Galaxy Systems in the Optical and Infrared

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Plan of the lectures:

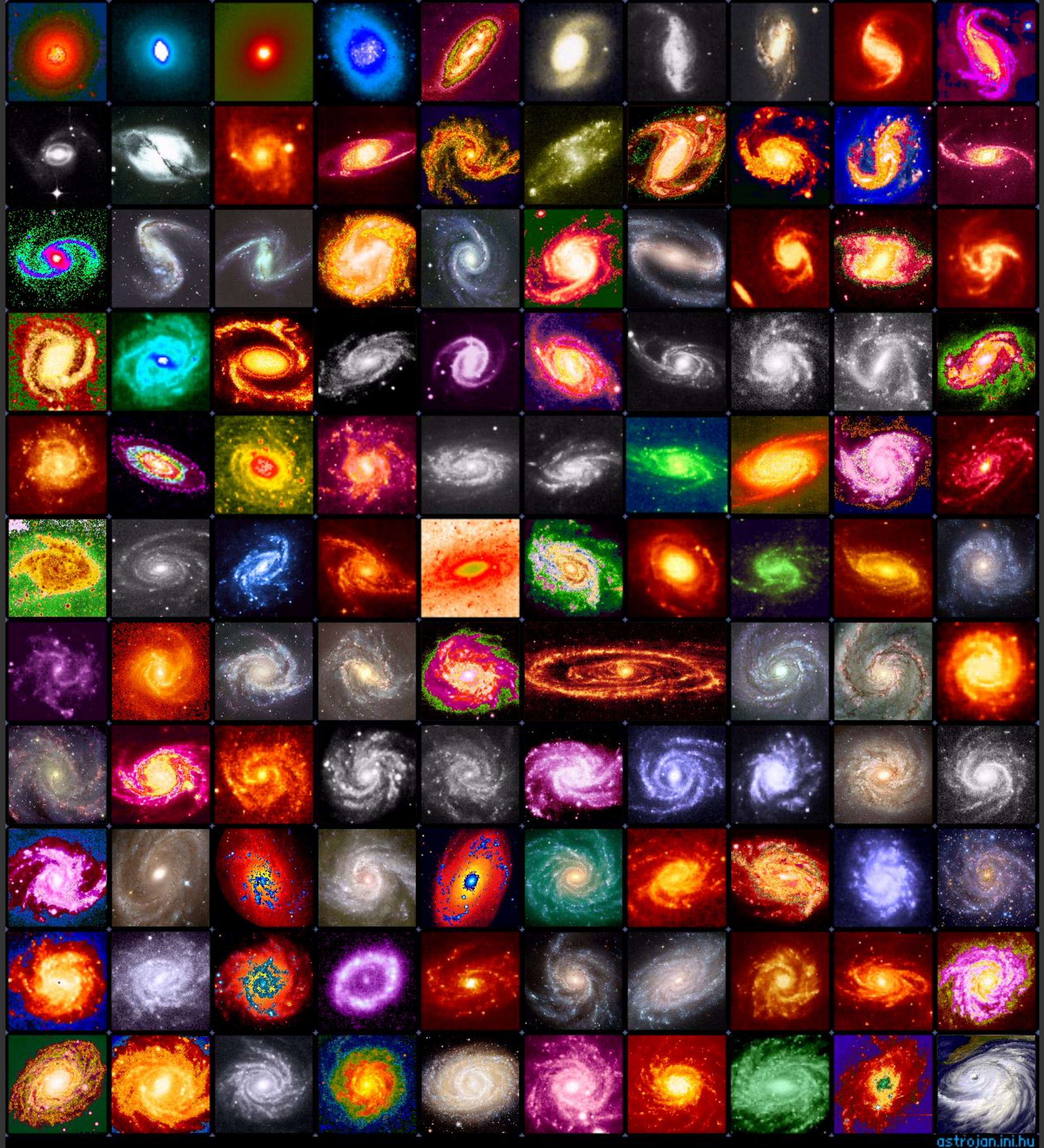
I. Identification, global properties, and scaling relations

II. Structure and dynamics

III. Properties of the galaxy populations

Introduction

The most striking characteristics
of the cluster galaxy population:
its morphology mix



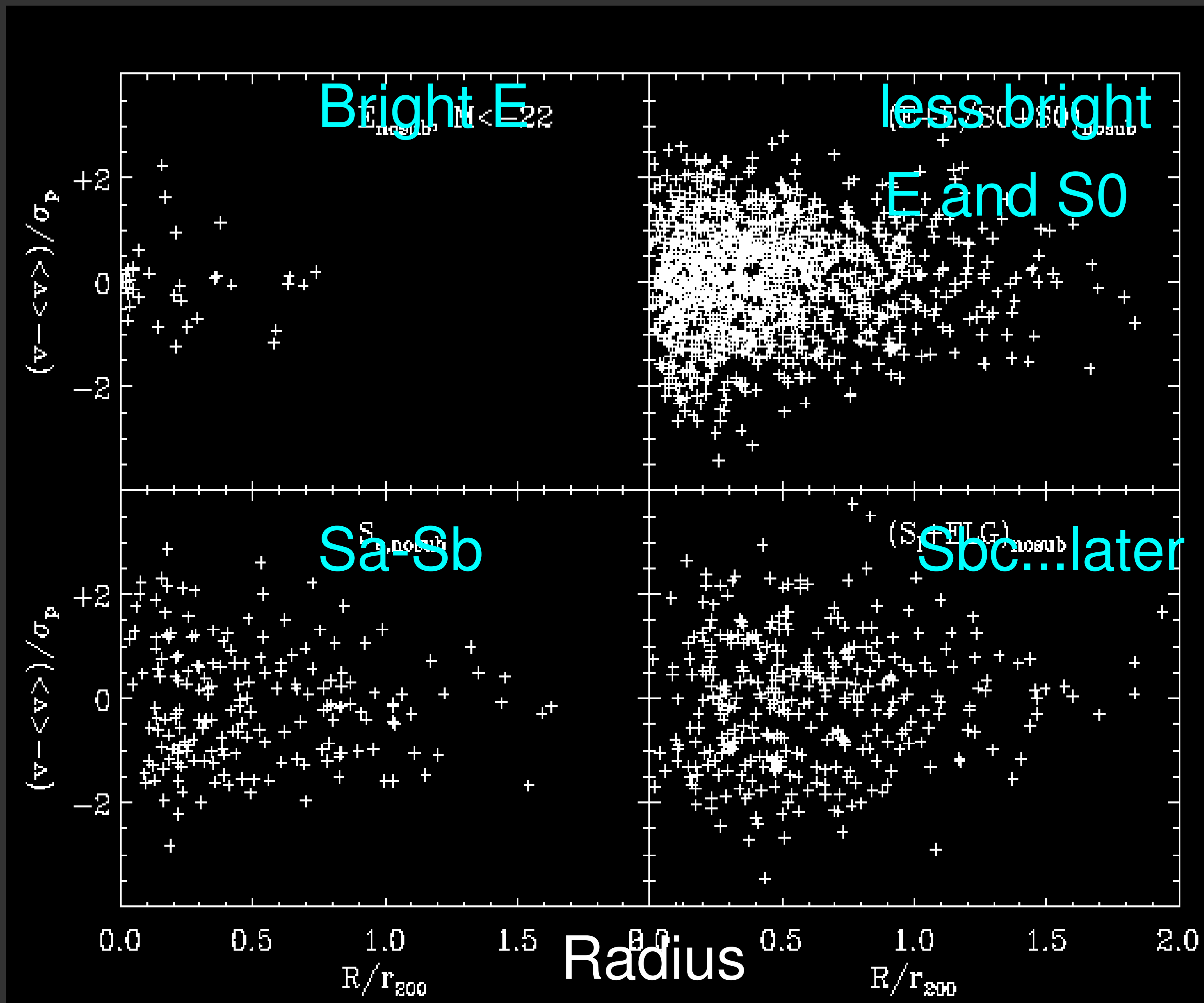
Field

Cluster

Morphology+Luminosity Segregation ⇨

segregation in projected phase-space

Velocity



(B.+02)

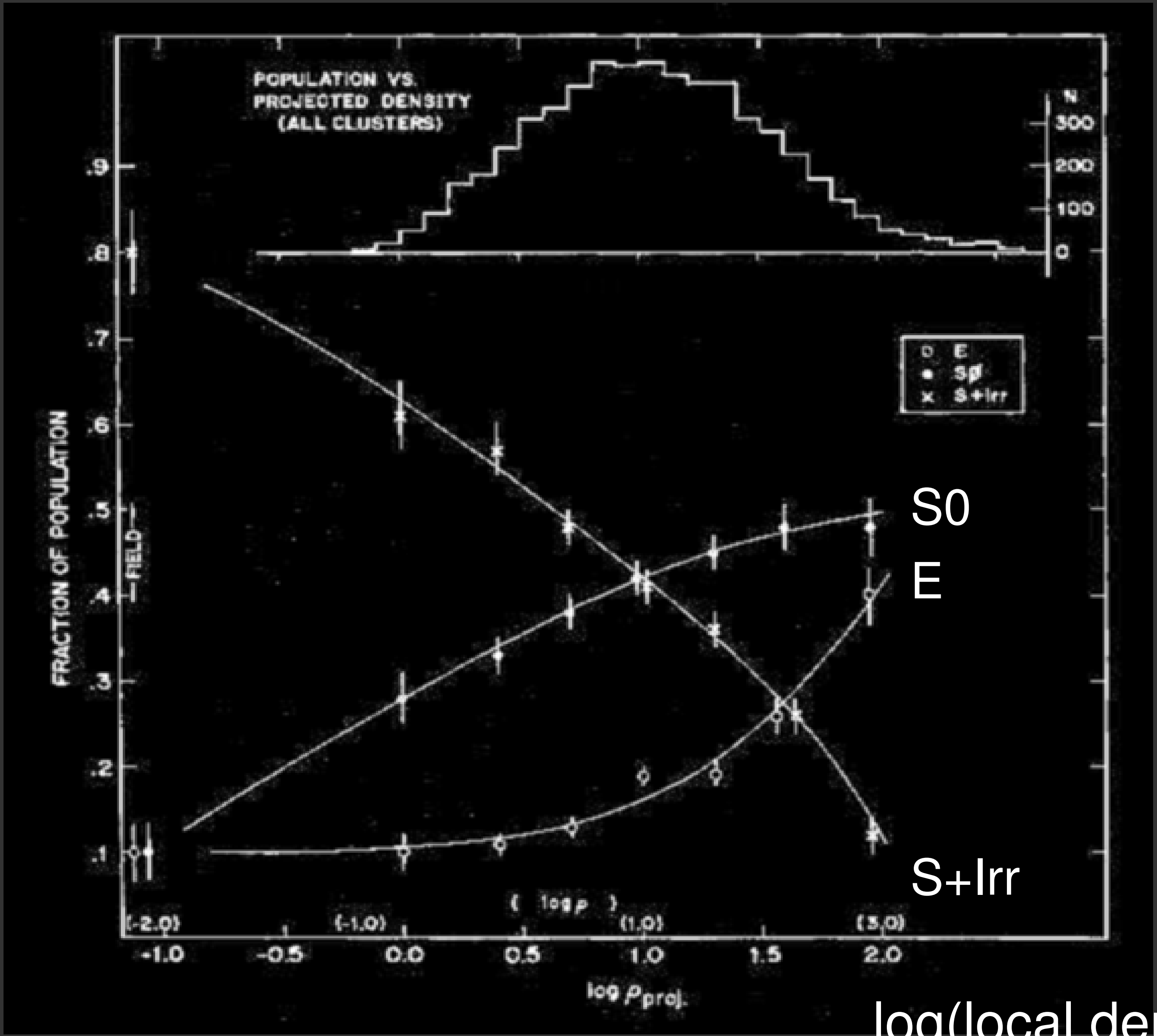
Why do the galaxies care about
the density of the environment?

Analyse the properties of
cluster galaxy populations
in relation to their environment
as a function of redshift

$\Rightarrow$ mechanisms of galaxy evolution

The properties of cluster galaxies: morphologies

Regular trend of morphology change with density



(Dressler 80)

Fraction

S0

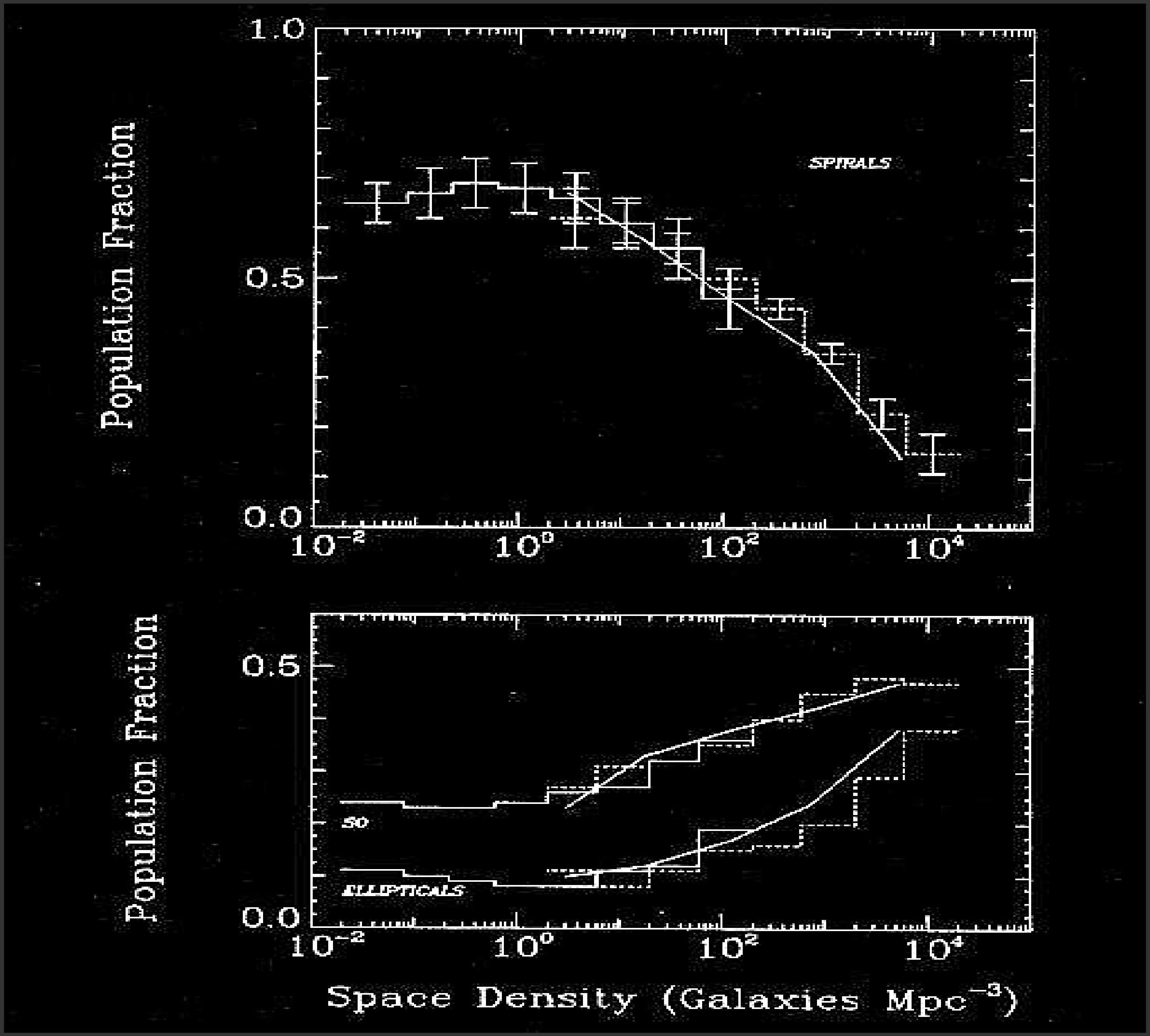
E

S+Irr

log(local density)

Regular trend of morphology change with density

(Postman & Geller 84)



Spirals

S0

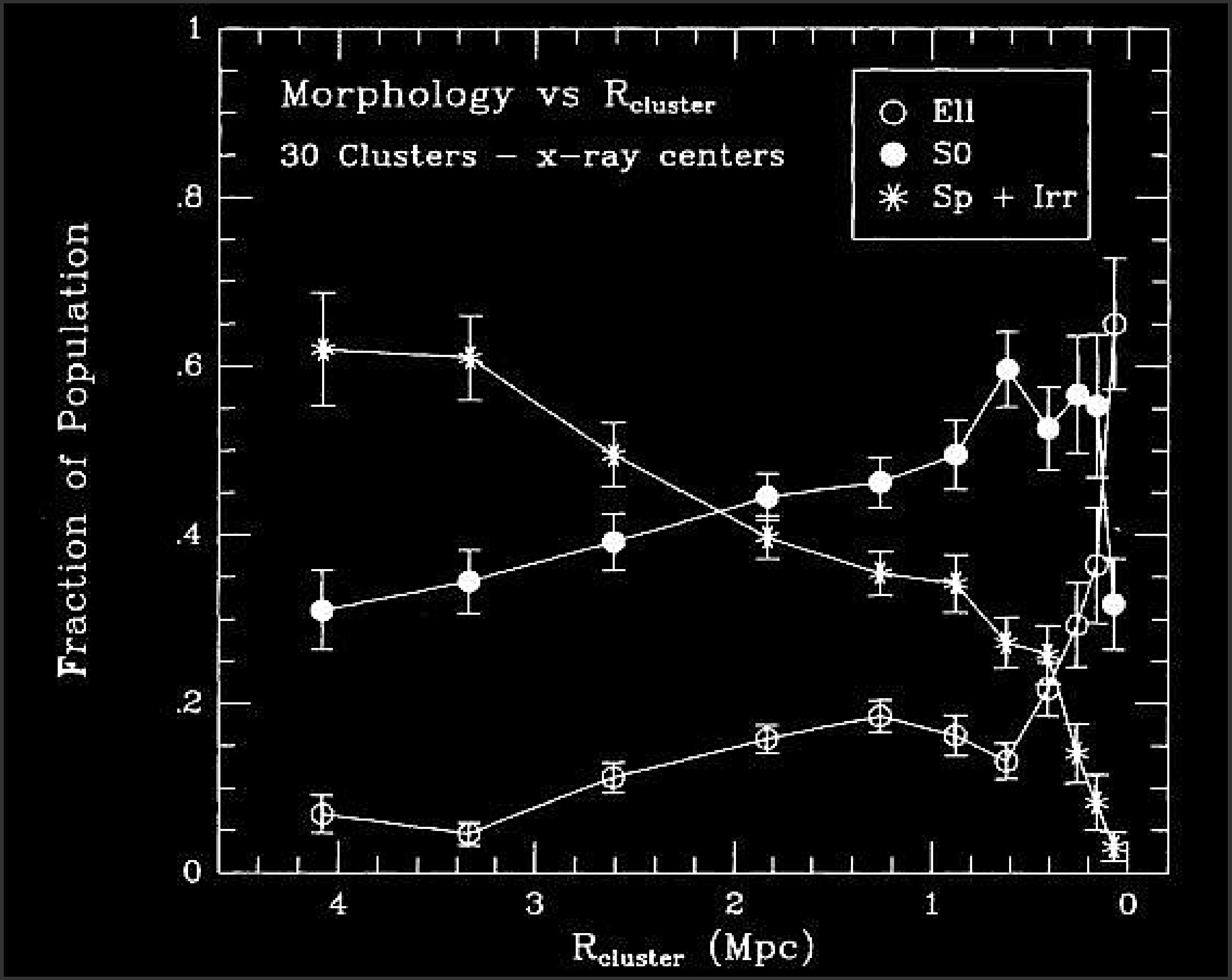
Ellipticals

log(local density)

Another example of morphology vs. density

Regular trend of morphology change with radius

(Whitmore+93)



Ellipticals

S0

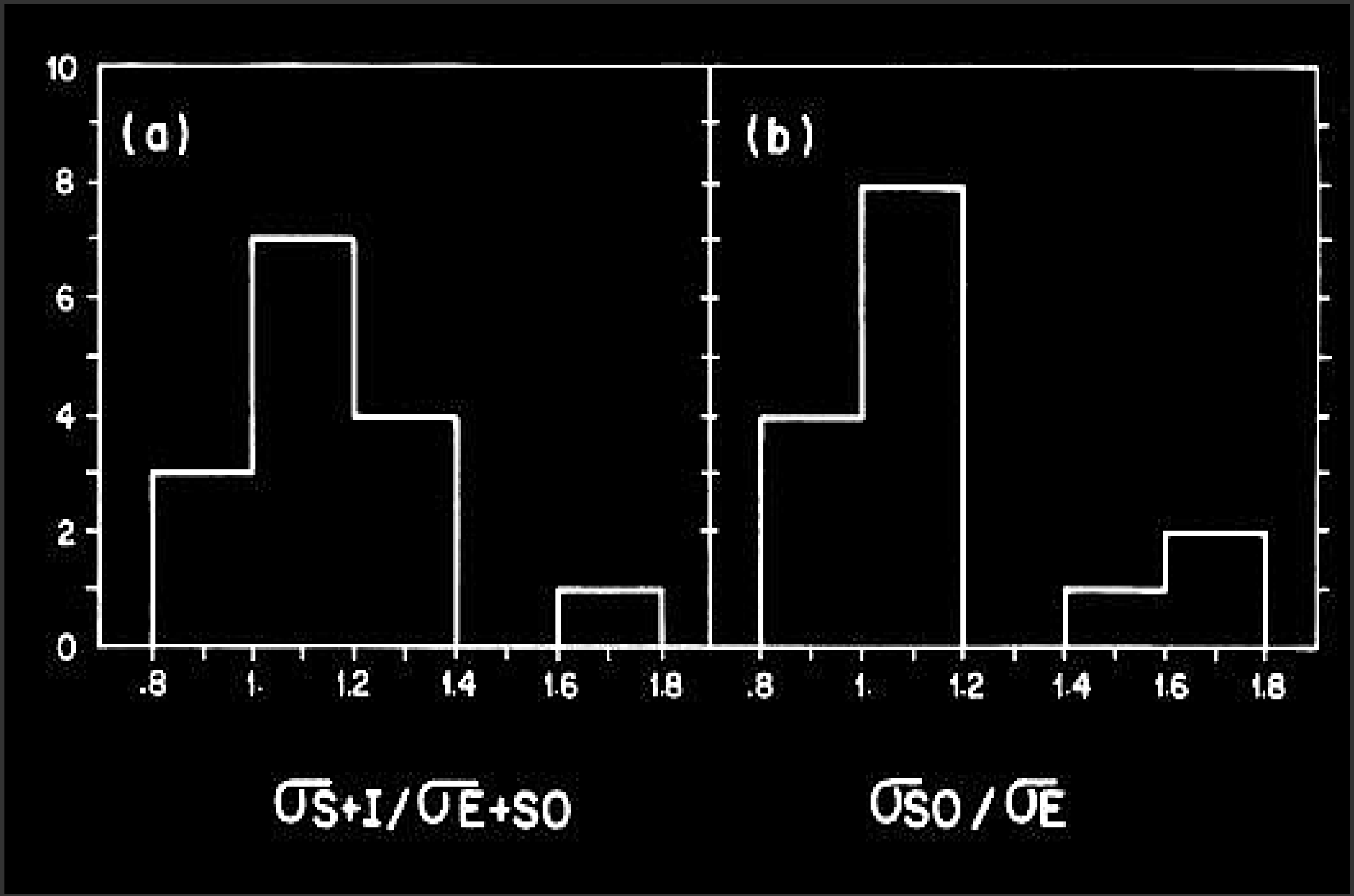
S+Irr

clustercentric distance

- Morphology-Density Relation (MDR)
- Morphology-Radius Relation (MRR)

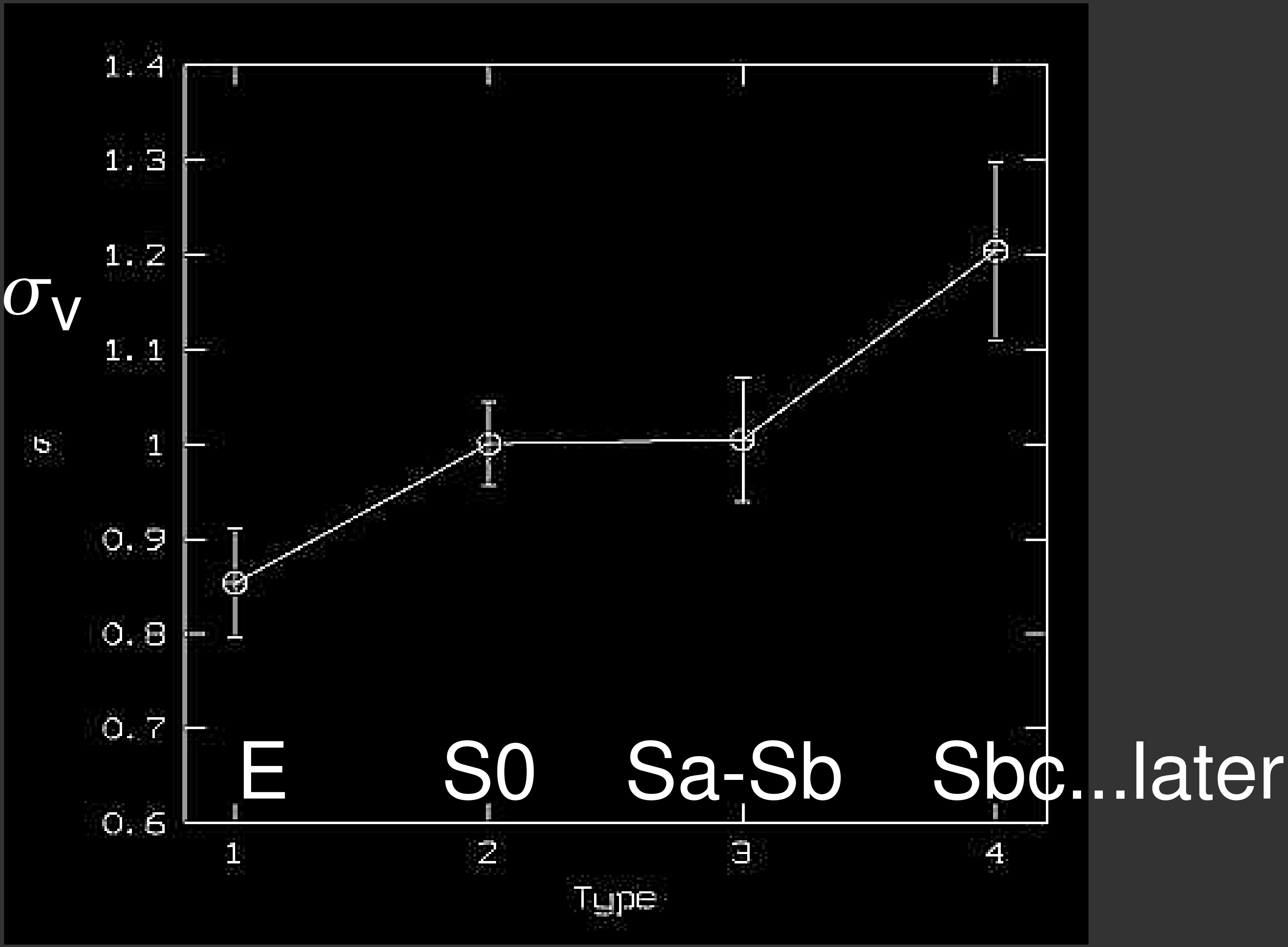
...but also:

- Morphology-Velocity Relation (MVR)



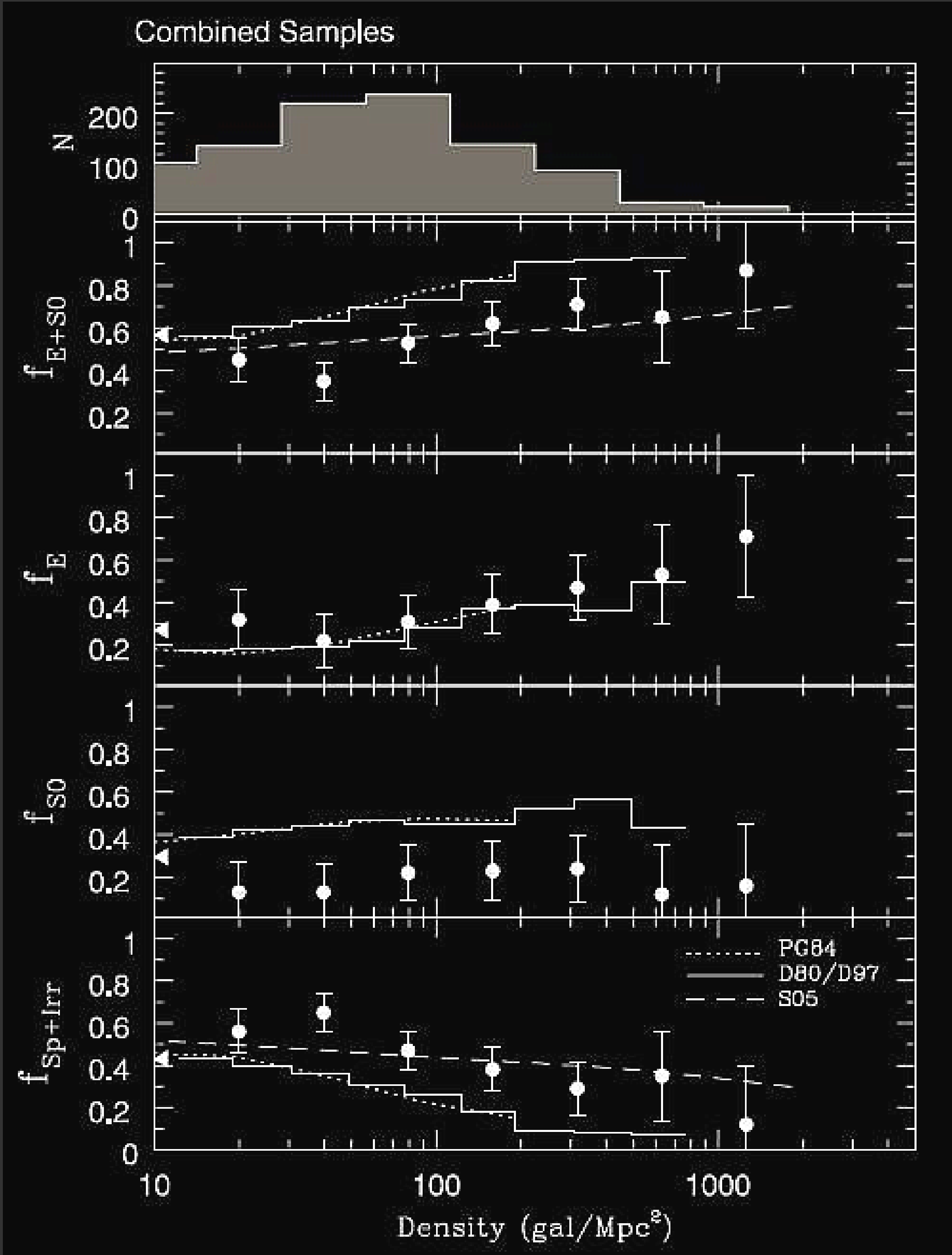
(Sodré+89)

Morphology-Velocity Relation (MVR)



(Adami+98)

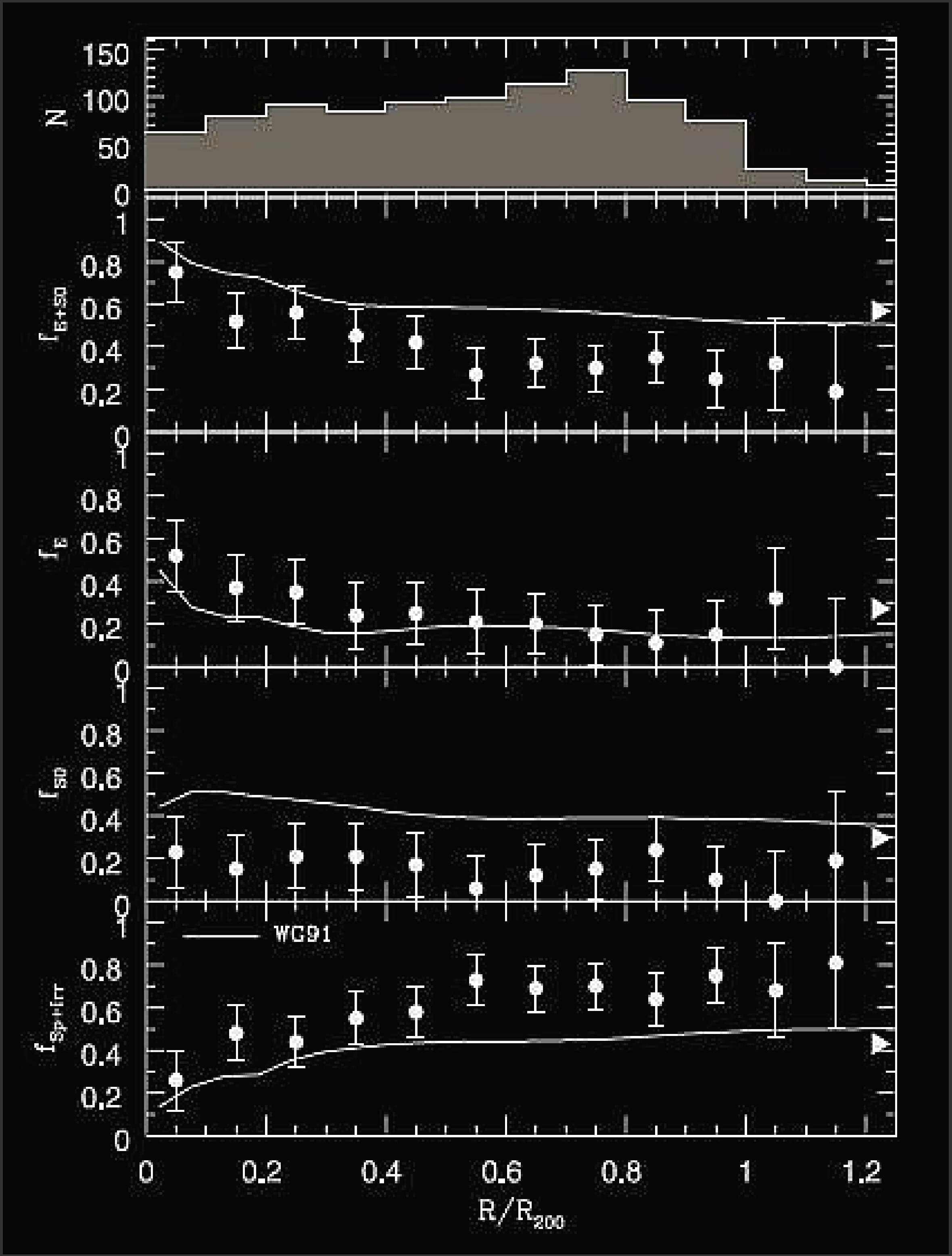
Another example of velocity vs. morphology



The MDR at z~1:

still there, but
less S0, more S

(Postman+05)

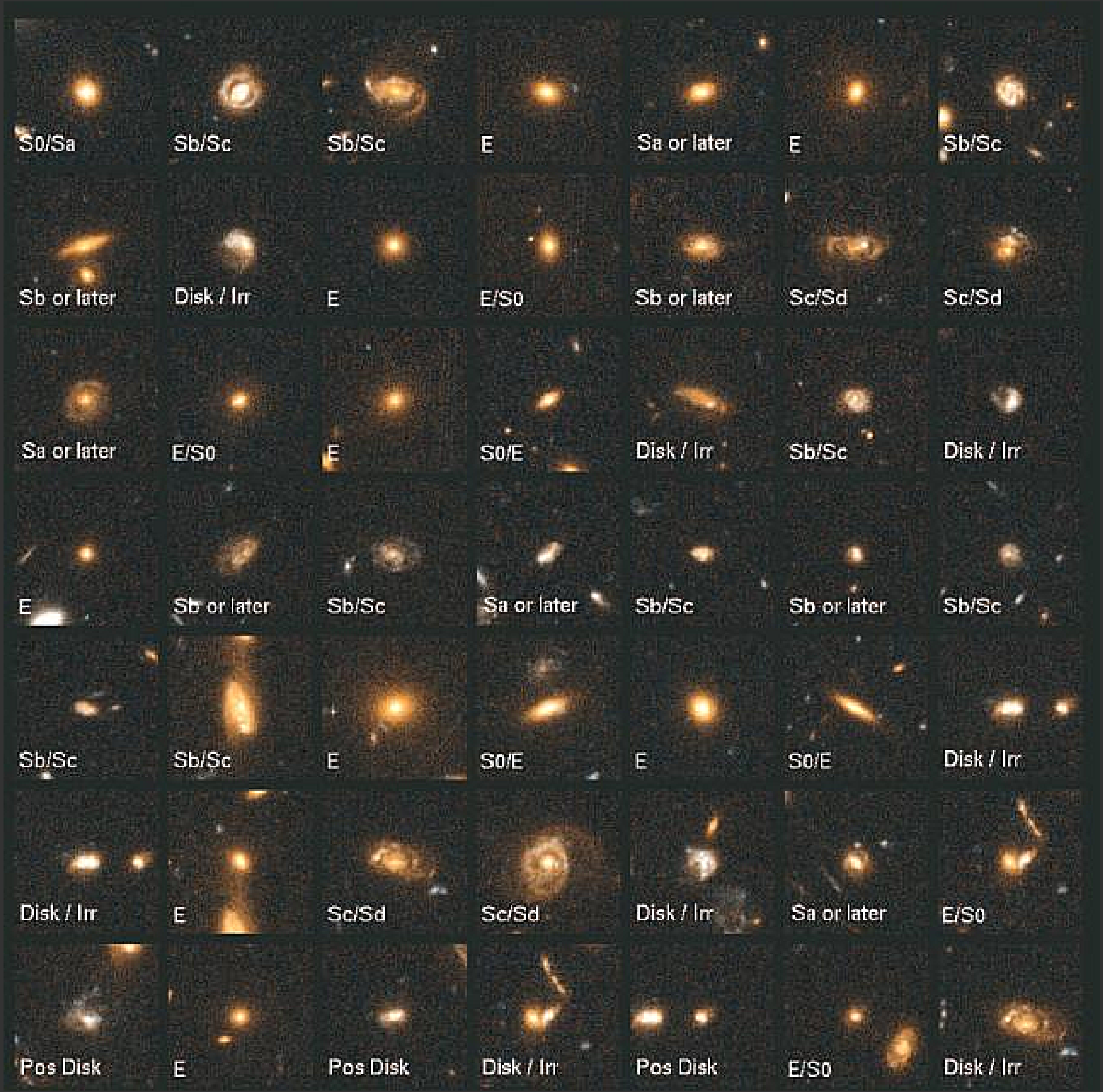


The MRR at z~1:

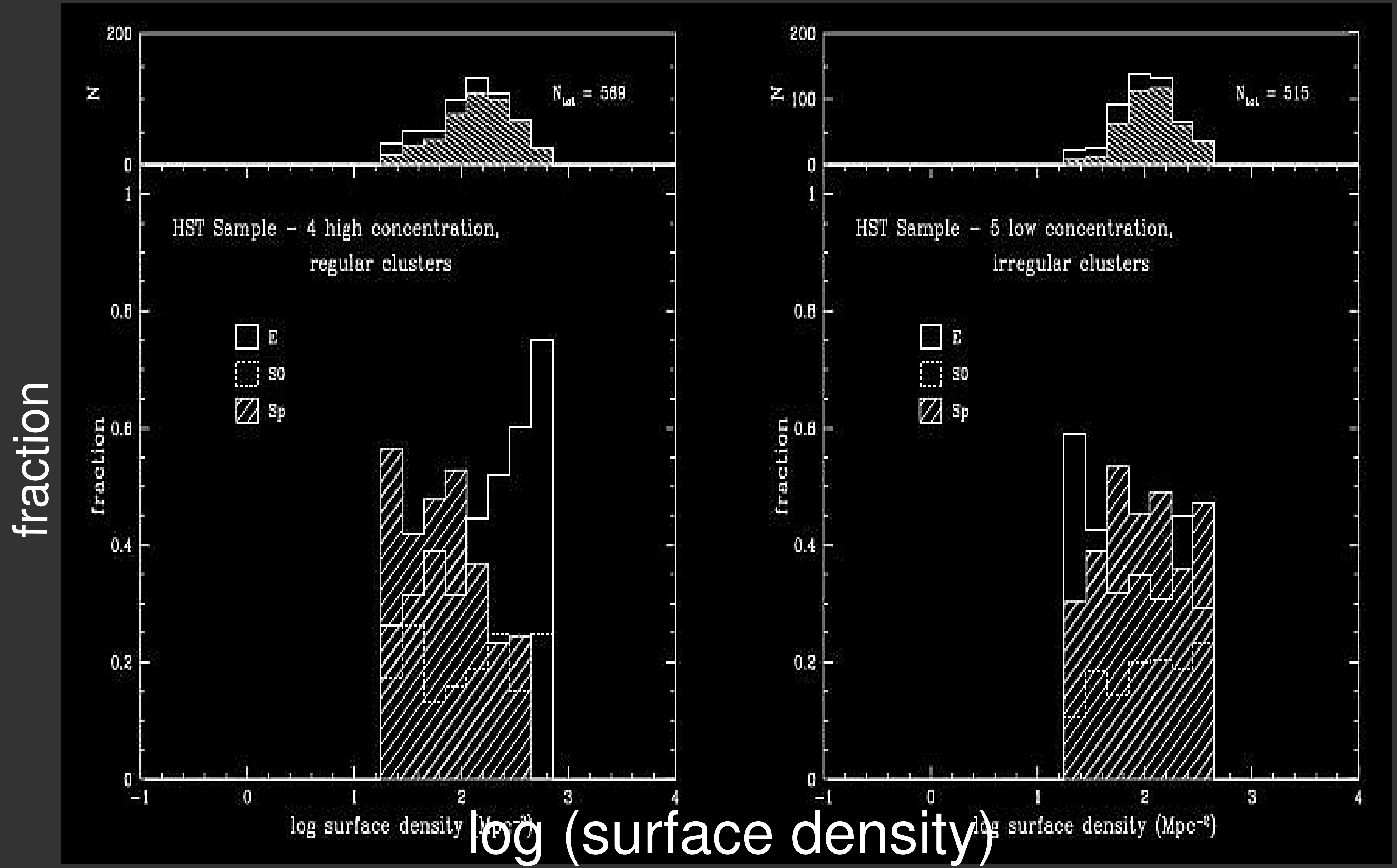
still there, but
less S0, more S

(Postman+05)

Brightest galaxies in two z~1 clusters (Postman+05)

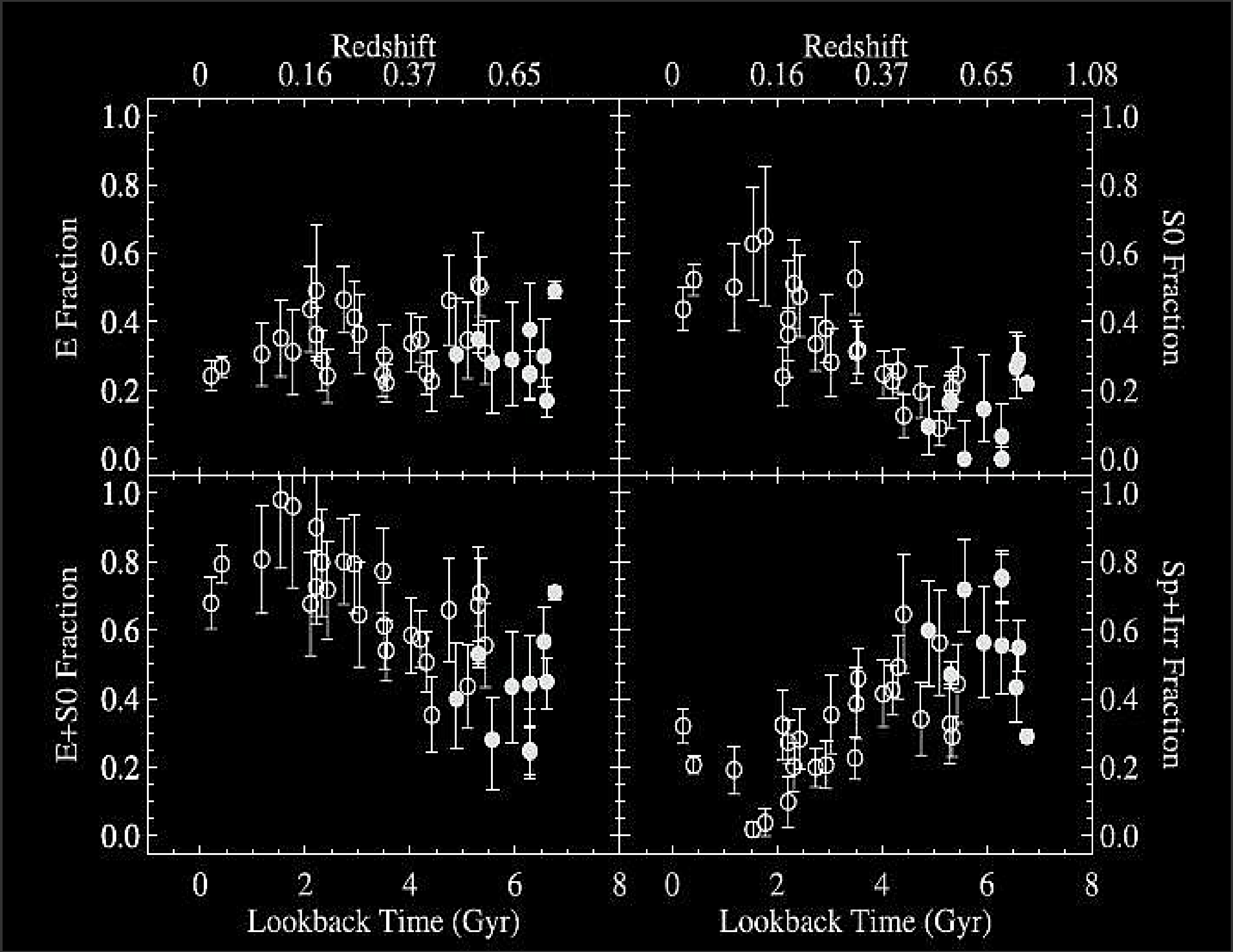


MDR not present in medium-z irregular clusters



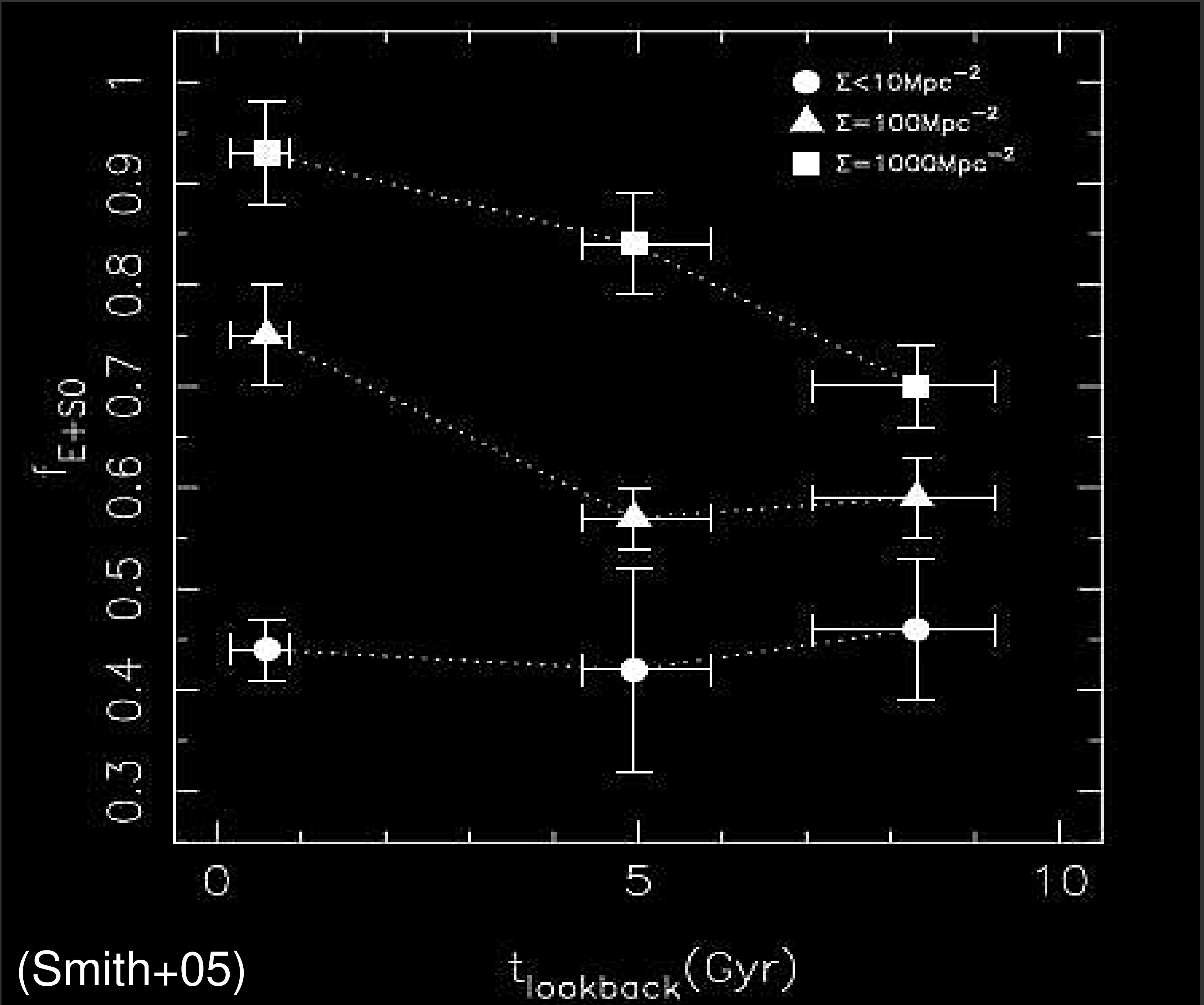
(Dressler+ 97)

Most MDR evolution occurs at z<0.5



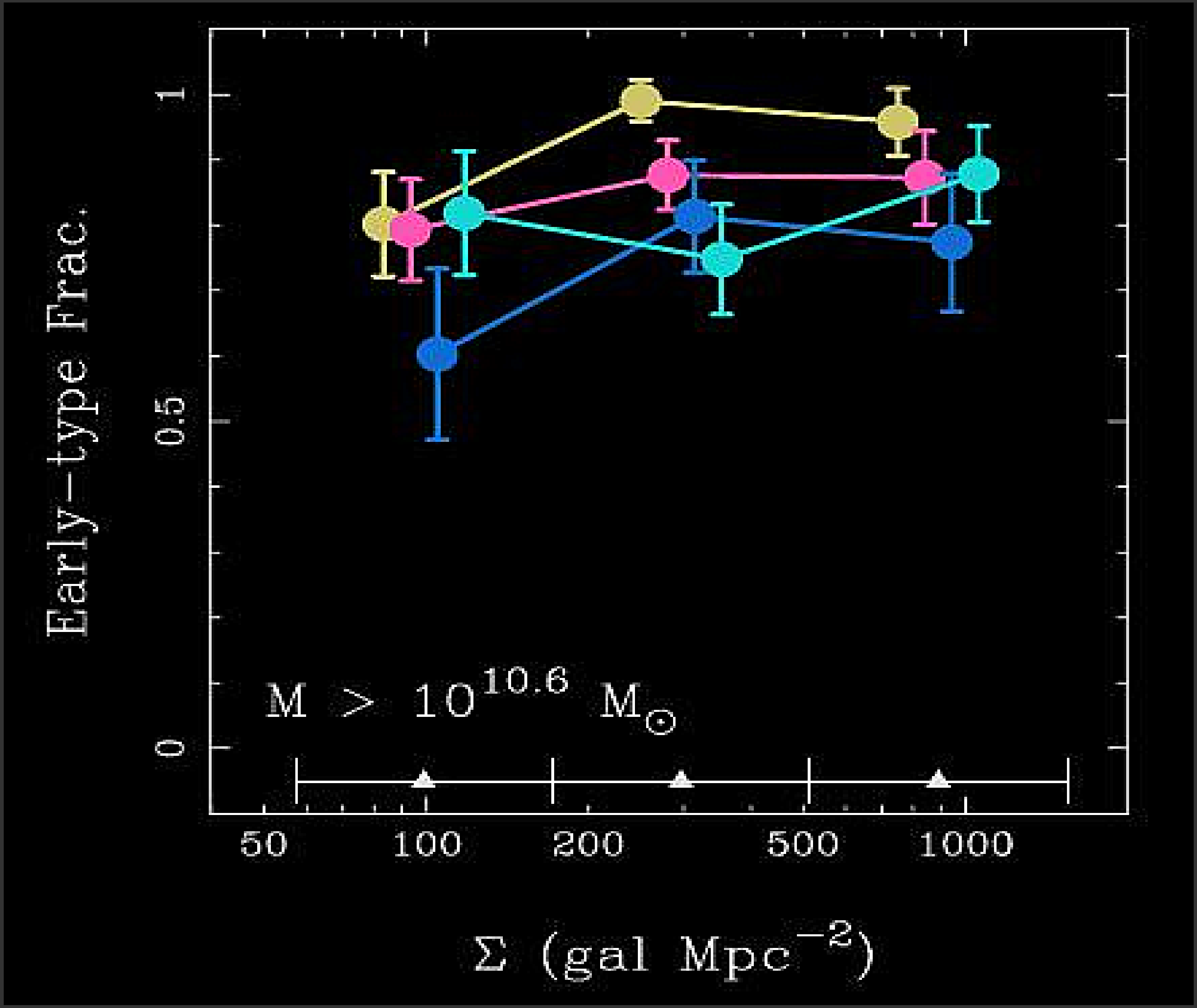
(Desai+07)

S0 form earlier in higher density regions



(Smith+05)

Less evolution for more massive galaxies



Redshifts:

0.02

0.33

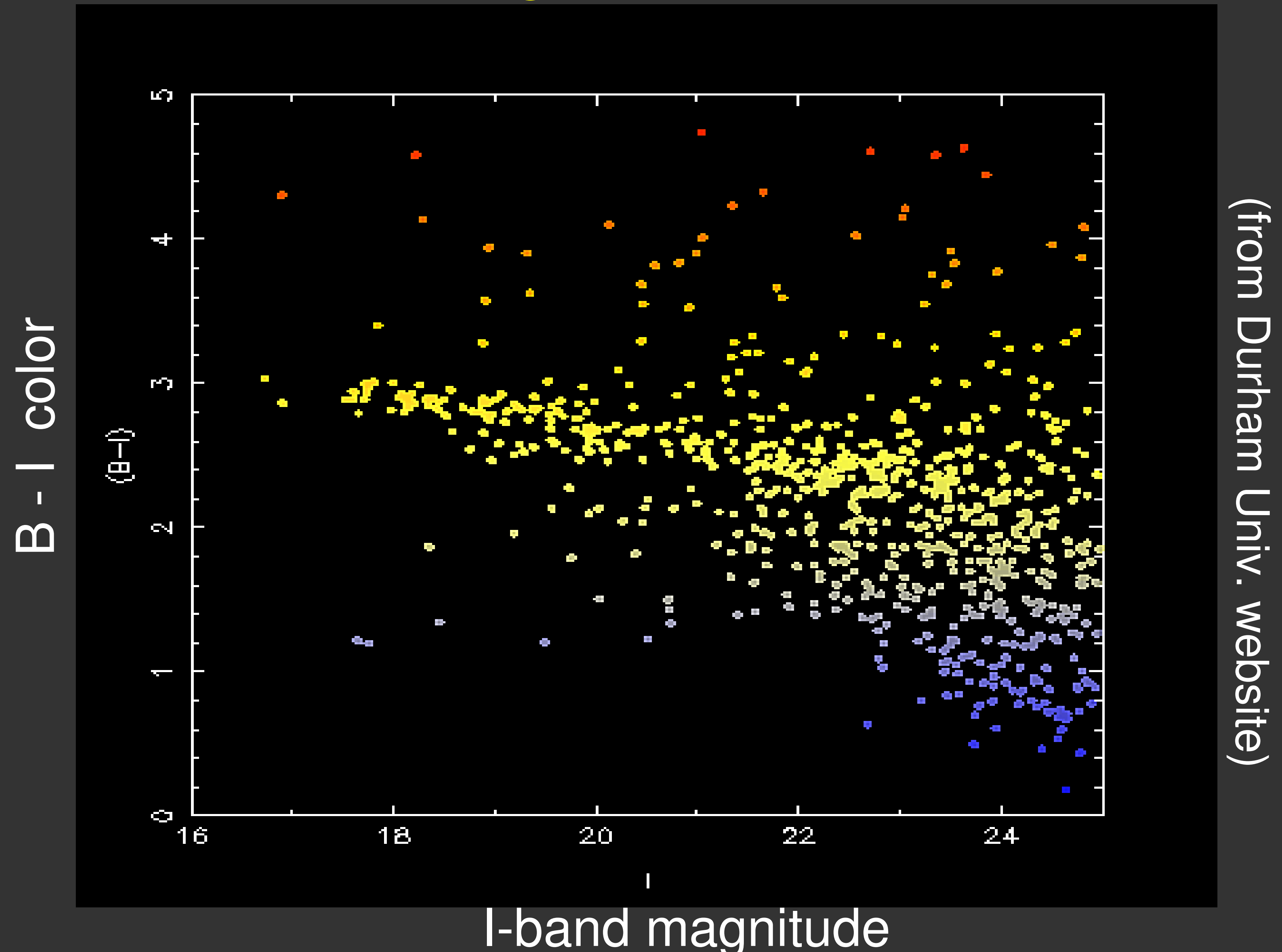
0.59

0.83

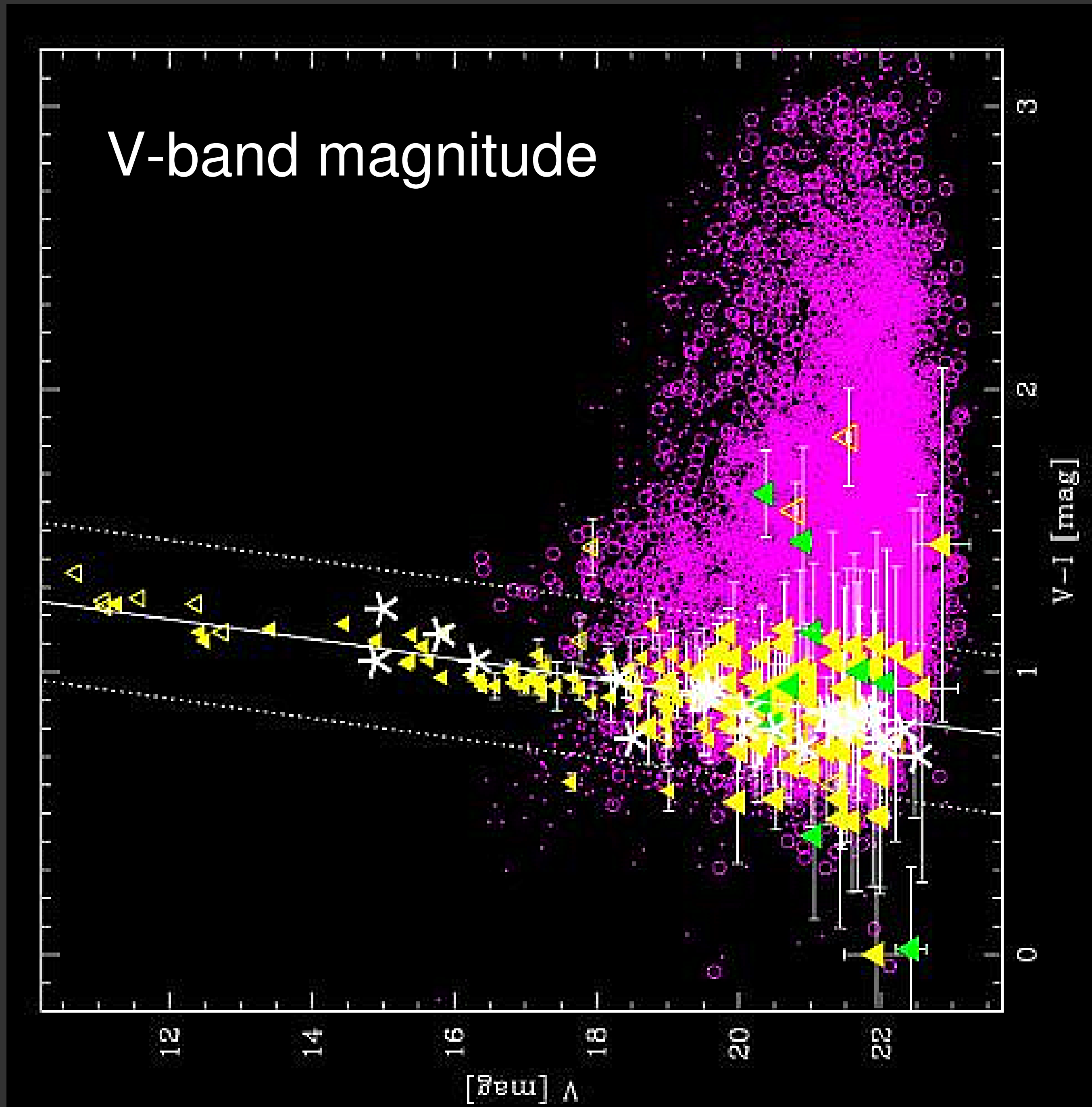
(Holden+07)

The properties of cluster galaxies: colors

The color-magnitude relation, CMR

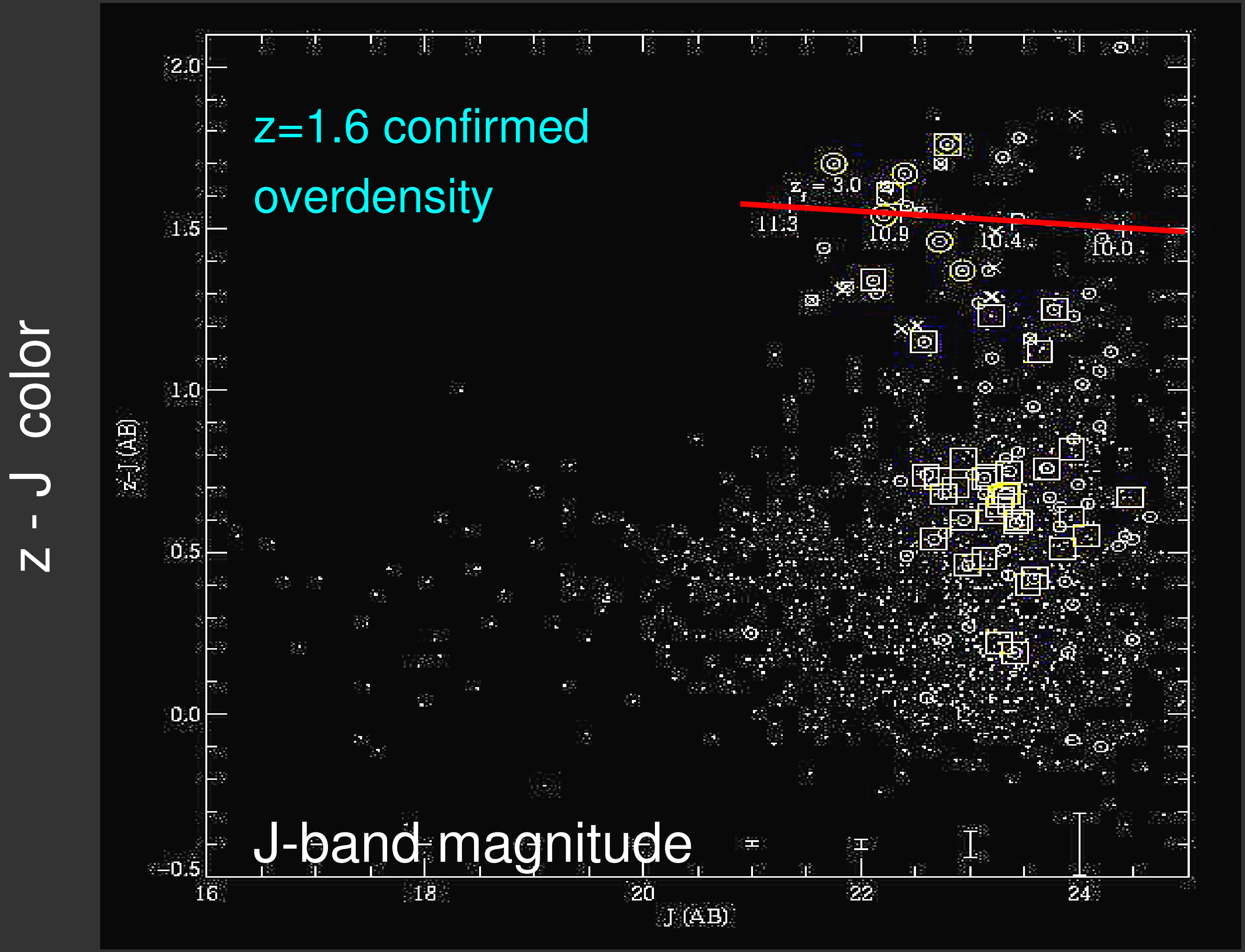


CMR also for dwarf galaxies



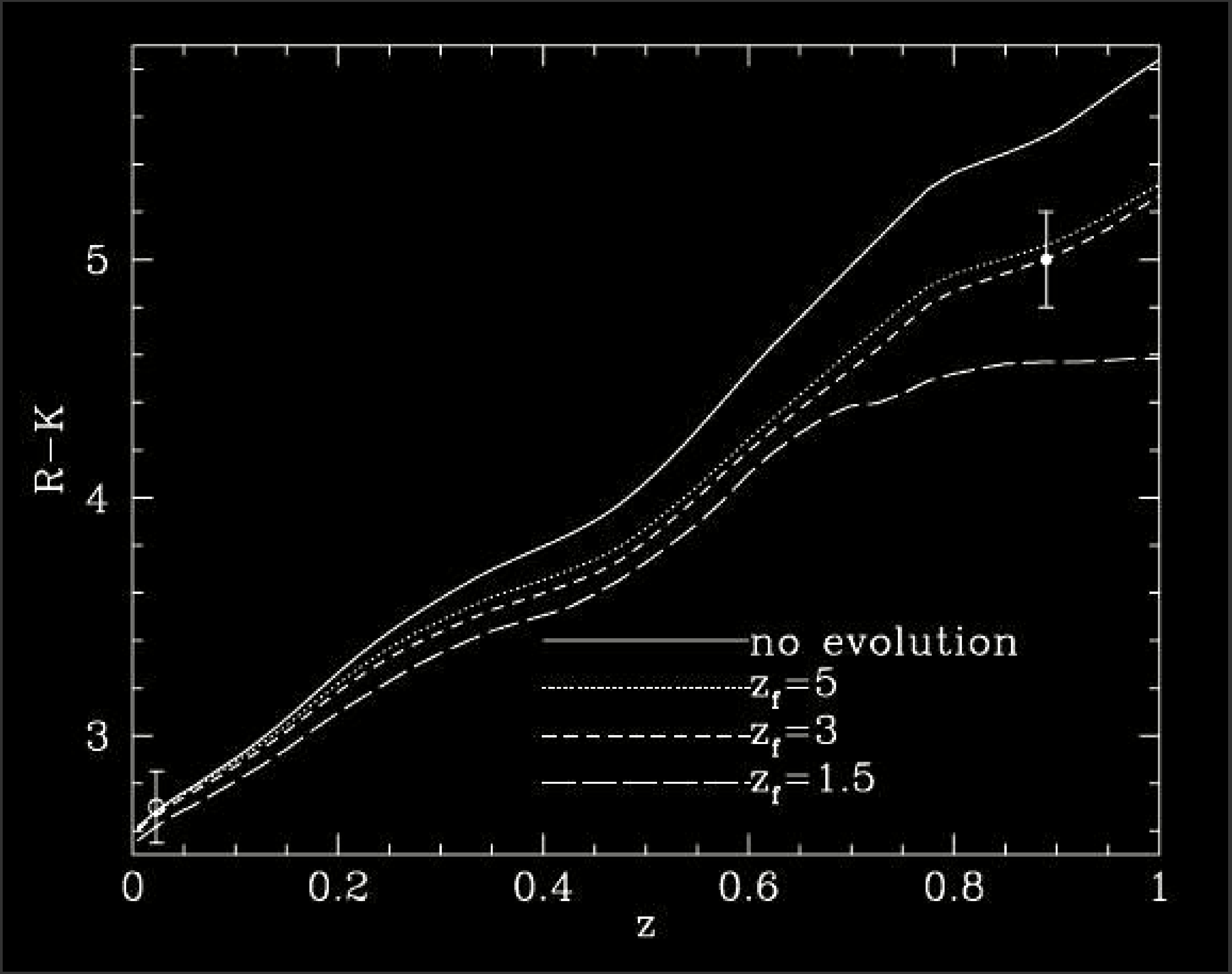
(Hilker+03)

CMR also at high-z



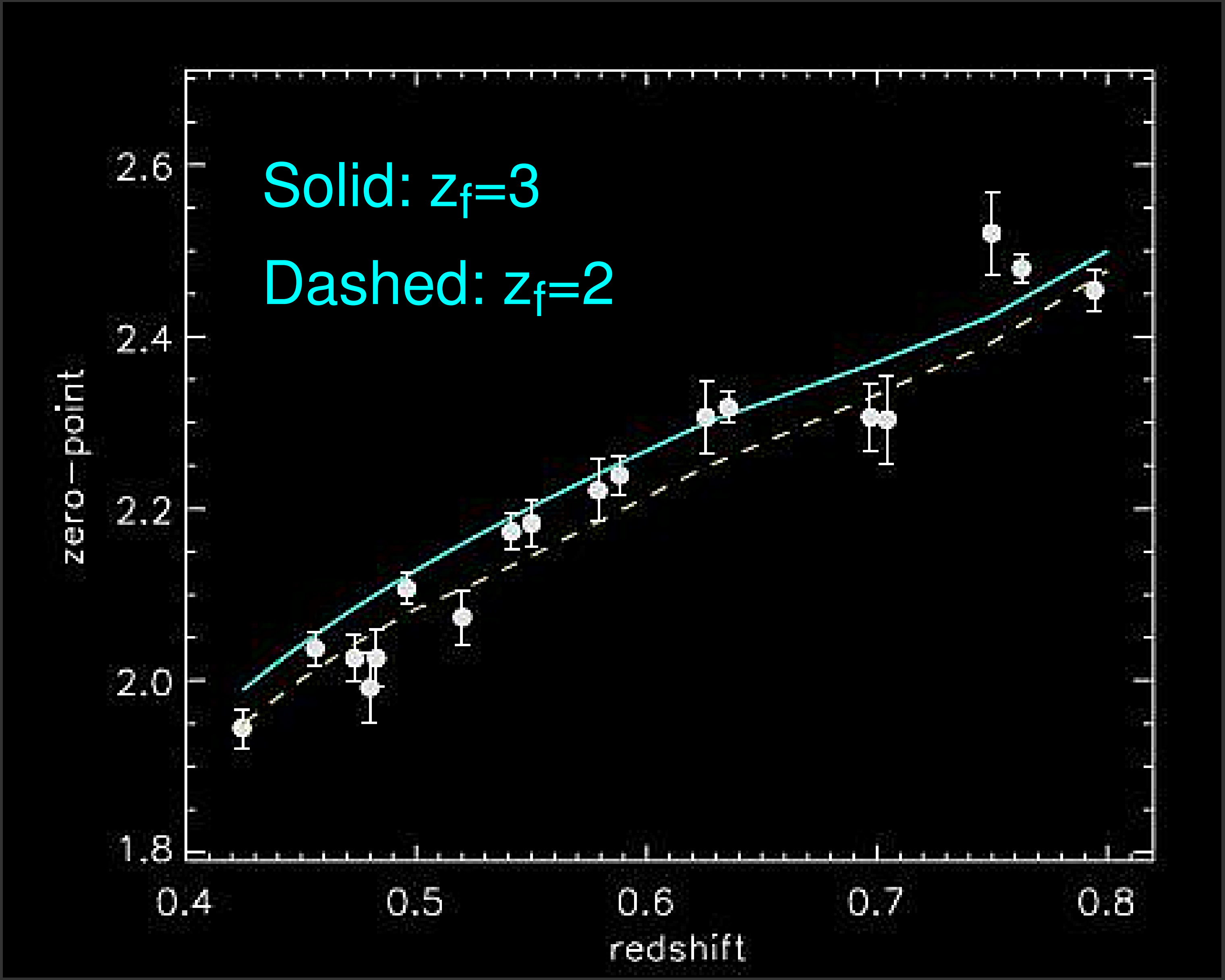
(Kurk+08)

CMR zero-point vs. z ⇒ $z_f \geq 2$



(Ellis+06)

CMR zero-point vs. z ⇒ $z_f \geq 2$

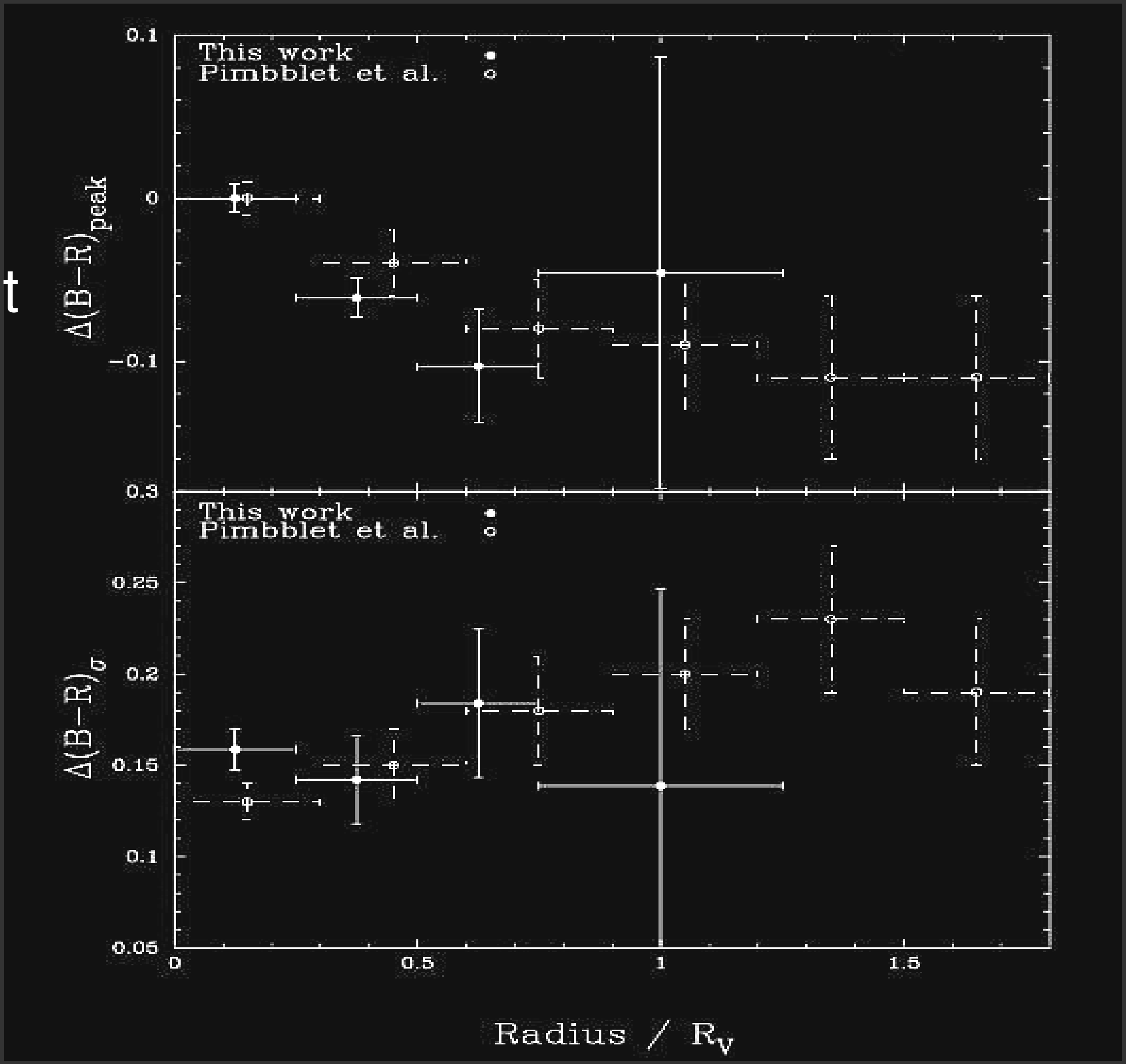


(De Lucia+07)

CMR vs. R ⇒ age gradient

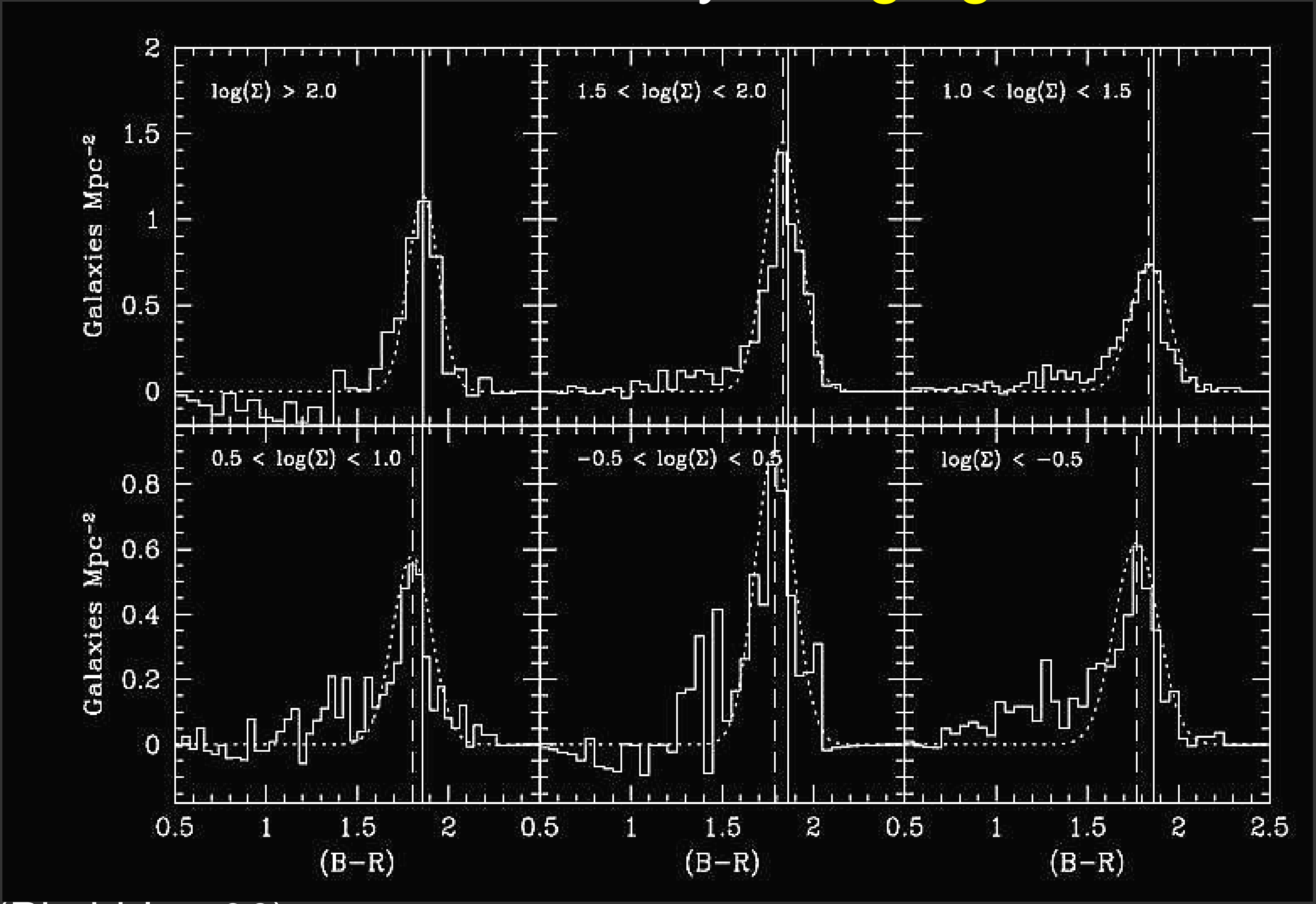
zero-point

scatter



(Wake+05)

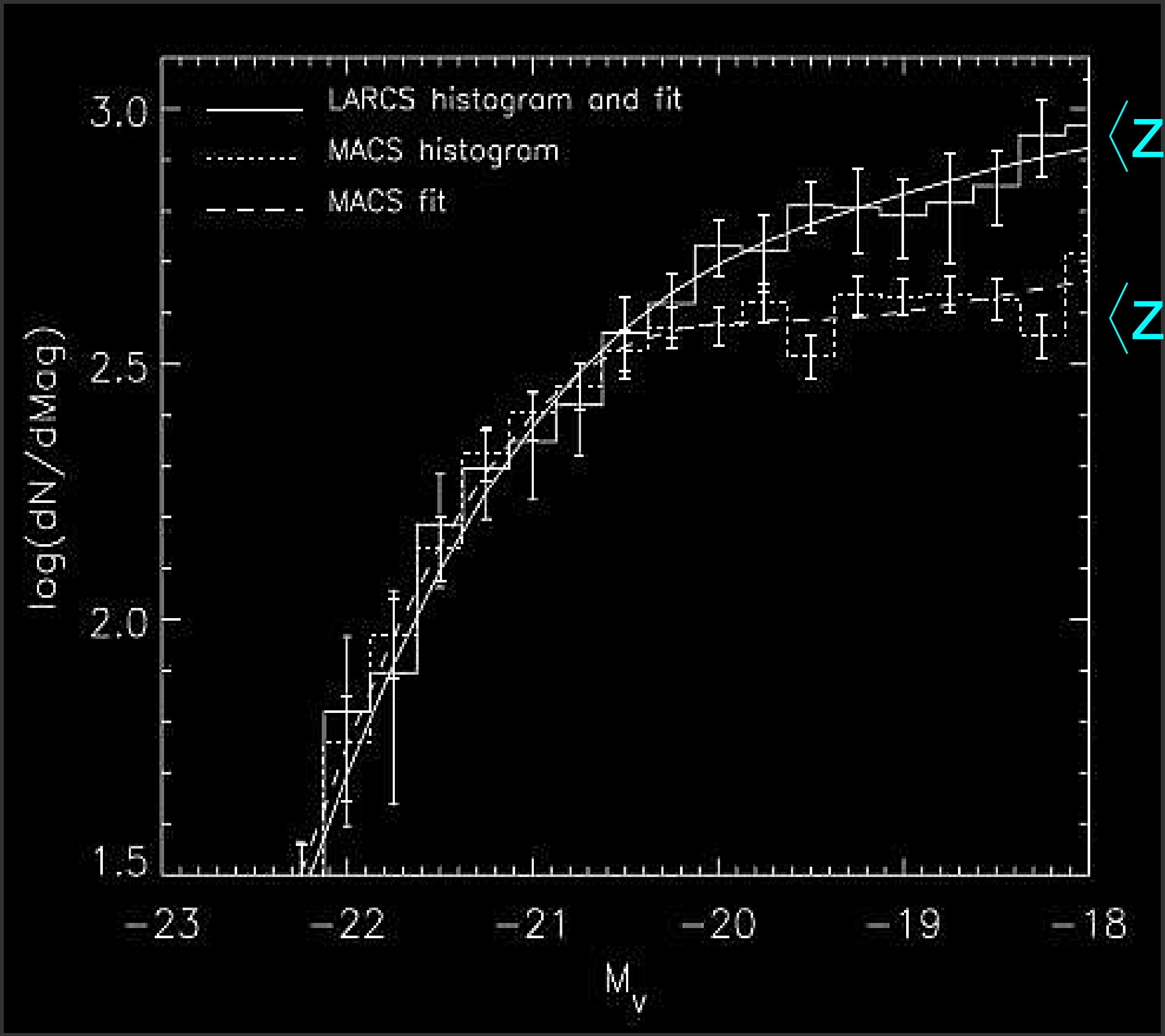
CMR vs. local density ⇒ age gradient



(Pimbblet+06)

CMR faint-end forms at low-z

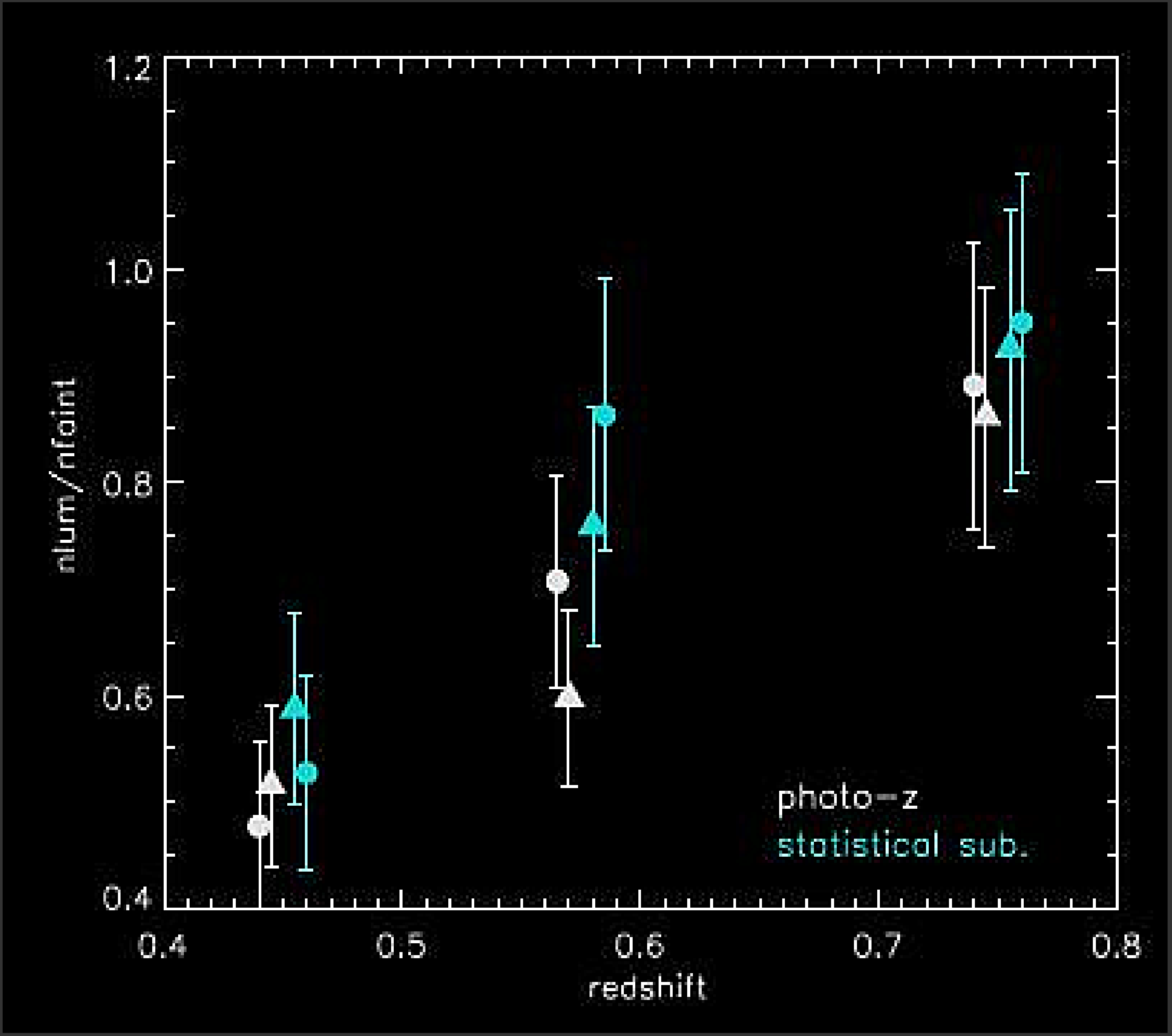
Red-galaxy luminosity functions for two cluster samples



(Stott+07)

CMR faint-end forms at low-z

Bright-to-faint red galaxies number ratio



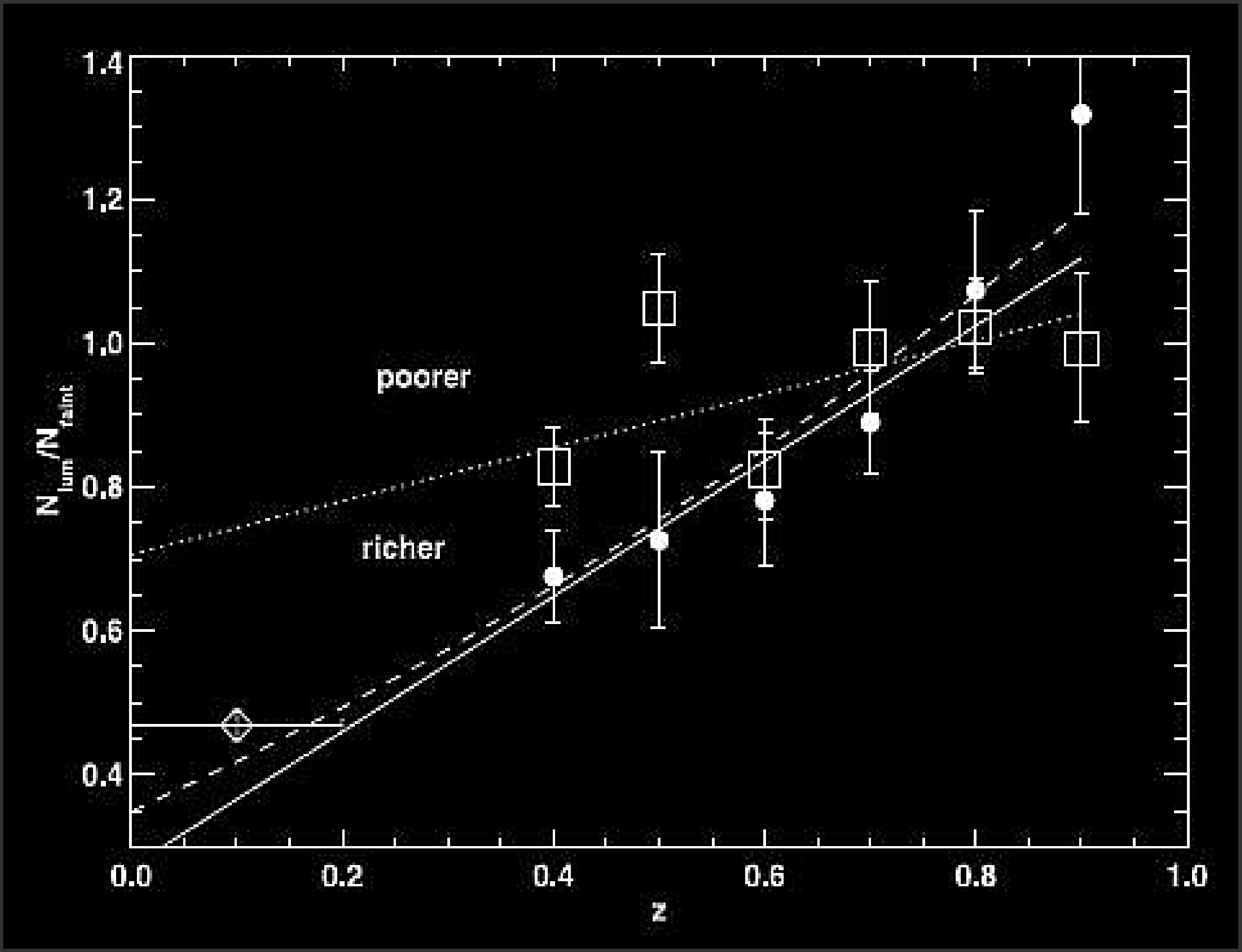
redshift

(De Lucia+07)

CMR faint-end forms at low-z

...more rapidly in higher-M clusters

Bright-to-faint red galaxies number ratio



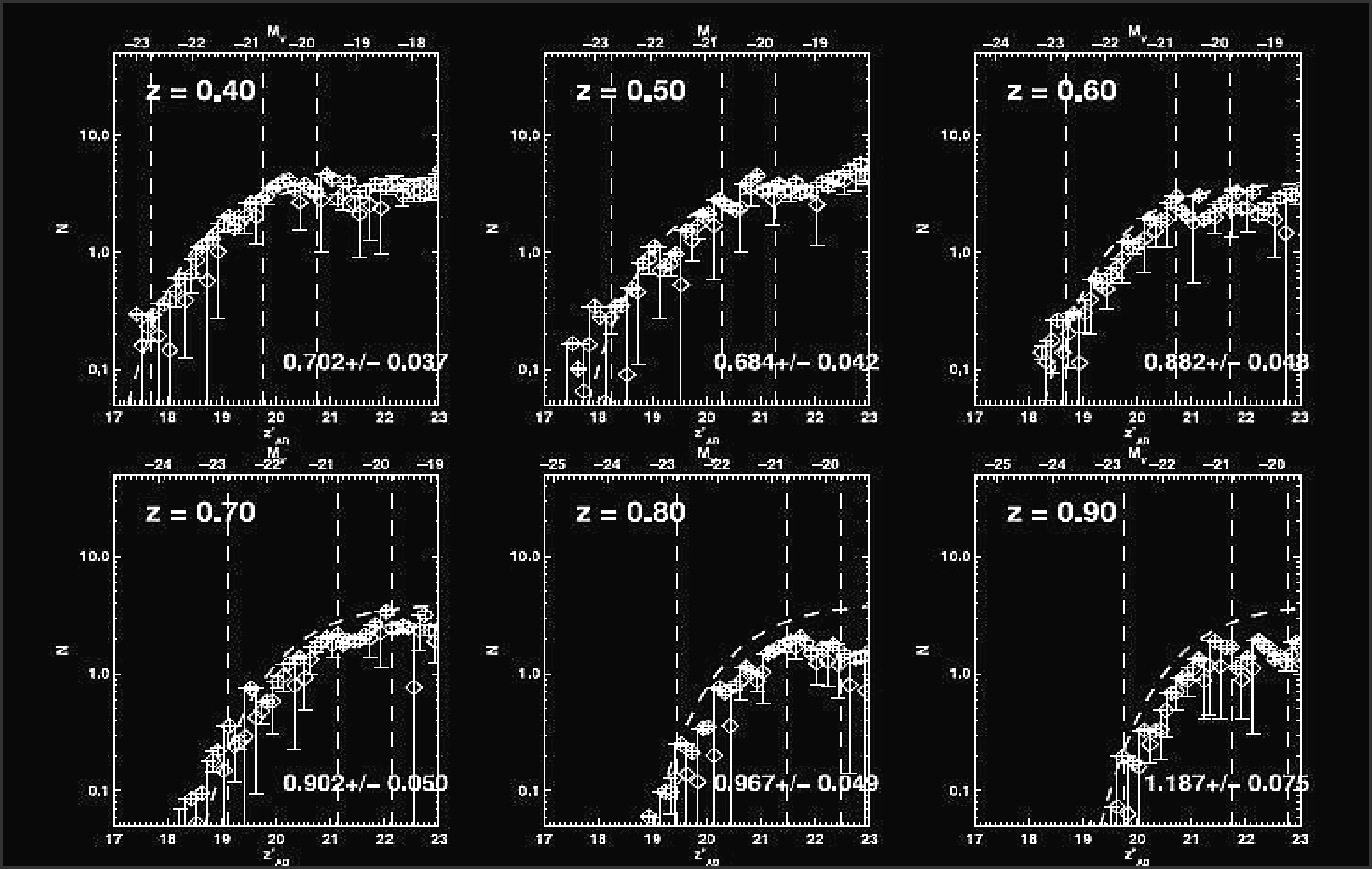
redshift

(Gilbank+08)

CMR faint-end forms at low-z

...at the expense of blue galaxies

LF Red gals

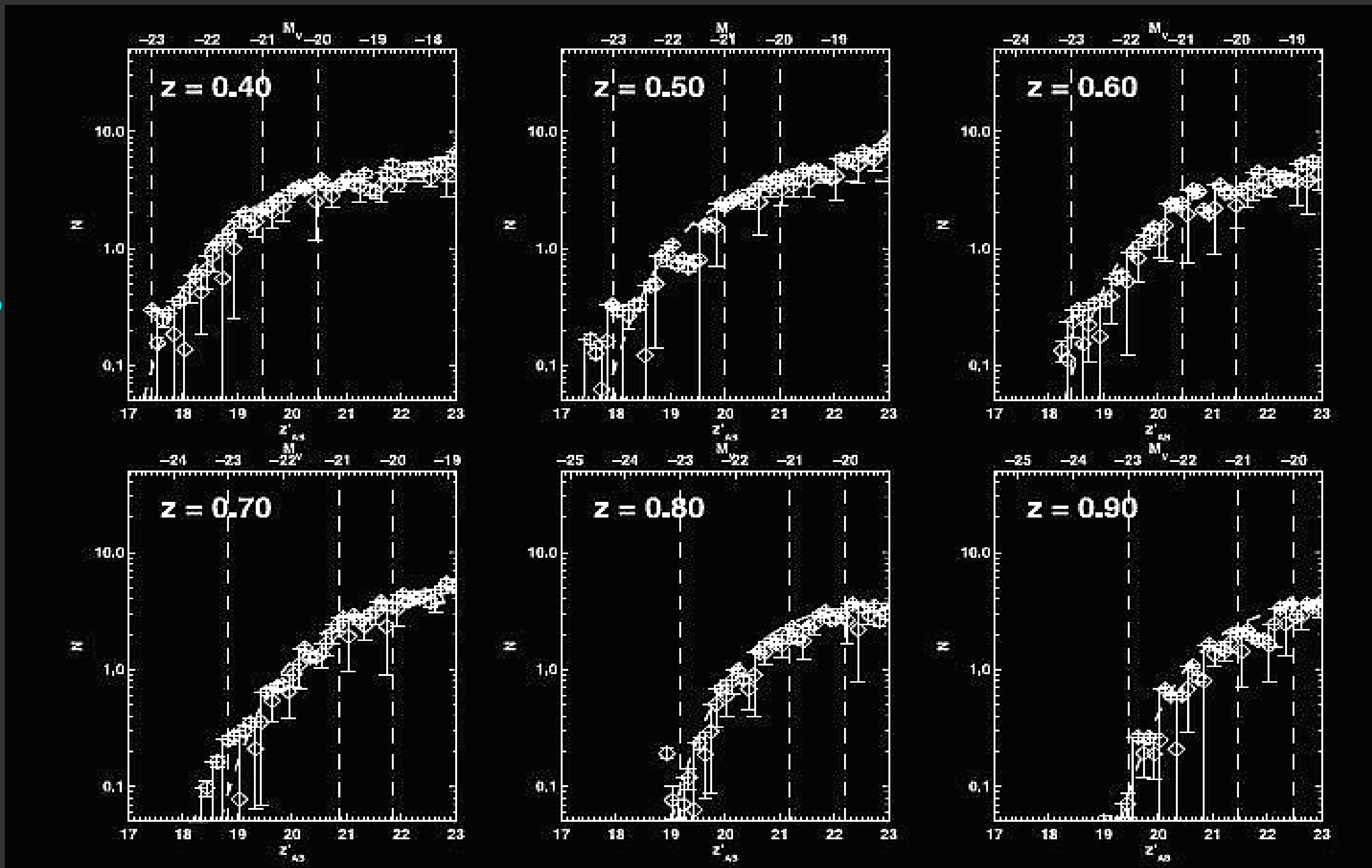


(Gilbank+08)

CMR faint-end forms at low-z

...at the expense of blue galaxies

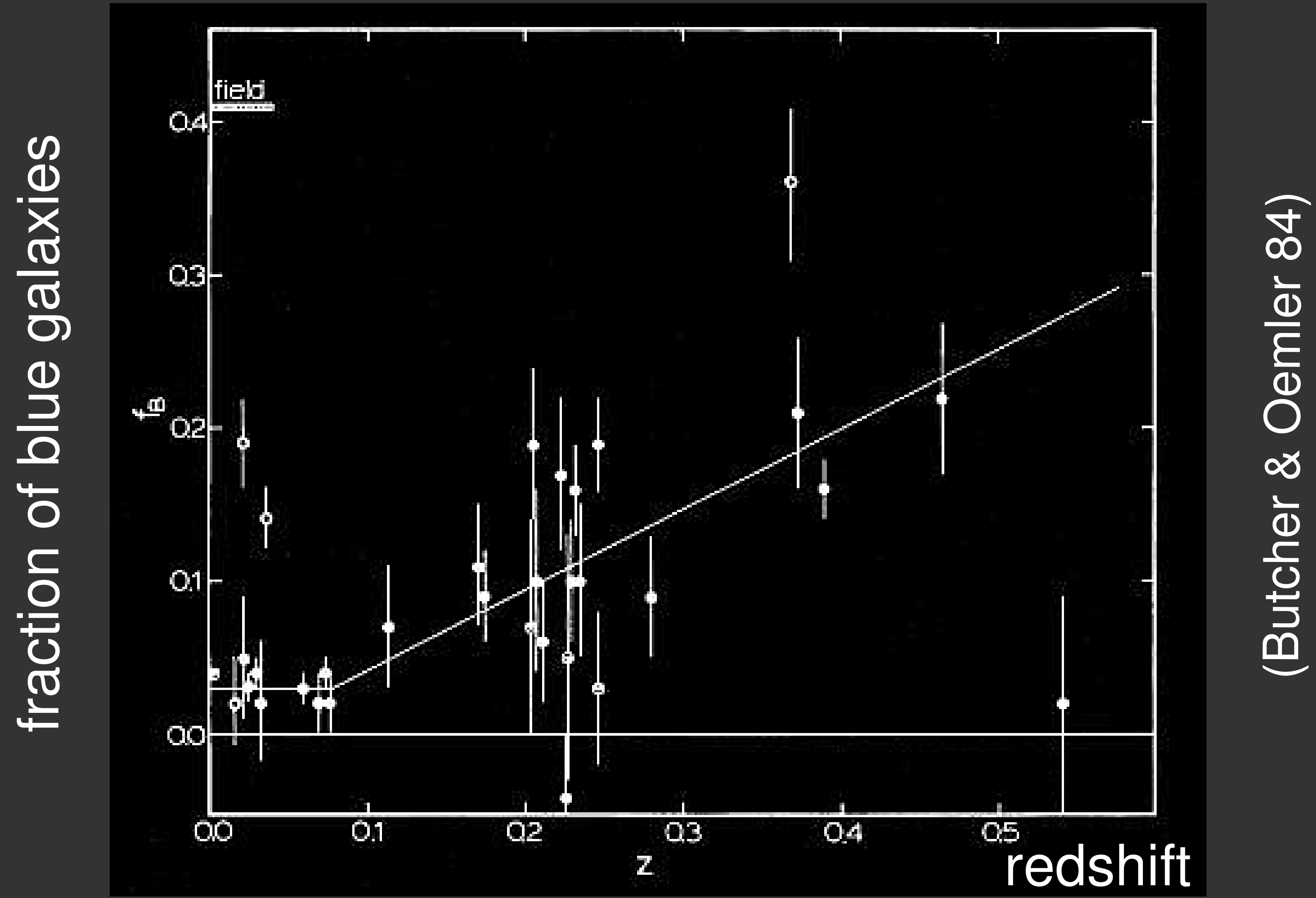
LF
All
gals



(Gilbank+08)

Blue galaxies → red galaxies with time

f_B ↑ with z ... the Butcher-Oemler effect

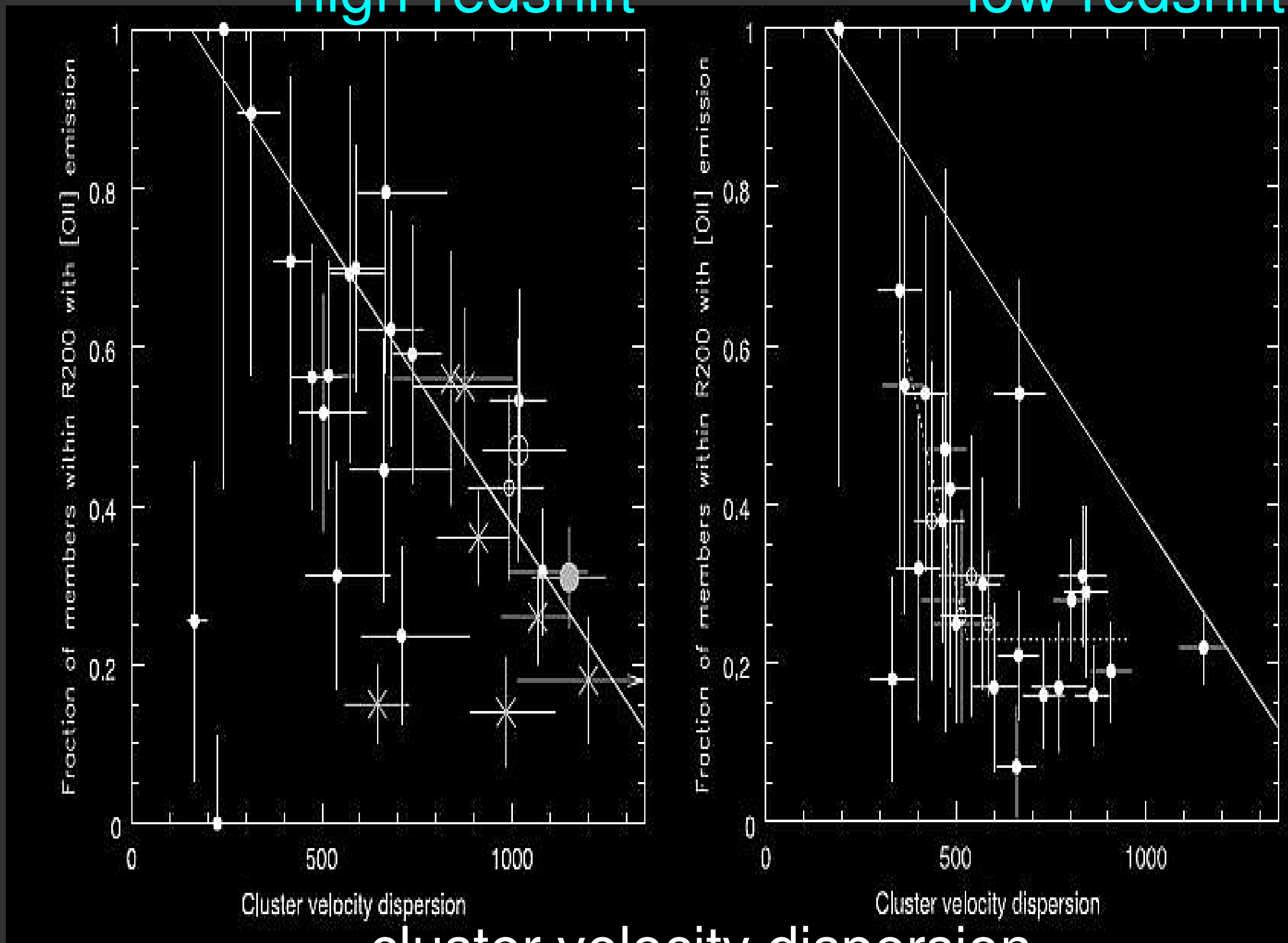


f_{ELG} ↑ with z ... the spectroscopic B-O effect

high-redshift

low-redshift

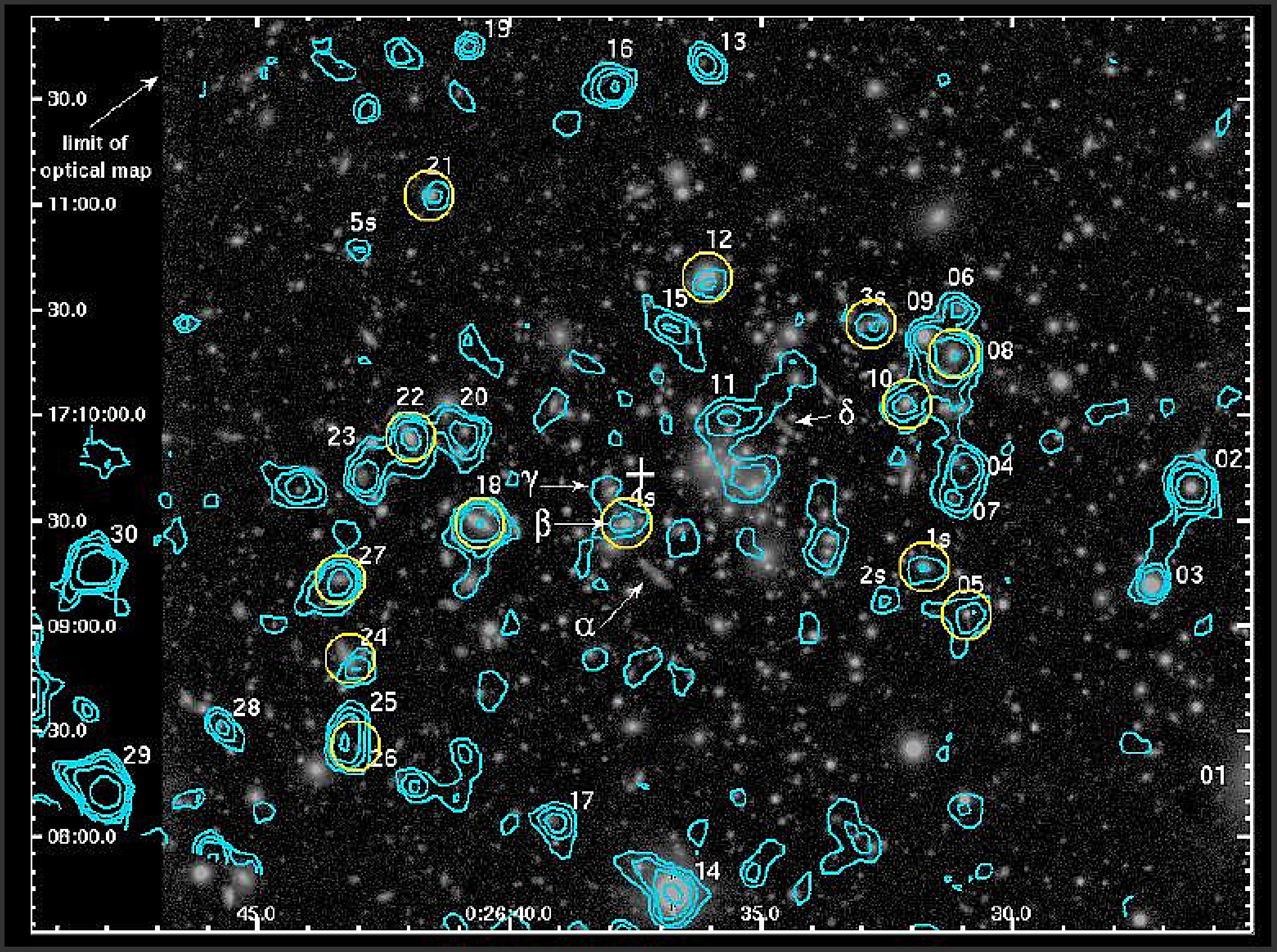
fraction of emission-line galaxies



cluster velocity dispersion

(Poggianti+ 06)

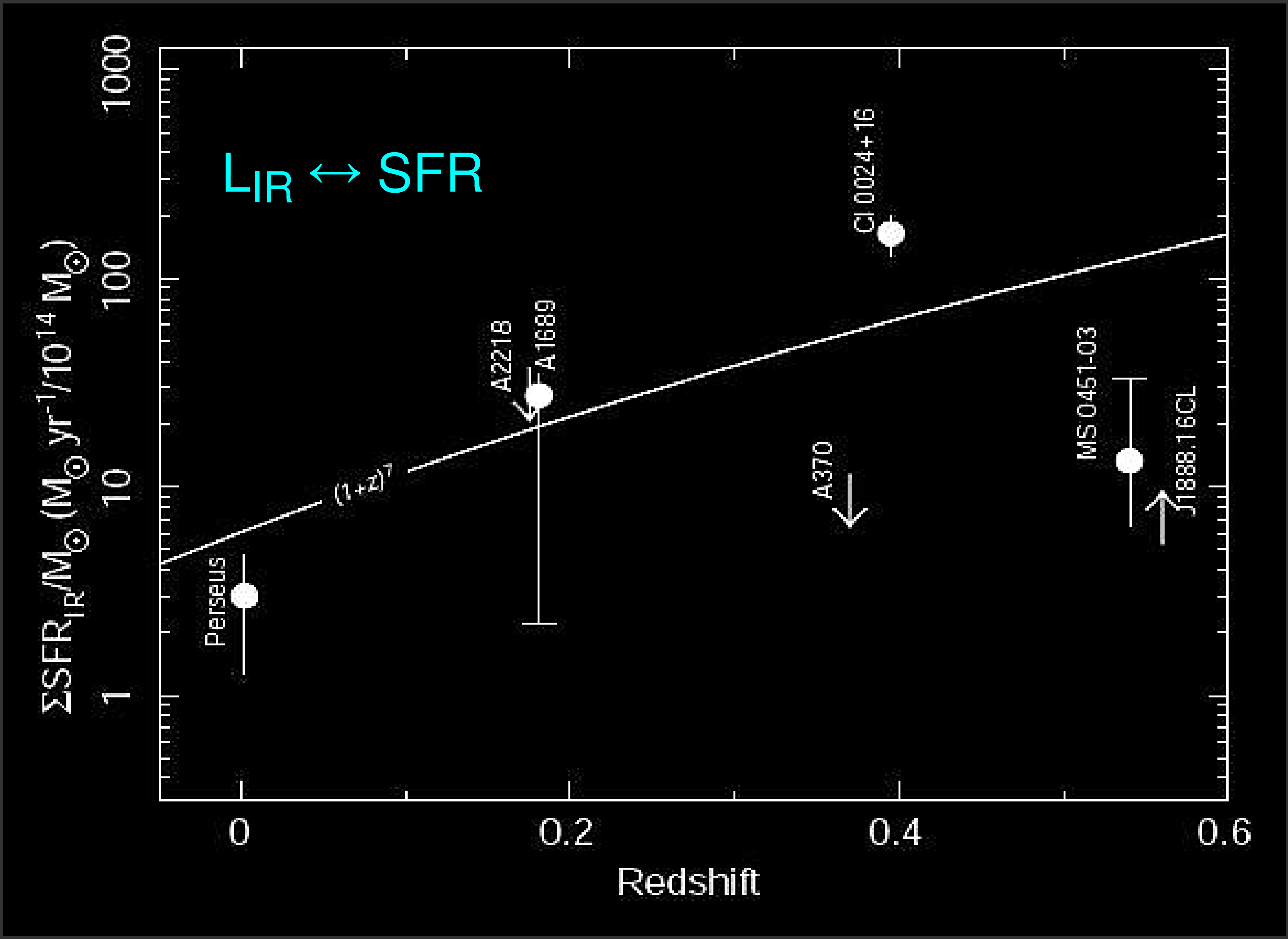
$f_{\text{IR-emitters}}$ ↑ with z ... the IR B-O effect



(Coia+ 05)

IR emission contours & optical image

$f_{IR\text{-}emitters}$ ↑ with z ... the IR B-O effect



(Geach+ 06)

SFR per unit mass increases with redshift

Cluster galaxy **color evolution**

occurs later

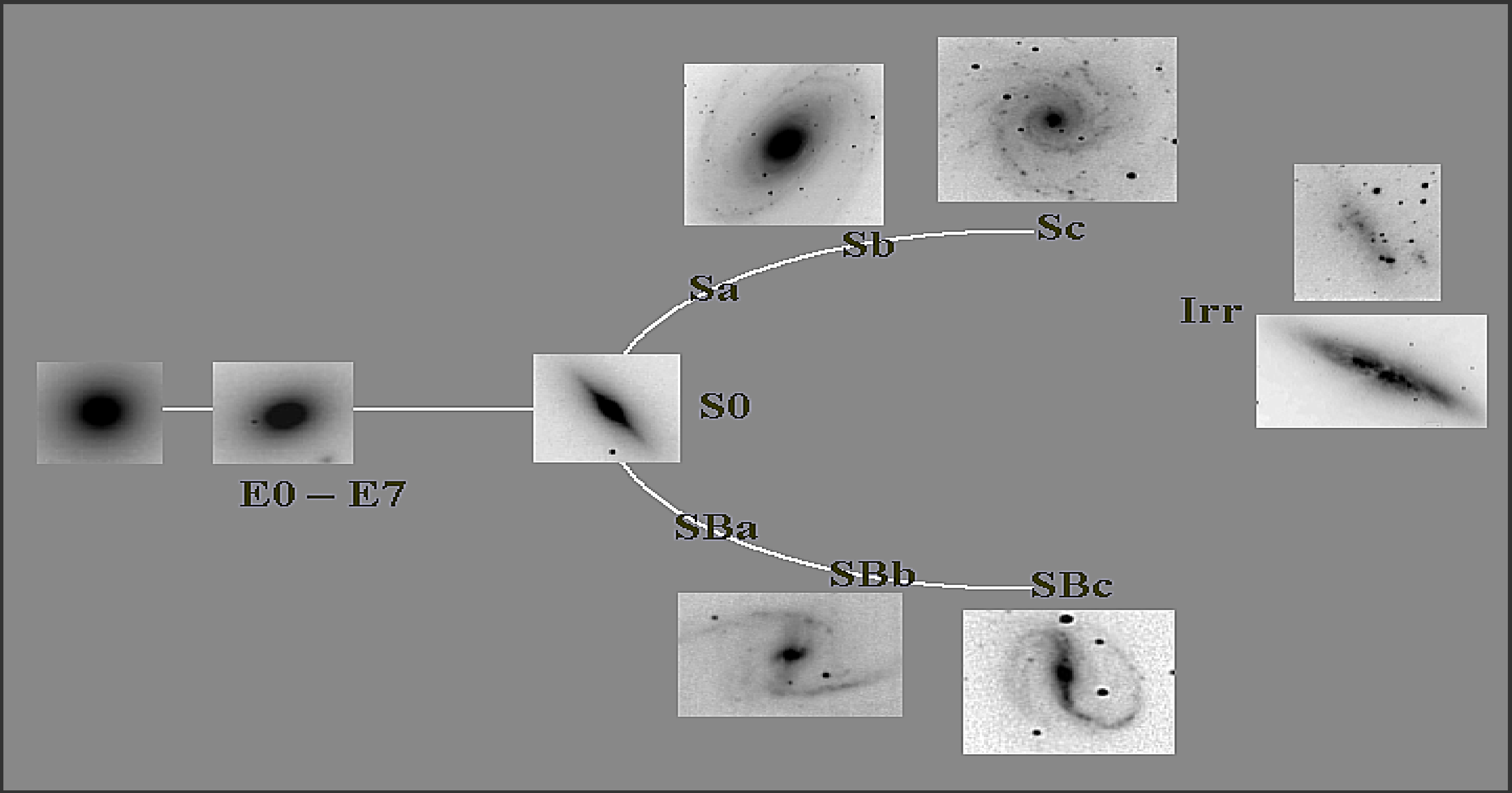
- → for fainter galaxies
- → in the *lower density* cluster regions
- → for **less massive** clusters

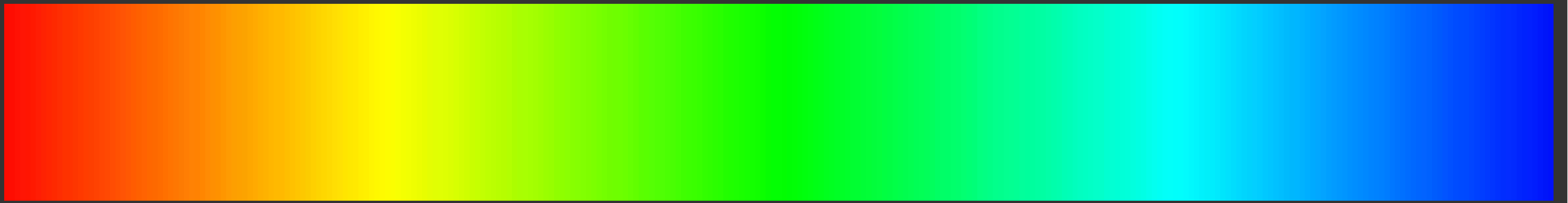
Cluster galaxy *morphological* **evolution**

occurs later

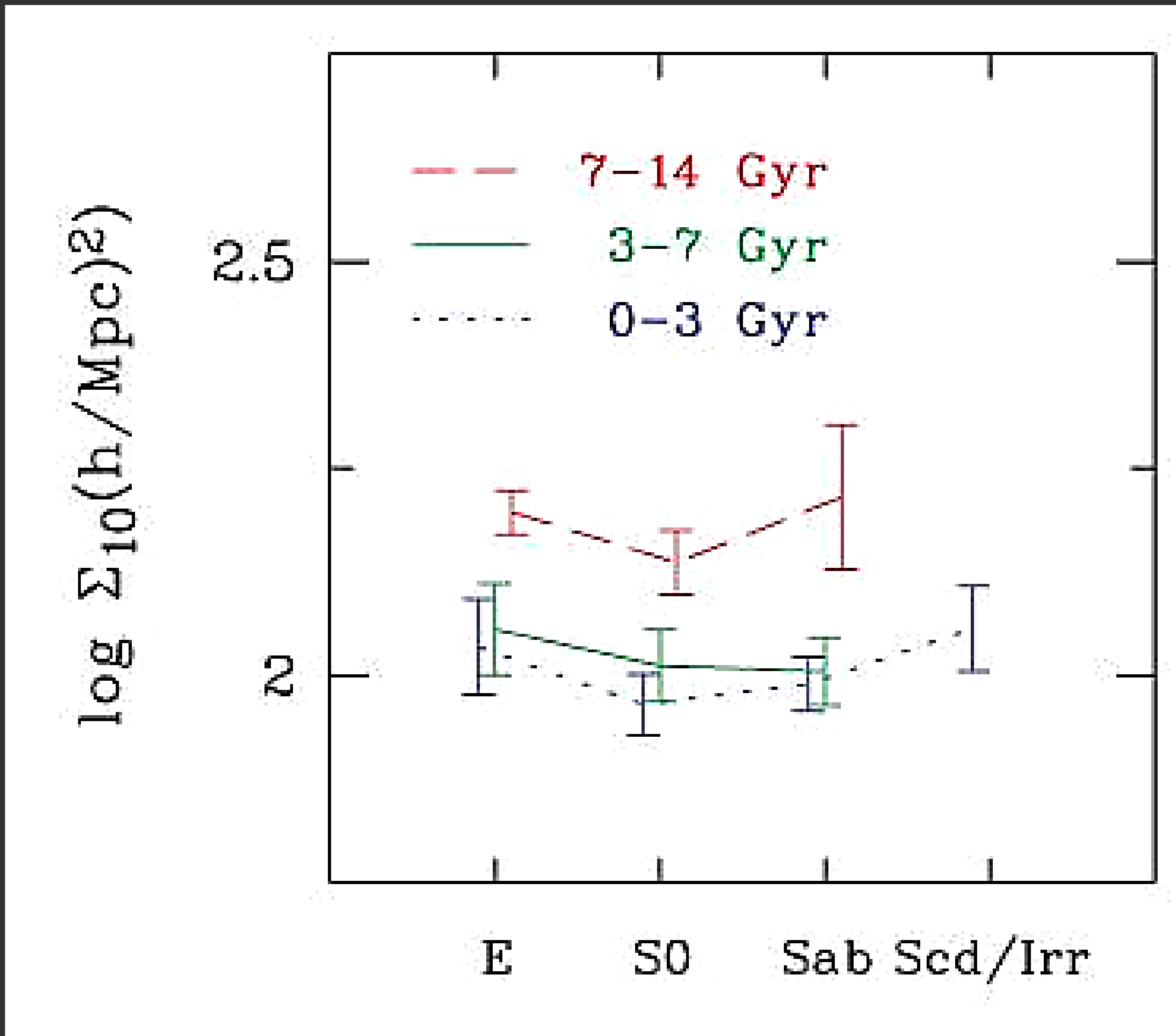
- ➔ for fainter galaxies
- ➔ in the *lower density* cluster regions
- ➔ for **less massive** clusters

CMR & MDR: the same phenomenon?





CMR & MDR: the same phenomenon?



Color ⇒ age

No MDR at fixed age ⇒ CMR more fundamental

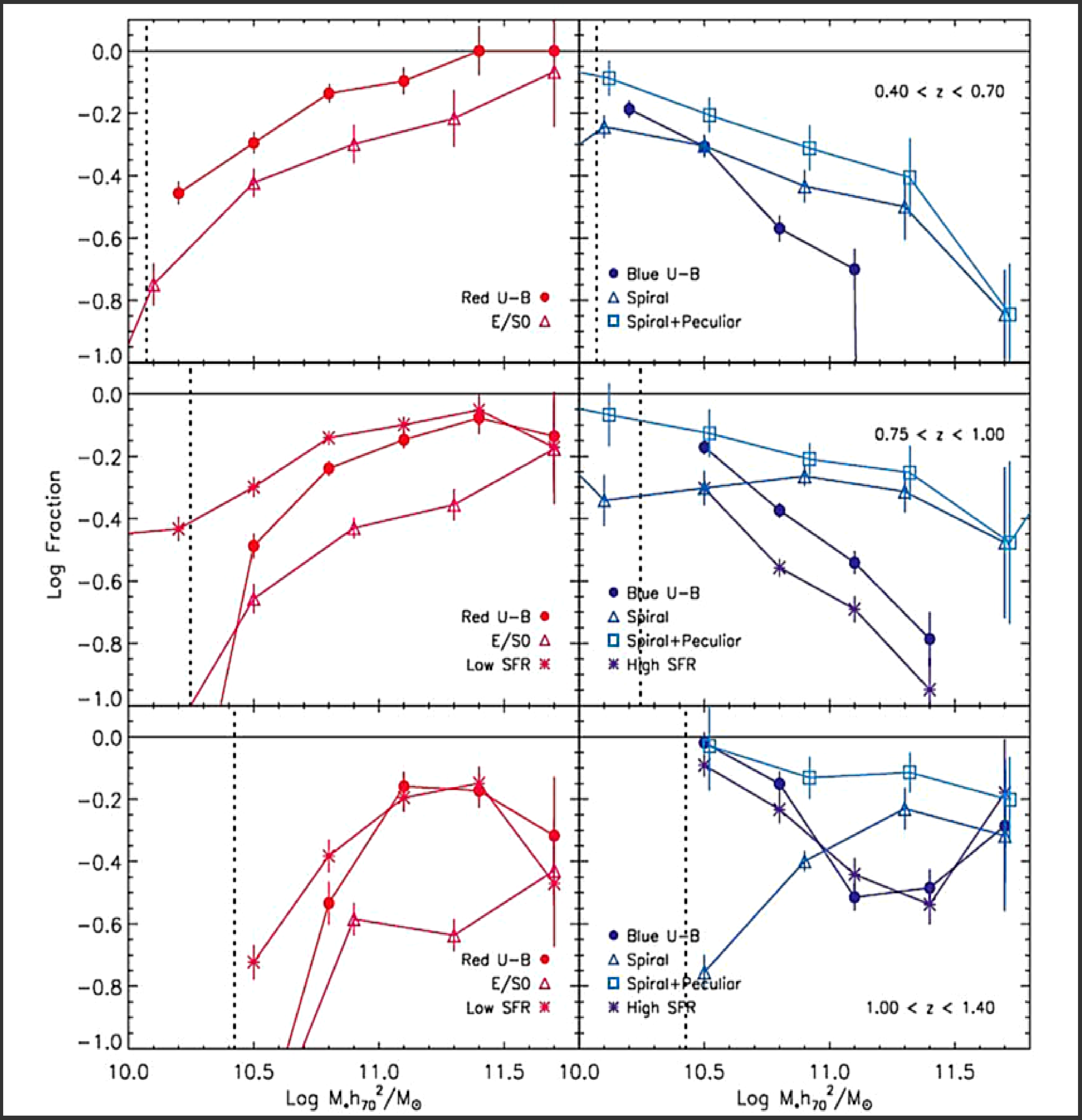
CMR & MDR: the same phenomenon?

CMR more fundamental

CMR evolution proceeds faster:

- ✔ evolution of galaxy mass function

Galaxy Mass Function becomes dominated by RED galaxies before becoming dominated by EARLY type galaxies



log (M)

(Bundy+06)

CMR & MDR: the same phenomenon?

CMR more fundamental

CMR evolution proceeds faster:

- ✔ evolution of galaxy mass function
- ✔ passive, red cluster spirals

Normal S

Passive spectrum, blue disk

Passive spectrum red disk

(Moran+07)

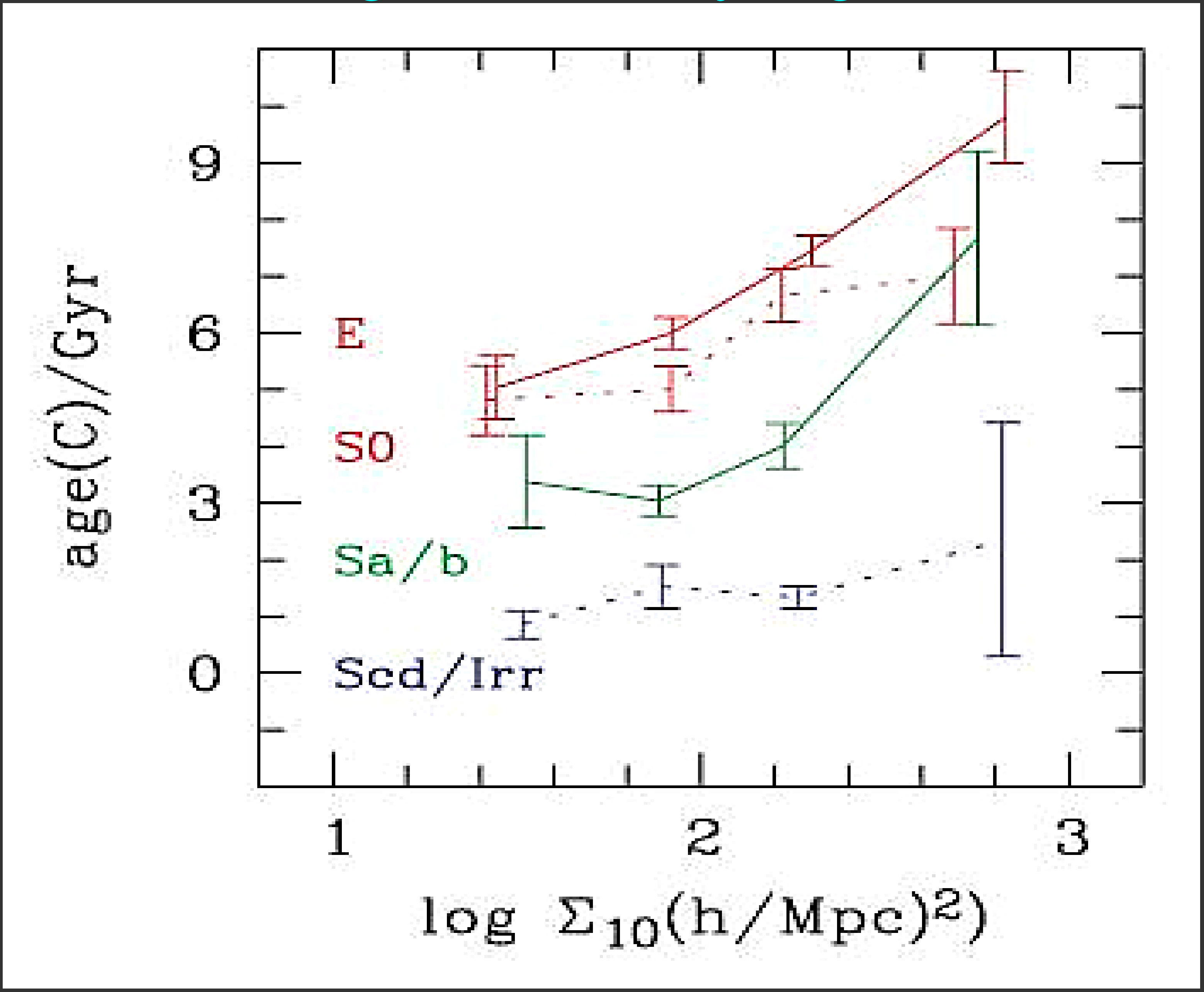
CMR & MDR: the same phenomenon?

CMR more fundamental

CMR evolution proceeds faster:

- ✔ evolution of galaxy mass function
- ✔ passive, red cluster spirals
- ✔ early-S with = age of S0

Sa/b and S0 have = age in highest-density regions



The properties of cluster galaxies: masses

Early-type galaxies lie on a Fundamental Plane

ETG FP

relates their

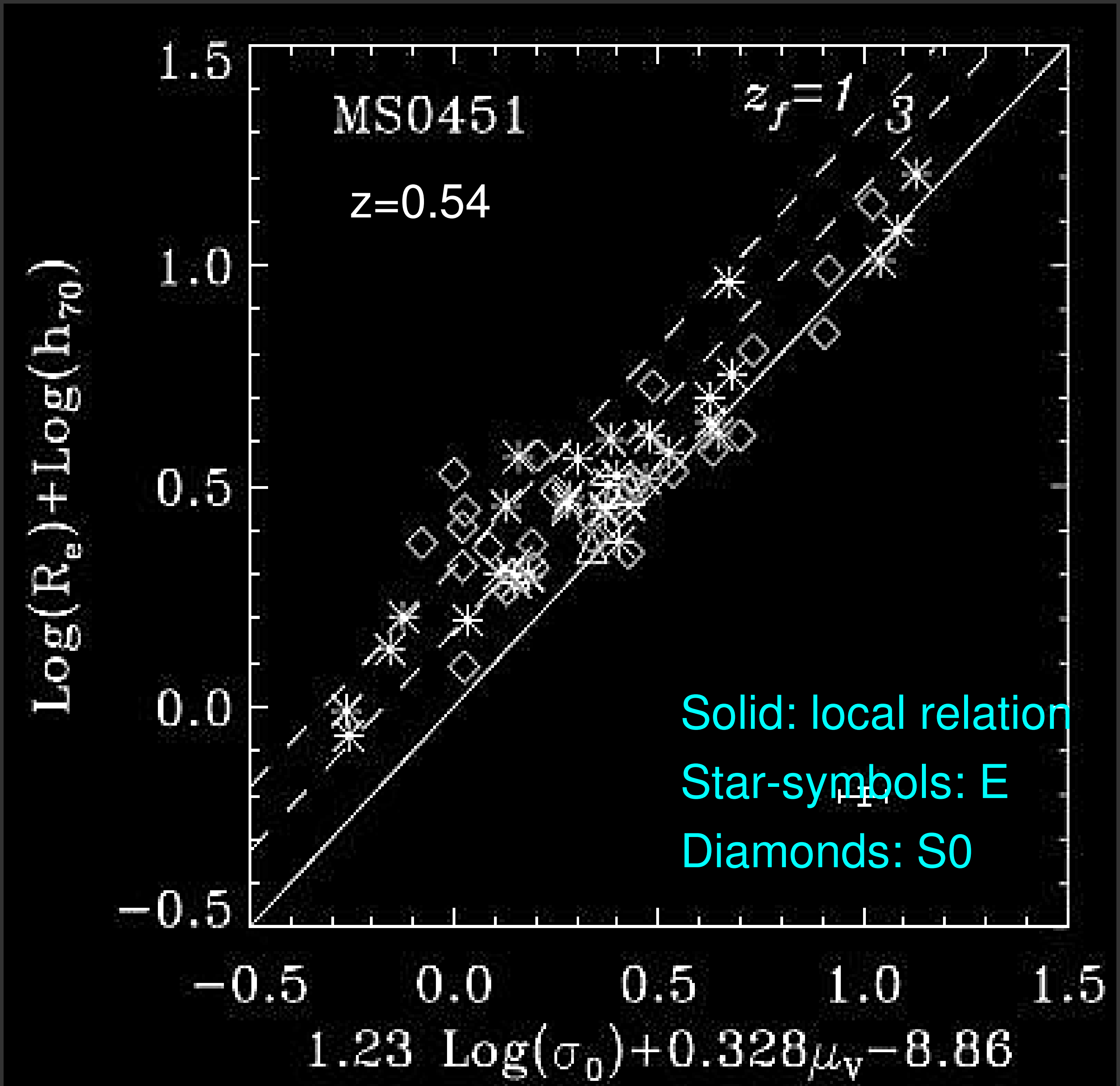
central σ_v

surf. brightness

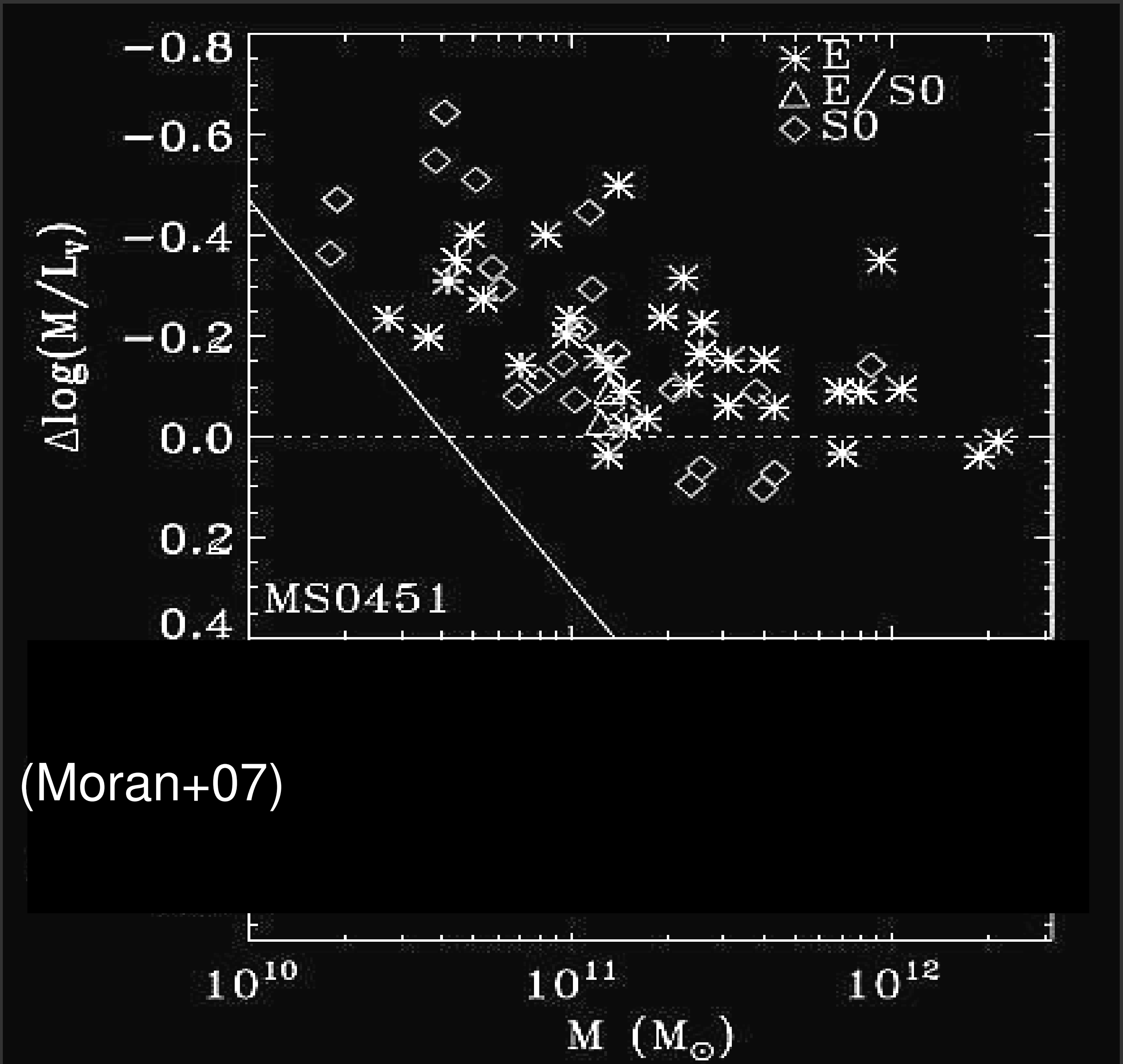
effective radius

FP ⇨ $z_f \geq 2$

(Moran+07)



Deviation from FP expressed as M/L difference



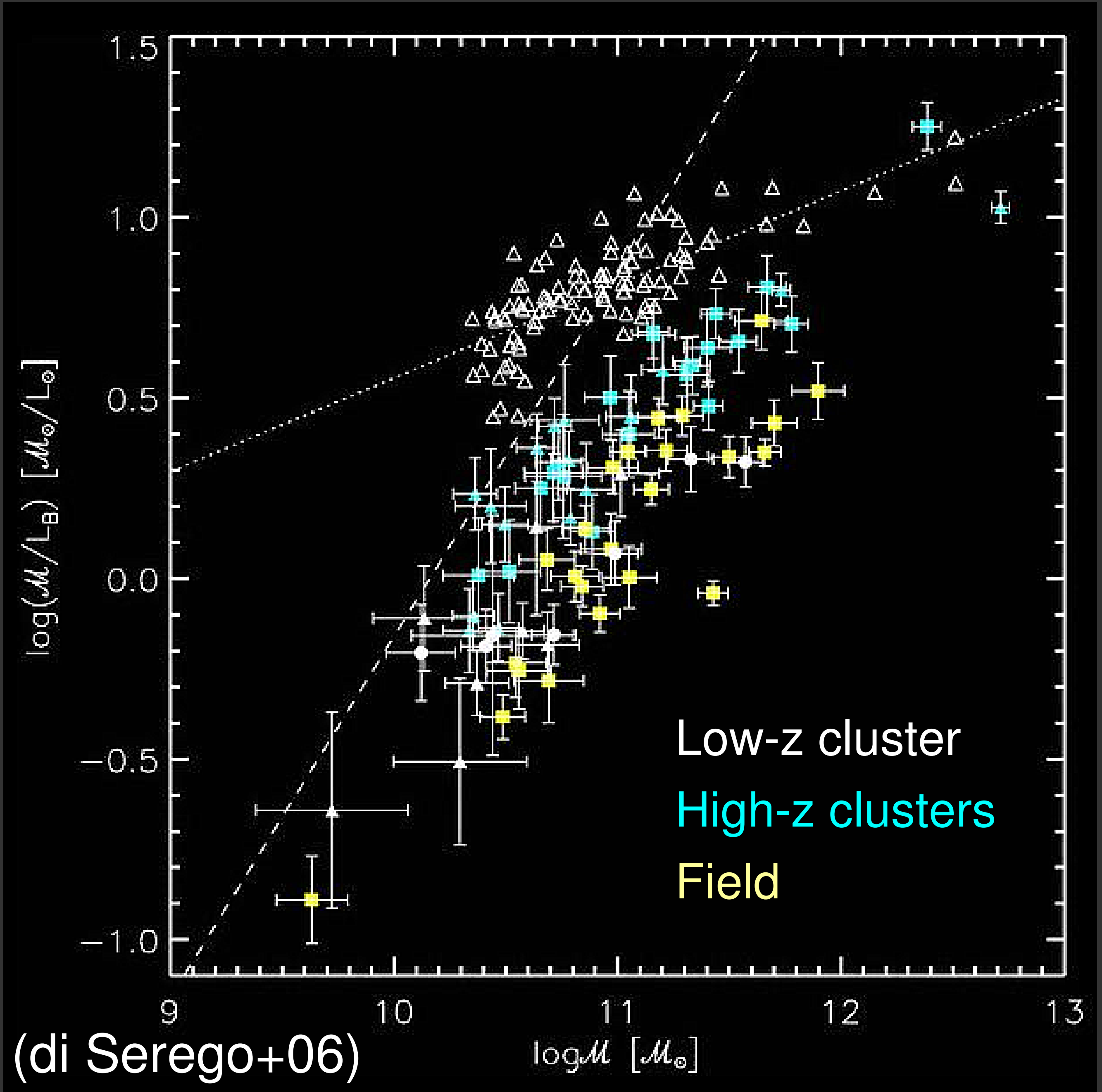
(Moran+07)

Lower M/L for

less massive ETG

⇒ younger age

Deviation from FP expressed as M/L difference



(di Serego+06)

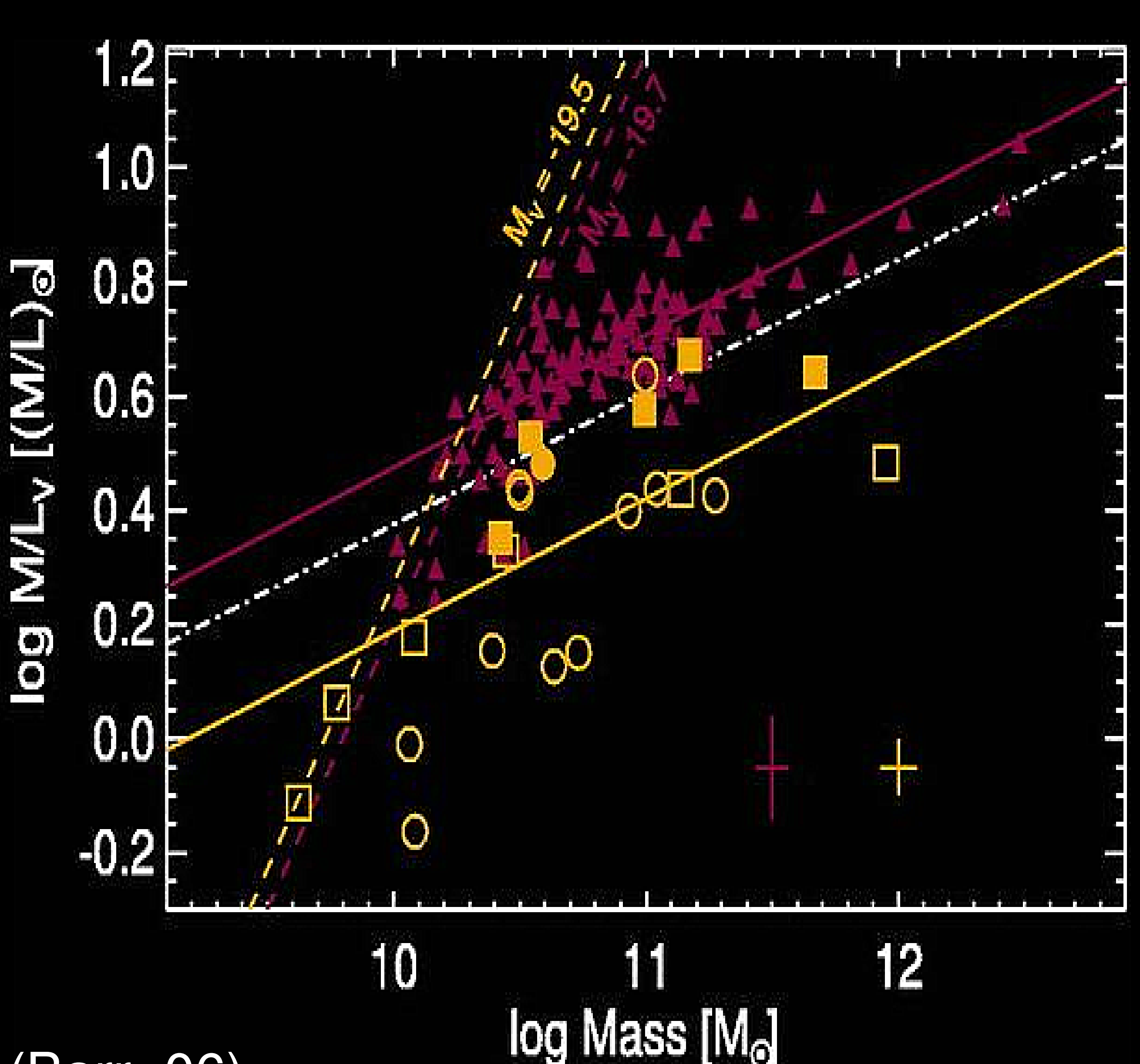
Lower M/L for less massive ETG

⇒ younger age

Also:

field ETG younger than cluster ETG

Deviation from FP expressed as M/L difference



(Barr+06)

Lower M/L for less massive ETG
⇒ younger age

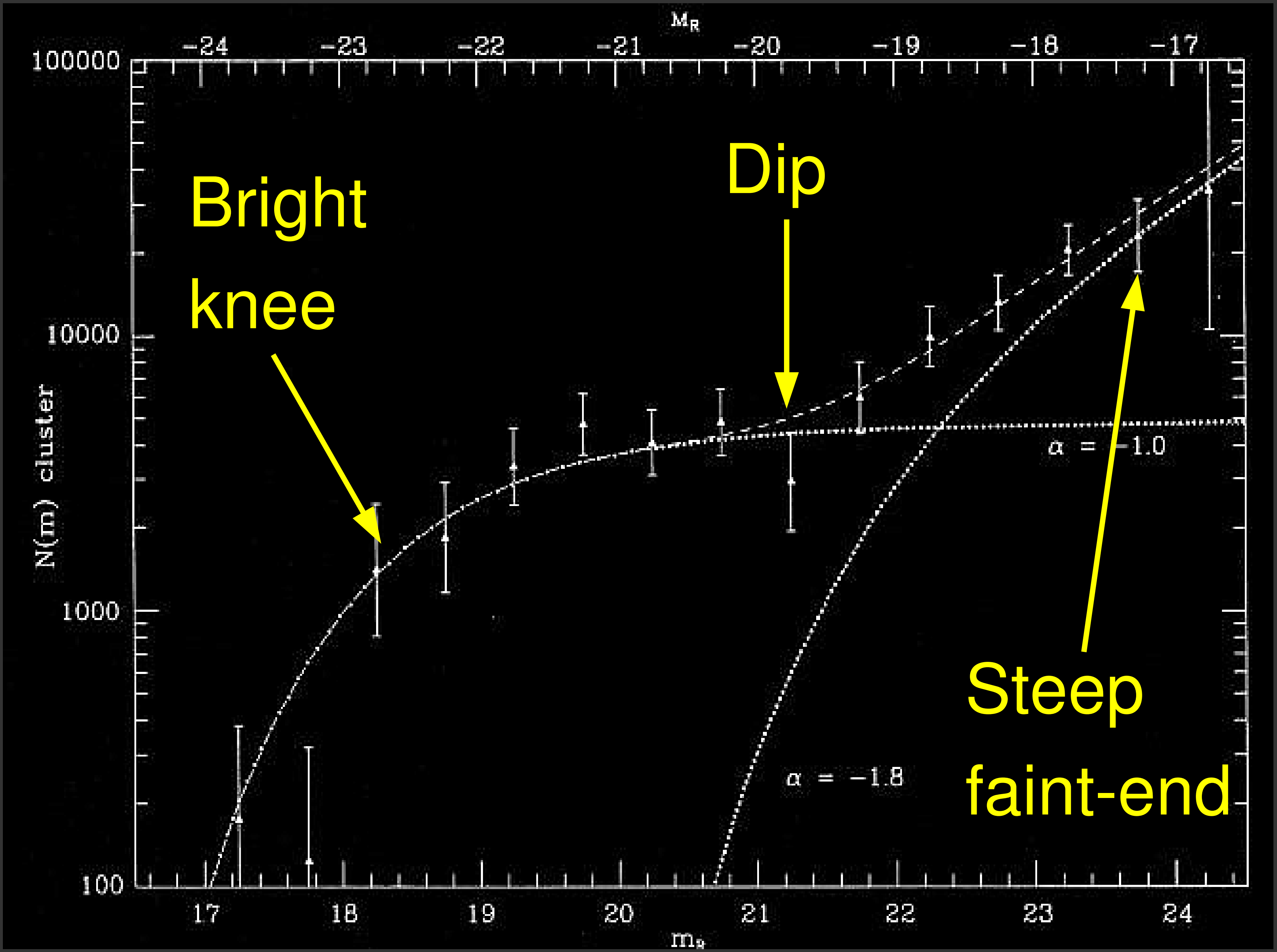
Also:

cluster S0 younger than cluster E

FP analysis supports conclusions from CMR and MDR analyses

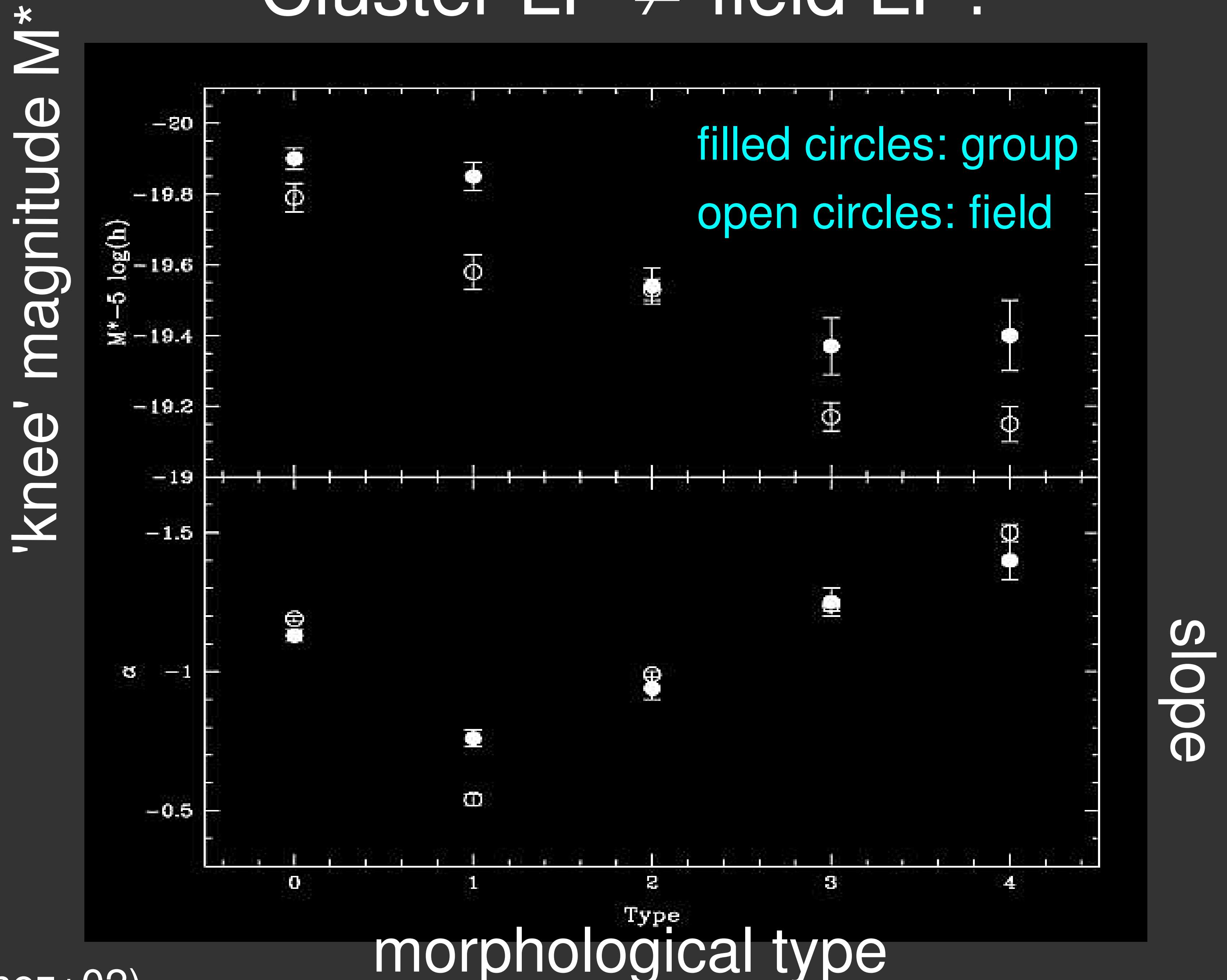
The properties of cluster galaxies: luminosities

Cluster LF ≠ field LF?



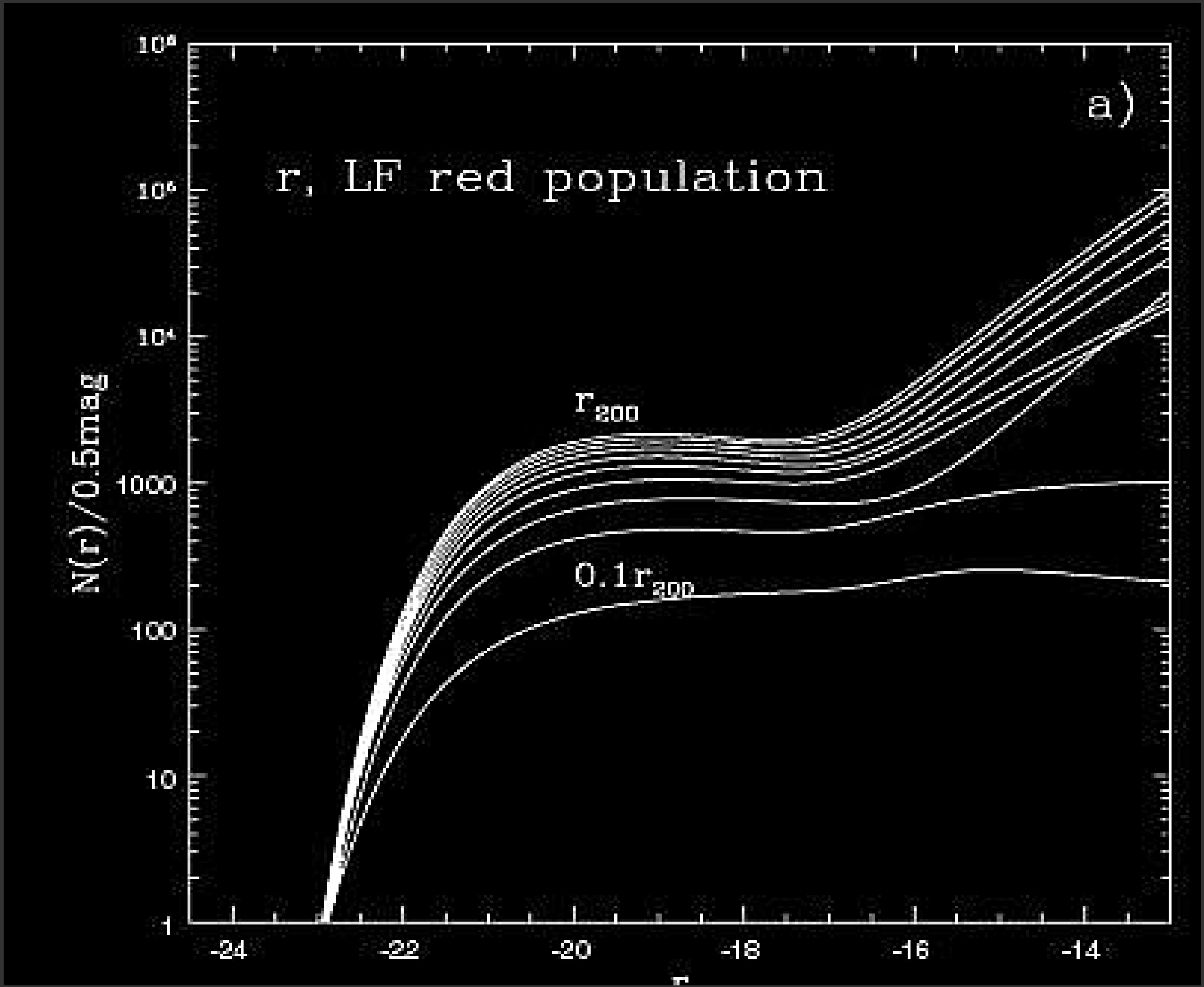
(Driver+04)

Cluster LF ≠ field LF?



(MartÍnez+02)

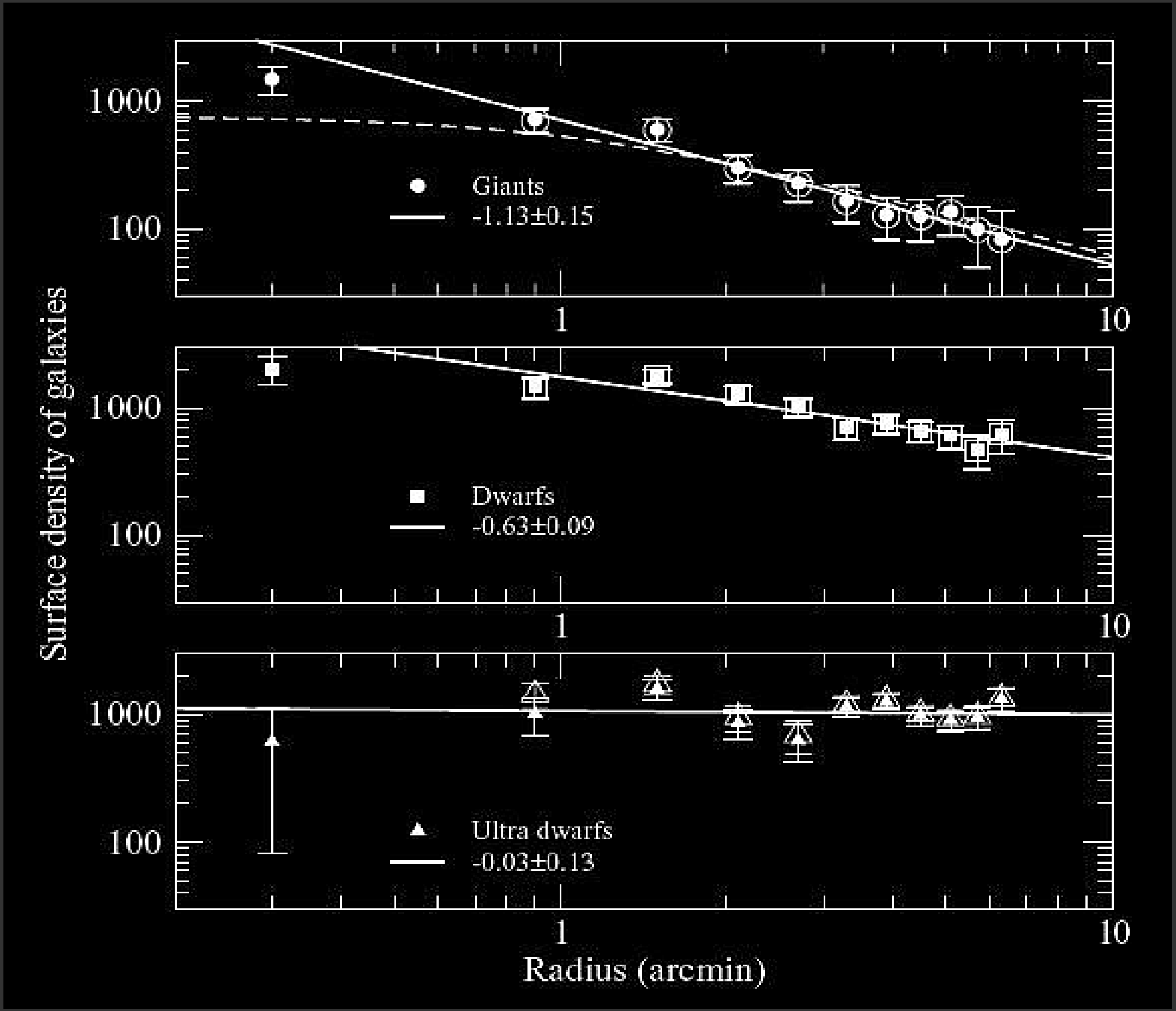
Cluster LF: shallower slope at small radii



(Popesso+06)

Cluster LF: shallower slope at small radii

...a.k.a. “luminosity segregation”

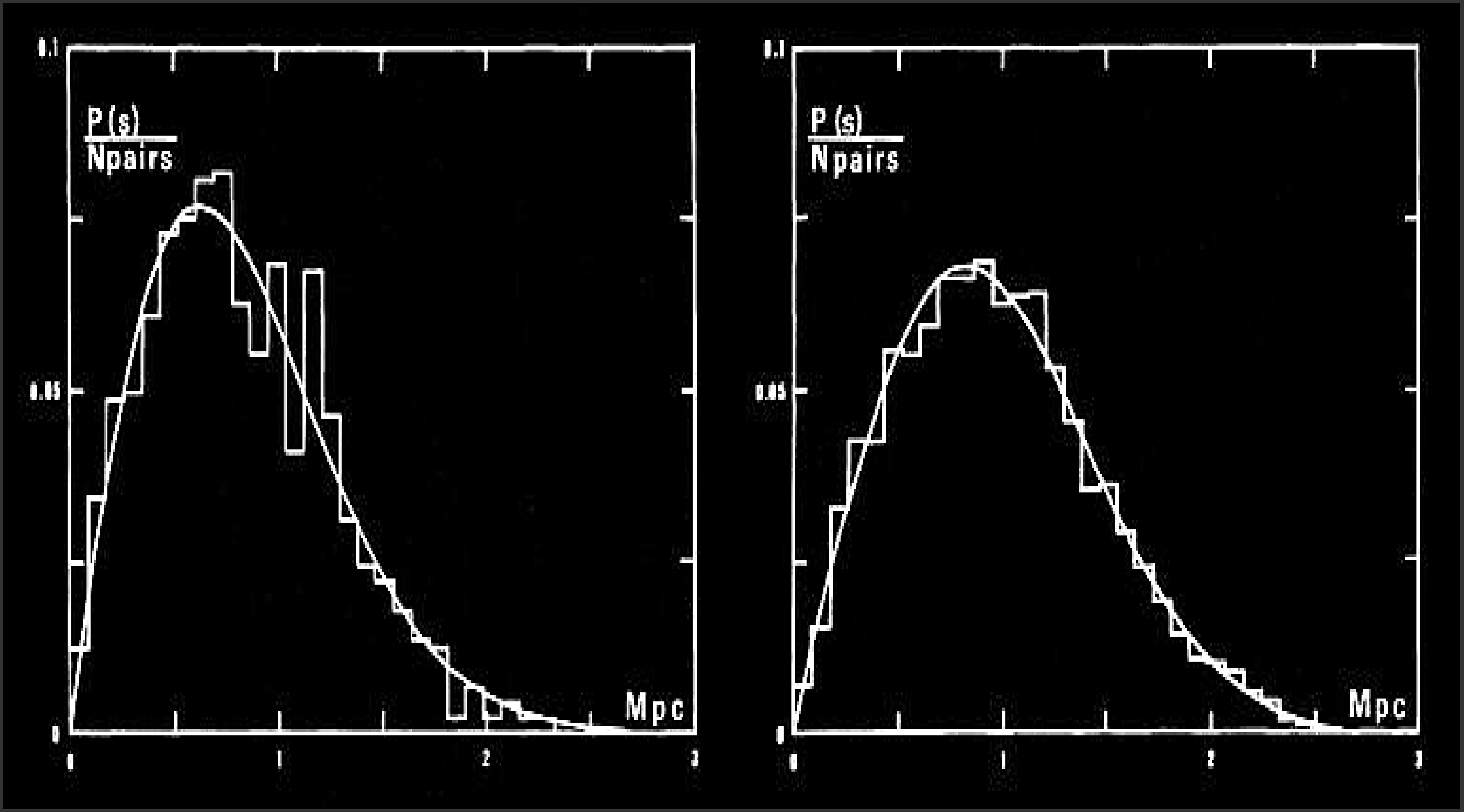


(Pracy+04)

Luminosity segregation:

brighter galaxies closer to R=0

(Capelato+80)



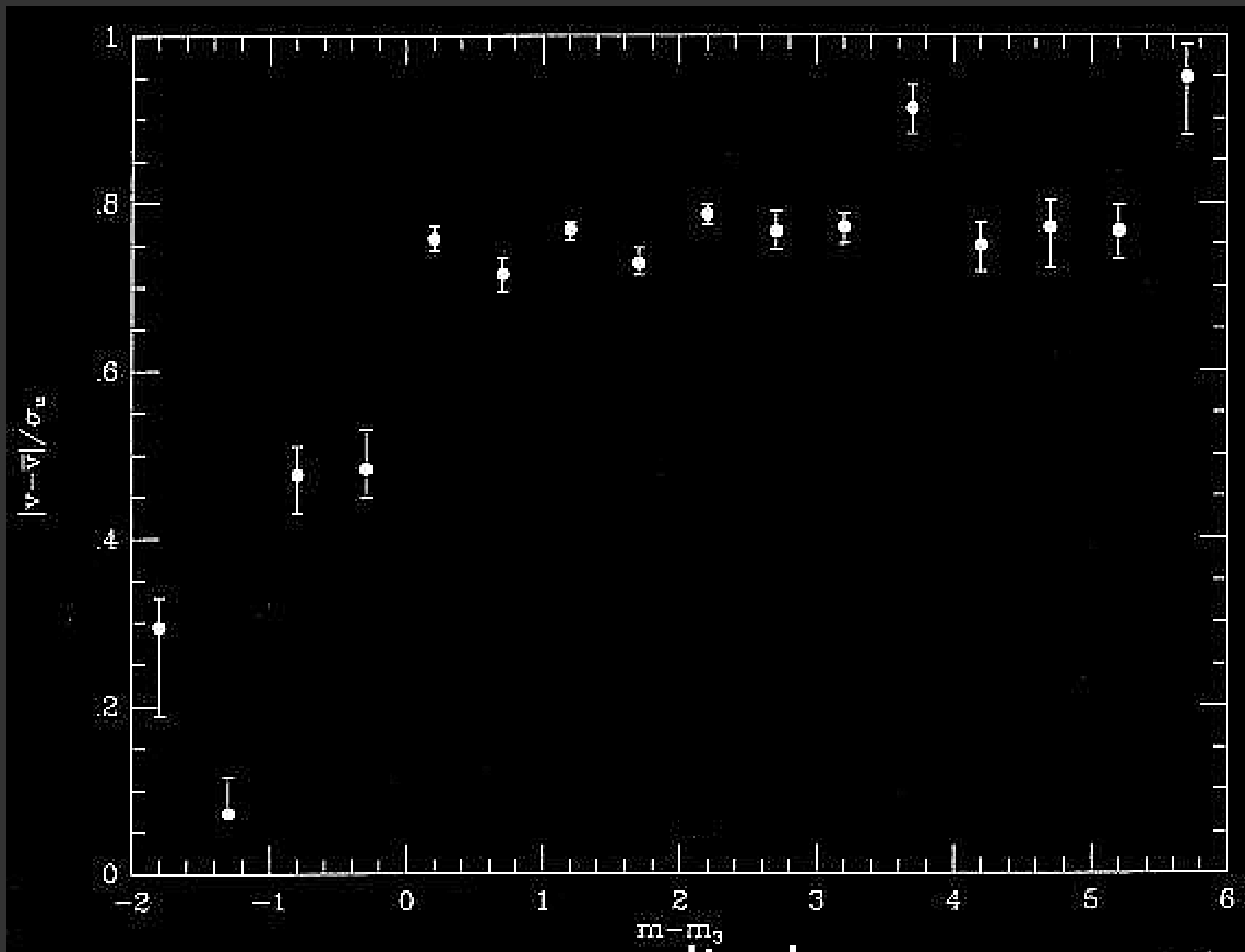
Spatial distributions of bright and faint galaxies

Another example of luminosity vs. density

Brighter galaxies closer to cluster center

but also closer to $\langle V \rangle_{cluster}$

velocity

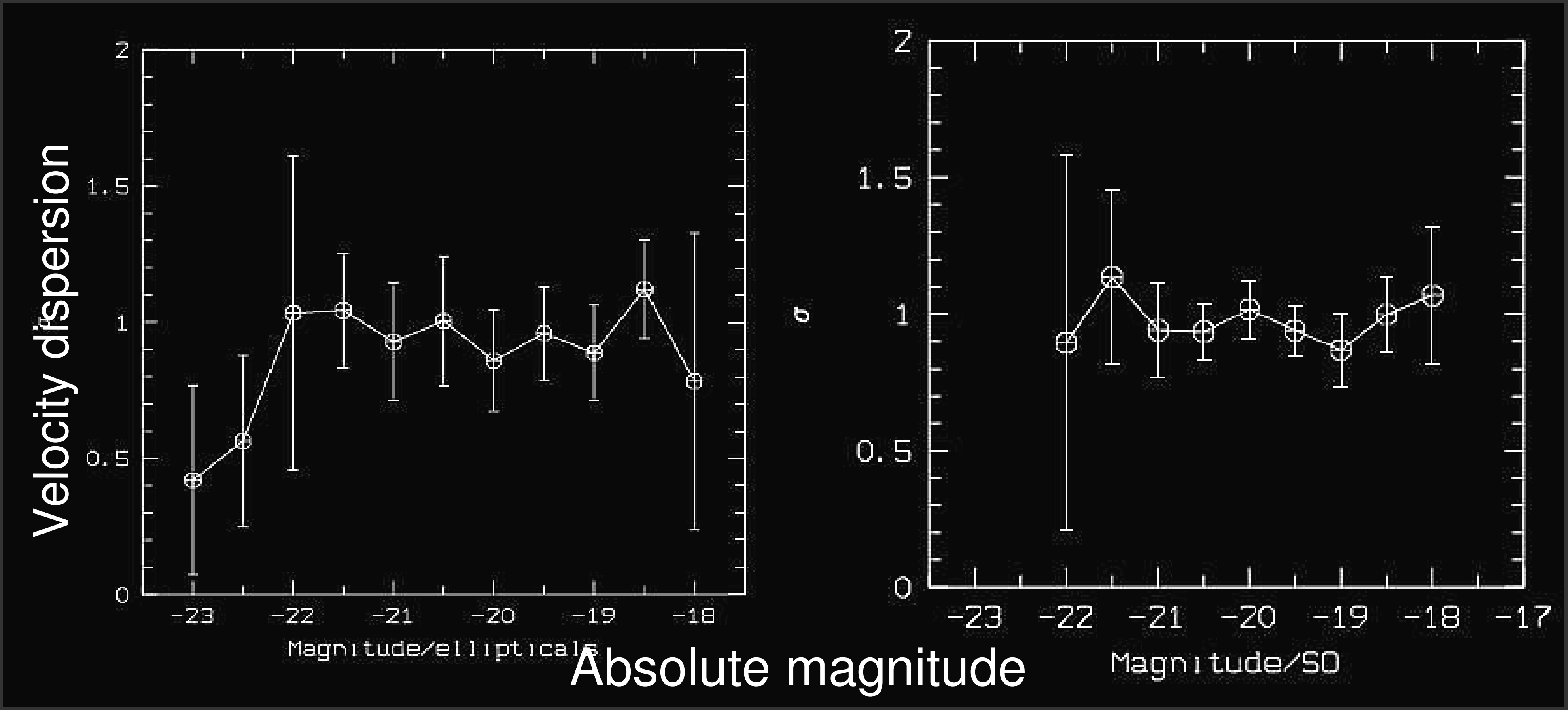


magnitude

(B.+92)

Brighter galaxies closer to cluster center

but also closer to $\langle V \rangle_{cluster}$



(Adami+98)

Luminosity segregation: Ellipticals, not S0

Brightest Cluster Galaxies:

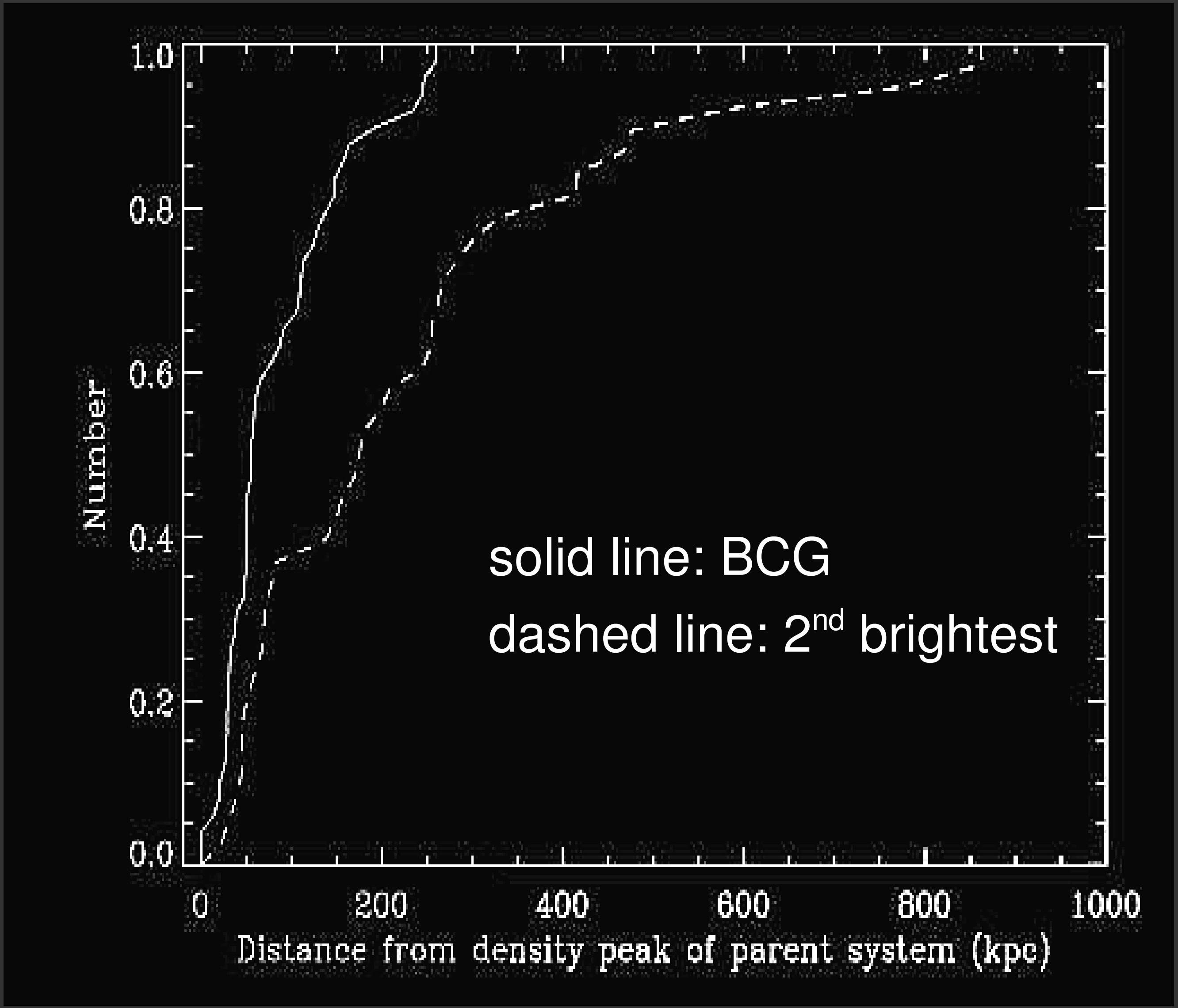
sizes > field galaxies
with = luminosities

BCG intimately related to their cluster

Central location

Alignenent

$L_{BCG} \leftrightarrow M_{cluster}$



(Ramella 07)

BCG intimately related to their cluster

Central location

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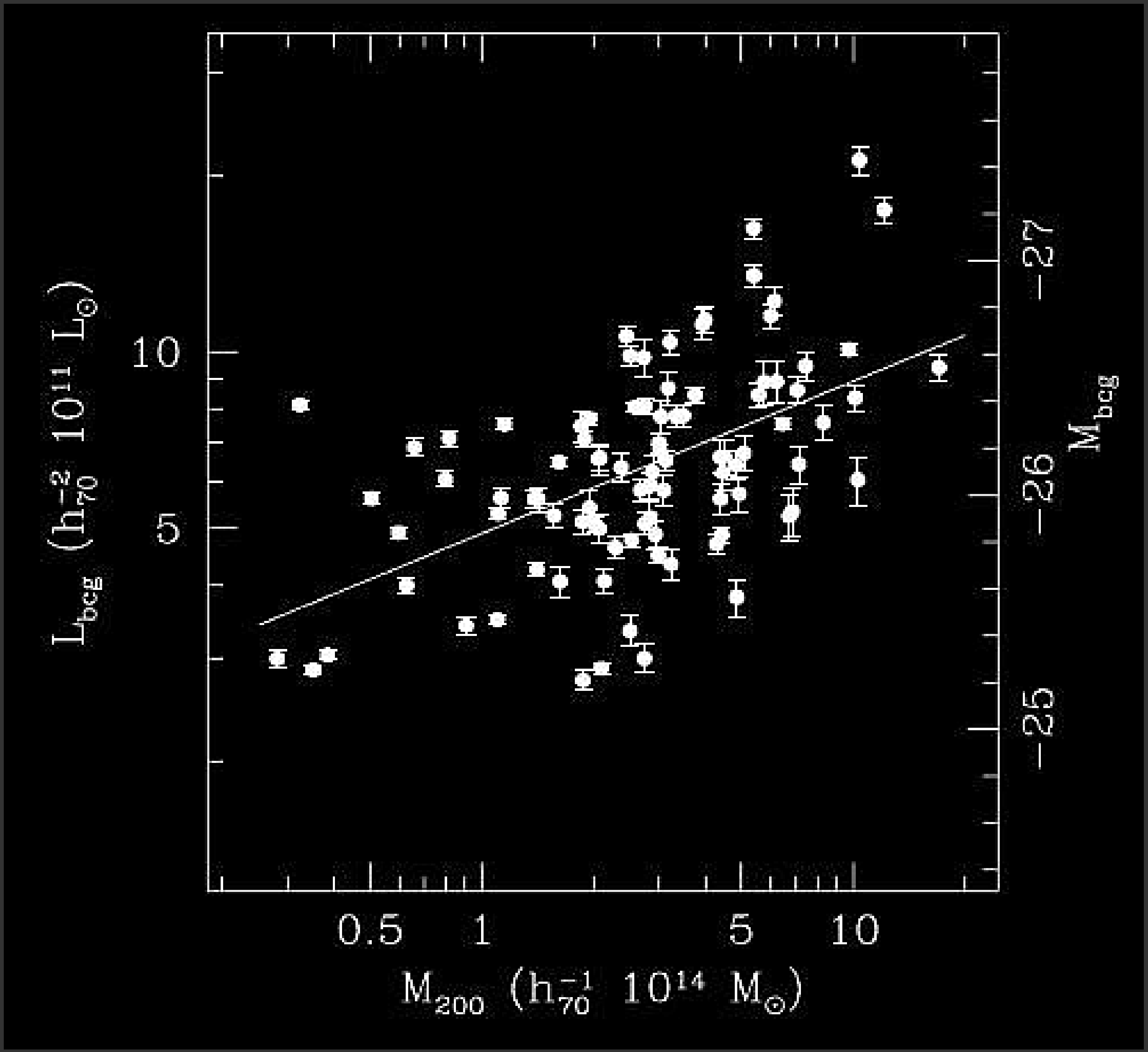
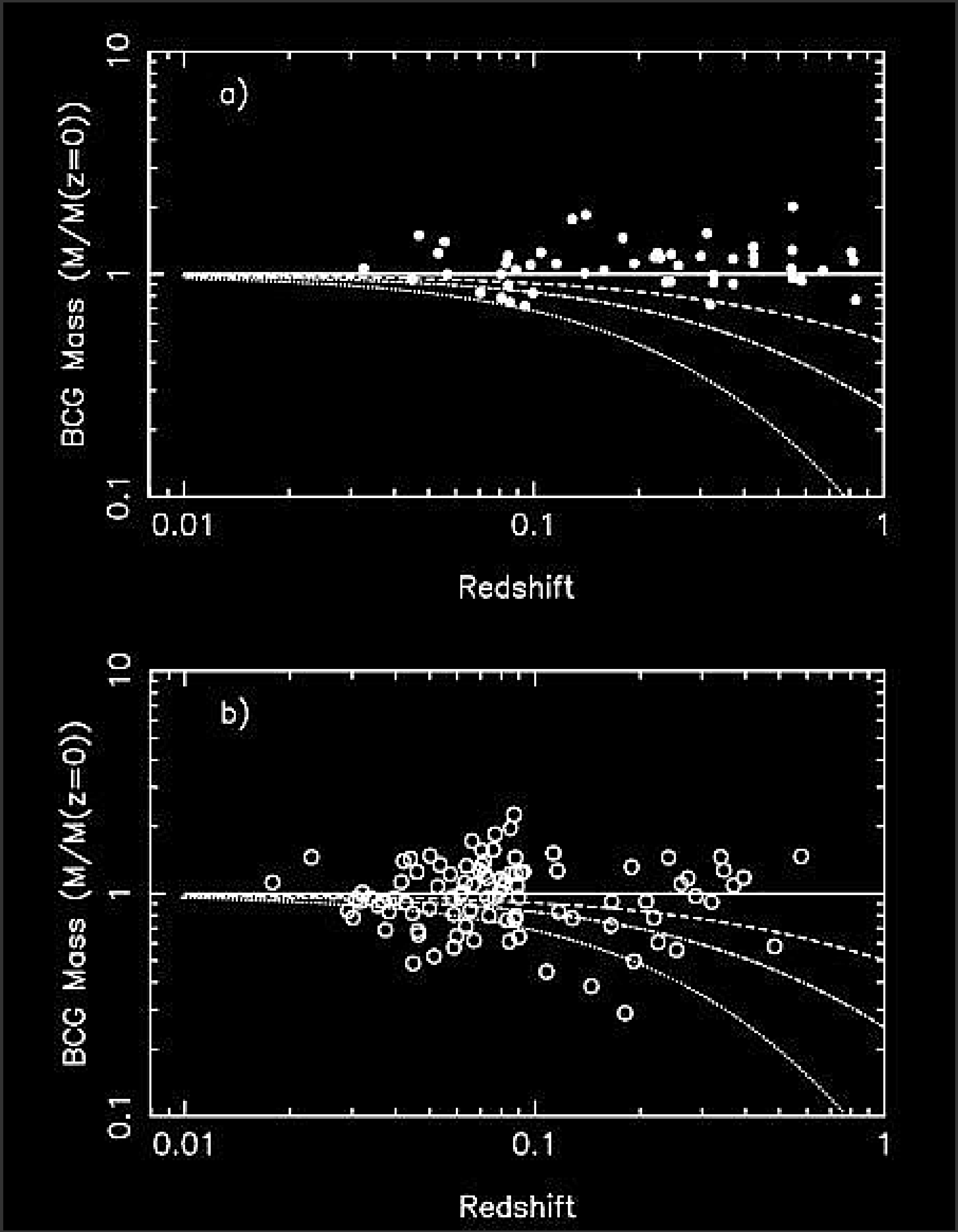


(Lin & Mohr 04)



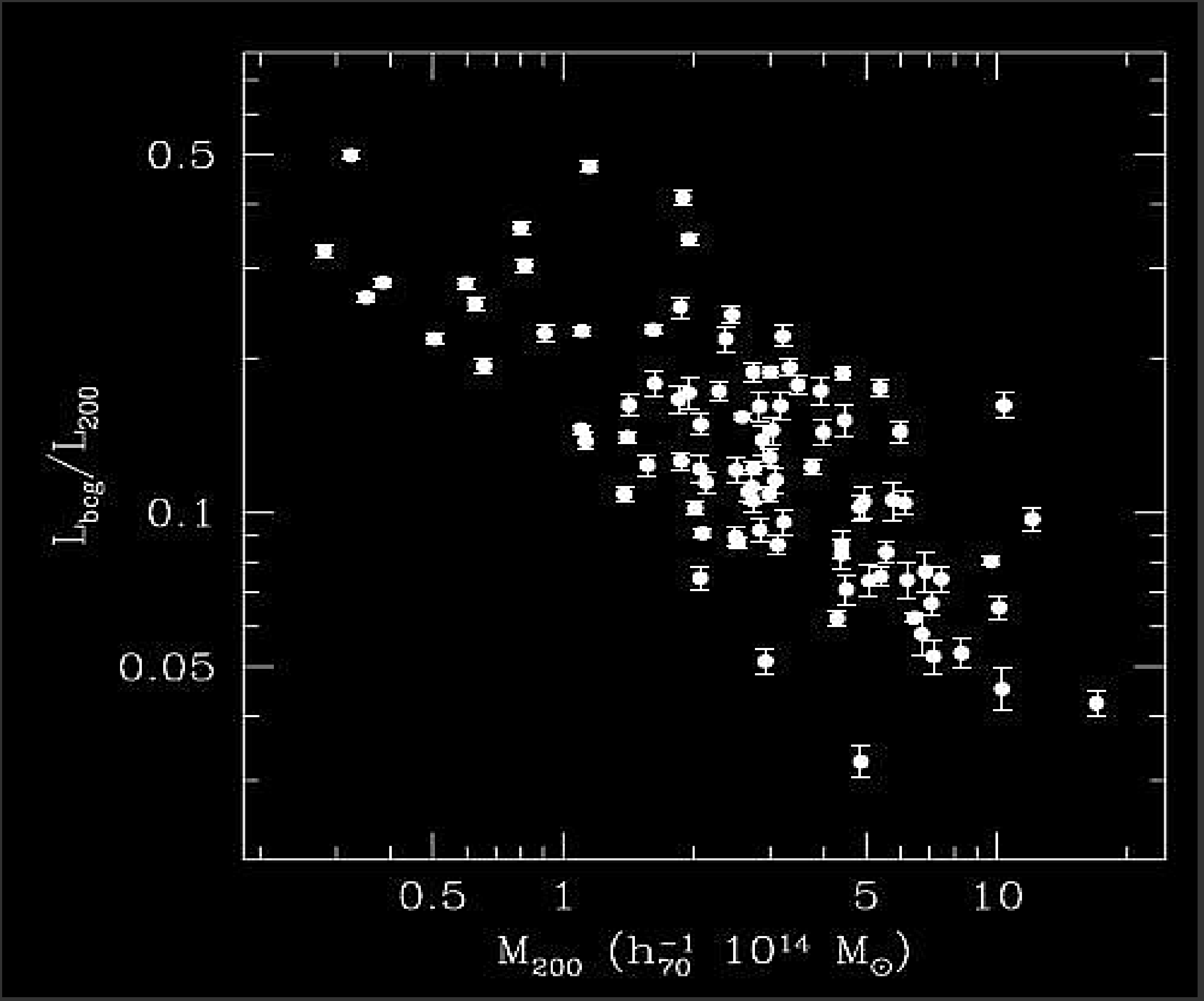
BCG color $\Rightarrow z_f \geq 2$

...but BCG stellar mass increased since z~1 in low-M clusters

(Brough+02)

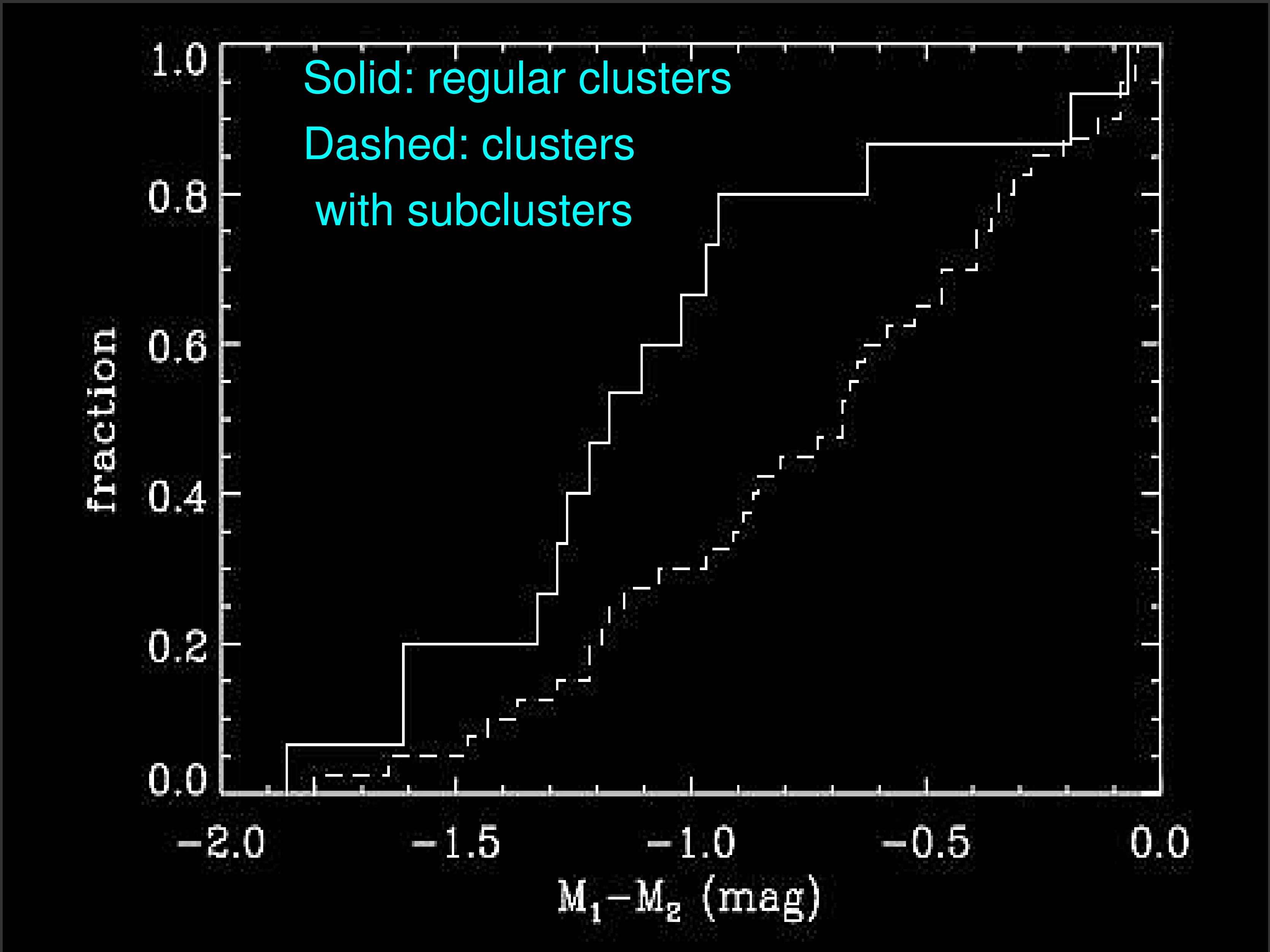
BCG in lower-M clusters keep growing as their host clusters grow

Fraction of total cluster light in the BCG anti-correlated with cluster mass



(Lin & Mohr 04)

Lum(BCG)/Lum(2nd brightest) ↑ in more regular (more evolved?) clusters

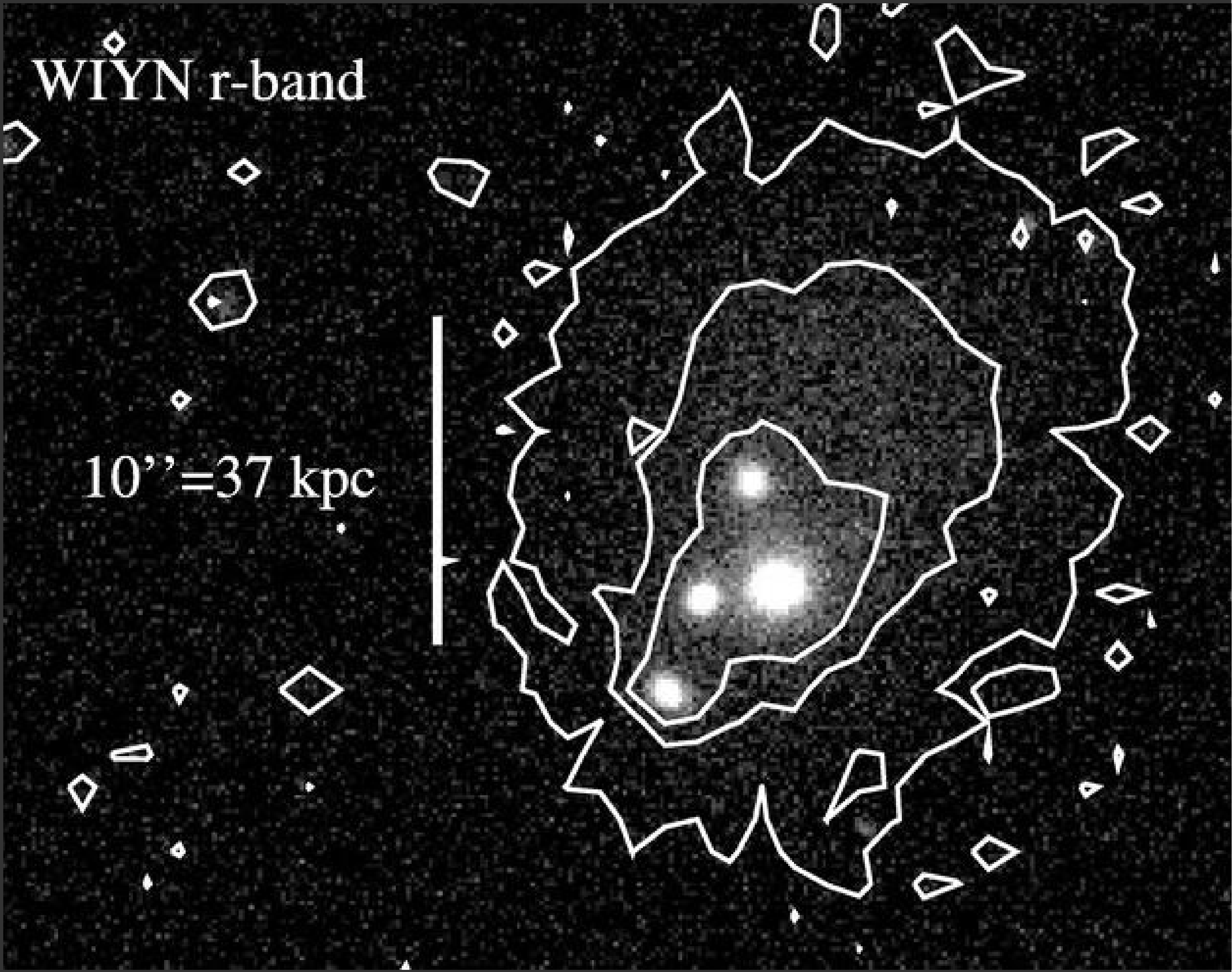


(Ramella+07)

BCG ↔ companions merger expected in ~0.1 Gyr

z=0.39 cluster

optical surface-brightness contours



(Rines+07)

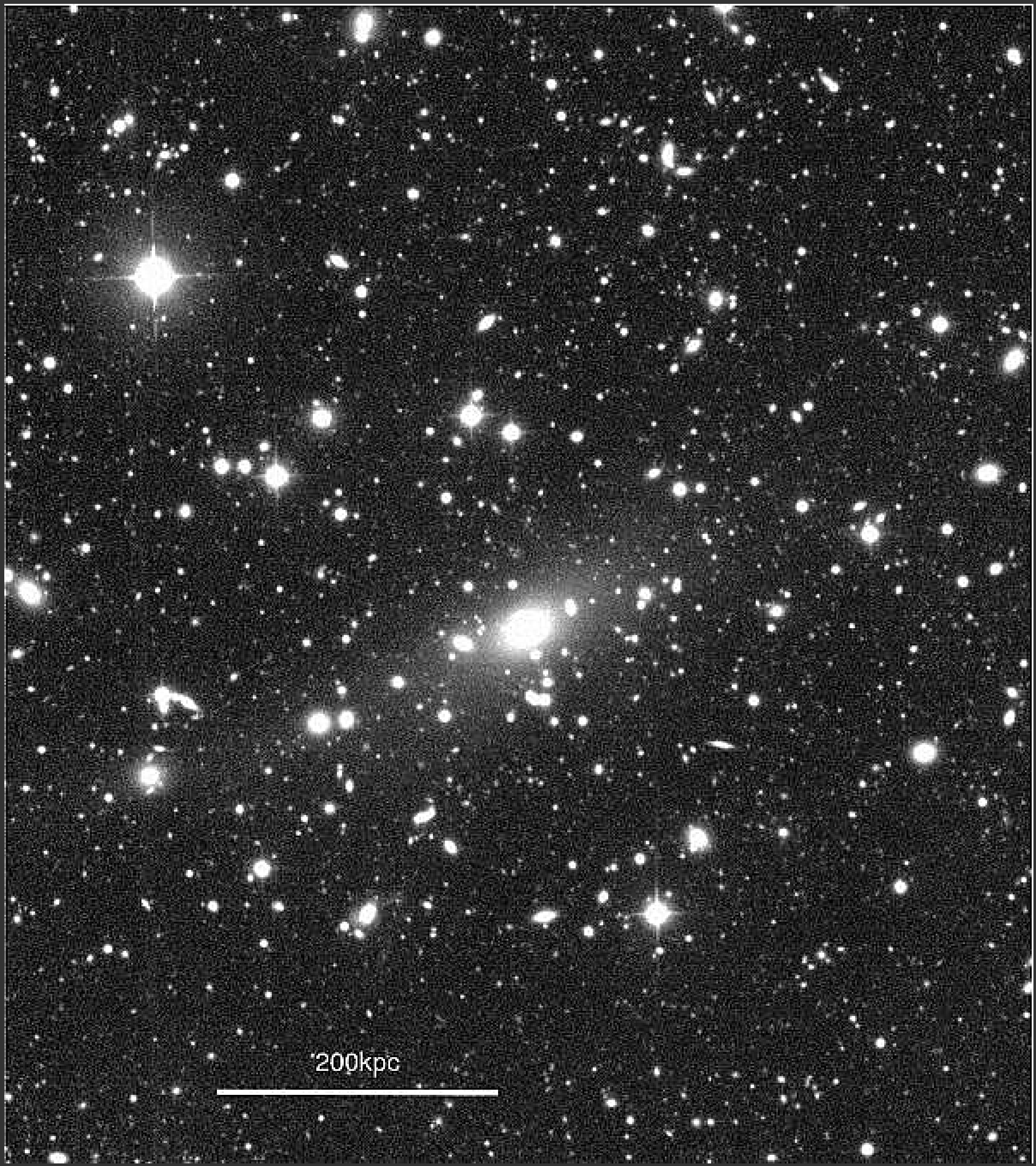
Intra-Cluster Light related to BCG

Similar colors

Aligned

Clusters with brighter BCG also have higher ICL surface brightness

ICL light ~ 5-25 % total light



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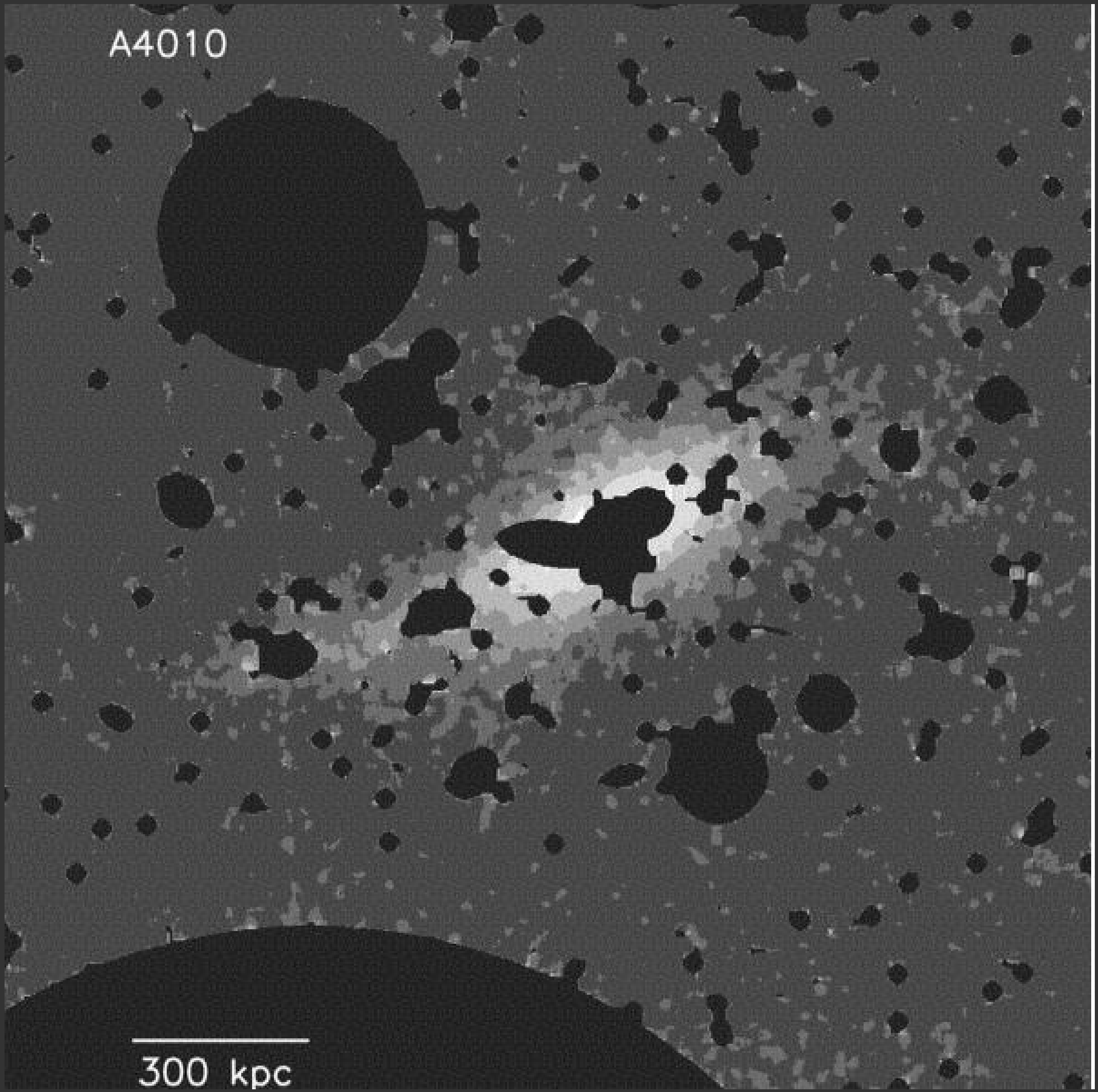
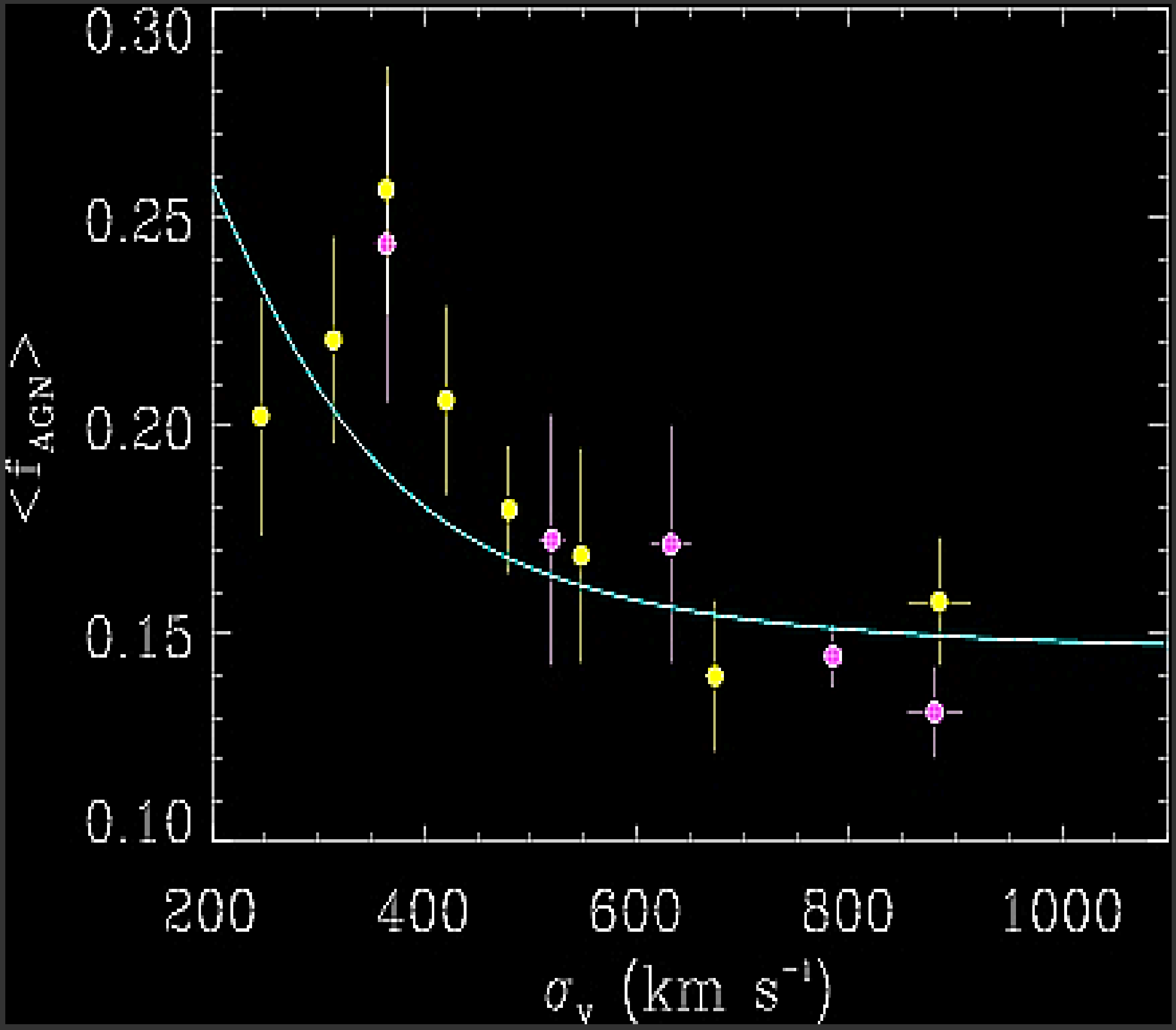


The properties of cluster galaxies: nuclear activity

AGN fraction:

no (?) dependence on local density

but strong dependence on σ_v



(Popesso & B. 06)

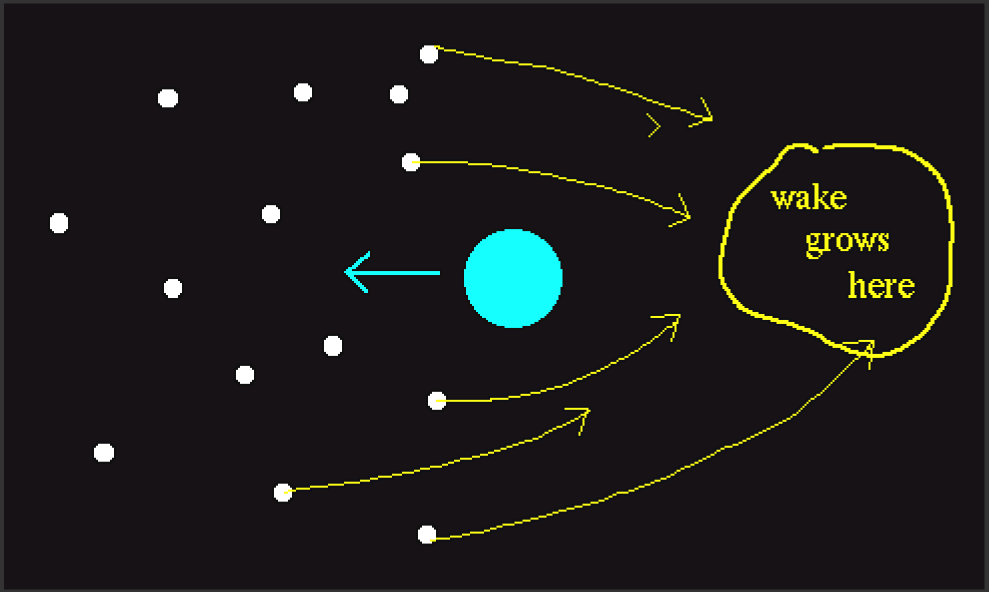
Physical processes

Processes capable of affecting cluster (and group) galaxy properties:

- ● dynamical friction
- ◆ galaxy-galaxy collisions → tidal effects & mergers
- ◆ tidal forces induced by cluster $d\phi/dr$ → tidal truncation
- ◆ ram-pressure stripping

Starvation can result from any of the ◆ processes as the galaxy gas is expelled or consumed

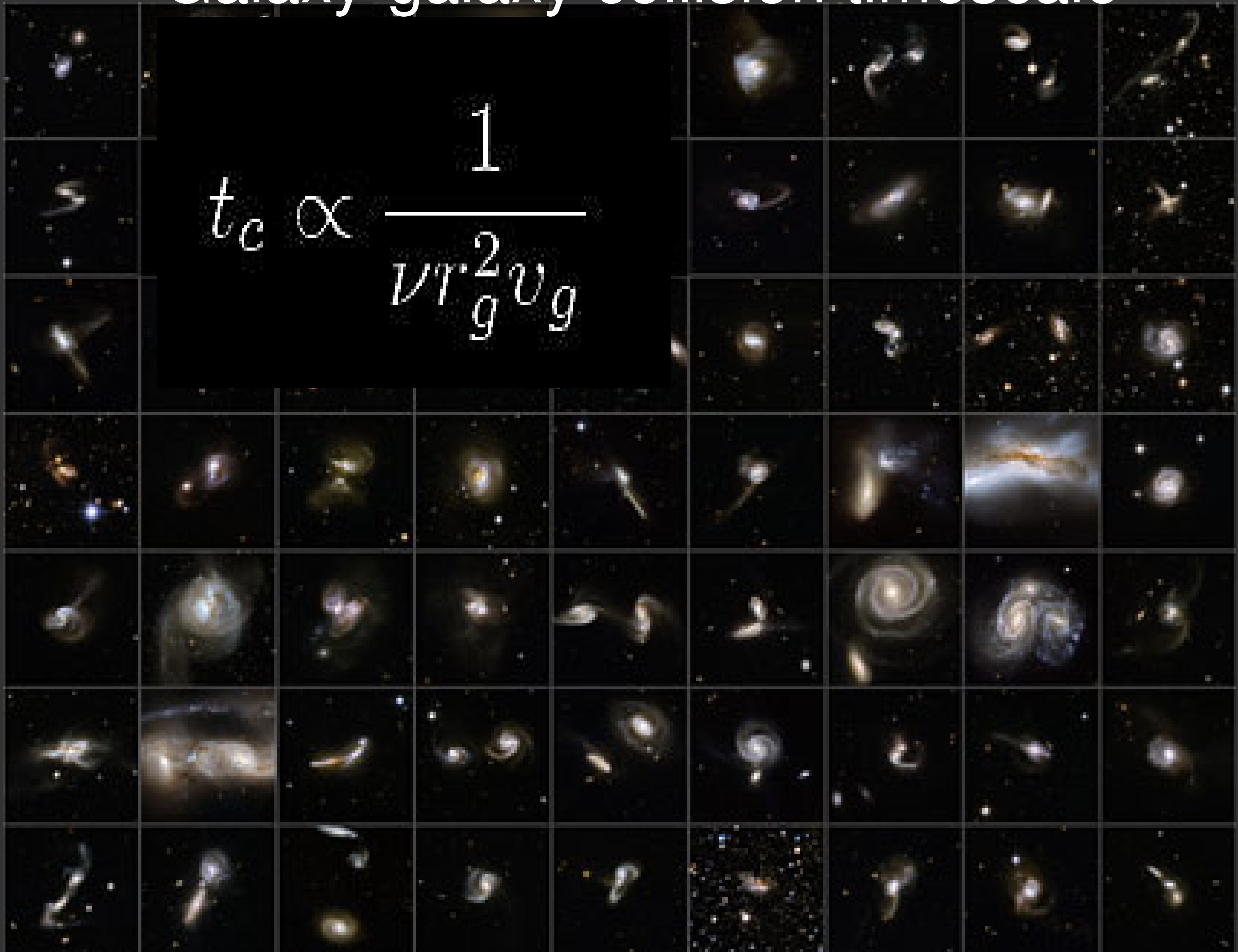
Dynamical friction timescale



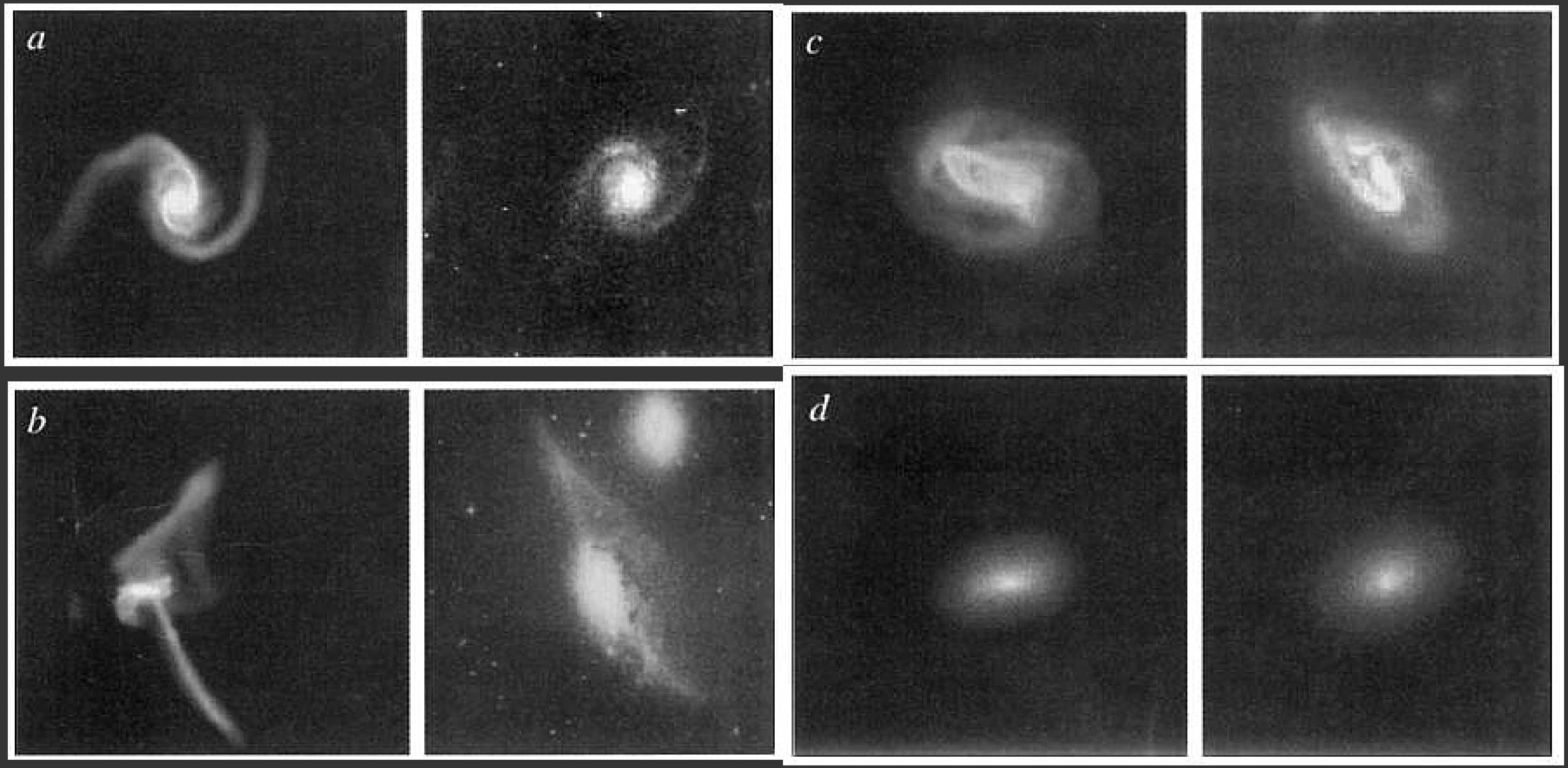
$$t_{df} \propto \frac{v_g^3}{m_g \rho}$$

Galaxy-galaxy collision timescale

$$t_c \propto \frac{1}{\nu r_g^2 v_g}$$



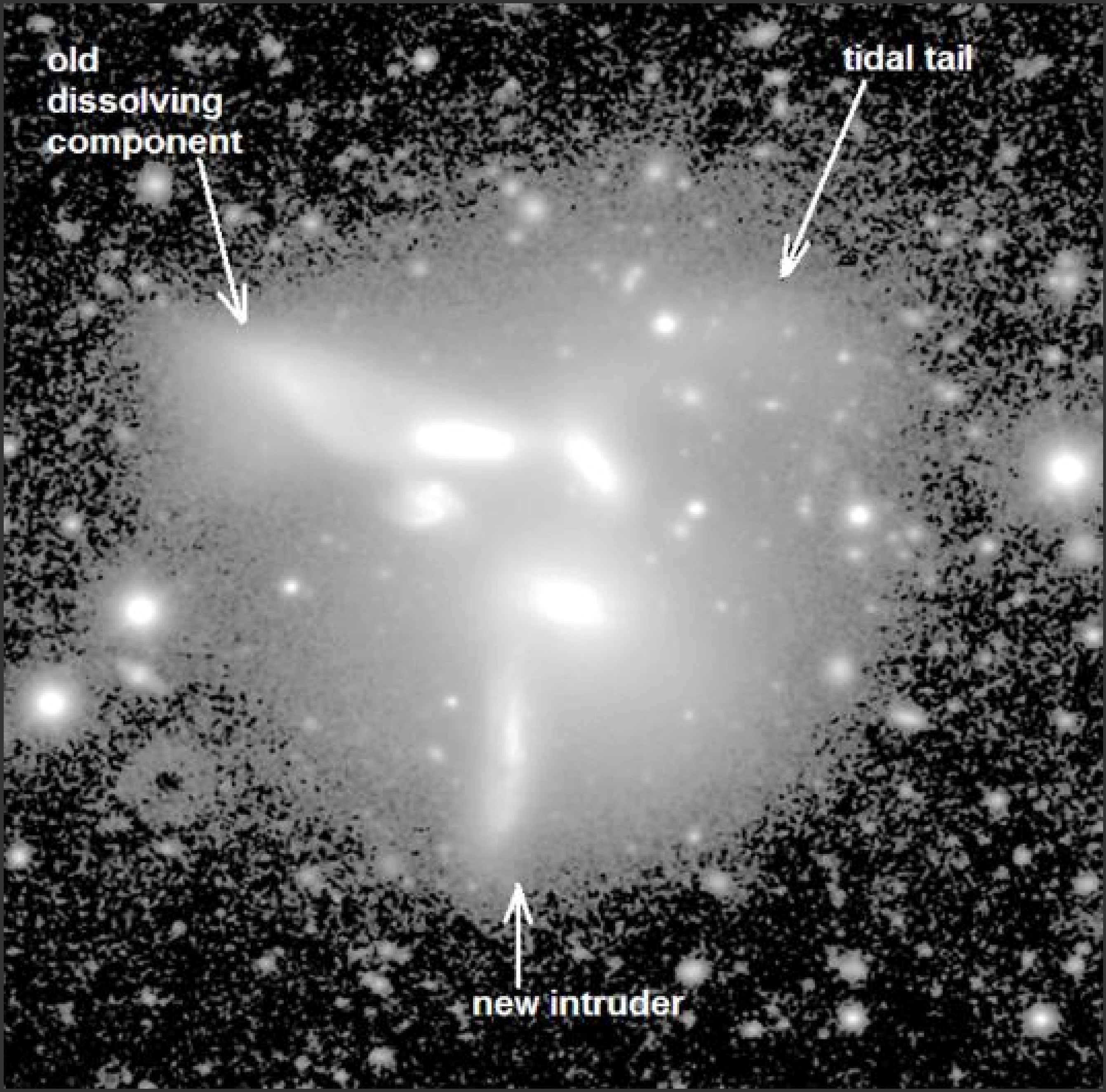
Rapid collisions → 'harassment'



⇨ Morphological evolution

(Moore+96)

Collisions → gas expelled by tidal forces



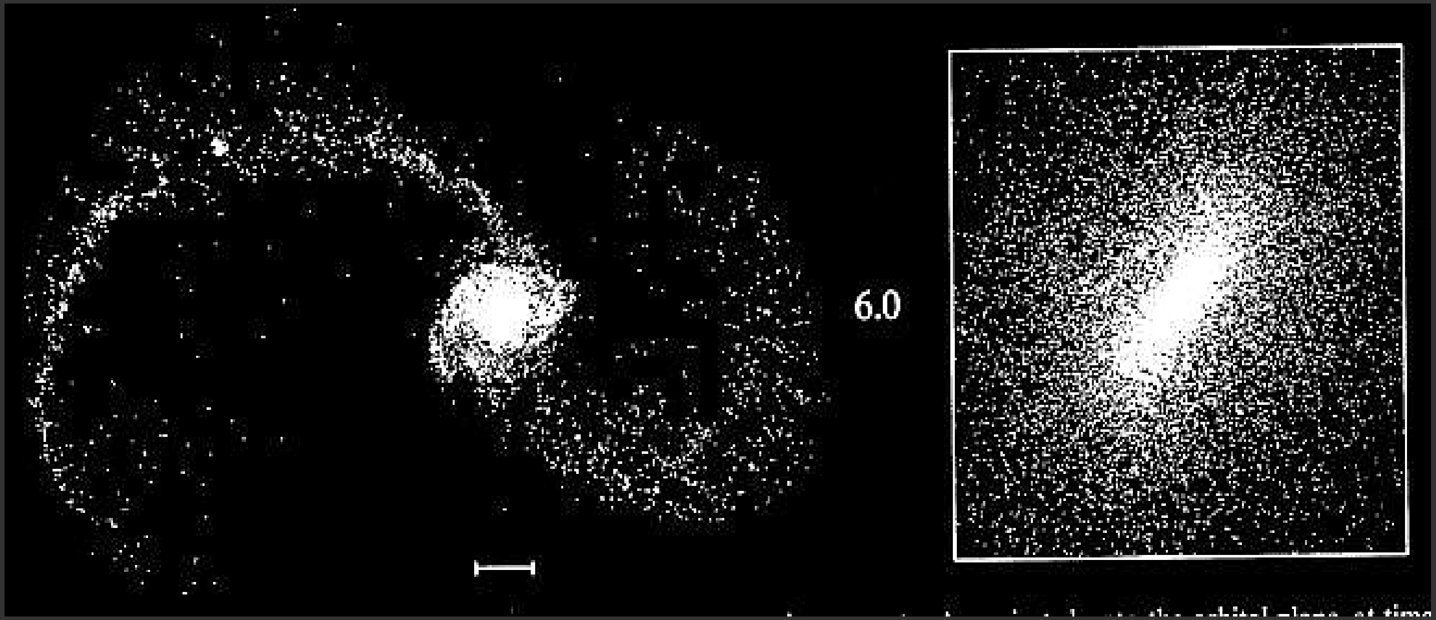
(Durbala+08)

Slow collisions → mergers

$$t_m \propto \frac{\sigma_v^3}{\sigma_g^4 r_g^2 \nu}$$

Merger timescale

Leading to tidal gas loss
and morphological evolution



(Barnes 92)

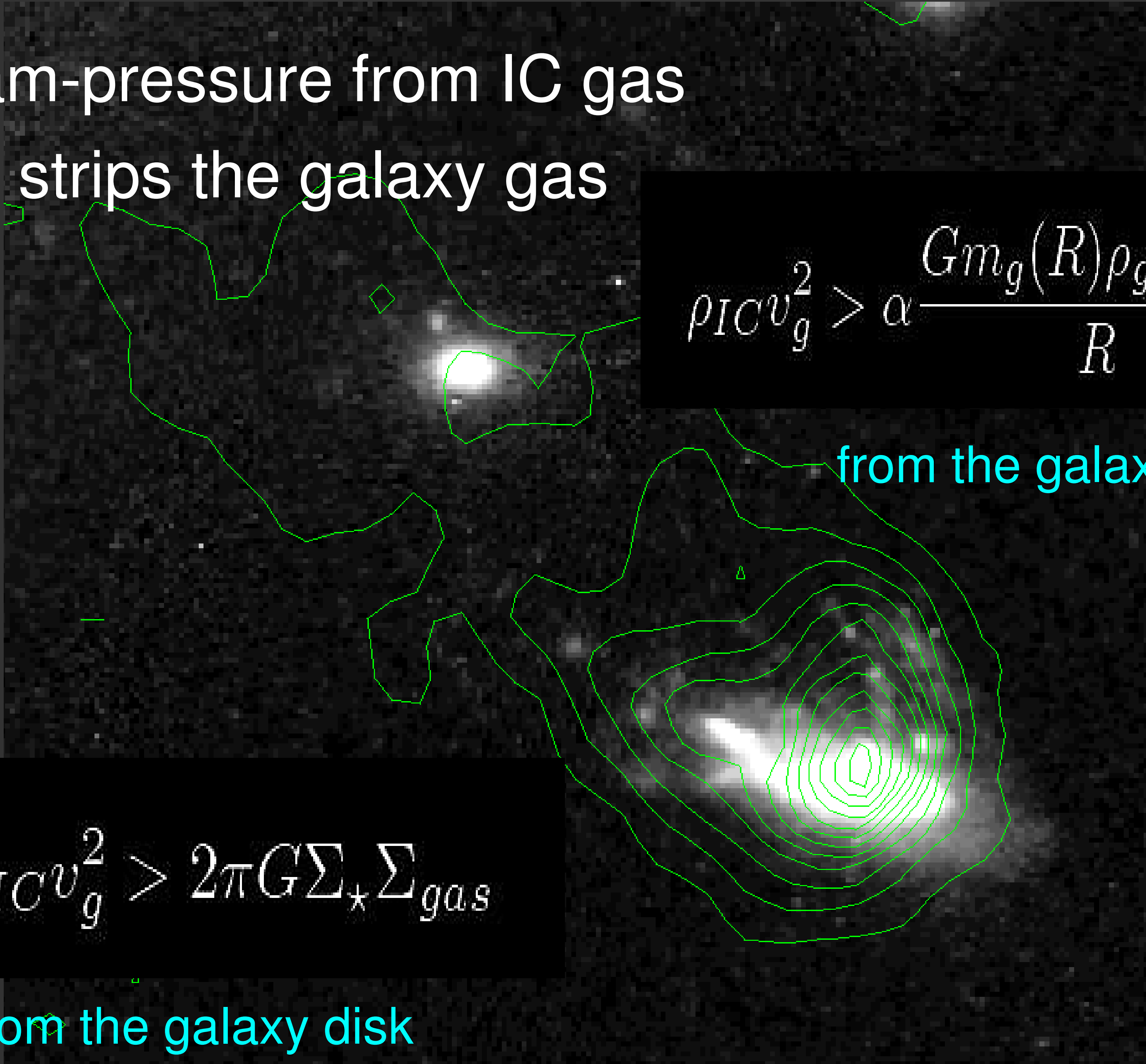
Galaxy orbiting cluster suffers tidal truncation outside r_t:

$$r_t \approx r_c \frac{\sigma_g}{2\sigma_v}$$

$r_c \approx 2\, r_{pericenter}$

BCG at r=0 not truncated, symmetric external forces

Ram-pressure from IC gas strips the galaxy gas



$$\rho_{IC} v_g^2 > \alpha \frac{G m_g(R) \rho_{gas}(R)}{R}$$

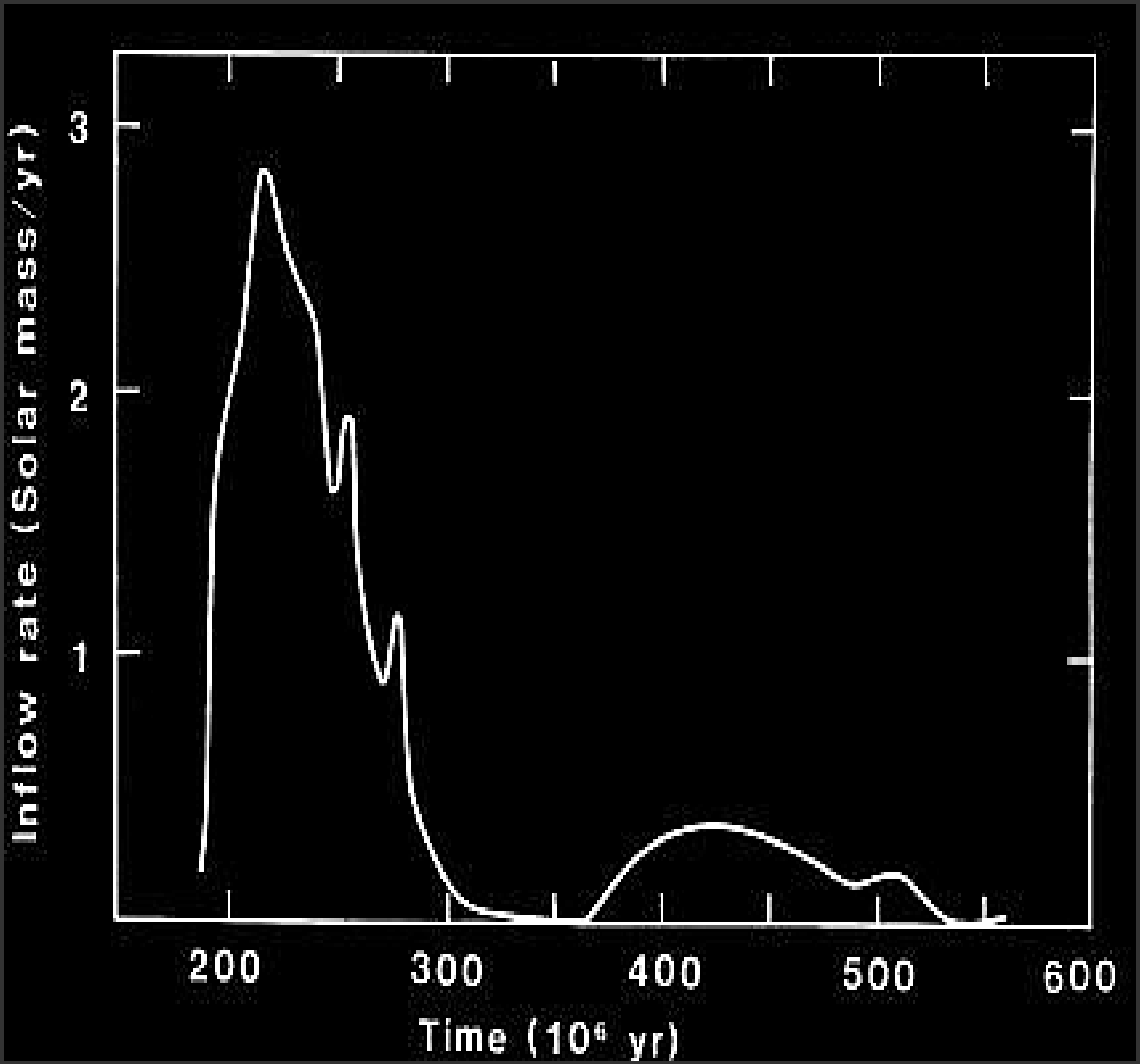
from the galaxy halo

$$\rho_{IC} v_g^2 > 2\pi G \Sigma_\star \Sigma_{gas}$$

from the galaxy disk

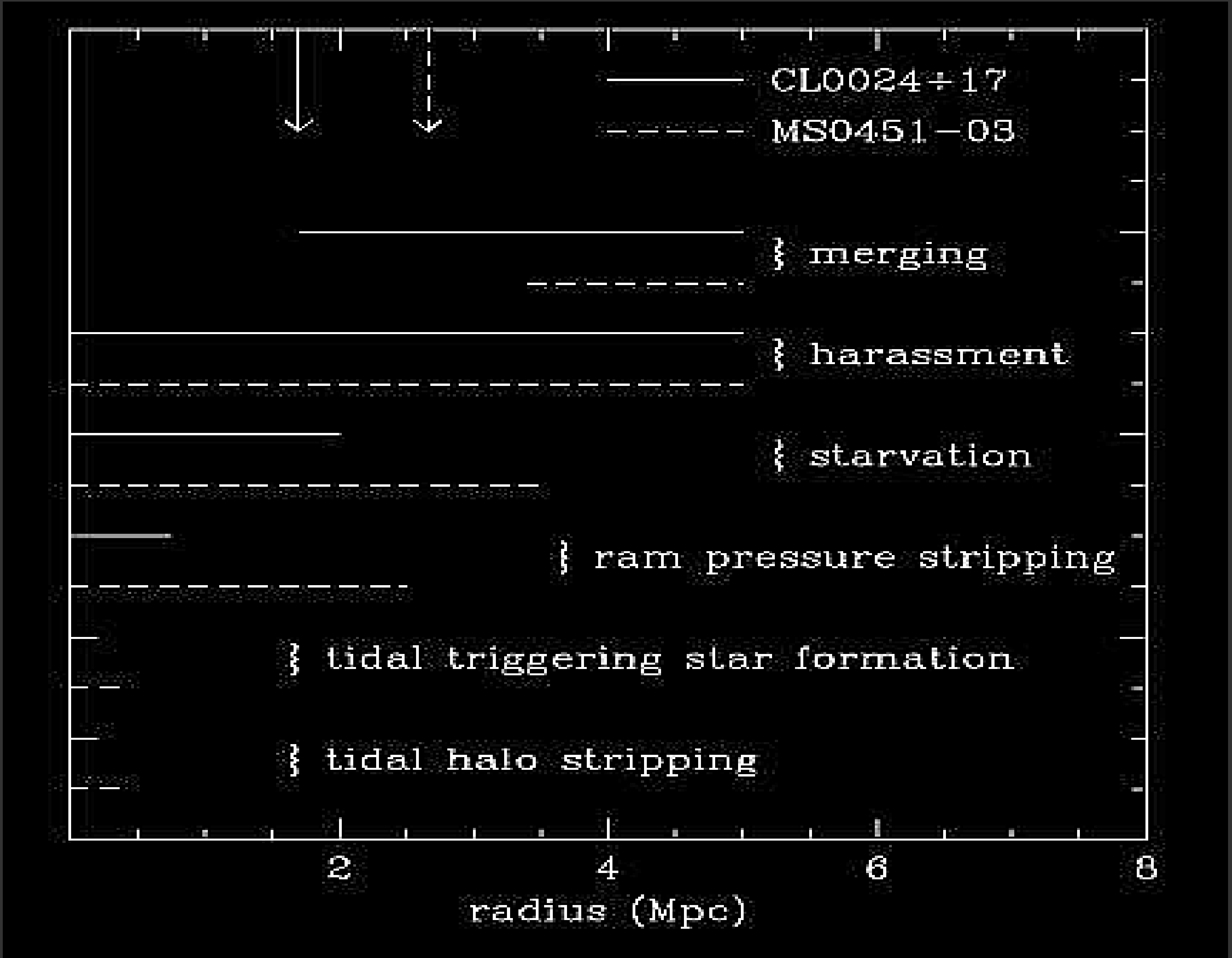
Tidal or ram compression of galactic gas

→ central starburst



(Byrd & Valtonen 90)

Different processes are efficient in different environments



(Moran+07)

Evolutionary scenarios

'Nature' vs. 'nurture'?

Nature:

CMR and MDR in place at high-z

Bright ETG undergo only passive evolution

Nurture (?):

S0, fainter ETG, ETG in lower-density regions are younger, especially in low-M irregular clusters

Cluster LF $\neq$ field LF (BCG, ICL)

Use Ockham's razor:

no nurture if nature suffices

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Hierarchical cosmological models

naturally predict biased galaxy formation:

more **massive** galaxies form *earlier* in **denser**
environment (*earlier* collapse of density fluctuations)
hence they form their stars, run out of fuel,
and stop forming stars *earlier*

"Downsizing"

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NEW INSIGHT ON GALAXY FORMATION AND EVOLUTION FROM KECK SPECTROSCOPY OF THE HAWAII DEEP FIELDS

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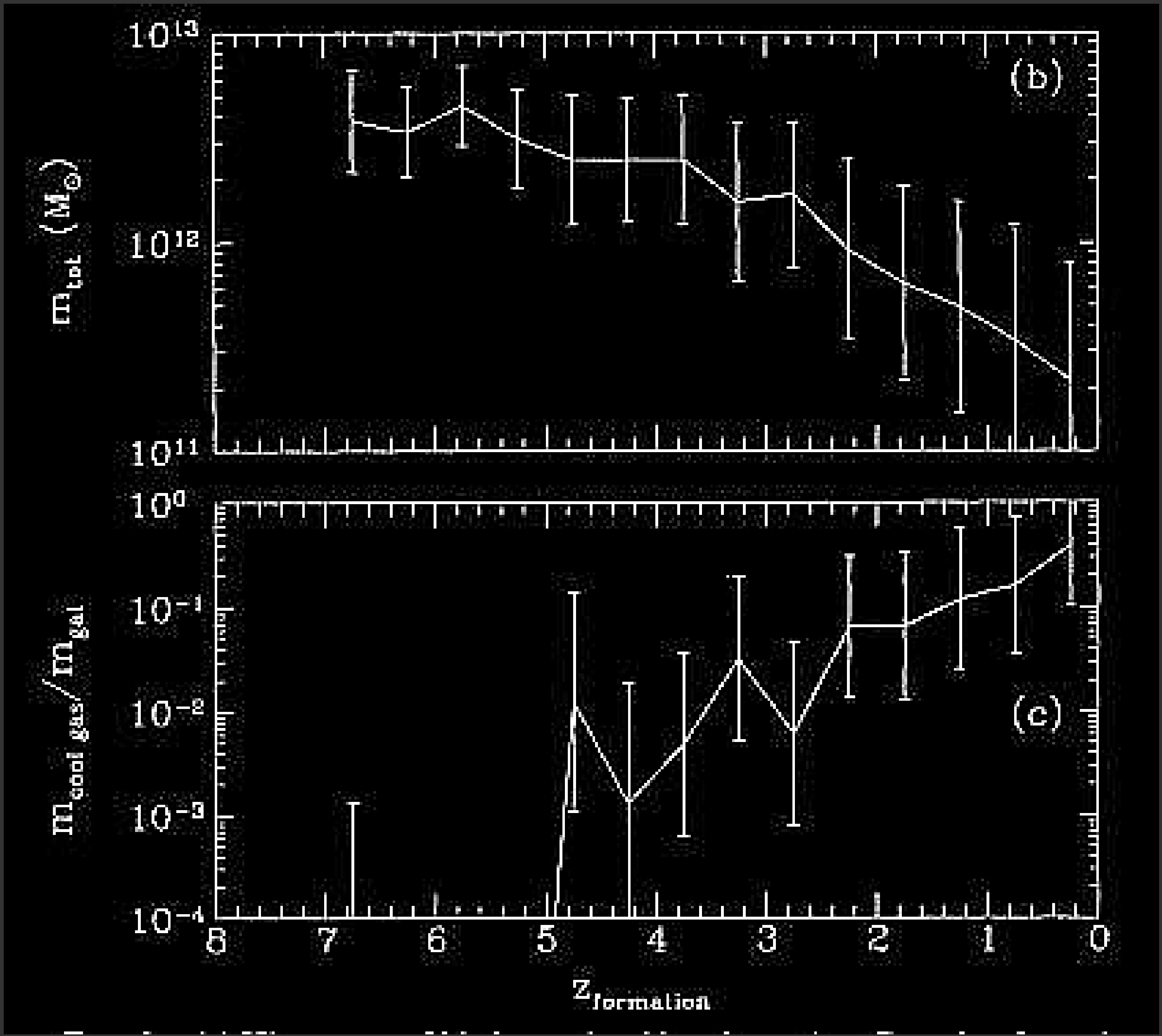
ABSTRACT

$z=0.8$ and $z=1.6$, and also that galaxy formation took place in "downsizing," with more massive galaxies forming at higher redshift. The late galaxy formation accounts for the

Numerical simulations:

Galaxy mass

(Gas mass) /(total mass)



formation redshift

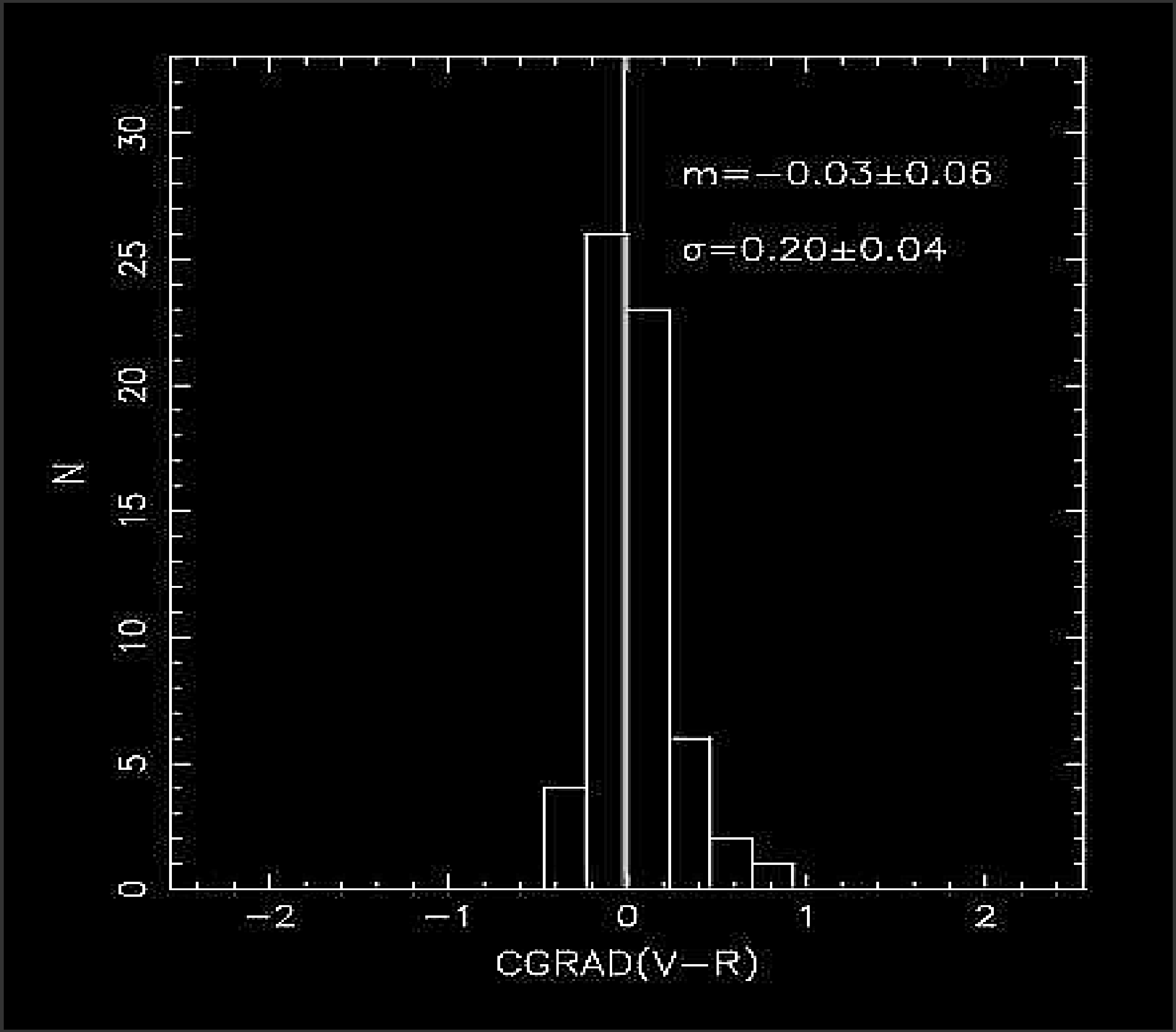
(Cen & Ostriker 93)

But *nurture* does play a role in hierarchical models: galaxies grow via mergers

Mergers → increase galaxy masses
destroy disks and spiral arms
reduce angular momentum
trigger starbursts (reduce gas content)
form central Black Holes and AGNs
(AGN feedback quench SF)

Mergers effective in high-density regions with low-σ_v (at early-times or via dynamical friction)

Merger origin of ellipticals: flat metallicity and color gradients

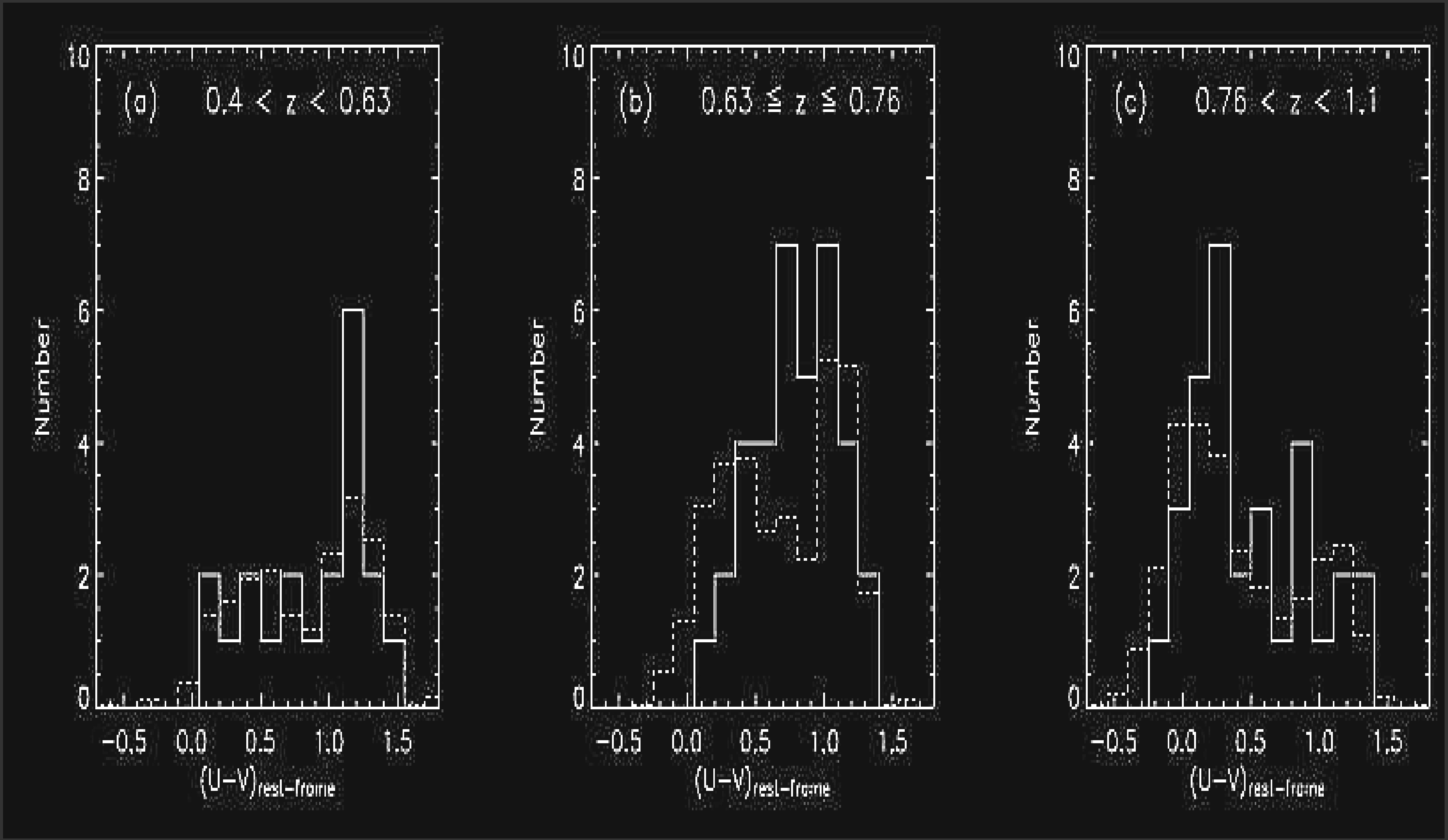


(La Barbera+04)

Merger origin of AGN:

host galaxy colors and morphologies

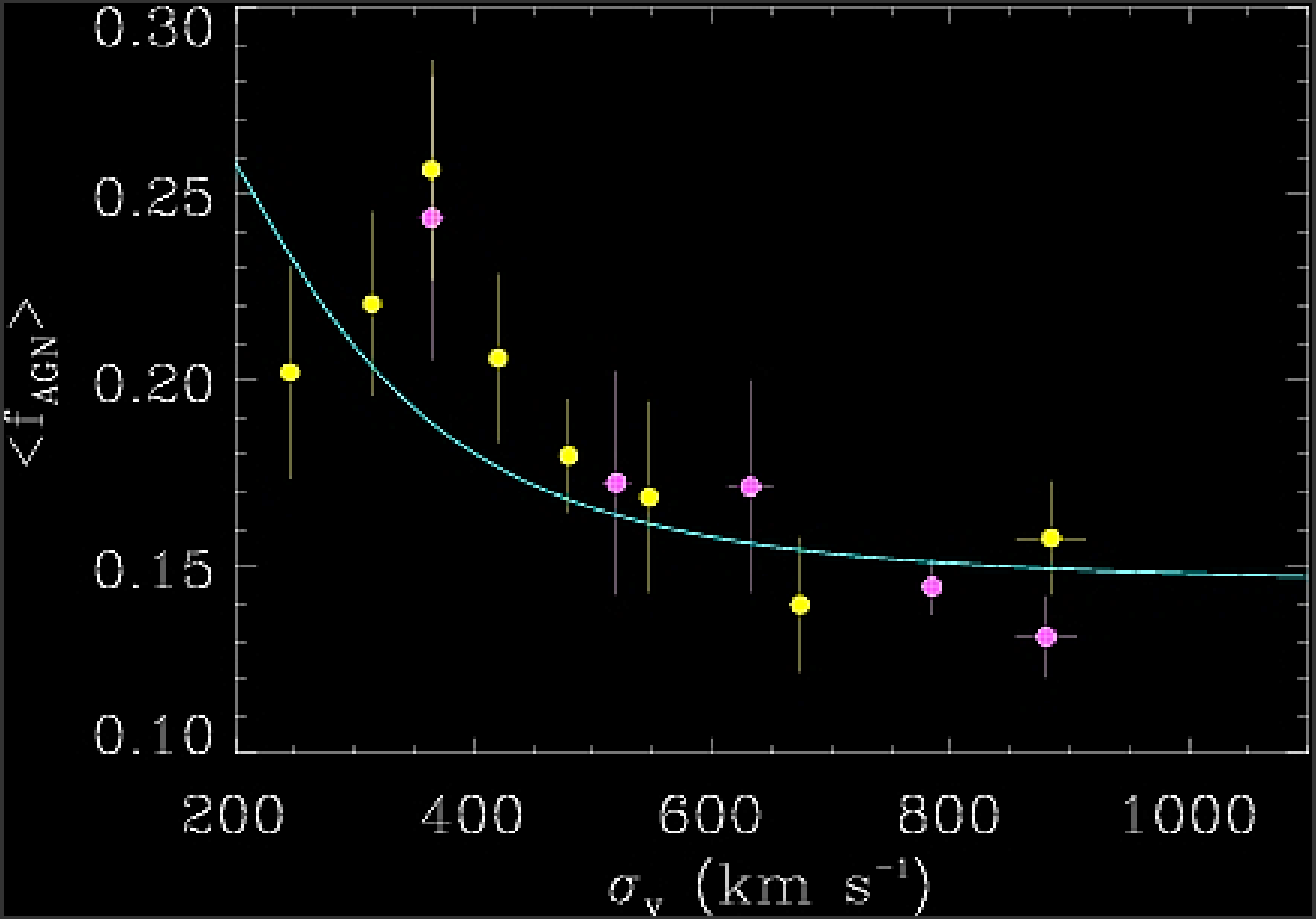
☞ 1-4 Gyr old starburst



(Silverman+08)

Merger origin of AGN:

fraction vs. σ_v fitted by merger model



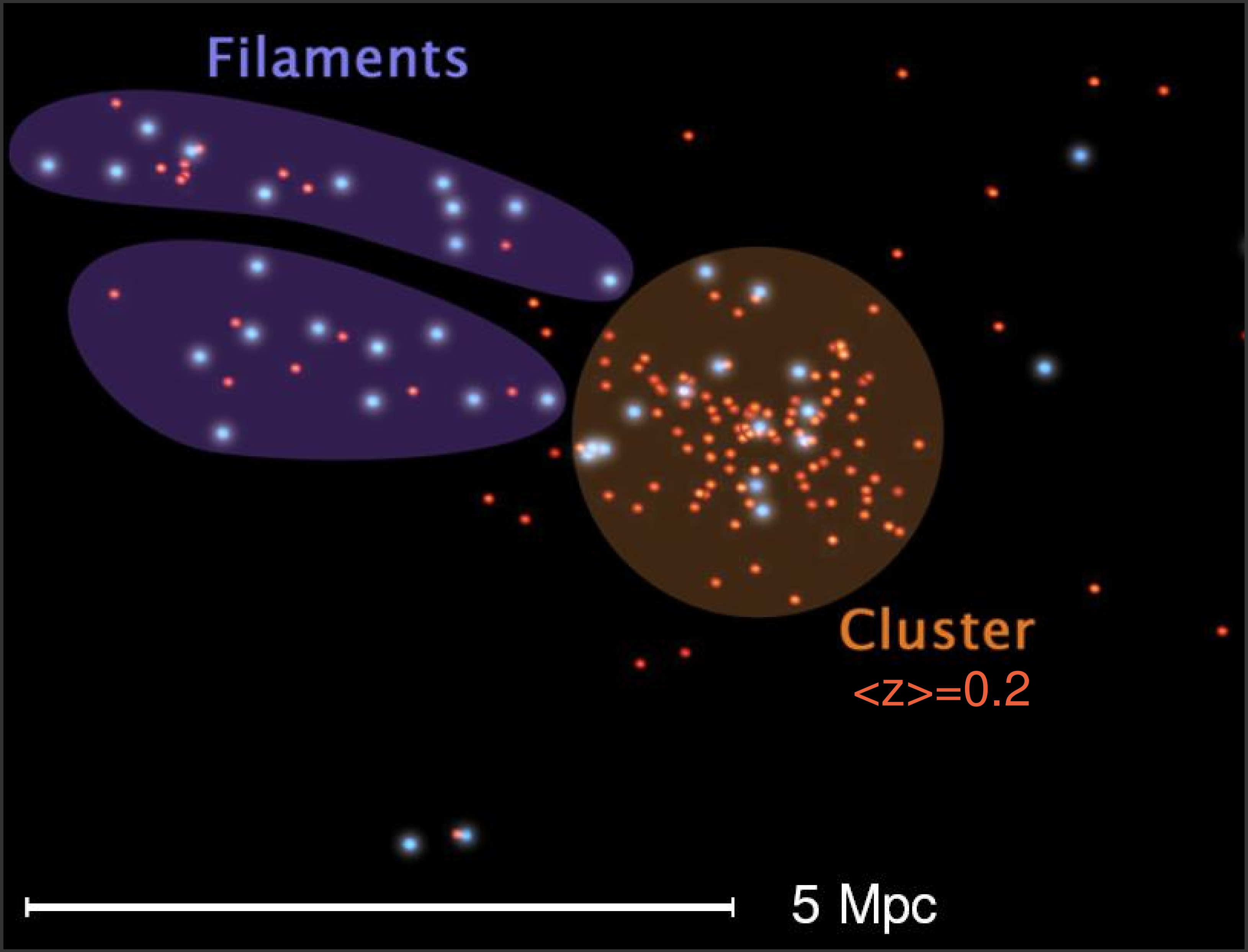
(Popesso & B. 06)

Mergers become inefficient at later times in galaxy clusters when $\sigma_{\mathrm{v}} \uparrow$

Mergers become inefficient at later times
in galaxy clusters when σ_V ↑

Mergers at later times
can still operate in lower-σ_V
but relatively high-density regions,
i.e. groups (subclusters) and filaments

Mergers suggested by starburst activity in galaxies of cluster-feeding filaments



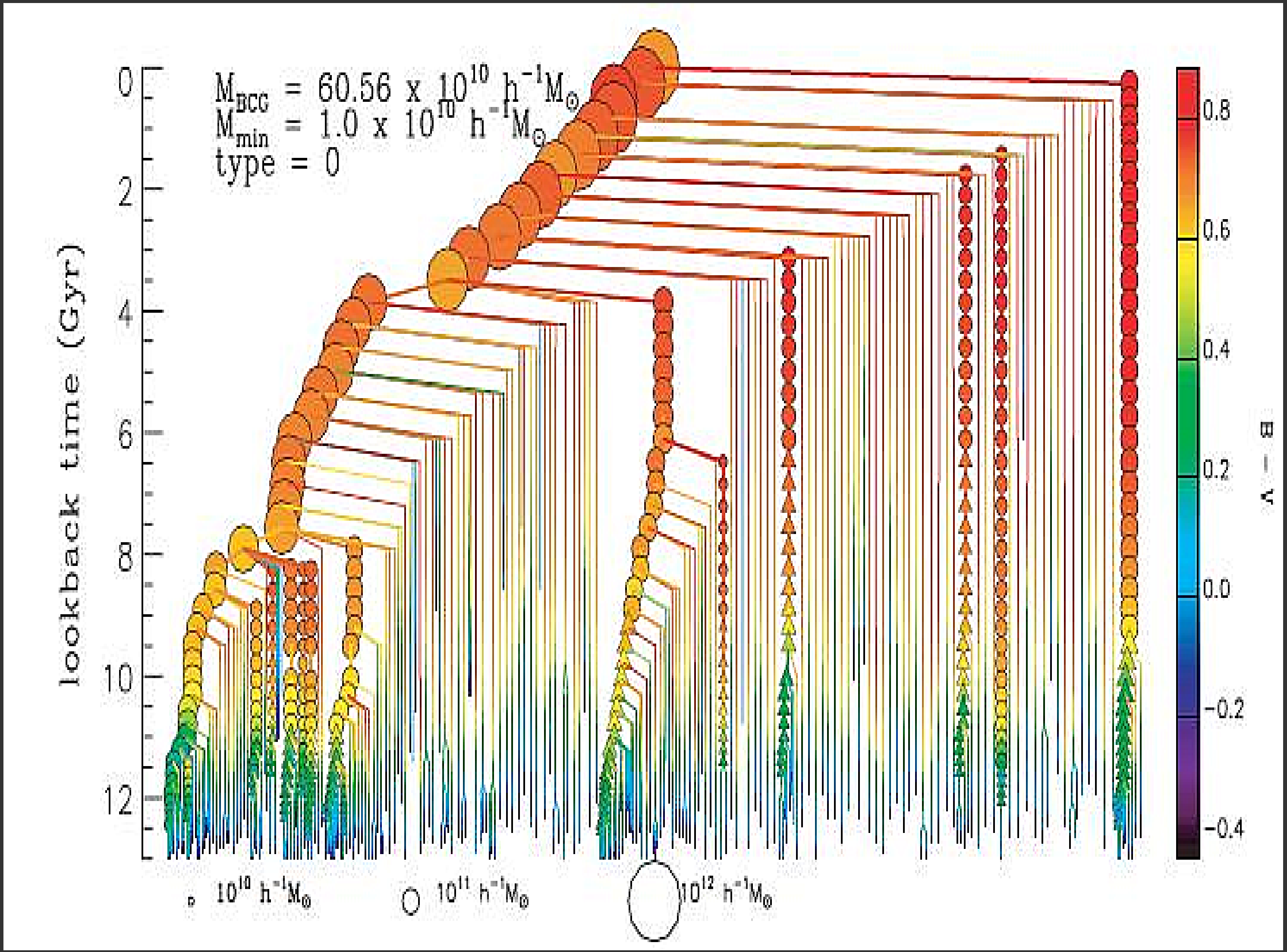
(Fadda+08)

Dynamical friction ⇒

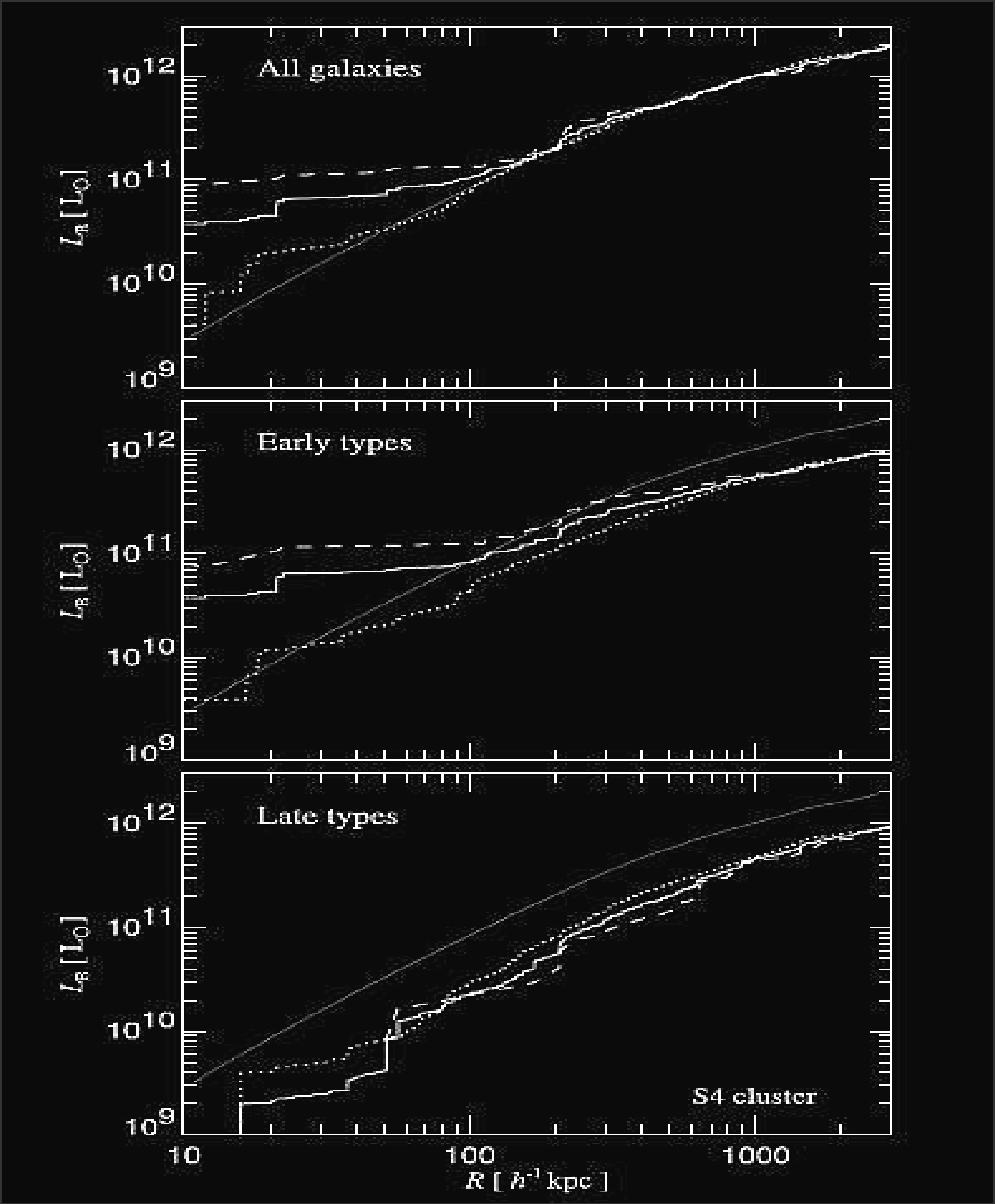
merger continues until late in central cluster region

BCG continues to grow up

(De Lucia & Blaizot 07)



Dynamical friction and mergers can explain luminosity segregation



(Springel+01)

Merger explains bright part of LF cluster vs. field $\neq$

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Mass of merger products $< \sum$(progenitor masses)

⇨ lost mass during mergers create ICL

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Mass of merger products $< \sum$(progenitor masses)

⇨ lost mass during mergers create ICL

Faint-end LF maybe created from tidal dwarfs

(they cannot survive in the central cluster regions)

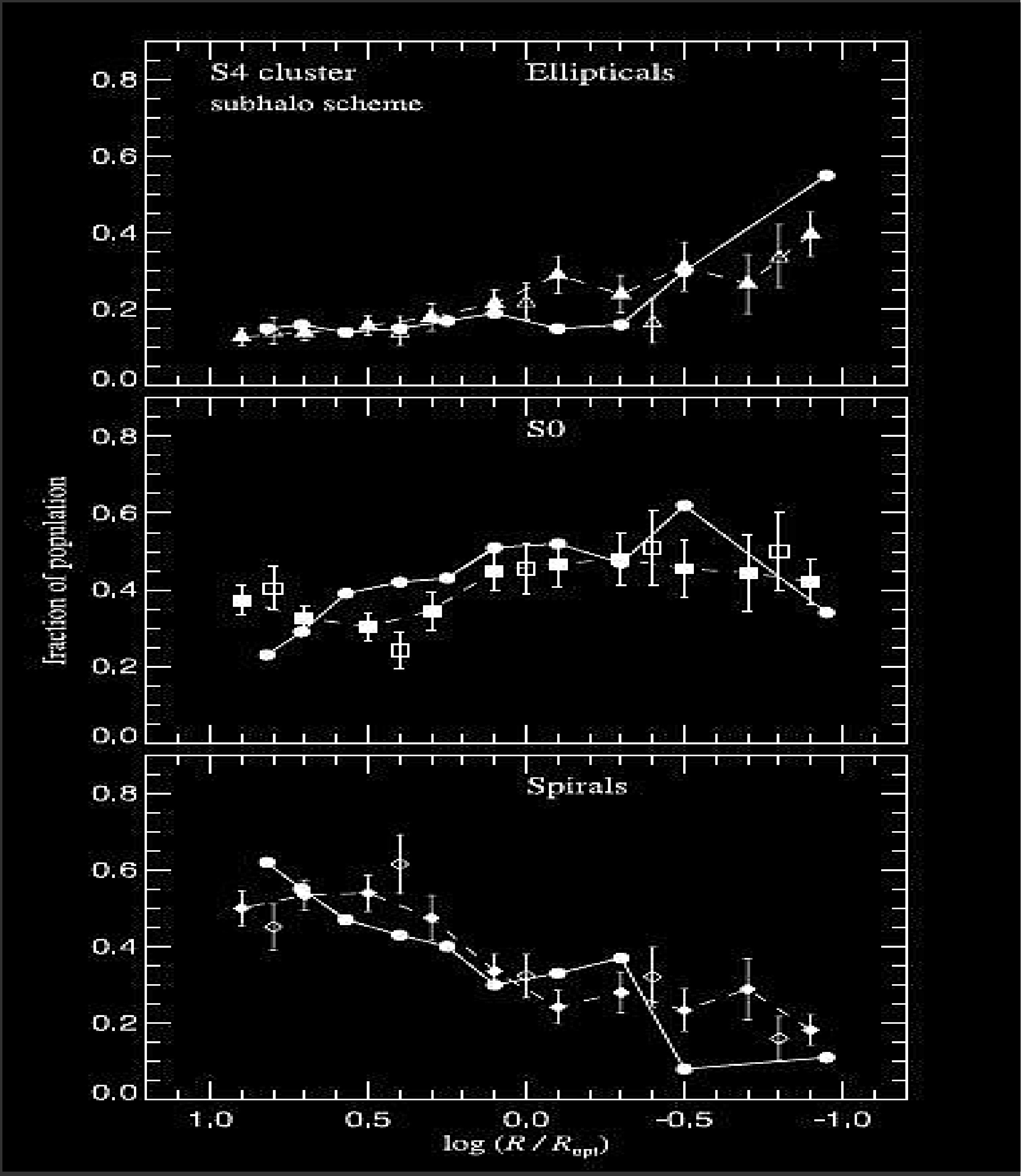
Hierarchical clustering CDM numerical simulation with:

cooling, star formation, SN feedback, dynamical friction, mergers

⇒ MRR ~ OK

S0? not really

(Springel+01)



Producing S0:

low-luminosity S0 from fading spirals

Spiral gas removed via tidal effects, ram-pressure

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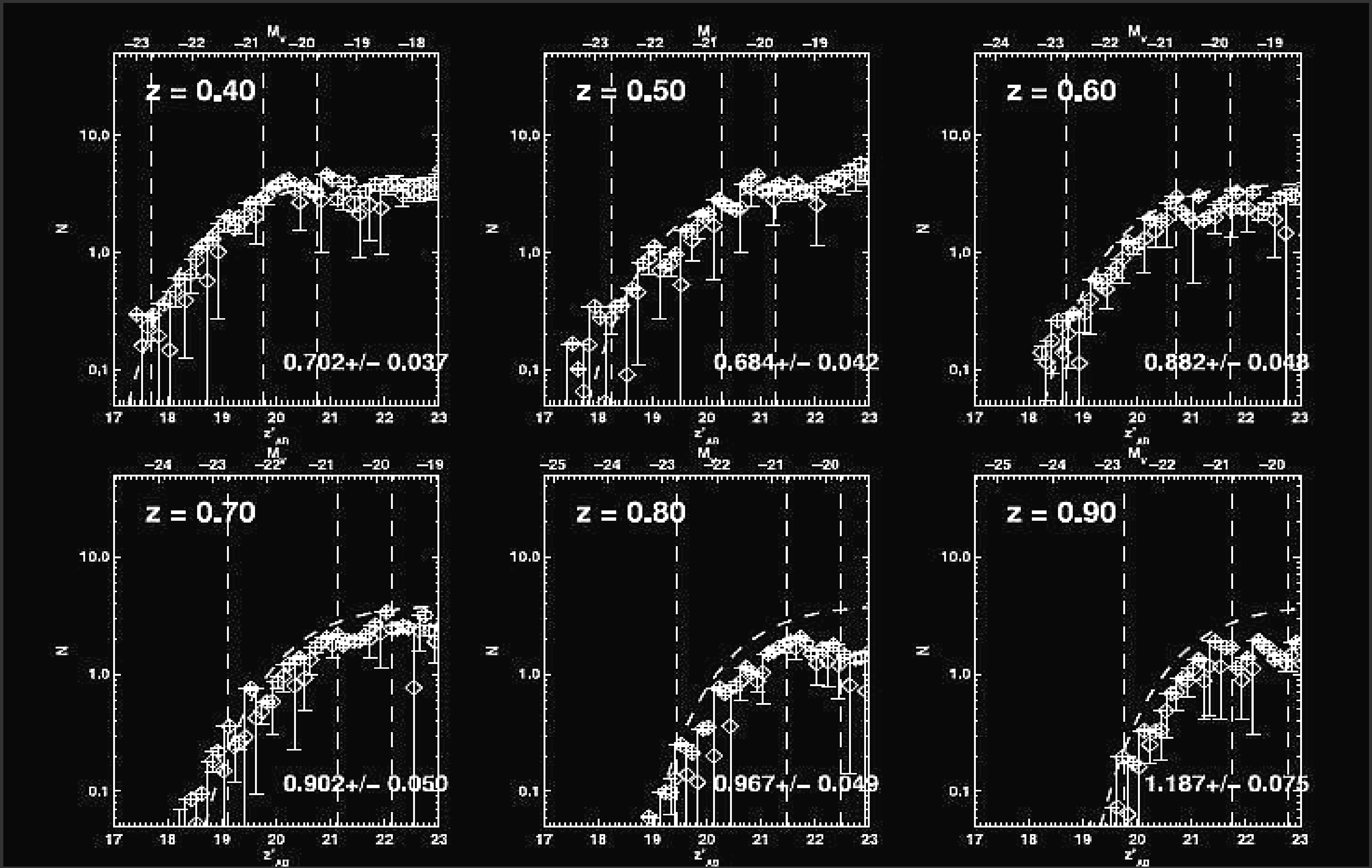
A thesis supported by the analyses of:

- ✔ Blue vs. Red LF evolution

CMR faint-end forms at low-z

...at the expense of blue galaxies

LF Red gals



(Gilbank+08)

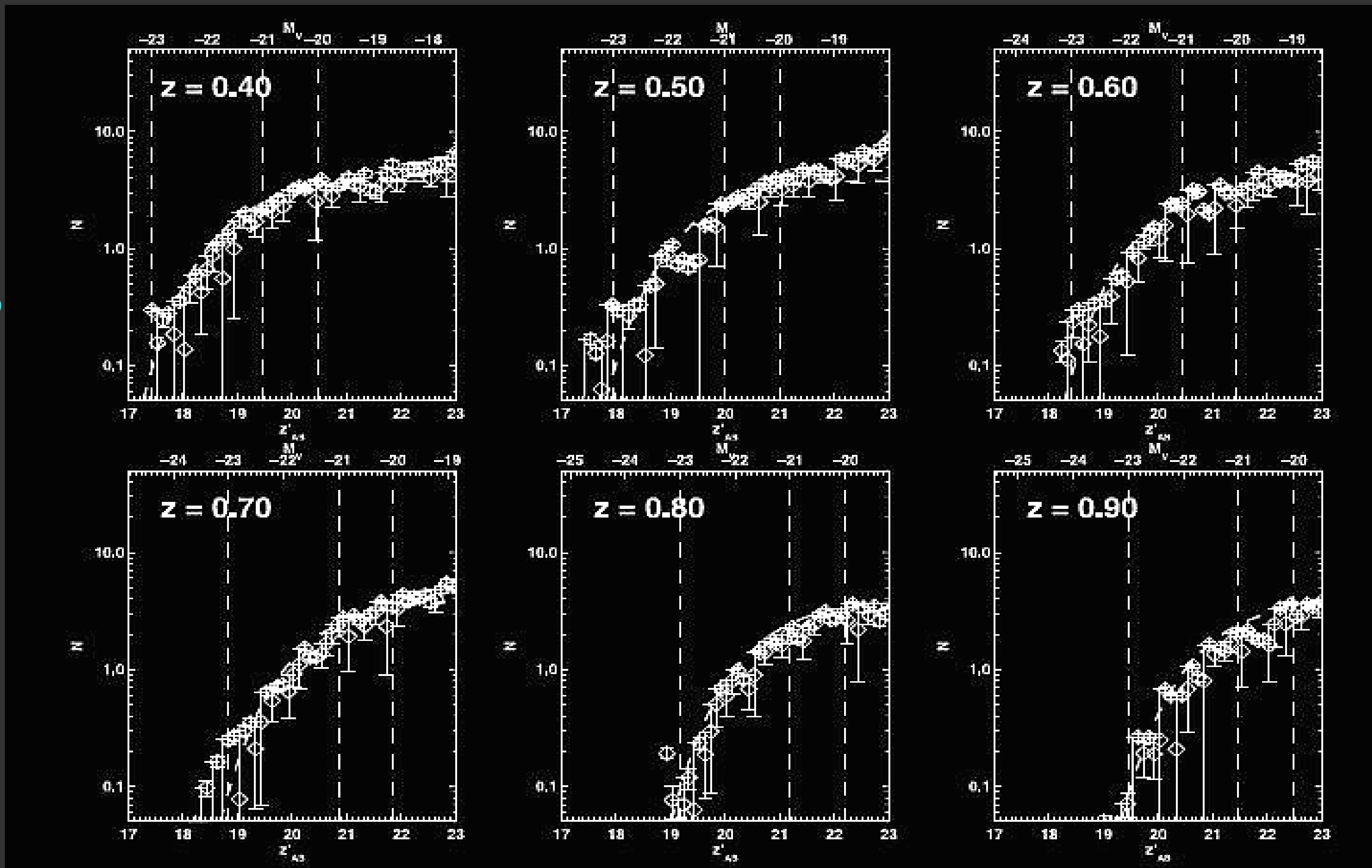
CMR faint-end forms at low-z

...at the expense of blue galaxies

LF

All

gals



(Gilbank+08)

Producing S0:

low-luminosity S0 from fading spirals

Spiral gas removed via tidal effects, ram-pressure

A thesis supported by the analyses of:

- ✔ Blue vs. Red LF evolution
- ✔ Existence of an intermediate galaxy class

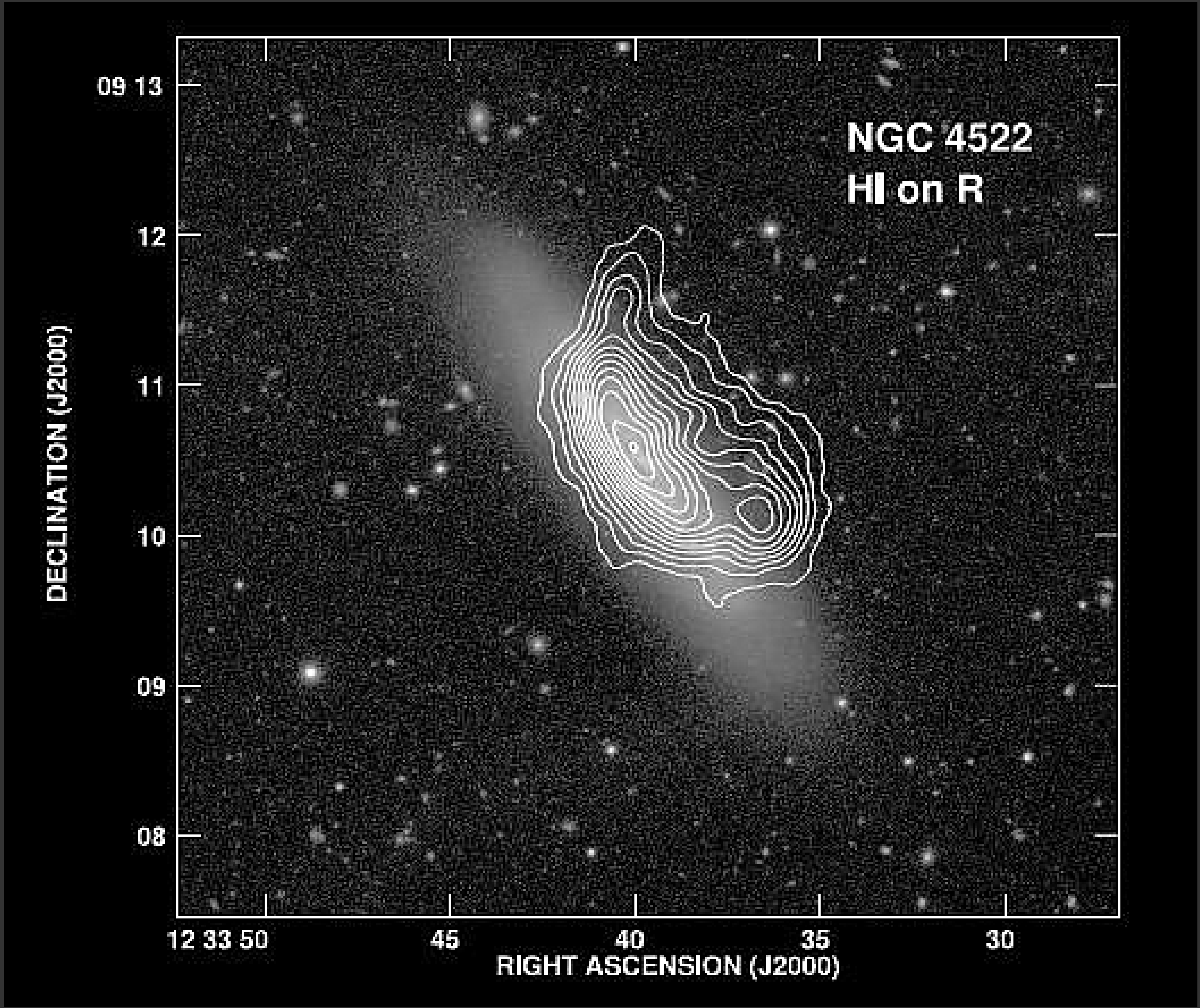
passive S, HI-deficient S

Normal S

Passive spectrum, blue disk

Passive spectrum red disk

(Moran+07)


NGC 4522
HI on R
09 13
12
11
10
09
08
DECLINATION (J2000)
12 33 50
45
40
35
30
RIGHT ASCENSION (J2000)

(Kenney+04)

Producing S0:

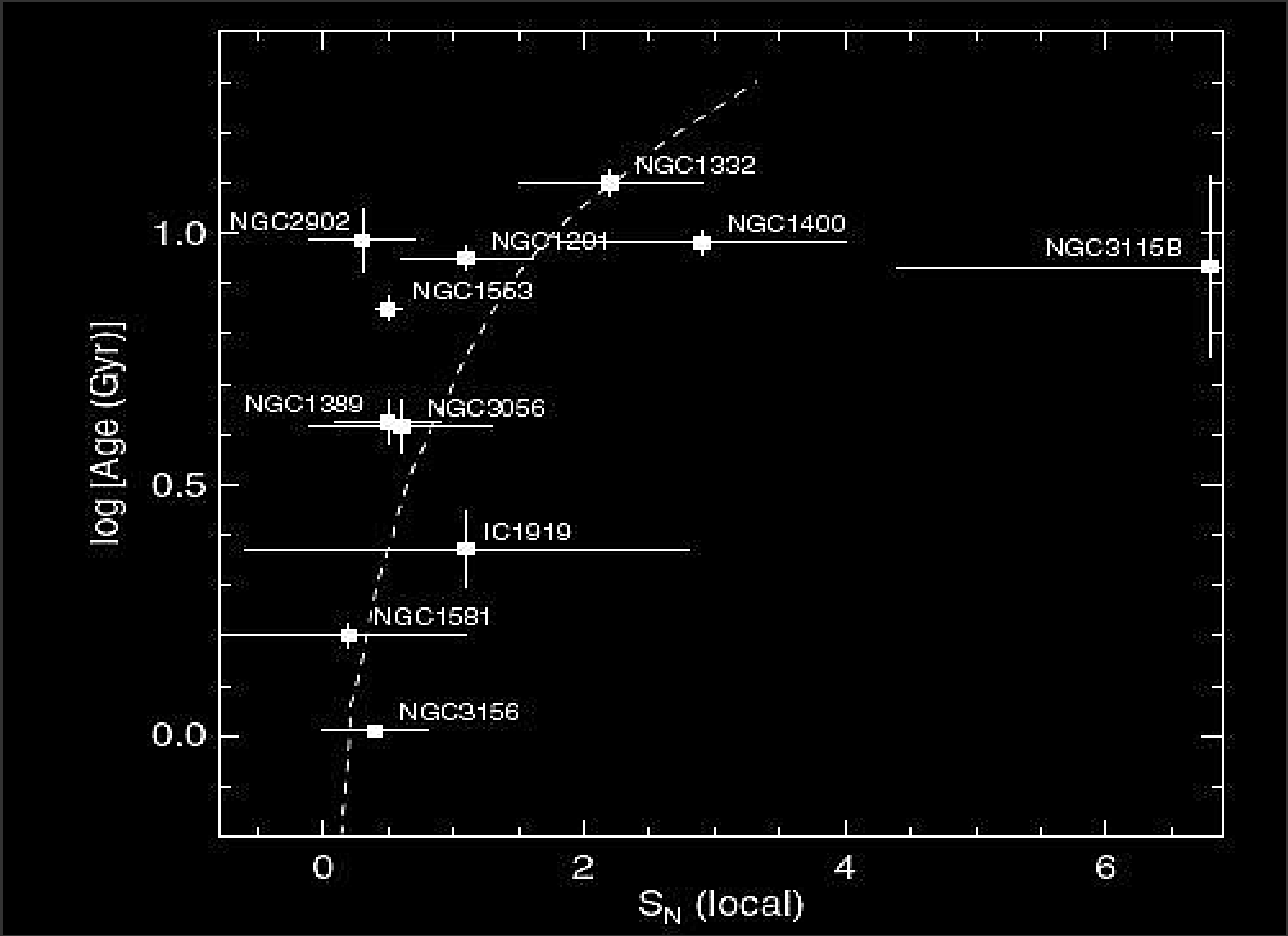
low-luminosity S0 from fading spirals

Spiral gas removed via tidal effects, ram-pressure

A thesis supported by the analyses of:

- ✔ Blue vs. Red LF evolution
- ✔ Existence of an intermediate galaxy class
- ✔ Specific number of globular clusters

When age ↑ $S_N \equiv N_{GC}$ / Lum ↑



(Barr+07)

Producing S0:

High-luminosity S0, fading spirals insufficient

Must increase bulge luminosity

Via minor mergers

and/or

tidally-induced central stabursts

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High-luminosity S0, fading spirals insufficient

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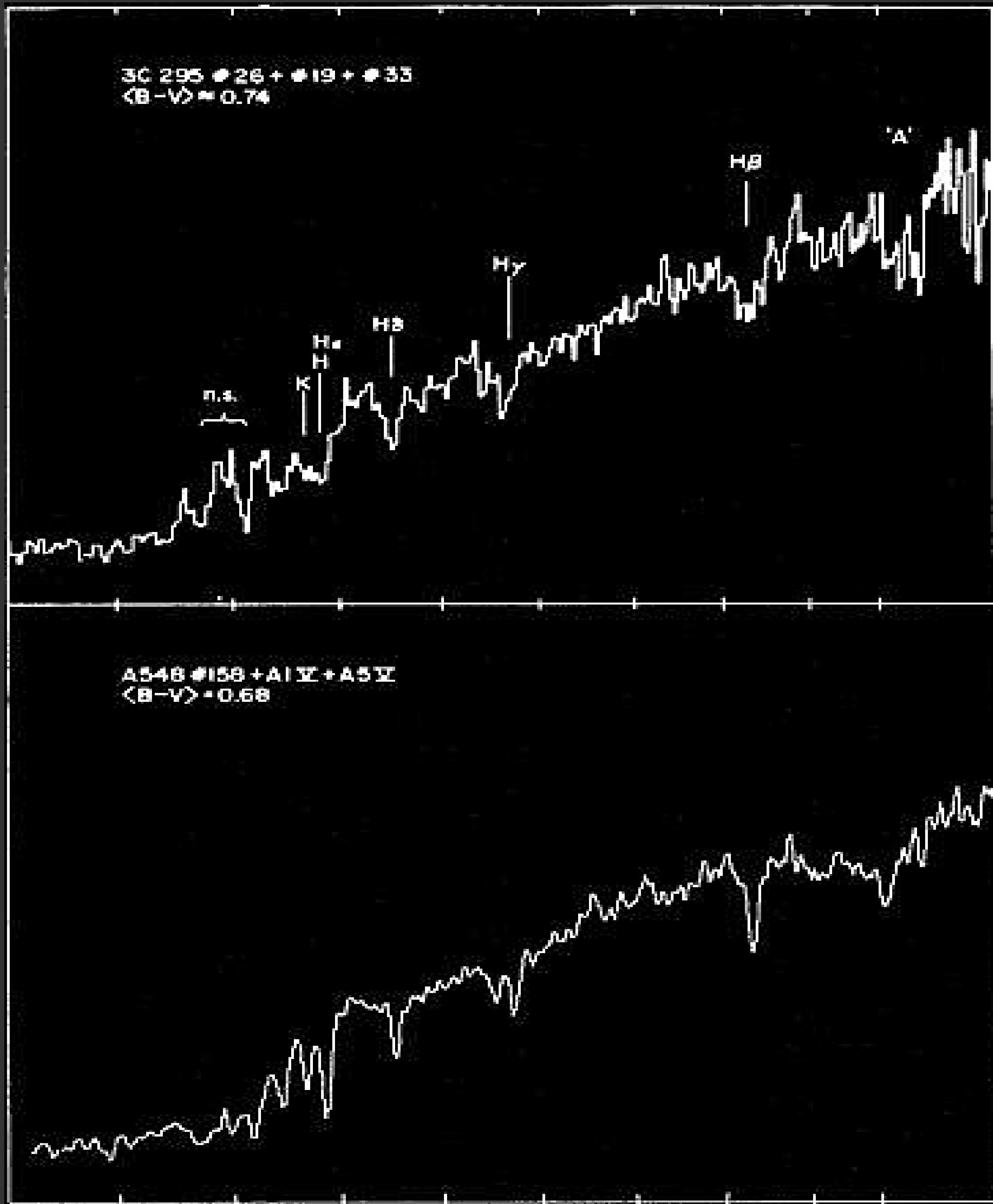
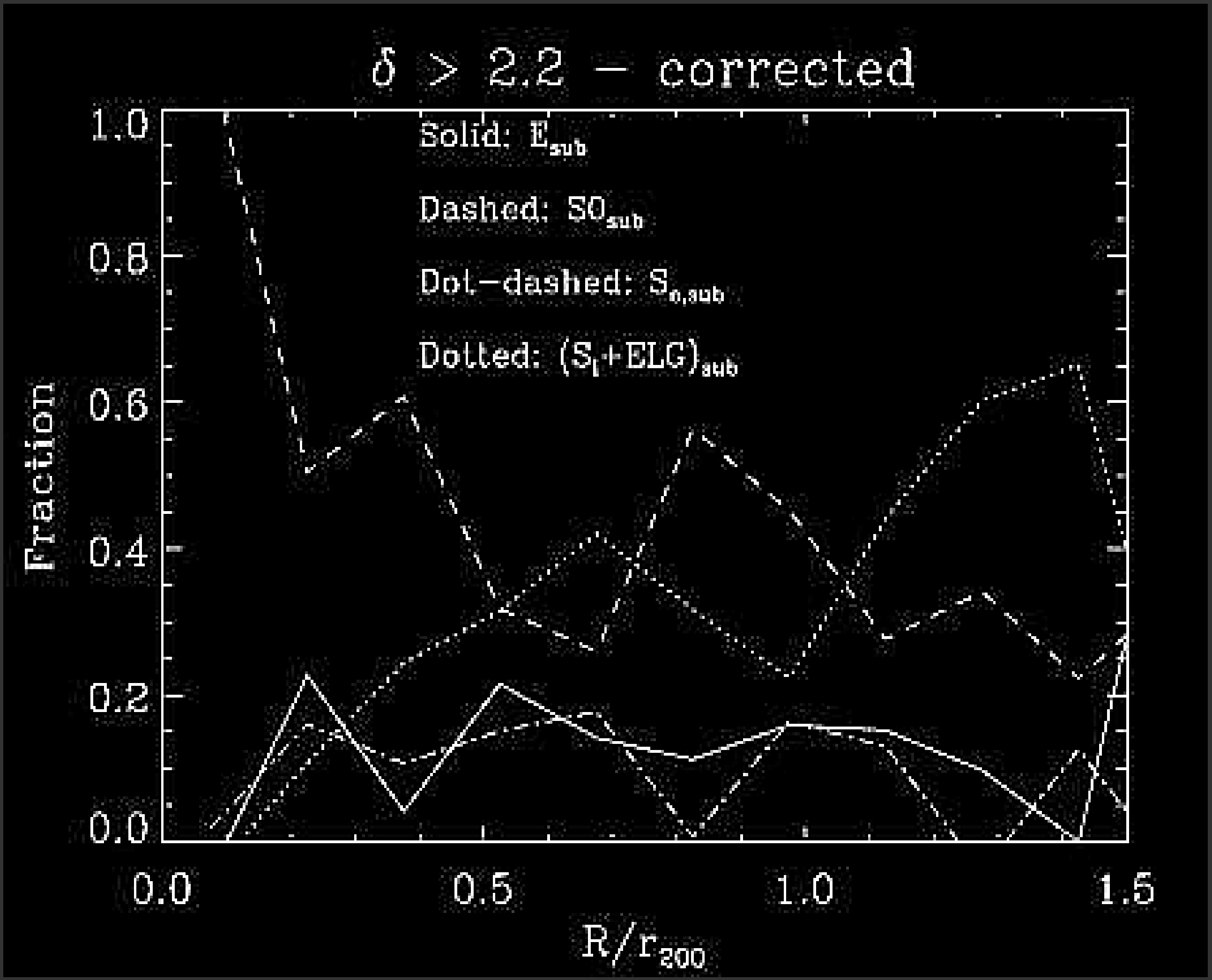
Possible progenitors: E+A galaxies



Spectrum with strong Balmer lines fit by Elliptical-like + A stars (post-starburst)

(Dressler+Gunn 83)

Recent creation of bright S0 can occur in low-σ_V subclusters

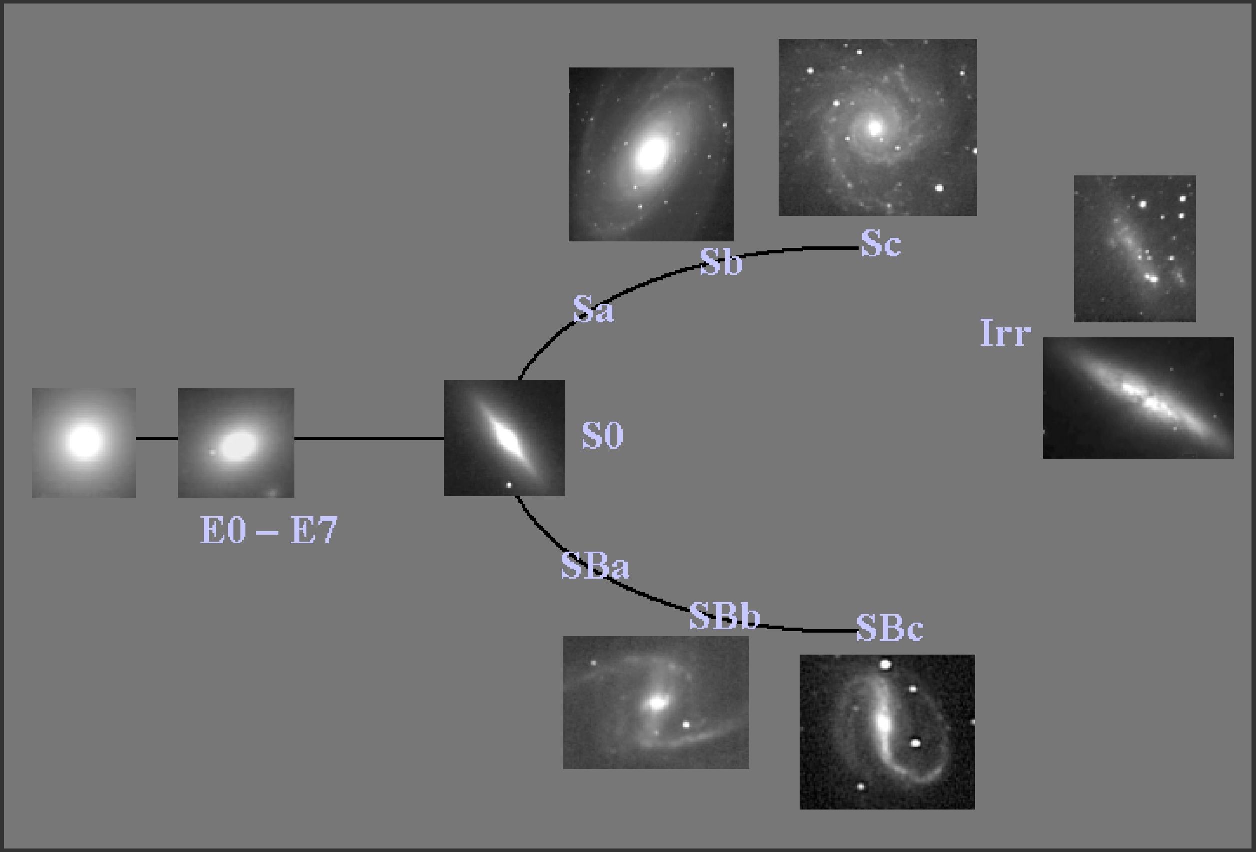


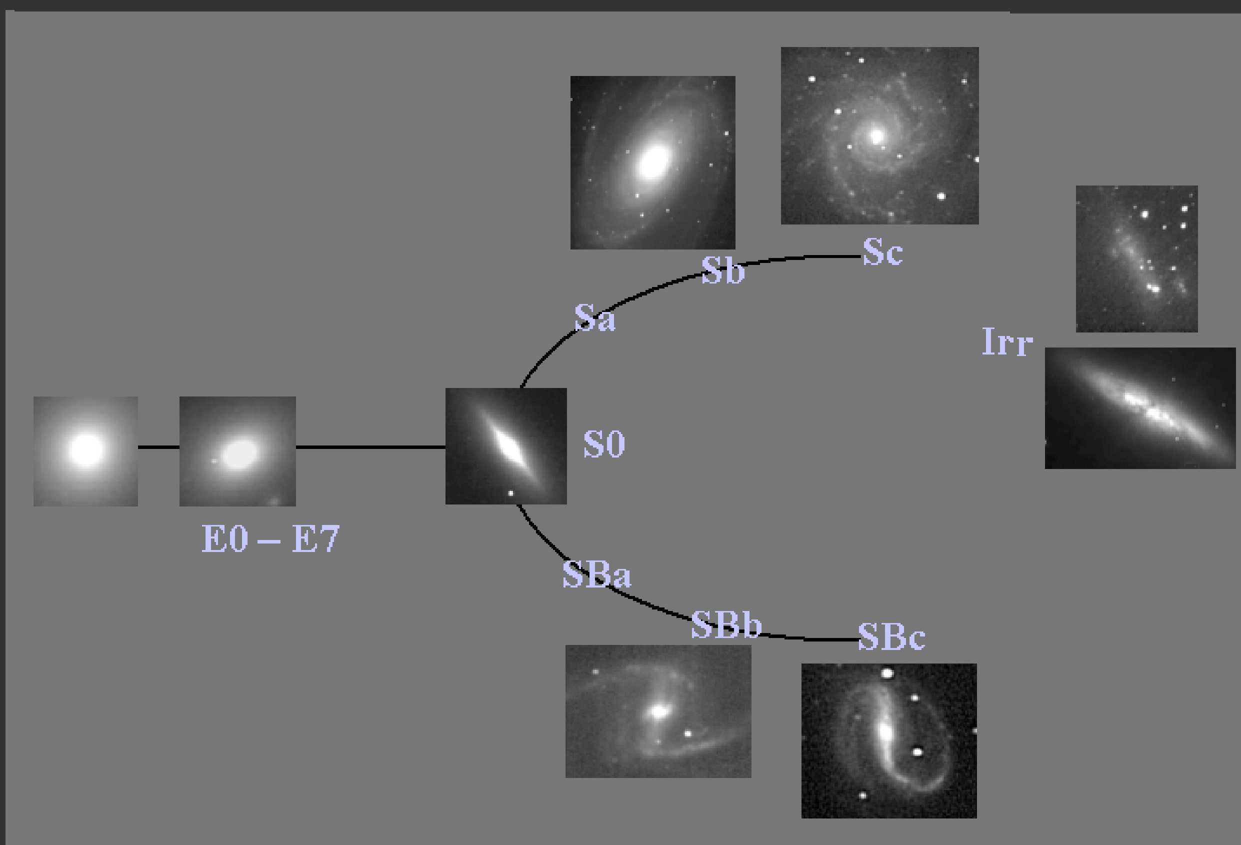
(B.+02)

Observational evidence for a high fraction of S0 in subclusters

Conclusions:

We are close to understand
the physical meaning of
the Hubble tuning fork!


Sb
Sc
Sa
Irr
S0
E0 – E7
SBa
SBb
SBc



E0 – E7
S0
Sa
Sb
Sc
SBa
SBb
SBc
Irr

Thank you for the attention!