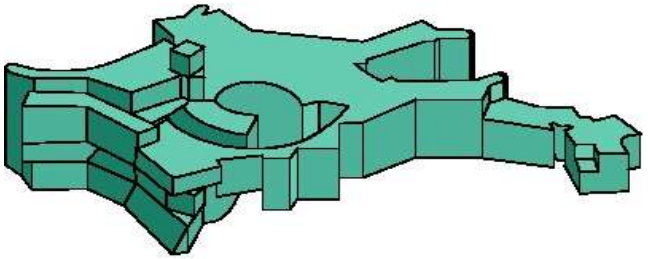
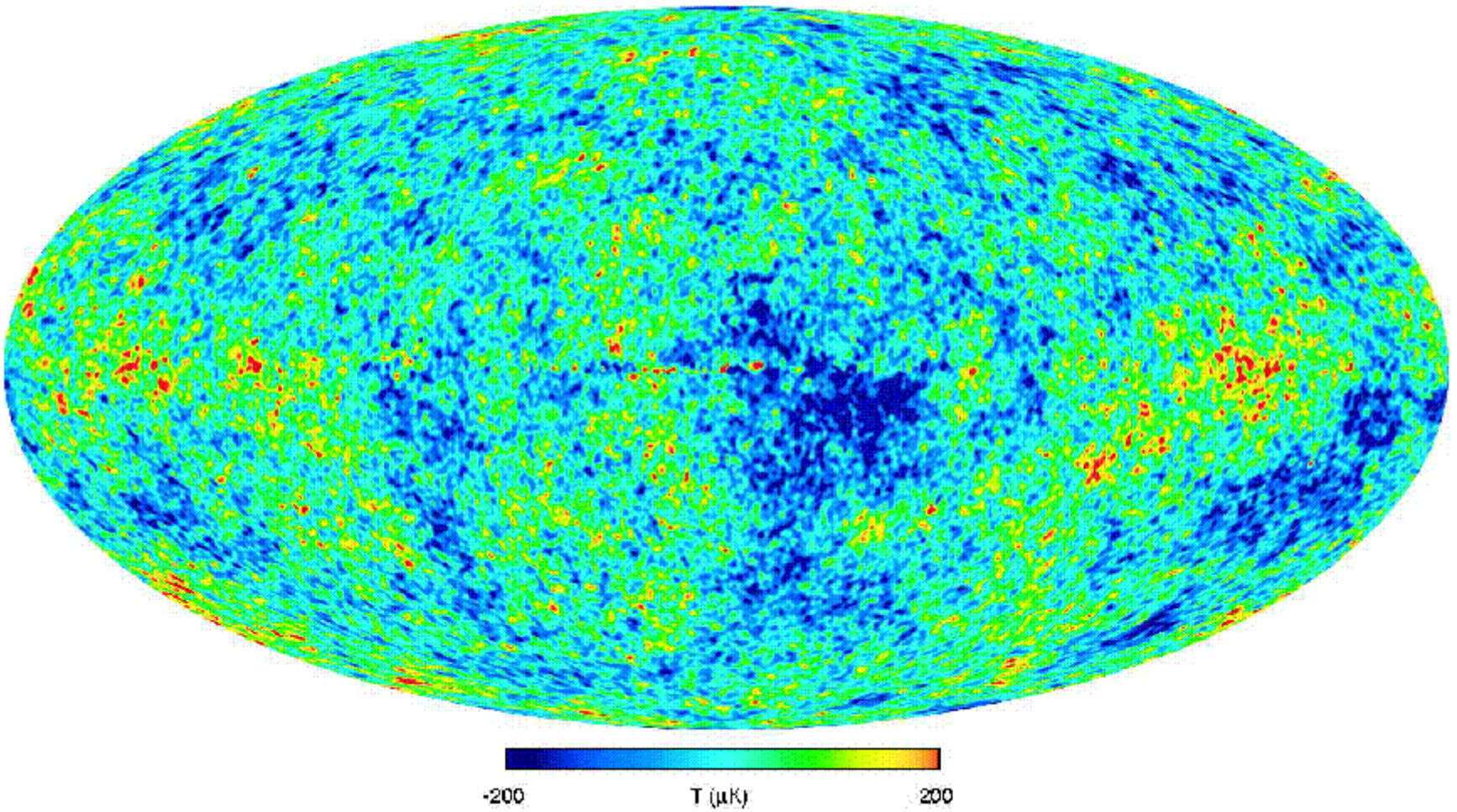


IAU Joint Discussion # 10
Sydney, July, 2003

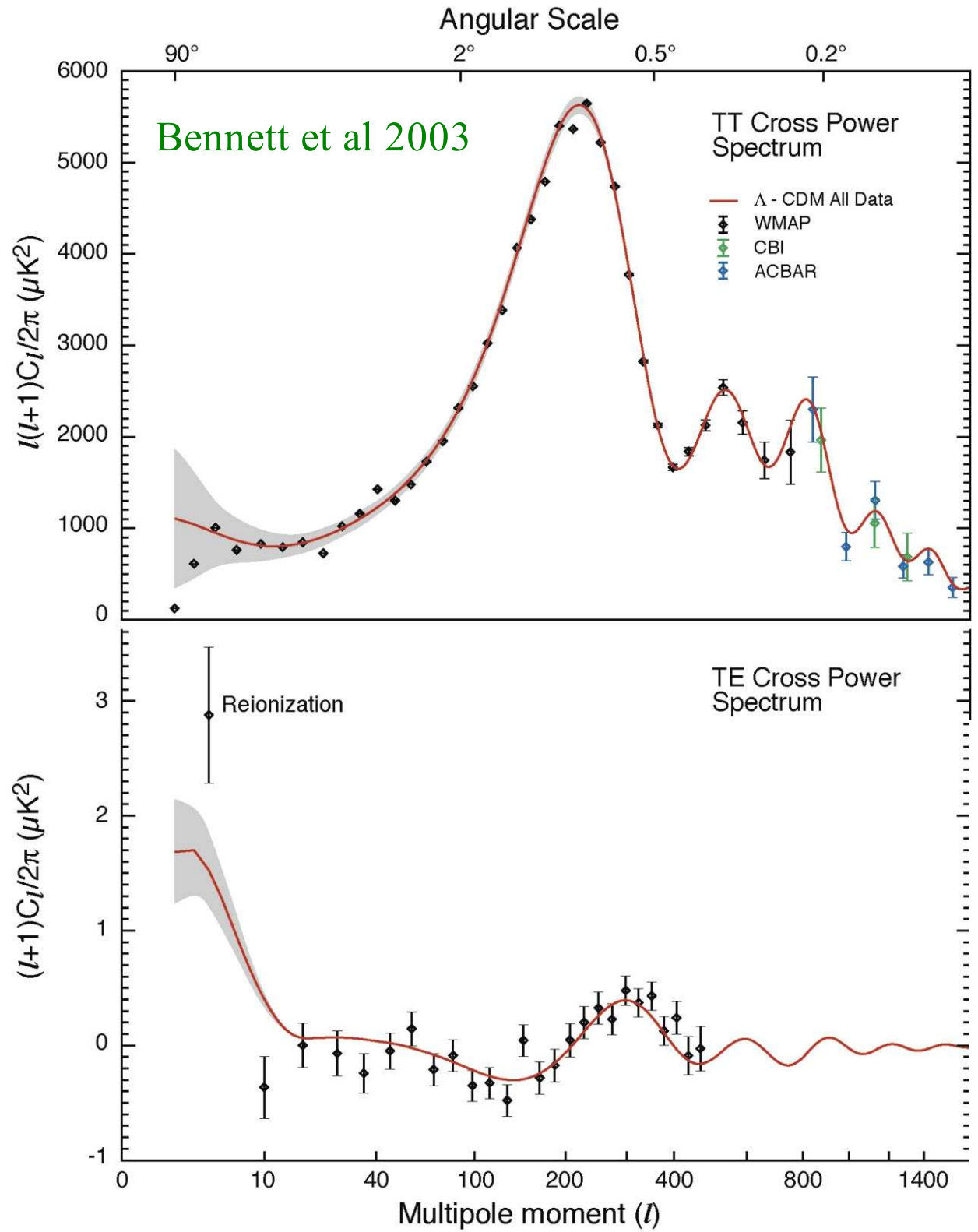
The Formation and Evolution of Galaxy Clusters

Simon D.M. White
Max Planck Institute for Astrophysics

The *WMAP* of the whole CMB sky

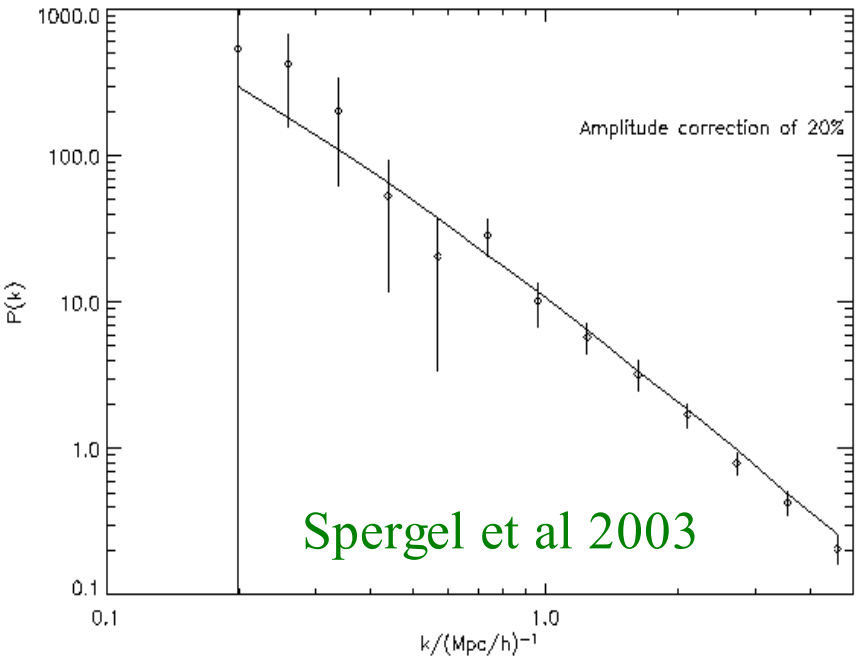


Bennett et al 2003



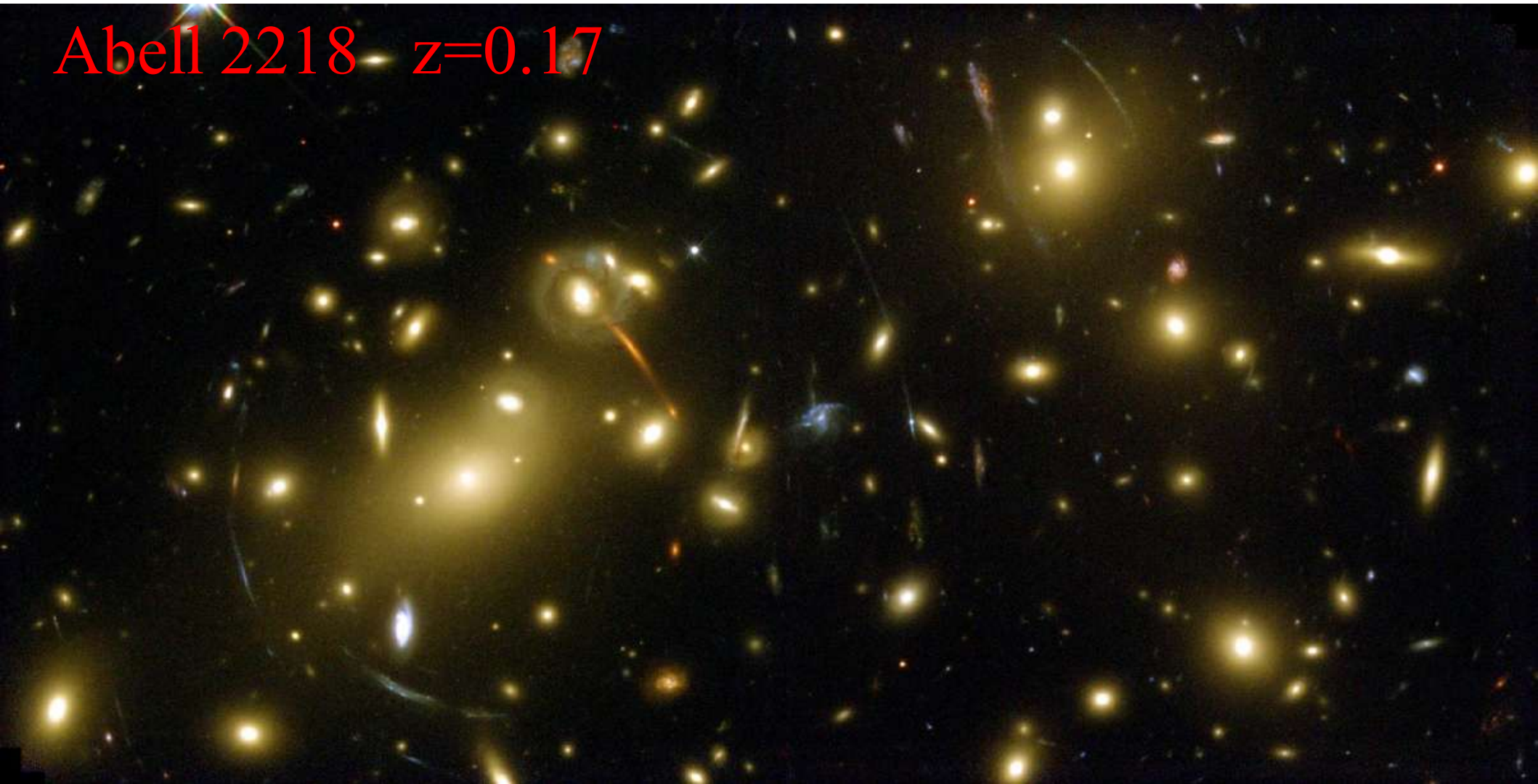
- $> 10^5$ near-independent 5σ temperature measurements
- Gaussian map: PS fit by a CDM model with parameters consistent with other data
- Extrapolation fits the Ly-α forest power spectrum

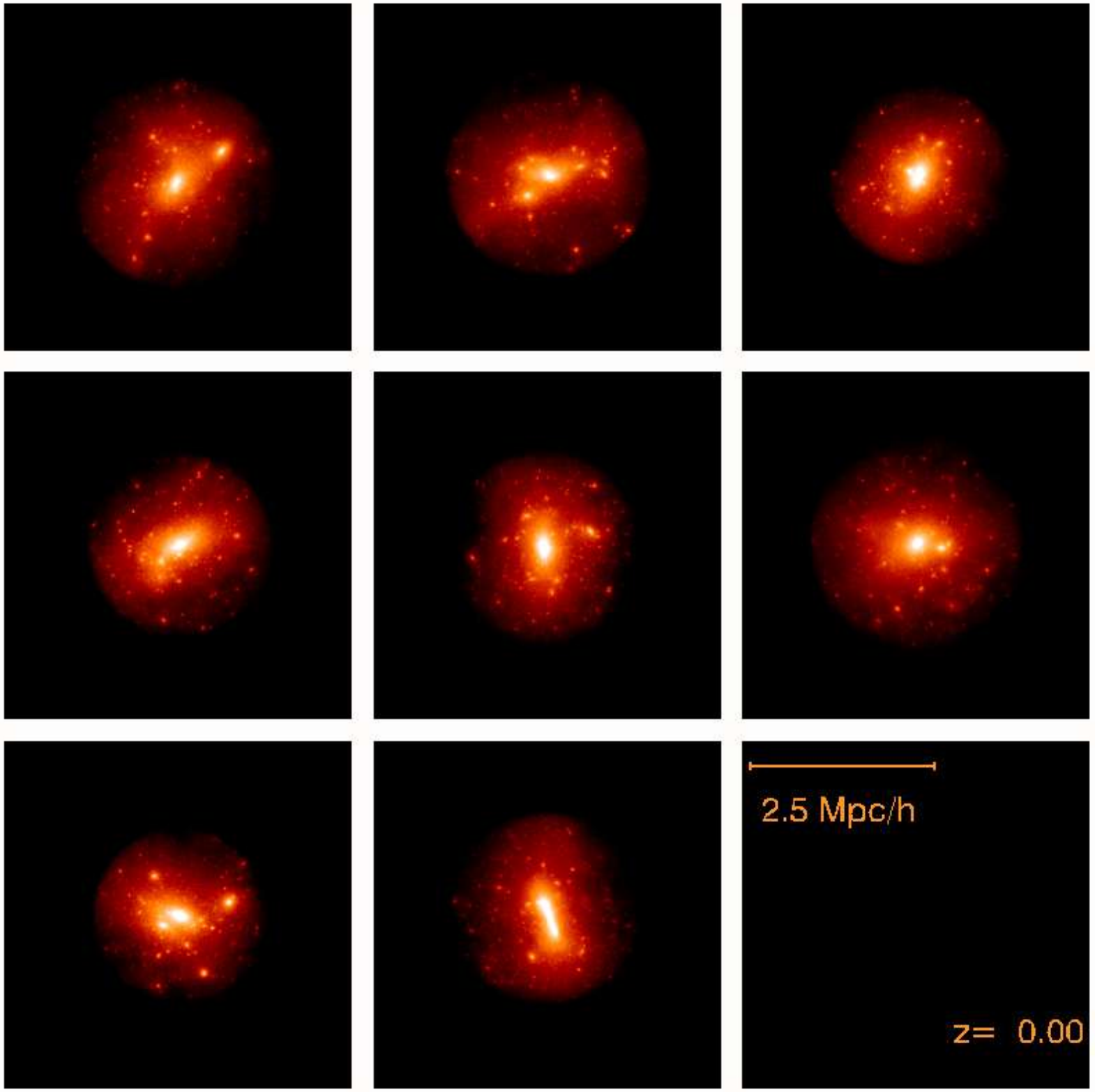
Confirms standard model to scales well below those of clusters and bright galaxies



Gravitational lensing by a galaxy cluster

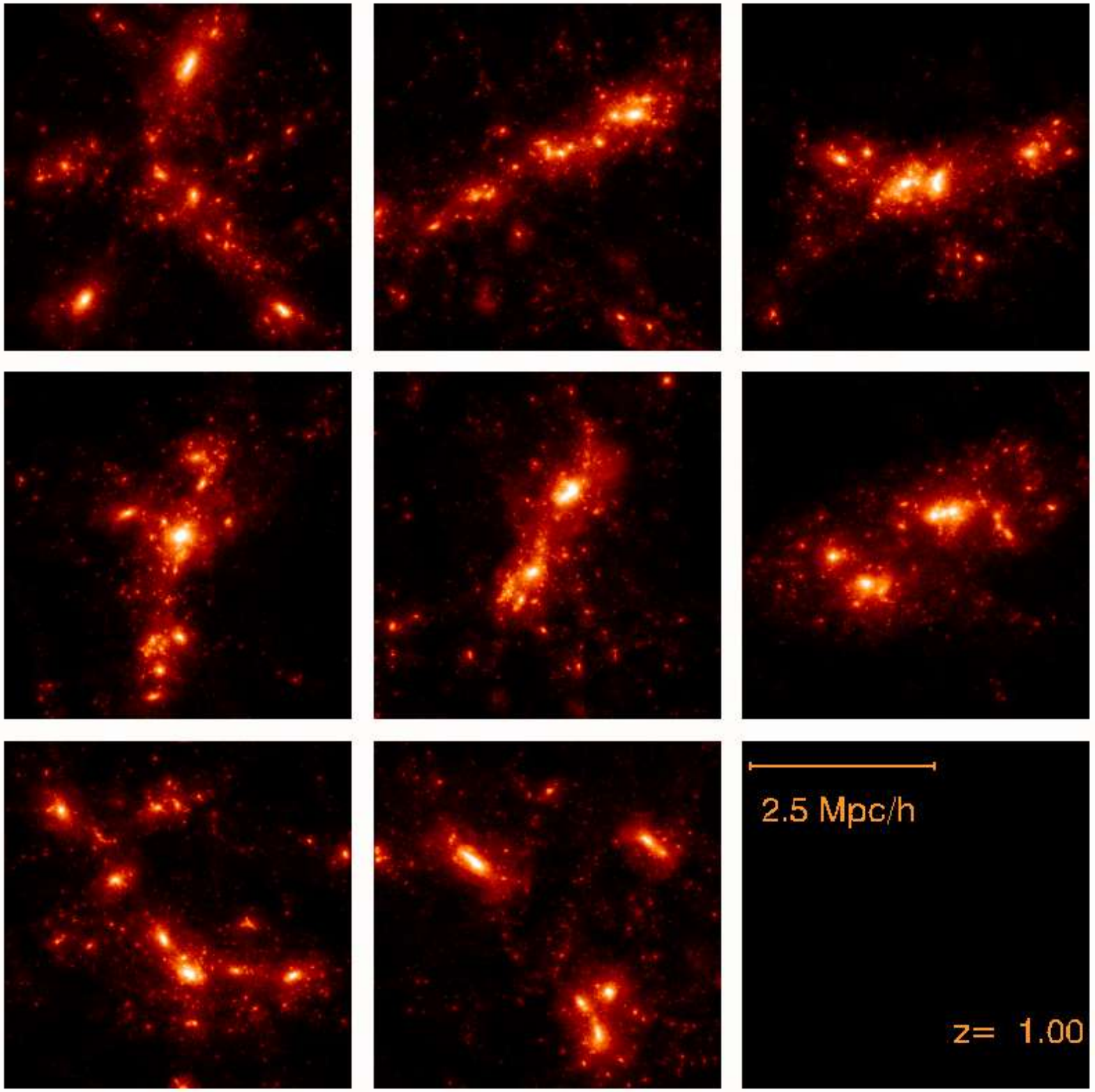
Both strong lensing and X-ray data indicate that many/most clusters have compact cores or cusps and an NFW-like density structure





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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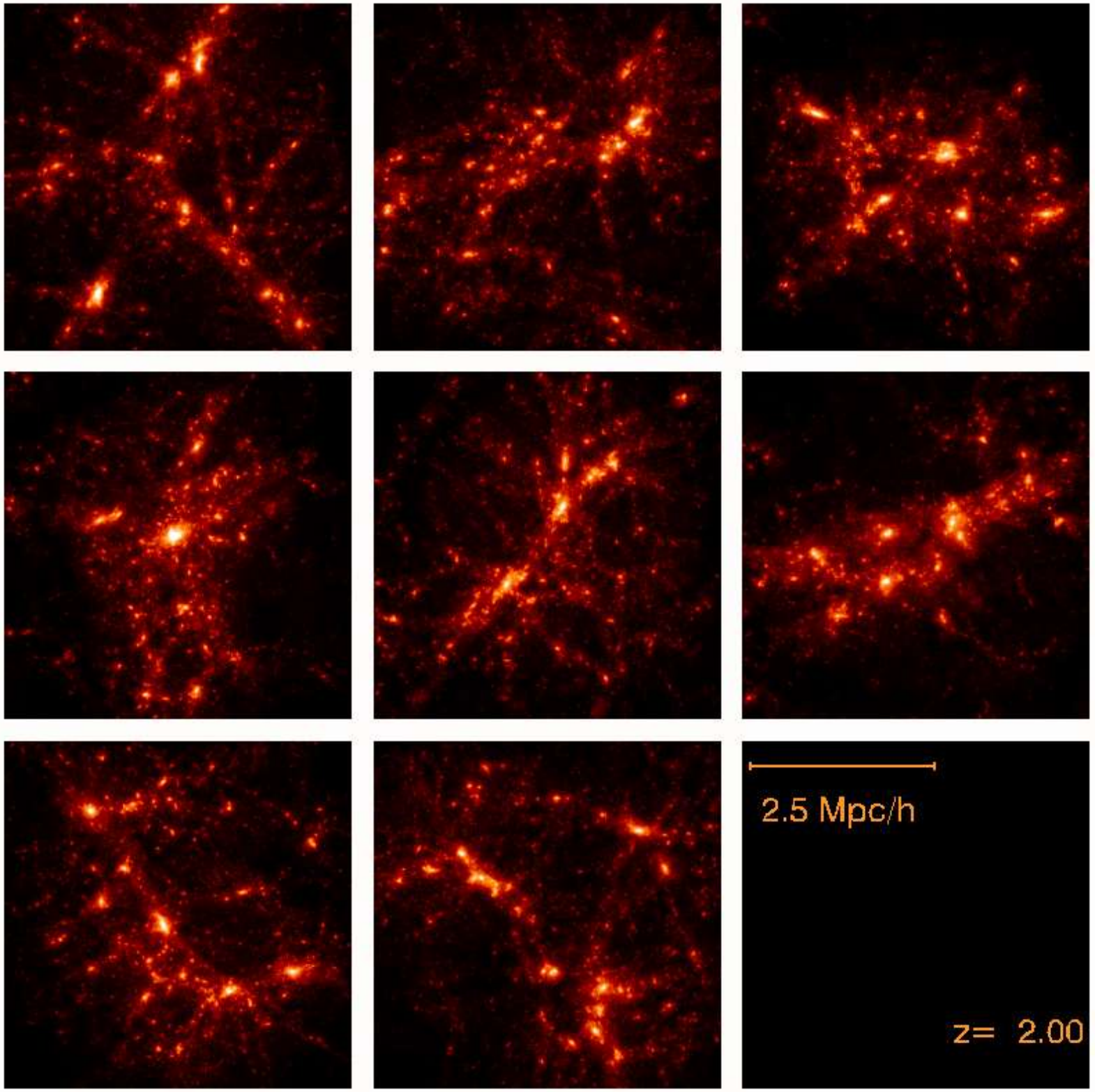

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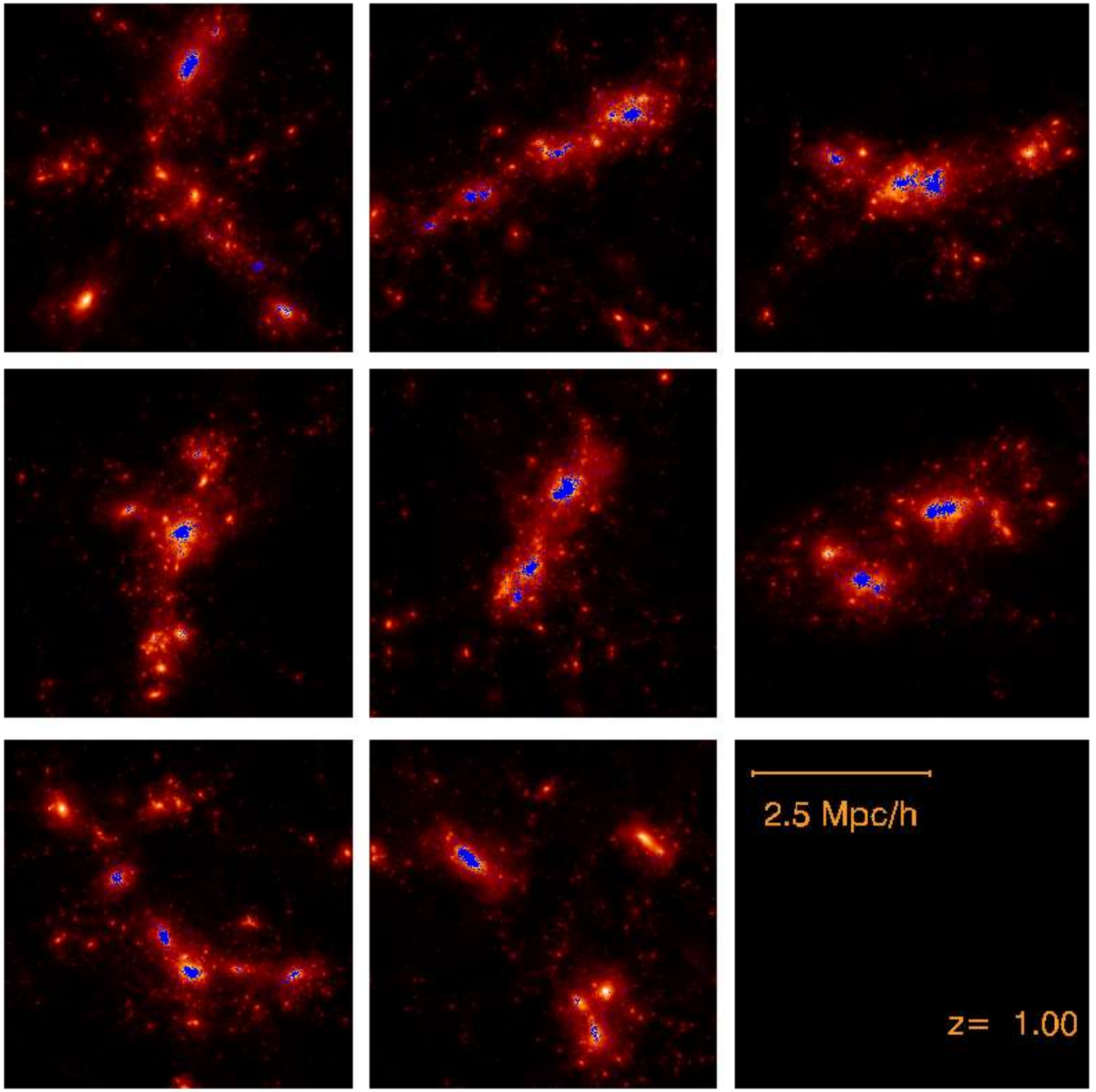

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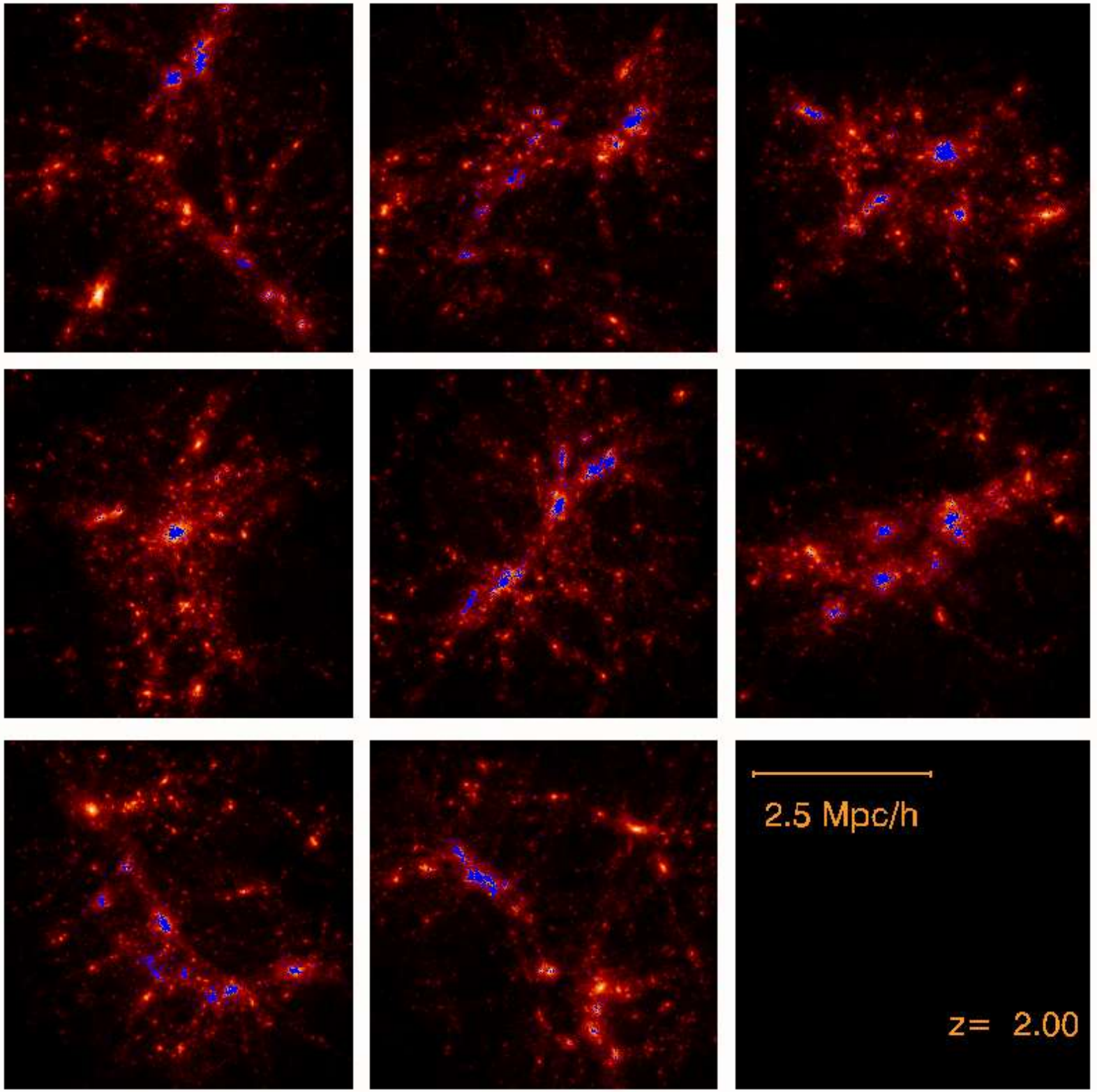
- DM within 20kpc at $z = 0$ is shown blue



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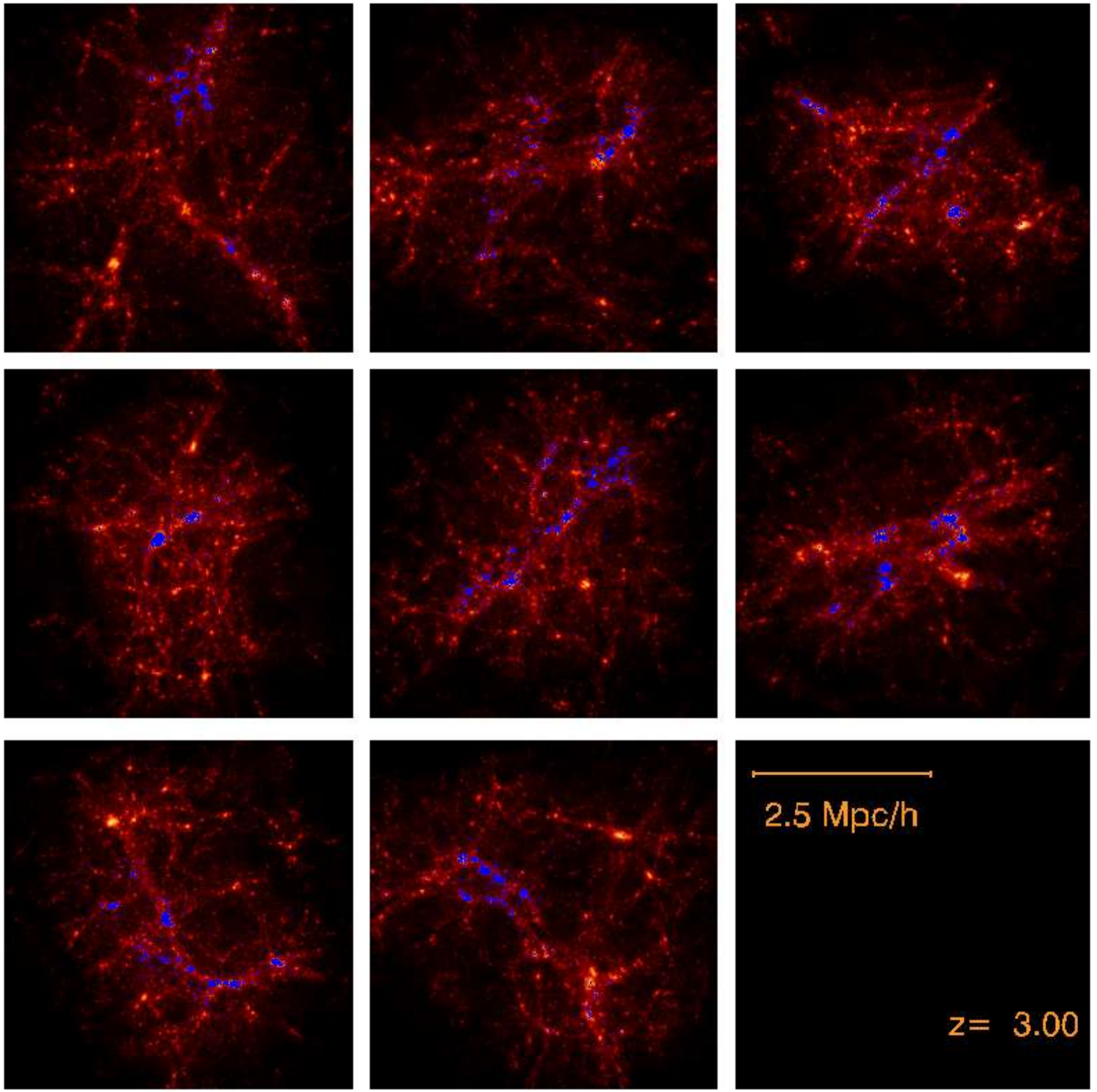

Cluster structure in ΛCDM

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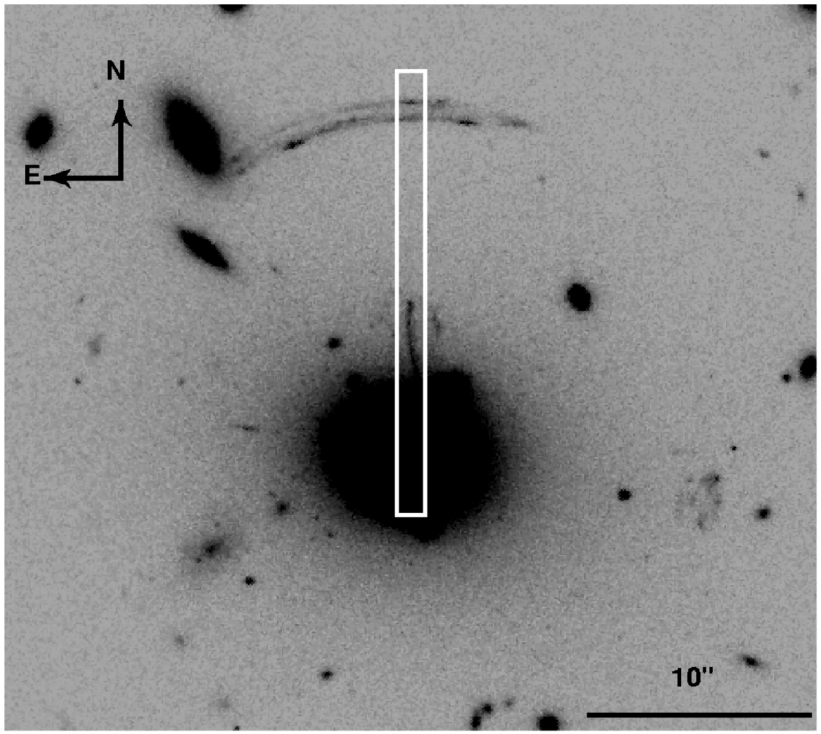
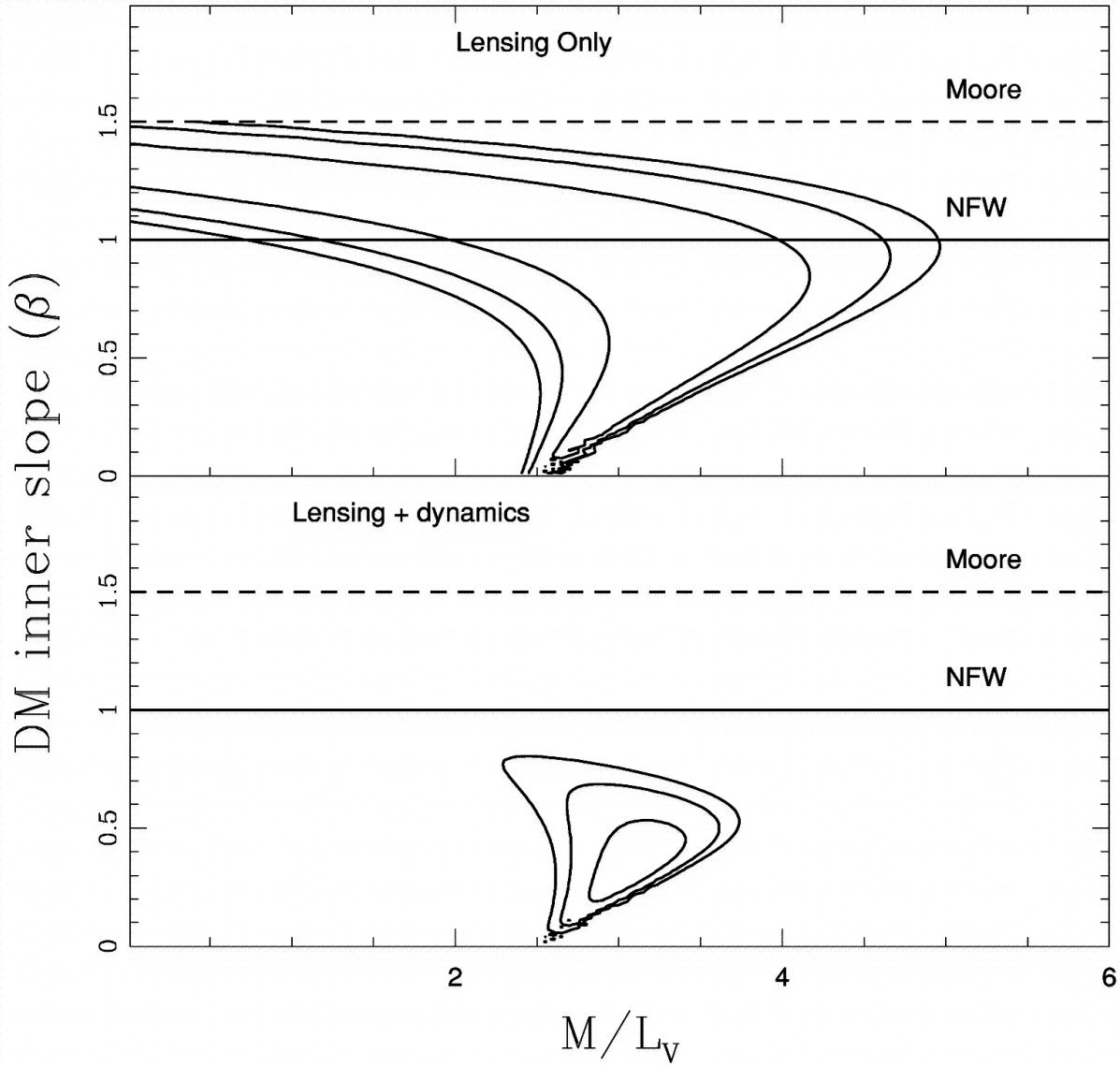
Constraining DM properties with strong lensing

Sand, Treu & Ellis 2002





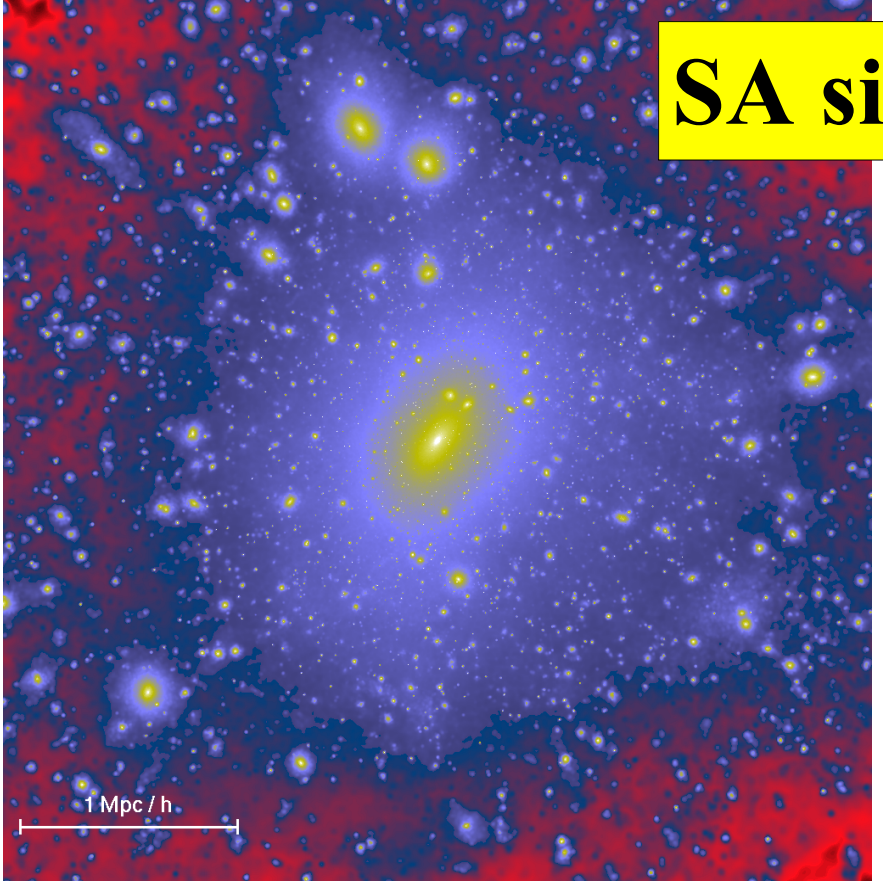
- Model potential as power law DM + galaxy with constant M/L
- Consistency with radial arc, tangential arc & velocity dispersion profile

→ inner slope of DM profile shallower than NFW

Galaxy formation in the standard paradigm

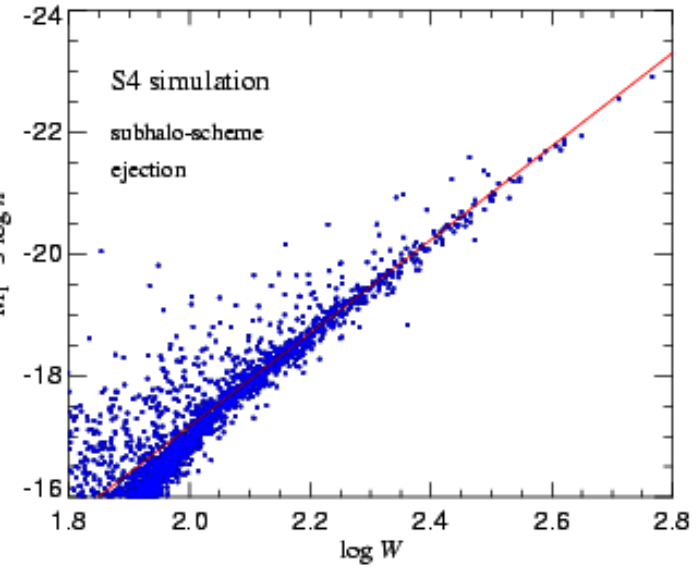
- Nonlinear dark matter clustering under gravity
  - ➡ hierarchical "dark halo" growth by accretion and merging
- Infall and shock heating of diffuse gas
  - ➡ hot gas "atmospheres" in halos (e.g. the intracluster gas)?
- Cooling and condensation of gas into "protogalaxies"
  - ➡ rotationally supported disks?
- Star formation in disks or during protogalactic collapse
  - ➡ disk galaxies or "primordial" spheroids
- Feedback from UV 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

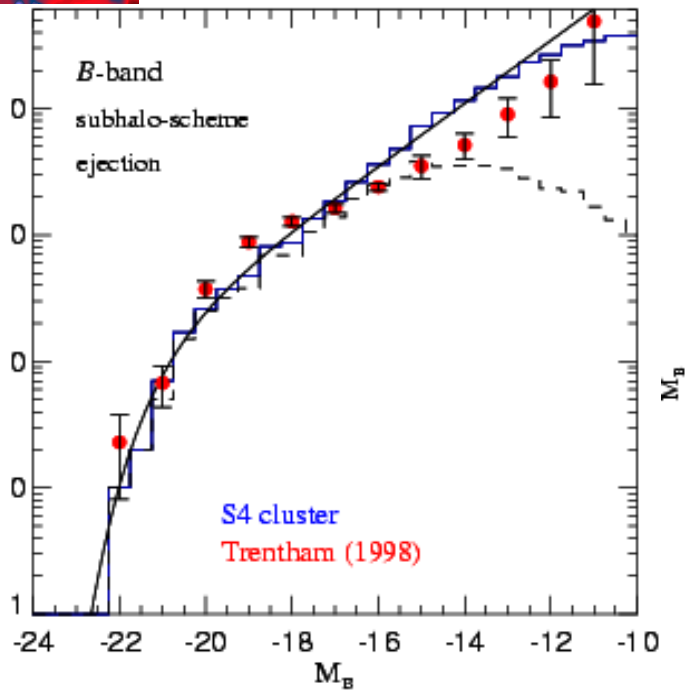
SA simulation of cluster formation

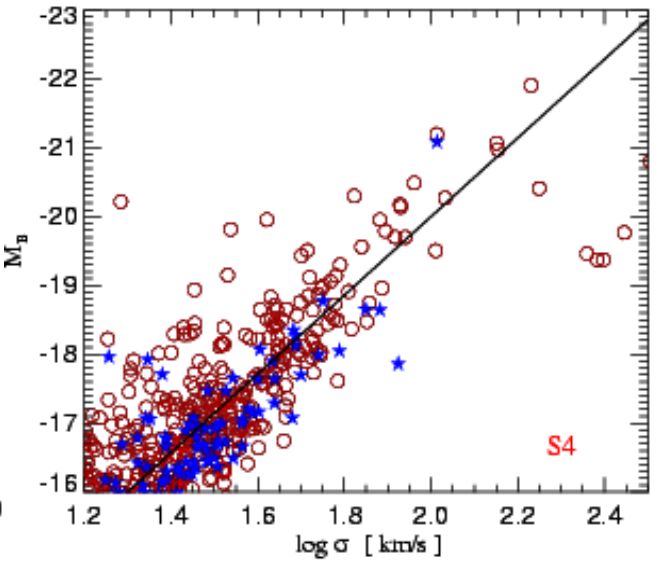


- Semi-analytic methods allow the simulation of a Coma cluster following all galaxies with $M_B < -12$
- Nearly all galaxies with $M_B < -16$ retain their own dark halos
- Protocluster can be analysed at high z

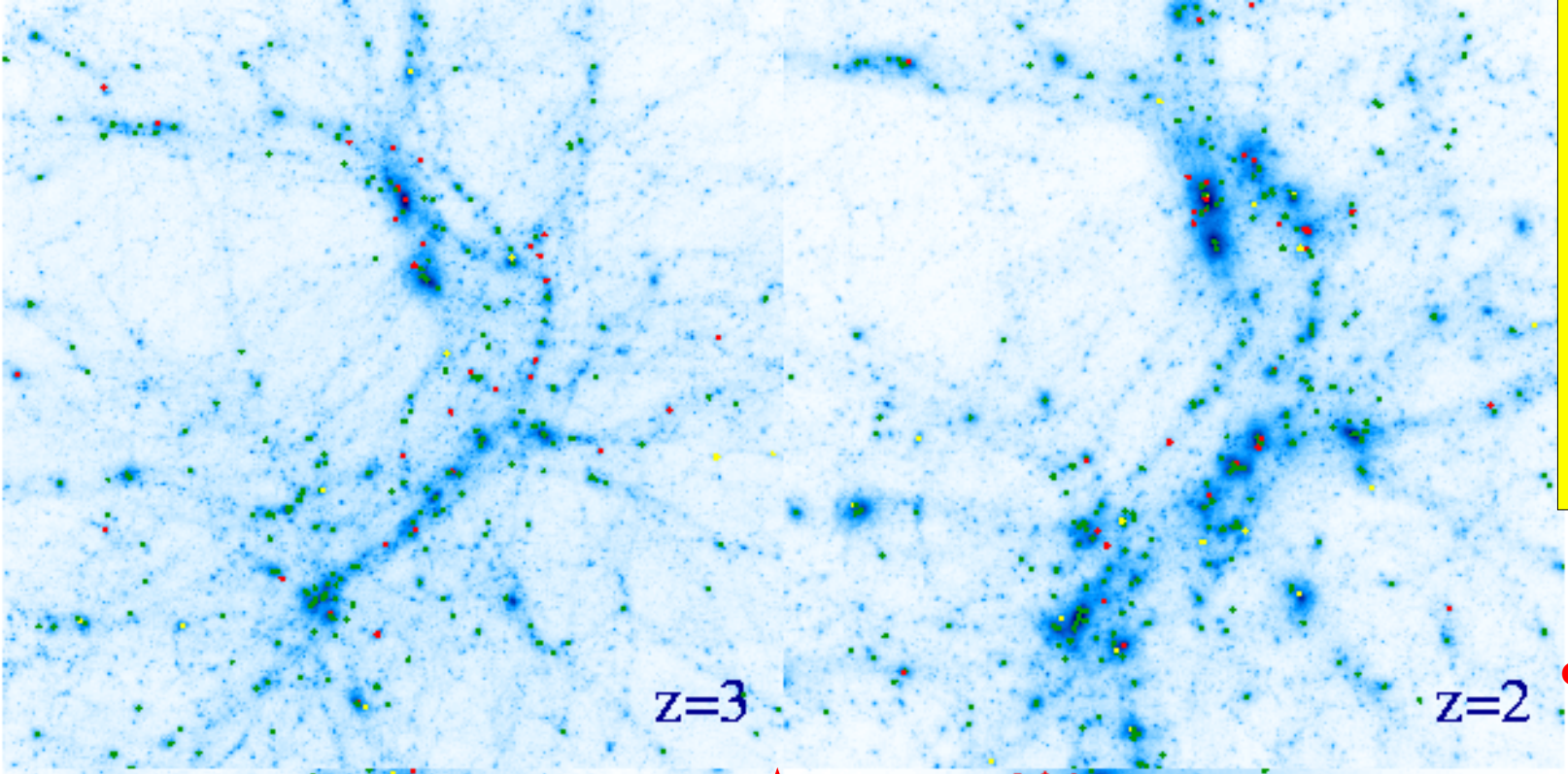
Springel et al 2001

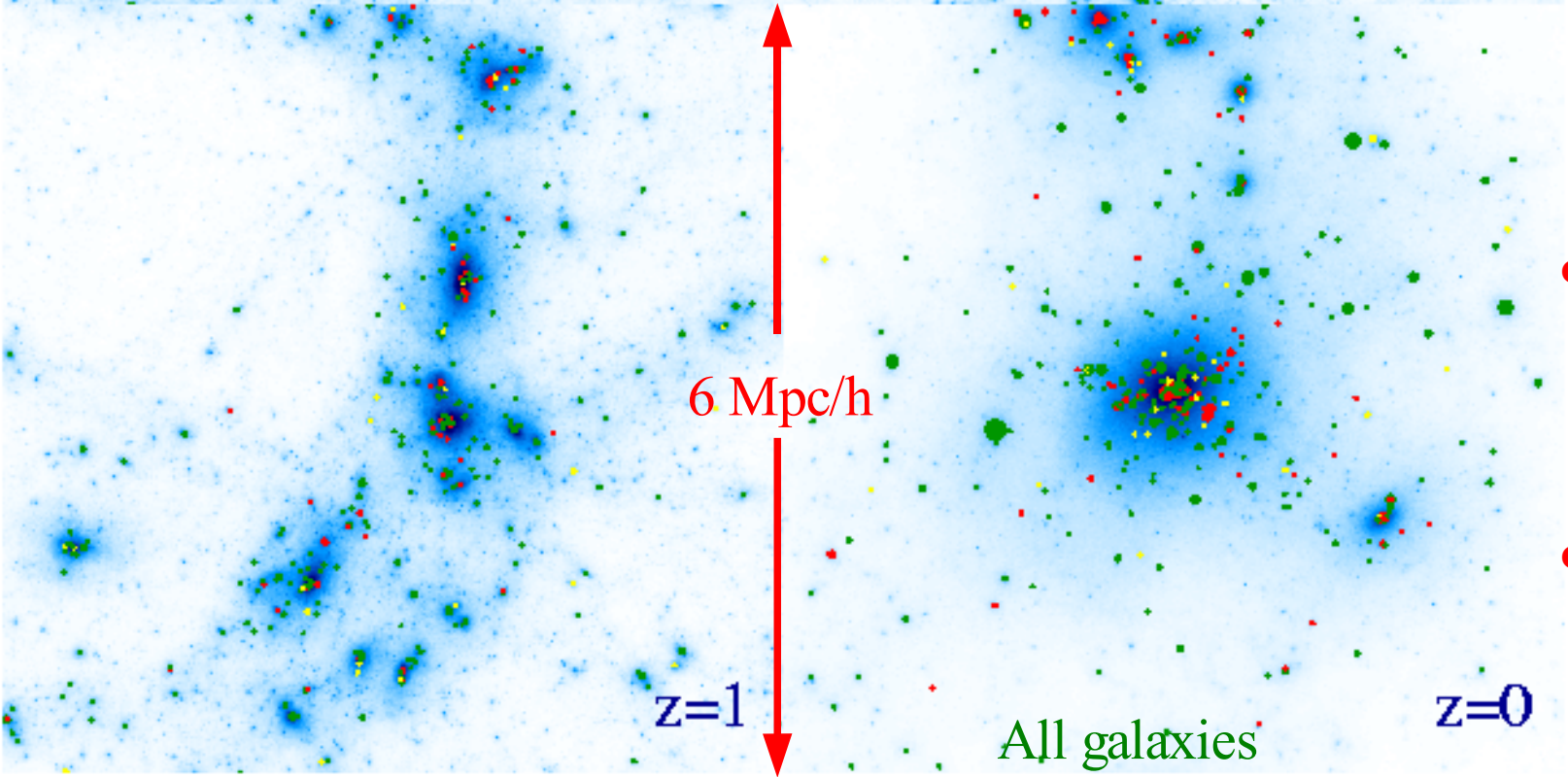






Evolution of the galaxy population in a Coma-like cluster

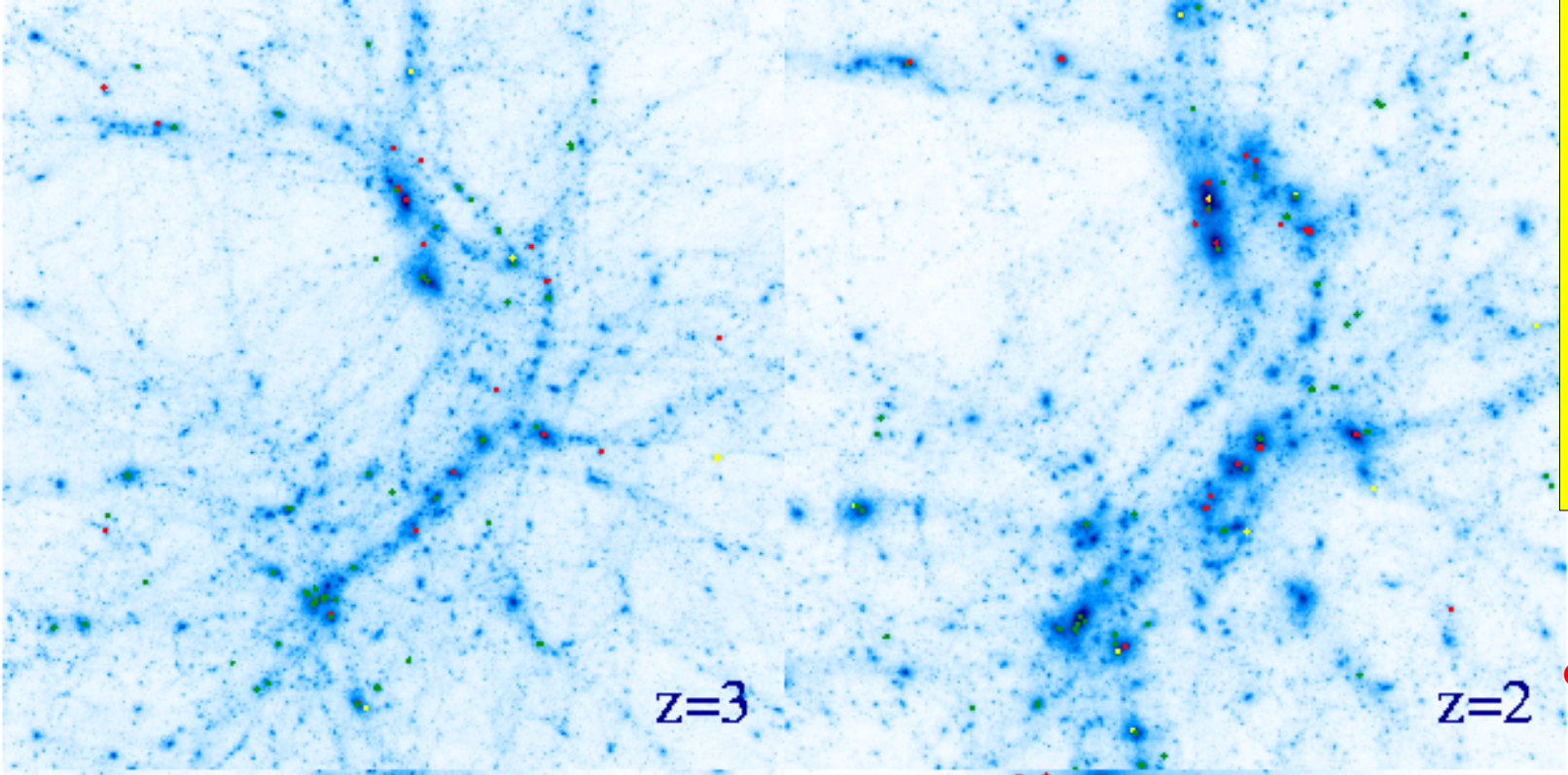


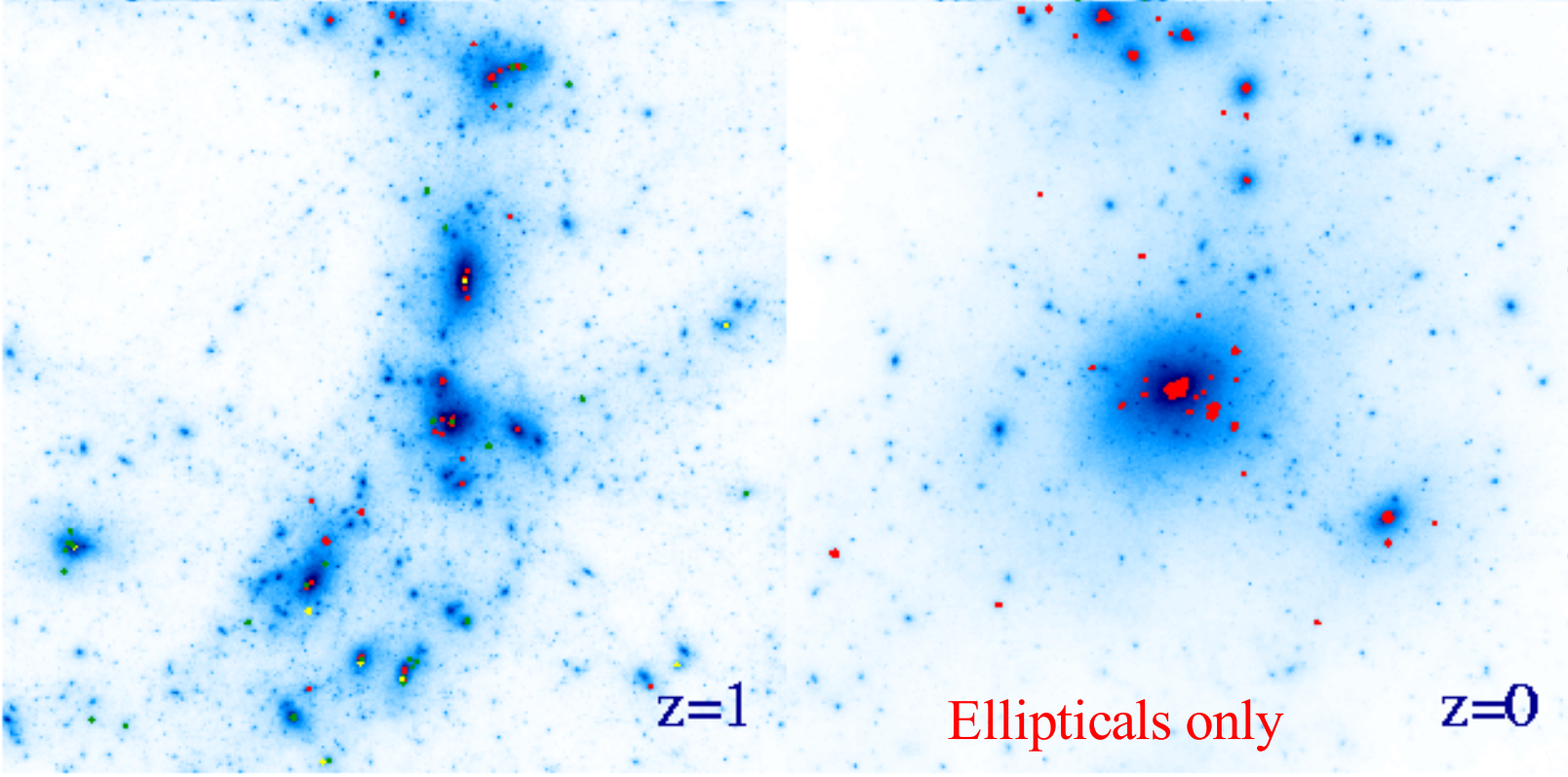


Springel et al 2001

- Formation of the galaxies tracked within evolving (sub)halos
- Luminosity and mass of galaxies is uncertain
- Positions and velocities are followed well

Evolution of the galaxy population in a Coma-like cluster

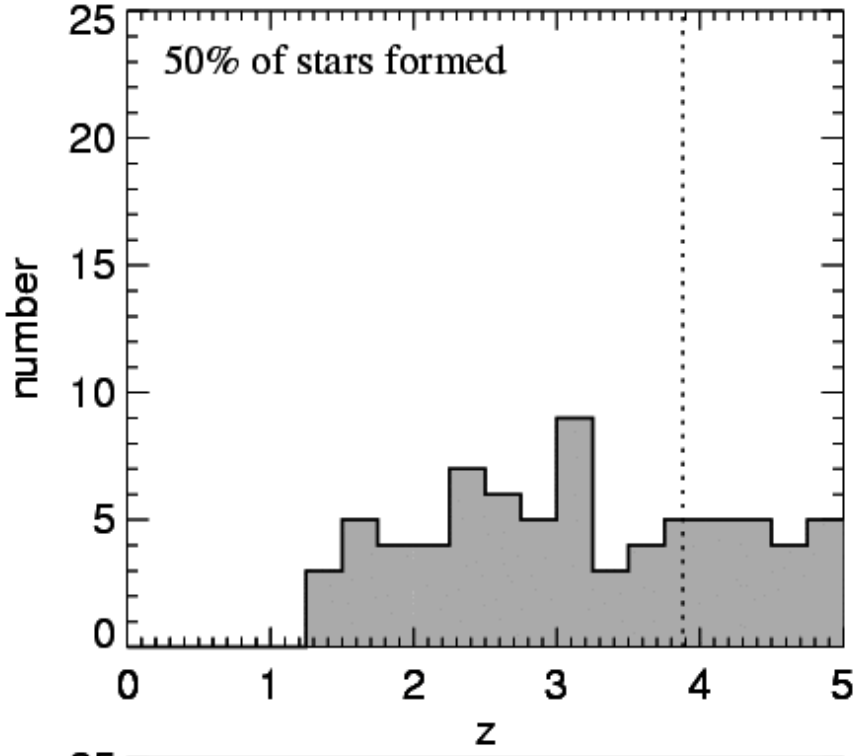


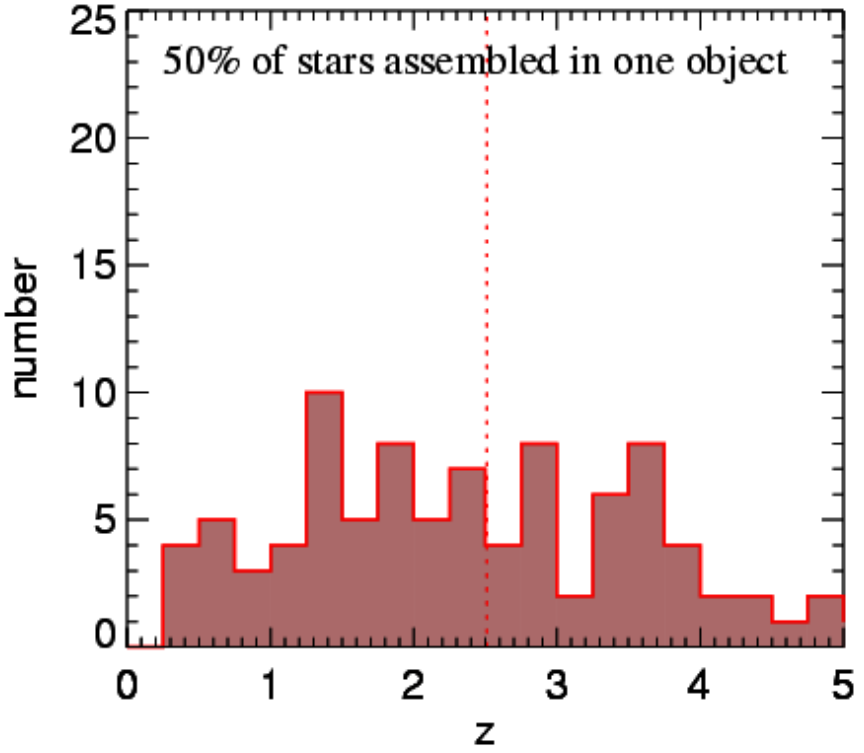


Ellipticals only

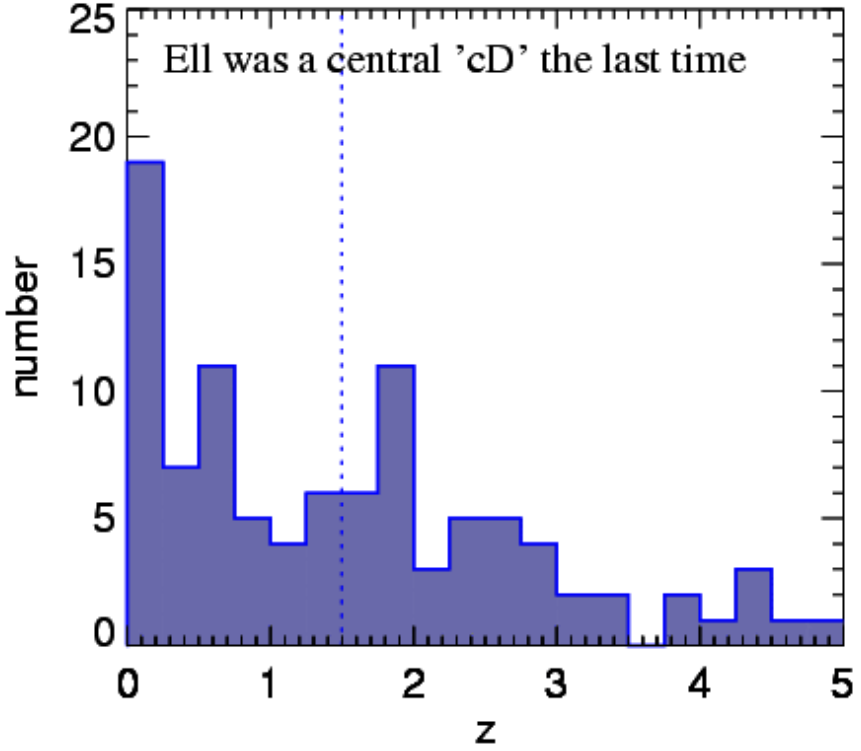
Springel et al 2001

- Formation of the galaxies tracked within evolving (sub)halos
- Luminosity and mass of galaxies is uncertain
- Positions and velocities are followed well



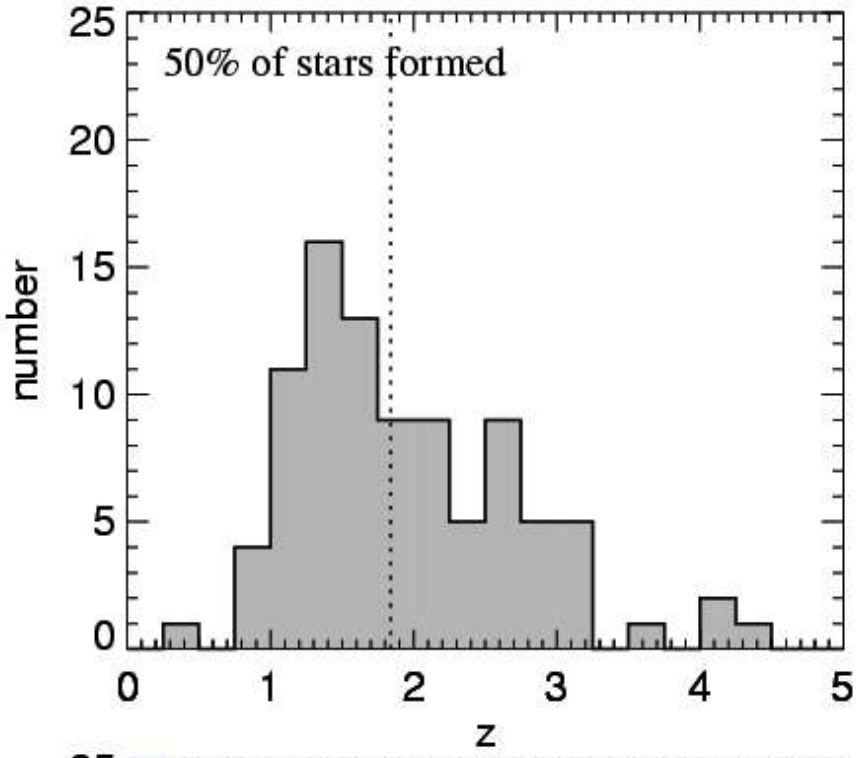


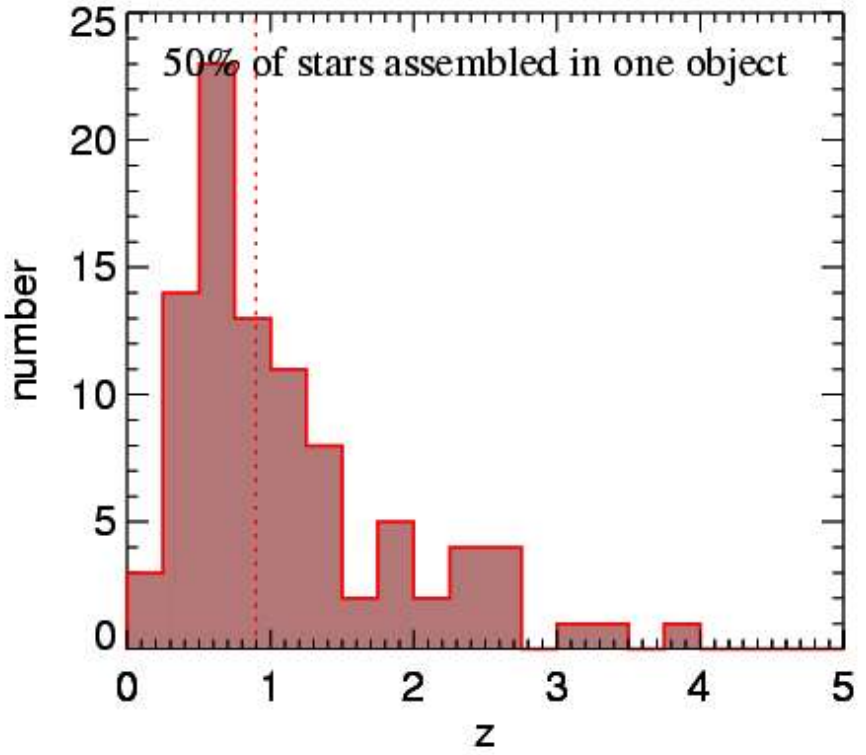
Springel et al 2003



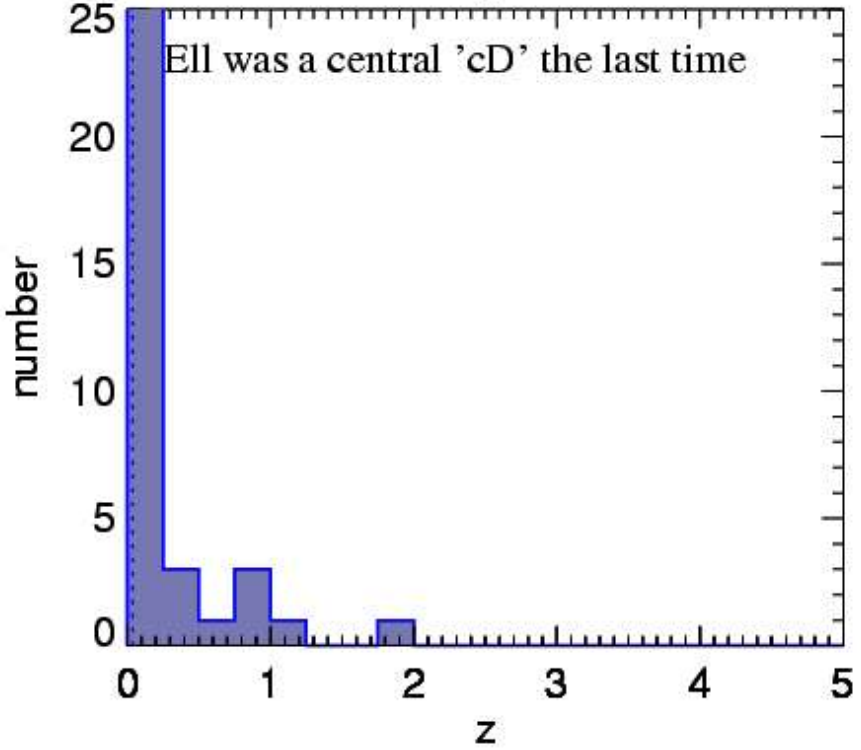
Formation histories of cluster ellipticals

- 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





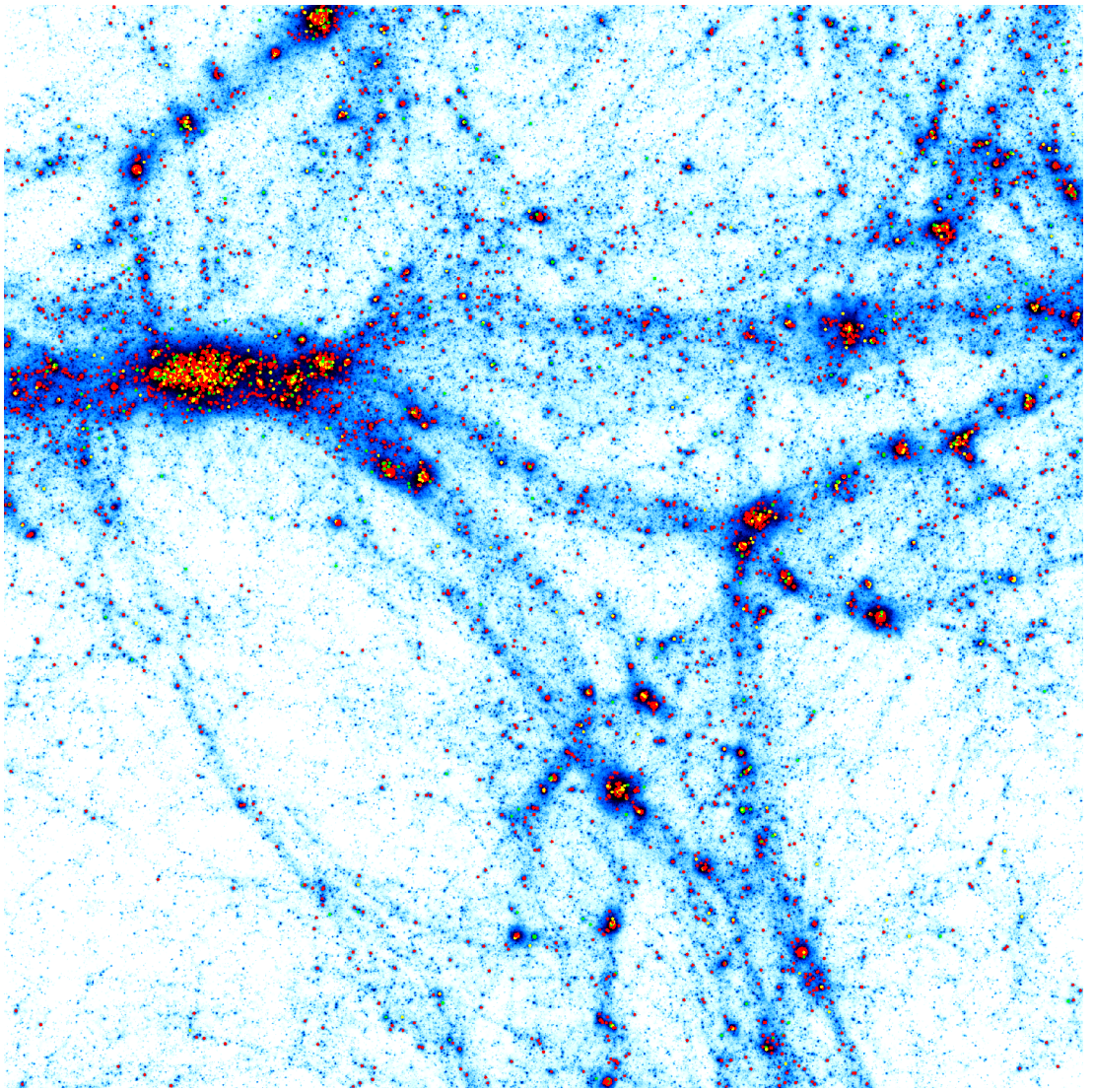
Springel et al 2003

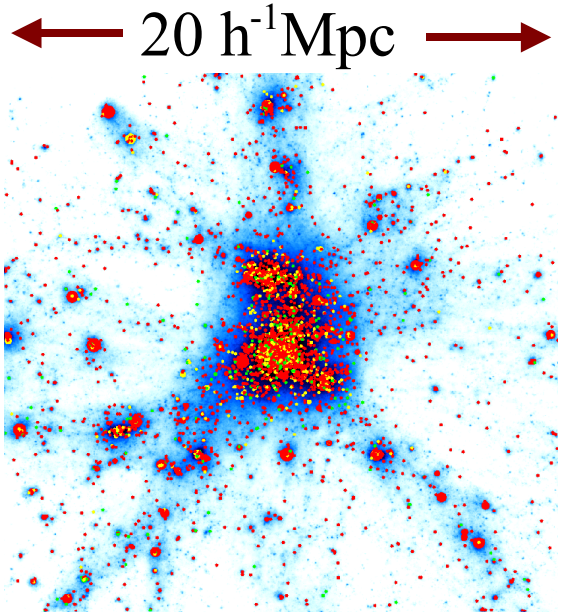


Formation histories of field ellipticals

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

Field vs cluster evolution of the galaxy population





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

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

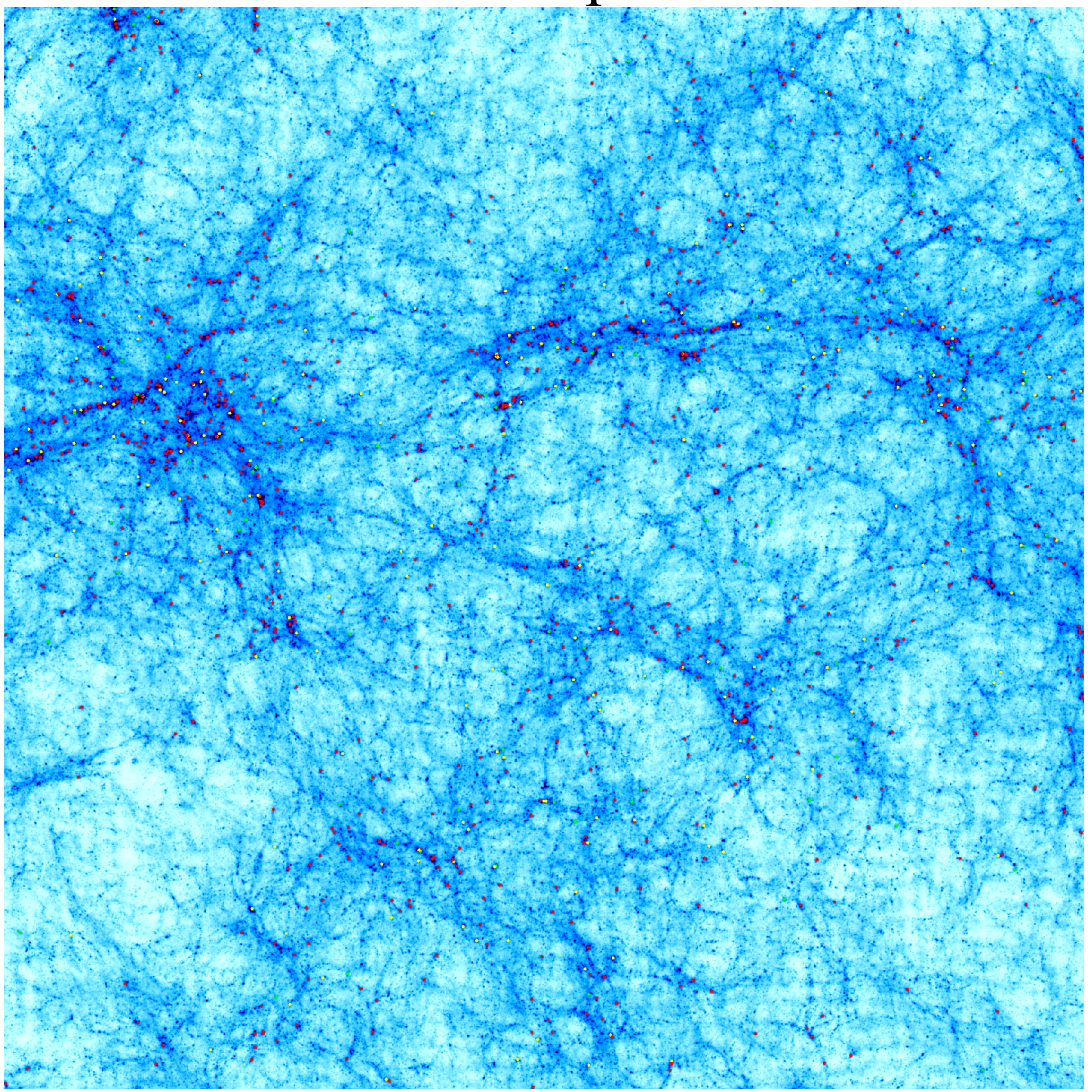
$M_{gal} > 10^9 M_{sun}$

$z = 0$

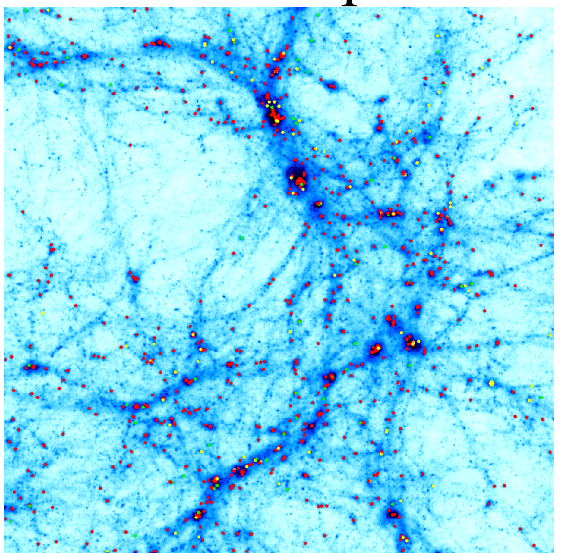
Stoehr et al 2002

Field vs cluster evolution of the galaxy population

40 h^{-1}Mpc



20 h^{-1}Mpc



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

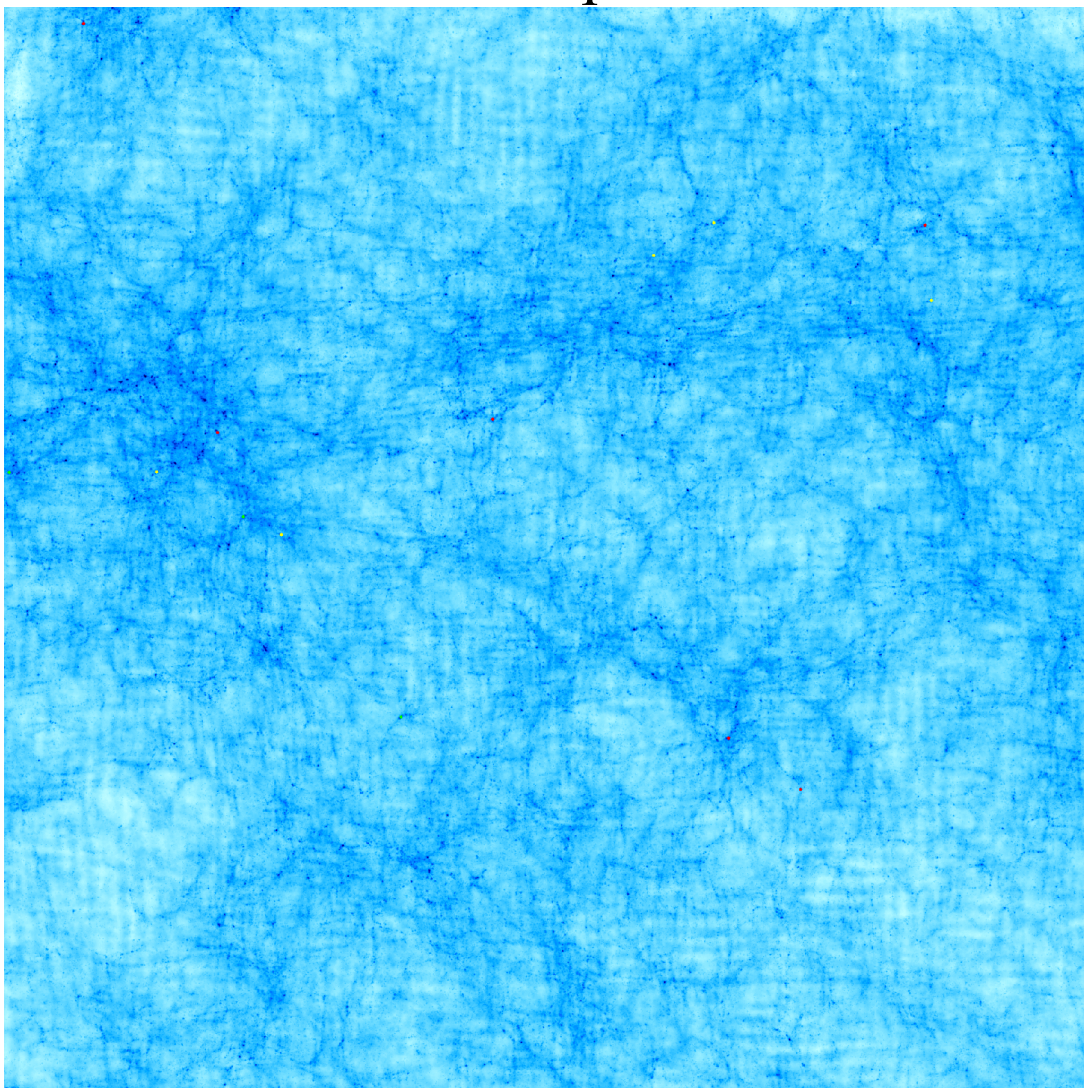
$\rho_* = 0.17 \langle \rho_0 \rangle$

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

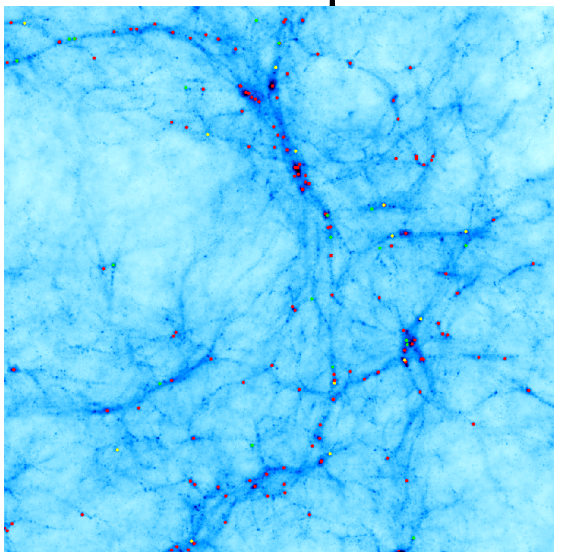
$z = 5$

Field vs cluster evolution of the galaxy population

40 h^{-1}Mpc



20 h^{-1}Mpc



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

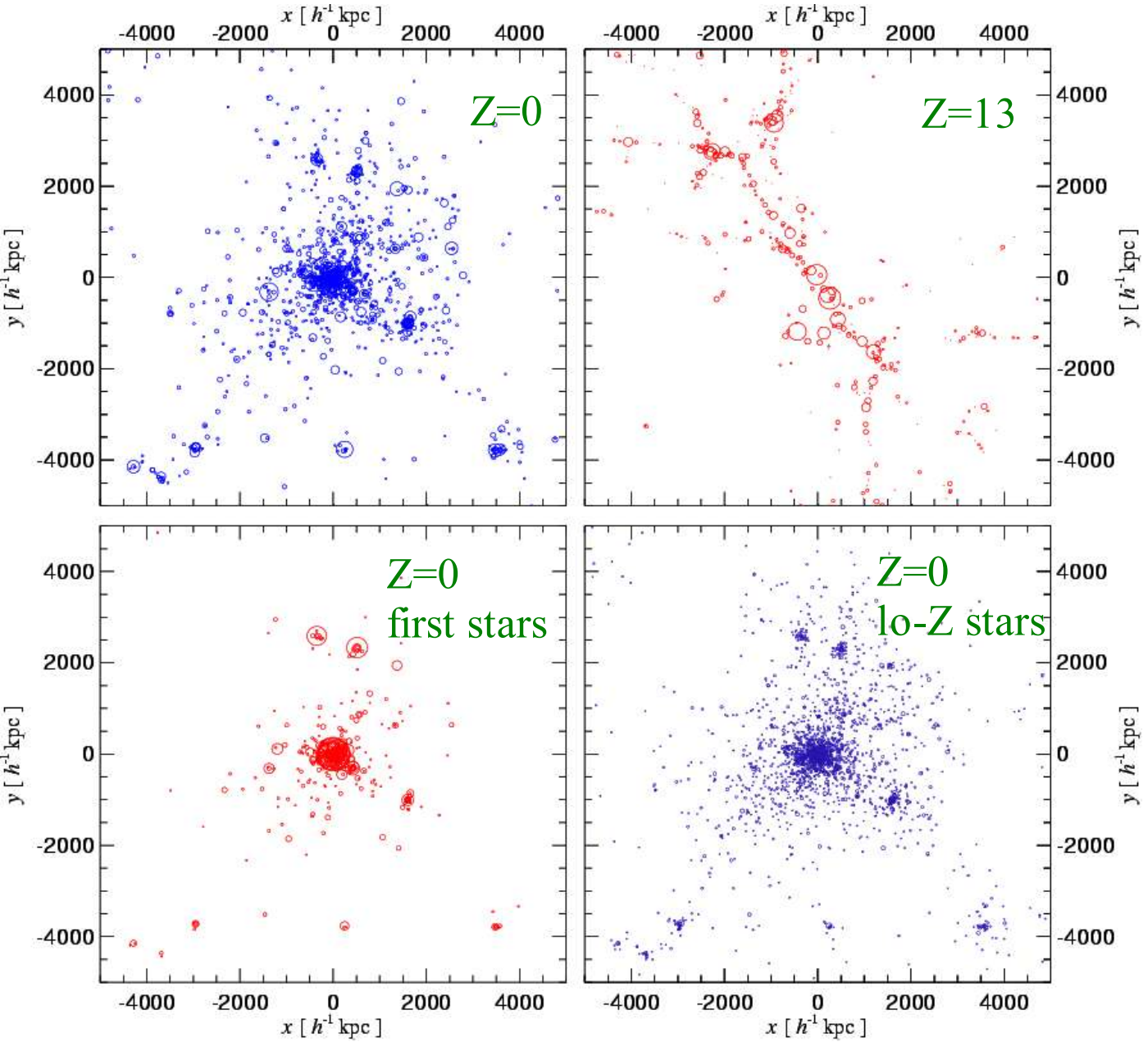
$\rho_* = 0.018 \langle \rho_0 \rangle$

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

$z = 10$

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

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 gas is inhomogeneous, subsonically turbulent and poorly mixed
- 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.