Distant Clusters of Galaxies
Ringberg, October, 2005

The Formation and Evolution of Galaxy Clusters

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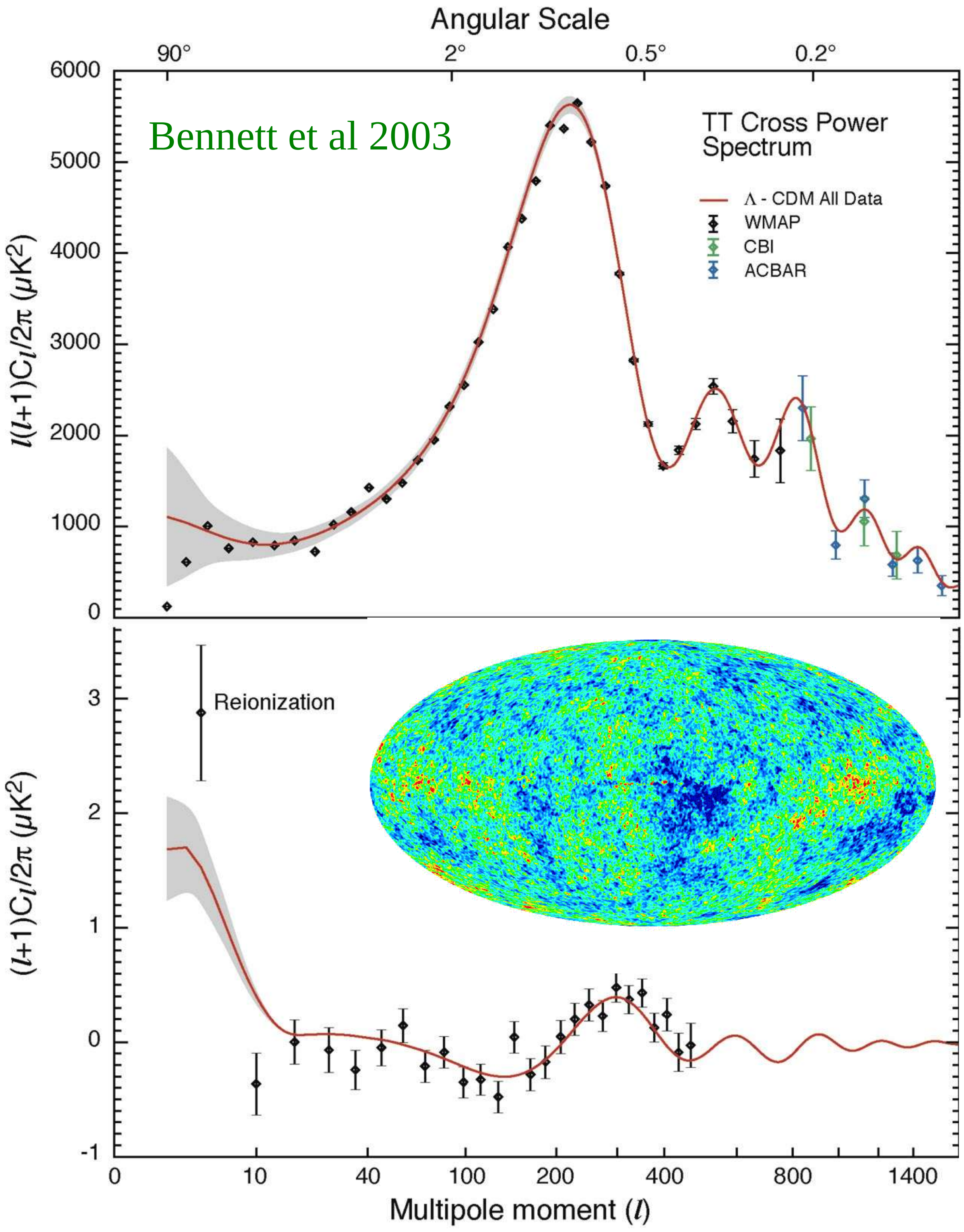
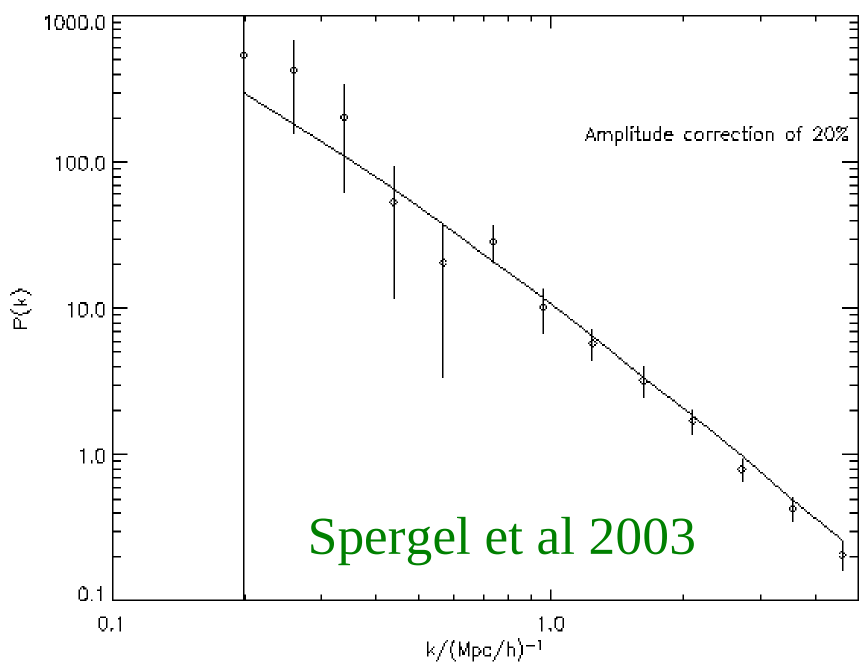
Max Planck Institute for Astrophysics



- > 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



With the establishment of a standard structure formation paradigm, cluster studies split into three main threads

A: Tests of the paradigm / measurement of its parameters

- -- Statistics of matter distribution (Gaussian/non-Gaussian)
- -- Nature of dark matter (core structure, cluster galaxy halos)
- -- Nature of dark energy (N(M, z), baryon wiggles)
- -- Estimation of Ω_m, Ω_b / Ω_m, w, ...

B: Studies of the intergalactic medium

- -- thermodynamic history (heating, cooling, phase structure)
- -- enrichment history (Pop III, wind properties, mixing)
- -- nonthermal components (B-fields, CR's, radio bubbles)

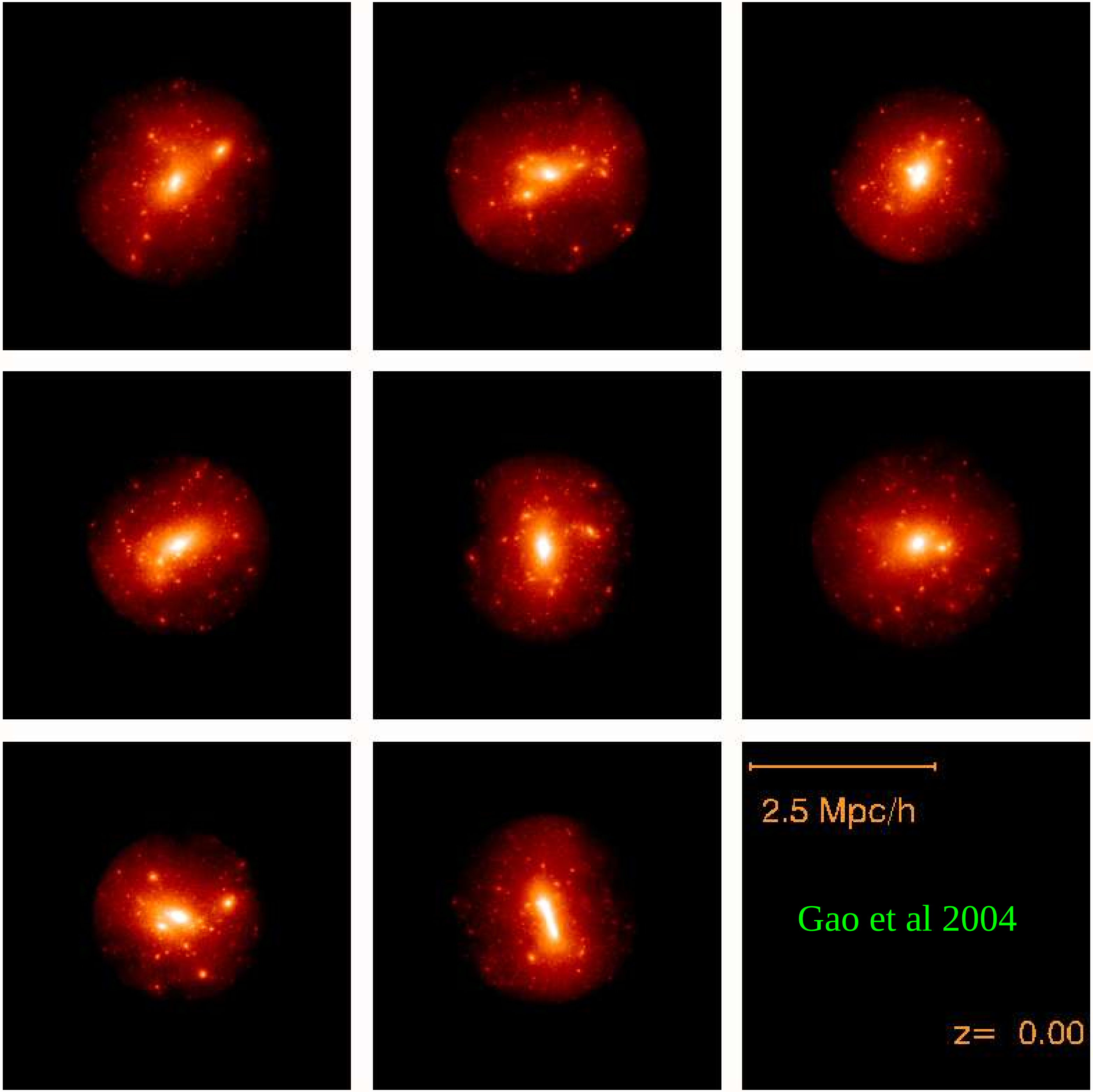
C: Studies of galaxy evolution

- -- density vs mass, structure, SFR... (<u>not</u> “morphology”!)
- -- early vs late imposition of trends (Nature vs Nurture)
- -- relation between galaxy and SMBH evolution

In the standard paradigm:

- clusters grow from inhomogeneous infall along filaments
- they have no edges – on large scales they become part of a globally homogeneous “cosmic web” -- on small scales their internal structure remembers their assembly history
- the 3-D structure around typical massive clusters is complex with many interacting sheets and filaments
- shock structures around clusters are extended and complex, punctuated by infalling cool clumps on the filaments → cold fronts, etc.

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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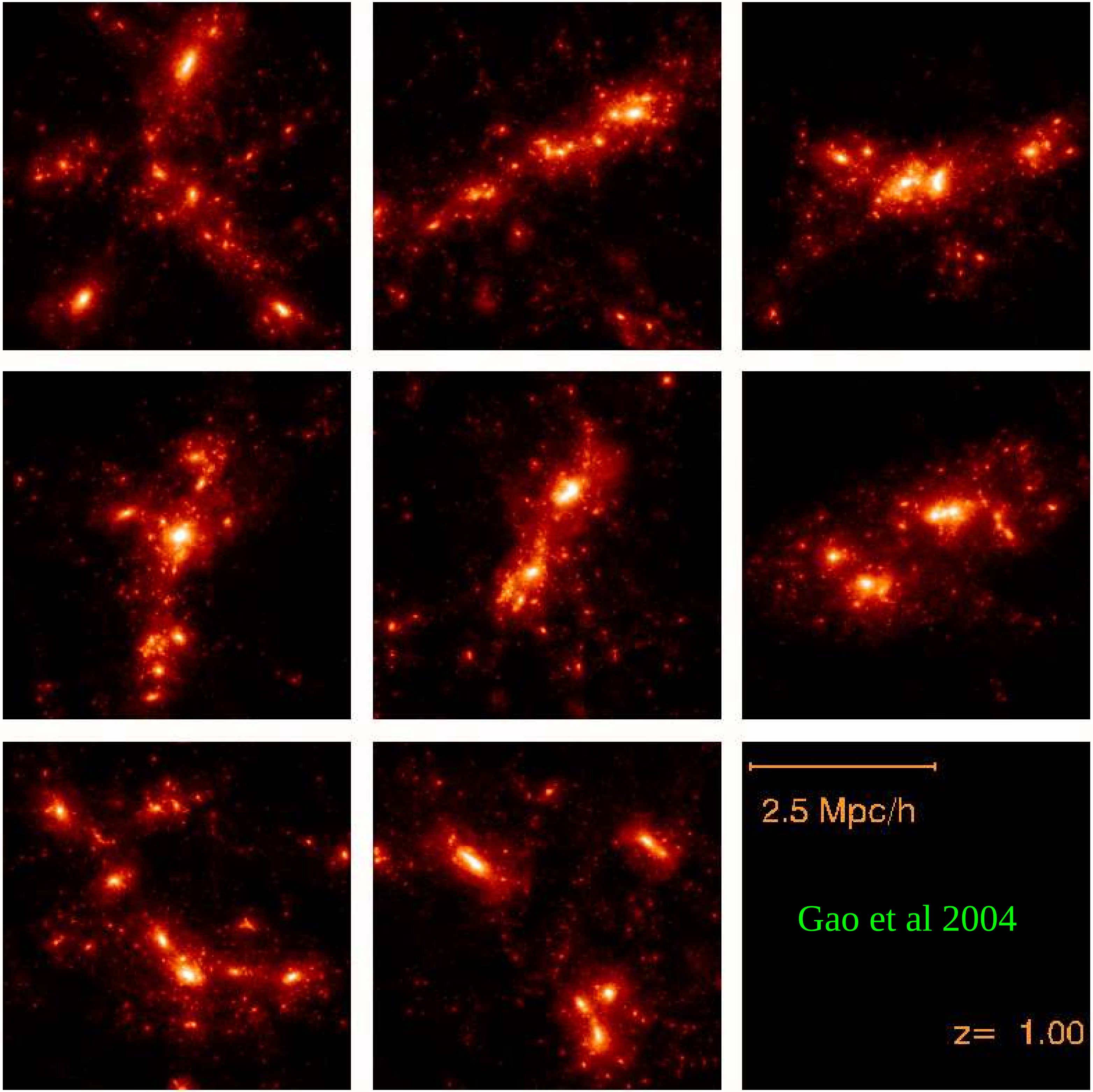

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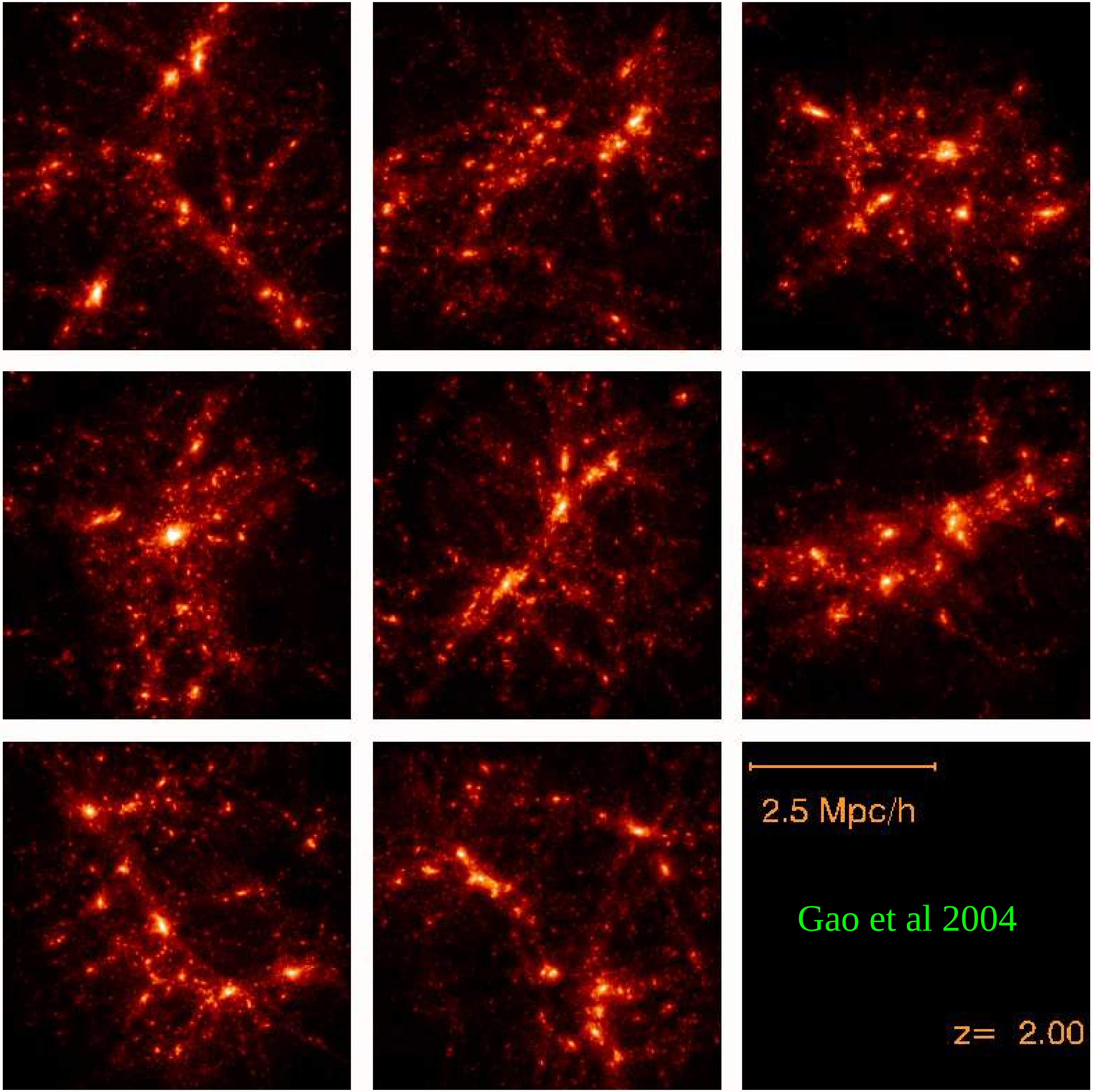

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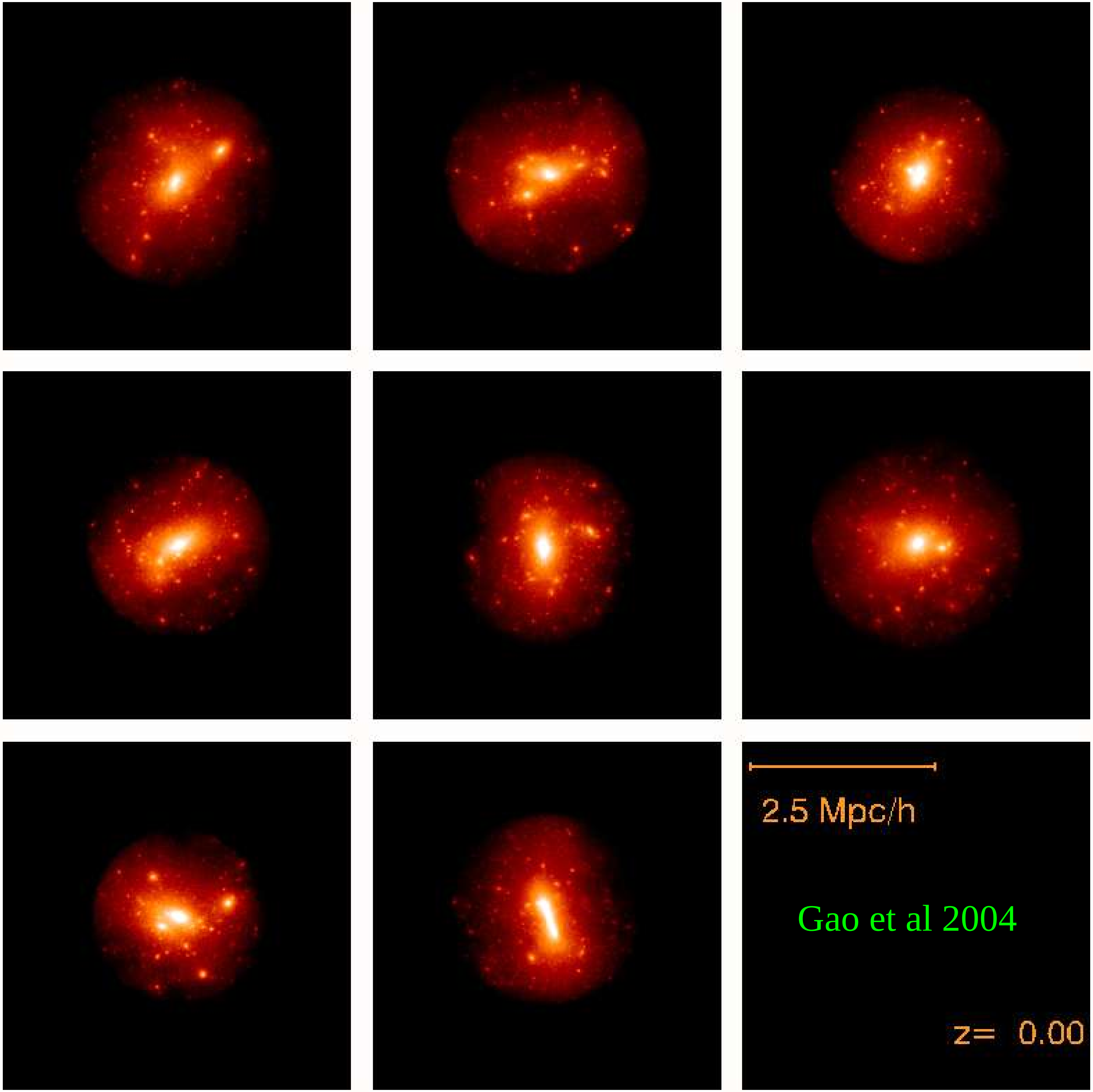

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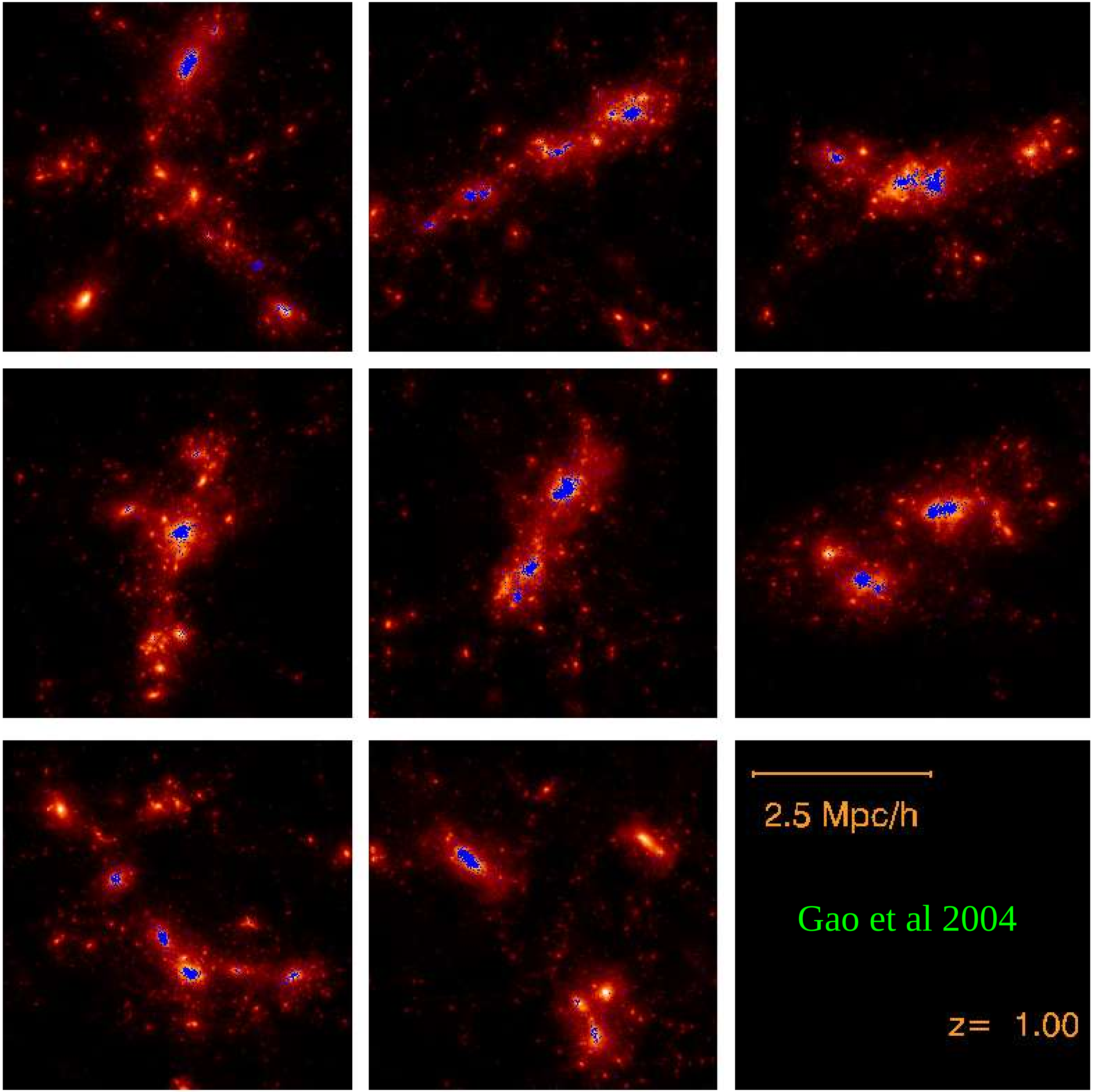

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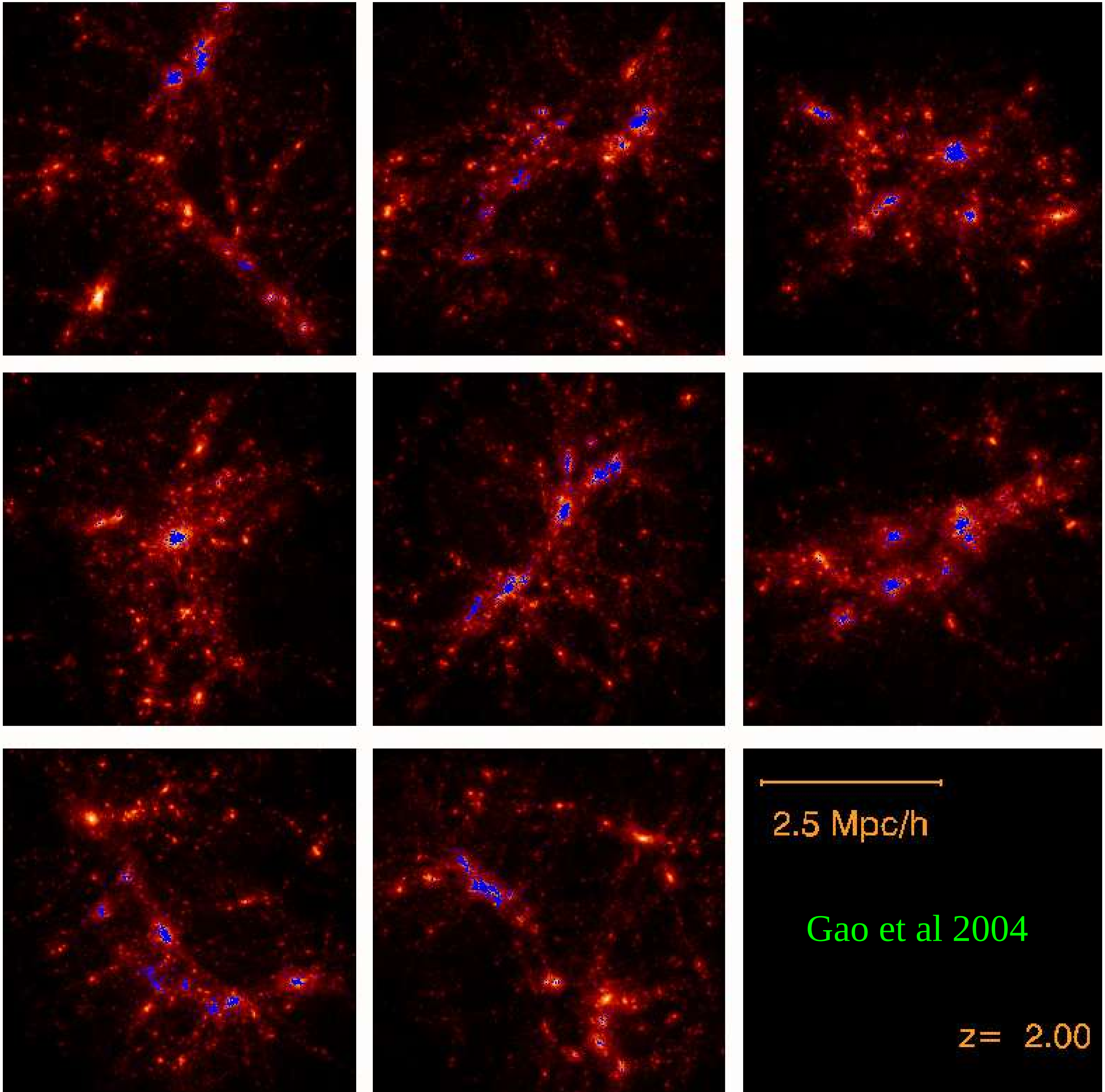
- DM within 20kpc at z = 0 is shown blue

Cluster structure in ΛCDM



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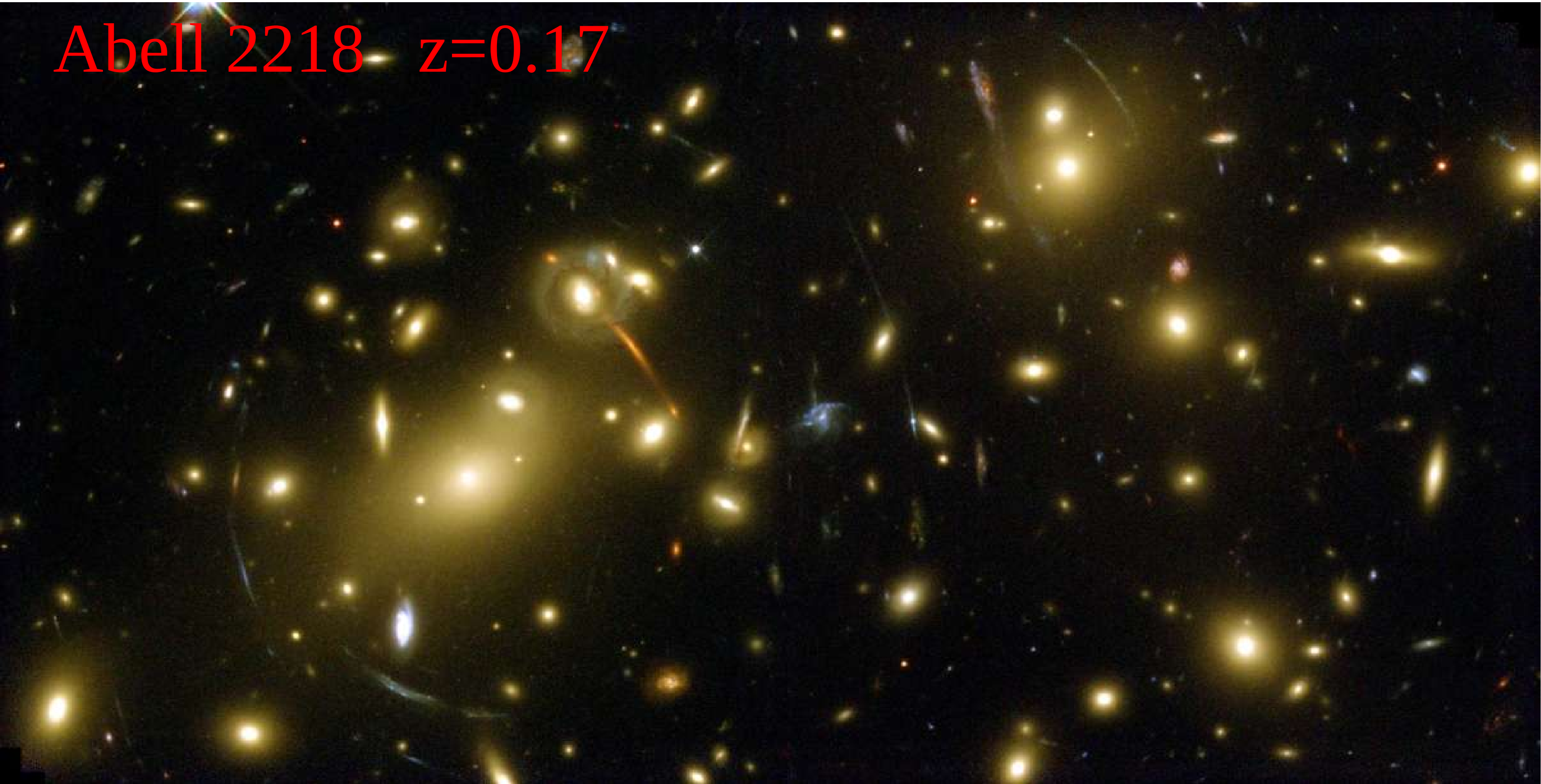
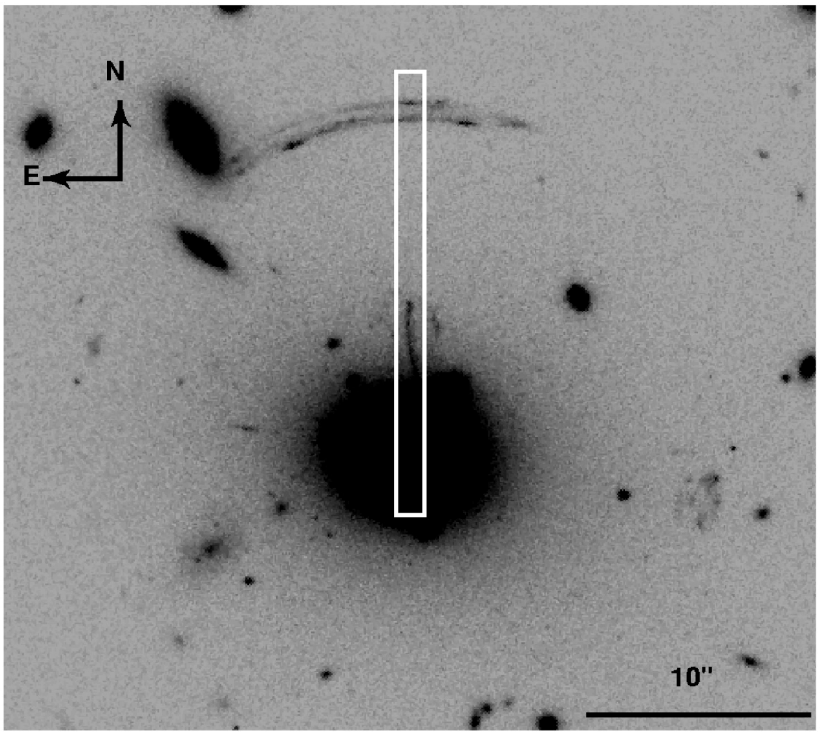
Gravitational lensing by a galaxy cluster

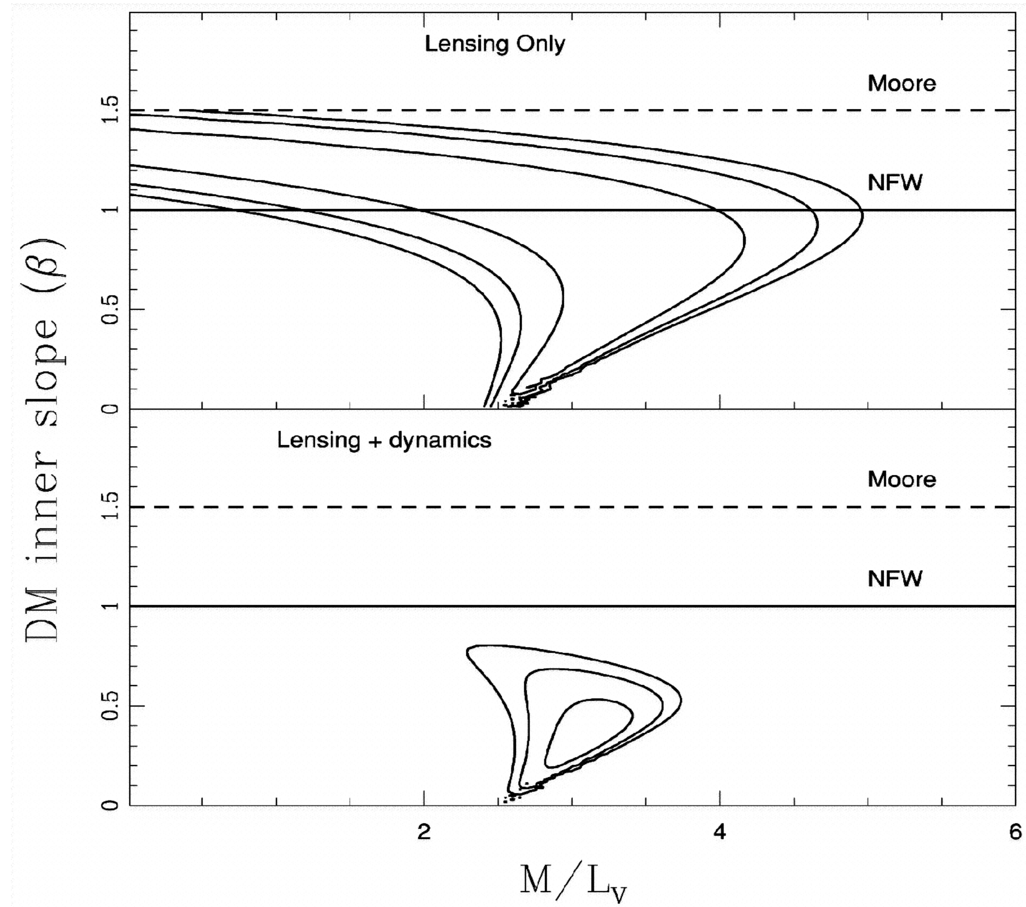
Both strong lensing and X-ray data indicate that many/most clusters have compact cores or cusps and an NFW-like density structure



Constraining DM properties with strong lensing ?

Sand, Treu & Ellis 2002

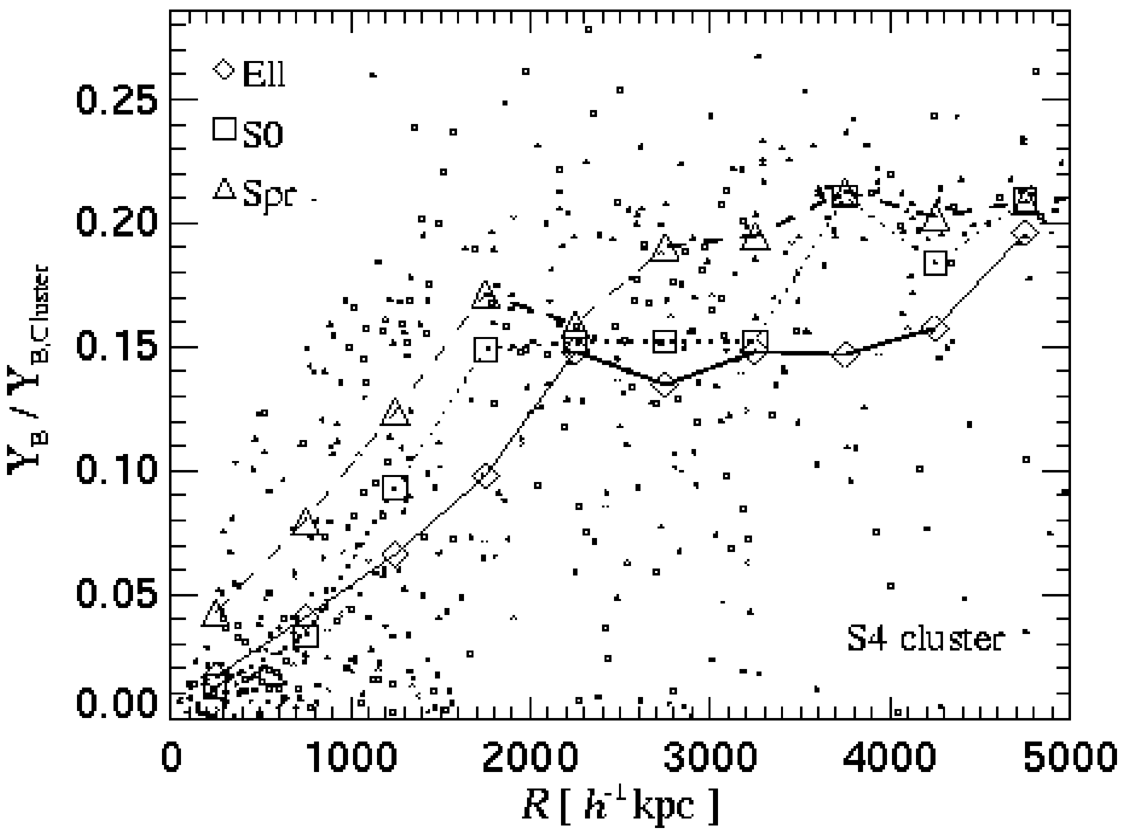


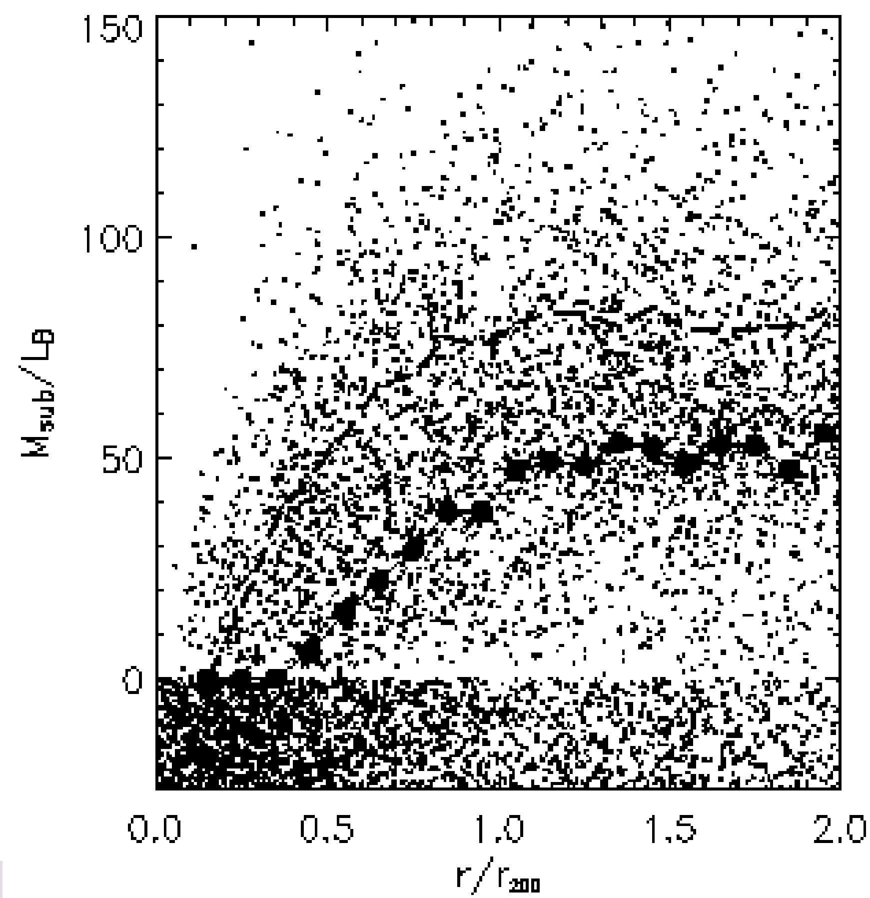


- Model potential as power law DM + galaxy with constant M/L
- Consistency with radial arc, tangential arc & velocity dispersion profile
  → inner slope of DM profile shallower than NFW
- Constraint is substantially weakened if the inner DM distribution can be significantly flattened (Bartelmann & Meneghetti 2004, Dalal & Keaton 2004)

Halos of galaxies in clusters

- The halos of cluster galaxies are less massive at smaller radii
- E's have smaller halo masses than disk galaxies of the same L
- Many galaxies have almost all their halo (and some stars?) stripped

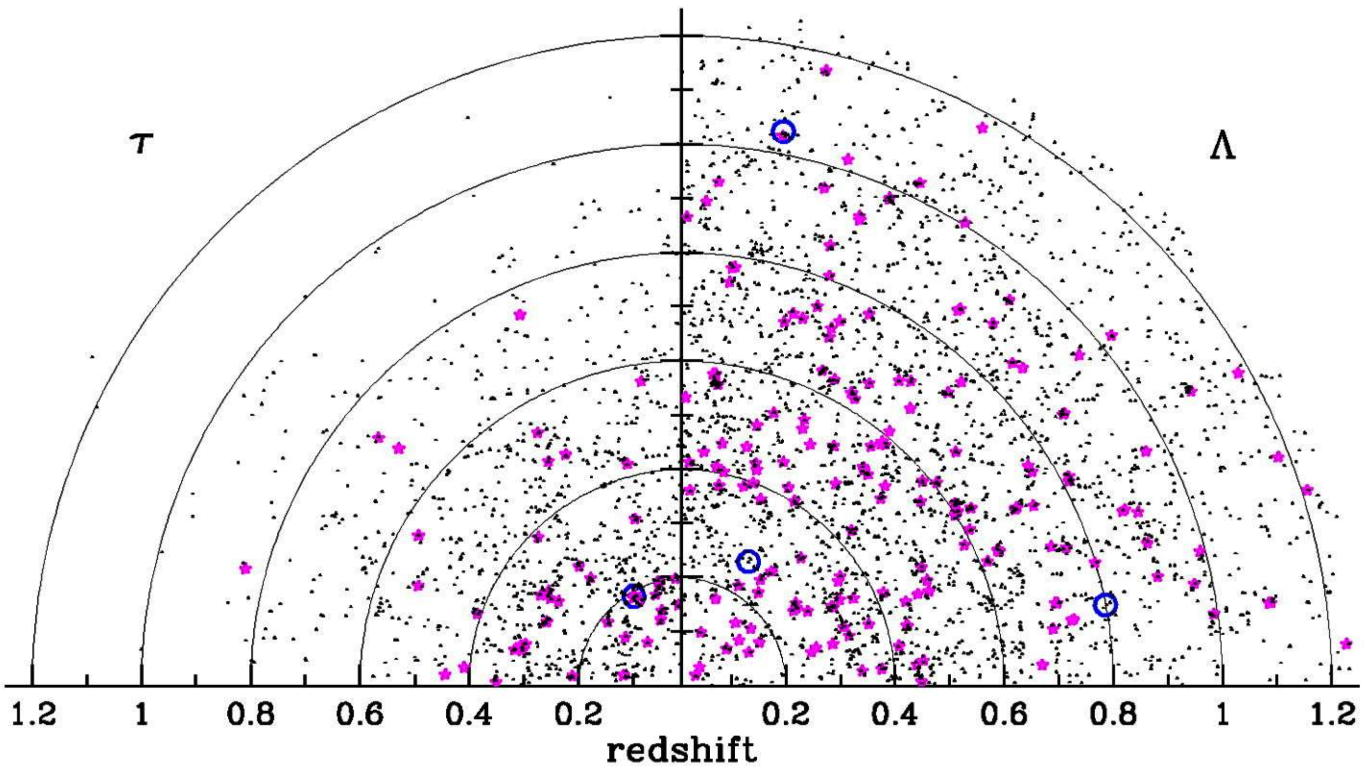




Springel et al (2001) All resolved subhaloes   Gao et al (2004) All galaxies M < -17

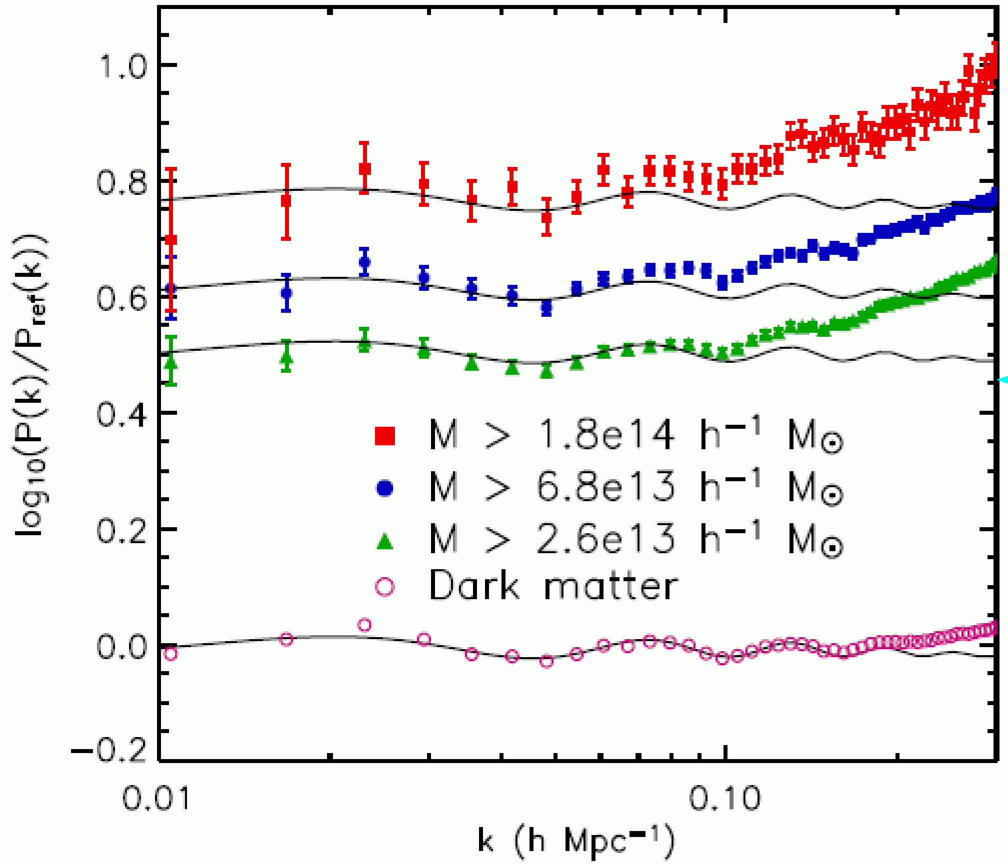
Cluster abundance evolution as an estimate of Ω

Evrard et al 2002



Differing symbols denote clusters of differing mass

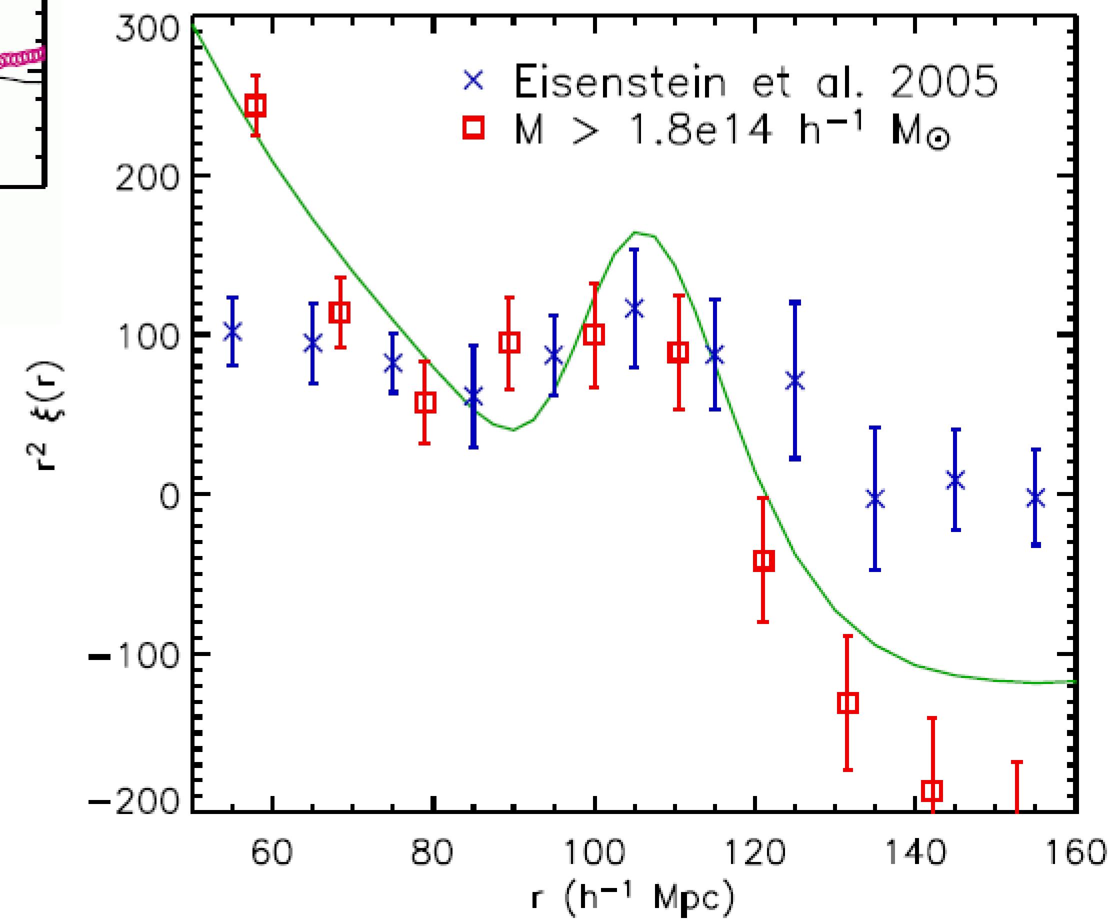
- Cluster abundance by *mass* evolves more slowly for lower Ω
- Observed abundance of hot clusters at large z indicates a low density universe
- This inference could be messed up by evolution in the mass-temperature relation



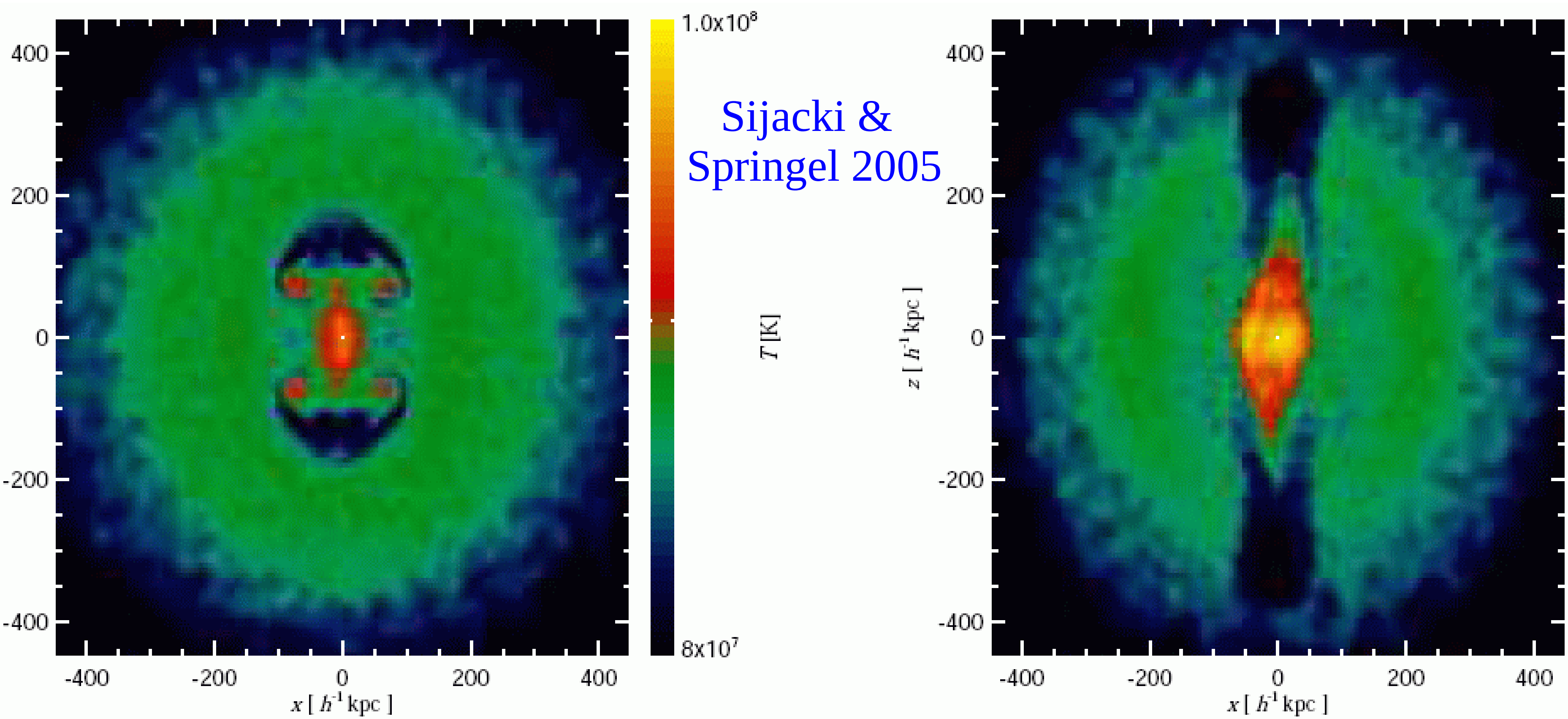
Hubble Volume Simulation

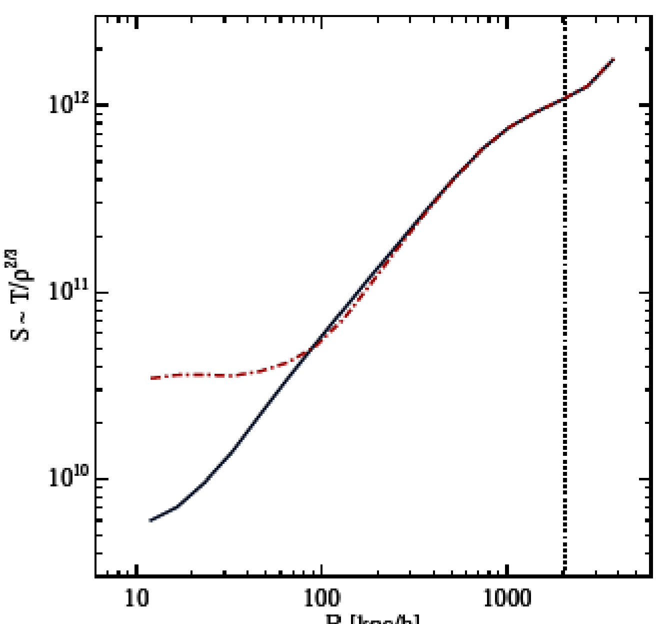
At z=1 the power spectrum of the cluster distribution shows baryon wiggles in a distorted form

These also show up in the autocorrelation function



Angulo et al 2005

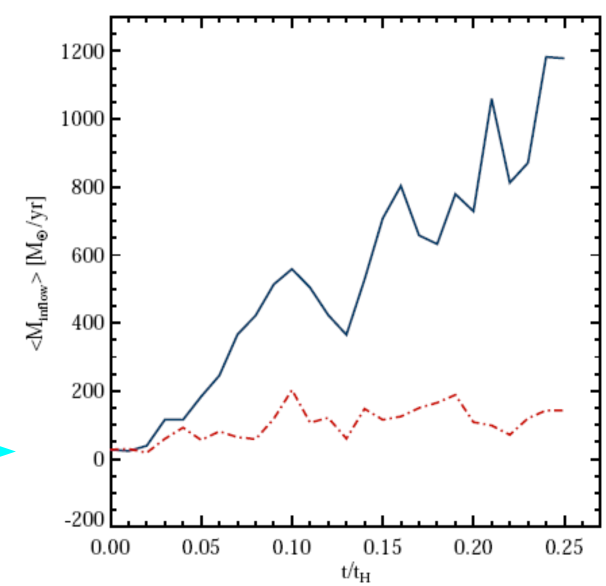




Radio bubble heating can

produce an entropy floor

stabilise cooling rate



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, galactic winds and AGN
  → reionisation and enrichment of the intergalactic medium
  regulation of star formation within galaxies
- Merging of galaxies
  → starbursts
  morphological transformation : disks → spheroids

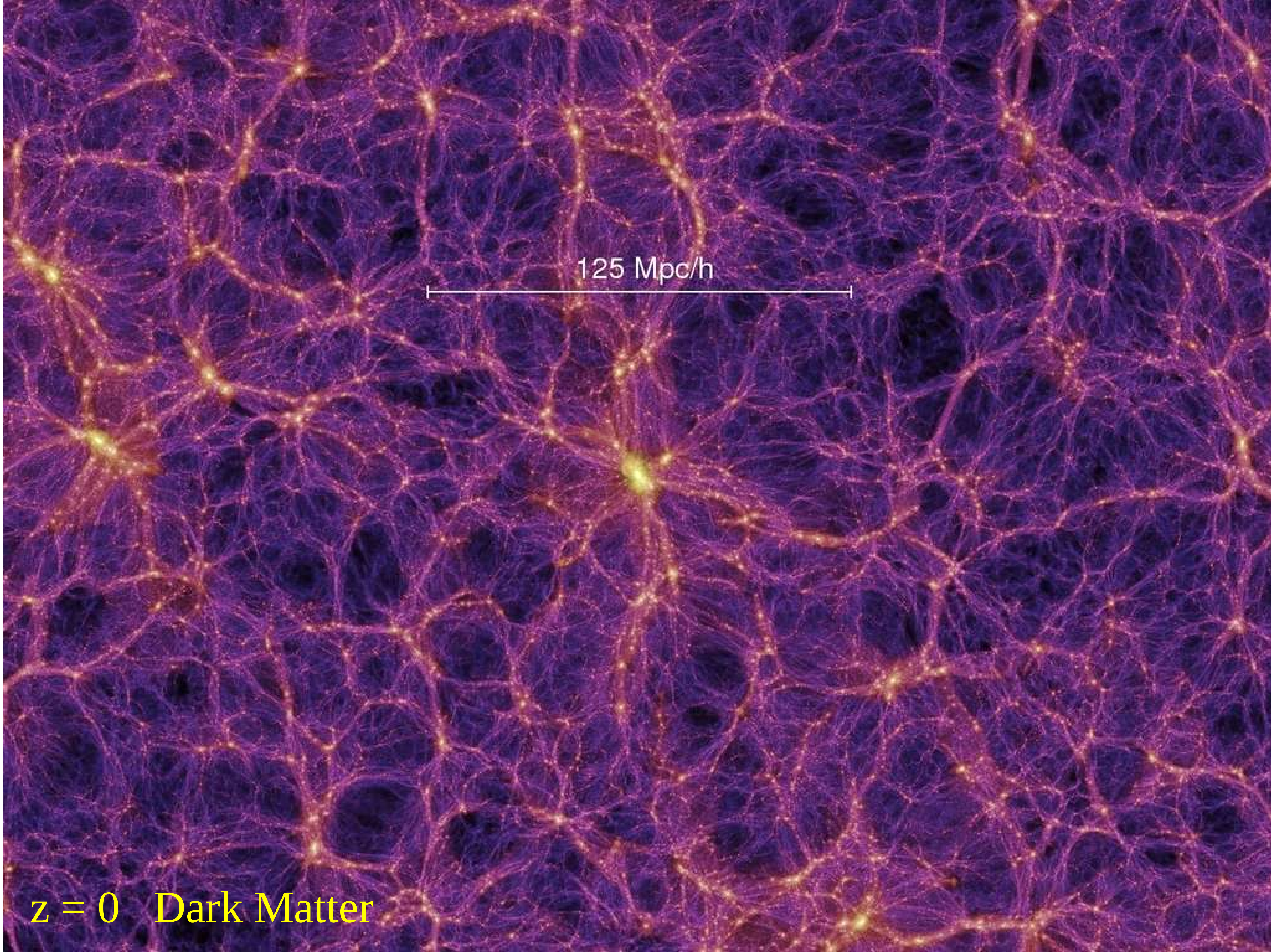
Environmental/cluster processes

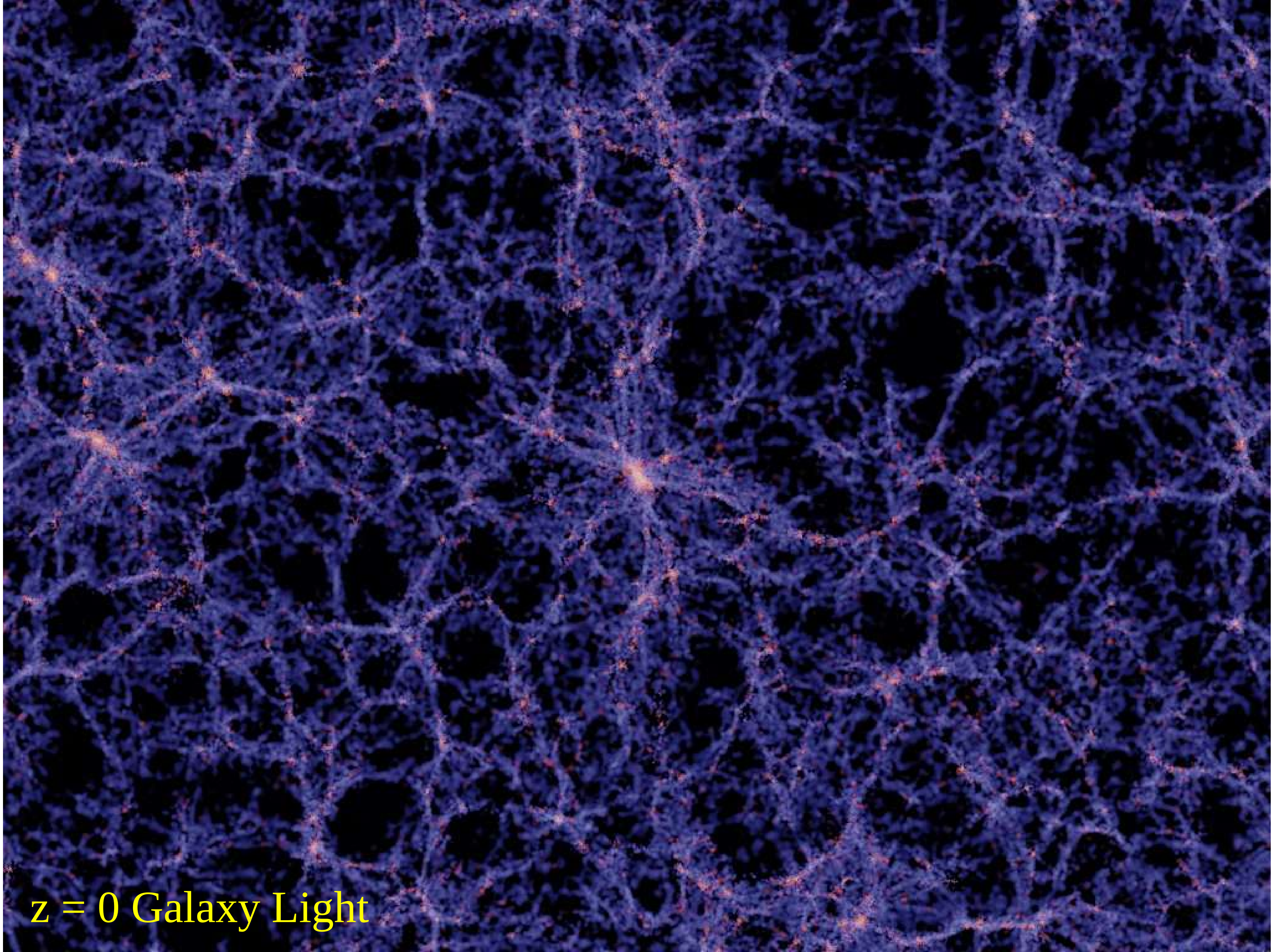
Included in standard SA simulations

- Formation bias
- Merging
- “Strangulation”
- “Cannibalism”
- Cooling flow accretion

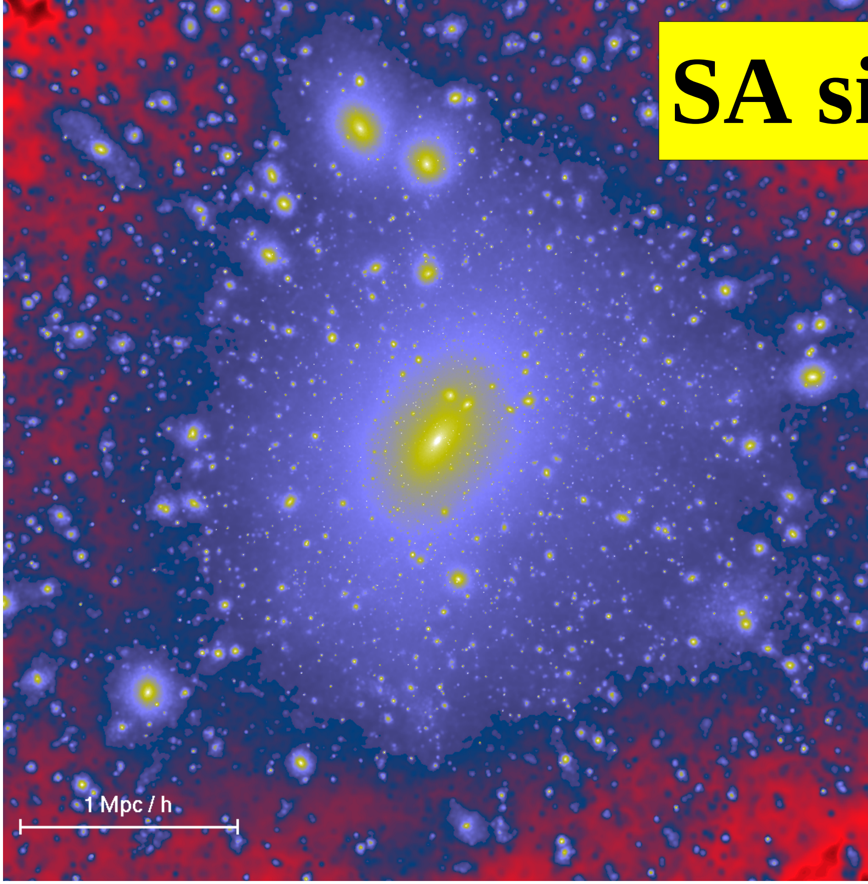
Not yet included in standard SA simulations

- “Harrassment”
- Tidal stripping/ICL formation
- Ram pressure stripping
- Evaporative stripping
- Pressure induced starbursts


125 Mpc/h
z = 0 Dark Matter

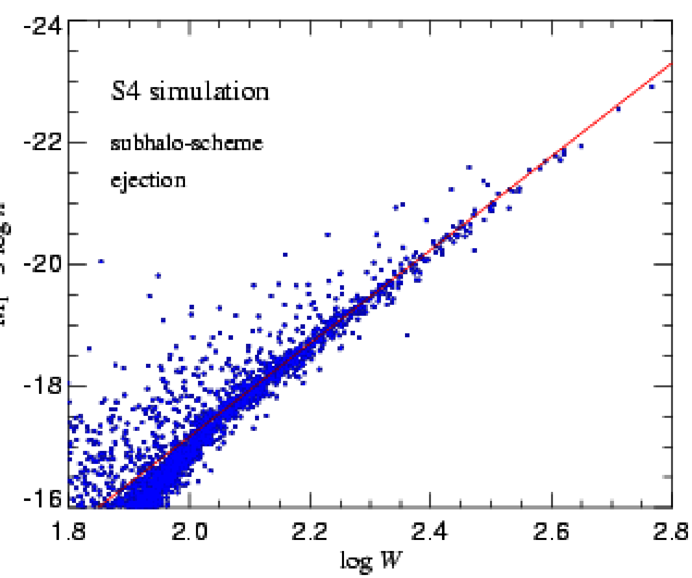

z = 0 Galaxy Light

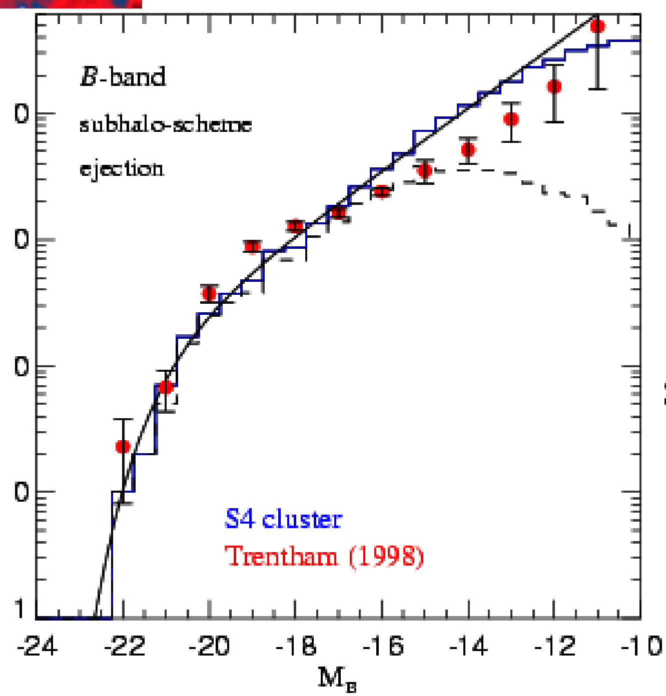
SA simulation of cluster formation

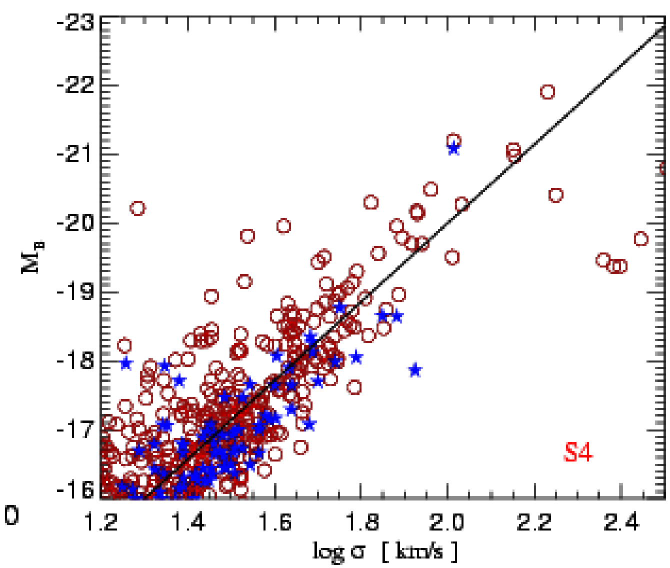


- Semi-analytic methods allow the simulation of a Coma cluster following all galaxies with $M_B < -12$
- Nearly all galaxies with $M_B < -16$ retain their own dark halos
- Protocluster can be analysed at high z

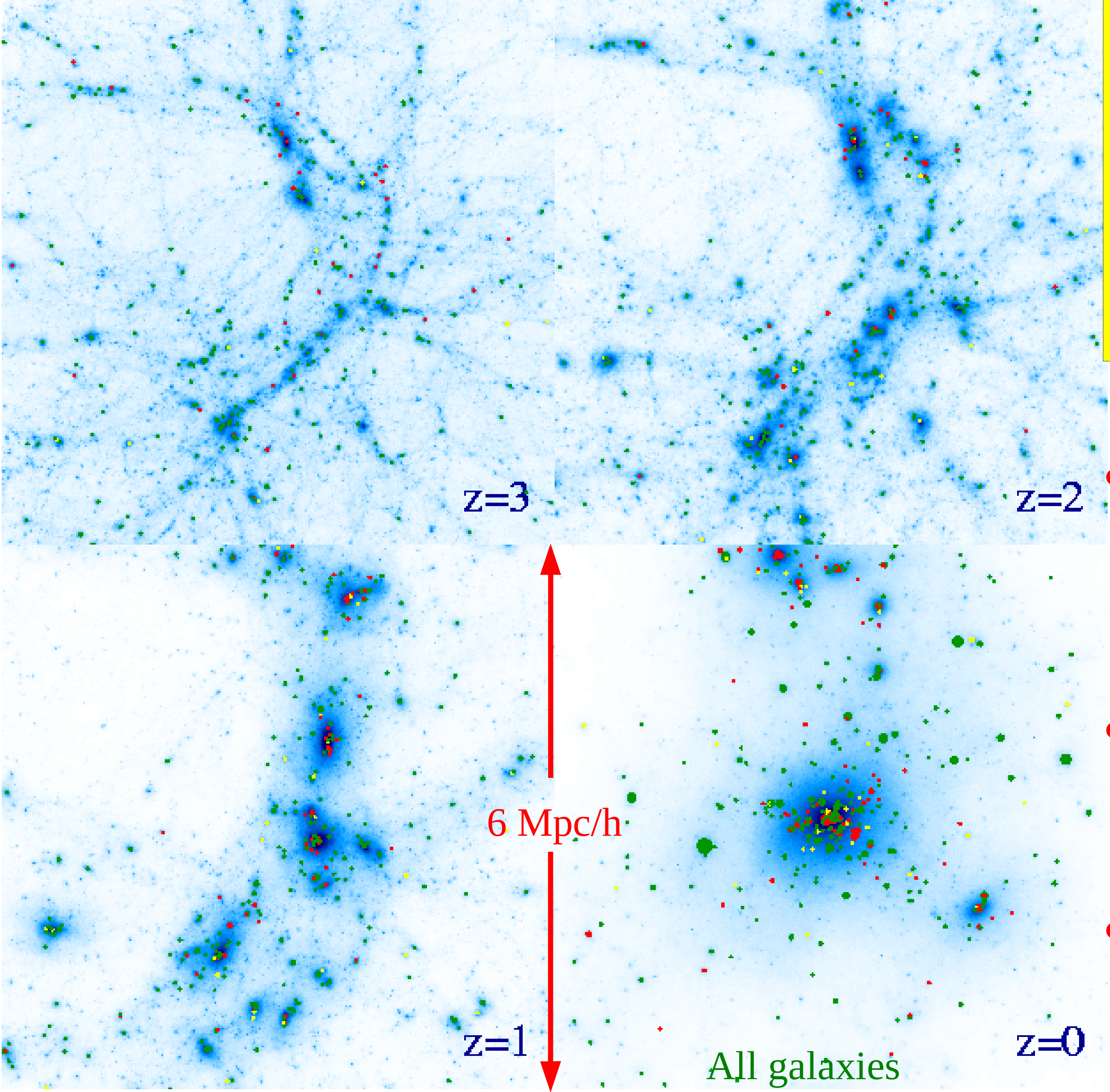
Springel et al 2001







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 model-dependent
- Positions and velocities are followed well

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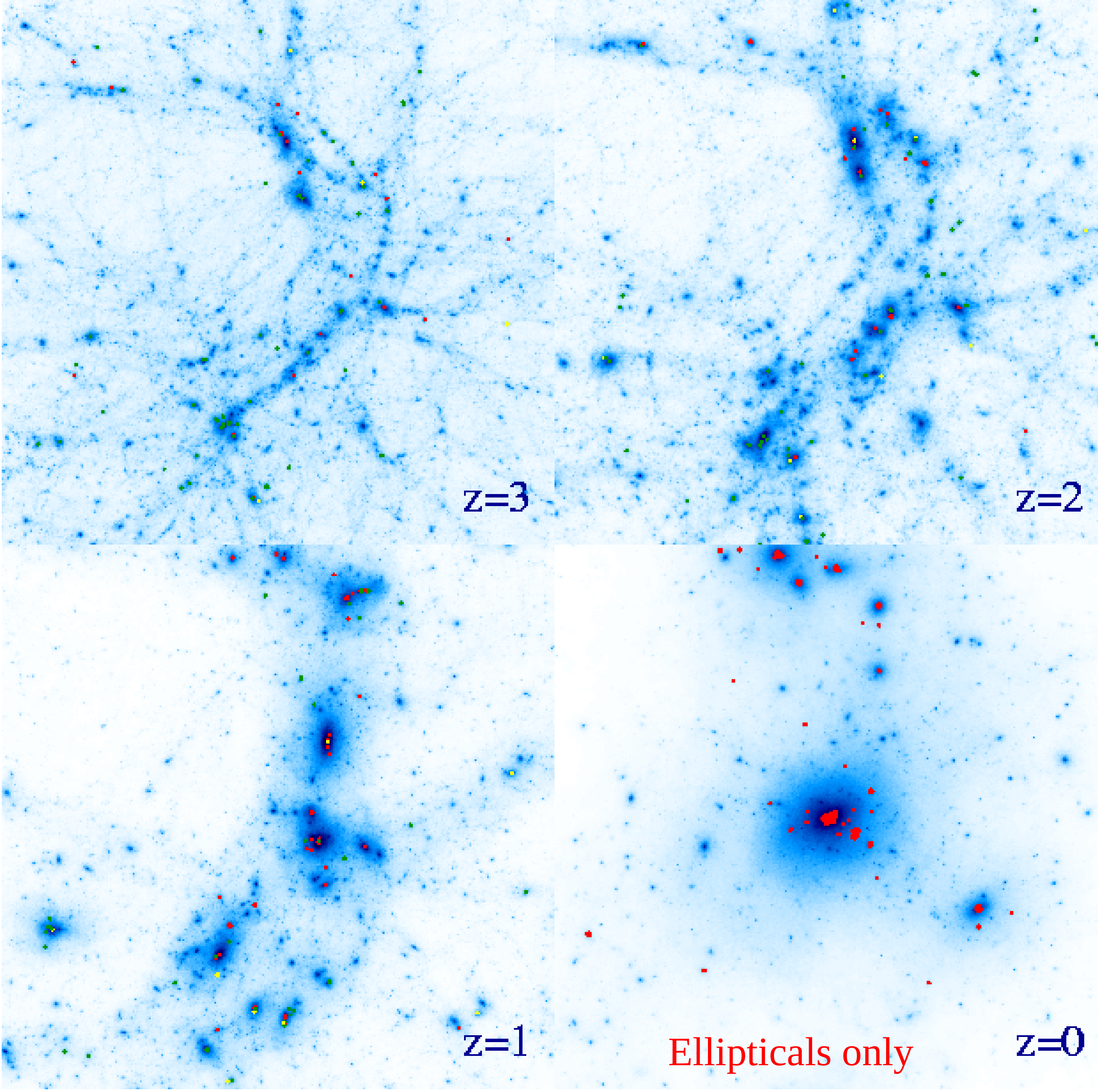

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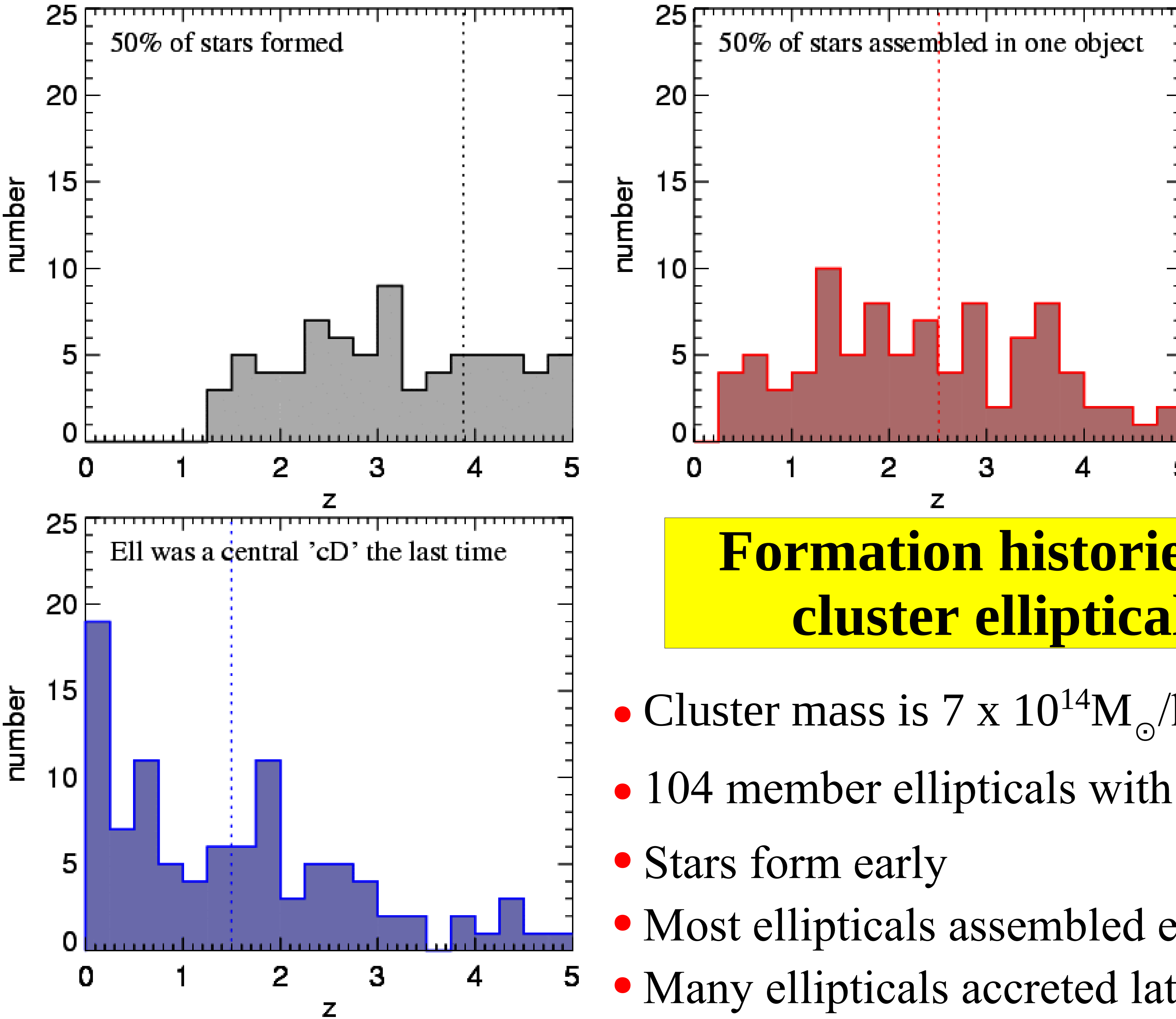
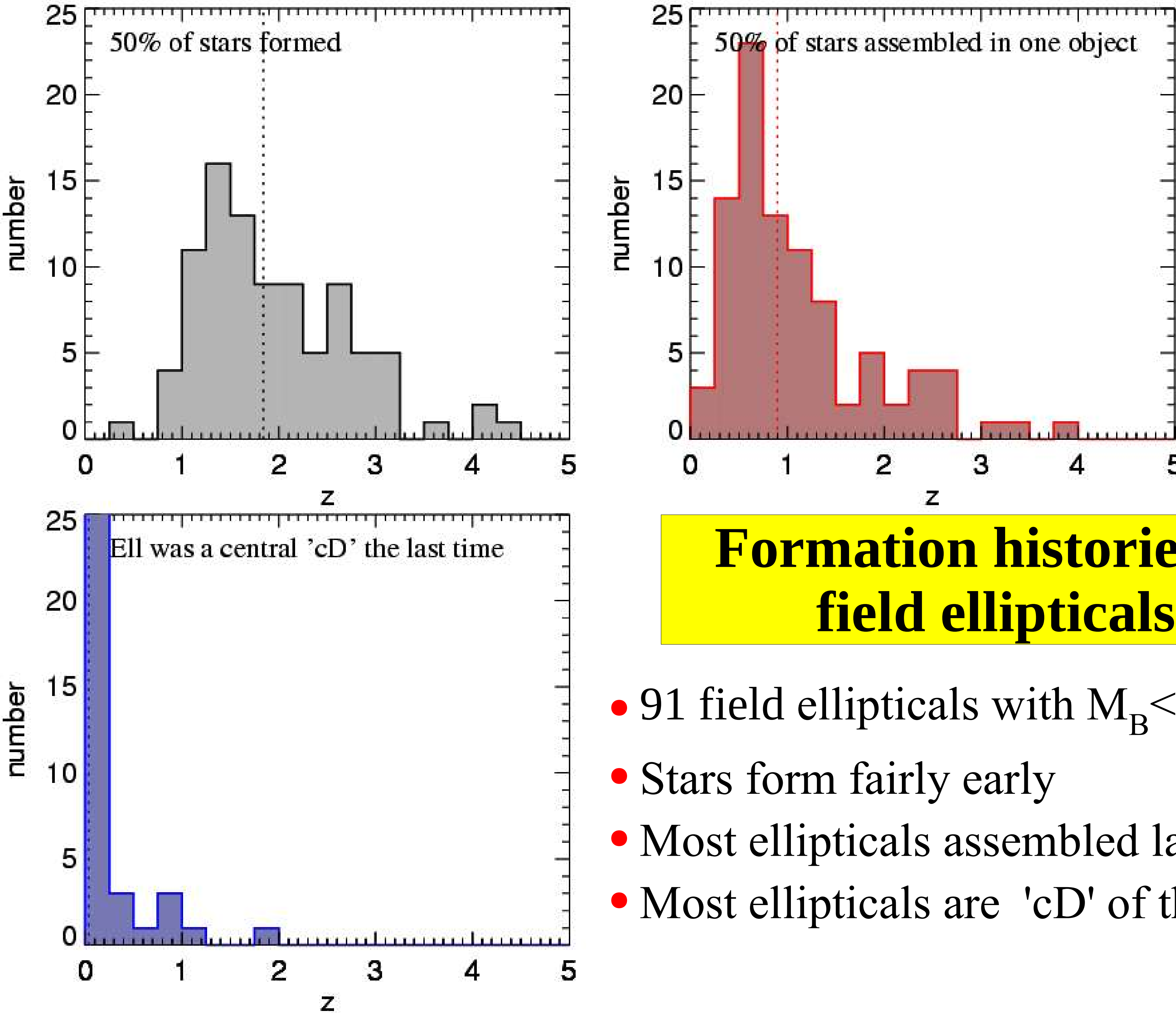


Springel et al 2001

Formation histories of cluster ellipticals

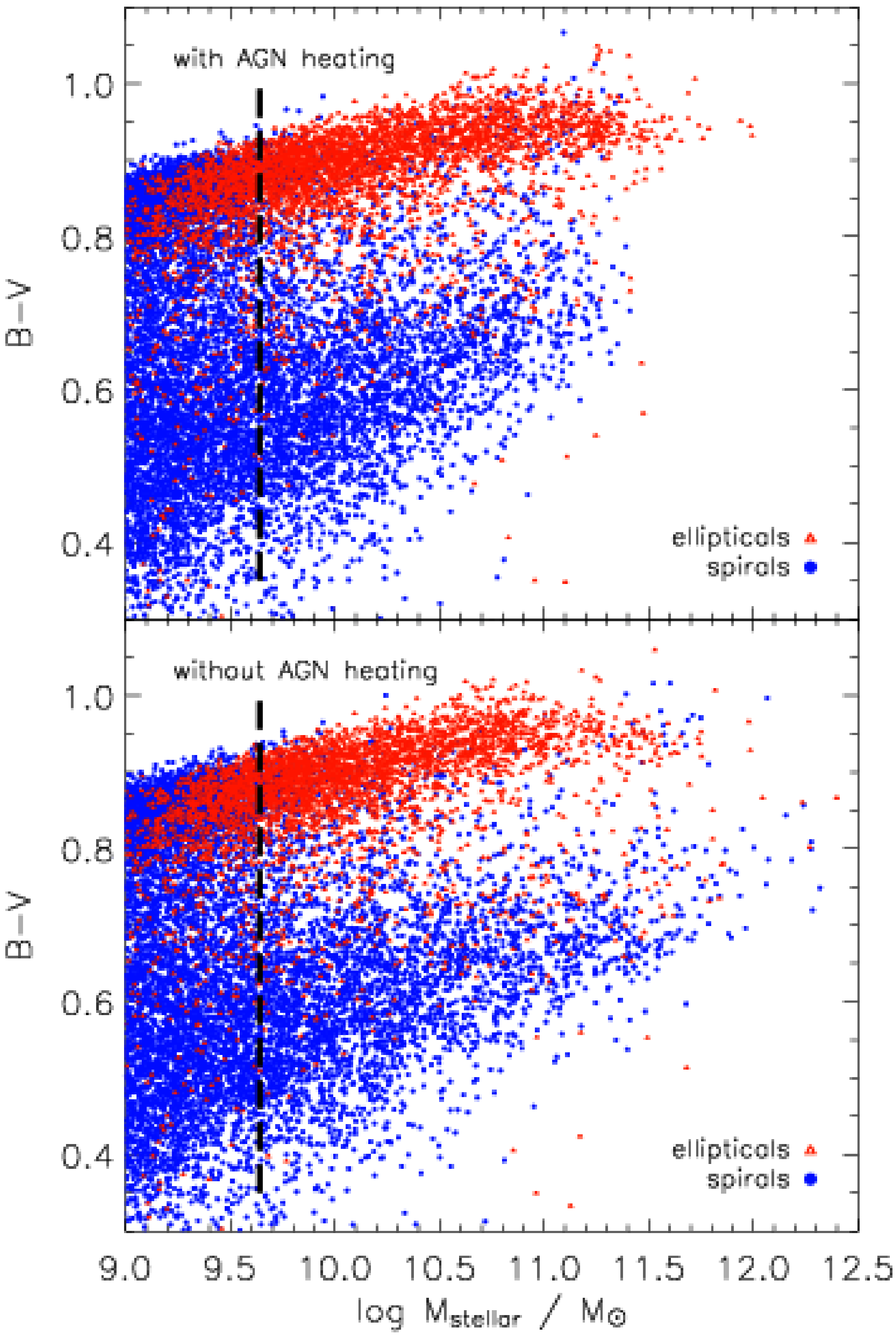
- Cluster mass is 7 x $10^{14} M_{\odot}/h$
- 104 member ellipticals with $M_B < -18$
- Stars form early
- Most ellipticals assembled early
- Many ellipticals accreted late



Springel et al 2001

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

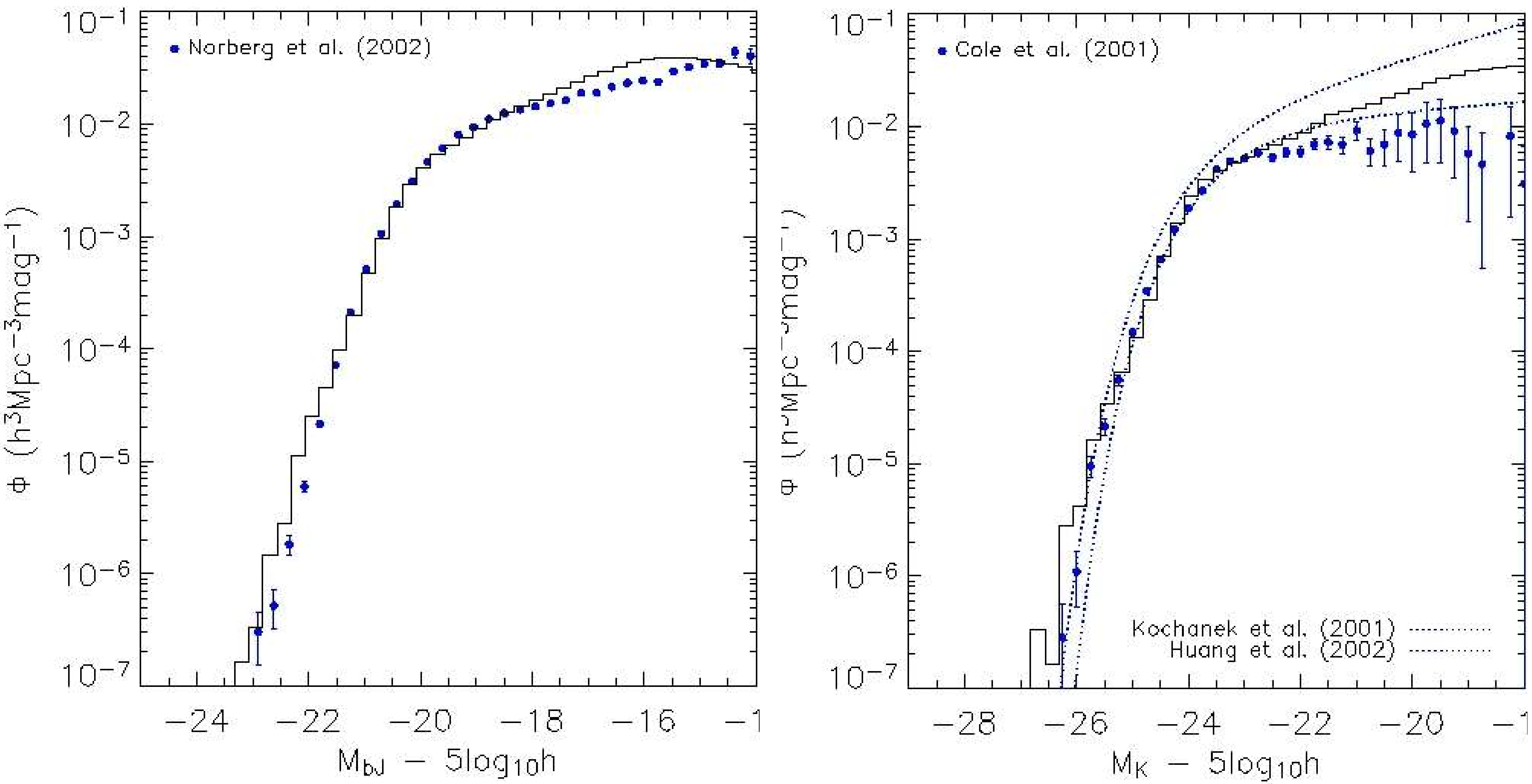


The effects of "radio mode" feedback on z=0 galaxies

Croton et al 2005

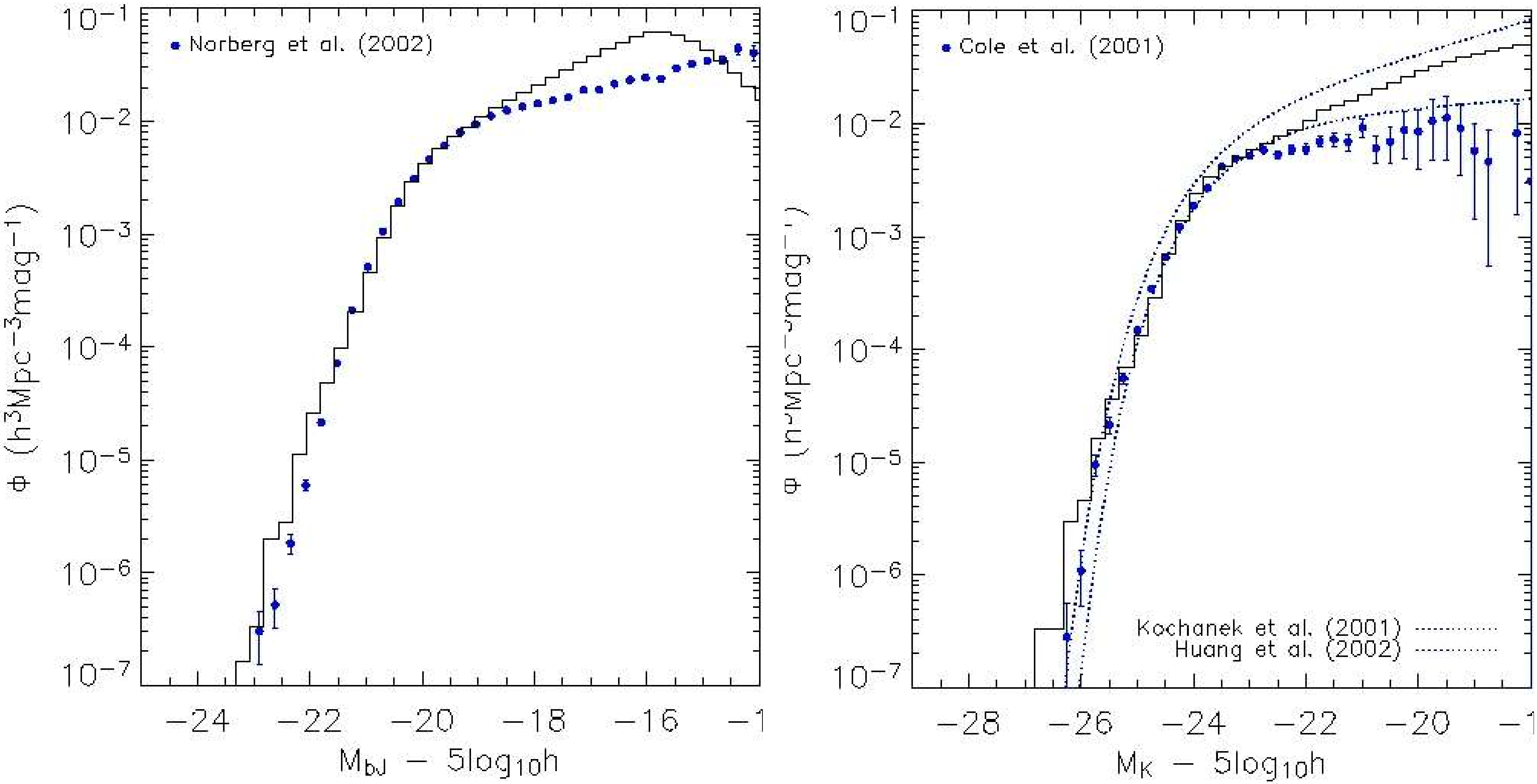
- In the absence of a "cure" for the cooling flow problem, the most massive galaxies are:
  - too bright
  - too blue
  - disk-dominated
- With cooling flows suppressed by "radio AGN" these galaxies are
  - less massive
  - red
  - elliptical

Effect of feedback on the Luminosity Function



Full model with reionisation, AGN and SN feedback Croton et al 2005

Effect of feedback on the Luminosity Function



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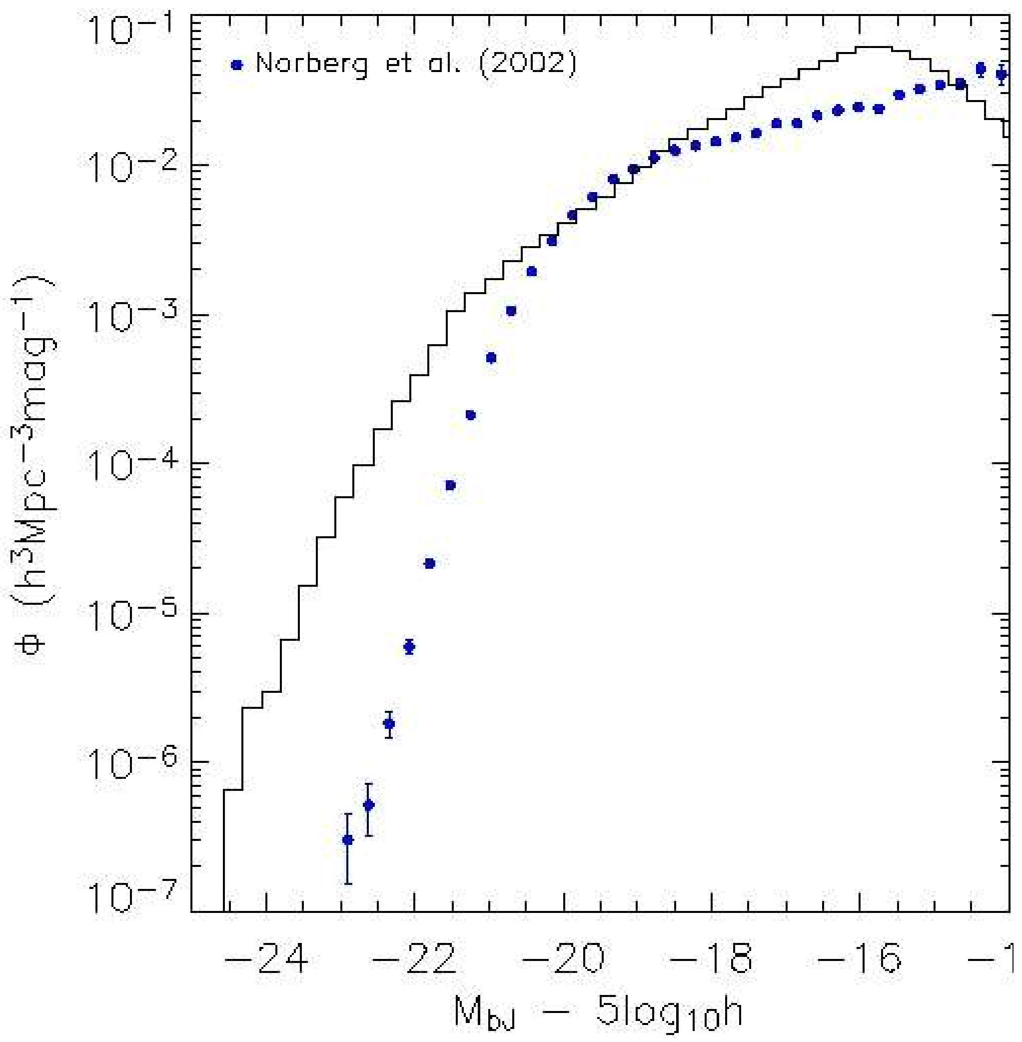

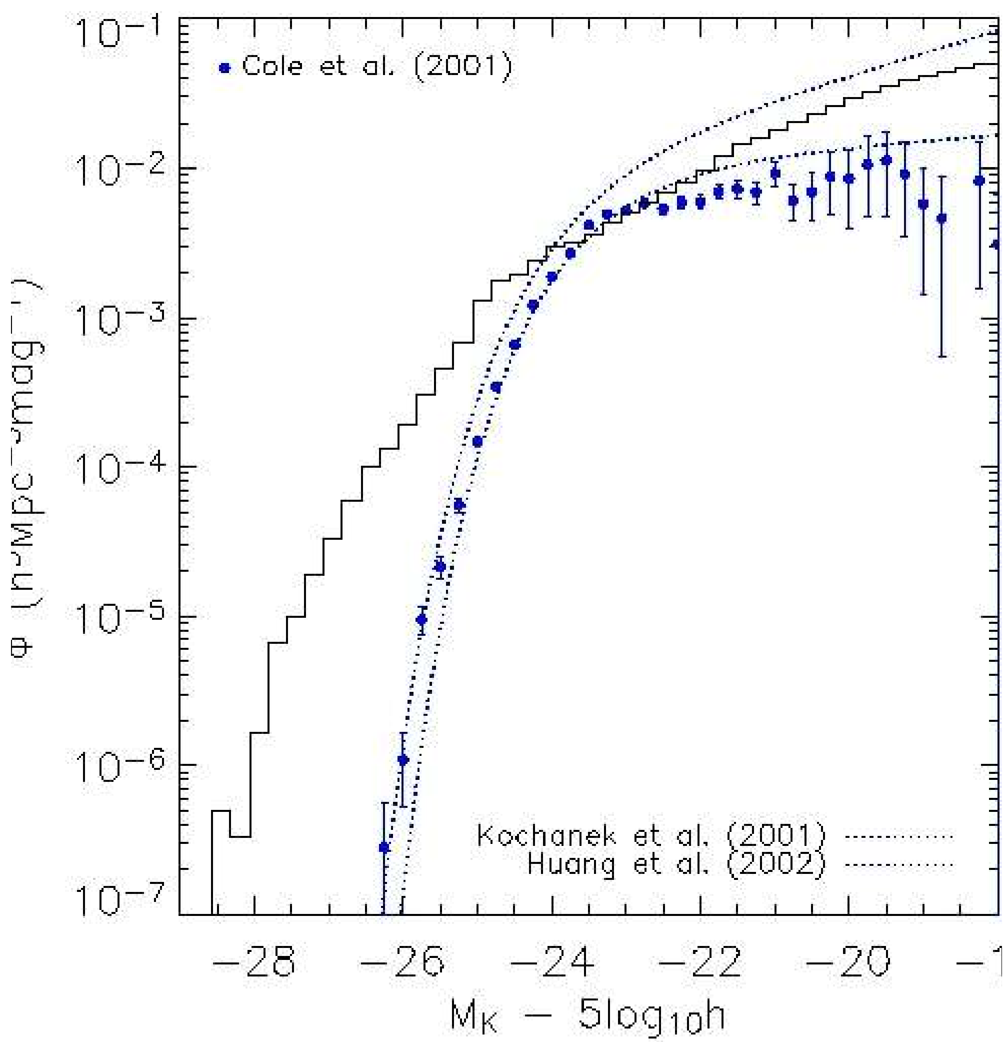

Full model with ~~reionisation~~, ~~AGN~~ and SN feedback Croton et al 2005

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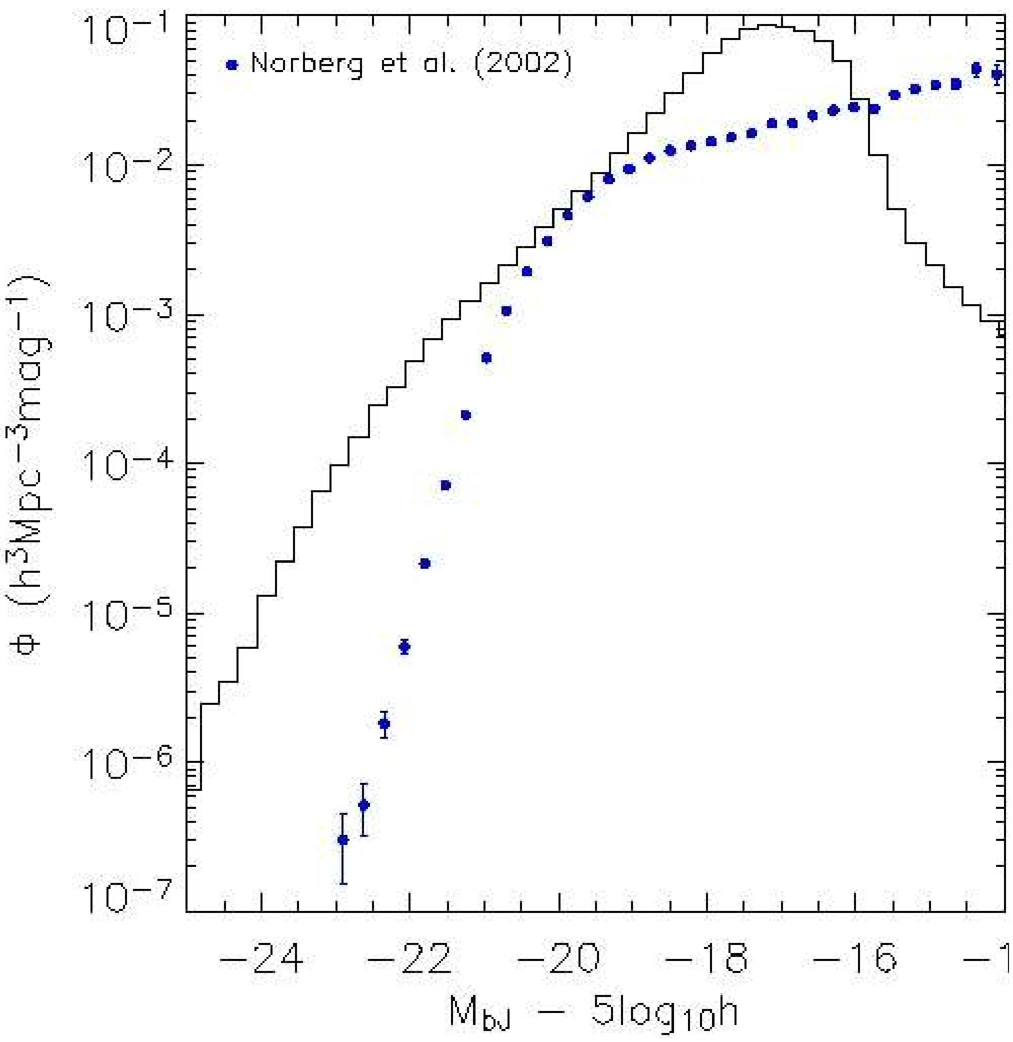

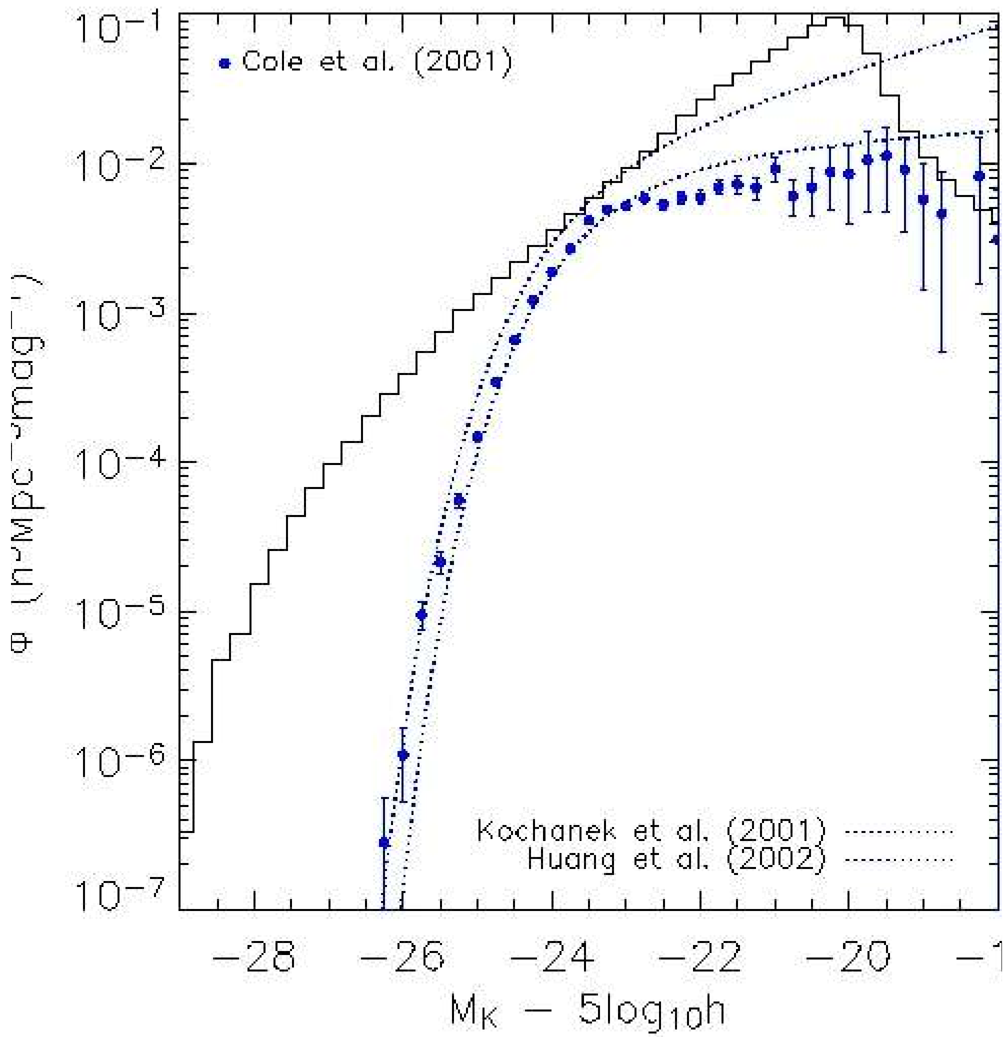

Full model with ~~reionisation~~, ~~AGN~~ and ~~SN~~ feedback   Croton et al 2005

EDisCS Participants

Co-I Team on Proposal 166.A-0162

A. Aragon (Nottingham, UK)
R. Bender (Munich, D)
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M. Bremer (Bristol, UK)
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D. Clowe (Bonn, D)
J. Dalcanton (Seattle, US)
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P. Jablonka (Meudon, F)
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R. Pello (Toulouse, F)
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H. Rottgering (Leiden, NL)
P. Schneider (Bonn, D)
S. White (MPA, D) **P.I.**
D. Zaritsky (Tucson, US)

Additional participants

M. Dantel (Meudon, F)
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C. Halliday (Padova, I)
B. Milvang-Jensen (MPE, D)*
S. Poirier (Meudon, F)*
G. Rudnick (MPA, D)
R. Saglia (MPE, D)
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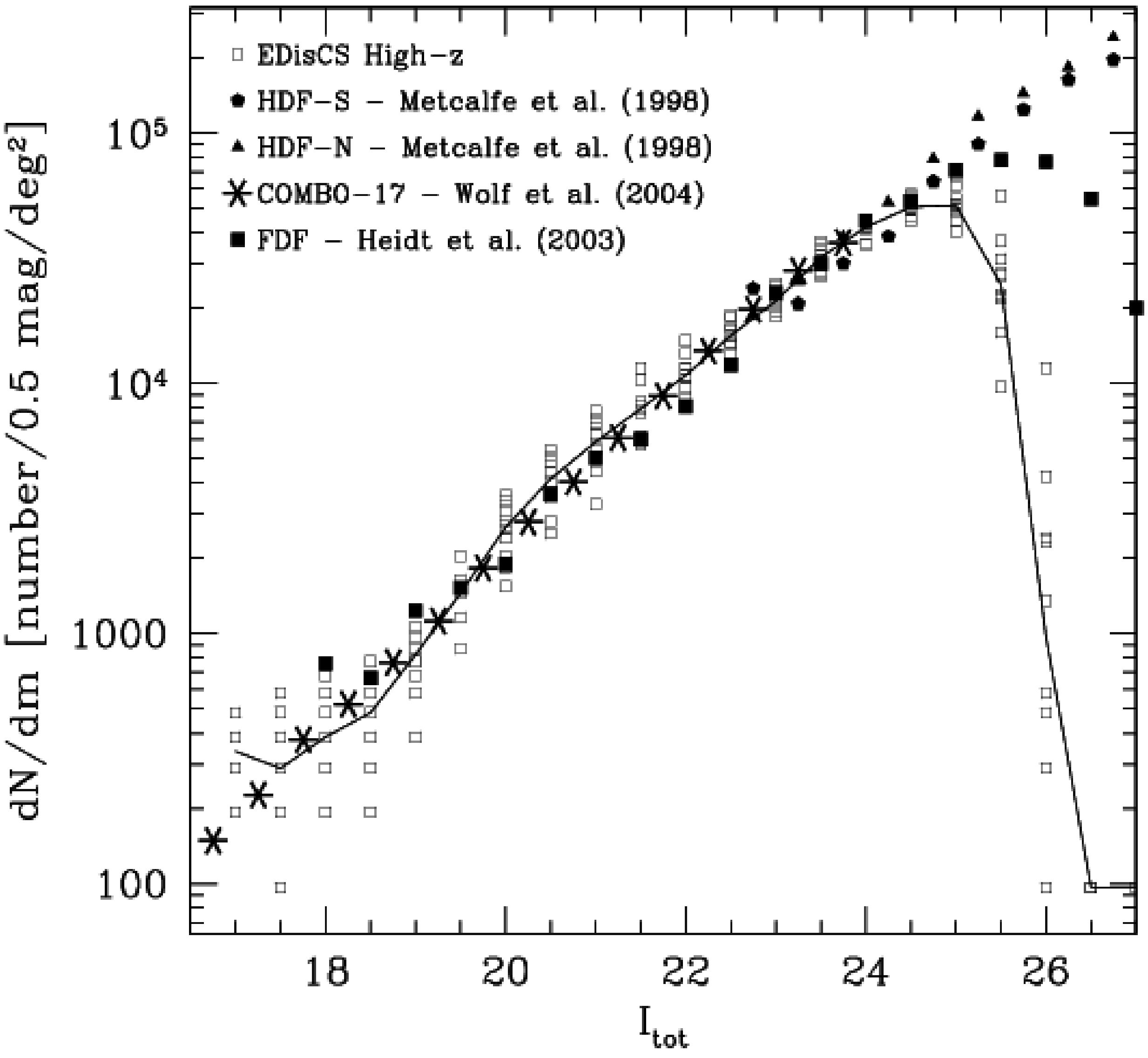
A. von der Linden (MPA, D)*

* =PhD stud.

The EDisCS Strategy

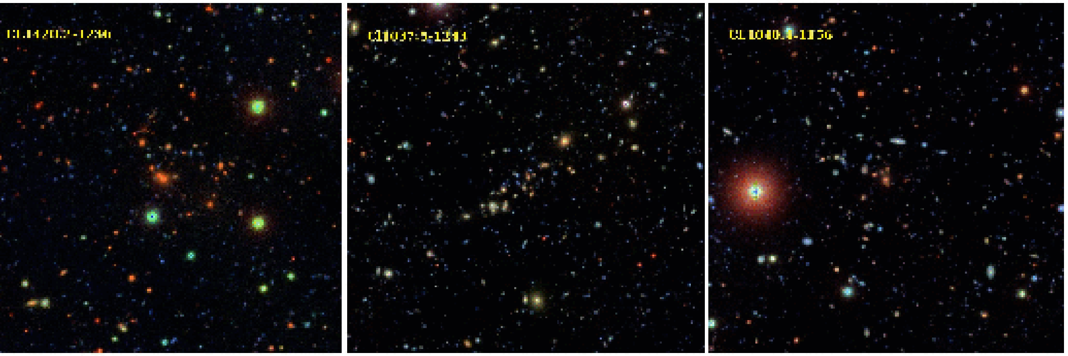
- Select 15 bright candidates with $z_{est} \sim 0.5$ and 15 with $z_{est} \sim 0.8$ from the Las Campanas Distant Cluster Survey (130 deg^2)
- Image each field in 2 bands for 20min with FORS2 (3 FORS nights)
- Select 10+10 best cluster fields for deep imaging: VRIJK at $z \sim 0.8$, BVIK at $z \sim 0.5$ (11 FORS + 20 SOFI nights)
- 30min exposure of one FORS2 mask of each field to confirm reality of cluster (1.5 FORS nights)
- 3 or 4 FORS2 masks of each confirmed field at longer exposure to get spectra of representative systems to I=23 (20.5 FORS nights)
- HST/ACS imaging of 10 most distant fields (80 orbits)
- WFI 3-colour imaging of all 20 fields to study large-scale environment of clusters (84 hours of WFI imaging)

36(+ 3) nights on FORS2 + 20(+ 11) nights on NTT/SOFI

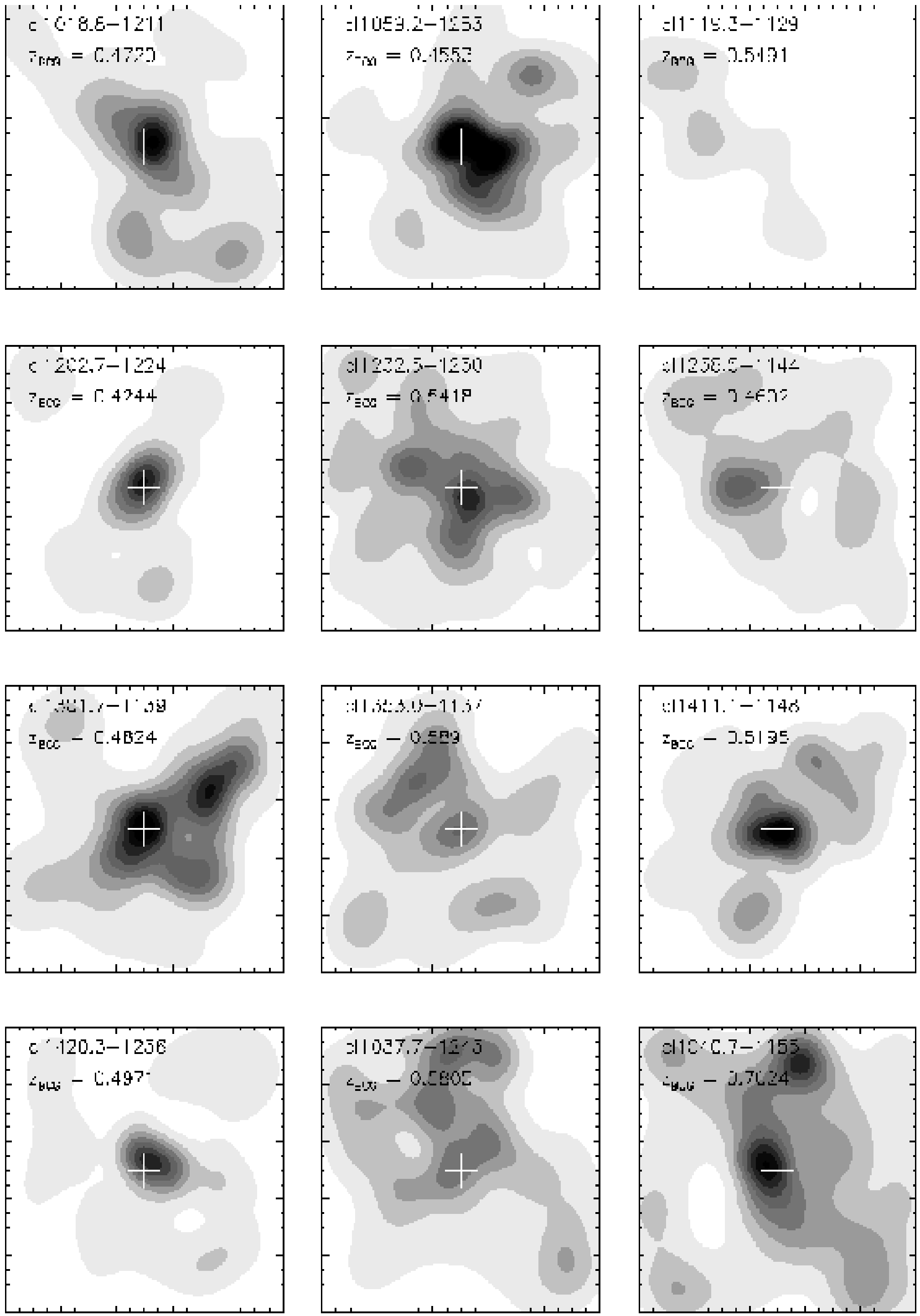


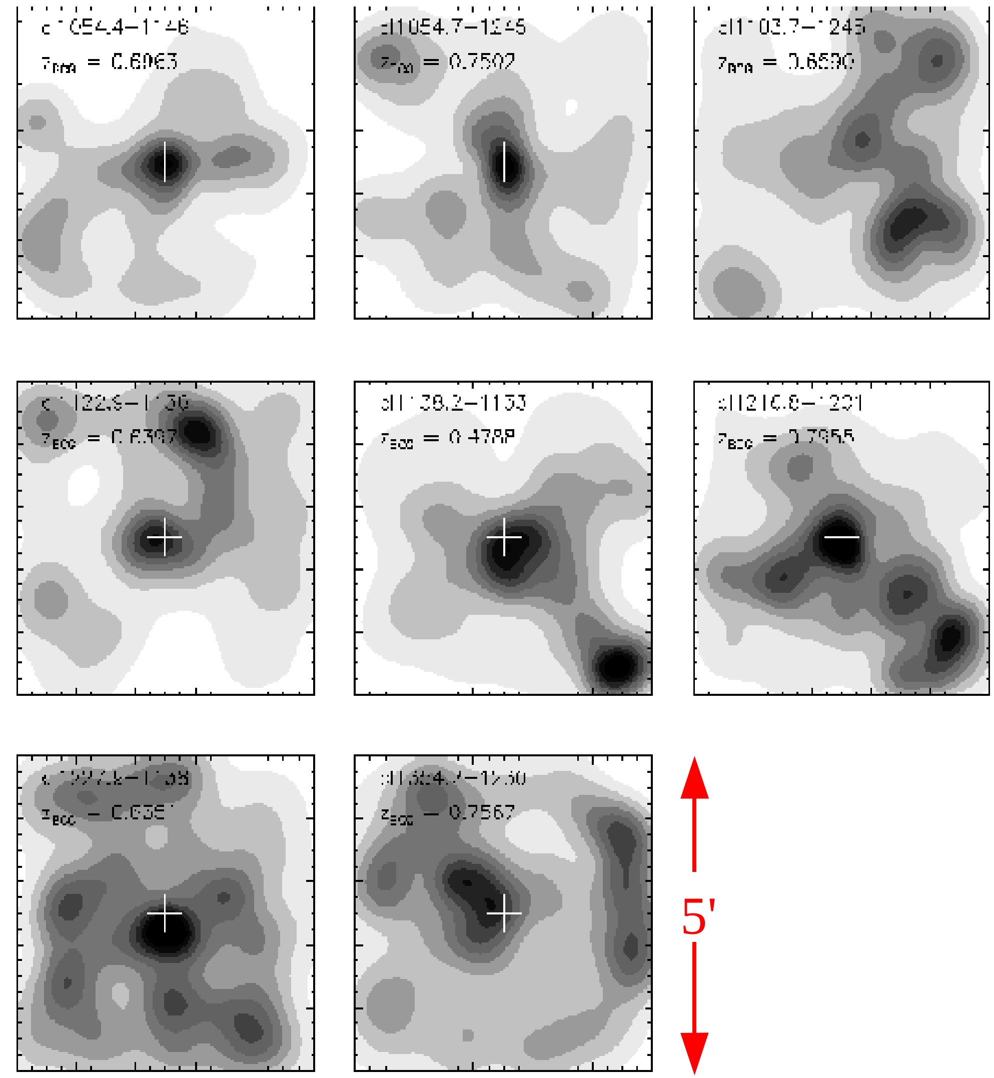
White et al 2004 A&A, subm.

EdisCS provides deep 4/5-band optical/OIR photometry over 0.15 square degrees with excellent image quality



The EdisCS sample contains a wide variety of clusters





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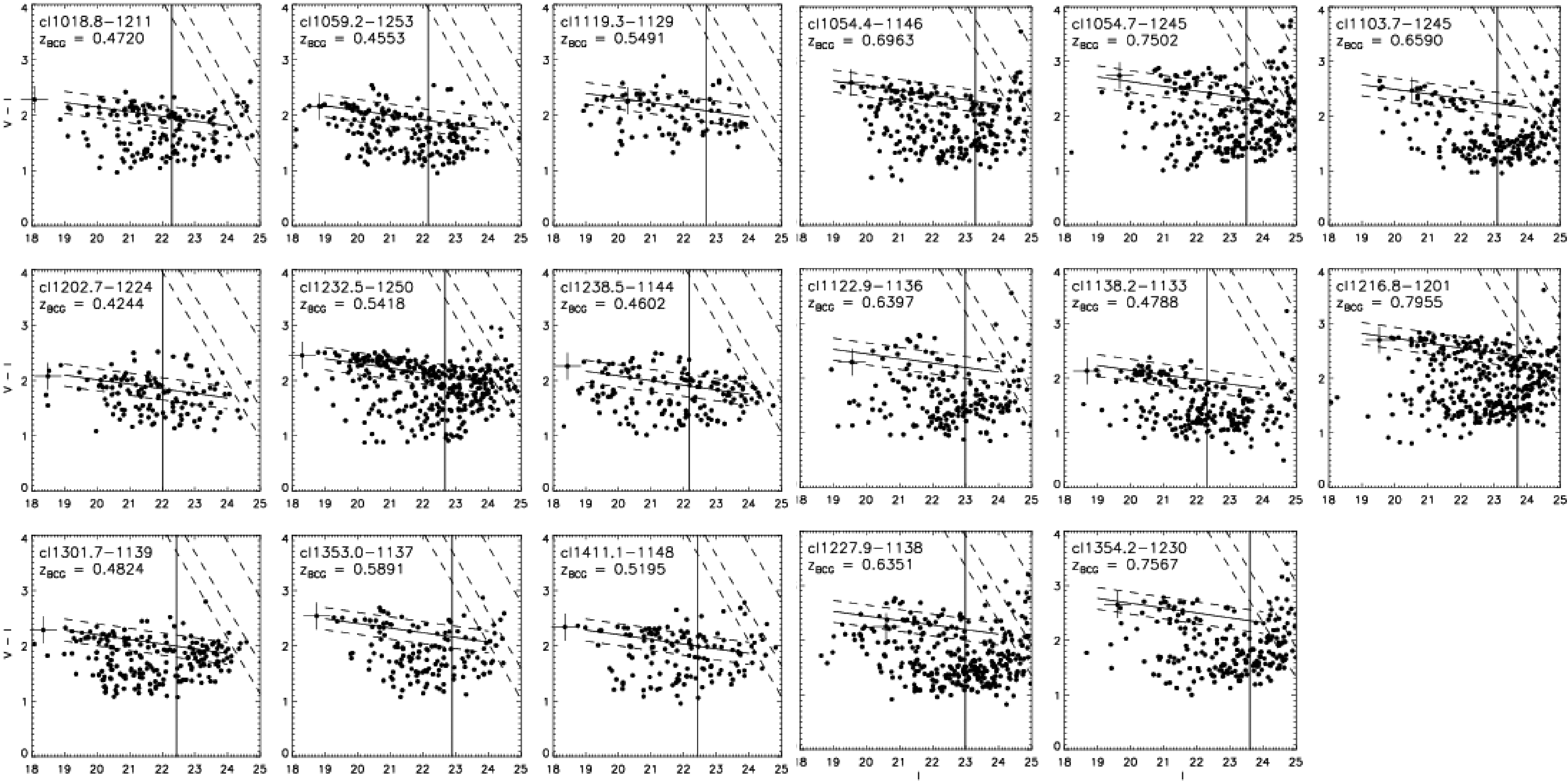
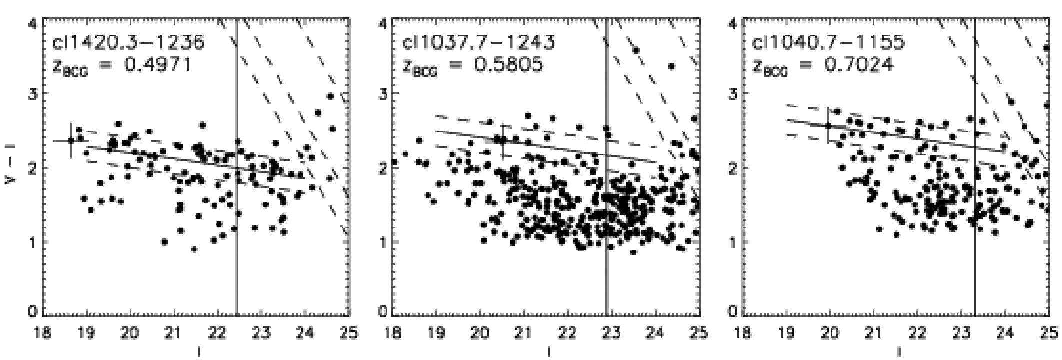
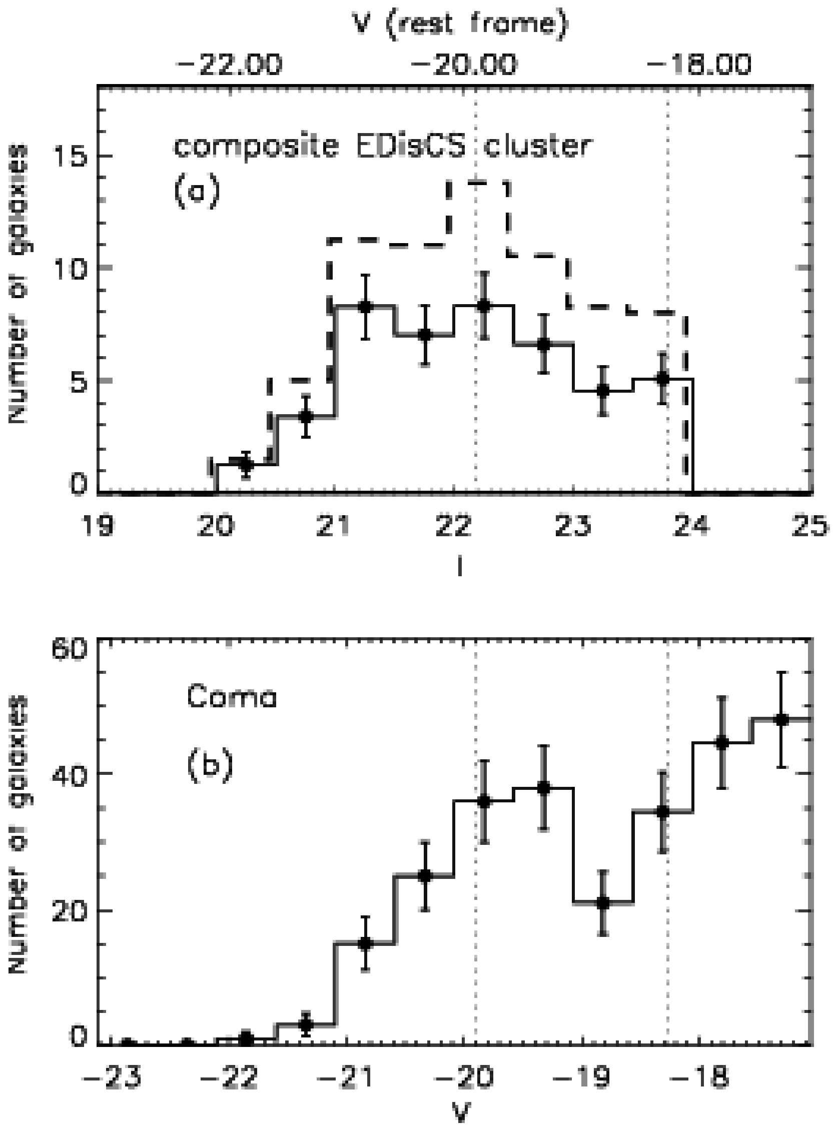
Structure after removal of photo-z non-members





V-I vs I CM diagrams after removal of photo-z non-members

Clusters have a range of richness and of blue galaxy fraction



Luminosity Function of 'passive' Galaxies

De Lucia et al 2004 ApJ Lett 610, L77

The ratio of luminous ($L/L^* > 0.4$) to faint ($0.4 > L/L^* > 0.1$) red-sequence galaxies is

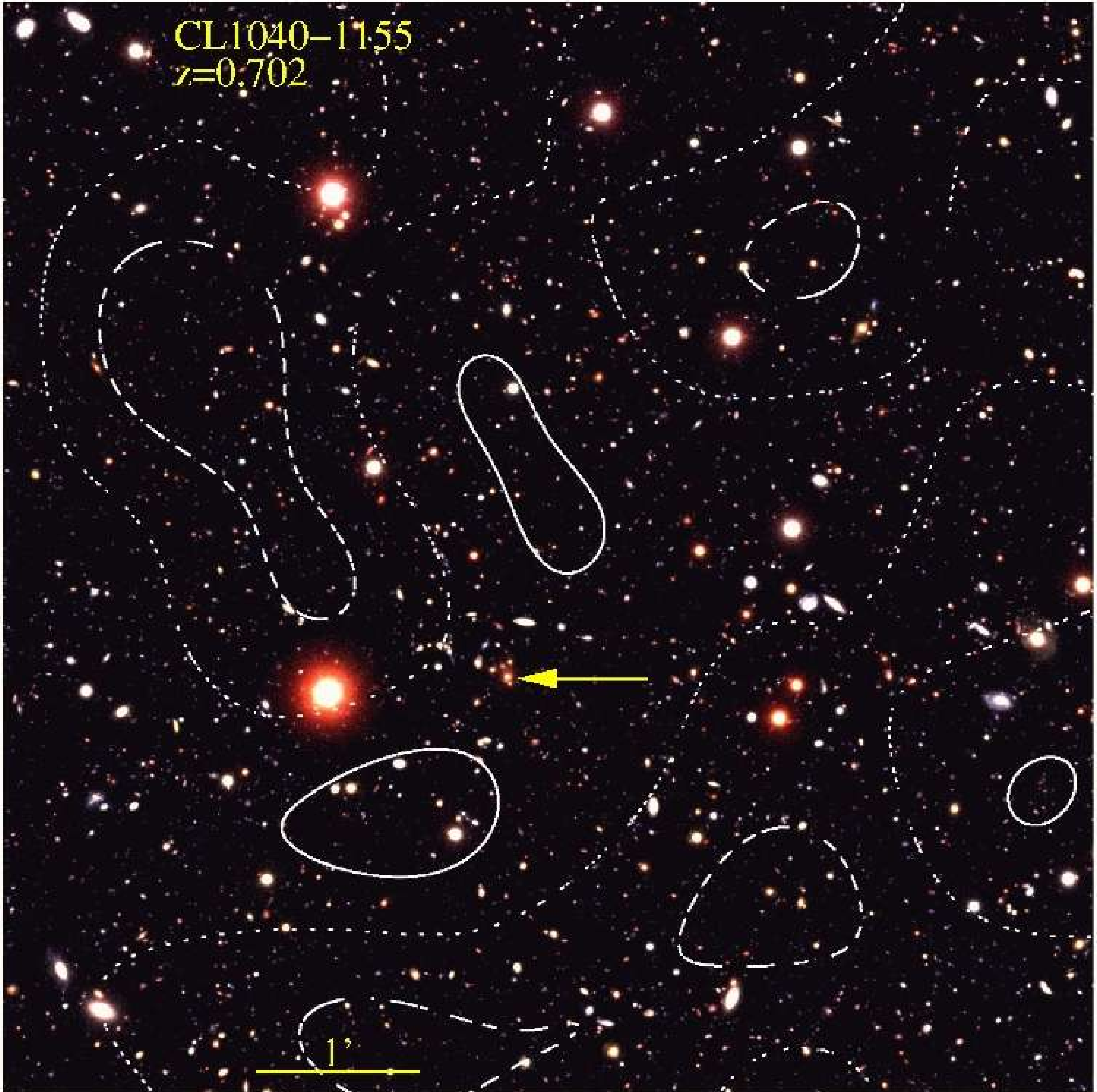
$$0.81 \pm 0.18$$

in 4 distant ($z \sim 0.75$) EDisCS clusters but is only

$$0.34 \pm 0.06$$

in the Coma cluster

Low mass galaxies evolve onto the passive red sequence later than high mass galaxies



Clowe, Halliday

High redshift but no detected lensing

σ_{clus}=453±41km/s

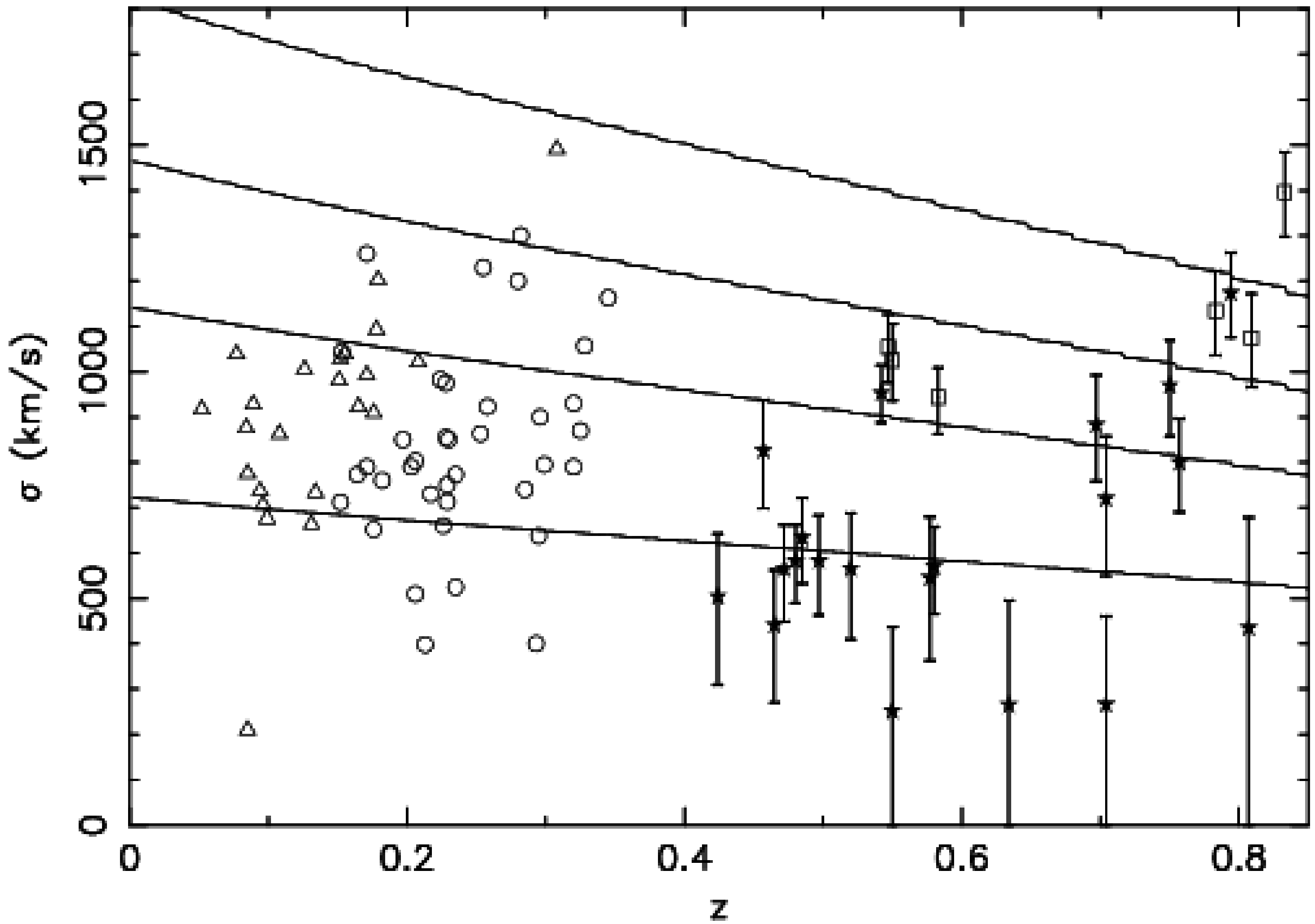
from measured redshifts

High redshift with strong lensing

σ_{clus}=1034±46

from measured redshifts

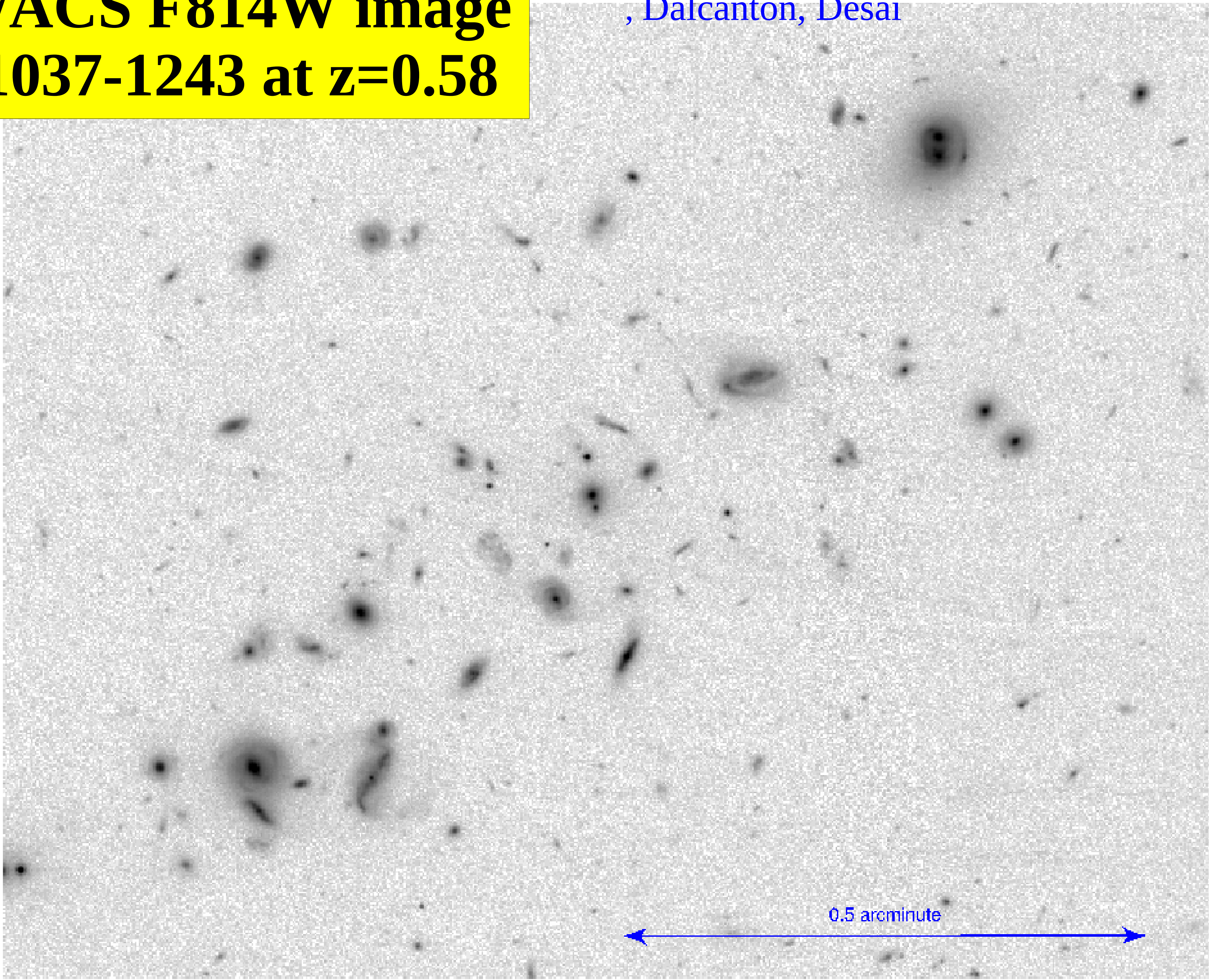
Lensing strength of EDisCS clusters vs redshift



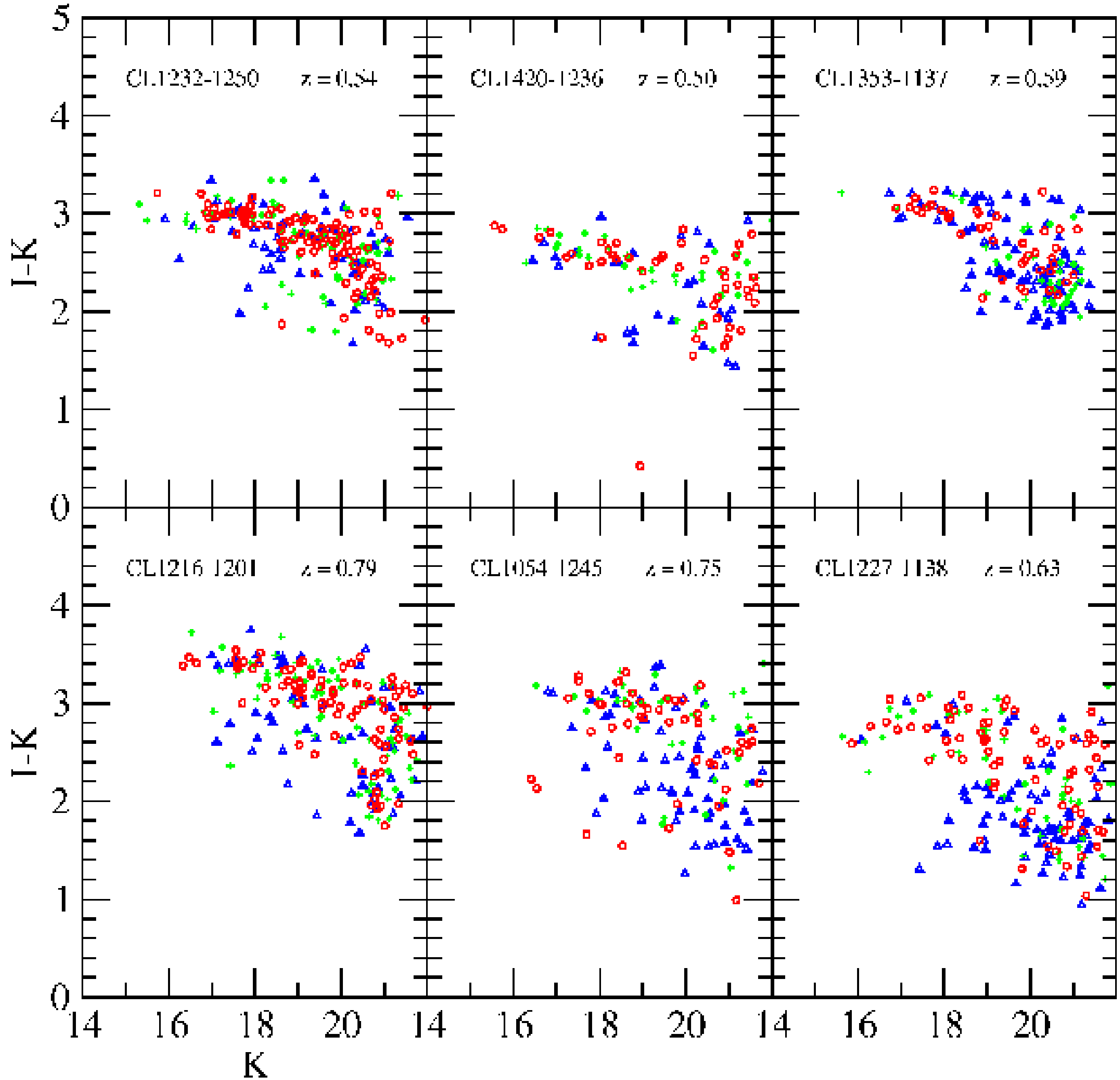
Clowe et al 2005
A&A, in press

HST/ACS F814W image of cl1037-1243 at z=0.58

, Dalcanton, Desai



Colour-Magnitude-Morphology Diagrams

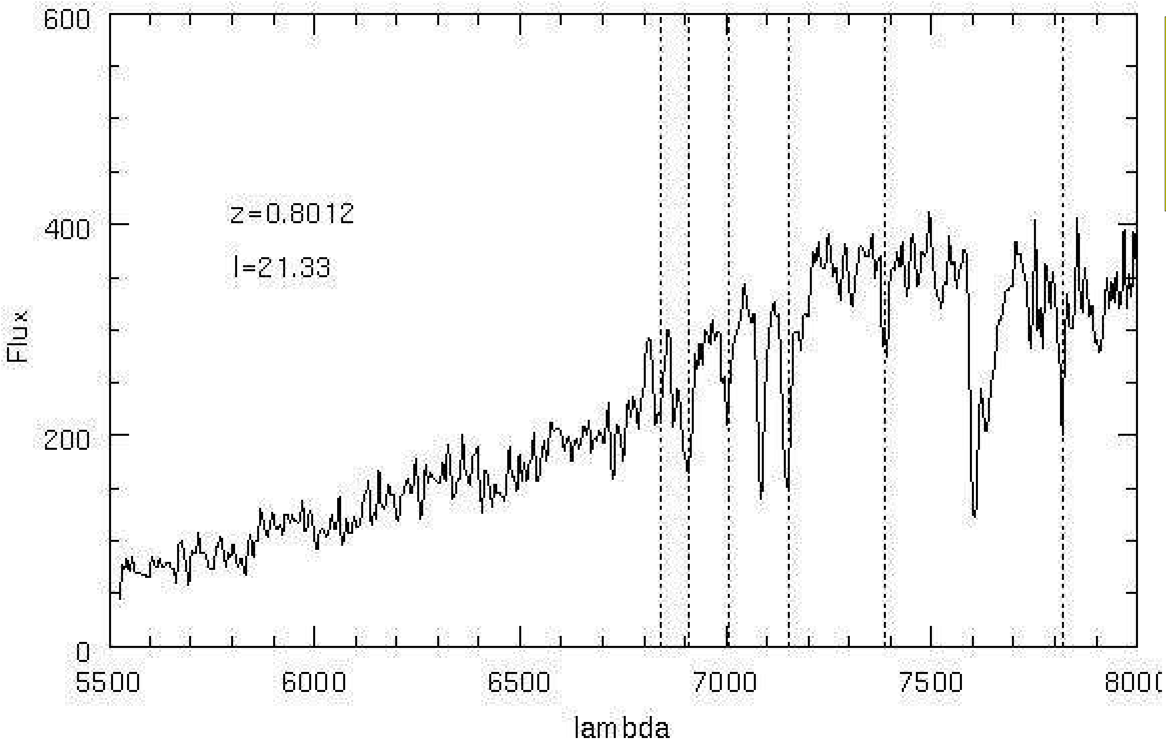


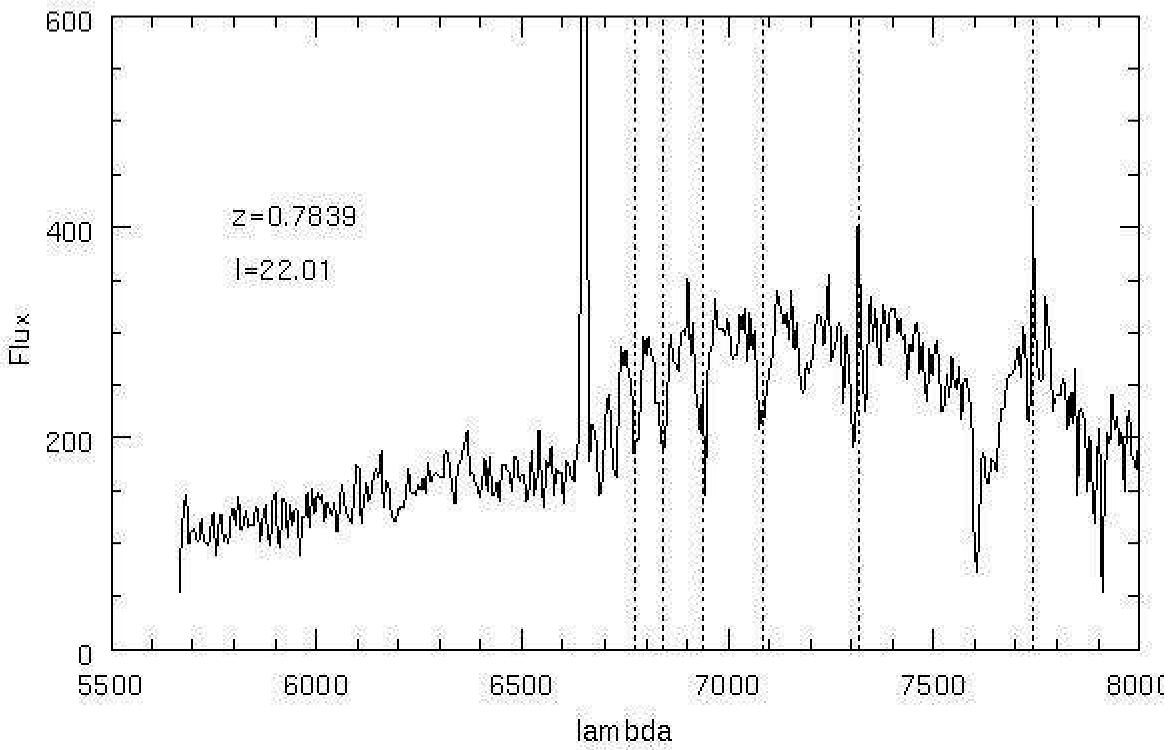
Simard

- Field corrected C-M diagrams for typical clusters
- 'Morphologies' are B/T values derived from the 2D image fitting code GIM2D
- Clusters show a wide range of richness
- Strength of red sequence and of blue 'B-O' population is variable
- Many disky galaxies on the red sequence

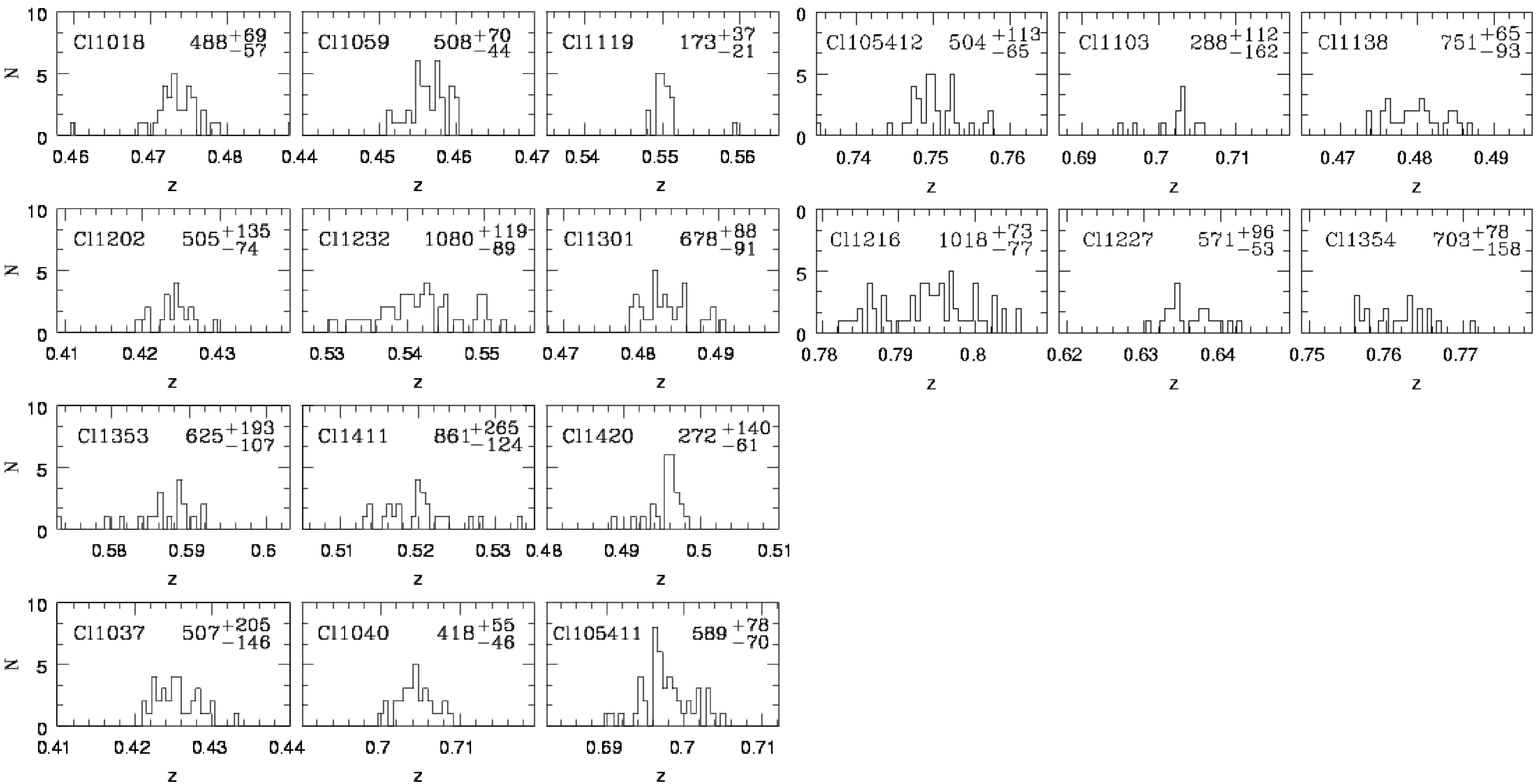
EDisCS Spectra

Halliday, Poggianti





- FORS2 spectra are of very high quality
- Redshifts can measured to I ~ 23
- Line indices can be measured to I ~ 22.5
- Velocity dispersions can be measured accurately to I ~ 21.5



Velocity dispersions vary from ~200 to ~1100 km/s

Halliday et al 2004 A&A 427, 397; Milvang-Jensen et al in prep.

Statistics for spectroscopy

Spectra	2077
Redshifts	~ 1900
Cluster members	~ 670
Line index measurements	~ 900
Velocity dispersions	~ 150
Rotation curves	~ 350

Accurate line indices for fainter galaxies can be obtained by stacking spectra for similar systems