Evolution of Cluster Galaxies

The Butcher-Oemler Effect

Observed Phenomena of Cluster Galaxies

- Morphology-Density relation
- Old (co-eval) ellipticals
- Butcher-Oemler effect
- E+A galaxies
- S0 problem
- CD galaxies
- Suppression of SFR
- Disk galaxies
- Dwarf galaxies
- Interactions/Mergers

Early Processes

Formation of Initial Generation of Cluster Galaxies

- Morphology-Density relation
- Old (co-eval) ellipticals
- Interactions/Mergers

Late Processes

Infall of Field Galaxies

- S0 problem
- Butcher-Oemler effect
- E+A galaxies
- Suppression of SFR
- Interactions/Mergers

September 2000

The Butcher-Oemler Effect

The first evolutionary effect discovered among the galaxy population

Discover as a photometric effect

Followed-up with spectroscopy of blue galaxies

Caveats: If you read

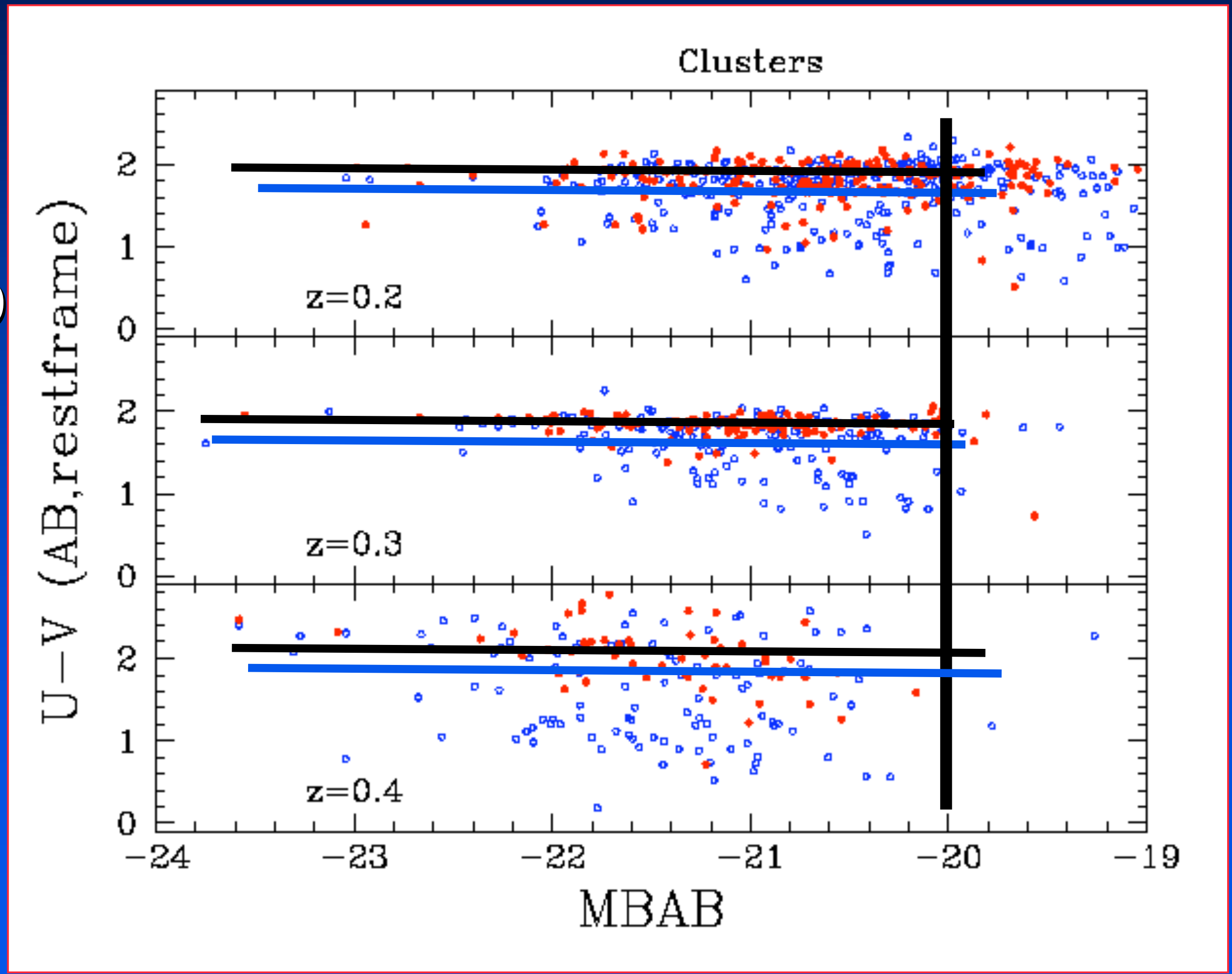
"enhanced star formation" . . . . .   "enhanced" relative to what?

"excess of . . . . galaxies" . . . . .   "excess" compared to what?

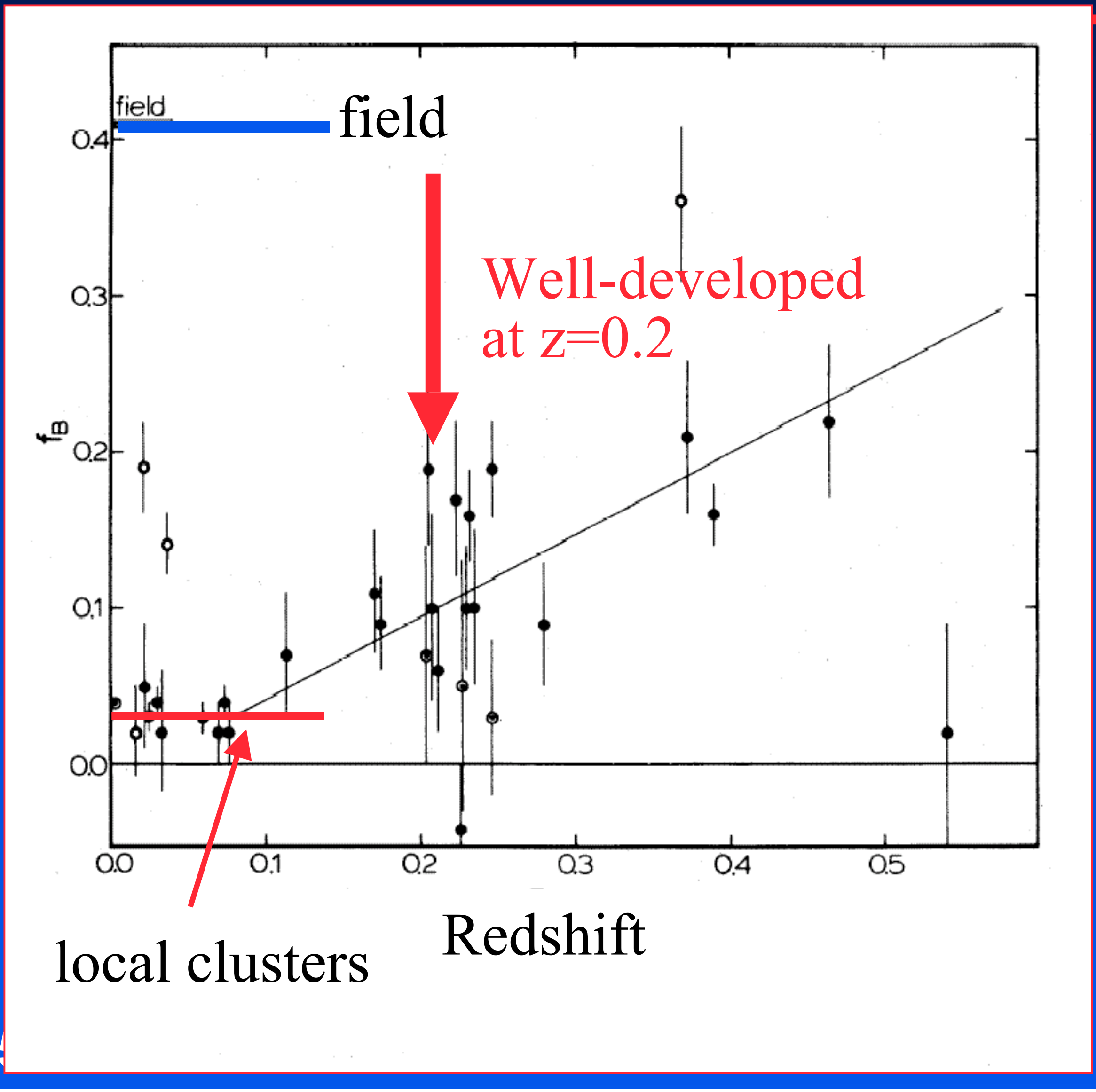
Butcher-Oemler Effect: Blue cluster galaxies

Blue galaxies:

- M(B) < -20
- B-V more than 0.20 mag bluer than the red (E/S0) sequence)



The Butcher-Oemler effect: Fraction of galaxies that are blue



The field fraction is at z = 0

There is large scatter in the correlation

B-O effect is well-developed by z = 0.2 (2 Gyrs in the past)

This is a different time-scale from Dressler's N(S0)/N(E)

Butcher & Oemler (1984)

- A sample of 33 clusters with $0.003 < z < 0.54$ shows evolution in the fraction of galaxies with B-V colors at least 0.20 mag bluer than the ridge line of early-type galaxies ($M(B) < -20$)

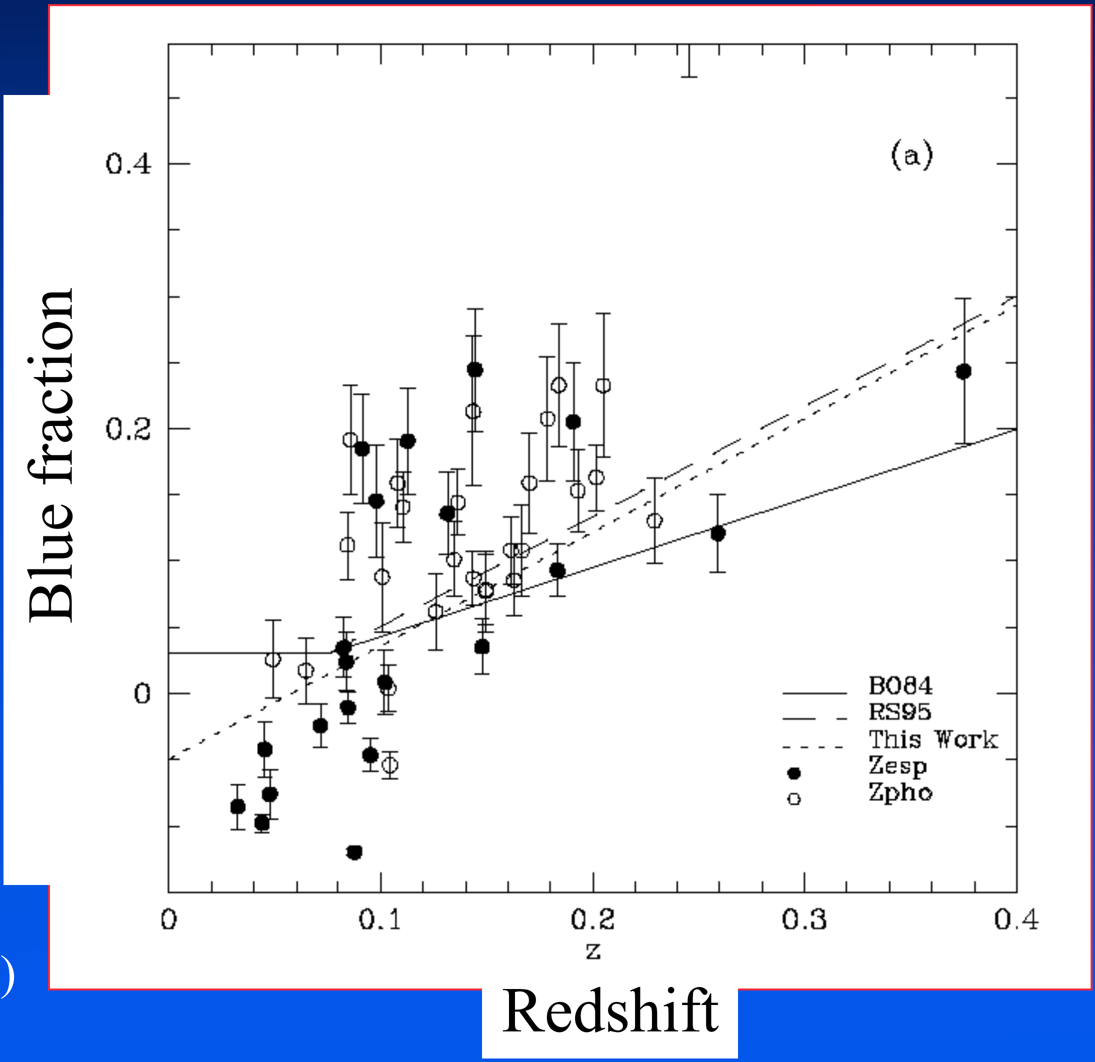
- The B-O effect is well-developed by $z = 0.2$ (2 Gyrs in the past)

- Is there real scatter in the trend?

The Butcher-Oemler effect

There is a wide range of values of the blue fraction

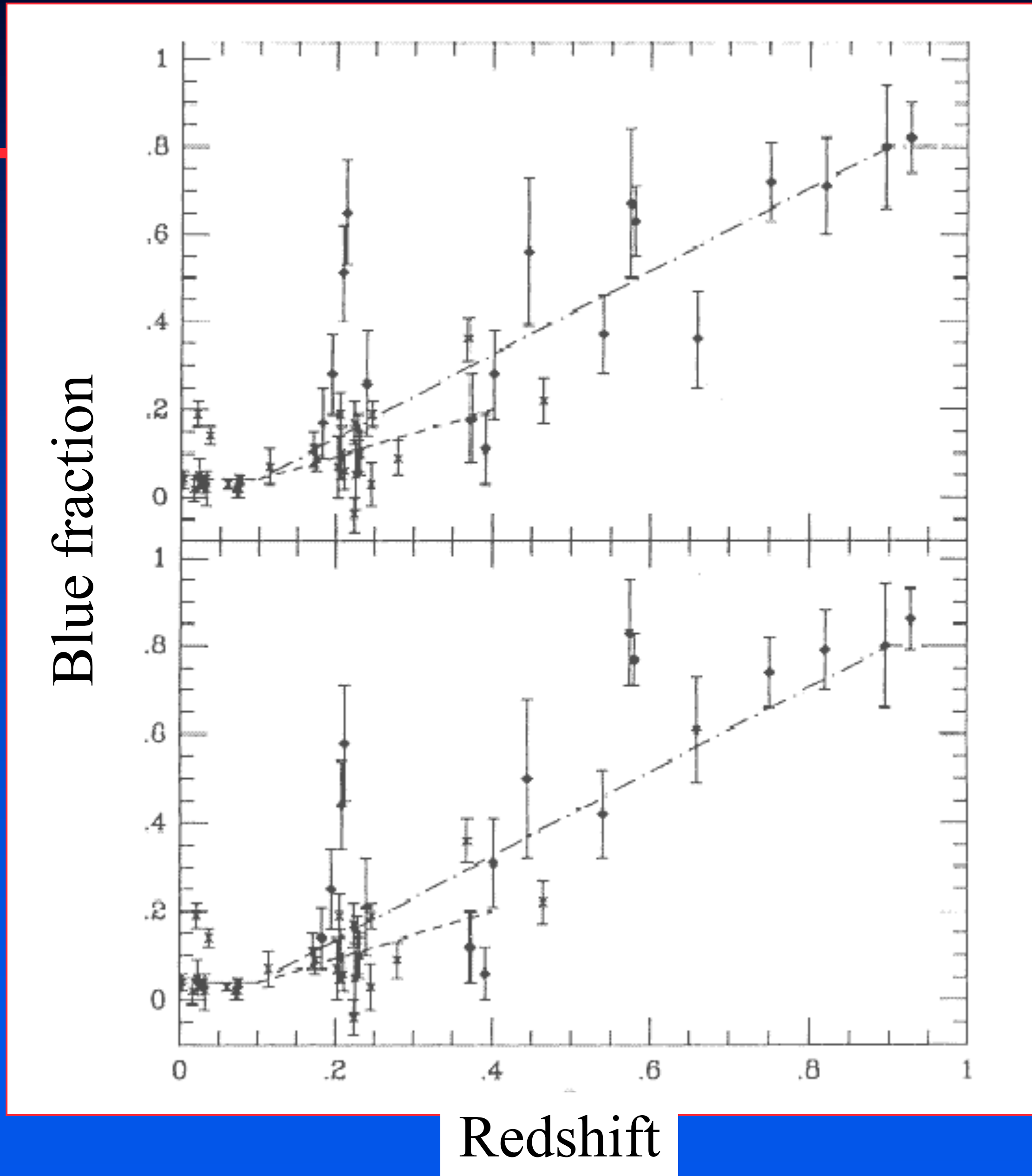
Blue fraction shows dispersion



Margoniner & de Carvalho (2000)

The Butcher-Oemler effect at higher redshift

B-O effect extends to z = 1



Rakos & Schombert (1995)

What are the Butcher-Oemler galaxies ?

Imaging

CFHT, UH, HST

Morphology ?
Interactions ?
Mergers ?

Spectroscopy

Star-formation ?
History ?
Starbursts ?

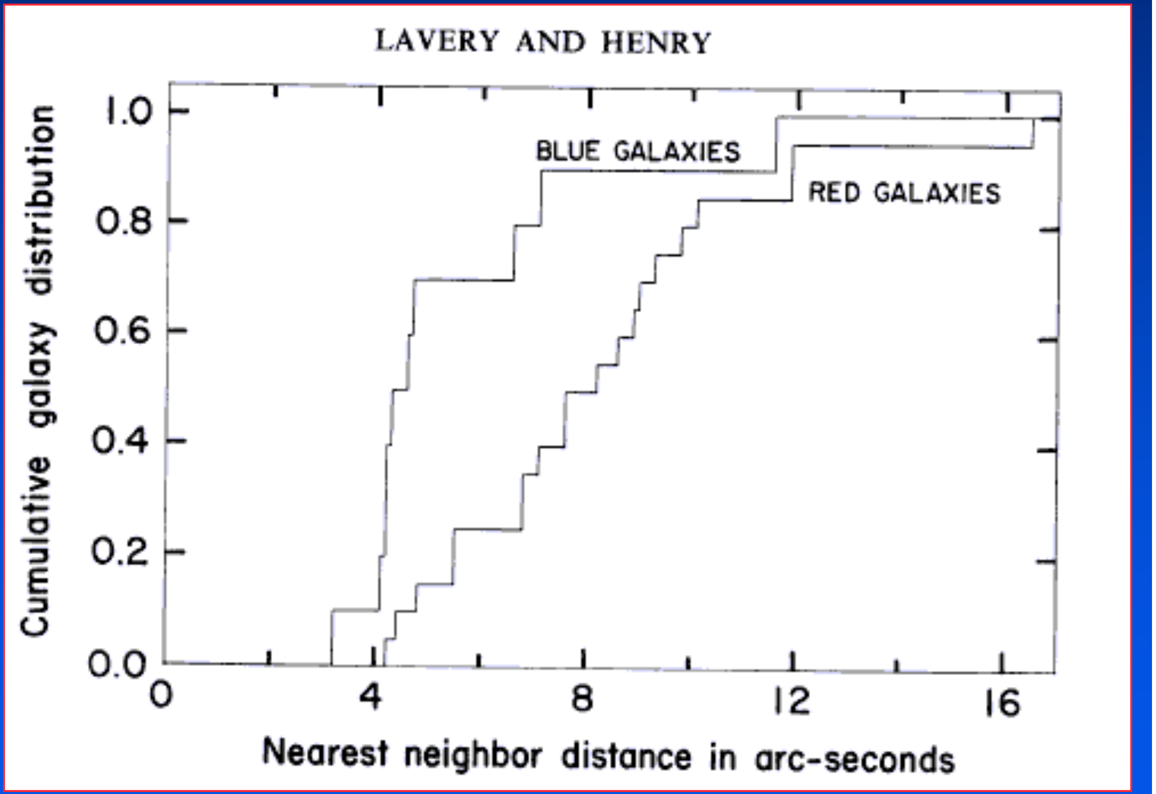
Imaging of Butcher-Oemler galaxies

Lavery & Henry 1988

10 blue emission-line galaxies

Blue galaxies have a nearest neighbor distribution that is different at the 98% level from that of red galaxies

Galaxy-galaxy interactions may induce starbursts and are an active agent of the B-O effect



Imaging of Butcher-Oemler galaxies

Lavery & Henry 1988,1994
Lavery et al. 1992

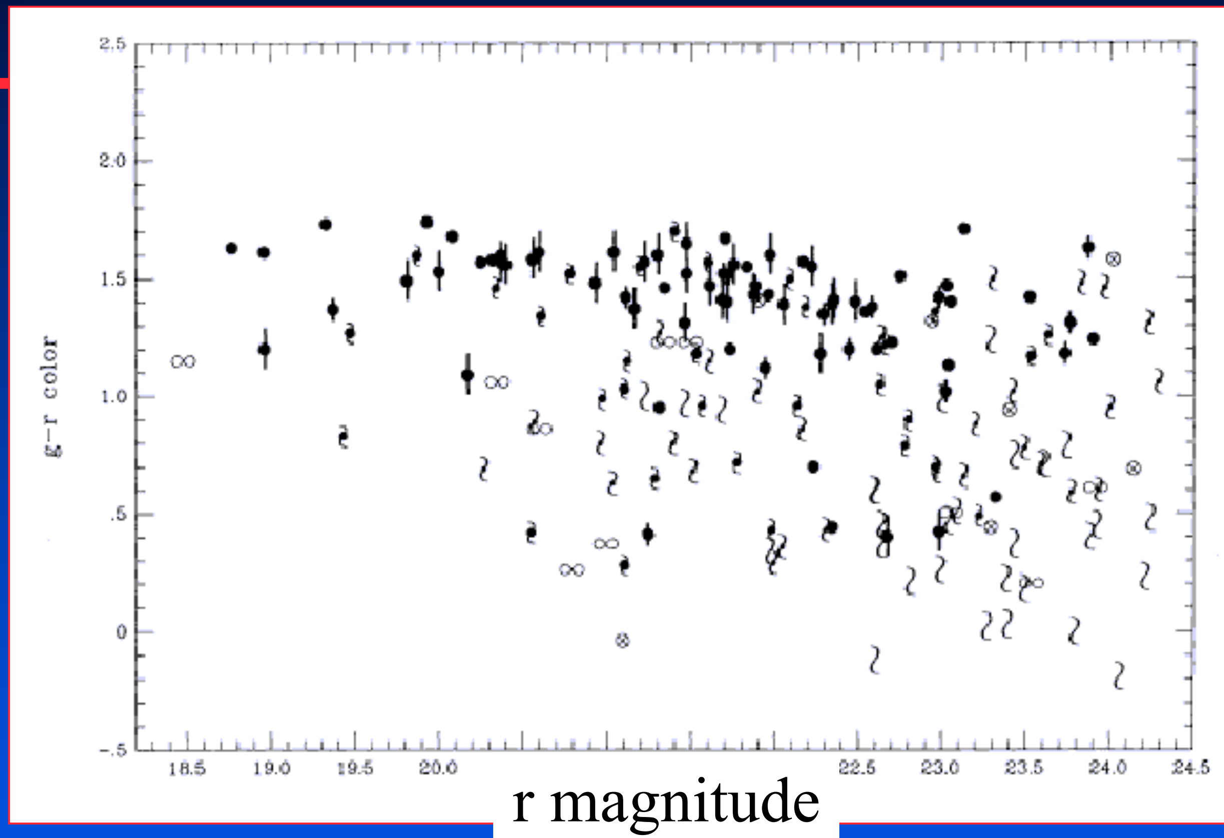
At least 50% of blue cluster galaxies at z ~ 0.2 are in disk systems

Star formation is spread over the disks rather than centrally concentrated

Galaxy-galaxy interactions appear to be responsible for the enhanced star formation rate in some of these galaxies

HST imaging of Butcher-Oemler galaxies

Dressler et al 1994
Couch et al 1994
WFPC,WFPC2

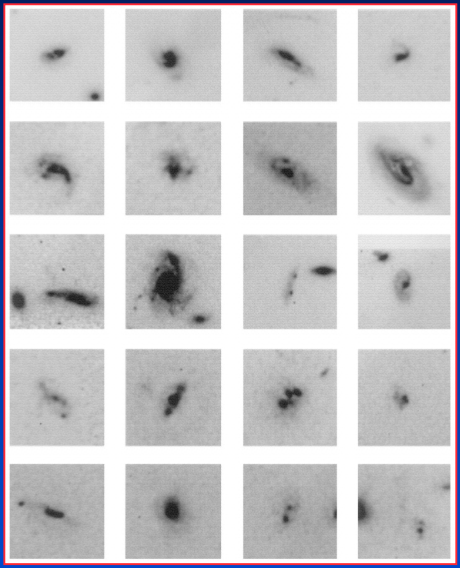


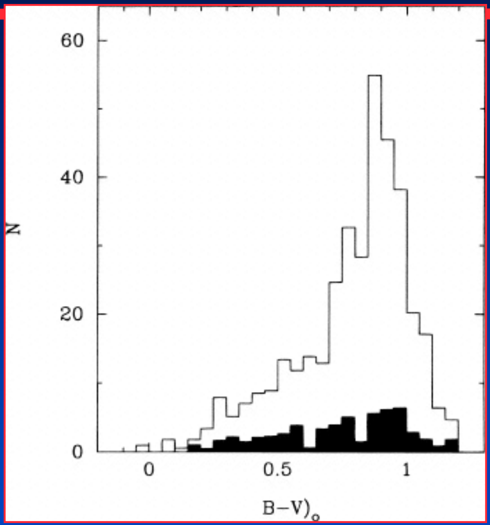
- Blue B-O galaxies are disk-dominated or Irregular systems
- Mergers/interactions are frequent and appear to play a role in the B-O effect

HST imaging of Butcher-Oemler galaxies: Oemler 1997

Oemler et al 1997: Four rich clusters at z ~ 0.4

Probable mergers





- Most galaxies can be accommodated within the normal Hubble sequence
- Although mergers/interactions are common they cannot account for most of the blue galaxies
- The spectroscopic samples are concentrated on the brightest blue galaxies and this results in a bias if starbursts enhance luminosity (page 570)

HST imaging of Butcher-Oemler galaxies: Oemler 1997

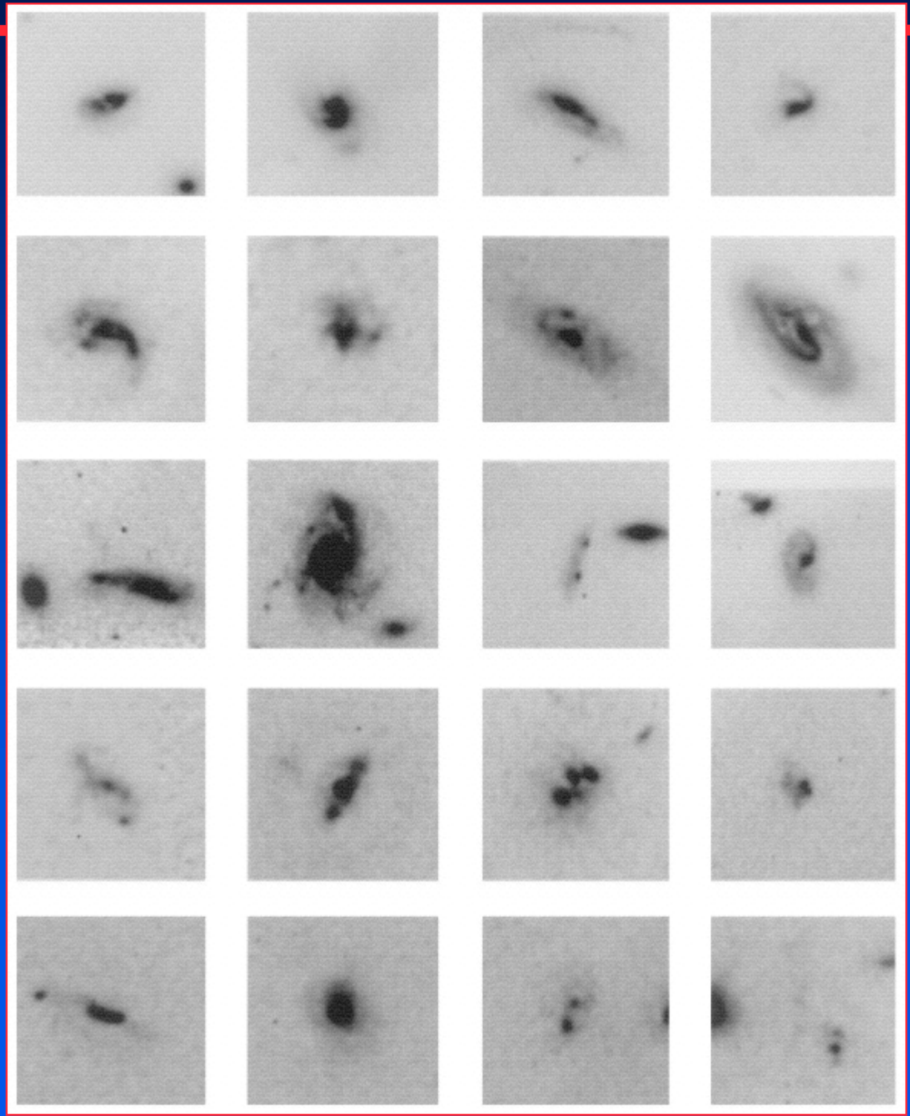
• Most galaxies can be accommodated within the normal Hubble sequence

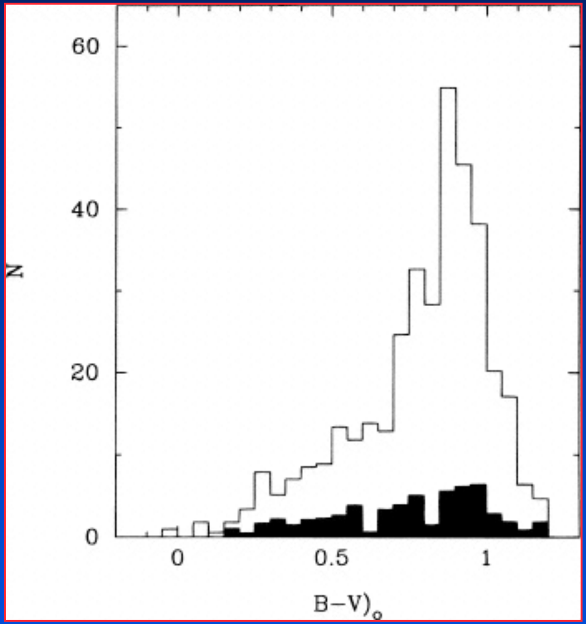
• Merging/Interacting galaxies are ~ 20% of the population

•Although mergers/interactions are common they cannot account for most of the blue galaxies

HST imaging of Butcher-Oemler galaxies: Oemler 1997

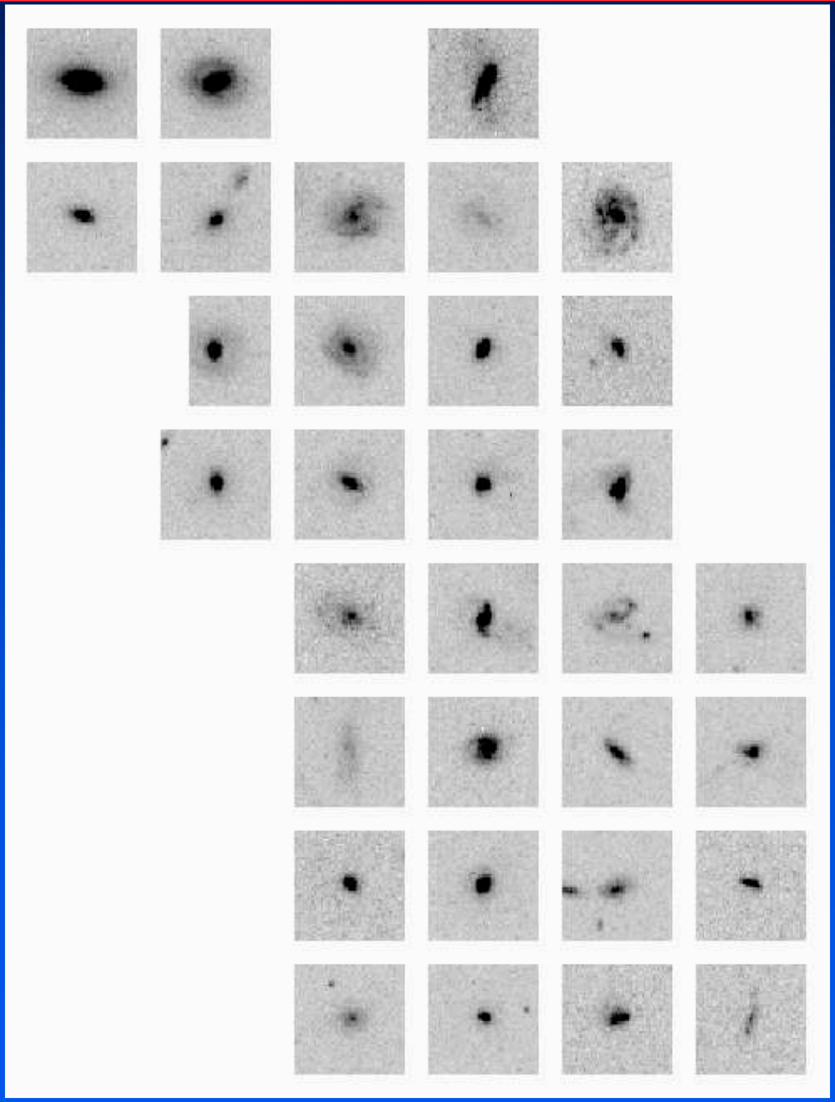
Probable mergers





Oemler et al 1997: Four rich clusters at z ~ 0.4

Field galaxies at z > 0.5 (Schade et al 1995)



HST imaging of Butcher-Oemler galaxies: Oemler 1997

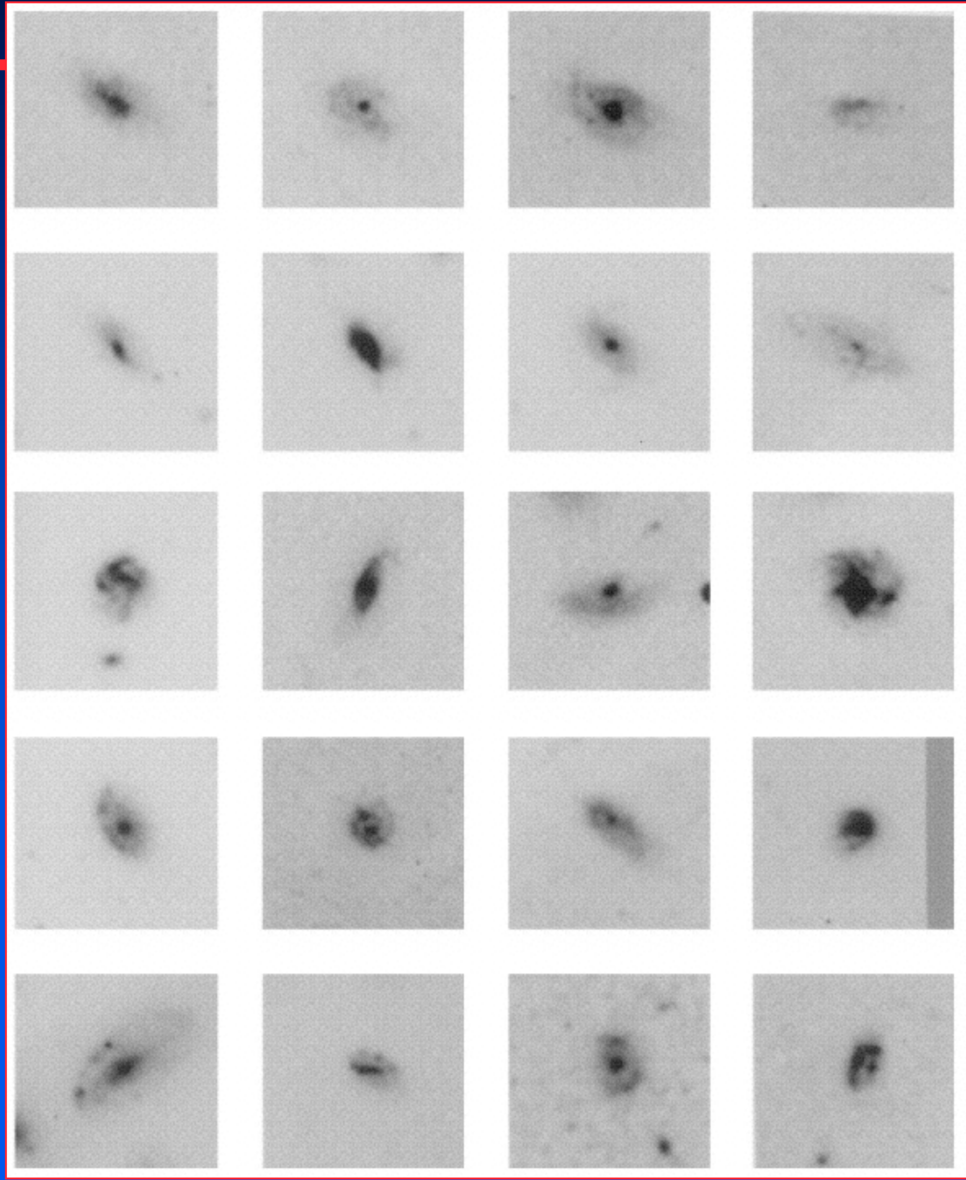
• The spectroscopic samples are concentrated on the brightest blue galaxies and this results in a bias if starbursts enhance luminosity:

If 15% of galaxies have luminosities enhanced by 50% then a cut at M*+3 contains 18% of such objects. A cut at M*-1 contains 41% of such objects.

• The interacting galaxies seem to be responsible for most of the galaxies that show spectroscopic signs of starbursts.

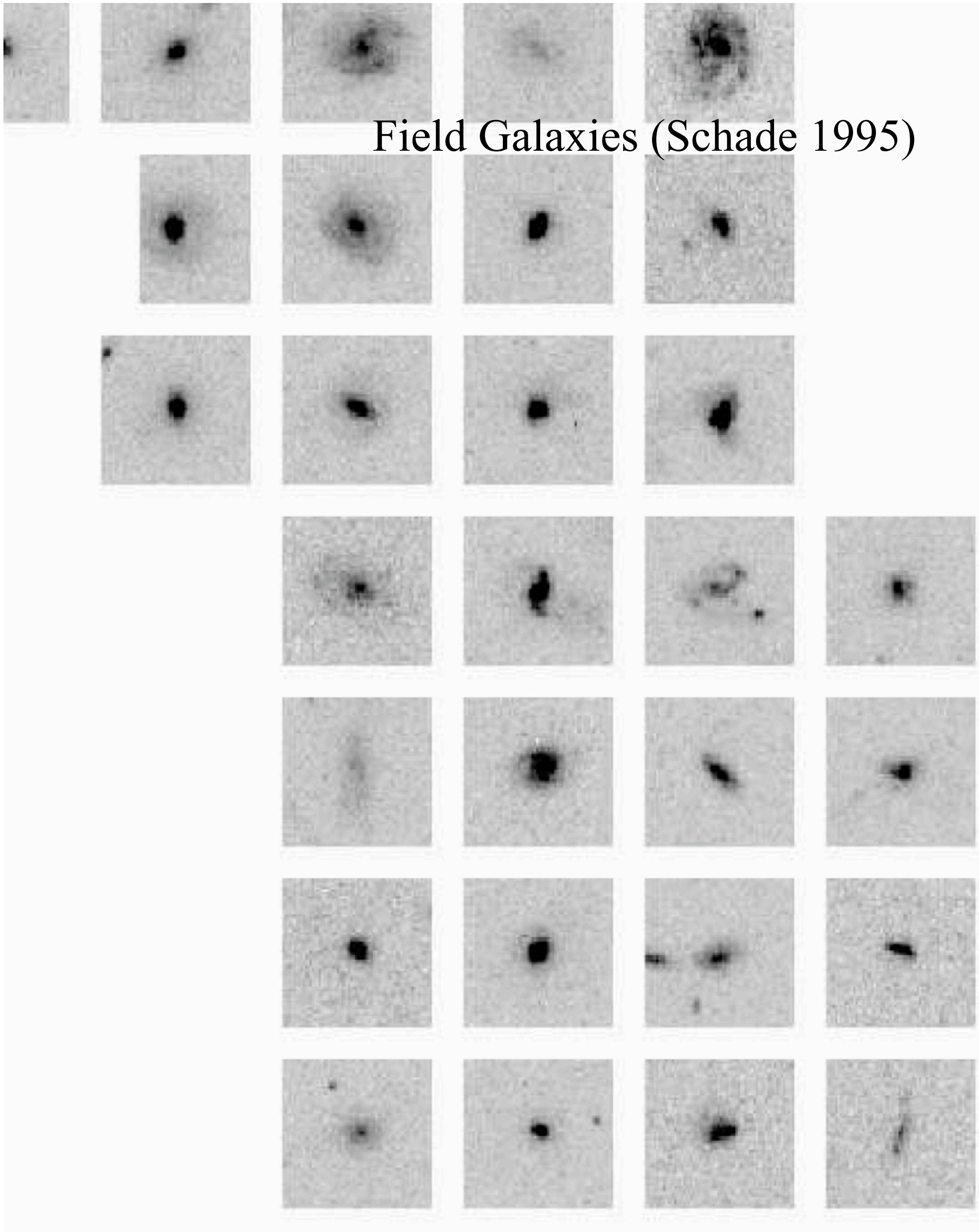
HST imaging of Butcher-Oemler galaxies: Oemler 1997

A sample of spiral galaxies from all four clusters showing peculiar patterns of star formation

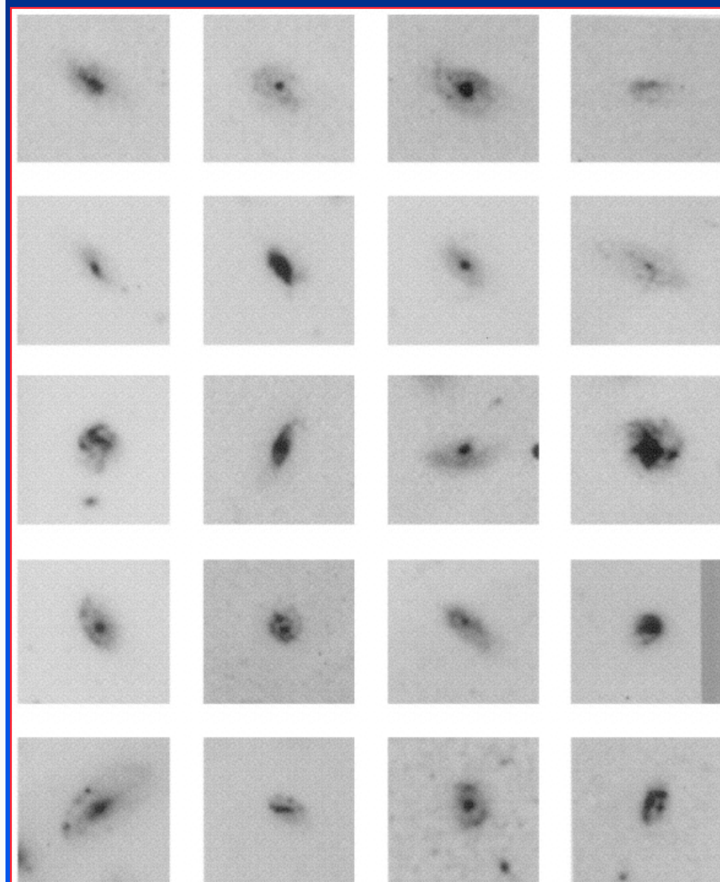


Butcher-Oemler galaxies

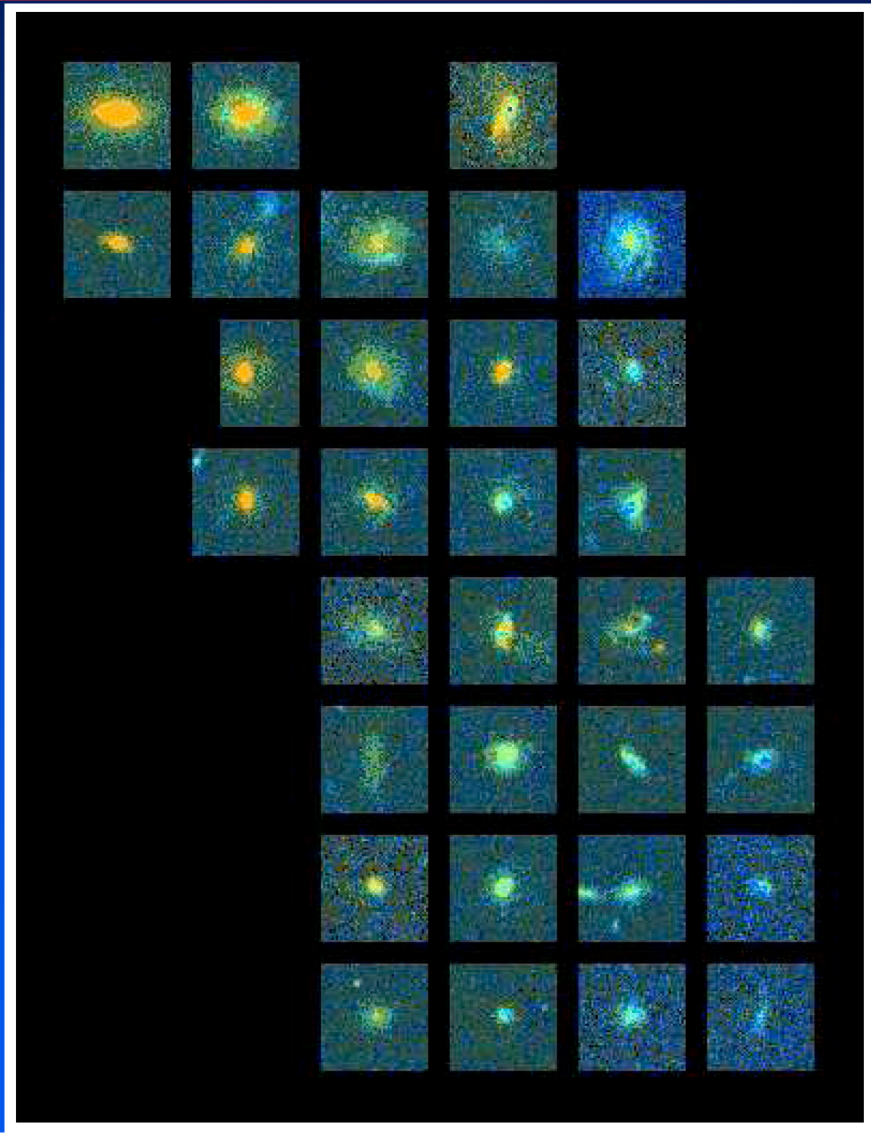
Compare cluster and field



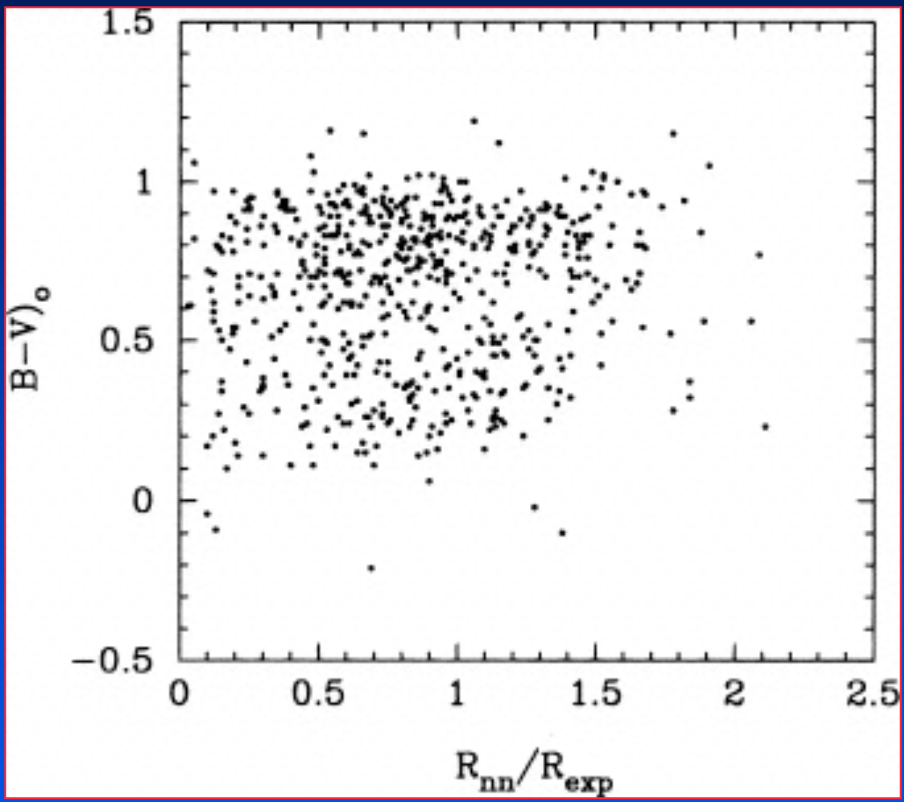
Field Galaxies (Schade 1995)

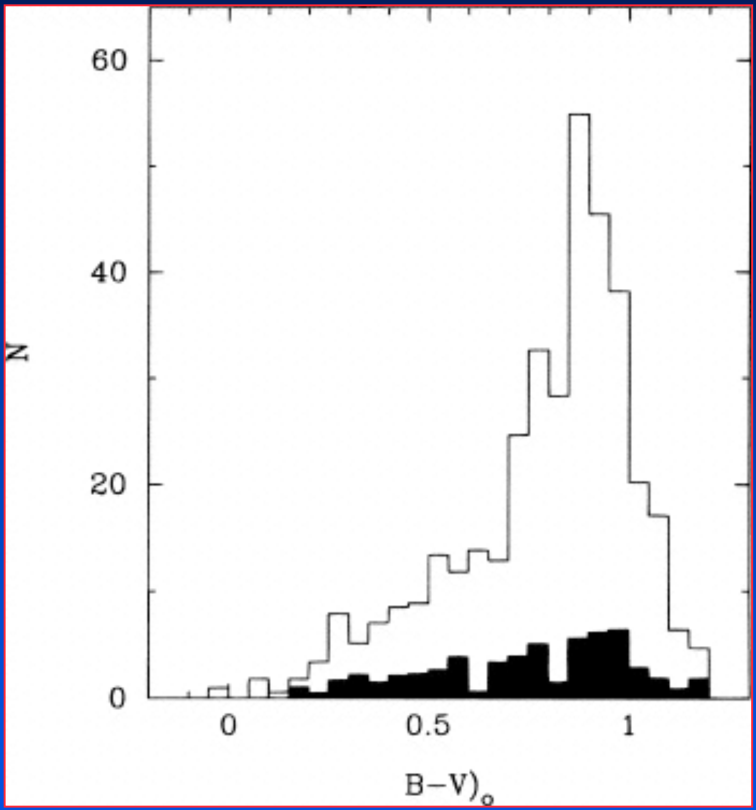


Field galaxies at z > 0.5 (Schade et al 1995)



HST imaging of Butcher-Oemler galaxies: Oemler 1997





Distance to nearest neighbor versus color: NO EFFECT

Color distributions: SOLID = Merger/Interactions

Spectroscopic investigations of cluster and field galaxies

The historical approach would discuss Dressler & Gunn (1982, 1983) Couch et al. 1987,1994

Starbursts

Post-starburts

E+A galaxies

k + A galaxies

Spectroscopic investigations of cluster and field galaxies

Balogh et al (1997)

CNOC:

15 Rich clusters

$0.2 < z < 0.55$

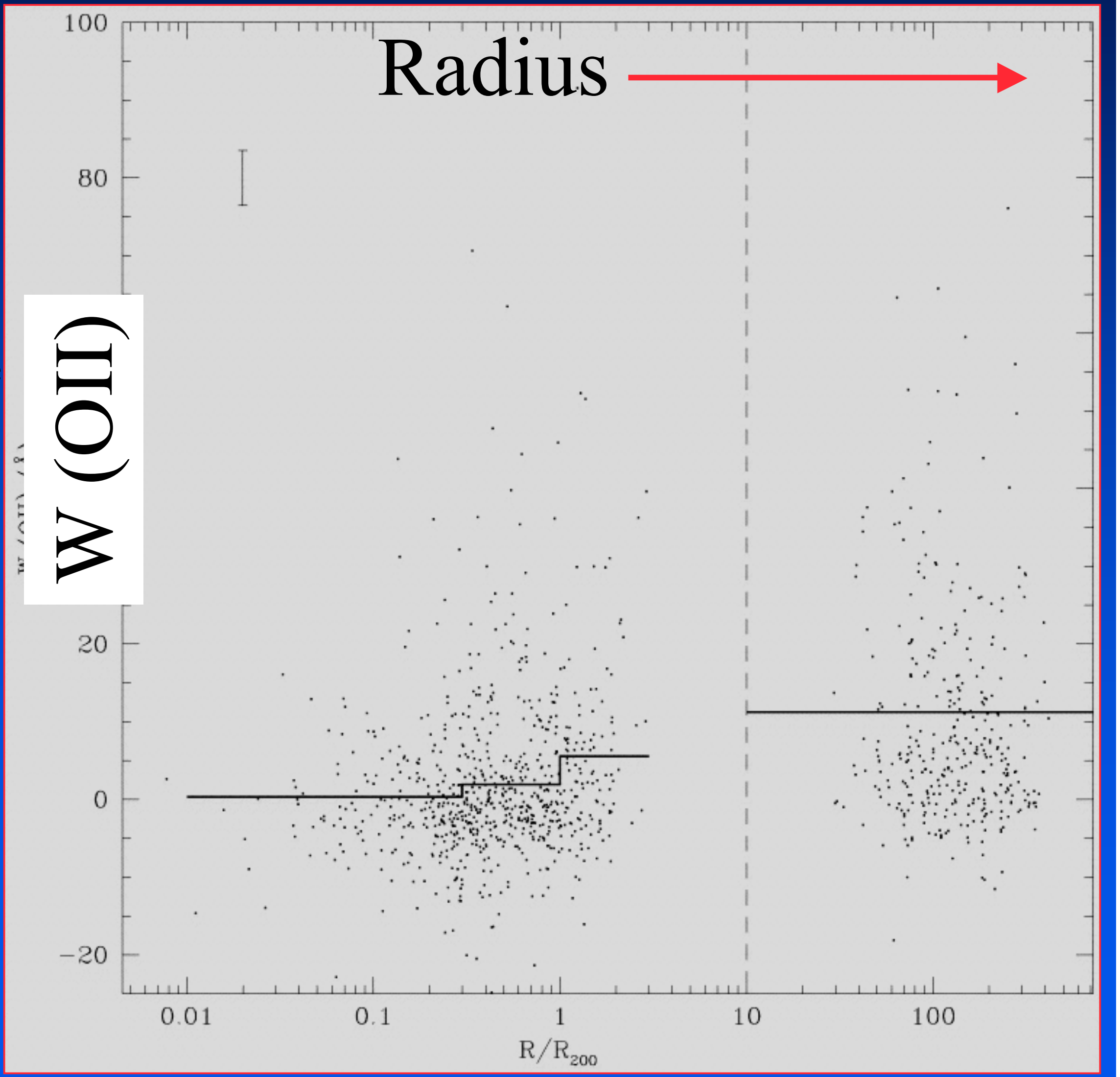
Cluster galaxies at all radii have suppressed star formation relative to field galaxies at the same redshifts.

OII emission equivalent width:

Clusters 3.8 +- 0.3 Angstroms

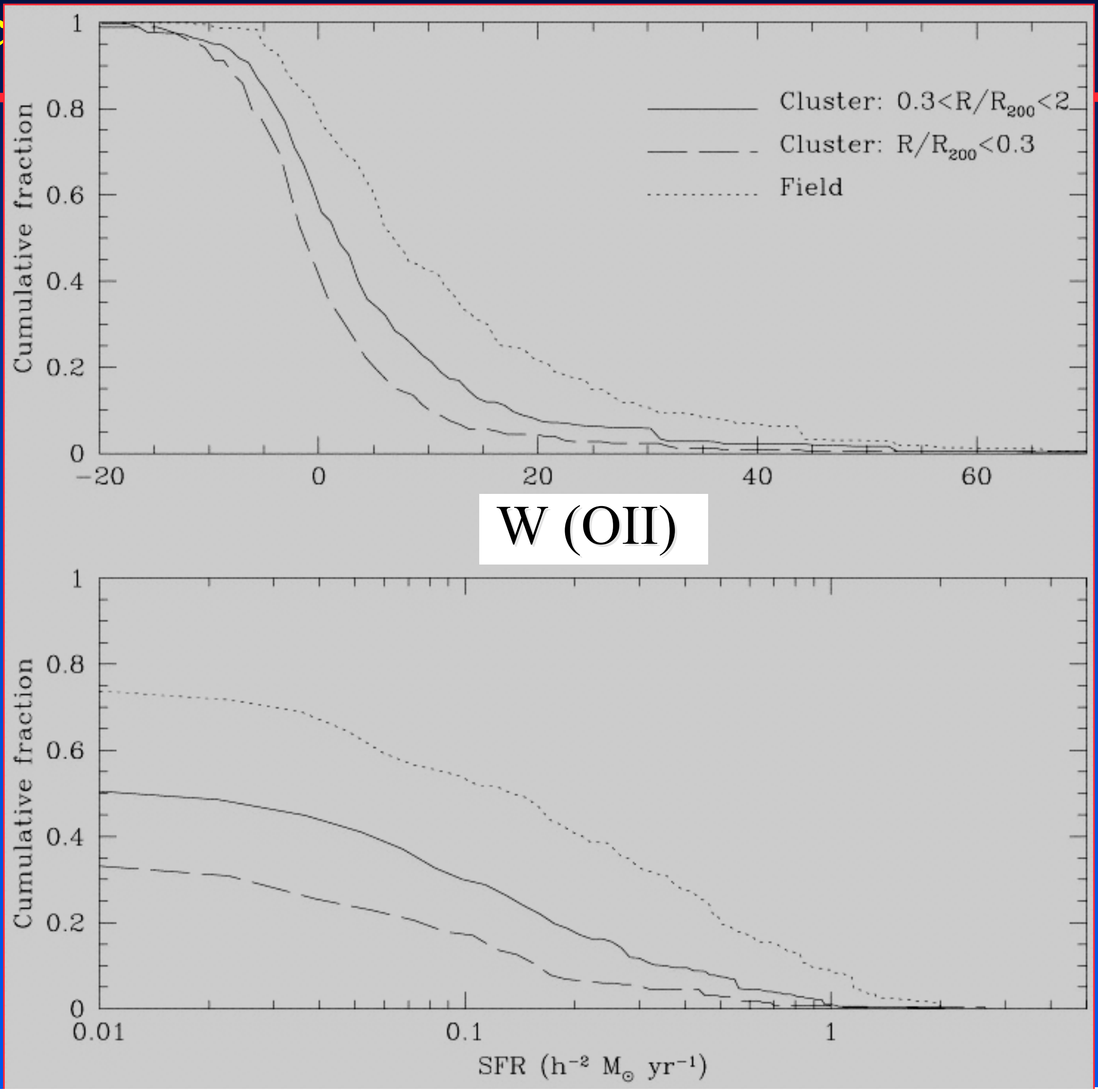
Field 11.2 +- 0.3 Angstroms

<u>There is no induced, excess star formation in clusters</u>



Spectroscopic

Balogh et al (1997)

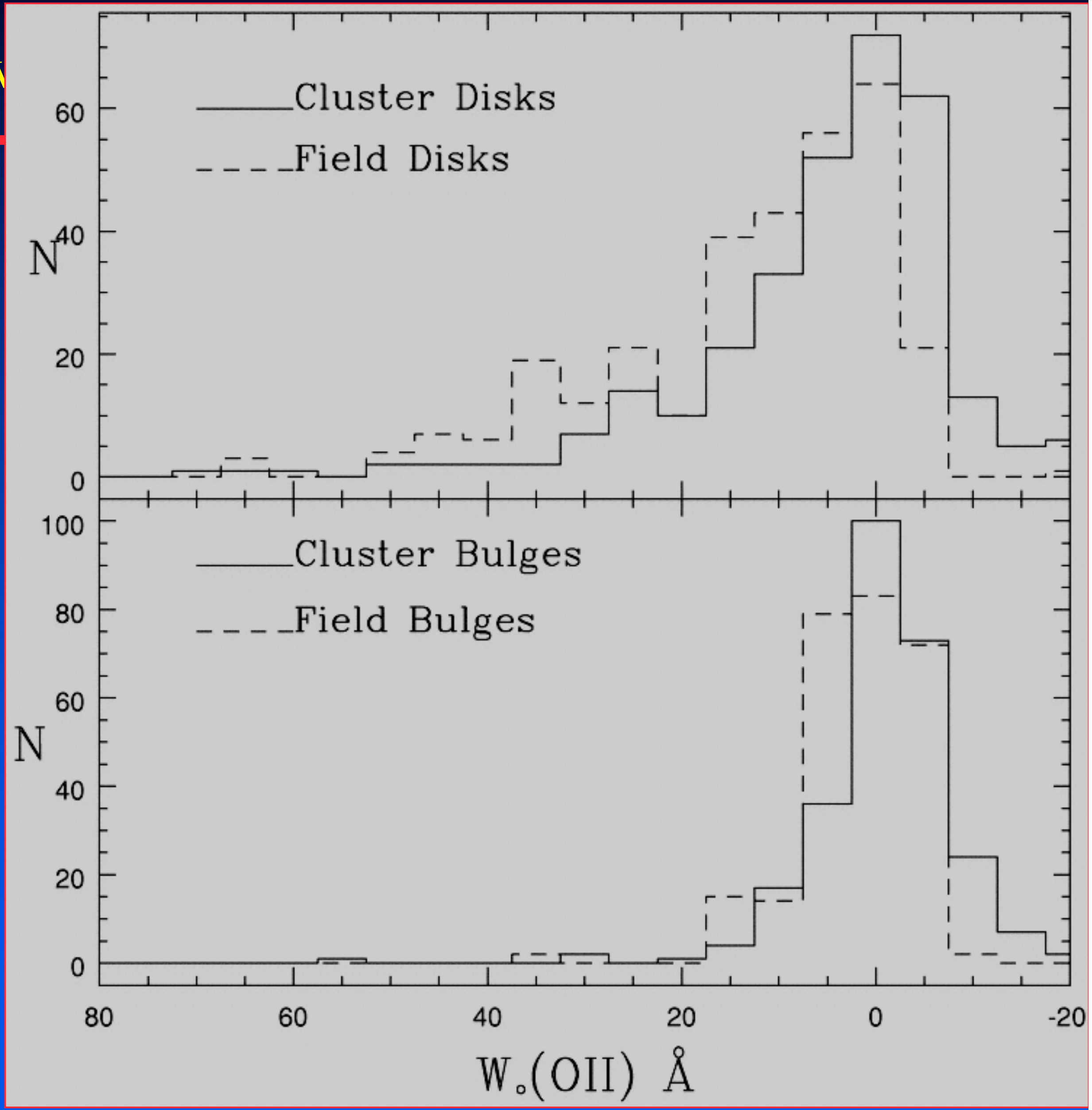


Spectroscopic inv

Balogh et al (1998)

The difference in star formation properties is **NOT** a result of the morphology-density relation

(These are both different at the 99% signicicance level)

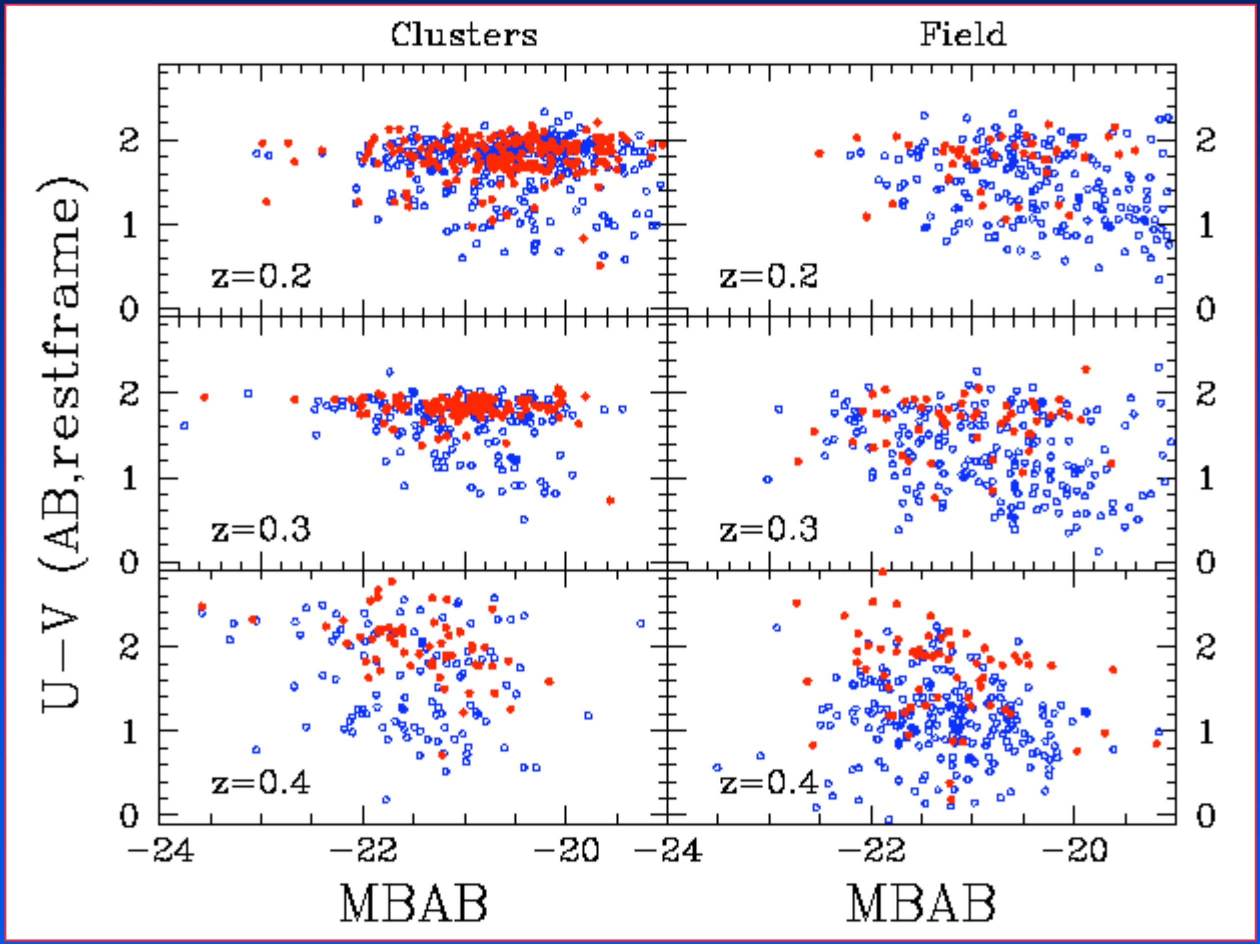


Star formation in clusters

- There is no global excess of star formation in clusters relative to the field
- Star formation is suppressed in cluster galaxies
- This is not due to the morphology-density relation

Galaxies of all morphological types that are associated with clusters have star formation rates that are SUPPRESSED relative to similar galaxies in the field

The field galaxy population is evolving



Spectroscopic investigations of Butcher-Oemler galaxies

Dressler & Gunn 1982,1983

A small sample

Couch & Sharples 1987

Most of the blue excess arises from a population that has undergone a burst of star formation recently (0.1 to 1.5 Gyr prior to observation). In the remainder a substantial burst is still in progress

Spectroscopic diagnostics of star formation history

Equivalent width of OII is an indicator of present star formation rate

Equivalent width of H-delta is an indicator of recent star formation

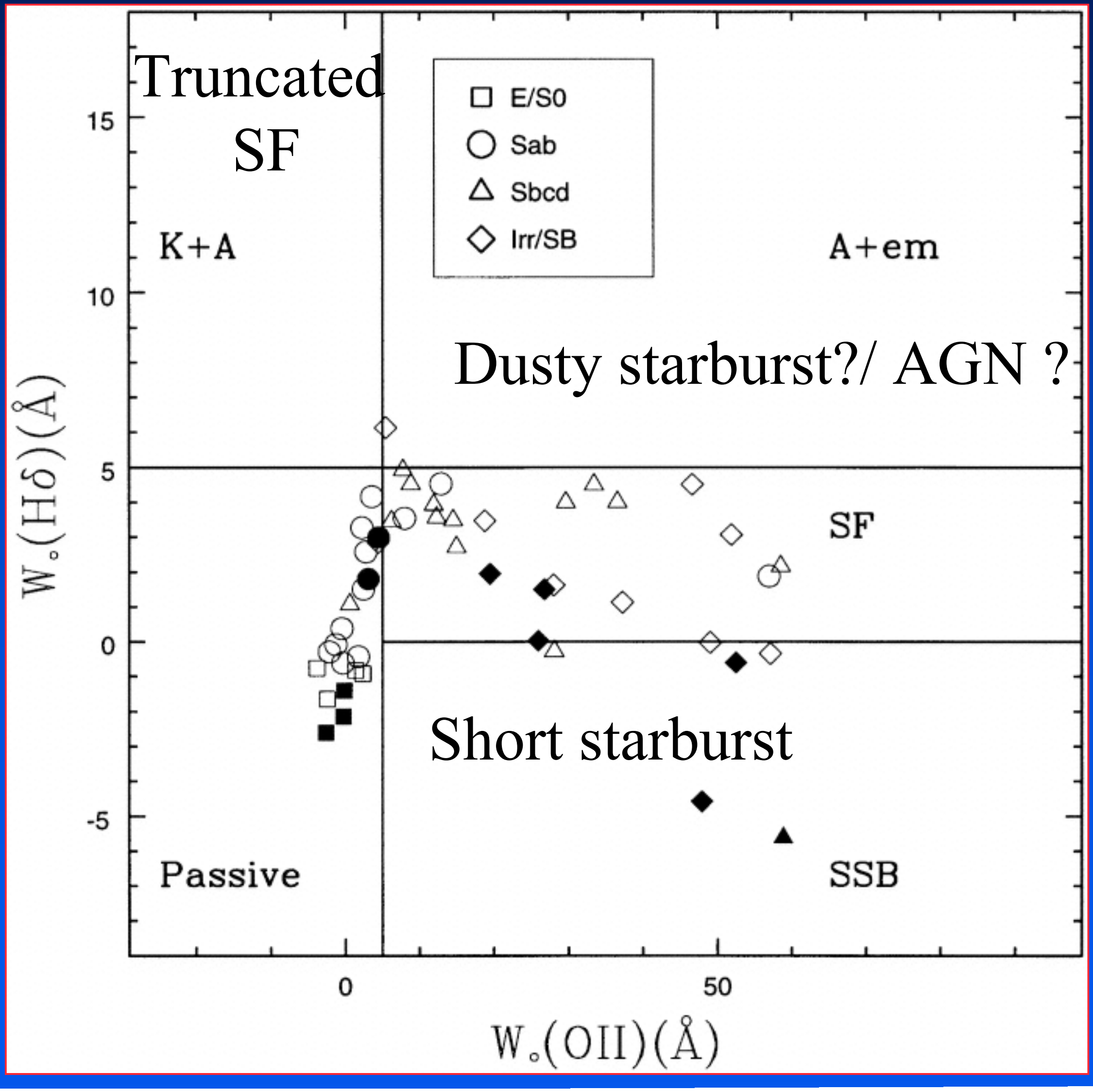
The OII H-delta plane can provide discrimination between starbursts and normal rates of star formation

Spectroscopic investigations of Butcher-Oemler galaxies

Comparison of starbursts and post-starburst frequency between cluster and field

CNOC Data

Diagnostic diagram
Balogh et al. (1999)



Questions

- Does association with cluster induce star formation in disk galaxies?
- Does association with cluster induce bursts of star formation?
- Does association with the cluster truncate SF in post-starburs galaxies?

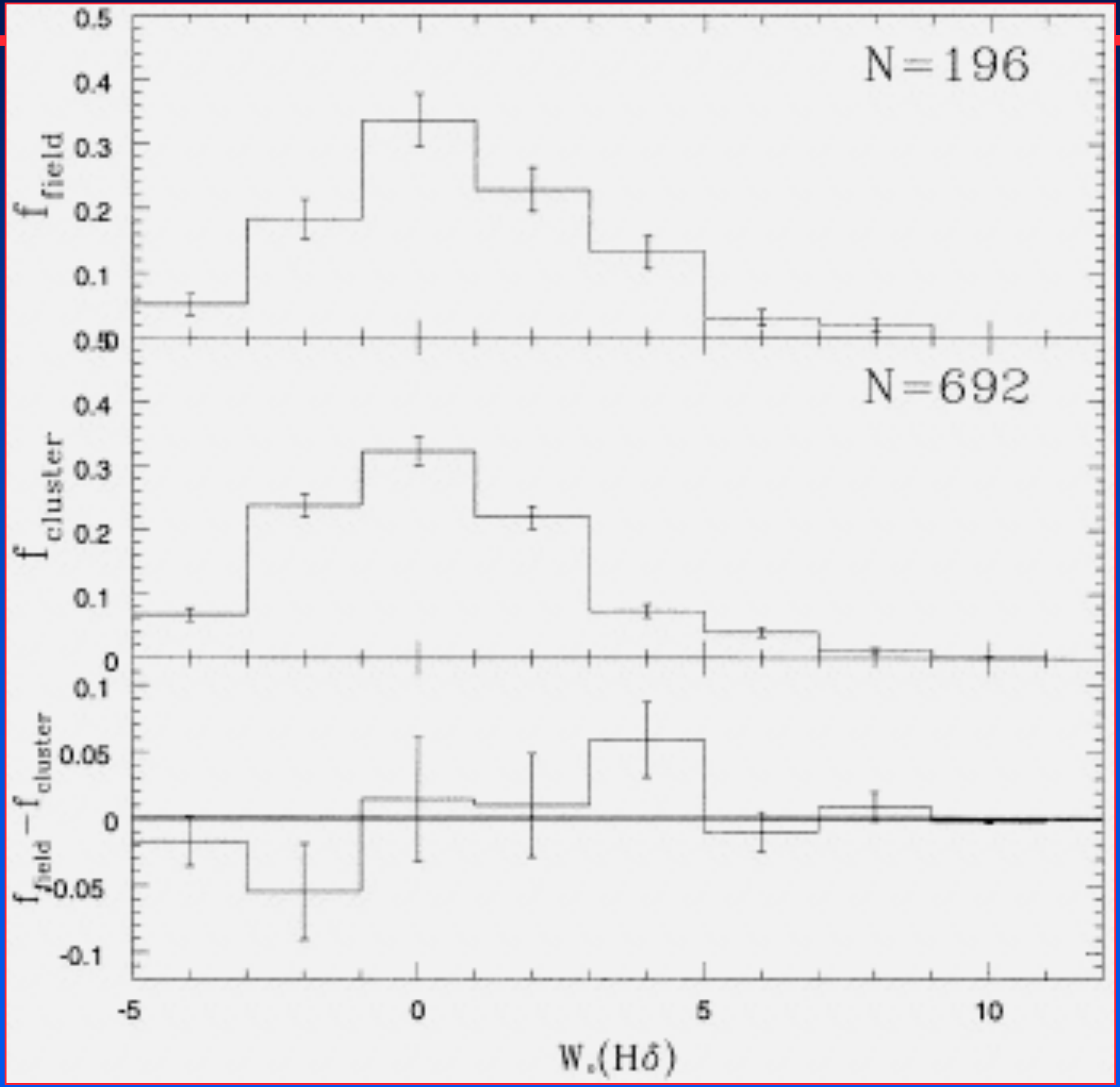
Spectroscopic investigations of cluster galaxies

Comparison of the frequency of Hδ in clusters and field

Assume Hδ is an indicator of recent star formation

CNOC data

FIELD identical to CLUSTERS



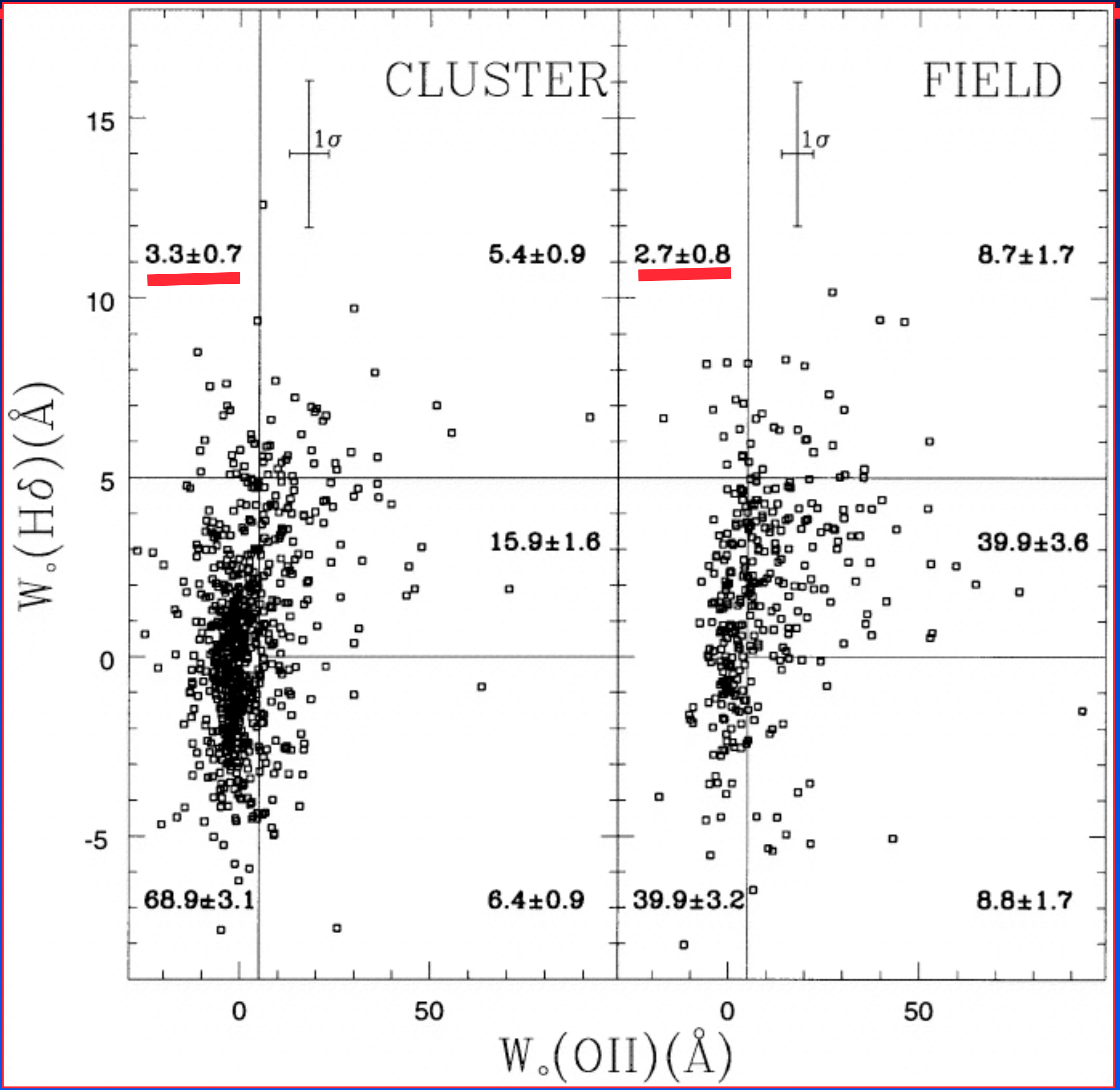
Spectroscopic investigations of cluster galaxies

Balogh et al (1999)

corrected for scatter

Field and cluster are

consistent

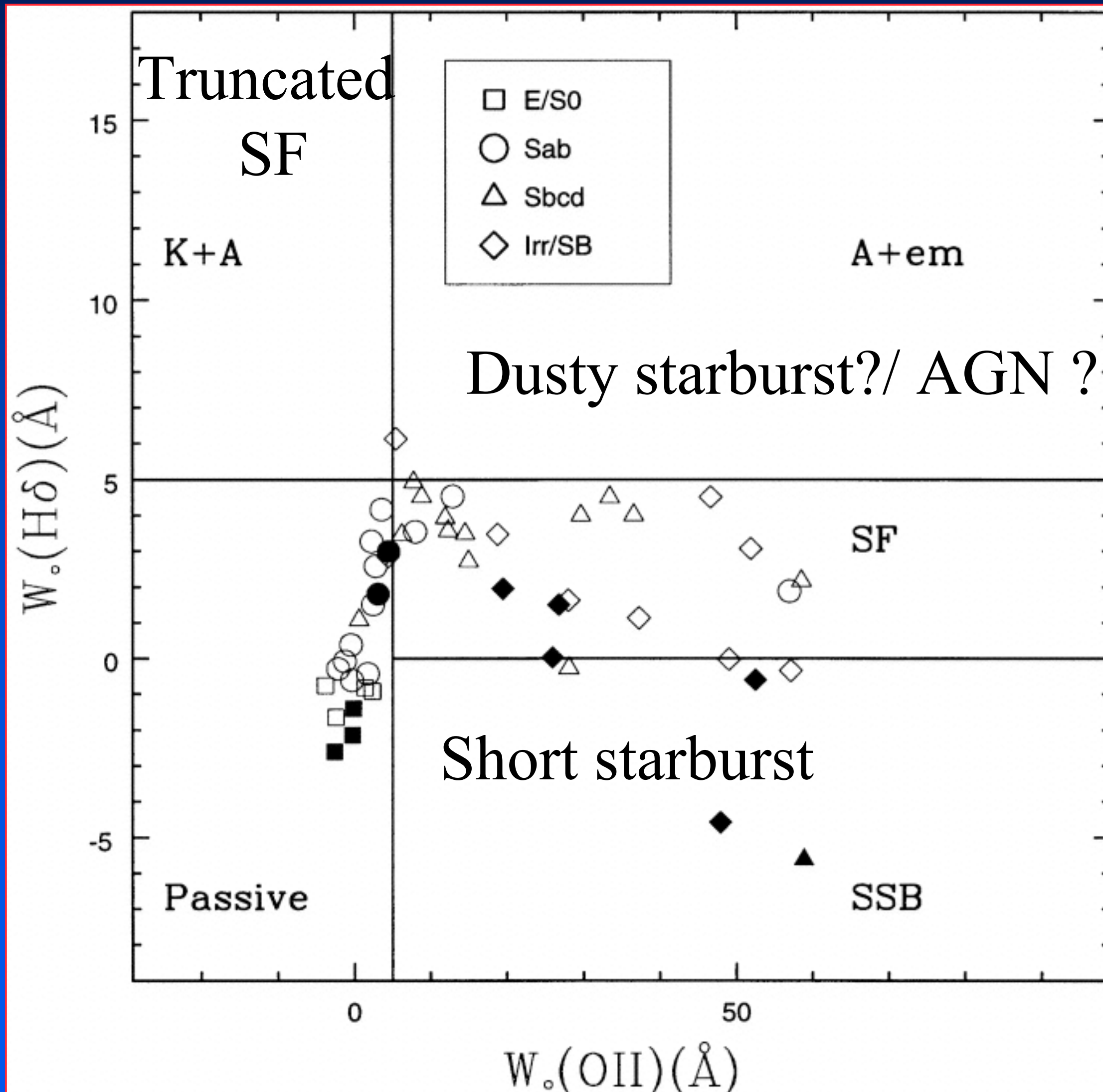


Spectroscopic investigations of Butcher-Oemler galaxies

Comparison of starbursts and post-starburst frequency between cluster and field

CNOC Data

Diagnostic diagram
Balogh et al. (1999)



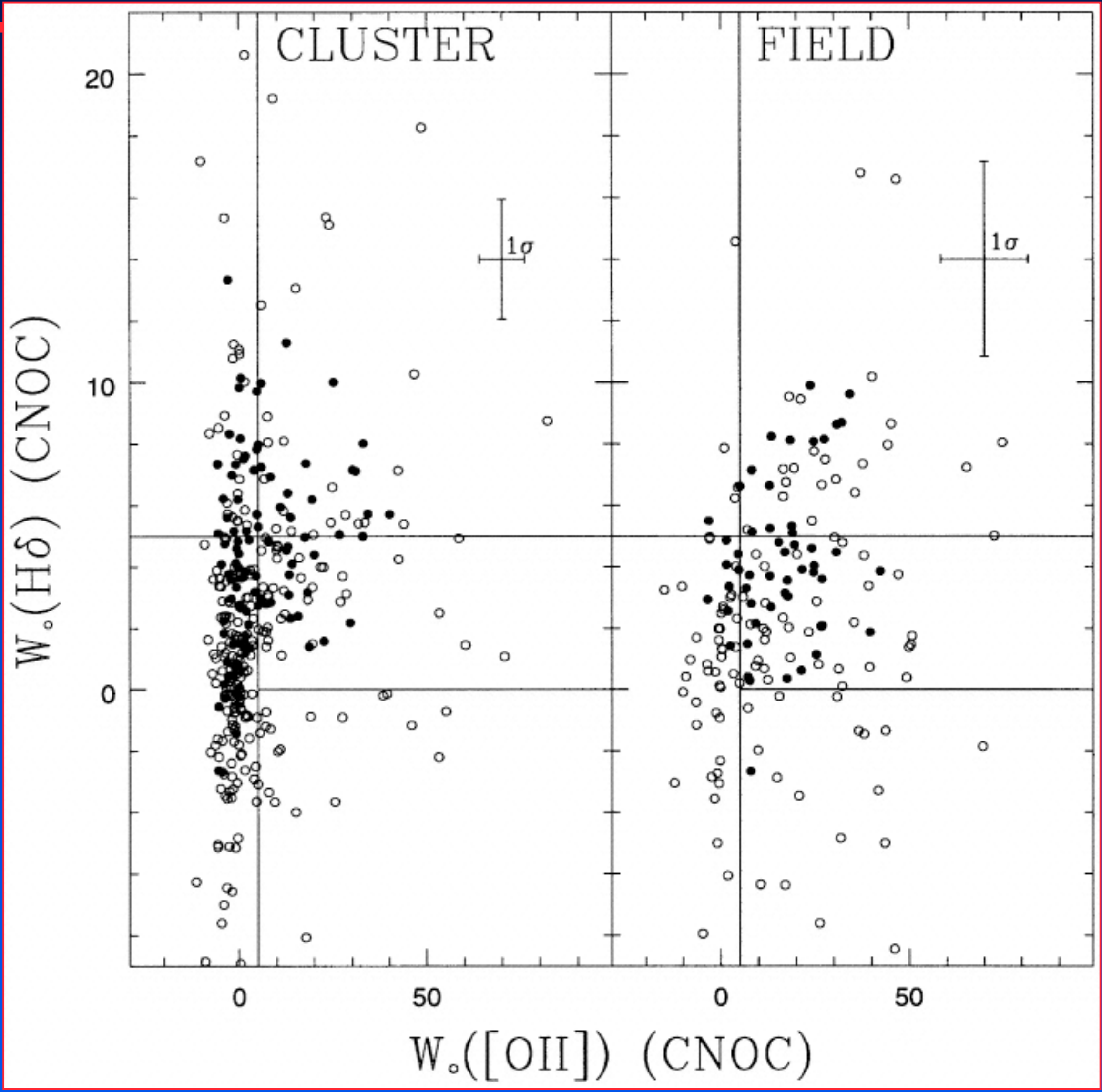
Spectroscopic investigations of cluster galaxies

Balogh et al (1999):

Analysis of Dressler (1999) raw counts

Dressler et al find a factor of 10 times more k+A galaxies in clusters compared to the field

What is the source of the discrepancy?



Spectroscopic investigations of cluster galaxies

1) Different set of clusters: clusters are a heterogeneous population

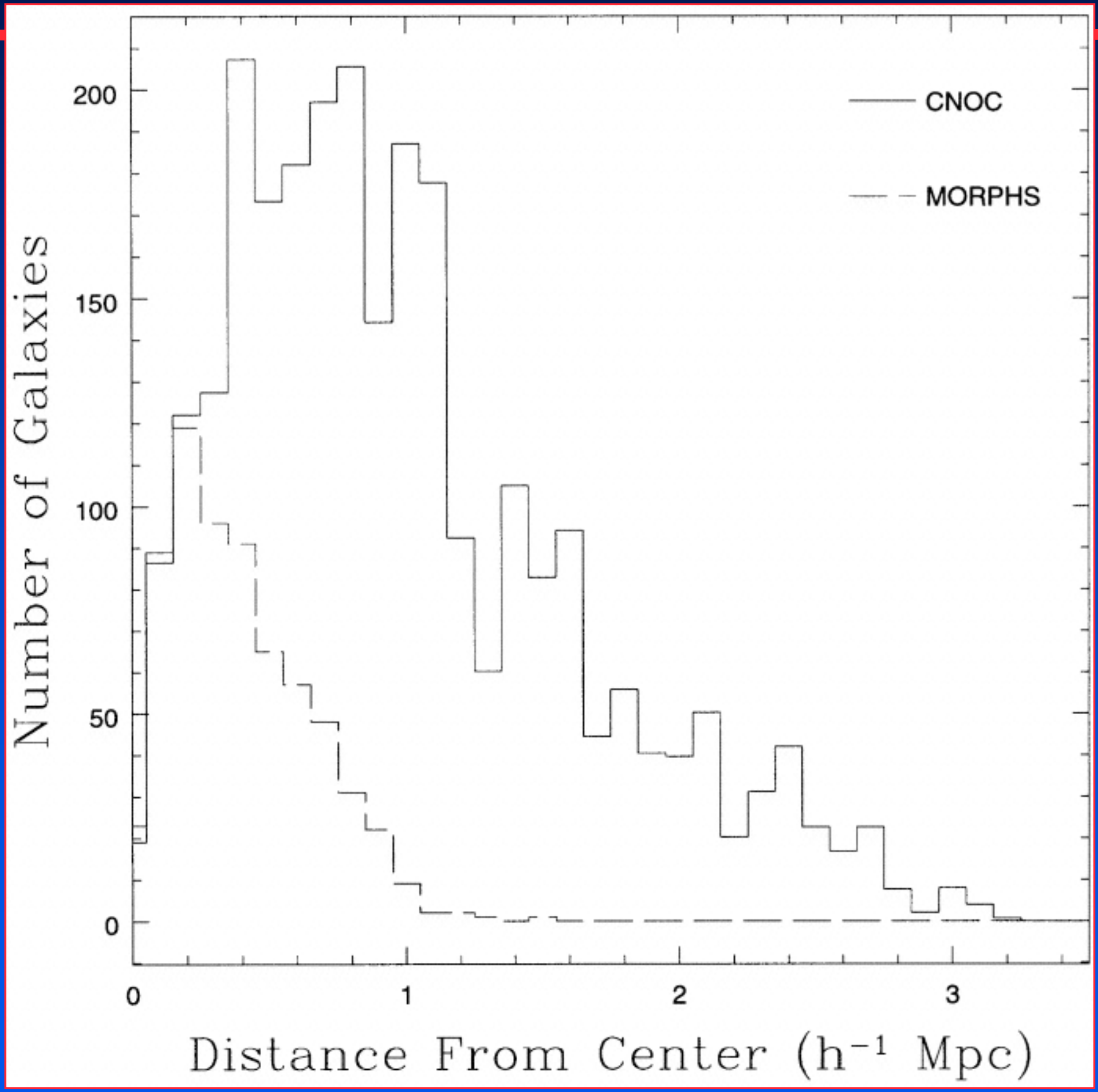
2) Different selection of the galaxies for spectroscopy

3) Different treatment of errors by Balogh et al. (1999)

4) CNOC galaxies sample a larger region of the cluster

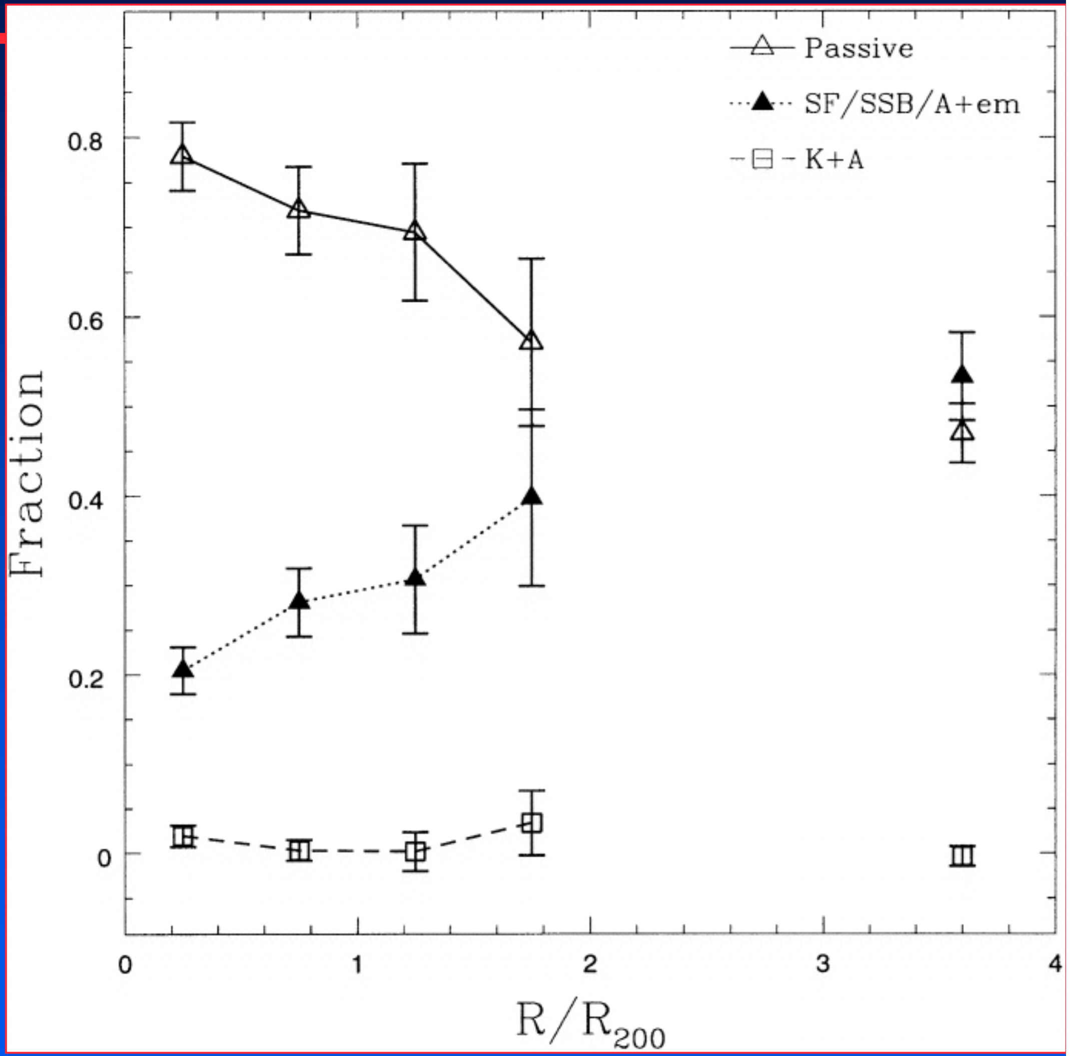
Spectroscopic investigations of cluster galaxies

Different regions sampled by CNOC and Dressler et al.



Spectroscopic investigations of cluster galaxies

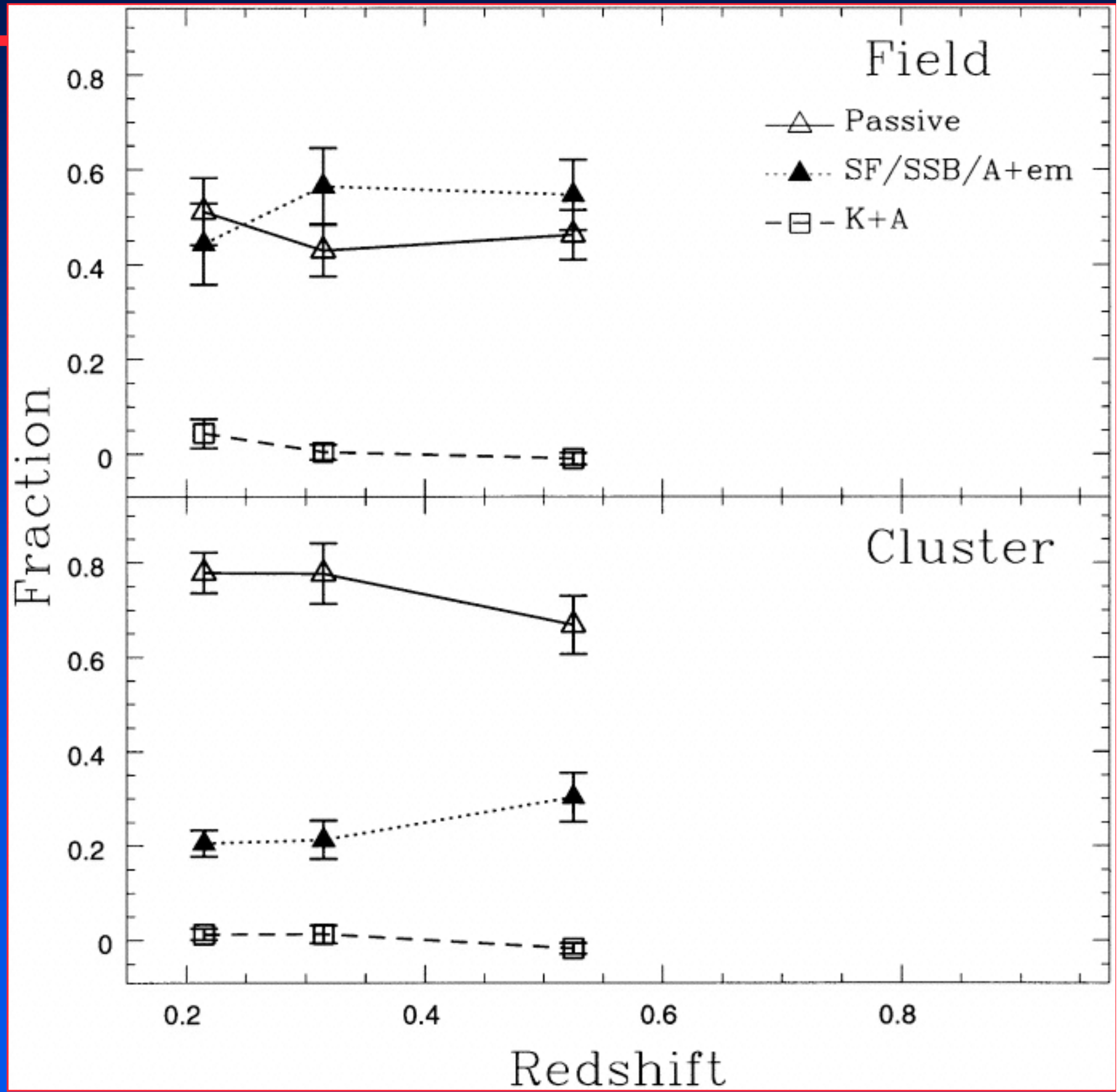
Fractions of galaxies of different spectroscopic classes as a function of radius in clusters



Spectroscopic investigations of cluster galaxies

Evolution with redshifts of the fractions of each spectroscopic class

No increase in the k+A fraction with redshift



Evolution of Cluster Galaxies

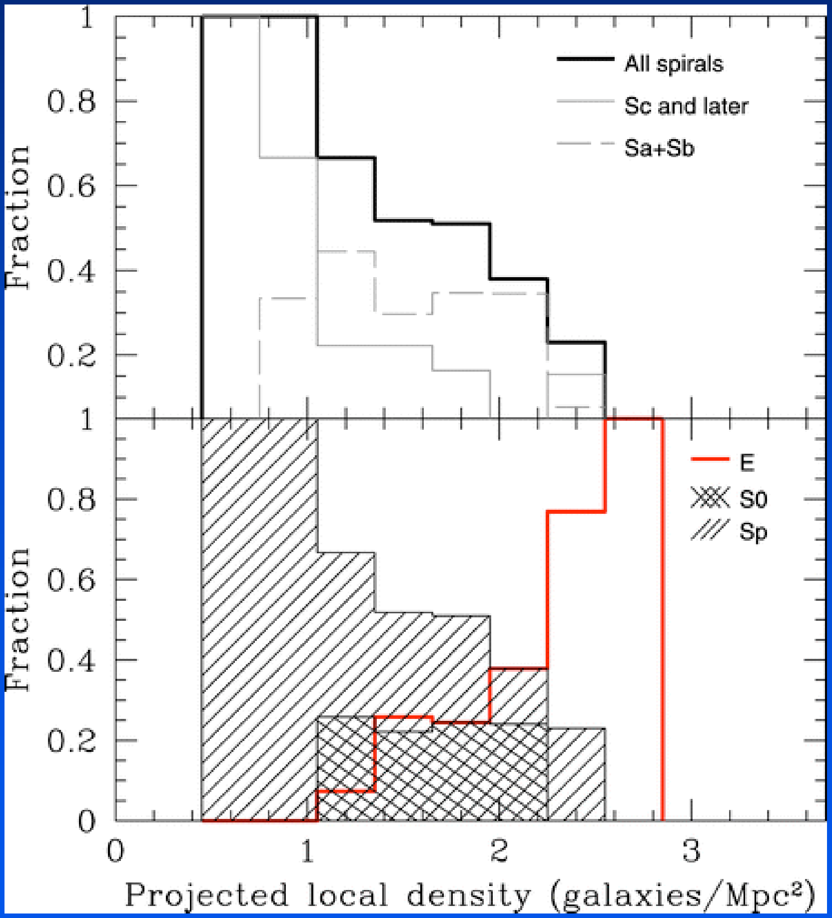
There exists a discrepancy between the results of Balogh et al and Dressler et al that needs to be resolved.

The “One Universe” theorem

Selection effects are almost certainly the problem

Poggianti 2008

- Fig. 11.—Morphology density relation for EDisCS spectroscopically confirmed cluster members. Fraction of each morphological type in various density bins. In the bottom panel the thick black histogram shows E galaxies, the double-shaded histogram shows S0 galaxies, and the single-shaded histogram shows spiral galaxies. In the top panel, the thick solid histogram shows all spirals, the long-dashed histogram shows early-type spirals (Sa and Sb), and the thin solid histogram shows late-type spirals (Sc and later types). Note that the highest density bin is only populated by ellipticals.



Spitzer: 24 micron B-O effect (Saintonge et al 2008)

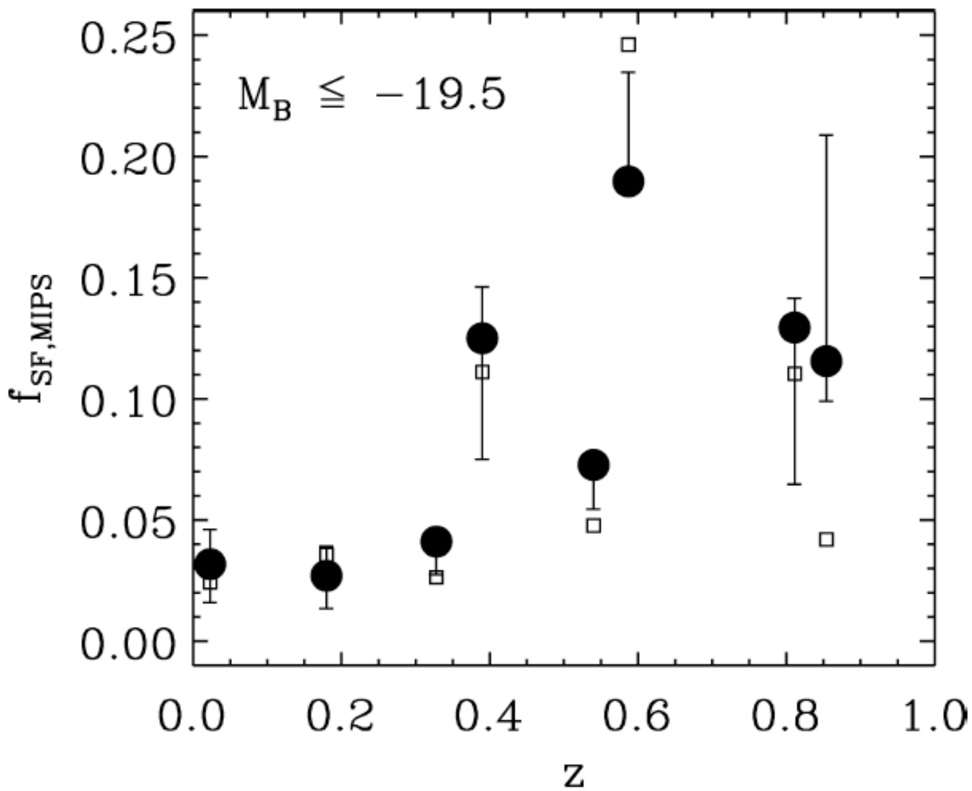


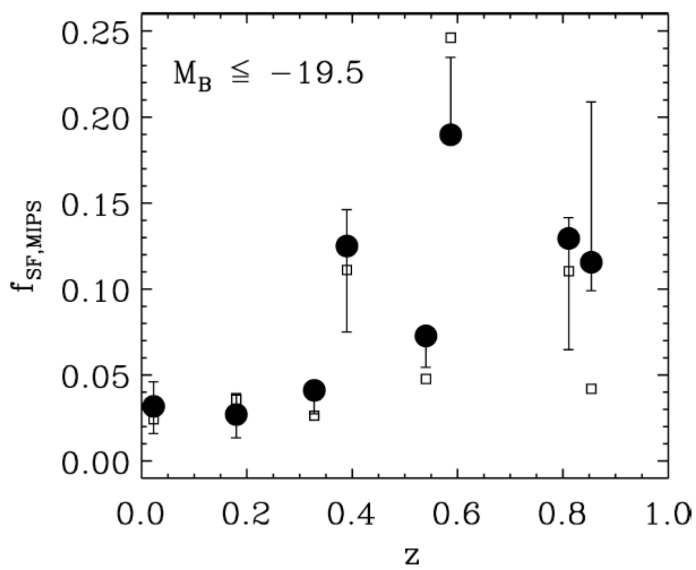
FIG. 2.—Fraction of confirmed cluster galaxies that are star forming as revealed by the MIPS 24 μm observations. Only considered are members with MIR SF rates $\geq 5\ M_\odot\ \mathrm{yr}^{-1}$ that are brighter than $M_B = -19.5$ and located within 1 Mpc of the cluster centers (*filled circles*) and 500 kpc (*open squares*). The points for the two $z \sim 0.83$ clusters are offset slightly in z for clarity.

8 masive clusters
0.02 < z < 0.83
Galaxies with SFR > 5 Msun/year

Spitzer: 24 micron B-O effect (Saintonge et al 2008)

All galaxies

Most massive galaxies



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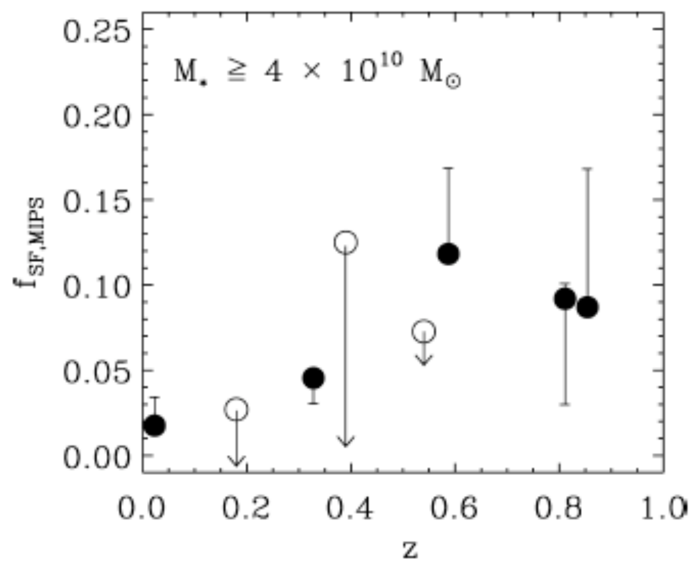

FIG. 3.—As in Fig. 2, the fraction of confirmed star-forming cluster galaxies (MIR SF rate $\geq 5\ M_{\odot}\ yr^{-1}$, $M_B \leq -19.5$, $R_P < 1$ Mpc), but now with the additional stellar mass cutoff of $\log_{10}(M_*) \geq 10.6$ for the five main clusters (*filled circles*). Stellar masses are not available for the remaining three clusters; they are shown as upper limits (*open circles*).

Spitzer: 24 micron B-O effect (Saintonge et al 2008)

Butcher-Oemler effect confirmed in 24 micron data

Not only an effect among low mass galaxies

Increasing fraction of dusty starbursts with redshifts

RCS: 1000 clusters z=0.45 to z=0.9

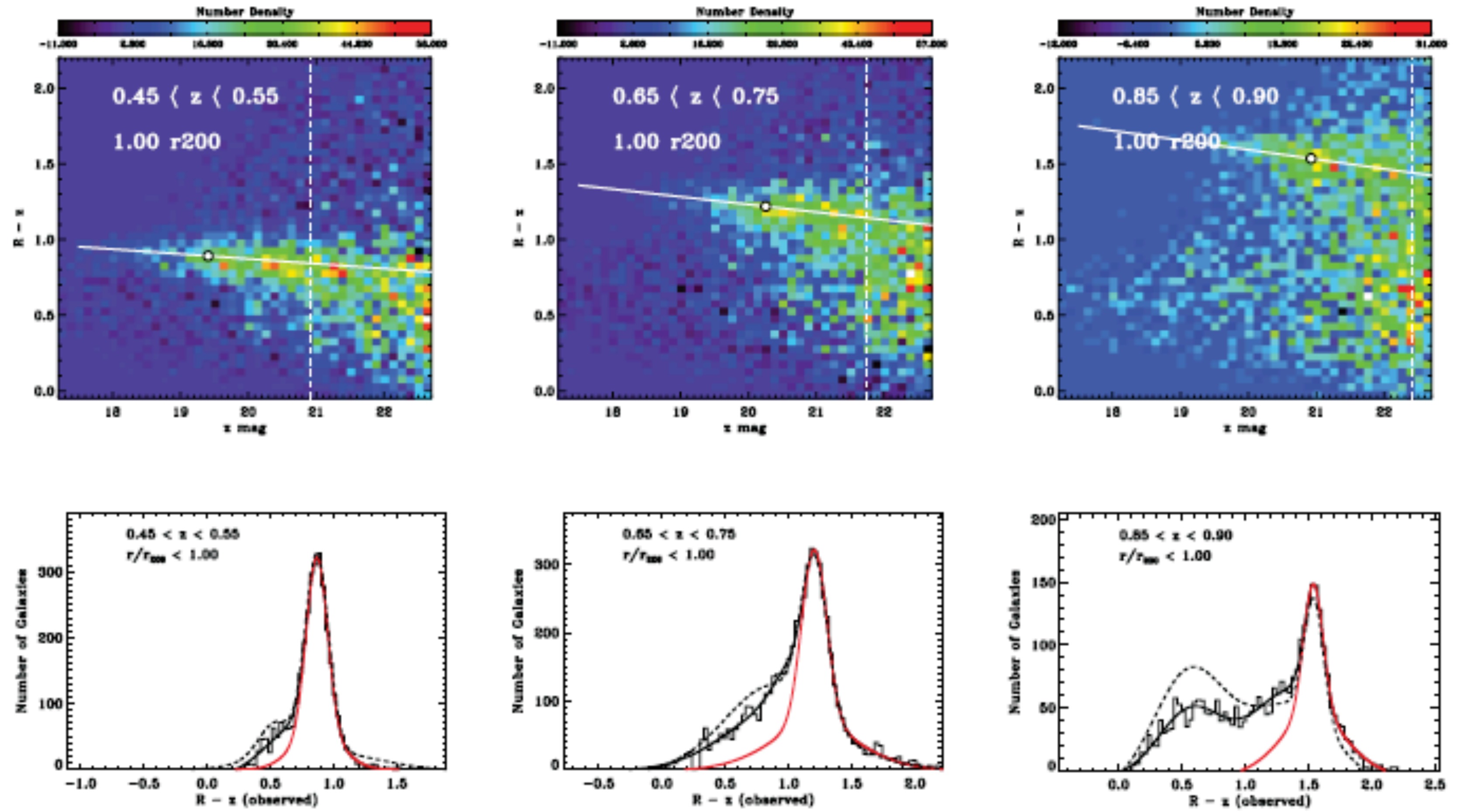

FIG. 5.—*Top*: Background-subtracted color-magnitude distributions. *Bottom*: Color distribution after $k + e$ correction. The histogram and the solid line shows the distribution after applying a differential k-correction for non-red-sequence galaxies (see § 3.2.2), while the dashed lines show the distribution before such a correction was made. The red curve is our model for the red distribution used to compute the red fraction. The plots for are redshift slices $0.45 < z_{ph} < 0.55$ (*left*), $0.65 < z_{ph} < 0.75$ (*middle*), and $0.85 < z_{ph} < 0.90$ (*right*).

RCS: 1000 clusters z=0.45 to z=0.9

Loh, et al ApJ 680, 214, 2008
K+e corrections

The blue galaxy population as f (spectral type)

No. 1, 2008 COLOR BIMODALITY IN GALAXY CLUSTERS 221

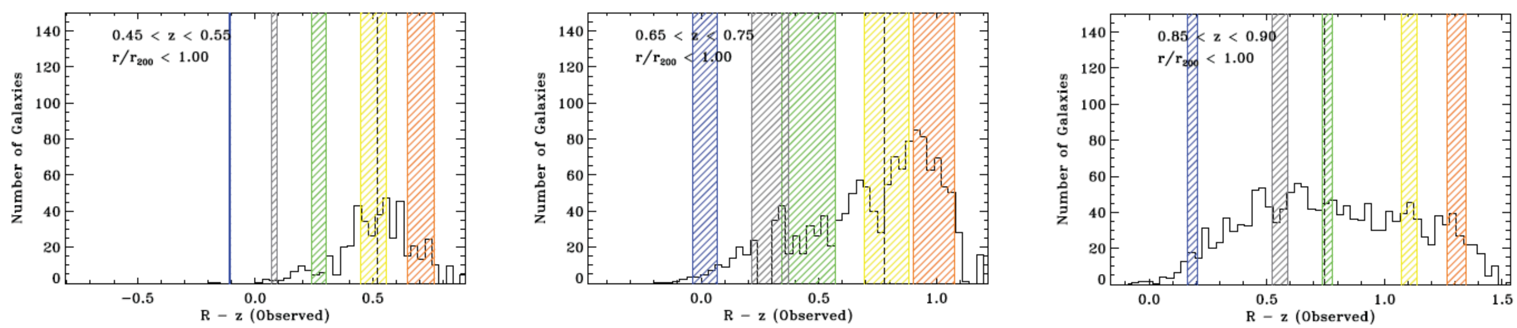

Fig. 7.—Blue distributions of galaxies after correction for the red sequence (*solid histograms*). The shaded bands in each plot are the expected color for different spectral types, ranging from Sab (*far right*), Sbc, Im, and starburst (SB1, SB2; *far left*), synthesized using a single representative SED for each type (see text). The width of the band reflects the finite redshift range in each subsample and the color variation as the filters shifts along the SED with redshift. The plots are for redshift slices $0.45 < z_{ph} < 0.55$ (*left*), $0.65 < z_{ph} < 0.75$ (*middle*), and $0.85 < z_{ph} < 0.90$ (*right*). The vertical dashed lines indicate the median colors of the distributions, also plotted in Fig. 4.

- Observed B-O effect is consistent with a normal coeval field population

RCS: 1000 clusters z=0.45 to z=0.9

- Red fraction evolves at all radii
- Blue galaxies may be newly infalling?
- Starbursts are less than 5% of the blue population
- Observed B-O effect is consistent with a normal coeval field population

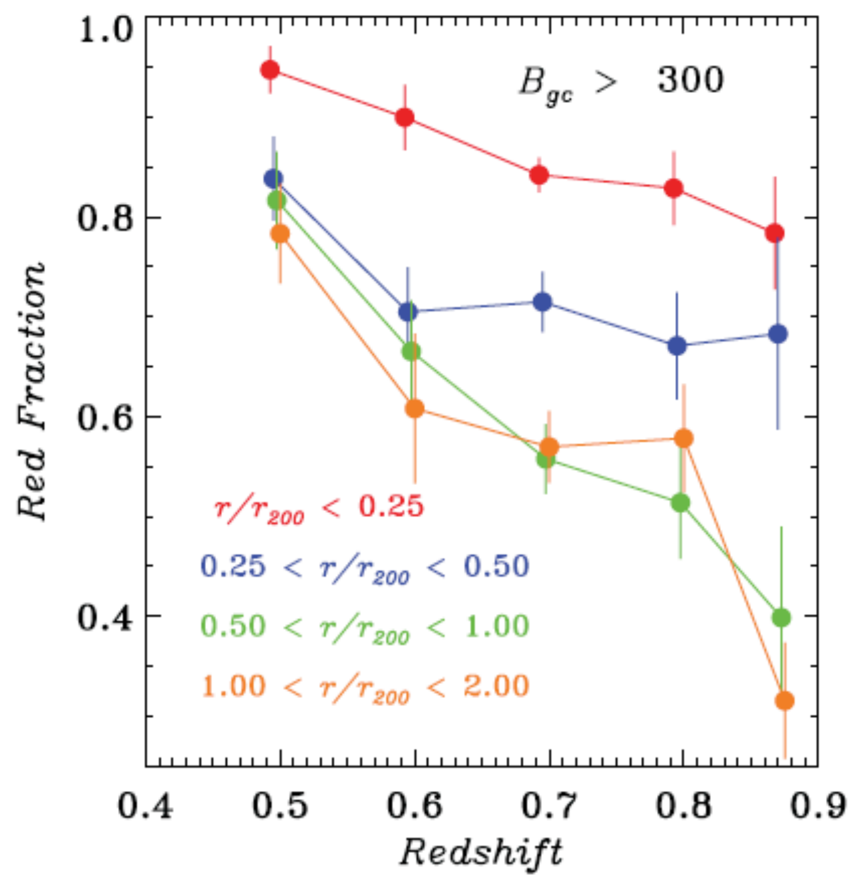

FIG. 6.—Red fraction as a function of redshift for galaxies with $r/r_{200} < 0.25$ (core), $0.25 < r/r_{200} < 0.5$, $0.5 < r/r_{200} < 1.0$, and $1.0 < r/r_{200} < 2.0$ (outskirts) and brighter than $M^* + 1.5$.

Star formation in clusters

- There is no global excess of star formation in clusters relative to the field
- Star formation is suppressed in cluster galaxies
- This is not due to the morphology-density relation

Galaxies of all morphological types that are associated with clusters have star formation rates that are SUPPRESSED relative to similar galaxies in the field

Summary of evolution of cluster elliptical galaxies

- Cluster (and field) ellipticals evolve in luminosity in a manner consistent with the implied ages and with passive evolution
- The homogeneity of the E/S0 populations persists to z = 0.5 and implies a formation epoch at least a few Gyrs earlier (z > 1)
- The color of the ellipticals evolves in a manner consistent with the implied ages and with passive evolution
-

Observed Phenomena of Cluster Galaxies

- Morphology-Density relation
- Old (co-eval) ellipticals
- Butcher-Oemler effect
- E+A galaxies
- S0 problem

- CD galaxies
- Suppression of SFR
- Disk galaxies
- Dwarf galaxies
- Interactions/Mergers

Early Processes

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Omega from cluster Mass and field luminosity density

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GALAXY CLUSTER VIRIAL MASSES AND Ω

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ABSTRACT

The mean density of the universe is equal to the mass of a large galaxy cluster divided by the equivalent comoving volume in the field from which that mass originated. To reexamine the rich cluster Ω-value the CNOC Cluster Survey has observed 16 high X-ray luminosity clusters in the redshift range 0.17–0.55, obtaining approximately 2600 velocities in their fields. The systemic redshift, the rms line-of-sight velocity dispersion σ_1, and the mean harmonic radius r_v are derived for each cluster using algorithms that correct for interlopers in redshift space and measure the angular extent of the sampling. The virial mass, and its internal error, are derived from σ_1 and r_v. The cluster luminosity is estimated from the K-corrected r-band luminosities of the cluster galaxies. Directly adding all the light to $M_r^K = -18.5$ mag, about $0.2L_*$, and extrapolating for the small amount of light below the limit, the average mass-to-light ratio of the clusters is $295 \pm 53\ h\ M_\odot\ L_\odot^{-1}$, and the average mass per galaxy to $M_r^K = -19.0$ mag is $4.2 \pm 1.1 \times 10^{12}\ h^{-1}\ M_\odot$. The clusters are consistent with having a universal M_v/L-value (within the errors of about 25%) independent of their velocity dispersion, mean color of their galaxies, blue galaxy content, redshift, or mean interior density. Using field galaxies within the same data set, with the same corrections, we find that the closure mass-to-light ratio, ρ_c/j, is $1025 \pm 140\ h\ M_\odot\ L_\odot^{-1}$, and the closure mass per galaxy to $M_r^K = -19.0$ mag, ρ_c/Φ, is $15.5 \pm 3.0 \times 10^{12}\ h^{-1}\ M_\odot$. Under the assumptions that the galaxies are distributed like the mass and that the galaxy luminosities and numbers are statistically conserved, assumptions that these data indirectly support, $\Omega_0 = 0.24 \pm 0.05 \pm 0.09$, where the errors are, respectively, the 1 σ random error and an estimate of the possible systematic error resulting from the normalization to galaxy content.

Omega from cluster Mass and field luminosity density

- M/L

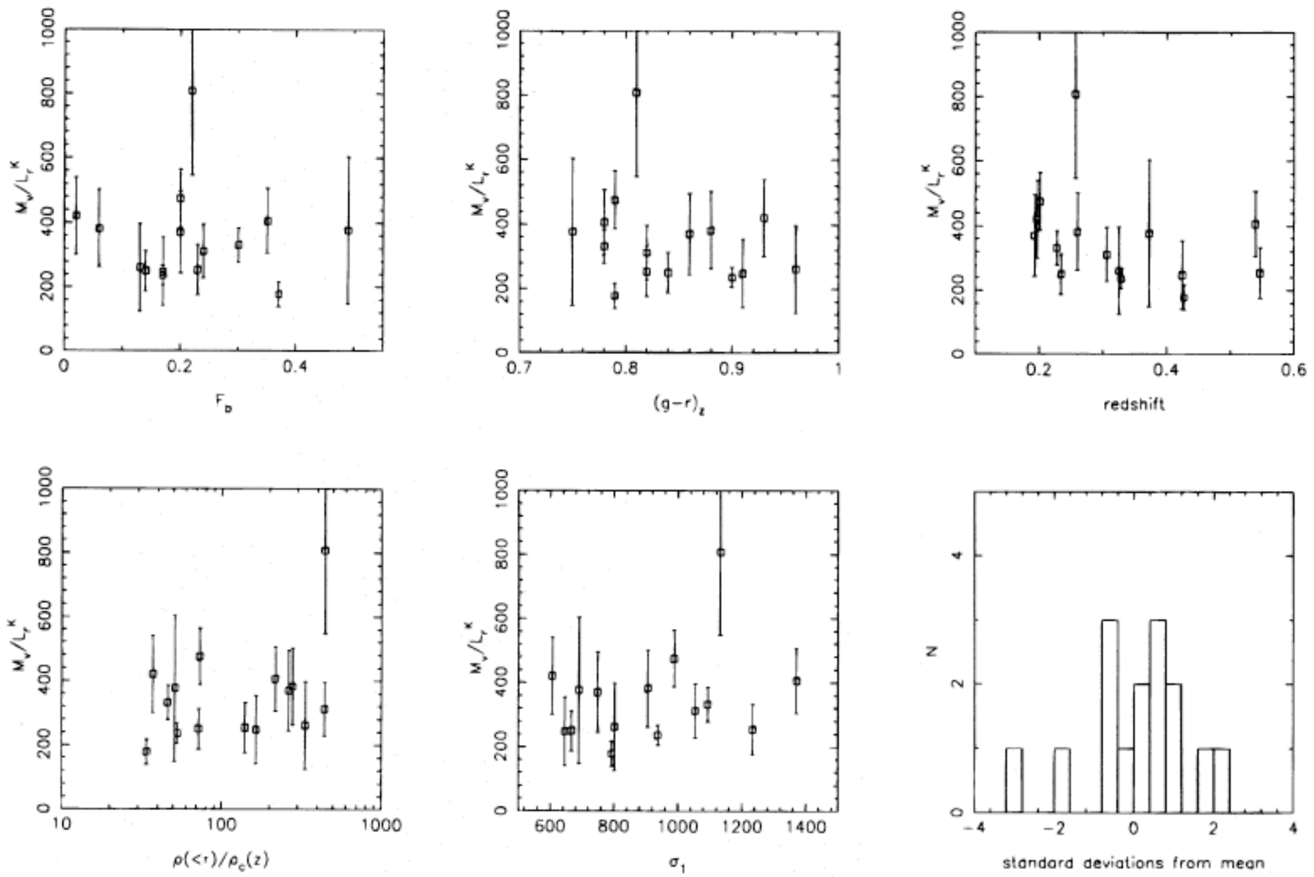

FIG. 5.—M_v/L ratio as a function of (*from left to right, top to bottom*) total blue fraction, color, redshift, mean interior density, and velocity dispersions, for $M_r^K = -18.5$ mag. The distribution of differences from the mean, ratioed to the estimated error, is in the lower right.

Omega from cluster Mass and field luminosity density

- Omega =0.24 +- 0.05 +- 0.09
- Consistent with present-day results

Lessons

- Field galaxy evolution needs to be folded in
- One Universe theorem
- Selection effects
- What you measure matters