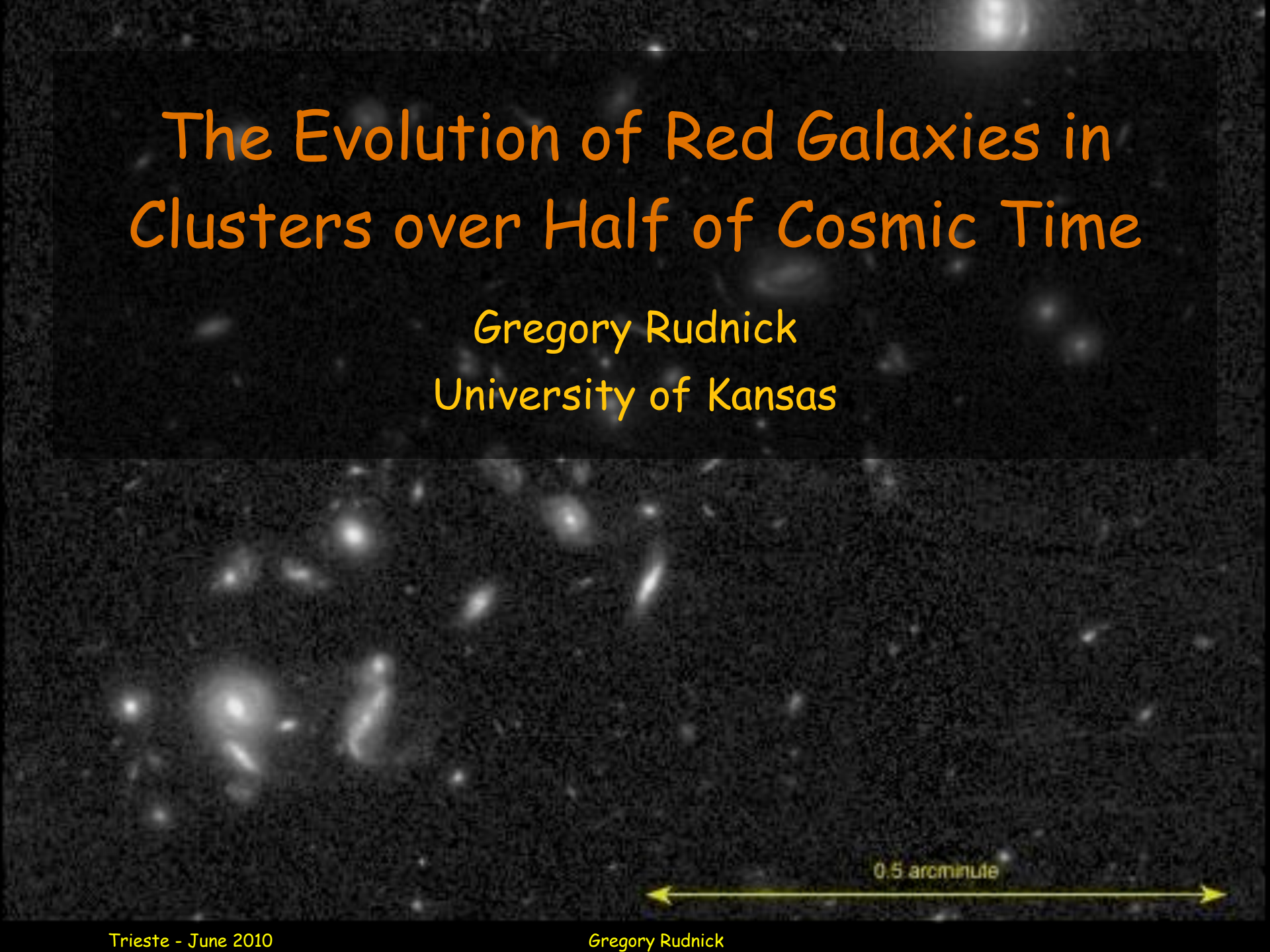
The Evolution of Red Galaxies in Clusters over Half of Cosmic Time

Gregory Rudnick
University of Kansas



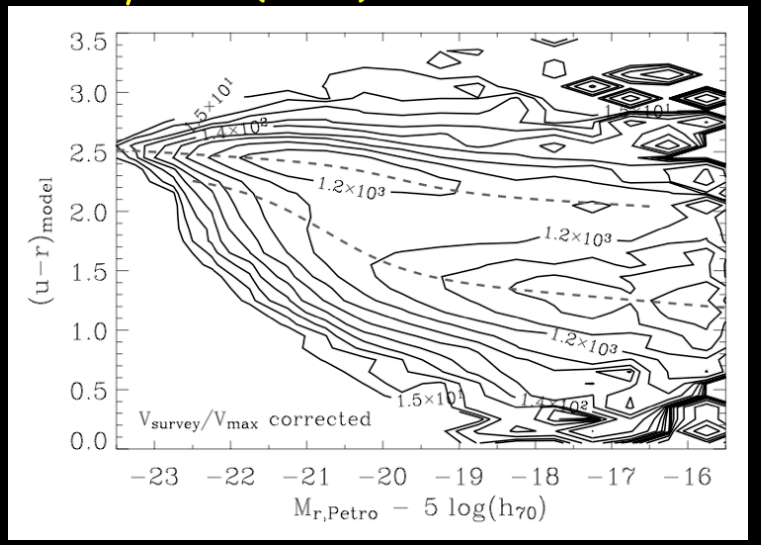
The Evolution of Red Galaxies in Clusters over Half of Cosmic Time

Gregory Rudnick
University of Kansas

What role does environment play in shaping galaxy evolution?

Baldry et al. (2004)

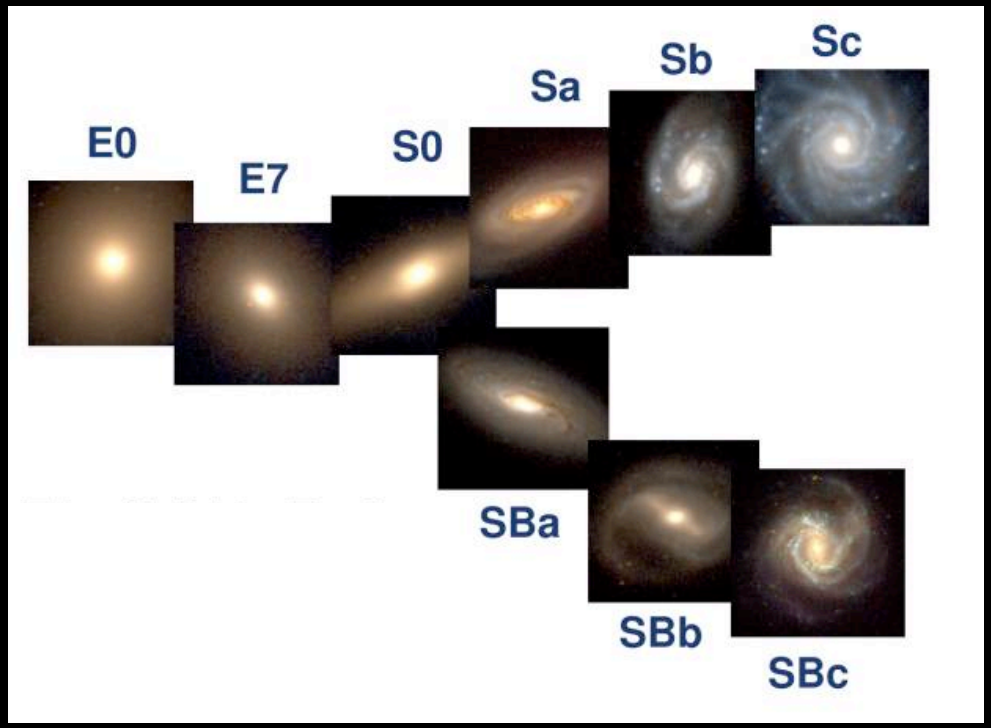
red



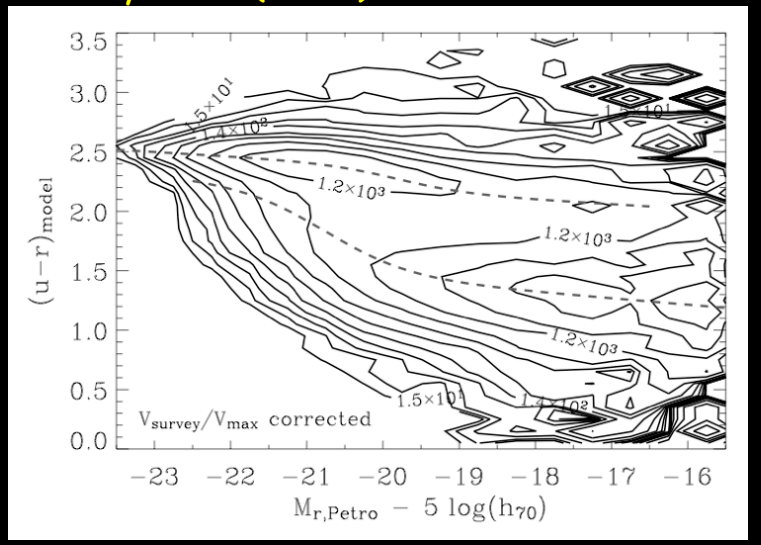
blue

bright

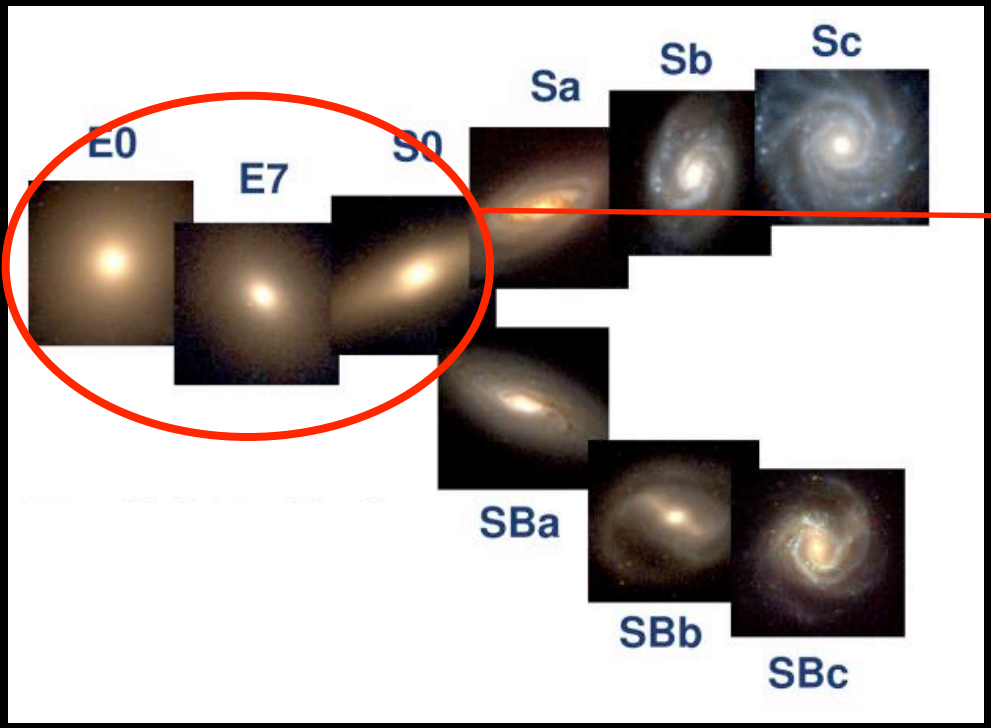
Galaxies are supposedly moved to the red sequence
by the truncation of star formation in blue galaxies



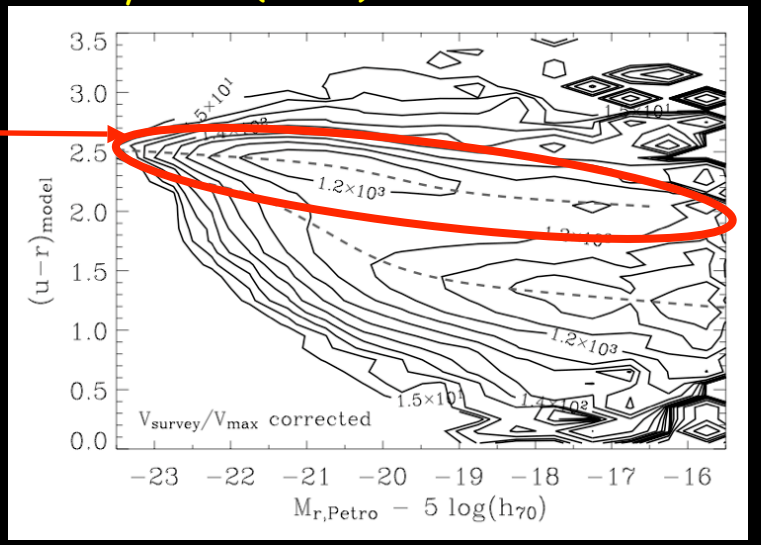
Baldry et al. (2004)



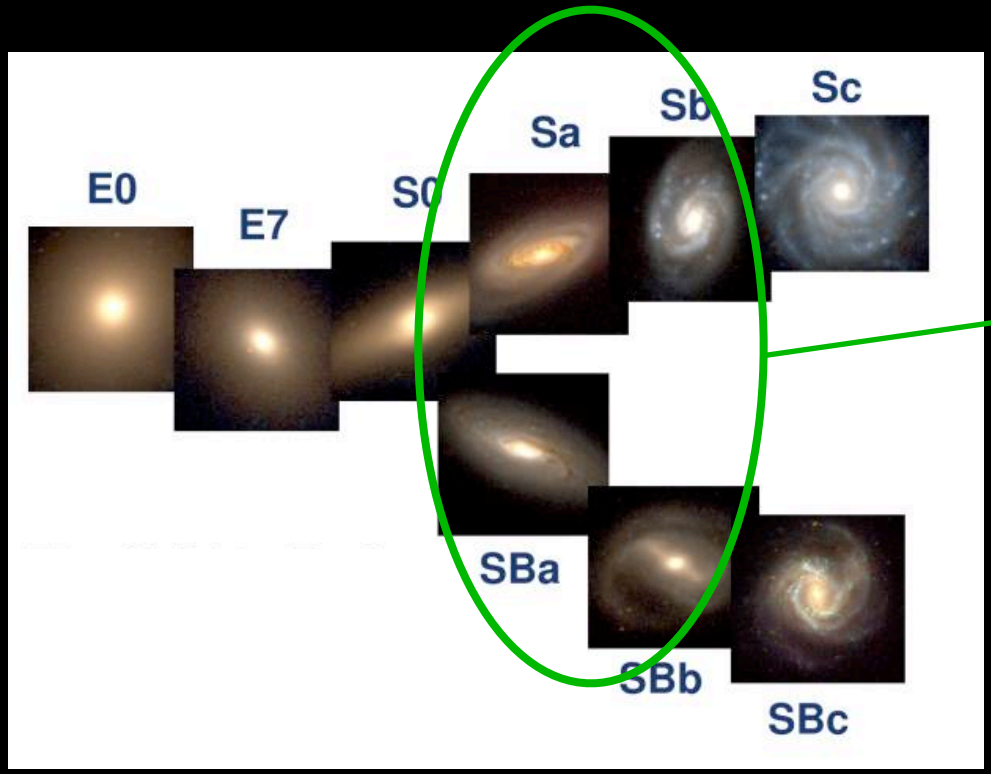
Galaxies are supposedly moved to the red sequence
by the truncation of star formation in blue galaxies



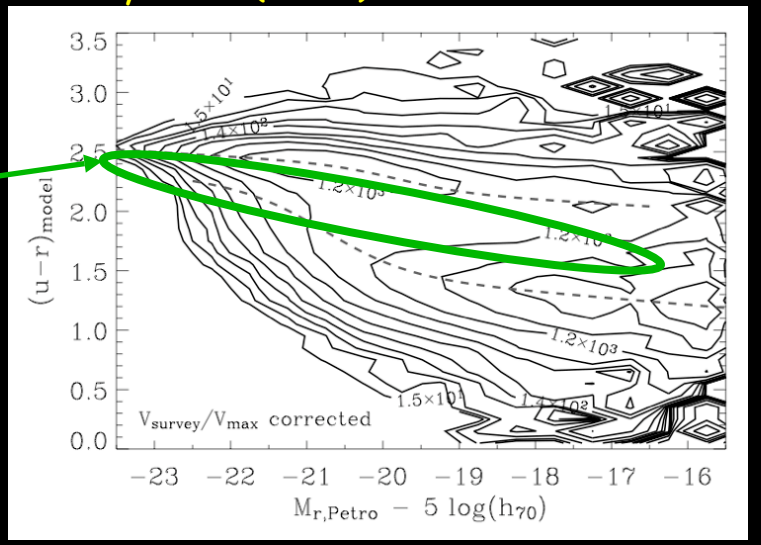
Baldry et al. (2004)



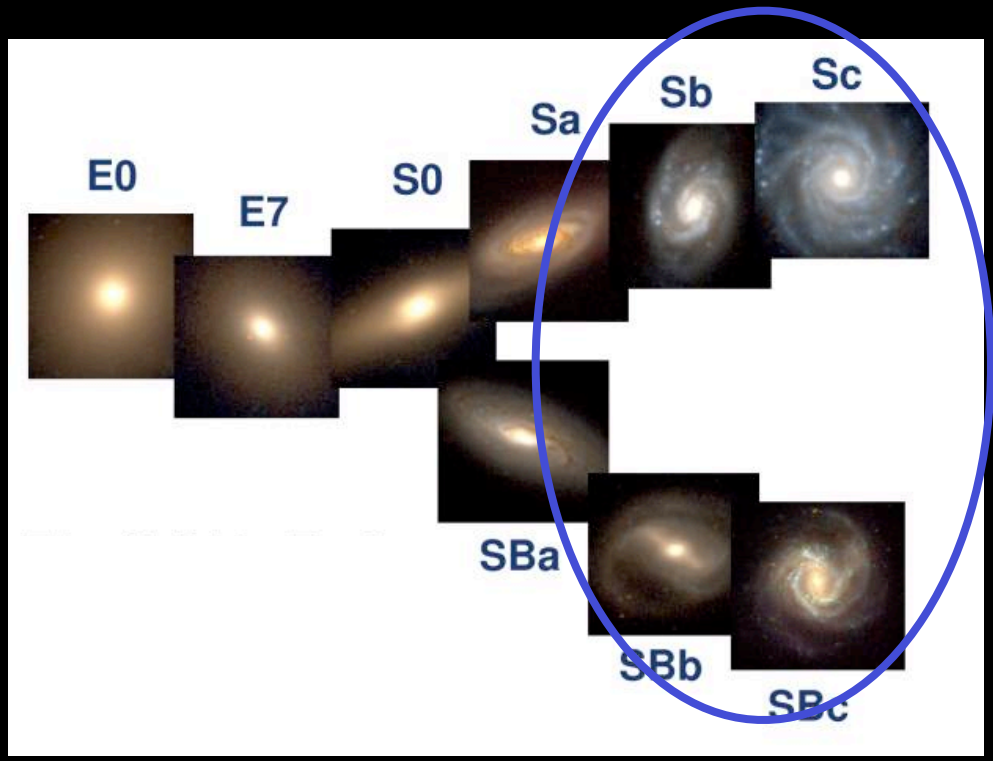
Galaxies are supposedly moved to the red sequence
by the truncation of star formation in blue galaxies



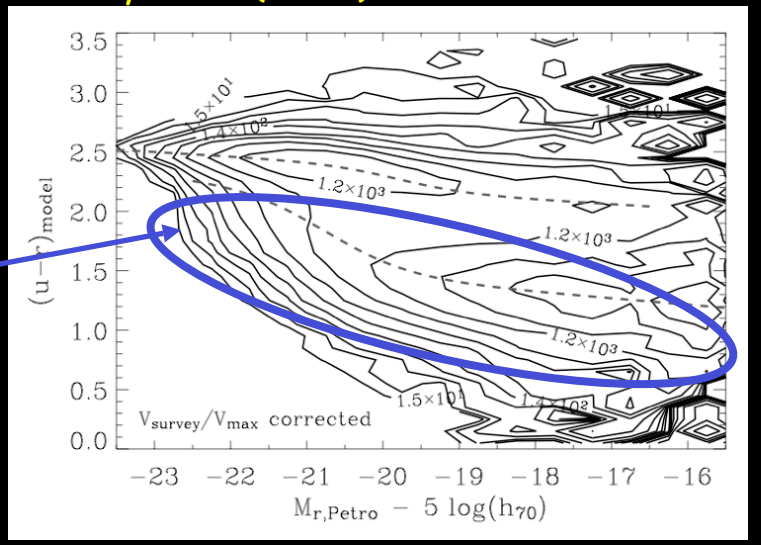
Baldry et al. (2004)



Galaxies are supposedly moved to the red sequence
by the truncation of star formation in blue galaxies



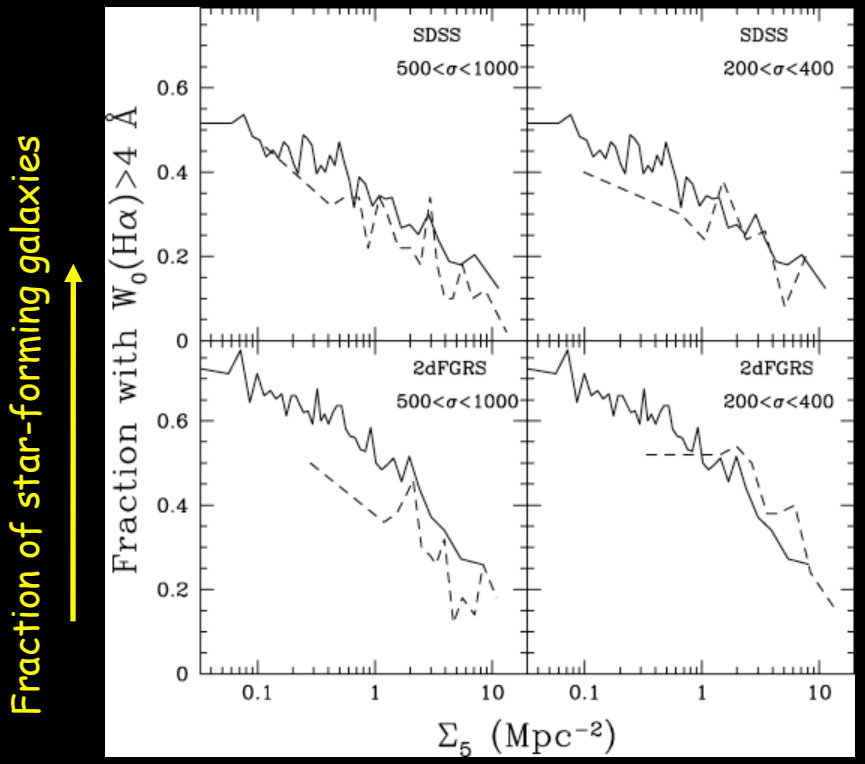
Baldry et al. (2004)



Galaxies are supposedly moved to the red sequence
by the truncation of star formation in blue galaxies

Environmental Effects on Galaxy Evolution

- relations between:
  - morphology and environment (e.g. Dressler)
  - star forming fraction and environment (Lewis et al. 2002; Gomez et al. 2003; Balogh et al. 2004)

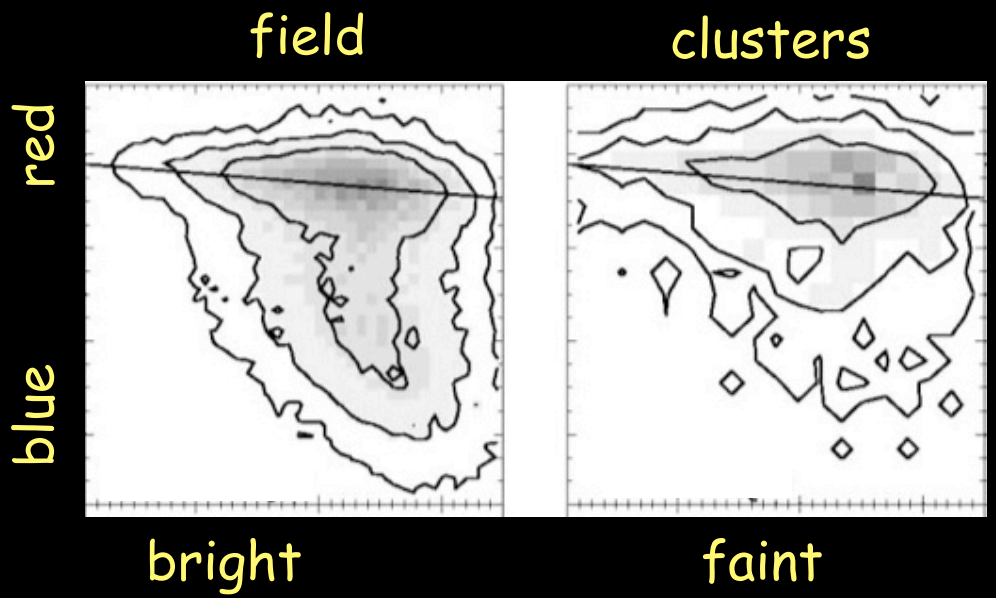


All galaxies

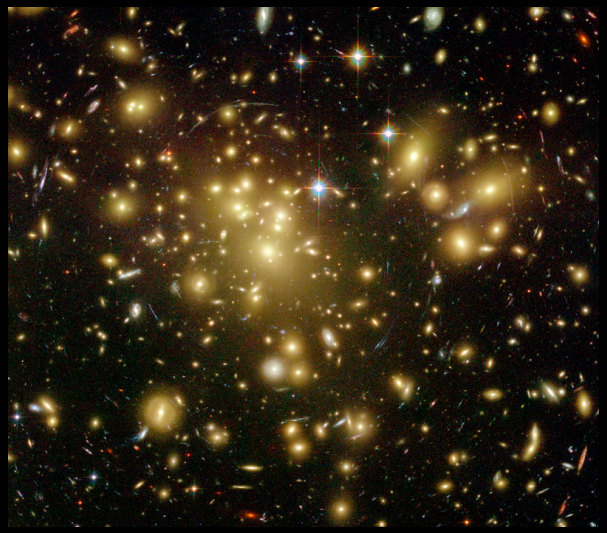
Galaxies in groups or clusters

Balogh et al. (2004)

Using red cluster galaxies to measure environmental effects



Hogg et al. (2004)



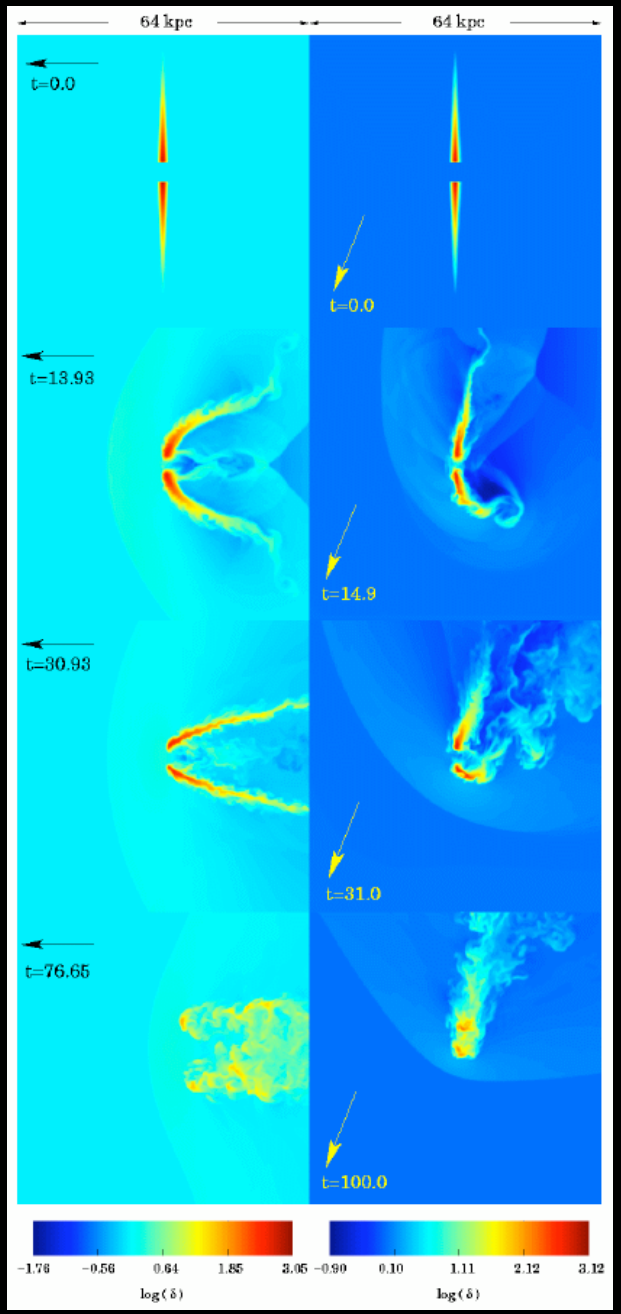
- Clusters are the most massive virialized systems in the Universe.
- probe the highest density environments

Specific Science Questions

- How did the red galaxy population in clusters get in place?
- When and how were relations between SF, morphology, and density imprinted?
- Are these relations different than in the field?
- How did these relations evolve?

How can galaxies be transformed from blue to red?

- Ram-pressure stripping
  - highest densities
  - transform blue galaxies in clusters to red
- Galaxy mergers
  - low densities
  - galaxies become red before they enter clusters
- Tidal interactions, strangulation, and galaxy harassment.
  - a large density range
  - Galaxies can be transformed in or out of clusters
- AGN
  - Unknown environmental dependence



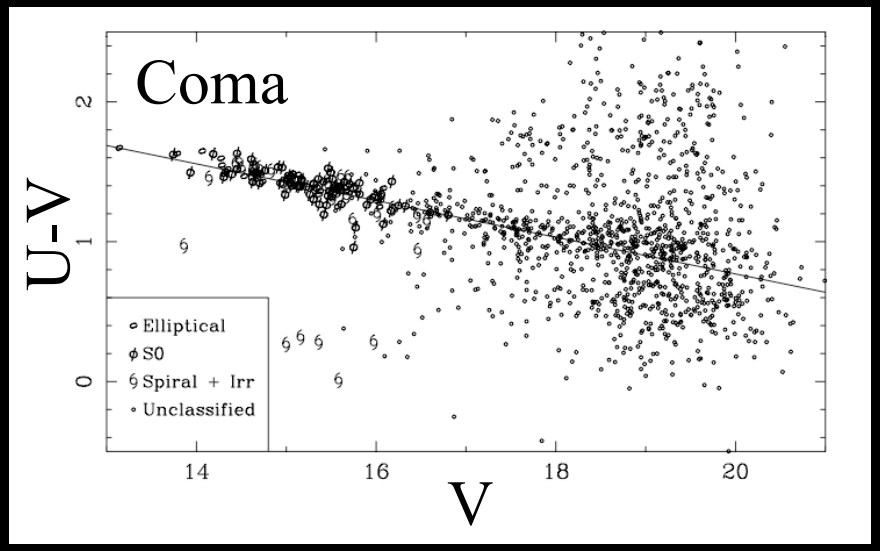
Quilis, Moore, Bower 2000

Clusters at Low Redshift

At low redshift there are many detailed studies of individual clusters, e.g. Terlevich et al. (2001), McIntosh et al. (2005), STAGES (Gray, Aragon-Salamanca, etc.)

red

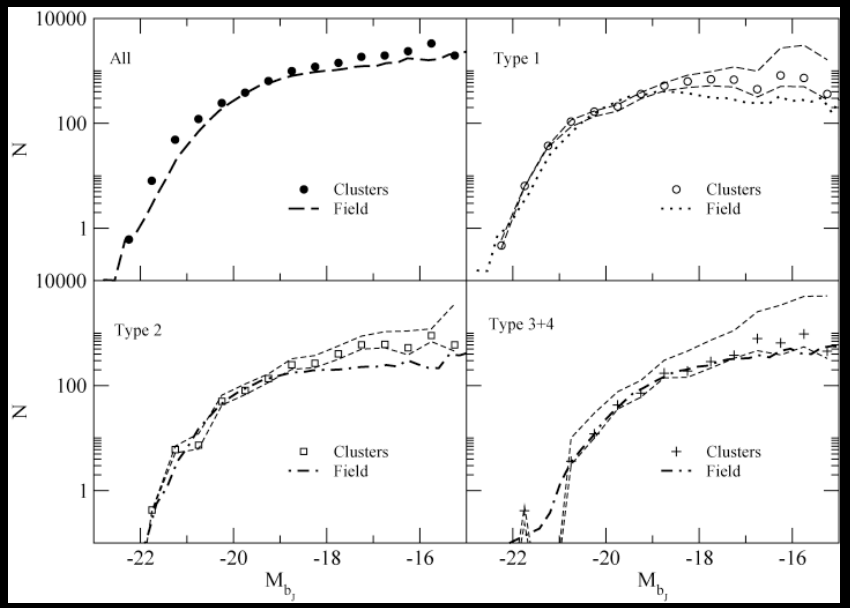
blue



bright

The Luminosity Function

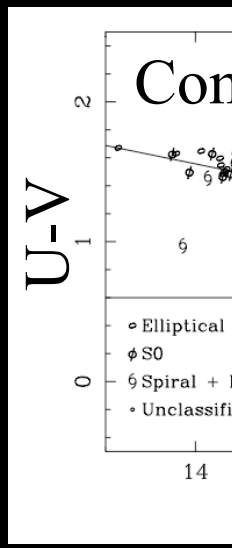
N

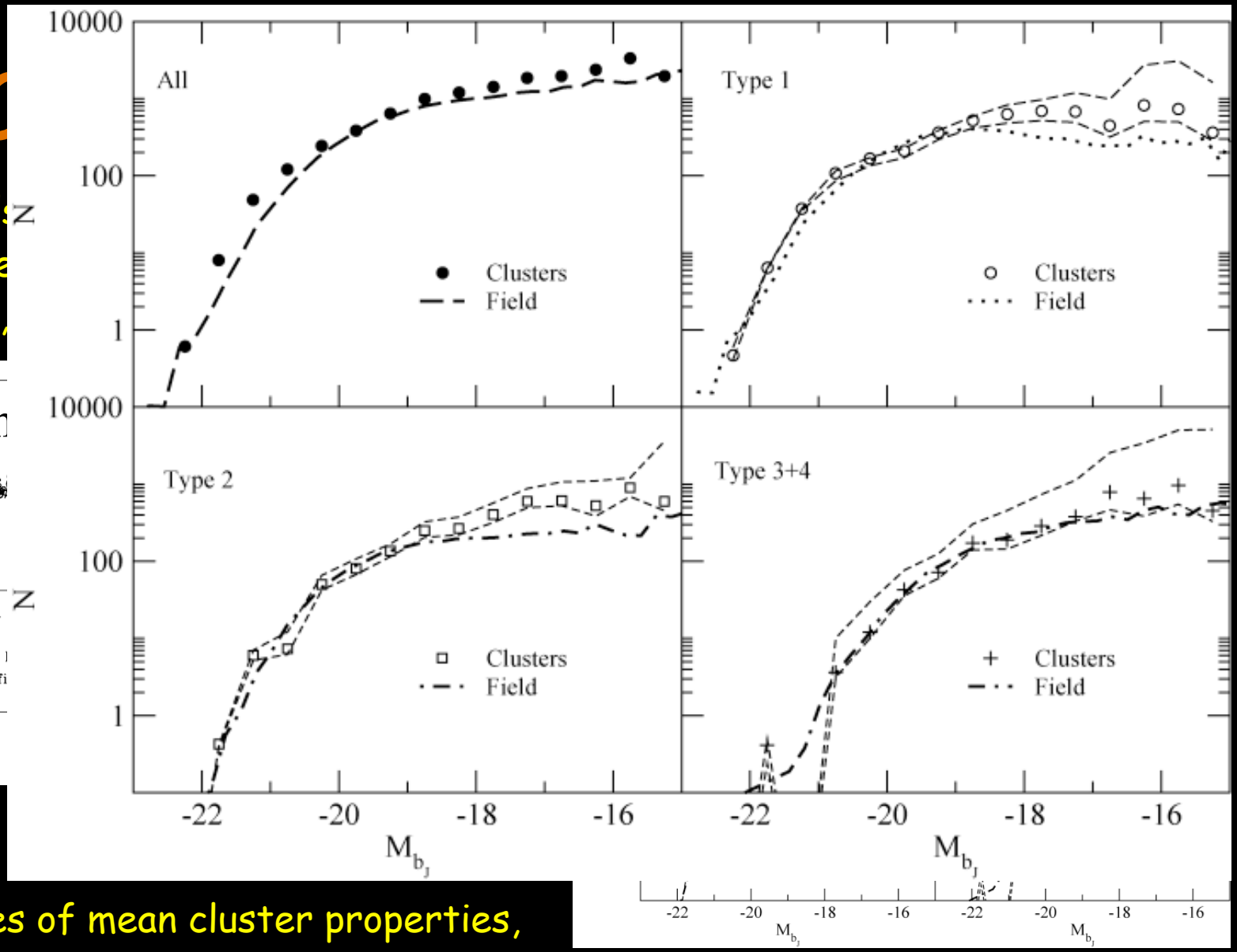


M_b

And studies of mean cluster properties, e.g. de Propris et al. (2003), Christlein & Zabludoff (2003)

At low reds
Terlevich e
Salamanca,





And studies of mean cluster properties, e.g. de Propris et al. (2003), Christlein & Zabludoff (2003)

M_b

Why are higher redshift studies necessary?

- By z=0 most galaxies in clusters are already red and dead
- Galaxy transformation happened at higher redshift
- Need to catch galaxy transformation in the act.

Outline

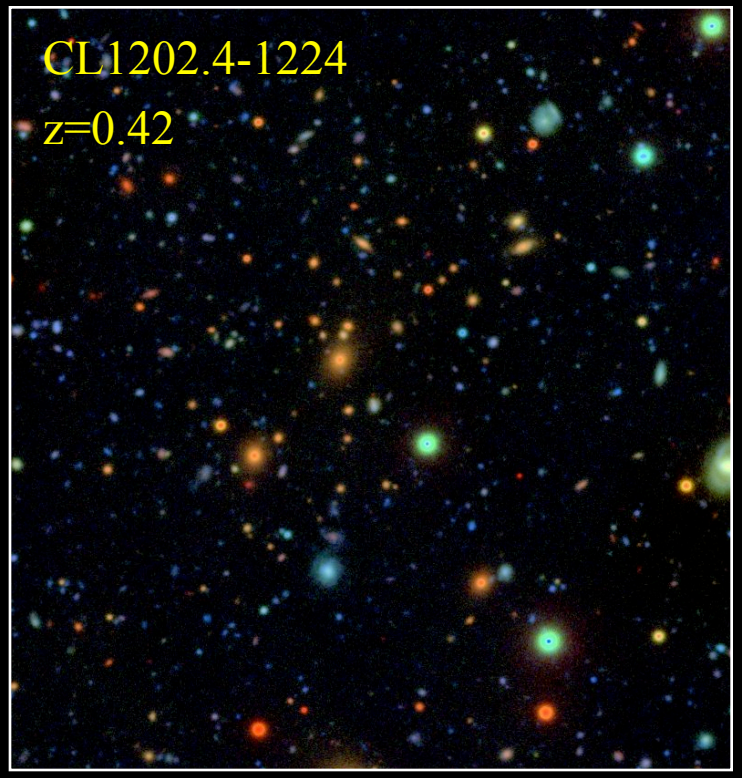
- Introduce EDisCS survey
- Measurements and evolution of red sequence LF
- Growth of the red sequence in clusters

The ESO Distant Cluster Survey: EDisCS

- ESO Large Program with 56 nights of Telescope time on the NTT and VLT
- 20 clusters at z=0.45-0.8
- Extensive multi-wavelength follow-up

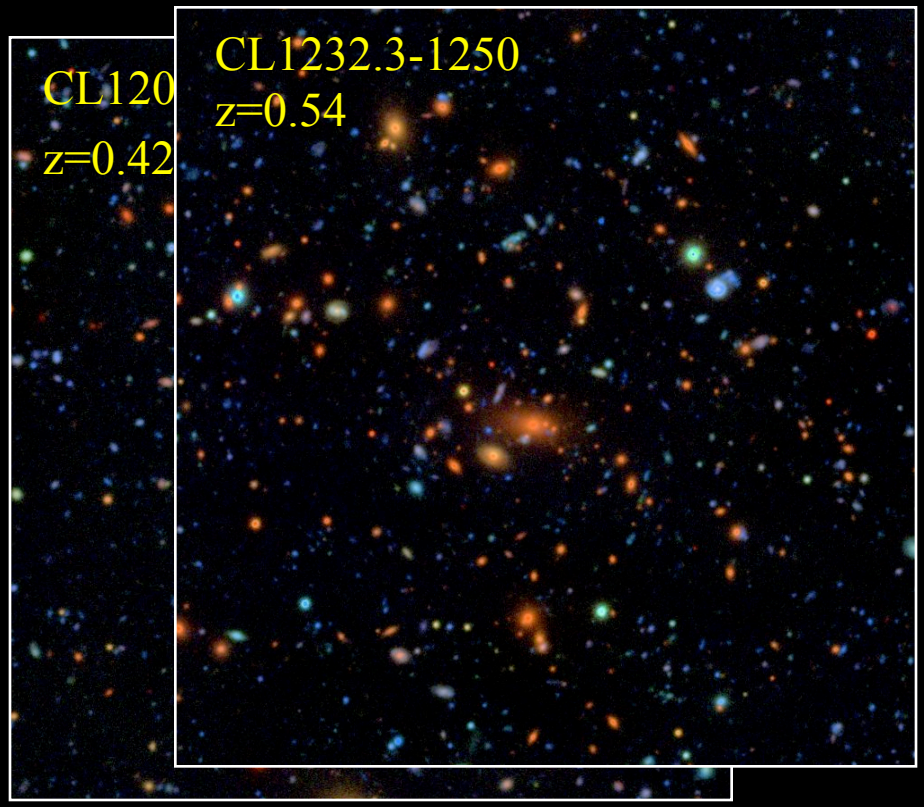
The ESO Distant Cluster Survey: EDisCS

- ESO Large Program with 56 nights of Telescope time on the NTT and VLT
- 20 clusters at z=0.45-0.8
- Extensive multi-wavelength follow-up



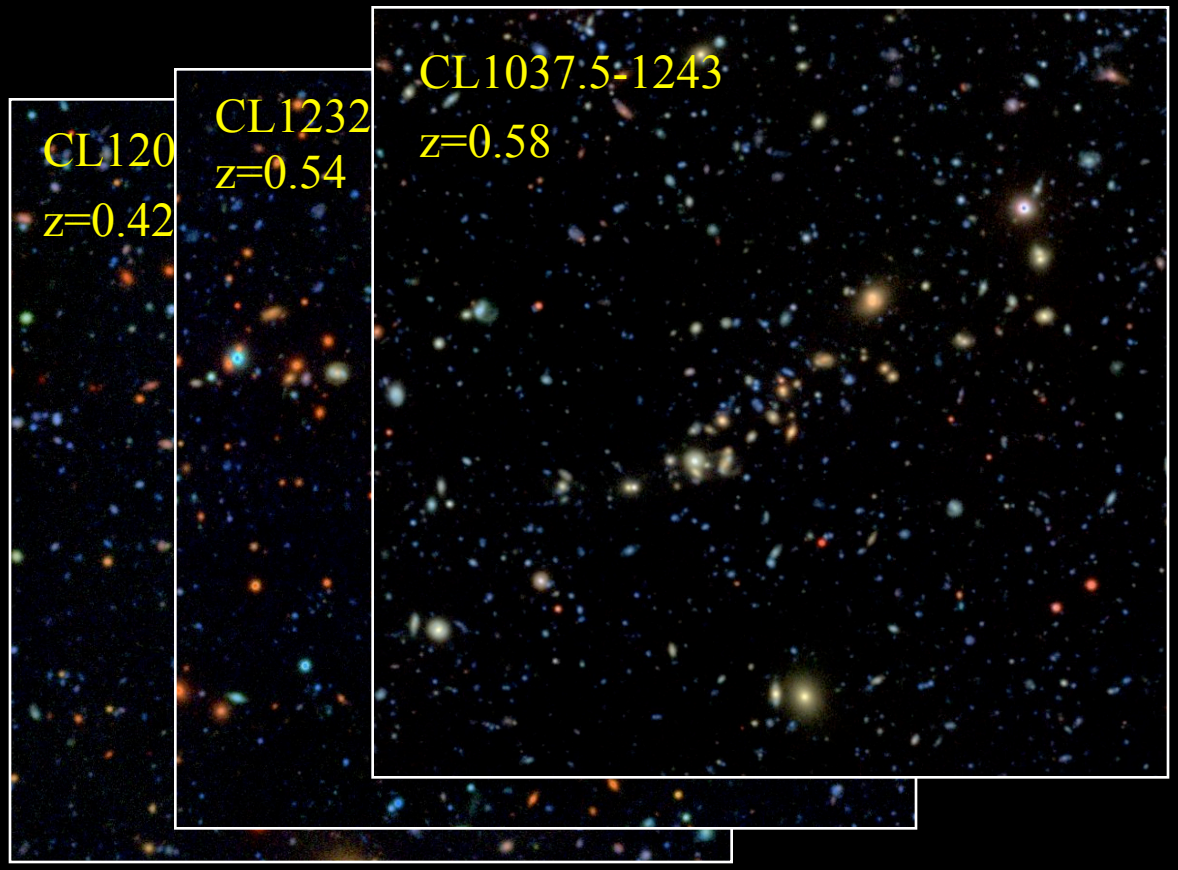
The ESO Distant Cluster Survey: EDisCS

- ESO Large Program with 56 nights of Telescope time on the NTT and VLT
- 20 clusters at z=0.45-0.8
- Extensive multi-wavelength follow-up



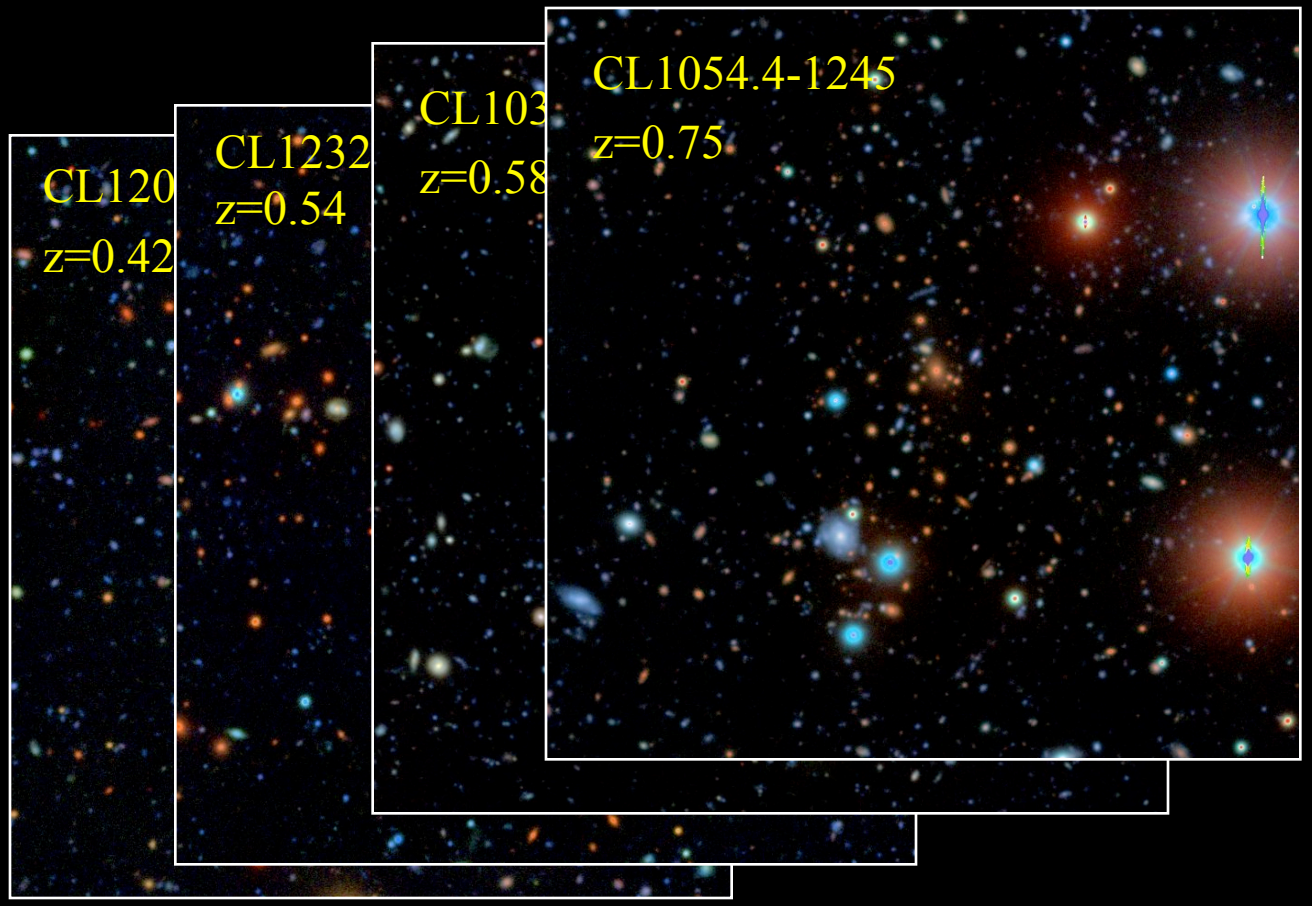
The ESO Distant Cluster Survey: EDisCS

- ESO Large Program with 56 nights of Telescope time on the NTT and VLT
- 20 clusters at z=0.45-0.8
- Extensive multi-wavelength follow-up



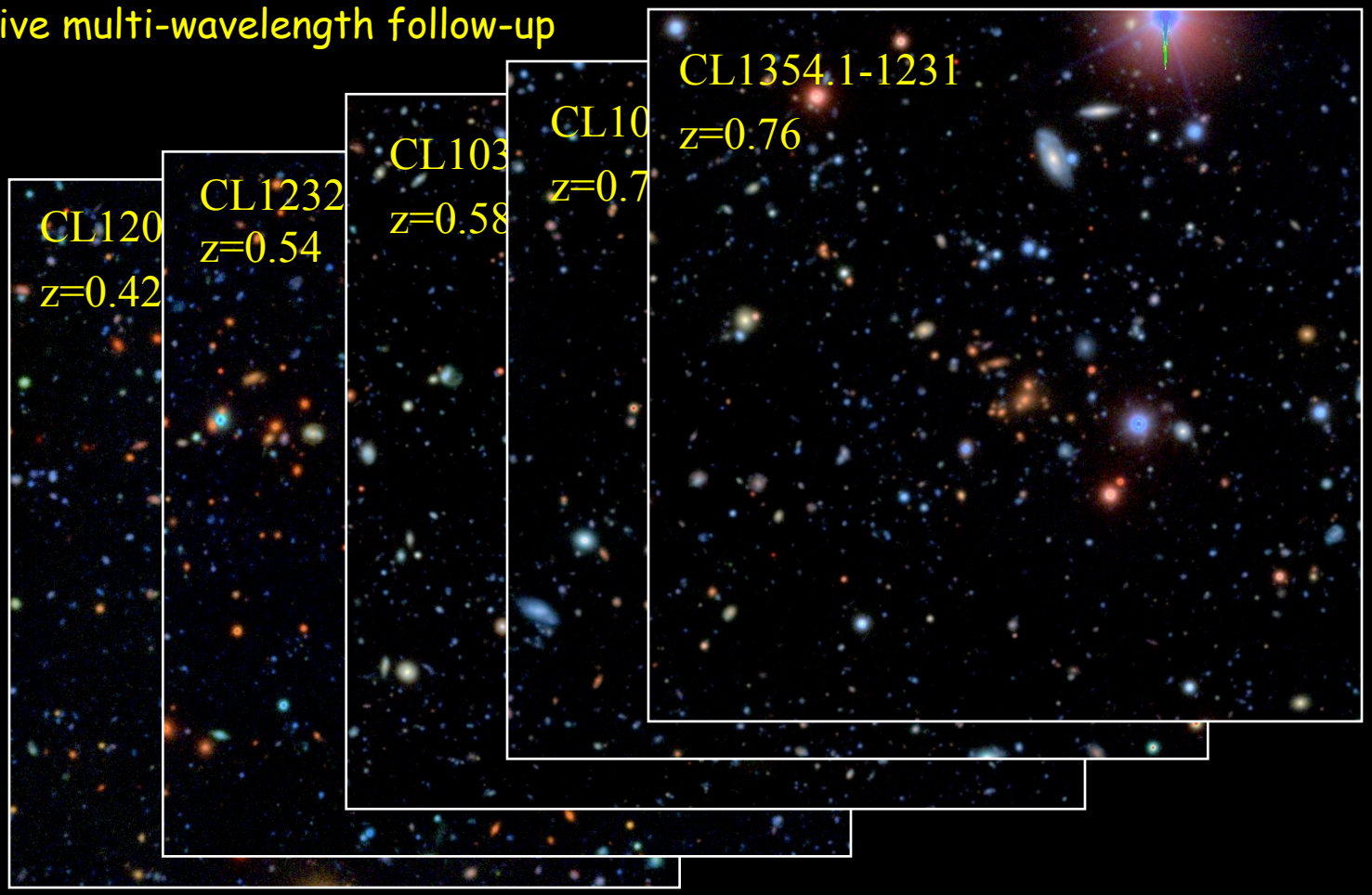
The ESO Distant Cluster Survey: EDisCS

- ESO Large Program with 56 nights of Telescope time on the NTT and VLT
- 20 clusters at z=0.45-0.8
- Extensive multi-wavelength follow-up

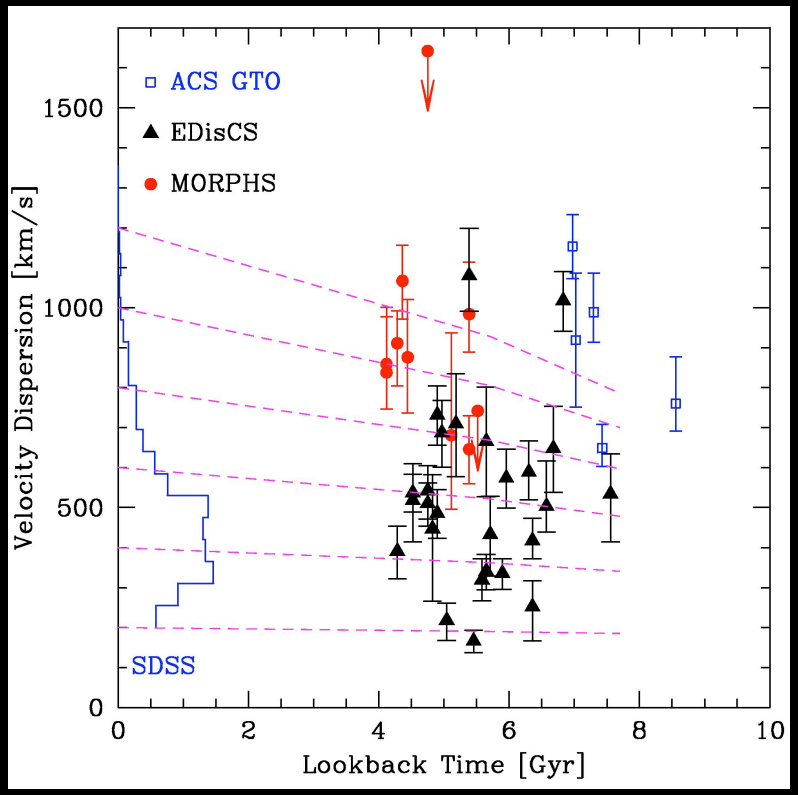


The ESO Distant Cluster Survey: EDisCS

- ESO Large Program with 56 nights of Telescope time on the NTT and VLT
- 20 clusters at z=0.45-0.8
- Extensive multi-wavelength follow-up



A sample of "normal" clusters at intermediate redshift



Milvang-Jensen et al. + GR (2008)

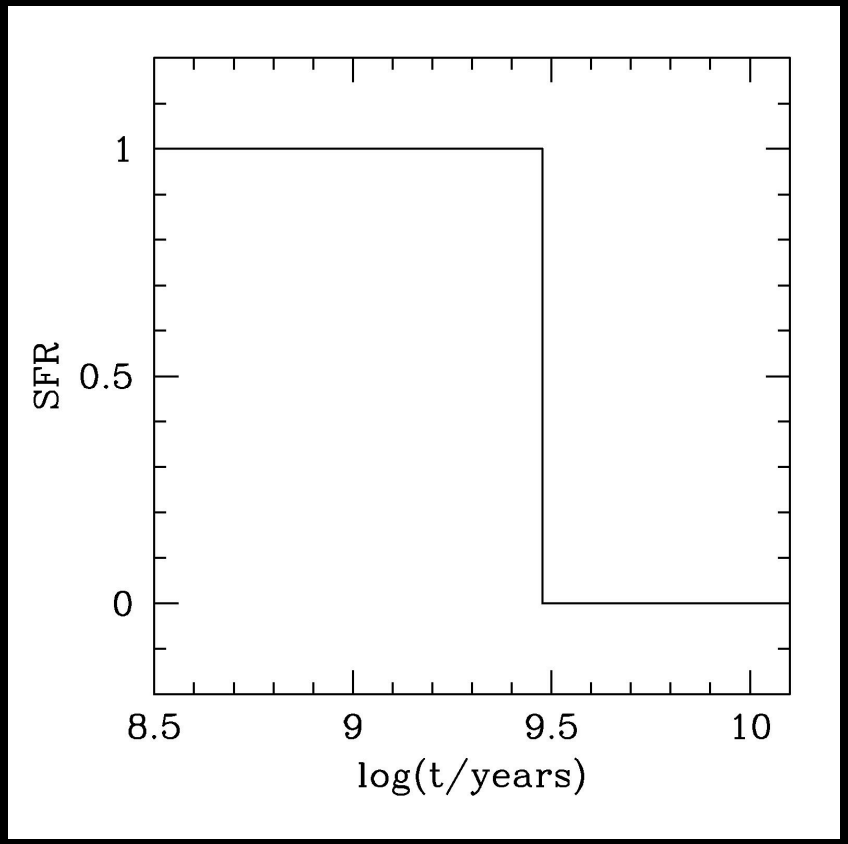
How does the red galaxy population in clusters assemble?

Strategy

Directly observe red sequence in clusters as a function of redshift

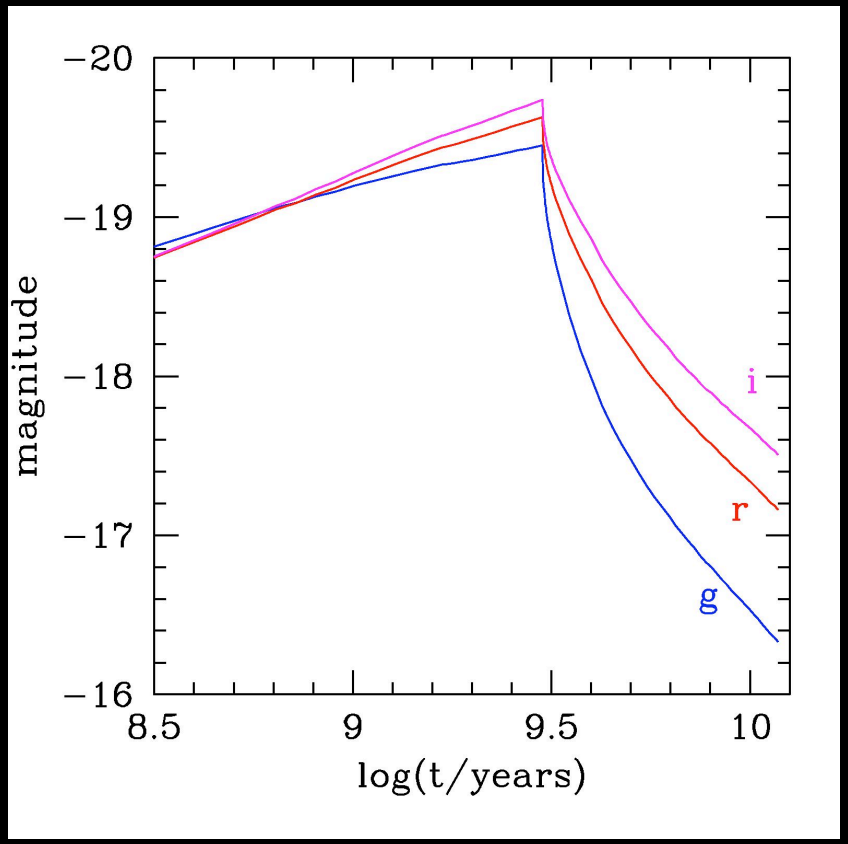
Stellar Populations Primer

z=2 z=0



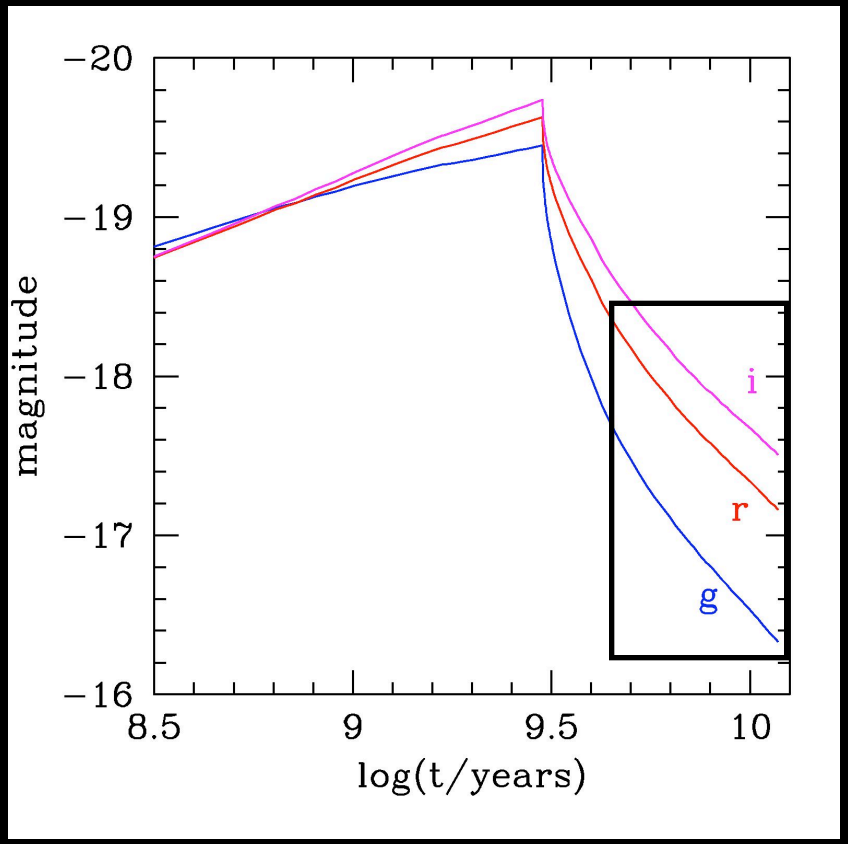
Stellar Populations Primer

z=2 z=0



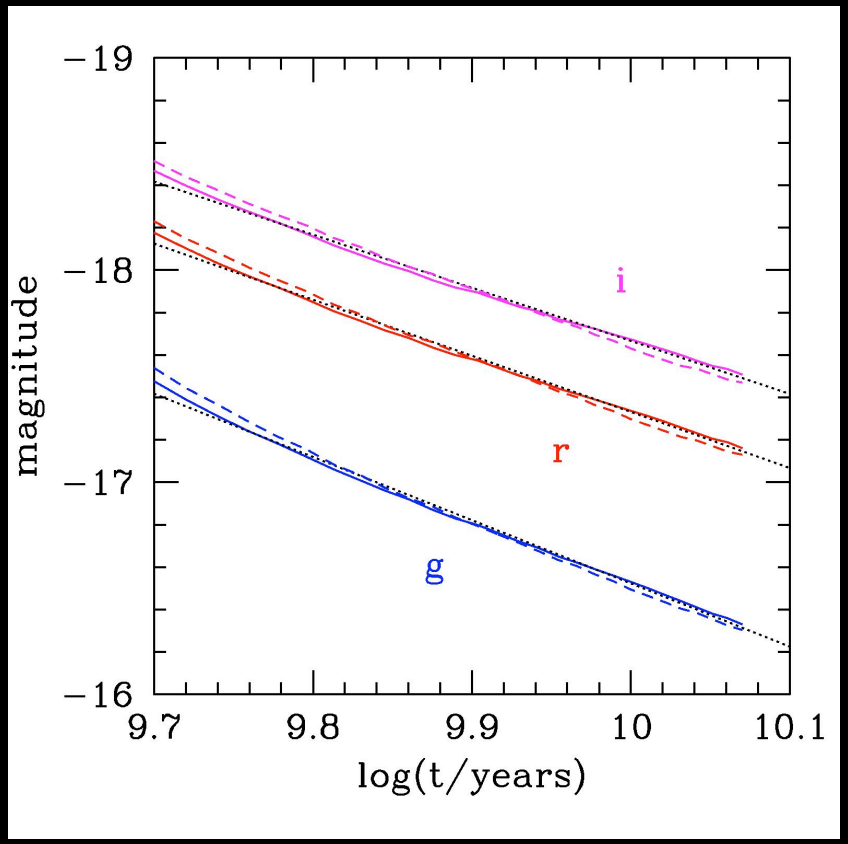
Stellar Populations Primer

z=2 z=0

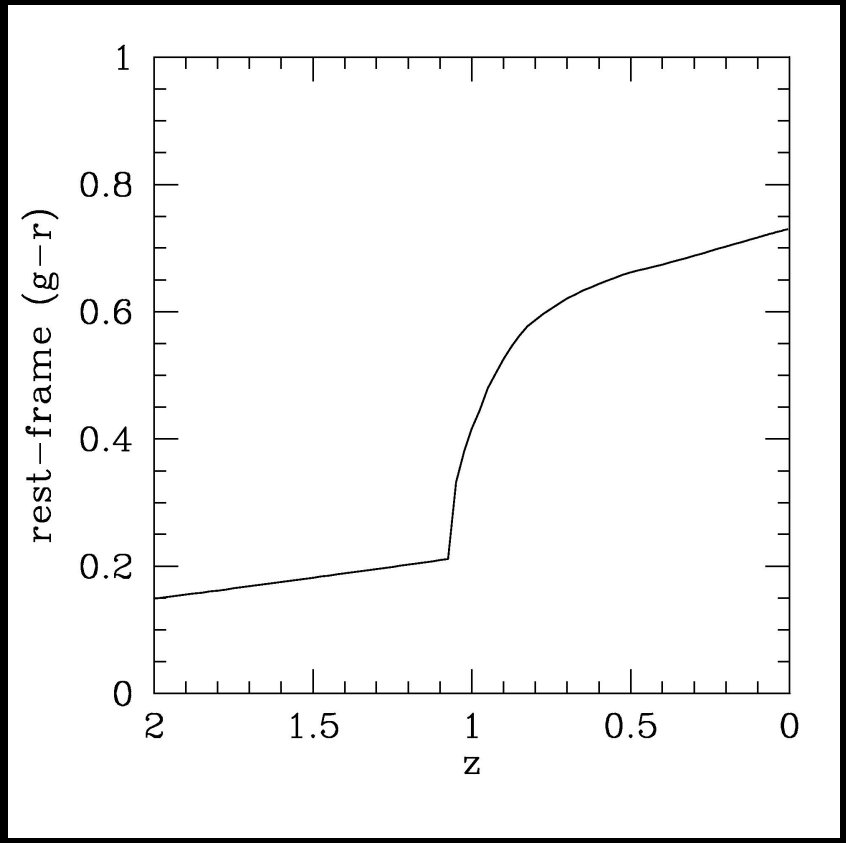


Stellar Populations Primer

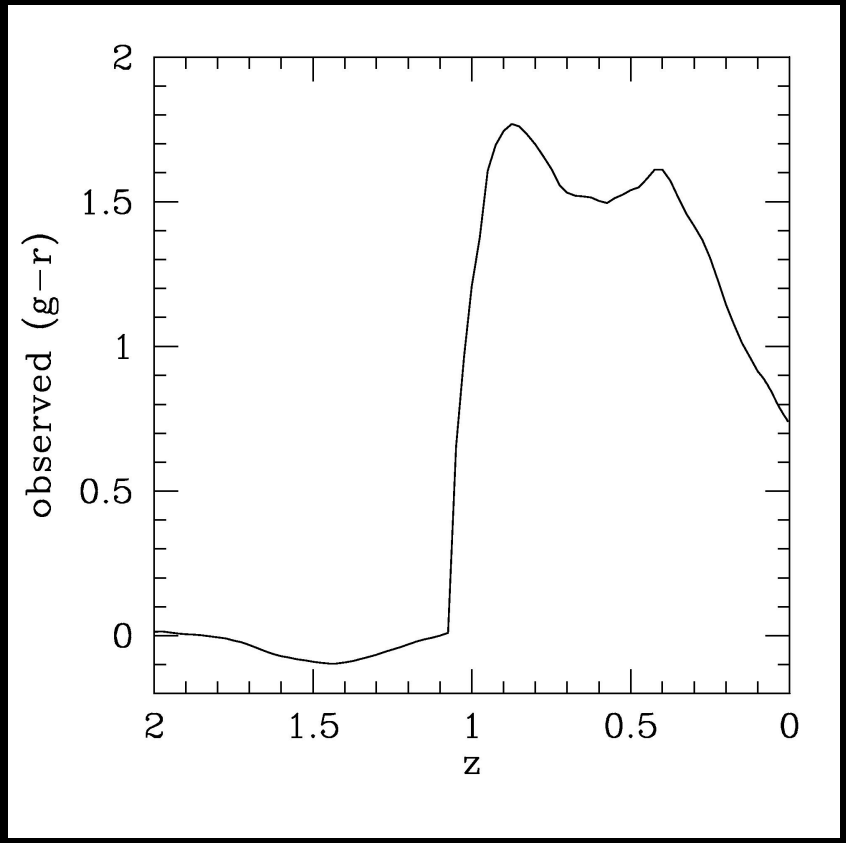
z=2 z=0



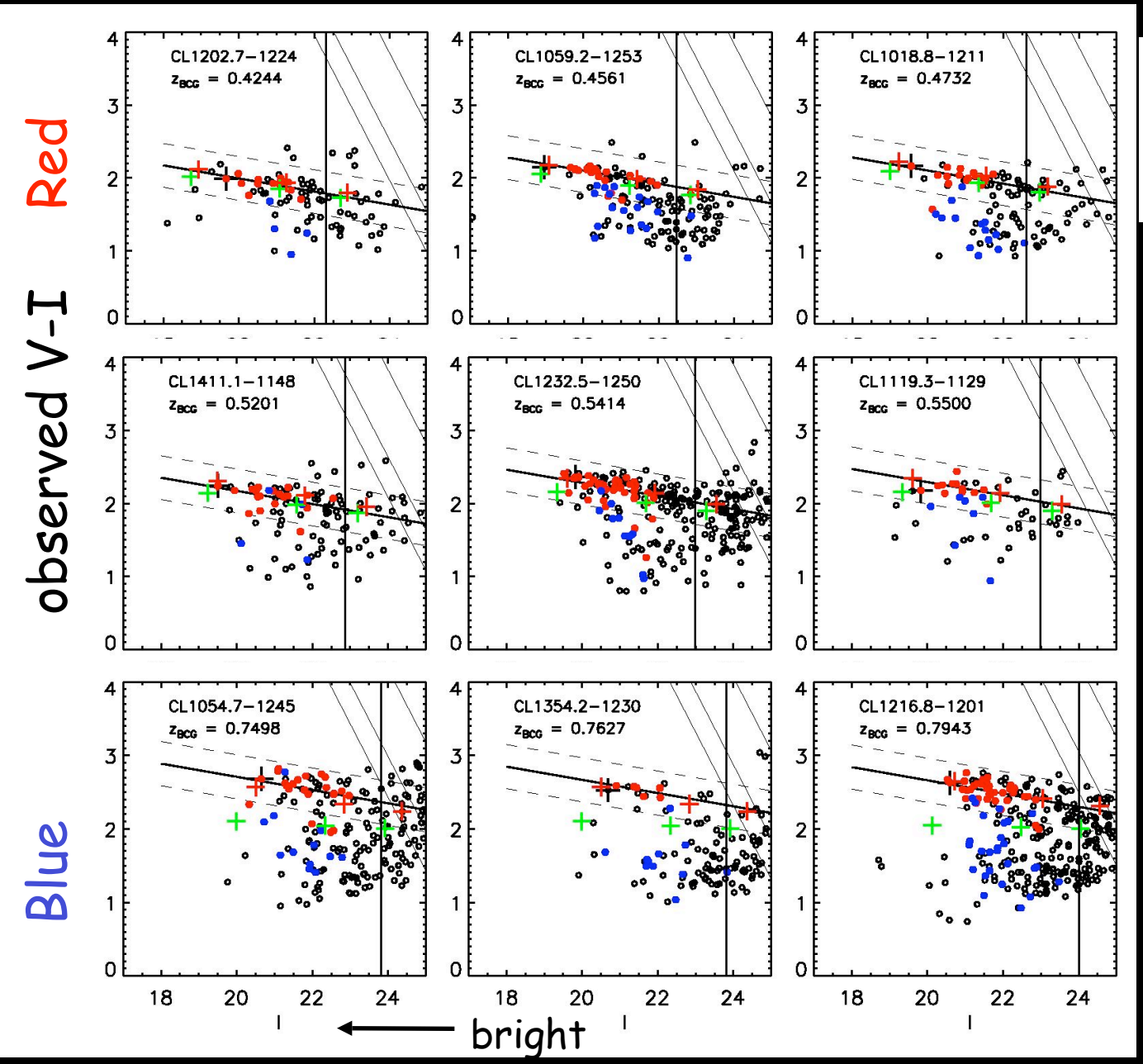
Stellar Populations Primer



Stellar Populations Primer



$z=0.42$ $t_{universe}=9$ Gyr



- Photometric redshifts
- Spec-z no emission
- Spec-z emission

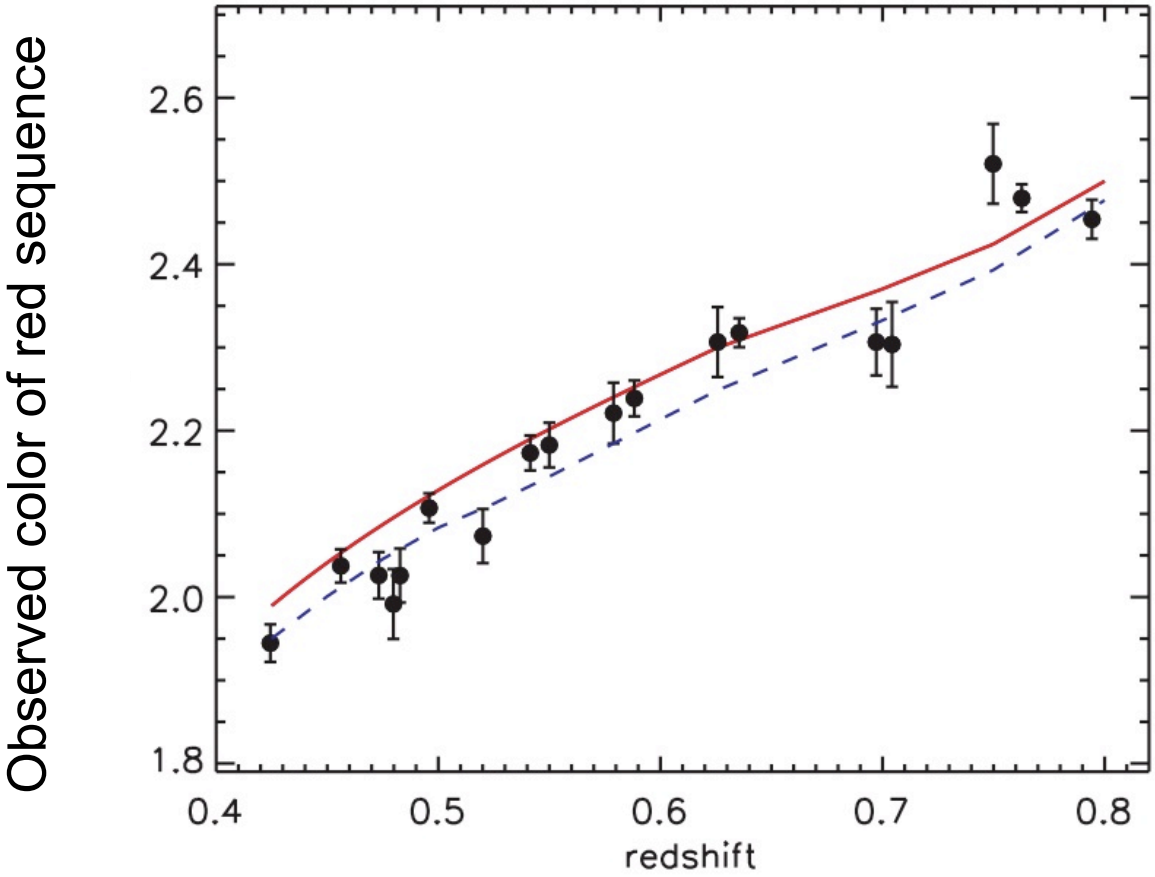
$(V-I)_{obs}$ straddles 4000 Ang break for all clusters

time

$t_{universe}=6.6$ Gyr

$z=0.8$

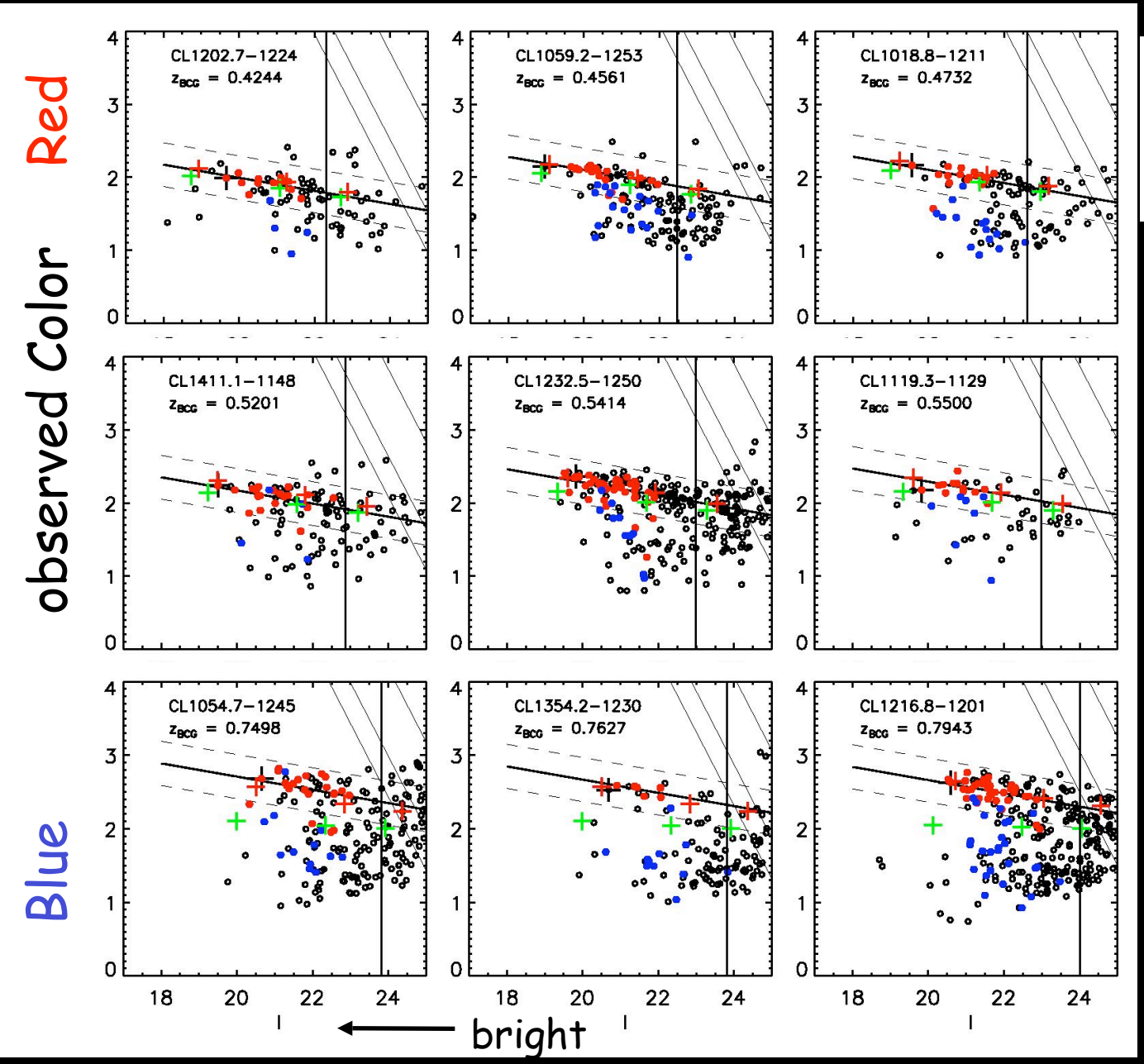
De Lucia et al. + GR (2007)



Bright cluster red sequence color evolves like a passively evolving population.

De Lucia et al. + GR (2007)

$z=0.42$ $t_{universe}=9$ Gyr



- Photometric redshifts
- Spec-z no emission
- Spec-z emission

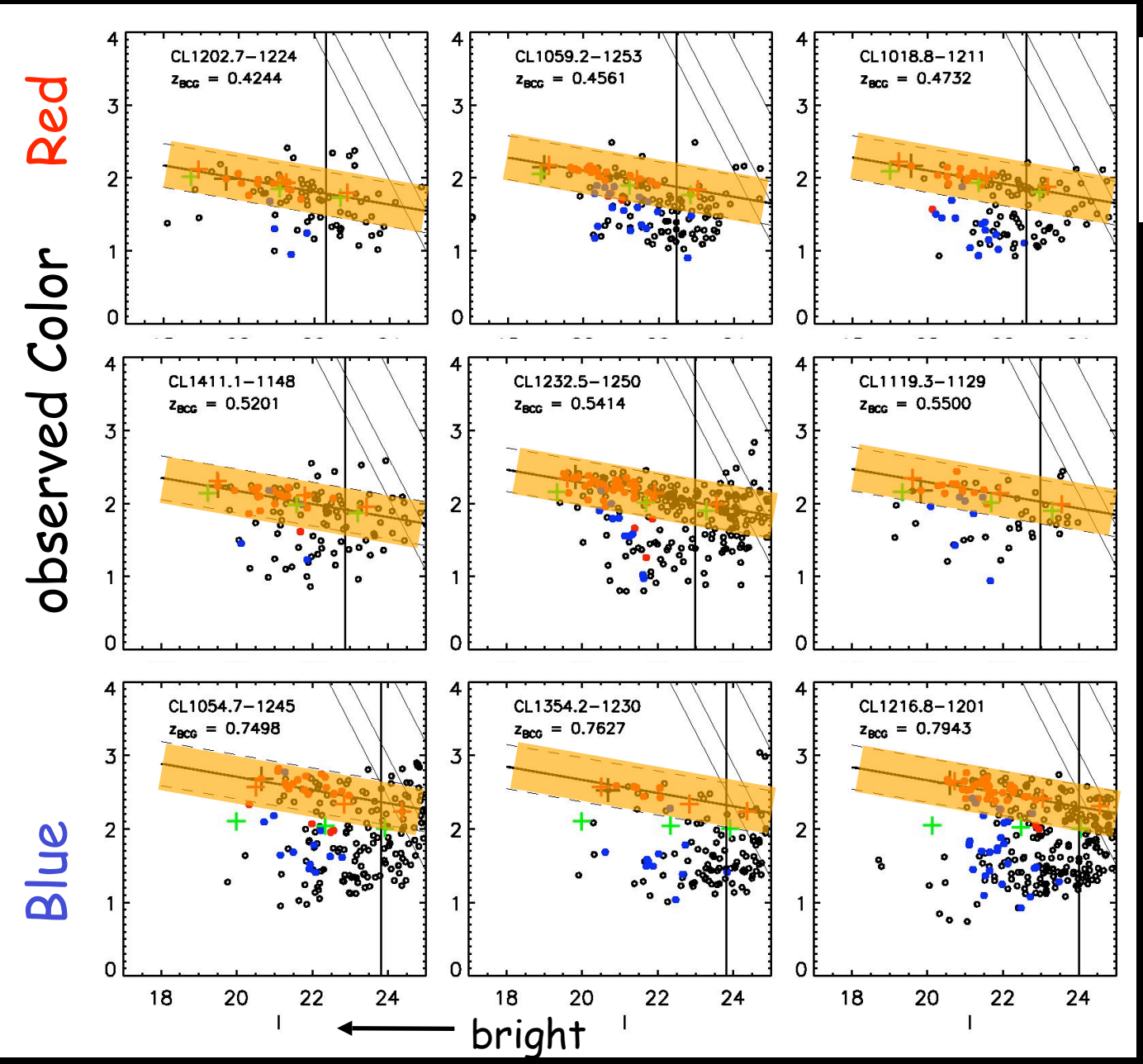
time

$t_{universe}=6.6$ Gyr

$z=0.8$

De Lucia et al. + GR (2007)

z=0.42 $t_{universe}$ =9 Gyr



- Photometric redshifts
- Spec-z no emission
- Spec-z emission

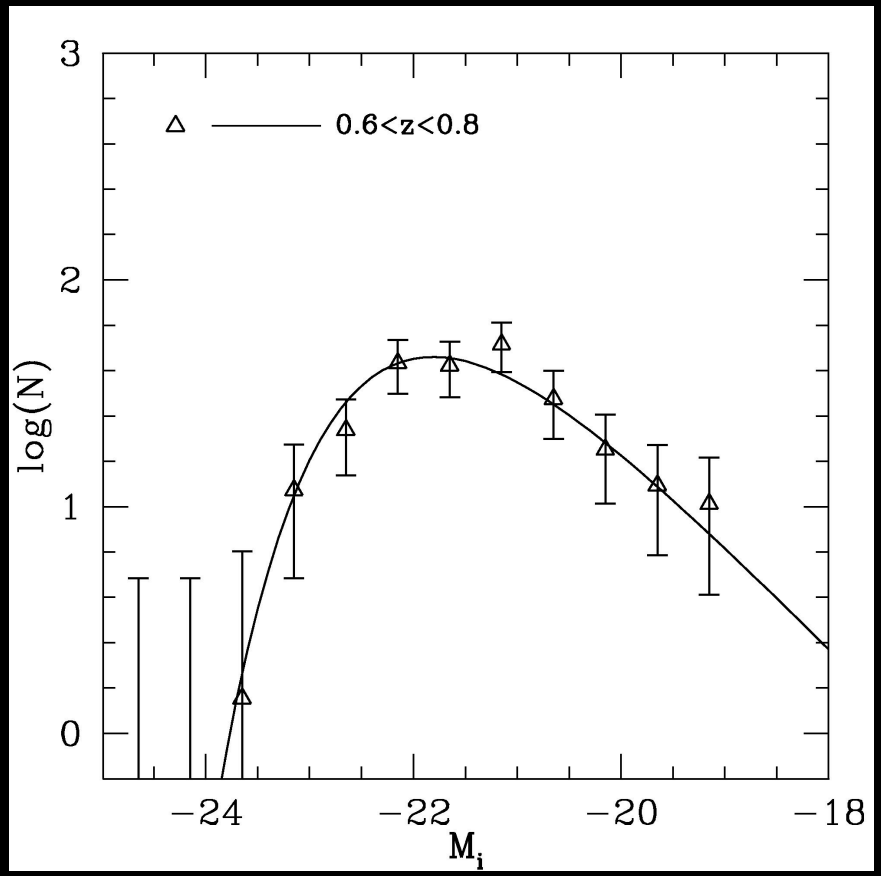
time

$t_{universe}$ =6.6 Gyr

z=0.8

De Lucia et al. + GR (2007)

redshift evolution of composite red sequence LF



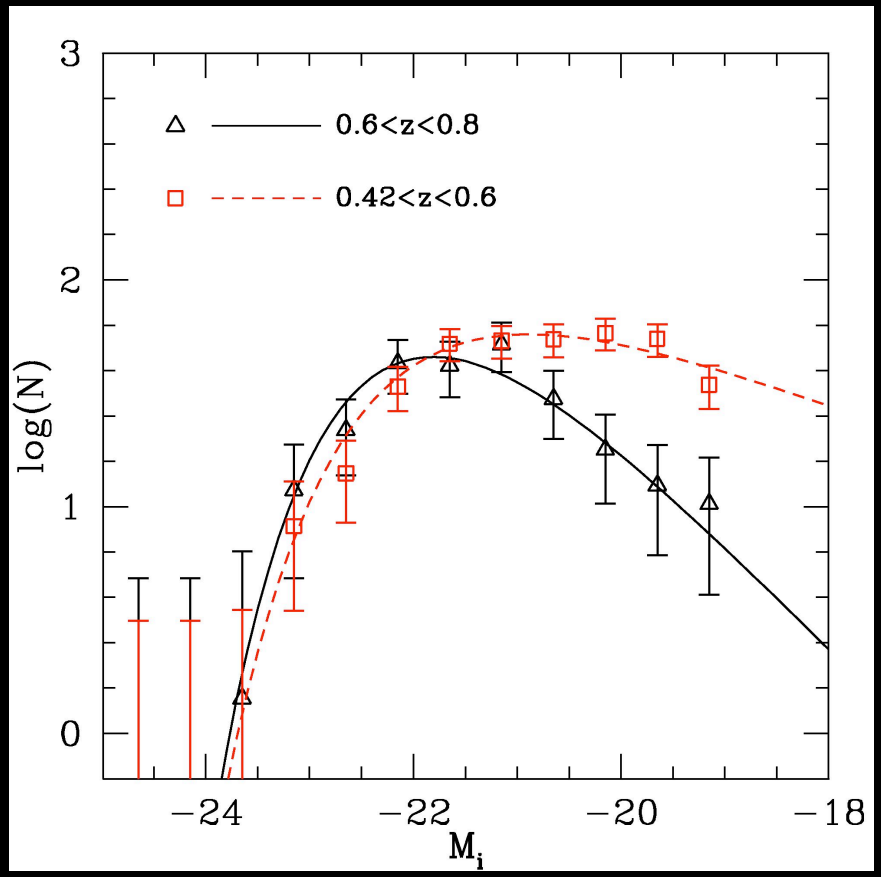
bright

faint

Luminosity and mass are well correlated for red galaxies.

Rudnick et al. (2009)

redshift evolution of composite red sequence LF



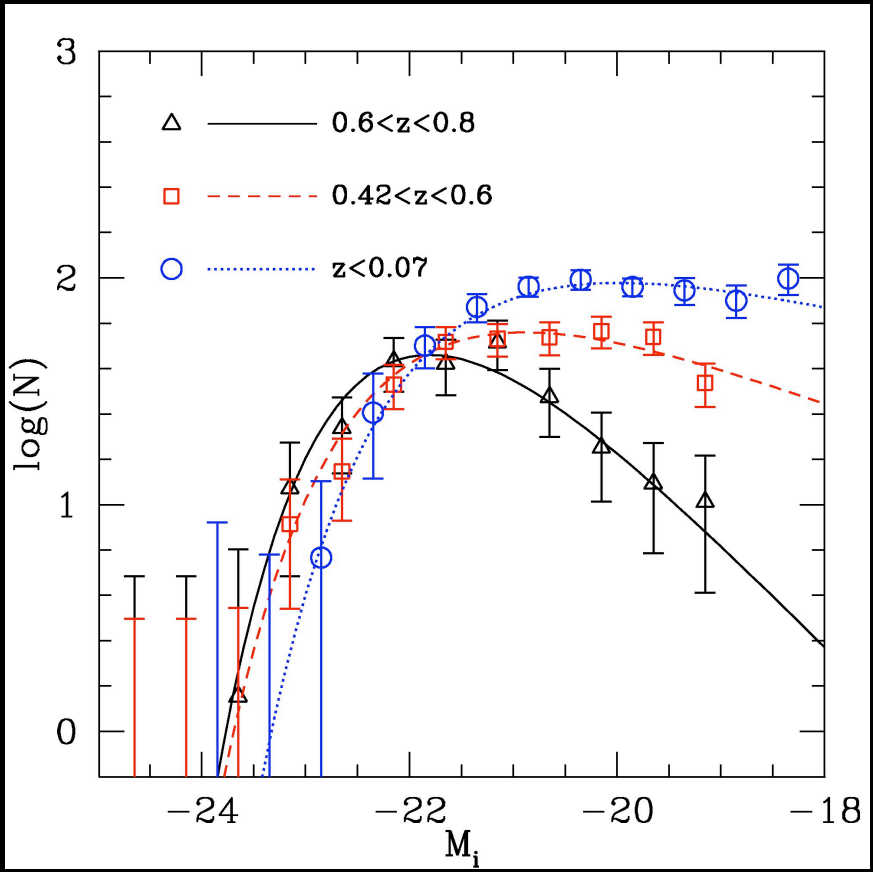
bright

faint

Luminosity and mass are well correlated for red galaxies.

Rudnick et al. (2009)

redshift evolution of composite red sequence LF



bright

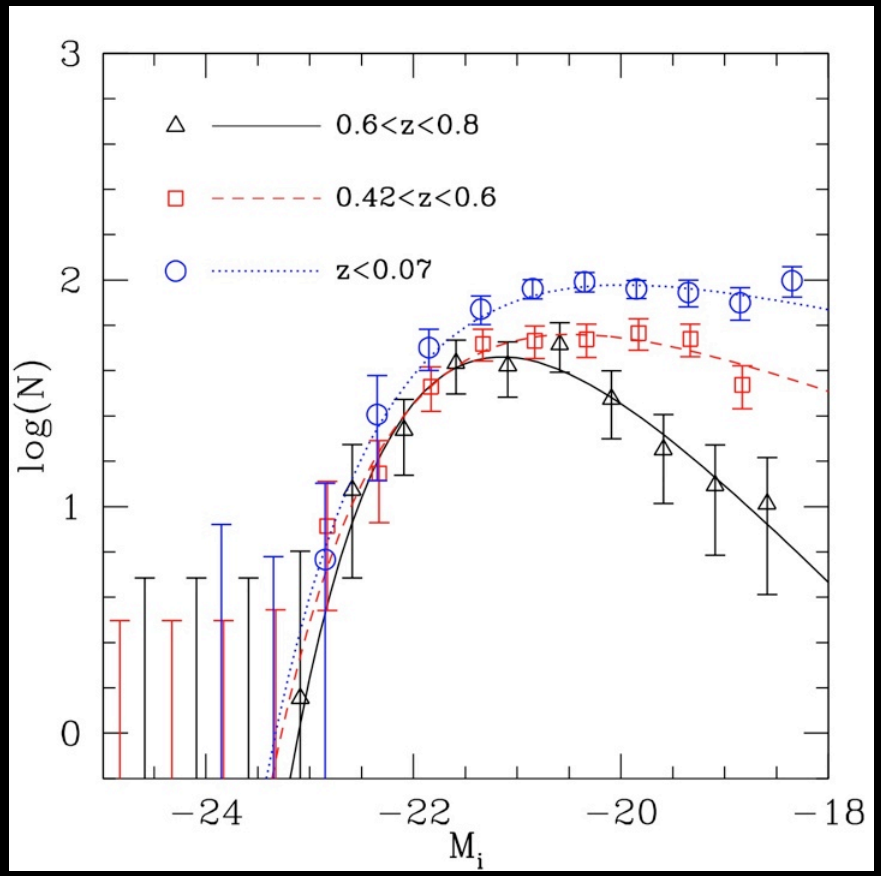
faint

Luminosity and mass are well correlated for red galaxies.

Rudnick et al. (2009)

redshift evolution of composite red sequence LF

Passive Evolution Corrected



bright

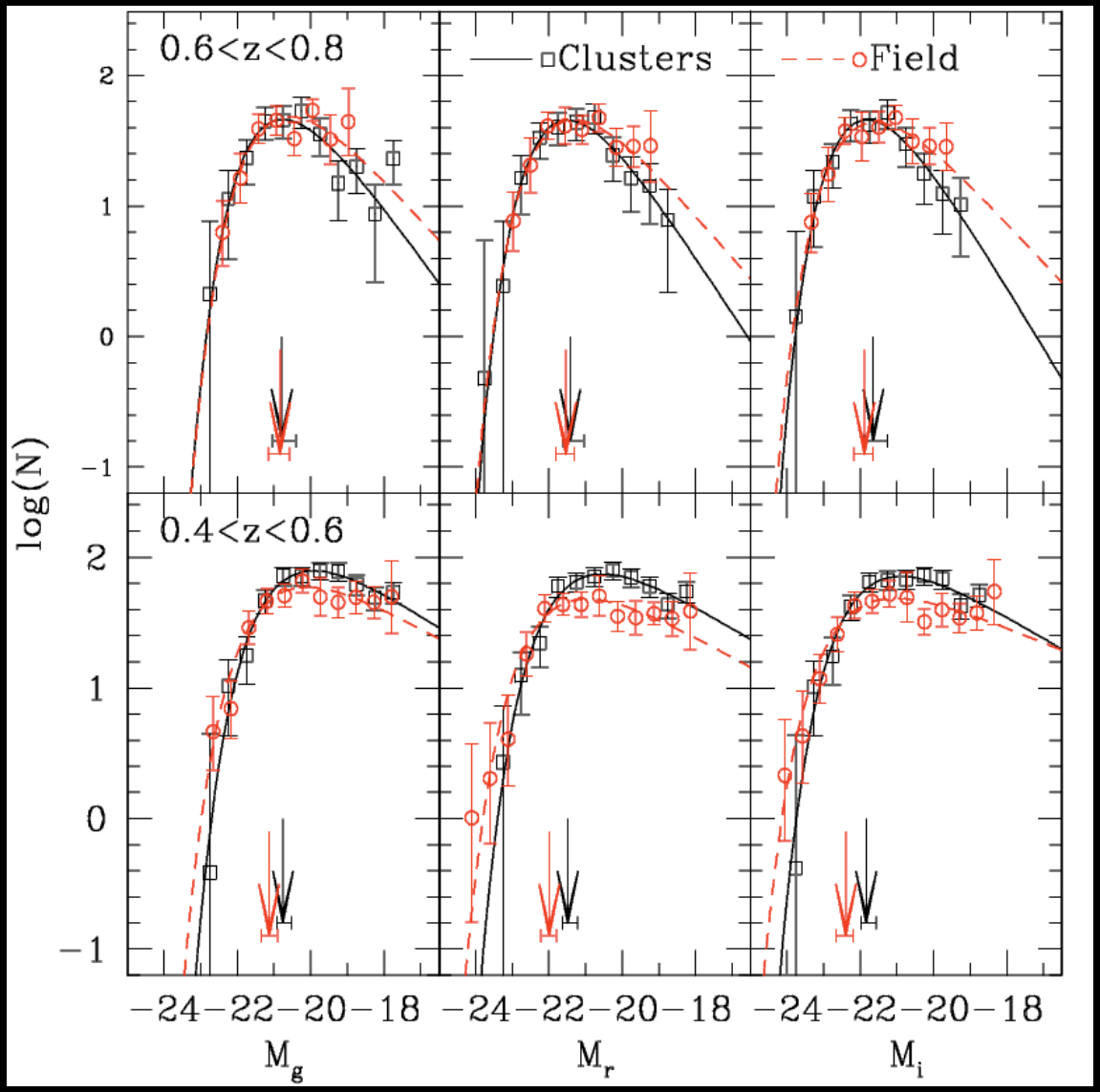
faint

Luminosity and mass are well correlated for red galaxies.

Mass dependent evolution

Rudnick et al. (2009)

Comparison to the field

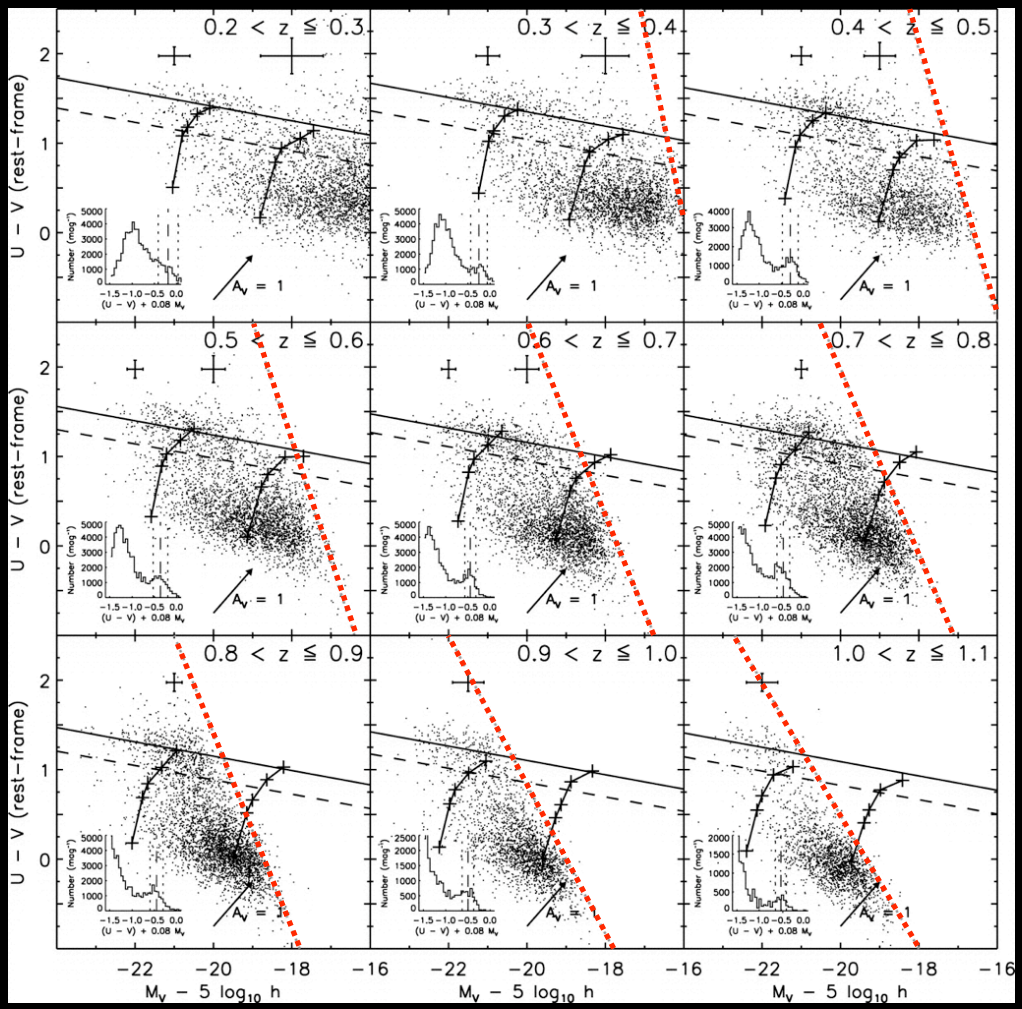


Preliminary evidence for difference between clusters and the field?

Rudnick et al. (2009)

Building up the red sequence

Building up the red sequence in the field

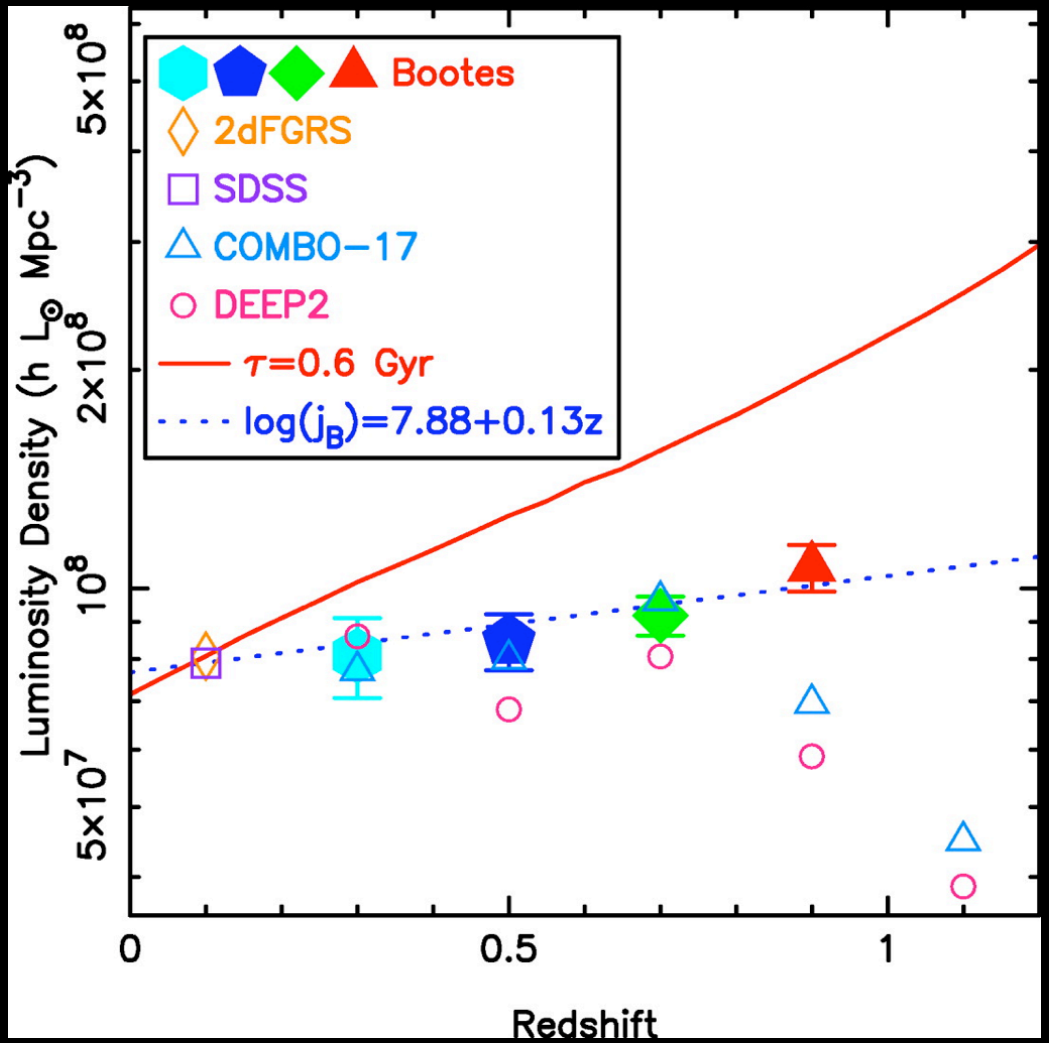


Bell et al. (2004)

red galaxies get redder with time or decreasing redshift

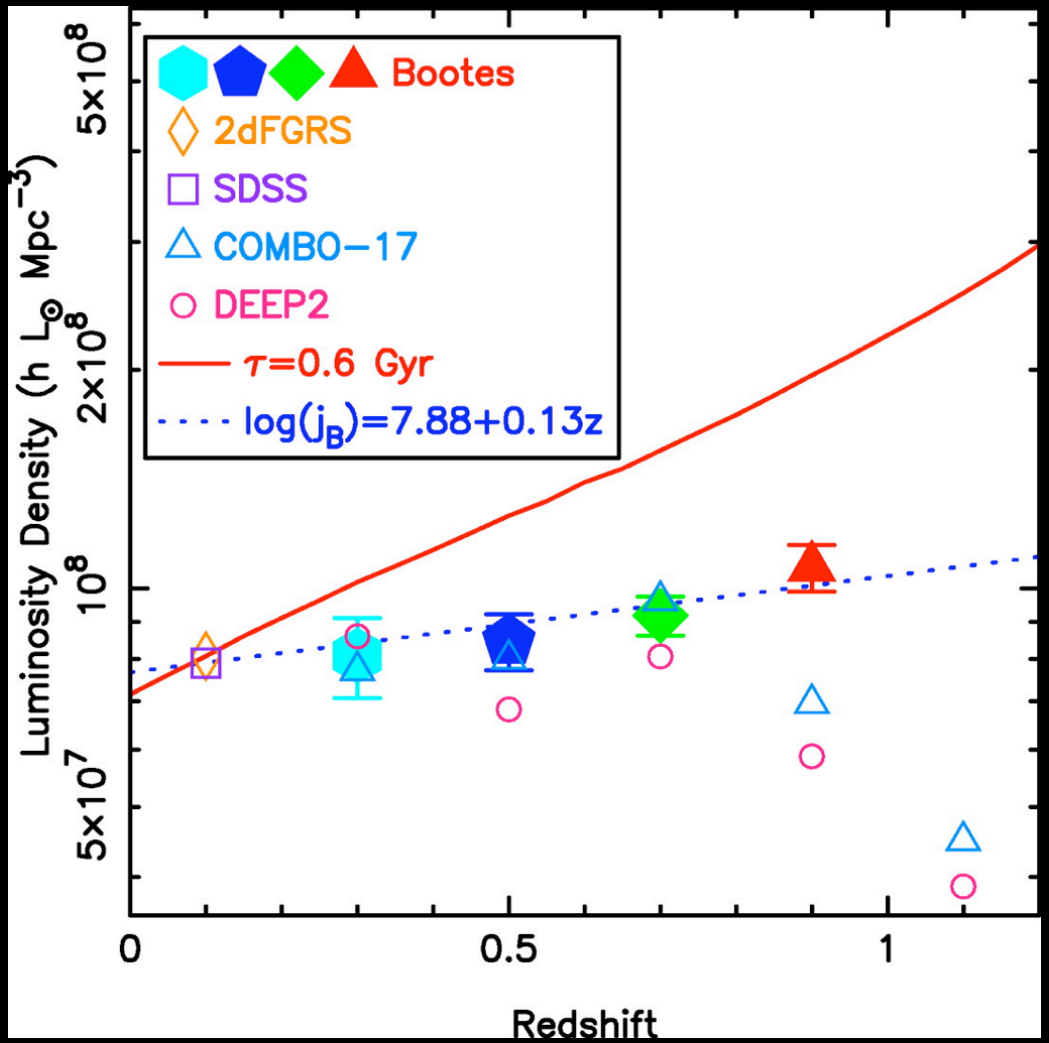
implies that their stellar populations are aging.

Building up the red sequence in the field



Reddening color predicts substantial fading toward lower redshift

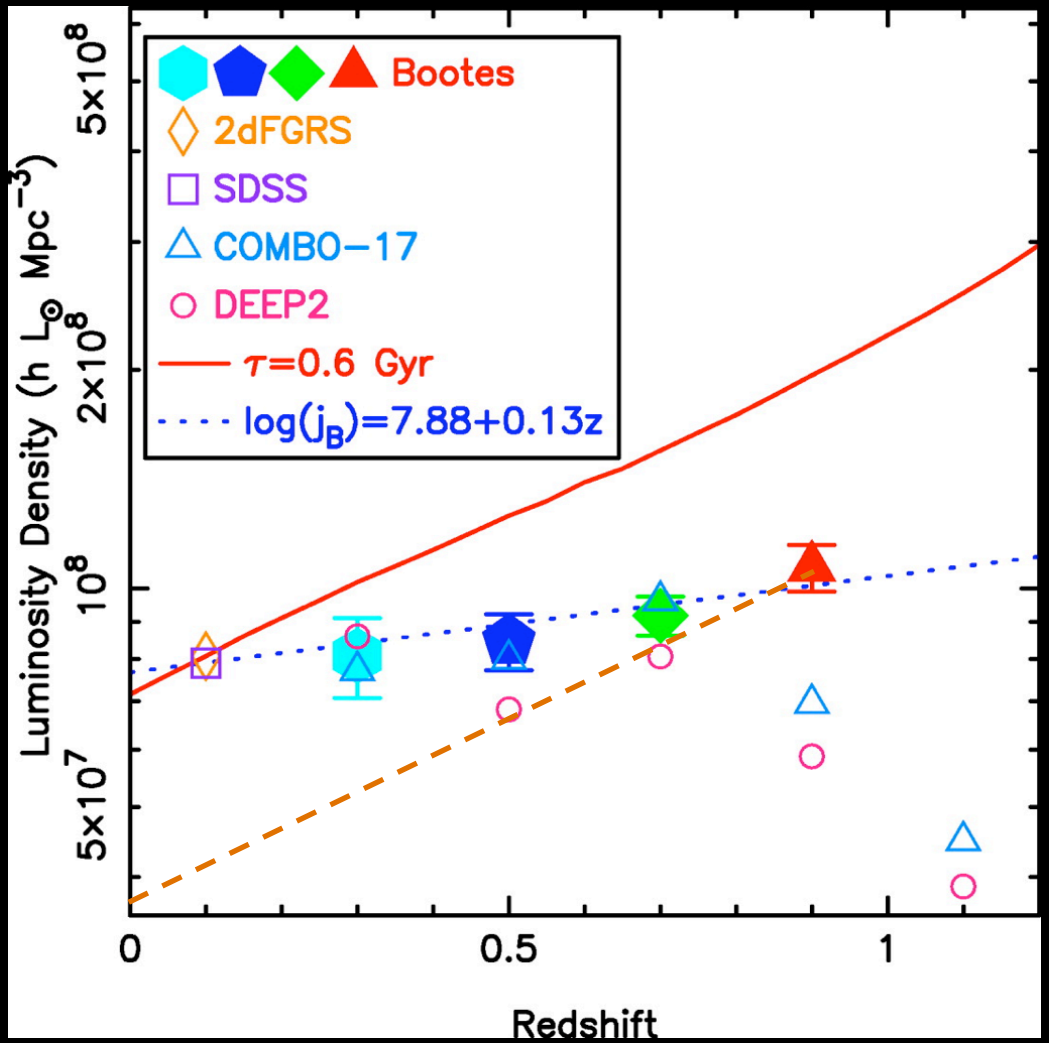
Building up the red sequence in the field



Reddening color predicts substantial fading toward lower redshift

Brown et al. (2007), Bell et al. (2004), Faber et al. (2007), Taylor et al. + GR (2009)

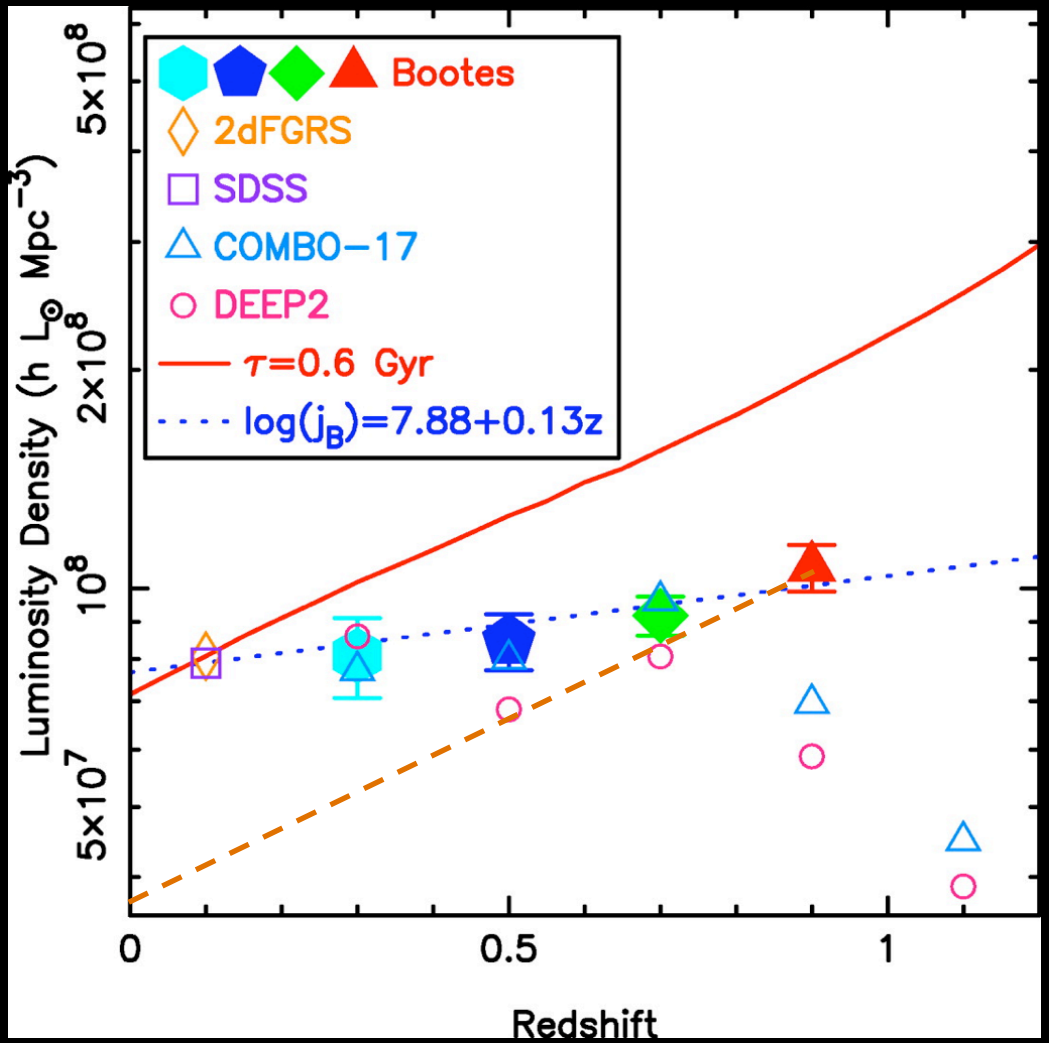
Building up the red sequence in the field



Reddening color predicts substantial fading toward lower redshift

Brown et al. (2007), Bell et al. (2004), Faber et al. (2007), Taylor et al. + GR (2009)

Building up the red sequence in the field

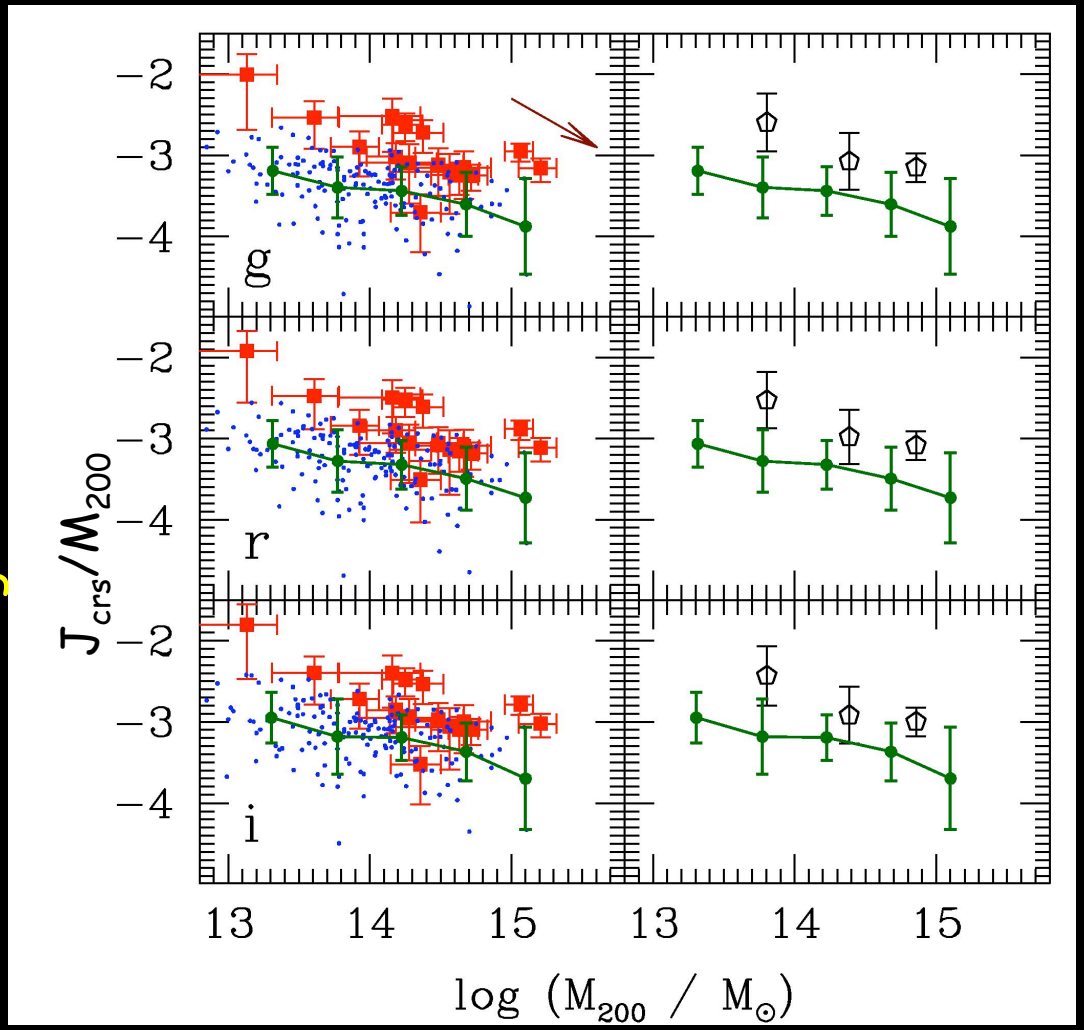


Reddening color predicts substantial fading toward lower redshift

Roughly constant observed luminosity density implies a growth of the red sequence.

Brown et al. (2007), Bell et al. (2004), Faber et al. (2007), Taylor et al. + GR (2009)

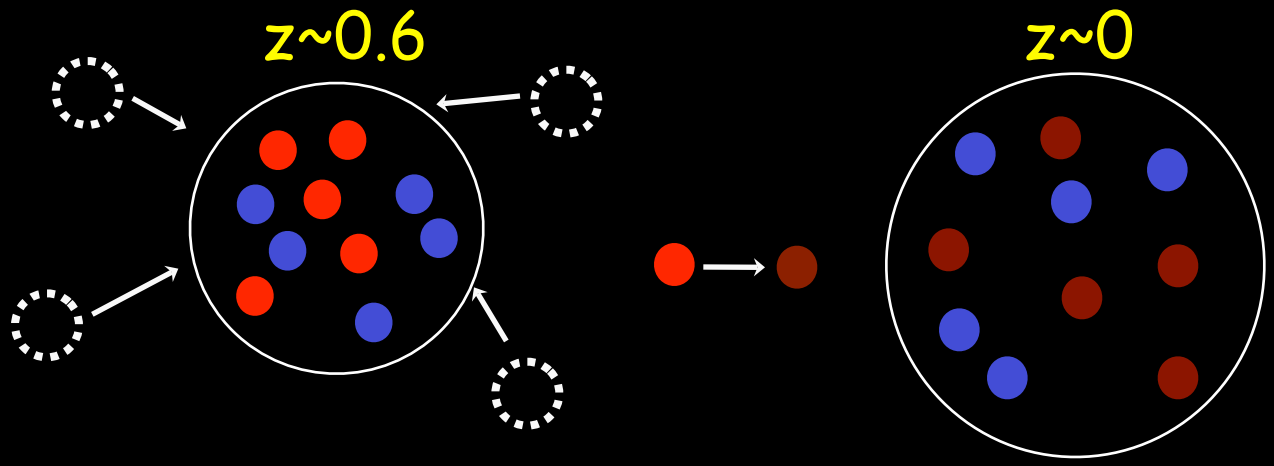
Building up the red sequence in clusters



Rudnick et al. 2009

- Calculate M_{200} from σ
- j_{crs}= integral of red galaxy LF
- Deviation from constant j_{crs}/M_{200}
- EDisCS clusters are more luminous than SDSS clusters
- But galaxies will passively fade

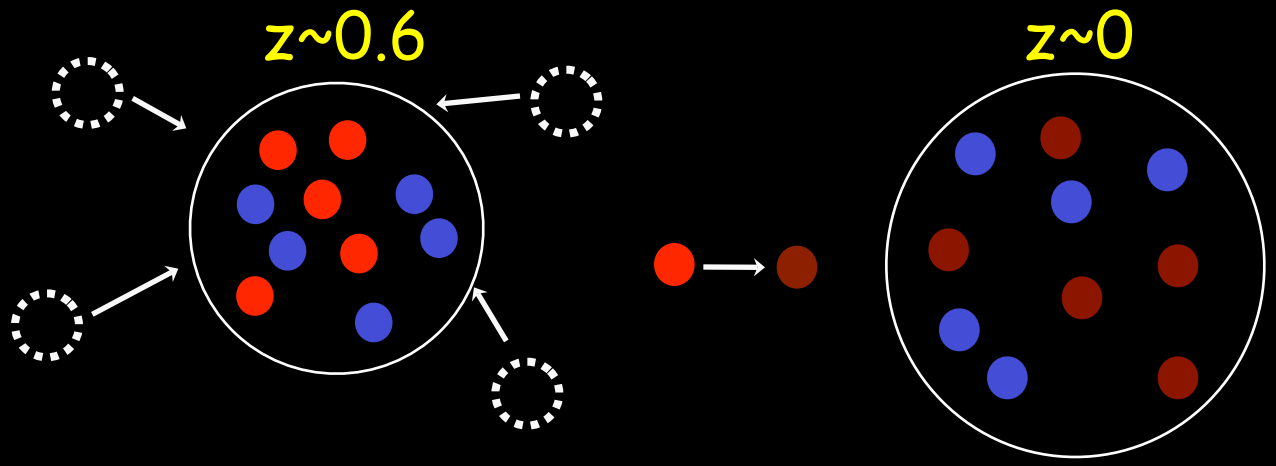
Toy Model 1

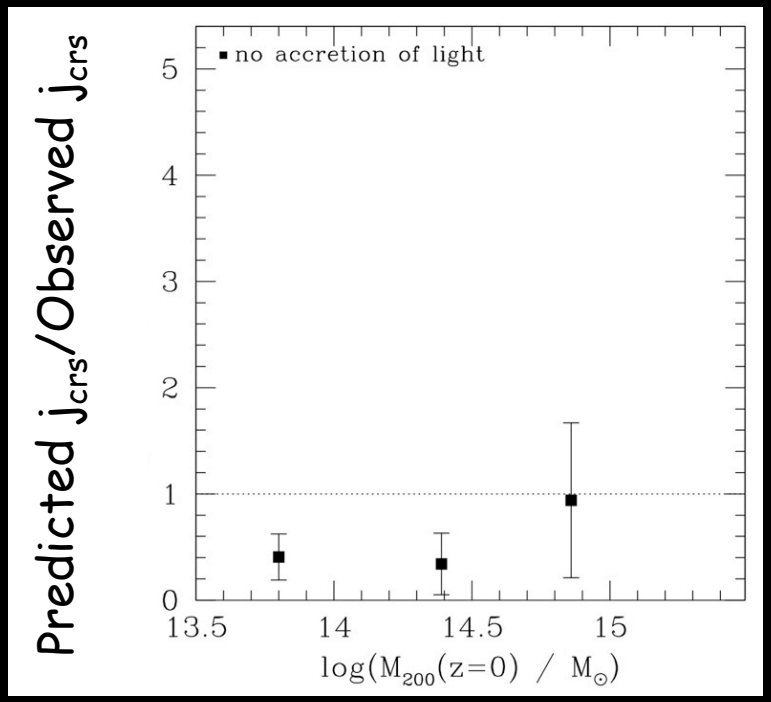


- Cluster mass grows
- No new galaxies accreted
- Red galaxies fade
- Predicted clusters are too faint

Rudnick et al. 2009

Toy Model 1

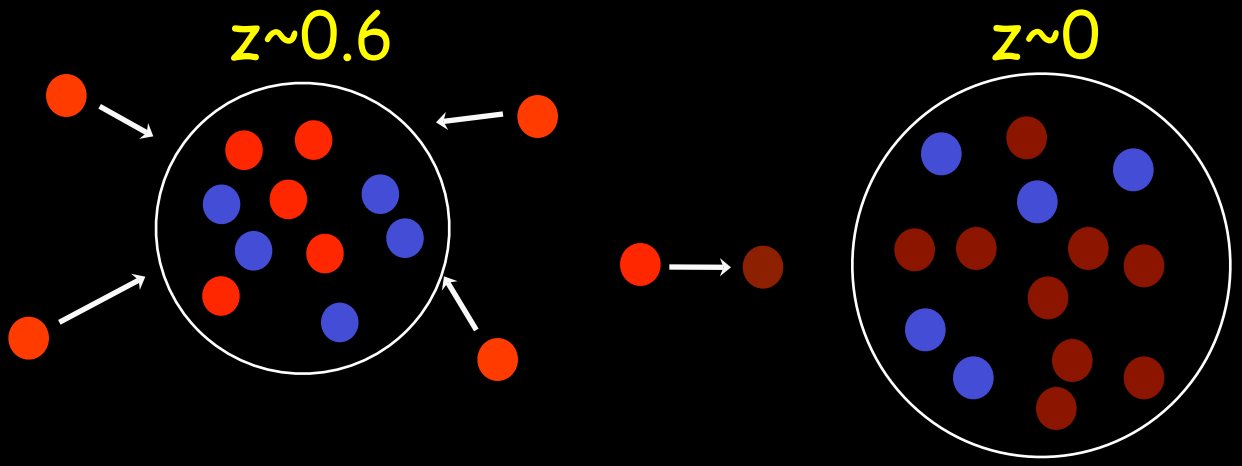




- Cluster mass grows
- No new galaxies accreted
- Red galaxies fade
- Predicted clusters are too faint

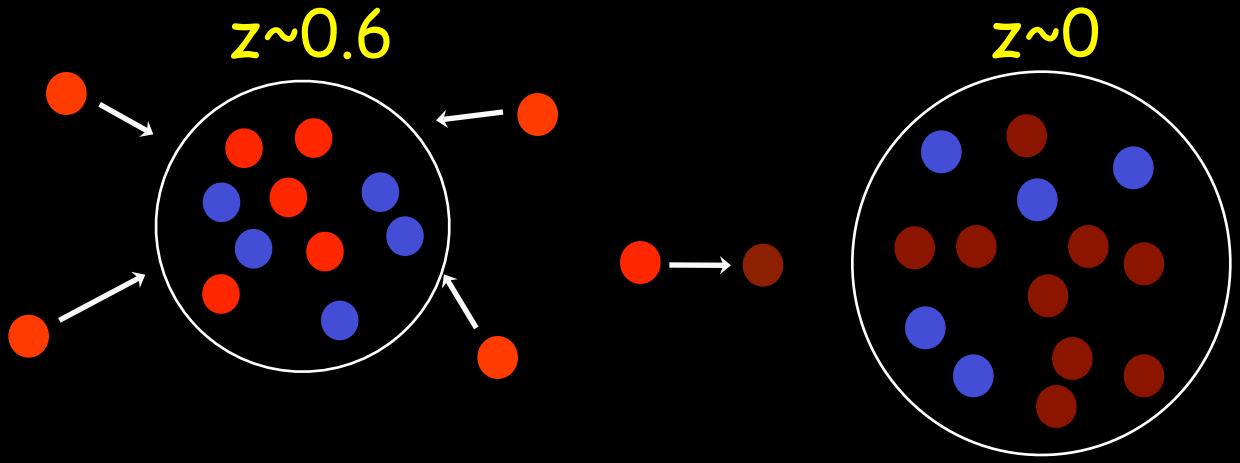
Rudnick et al. 2009

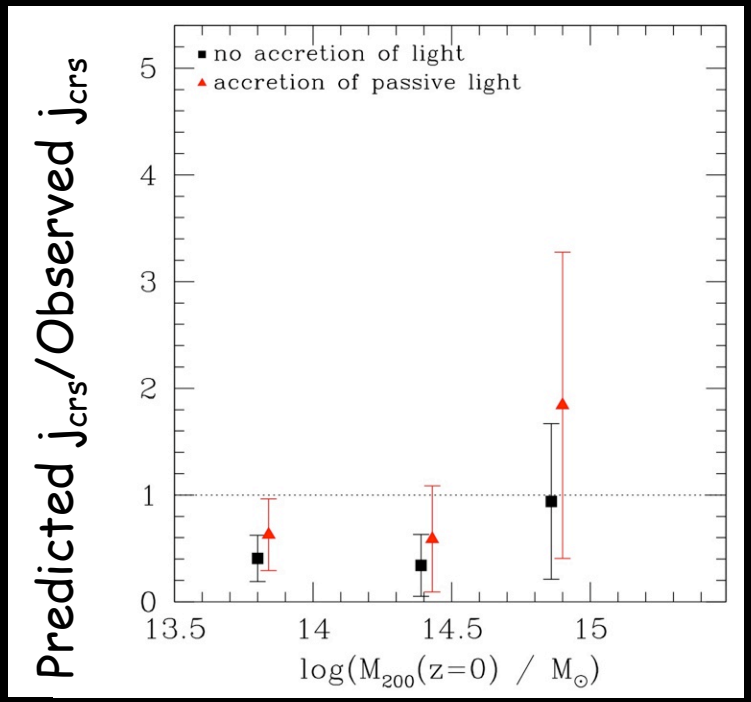
Toy Model 2



- Cluster mass grows
- Red galaxies fade
- Red field galaxies accreted

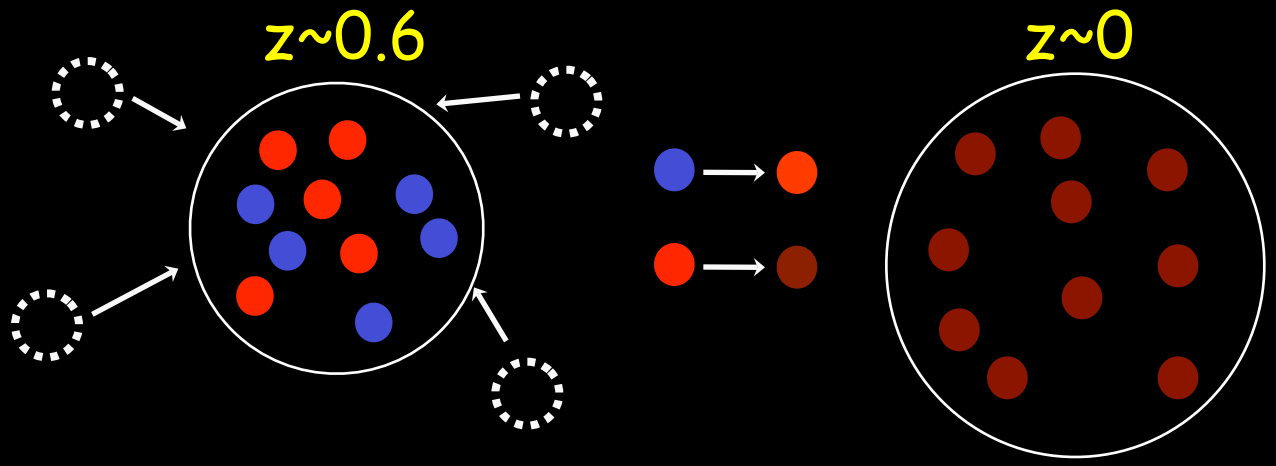
Toy Model 2





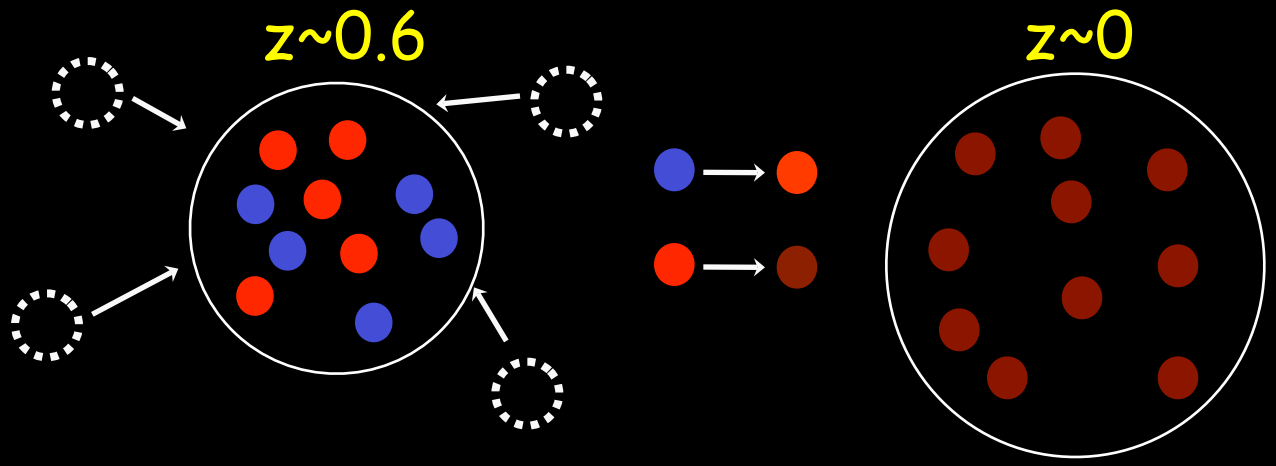
- Cluster mass grows
- Red galaxies fade
- Red field galaxies accreted

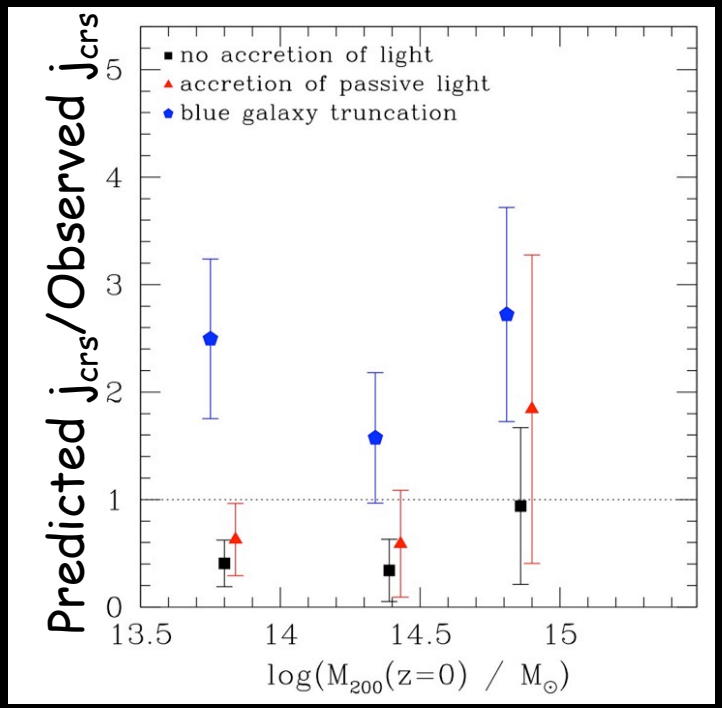
Toy Model 3



- Cluster mass grows
- Red galaxies fade
- No galaxies added
- Blue galaxies turned into red

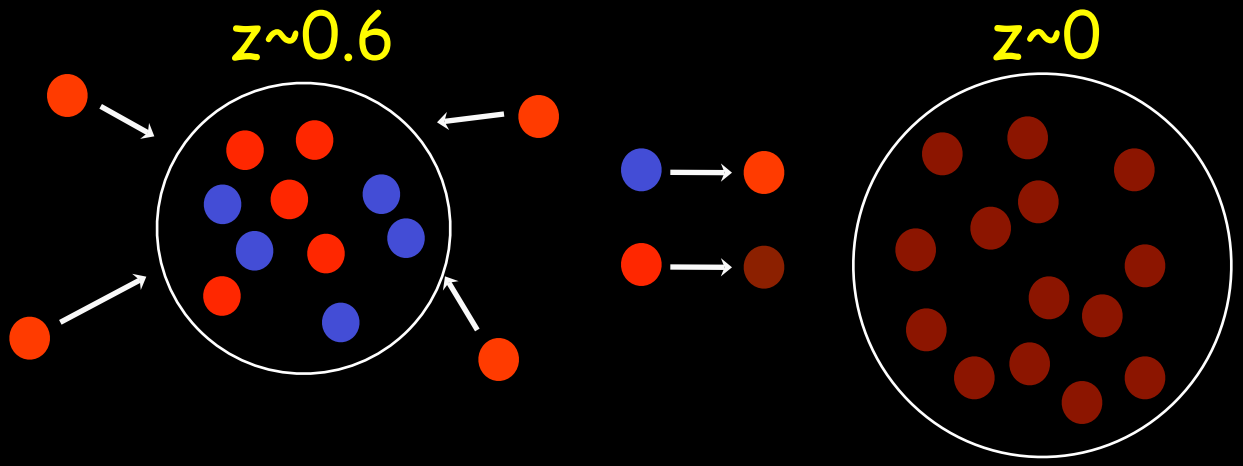
Toy Model 3





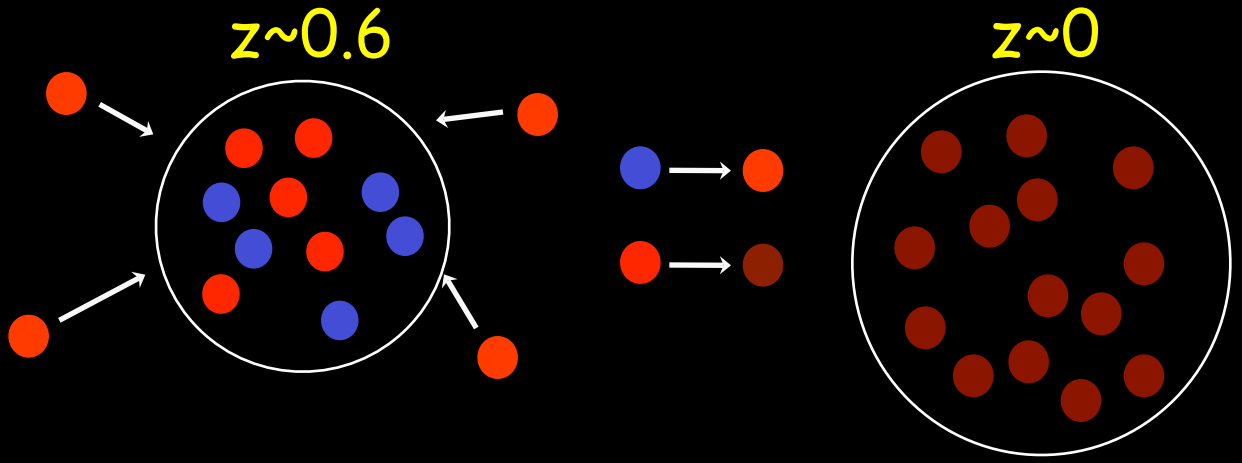
- Cluster mass grows
- Red galaxies fade
- No galaxies added
- Blue galaxies turned into red

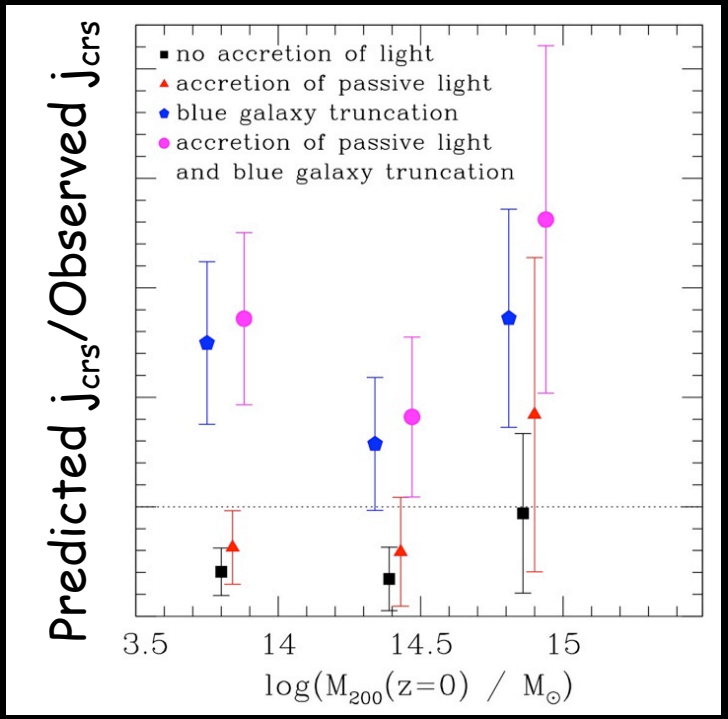
Toy Model 4



- Cluster mass grows
- Red galaxies fade
- Red galaxies added
- Blue galaxies turned into red

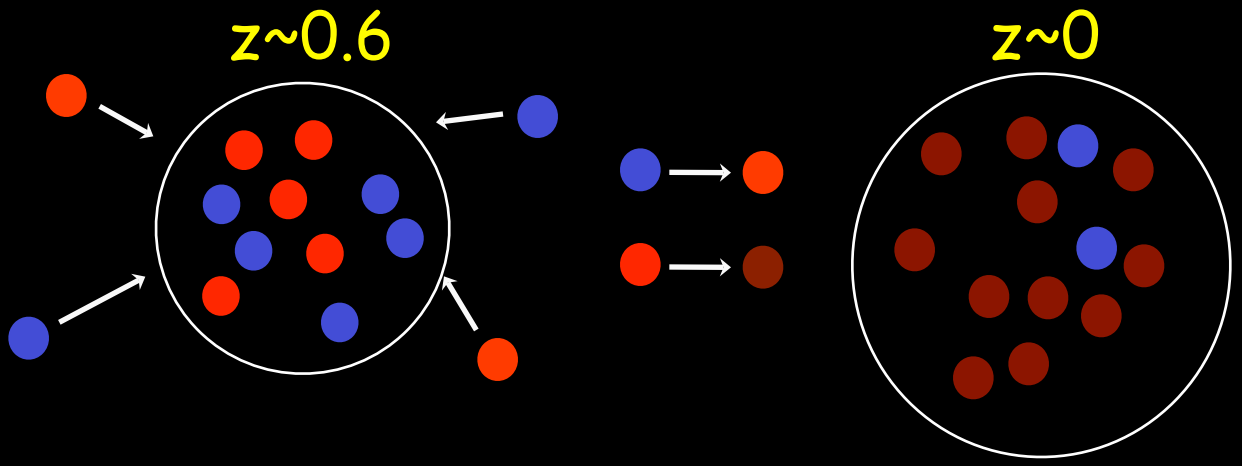
Toy Model 4





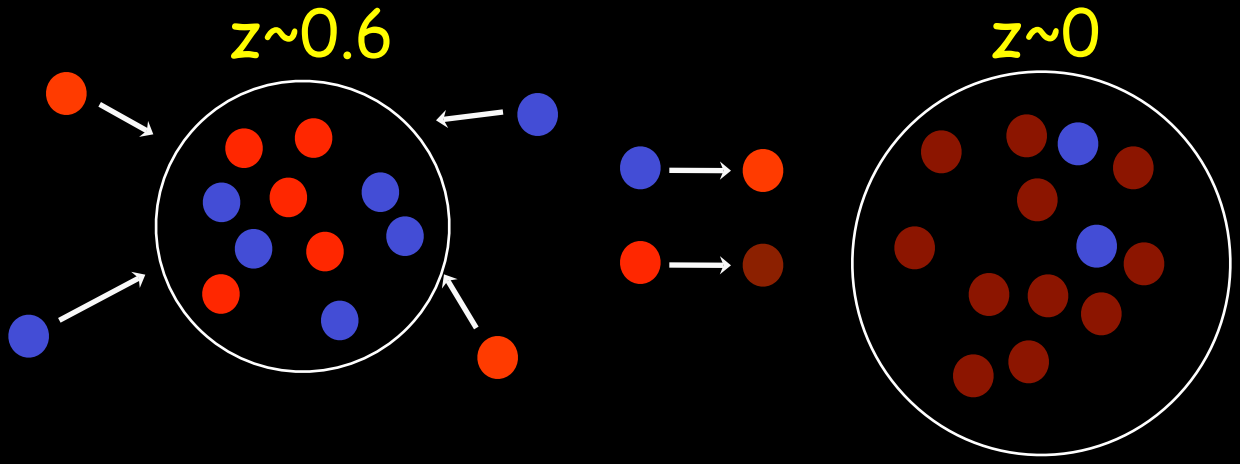
- Cluster mass grows
- Red galaxies fade
- Red galaxies added
- Blue galaxies turned into red

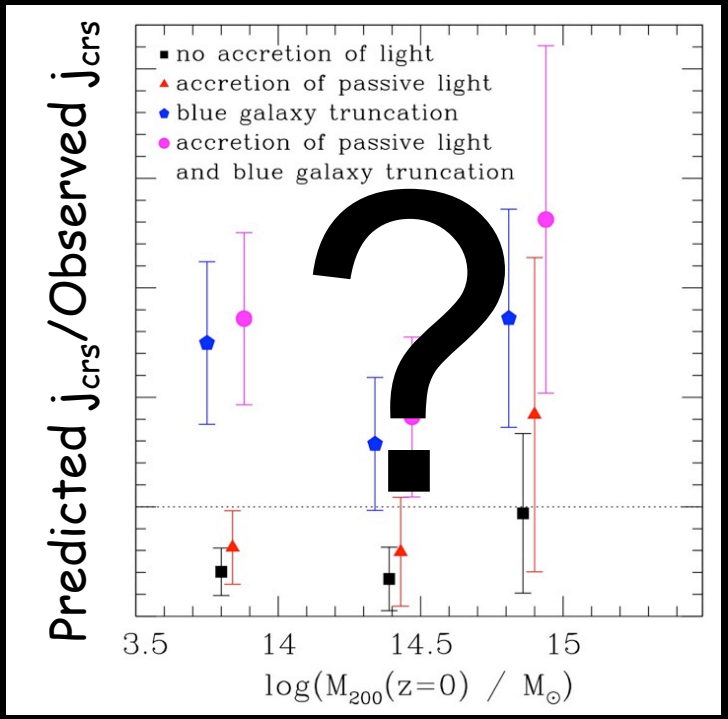
Reality



- Cluster mass grows
- Red galaxies fade
- Red and blue galaxies added
- Blue galaxies turned into red
- Some blue galaxies stay blue

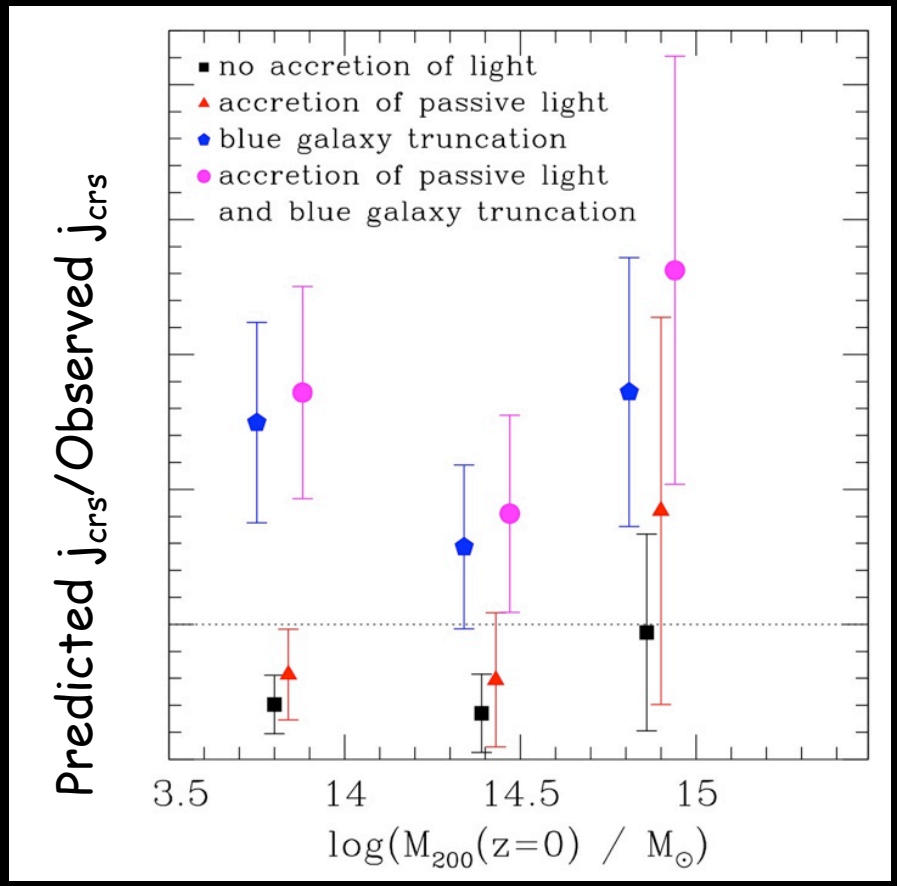
Reality





- Cluster mass grows
- Red galaxies fade
- Red and blue galaxies added
- Blue galaxies turned into red
- Some blue galaxies stay blue

How to make a local red sequence

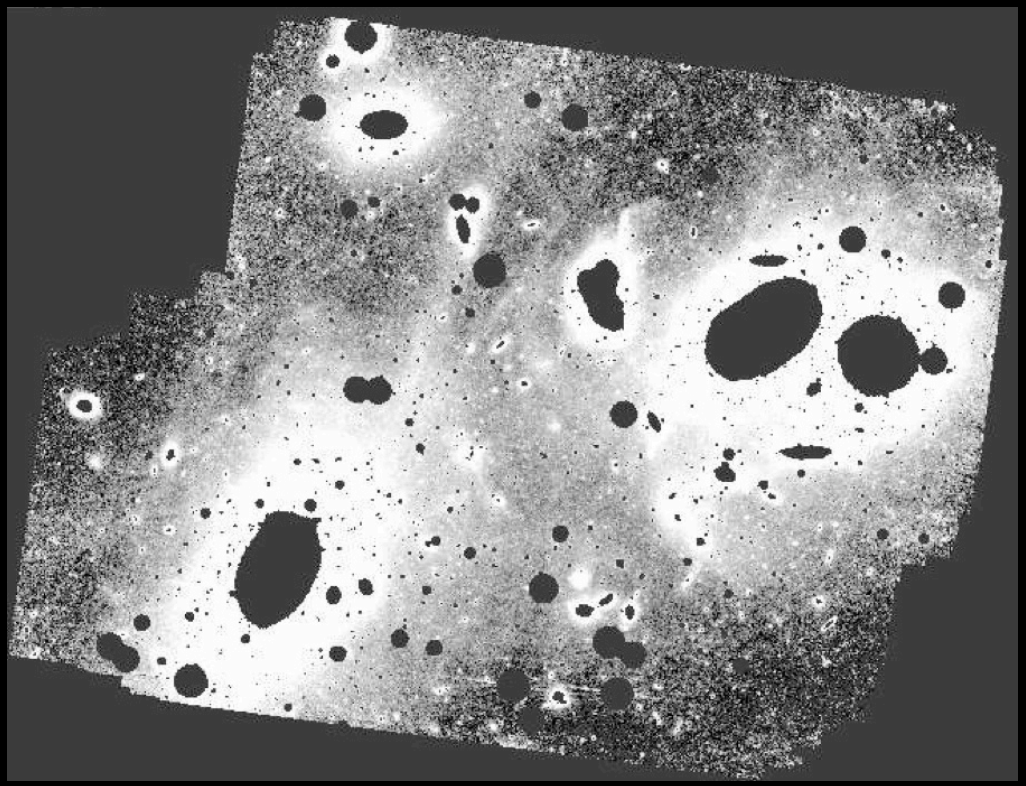


- ~1/3 local cluster red sequence galaxies are dusty (Wolf et al. 2005,2009)
- Cannabilism onto BCG (e.g. Ostriker & Tremain 1975)
  - Compatibility with observed BCG growth (e.g. Whiley et al. + GR 2008)?
- tidal stripping and ICL production

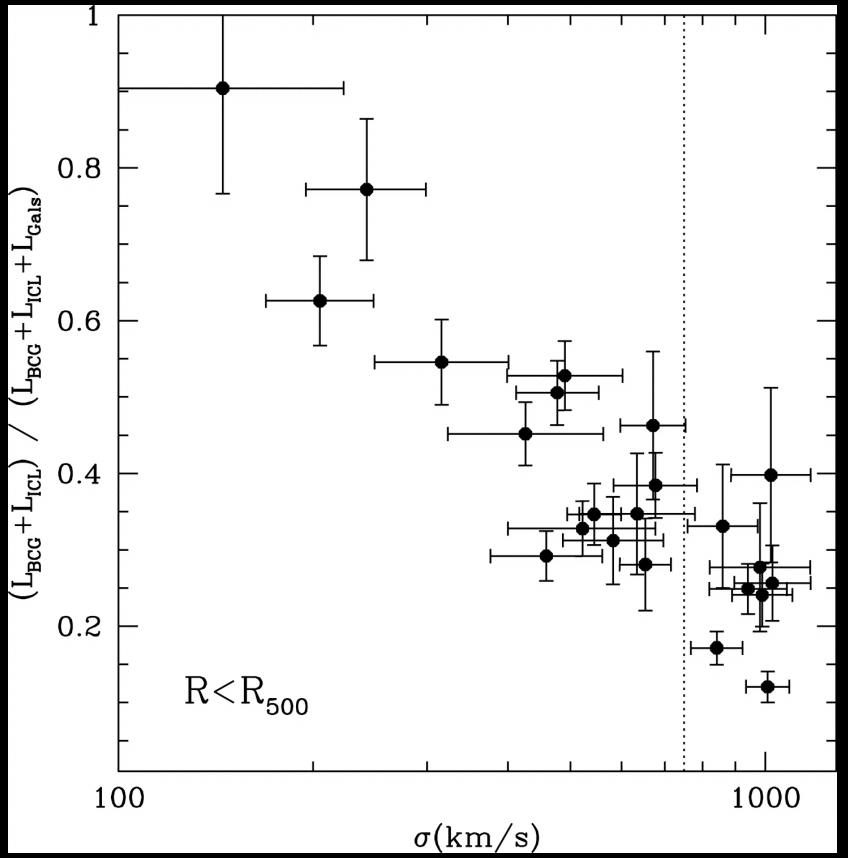
Stripping of stars from infalling galaxies?

Fraction of total stars in Intra-cluster light decreases with increasing mass.

Need better measurements.



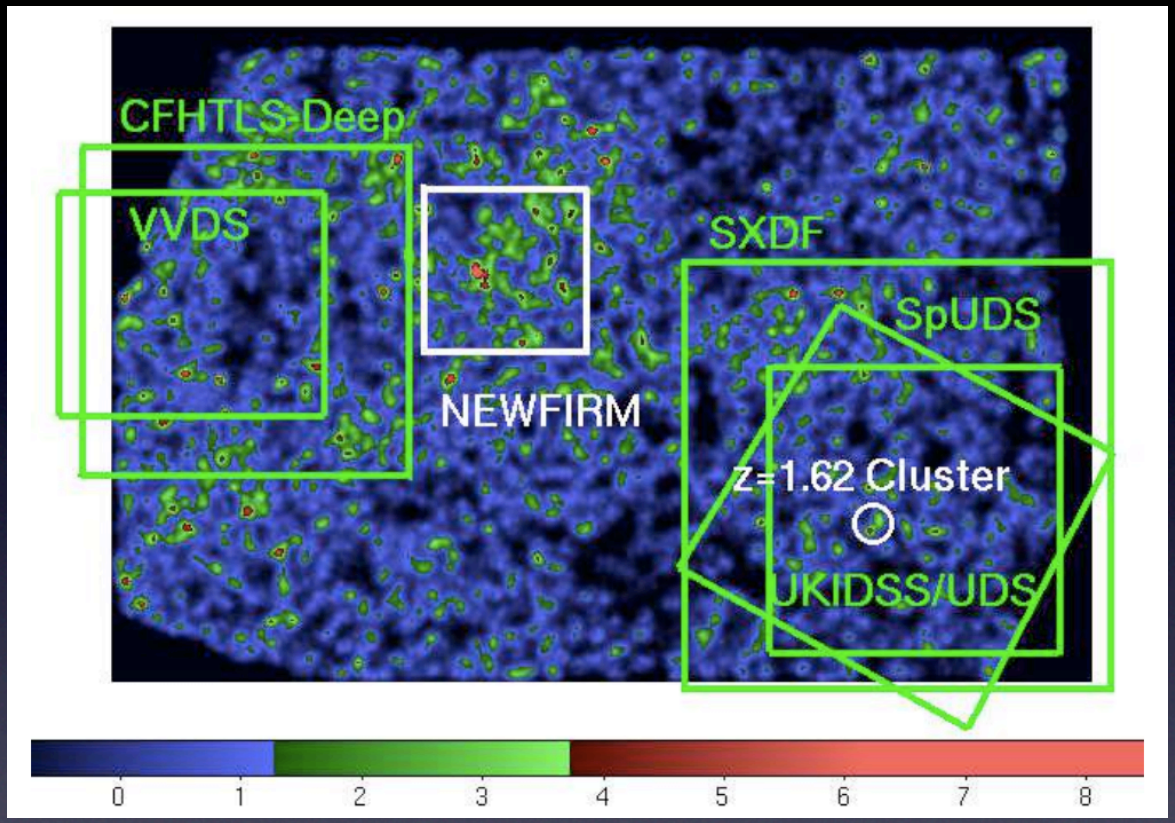
Mihos et al. (2005)



Gonzalez, Zaritsky, & Zabludoff (2007)
Monaco et al. (2006)

The most distant galaxy clusters

- Select optically faint galaxies with red IRAC colors
  - z>1.3 selection
- Look for overdensities on the sky
- Target promising candidates with spectroscopy



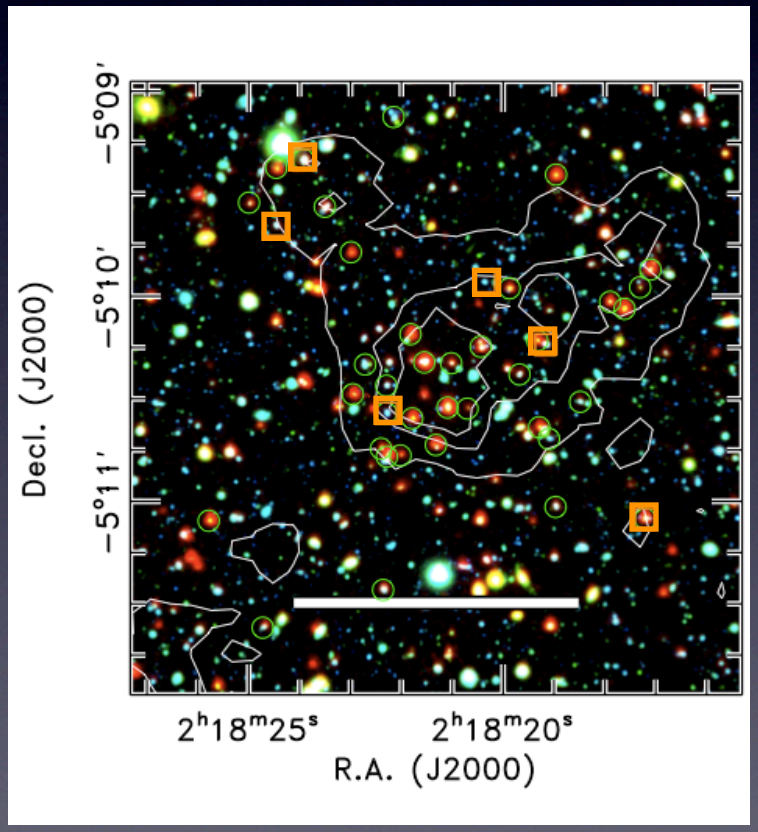
Papovich 2010; Papovich, et al. + Rudnick 2010

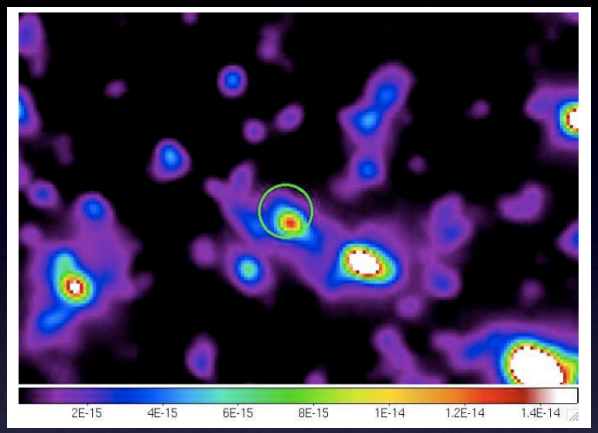
A z=1.62 galaxy cluster

6 spectroscopically confirmed members

20 σ above mean overdensity

later confirmed with x-rays





4 σ XMM/x-ray detection

spectroscopically confirmed member

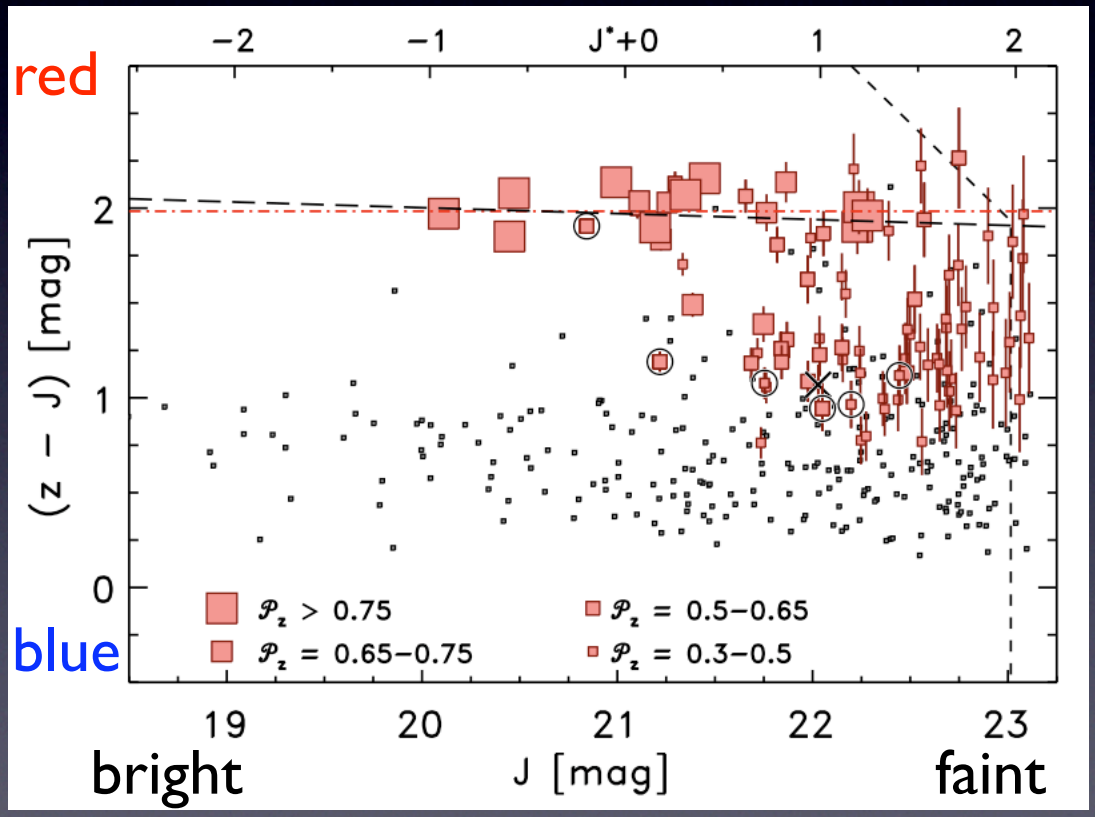
likely member

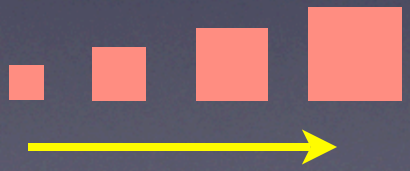
Papovich, et al. + Rudnick 2010

The red sequence at z=1.62

- Clear red sequence
- colors of bright galaxies consistent with z_{form}=2.40±0.15
- apparent lack of faint red galaxies

All galaxies within 2 arcmin of cluster



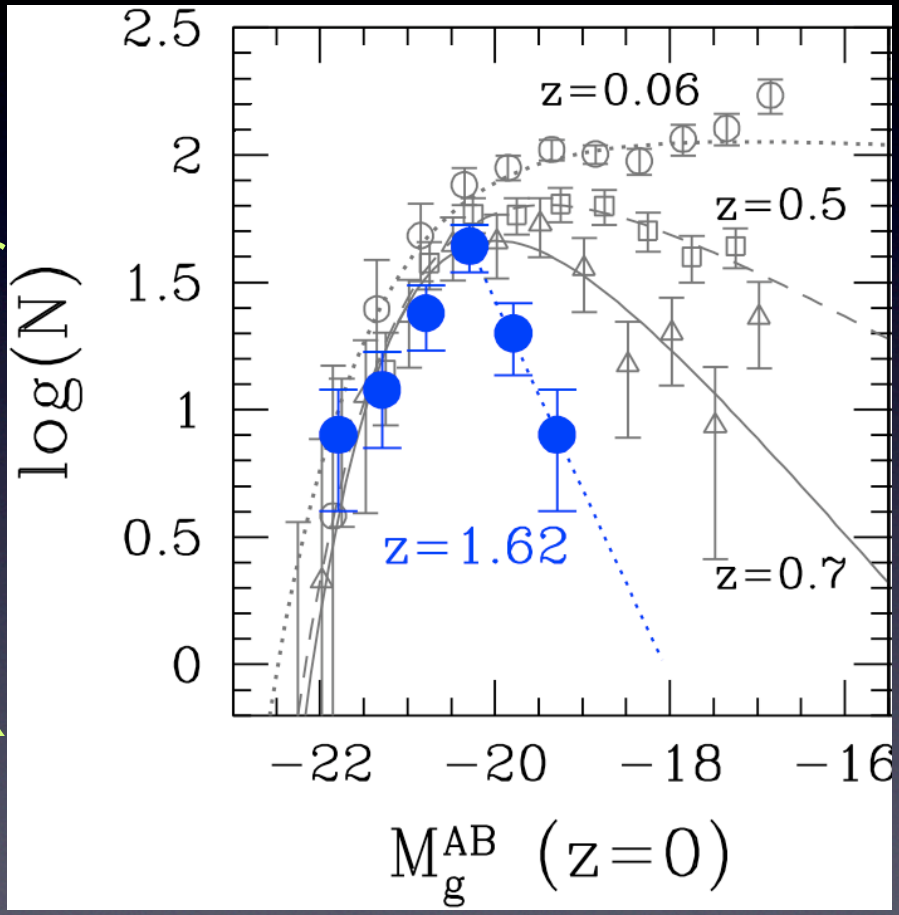


increasing likelihood of cluster membership

Papovich, et al. + Rudnick 2010

The red sequence LF at z=1.62

- Appears that most luminous red galaxies were formed at z~2.5
- Faint galaxies built up rapidly at later times
- Are there two different formation channels for red cluster galaxies?
- Need to confirm LF in this cluster with deep imaging (Gemini) and NIR spectroscopy (HST)



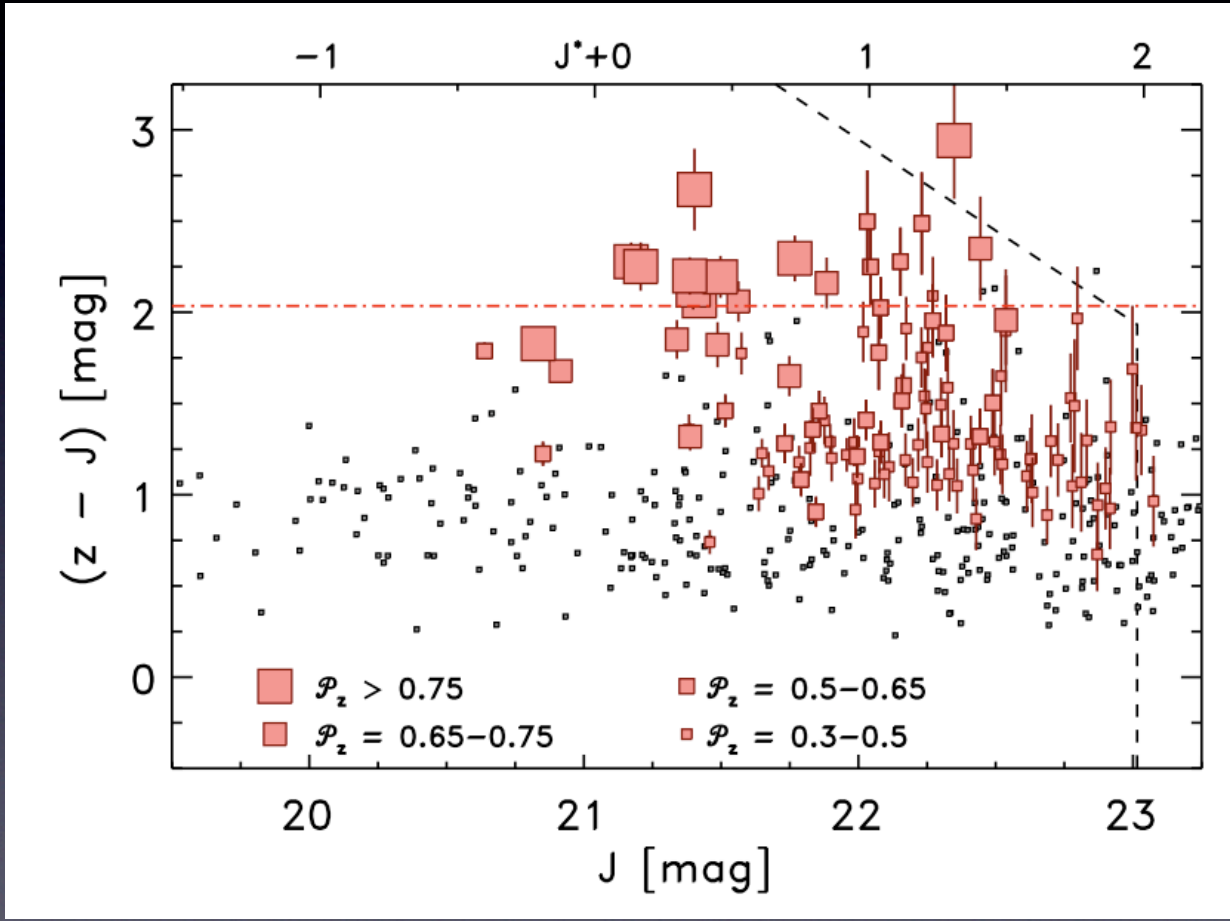
Rudnick et al. in prep

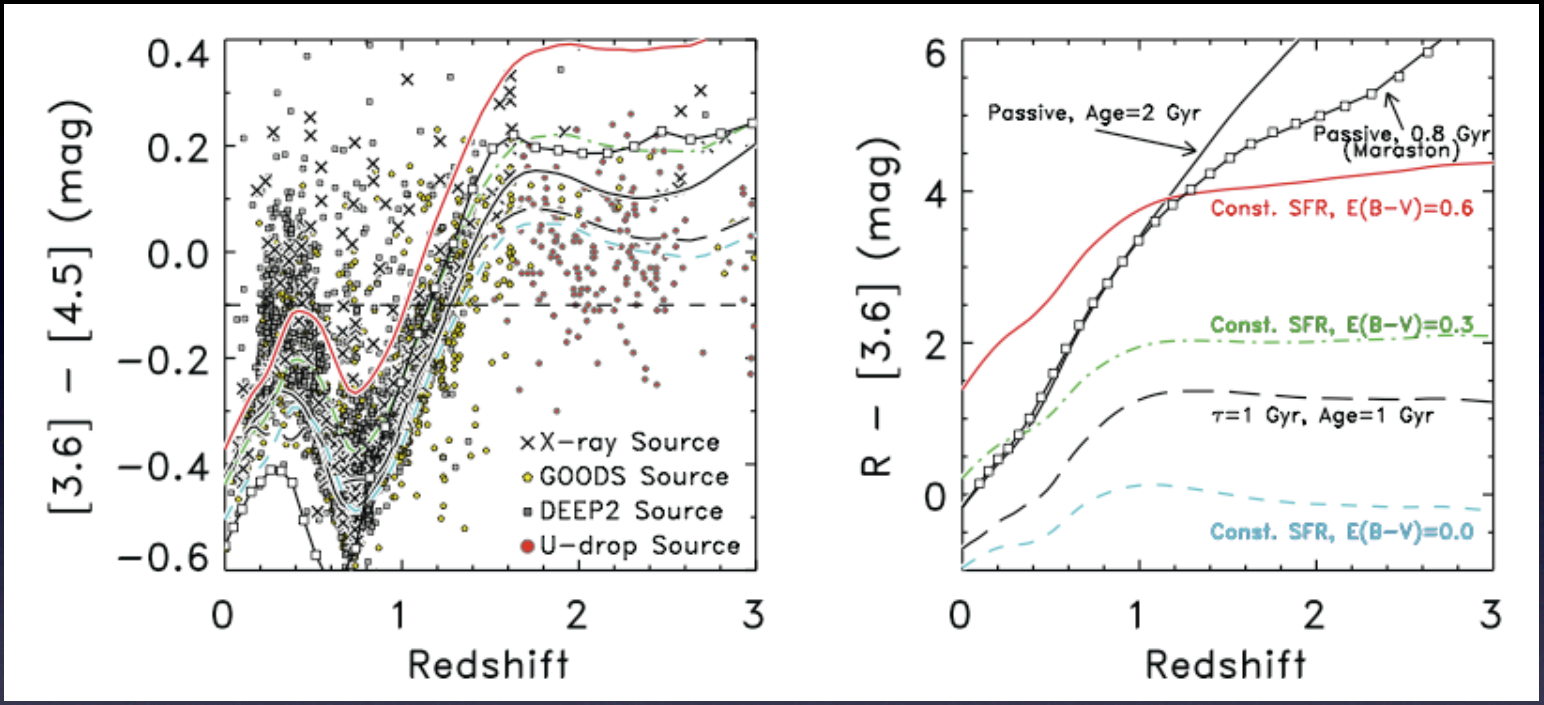
Conclusions

- The cluster red sequence grows in light/ mass at $z<0.8$
- The growth happens mainly in the faint galaxies
- There is a different growth rate in clusters of different sigma
- There is a different growth rate in clusters and the field.
- Not all stars accreted onto cluster at $z<0.8$ end up in red and dead cluster galaxies.

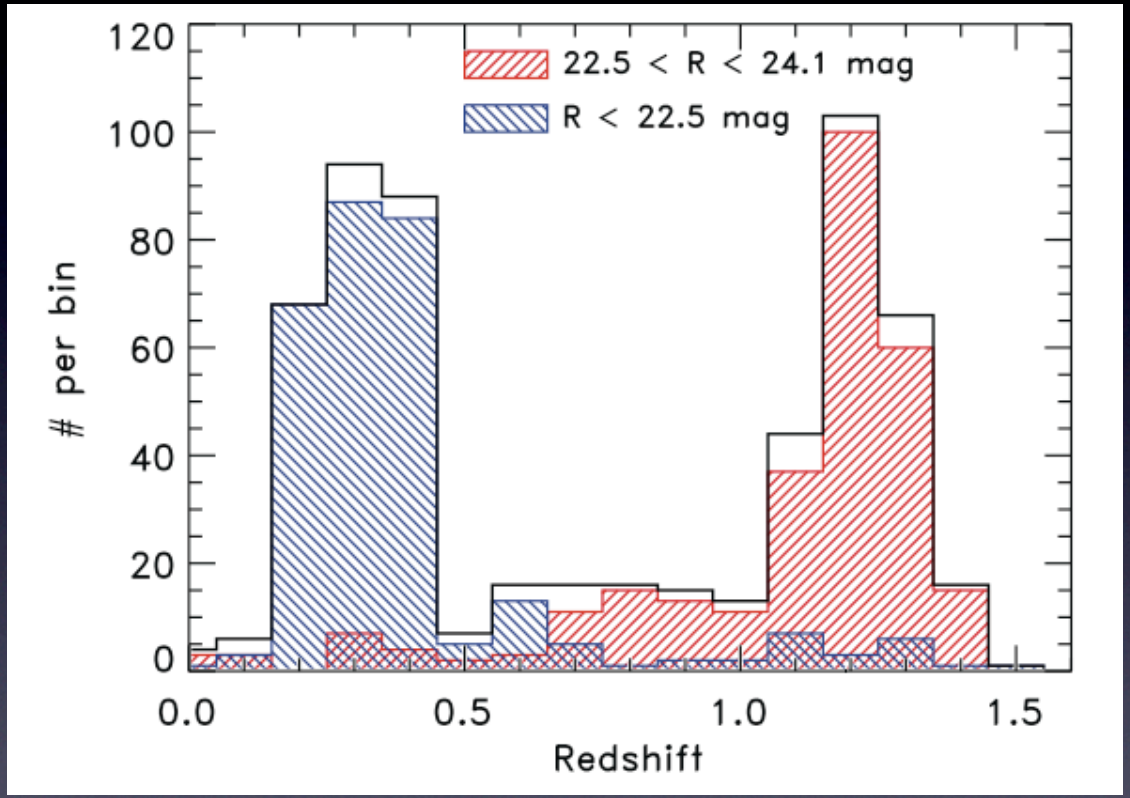
Building a larger sample

- z=1.7
- No spectroscopy, yet





Papovich 2010


22.5 < R < 24.1 mag
R < 22.5 mag
per bin
Redshift
0
20
40
60
80
100
120
0.0
0.5
1.0
1.5