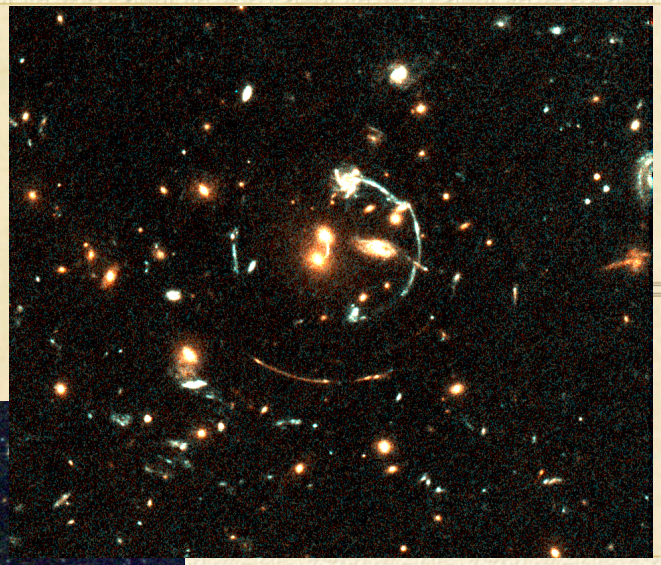
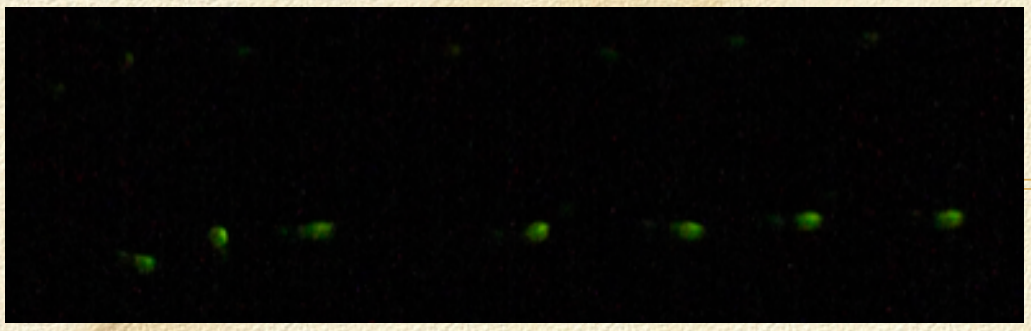
The Red-Sequence Cluster Survey

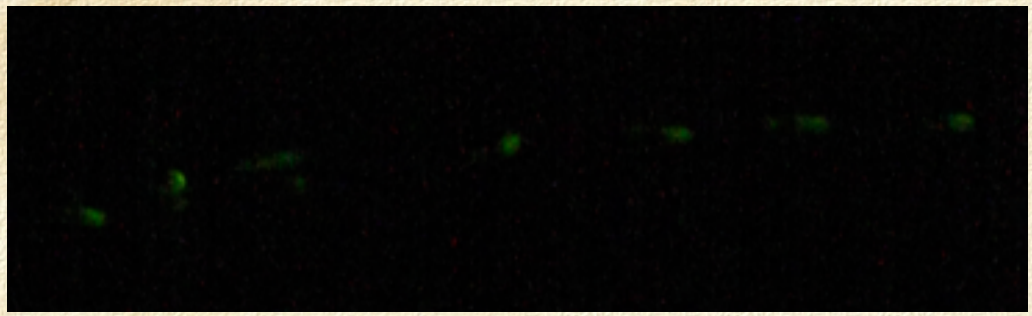


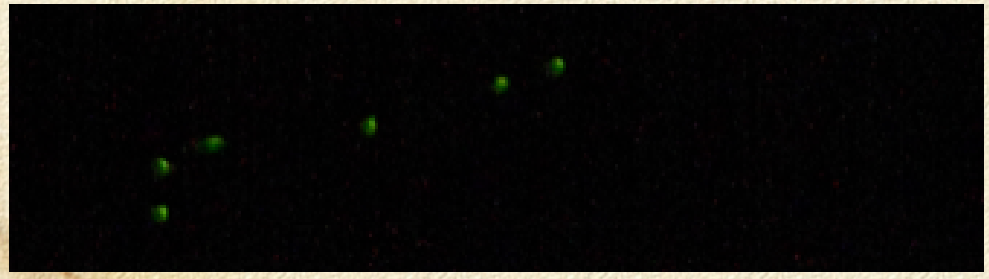
Howard Yee
University of Toronto

The RCS1/RCS2 collaboration

What we learned about **Fireflies**







Pictures courtesy of I-Hui (Tornado) Li

Canon 450D, f5.6, 2 second exposure, focal length 18mm

- they are green,
- strong evidence for synchronization;

- frequency: 3.5 - 3.9 /sec,
- no evidence of multiple frequencies,
- duty cycle ~10%

- proper motion detected: they are not blinking "christmas lights" on trees

The RCS1/2 Collaboration:

Howard Yee (U.Toronto);
Mike Gladders (U. Chicago)

D. Gilbank (U. Waterloo), H. Hoekstra (Leiden),
E. Ellingson (U. Colorada), R. Yan(U.Toronto),
B.C. Hsieh (ASIAA, Taiwan), S. Majumdar (Tata Inst., India),
T. Webb (McGill), A. Muzzin (Yale),
I.H. Li (Swinburne, Australia), K. Blindert (MPIA),
F. Barrientos (U. Catolica, Chile), A. Hicks (Michigan St.),
P. Hall (YorkU), M. Bautz (MIT), Lihwai Lin (ASIAA,Taiwan)

+ a number of students and postdocs and others at Chicago, UVic, McGill, NCU, NTU, ASIAA, York, CITA, Fermi Lab

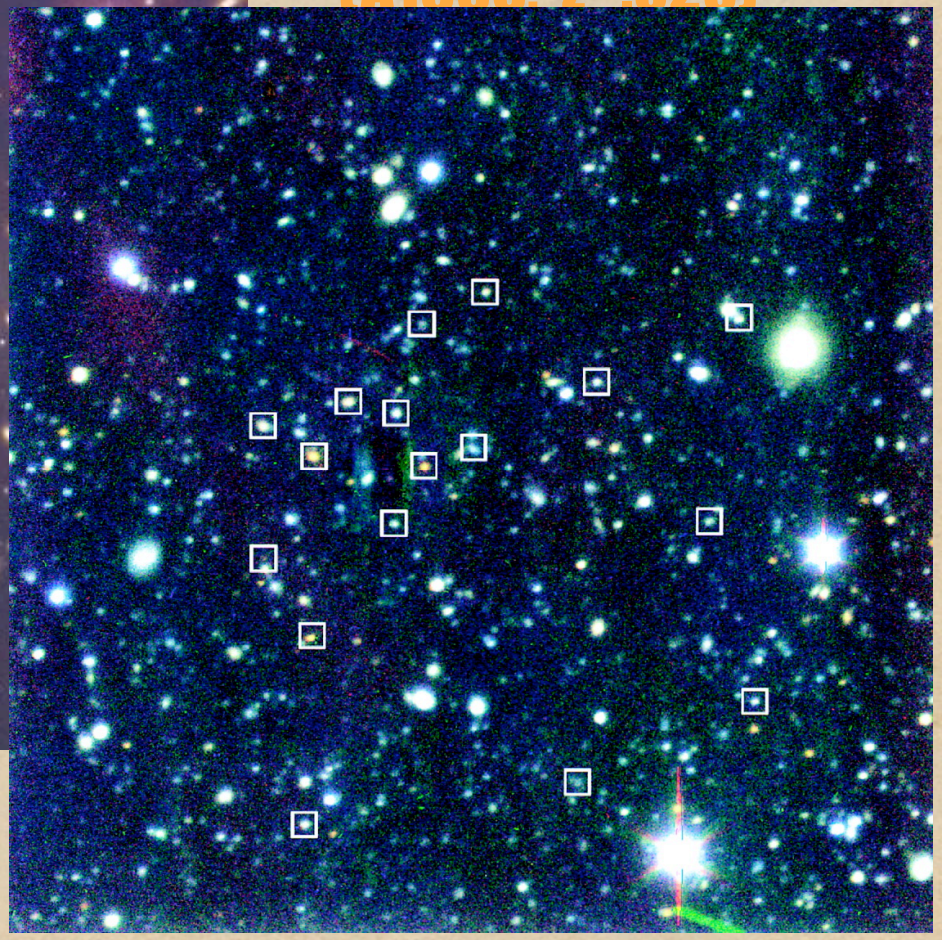
Outline:

- a summary of the RCS

- some results on the evolution of galaxy clusters:
  - ✦ For fun:
    - RCS2 strong lensing clusters; a supermassive z=0.7 cluster; a supercluster at z=0.9
  - ✦ the evolution of z' band cluster galaxy LF (z~0.4-1)
  - ✦ RCS1 galaxy groups
  - ✦ Red-Sequence dispersion at z~1

- The SpARCS survey: finding clusters at z>1

Coma
(A1656, z=.025)



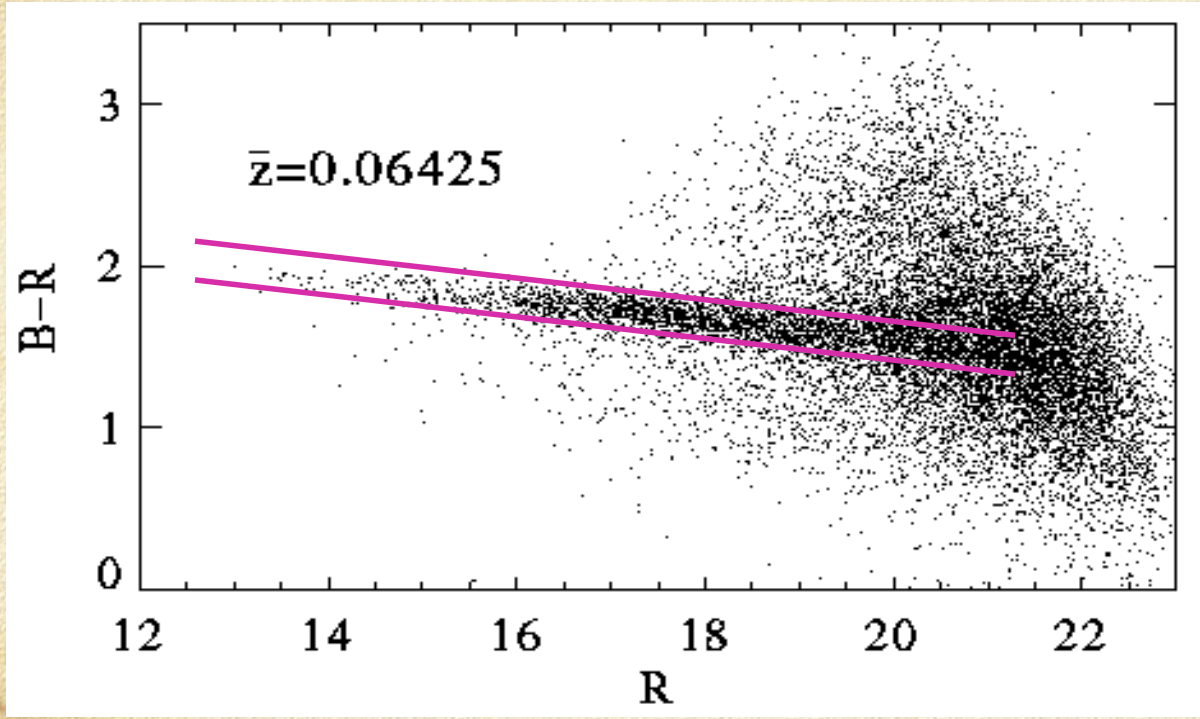
NOAO 0.9m, Lopez-Cruz & Yee

PDCS, z=0.83

The Cluster Red-Sequence Method

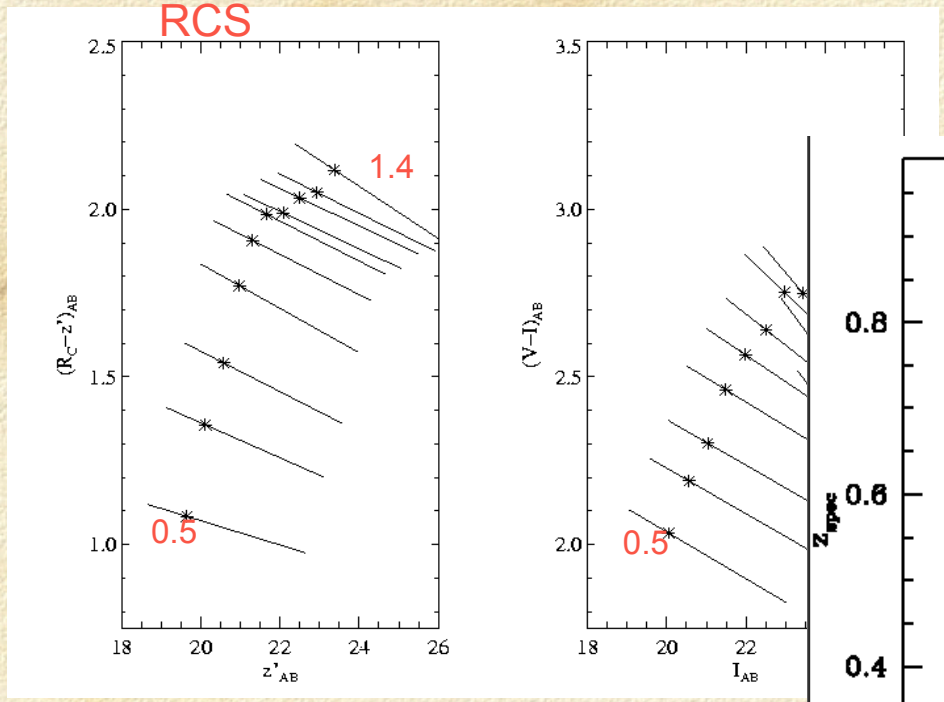
Gladders & Yee 2000, AJ, 120, 2148

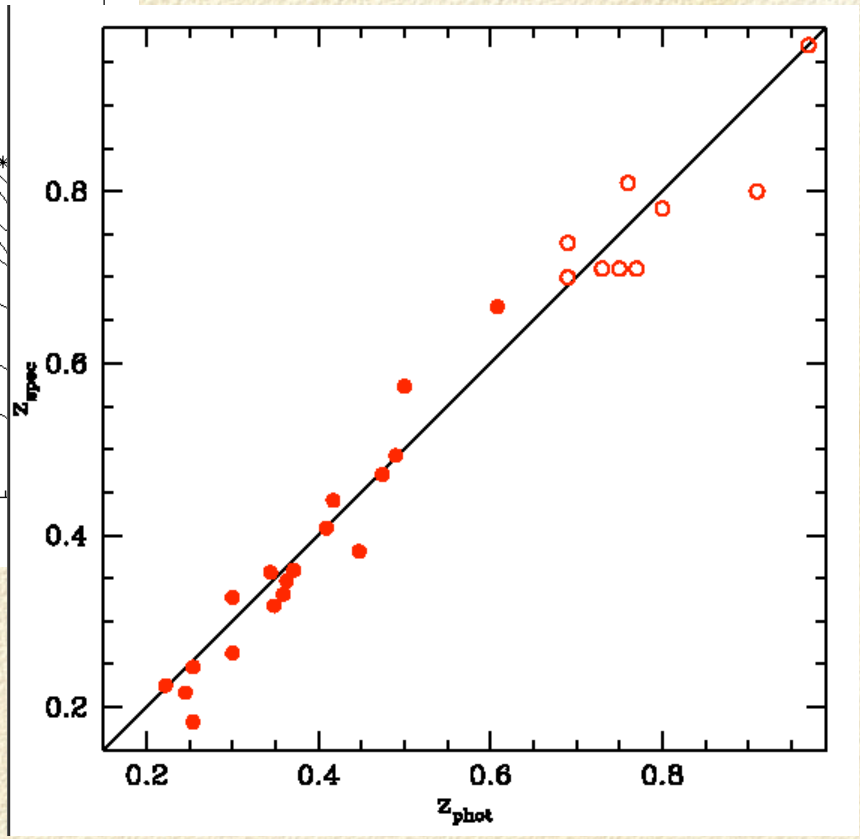
Uses the early-type (red) galaxies as markers for cluster detection



Requires only 2 filters: Inexpensive

Color-magnitude relation as a function of redshift





Red-sequence photo-z (2 filters)
vs spectral z (RCS1 data);
Δz~0.03 to 0.06;
as good as <0.02 for RCS2

The RCS1

Gladders and Yee, 2005, ApJS, 157,1

- 92 sq deg, 1998-2001
- total: 13 nights CFHT (12k), 17 nights CTIO (Mosaic Cam)

(including lost times)

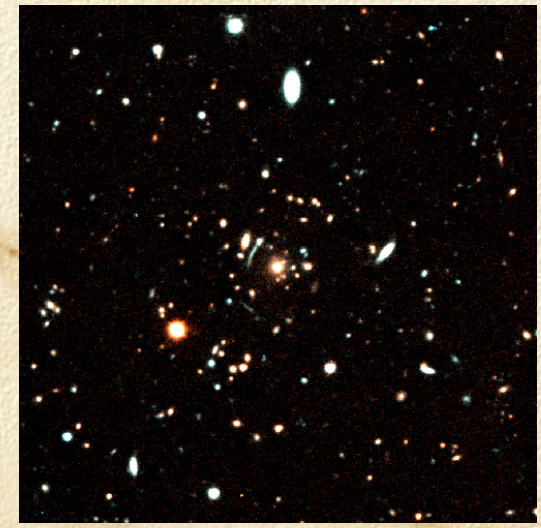
- R, z' bands: 15-25 min exposures

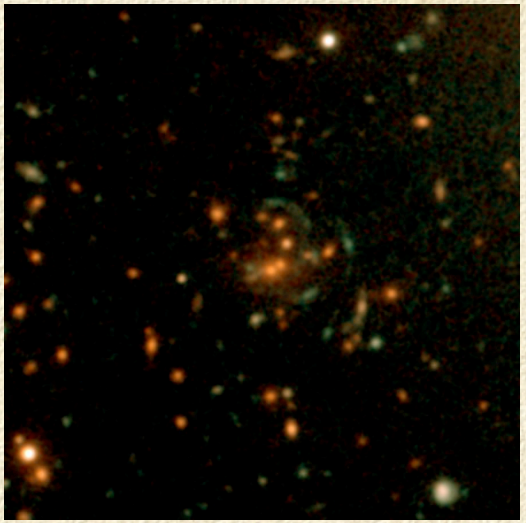
1/3 sq deg per pointing

Typical depth (5 sigma): z'~23.6, R~24.8

- 22 patches (typically 2.5x2.5 deg), distributed over RA & dec

plus V and B bands for CFHT patches (33 sq deg)





RCS2

www.RCS2.org

RCS2:

Yee et al. 2007, astro-ph/0701839

A ~1000 sq deg cluster survey, with a z ~1 limit
CFHT MegaCam (Canada/Taiwan)

- Observing completed Jan 2008: photometry (120m objects) mostly completed, preliminary cluster catalogs
- total 920 sq deg:
  770 sq deg +150 sq deg from CFHLS-Wide

Three filters:	z'	r'	g'	+ i' (from CFHQS)
exposure t:	6	8	4 min	5

5σ limits: 23.2 25.0 25.4 (AB magnitude)
Expected completeness (100%) depth:
750 km/s (5 kev) clusters at z~1

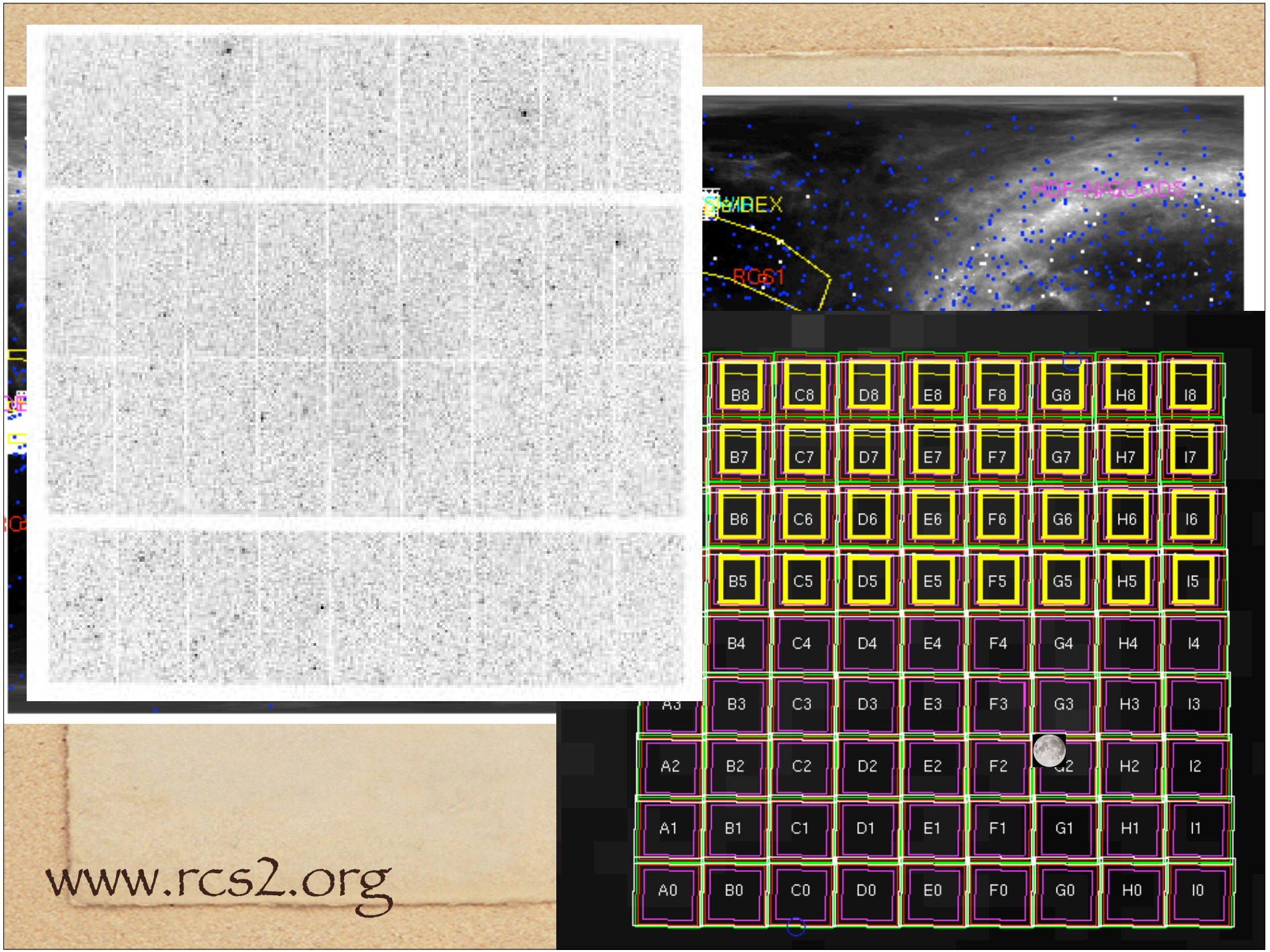
Main Science Goals: (RCS2)

- Constrain cosmological parameters
  Ω_m (to ~0.03), σ_8 (to ~0.05), w
- create a sample of ~150 strong lenses
- cluster evolution
- weak lensing, cosmic shear (wide/shallow)
- a very large sample of photo-z
  (useful $0.1<z<0.7$)

Cluster sample:

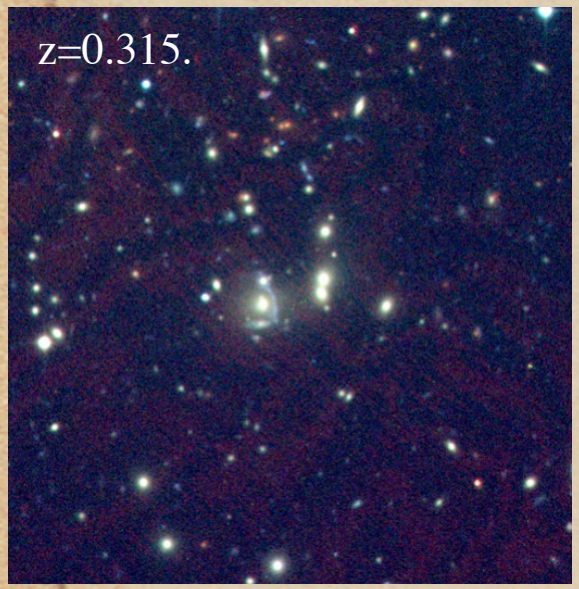
- optimized for z~0.1 to 1.0;

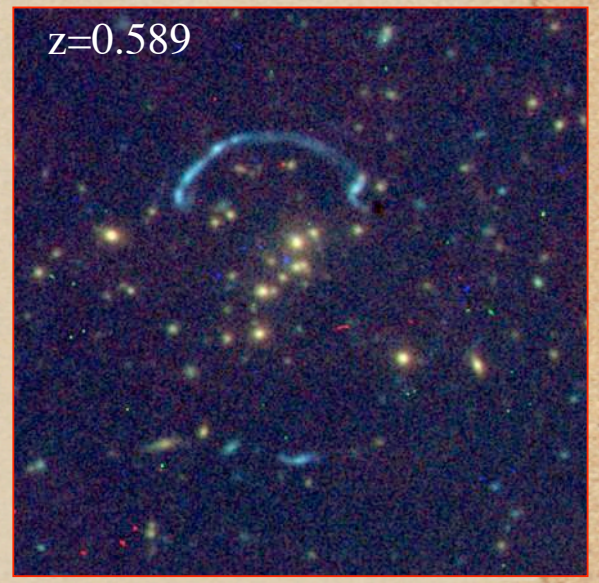
Total number of clusters (useful for cosmology) expected: ~ 15,000 ($>\sim 2\times10^{14}$)

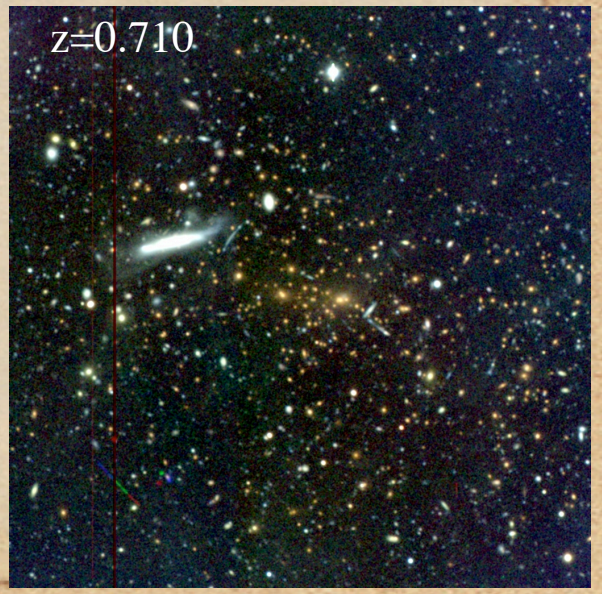

HDF-N/GOODS
B8 C8 D8 E8 F8 G8 H8 I8
B7 C7 D7 E7 F7 G7 H7 I7
B6 C6 D6 E6 F6 G6 H6 I6
B5 C5 D5 E5 F5 G5 H5 I5
B4 C4 D4 E4 F4 G4 H4 I4
B3 C3 D3 E3 F3 G3 H3 I3
A2 B2 C2 D2 E2 F2 H2 I2
A1 B1 C1 D1 E1 F1 G1 H1 I1
A0 B0 C0 D0 E0 F0 G0 H0 I0
www.rcs2.org

Strong lensing in RCS2 clusters

~80 systems so far
(~450 sq deg)

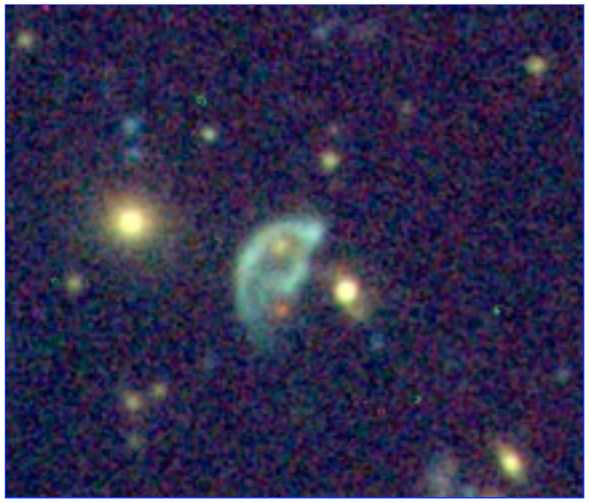


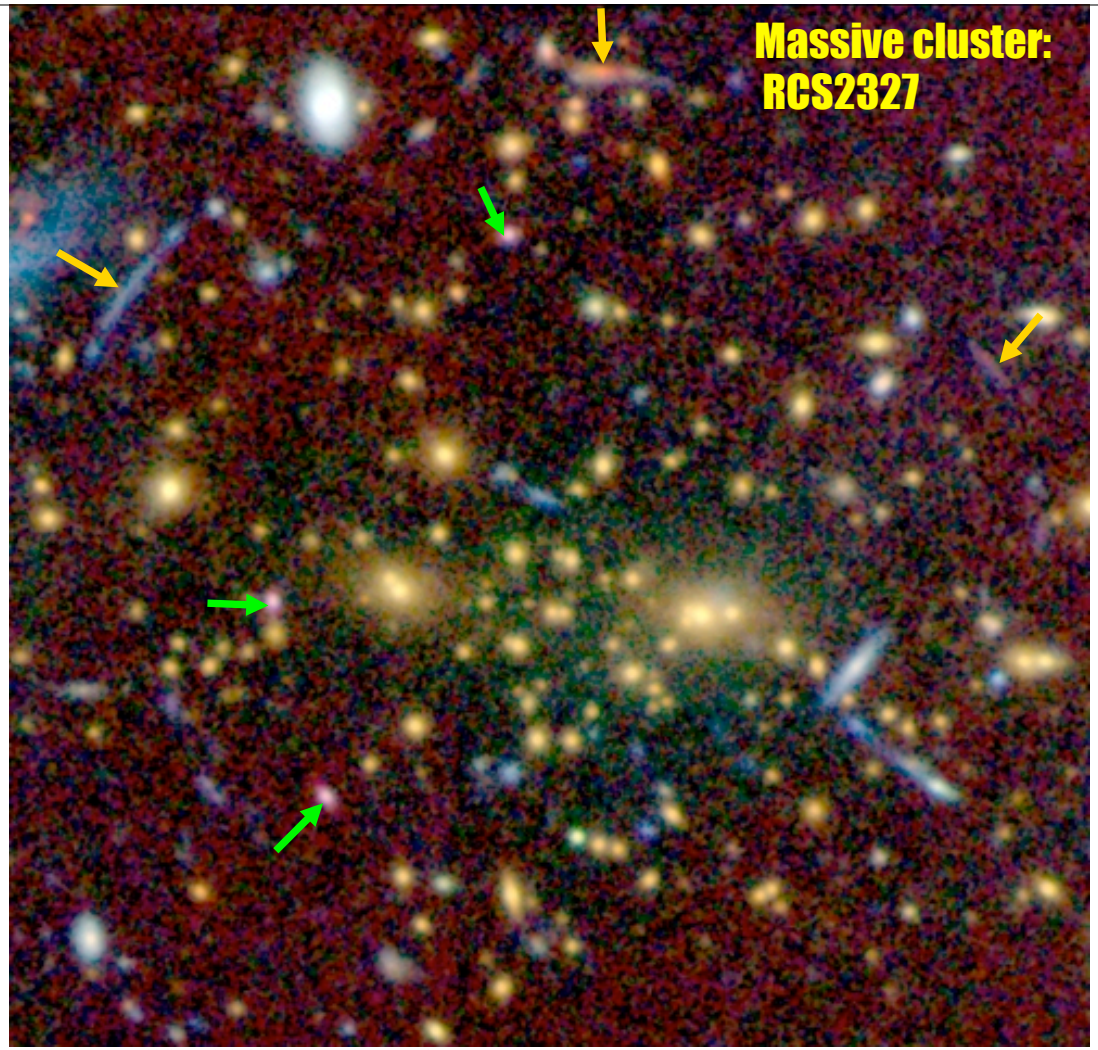




RCS-2: Strong Lensing Samples

Galaxy lenses

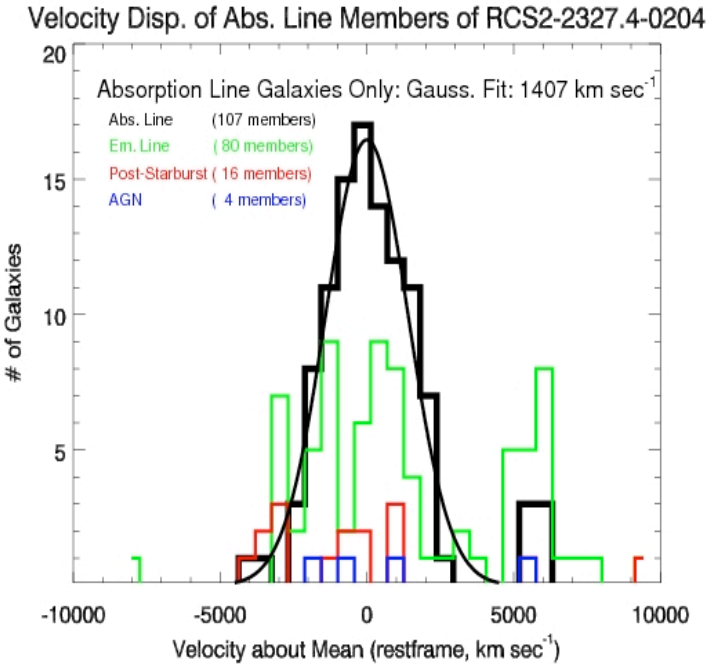


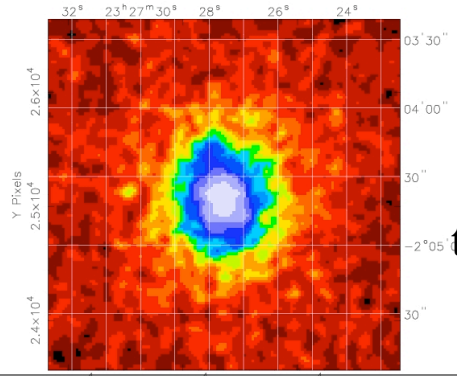


Einstein radius: 50”

Cluster Redshift: 0.6995

Source Redshift: 2.98



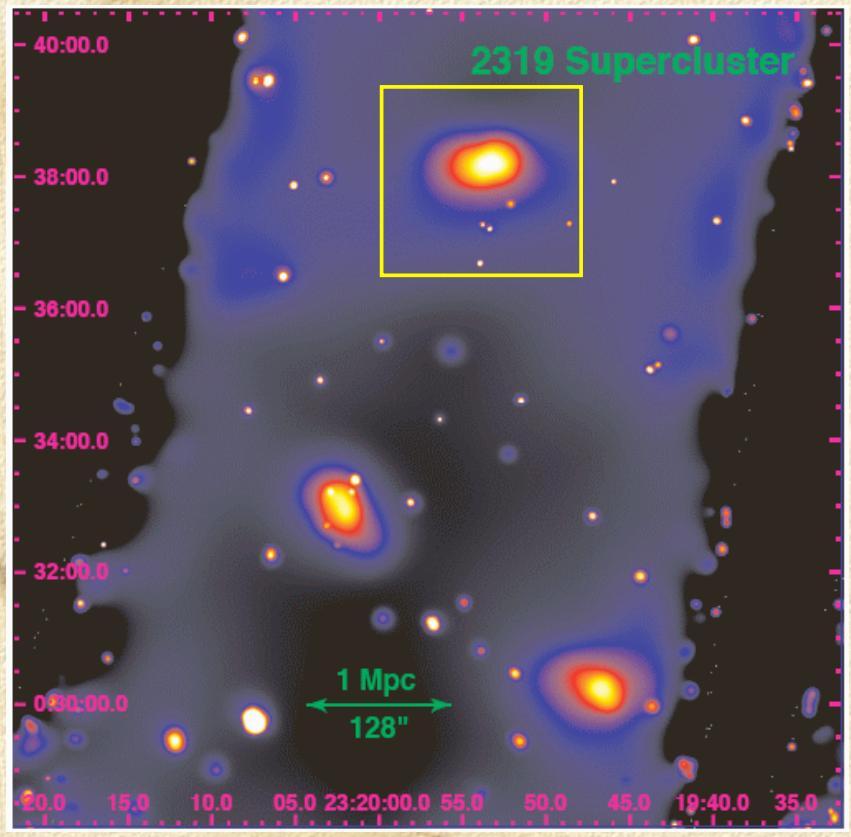


Preliminary x-ray temperature 10.5 keV

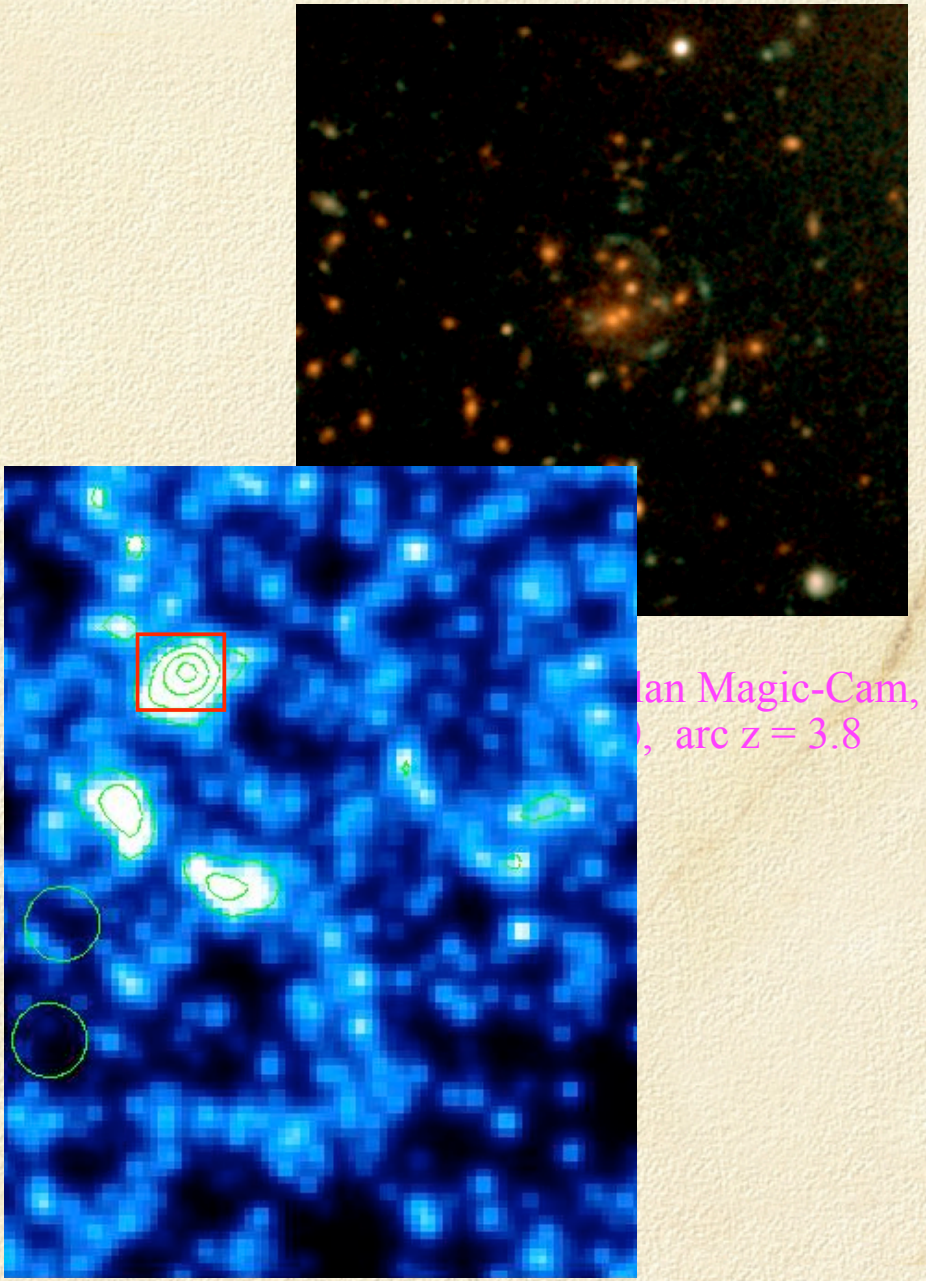
Velocity dispersion 1400 km/sec

Discovery of a Large scale structure at high-z

(Gilbank et al. 2008, ApJL, ;
arXiv:astro-ph/0803.1675)

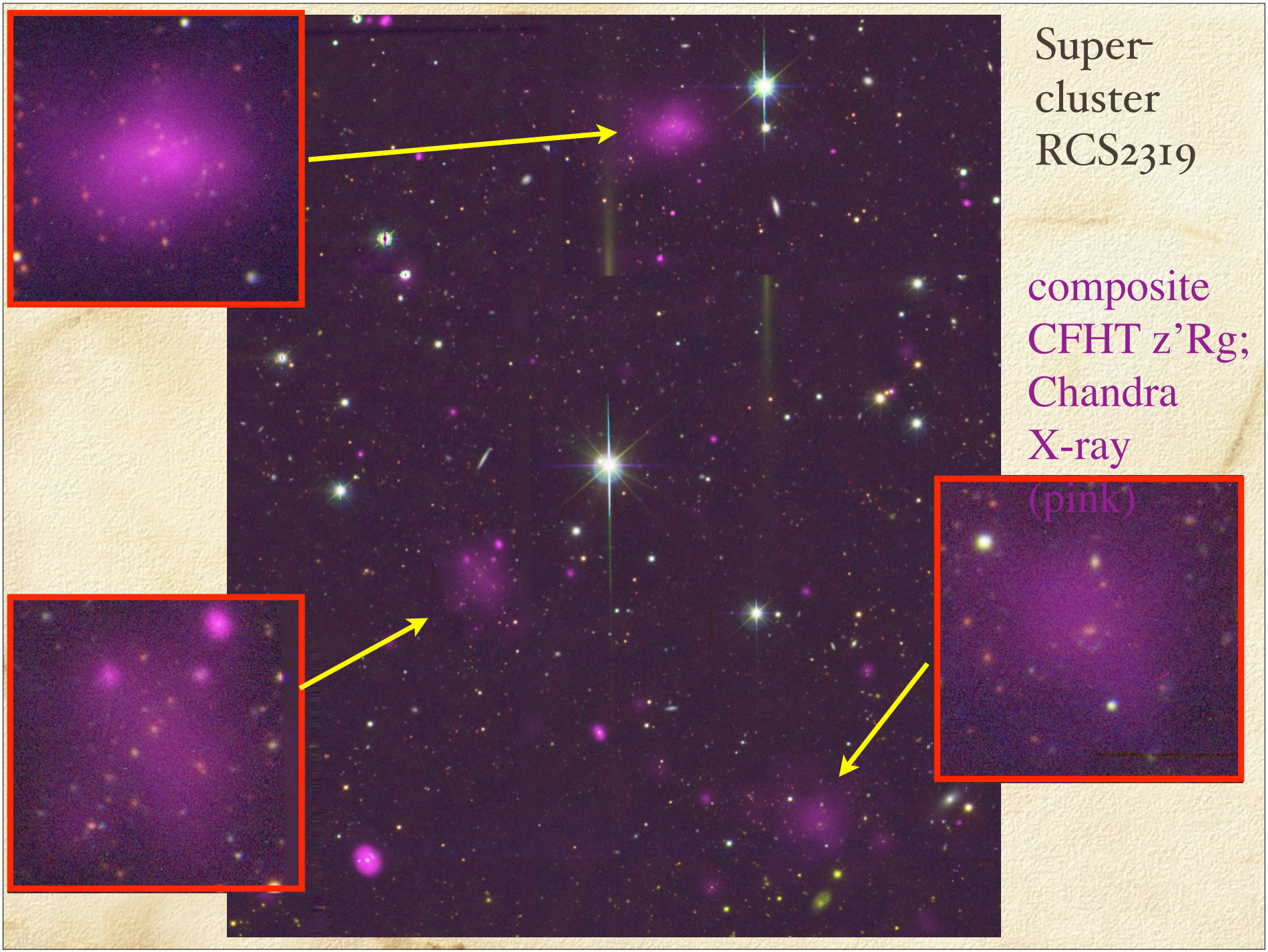


Chandra X-ray image

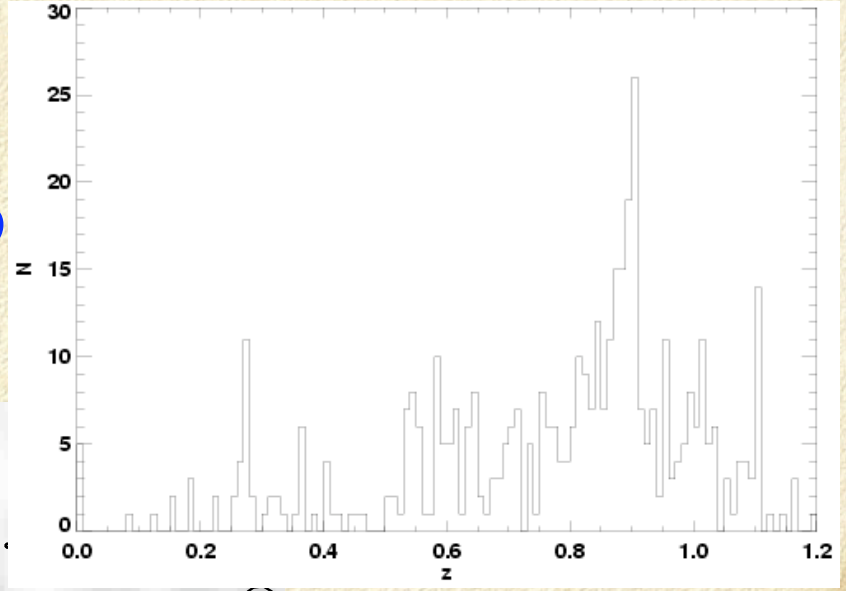


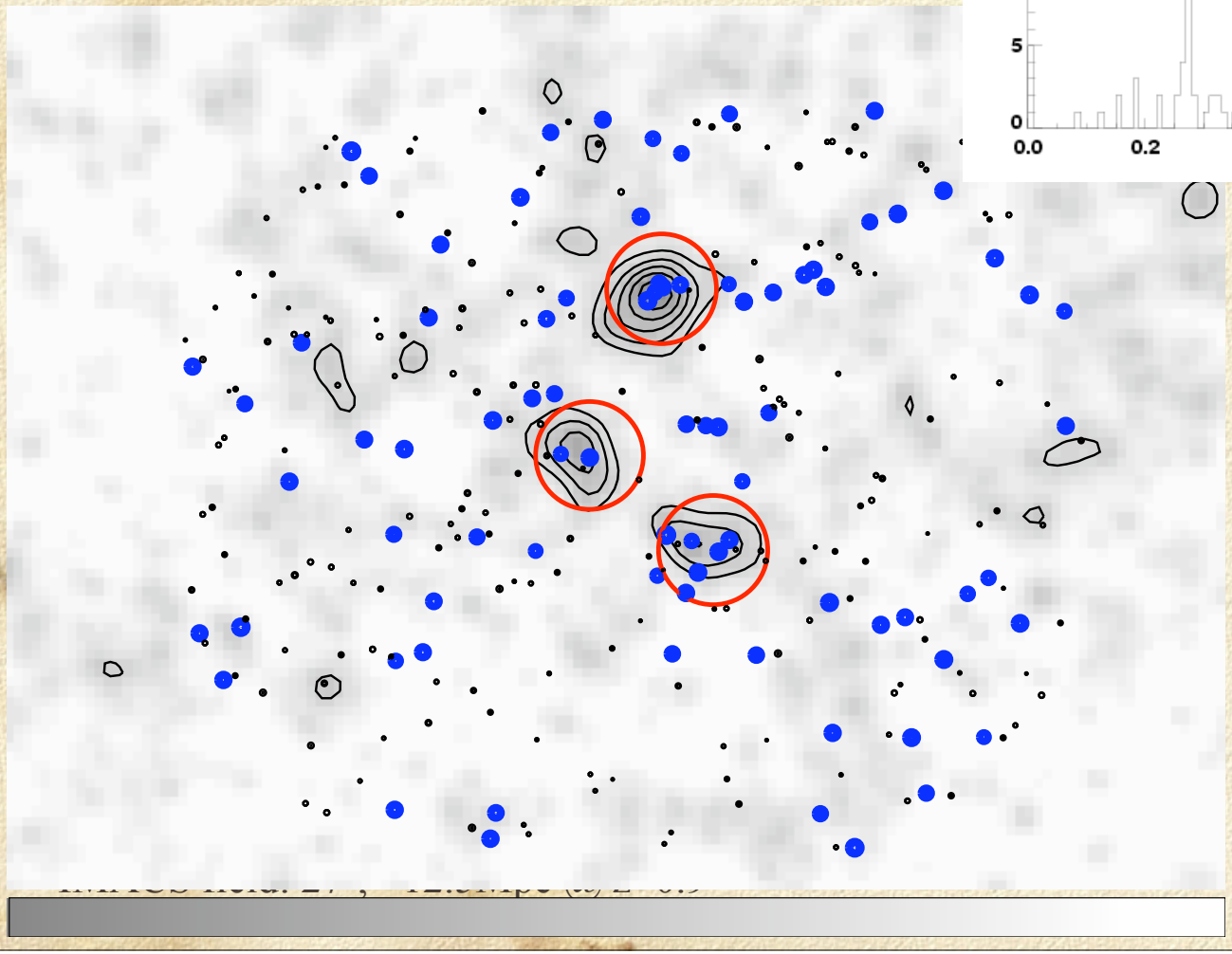
an Magic-Cam,
, arc z = 3.8

Red-sequence galaxy density, z=0.9 slice


Super-
cluster
RCS2319
composite
CFHT z'Rg;
Chandra
X-ray
(pink)

Magellan IMACS spectroscopy
one mask, ~420 redshifts
field size: 27'; ~13Mpc at z~0.9
the 3 clusters span ~6 Mpc





blue dots: z~0.9
black dots: "field"
red circles: X-ray positions
contour/gray scale: z=0.9 red sequence galaxy density

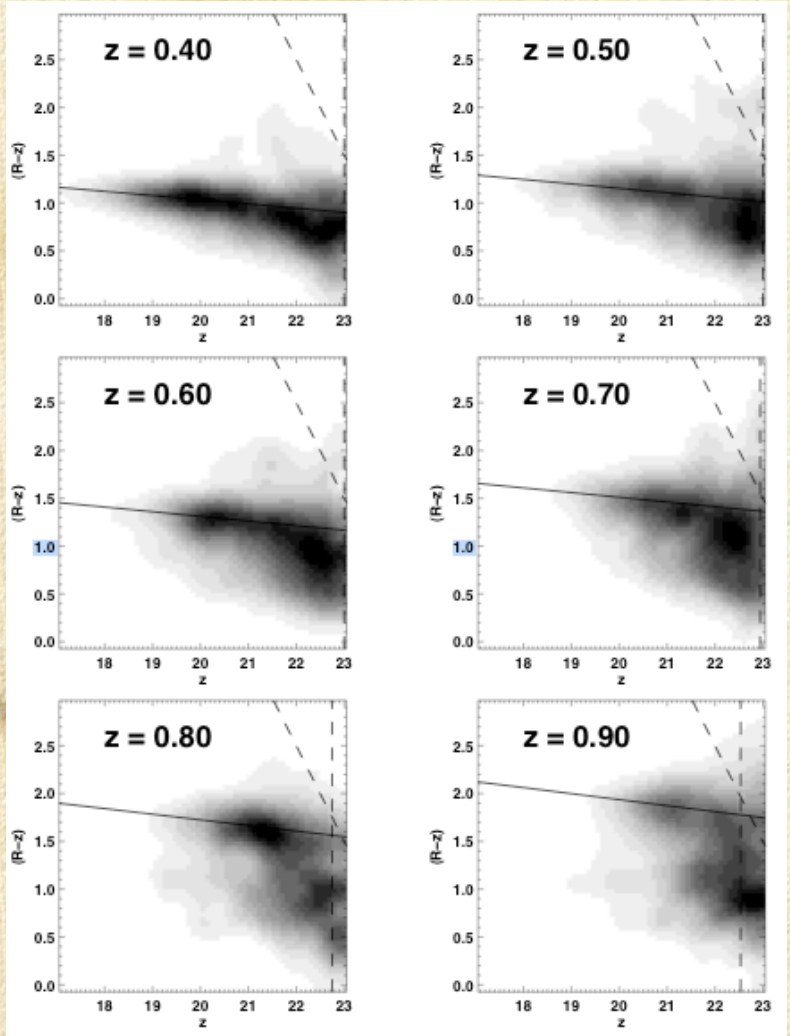
Additional IMACS spectroscopy (3500 slits)

Some Results on the evolution of cluster and group galaxies

Cluster Galaxy Luminosity Function

I. RCS1 z' band galaxy LF

Gilbank et al. 2008, ApJ, 673, 742

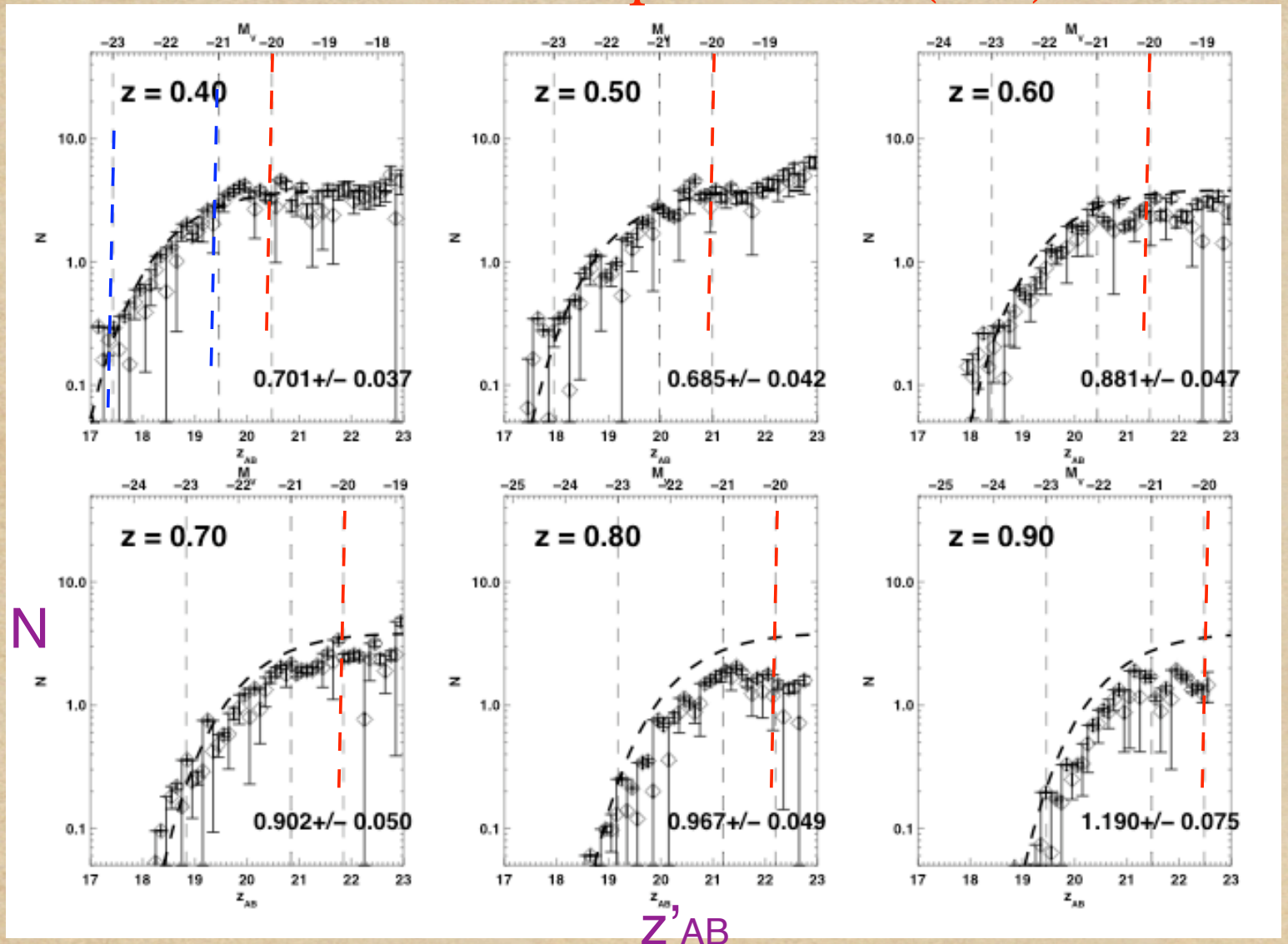


z' vs R-z' CMDs of stacked clusters, background subtracted

500 clusters, 30,000 red sequence galaxies

$0.35<z<0.95$

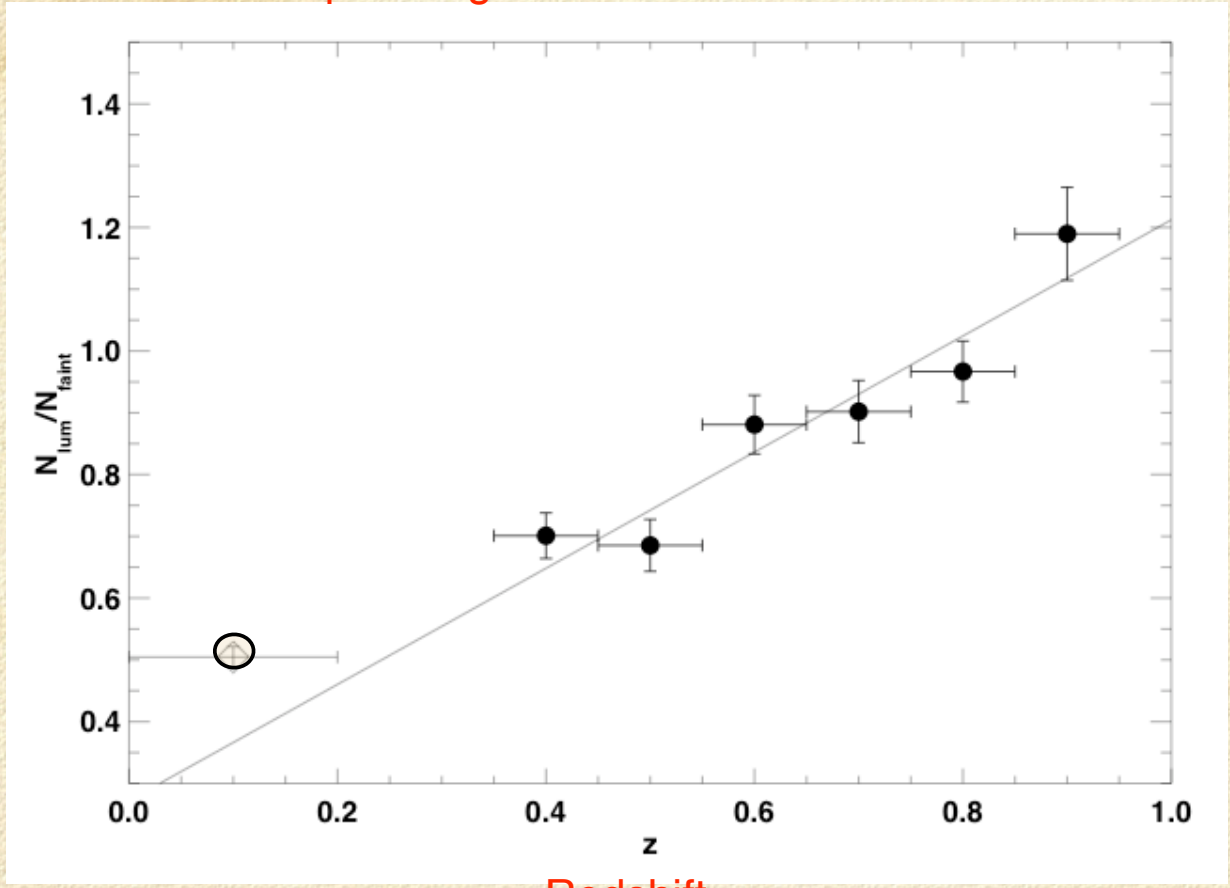
Red sequence LF (z'_{AB})



The Build-up of Faint Red Galaxies

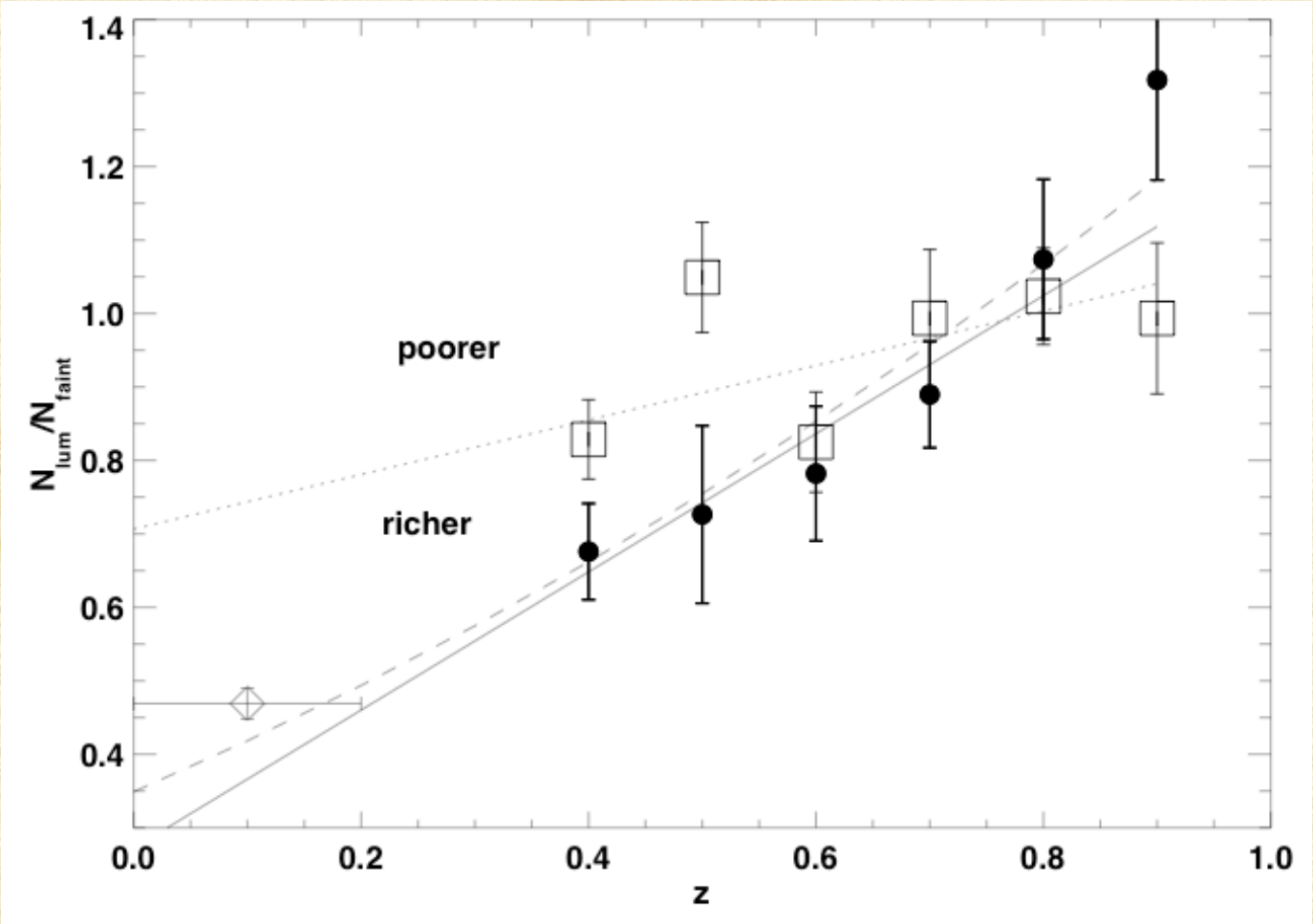
Ratio of bright (M<-21) to faint (-21<M<-20)
red-sequence galaxies as a function of redshift

$\frac{N\_bright}{N\_faint}$



Redshift

The build-up of the faint end LF of the red galaxies is consistent with having the blue cloud galaxies moving up to the red-sequence with decreasing redshift:
"down-sizing" interpretation of galaxy formation/evolution;
also see De Lucia et al 2007

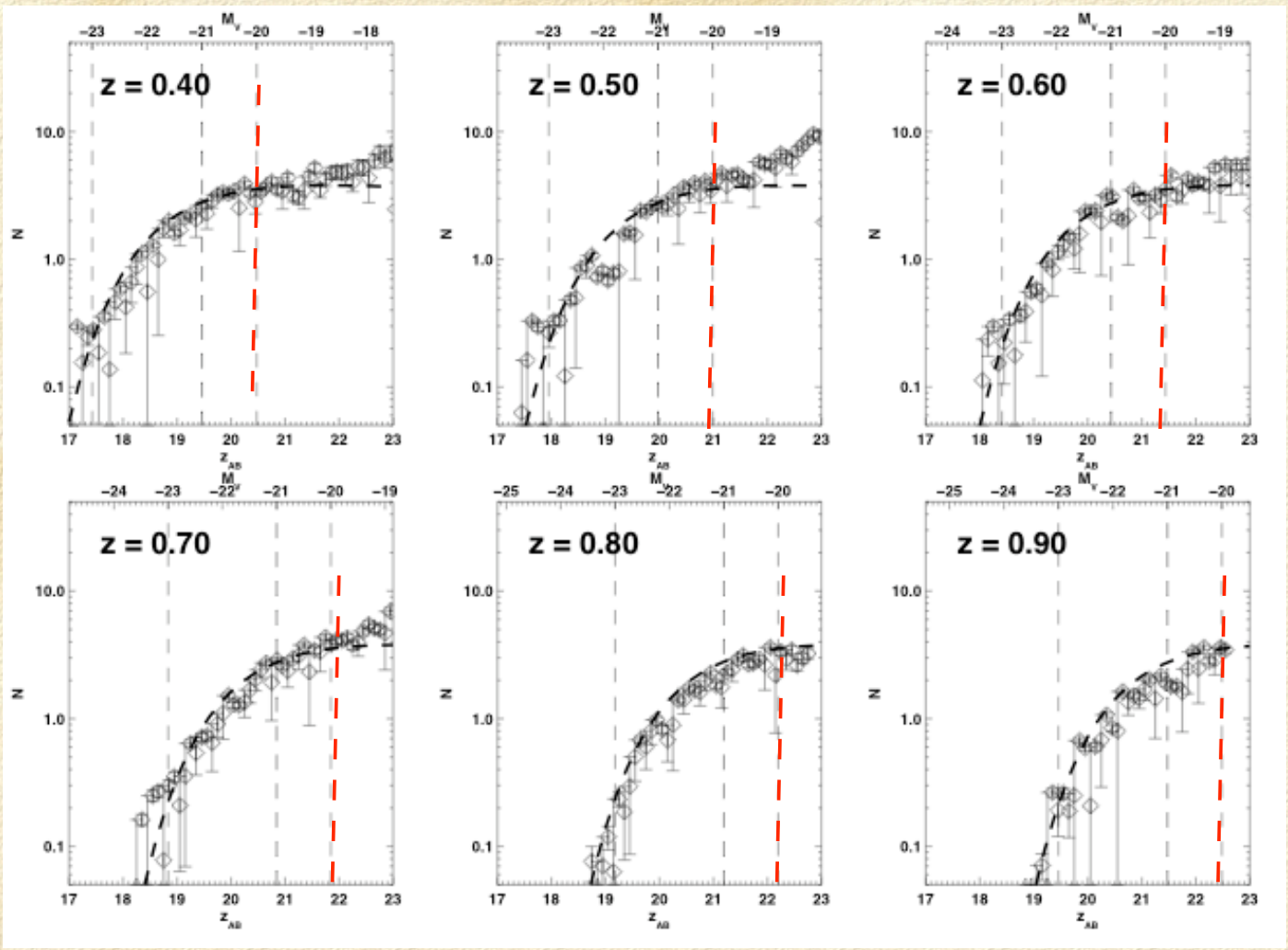


Rich: Bgc>800
(~650 km/s)

Poor: Bgc<500
(<500 km/s)

Dividing the sample into rich and poor clusters
- cluster halo mass influence build-up of faint end of red-sequence?

RCS2: 10 x larger sample size, to z~0.2



Total LF: dashed line: model ~corrected for star formation history (4Gy e-folding for blue galaxies, passive for red) and k-corrected to z=0 (roughly equivalent to total stellar-mass function).

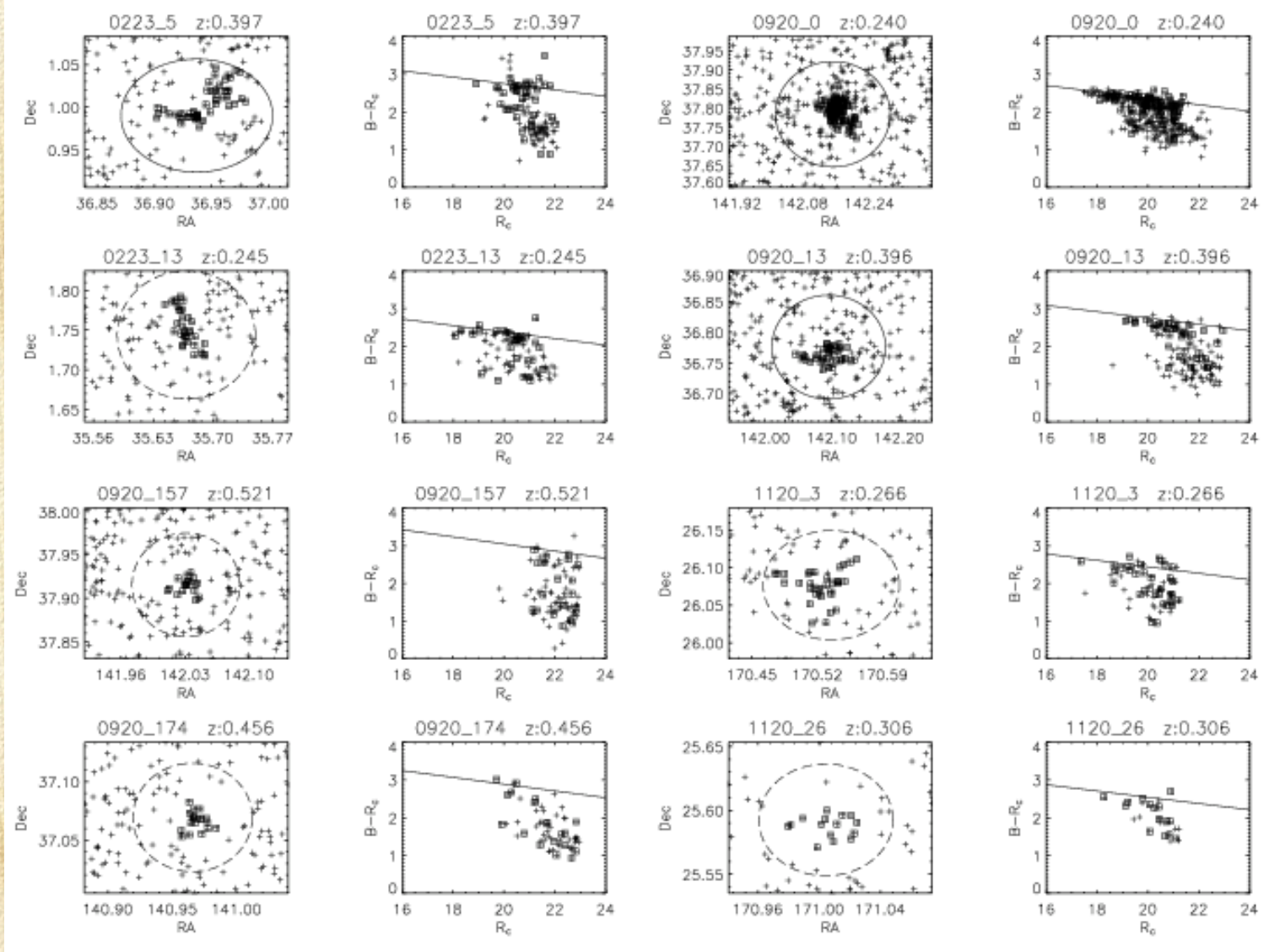
Galaxy Groups from RCS-I [I-Hui Li, et al.]

- z'RVB photo-z, 32 sq deg
- "probability-FoF" group finding algorithm (Li & Yee, AJ, 135, 809)

- total sample: 1220 groups; 0.2<z<0.55
  - ≥8 members (M*+2)
  - roughly halo mass limit ~2×10^{13} M_{sun}
  - ~complete sample to z~0.47 (~1000 groups)

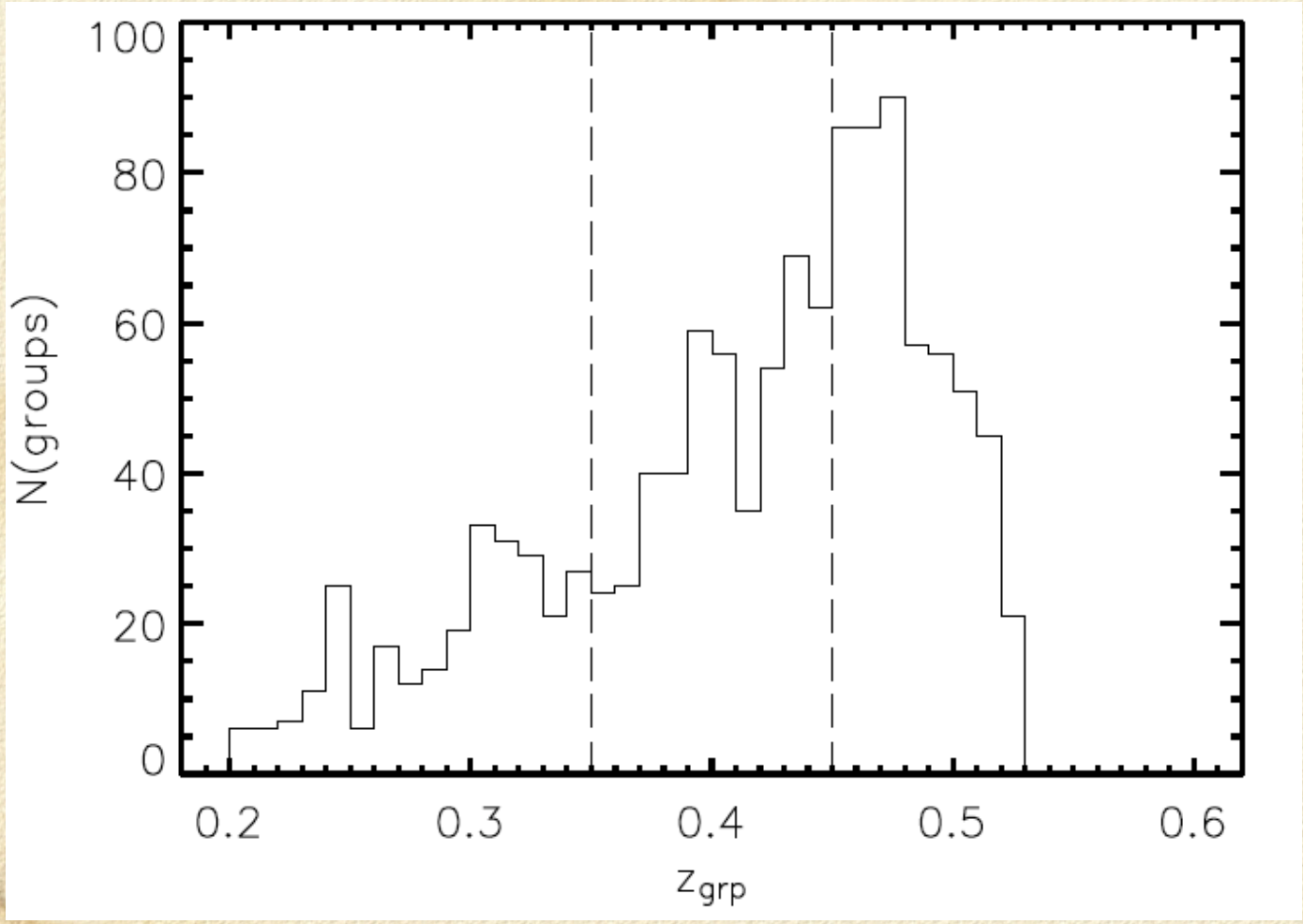
- AAT/AAOmega observations to produce a spectroscopic sample ~325 groups

Examples of RCS1 groups

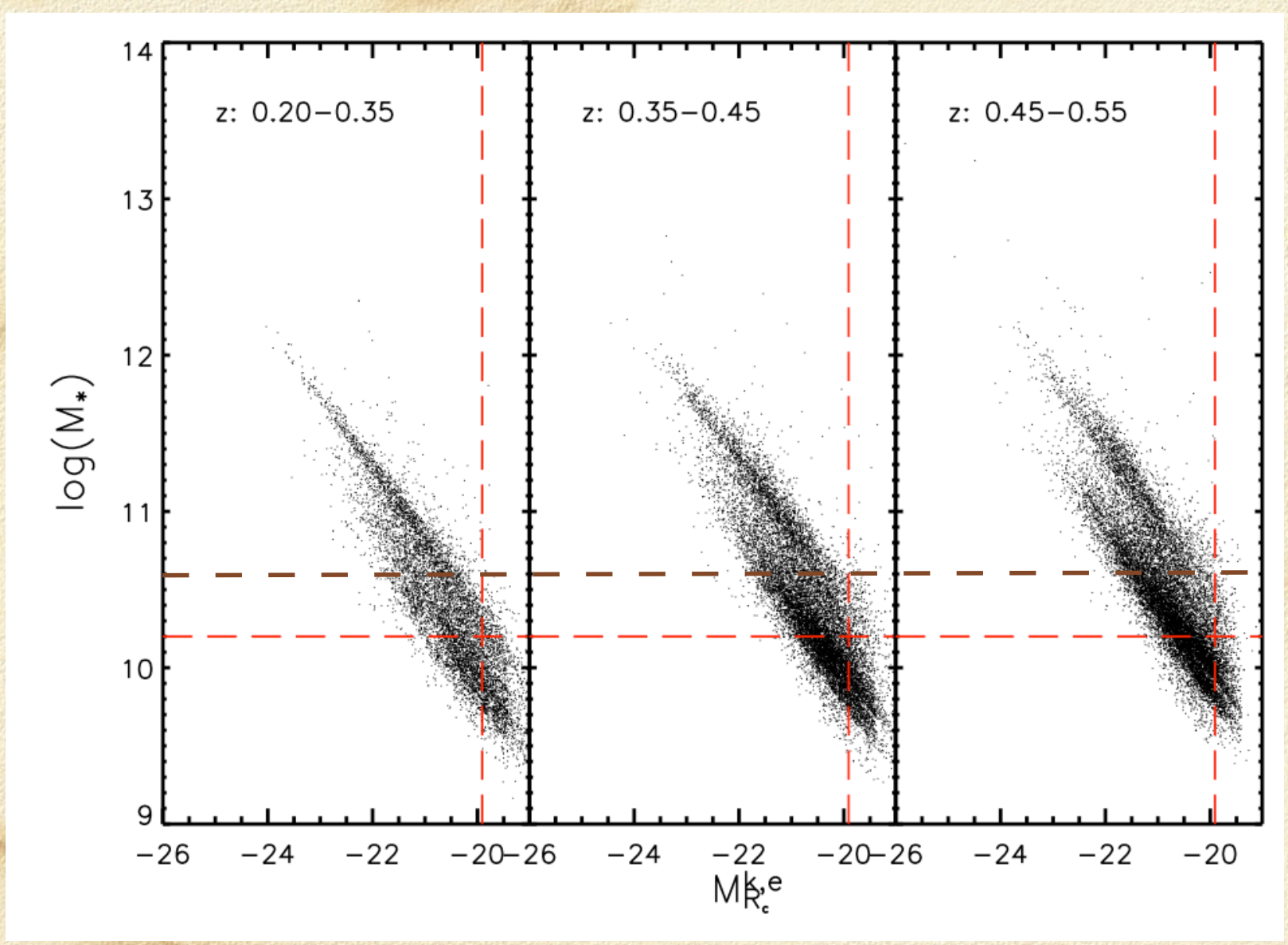


Circle: 1R200; squares: linked group members

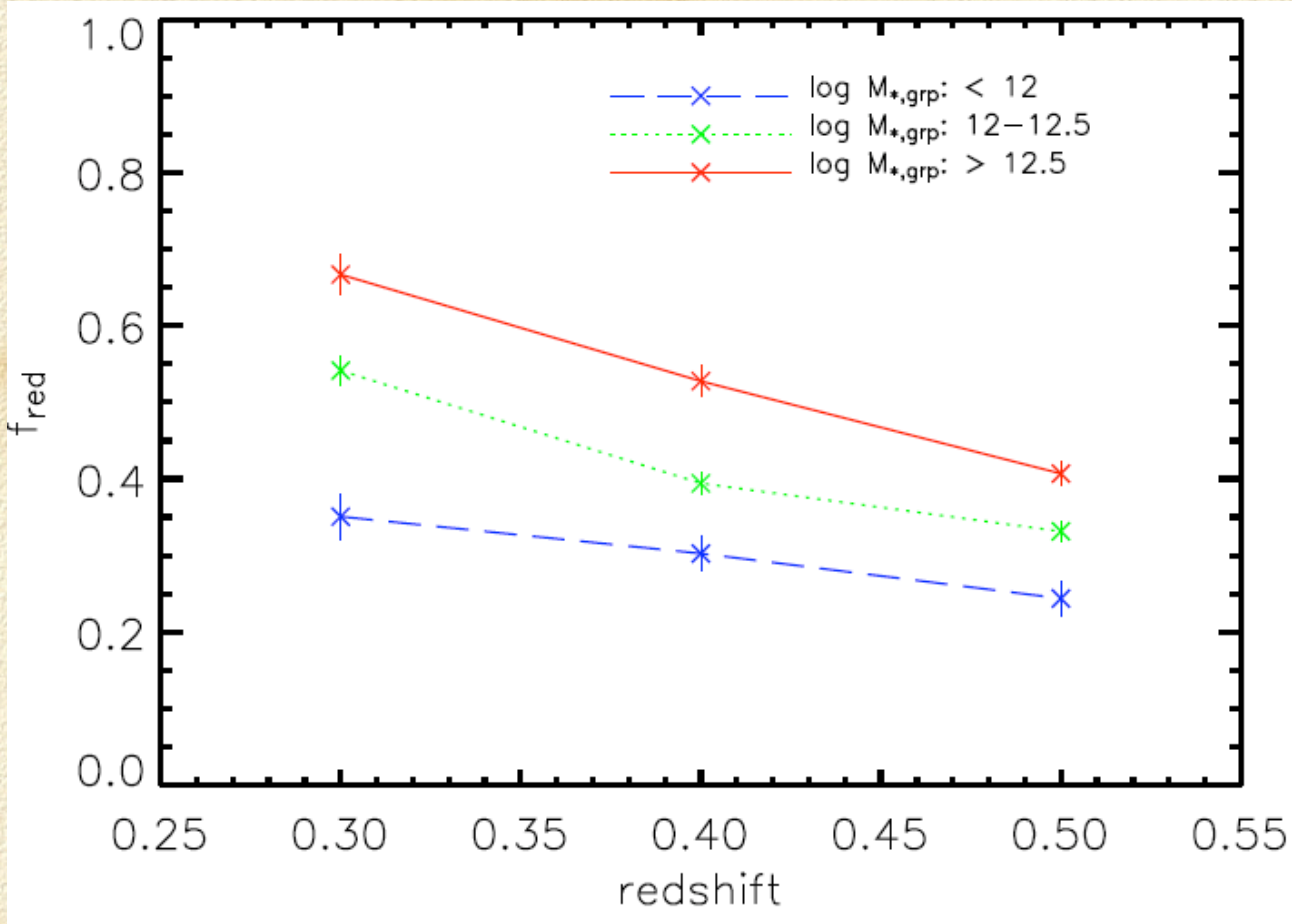
CMR: B-R vs R (observed), solid lines: theoretical red-sequence



Redshift distribution of group sample



Stellar mass (based on R and B-R color, Bell et al.)
vs absolute R mag (k- and e-corrected)

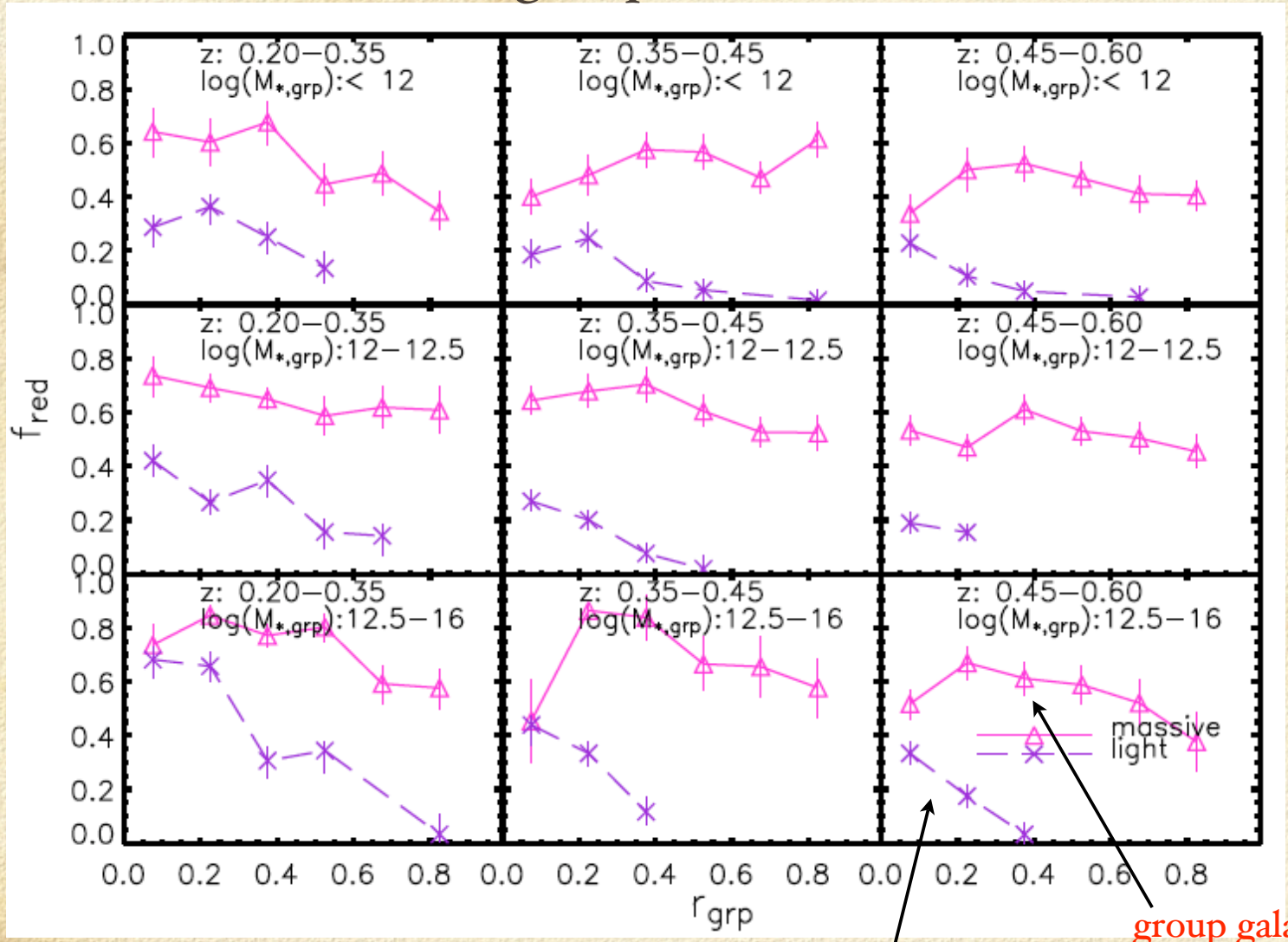


Groups are divided into different "mass" bins using total stellar mass

Butcher-Oemler effect for groups of different total stellar masses

Red fraction vs group-centric radius

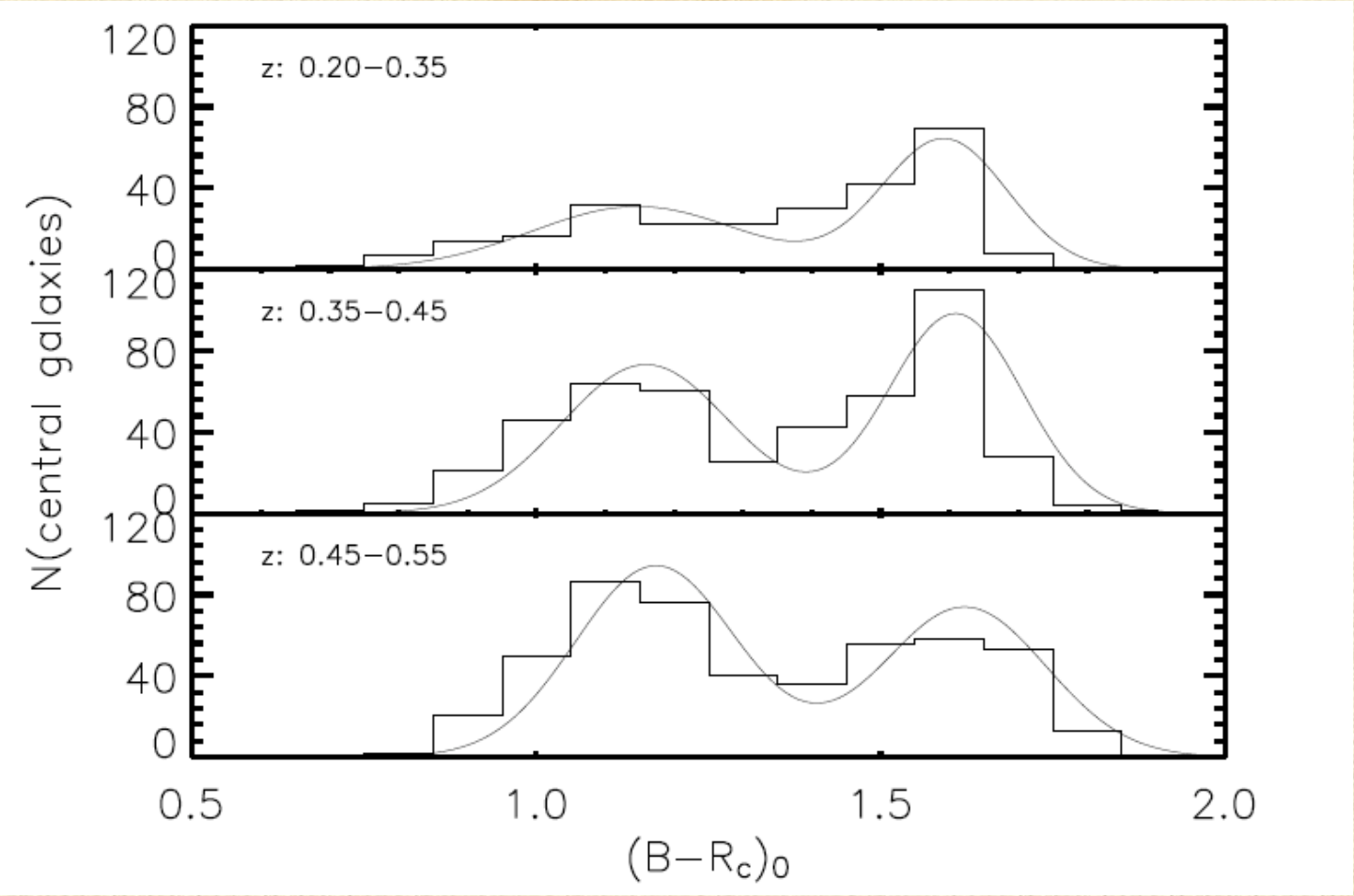
More massive groups



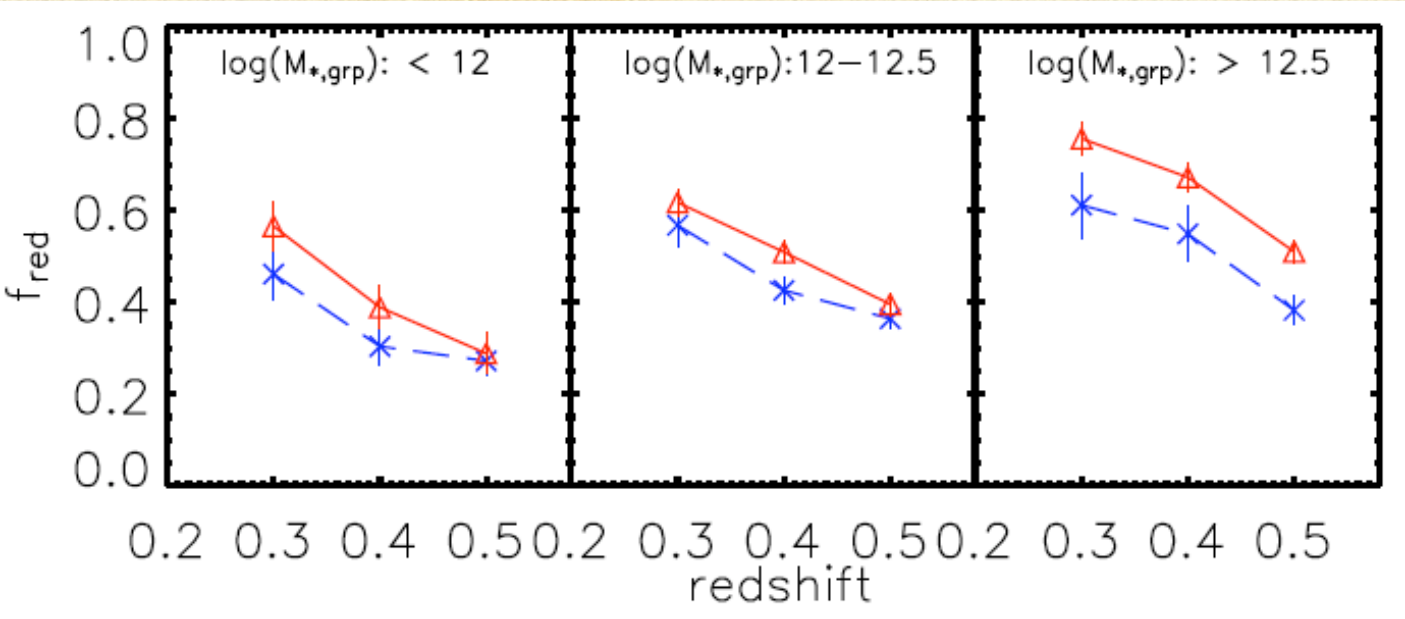
Higher redshift →

group galaxies with log M*<10.6

group galaxies with log M*>10.6



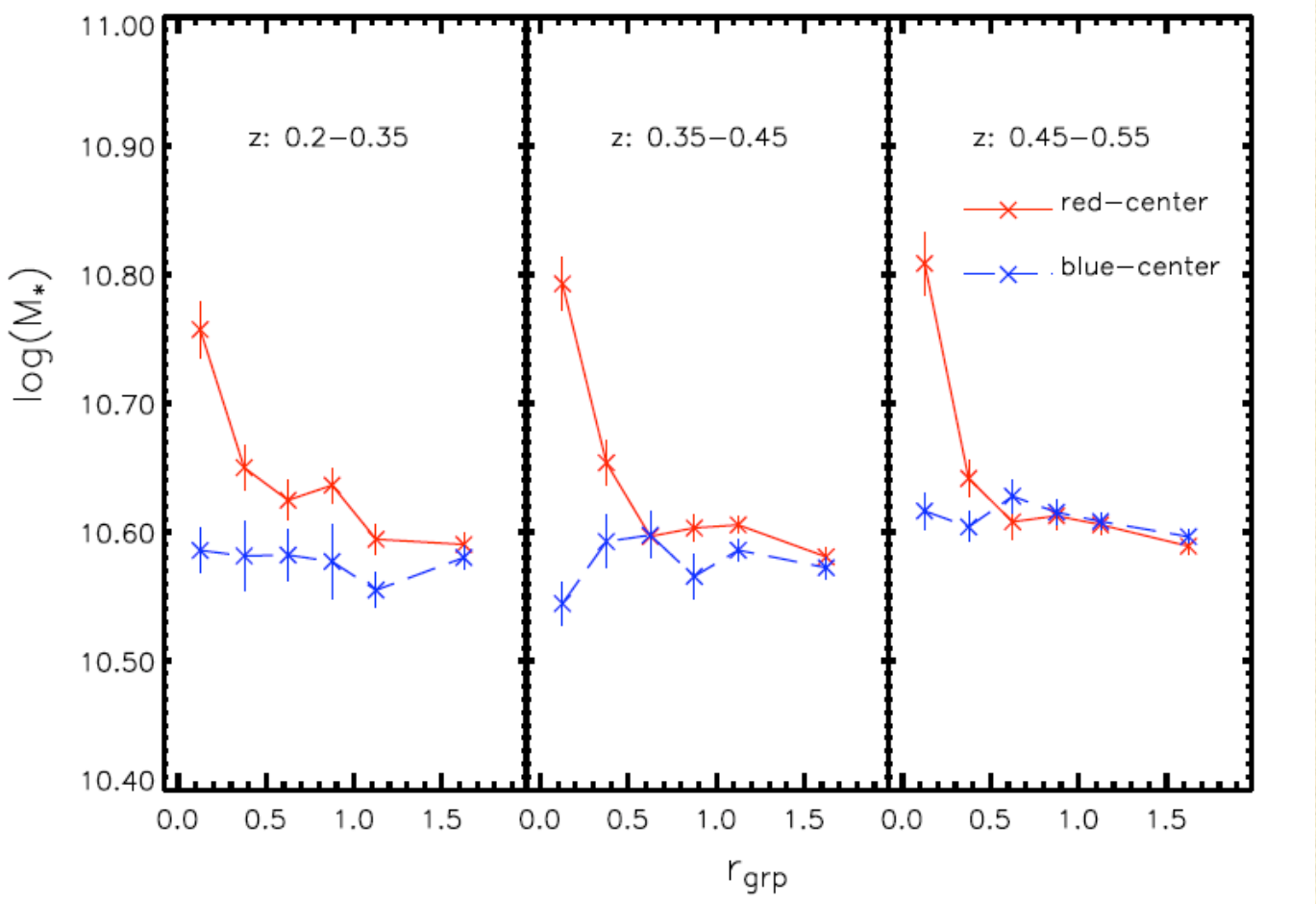
Color distribution of central group galaxies, divide groups into “blue-central” and “red-central” samples



- "red-central" groups have higher red fraction

- Weinmann et al. (2006) found a similar effect with SDSS groups at low z; they called this "galactic conformity"

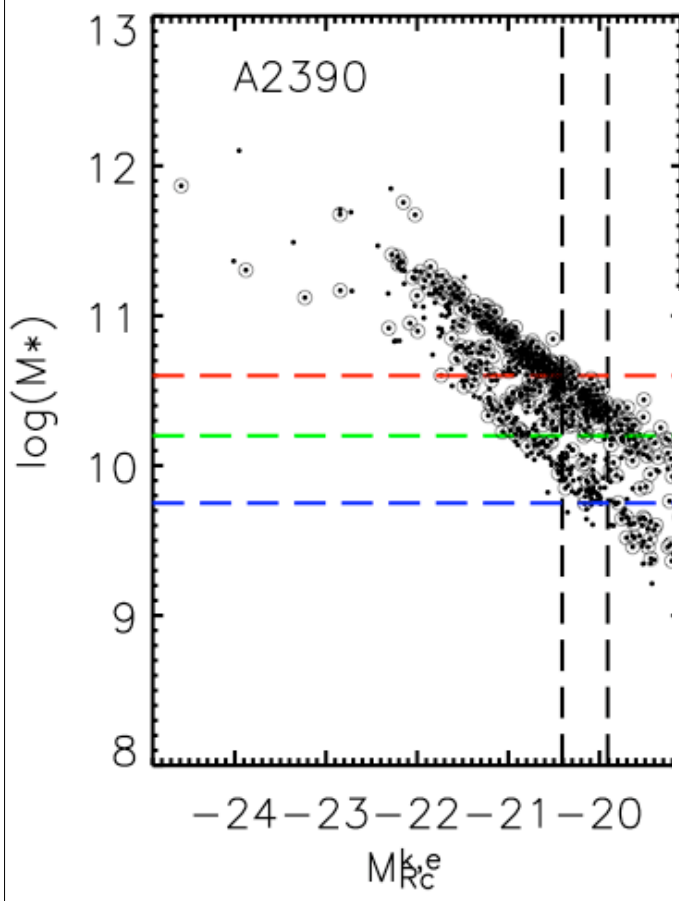
Average stellar mass per galaxy vs group-centric radius

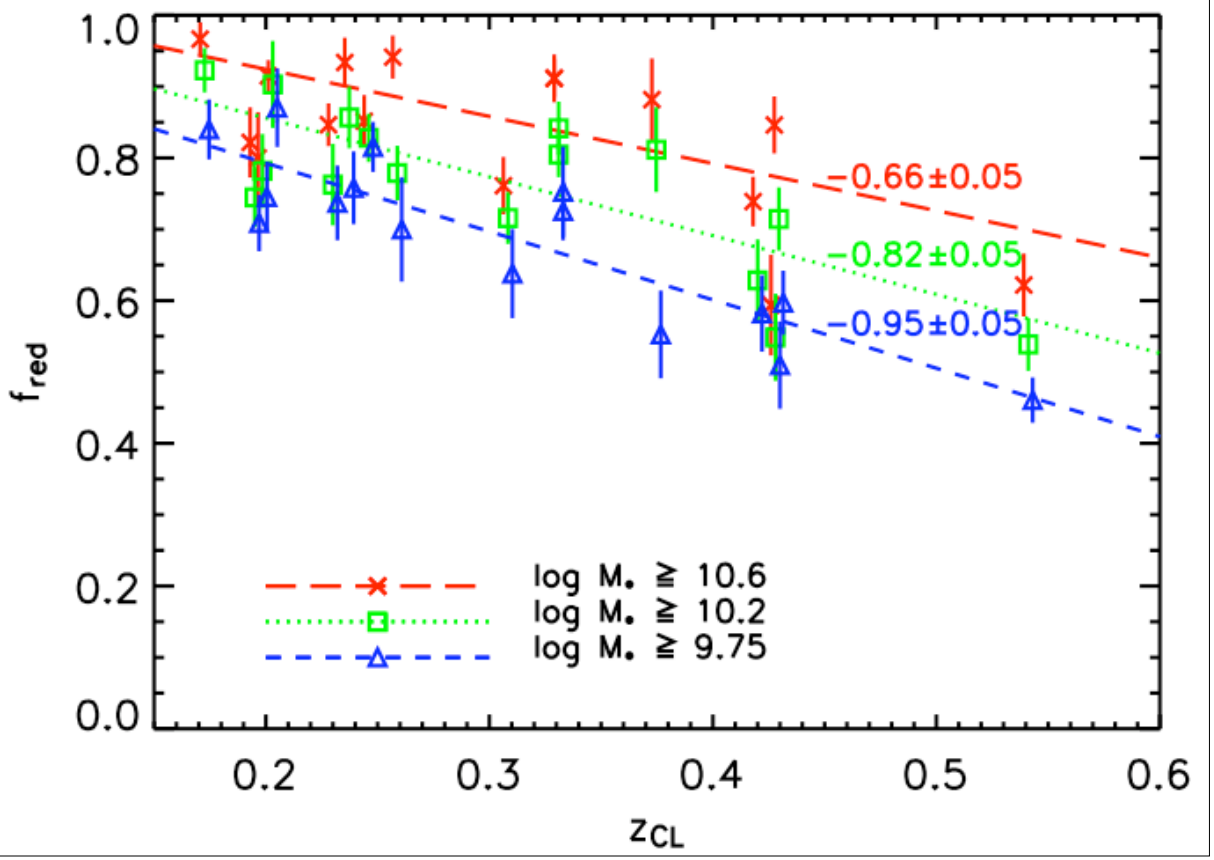


- average stellar mass is basically flat, except "red-central" groups have a strong increase in the core.

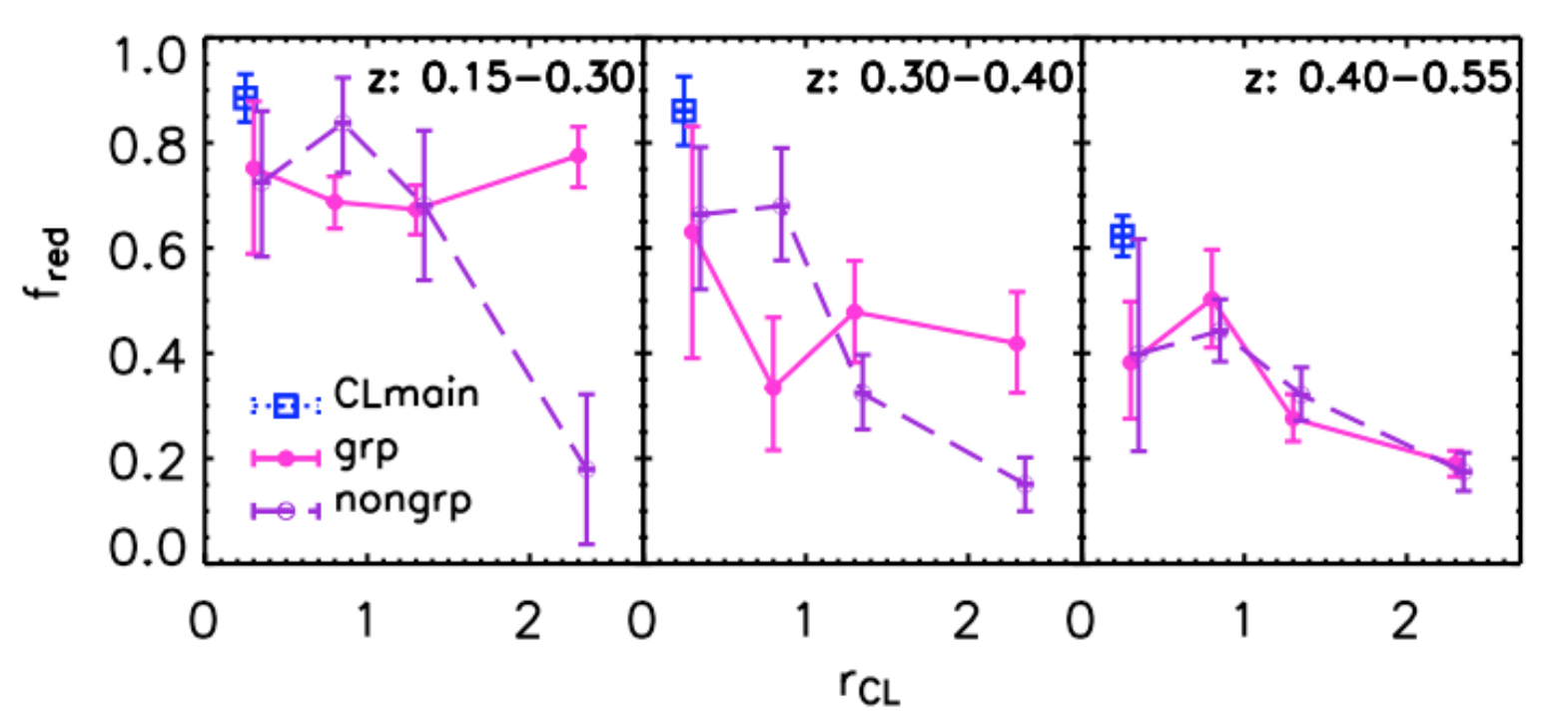
CNOC1 Cluster Galaxies:
16 clusters (z=0.17 to 0.55); photo-z (CFHT 12k)

(Li, Yee, & Ellingson, 2009, ApJ, in press)



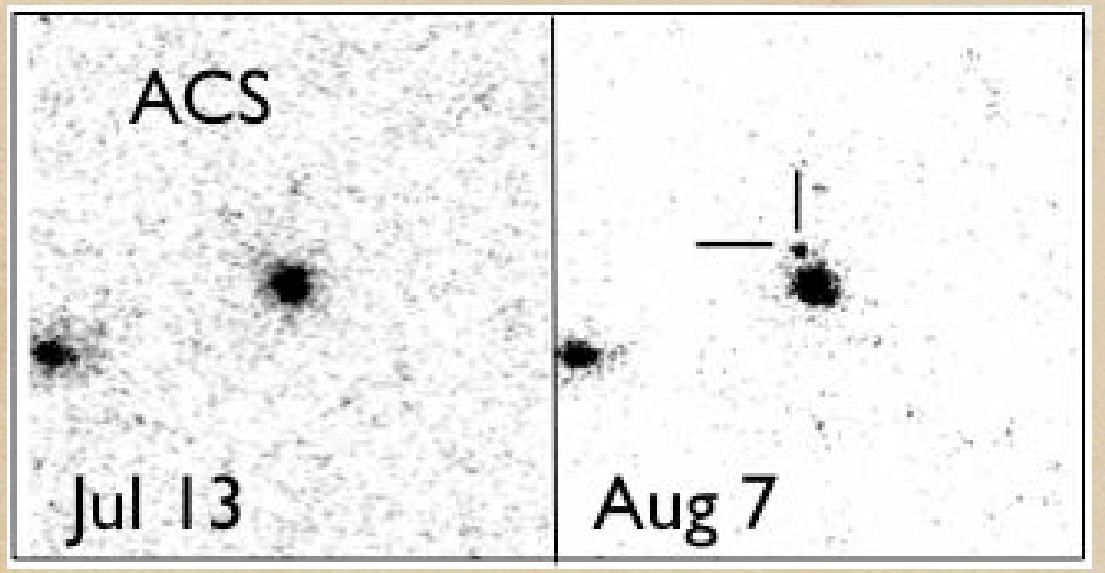


Evidence of pre-processing



Red fraction of galaxies in cluster redshift space;
groups selected by pFoF (≥8 members),
non-groups: ≤ 2 members

Red Squence at z>1
Deep HST images of z~1 RCS clusters

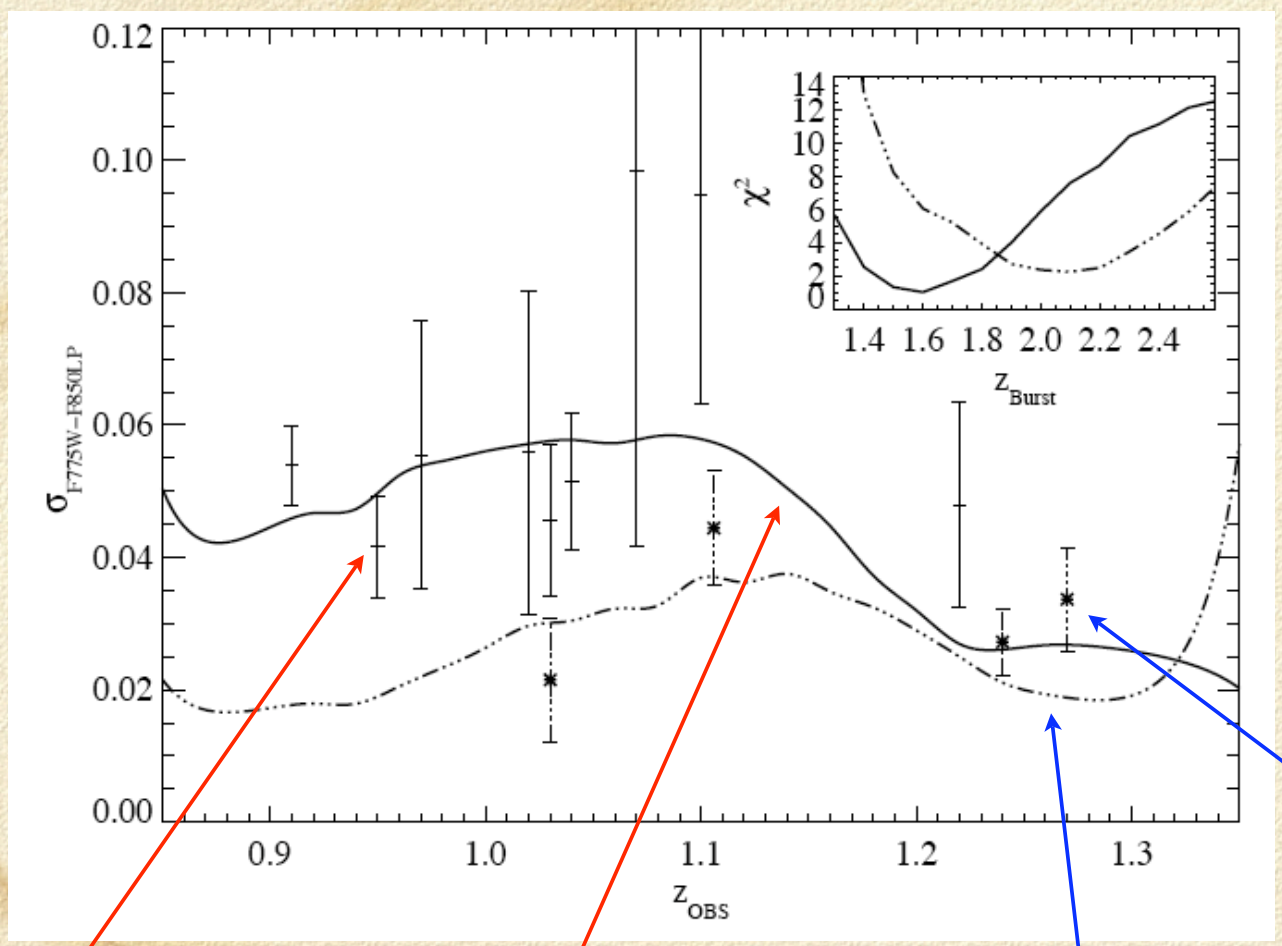


HST z~1 cluster SNe program (PI: Perlmutter)

example: SN in RCS 0221, cluster early-type galaxy, confirmed z = 1.02

Dispersion of Red-sequence

(Koester et al 2009, arXiv:0903.2478



Optical/IR selected clusters appear to be younger than X-ray selected clusters

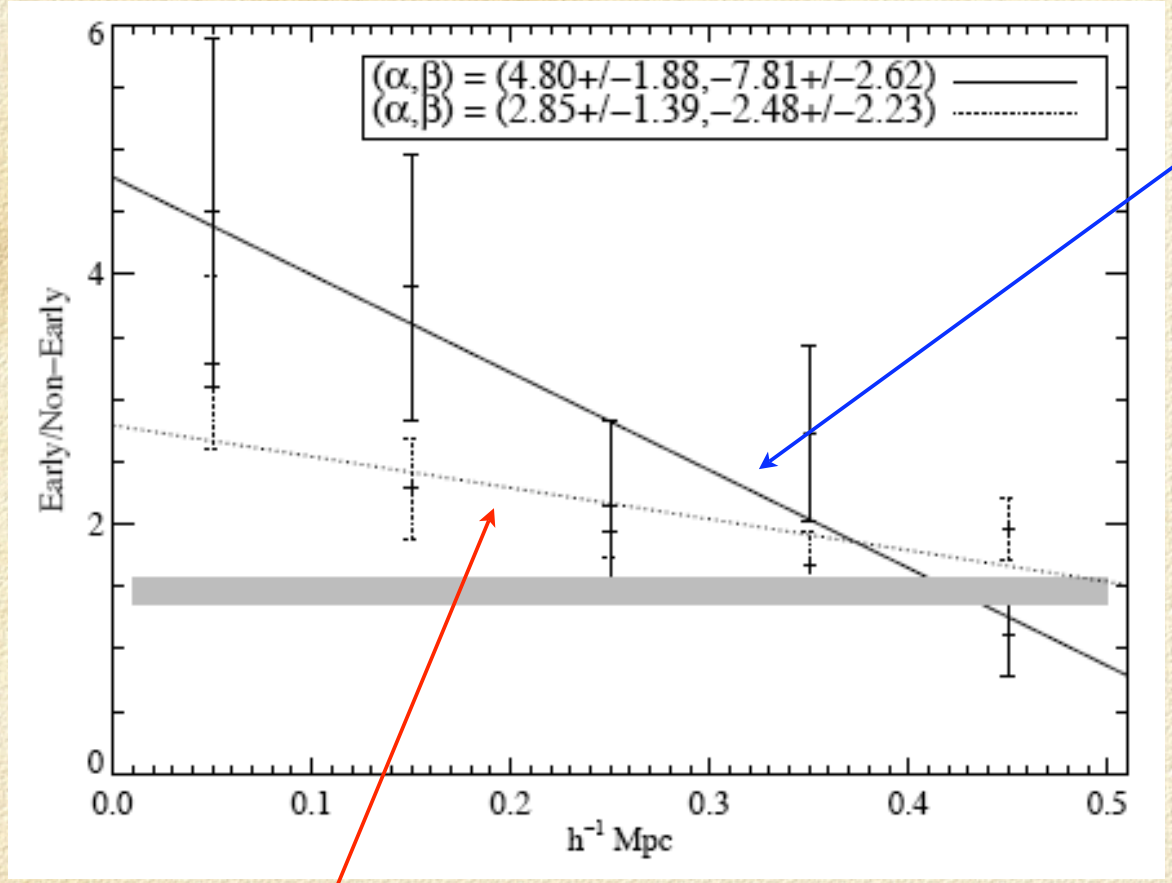
X-ray selected clusters

RCS/Optically-selected clusters

Model: z_sf>1.6

Model: z_sf>2.1

Early/non-early type (morphological) ratios



X-ray selected clusters

RCS/Optically-selected clusters

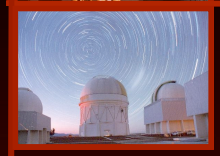
The Search for z >1 Clusters

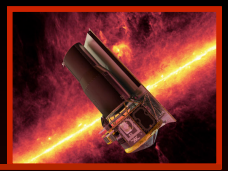
- the RCS technique is optimized when the 2 filters straddle the 4000A break.
- requires IR images for z>~1.
  - the cluster redshift "desert": 1.3<z<2

The SpARCS survey (Adam Muzzin, G. Wilson, Yee, +...)

- combining Spitzer SWIRE 3.6μm data (50 sq deg) with deep z' band (~2hr integration)
- CFHT (8 nights) + CTIO (15 nights); 6 patches
  -- search for clusters to z~1.8
  -- catalog of ~200 clusters with z>1

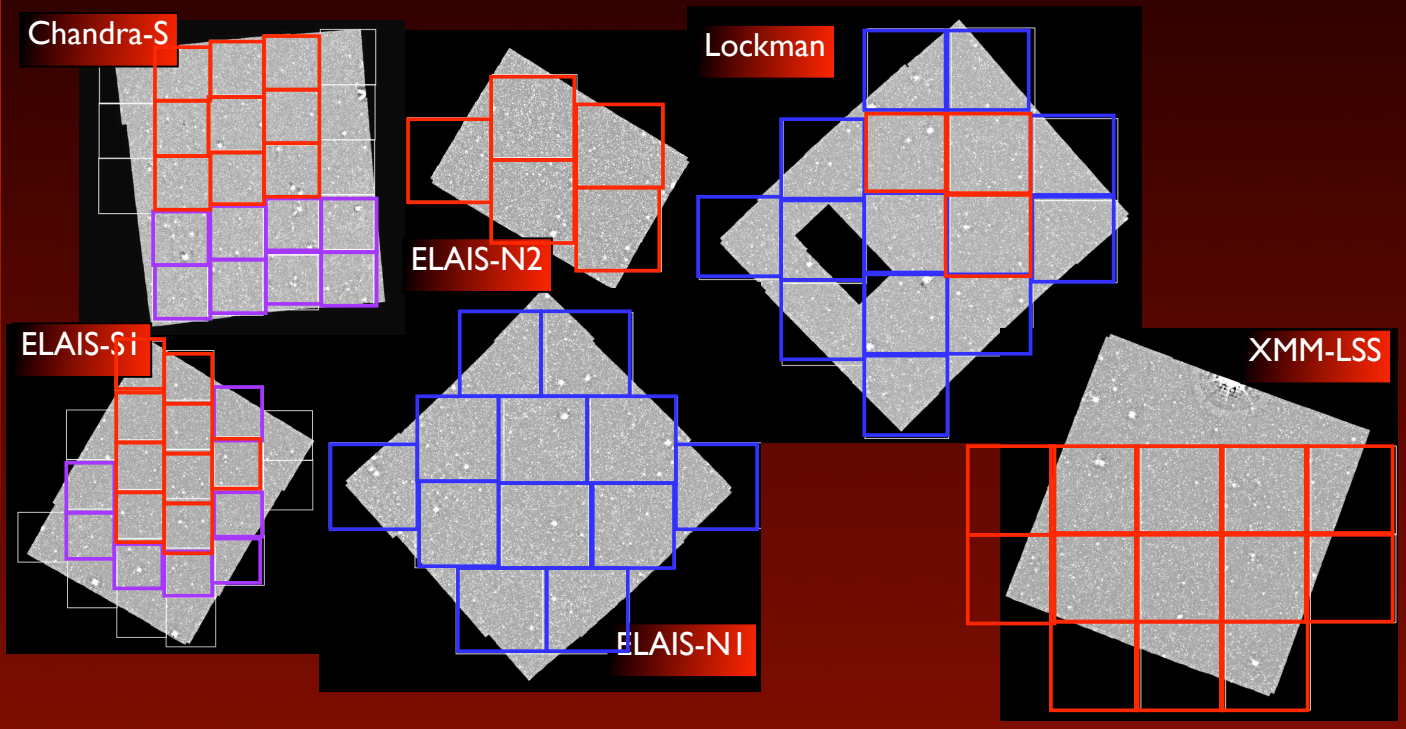
Muzzin et al. 2009, ApJ, in press
Wilson et al. 2009, ApJ, in press





Current area: Reduced, 22/48 deg^2

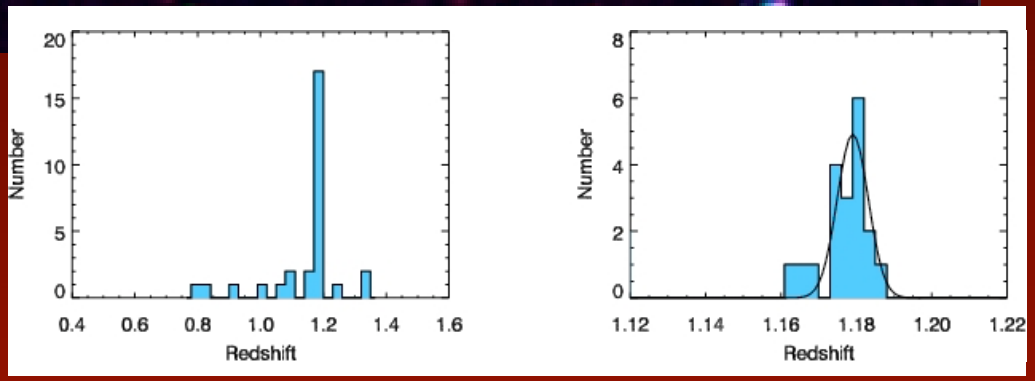
In hand, 24/48 deg^2



SpARCS ELAISN2-109

19 high-confidence members

z = 1.18



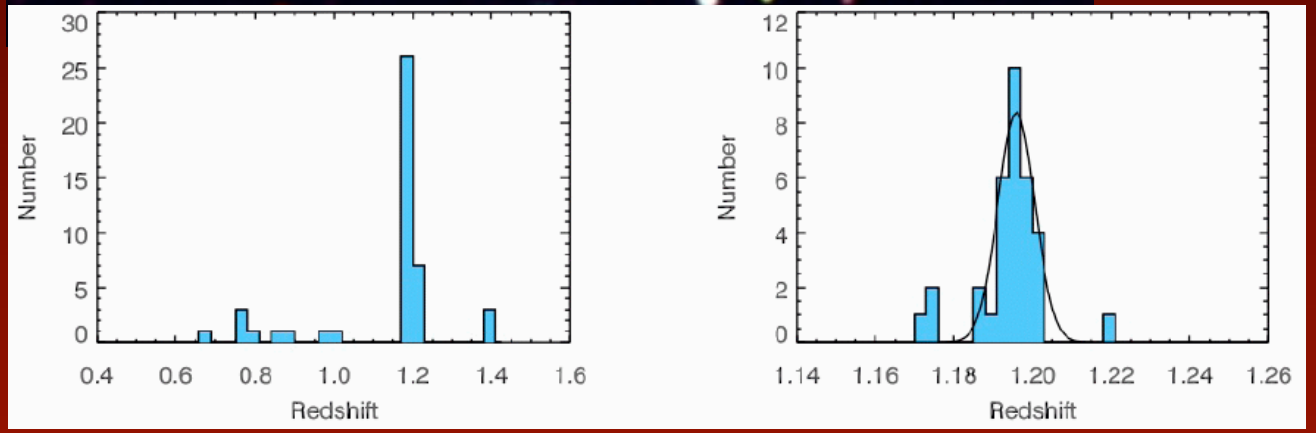
z = 1.1796

σ = 490 ± 140 km/s

SpARCS ELAISN2-117

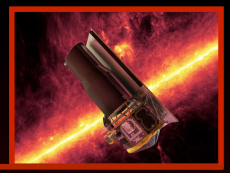
33 high-confidence members

z = 1.20

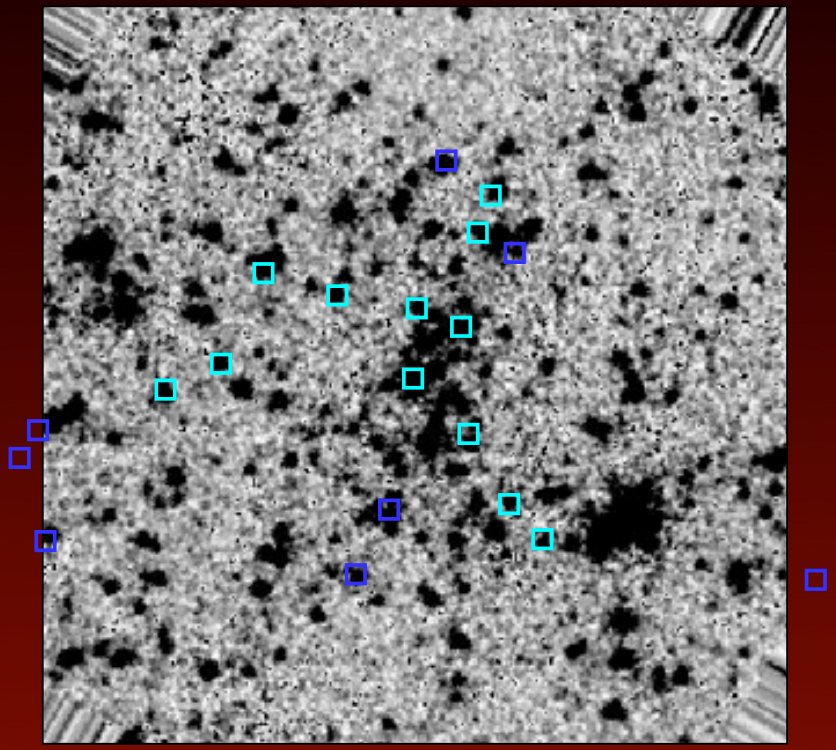


z = 1.1960

σ = 650 ± 150 km/s



10 Hr on-sky N&S mask
with GMOS-S



10 High confidence members,
z = 1.34
vel dispersion = 1050±230 km/s

Summary:

- Fireflies are cool

- The optical/IR red-sequence method (and its variants) is a powerful and efficient method for creating large, well-characterized samples of cluster galaxies, covering up to z~1, and to z~2 with deep IR images.
- Large samples of lower mass groups can be generated using photo-z

- The RCS1 sample shows that the build-up of the faint end of the red-sequence occurs through out $0.1<z<1$, and there is evidence of "cluster down-sizing" in the build up.
- The dispersion of the red-sequence at $z>1$ is a useful tool for constraining cluster galaxy formation history; some differences between optical- and x-ray may exist
- galaxy groups show strong signs of pre-processing before falling into cluster environments
- population properties of group galaxy have a complex dependence on group halo mass and stellar mass, and also on the status of the central galaxy.

- Still larger samples of clusters covering a good redshift and richness range are needed for the study of the evolution of clusters, groups, and their member galaxies.