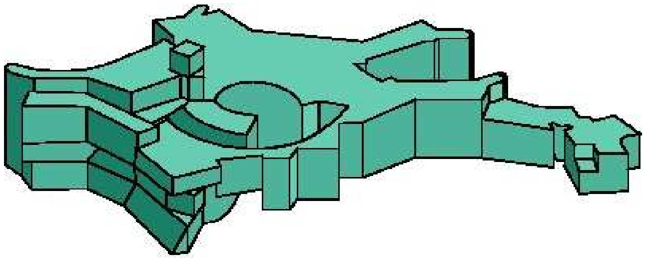
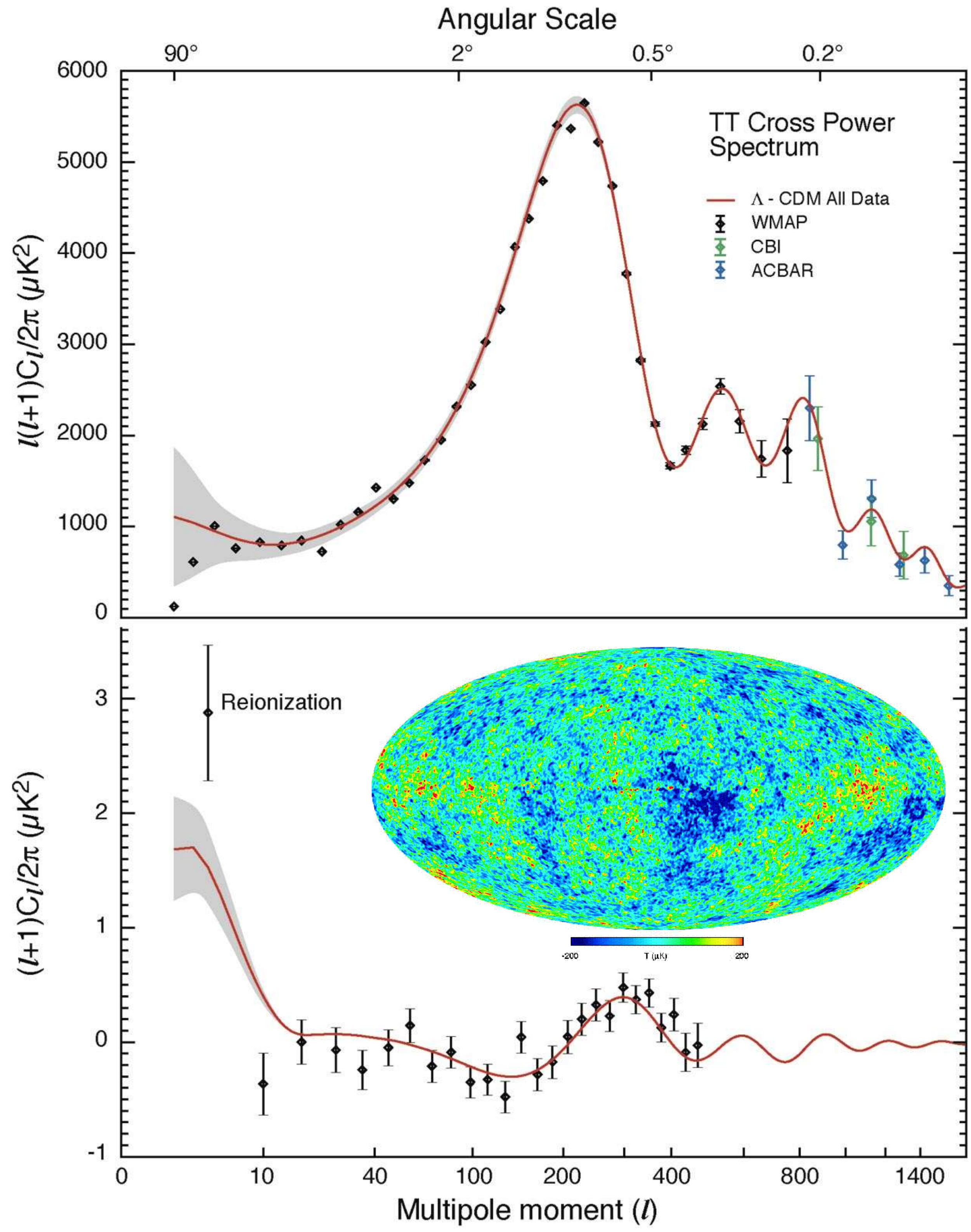


Venice, October 2003

# The Formation of Galaxies: connecting theory to data


*Simon D.M. White*

*Max Planck Institute for Astrophysics*




# The Emergence of the Cosmic Initial Conditions

- $> 10^5$ independent $\sim 5\ \sigma$ measurements of T are fit by an *a priori* model with 6 (physical) parameters

- Best flat $\Lambda$CDM model has:

(Bennett et al 2003)

$t_o = 13.7 \pm 0.2$ Gyr

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

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

$\Omega_b = 0.044 \pm 0.004$

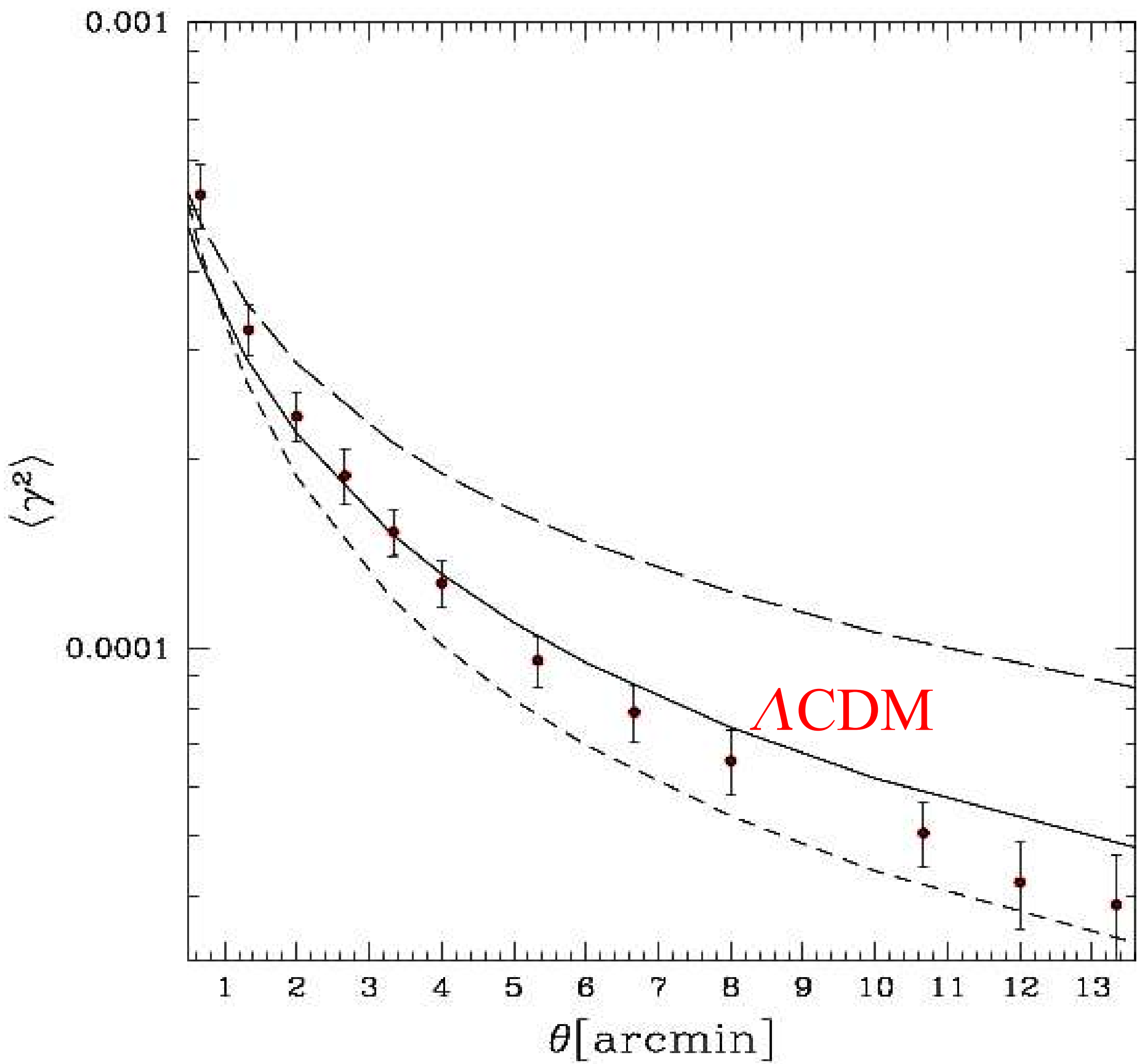
$\tau_e = 0.17 \pm 0.07$

- <u>Smallest</u> scales fitted give rise to rich galaxy clusters

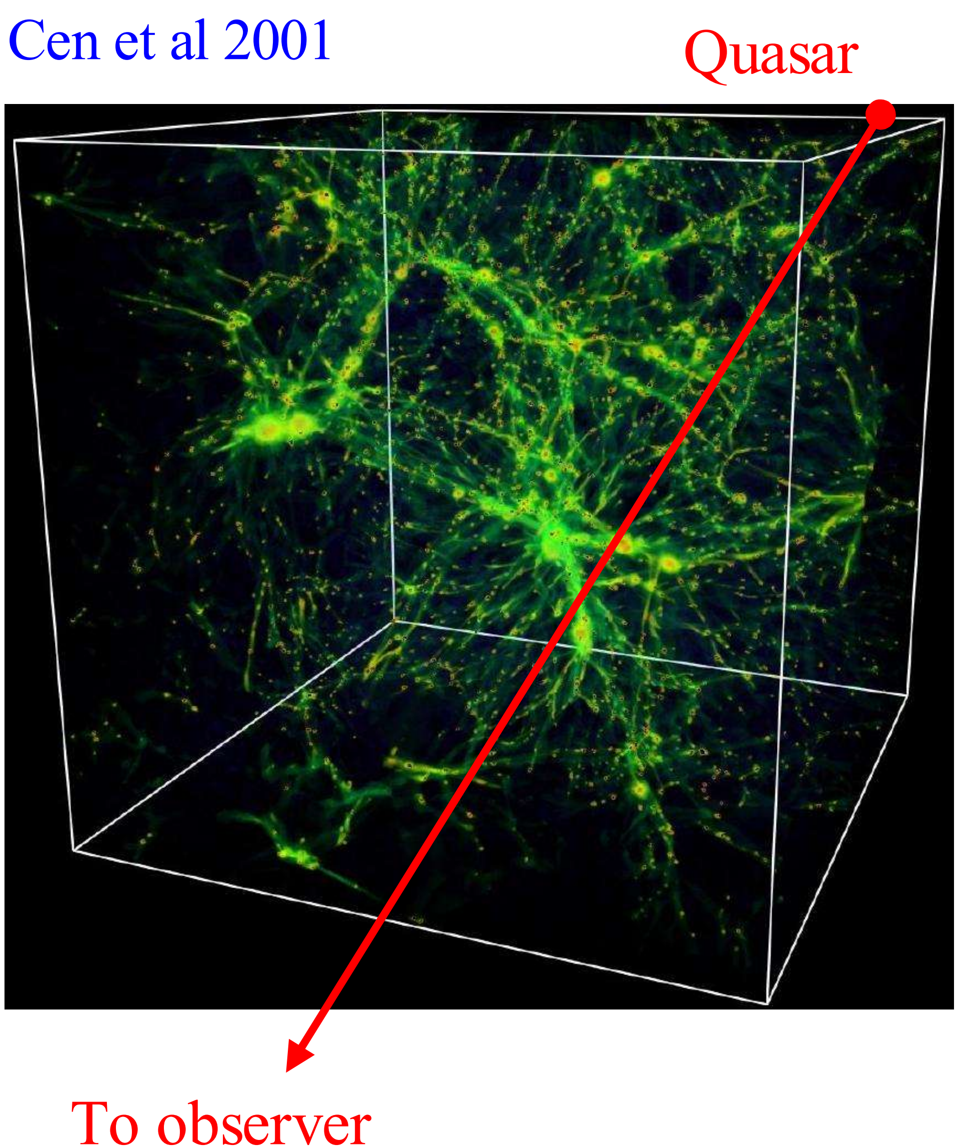
# A measurement of dark matter clustering

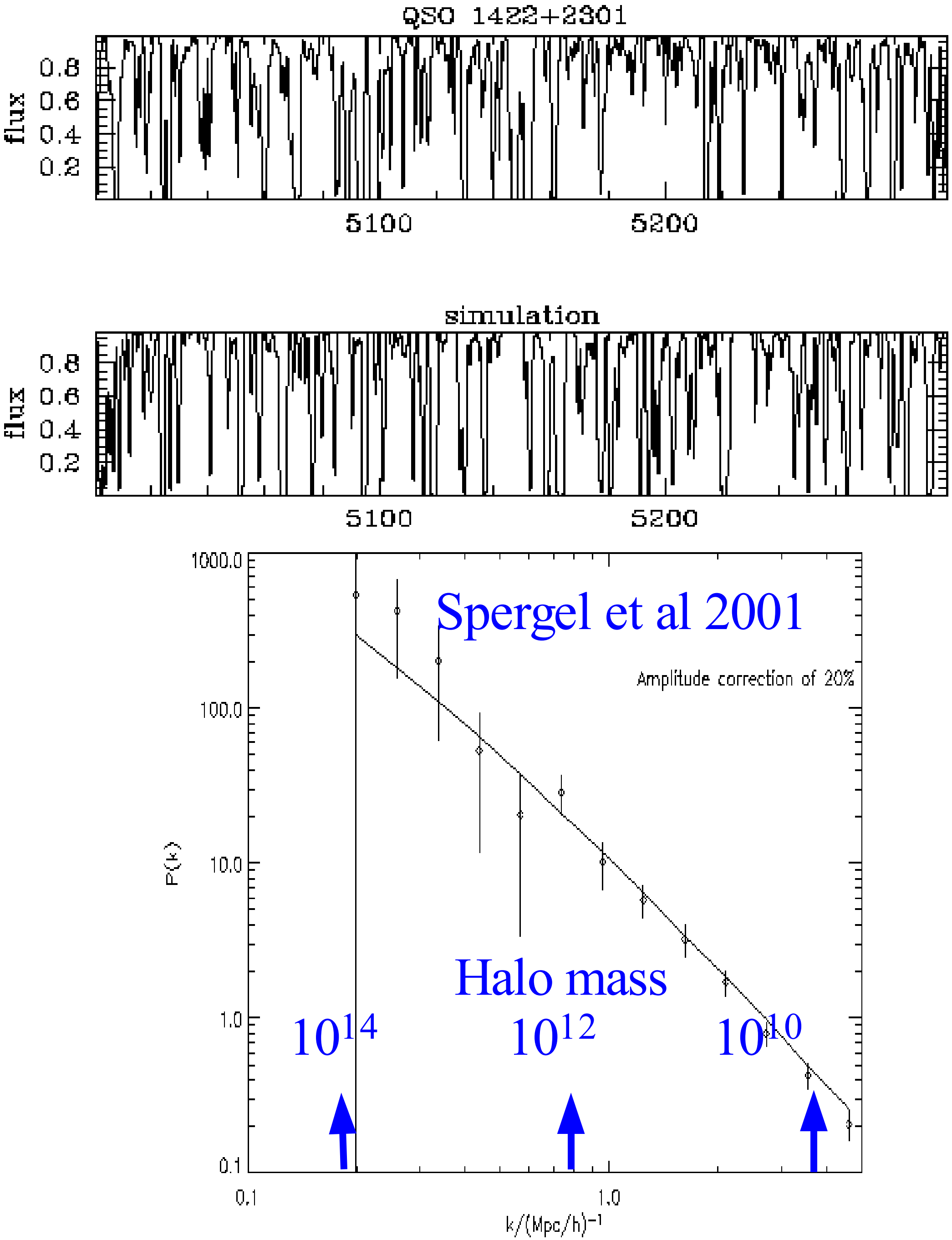
Van Waerbeke et al 2001

- $<\gamma^2>$ is the mean square gravitational shear of background galaxy images within circles of radius $\vartheta$.
- It is proportional to the mean square lensing mass within these circles
- On scales of a few arcmin the signal is dominated by *nonlinear* DM clustering, i.e. by the dark halos of galaxies and galaxy groups



# Structure in the intergalactic medium



# Status of $\Lambda$CDM as a structure formation model

- CMB data confirm the material content of the Universe and the linear initial conditions convincingly down to $\sim$ rich cluster scales
- Cosmic shear data confirm the predicted nonlinear structure convincingly down to $\sim$ Milky Way halo scales
- Lyman $\alpha$ forest data *appear* to confirm the model down to halo mass scales $\sim 10^{10}\,M_\odot$ or baryon mass scales $\sim 10^{9}\,M_\odot$

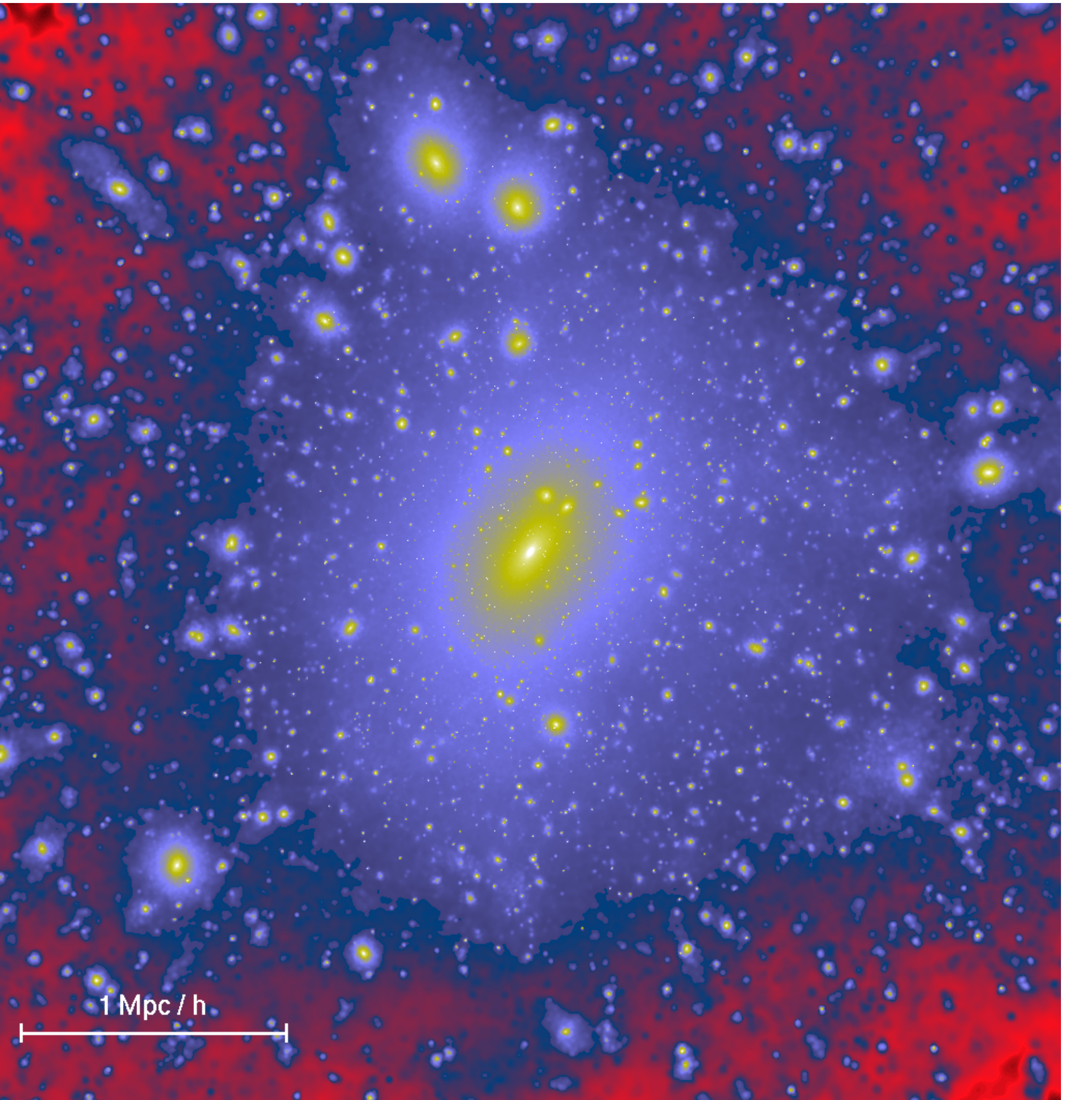
## Uncertainties/conflicts

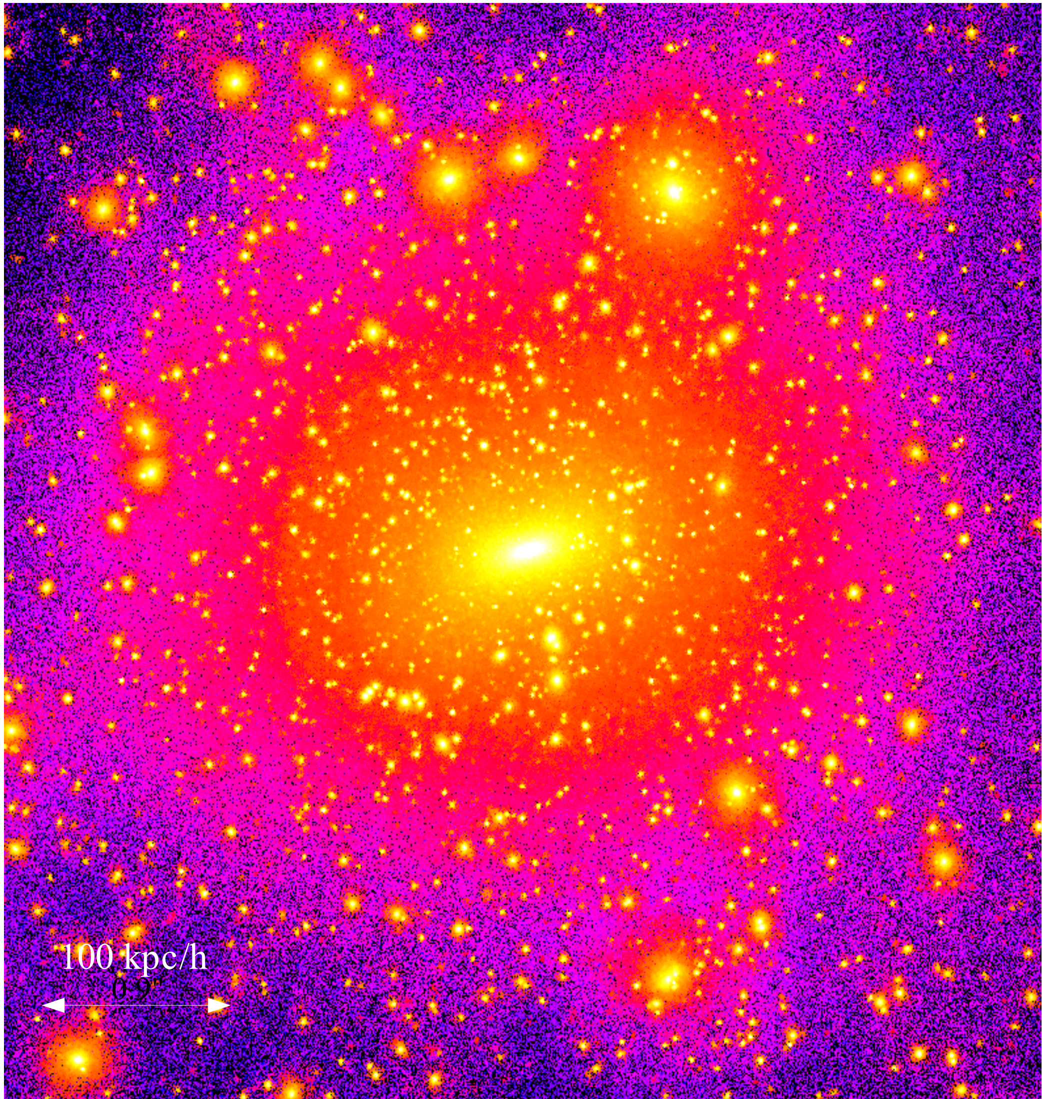
- Slope $n \sim 1$ of the primordial power spectrum
- Possible spectral cut-off on small scales
- Modifications from new DM physics - warm dark matter?
  - self-interacting dark matter?
- Data conflicts in high density regions - galaxy/cluster cores?
  - substructure abundance?

# Small-scale structure in $\Lambda$CDM halos

A rich galaxy cluster halo
Springel et al 2001

A 'Milky Way' halo
Power et al 2002



# Goals for a galaxy formation theory

- Predict the sizes, stellar masses and characteristic velocities of galaxies, their distributions and the relations between them
- Predict bulge/disk ratios, gas/star ratios and their distributions as a function of global galaxy properties
- Predict distributions of chemical abundances within and among galaxies and in the intergalactic medium
- Predict the relation between galaxy properties and galactic environment
- Predict all of the above as a function of redshift and clarify the relation between objects seen at different redshifts
- Clarify the relation between galaxy formation and SMBH formation -- between QSO's and bulge (?) formation

Many of these things are observationally poorly determined

# Additional physics needed for galaxy formation

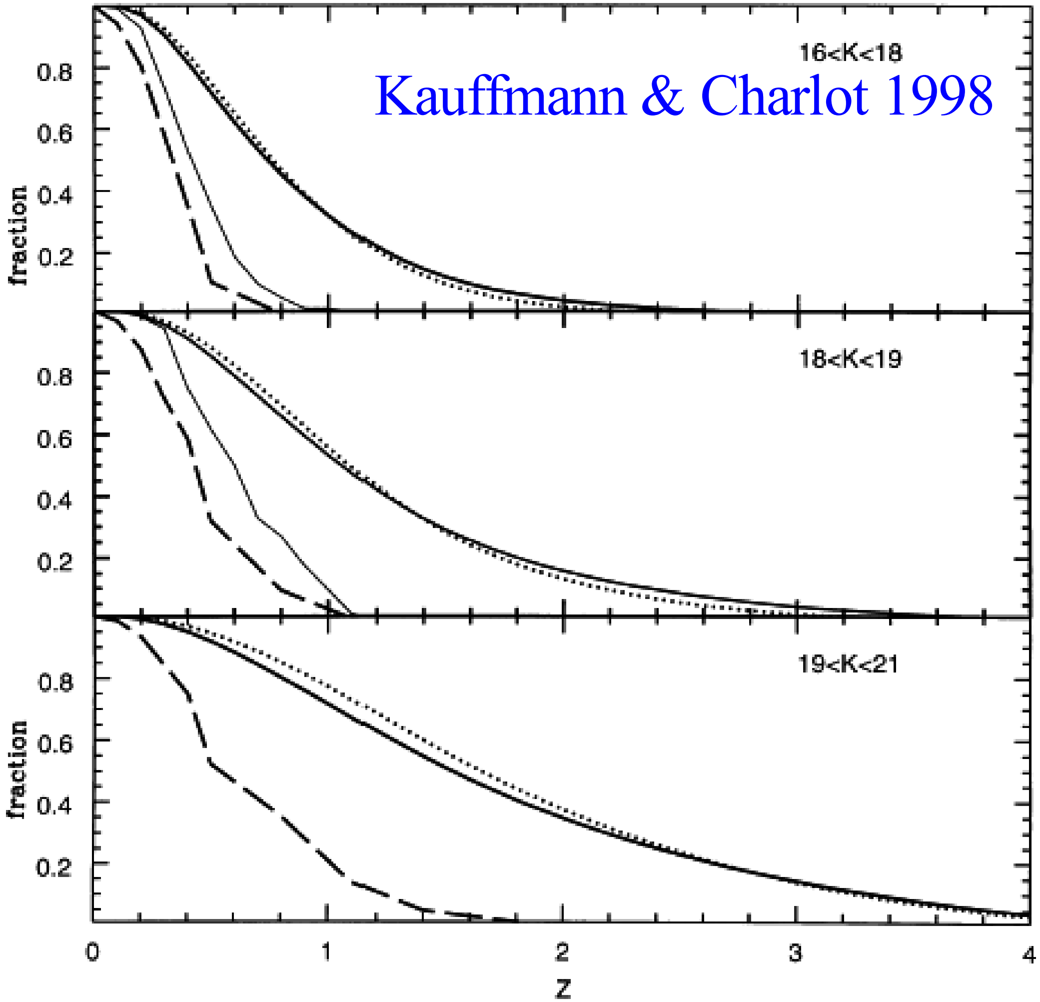
- Gas cooling -- metal content, phase structure, conductivity
- Star formation -- threshold, efficiency, IMF
- Stellar evolution -- spectrophotometric evolution, metal yields
- Dust evolution -- formation, redistribution, heating/cooling
- Wind evolution -- fountains, winds, IGM heating, metal mixing
- AGN evolution -- BH growth, feedback to galaxy and environment
- Reionisation -- suppression of dwarf galaxy formation
- Galaxy interactions/mergers -- morphological transformation

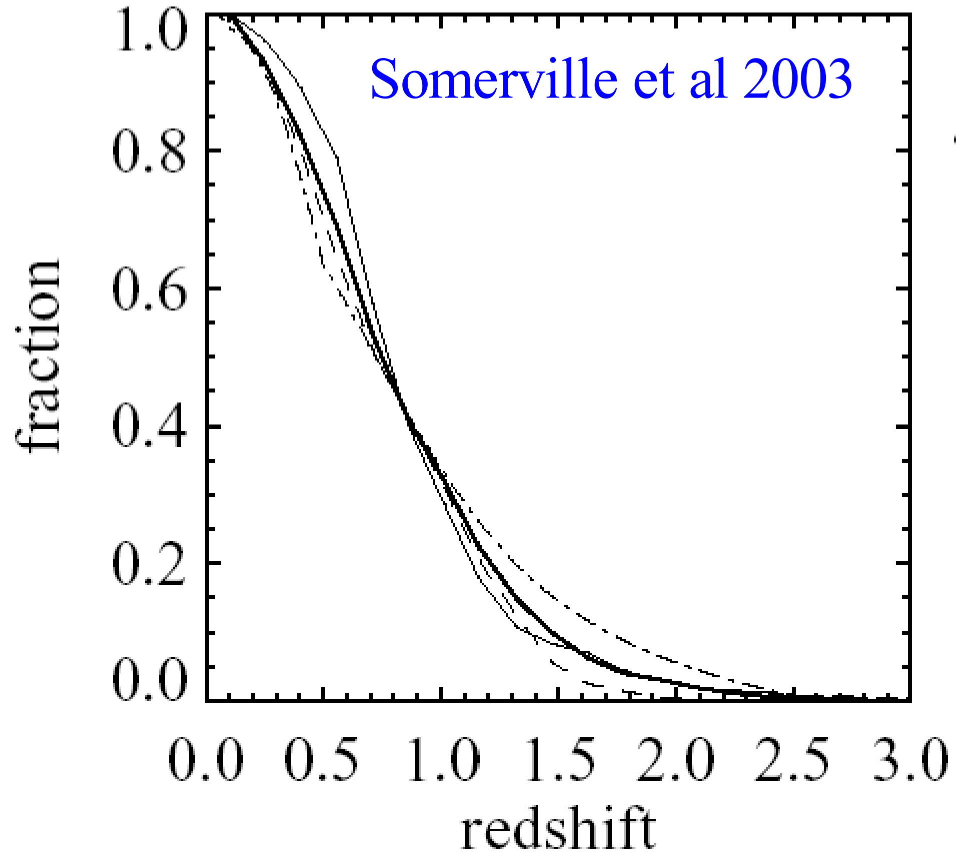
Only the last can be simulated realistically *ab initio*

→ semi-analytic (phenomenological) techniques ←

N.B. SA modelling is a *technique* for studying galaxy formation
Published models are *not* intended/expected to be definitive
Multiwavelength data will require *more* such modelling

# Predicted redshift distributions in K-limited surveys

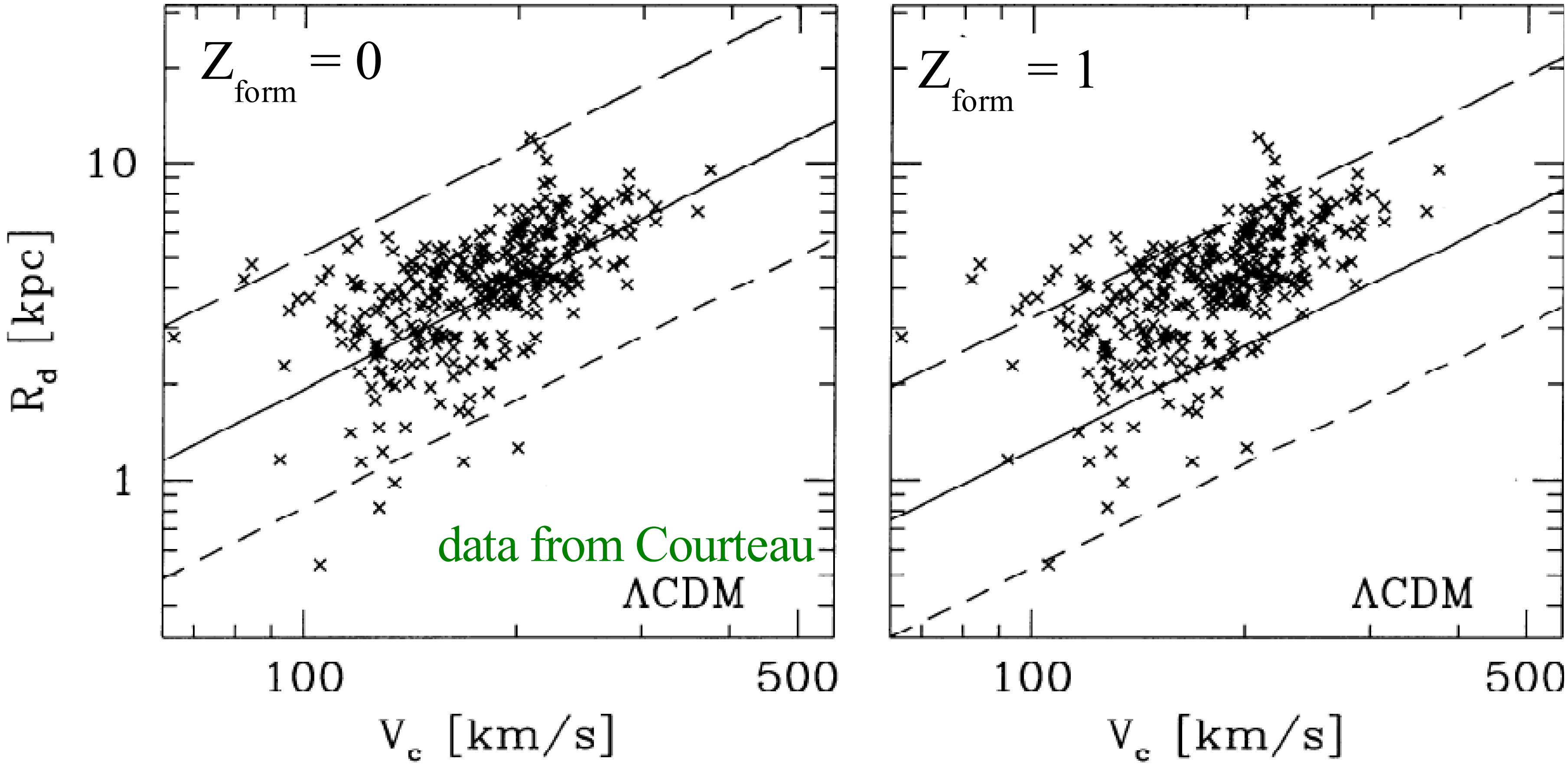



- For the data: $z_{median}$(K=20) has been stable at $z = 0.73$
- For the SA models: $z_{median}$(K=20) has increased from 0.52 to 0.72
- For the PLE models: $z_{median}$(K=20) has decreased from 1.33 to 0.72

# Present sizes of galaxy disks

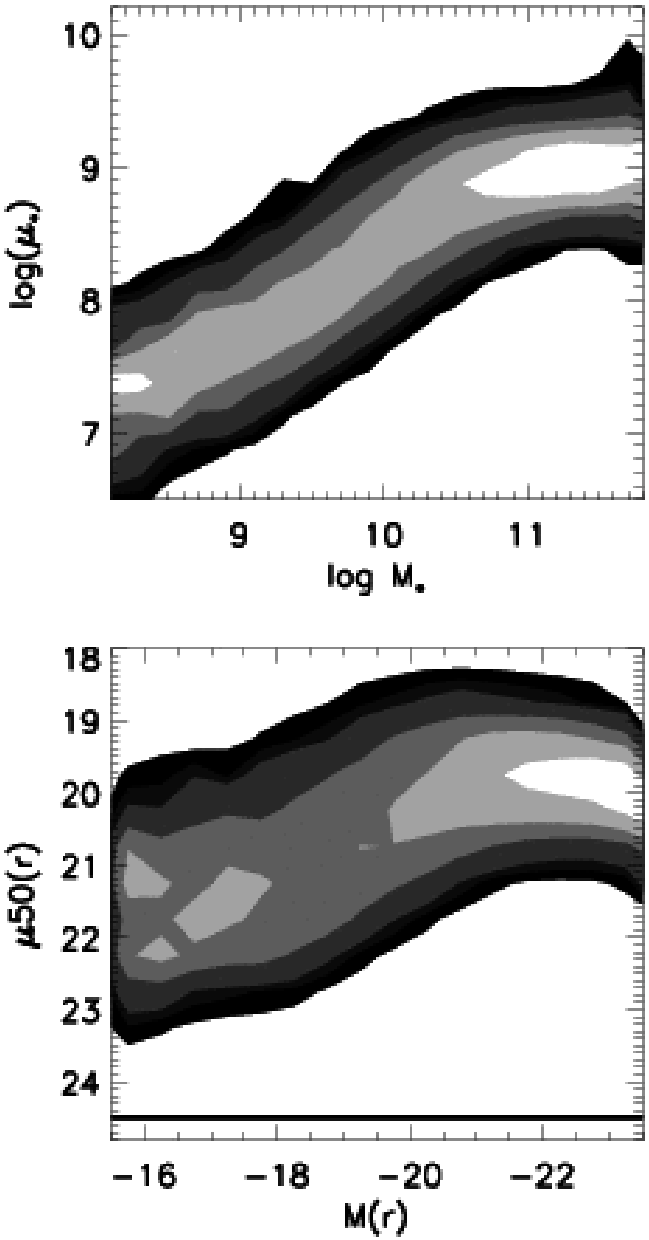
Mo, Mao, White 1998

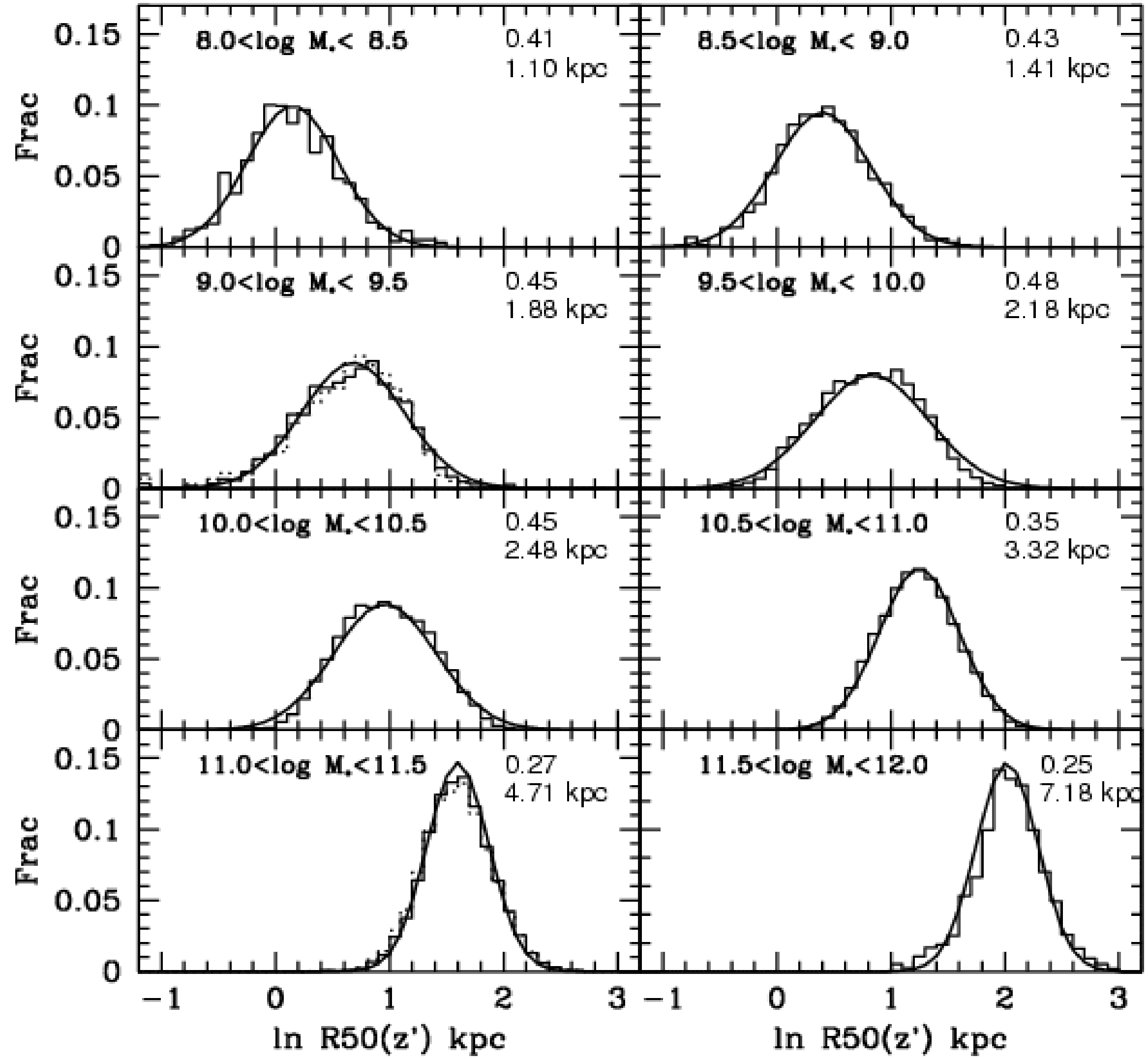



- Angular momentum from hierarchical clustering can explain disk size distribution *provided* disks assemble late
- Angular momentum losses in simulations of spiral galaxy formation in $\Lambda$CDM lead to disks which are too small

# Galaxy sizes from SDSS data

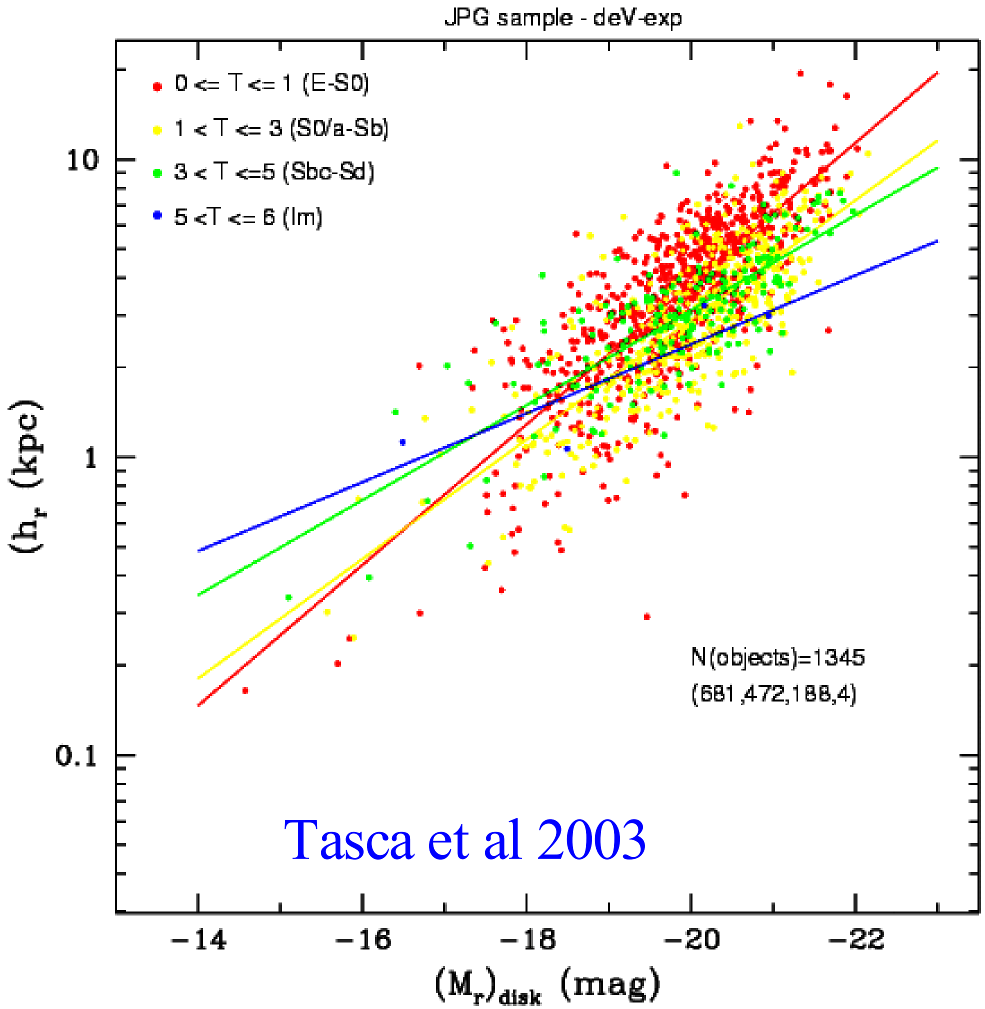
Kauffmann et al 2003

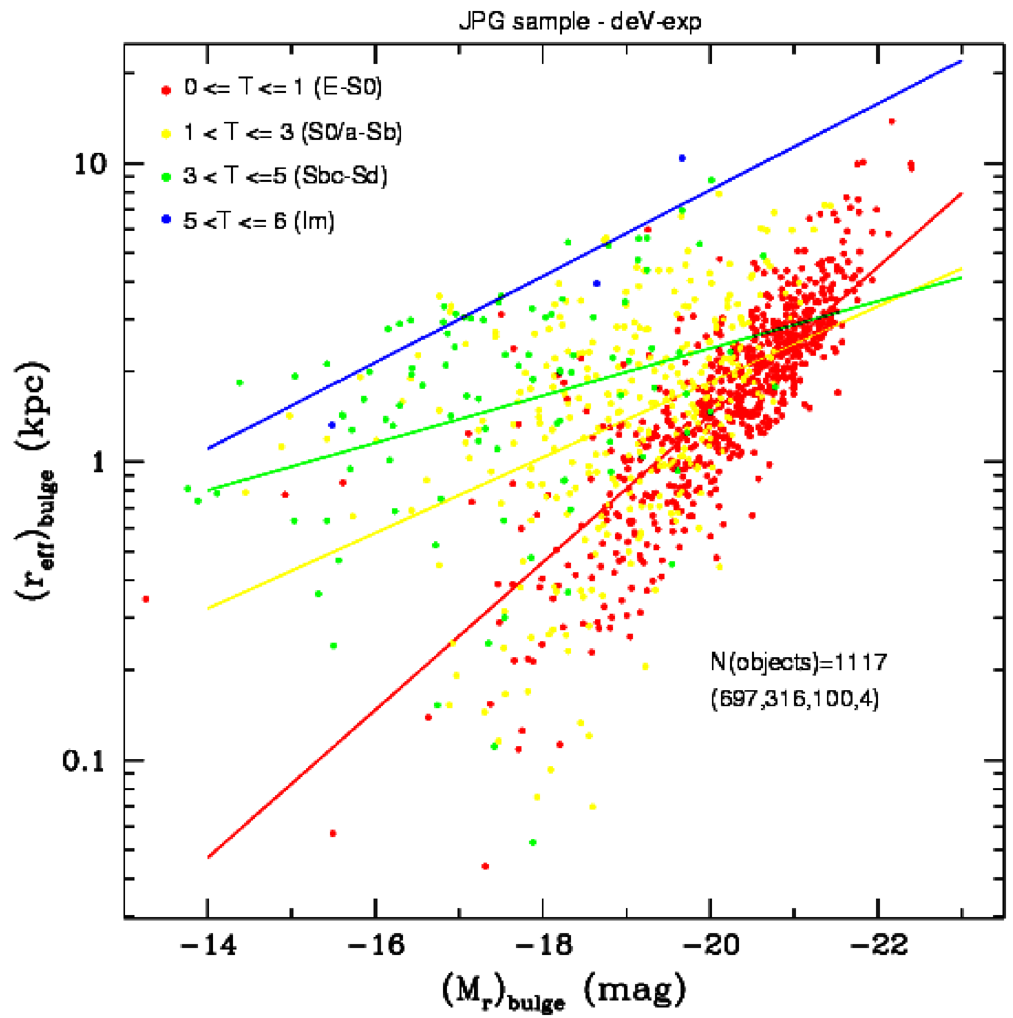



- Stellar mass -- surface mass density relation is tight and changes its behaviour at $M_* \sim 3 \times 10^{10} M_\odot$
- Size distribution at low mass as predicted by simple theory

# Disk-bulge decompositions of SDSS galaxies

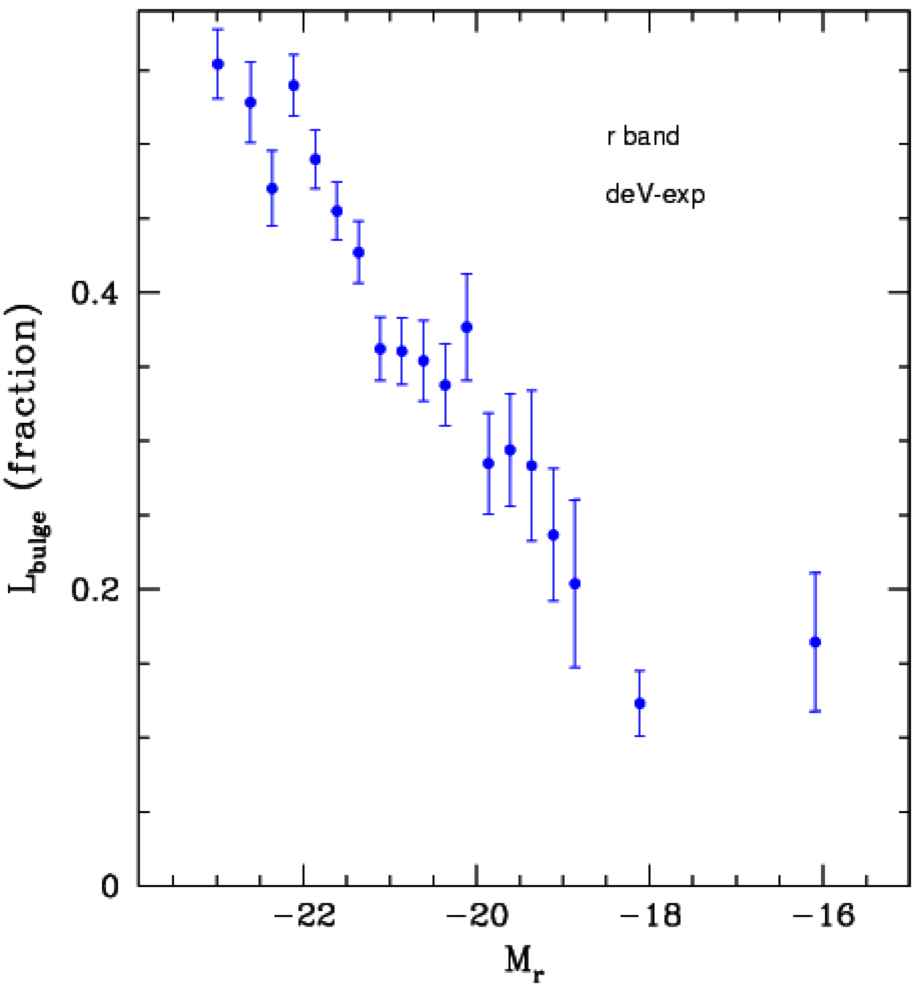



- GIM2D decompositions of a magnitude limited sample of large visually classified galaxies
- Disk (but not bulge) scalings consistent across Hubble types

# Light fraction in bulges in the local Universe

Tasca et al 2003




The mean fraction of galaxy light in the bulge component is a strong function of absolute magnitude

Independent *r* and *i* band analyses give very similar values

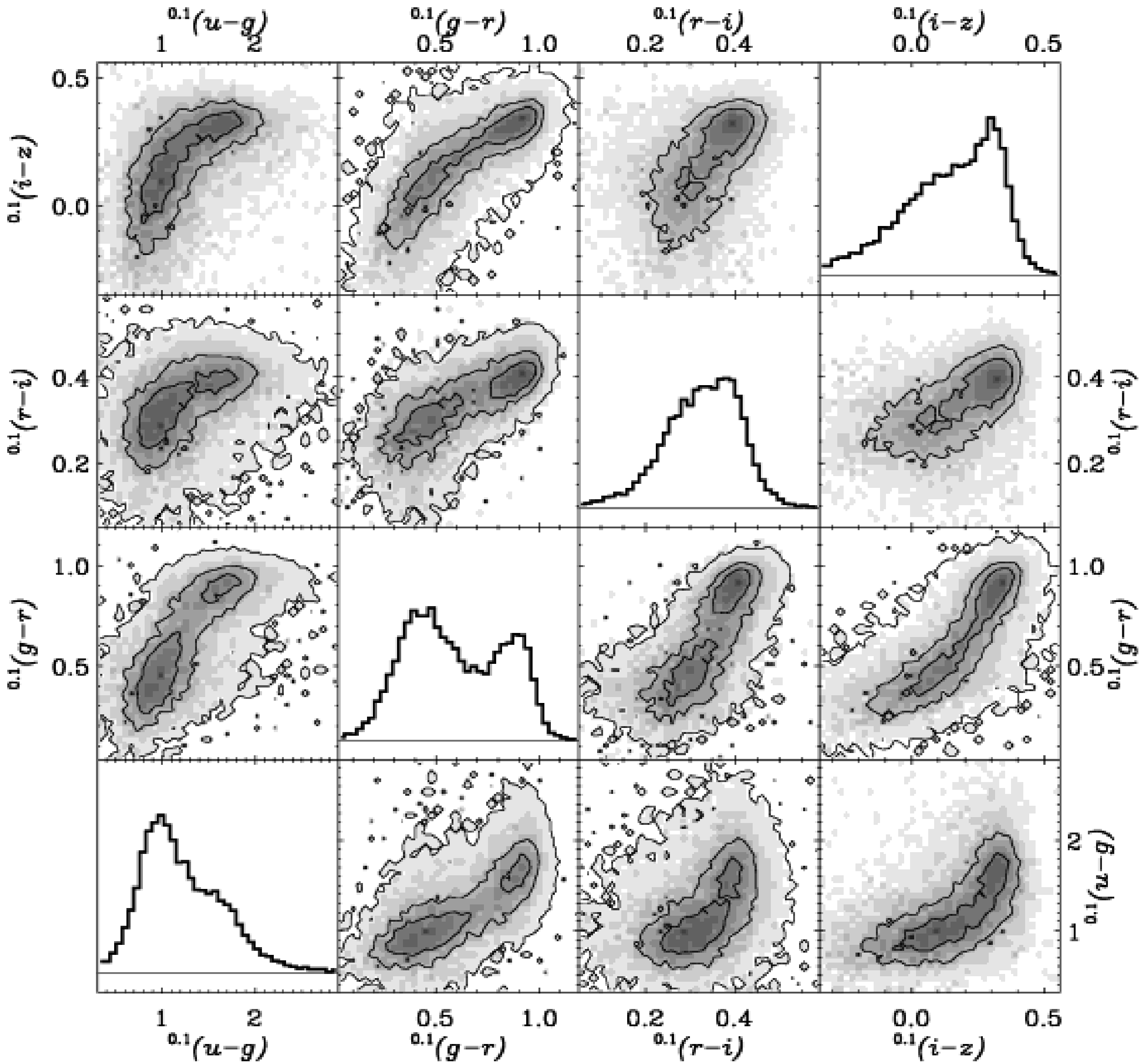
Combining with the SDSS LF's gives volume-averaged values for the fraction of light in bulges

$$F_{bulge} = \begin{array}{ll} 0.308 \pm 0.009 & i \text{ band} \\ 0.297 \pm 0.009 & r \text{ band} \end{array}$$

See Lidia Tasca's poster

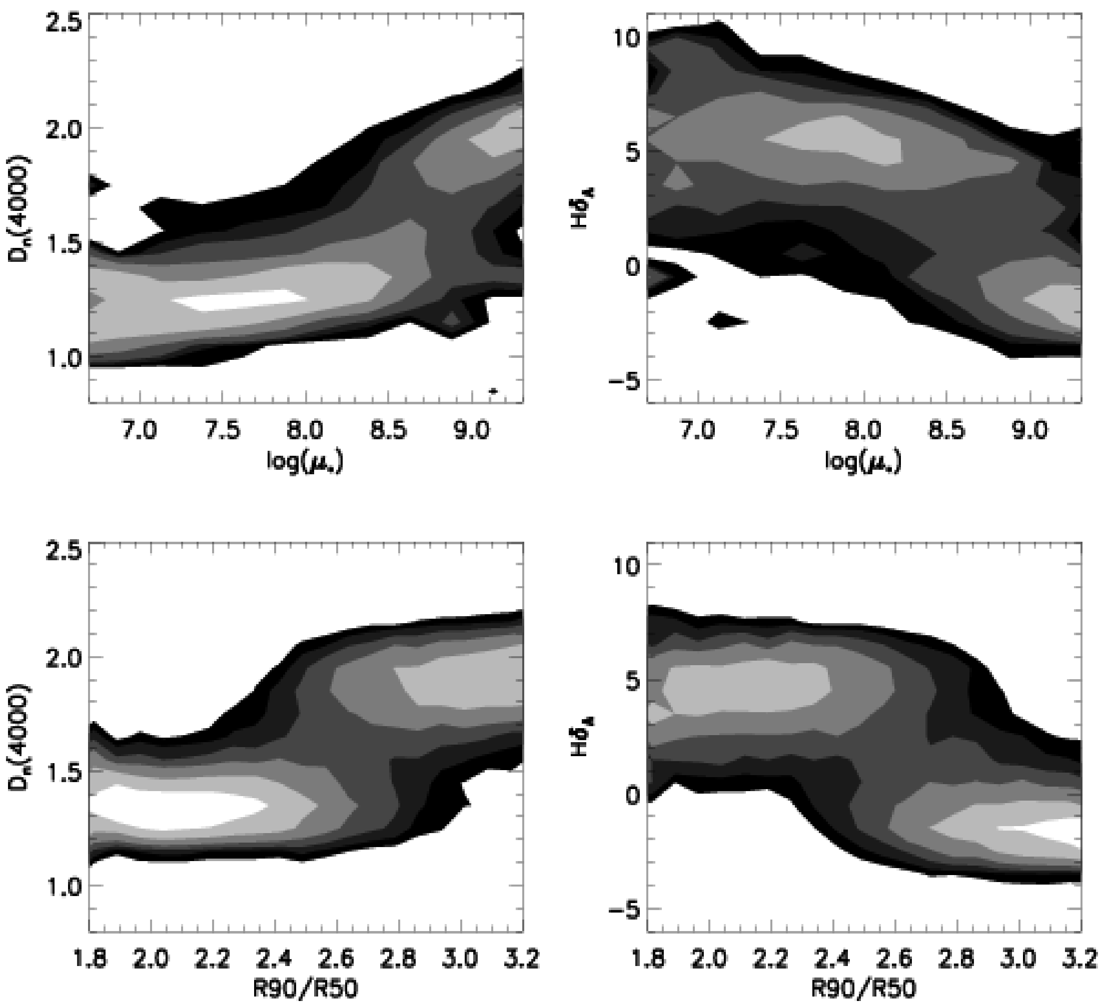
# Galaxy Population is Bimodal in Colour-Colour Space

Blanton et al 2003



# Trends in Stellar Age Indicators as a Function of Galaxy Structural Parameters

Kauffmann et al 2003



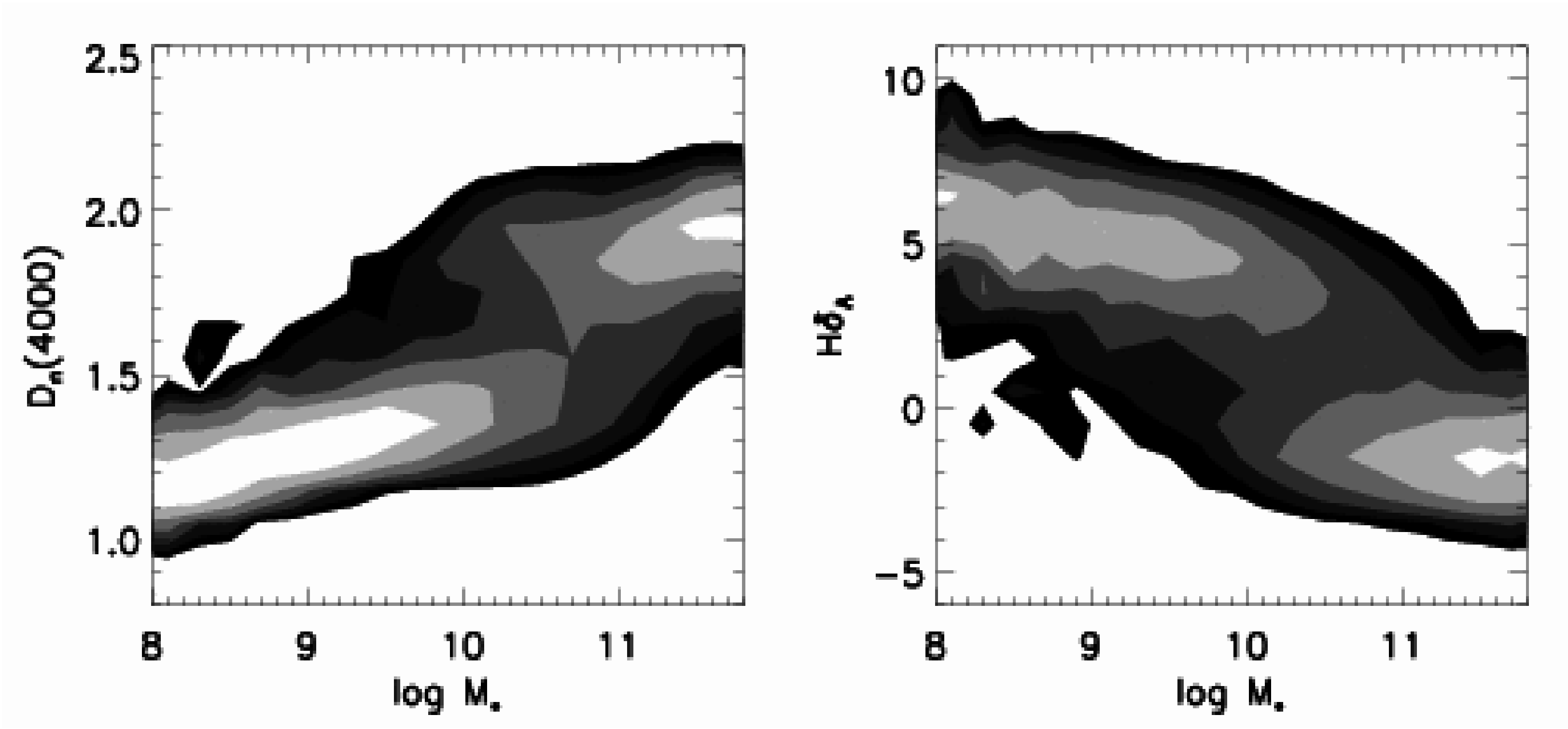

Spectral indices are much more sensitive to age effects than colours

They are less dependent on metallicity and do not depend at all on dust

Galaxies with high/low concentration and mass density contain only old/ some young stars

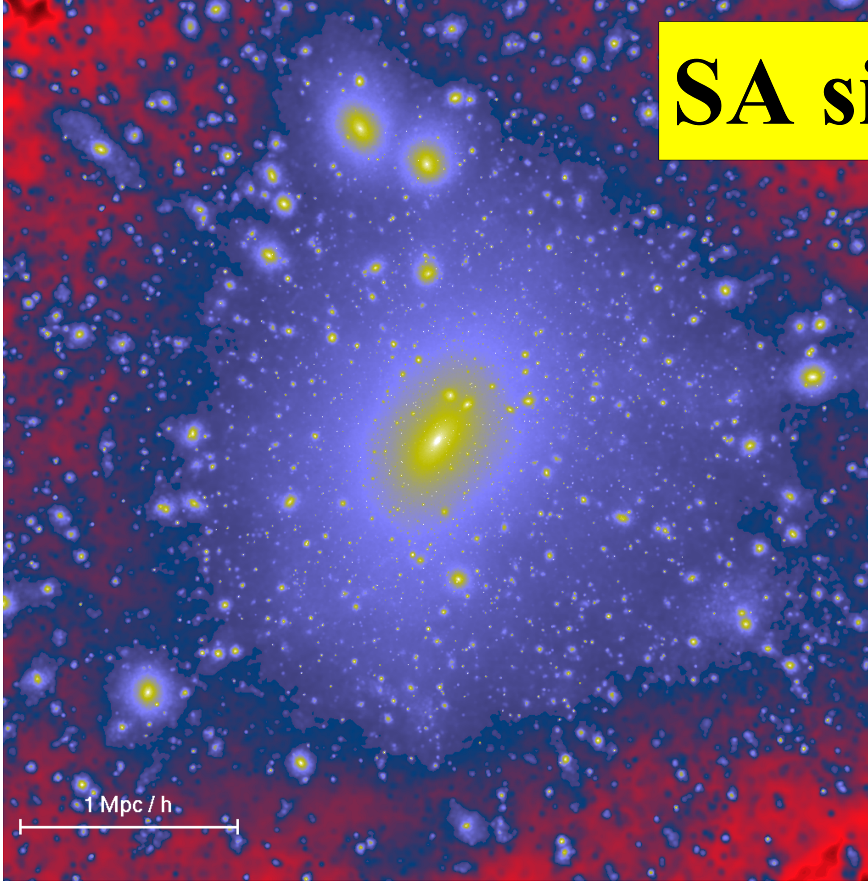
# Trends in Stellar Age Indicators as a Function of Stellar Mass

Kauffmann et al 2003



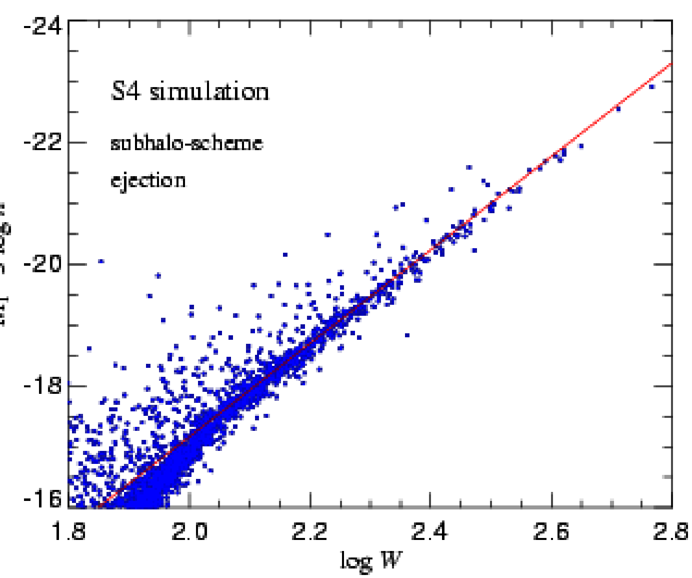

Transition in spectral properties at 3 x $10^{10}$ $M_\odot$

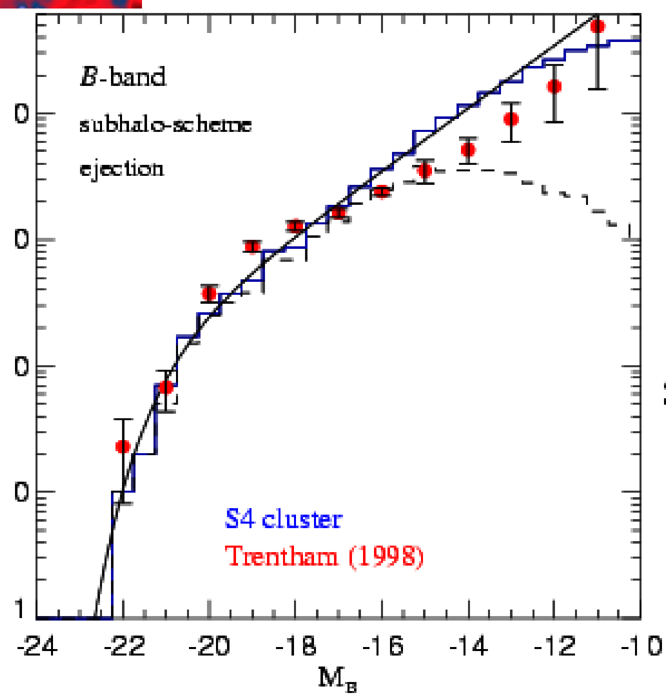
# SA simulation of cluster formation

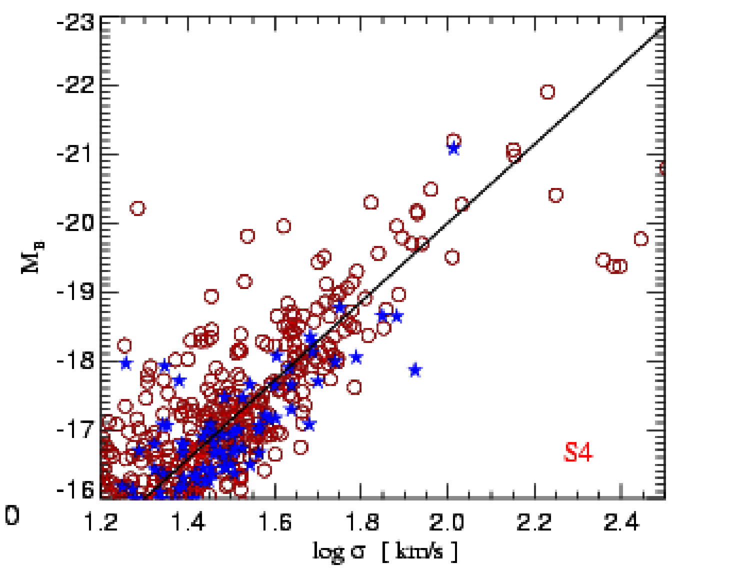



- Semi-analytic methods allow the simulation of a Coma cluster following all galaxies with $M_B < -12$
- Nearly all galaxies with $M_B < -16$ retain their own dark halos
- Protocluster can be analysed at high z

Springel et al 2001

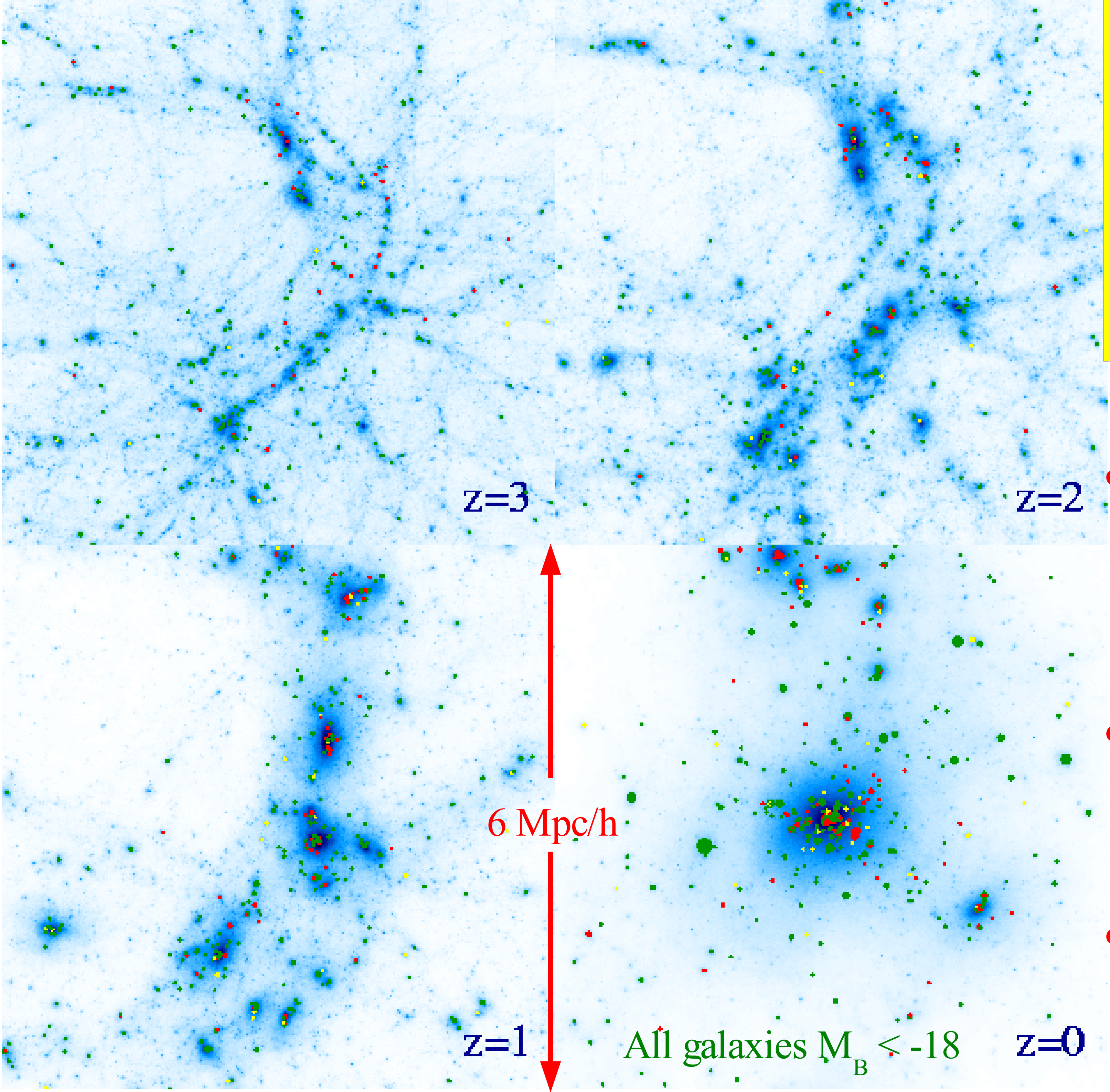


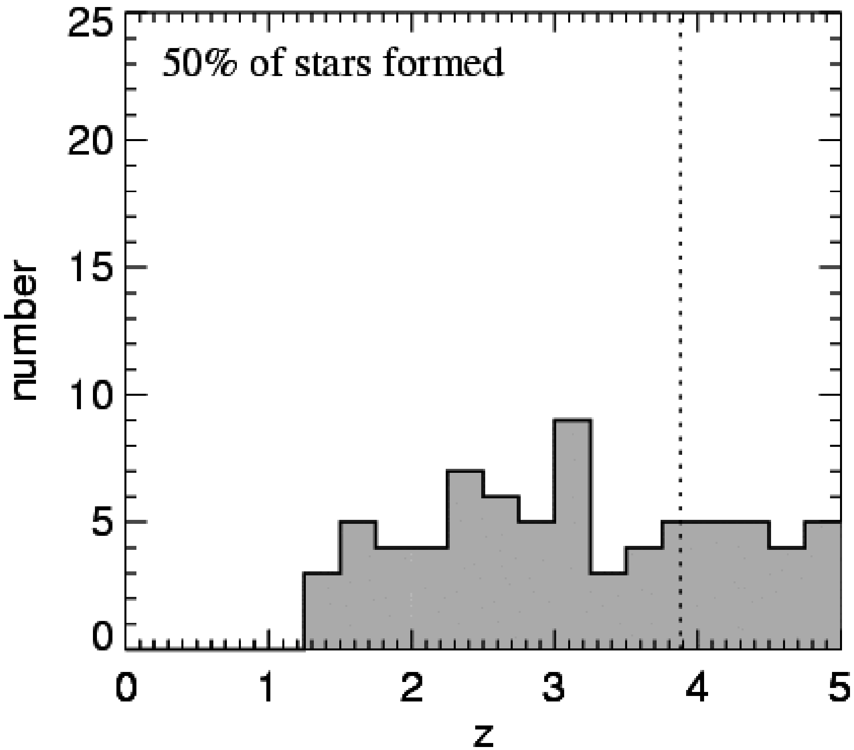



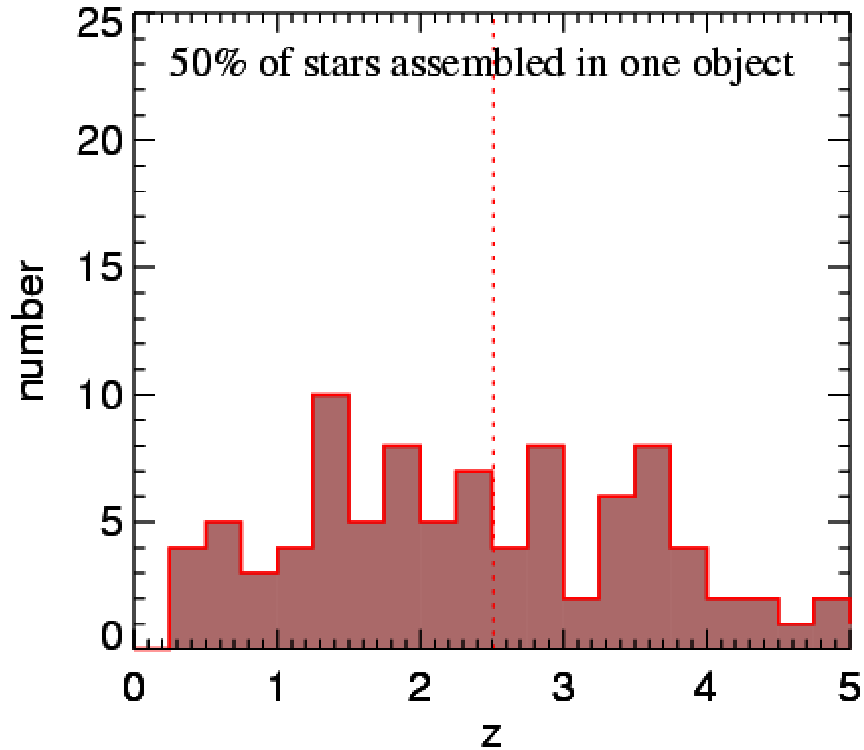
# Evolution of the galaxy population in a Coma-like cluster

Springel et al 2001

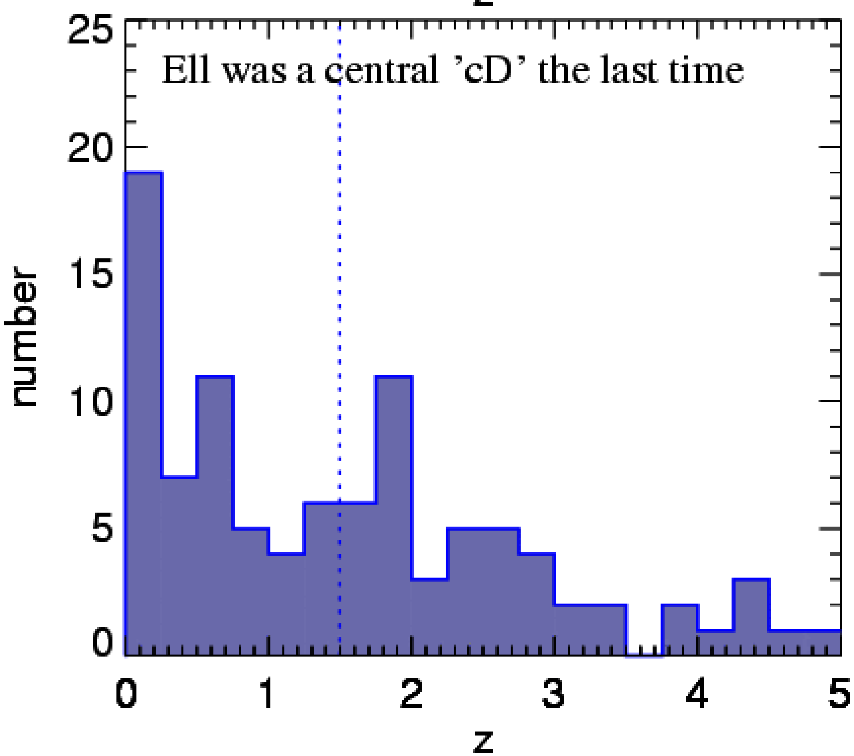



- Formation of the galaxies tracked within evolving (sub)halos
- Luminosity and mass of galaxies is uncertain
- Positions and velocities are followed well



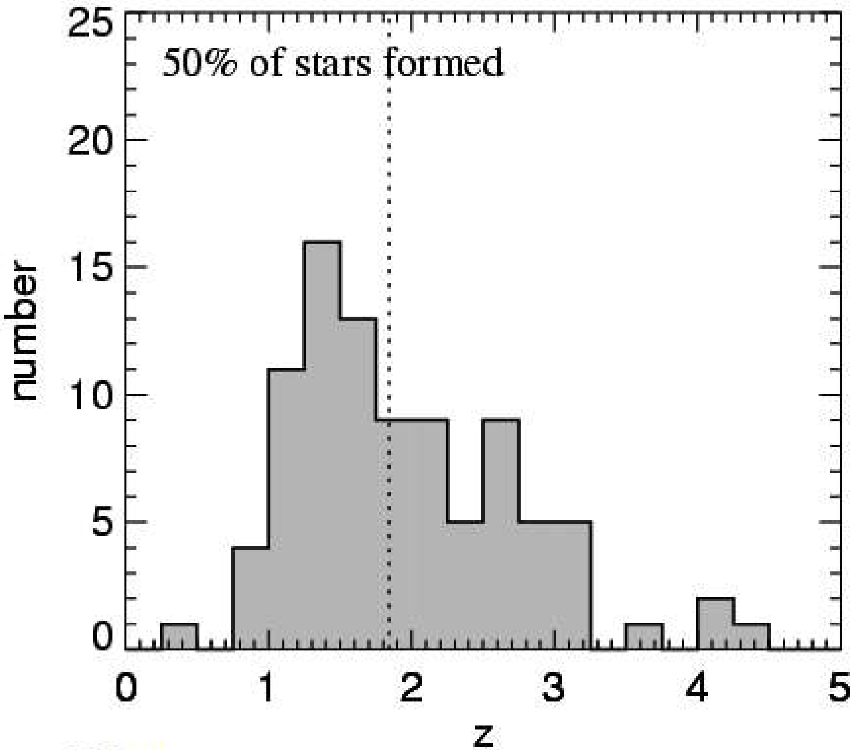



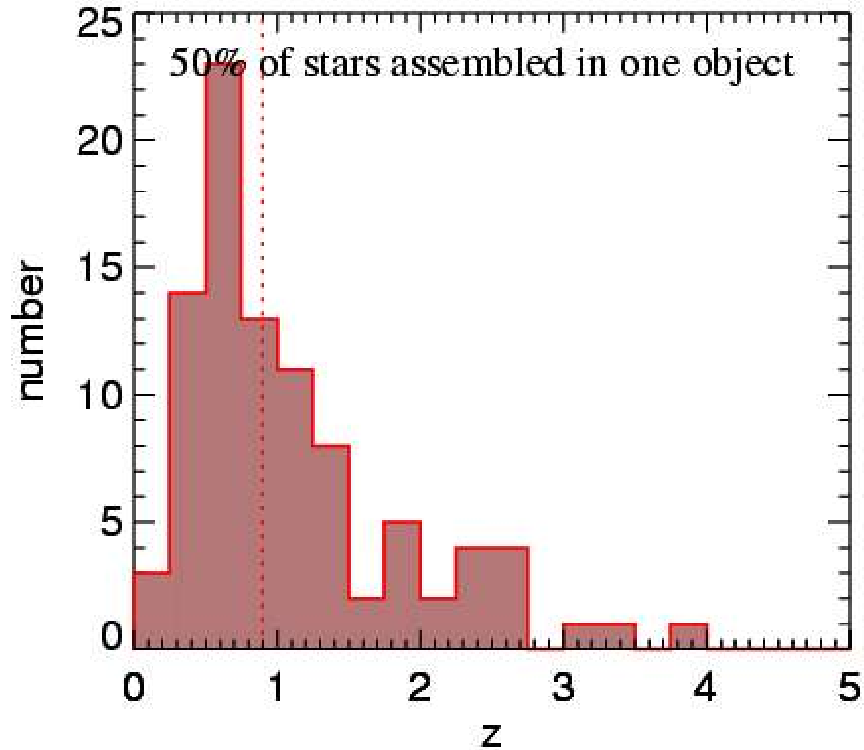

Springel et al 2003



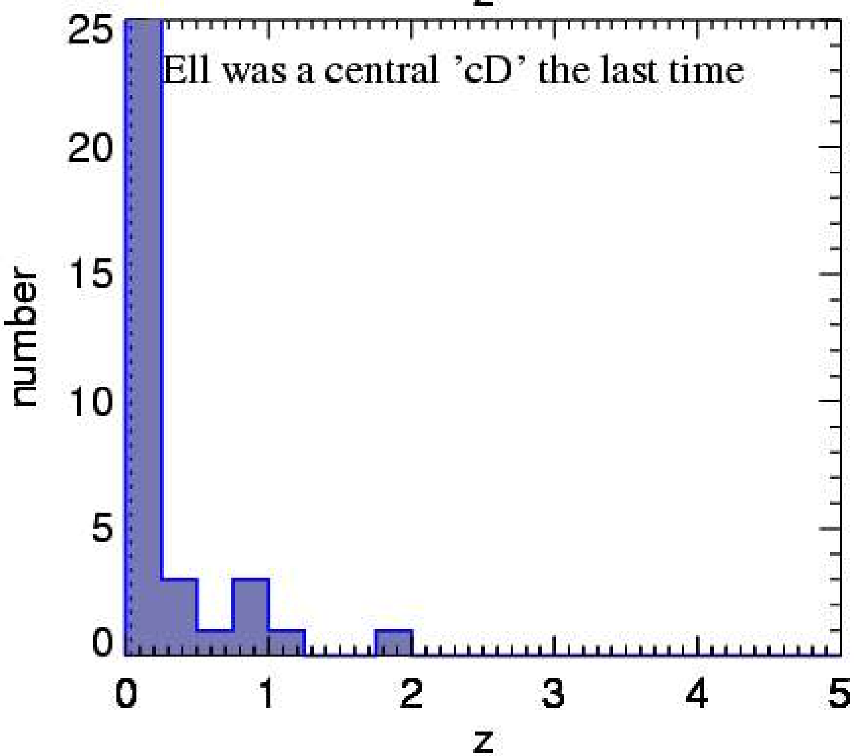

# Formation histories of cluster ellipticals

- 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



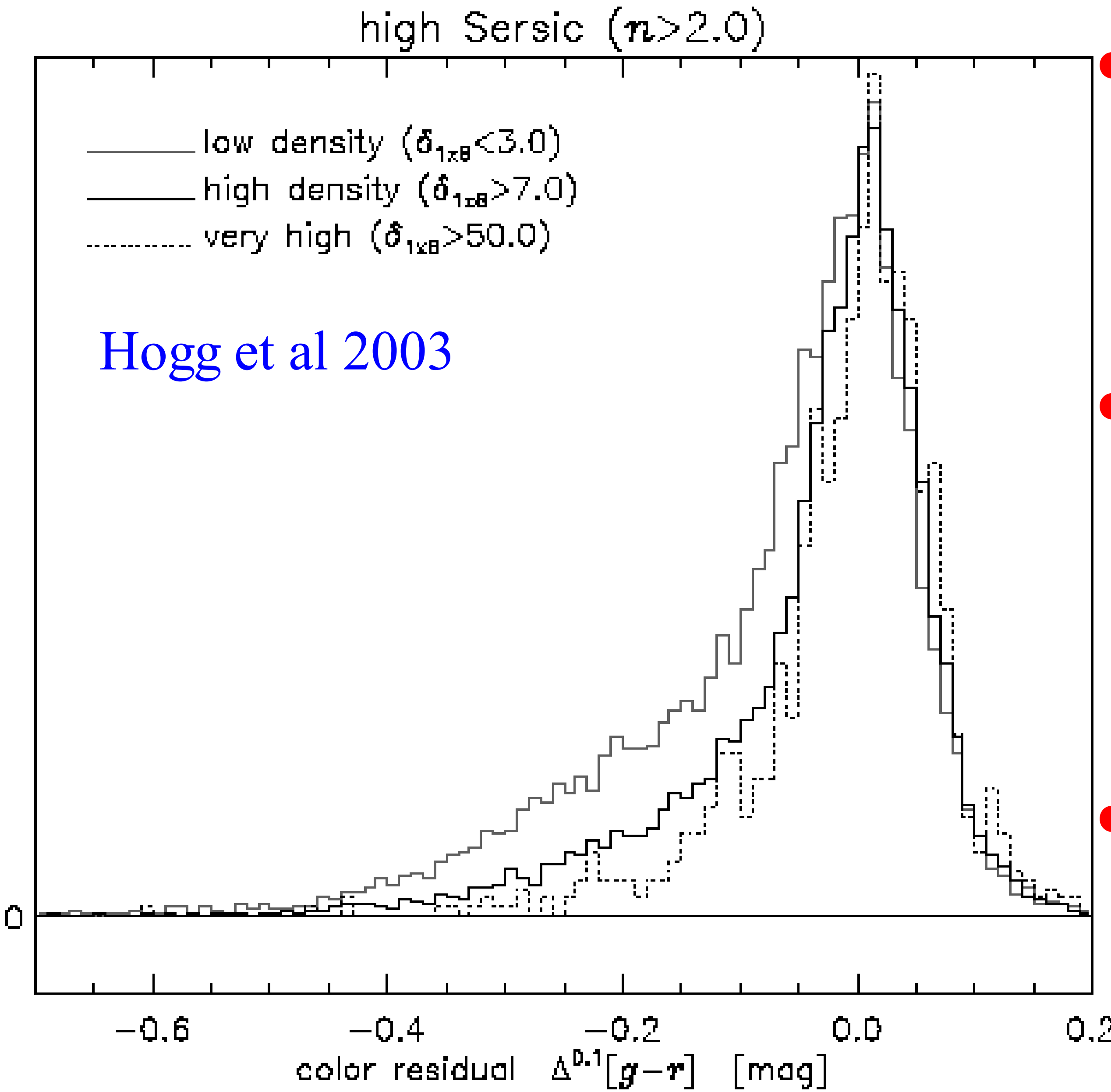

Springel et al 2003




# Formation histories of field ellipticals

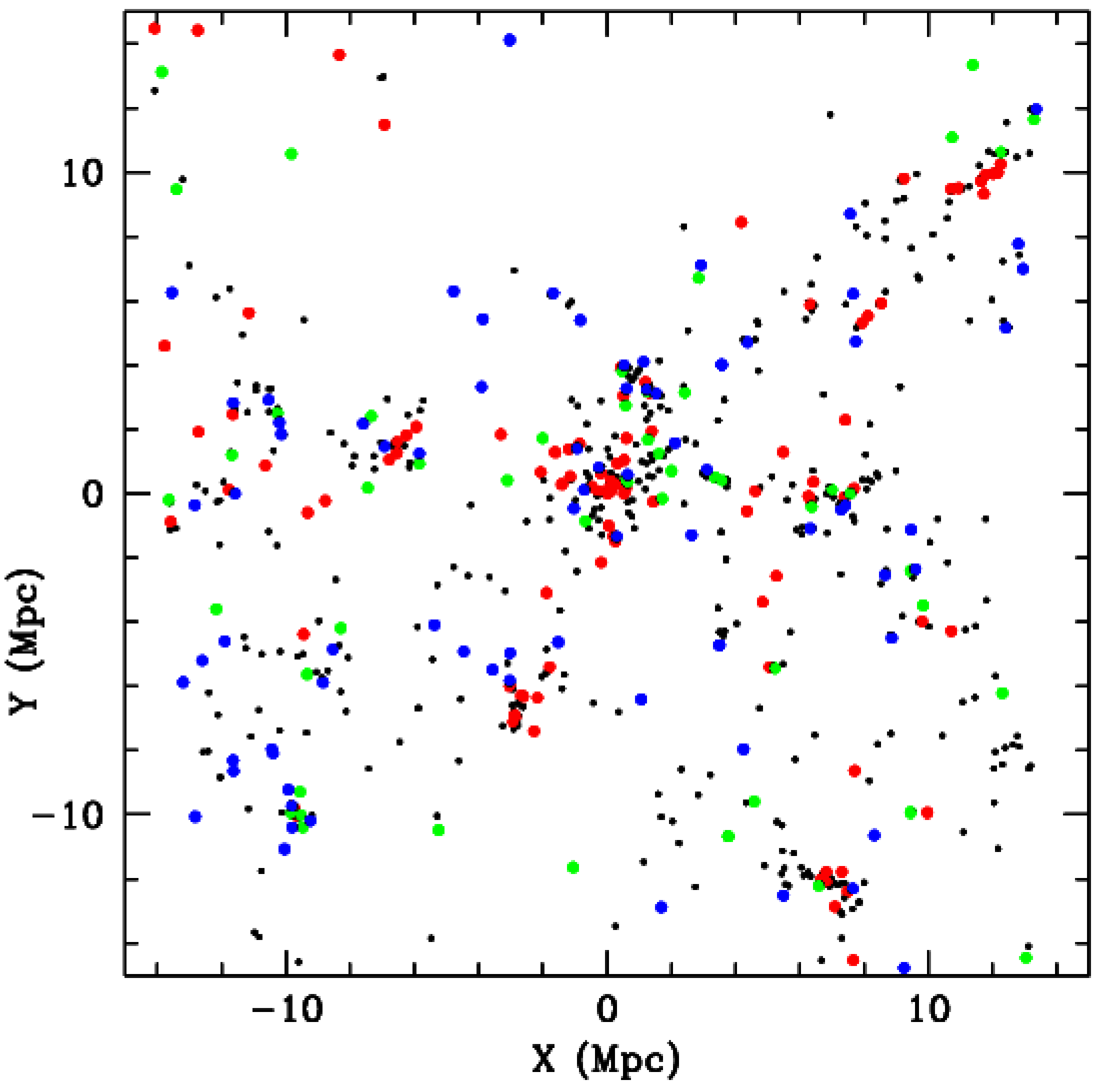
- 91 field ellipticals with $M_B < -18$
- Stars form fairly early
- Most ellipticals assembled late
- Most ellipticals are 'cD' of their groups

# Deviations of SDSS early-type galaxies from their mean L – (g-r) relation: environment dependences




- Early types in low density regions show a tail of bluer objects not present in high density regions
- The sharp cut-off in colour on the red side is 0.01 redder in the high density regions than in the low
  → 0.8 Gyr older?
- Colours are a blunt tool
  Effects are seen more easily in spectra

# Environment dependence of stellar populations




Kauffmann et al 2004

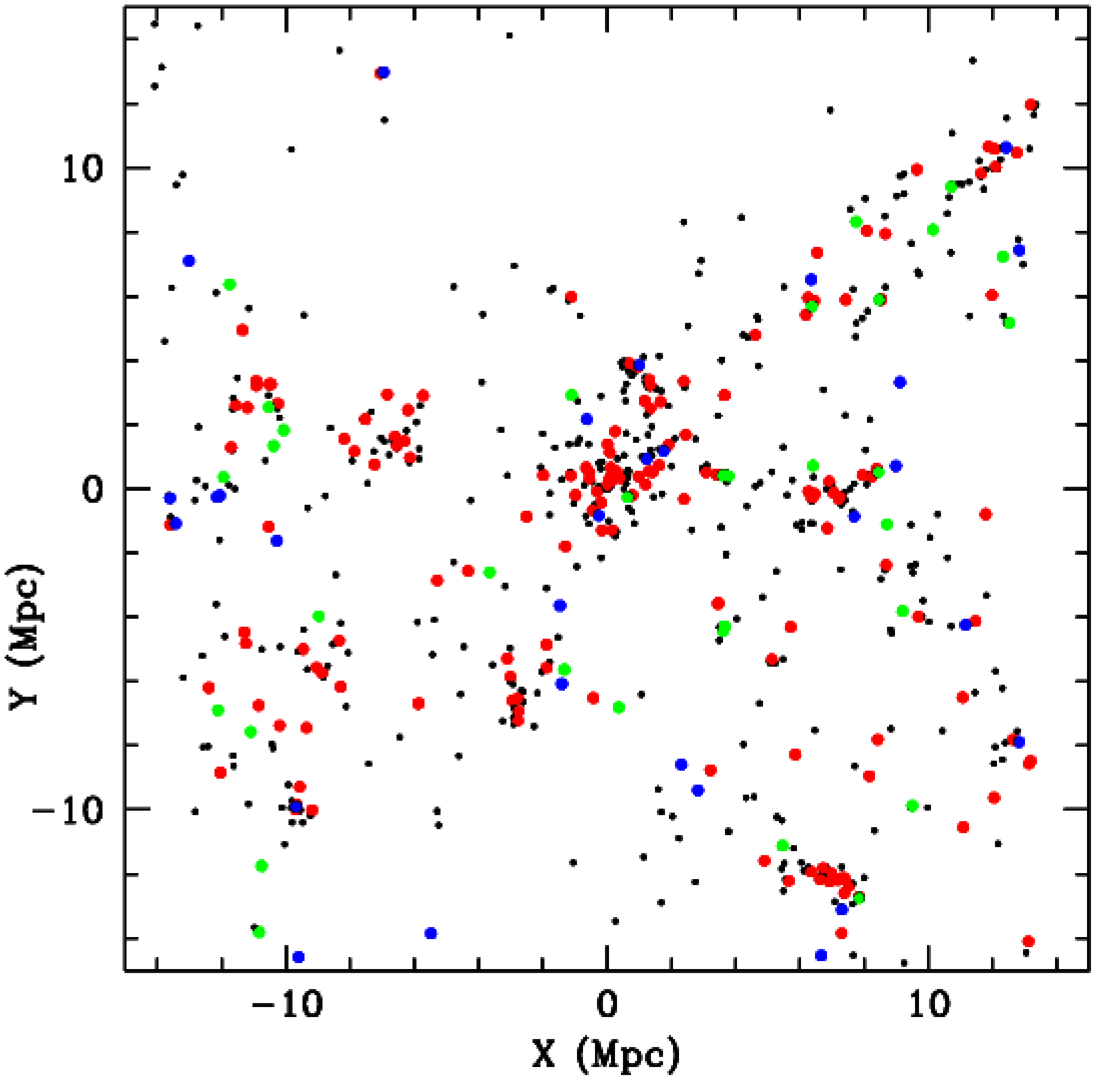
SDSS spectroscopic sample
$z = 0.05$
Depth of slice $\pm$ 500 km/s

Galaxies with $M_* < 3 \times 10^{10}$

Colour code indicates the value of $D_n(4000)$

Oldest galaxies are in the densest regions

# Environment dependence of stellar populations




SDSS spectroscopic sample

$z = 0.05$

Depth of slice ± 500 km/s

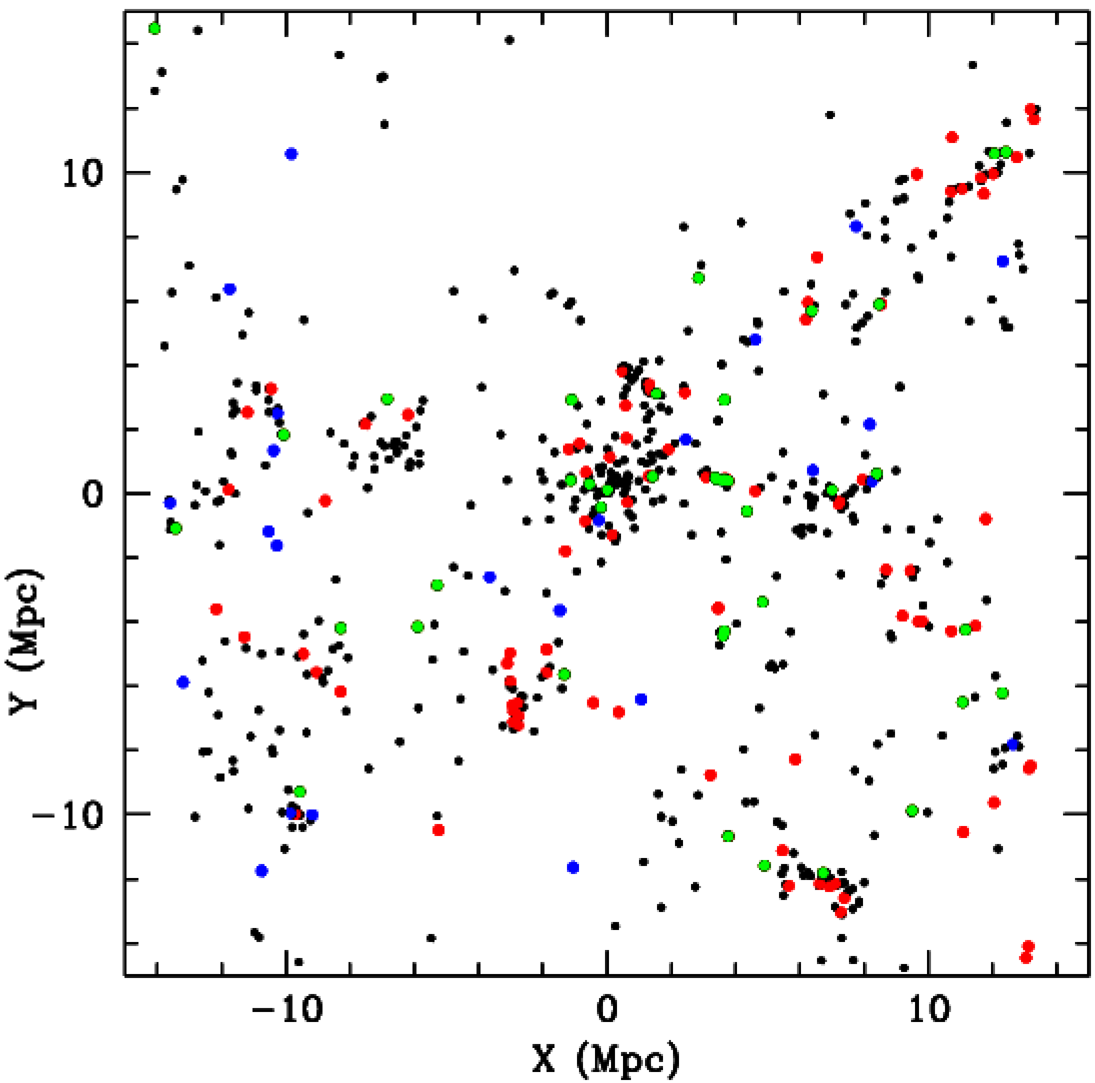
Galaxies with $M_* > 3 \times 10^{10}$

Colour code indicates the value of $D_n(4000)$

High mass galaxies are older and are in denser regions

Kauffmann et al 2004

# Environment dependence of stellar populations




Kauffmann et al 2004

SDSS spectroscopic sample
z = 0.05
Depth of slice ± 500 km/s

Galaxies with type 2 AGN

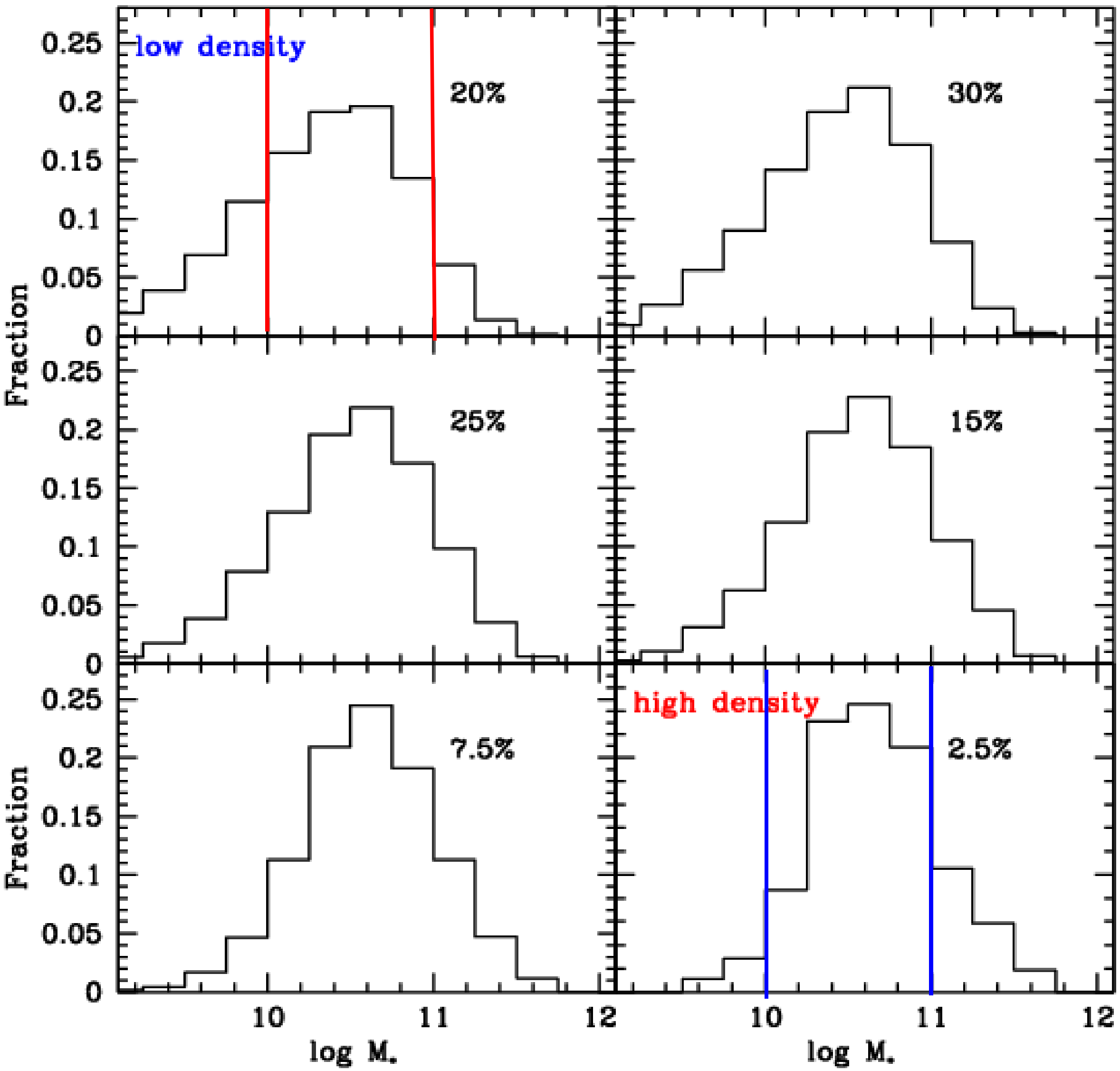
Colour code indicates AGN luminosity (in [OIII])

Many *high mass* galaxies are AGN

Brighter AGN have younger stars and are less clustered

# The Dependence of Galaxy Mass on Local Density

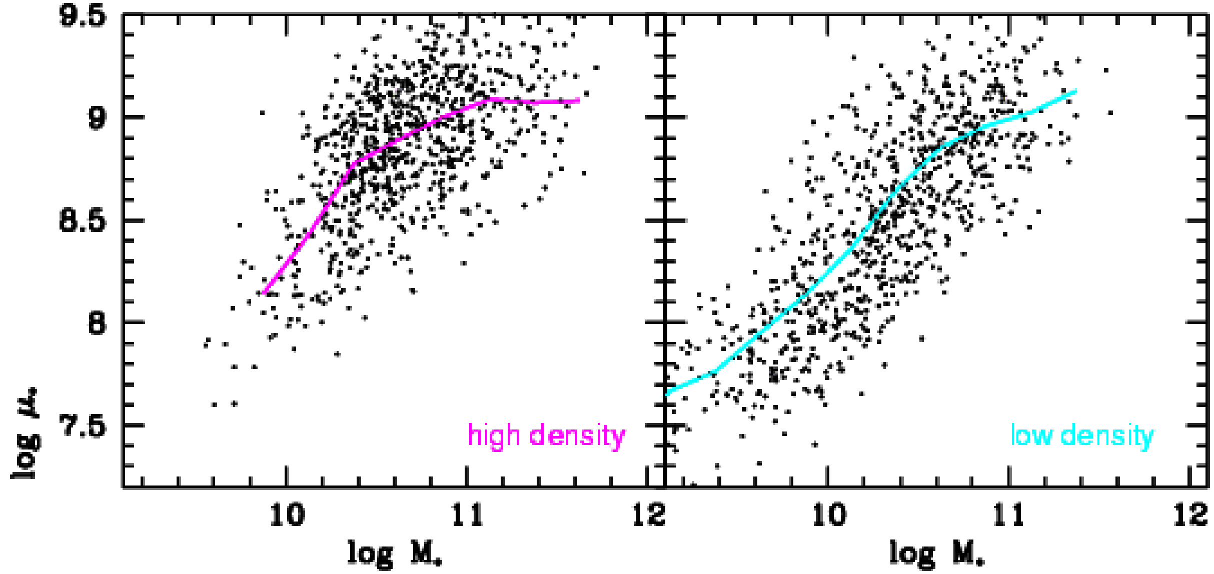
Kauffmann et al 2004

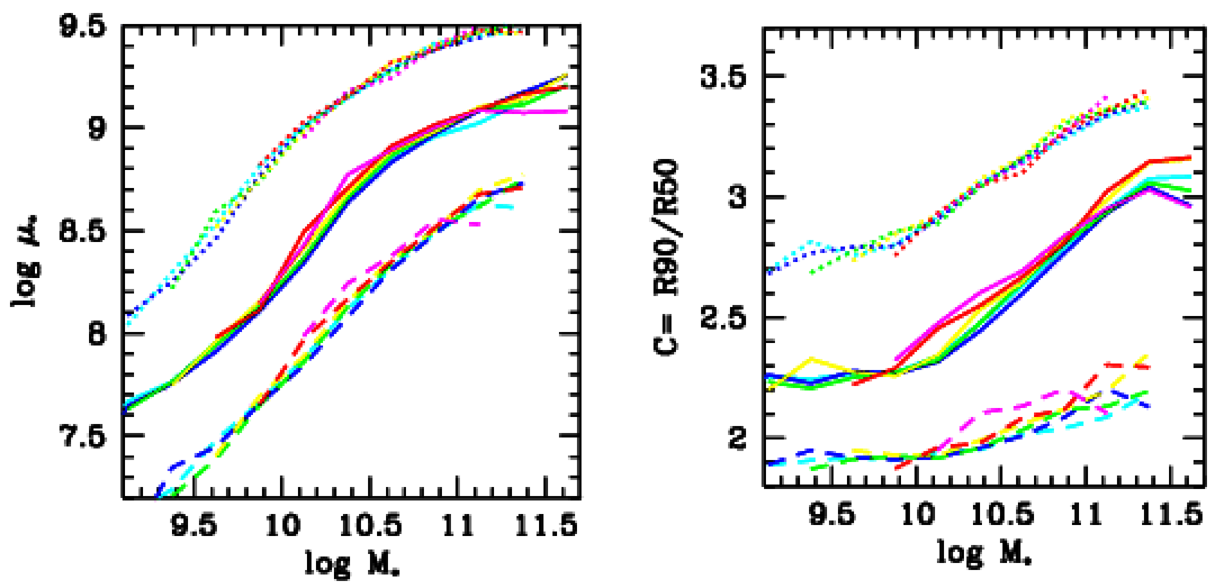



The stellar mass distribution of galaxies shifts to higher masses in higher density regions

However, the relation between galaxy structure and mass does NOT depend on density! There is NO morphology density relation at fixed stellar mass!

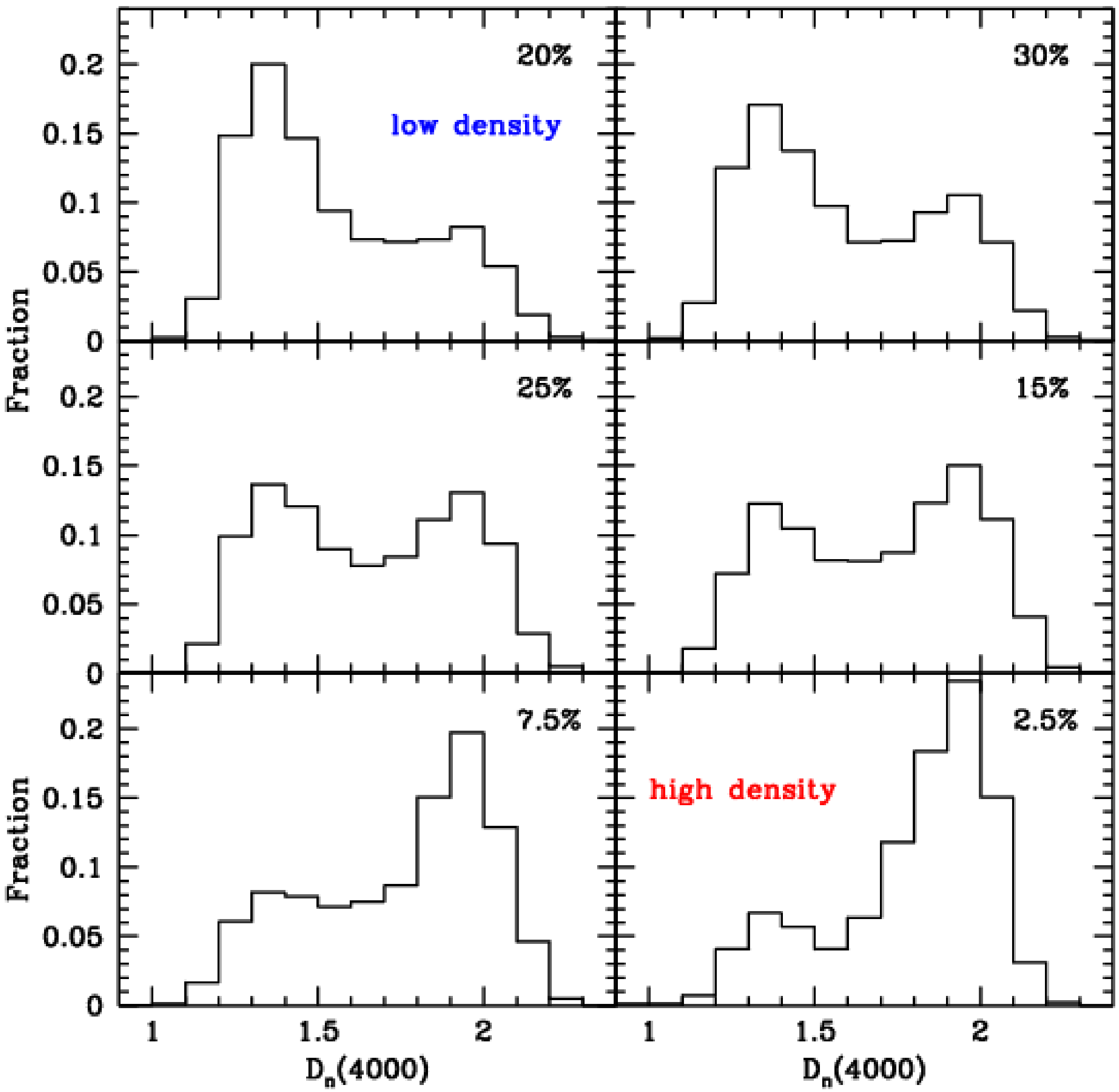
Kauffmann et al 2004



# The Dependence of Stellar Age on Local Density

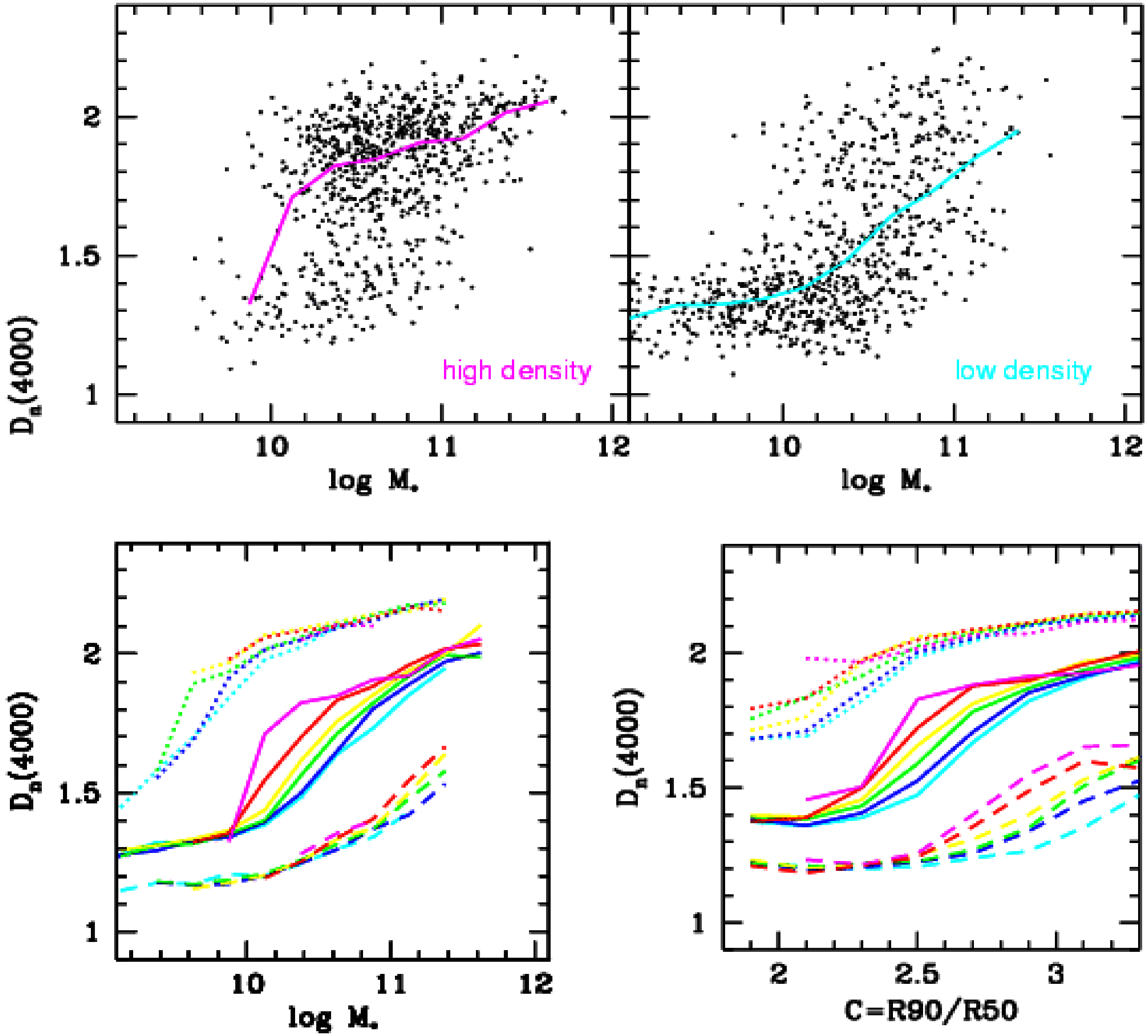
Kauffmann et al 2003




Galaxies in lower density regions have younger stellar populations

The relation between age and galaxy mass/structural parameters exhibits a *strong* dependence on density.

Kauffmann et al 2004

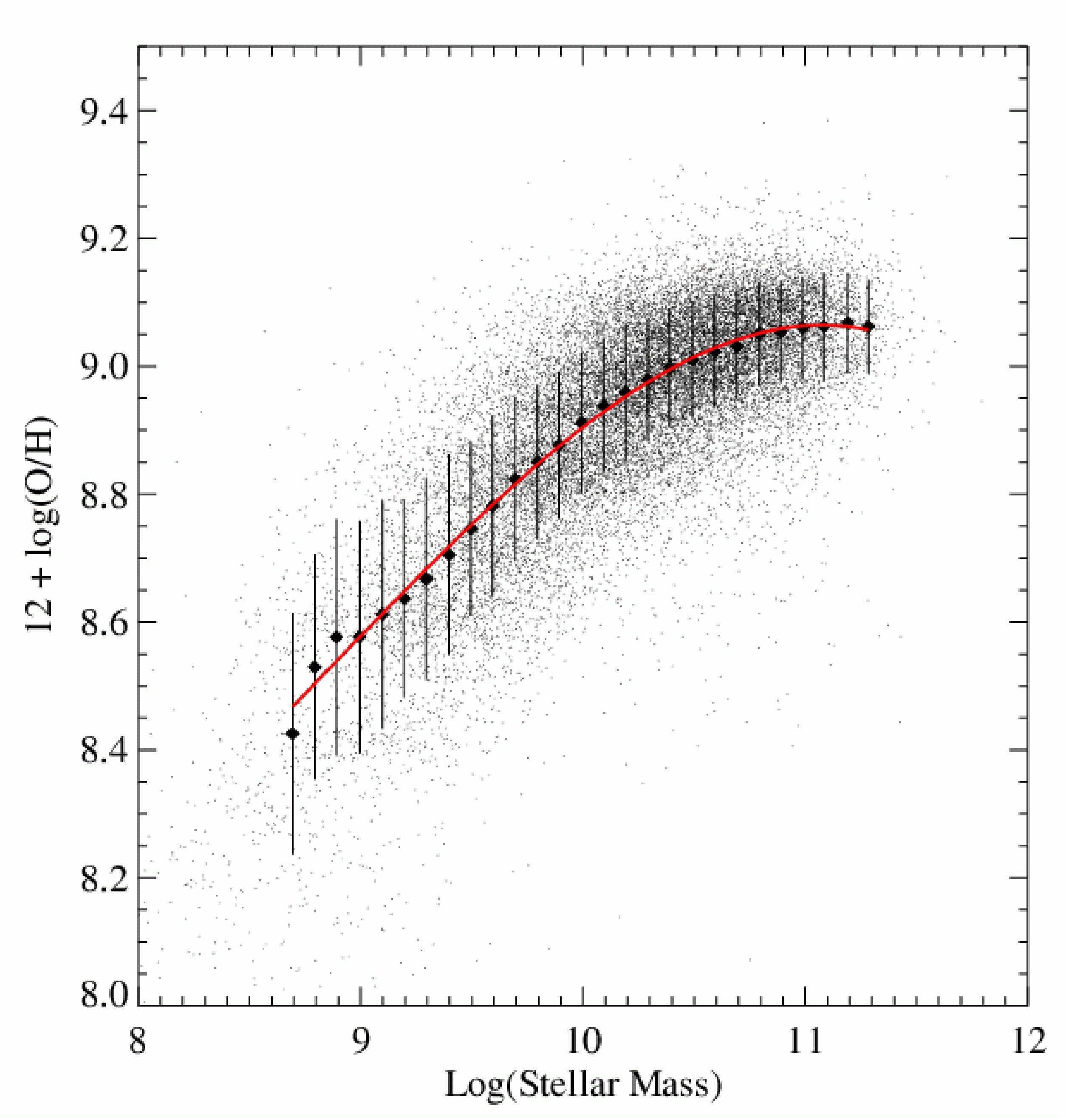


# The Mass-Metallicity Relation in SDSS

The RMS scatter is only +/- 0.1 dex

A pronounced turnover is evident at high mass

Tremonti et al 2003



# Testing Closed Box Chemical Evolution Models:

## Estimating the gas mass fraction

We have no *direct* knowledge about the gas mass fraction but we can approximate it

$H\alpha_{dered} \rightarrow$ SFR (in the fiber)

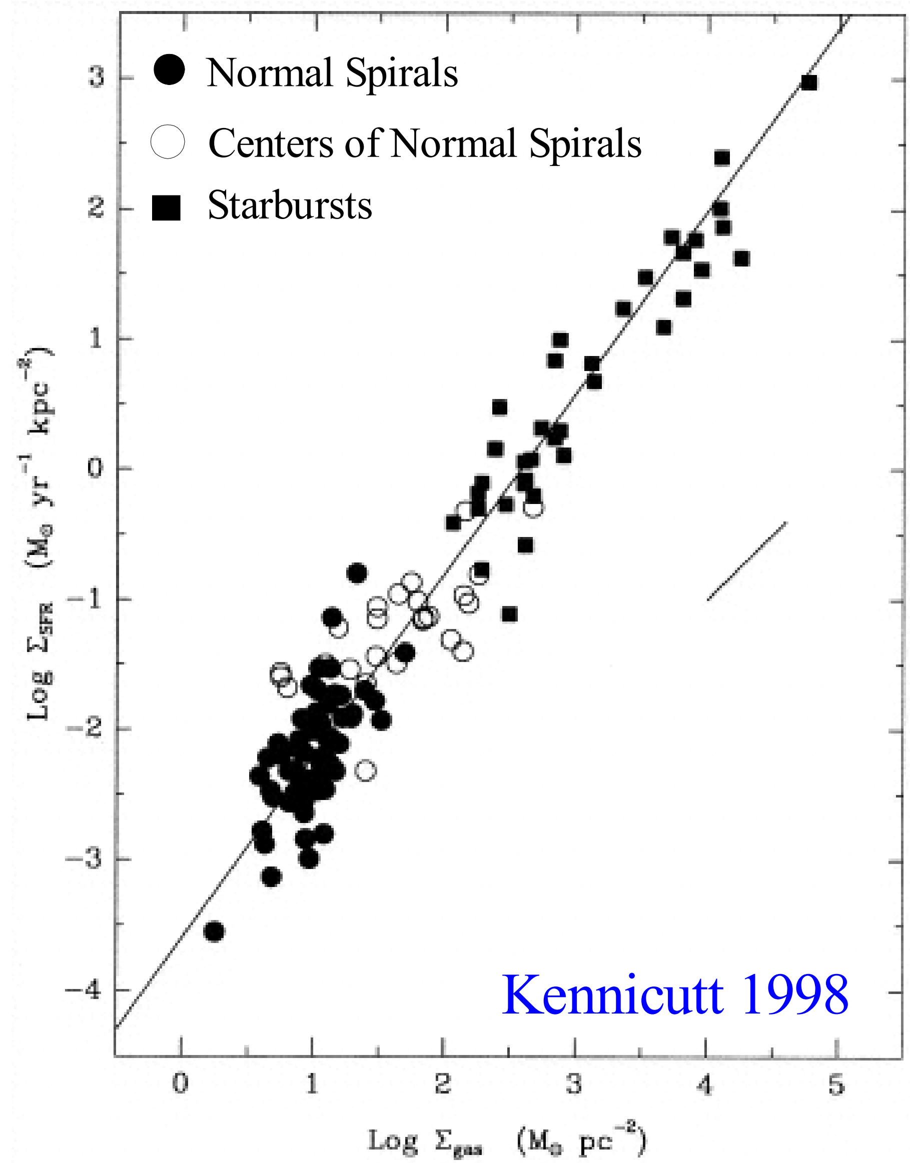
$\Sigma_{SFR} = SFR / A_{fiber}$

$\Sigma_{SFR} \rightarrow \Sigma_{gas}$

$\Sigma_{star} = (M/L)\ L_{z\ fiber} / A_{fiber}$

$\mu_{fiber} = \Sigma_{gas} / (\Sigma_{gas} + \Sigma_{star})$

Tremonti et al 2003




Kennicutt 1998

# Testing Closed Box Chemical Evolution Models

$Z = y\, ln(1/\mu)$

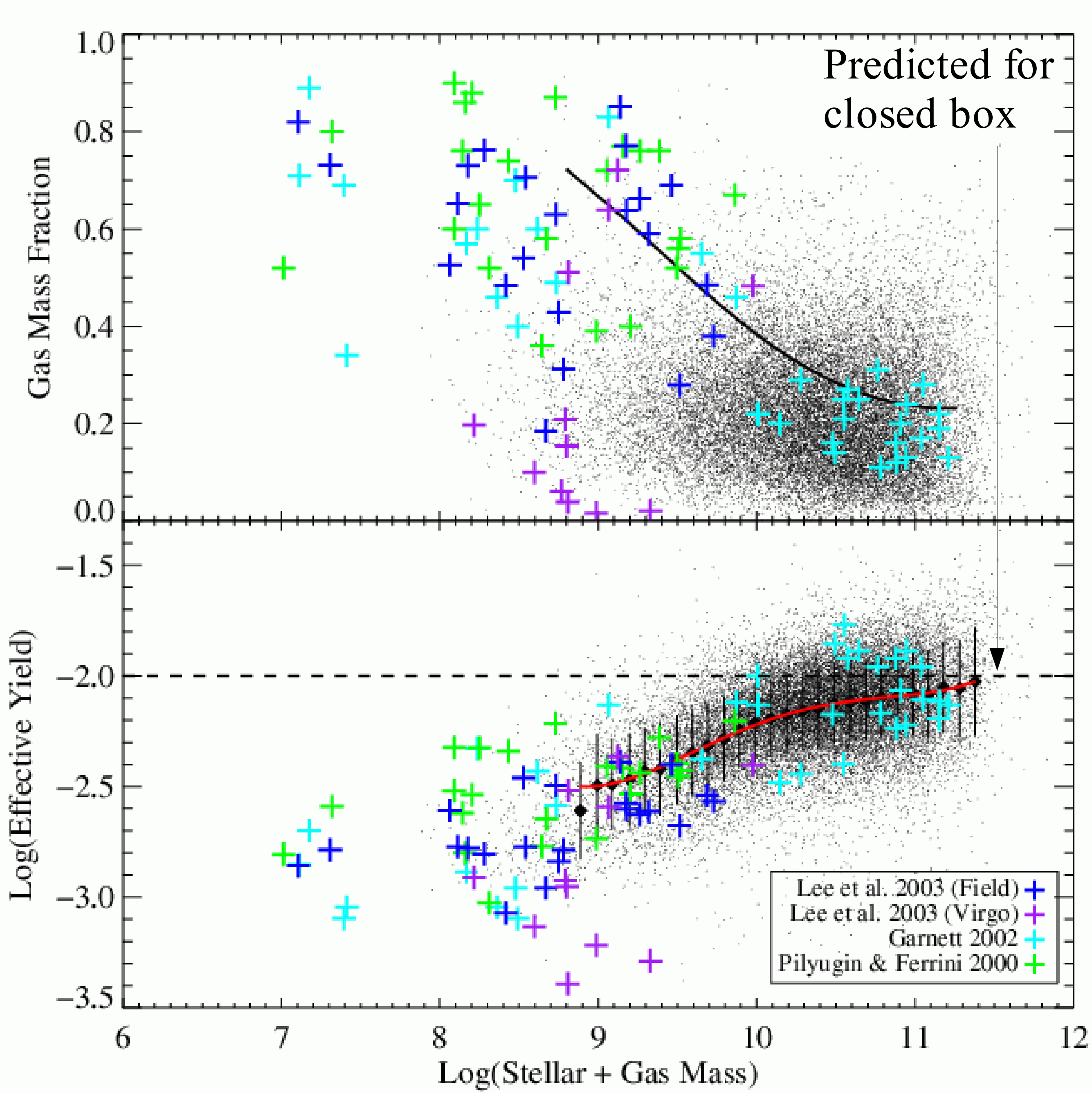
We define the effective yield:

$$y_{eff} = Z / ln(1/\mu)$$

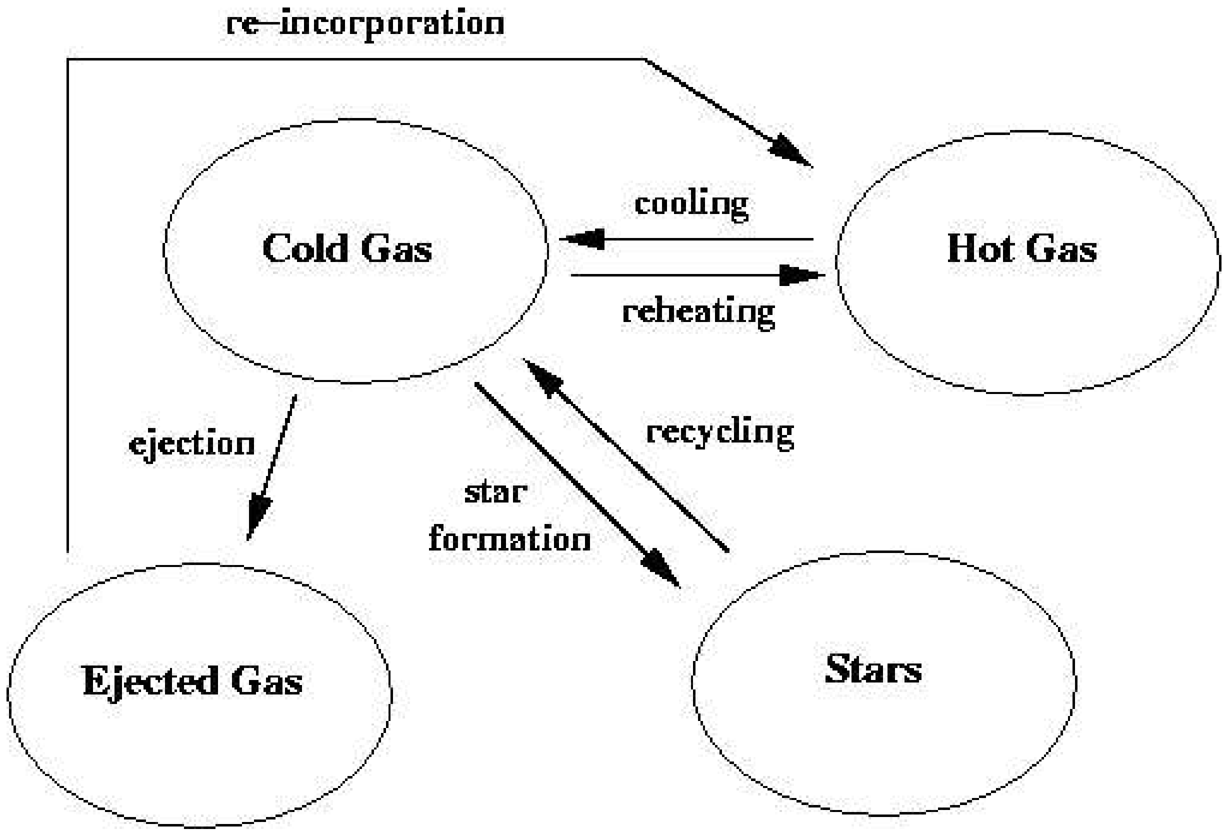
$y_{eff} = y_{true}$ when galaxies are closed boxes

*Evidence for metal loss below masses of $10^{10}\ M_{\odot}$*

Tremonti et al 2003



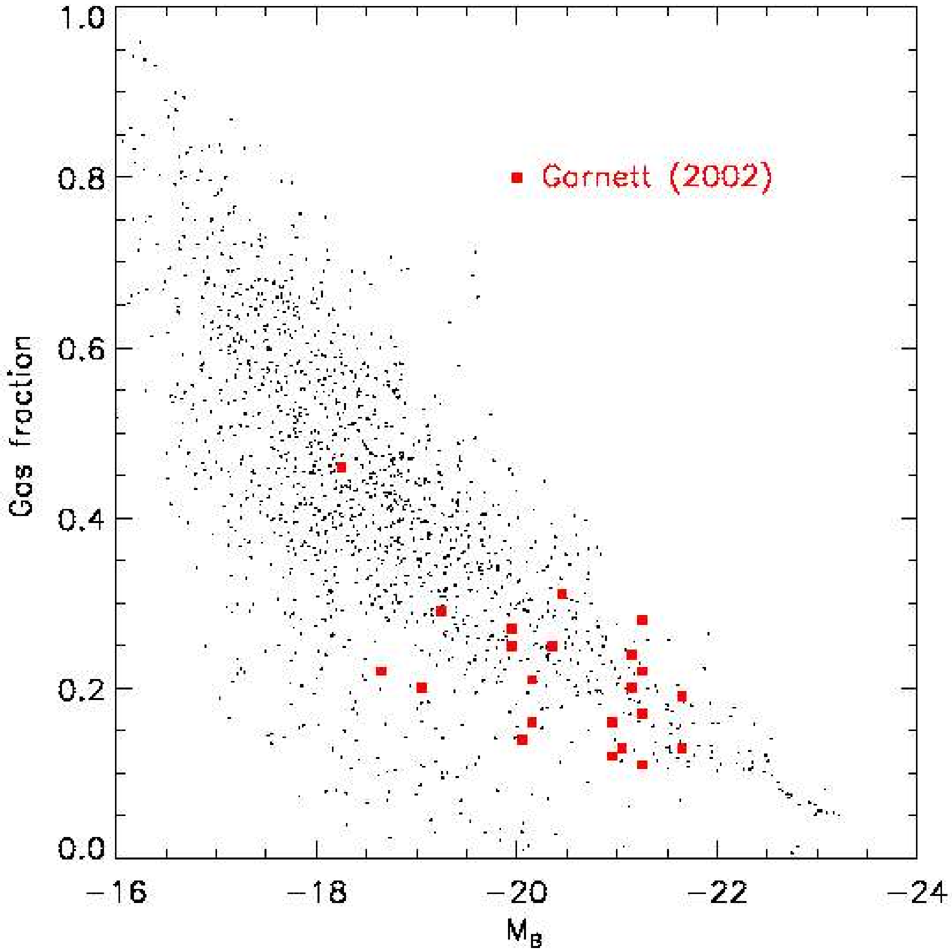
# Modelling metal enrichment requires following many mixing and exchange processes

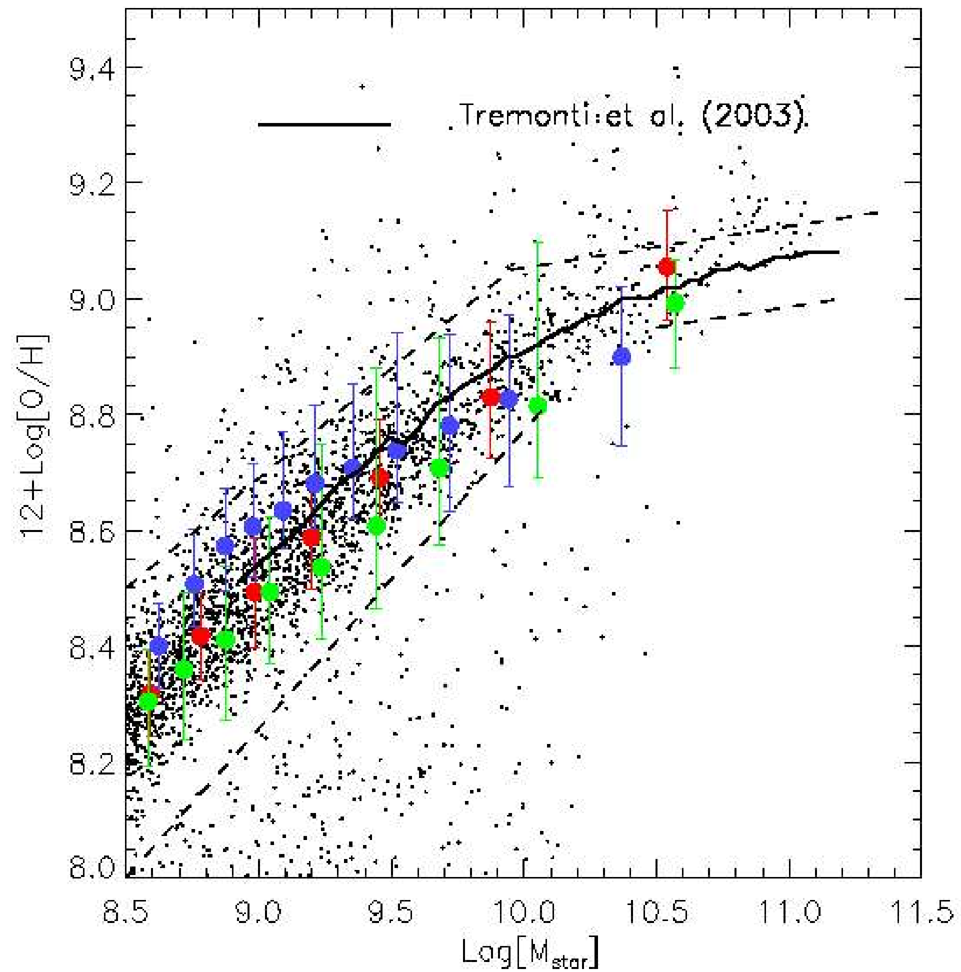



De Lucia et al 2003

# Modelling the enrichment of a cluster and its galaxies

De Lucia et al 2003



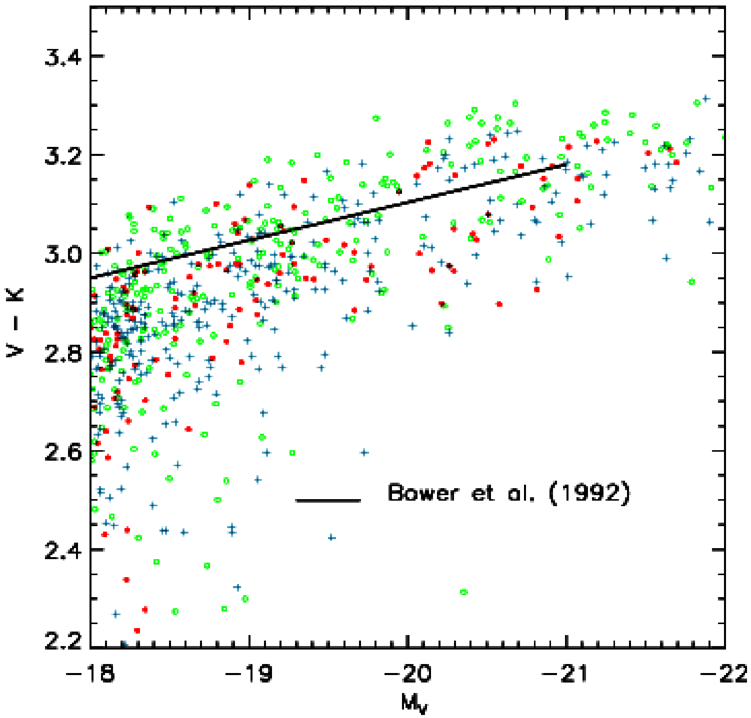



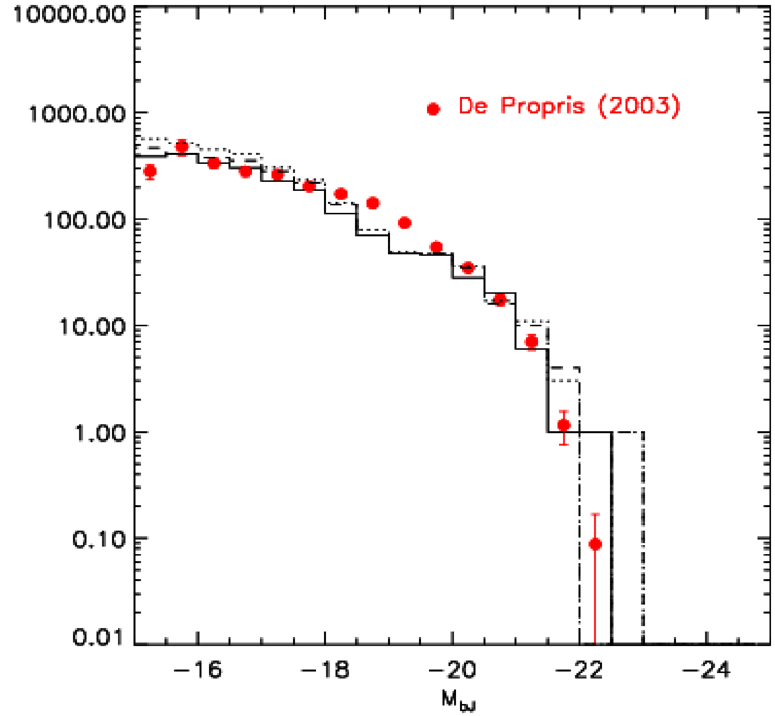

Reproducing the observed mass-metallicity and luminosity-gas fraction relations requires star-formation efficiency to increase with $V_{circ}$

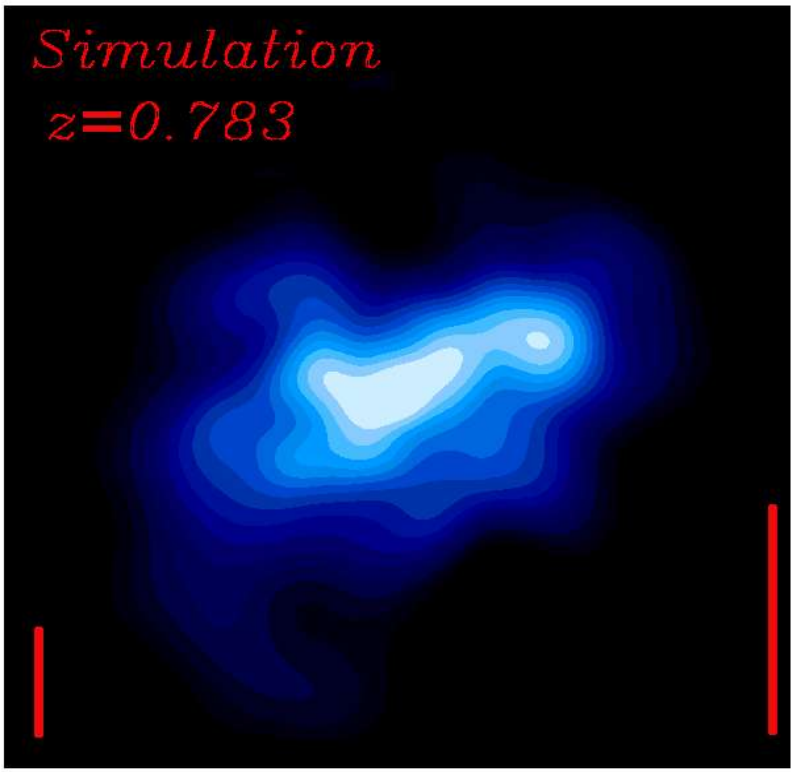
Reproducing the mean metallicities of the galaxies and the ICM requires an (overly) high yield and a high ejection efficiency

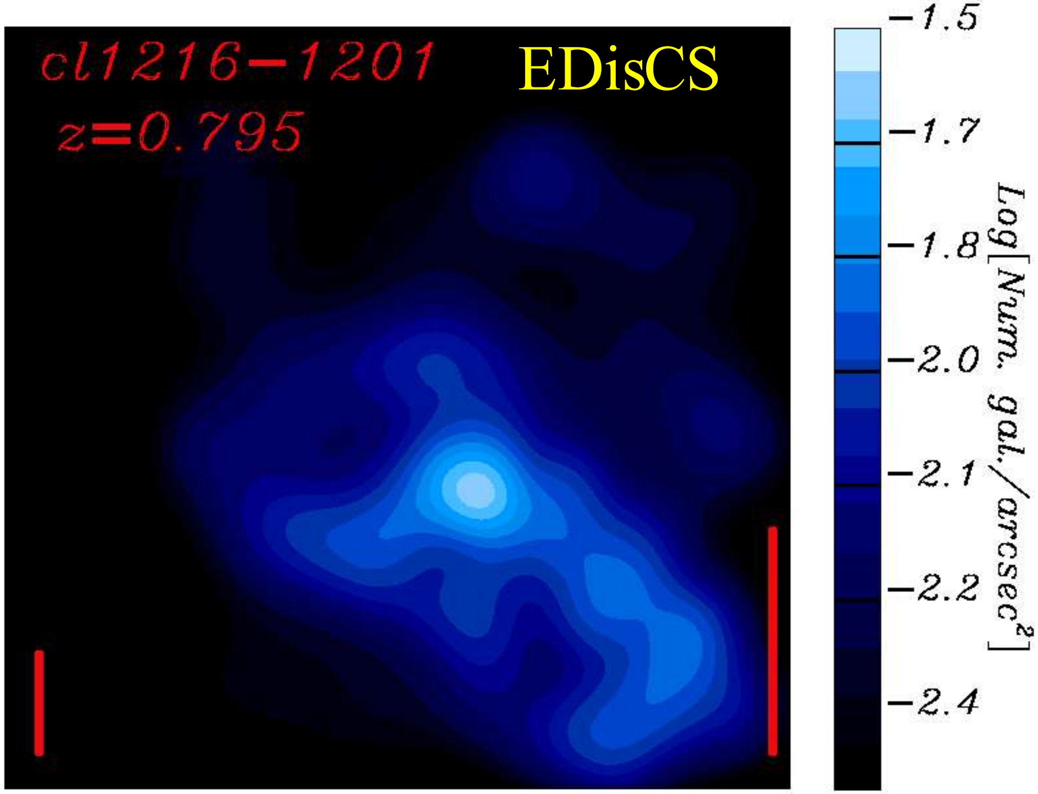
# Simulated cluster properties

De Lucia et al 2003



# Critical issues for galaxy formation

- Origin of the bright and faint cutoffs in the luminosity function
- Relative prevalence of disks/spheroids -- violent/quiescent modes
- Sizes of disks and spheroids -- $J$ evolution, merging
- Efficiency/IMF of star formation -- understanding down-sizing
- Efficiency of feedback -- heating/enrichment of galaxies/IGM
- Relation of SMBH growth to galaxy formation -- QSOs/starbursts

Interpretation of large multiwavelength datasets will require careful quantitative analysis using detailed physical models in the context of a standard structure formation paradigm