Pasadena, January 2003

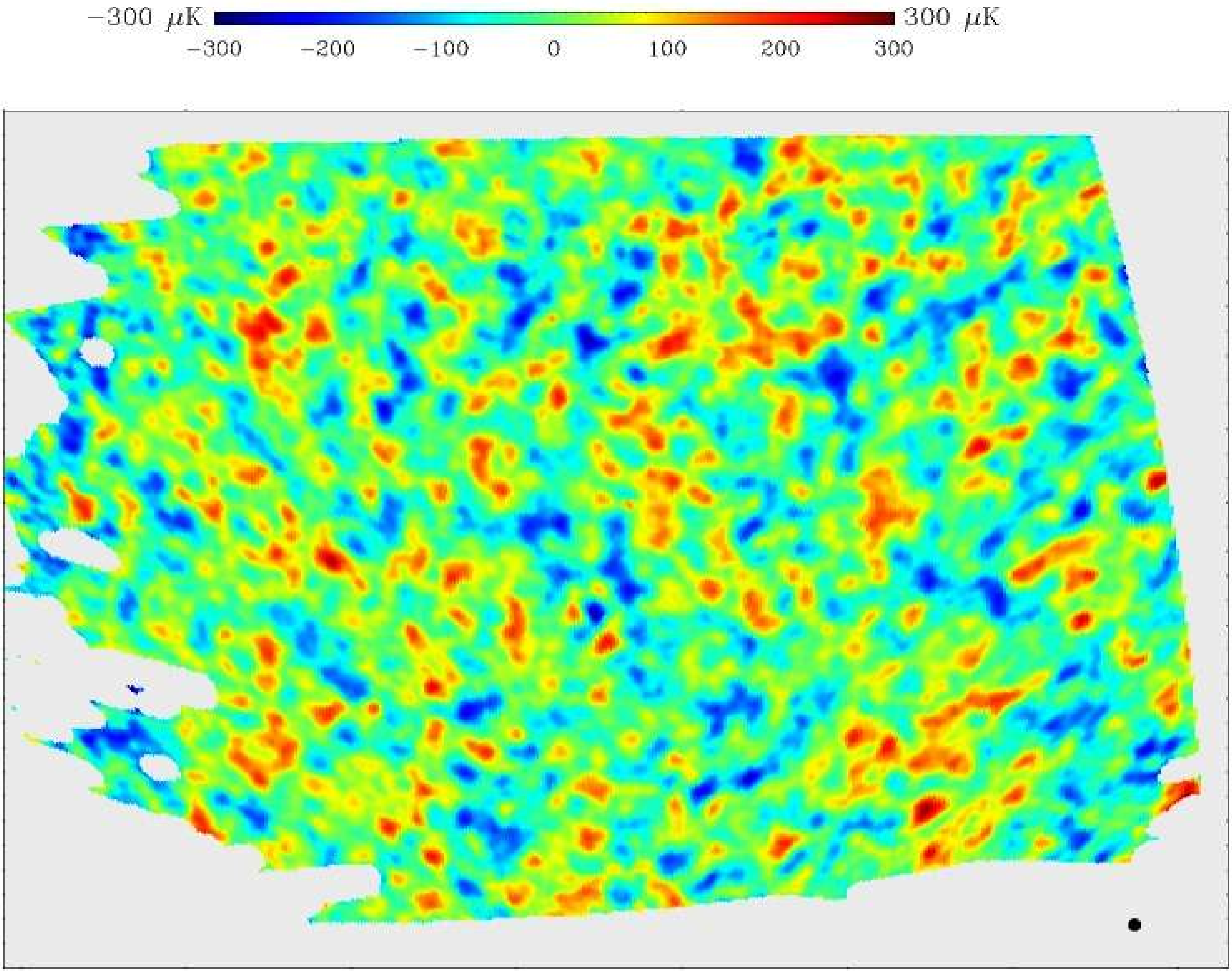
The growth of clusters and its cosmological context

Simon D.M. White
Max Planck Institute for Astrophysics

A standard paradigm for cosmic evolution

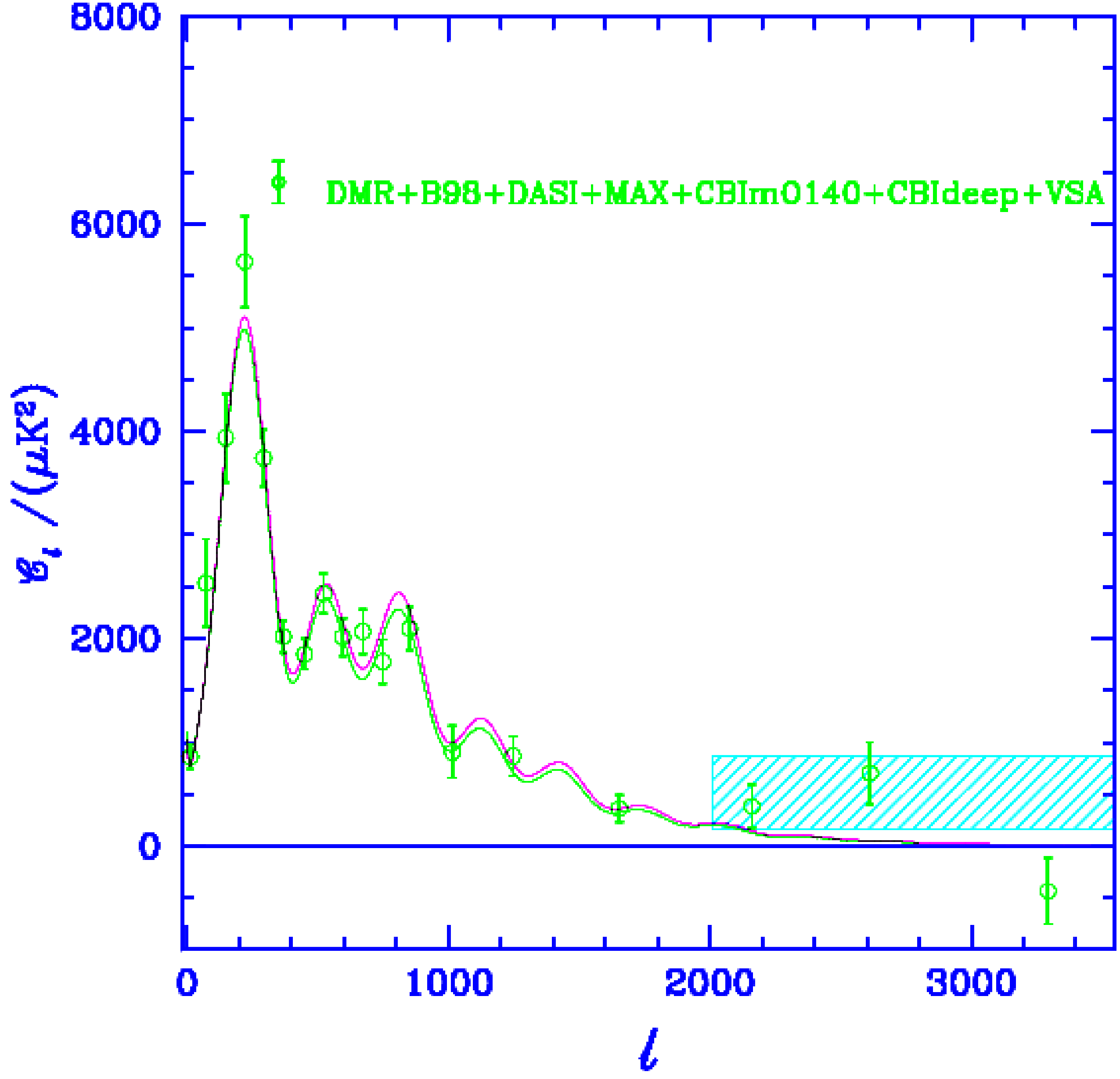
- The Universe began about 14 Gyrs ago in an almost uniform and isotropic Hot Big Bang
- All structure originated as zero-point fluctuations of a free quantum field during an early ($\sim 10^{-30}$s) period of inflation
- The current mass/energy content of the Universe is:
  - -- 70% 'dark energy' (cosmological constant or quintessence?)
  - -- 30% cold dark matter (axions, neutralinos,...?)
  - -- 4% baryonic matter (of which 1/10 lies in galaxies)
  - -- 0.1% neutrinos
  - -- 0.01% radiation (the cosmic microwave background)
- Structure growth is driven (almost) entirely by gravity
- Galaxies form when gas cools and condenses within the potential wells of dark matter 'halos'

The Boomerang Map: 150 GHz



The Emergence of the Cosmic Initial Conditions

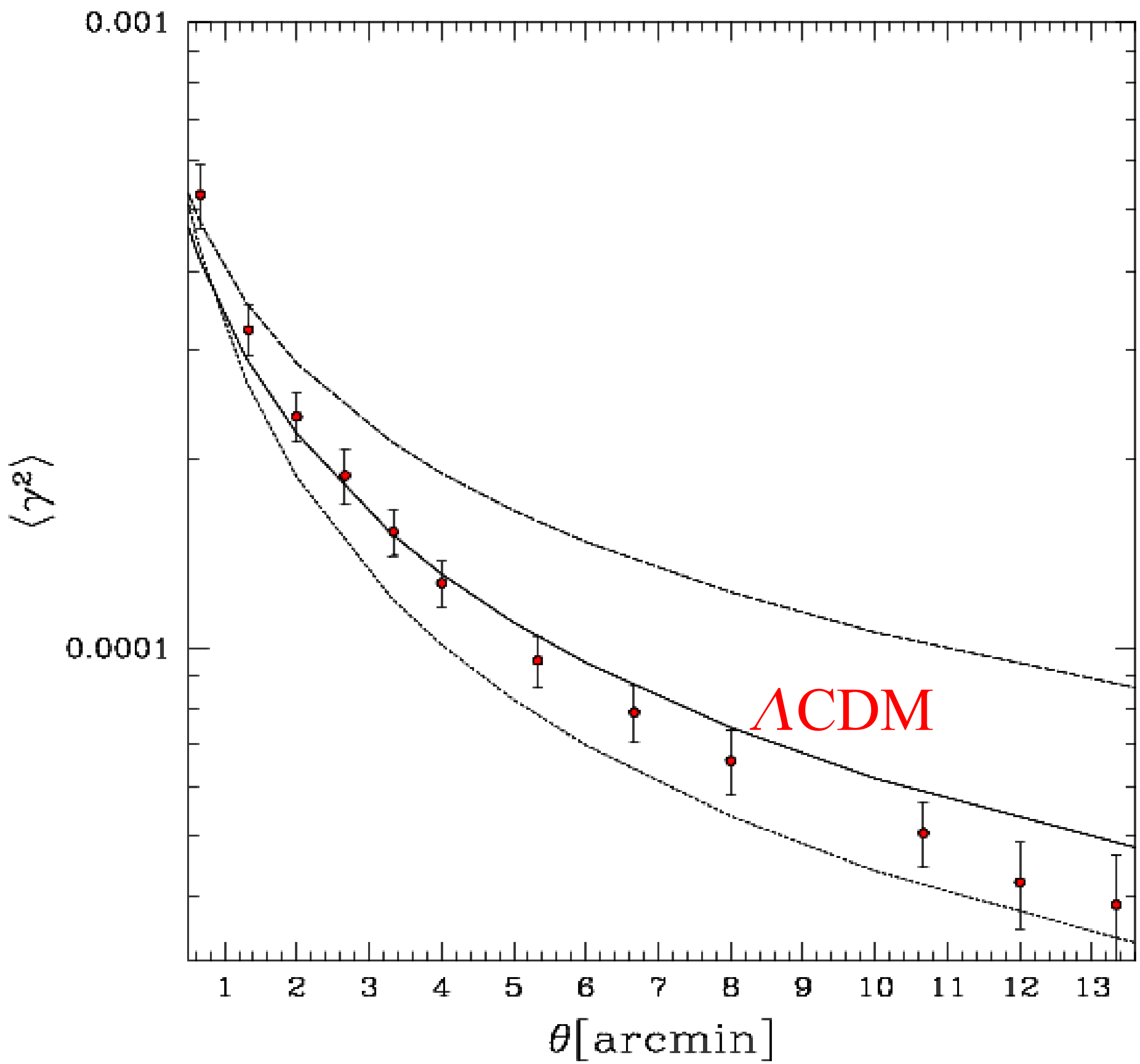
Bond et al 2002



A measurement of dark matter clustering

Van Waerbeke et al 2001

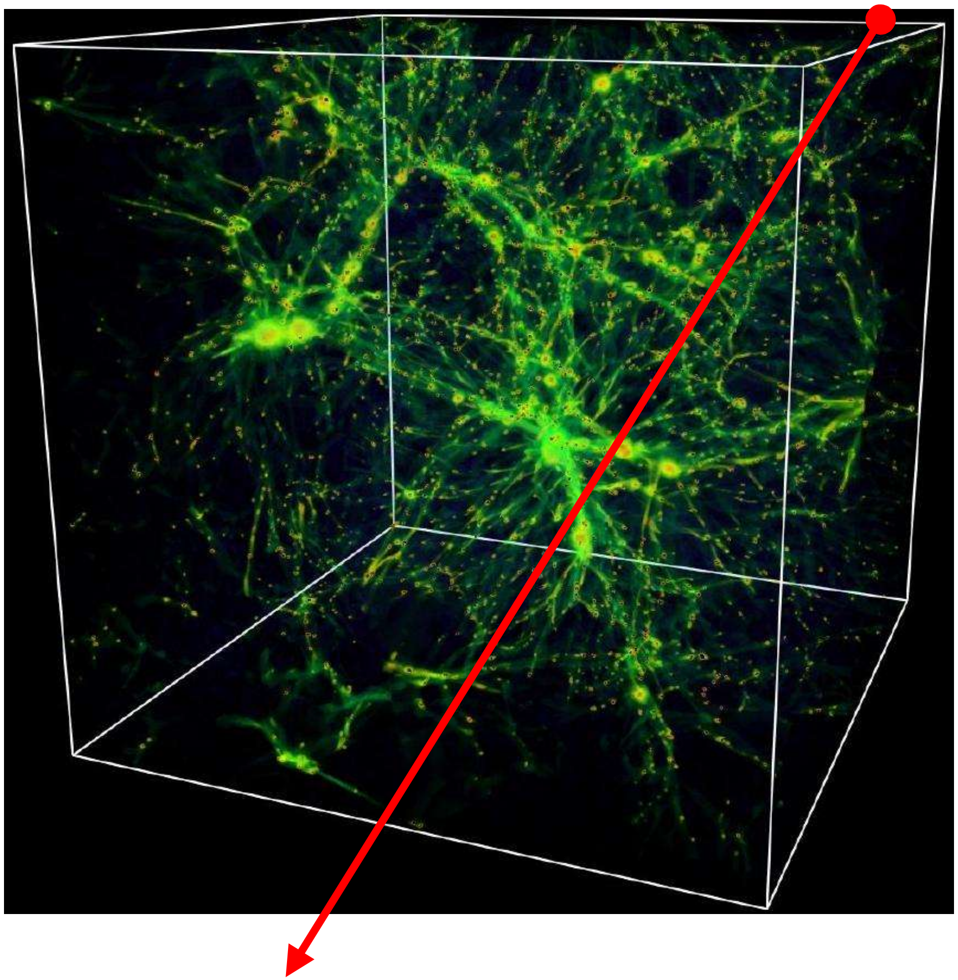
- $<\gamma^2>$ is the mean square gravitational shear of background galaxy images within circles of radius ϑ.
- It is proportional to the mean square lensing mass within these circles
- Signal on small scales is dominated by galaxy halos at z~0.4
- Fitting requires nonlinear ΛCDM prediction



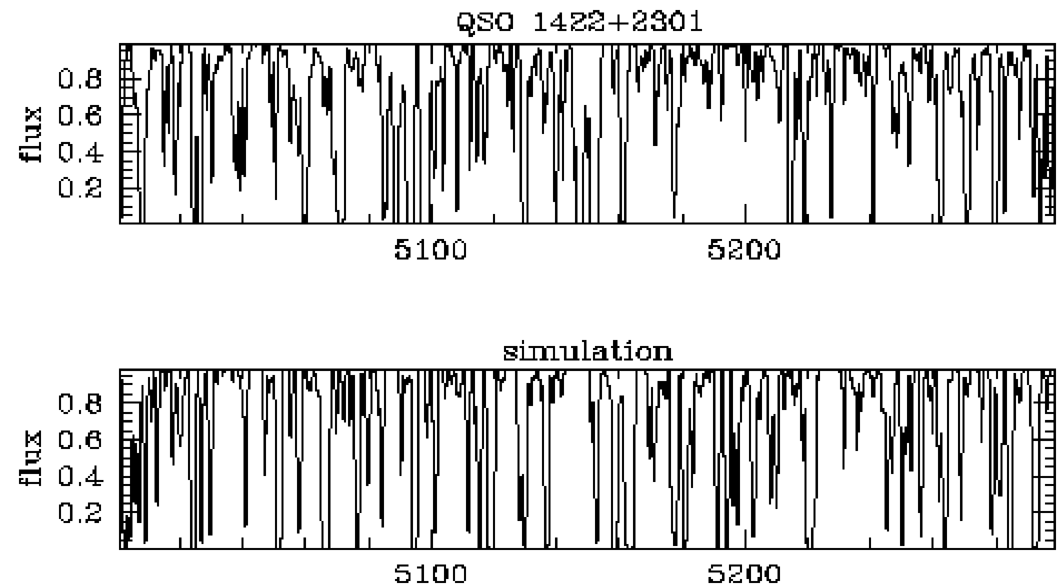
Mapping the intergalactic medium

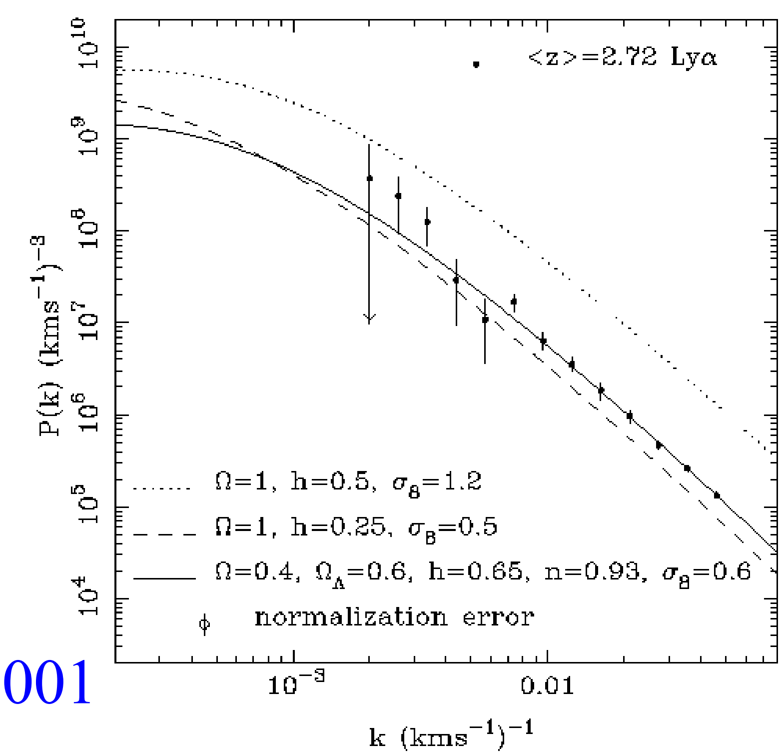
Cen et al 2001

Quasar

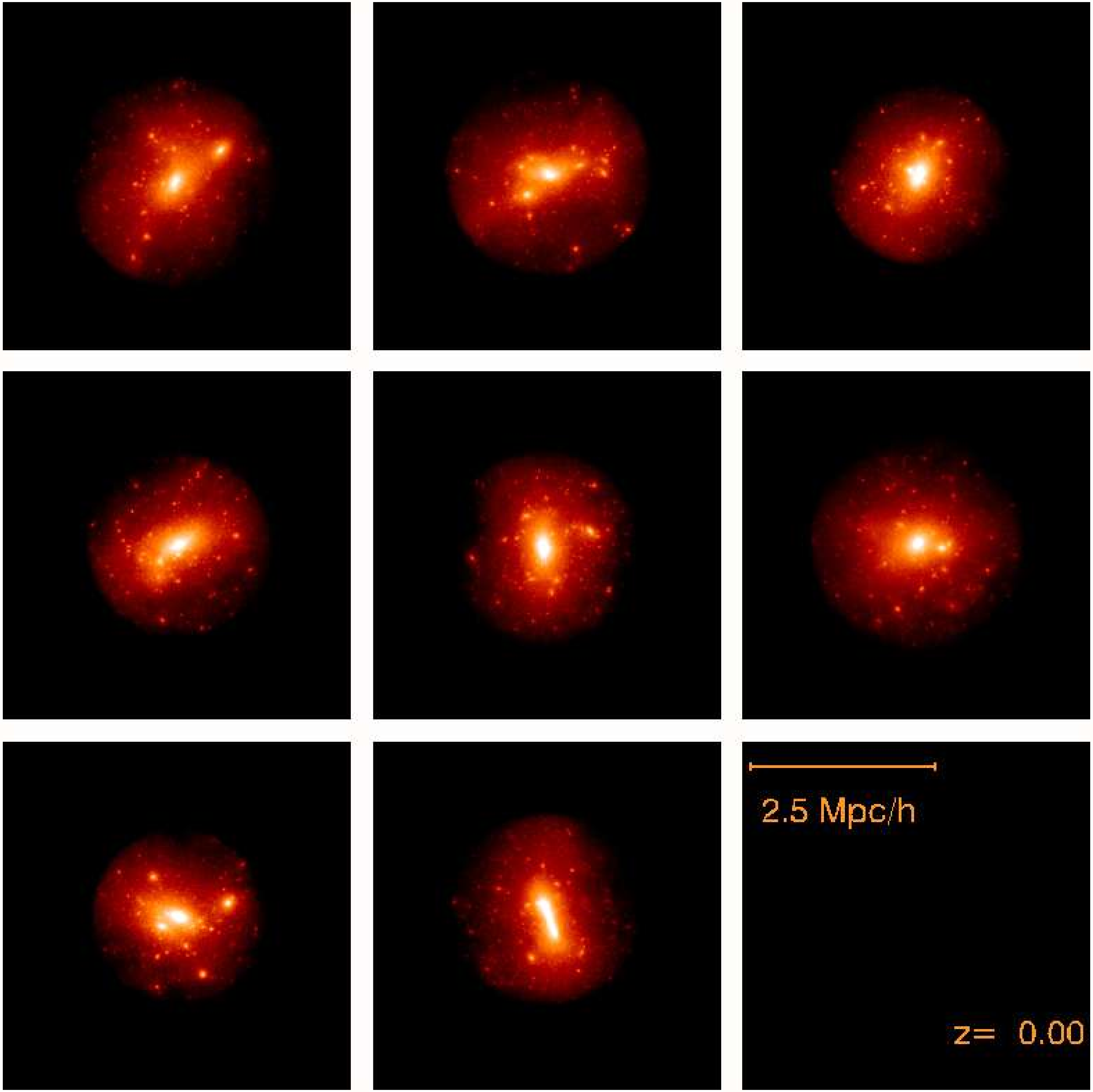


To observer



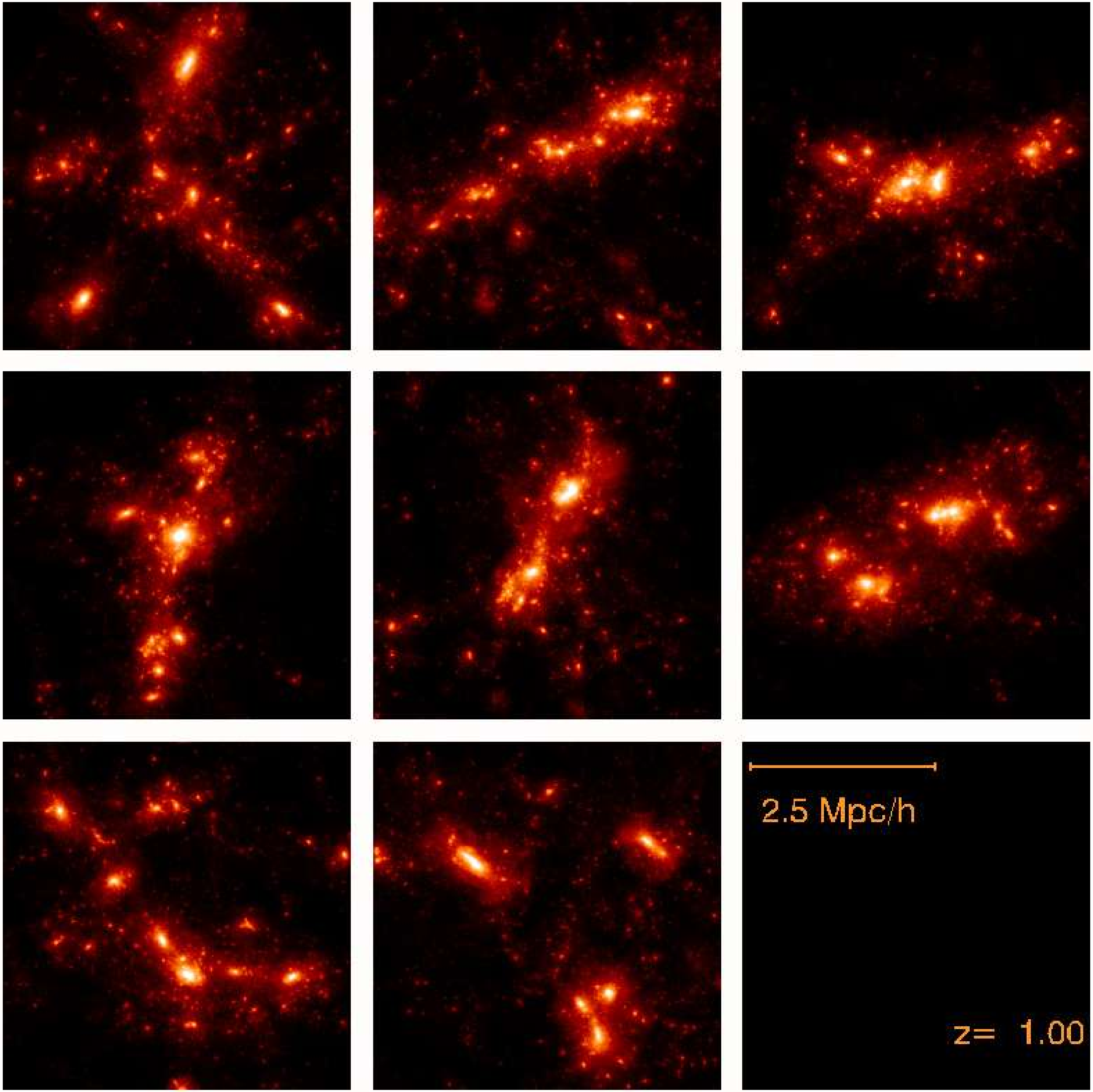


Croft et al 2001



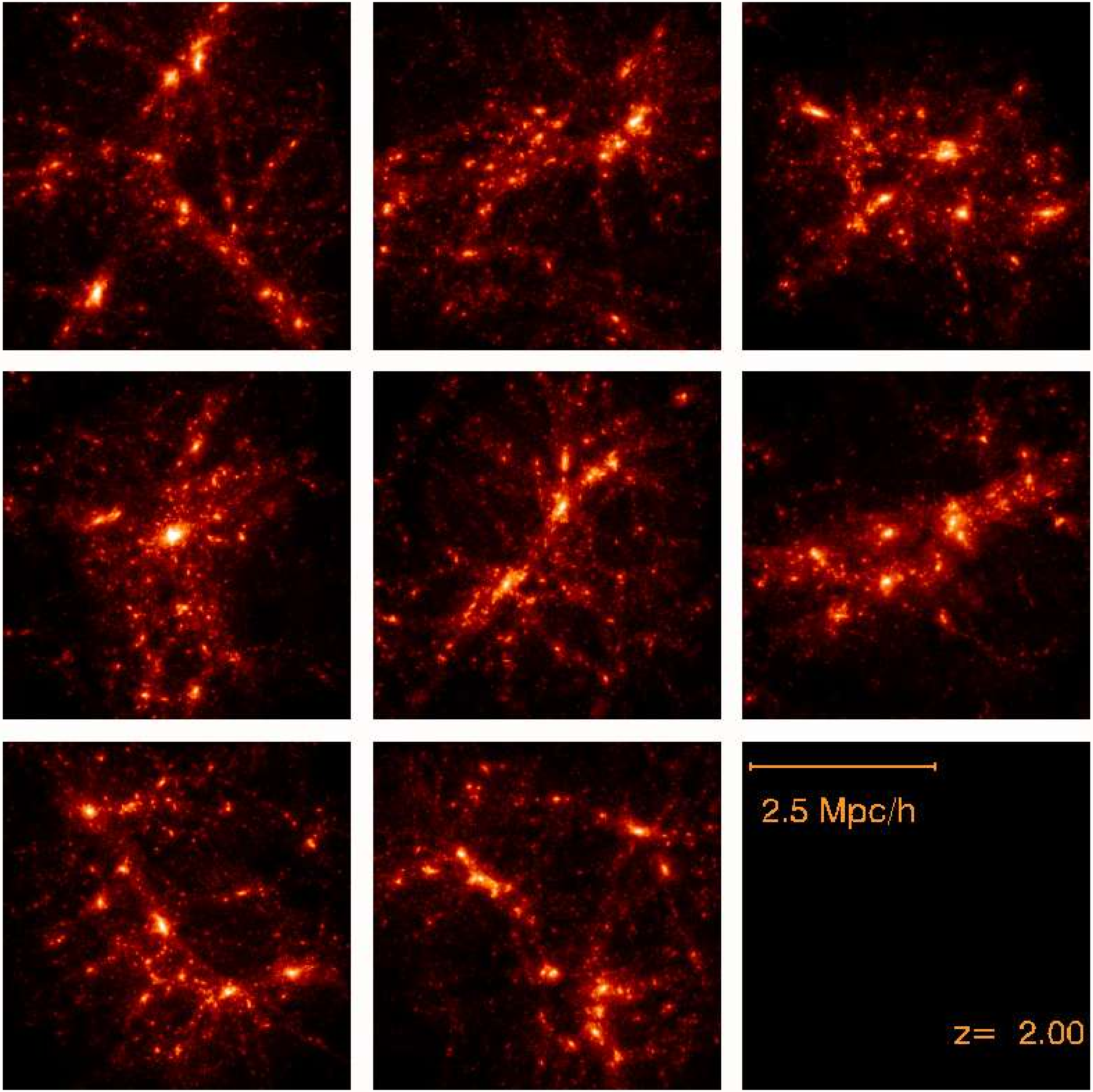
Cluster structure in ΛCDM

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



Cluster structure in ΛCDM

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



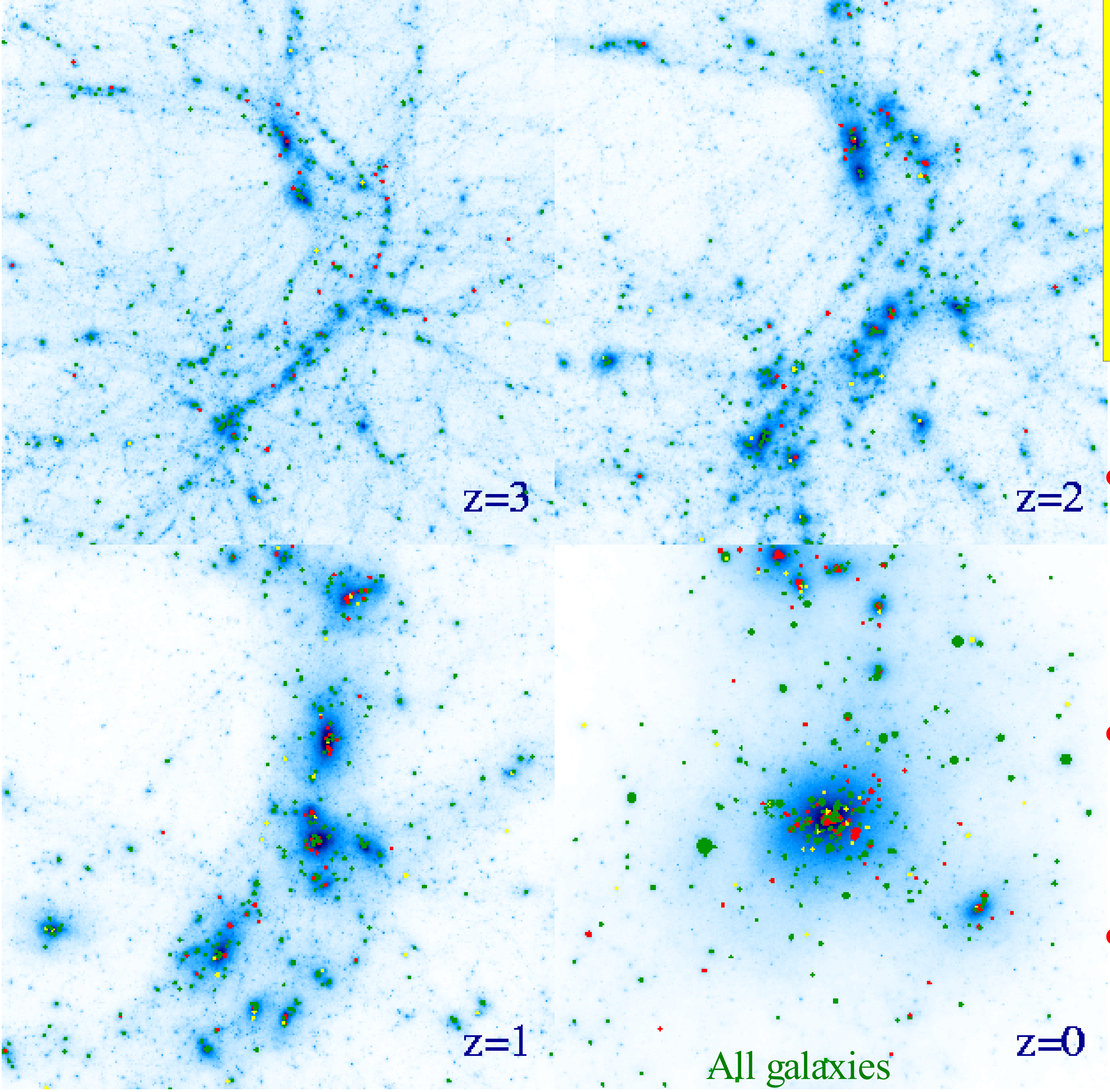
Cluster structure in ΛCDM

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

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

Evolution of the galaxy population in a Coma-like cluster

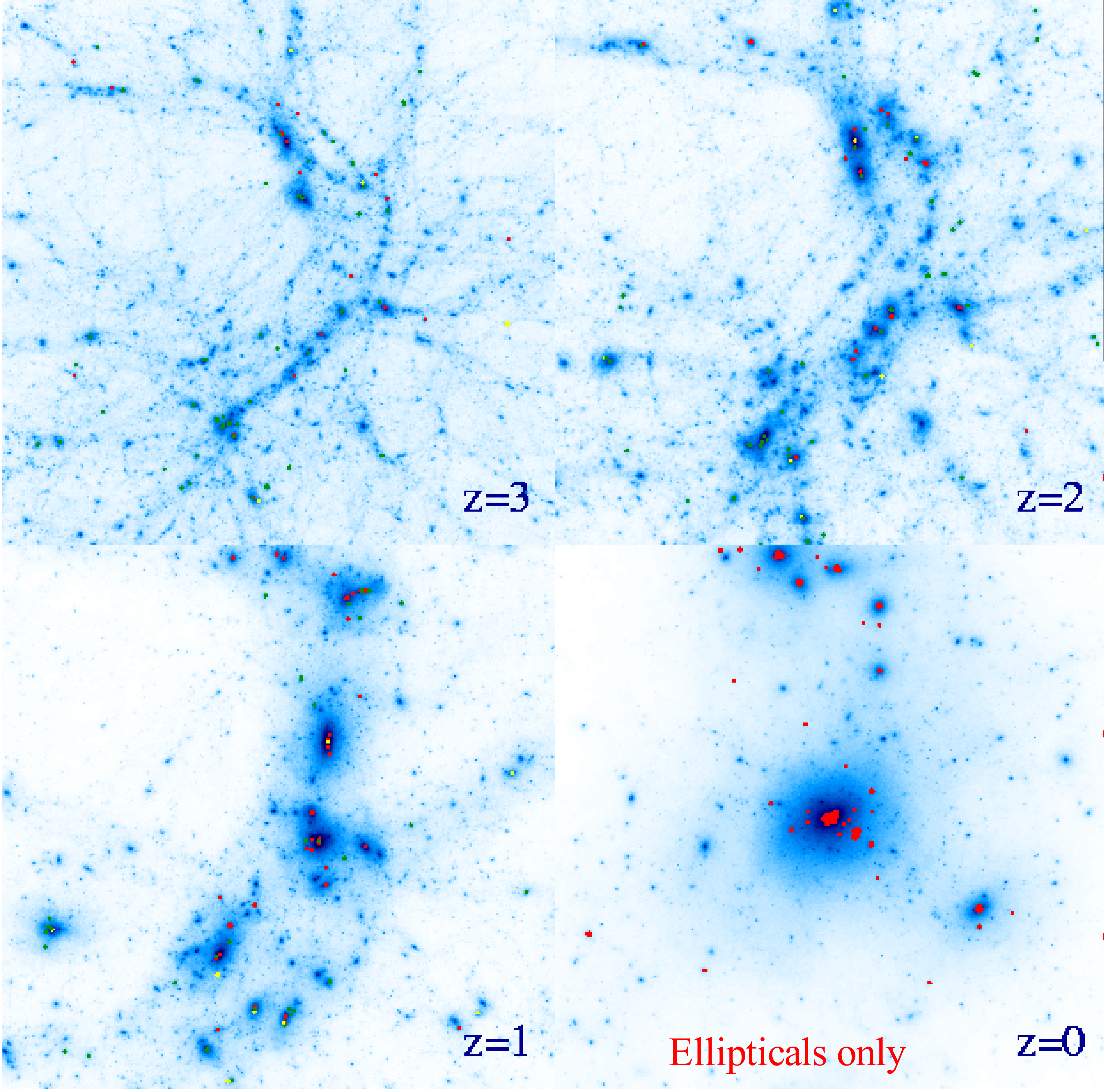


Springel et al 2001

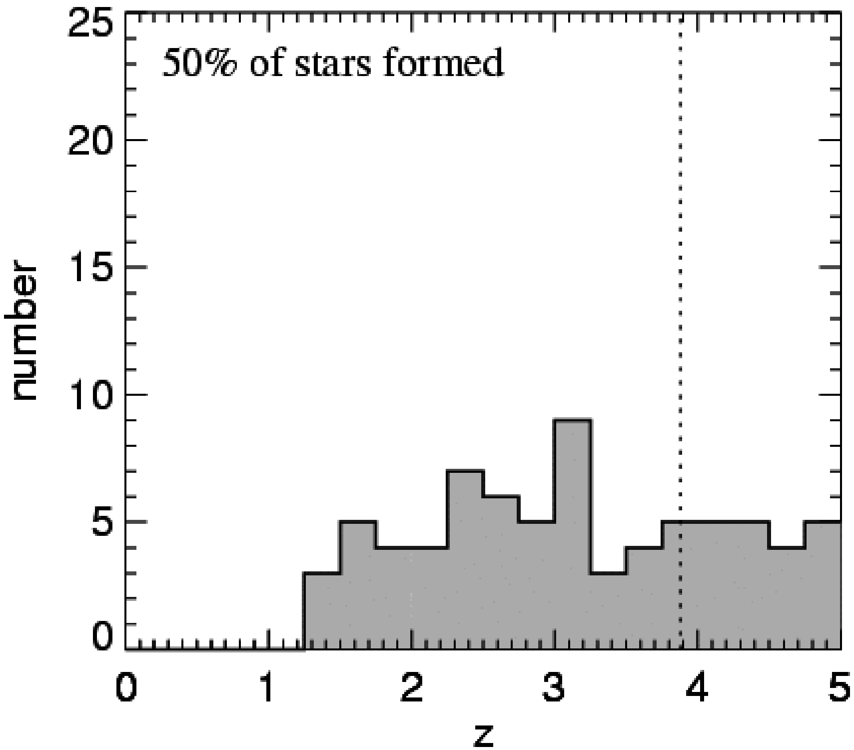
- Formation of the galaxies tracked within evolving (sub)halos
- Luminosity and mass of galaxies is uncertain
- Positions and velocities are followed well

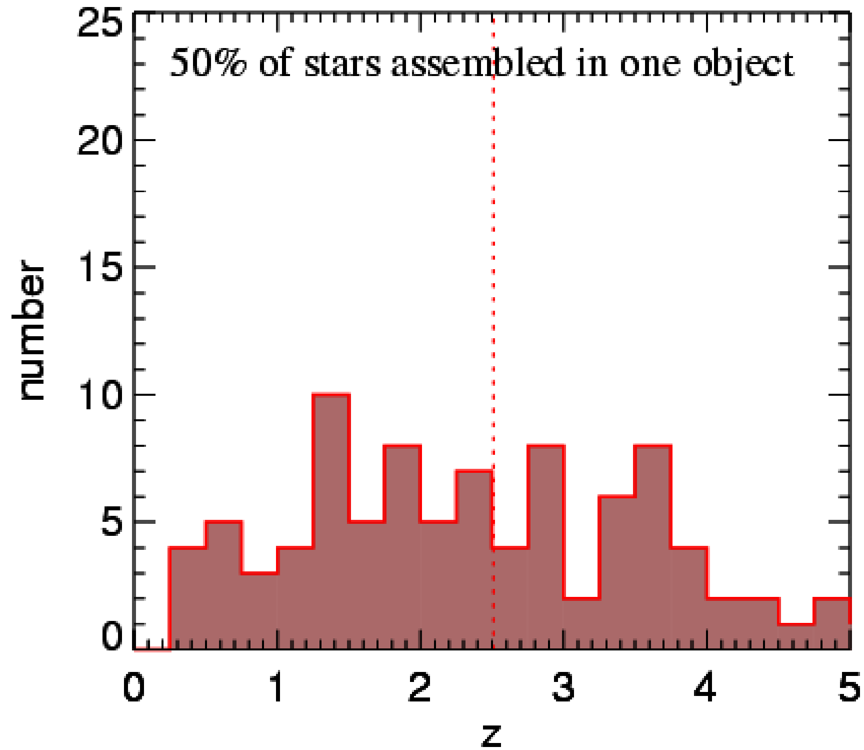
Evolution of the galaxy population in a Coma-like cluster

Springel et al 2001

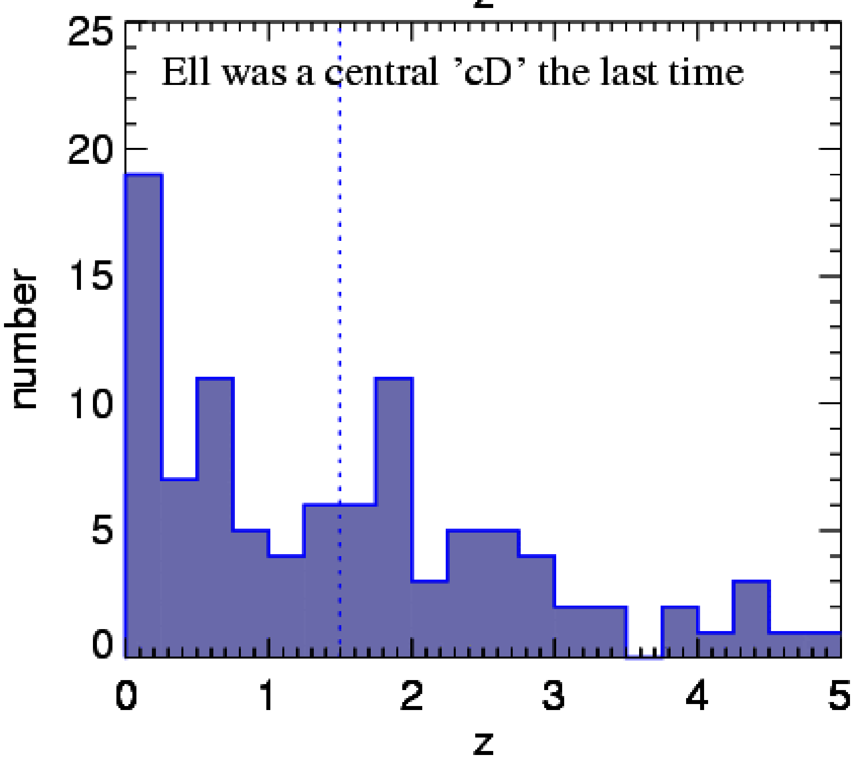


- Formation of the galaxies tracked within evolving (sub)halos
- Luminosity and mass of galaxies is uncertain
- Positions and velocities are followed well



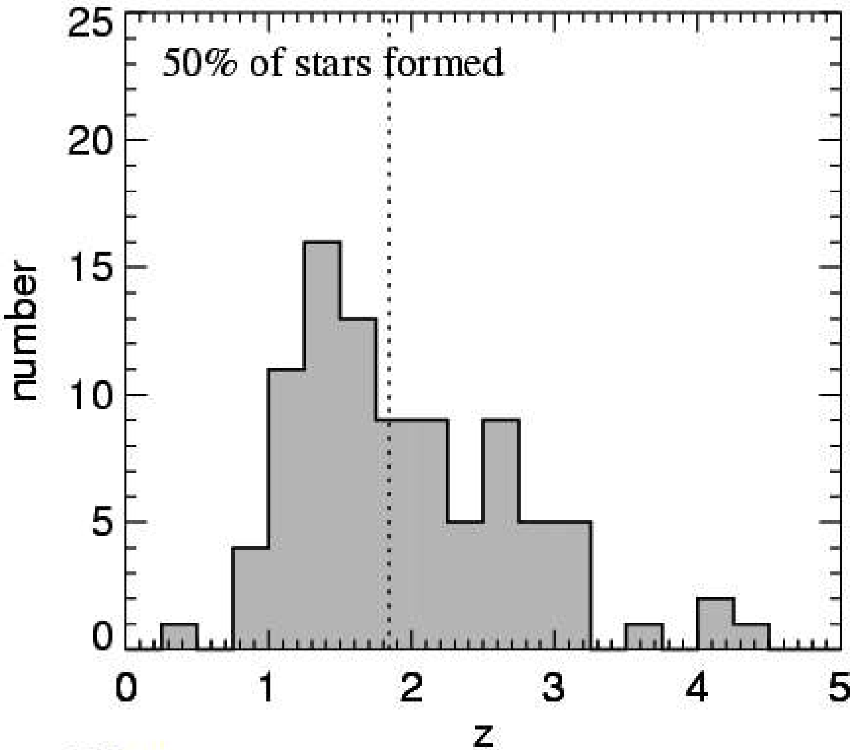


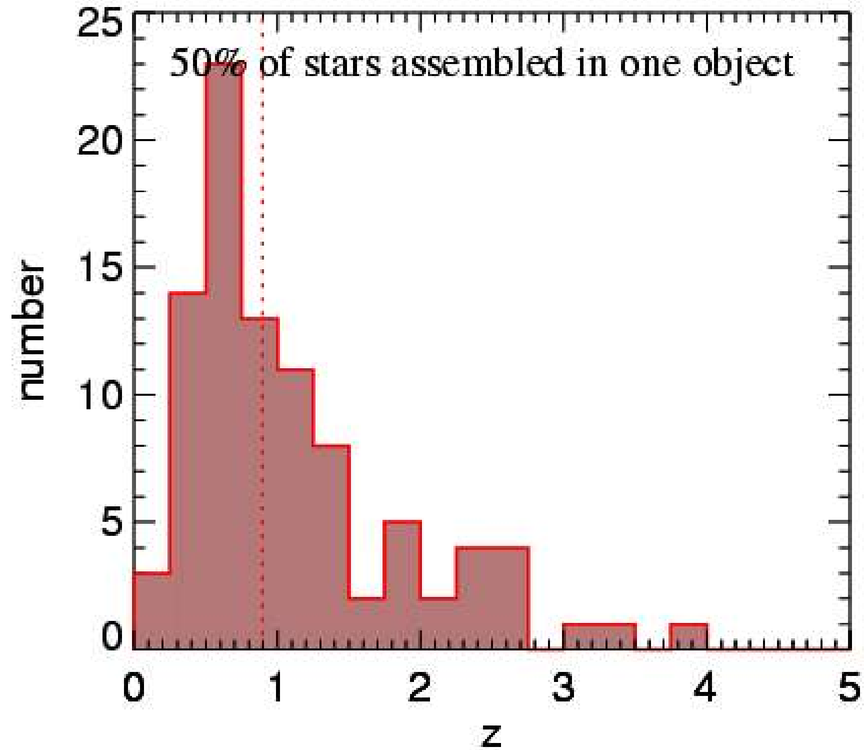
Springel et al 2003



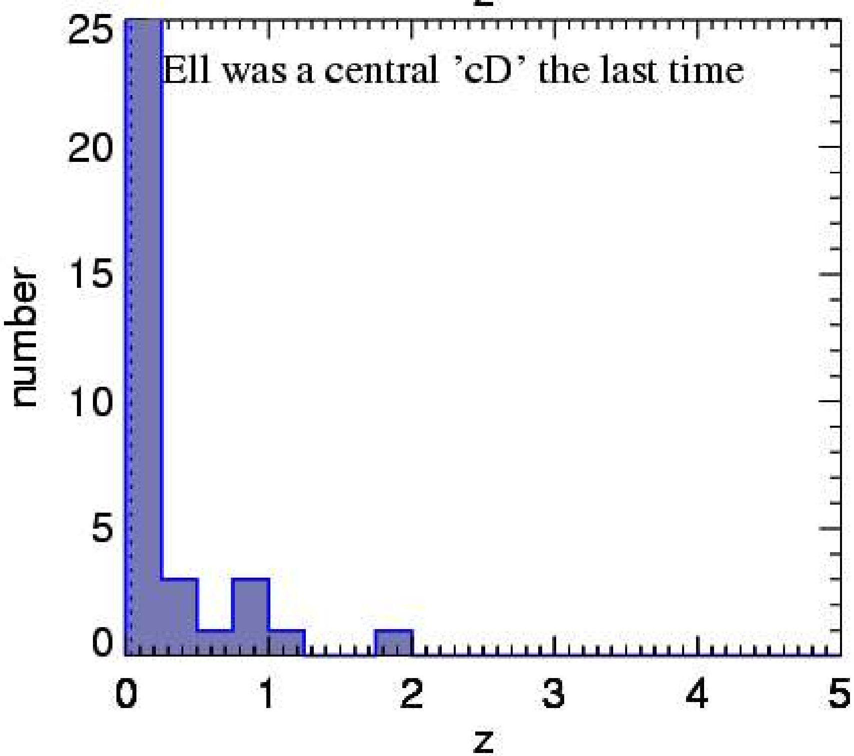
Formation histories of cluster ellipticals

- 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



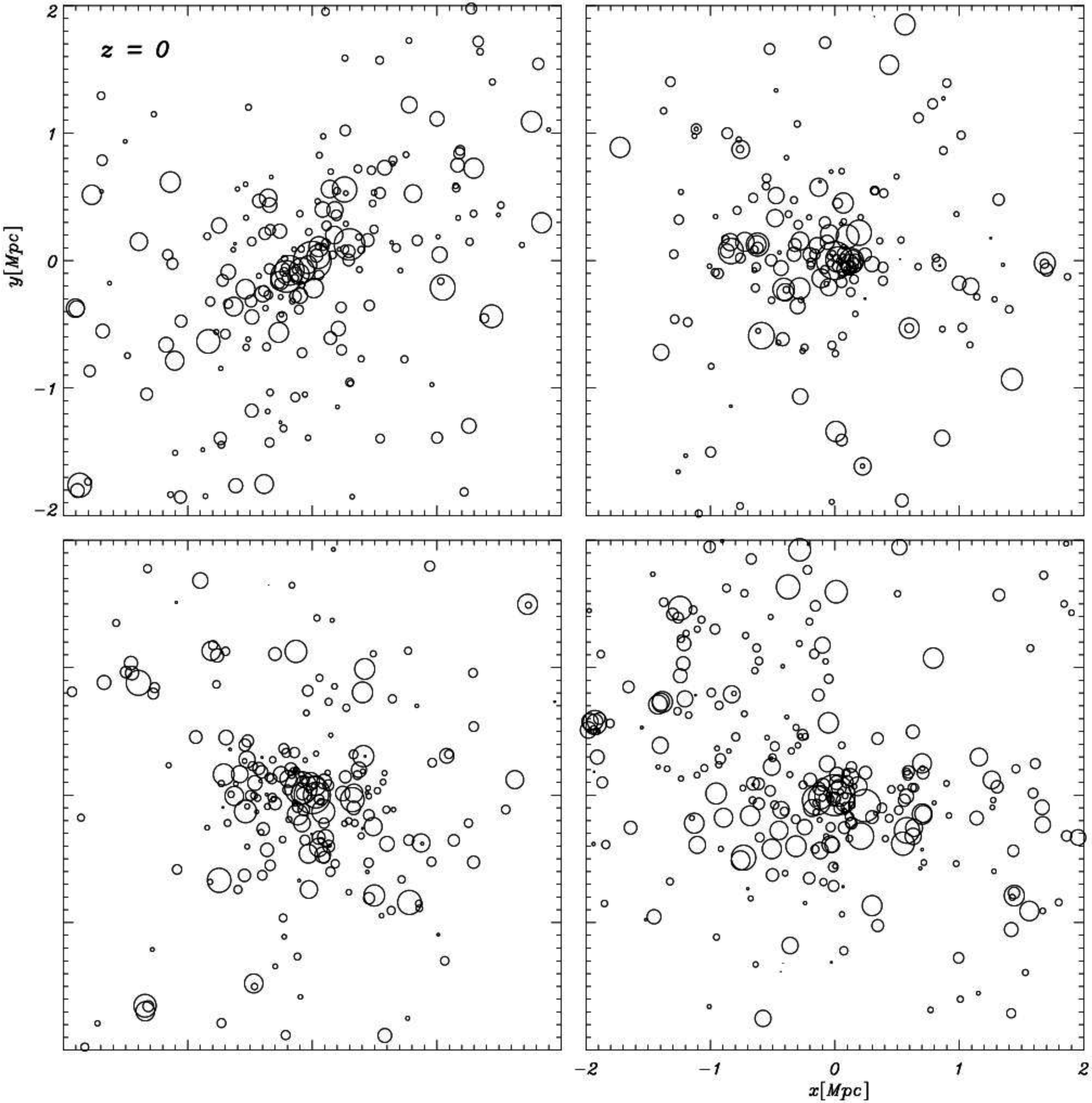


Springel et al 2003



Formation histories of field ellipticals

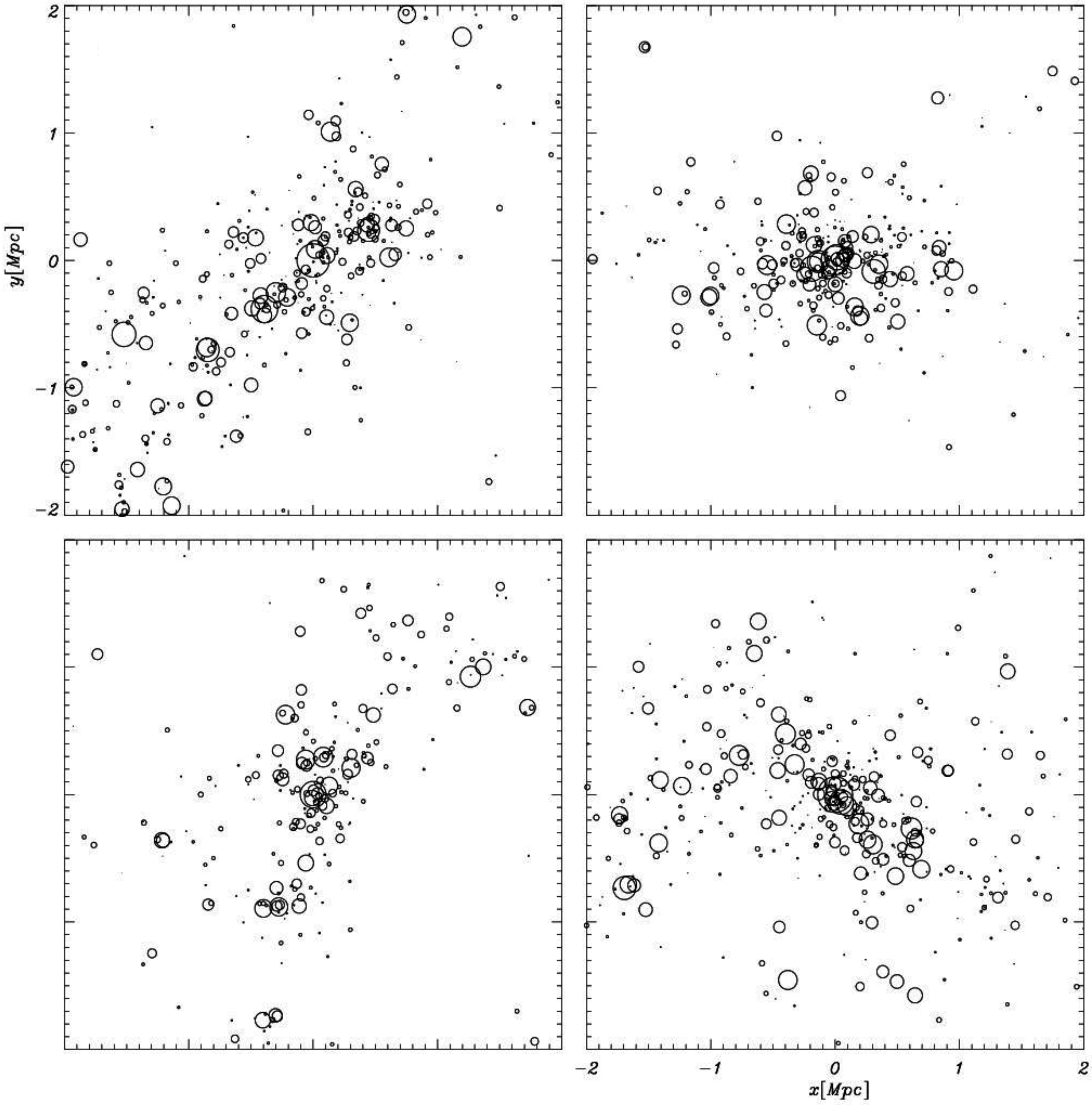
- 91 field ellipticals with $M_B < -18$
- Stars form fairly early
- Most ellipticals assembled late
- Most ellipticals are 'cD' of their groups



Simulations of 'Coma' clusters at z = 0

De Lucia et al 2003

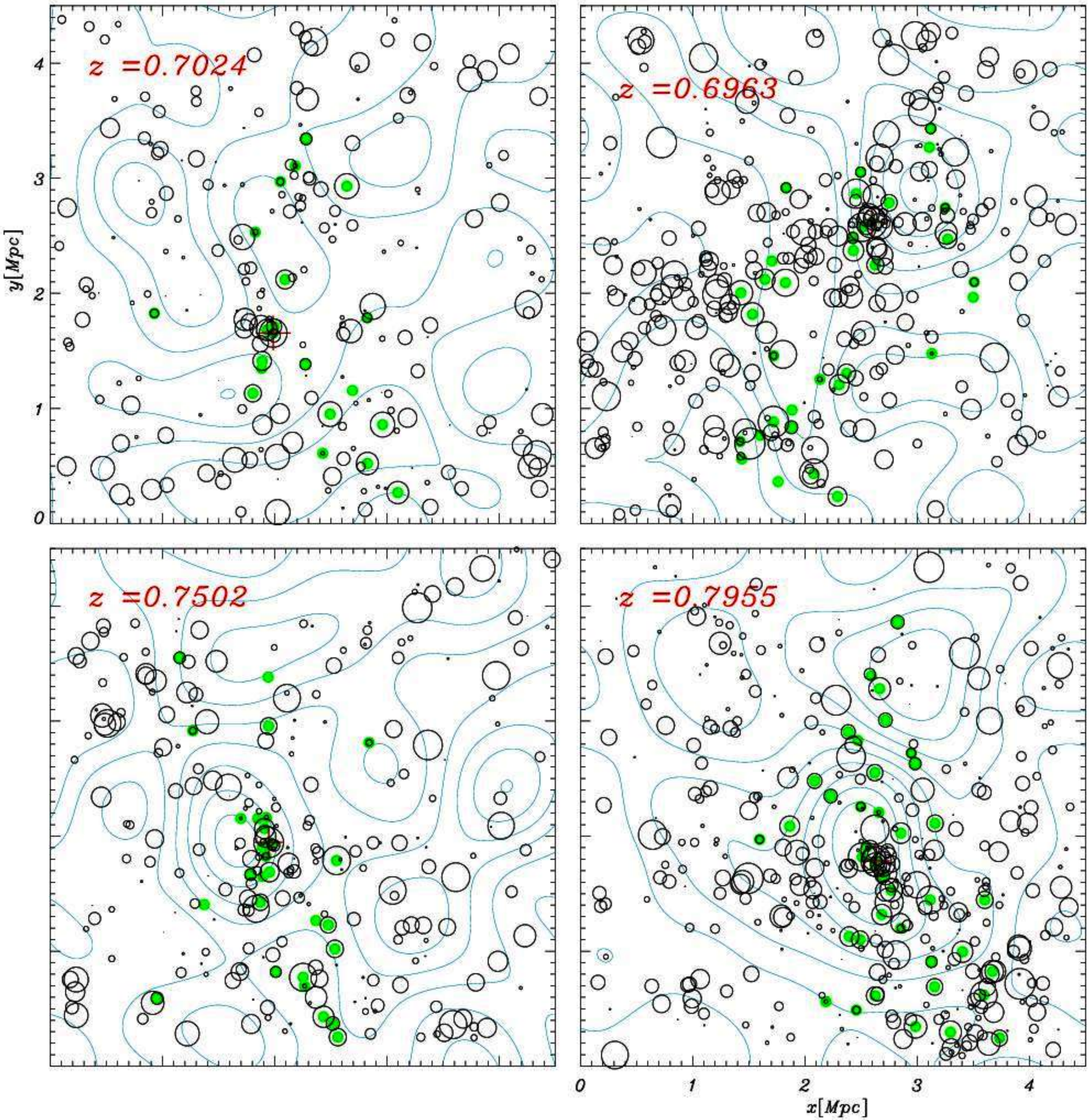
- Plotted region is a cube of physical side 4 Mpc
- Symbol size shows rest-frame V-band luminosity



Simulations of 'Coma' clusters at z = 1

De Lucia et al 2003

- Plotted region is a cube of physical side 4 Mpc
- Symbol size shows rest-frame V-band luminosity

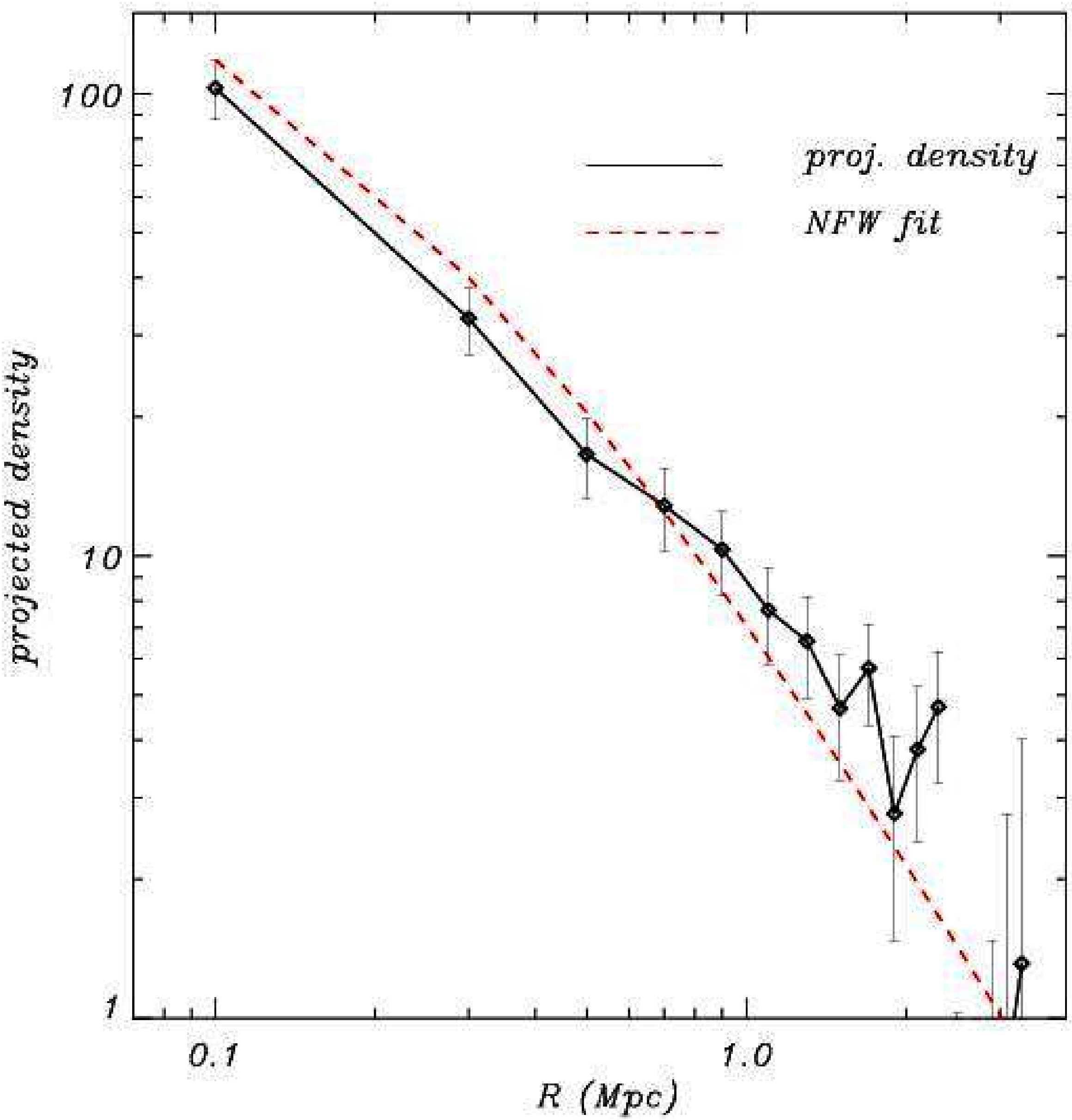


Observations of EDisCS clusters at z ~ 0.75

De Lucia et al 2003

- Plotted region has side 4 Mpc
- Photo-z members only are plotted
- Contours are weak lensing map
- Symbol size shows rest-frame V-band luminosity

Mean density profile of z ~ 0.75 EDisCS clusters



De Lucia et al 2003

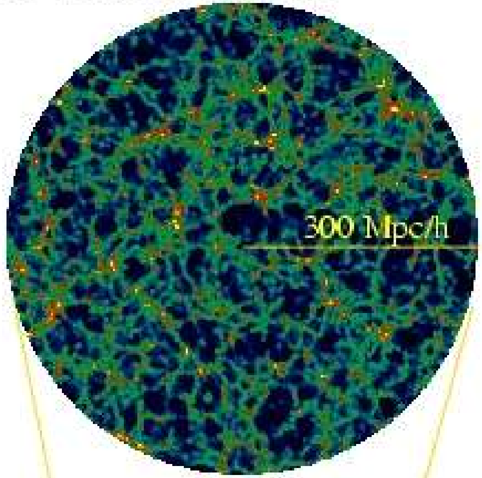
- Four clusters stacked with 0.7 < z < 0.8
- Profiles centered on the BCG

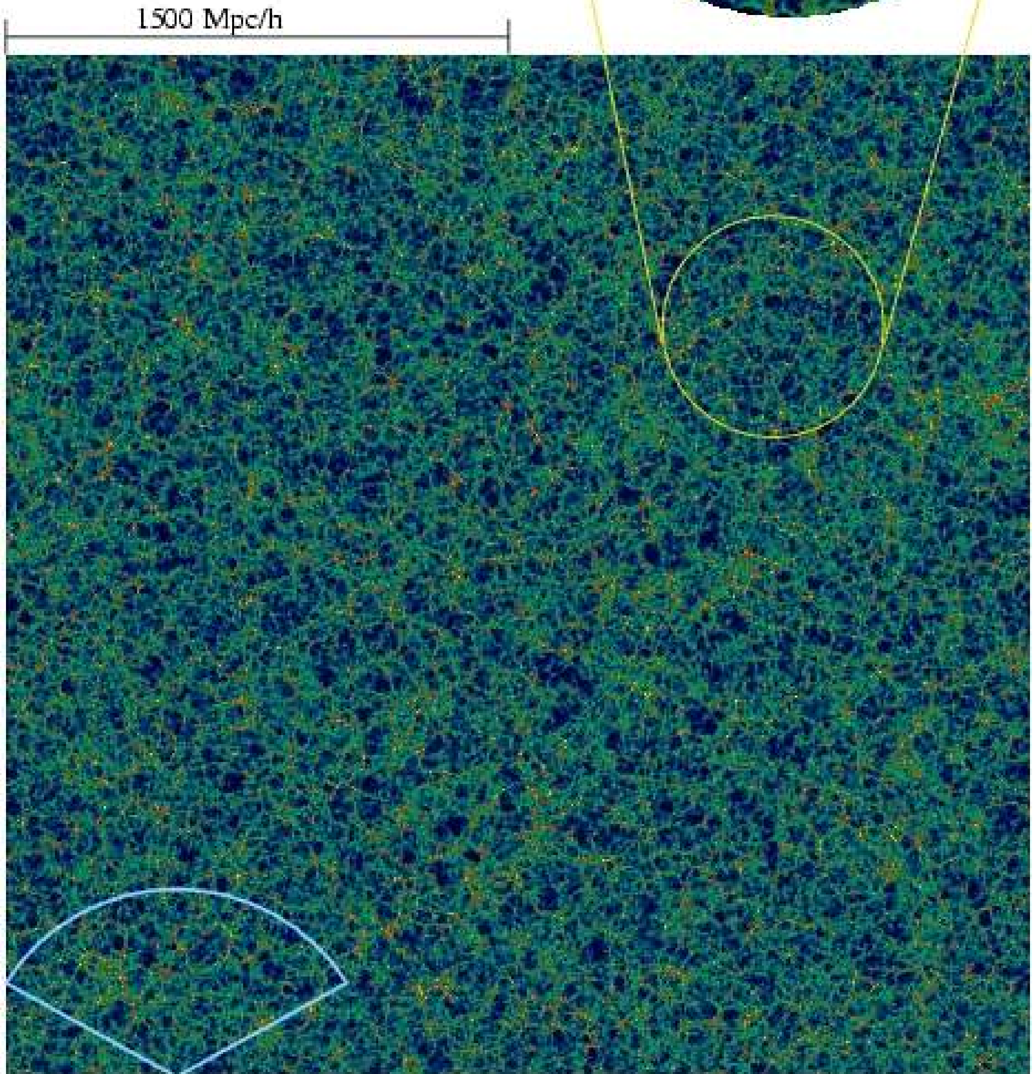
Uses of clusters in cosmology

- Cluster abundance to measure fluctuation amplitude σ_8
- Cluster abundance evolution to measure Ω_m
- Cluster baryon fraction to estimate Ω_b/Ω_m
- Cluster distribution to estimate power spectrum of LSS
- Cluster core structure as a test of the nature of DM
- Clusters as laboratories for galaxy evolution processes

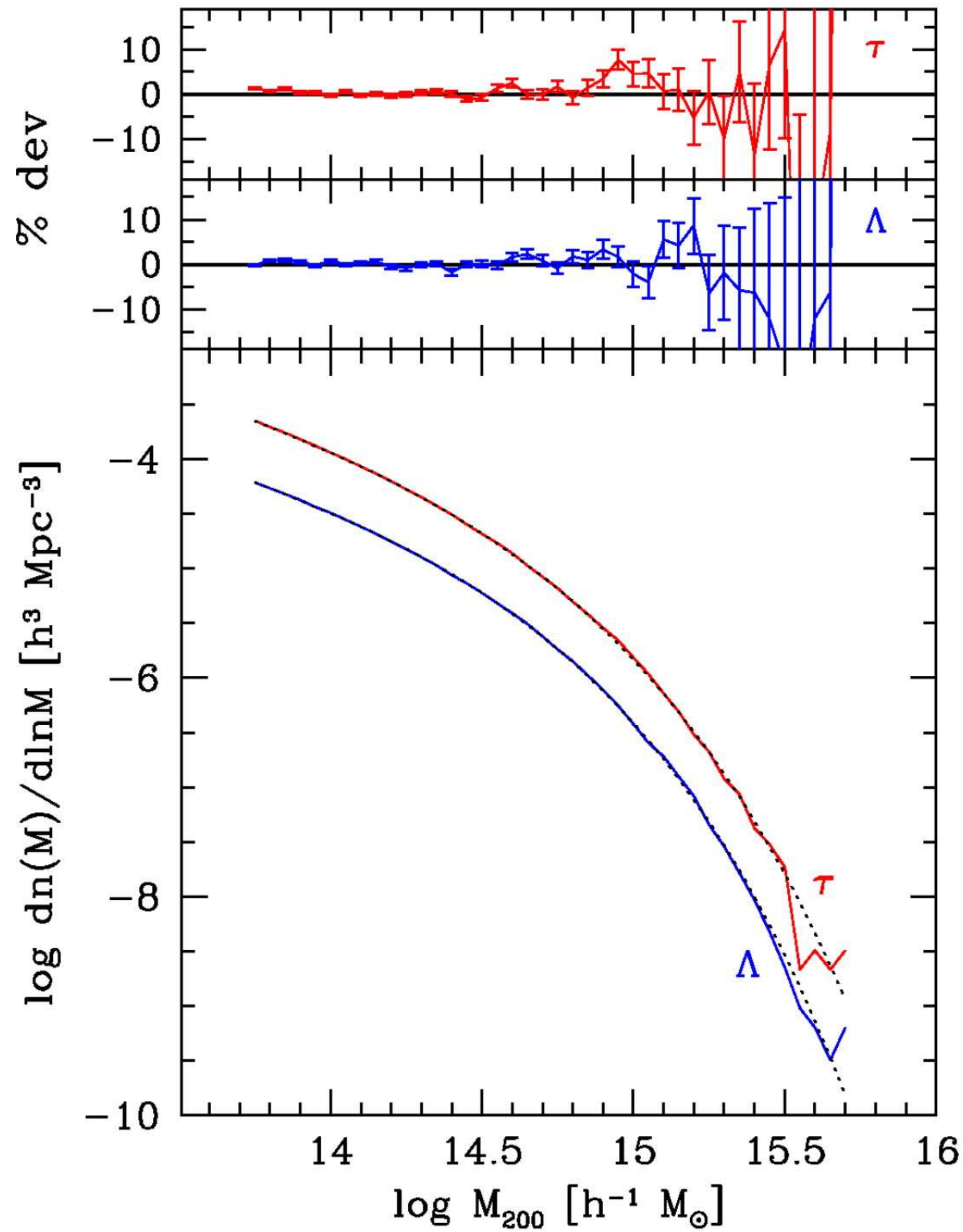
The Hubble Volume Simulation

Ω=0.3, Λ=0.7, h =0.7,
σ_8=0.9 (ΛCDM)
3000 x 3000 x 30 h^{-3}Mpc^3
P^{3}M: z_i=35, s=100 h^{-1}kpc
1000^3 particles, 1024^3 mesh
T3E(Garching) - 512cpus
M_{particle} = 2.2 x 10^{12} h^{-1} M_{sol}





Evrard et al 2002
The Virgo Consortium



Recent σ_8 estimates

E. Pierpaoli, S. Borgani, D. Scott & M. White 2003

Authors	σ_8	error	Γ	Method
Van Waerbeke et al. (2001)	0.88	0.05		WL
Van Waerbeke et al. (2002)	0.98	0.06	0.2	WL
Bacon et al. (2002)	0.97	0.13	–	WL
Refregier et al. (2002)	0.93	0.17	0.21	WL
Hoekstra et al. (2002)	0.87	0.03	–	WL
Brown et al. (2002)	0.74	0.09	–	WL
Hamana et al. (2002)	0.73	0.27	0.21	WL
Bahcall et al. (2002)	0.72	0.06		OC
Viana et al. (2002)	0.61	0.10	0.1	WLC
Blanchard et al. (2000)	0.75	0.02	–	XTF
Henry (2000)	0.77	0.15	–	XTF
Oukbir & Arnaud (2001)	0.91	–	–	XTF
Pierpaoli et al. (2001)	1.02	0.07	0.23	XTF
Seljak (2001)	0.61	0.06	0.23	XTF
Reiprich & Böhringer (2002)	0.68	0.13	0.17	XLF
Borgani et al. (2001)	0.67	0.06	0.23	XLF
Schuecker et al. (2002)	0.71	0.03	–	XLF
Allen et al. (2002)	0.72	0.02	–	XLF
Lahav et al. (2001)	0.73 – 0.83	0.07	0.21	PS
Szalay et al. (2001)	0.91	0.06	0.19	PS
Bond et al. (2002)	≥ 1	–	–	SZ PS
Komatsu & Seljak (2002)	1.05	0.05	–	SZ PS

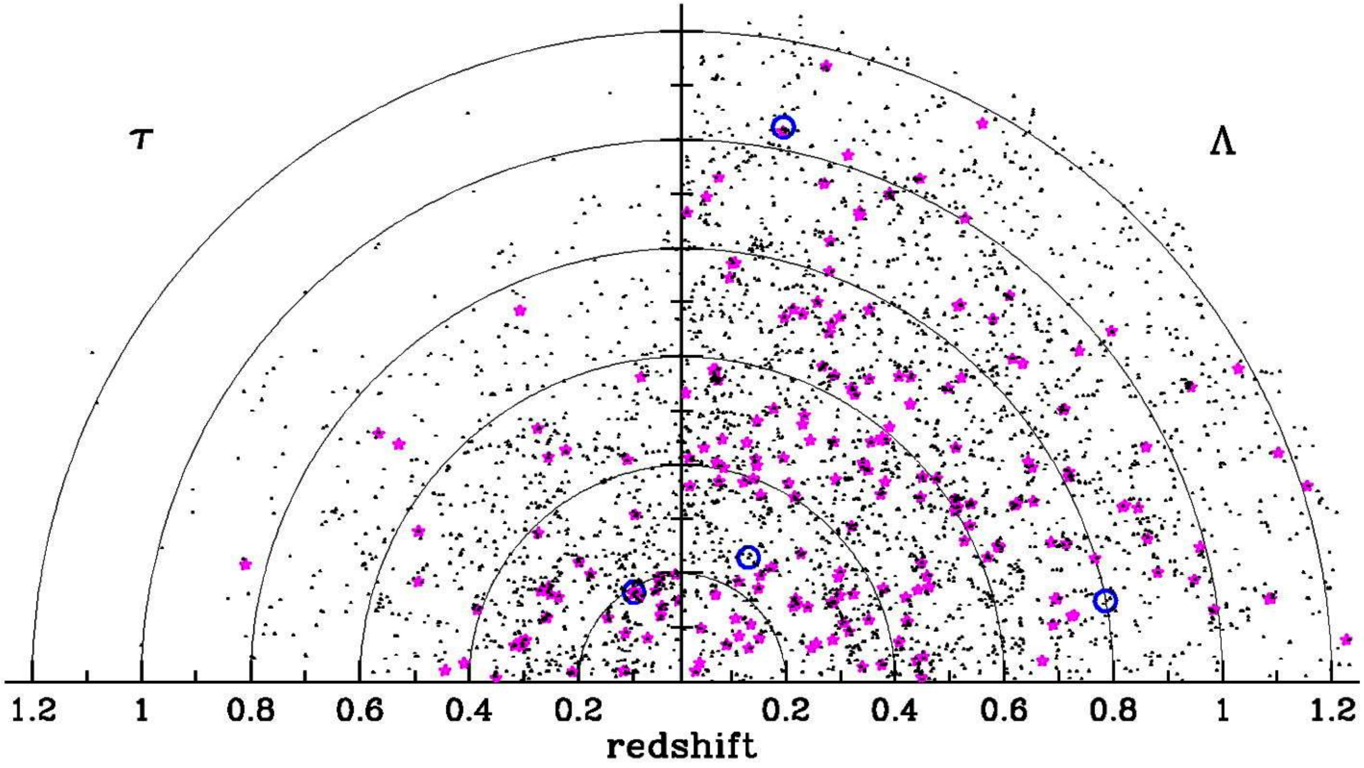
$\sigma_8 = 0.78$ in 2003 ← (Pierpaoli et al. (2001), 1.02)

Cluster Abundance (rows Bahcall et al. (2002) to Allen et al. (2002))

(Evrard et al 2002 → $\sigma_8 = 1.04$)

Cluster abundance evolution as an estimate of Ω

Evrard et al 2002

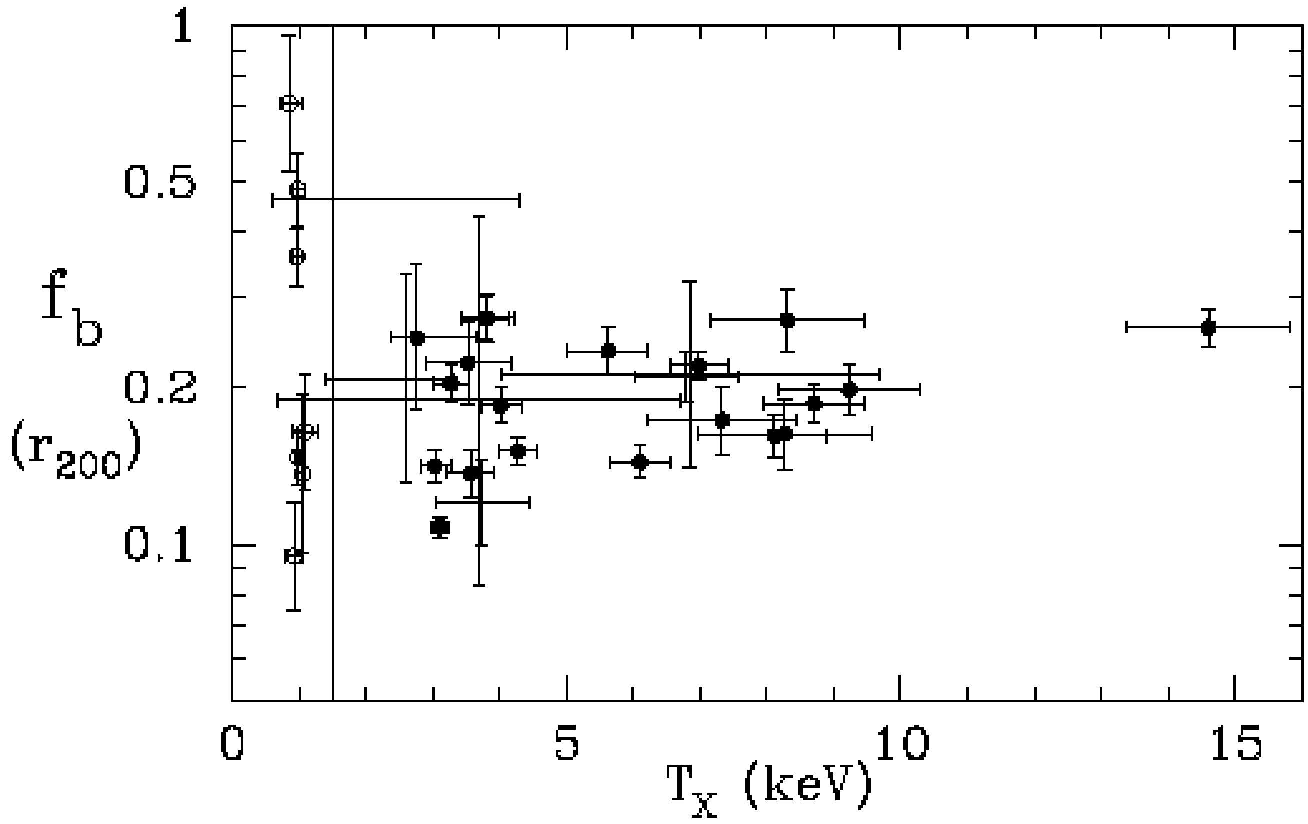


Differing symbols denote clusters of differing mass

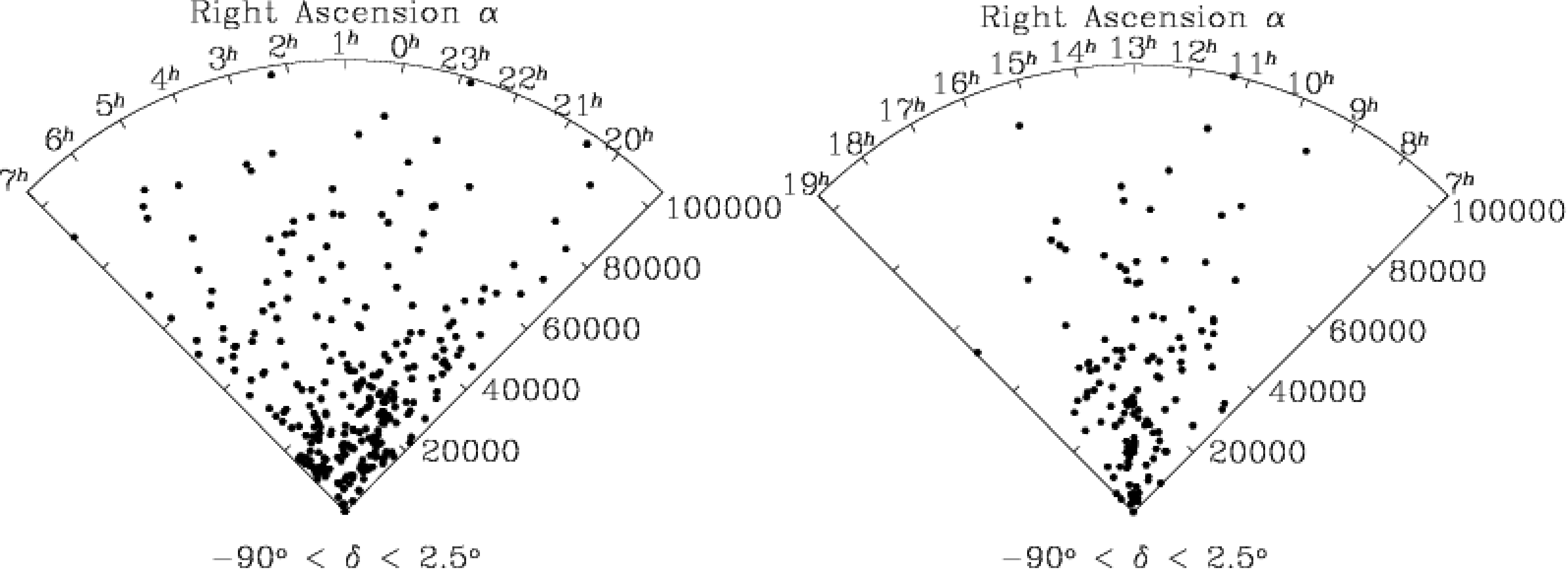
- Cluster abundance by *mass* evolves more slowly for lower Ω
- Observed abundance of hot clusters at large z indicates a low density universe
- This inference could be messed up by evolution in the mass-temperature relation

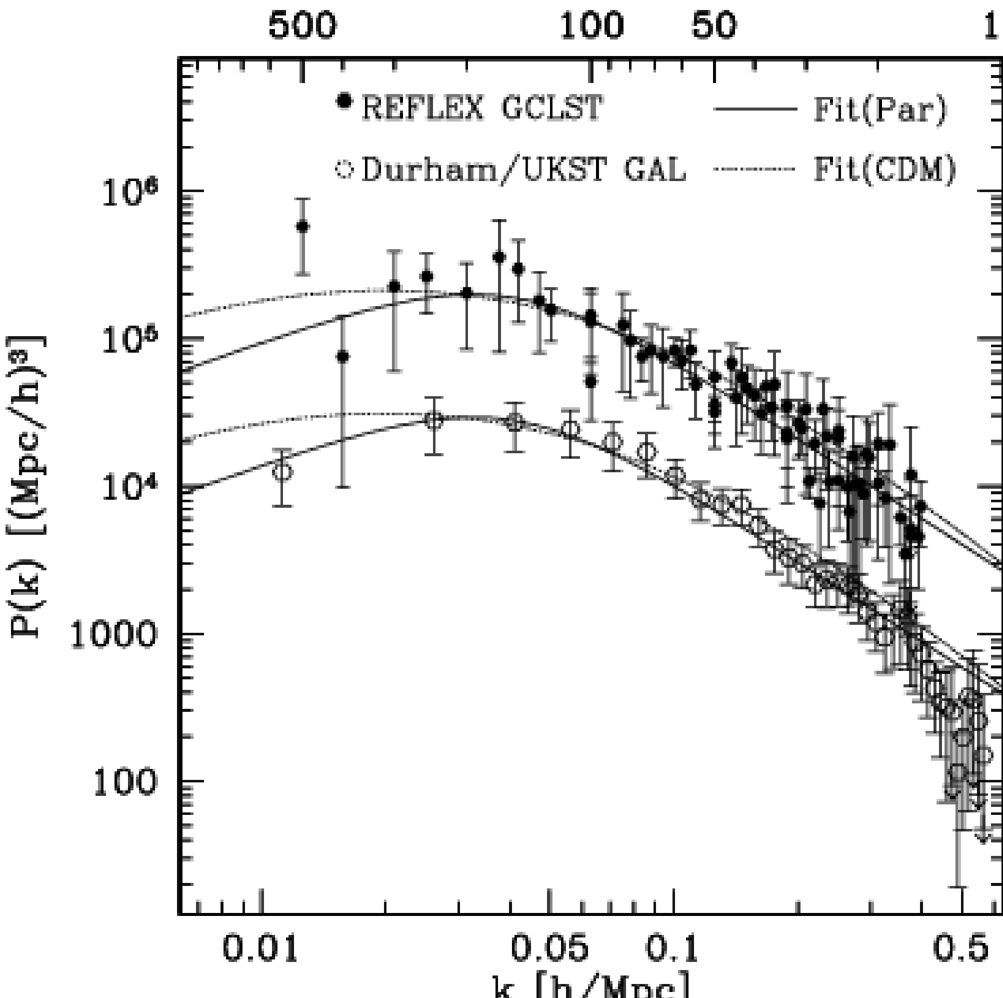
Cluster/group baryon fractions within R_{200}

Roussel, Sadat & Blanchard 2001



- Virial masses from *extrapolating* an isothermal β-model





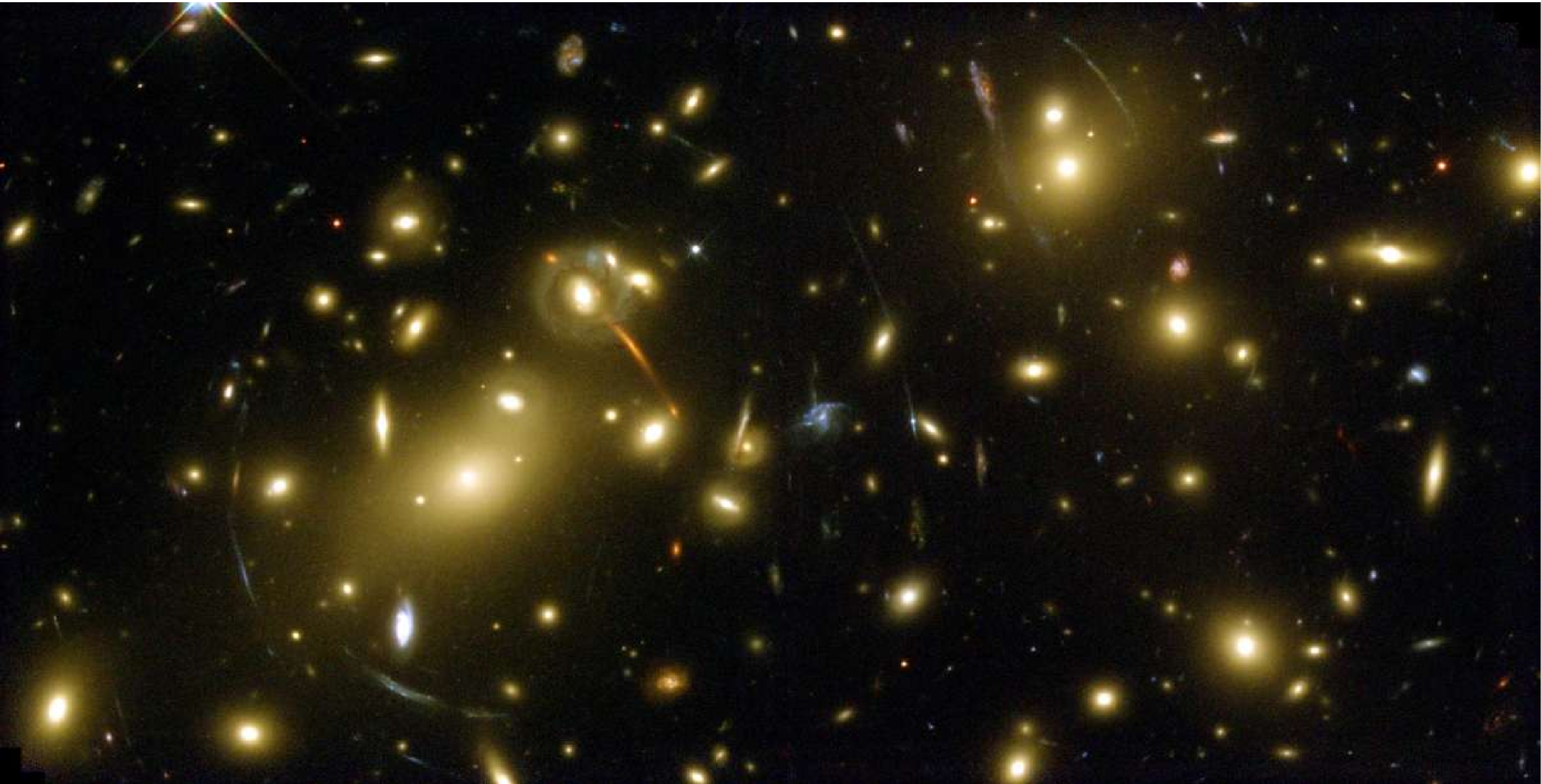
Constraining large-scale structure with cluster surveys

Schuecker et al 2001

- Power spectrum from the REFLEX survey of 452 X-ray selected clusters

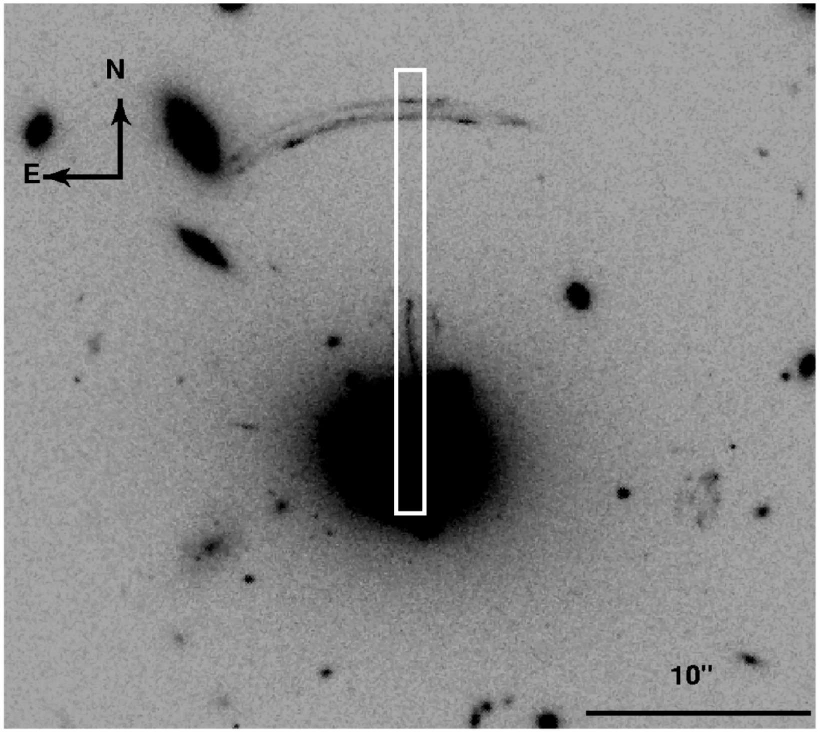
Gravitational lensing by a galaxy cluster

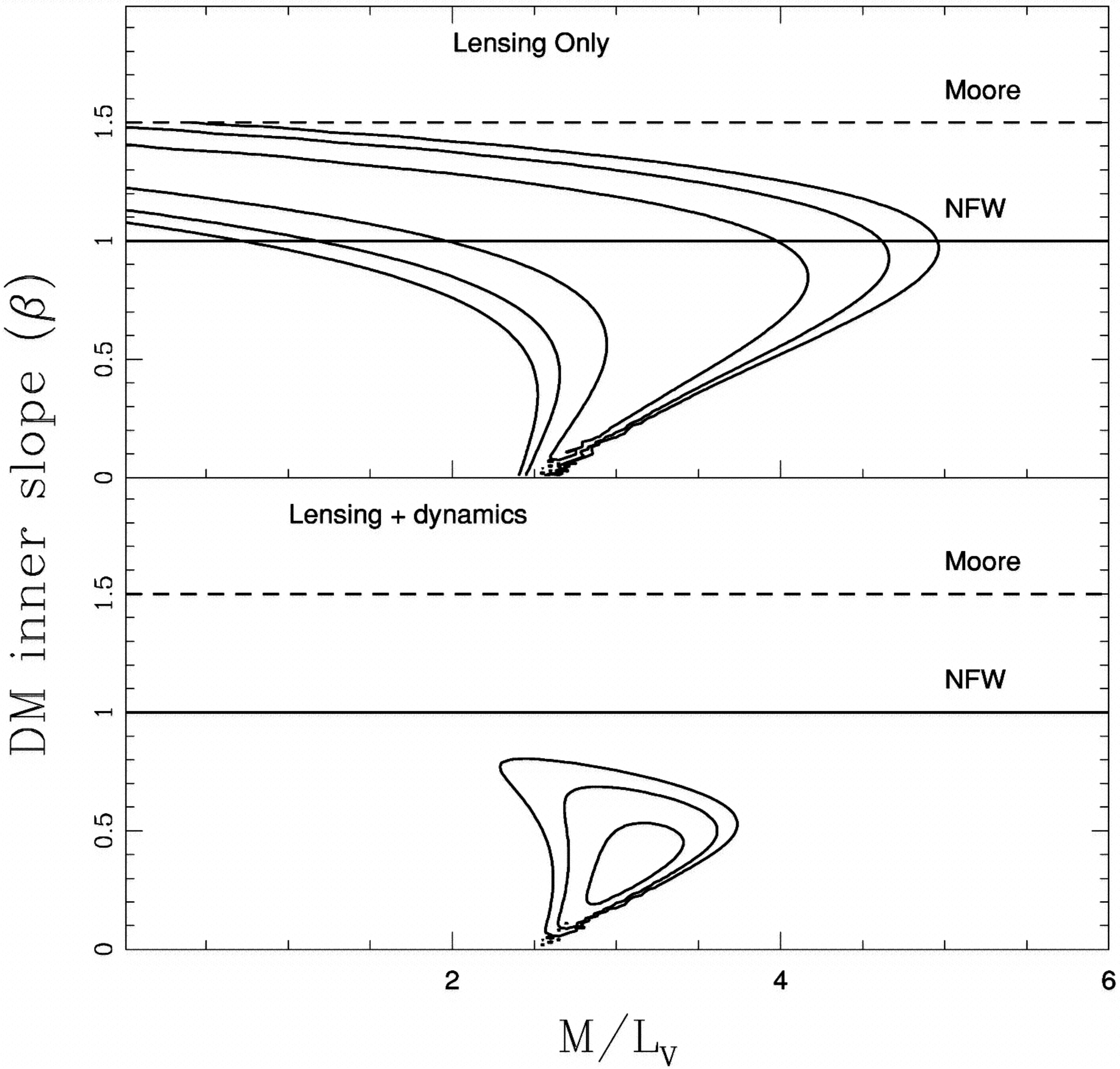
Abell 2218 z=0.17



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

Uses of clusters in cosmology

- Cluster abundance to measure fluctuation amplitude σ_8

  Problem: converting cluster observables (L, T,...) to mass

- Cluster abundance evolution to measure Ω_m

  Problem: possible evolution of the L-M or T-M relations

- Cluster baryon fraction to estimate Ω_b/Ω_m

  Problems: clumping, extrapolation to R_{200}

- Cluster distribution to estimate power spectrum of LSS

  Problem: sparse sampling

- Cluster core structure as a test of the nature of DM

  Problem: How does cD assembly affect DM profile?

- Clusters as laboratories for galaxy evolution processes