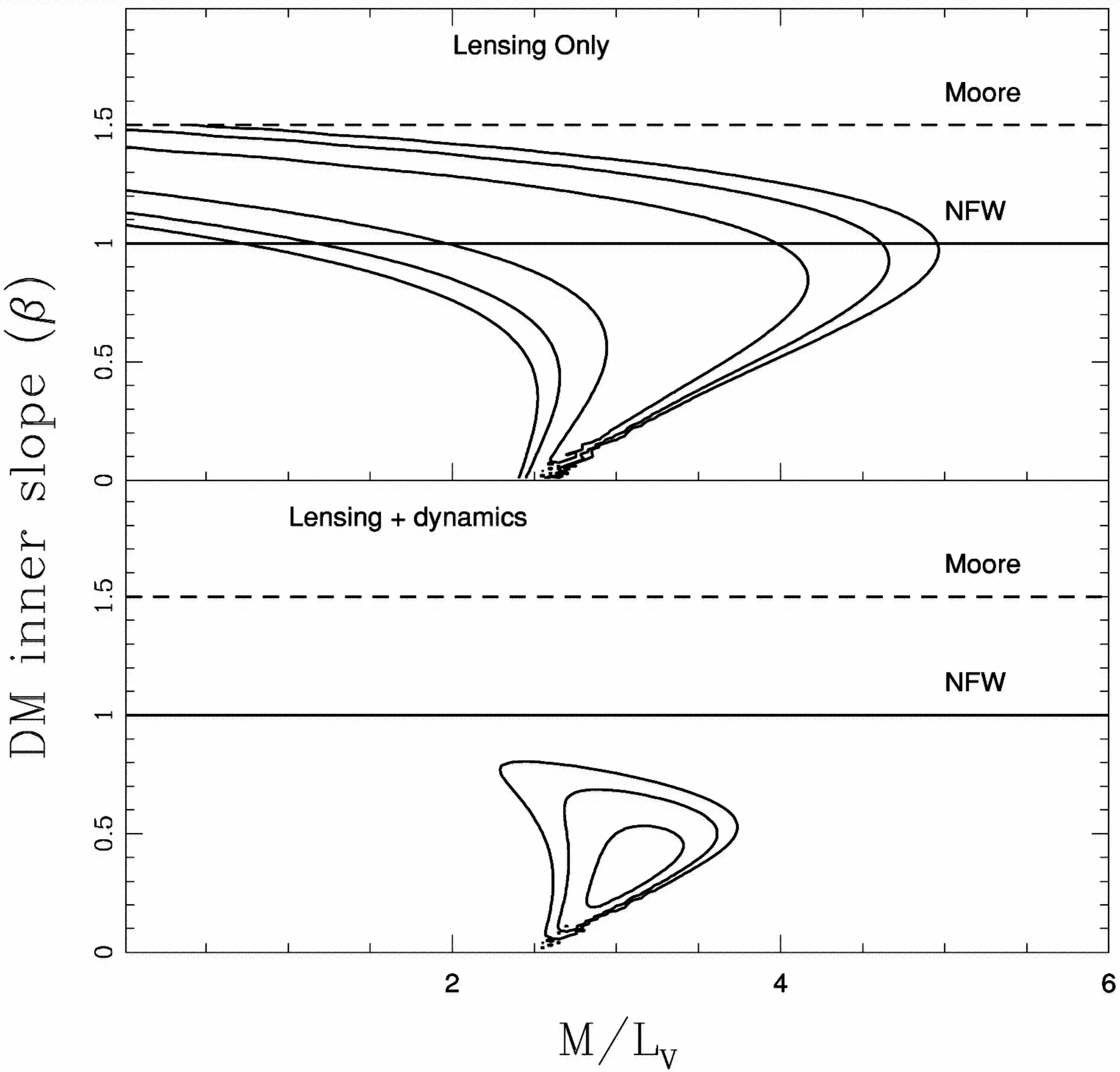


- All clusters have nearly the same mass within 10 kpc/h
- This mass does not vary much for z < 6 in the most massive progenitors
- The *fraction* of the < 10 kpc/h z = 0 particles which are in the most massive progenitor drops with increasing z
- cD galaxies must assemble late by merging

Constraining DM properties with strong lensing

Sand, Treu & Ellis 2002

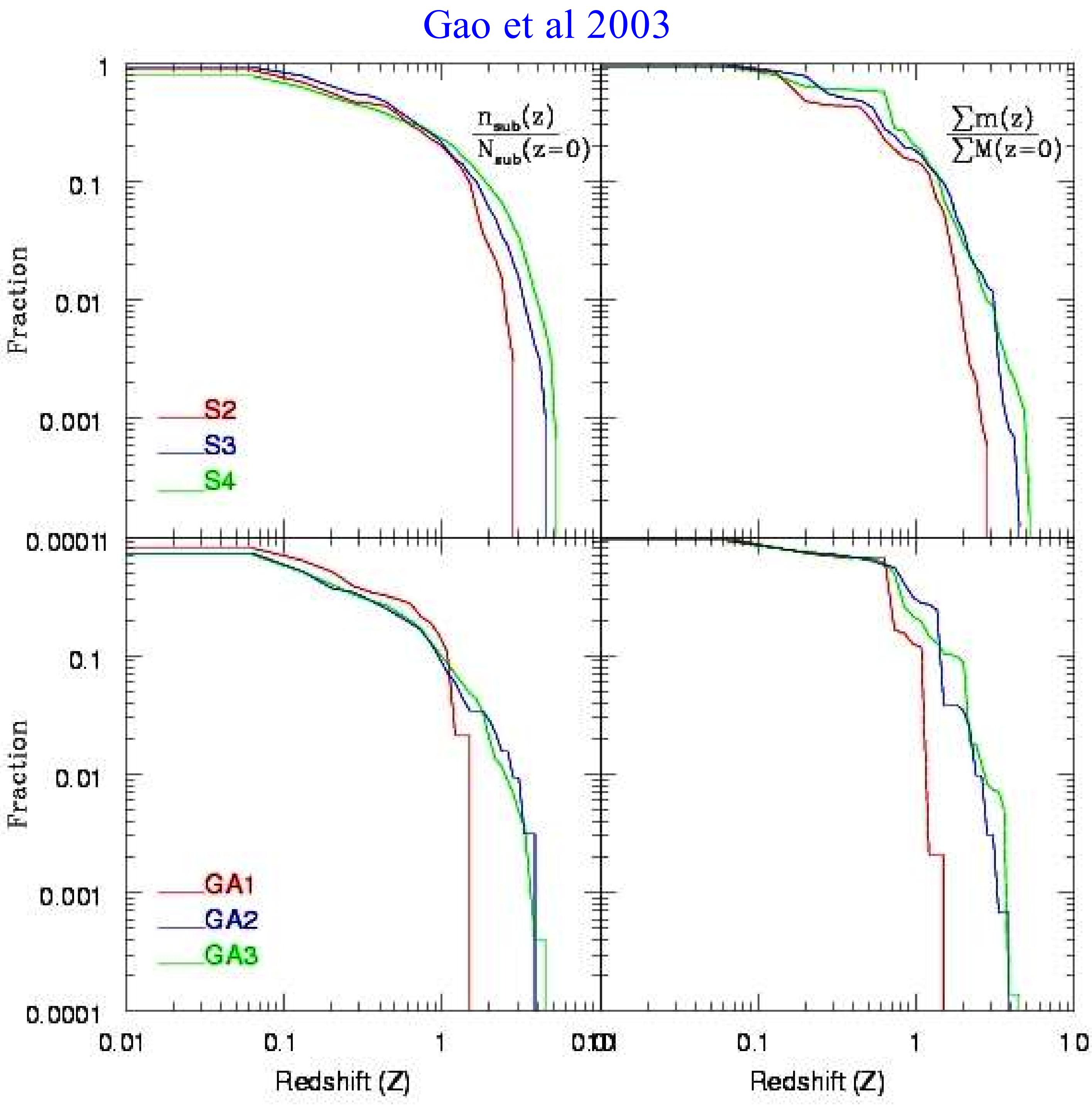




- Model potential as power law DM + galaxy with constant M/L
- Consistency with radial arc, tangential arc & velocity dispersion profile

→ inner slope of DM profile shallower than NFW

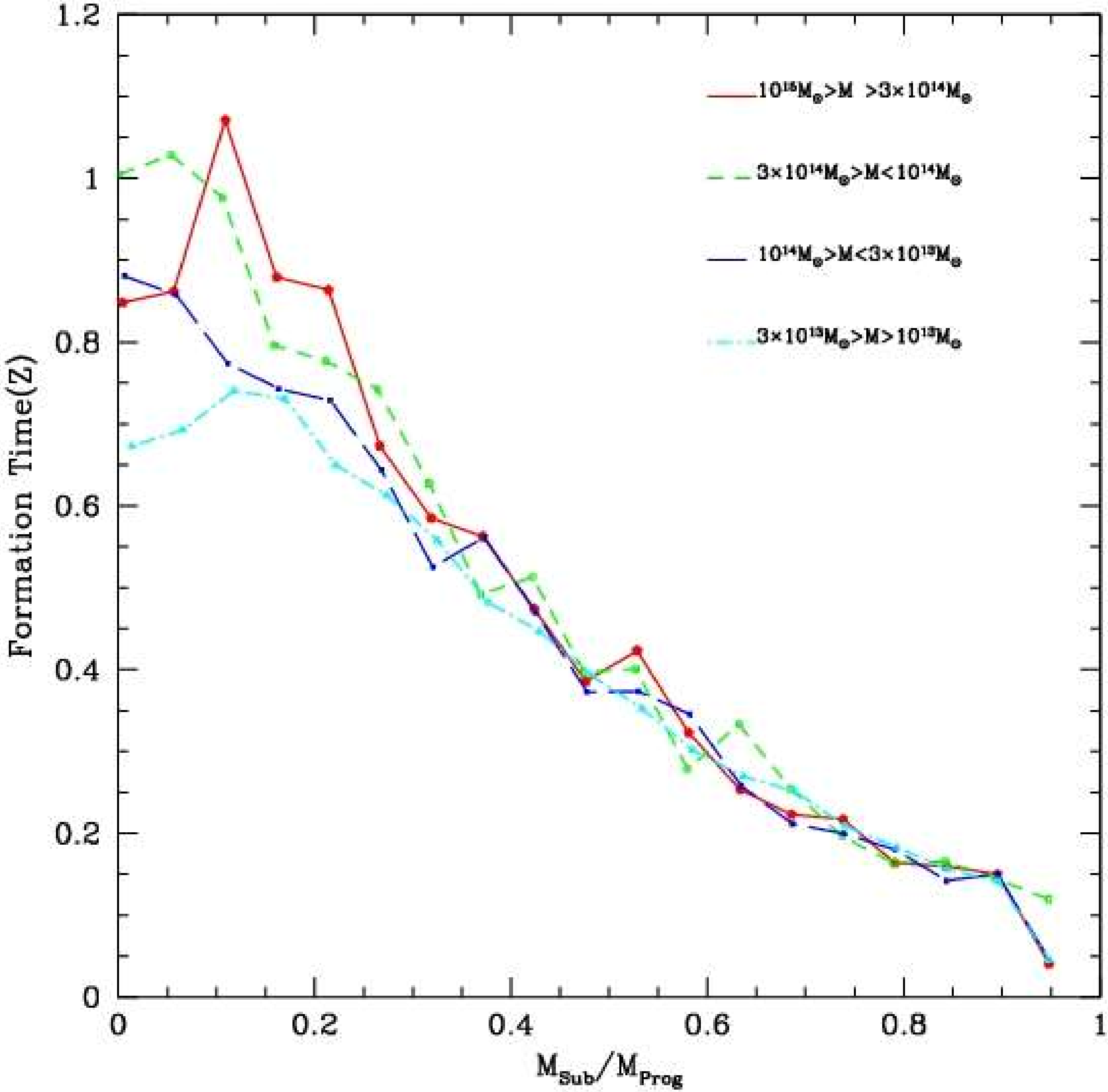
When are sub-halos accreted?



Most of the subhalos (and most of the mass in subhalos) first became a subhalo at *late* times

60% after z = 0.5
80% after z = 1.0

Gao et al 2003



Mass loss vs Accretion time

Subhalos which have lost little mass were accreted recently

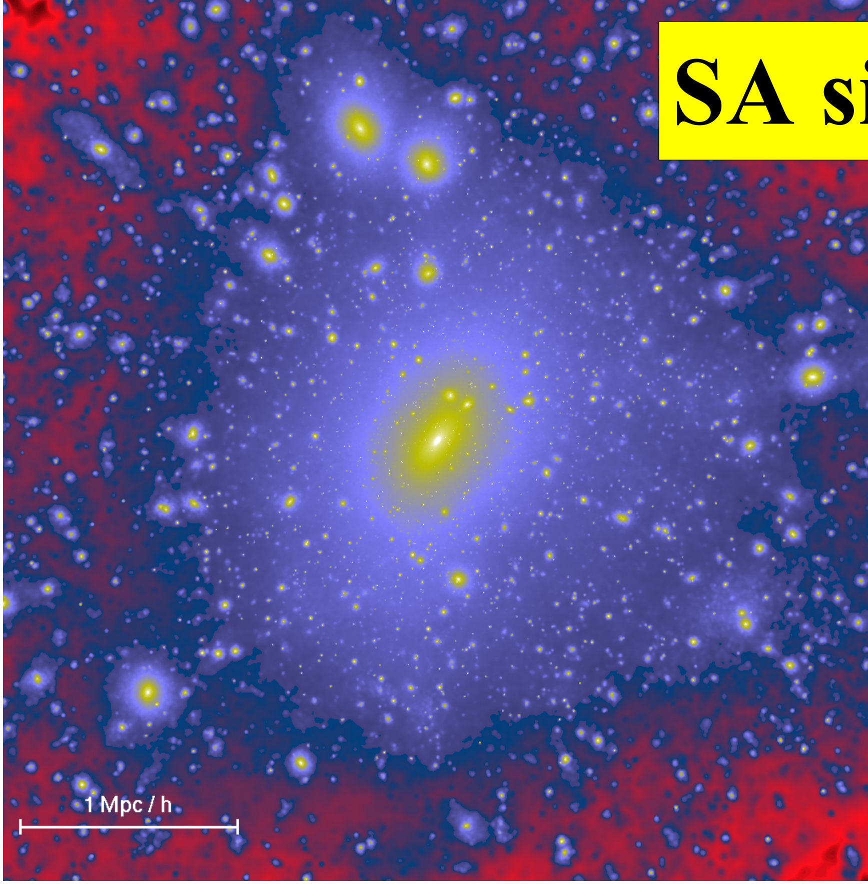
Subhalos retaining more than half their mass have $\langle z_{acc}\rangle \sim 0.3$

Subhalos retaining <0.1 of their mass have $\langle z_{acc}\rangle \sim 0.9$

Galaxy formation in the standard paradigm

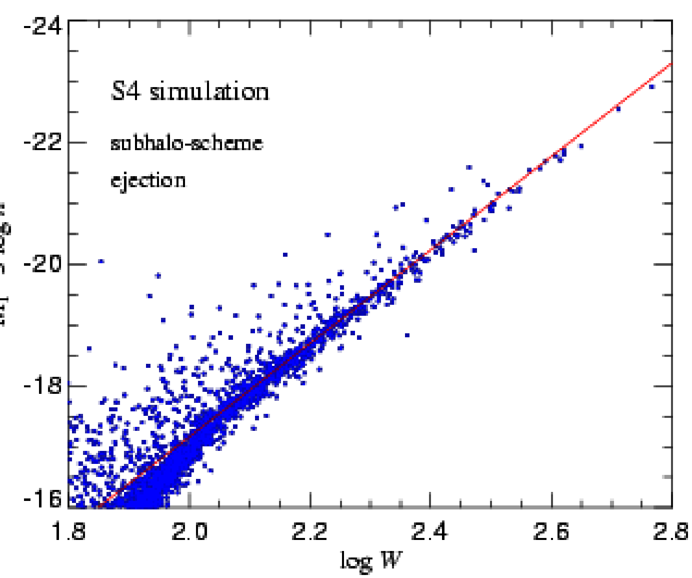
- Nonlinear dark matter clustering under gravity
  → hierarchical "dark halo" growth by accretion and merging
- Infall and shock heating of diffuse gas
  → hot gas "atmospheres" in halos (e.g. the intracluster gas)?
- Cooling and condensation of gas into "protogalaxies"
  → rotationally supported disks?
- Star formation in disks or during protogalactic collapse
  → disk galaxies or "primordial" spheroids
- Feedback from star and AGN radiation and galactic winds
  → reionisation and enrichment of the intergalactic medium
  regulation of star formation within galaxies
- Merging of galaxies
  → starbursts
  morphological transformation : disks → spheroids

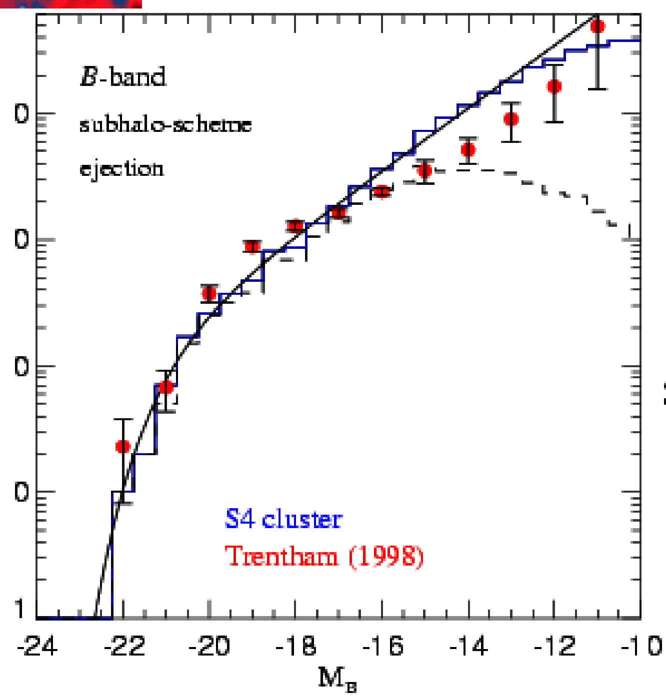
SA simulation of cluster formation

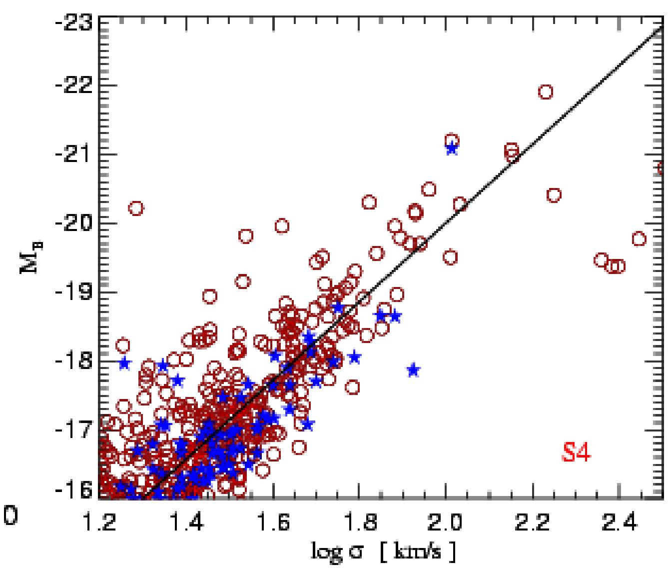


- Semi-analytic methods allow the simulation of a Coma cluster following all galaxies with $M_B < -12$
- Nearly all galaxies with $M_B < -16$ retain their own dark halos
- Protocluster can be analysed at high z

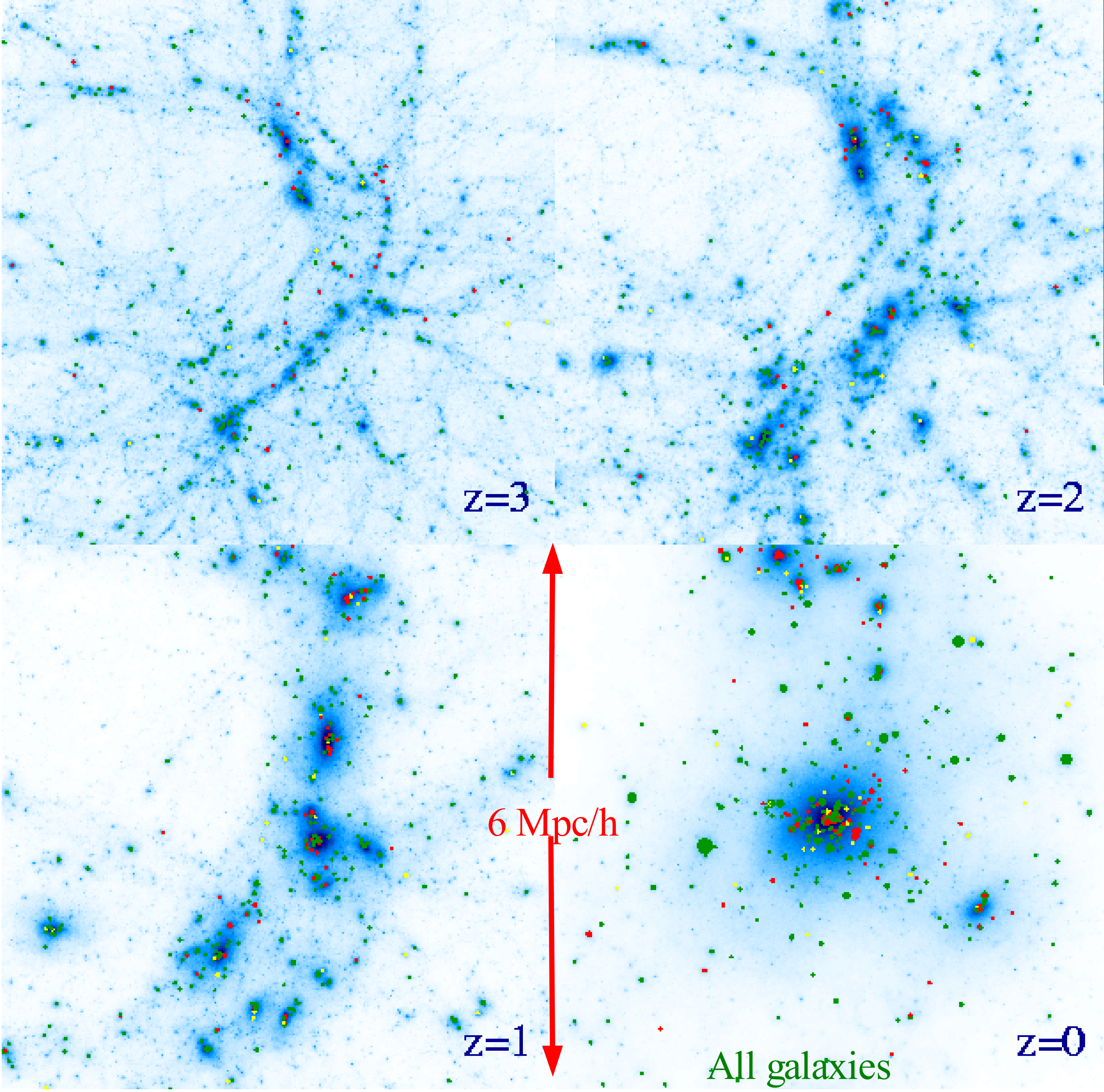
Springel et al 2001







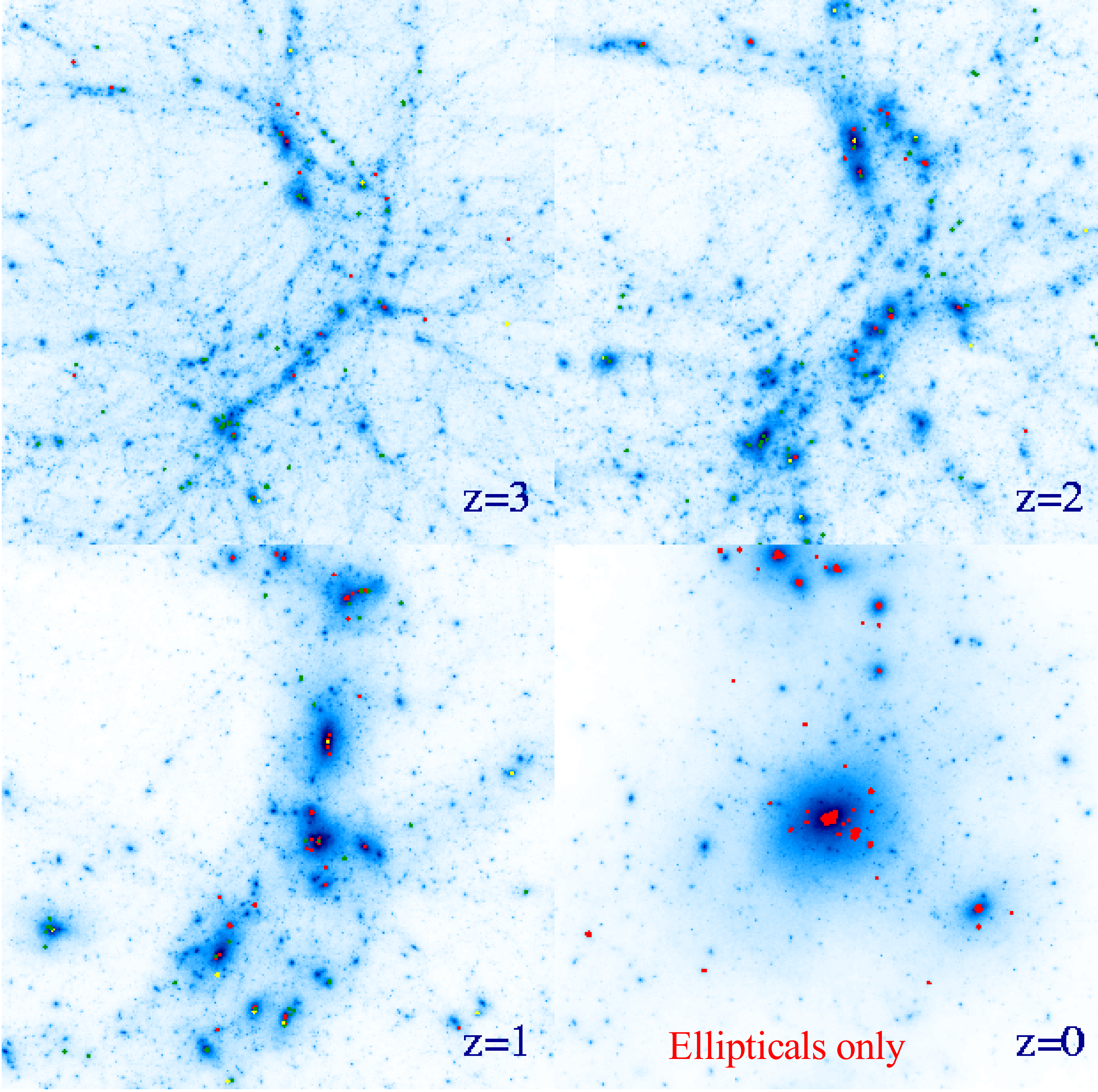
Evolution of the galaxy population in a Coma-like cluster



Springel et al 2001

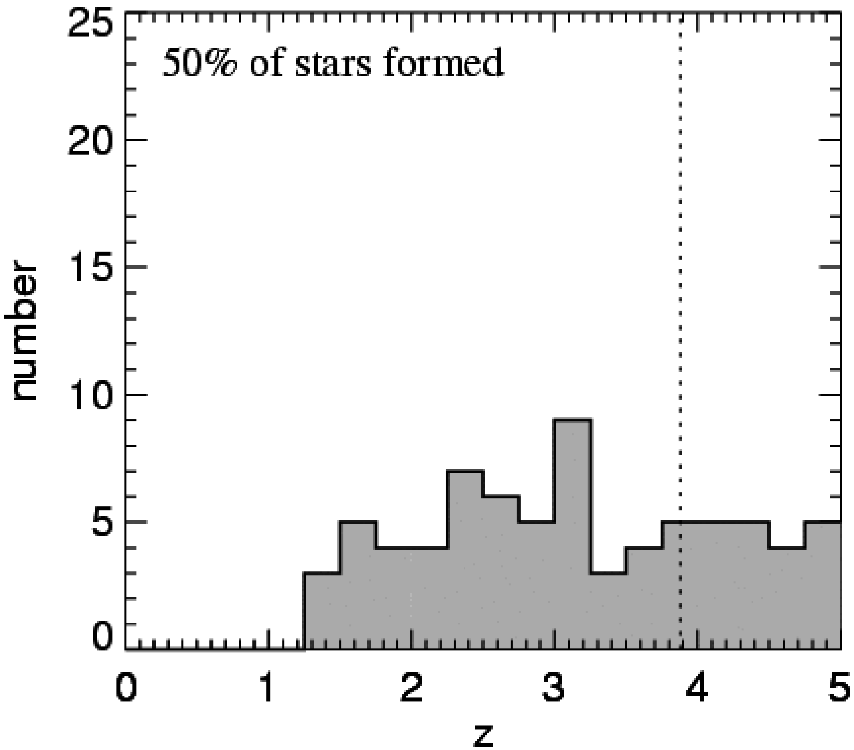
- Formation and merging tracked within evolving (sub)halos
- Luminosities and star masses are uncertain
- Positions and velocities are followed well

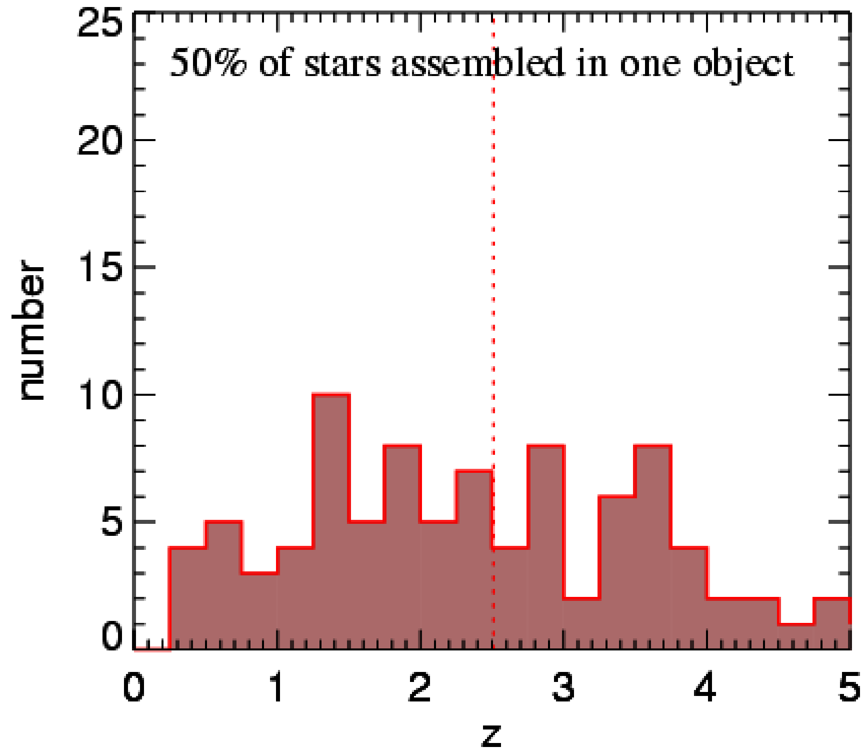
Evolution of the galaxy population in a Coma-like cluster



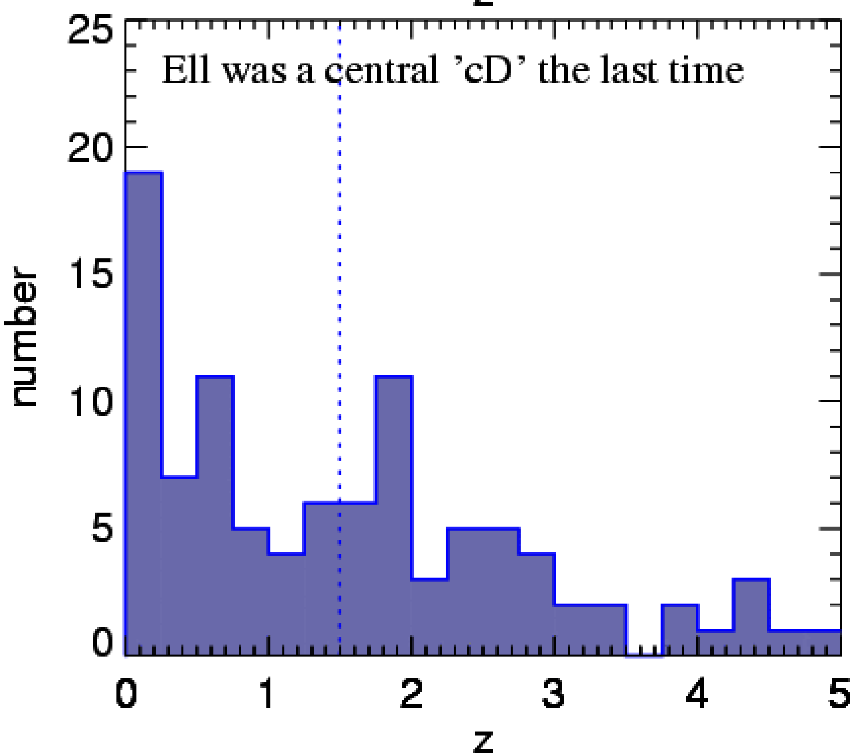
Springel et al 2001

- Tracking of star formation and of merging allows a B/D ratio to be assigned to each object
- Mergers which create bright E's are followed explicitly in the DM simulation



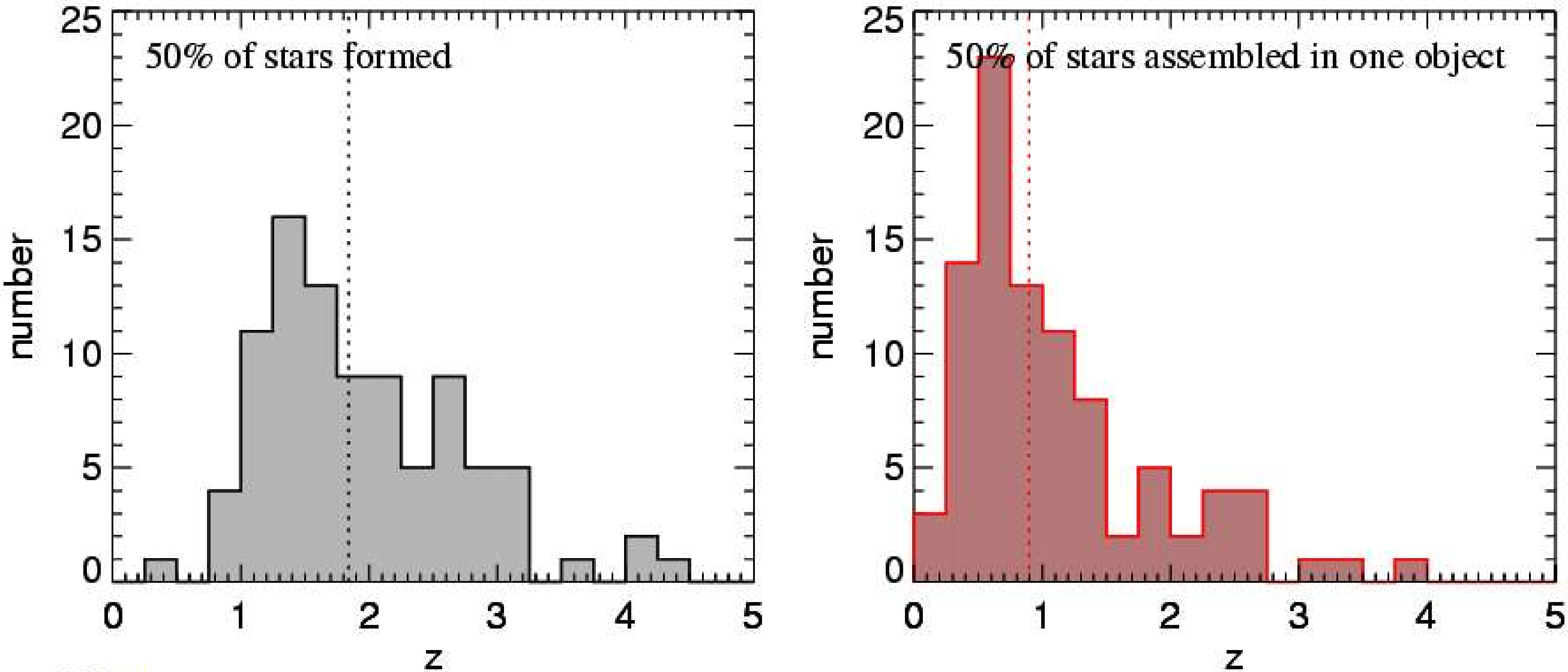


Springel et al 2003

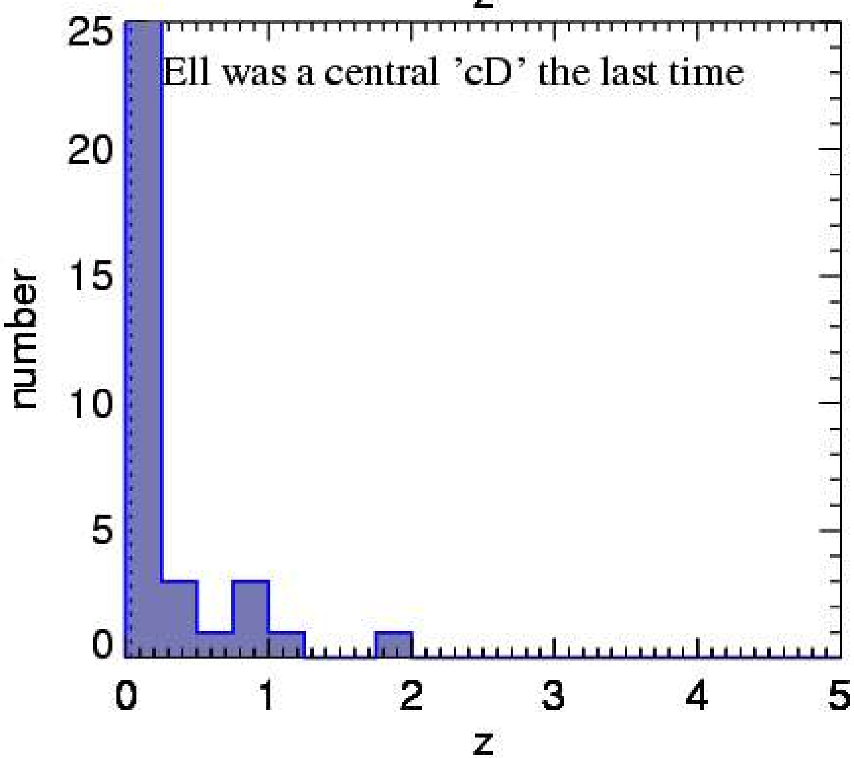


Formation histories of cluster ellipticals

- Cluster mass is 7 x $10^{14} M_{\odot}/h$
- 104 member ellipticals with $M_B < -18$
- Stars form early
- Most ellipticals assembled early
- Many ellipticals accreted late



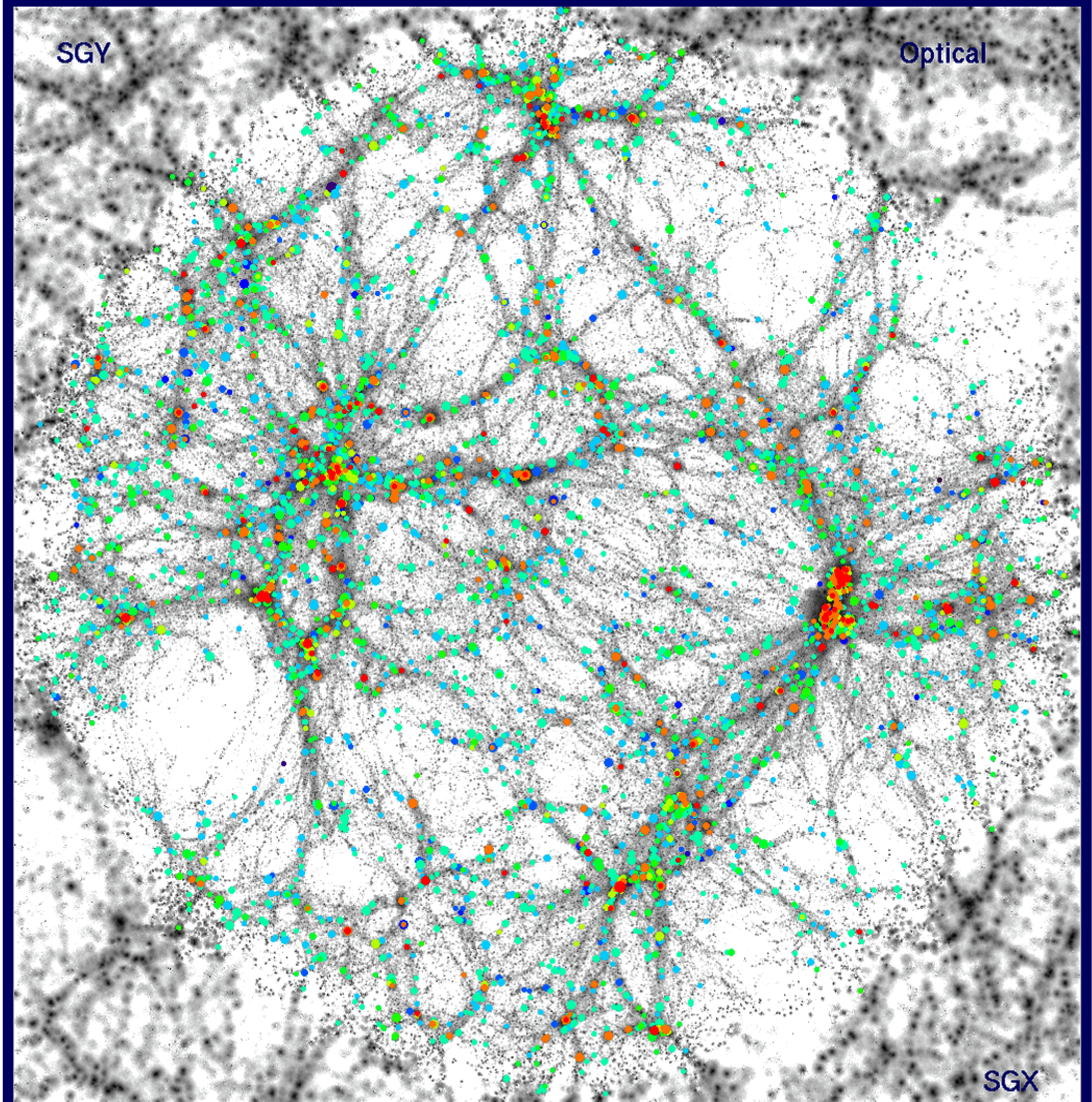
Springel et al 2003



Formation histories of field ellipticals

- 91 field ellipticals with M_B< -18
- Stars form fairly early
- Most ellipticals assembled late
- Most ellipticals are 'cD' of their groups

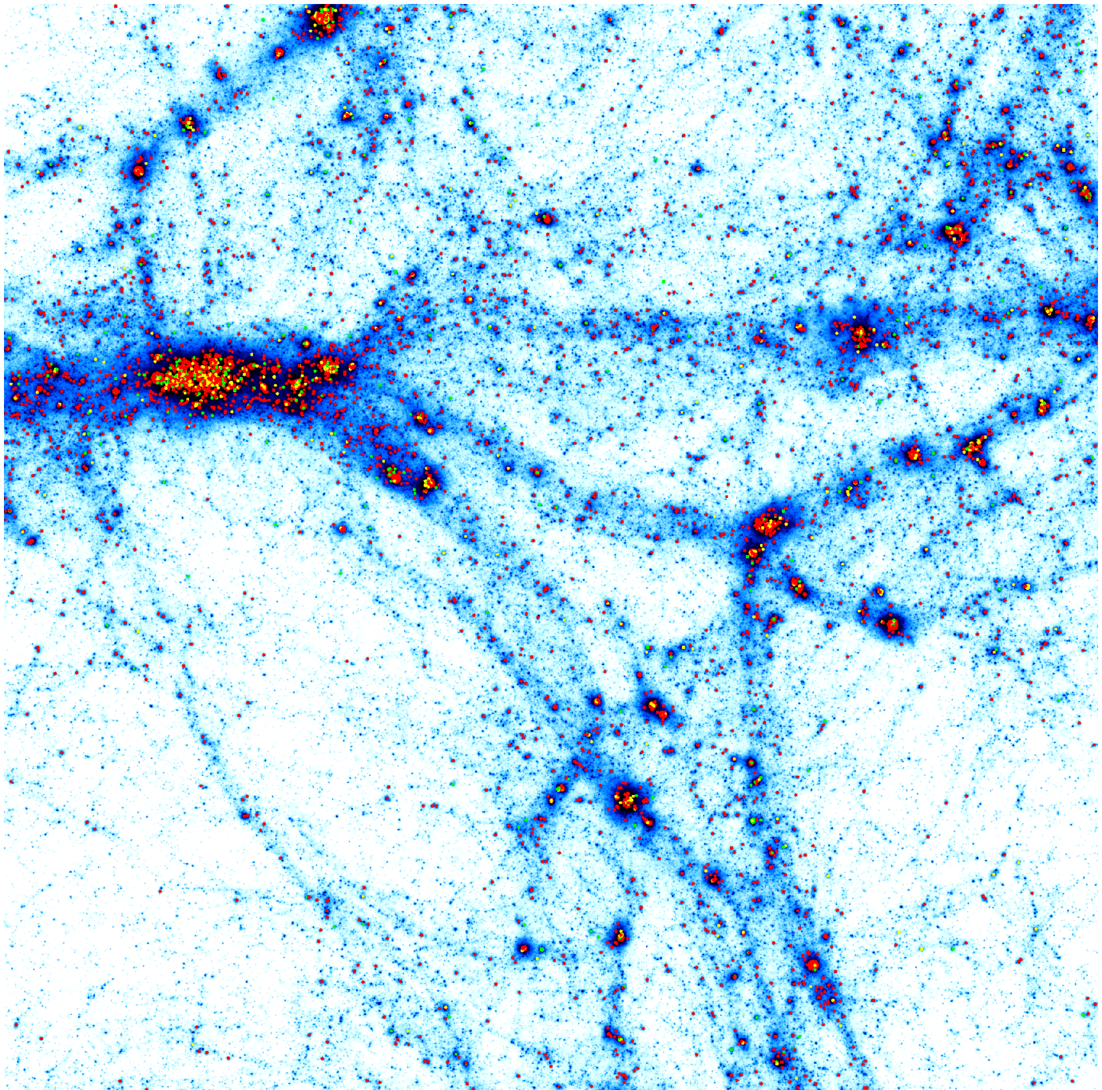
The local Universe *with* galaxies



Mathis et al 2001

Field vs cluster evolution of the galaxy population

40 h^{-1}Mpc



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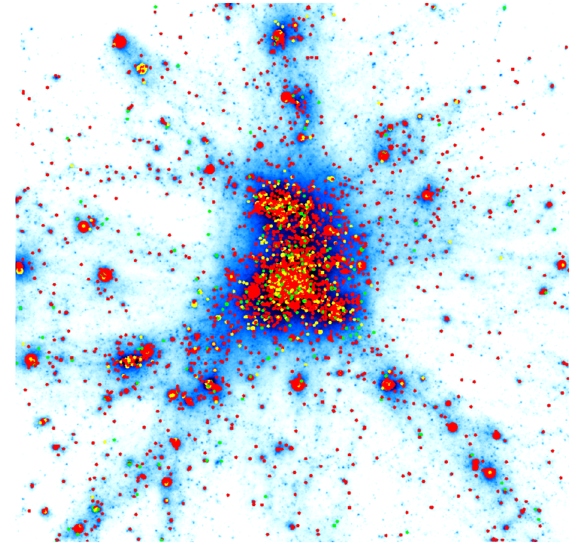


$\rho_* = 3.5 \langle \rho_0 \rangle$

$\rho_* = 0.9 \langle \rho_0 \rangle$

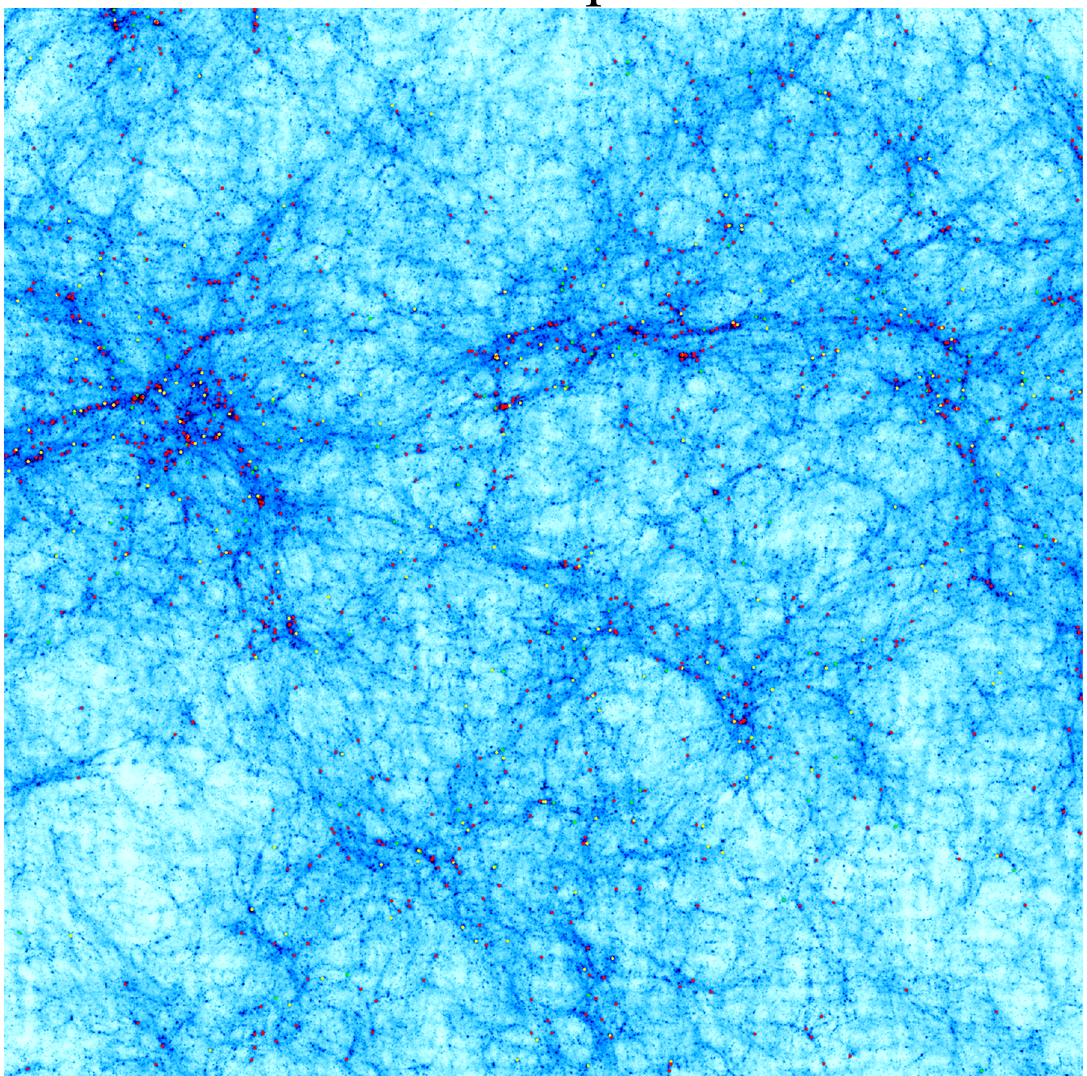
$M_{gal} > 10^9 M_{sun}$

$z = 0$

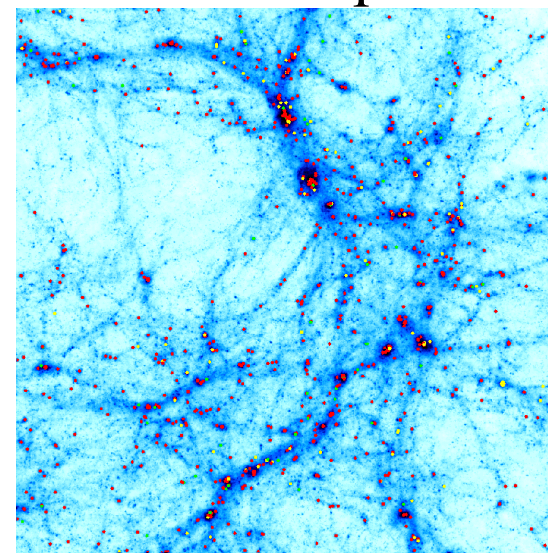
Stoehr et al 2003

Field vs cluster evolution of the galaxy population

40 h^{-1}Mpc



20 h^{-1}Mpc



$\rho_* = 0.5 \langle \rho_0 \rangle$

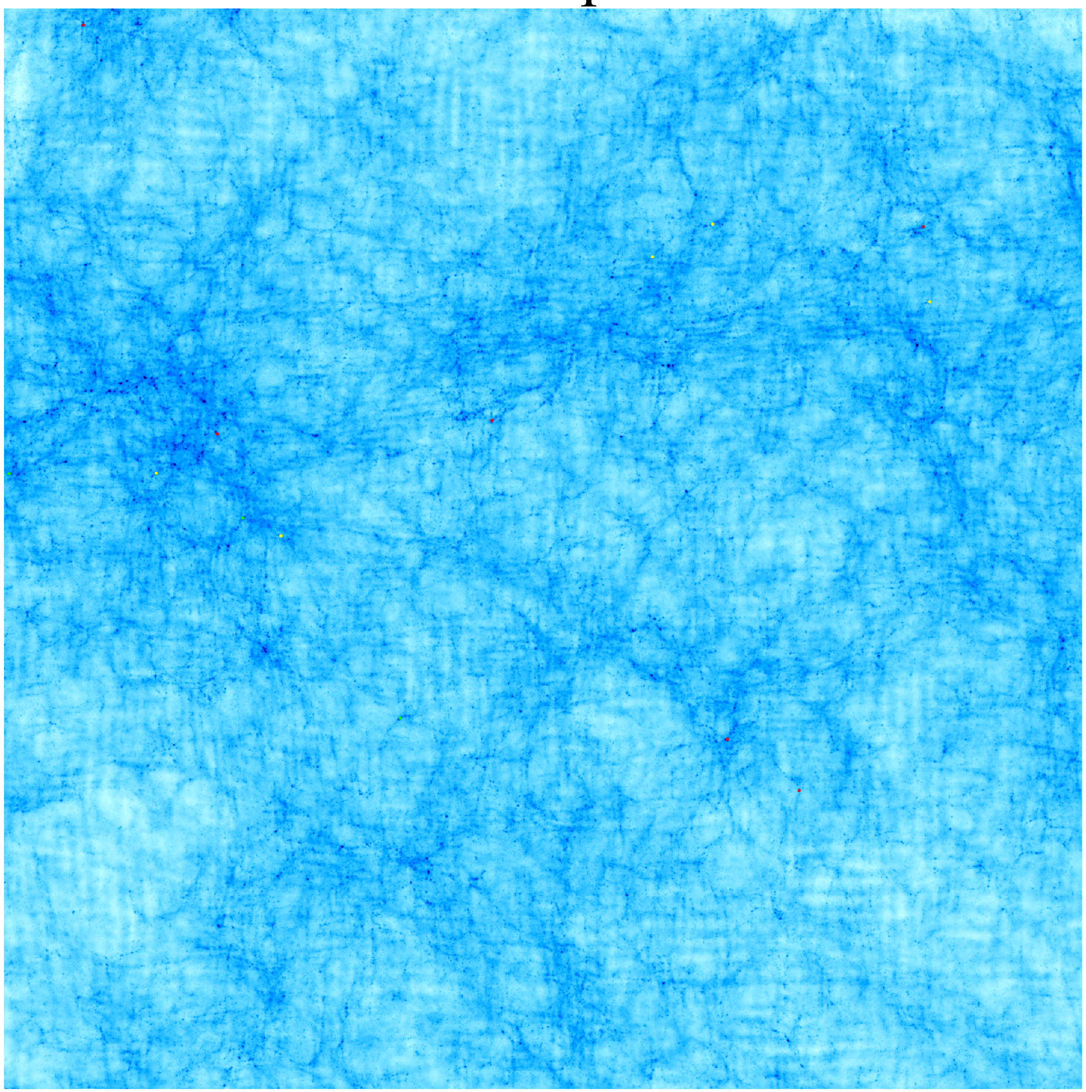
$\rho_* = 0.17 \langle \rho_0 \rangle$

$M_{gal} > 10^9 M_{sun}$

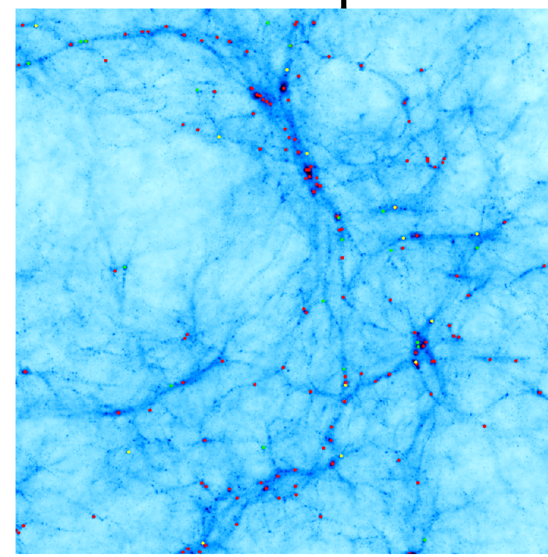
$z = 5$

Field vs cluster evolution of the galaxy population

40 h^{-1}Mpc



20 h^{-1}Mpc



$\rho_* = 0.093 \langle \rho_0 \rangle$

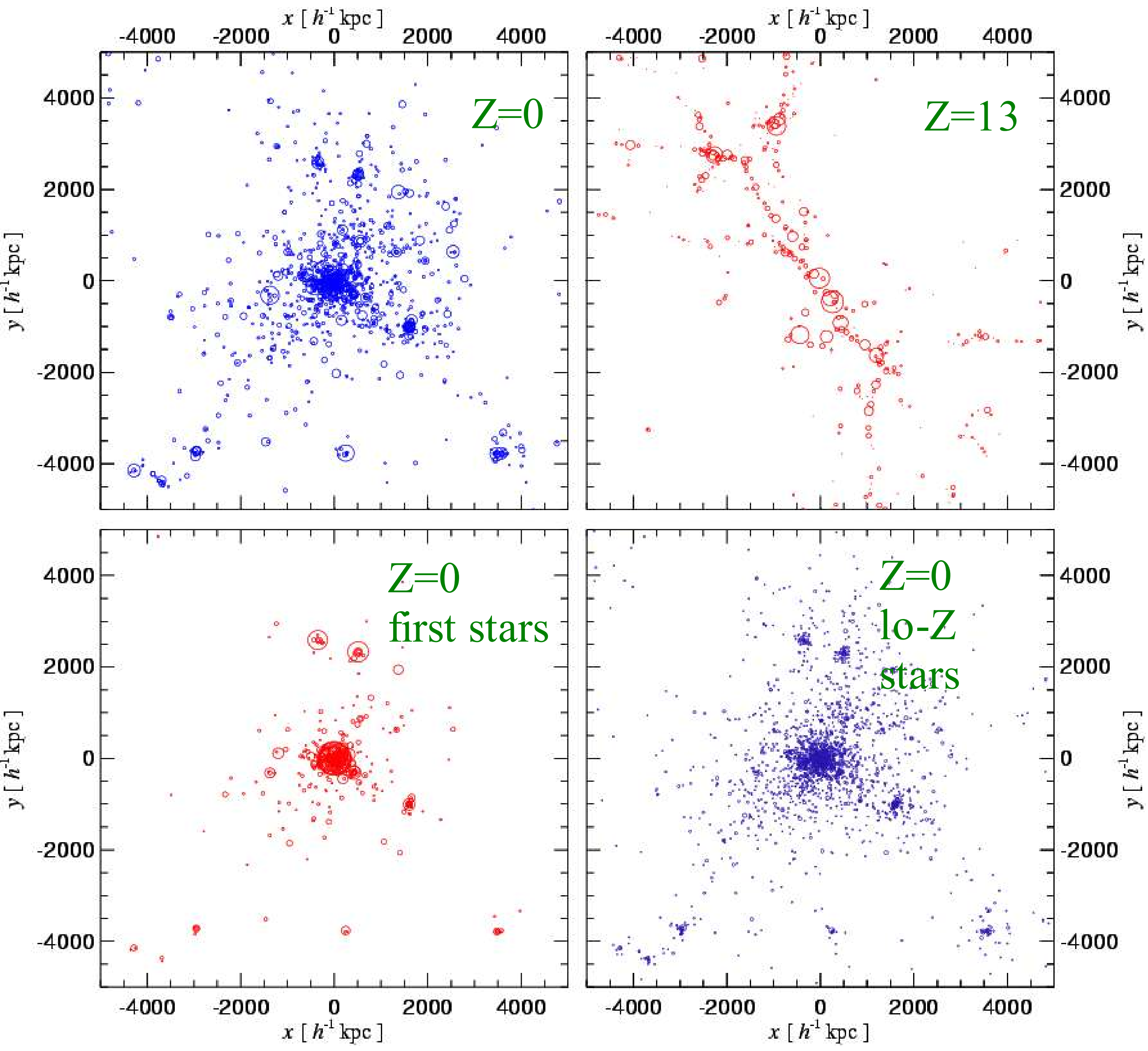
$\rho_* = 0.018 \langle \rho_0 \rangle$

$M_{gal} > 10^9 M_{sun}$

$z = 10$

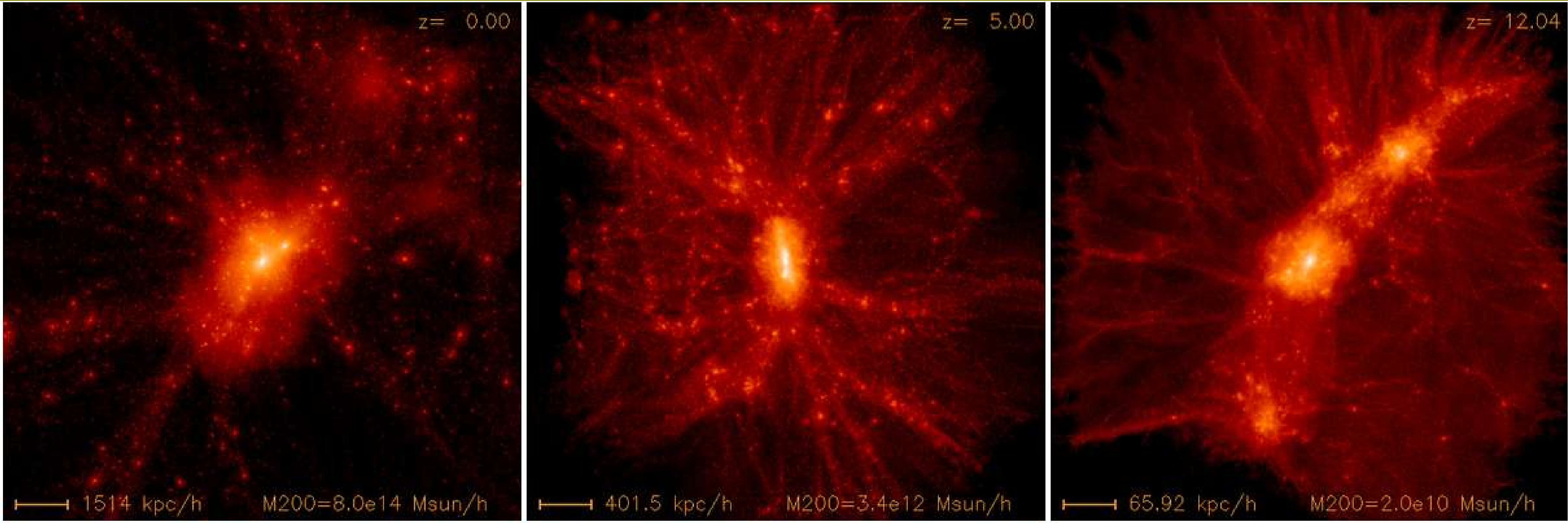
Where are the first stars now?

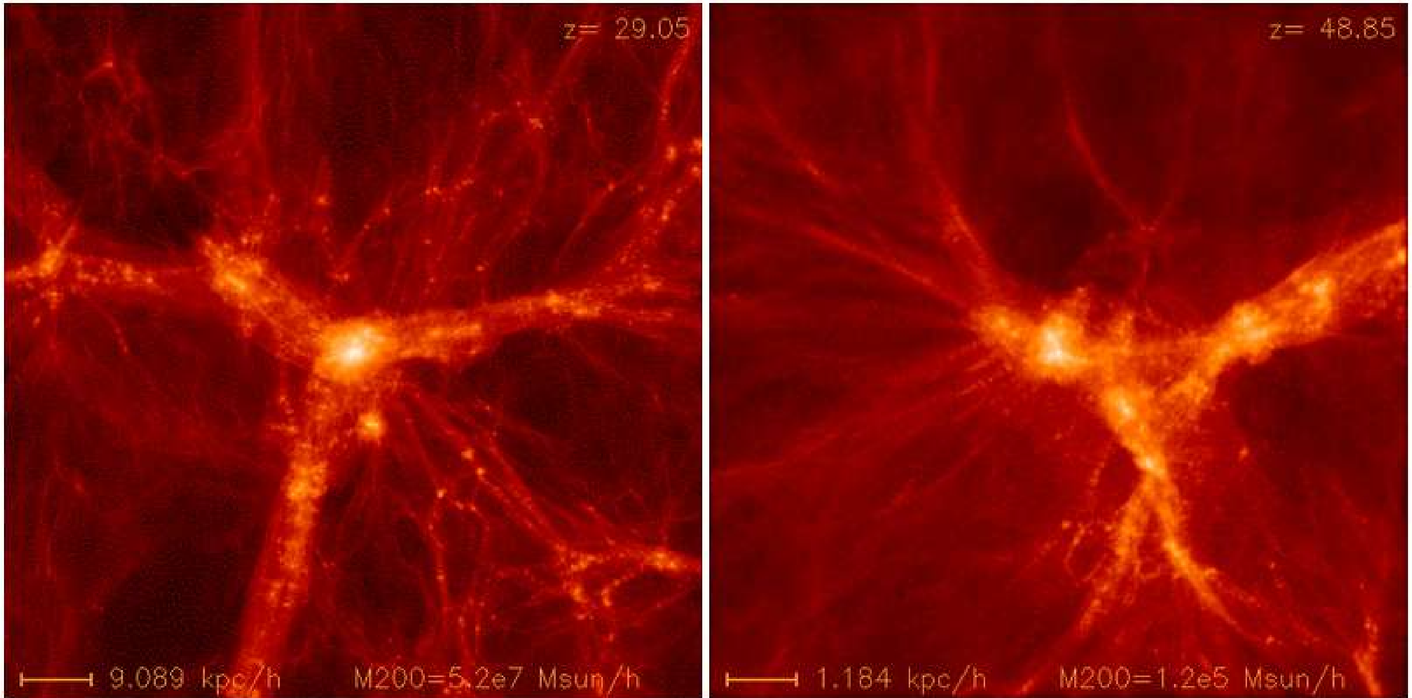
White & Springel 1999



- By z=13 about 1% of the stars that end up in a rich cluster have already formed
- These stars are to be found in galaxies that are *already* in large-scale structures
- More than half of them end up in the final cD
- Stars formed in the *lowest mass* objects are distributed like typical stars

Most massive progenitor of a ΛCDM rich cluster



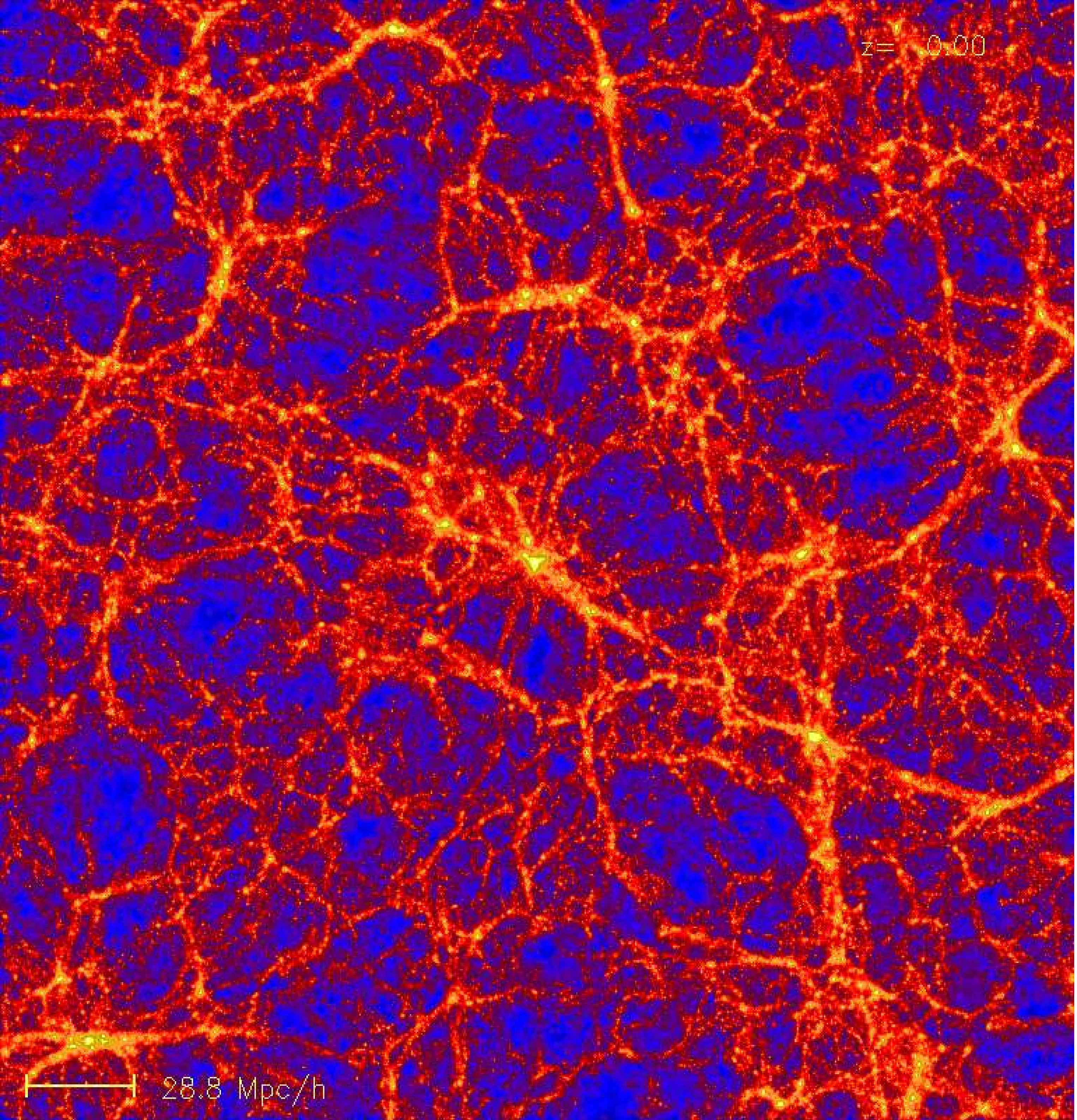


Each image is 10 R_{200} across and 2 R_{200} thick

$N_{200} \sim 10^6$ in all cases

Same colour table for δ in all cases

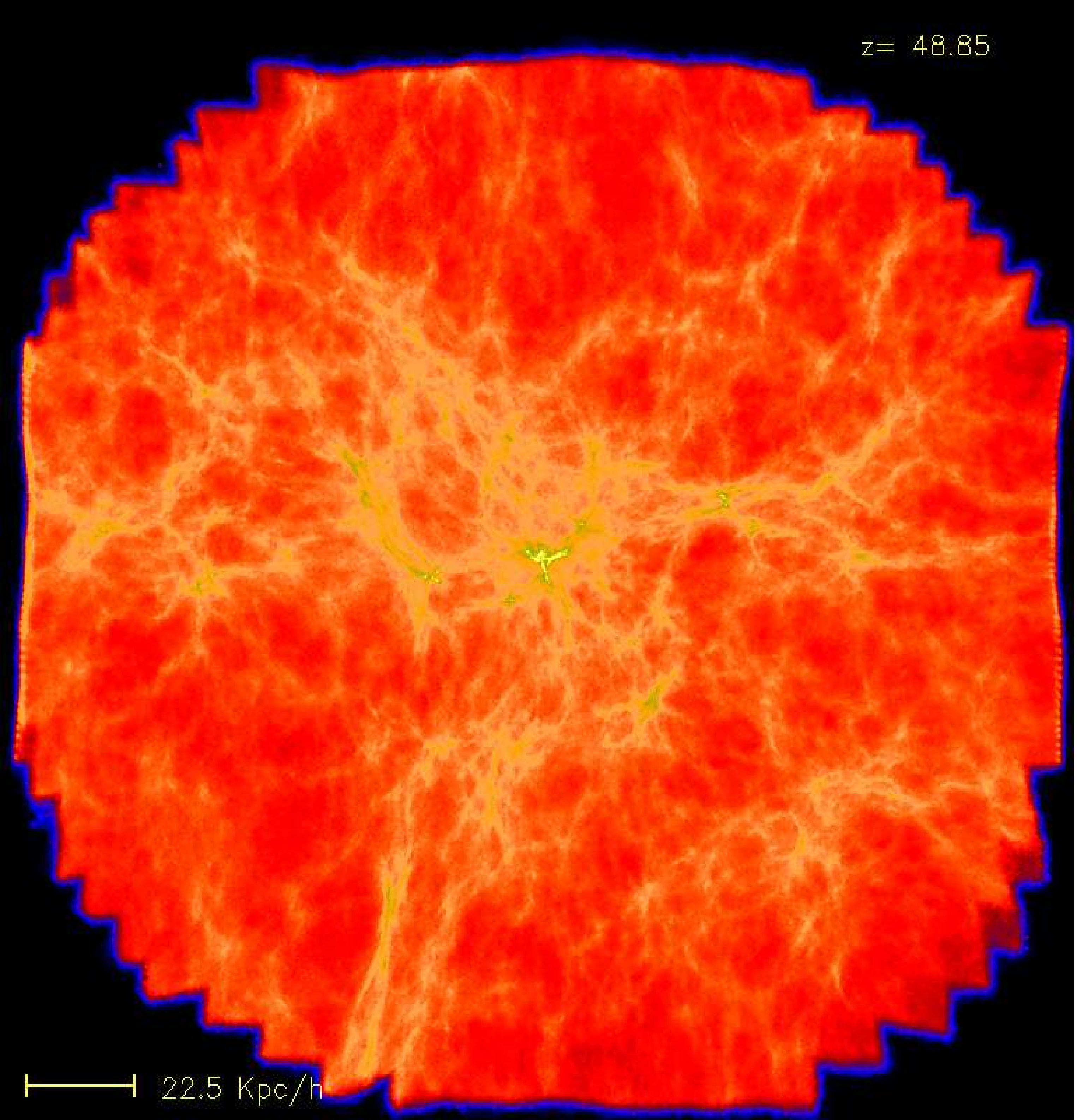
Gao et al 2003



- Slice 190 R_{200} wide and 10 R_{200} thick
- Colour table for δ identical at

$z = 0$ and $z = 50$

Gao et al 2003



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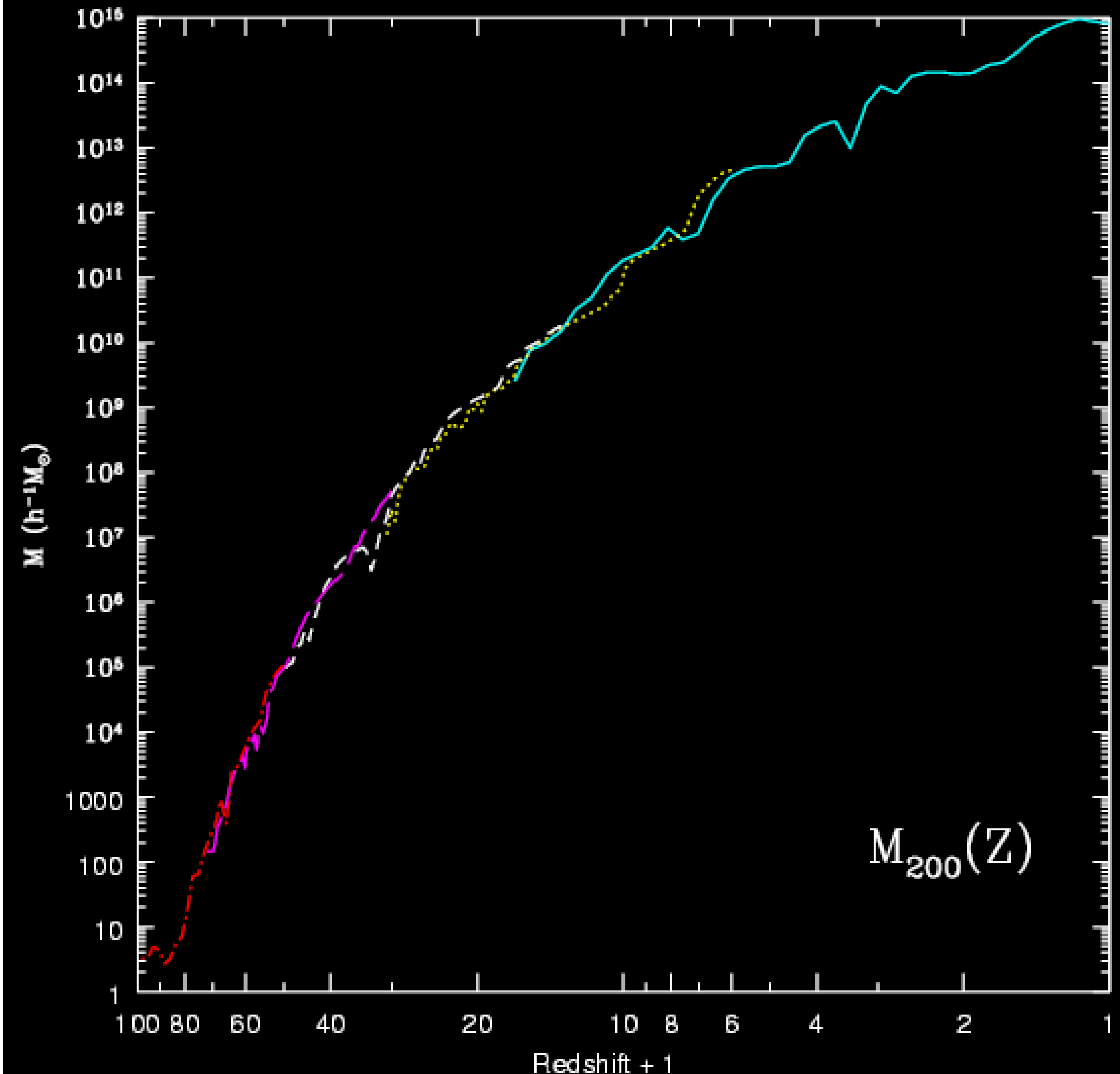


The most massive progenitor of a rich cluster has

$10^{15}\,M_\odot$ at $z = 0$

$10^{12}\,M_\odot$ at $z = 7$

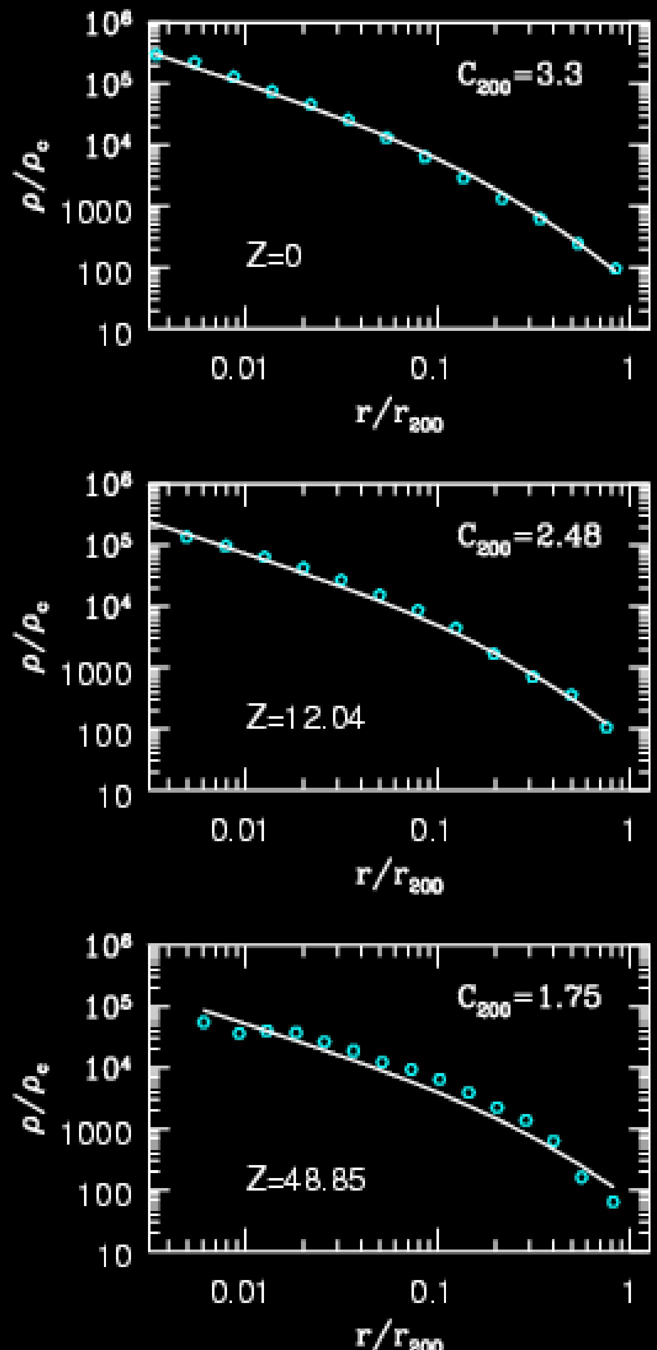
$10^{9}\,M_\odot$ at $z = 20$

$10^{6}\,M_\odot$ at $z = 40$

$10^{3}\,M_\odot$ at $z = 60$

$1.0\,M_\odot$ at $z = 85$

Gao et al 2003



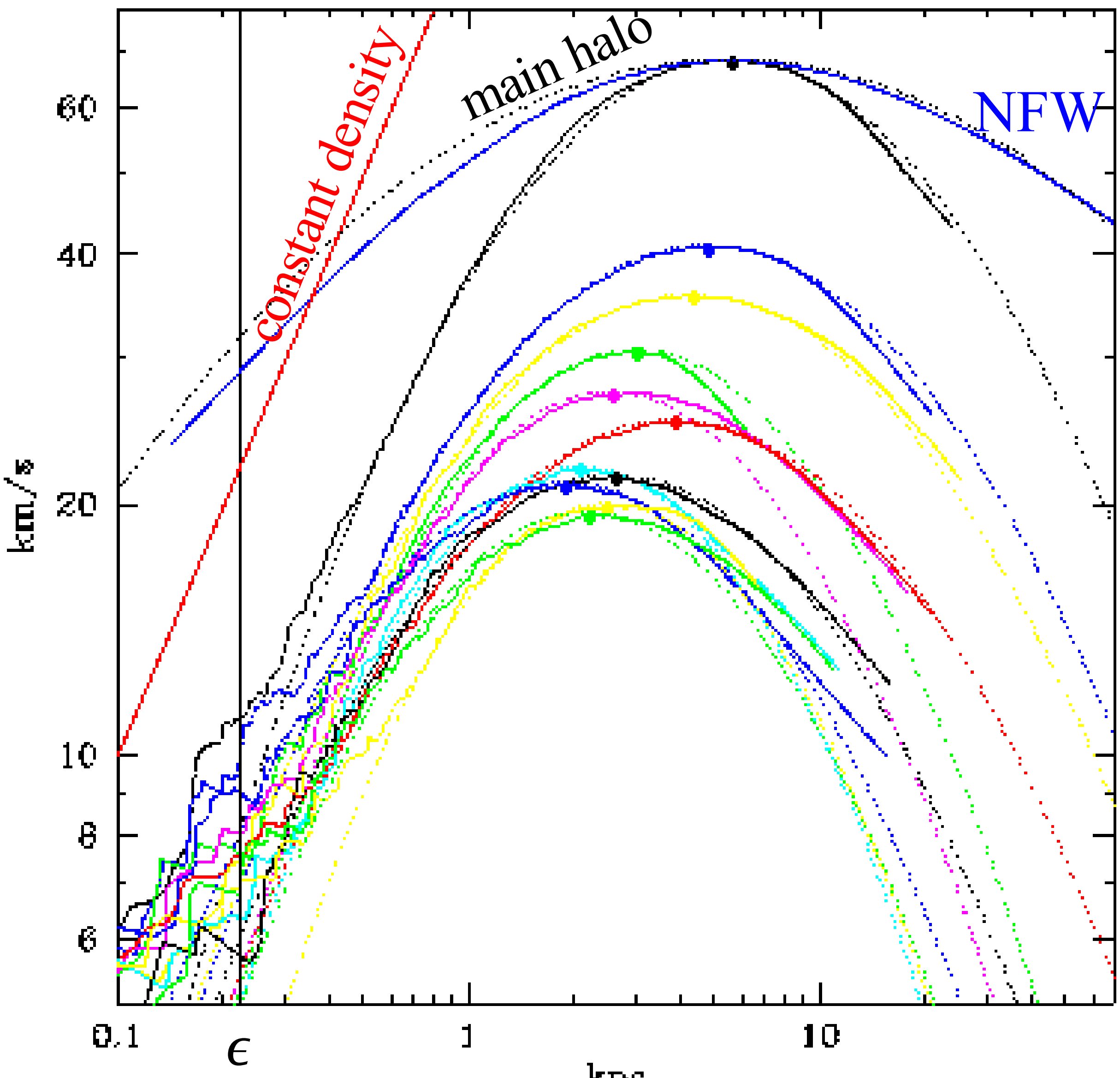
Profiles of massive progenitors are roughly NFW out to z = 50

Their concentration goes down weakly as redshift increases

Gao et al 2003

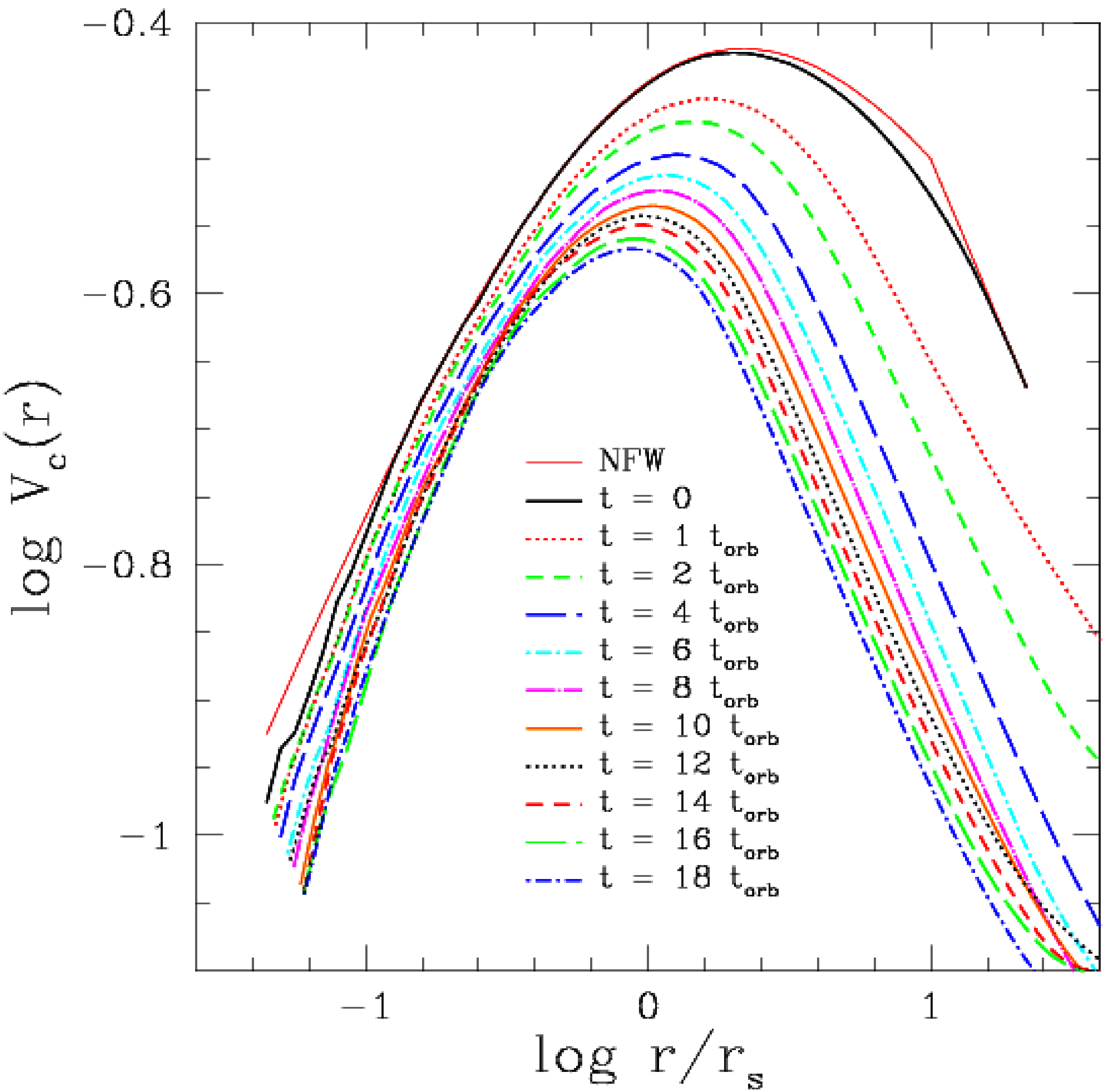
Satellite circular velocity curves

Stoehr et al 2003



- Circular velocity curves for 11 of the 30 most massive subhalos in a 10^7 particle 'Milky Way' halo
- The NFW and 'main halo' curves are scaled to the (r_m, V_m) of largest subhalo
- All curves are narrower than NFW or 'main halo'
- Many profiles approach a constant density core in their inner regions
- *The MOST MASSIVE of these potentials could host the observed satellites*

High resolution simulations of subhalo stripping



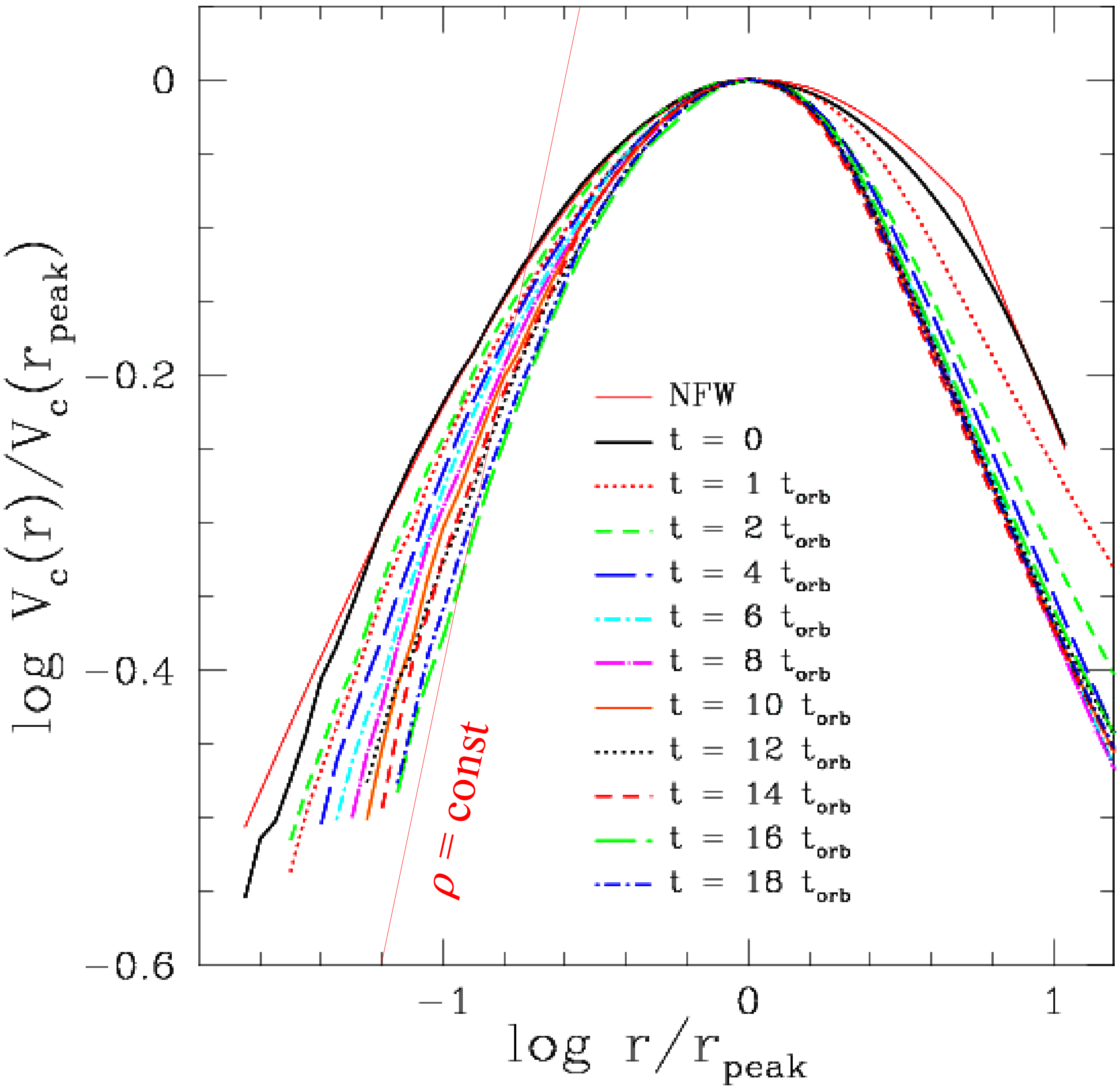
Hayashi et al 2003

Tidal stripping of an equilibrium NFW subhalo with N ~ 400,000 falling into a rigid NFW Milky Way.

R_{apo}=10 R_s R_{peri}= 3 R_s

Note that the amplitude of the $V_c(r)$ curve drops even in the inner regions

High resolution simulations of subhalo stripping



Hayashi et al 2003

Tidal stripping of a single NFW subhalo with N ~ 400,000 falling into a rigid NFW Milky Way

Note the steepening of the inner $V_c(r)$ curve

Cluster formation and evolution

- The initial conditions for cluster formation are now known down to scales much smaller than those responsible for building individual cluster galaxies
- Cluster assembly, even that of the innermost cluster core, occurred late, at $z < 1$ in most cases
- Clusters form by the infall of clumps along filaments
- Cluster assembly began early. The first cluster stars formed at $z > 40$. 1% may have formed by $z \sim 15$. The first stars are now mostly in the central massive galaxy.
- Cluster galaxies form stars early, assemble later and fall into the cluster later still.
- Subhalos have different *core* and outer structure than isolated halos of the same mass or V_{max}