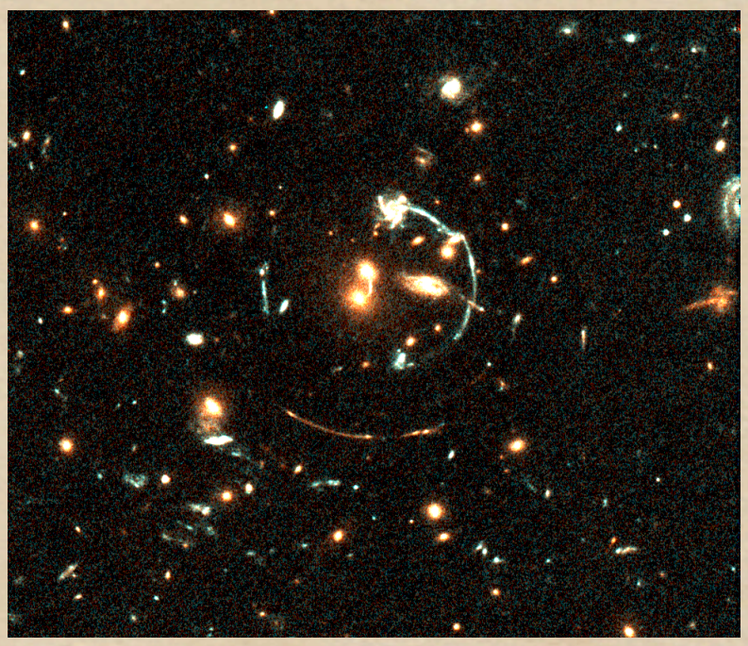
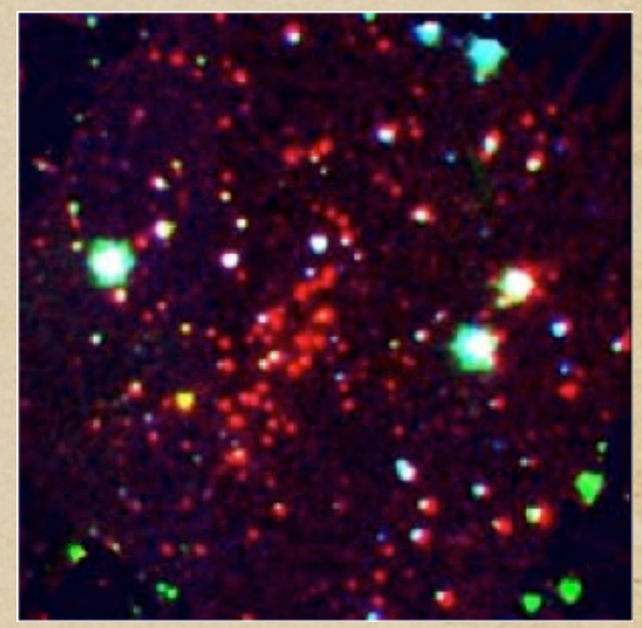
Chicago, Dec 2007

Optical/IR Surveys for High-Redsfift Galaxy Clusters





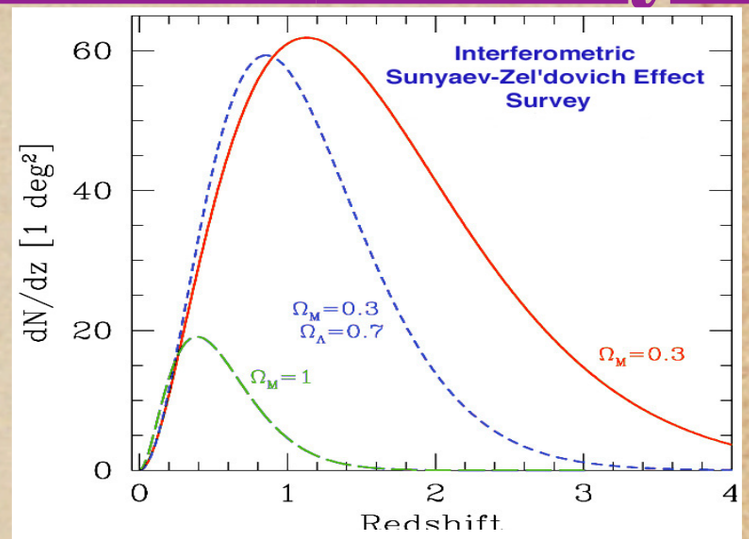
Howard Yee
Dept. of Astronomy & Astrophysics
University of Toronto

What I will talk about:

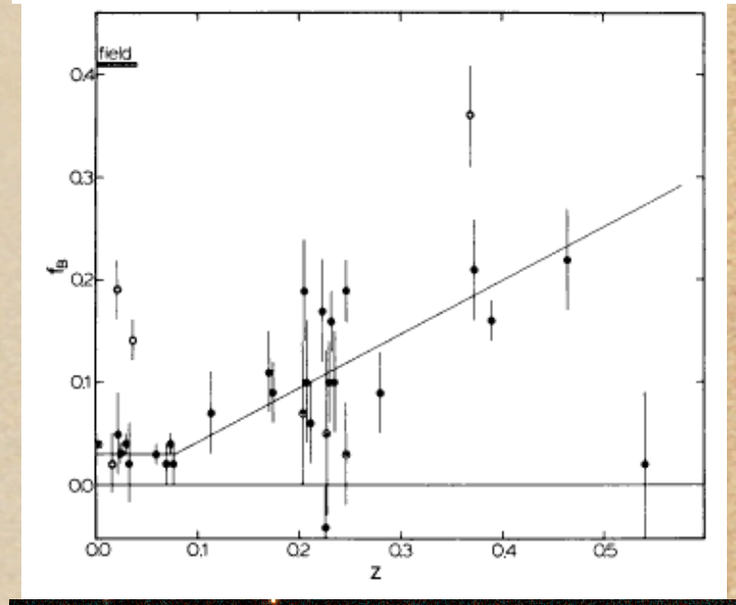
- Why high redshift clusters
- Optical/IR cluster finding techniques, a brief history
  the red-sequence method and variants
- Modern high-redshift optical/IR cluster surveys
  RCS1, RCS2, IRAC Shallow Survey, SpARCS
- some scientific results:
  - ✦ a determination of Ω_m , σ_8
  - ✦ Chandra-X-ray obs. of RCS clusters
  - ✦ a supercluster at z=0.
  - ✦ the evolution of z' band cluster galaxy LF (z~0.3-1)

Scientific motivation for galaxy cluster surveys:

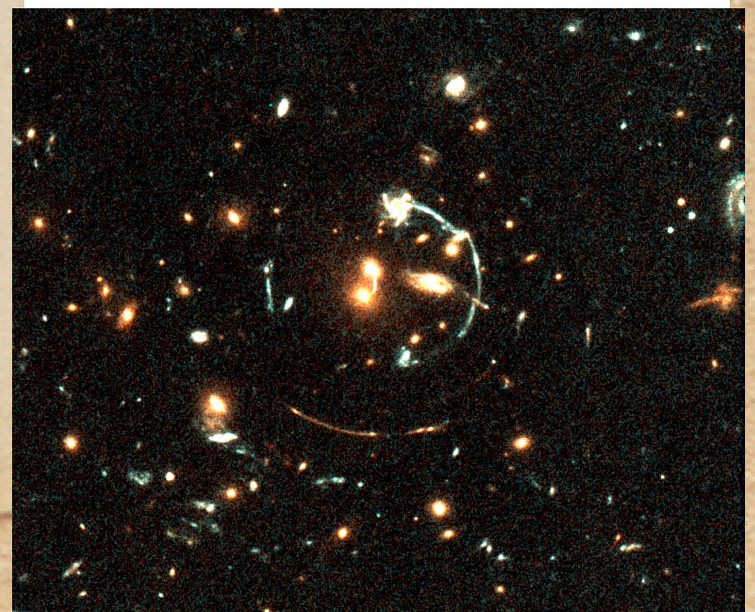
1. Growth of structures: the measurement of cosmological parameters:
   Ω_m , σ_8 , w



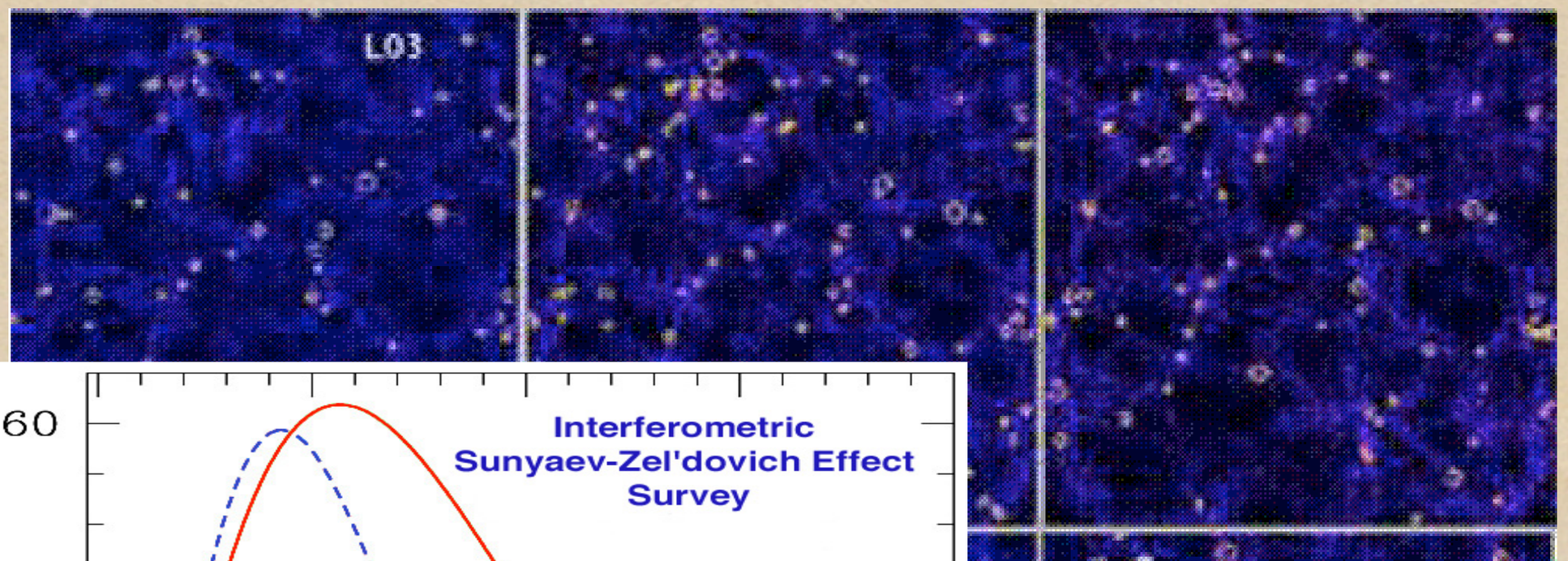
2. Galaxy evolution and cluster physics: effects of environment

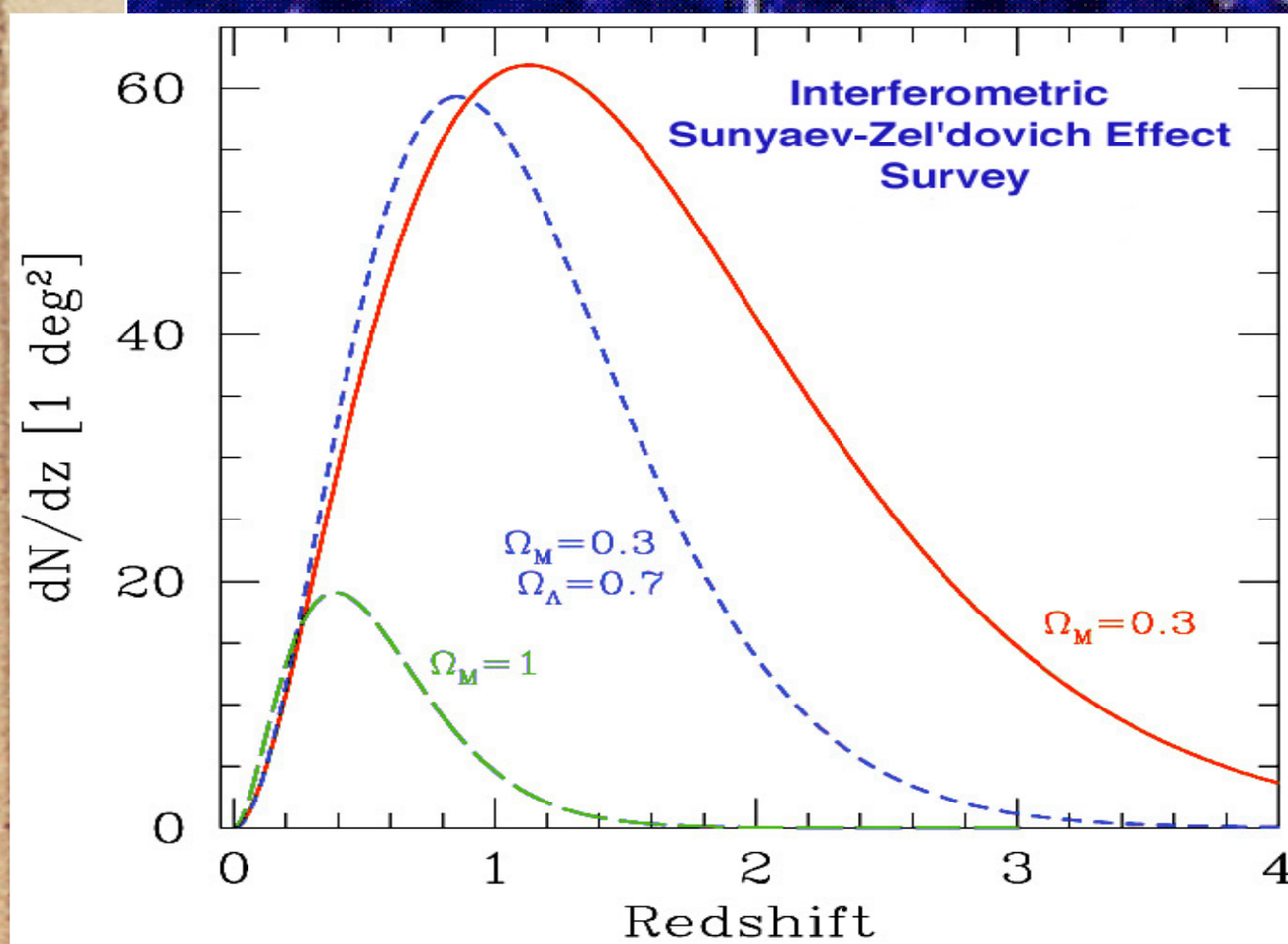


3. Using galaxy clusters potential as gravitational lens “telescopes”.

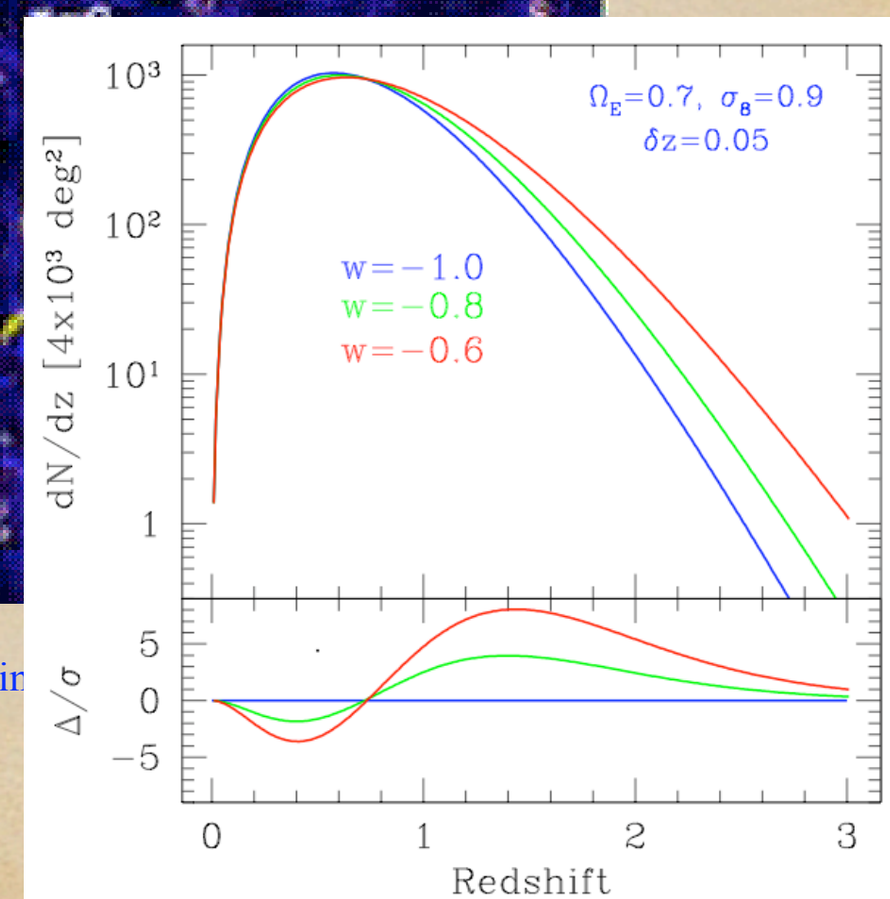


ΛCDM, Ωm=0.3

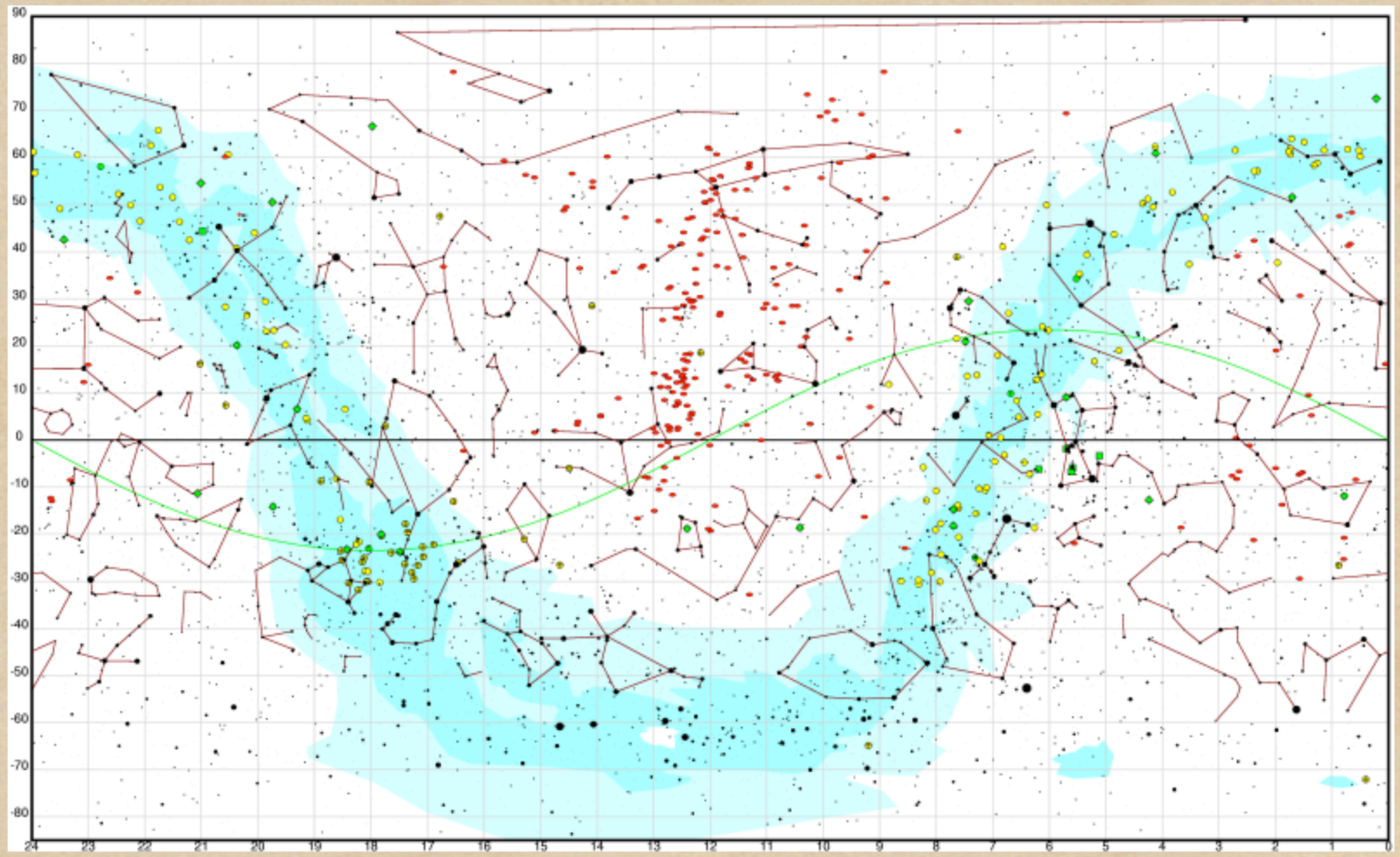




-body sim



A Brief History of Cluster Surveys



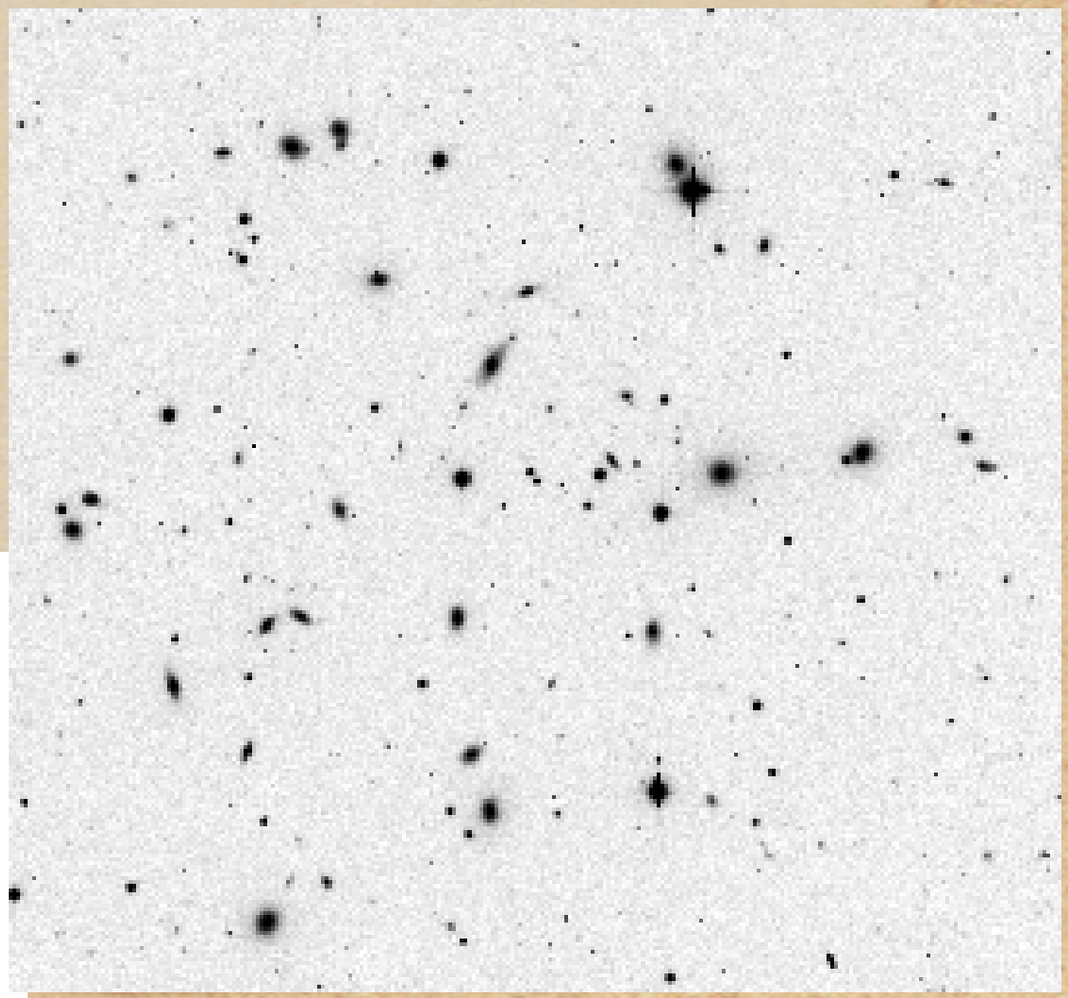
Herschel 400 -- red= spiral nebulae

A Brief History of Cluster Surveys

- First systematic search: Abell catalog (1958, ApJS)
  - criteria: ≥50 galaxies within m_3 to m_3+2 within radius of 1.7'/z, (about 2Mpc), where z is estimated by eye (z<0.2)
  - used Palomar Optical Sky Survey plates
  - cataloged a total of 2717 clusters, with 1683 satisfying above
  - divided clusters into Abell richness classes

Table 1. Table 1: Abell Richness Class

	Abell 0	Abell 1	Abell 2	Abell 3
N_{Abell}	35–45	45–75	75–125	125–200
Number	~ 1000	1224	383	6
σ (km s^{-1})	600	750	950	1250
Mass (10^{14}M$_\odot$)	2	4	9	15



Abell168, z=0.045

✦ Zwicky: same data, but different method: isopleth
>50 galaxies within contour @2x background

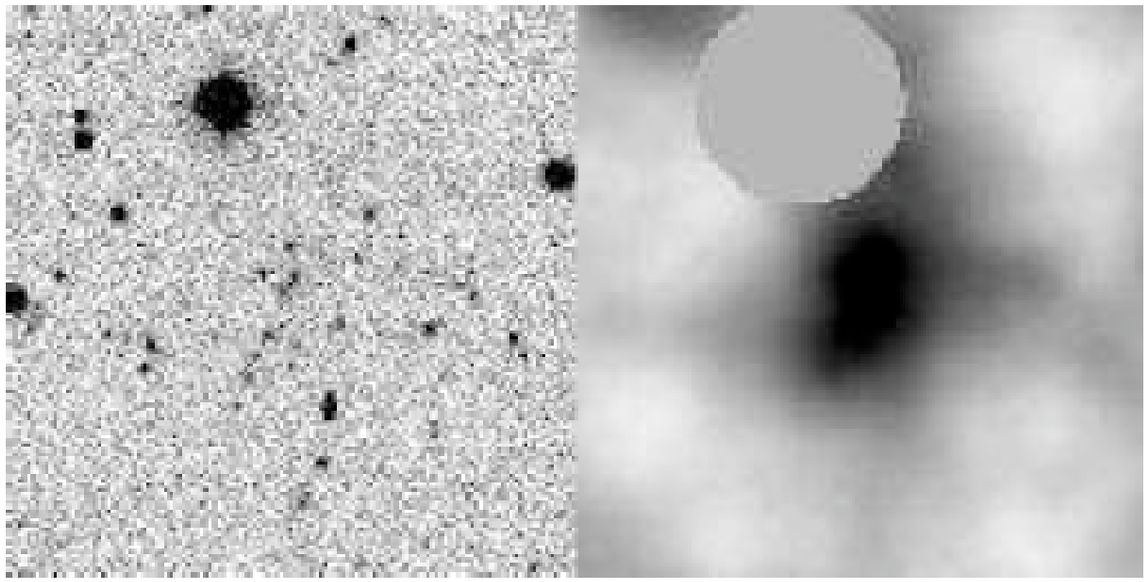
✦ Some later photographic surveys:
GOH (1986, Palomar Schmidt+5m plates
attempt to find high-z clusters
UK Schmidt
-APM (1992)
4300 sq deg, digitized images
240 clusters (≥ Abell 1)

✦ First digital CCD imaging survey:
PDCS (1996; Postman, Oke, Lubin);
Palomar 5m CCD drift scan; 5.1 sq deg, V=24
"matched filter" technique;
75 clusters, 0.2<z<1.2

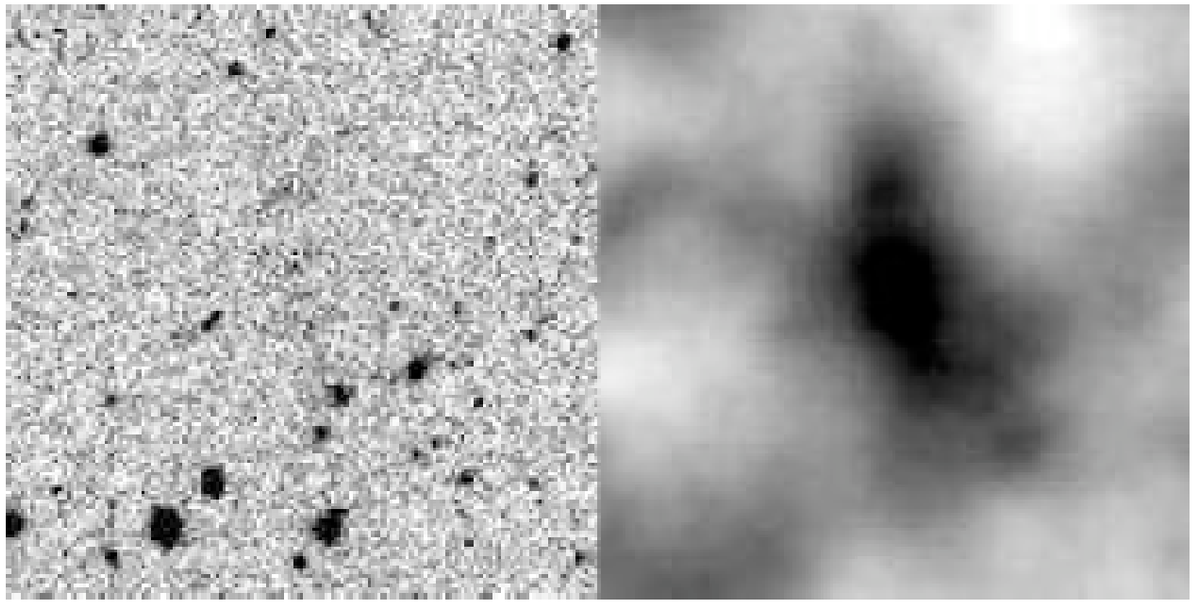
✦ The LCDCS:

another early attempt for high z clusters

- Gonzalez, Zaritsky et al. 2001
- 130 sq deg, Swope 1m drift scans
- 1073 clusters, 0.3<z<1.0; 30% false detections

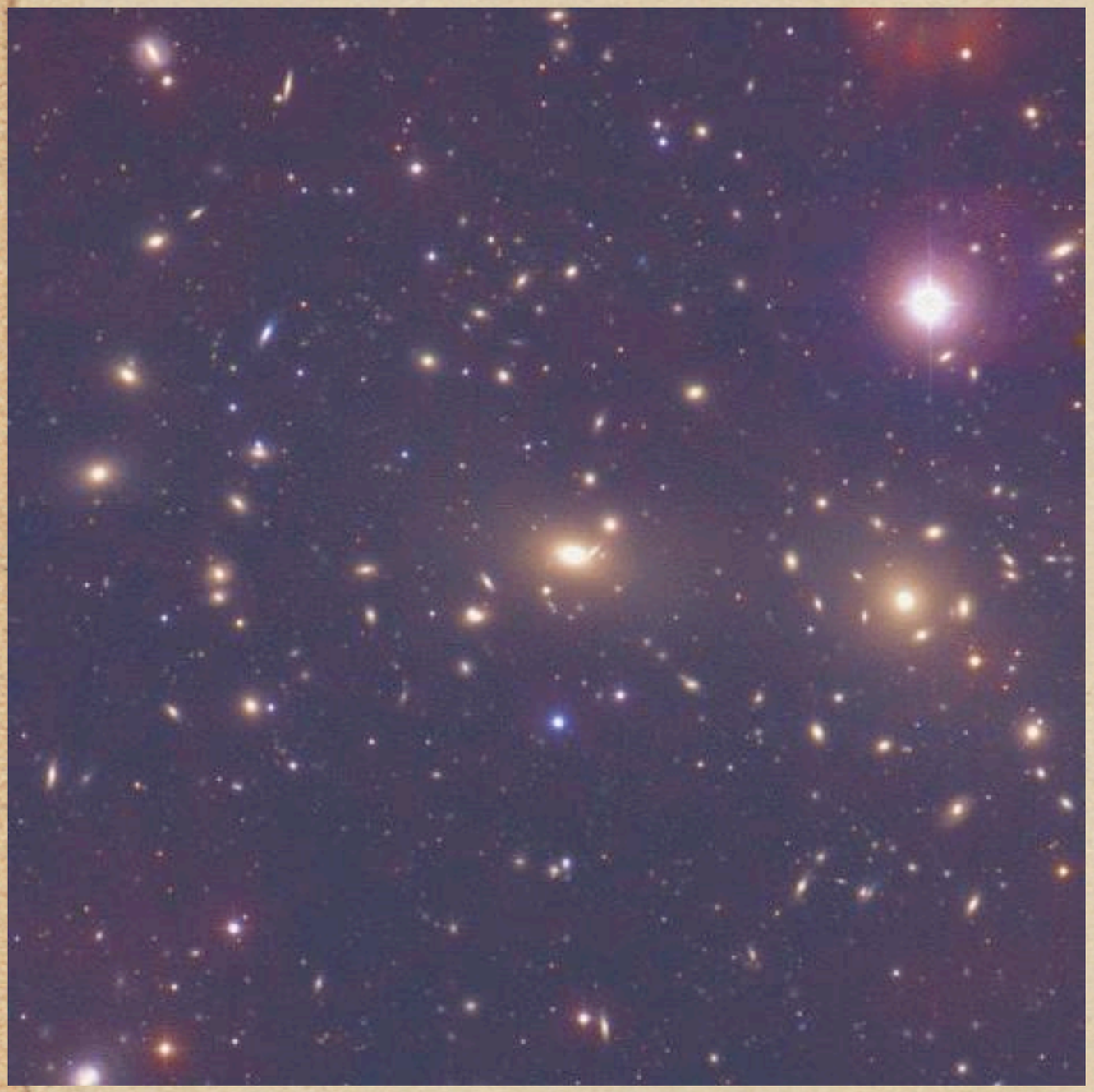


LCDCS 0130 (z_{est}=0.80)



LCDCS 0797 (z_{est}>0.85)

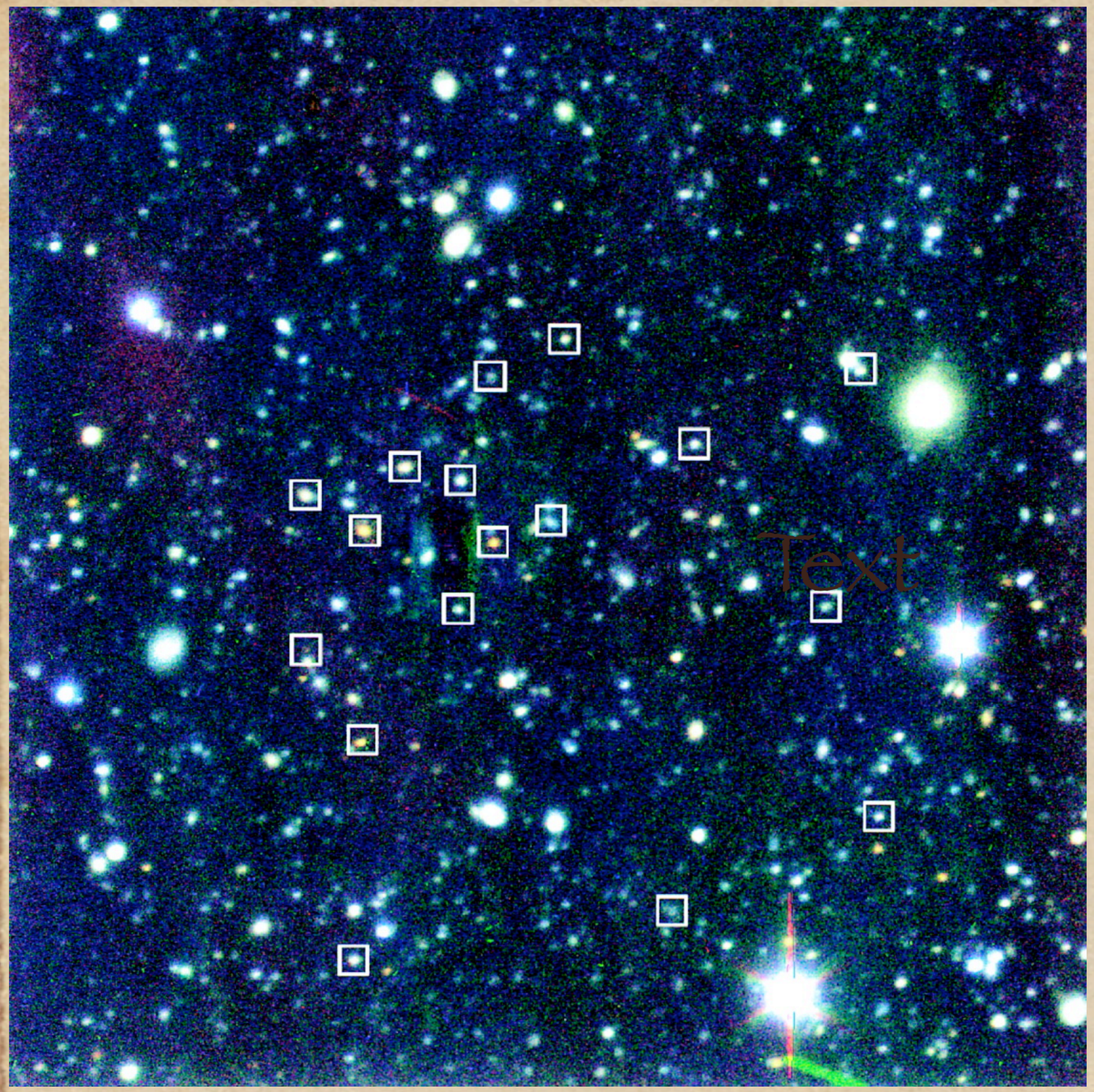
Best-known nearby rich cluster



NOAO 0.9m, Lopez-Cruz & Yee

Coma
(A1656, z=.025)

Richness~ Abell 2



PDCS 0223+0423, z=0.84

Postman, Lubin, Oke
"Match-filter" technique,
single filter

What is needed for a modern galaxy cluster survey:

- large area (10^2 to 10^3 sq deg)
- redshift to $>\sim 1$
- well-understood selection effects and completeness
- characterization of the sample:
  redshift and mass, [or more practically: mass proxy]

Cluster survey methods:

1. Optical/IR
2. X-ray
3. Sunyeav-Zeldovich effect

Modern Optical/IR Surveys for Galaxy Clusters:

- New large areal digital detectors
  (both optical [~1 sq deg] and IR [~1/10 sq deg])

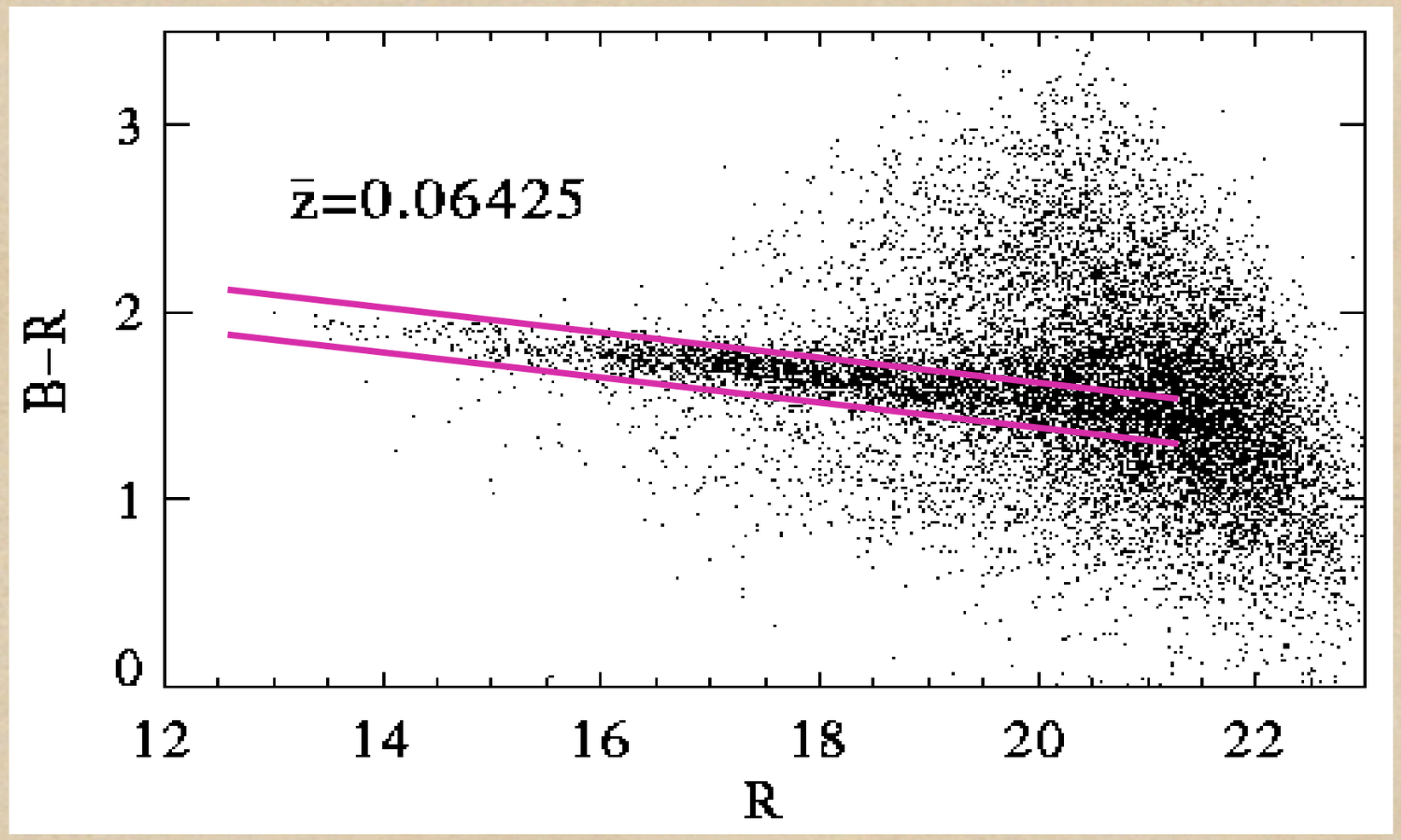
- New cluster search techniques using
  multiple filters

Low-z example: SDSS

The Cluster Red-Sequence Method

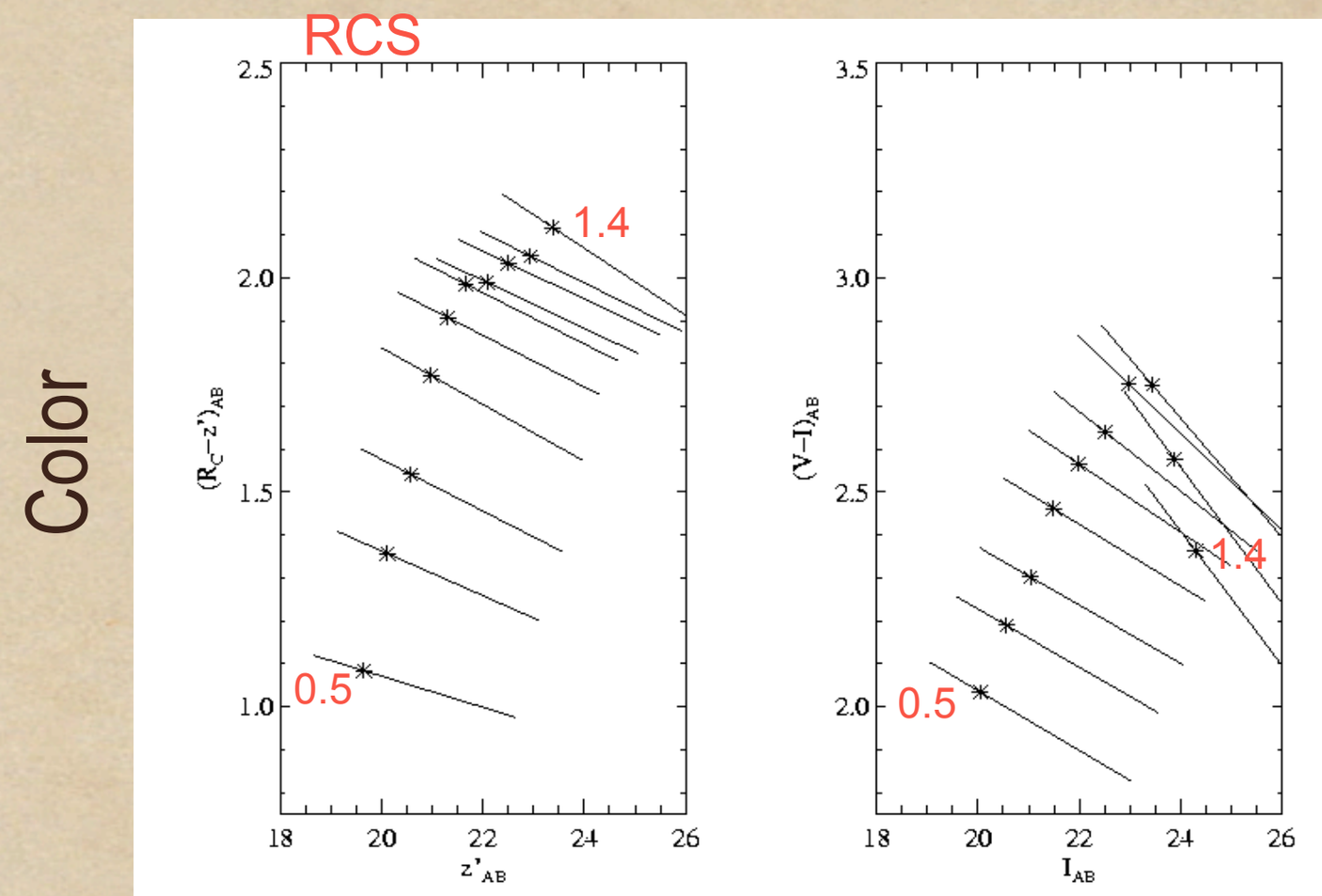
Gladders & Yee 2000, AJ, 120, 2148

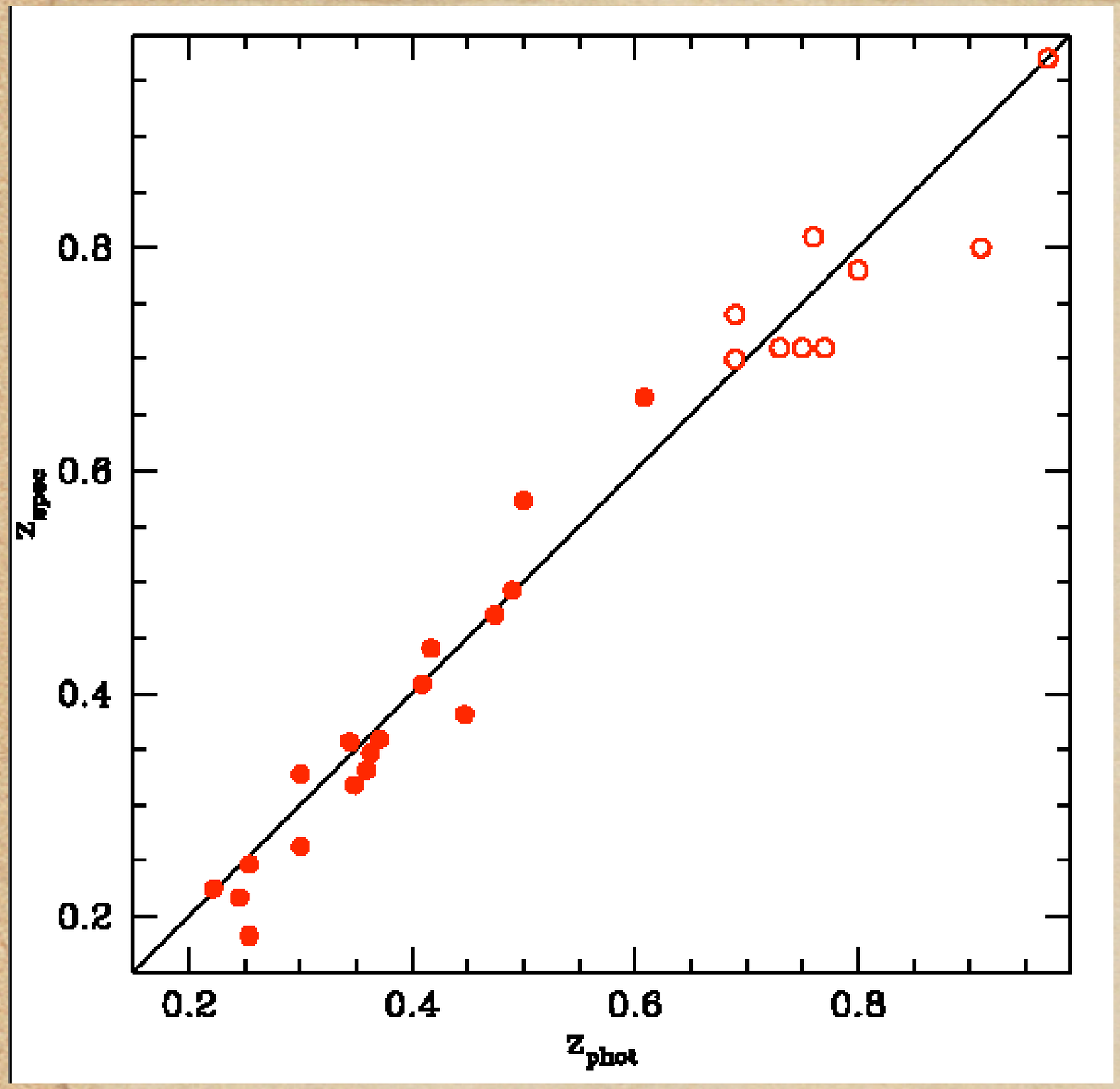
Uses the early-type (red) galaxies as markers for cluster detection



Requires only 2 filters: Inexpensive

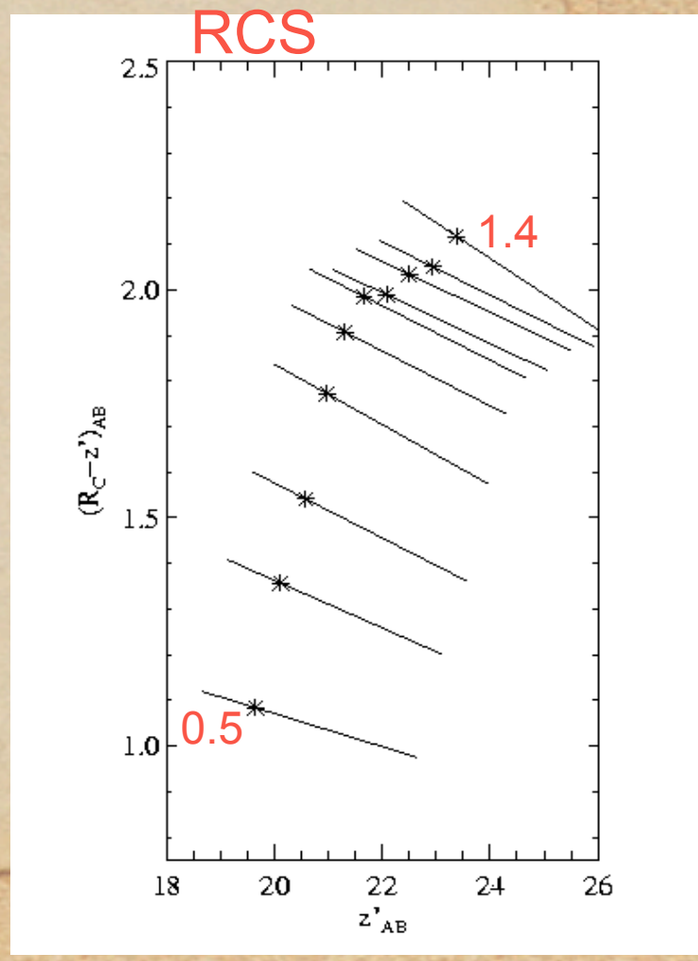
Color-magnitude relation as a function of redshift





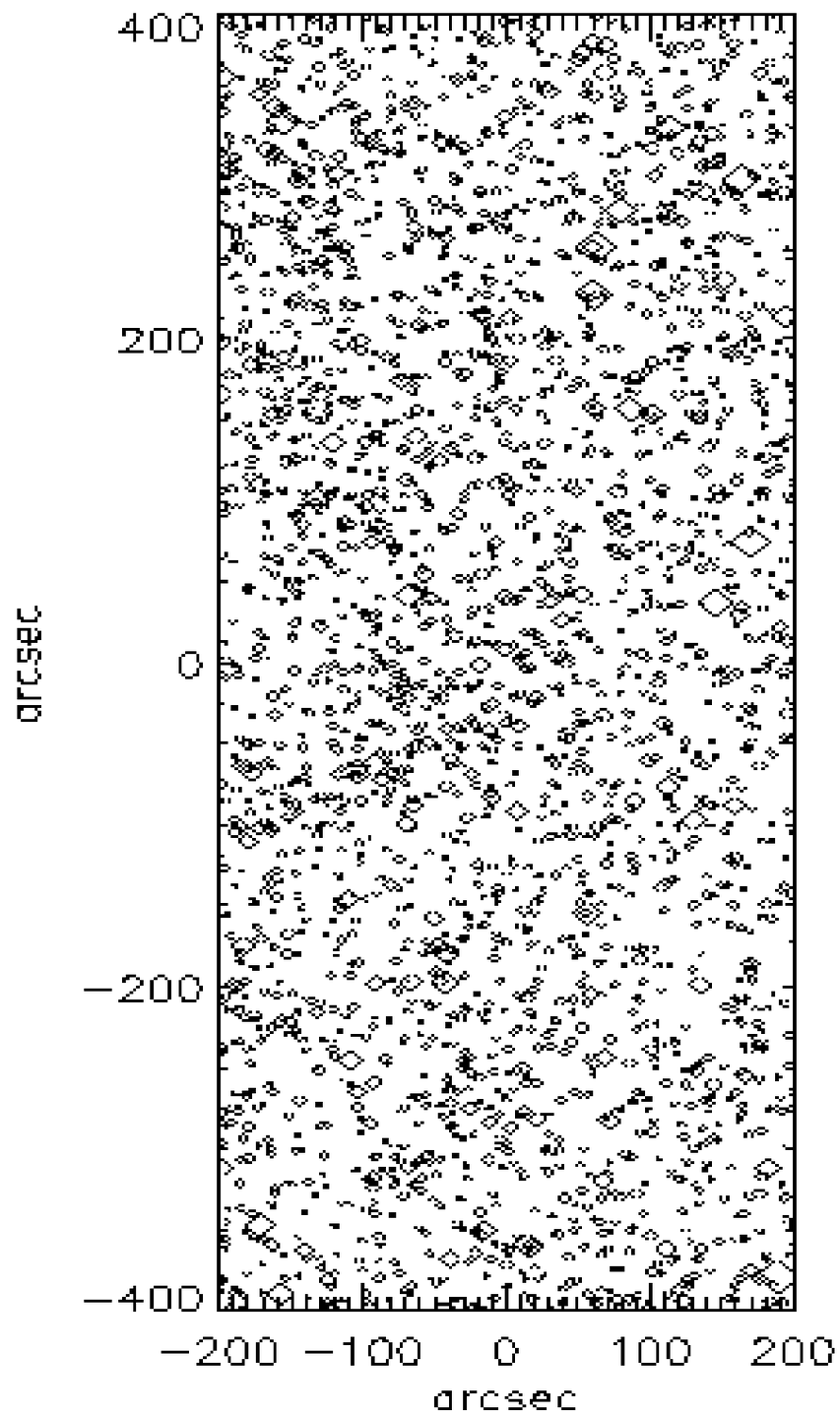
Red-sequence photo-z (2 filters) vs spectral z (RCS1 data);

$\Delta z \sim 0.04$ to 0.08

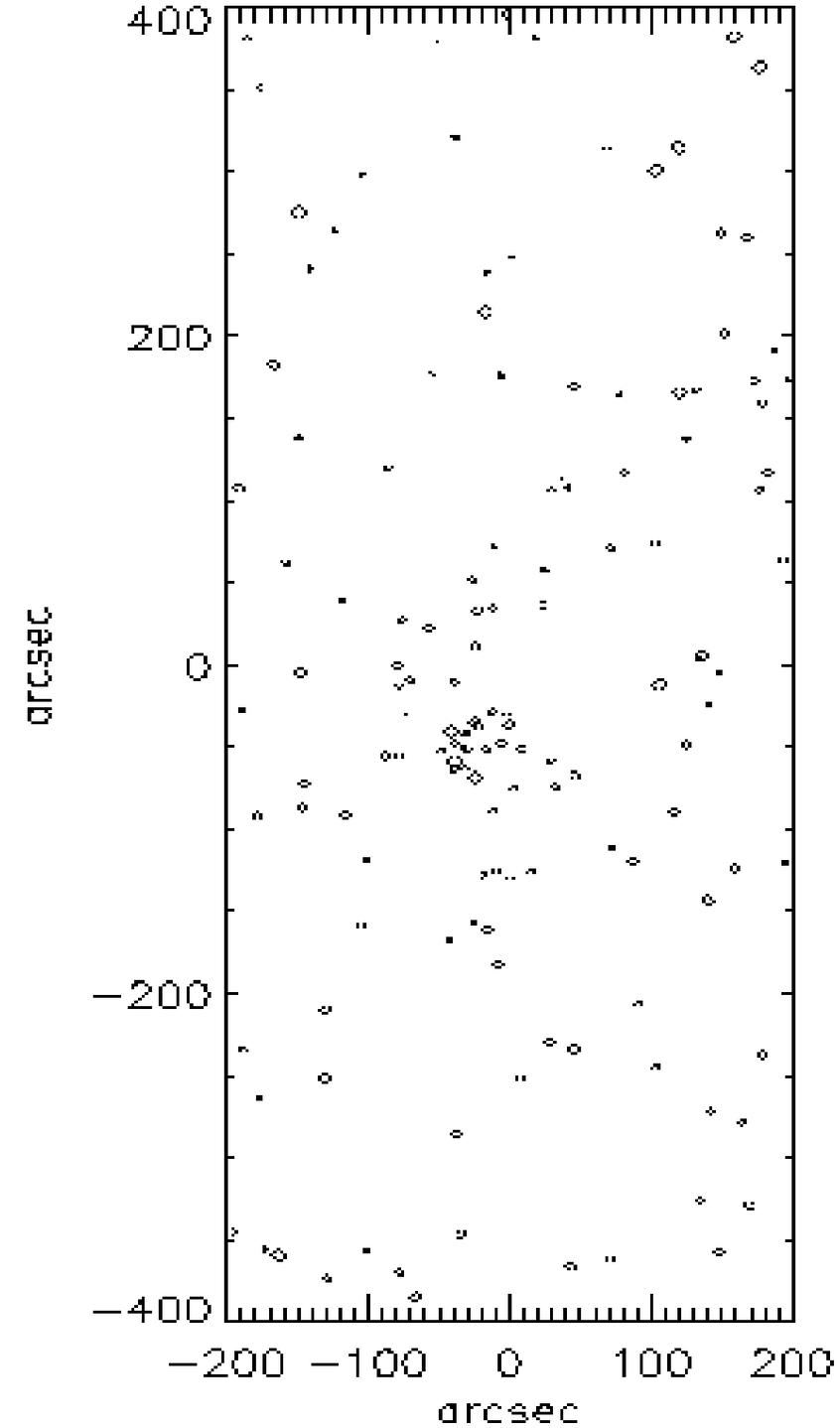


Rcs

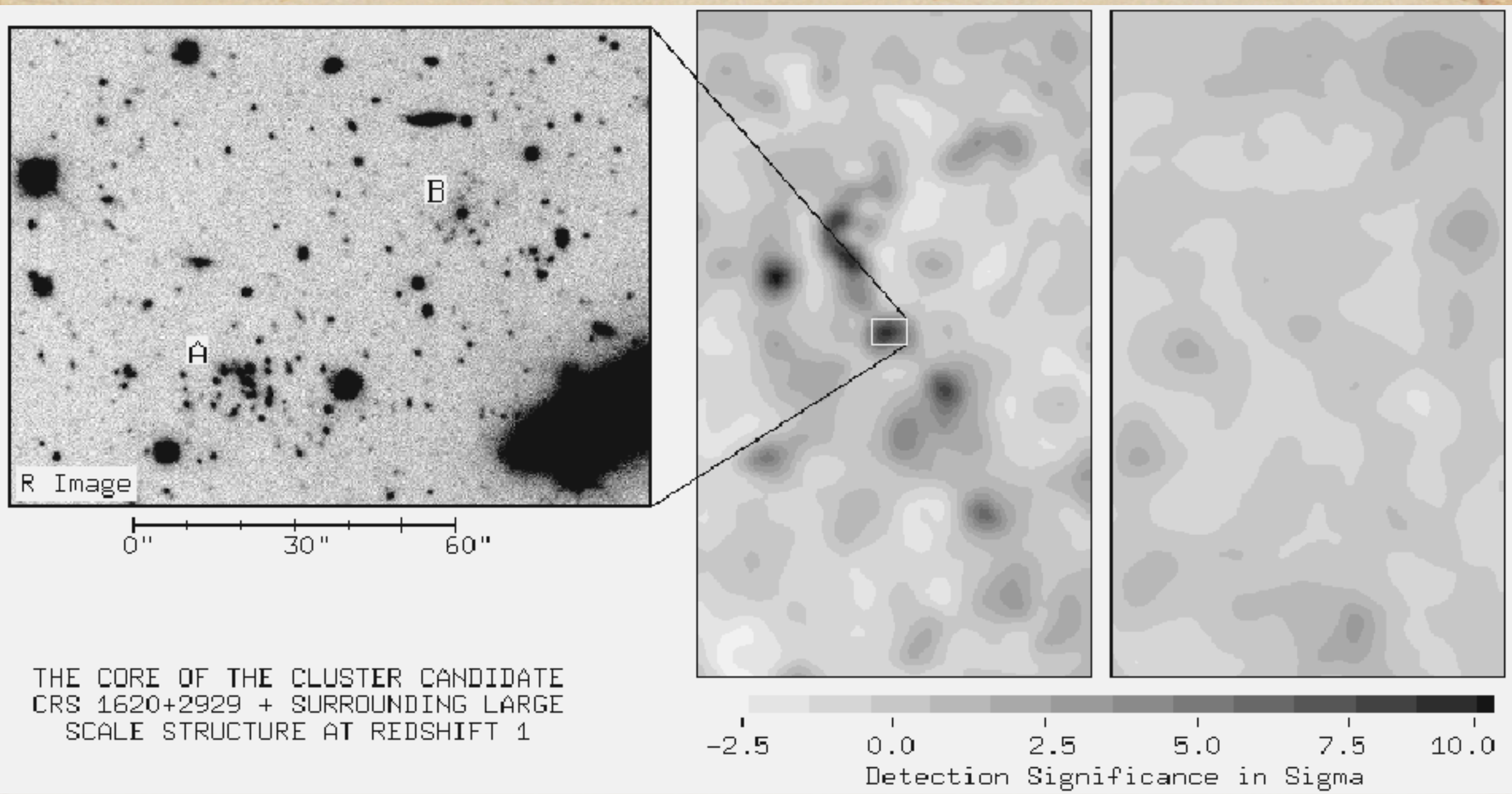
Simulated R-band field with a z=1, Abell richness 1 cluster embedded



All objects



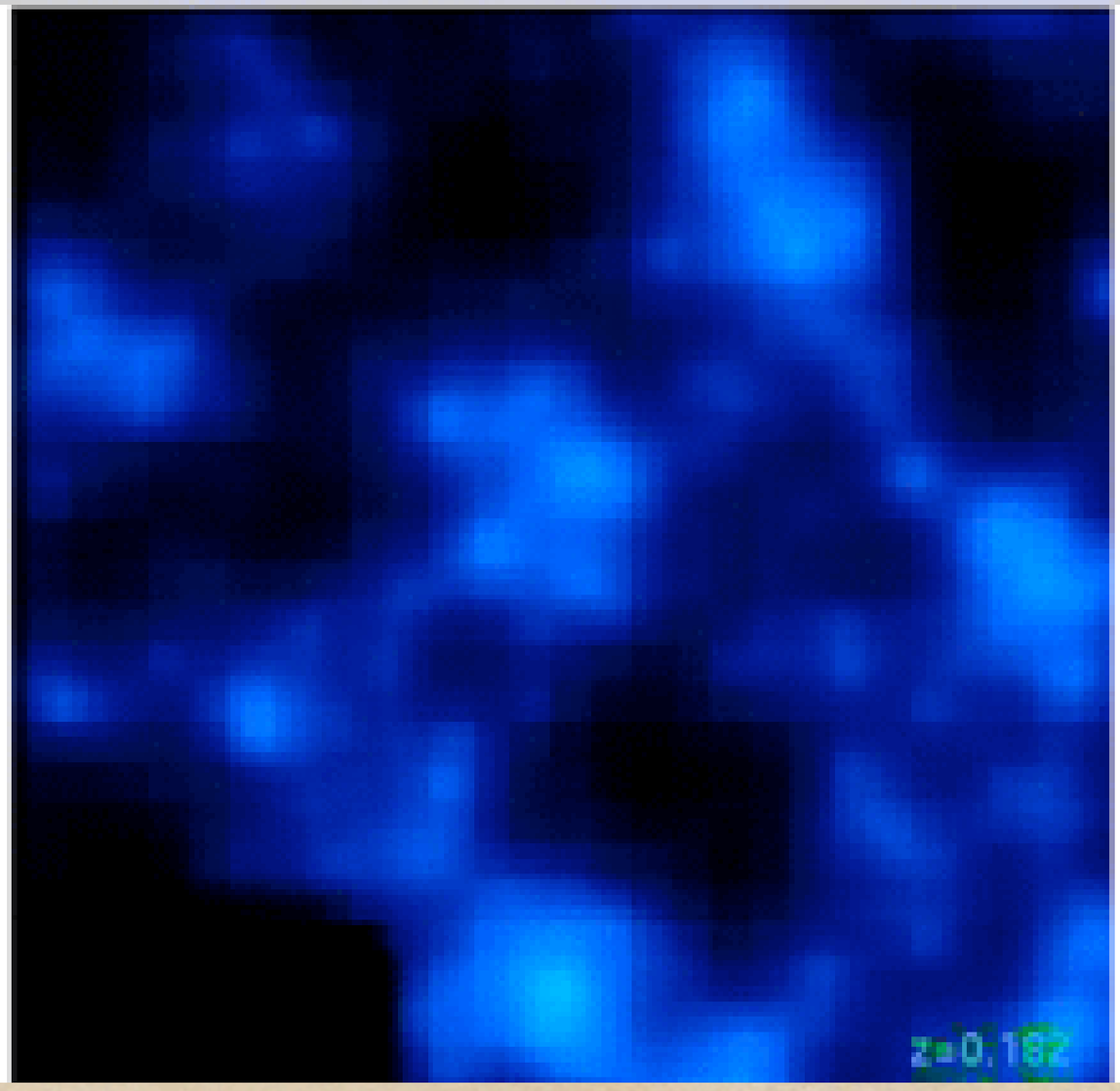
Objects in color slice



A z=0.89 RCS cluster

galaxies in color slice
(of z=0.9 ellipticals)

all galaxies



Galaxy density in different red-sequence slices
(Real data from RCS1)

The RCS1/2 Collaboration:

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

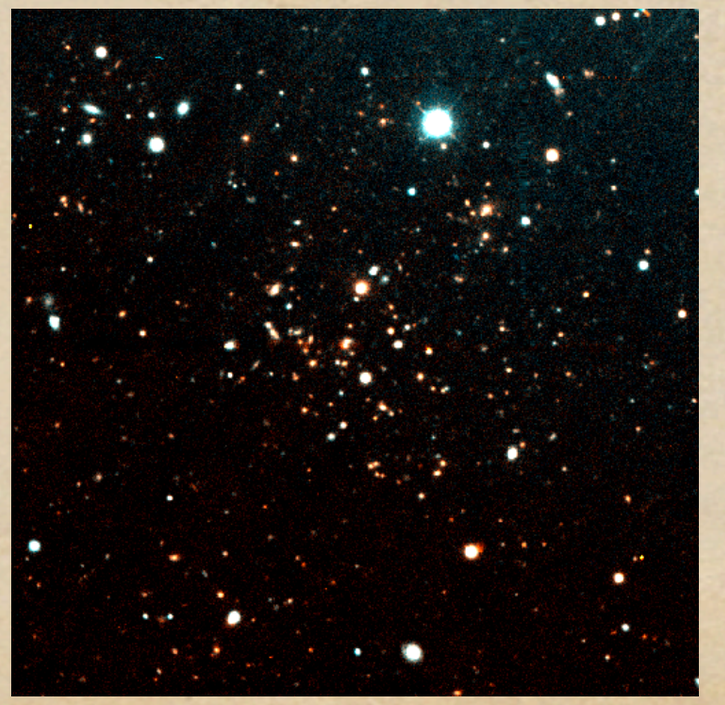
D. Gilbank (U. Waterloo), H. Hoekstra (UVic),
E. Ellingson (U. Colorada), R. Yan(U.Toronto),
S. Majumdar (Tata Inst., India), B.C. Hsieh (ASIAA, Taiwan),
T. Webb (McGill), A. Muzzin (Yale),
I.H. Li (Swinburne, Australia), K. Blindert (MPIA),
F. Barrientos (U. Catolica, Chile), A. Hicks (U. Virginia),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

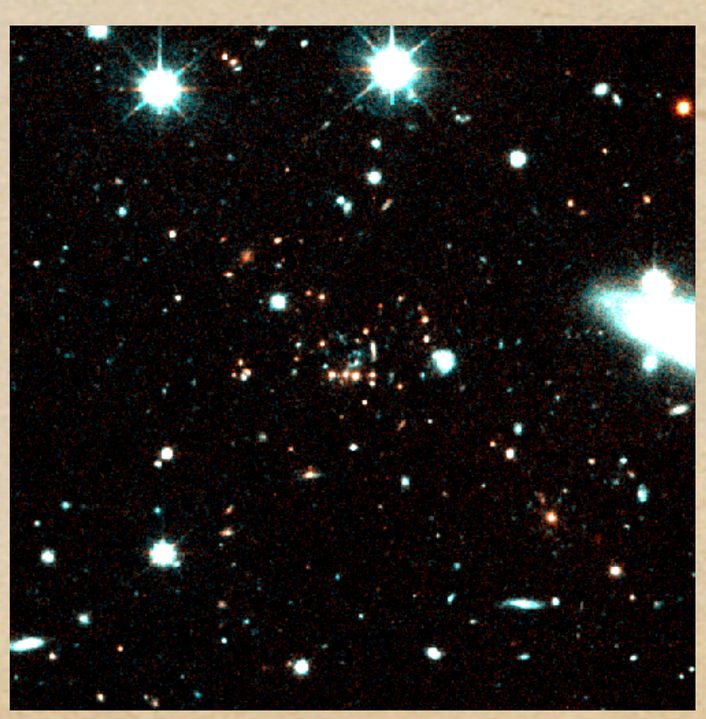
+ others and students and postdocs at Chicago, UVic, McGill, CITA, York, Waterloo, MIT, Michigan, NCU, ASIAA

The RCS1

Gladders and Yee, 2005, ApJS, 157,1

- 92 sq deg, 1998-2001
- total: 13 nights CFHT, 17 nights CTIO (including lost times)
- R, z' bands: 15-25 min exposure
  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 and Dec.





Main Science Goals: (RCS1)

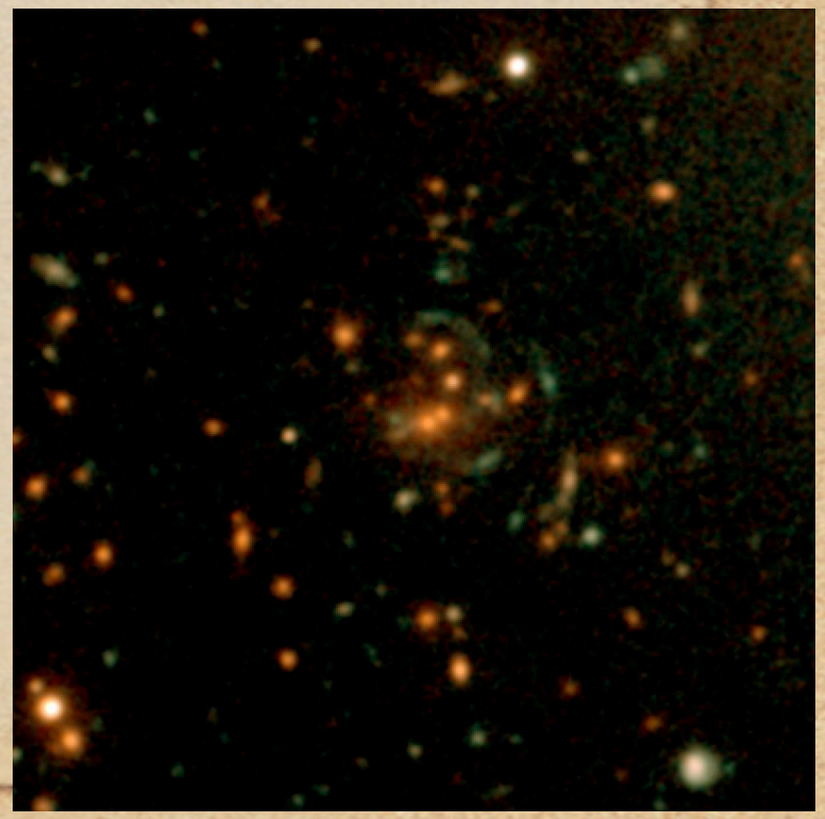
Measure Ω_m and σ_8,

cluster evolution

optimized for z~0.4 to 1.0;

usable range: z~0.25 to 1.3

Total number of clusters cataloged: ~8000 (3σ cut)



RCS2: www.RCS2.org

A ~1000 sq deg Cluster survey, with a *z* ~1 limit

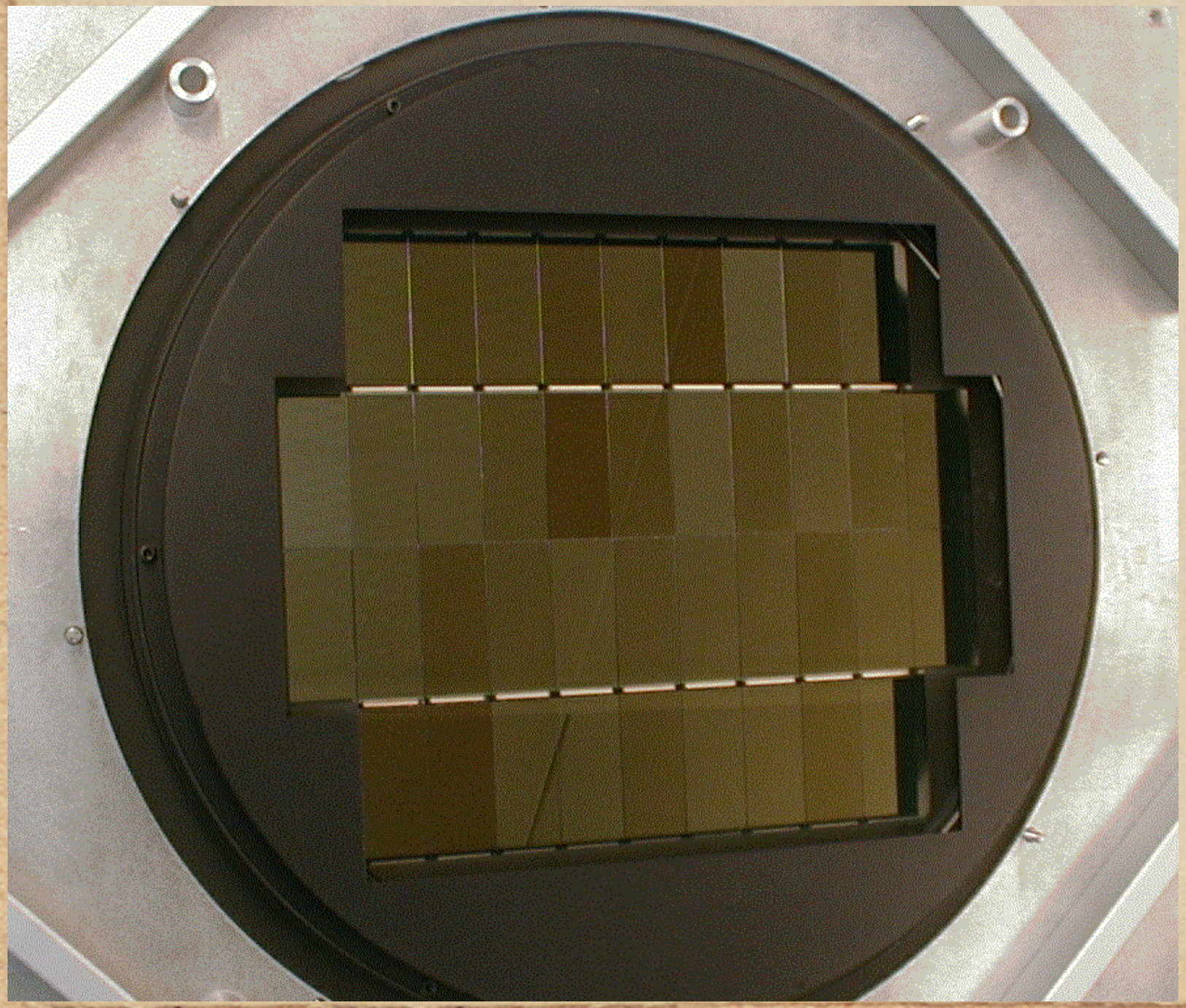
CFHT MegaCam (Canada/Taiwan)
~800 sq deg + 150 sq deg from CFHT-LS wide

Three filters:	**z'**	**r'**	**g'** (SDSS)
exposure t:	**6**	**8**	**4 min**

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

CFHT MegaCam:

CFHT MegaCam

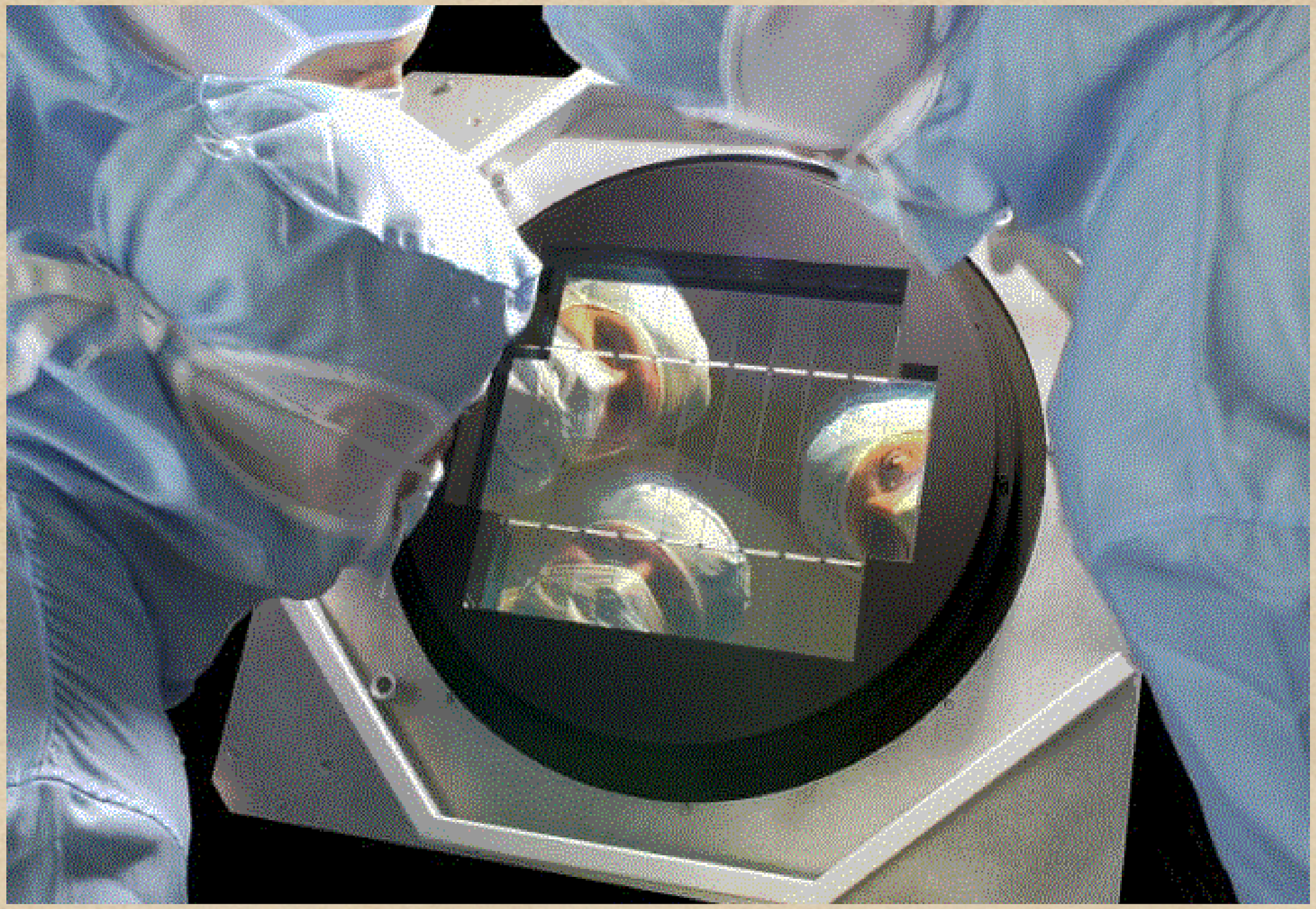


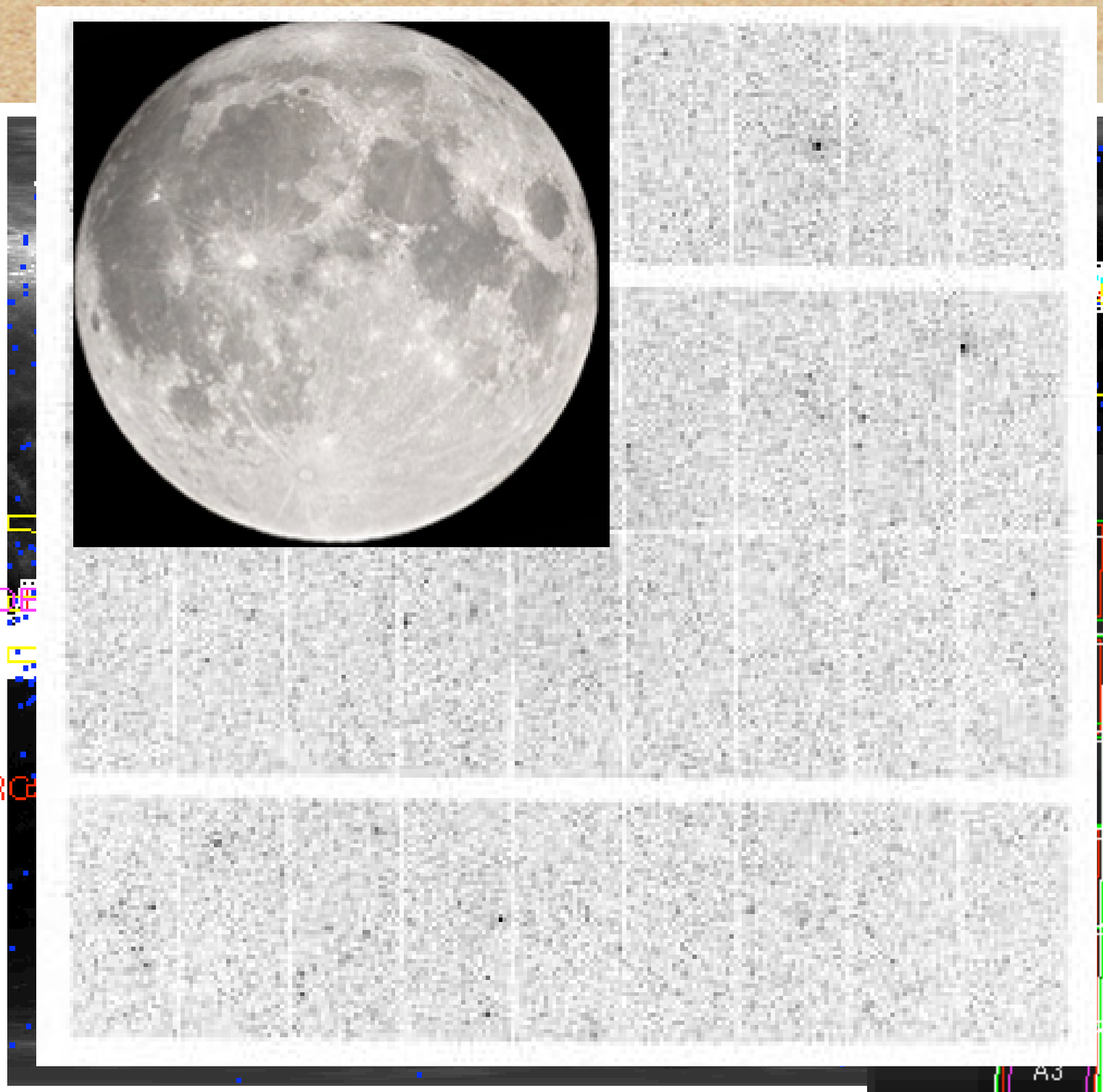
36 2k x 4.5k chips,
325M pixels

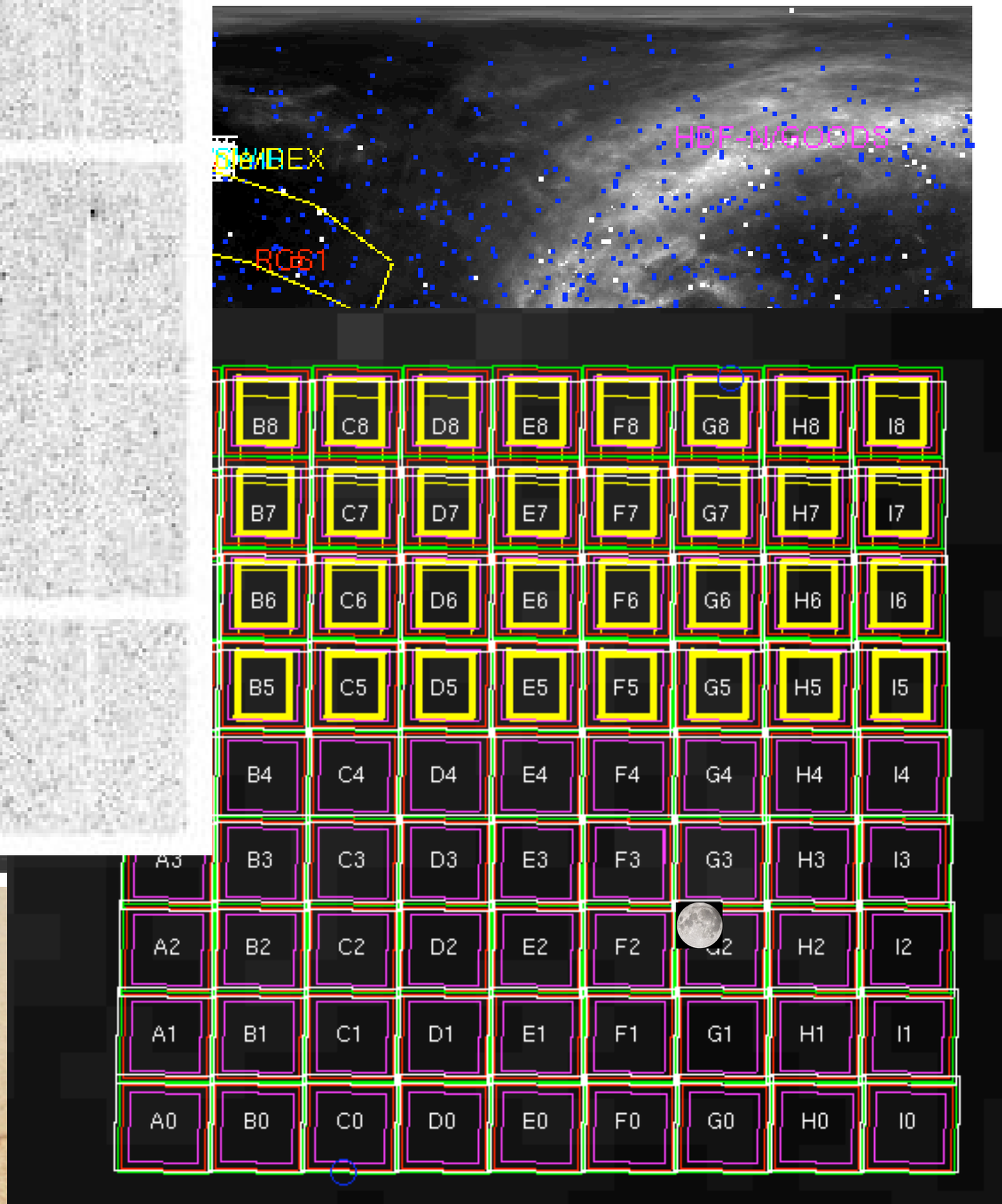
one image ~ 750Mb

0.18”/pix

field~ 1 sq deg






HDF-N/GOODS
RCS1
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 G2 H2 I2
A1 B1 C1 D1 E1 F1 G1 H1 I1
A0 B0 C0 D0 E0 F0 G0 H0 I0

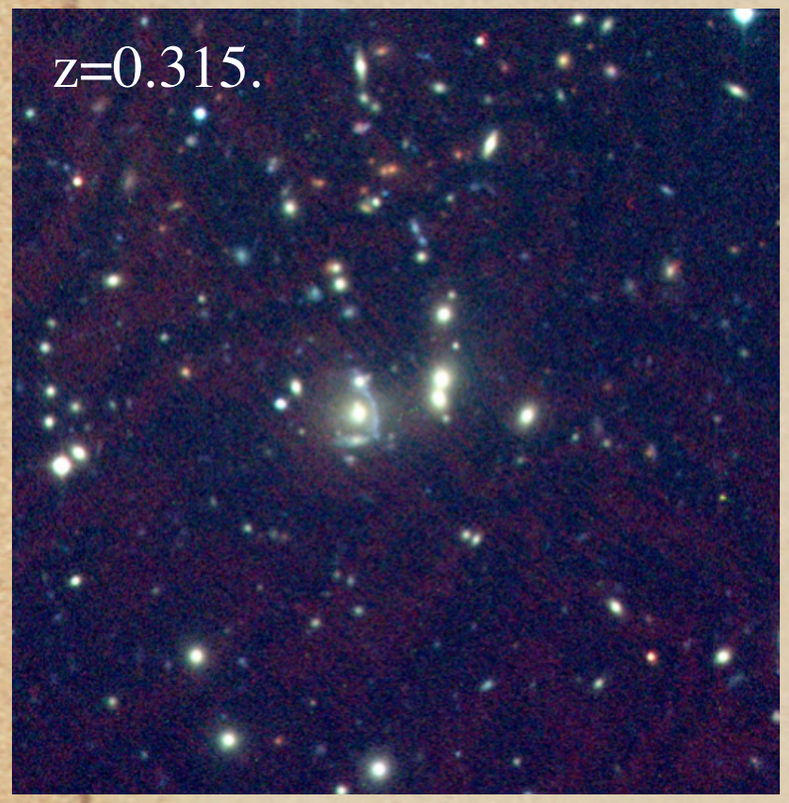
www.rcs2.org

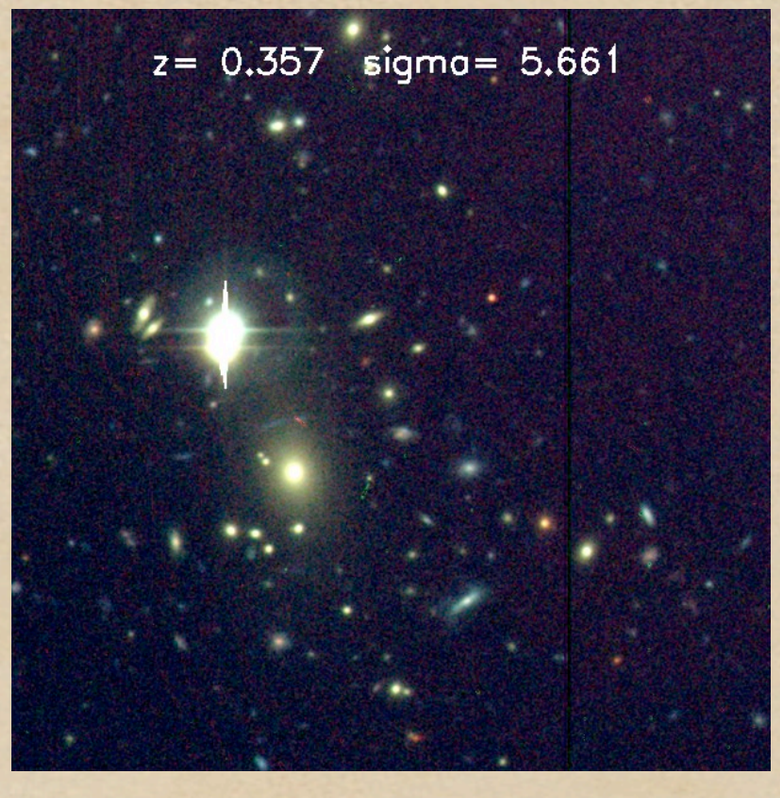
Main Science Goals: (RCS2)

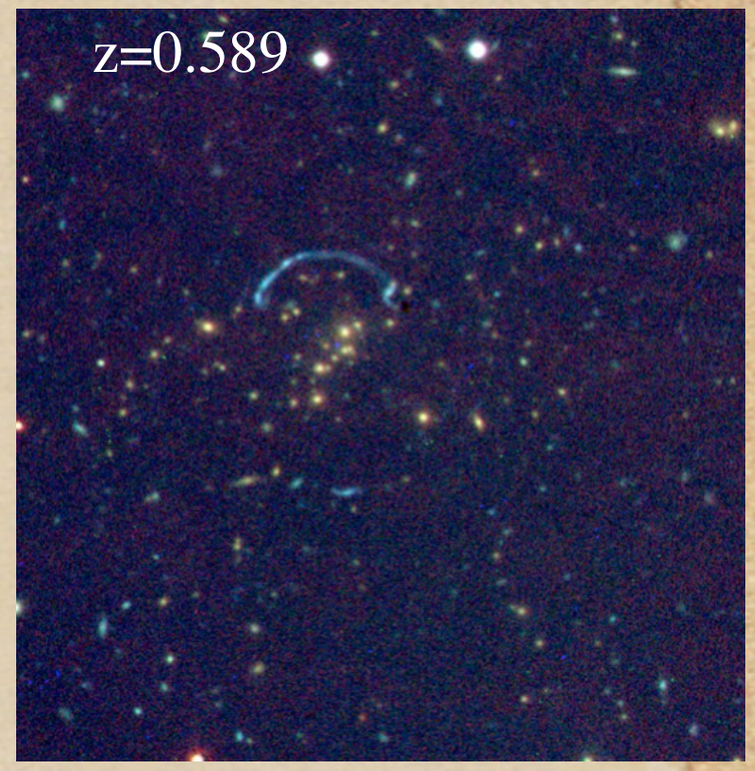
- Measure eqn of state of dark energy, $w=P/\rho$ (to ~0.15), Ω_m (to ~0.03), and σ_8 (to ~0.05)
- create a sample of ~100 strong lenses
- cluster evolution
- weak lensing (wide/shallow)
- photo-z (3/4-color) ~ 10-30 x 10^6 (useful) galaxies

optimized for z~0.1 to 1.0;
Total number of clusters (useful for cosmology) expected: ~ 20,000

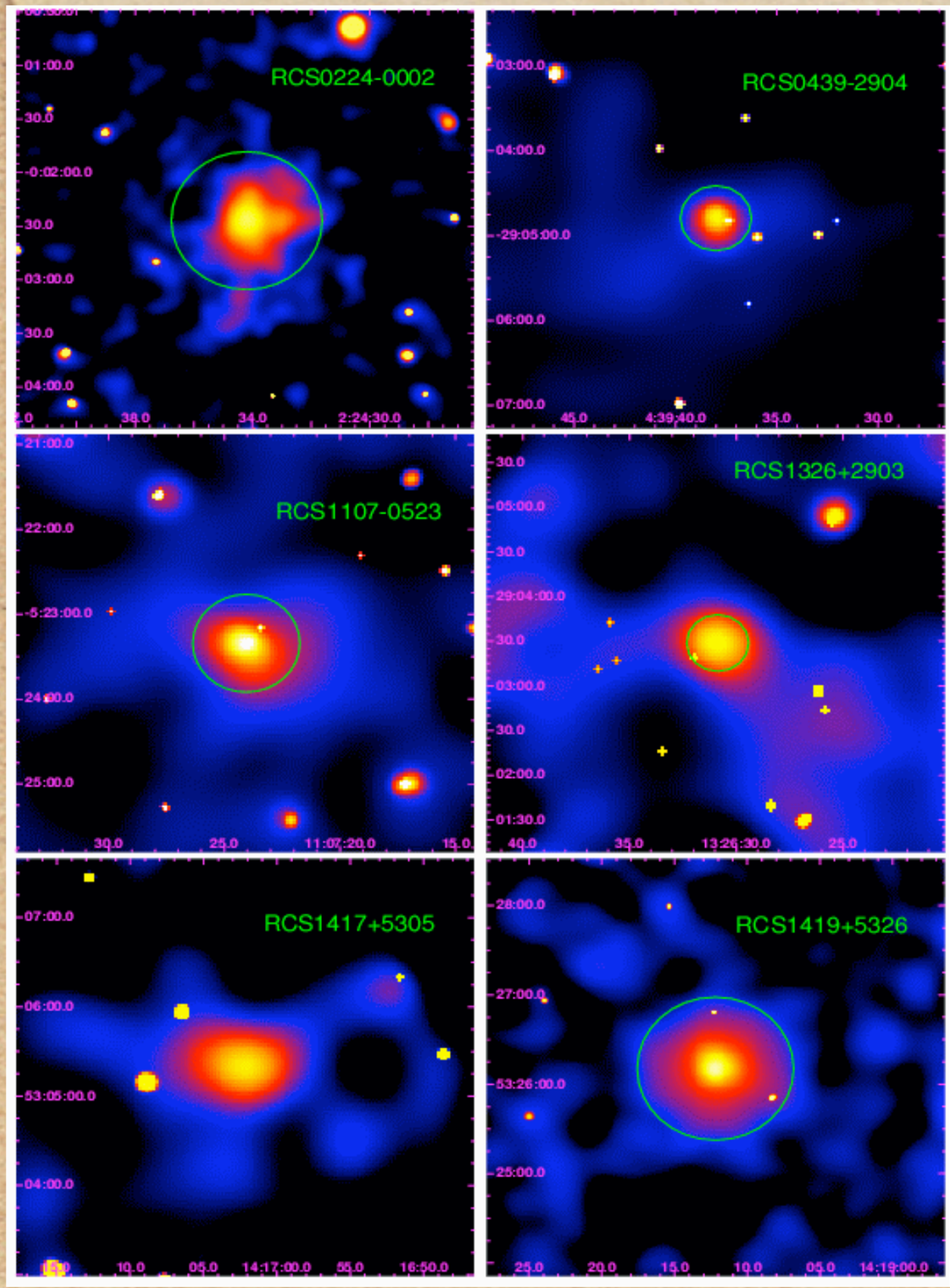
Strong lensing in RCS2 clusters







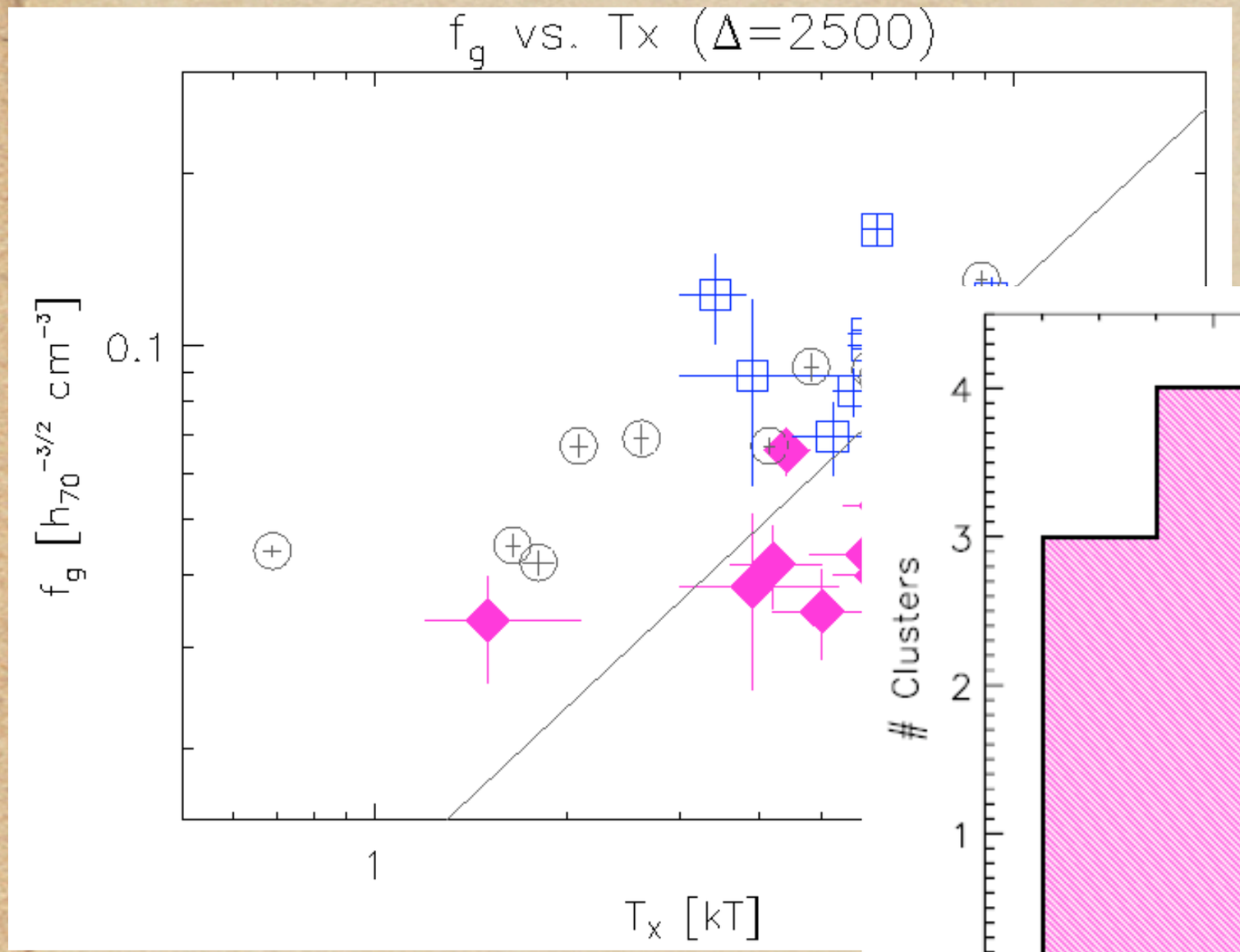
Chandra X-ray obs of 0.7>z>1.1 RCS clusters

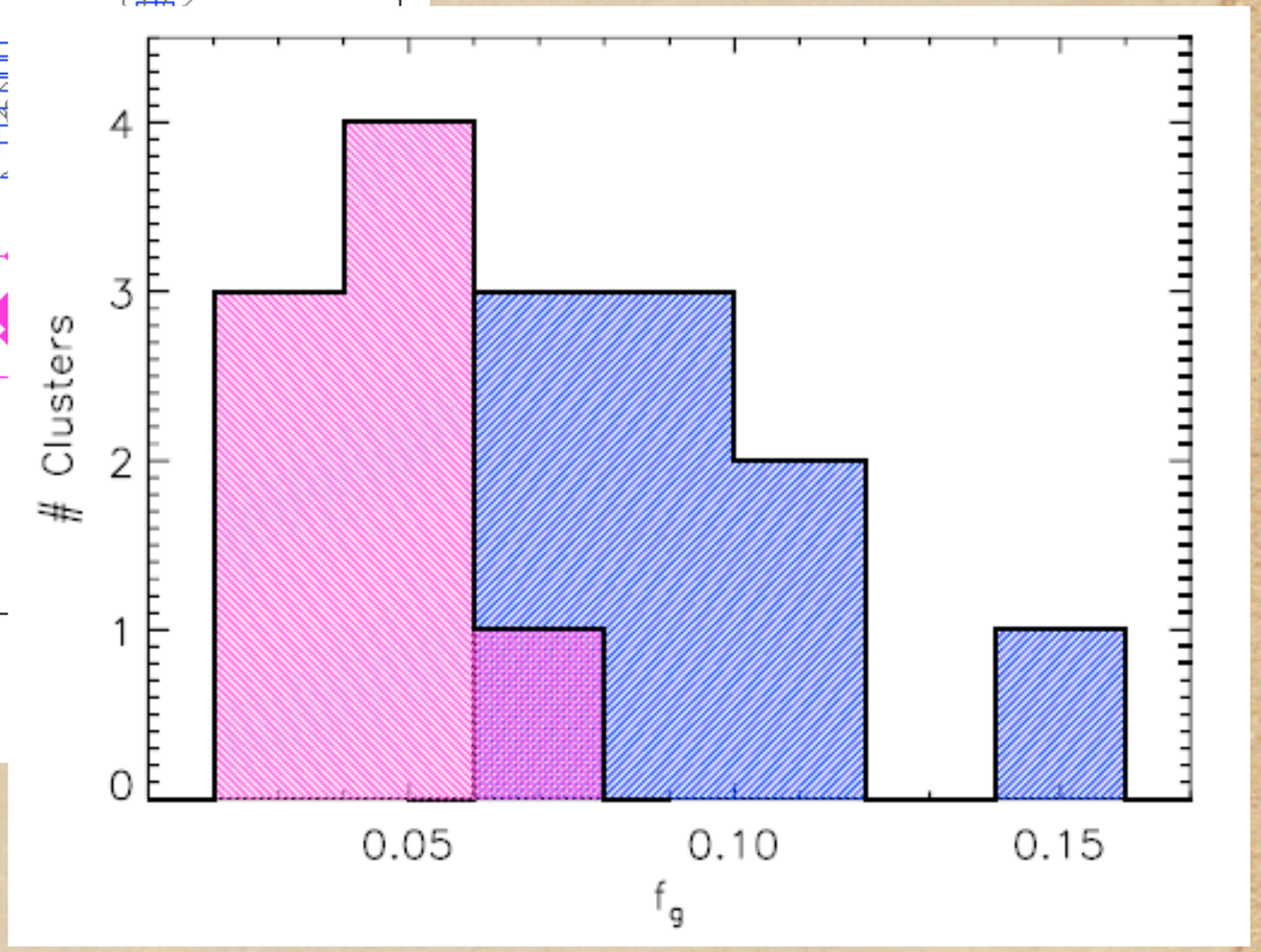


Hicks et al. 2007
(submitted to ApJ,
arXiv:0710.5513);
13 0.7<z<1.1 clusters

Gas mass fraction in clusters

pink: RCS clusters (0.65<z<1.1)
blue: CNOC1 clusters (0.15<z<0.55



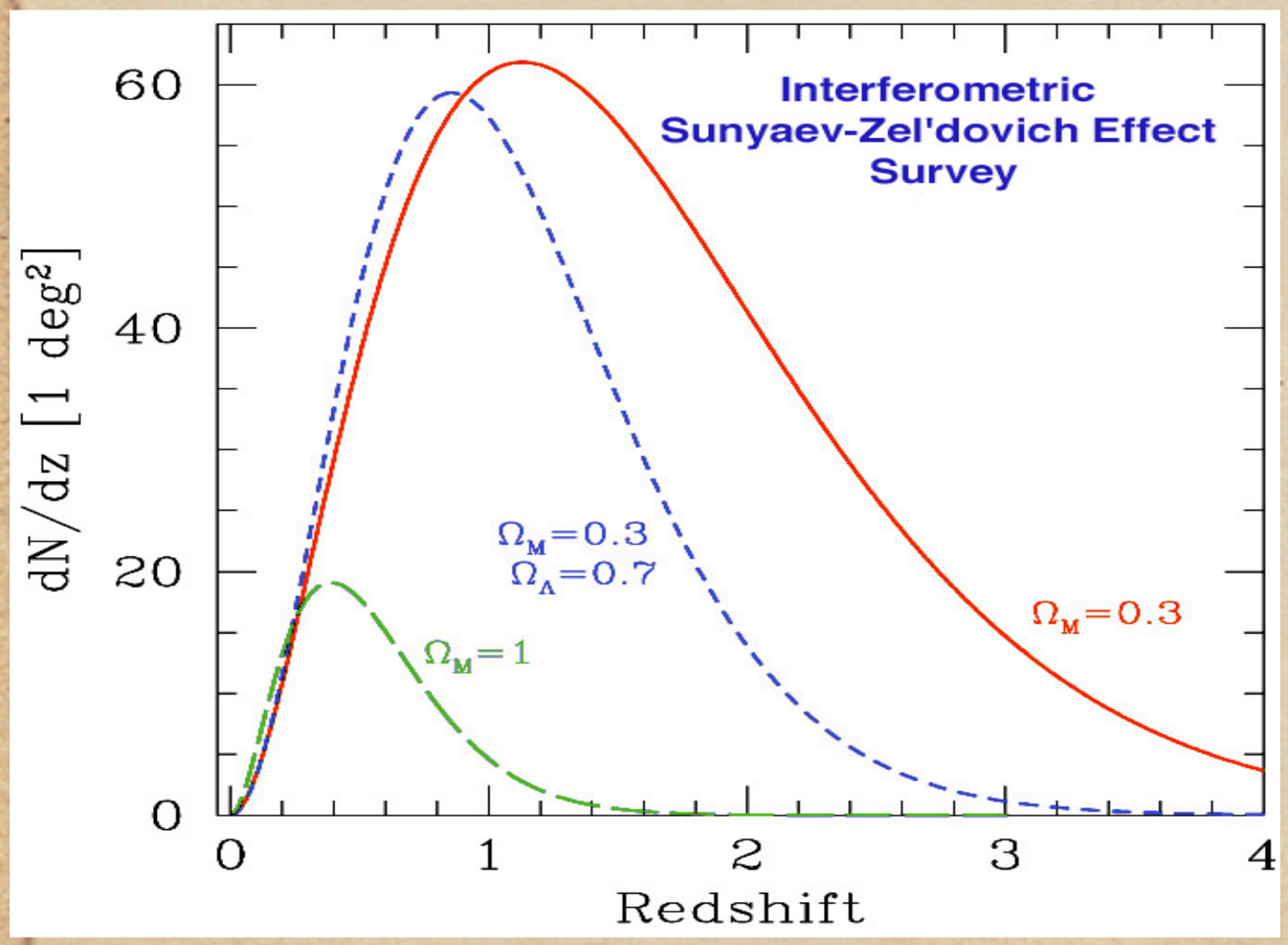


Is there an evolution of f_gas (~factor of 2) between z~0.35 to z~0.85?
- implications for X-ray and SZ cluster surveys

Cosmology with Clusters:

Number of clusters N(z) per unit z and angular area

$$\frac{dN(z)}{dz d\Omega} = \frac{dV}{dz\, d\Omega} n(z) = \frac{c}{H(z)} d_A^2 (1+z)^2 \int_0^\infty dM\, f(M) \frac{dn(M,z)}{dM}$$



f(M) links the "mass observable" to the mass

Mass Observables:

Examples: Tx, Lx, SZ flux, optical/IR richness or light

- Mass observable used for the RCS:

  optical richness B_{gc} (galaxy-cluster correlation amplitude:

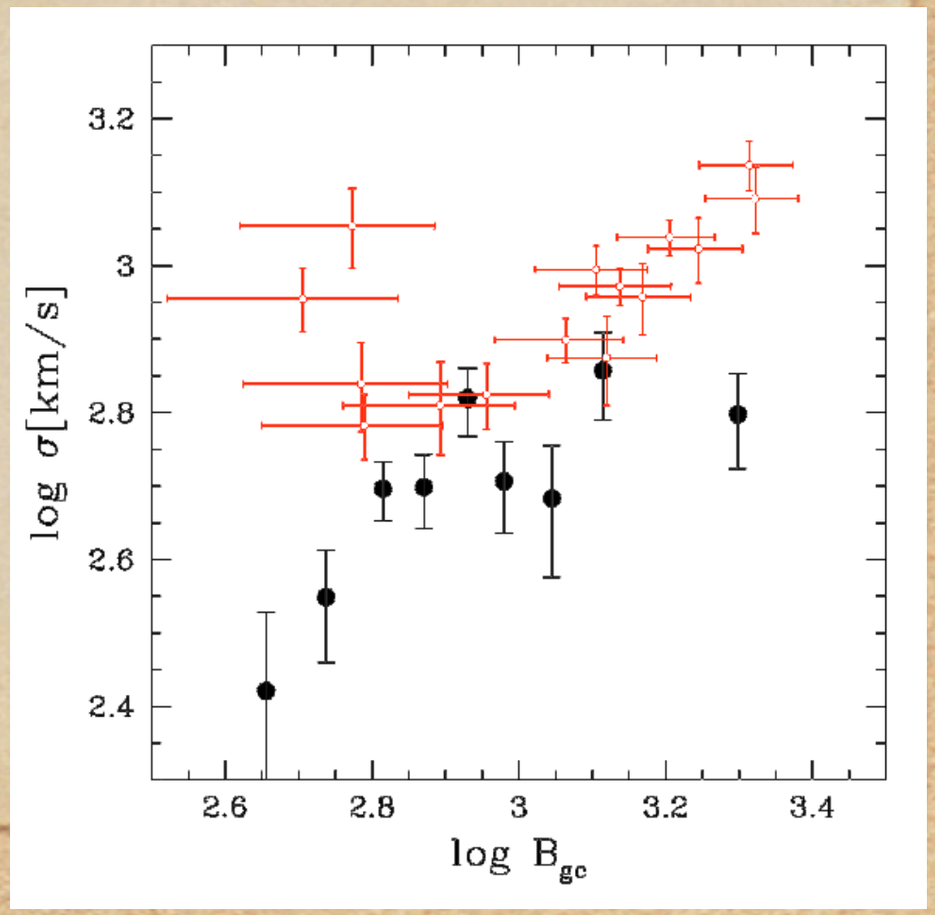
  $$\xi(r) = B_{gc} r^{-\gamma}$$

  net number of galaxies scaled by LF and spatial distribution;

  Longair & Seldner, 1979, MNRAS, 189, 433)

Mass - observable relation

$$M = A_{Bgc} B_{gc}^{\alpha} (1+z)^{\gamma}$$



RCS1 Cosmological Results:

(Gladders, Yee, Majumdar, Hoekstra, Barrientos, Infante, Hall, **2007, ApJ, 655, 128; astro-ph/0603588**)

Use Marko- Chain Monte Carlo fitting to Jenkin mass function (Subha Majumdar)

RCS1: 7- parameter fit; ~1000 clusters

Ω_m, σ_8,

$$\frac{dN(z)}{dz d\Omega} = \frac{dV}{dz\, d\Omega} n(z) = \frac{c}{H(z)} d_A^2 (1+z)^2 \int_0^\infty dM\, f(M) \frac{dn(M,z)}{dM}$$

h (WMAP prior)

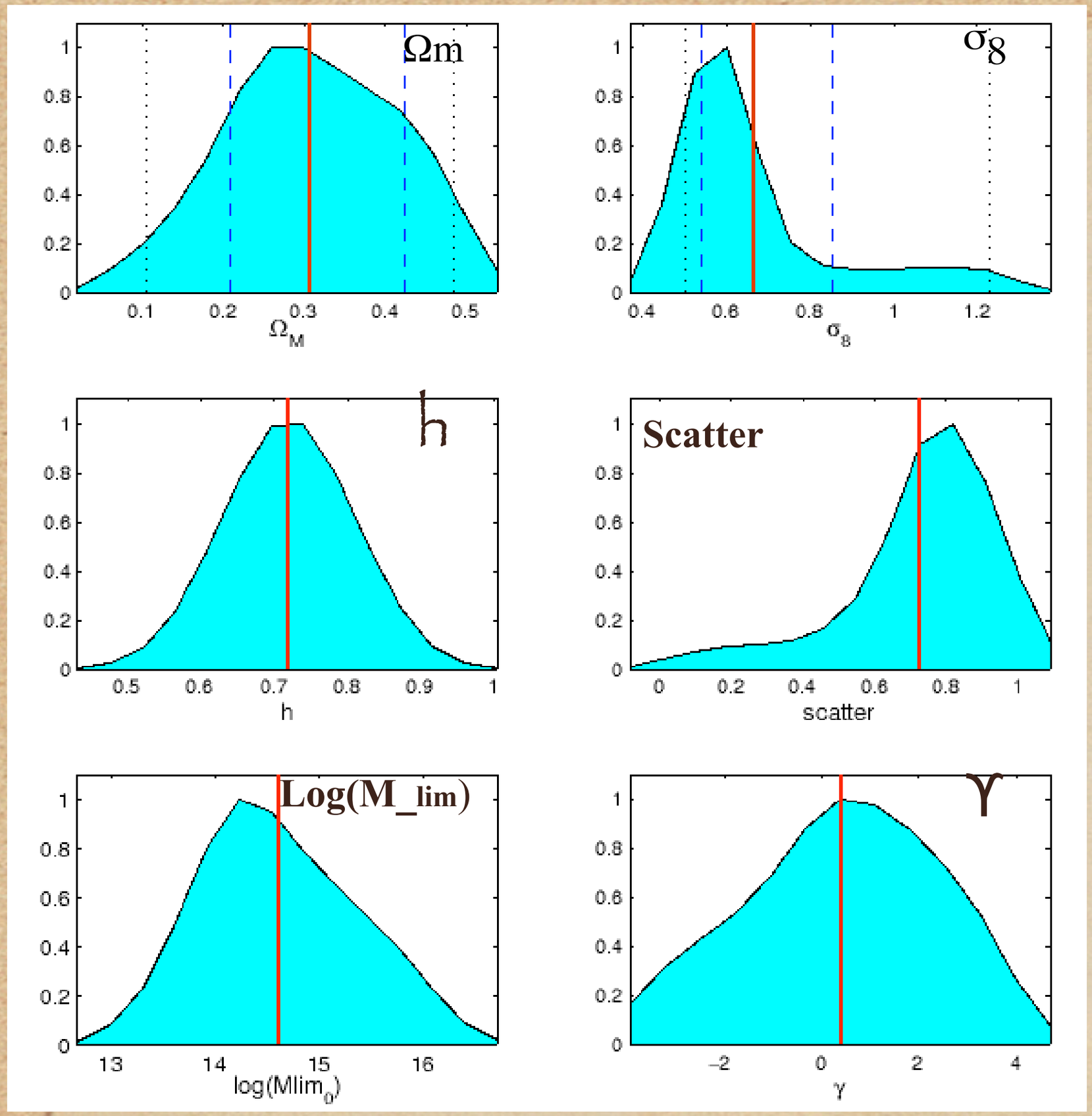
n_s (WMAP prior)

+ 3 cluster parameters

linking optical richness to mass: $M = A_{Bgc} B_{gc}^{\alpha} (1+z)^{\gamma}$

(3 parameters $M_{lim}=f(A, \alpha)$, γ, scatter)

(+ assume $\Omega_{tot}=1$)



$\Omega_m = 0.31$ +/- 0.10

$\sigma_8 = 0.67$ +/- 0.17

consistent with

WMAP year 3 result:

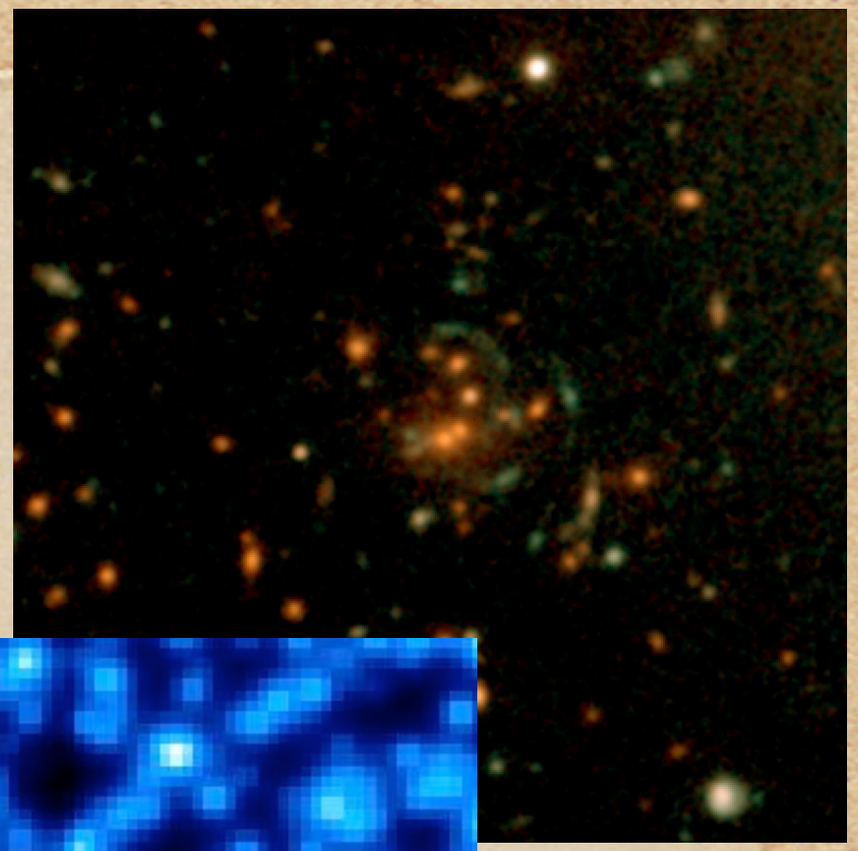
$\Omega_m = 0.24 - 0.27$

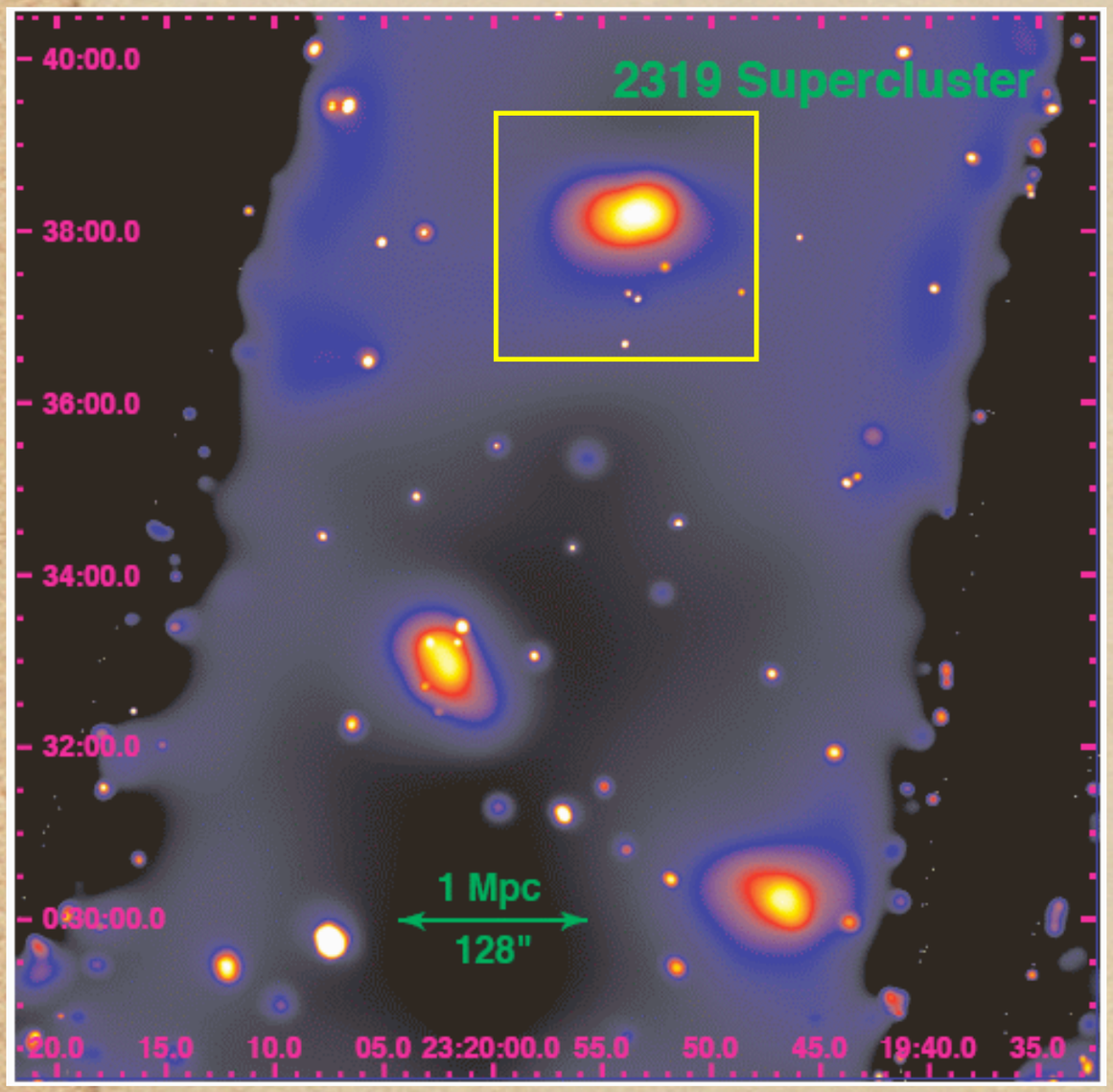
$\sigma_8 = 0.72 - 0.77$

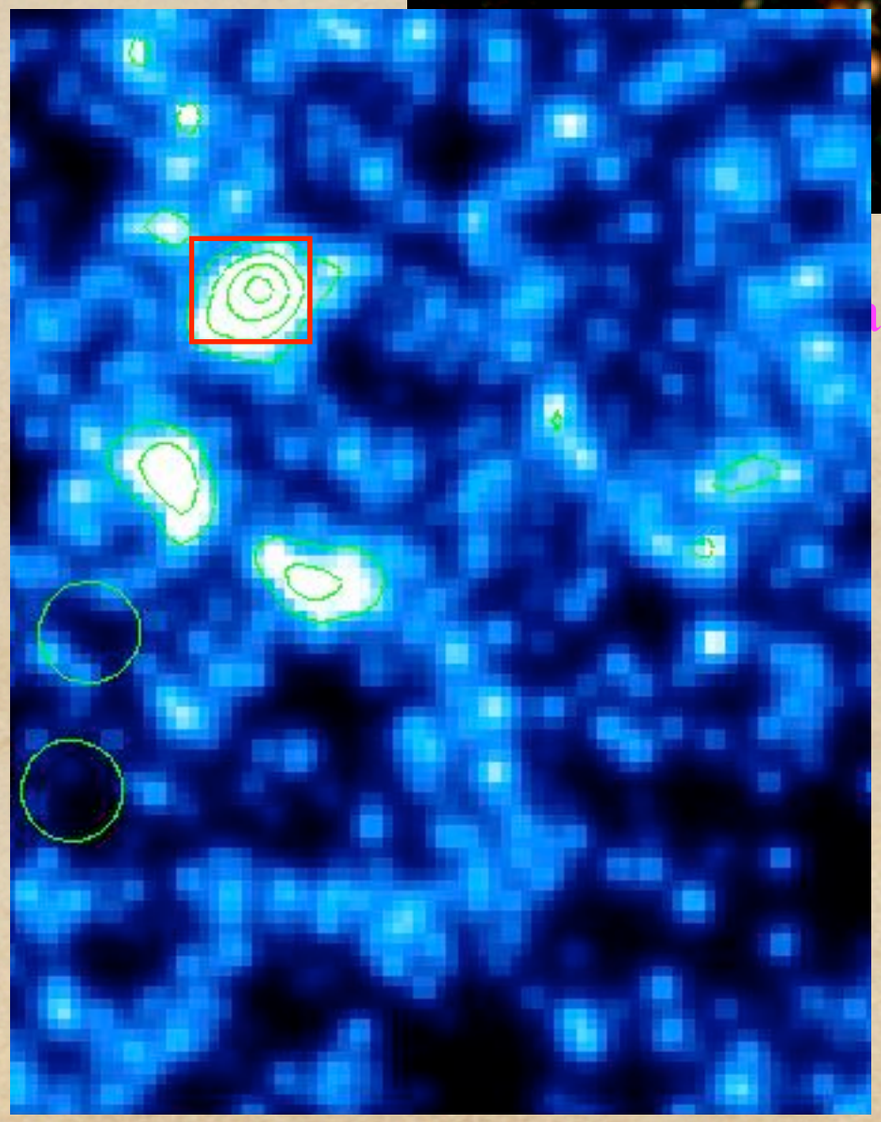
Cluster parameters are consistent with CNOC1 calibration

Marginalized likelihood

Mapping a
Large scale structure at high-z



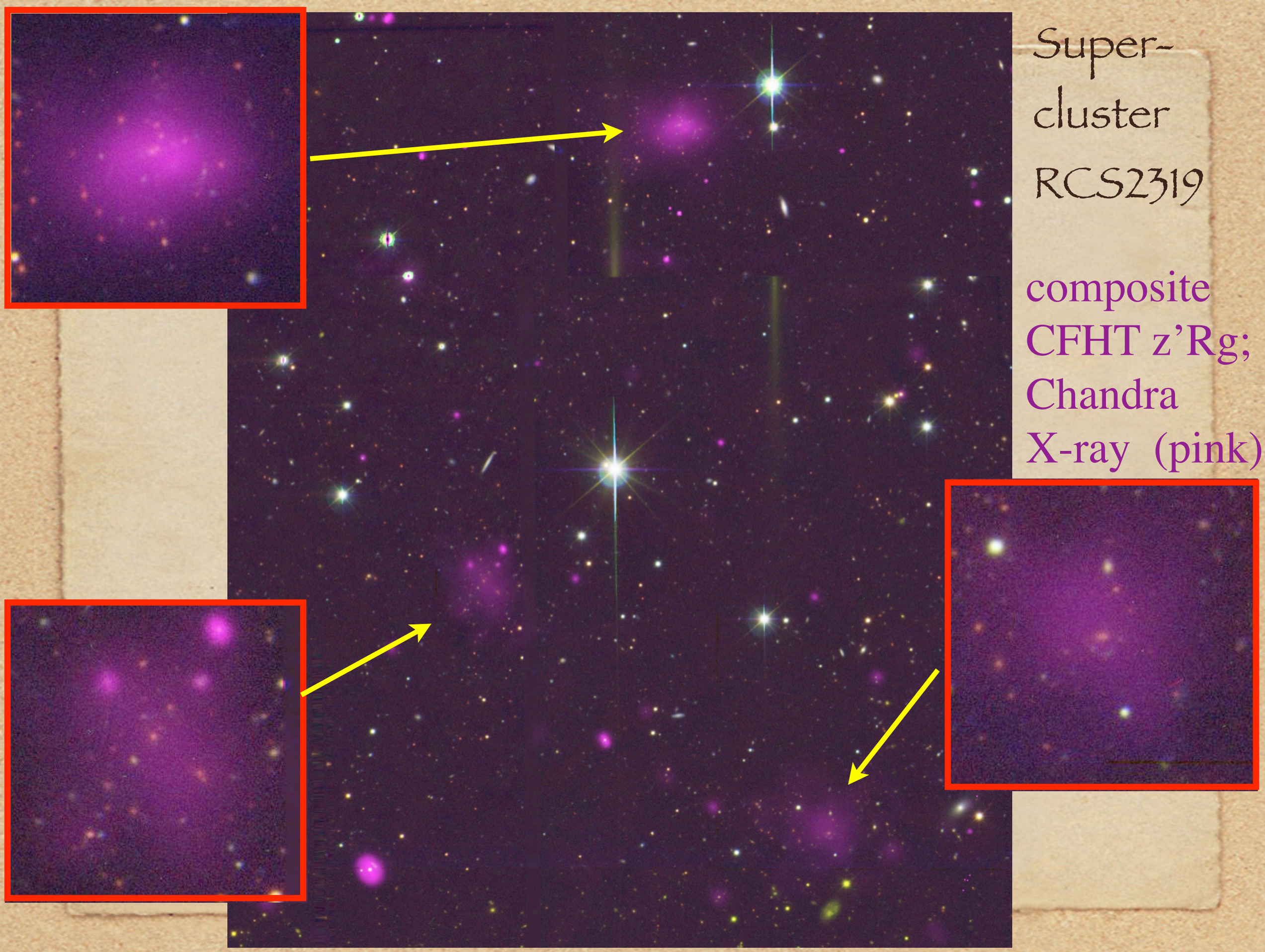




n Magic-Cam,
arc z = 3.8

Chandra X-ray image

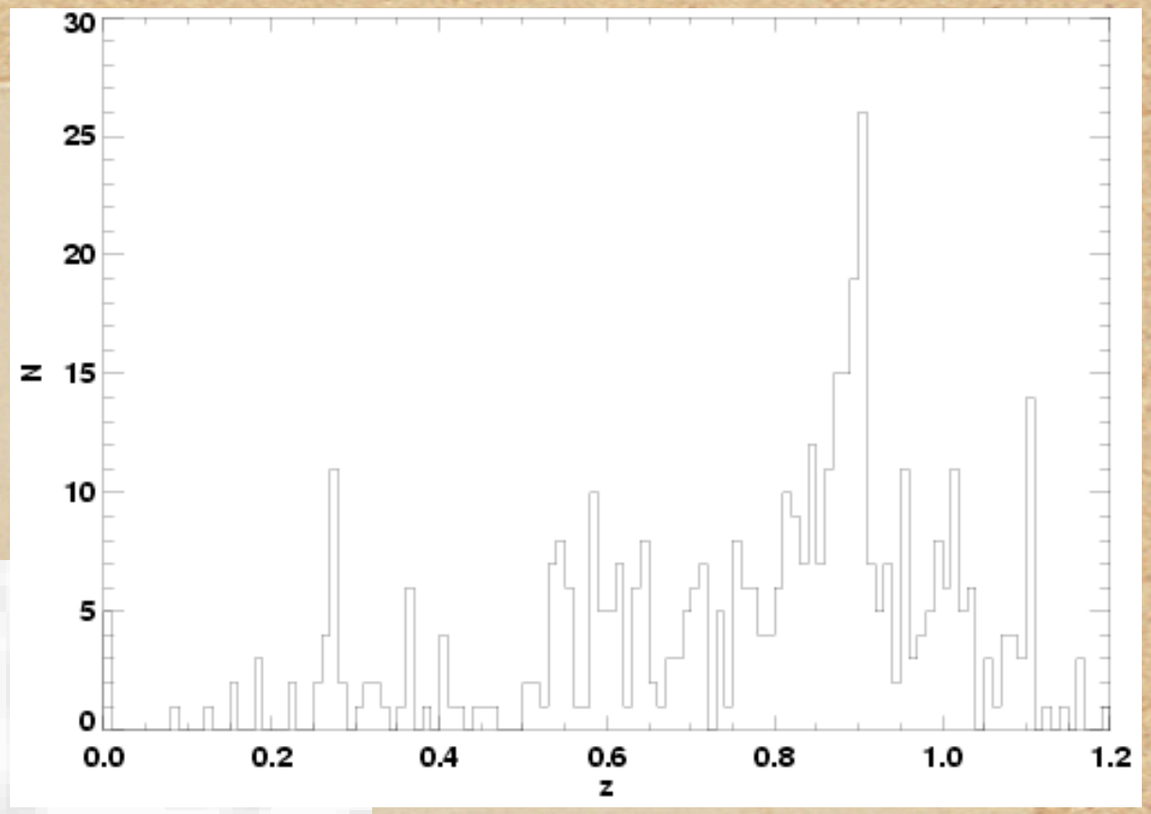
Red-sequence galaxy density, z=0.9 slice

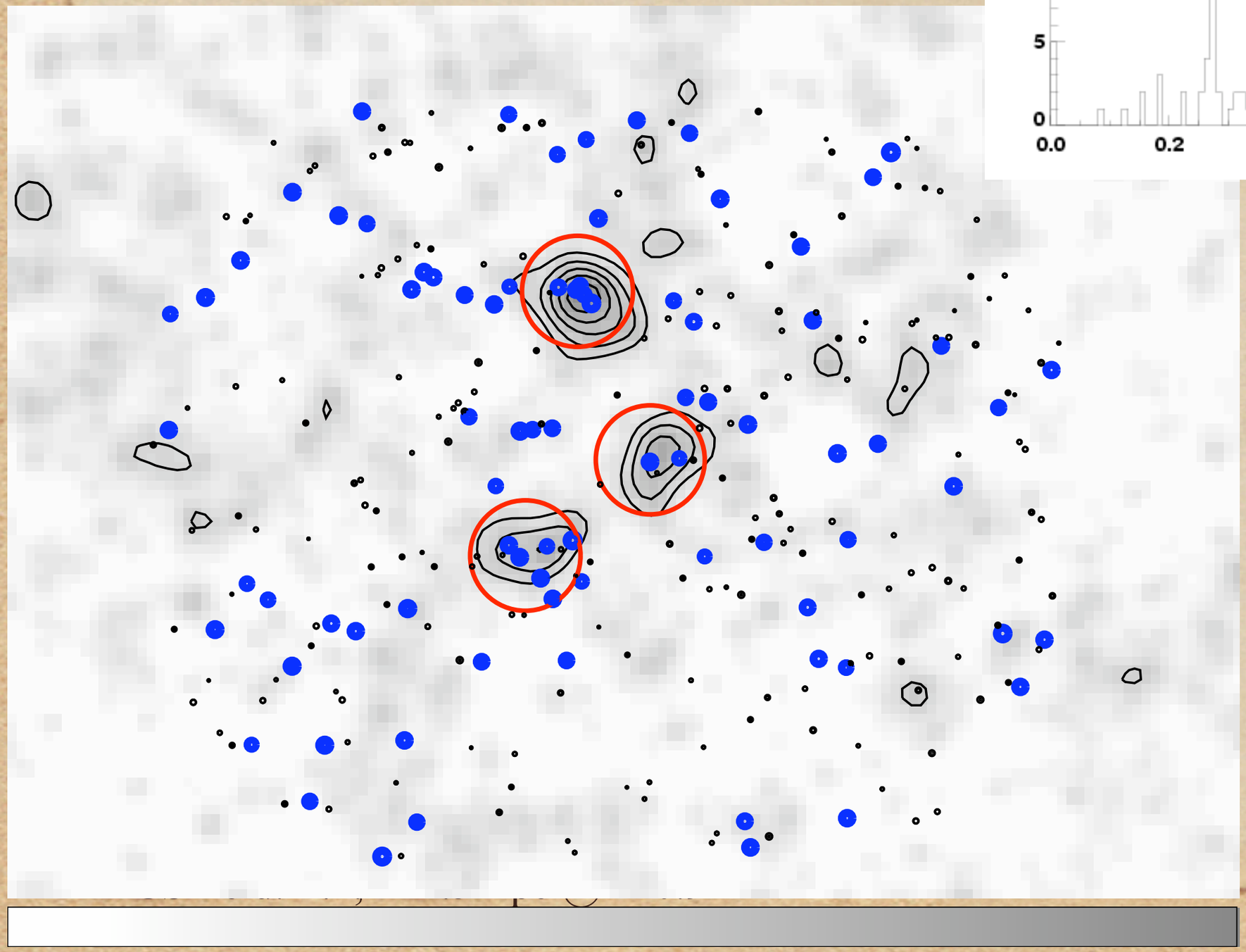


Super-cluster RCS2319

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

Magellan IMACS spectroscopy
one mask, ~420 redshifts
field size: 27'; ~20Mpc at z~0.9
the 3 clusters span ~7 Mpc





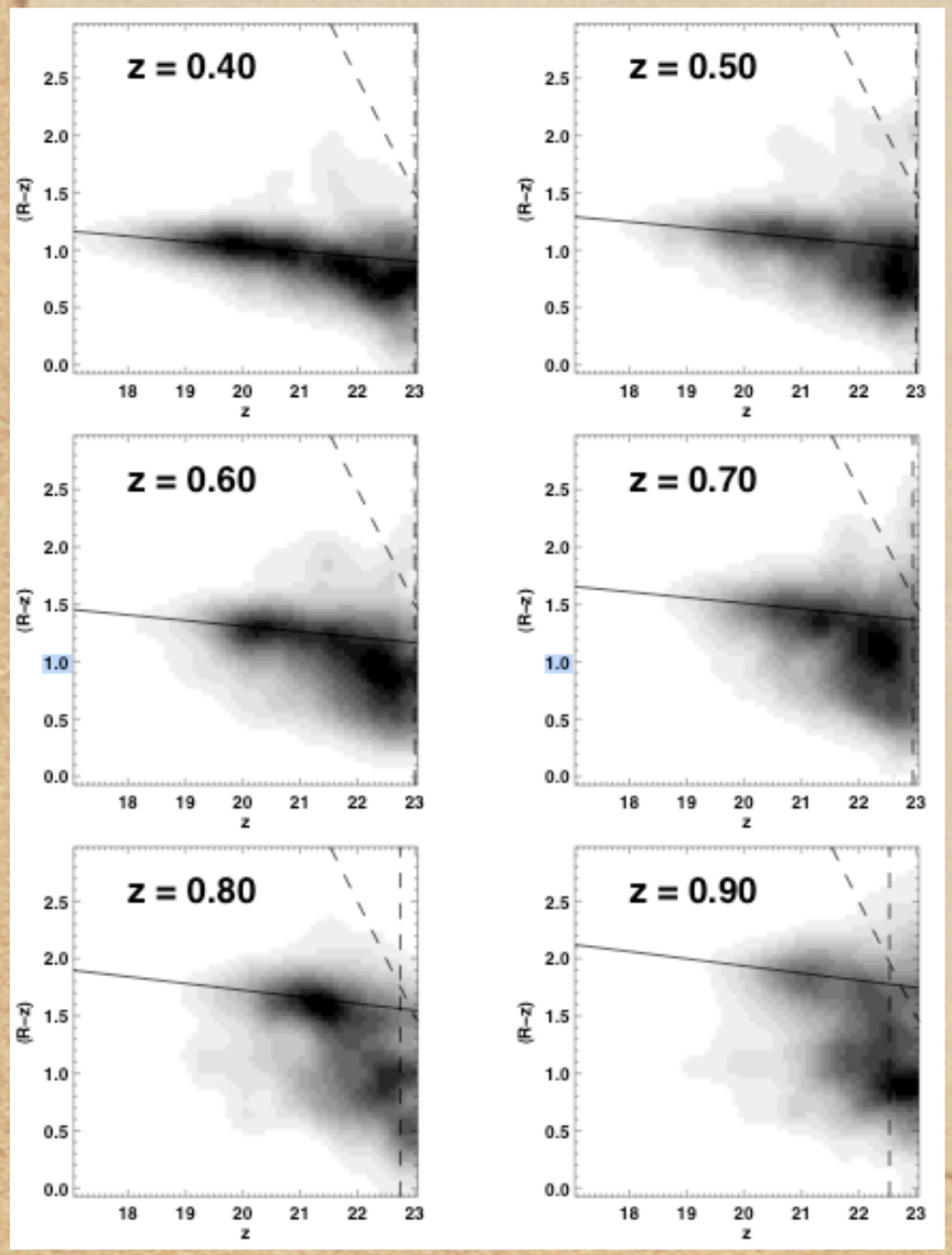
blue dots: z~0.9
black dots: "field"
red circles: X-ray positions
contour/gray scale: z=0.9 red sequence galaxy density

Additional IMACS spectroscopy (3500 slits) planned for Oct 2007

Cluster Galaxy Luminosity Function

I. RCS1 z' band galaxy LF

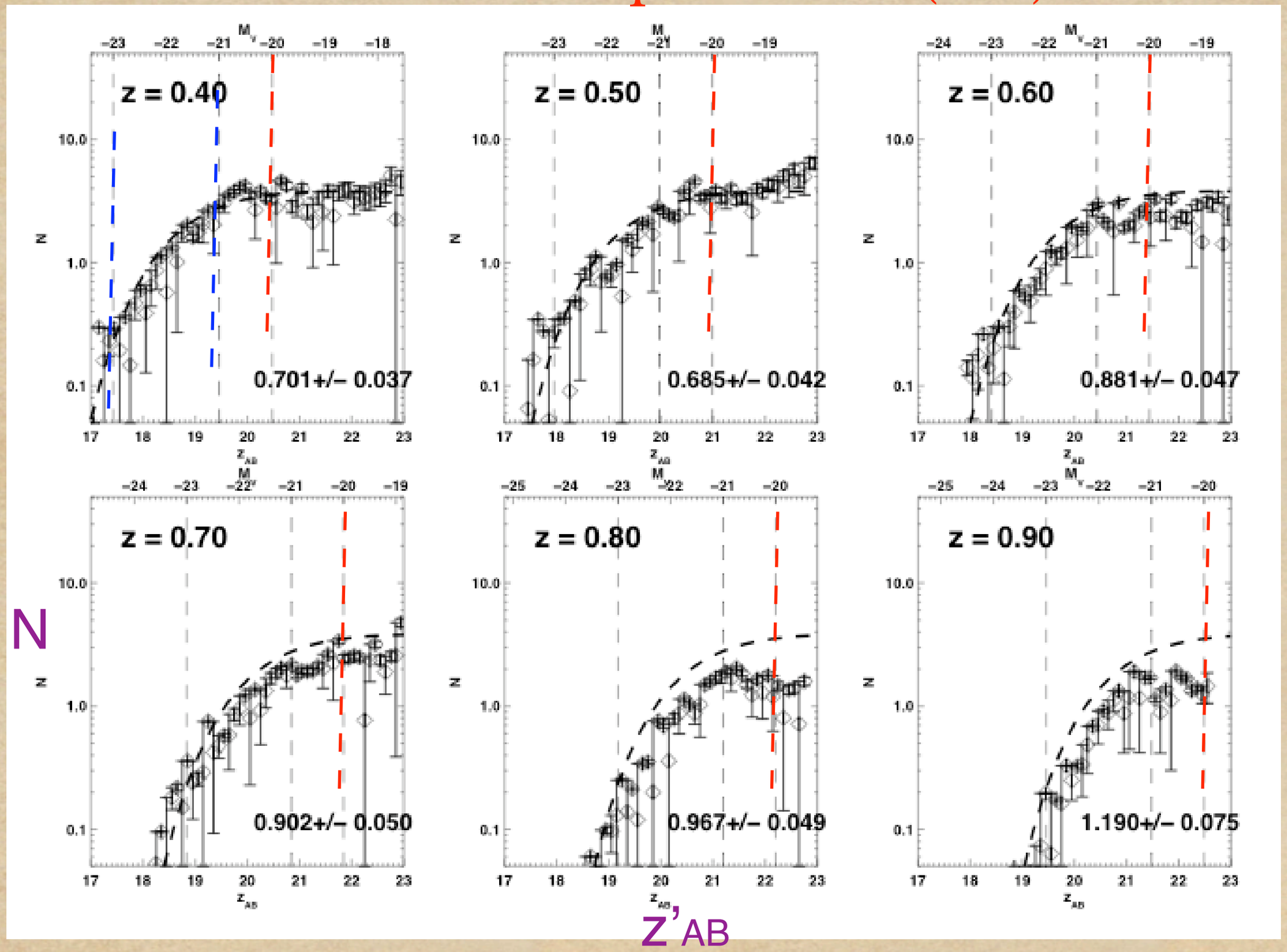
Gilbank et al. ApJ, in press
astro-ph/0710.2351



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})

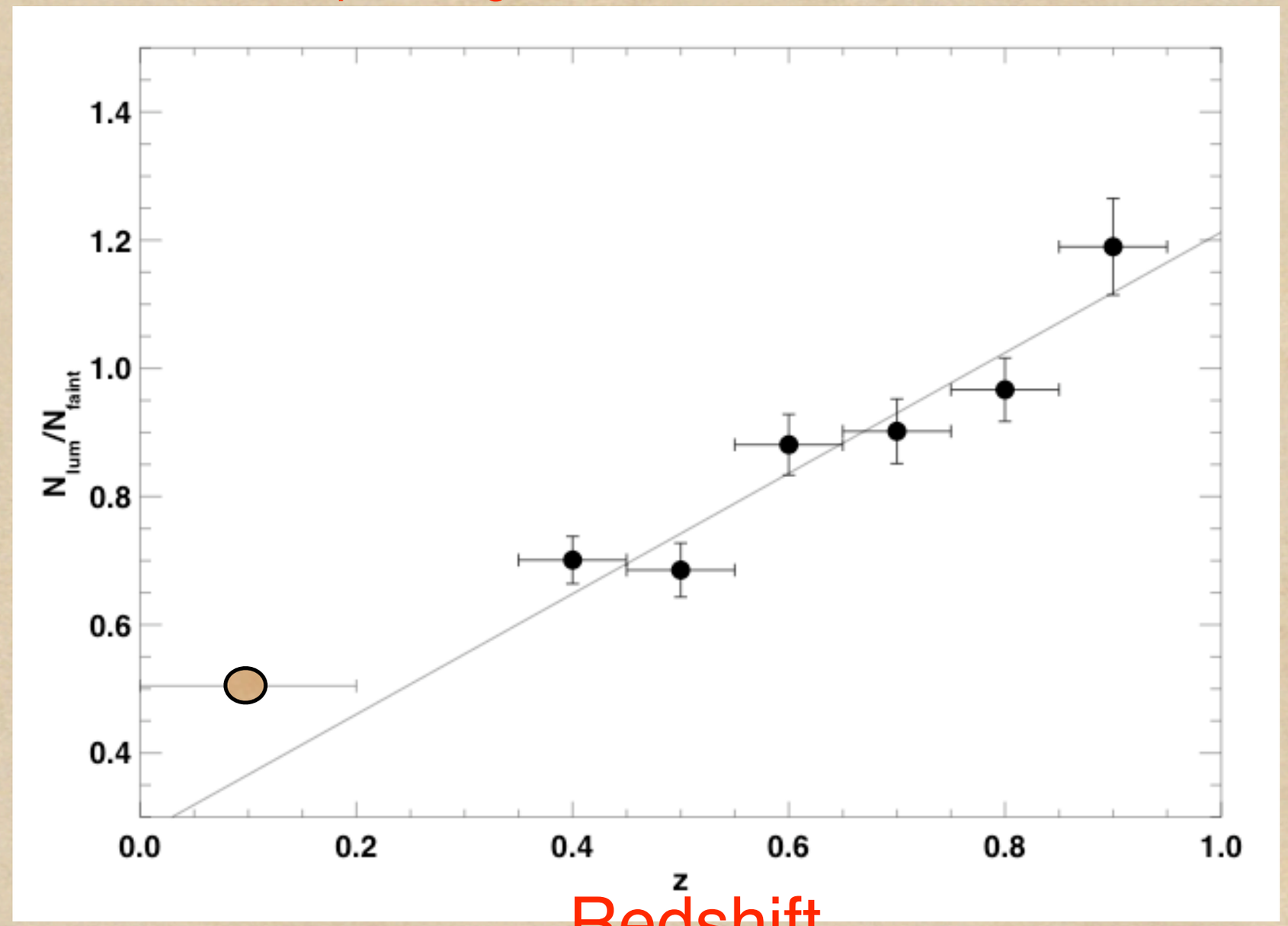


black dashed-lines: z=0.4 LF evolved passively

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

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

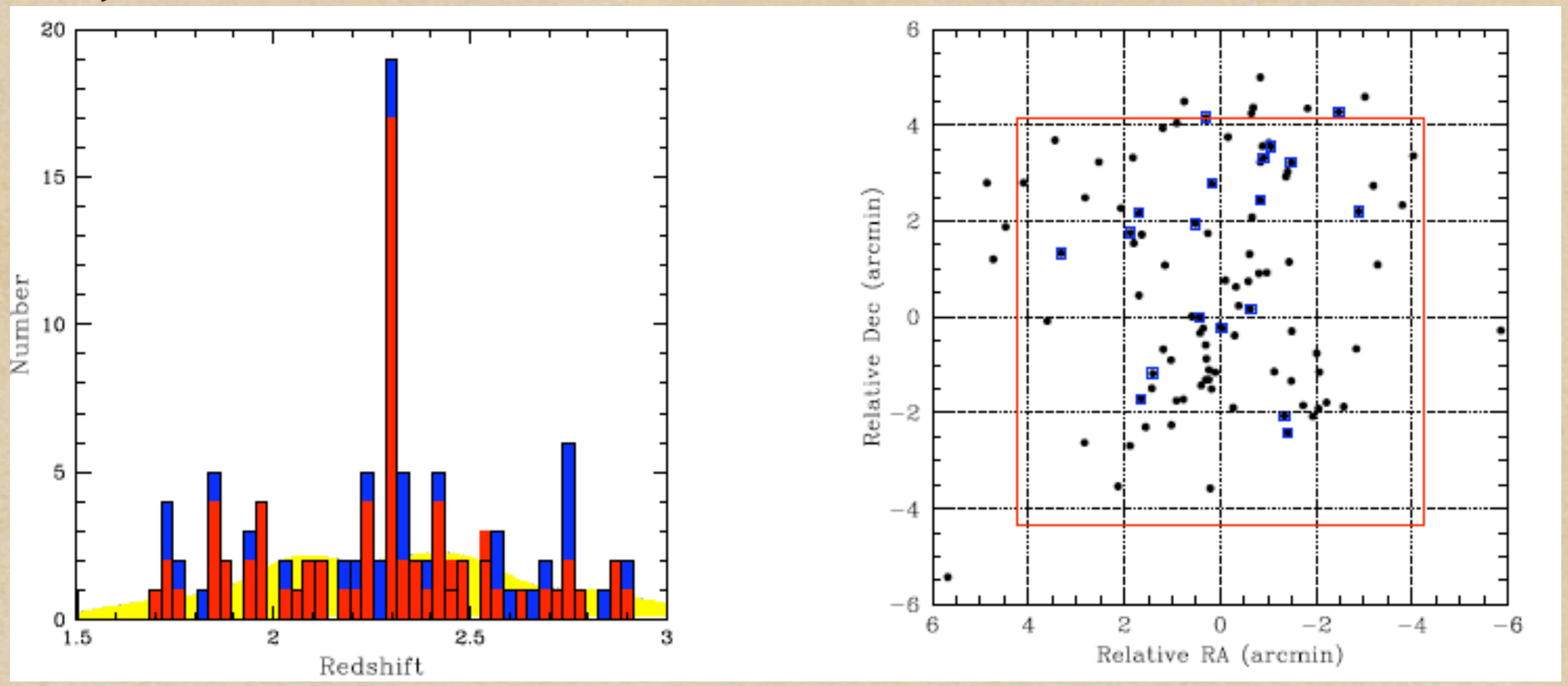


Redshift

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

The Search for z >1 Clusters

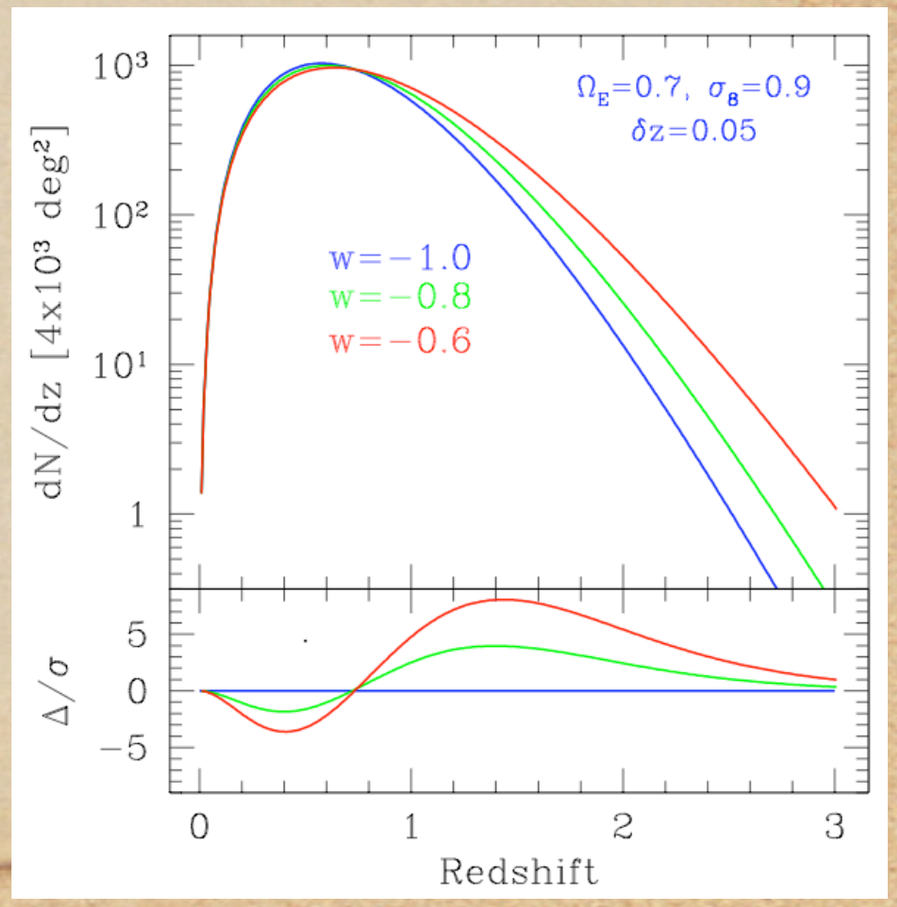
- at z>2.5: a "cluster" of Ly Break galaxies
  a proto-cluster? (Steidel et al, 2006)



- the cluster redshift "desert": 1.3<z<2

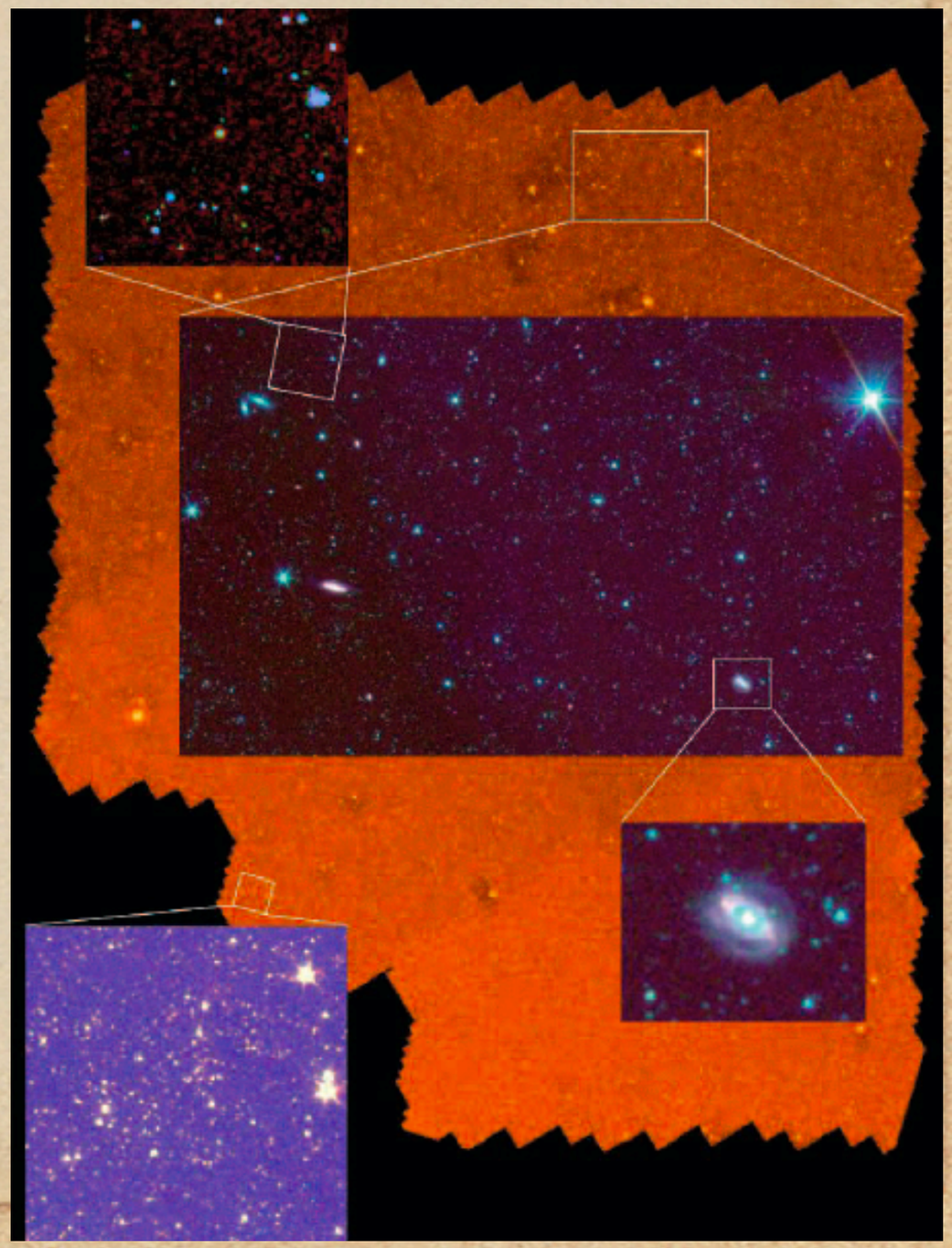
The Search for z >1 Clusters

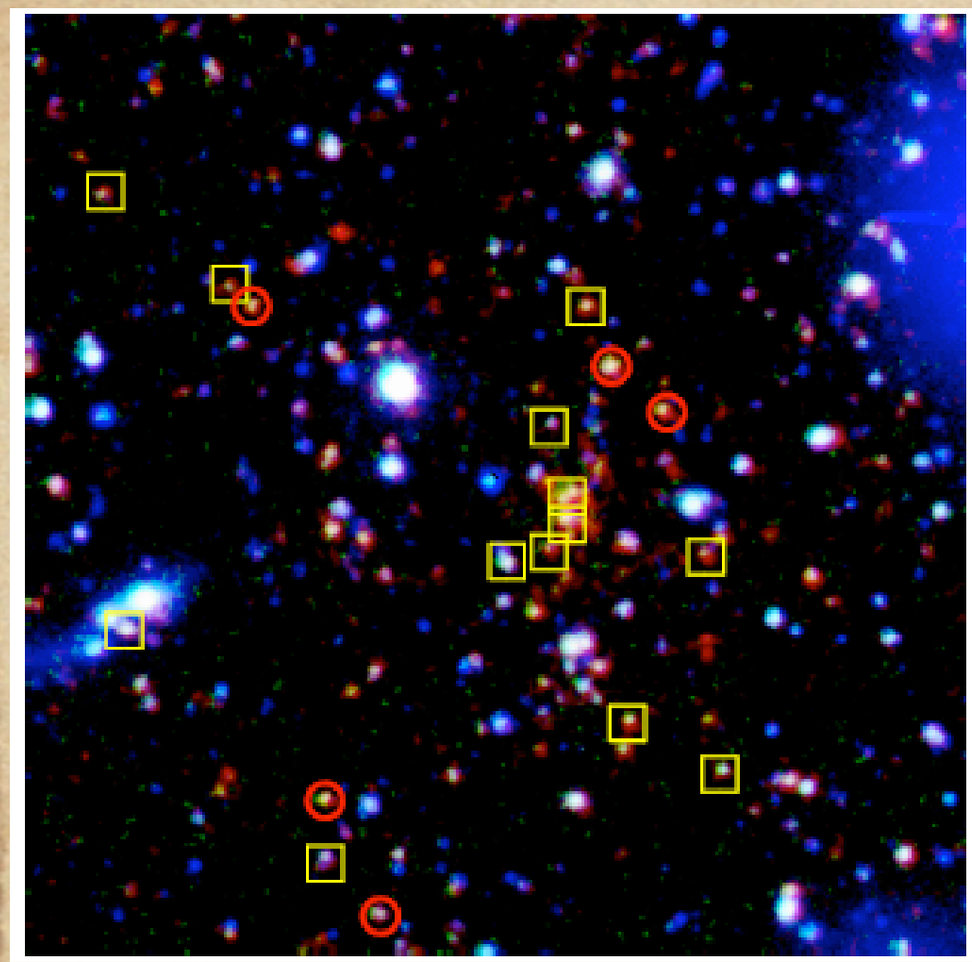
- the cluster redshift "desert": 1.3<z<2
- provides more leverage for w,
  (but, fewer clusters, and much more
  difficult to calibrate mass-observables).
- transition between "proto-clusters"
  and clusters
- the multi-color technique requires
  IR images for z>~1.2
- most efficient:
  combining Spitzer 3.6μm with
  optical data



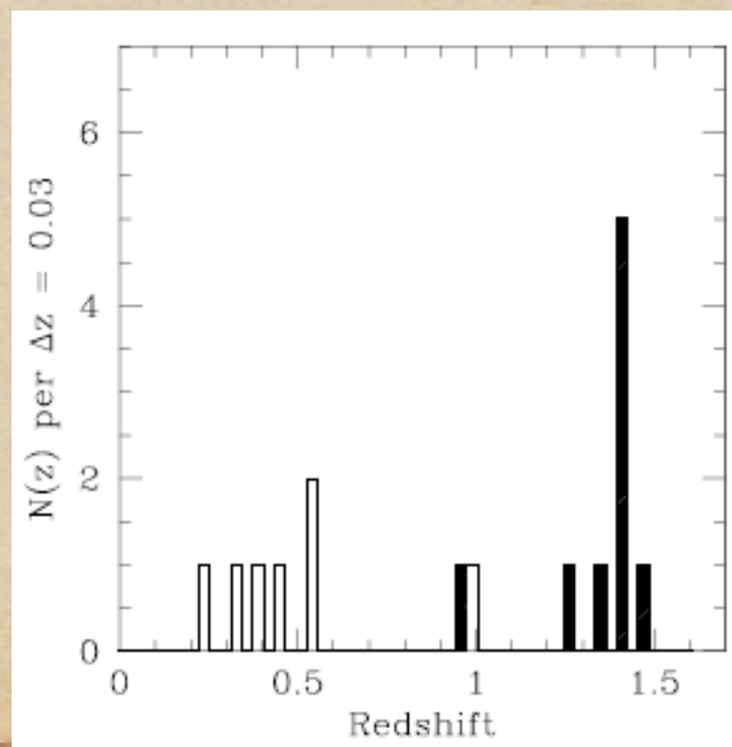
The IRAC Shallow Survey
(Eisenhardt et al, 2004)
8.5 sq deg in NOAO DWFS Bootes field

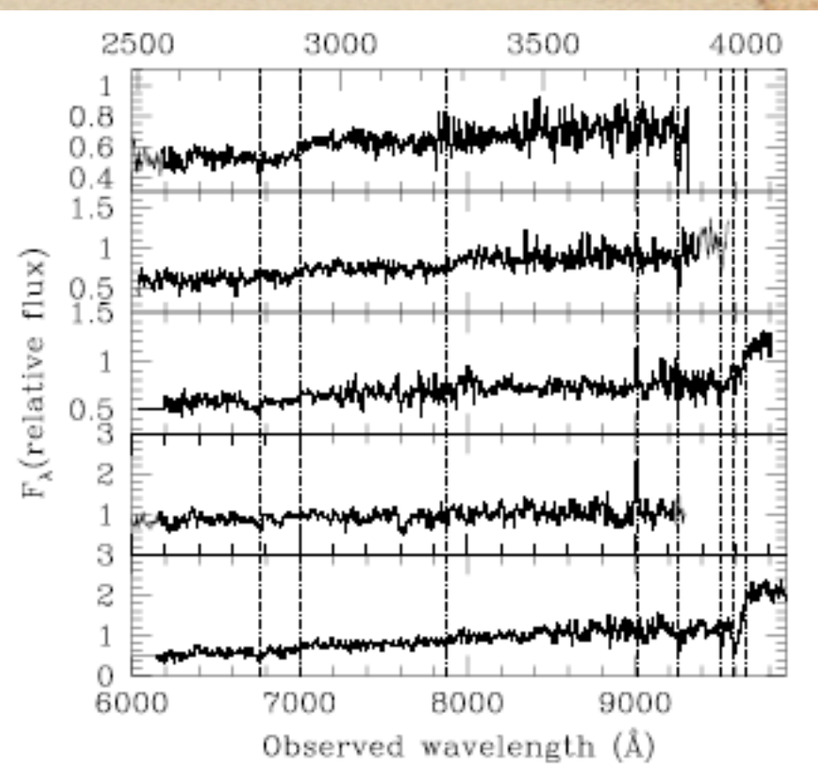
- use optical-IRAC photo-z
  to find clusters





Stanford et al (2006)
cluster at z=1.41

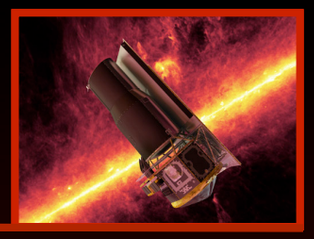




The SpARCS survey

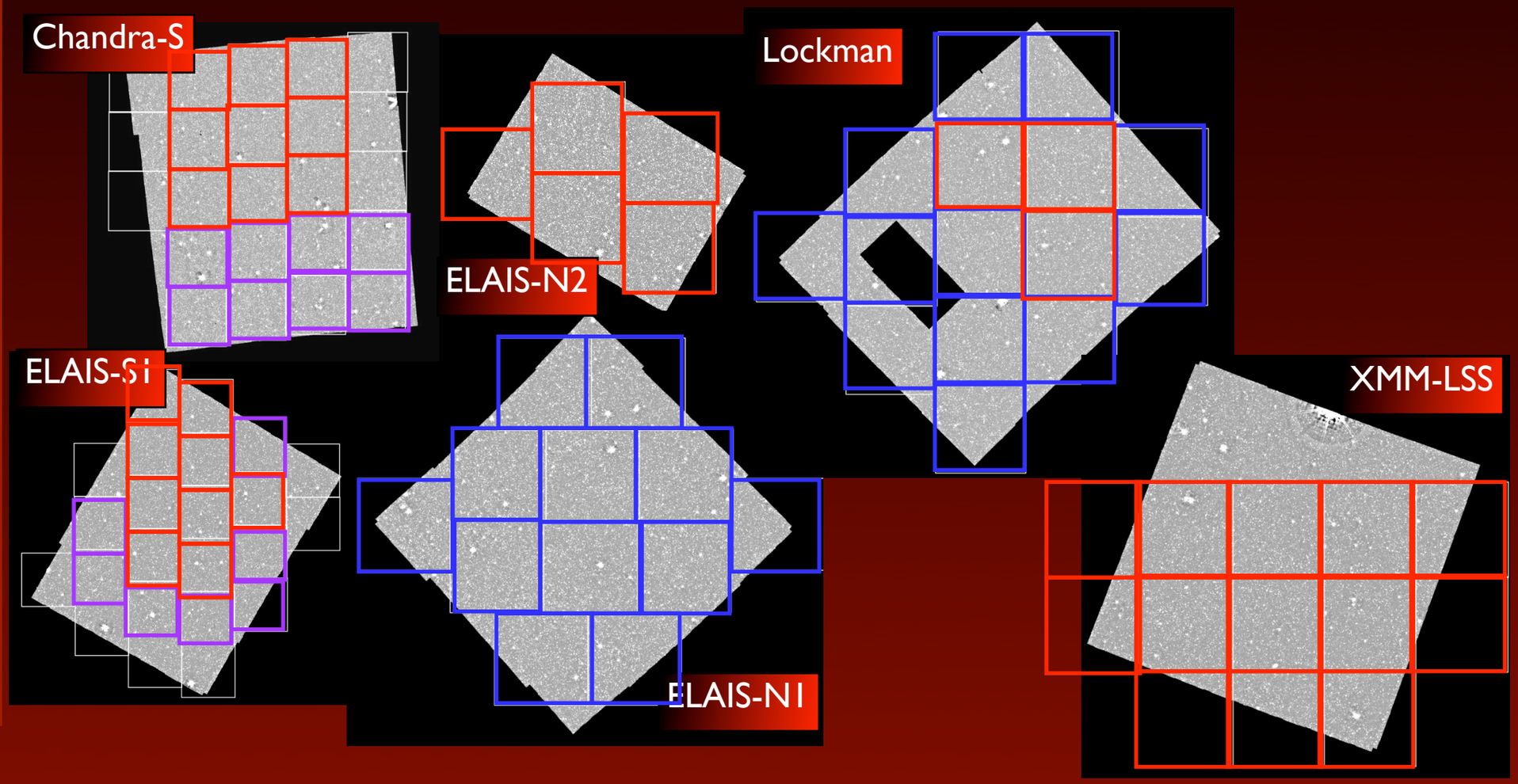
(A Muzzin, G. Wilson, +....)

- combining publicly Spitzer SWIRE 3.6μm data with 2hr integration optical z' band (CFHT 8 nights/ CTIO 15 nights);
  z'_AB ~24.2 (5 sigma)
- 4 patches, totaling 50 sq deg
  -- search for clusters to z~1.8

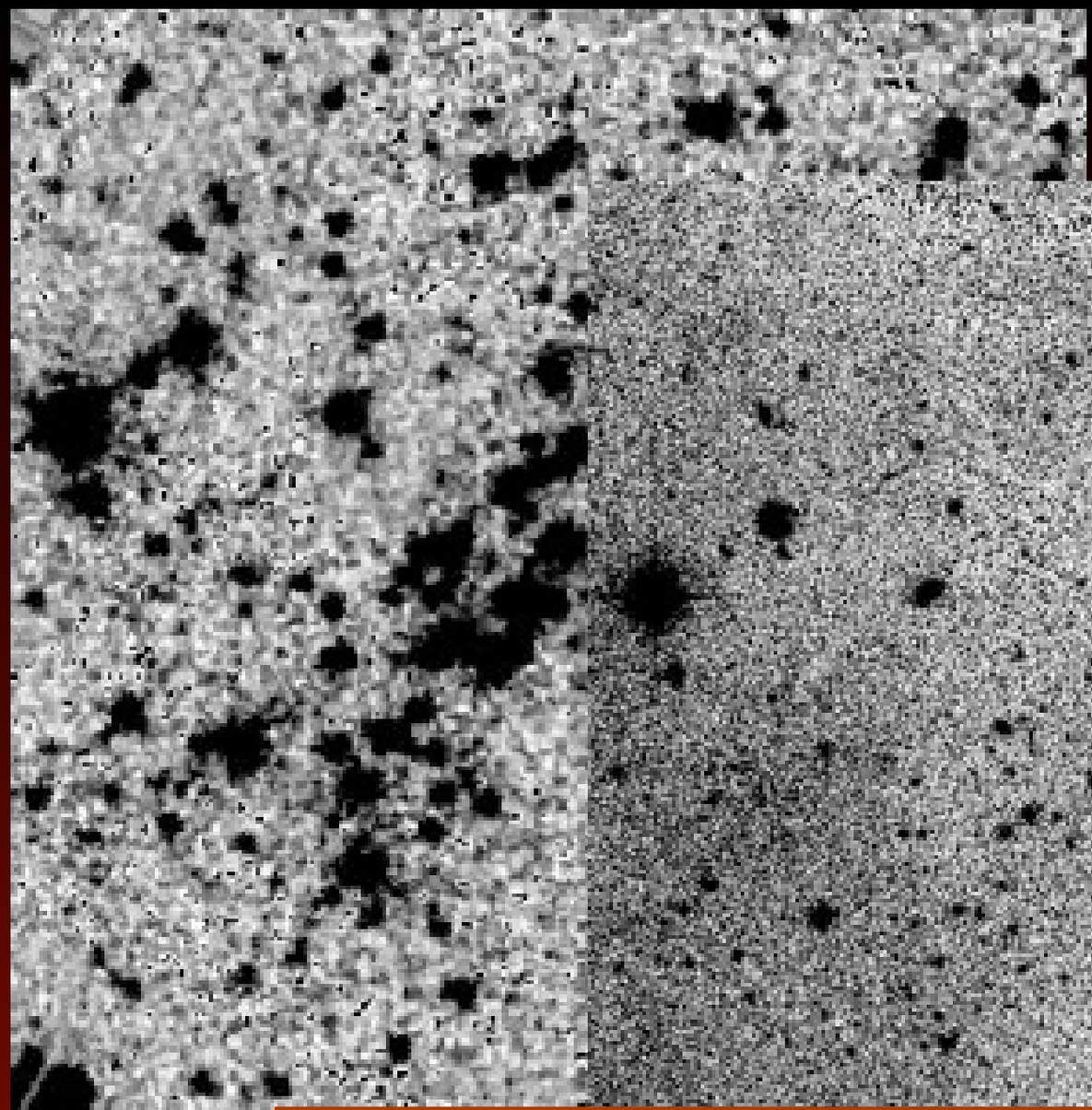


Current area: Reduced, 22/48 deg^2

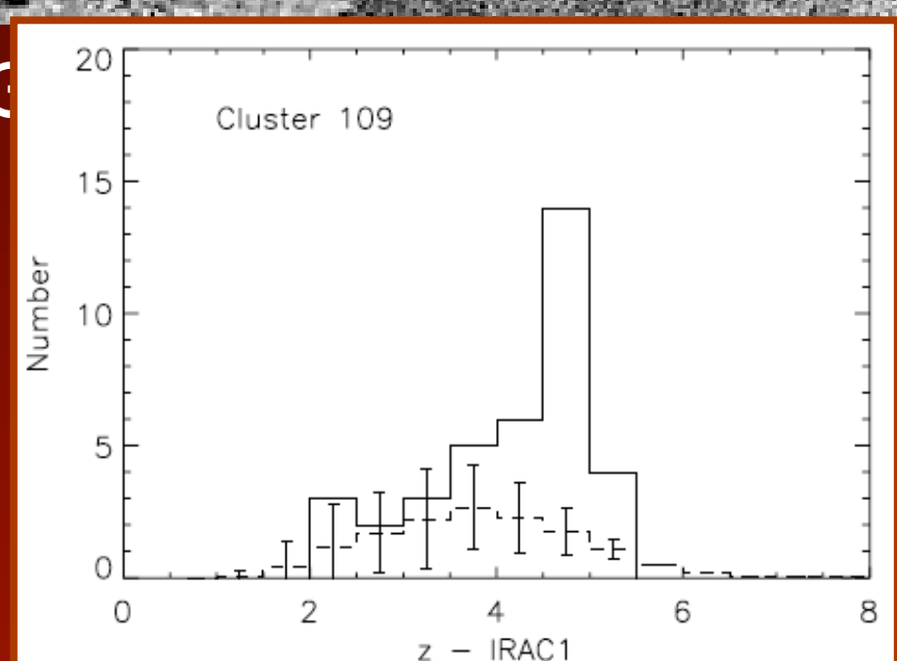
In hand, 44/48 deg^2

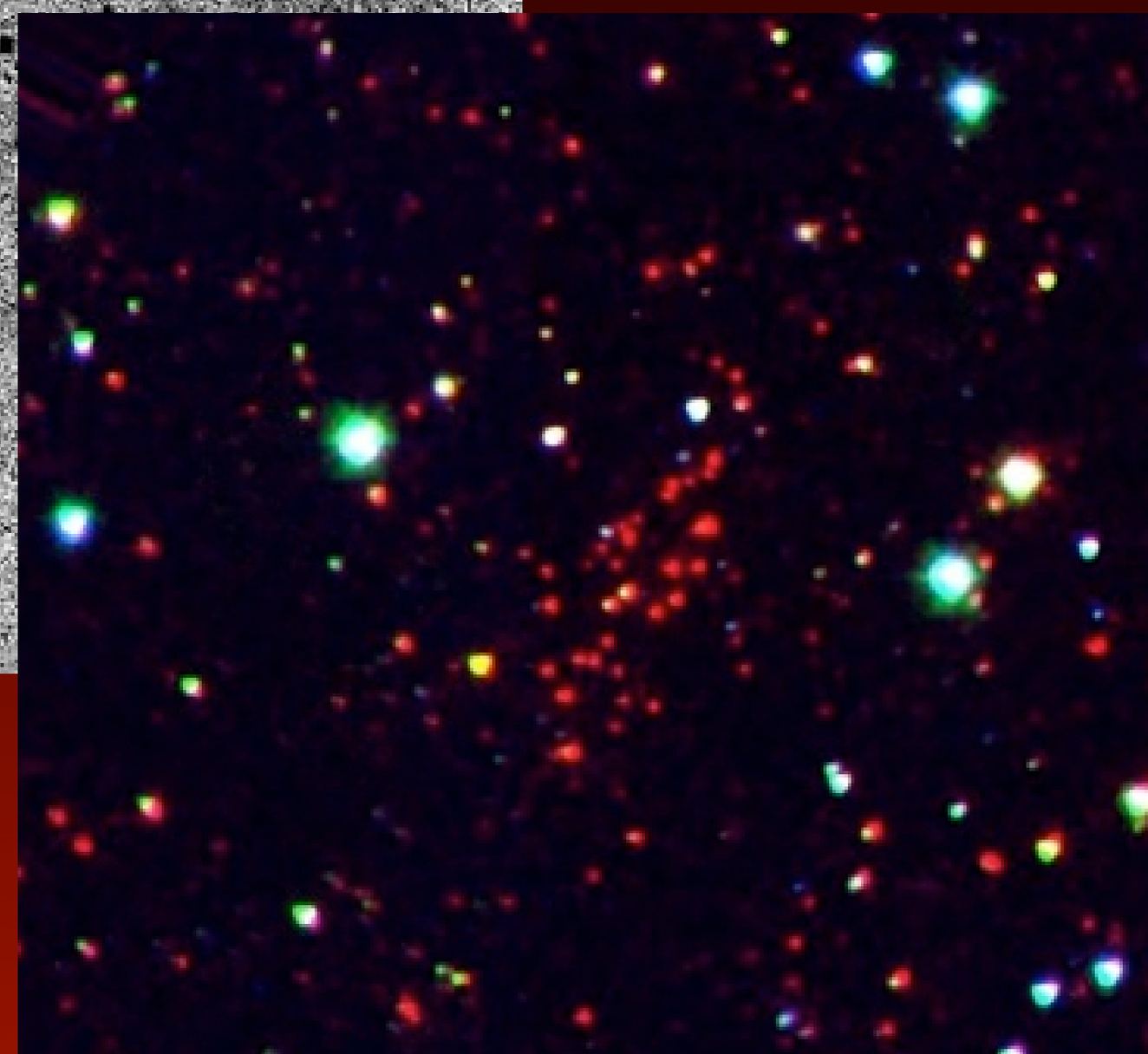


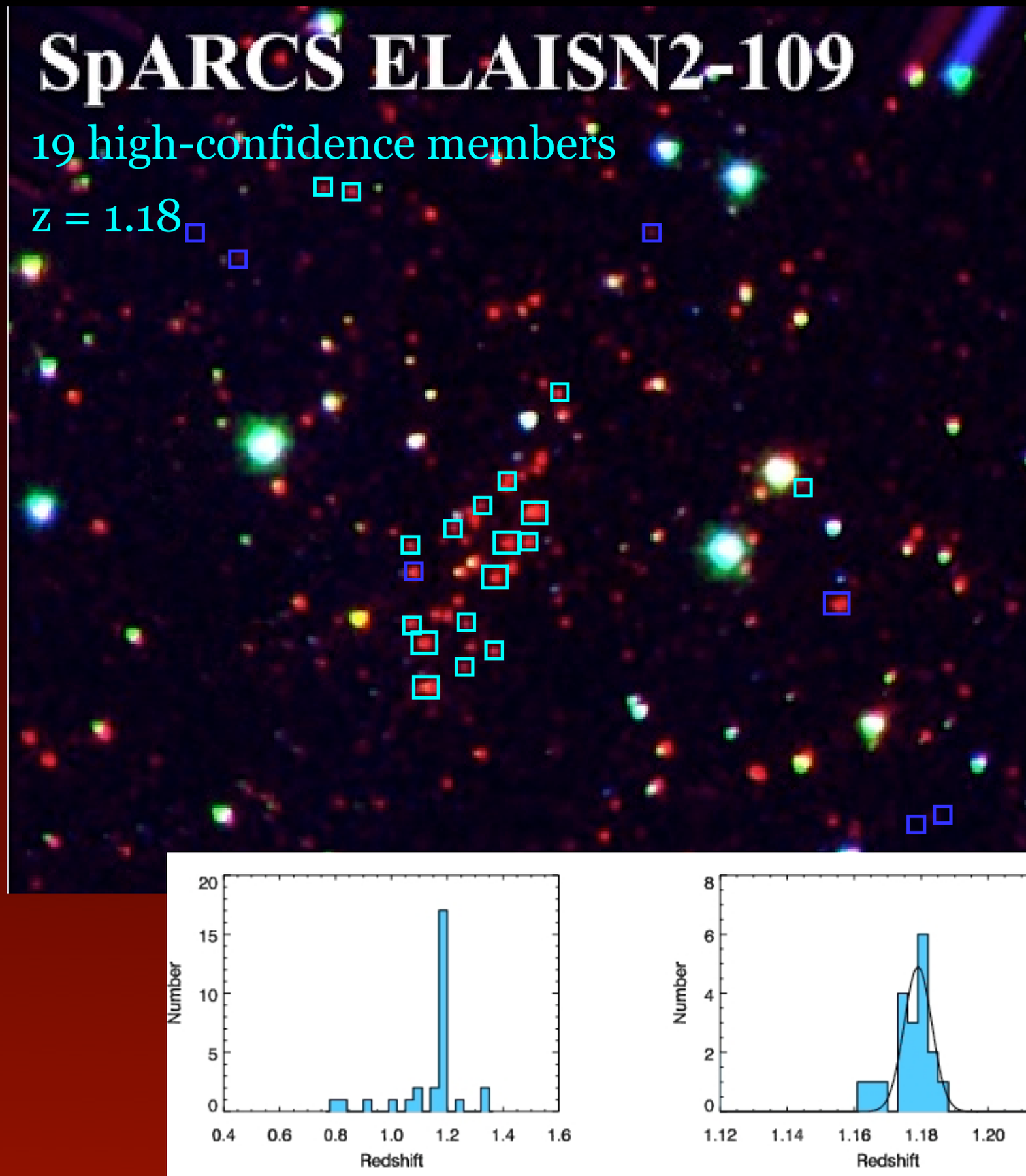
# SpARCS ELAISN2-109
zphot = 1.25



IRAC 3

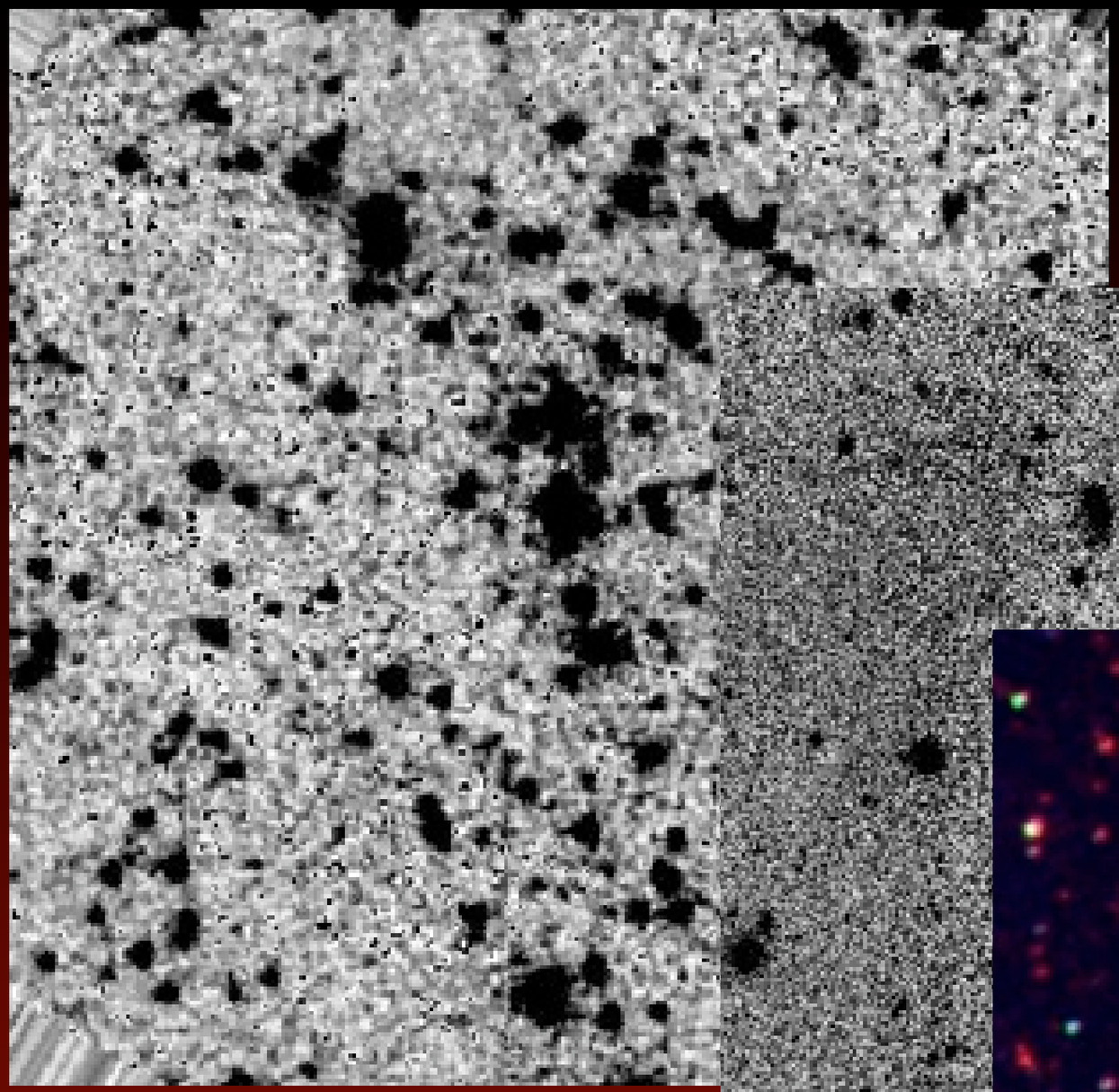


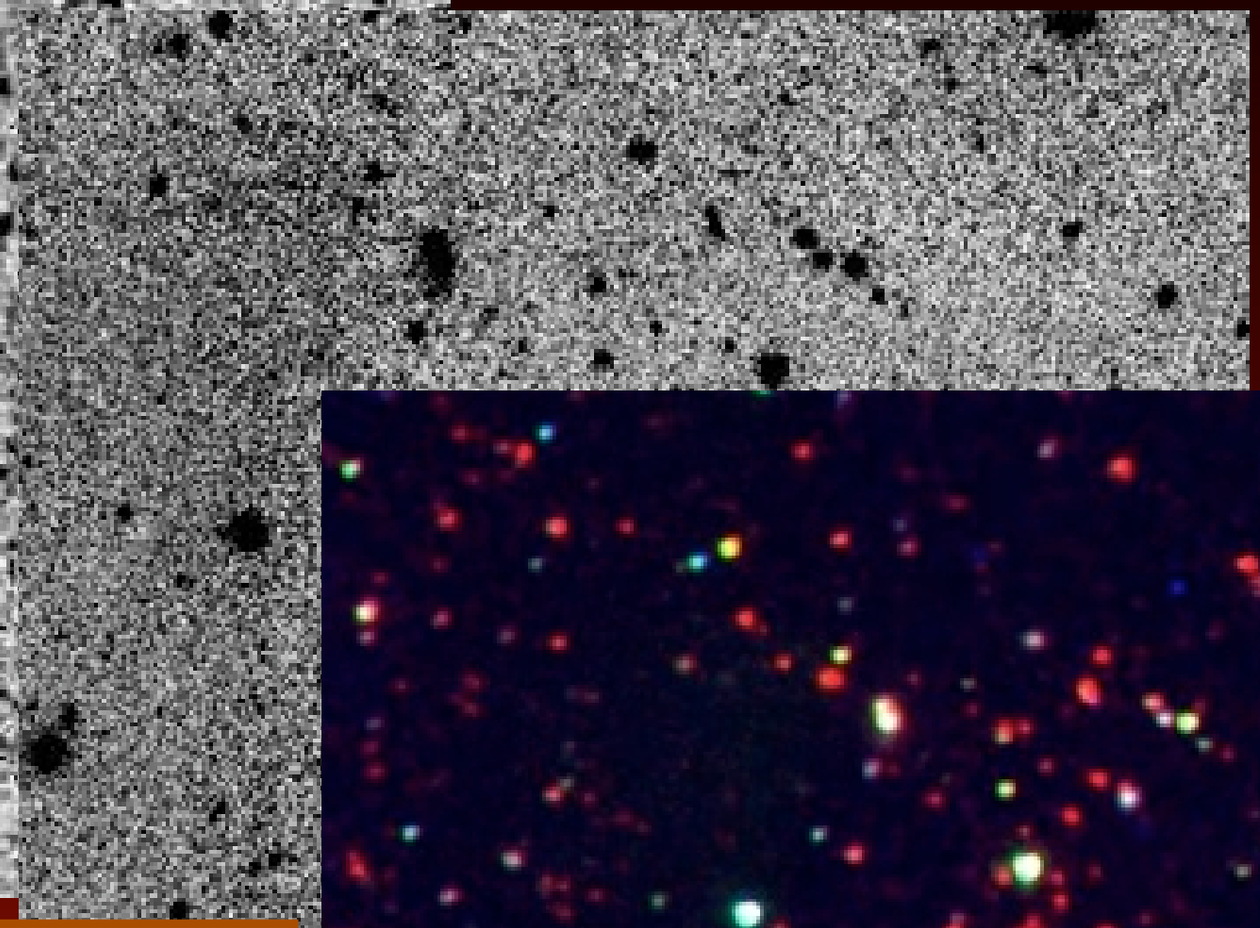




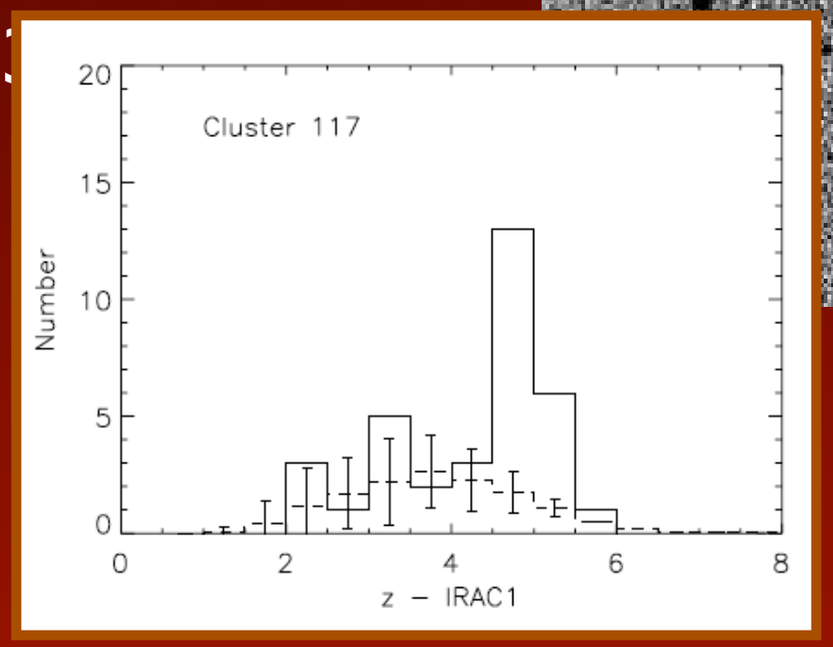
z = 1.1796
σ = 700 ± 200
km/s

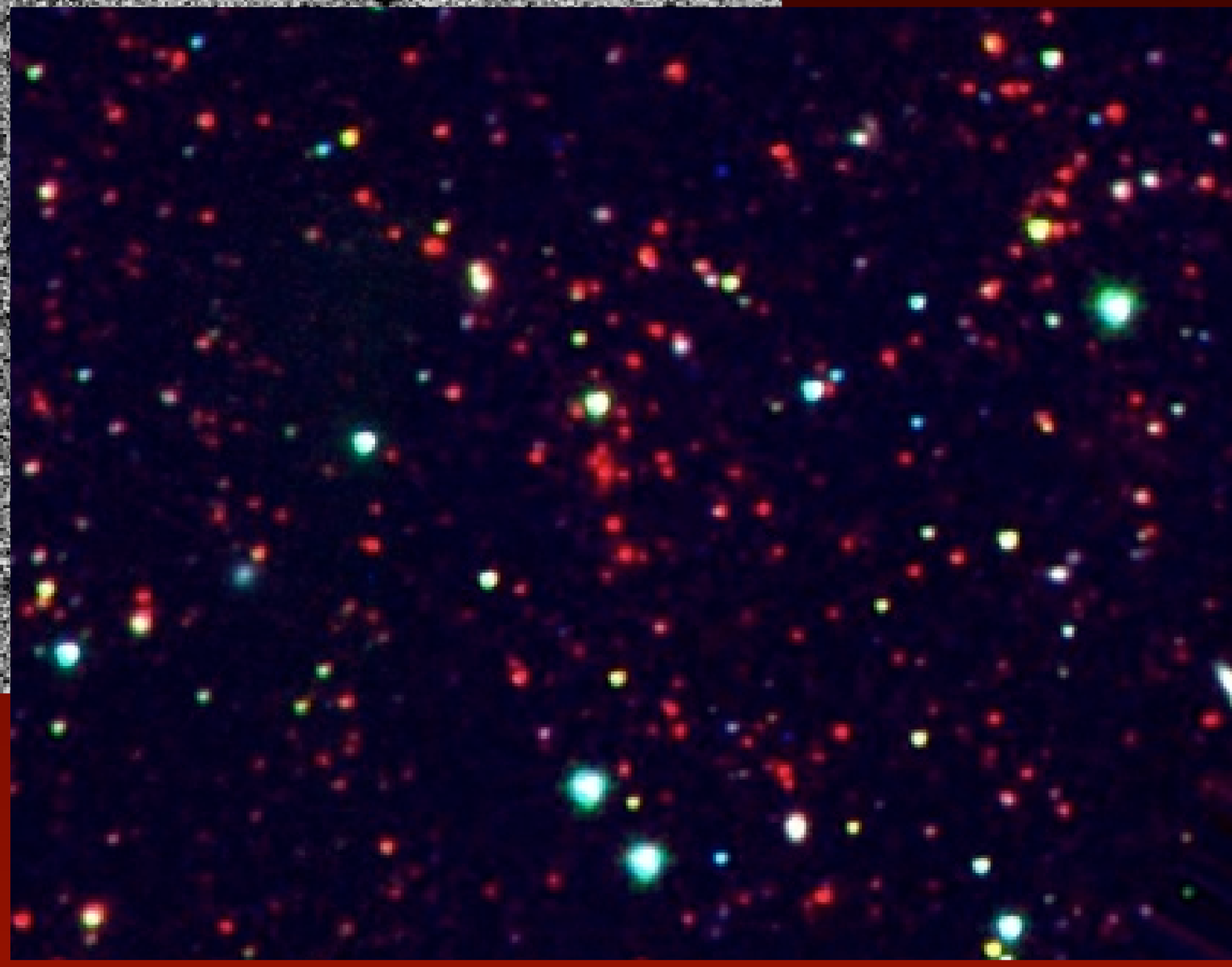
# SpARCS ELAISN2-117
zphot = 1.3

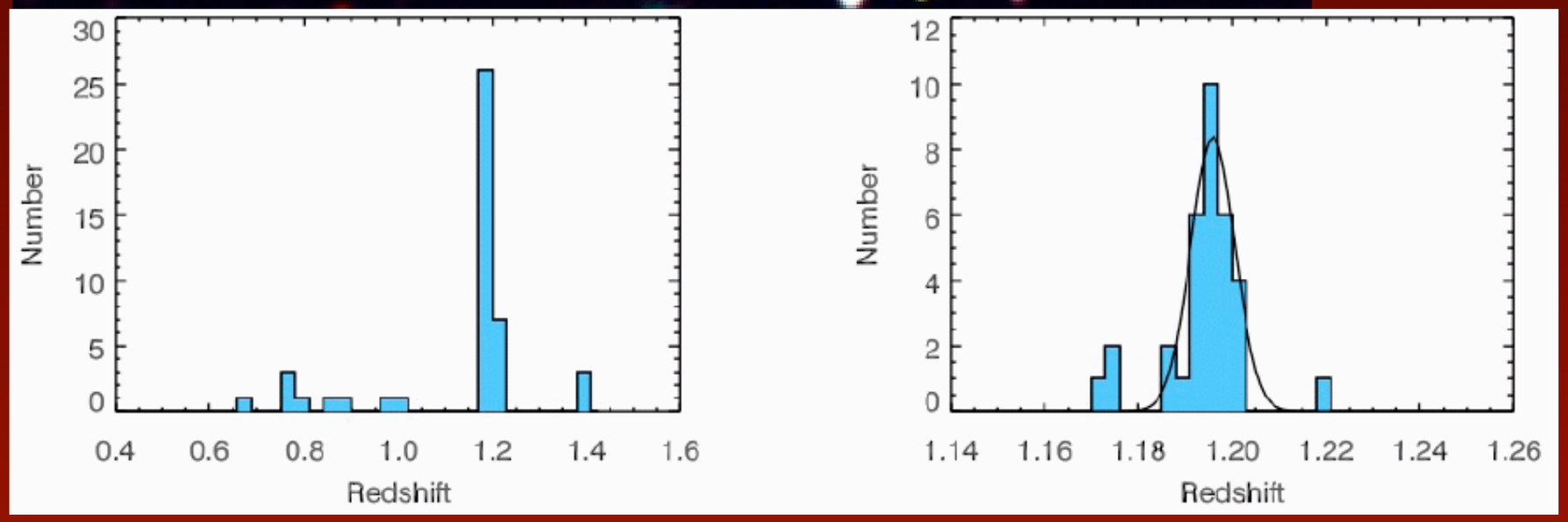




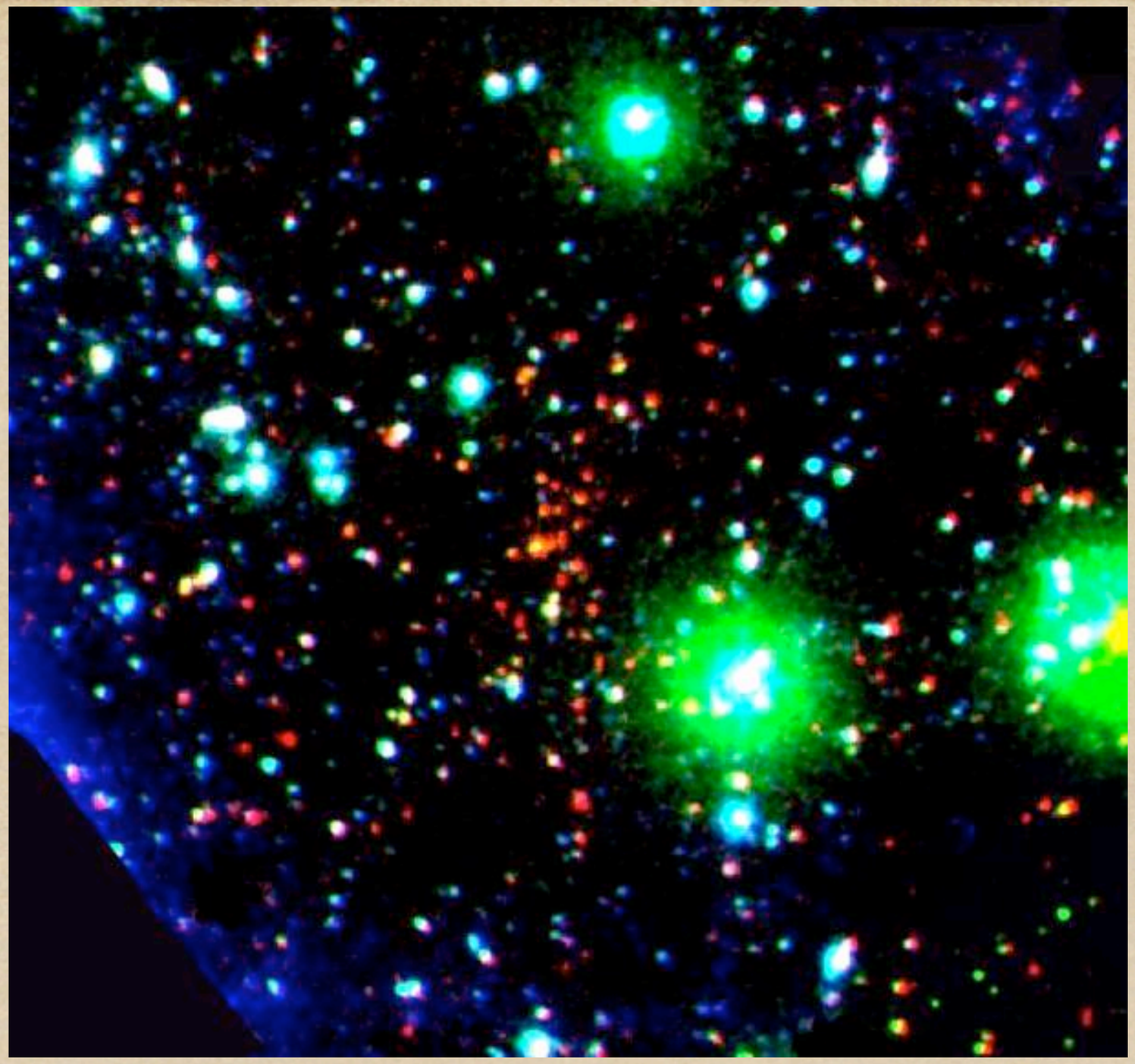
IRAC 1



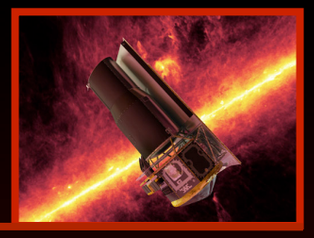




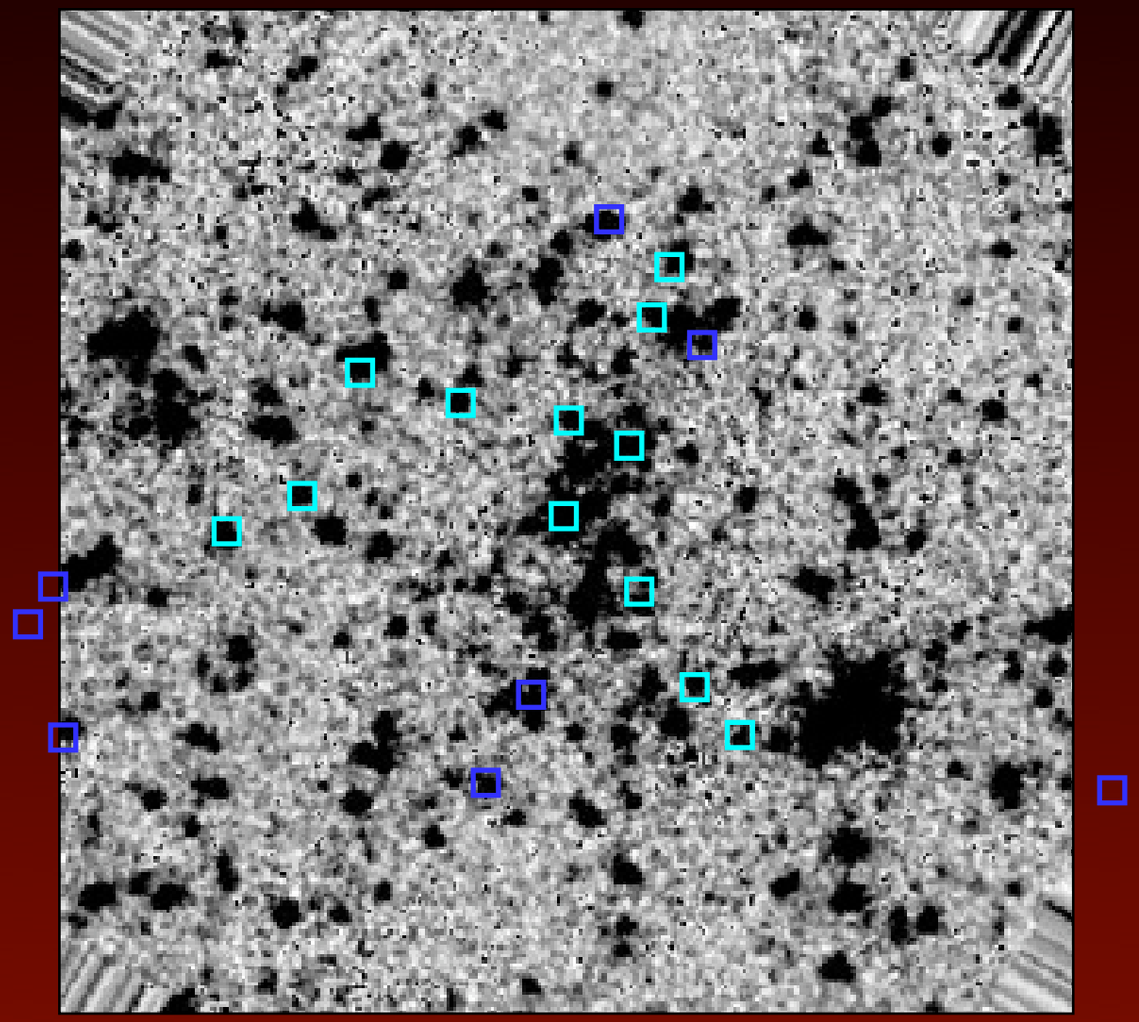
z = 1.1960
σ = 650 ± 150 km/s



Sp-EN175, z~1.60



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



10 High confidence members,
z = 1.34

Current spectroscopically confirmed high-z clusters

Most distant X-ray clusters	Most distant IR clusters
z = 1.45, XMMXCS J2215.9-1738	z = 1.41, ISCS J143809+3414
z = 1.39, XMMU J2235.3-2557	z = 1.34, SpARCS J0035.7-4312
z = 1.27, RDCS J0849+4452	z = 1.24, ISCS J1434.5+3427
z = 1.24, RDCS J1252.9-2927	z = 1.20, SpARCS J1638.8+4039
z = 1.22, XLSS J022303-043622	z = 1.18, SpARCS J1634.5+4021

Spitzer has nearly doubled the number of known distant clusters in just a few years!

Future Surveys that can be used for the seach of high-z clusters:

Talks on Thursday!

- Pan-STARRS, DES, LSST, WISE, NIRSS

- 500 sq deg Spitzer warm mission survey (to be proposed)

Summary:

- The optical/IR red-sequence method (and its variants) is a powerful and efficient method for creating well-characterized samples of cluster galaxies covering up to z~1, and potentially to z~2.
- The RCS1 sample demonstrates that clusters as a probe for cosmology is tractable, and potentially very powerful
- Large samples of clusters covering a good redshift and richness range will provide significant advances in the study of the evolution of clusters and cluster galaxies.