Title: The Red-Sequence Cluster Survey and its Applications to Cosmology

Date: Apr 30, 2009 11:00 AM

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Abstract: The Red-Sequence Cluster Survey (RCS2) is a 1000-square-degree, multi-color imaging survey carried out using MegaCam on the 3.6m CFHT which is optimized for the search of galaxy clusters with 0.15<z<1.0 using the red-sequence method. Designed to create a well-characterized, large sample of clusters, the survey has the main goals of constraining cosmological parameters, studying galaxy cluster evolution, and discovering a large sample of strong gravitational lenses. I will give a summary of the current status of the RCS2 survey and discuss preliminary results on cosmological parameter fitting. I will present some Some initial results from an extension of the RCS method to Spitzer IRAC images from the SWIRE database to search for galaxy clusters in the "cluster desert" redshift range of 1<z<2 will also be shown.

The Red-Sequence Cluster Survey

Howard Yee
University of Toronto
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& The RCS1/RCS2 collaboration

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RCS2

The RCS1/2 Collaboration:

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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,

Outline:

- a summary of the RCS:
    - the red-sequence method
    - the RCS1 and 2
- cosmological parameters from RCS1
- RCS2 strong lensing arcs
- The HST Cluster Supernova Survey
- The SpARCS survey: finding clusters at z>1

Scientific motivations for galaxy cluster surveys:

1. Growth of structures; the measurement of cosmological parameters.
2. Galaxy evolution and cluster physics: effects of environment, large scale structure
3. Using galaxy cluster potential as gravitational lens "telescope".

What is needed for a modern galaxy cluster survey:

- large area (10^2 to 10^3 sq deg)
- redshift to >~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 *(most efficient!)*
2. Sunyeav-Zeldovich effect
3. X-ray

(Approximately factors of 10 different in cost!)

Optical Search for Clusters

NOAO 0.9m, Lopez-Cruz & Yee

Coma
(A1656, z=.025)

Richness~ Abell 2

PDCS, z=0.83

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, overcoming most of the
  projection problems

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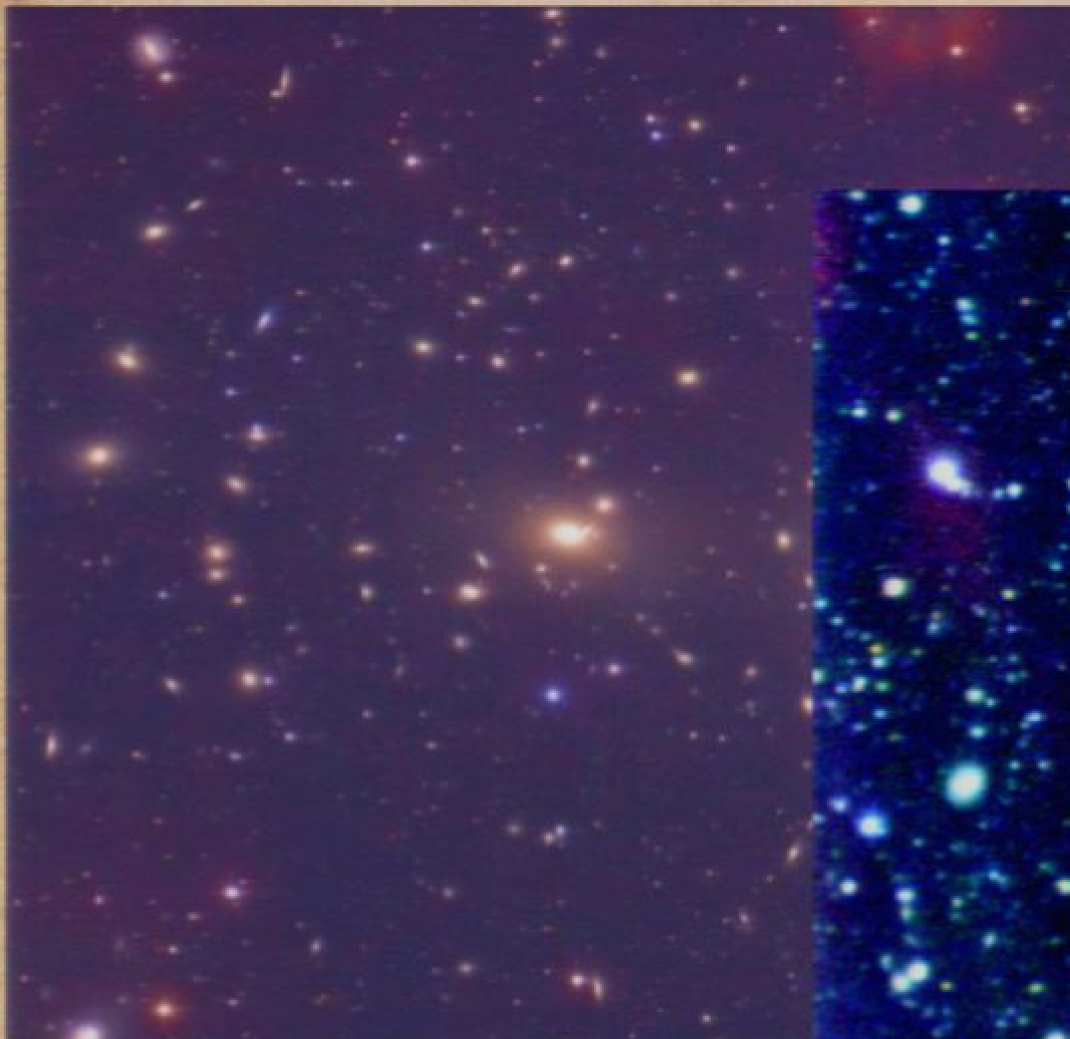
Optical Search for Clusters



Coma
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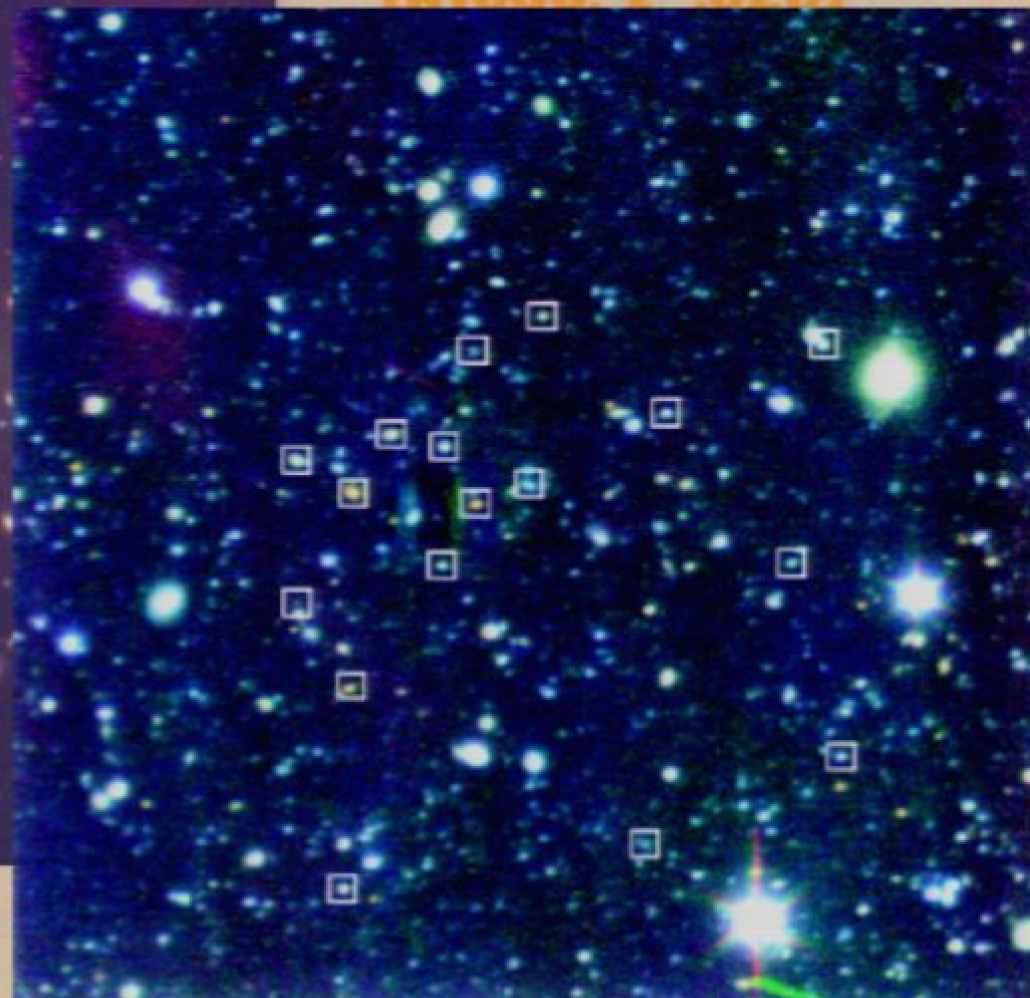

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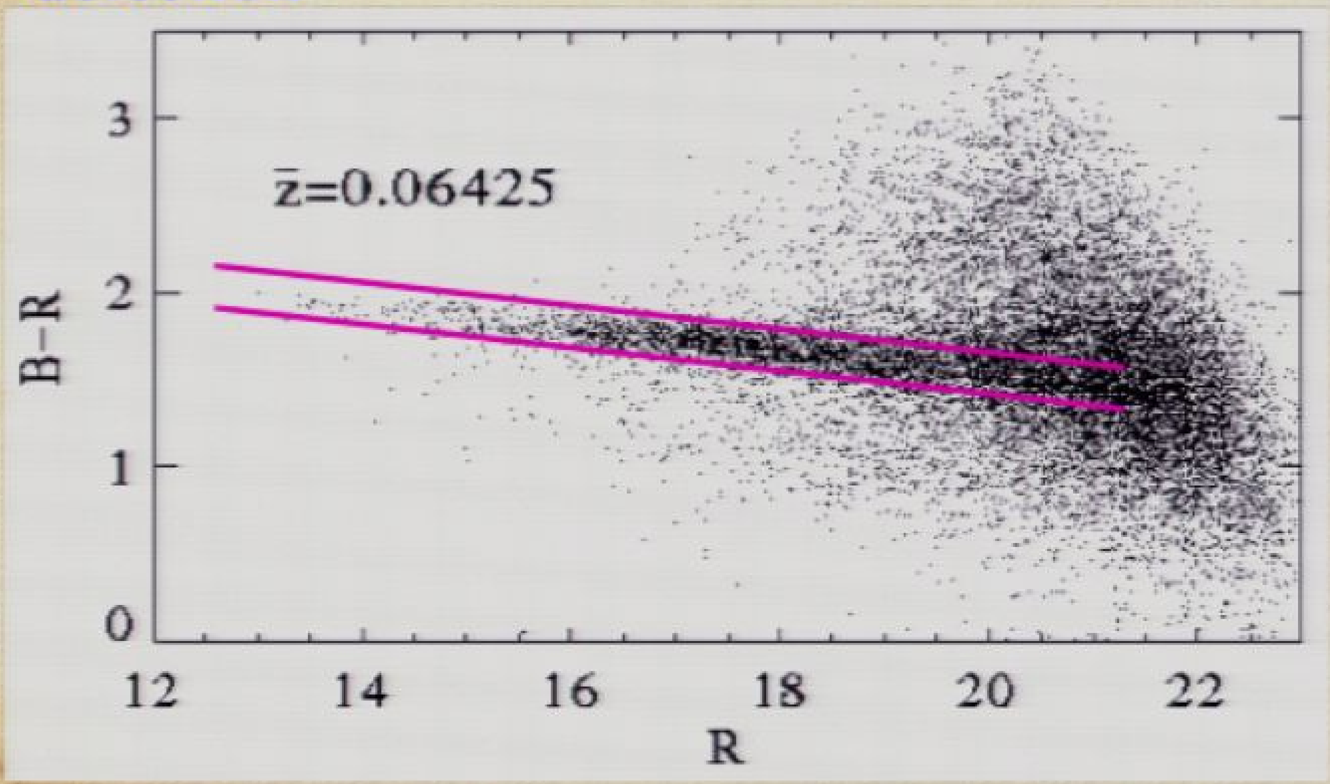
The Cluster Red-Sequence Method

Gladders & Yee 2000, AJ, 120, 2148

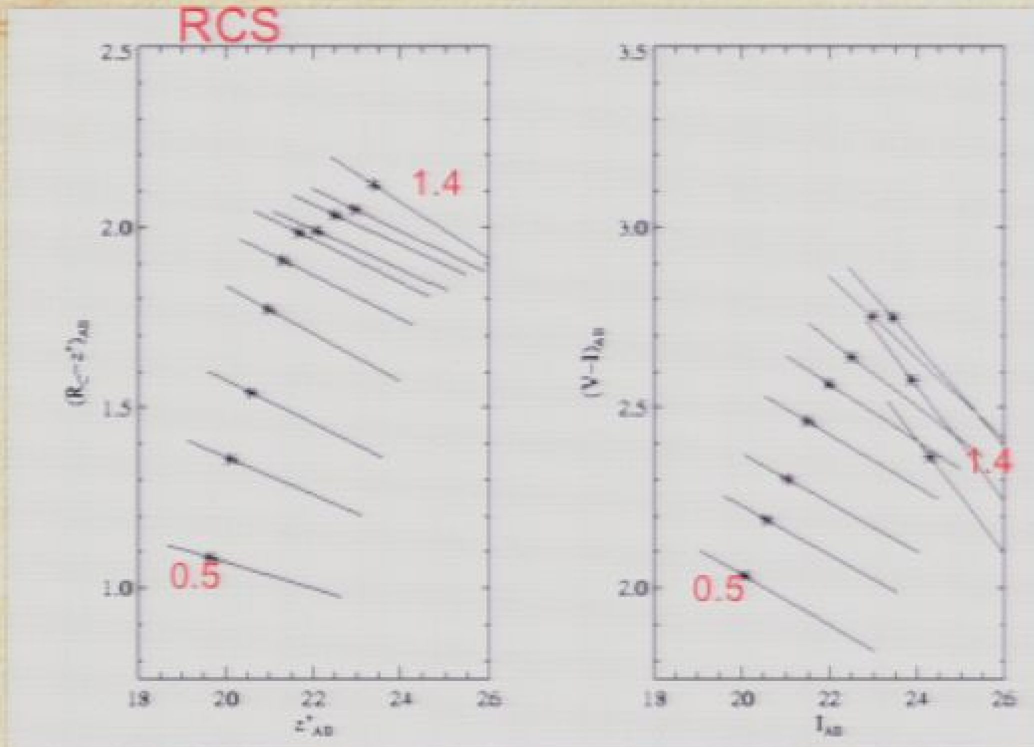
Uses the early-type (red) galaxies as markers for cluster detection



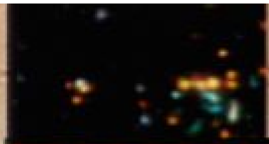
Requires only 2 filters: extremely efficient!

Color-magnitude relation as a function of redshift

Color



Magnitude

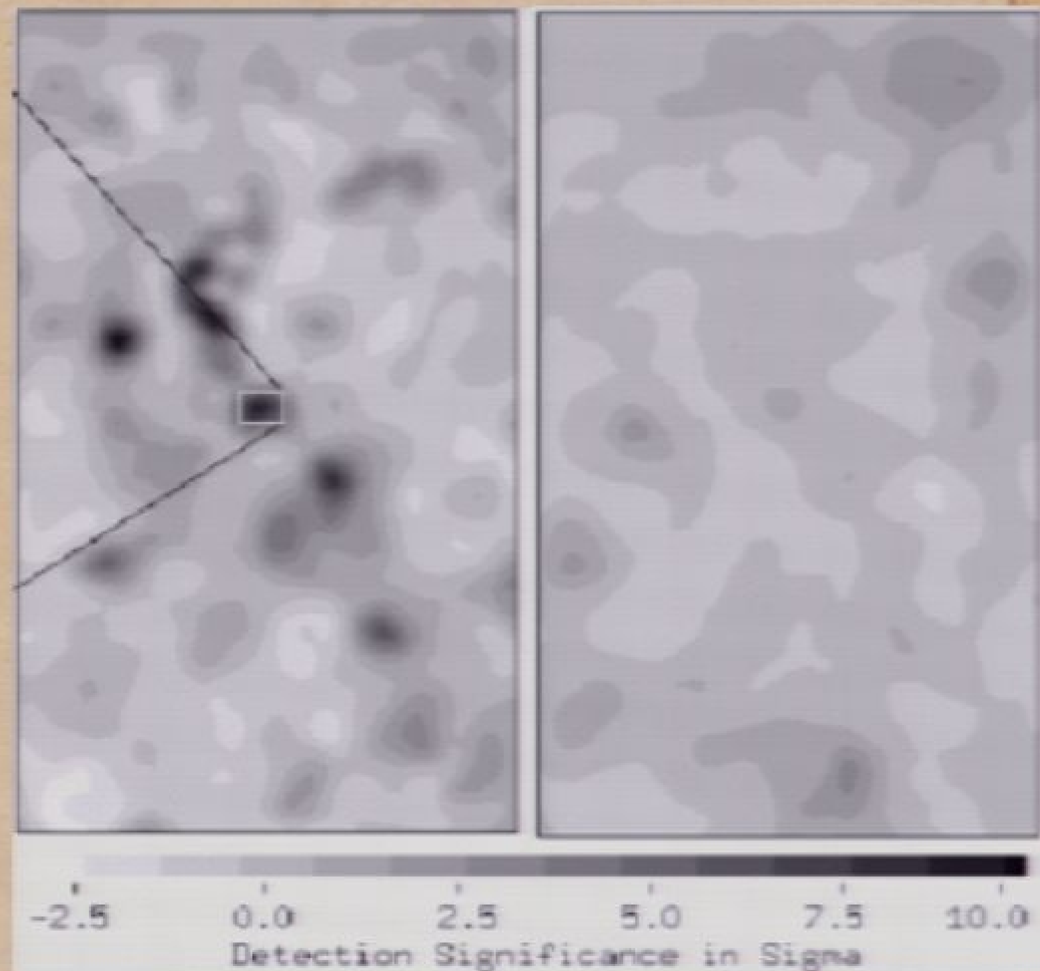


A z=0.89 RCS cluster

galaxies in color slice
(of z=0.9 ellipticals)

all galaxies

A z=0.89 RCS cluster



galaxies in color slice (of z=0.9 ellipticals)

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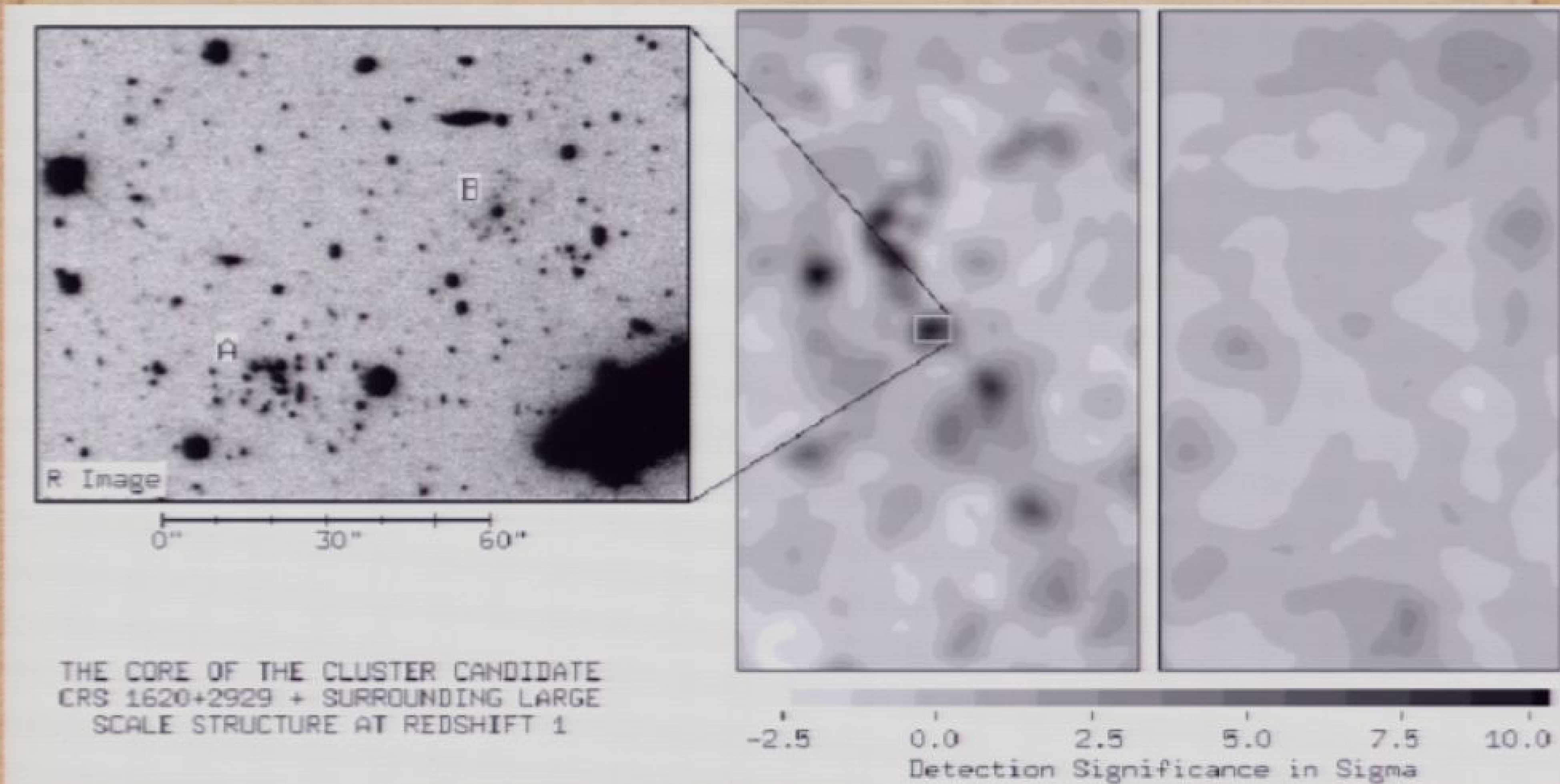

A z=0.89 RCS cluster

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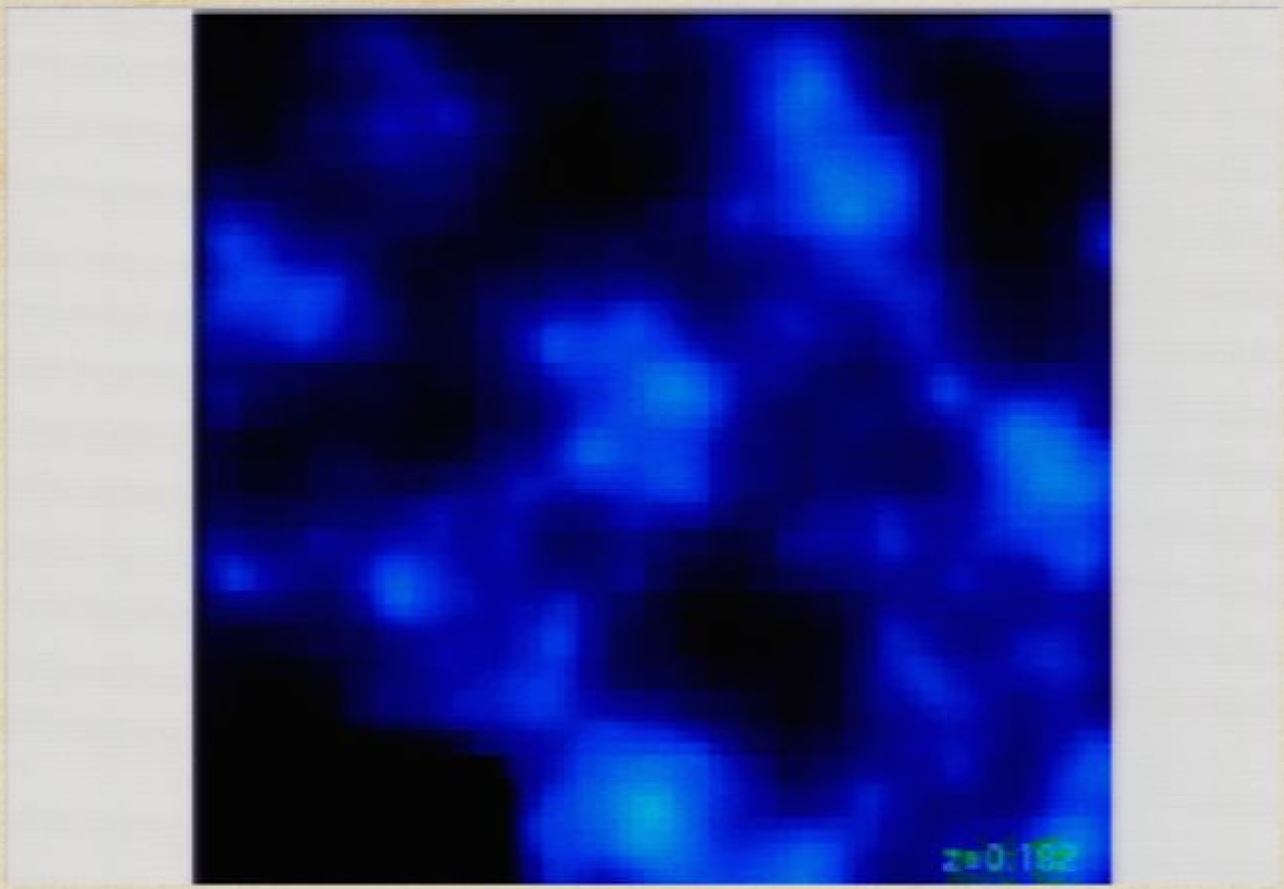
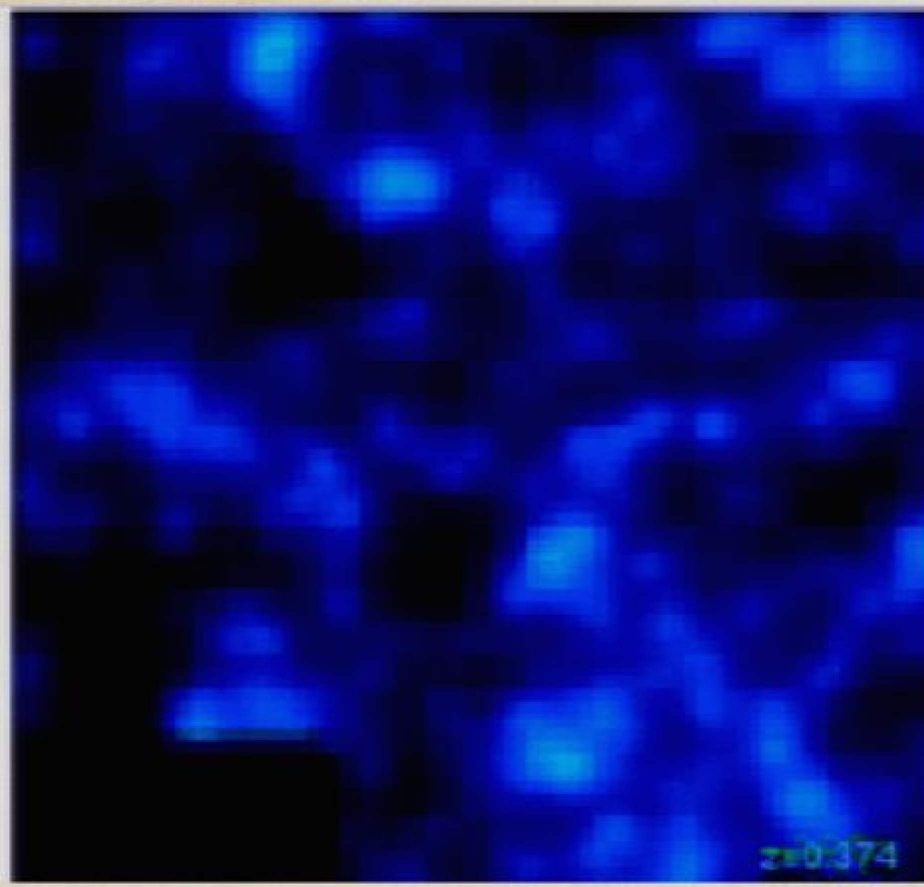
all galaxies



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



Galaxy density in different red-sequence slices
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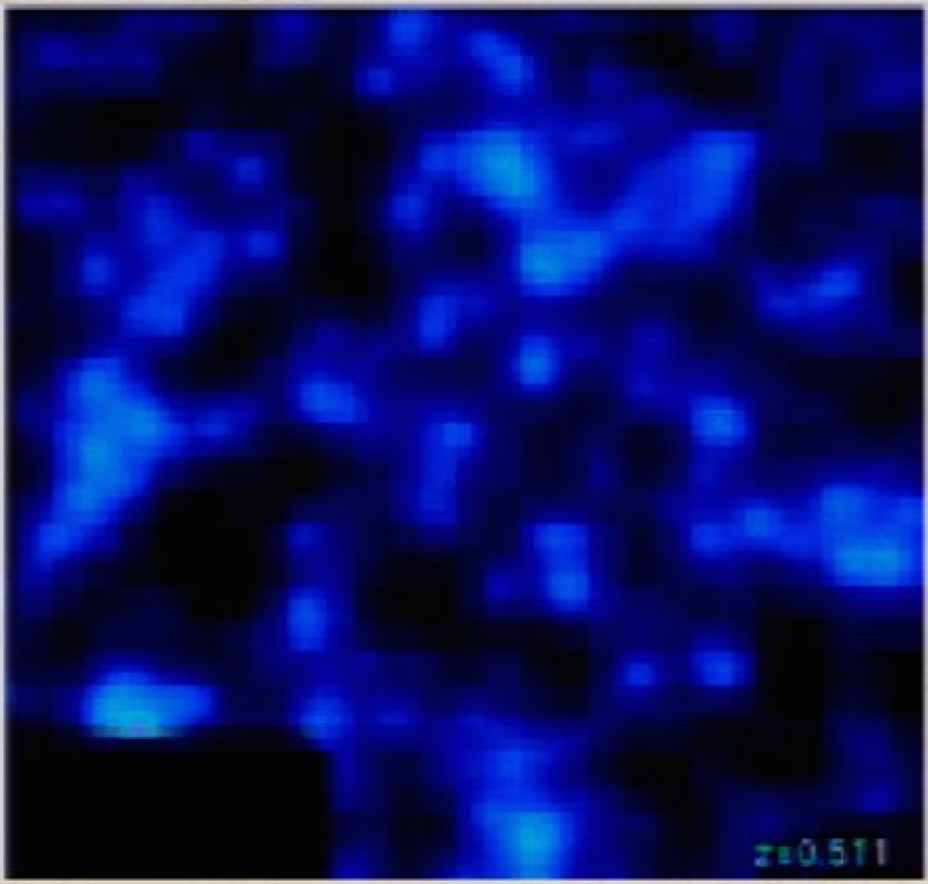

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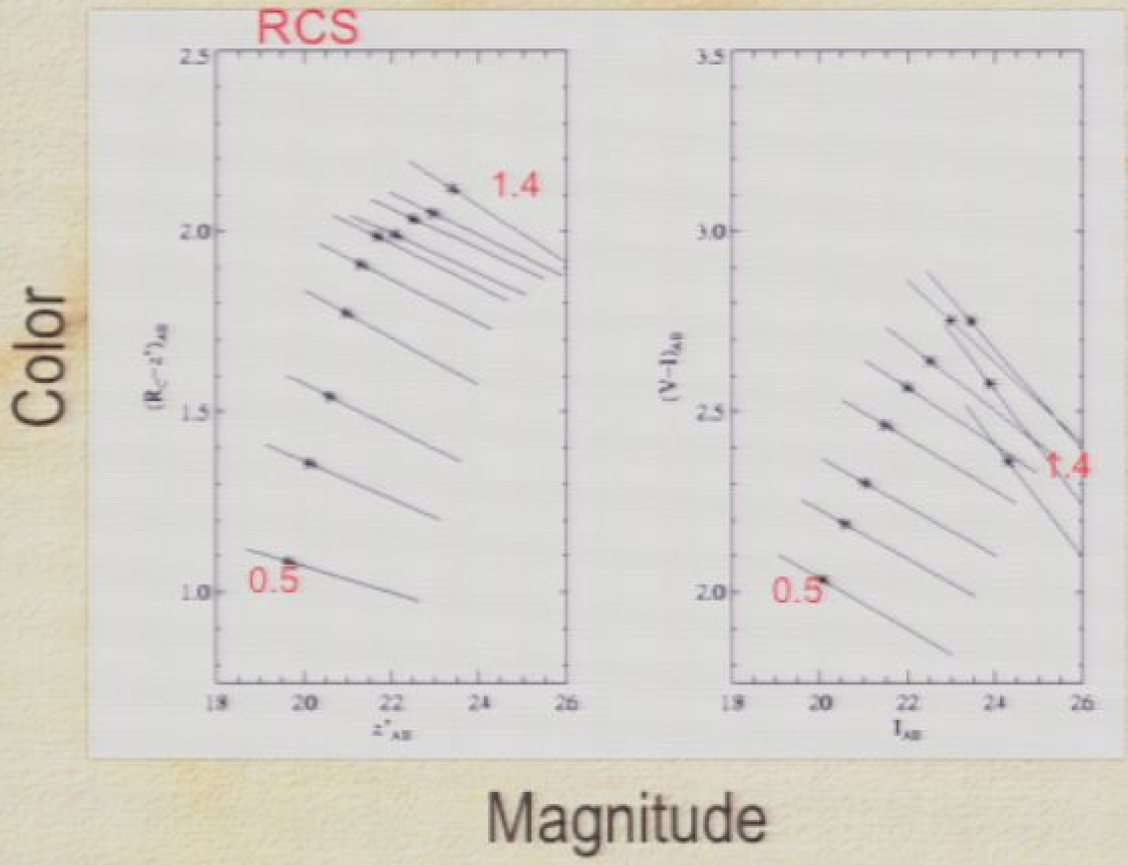
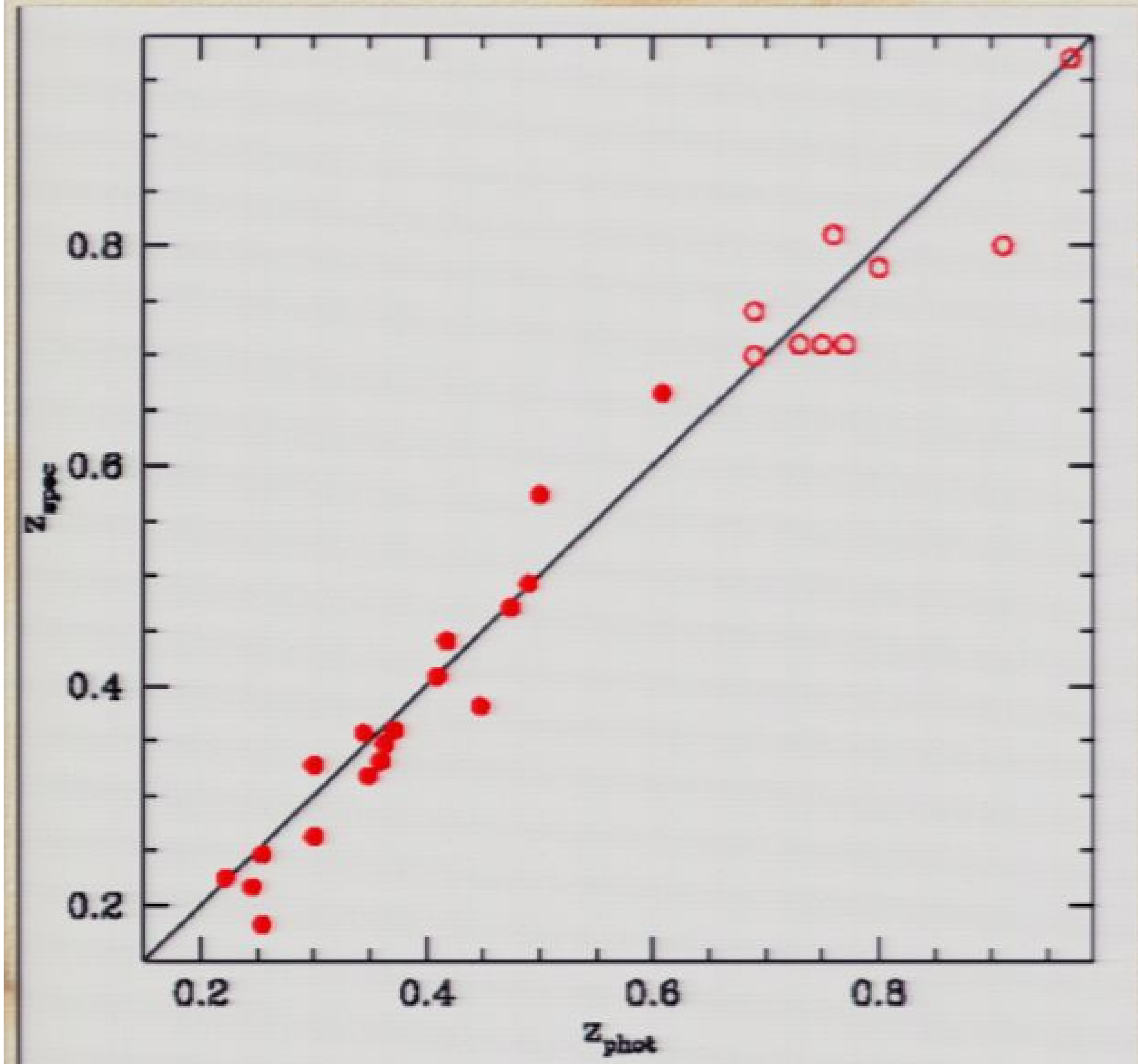
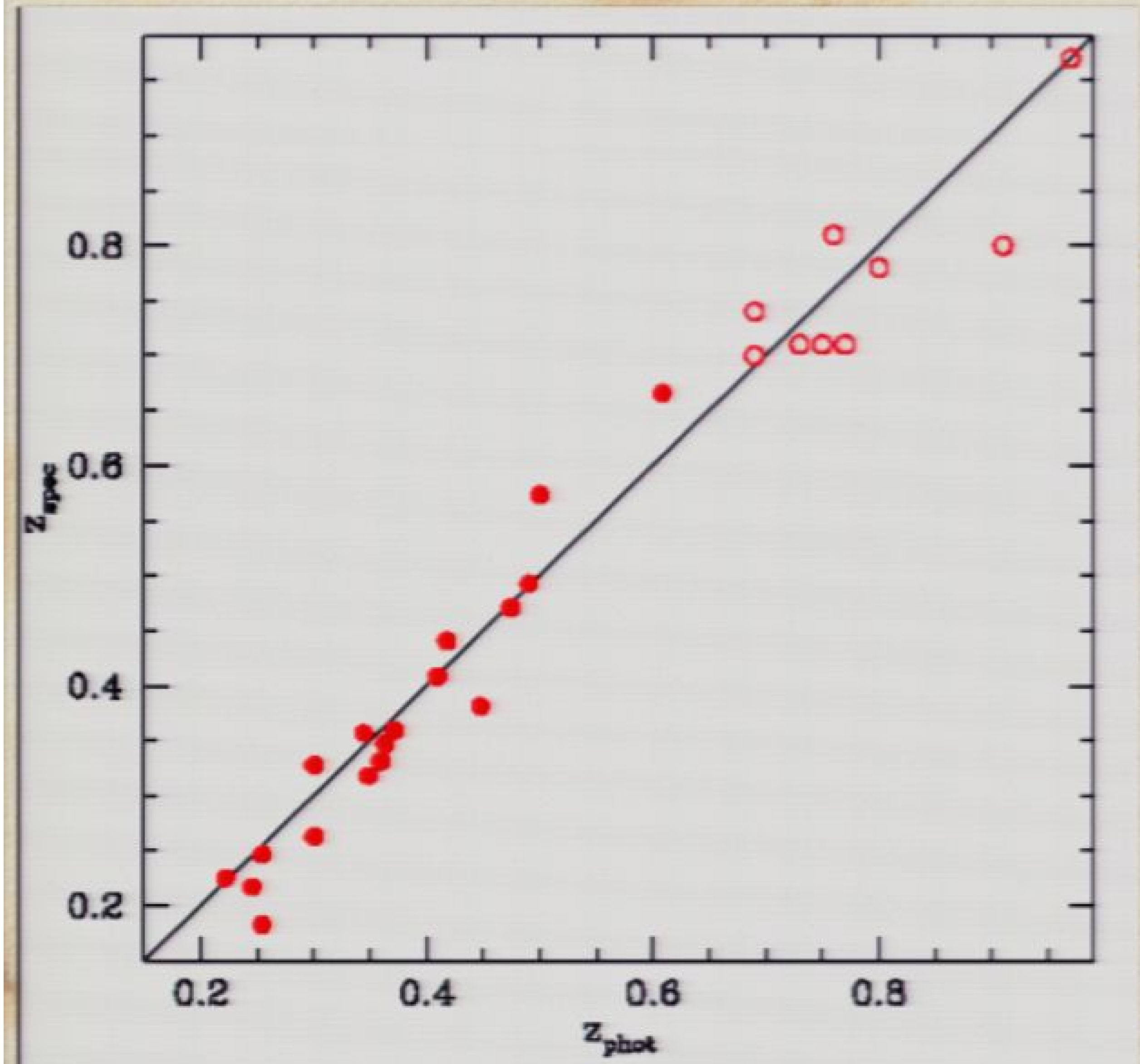


RCS
1.4
0.5
1.4
0.5
Color
Magnitude



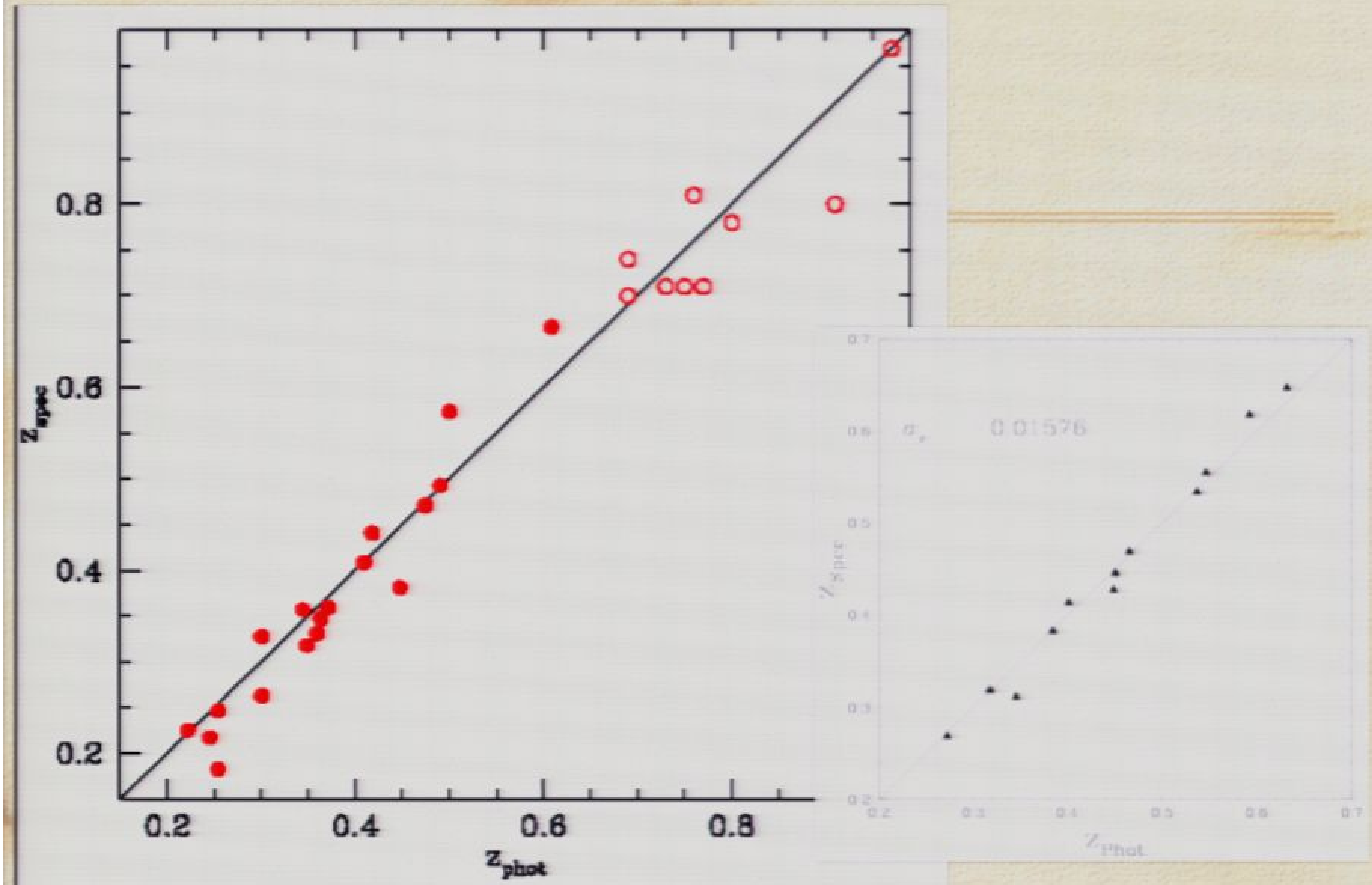
0.8
0.6
0.4
0.2
z_{spec}
0.2
0.4
0.6
0.8
z_{phot}



Red-sequence photo-z (2 filters) vs spectral z:

RCS1: Δz~0.03 to 0.06;

RCS2: Δz~0.015



Red-sequence photo-z (2 filters) vs spectral z:
RCS1: Δz~0.03 to 0.06;
RCS2: Δz~0.015

The RCS1

Gladders and Yee, 2005, ApJS, 157,1

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

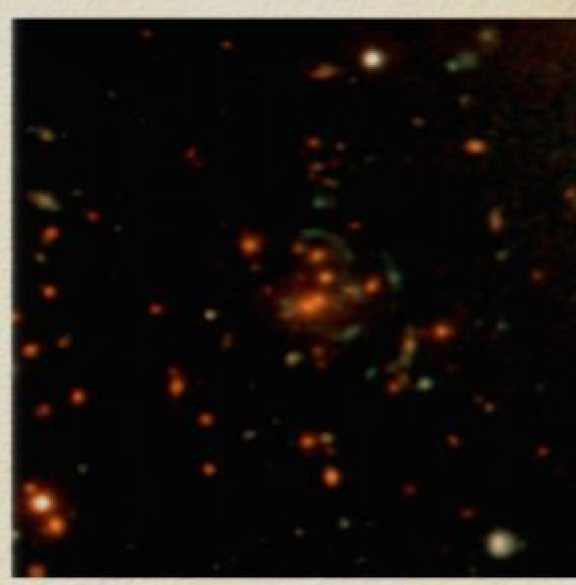
  (including lost times)

- 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





RCS2:

www.RCS2.org

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

- a Canada/Taiwan collaboration
- CFHT MegaCam

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

5σ limits: 23.2 25.0 25.4 (AB magnitude)

Expected completeness depth:

~2×10^{14} M_{sun} clusters at z~1

Yee et al. 2007, astro-ph/0701839

Main Science Goals: (RCS2)

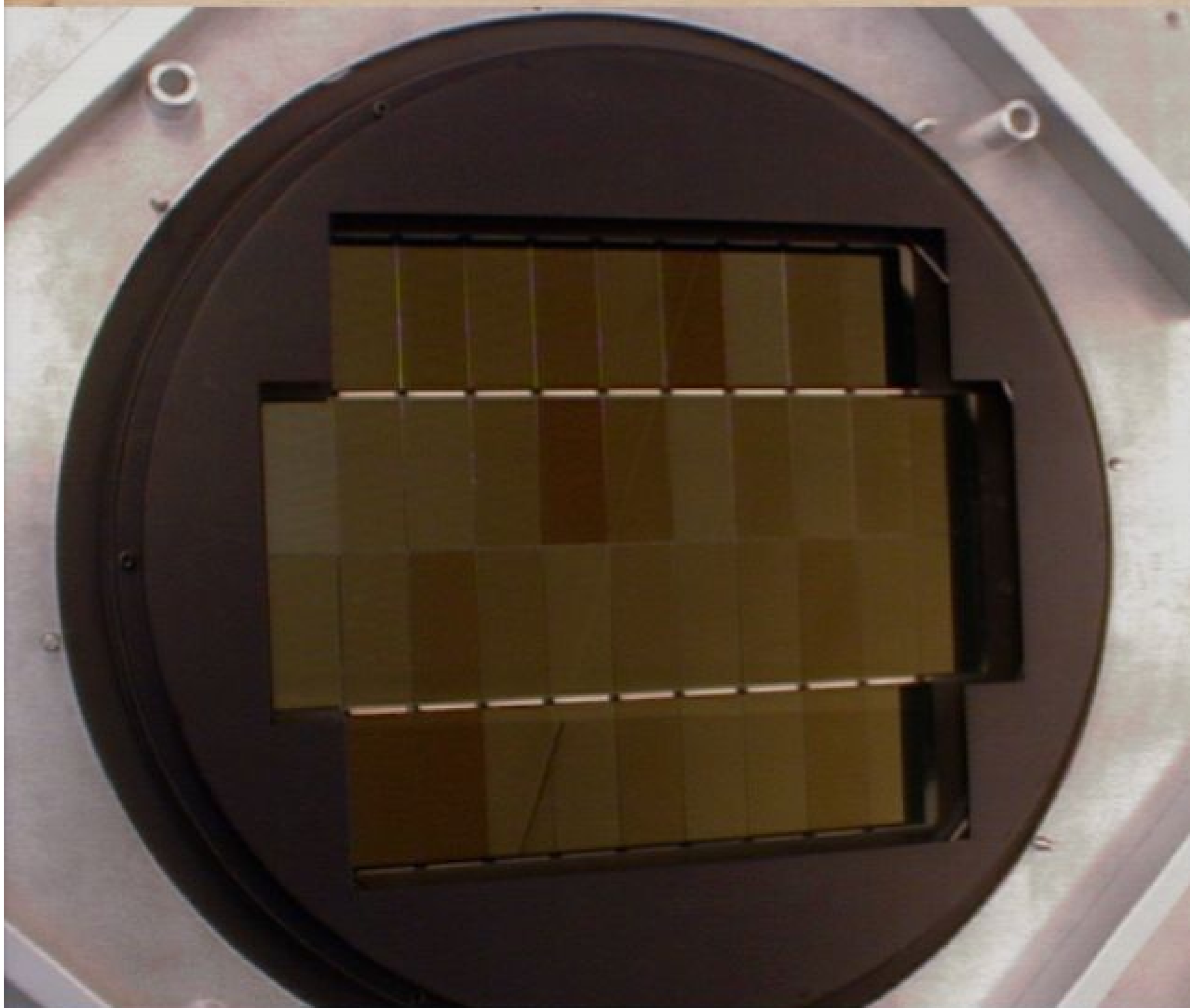
- Constrain cosmological parameters Ω_m, σ_8, and w
- create a sample of ~150 strong arc lenses
- cluster evolution
- weak lensing, cosmic shear (wide/shallow)
- a very large sample of photo-z (useful $0.1<z<0.7$)

Cluster sample:

- optimized for z~0.1 to 1.0;

Total number of clusters (useful for cosmology) expected: ~ 15,000 (>~ 10^{14})

CFHT MegaCam



36 2k x 4.5k chips,
325M pixels

one image ~ 750Mb

0.18"/pix

field~ 1 sq deg

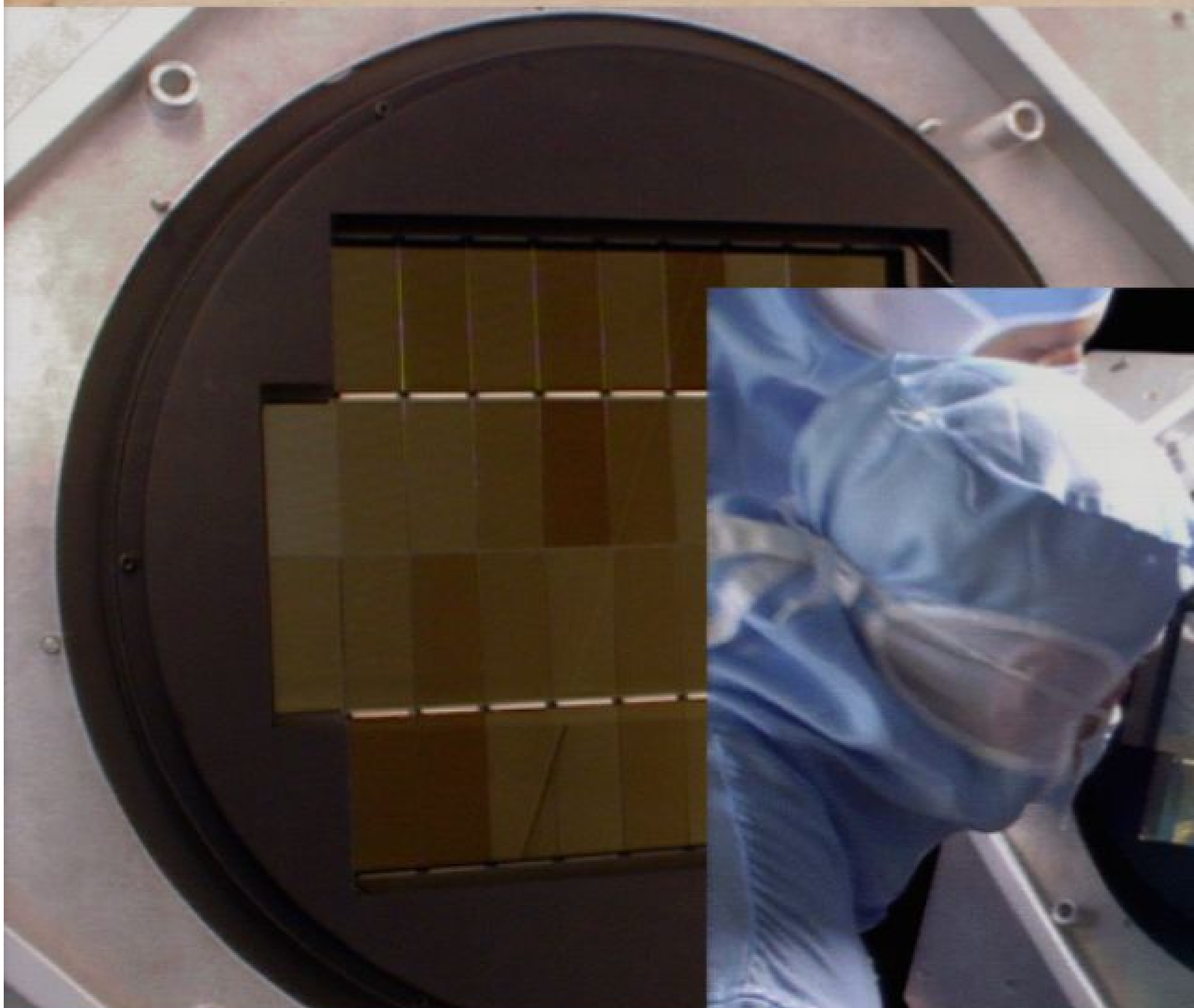
CFHT MegaCam

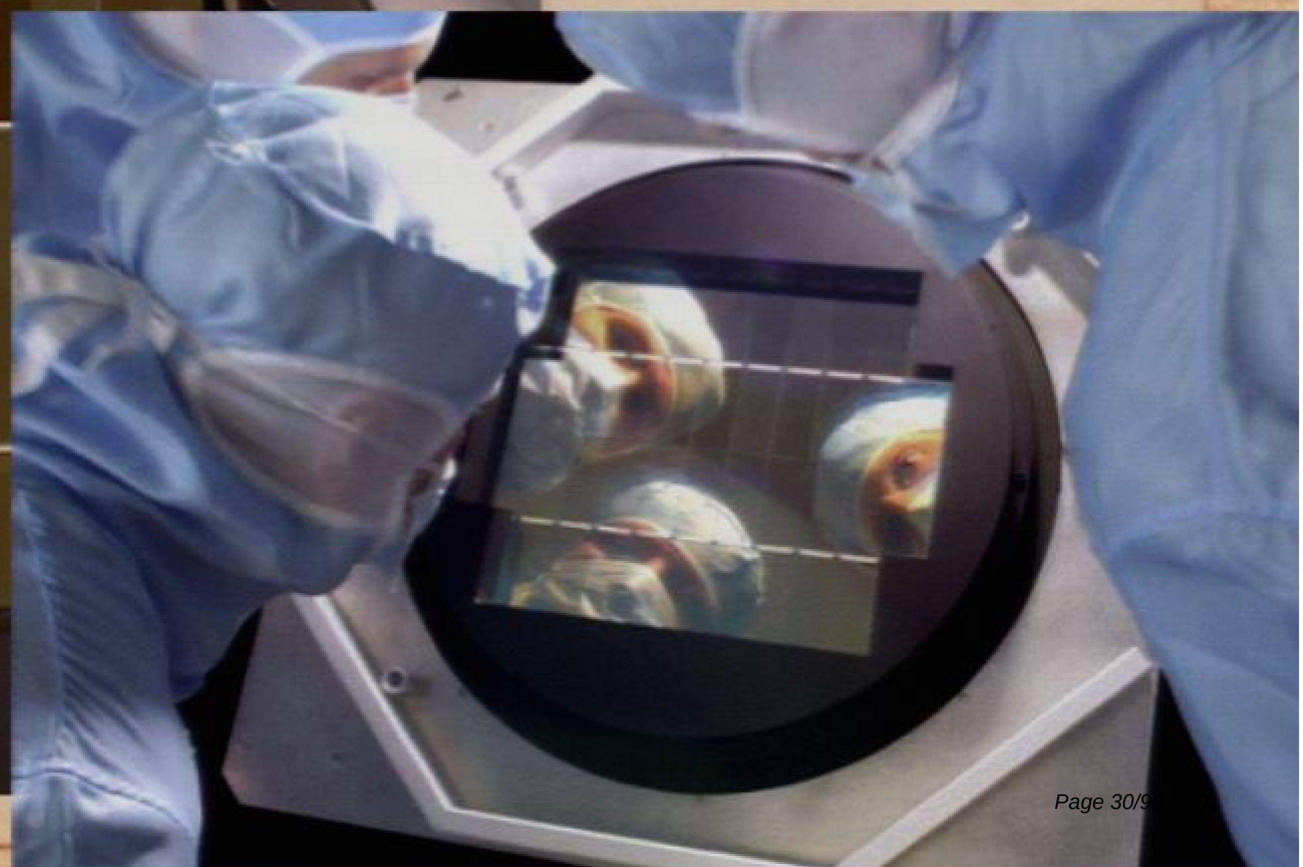
36 2k x 4.5k chips,
325M pixels

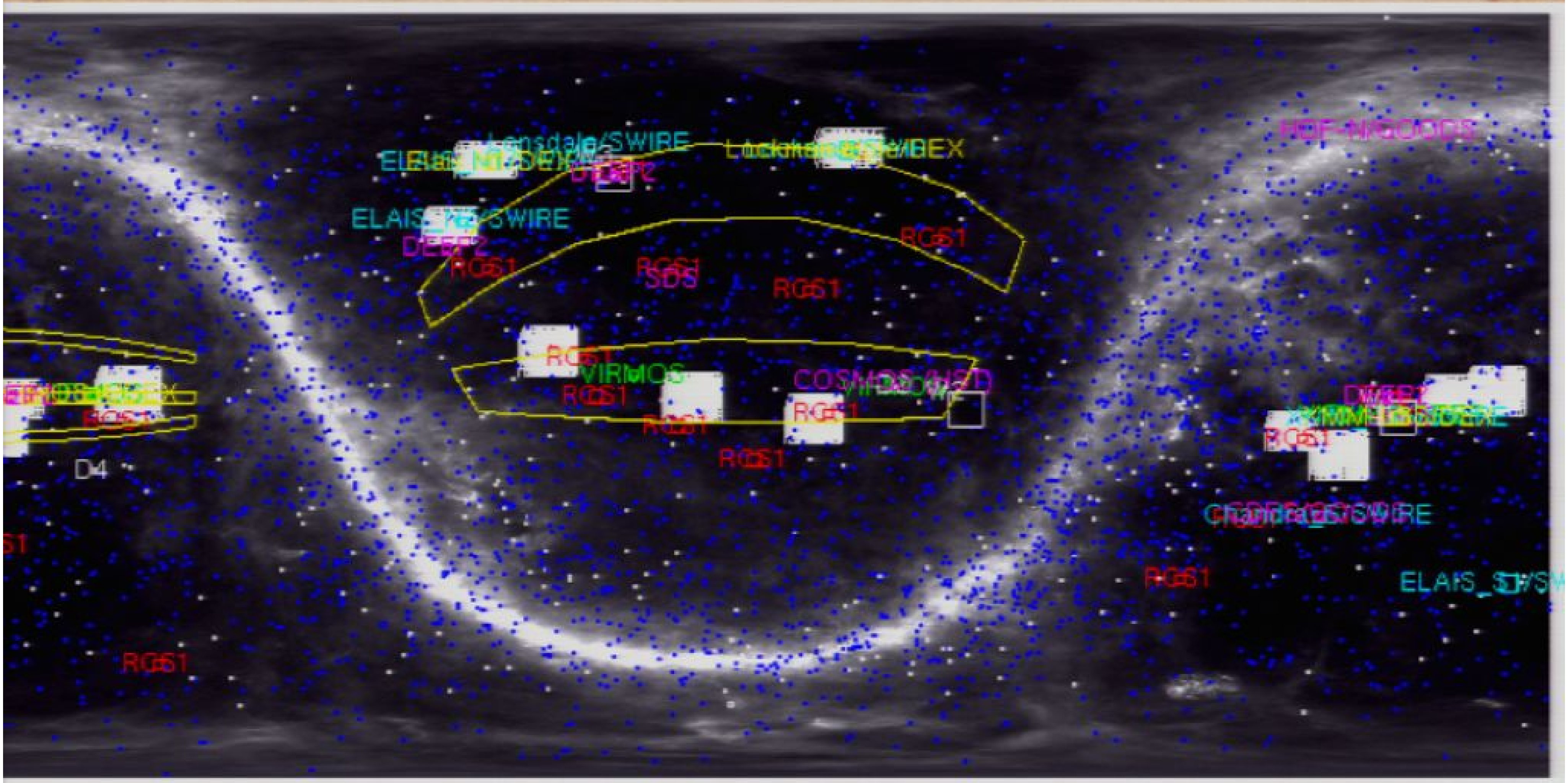
one image ~ 750Mb

0.18”/pix

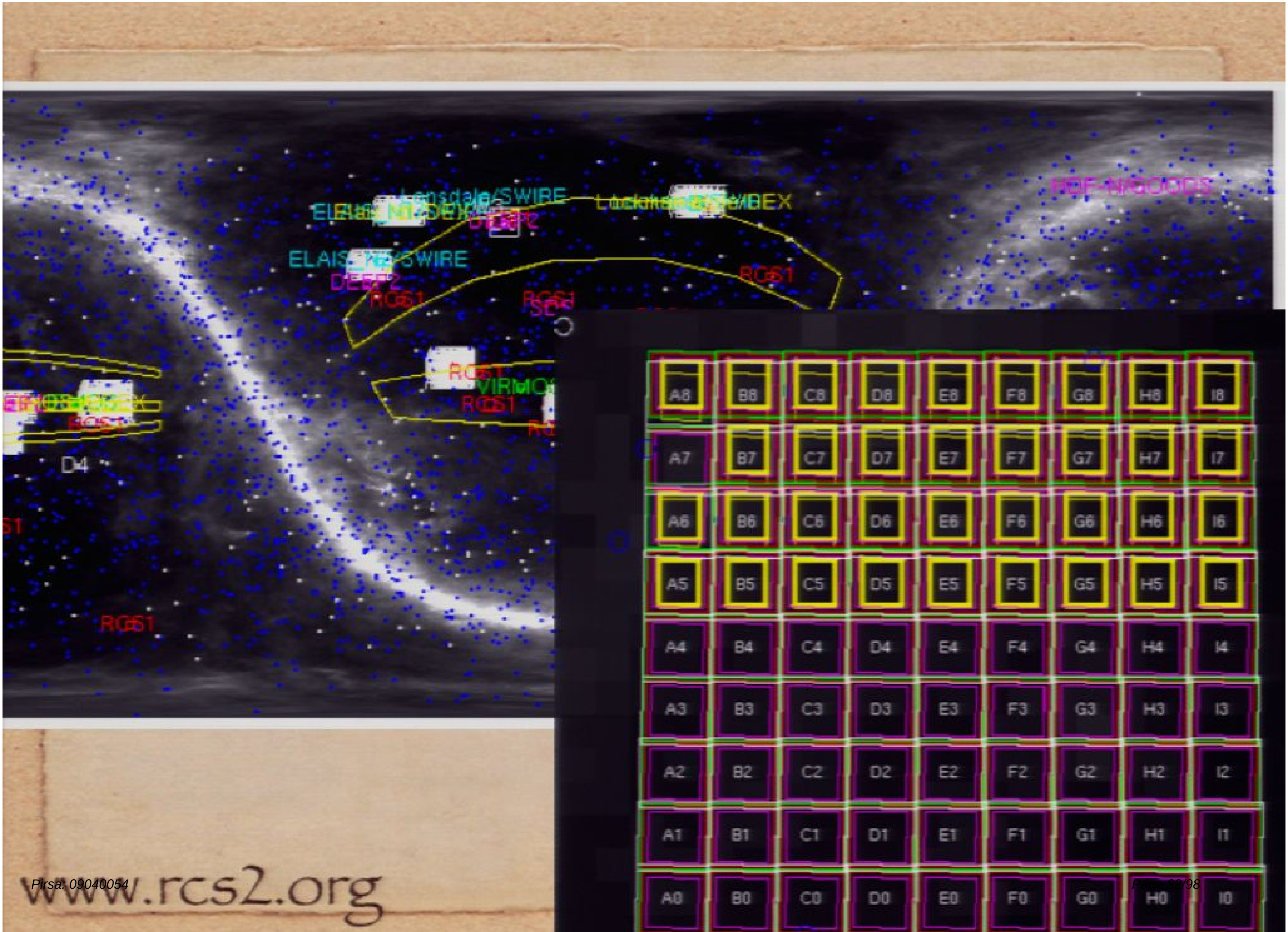
field~ 1 sq deg






ELAIS_N2/SWIRE
DEEP2
RCS1
SDS
VIRMOS
COSMOS/HST
HDF-N/GOODS
D4
ELAIS_S1/S

www.rcs2.org


ELAIS_N2/SWIRE
DEEP2
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Lockman/SWIRE
HDF-N/GOODS
VIRMOS
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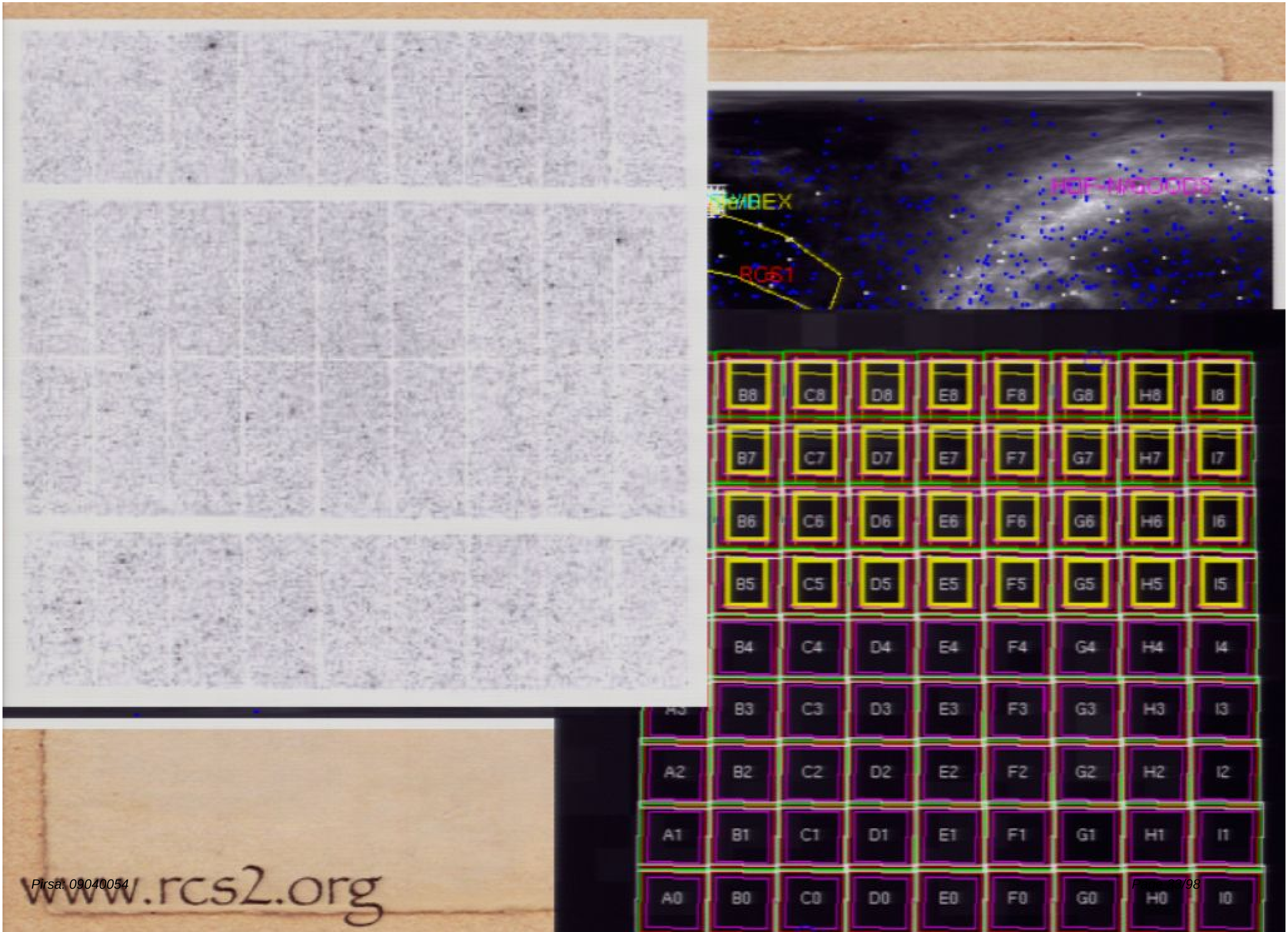
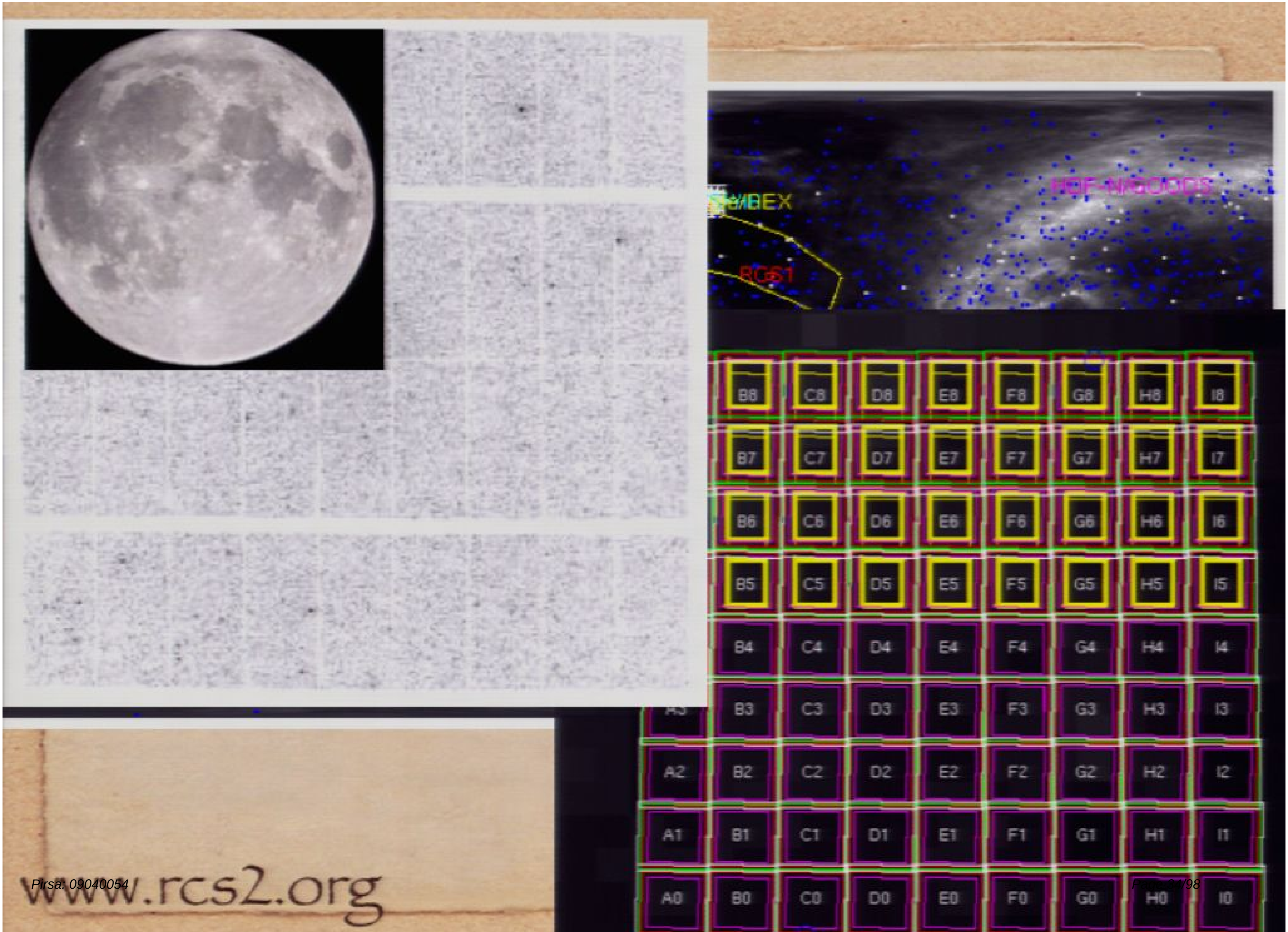

RCS1
B8 C8 D8 E8 F8 G8 H8 I8
B7 C7 D7 E7 F7 G7 H7 I7
B6 C6 D6 E6 F6 G6 H6 I6
B5 C5 D5 E5 F5 G5 H5 I5
B4 C4 D4 E4 F4 G4 H4 I4
B3 C3 D3 E3 F3 G3 H3 I3
A2 B2 C2 D2 E2 F2 G2 H2 I2
A1 B1 C1 D1 E1 F1 G1 H1 I1
A0 B0 C0 D0 E0 F0 G0 H0 I0
www.rcs2.org


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

Observing completed Jan 2008:

- total 920 sq deg:
  770 sq deg +150 sq deg from CFHLS-Wide

- photometry (120 million objects) mostly completed,
- preliminary cluster catalogs generated

The most massive cluster in RCS2 (so far):

z=0.70, ~5×10^{15} M_sun

Cosmology with Clusters Counts:

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

Determination of Ω_m and σ_8 from RCS1 (72 sq deg):

Gladders et al. ApJ, 2007, 655, 128 (astro-ph/0603588)

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:

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

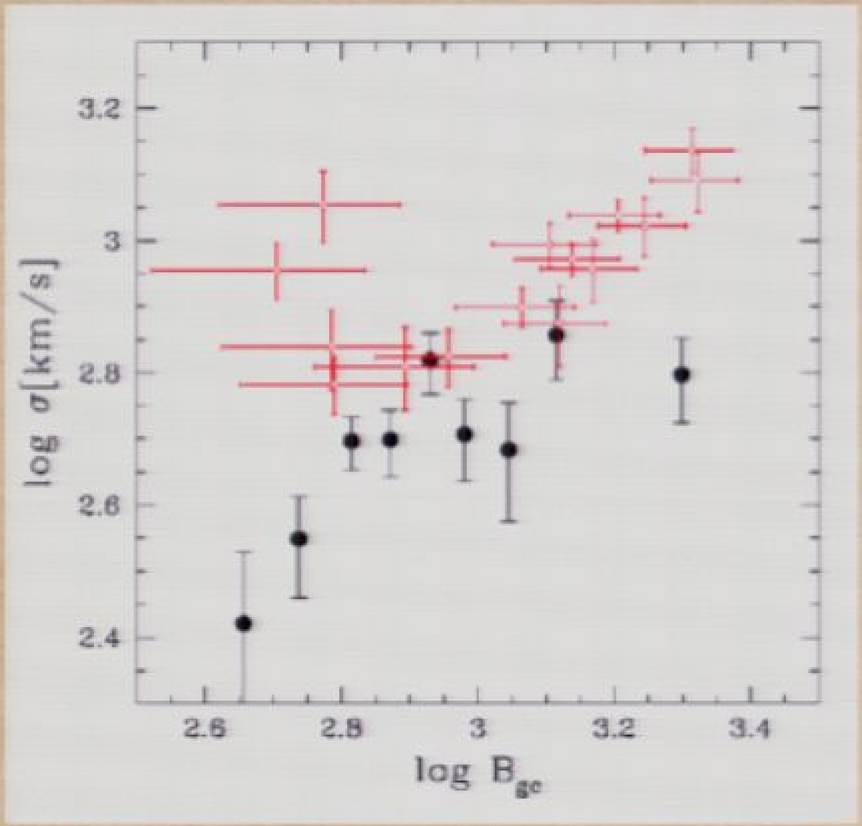
  net number of galaxies scaled by LF and spatial distribution;

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

  also see Yee & Ellingson 2003)

Mass - observable relation

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



CNOC1

+

RCS1 weak lensing

Mass Observables:

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

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  also see Yee & Ellingson 2003)

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

Mass - observable relation

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

use self-calibration method

(Majumdar & Mohr 2001)

RCS1 Cosmological Results:

(Gladders, Yee, Majumdar, Hoekstra, Barrientos, Infante, Hall, **2007, ApJ, 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,

h (WMAP prior)

n_s (WMAP prior)

+ 3 cluster parameters

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

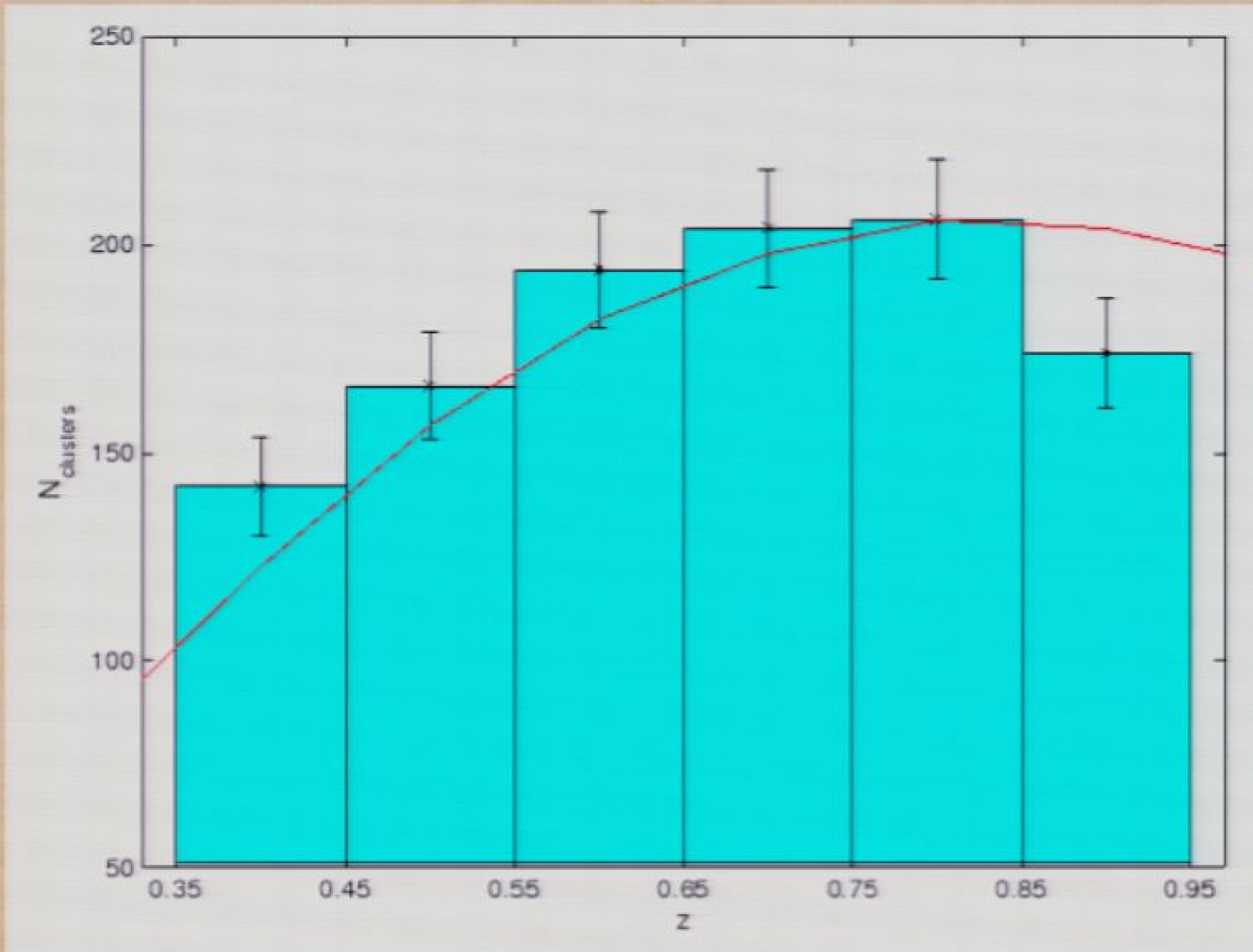
([A, α]=M_lim, γ, +scatter)

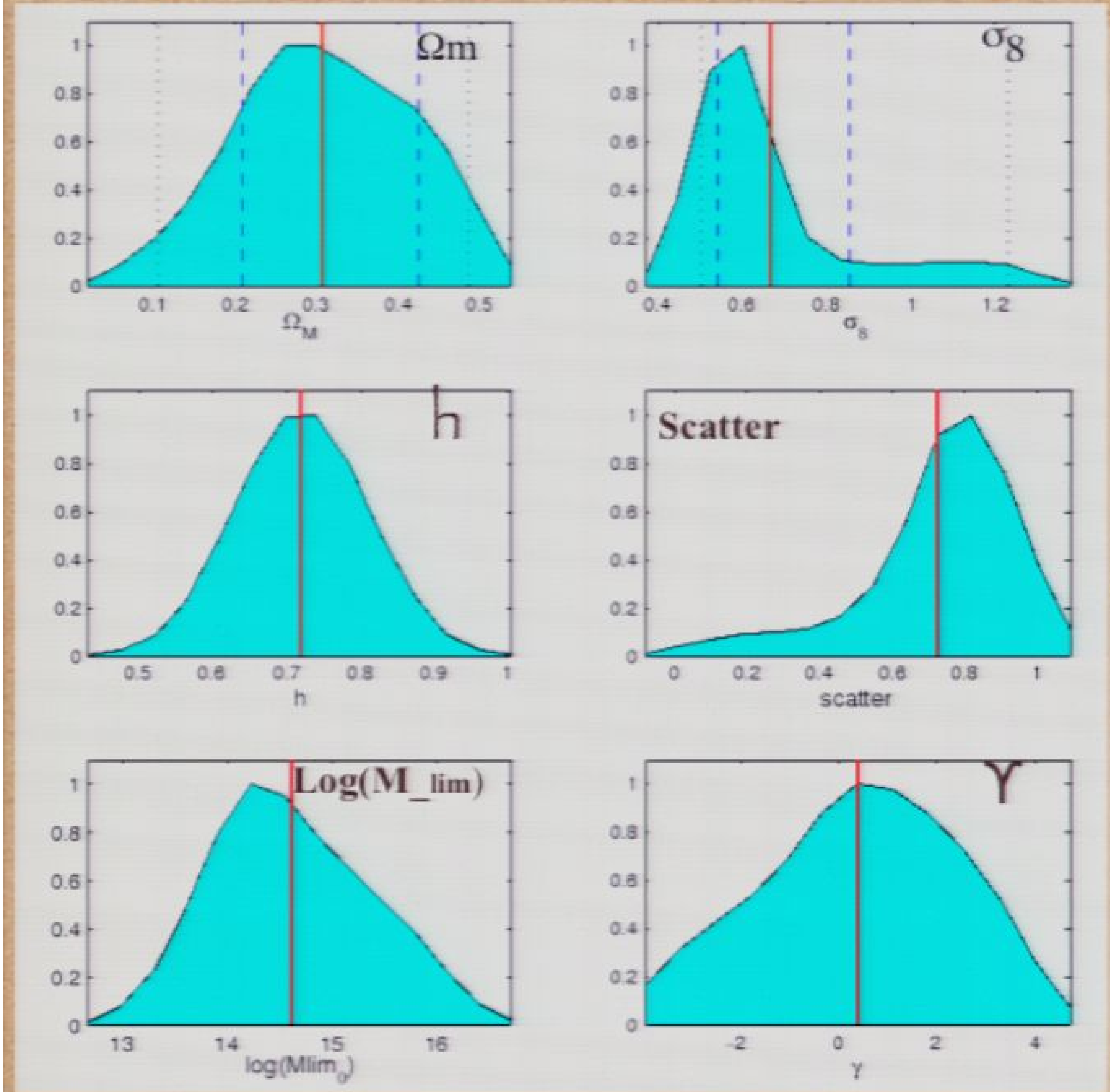
(+ Ω_{tot}=1)

PRIORS IN MCMC ANALYSIS

Parameter	Prior	Notes
Ω_m	0.05–0.55	Uniform
σ_8	0.40–1.30	Uniform
h	0.72 ± 0.08	Gaussian
Ω_b	0.046	Fixed
n	0.99	Fixed
A_{Bgc}	6–14	Uniform
α	0–3	Uniform
γ	–4 to 4	Uniform
f_{sc}	0–1	Uniform

Cluster counts vs redshift





$\Omega_m = 0.31$ +/- 0.10

$\sigma_8 = 0.67$ +/- 0.17

consistent with WMAP year 3/5 results:

Marginalized likelihood

DERIVED PARAMETERS FROM THE SELF-CALIBRATION ANALYSIS WITHOUT MASS-RICHNESS PRIORS

Parameter	Mean (68% Confidence Range)
Ω_m	$0.31^{+0.11}_{-0.10}$
σ_8	$0.67^{+0.18}_{-0.13}$
$\log(M_{\lim_0})$	$14.61^{+0.82}_{-0.70}$
γ	$0.40^{+2.11}_{-3.80}$
f_{sc}	$0.73^{+0.18}_{-0.16}$

Derived Parameters from the Self-Calibration Analysis without Mass-Richness Priors

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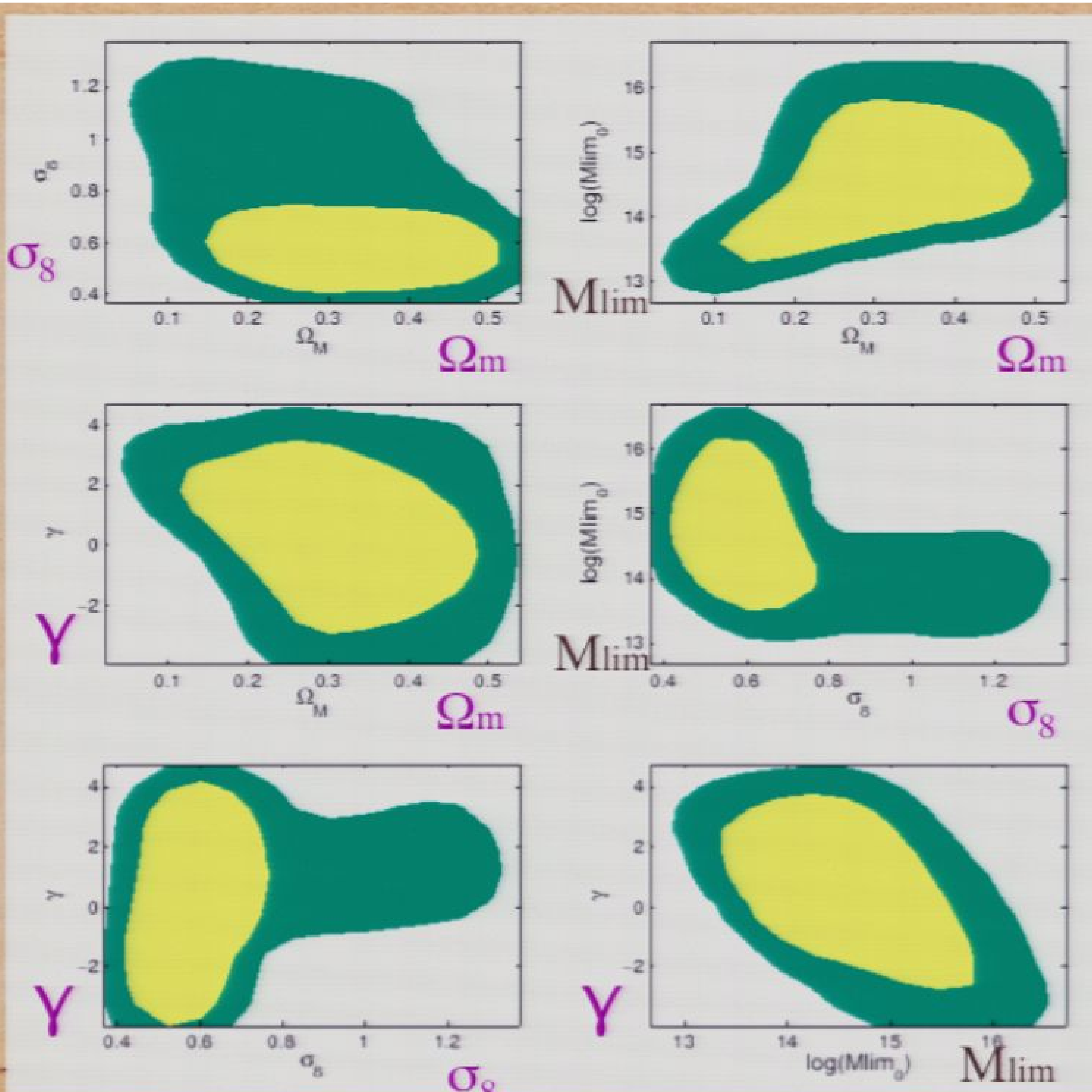
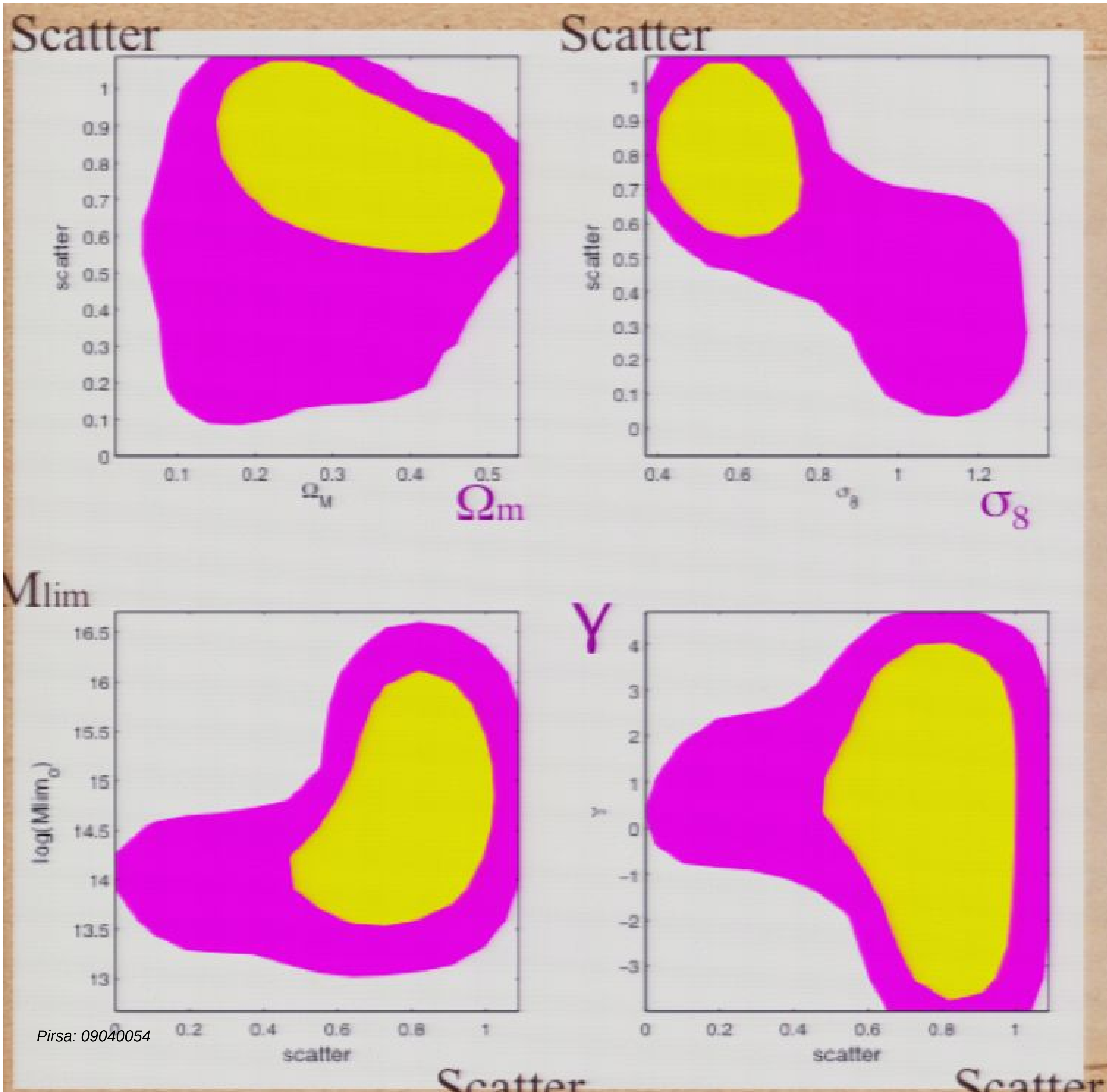
Derived Parameters from the Self-Calibration Analysis with Mass-Richness Priors

	Mean (68% Confidence Range)	
Parameter[a]	Blindert (2006) Priors	Yee & Ellingson (2003) Priors
Ω_m	$0.30^{+0.12}_{-0.11}$	$0.31^{+0.11}_{-0.10}$
σ_8	$0.70^{+0.27}_{-0.15}$	$0.68^{+0.22}_{-0.14}$
$A_{B_{gc}}$	9.61 ± 0.65	$10.27^{+0.67}_{-0.66}$
α	1.92 ± 0.24	1.70 ± 0.24
γ	$0.81^{+1.91}_{-1.66}$	$0.64^{+1.96}_{-1.90}$
f_{sc}	0.69 ± 0.20	$0.71^{+0.19}_{-0.17}$

[a] For the case with no priors, parameter values are as reported in Table 2, with values of $A_{B_{gc}}$ and α as reported in the text ($A_{B_{gc}} = 10.55^{+2.27}_{-1.71}$ and $\alpha = 1.64^{+0.91}_{-0.90}$).

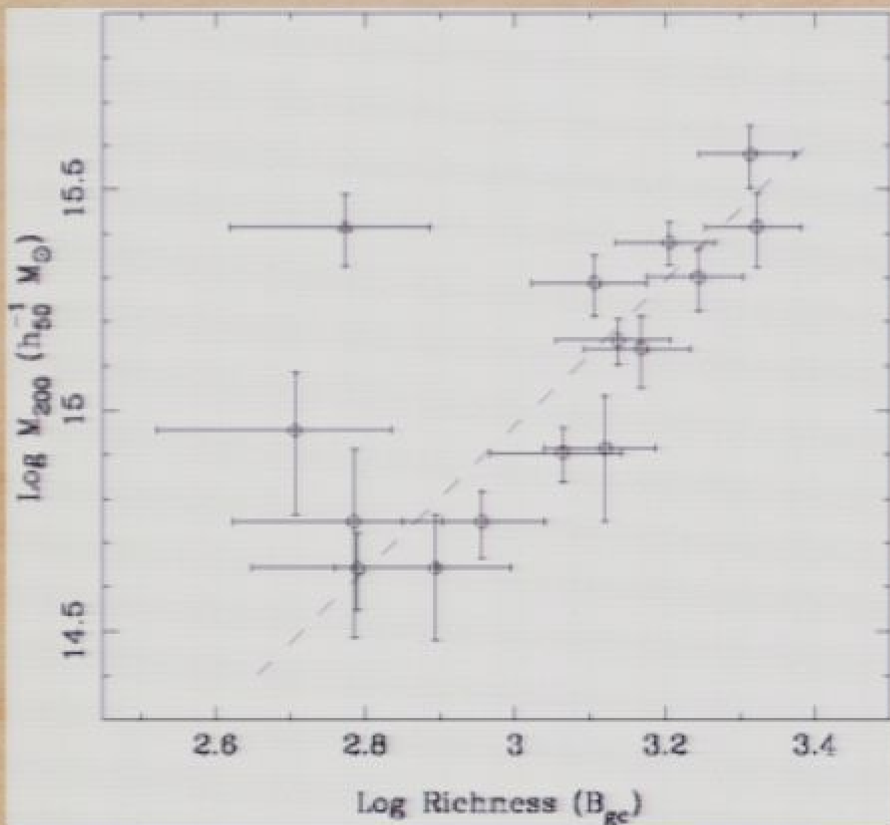

σ8
Ωm
Mlim
γ
ΩM
log(Mlim0)
σ8
γ
0.1
0.2
0.3
0.4
0.5
0.4
0.6
0.8
1
1.2
13
14
15
16
−2
0
2
4



Effects of scatter on the mass observable relation

RCS: cluster parameters

(red: derived from self-calibration;
blue: measured from CNOC1)



CNOC1,
Yee & Ellingson 2003

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

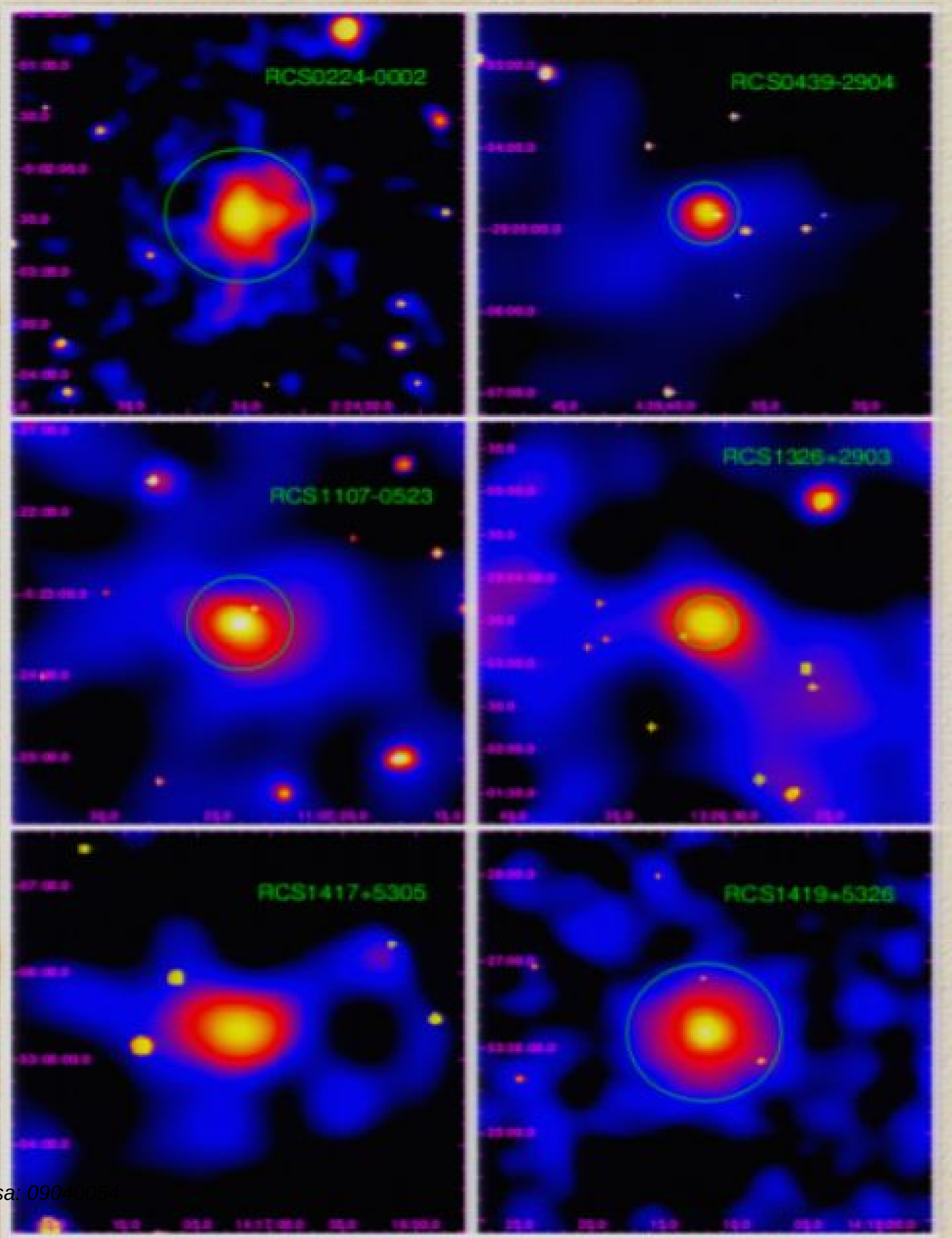
$\log(A_{Bgc})$ = 10.55 +/- 1.5)
(z=0.3) (10.05 +/- 0.89)

α = 1.64 +/- 0.79
(1.58 +/- 0.27)

γ = 0.40 +/- 2.5

scatter: 0.73+/-0.17
(0.65, RCS Blindert et al)

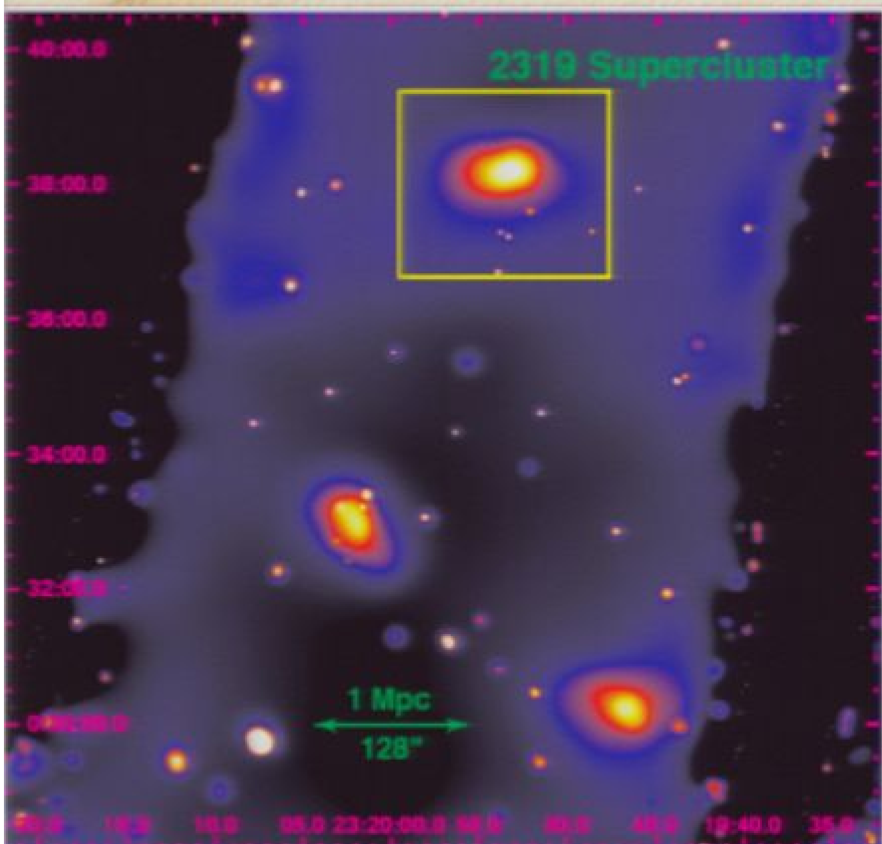
Chandra X-ray observation of 0.7>z>1.1 RCS clusters



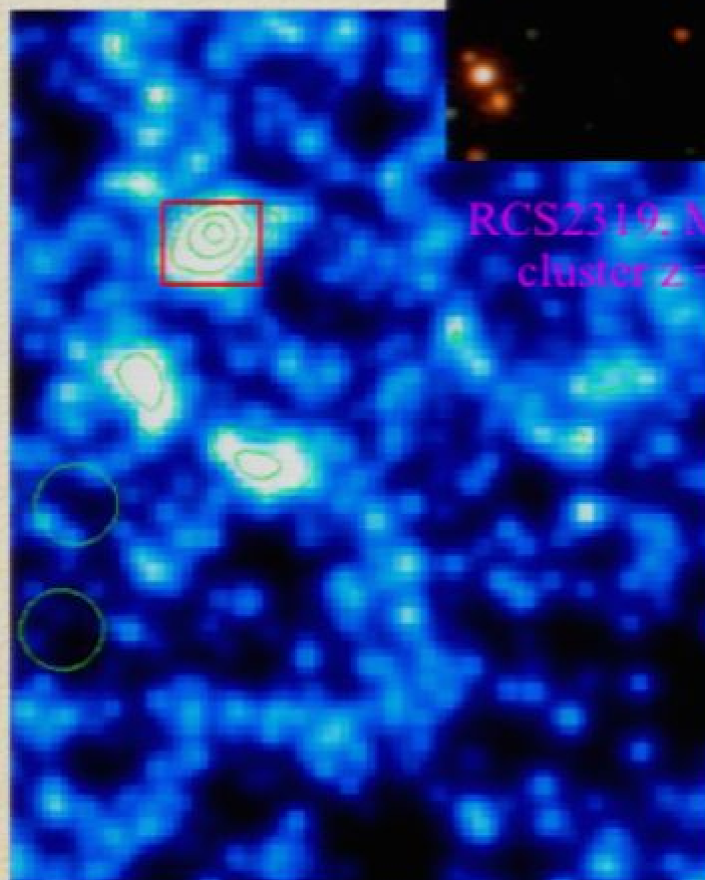
Hicks et al. 2008
(ApJ, 680, 1022)
arXiv:0710.5513);
13 0.7<z<1.1 clusters

Discovery of a Large scale structure at high-z

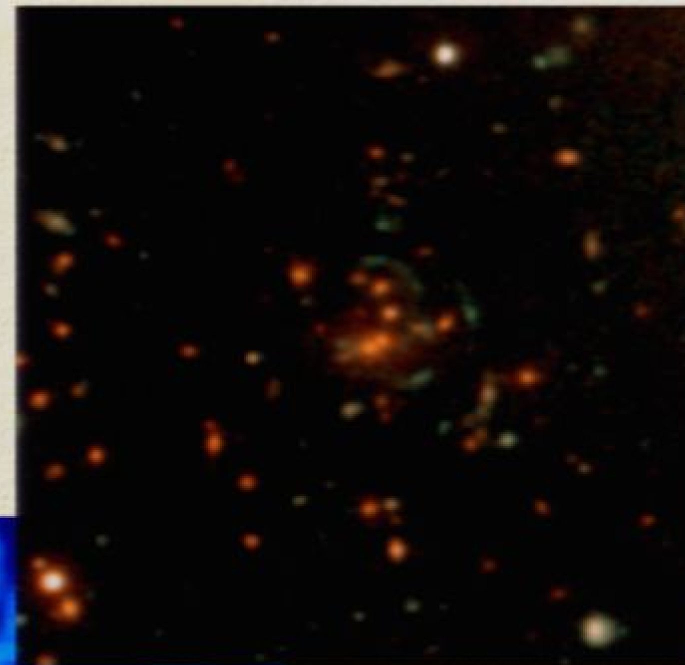
(Gilbank et al. 2008, ApJL, ;
arXiv:astro-ph/0803.1675)



Chandra X-ray image



Red-sequence galaxy density, z=0.9 slice

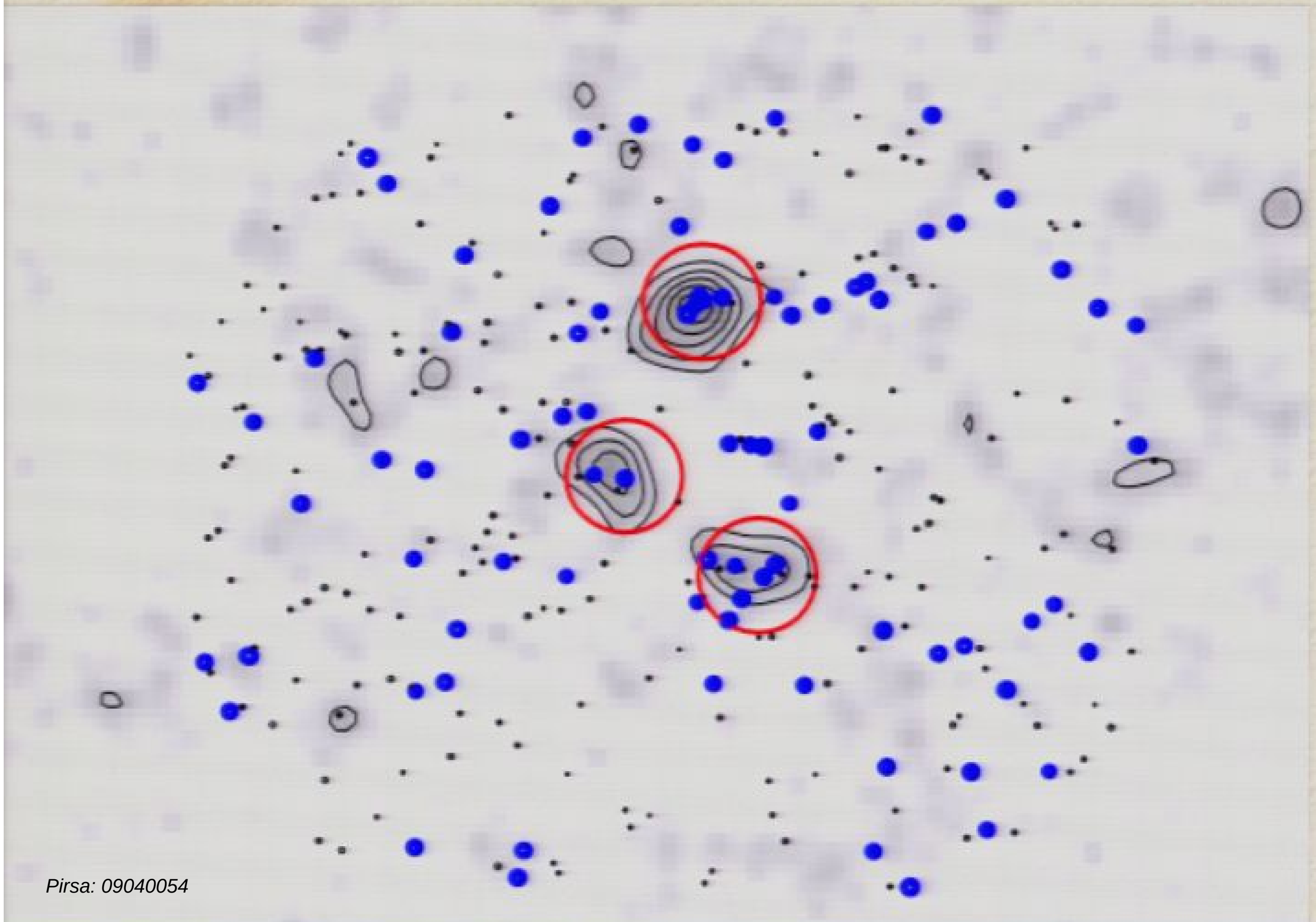


RCS2319, Magellan Magic-Cam, cluster z = 0.90, arc z = 3.8

Super-cluster RCS2319

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

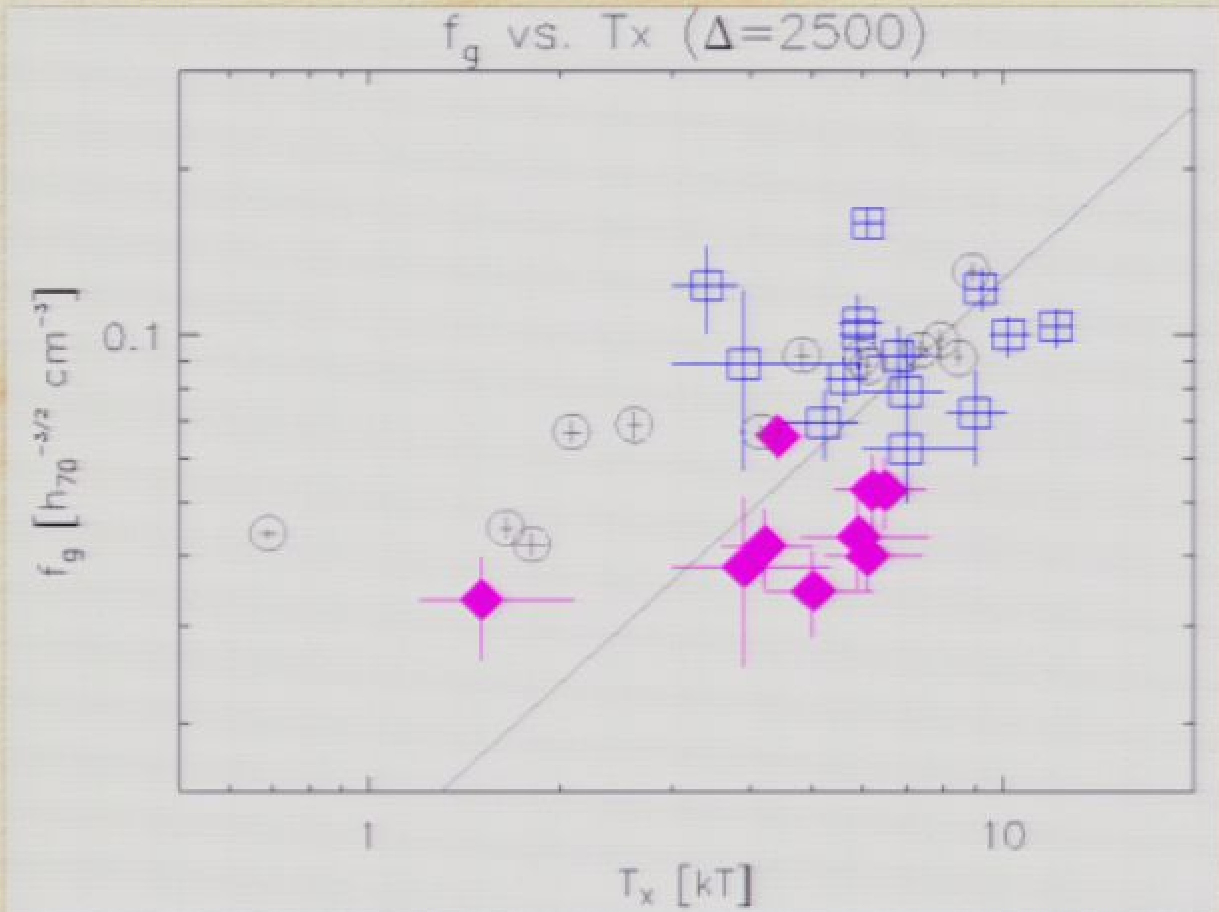
Magellan IMACS spectroscopy
one mask, ~420 redshifts
field size: 27'; ~13Mpc at z~0.9
the 3 clusters span ~6 Mpc



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

Gas mass fraction (f_{gas}) 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

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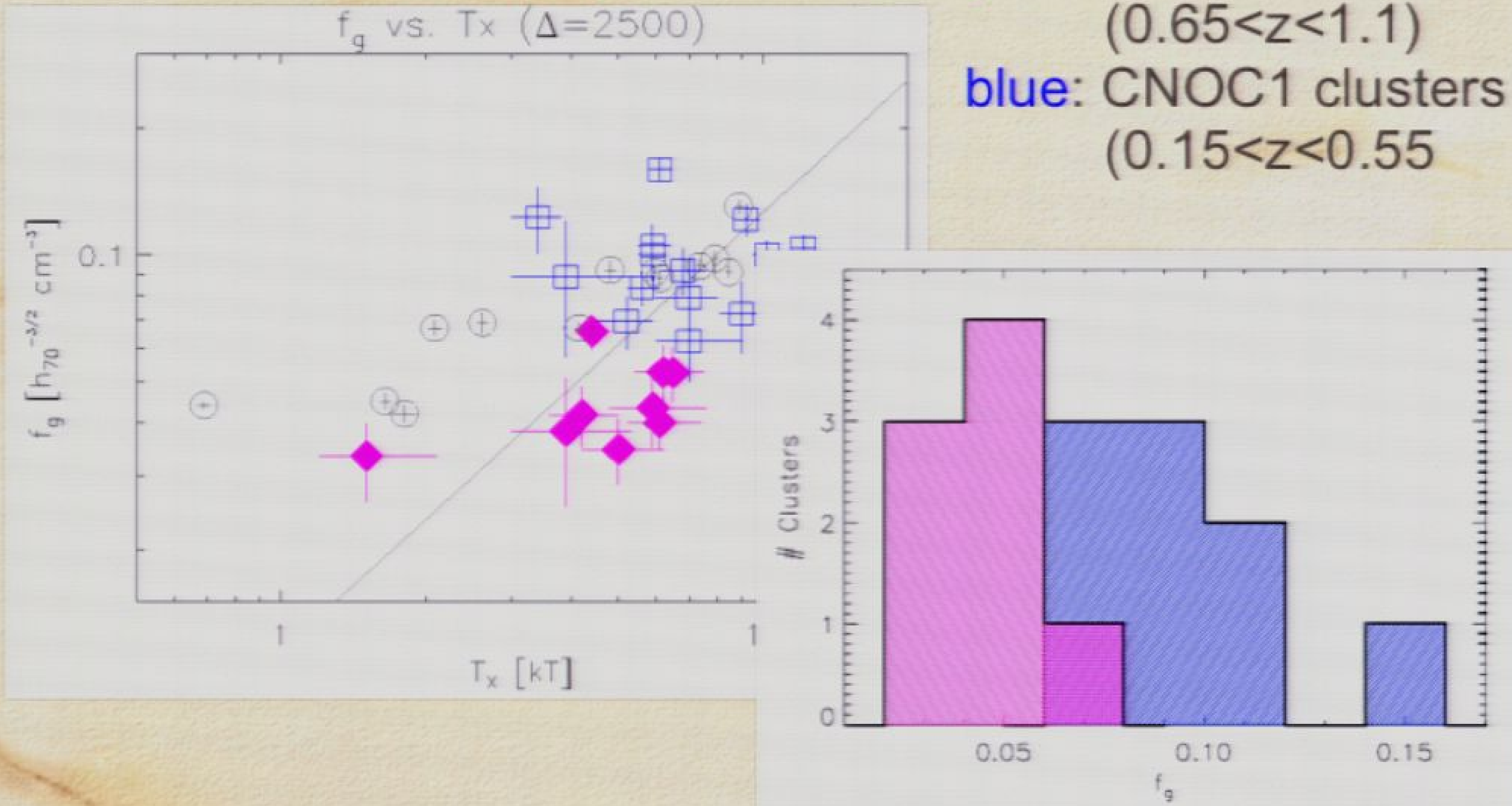

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RCS-2: Strong Lensing Samples

Gladders et al.

~80 systems so far
(~450 sq deg)

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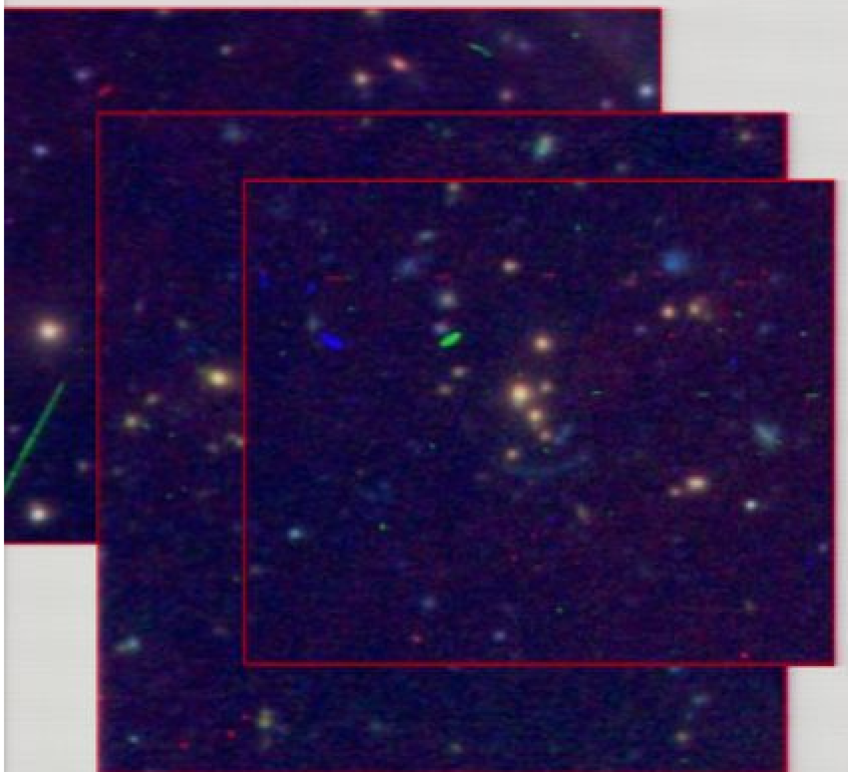

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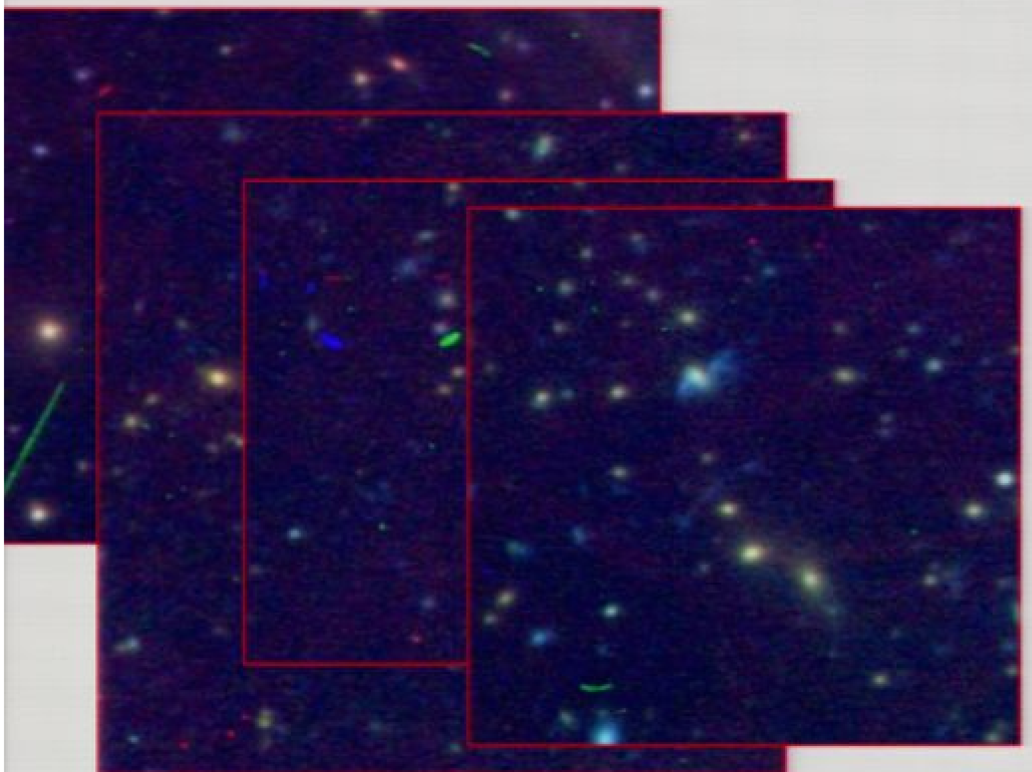

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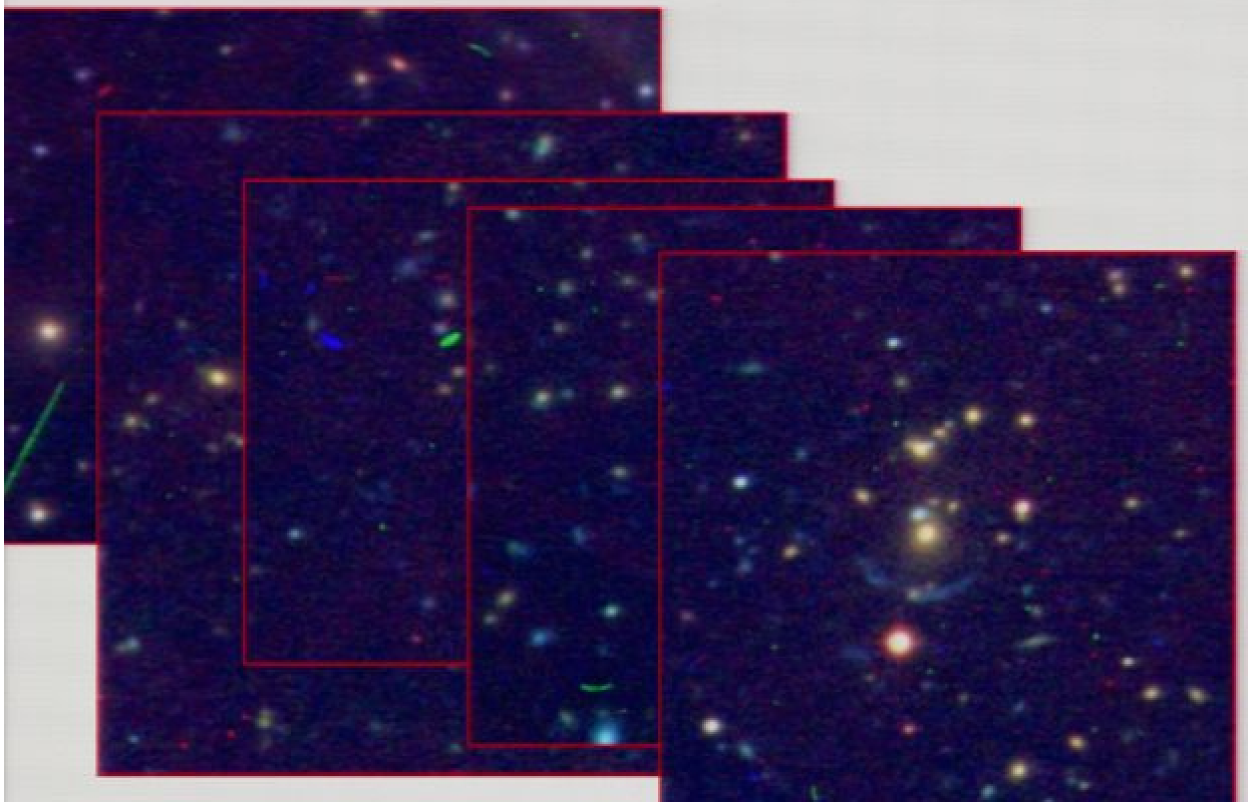

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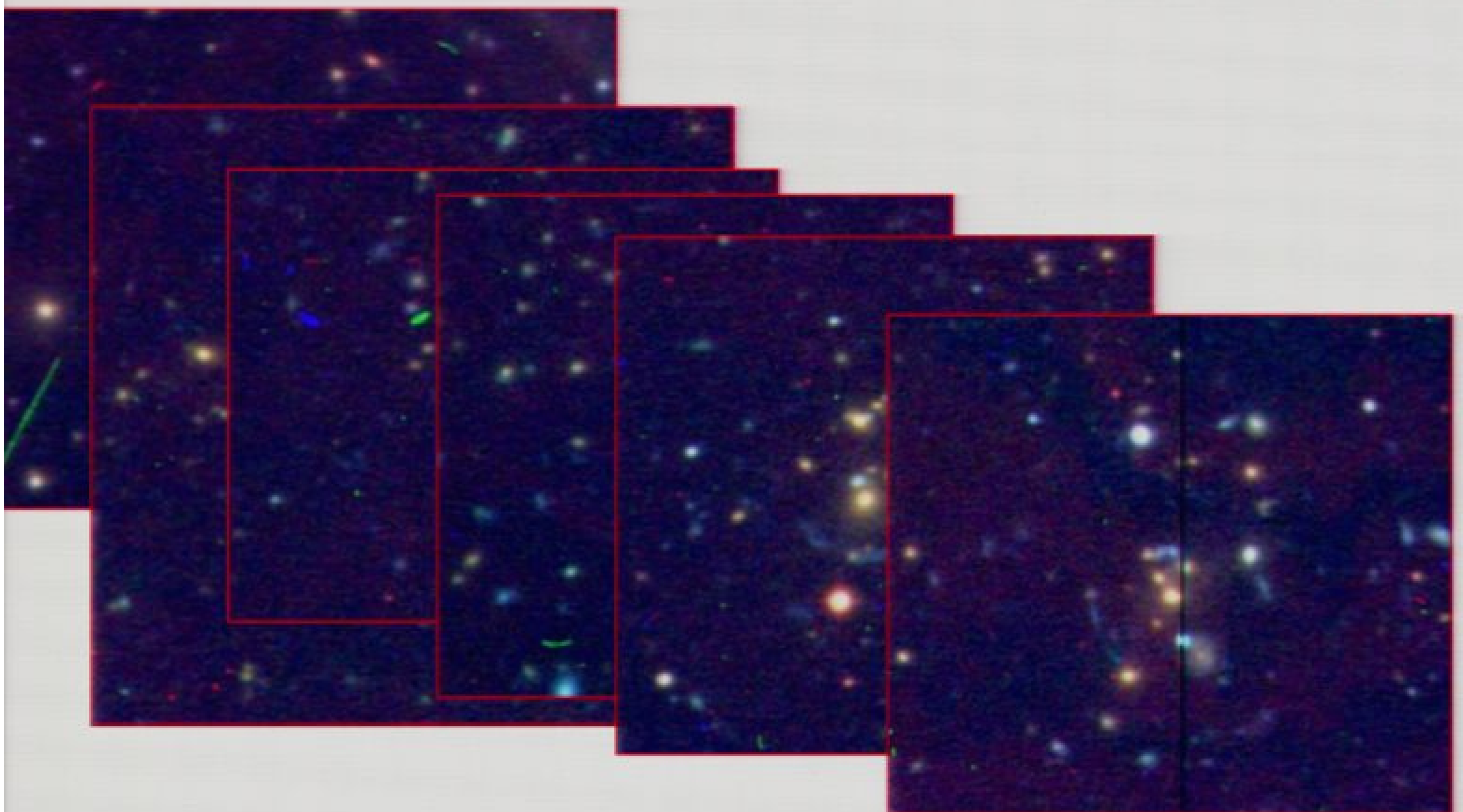

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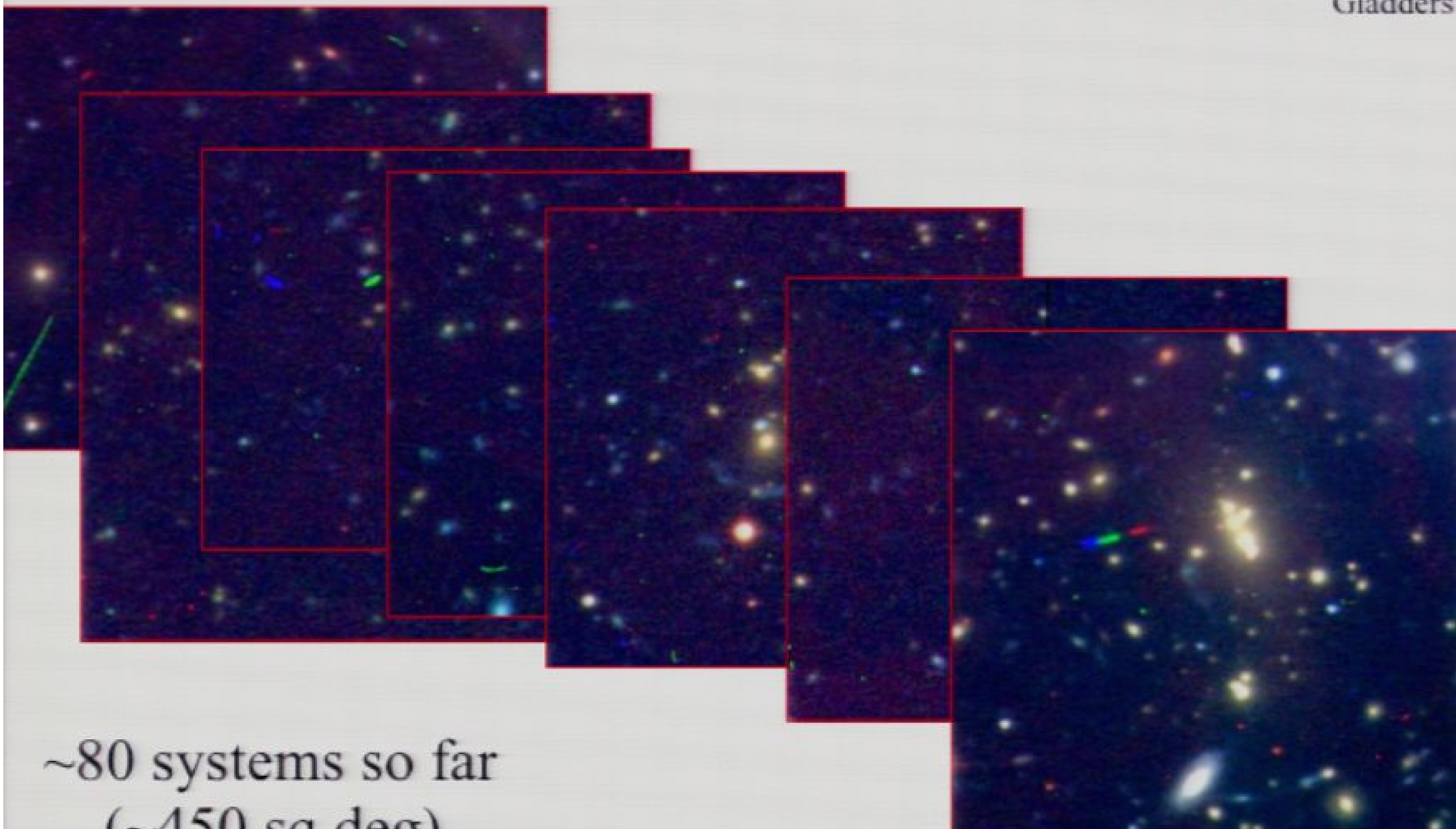

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Gladders et al.

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RCS-2: Strong Lensing Samples

Galaxy lenses

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Galaxy lenses

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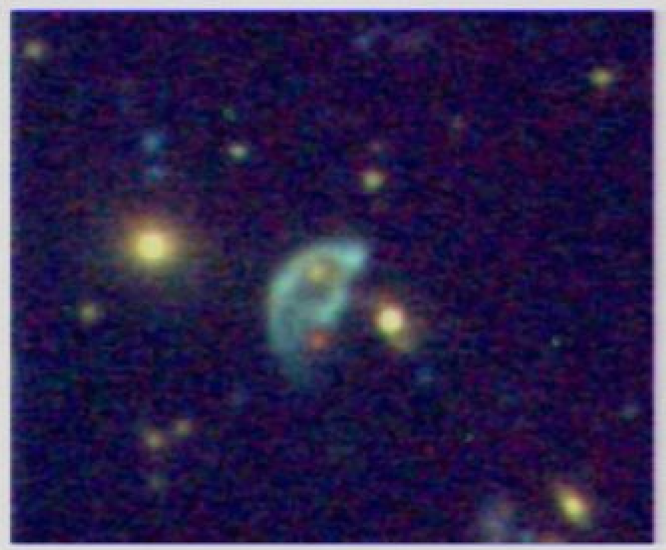
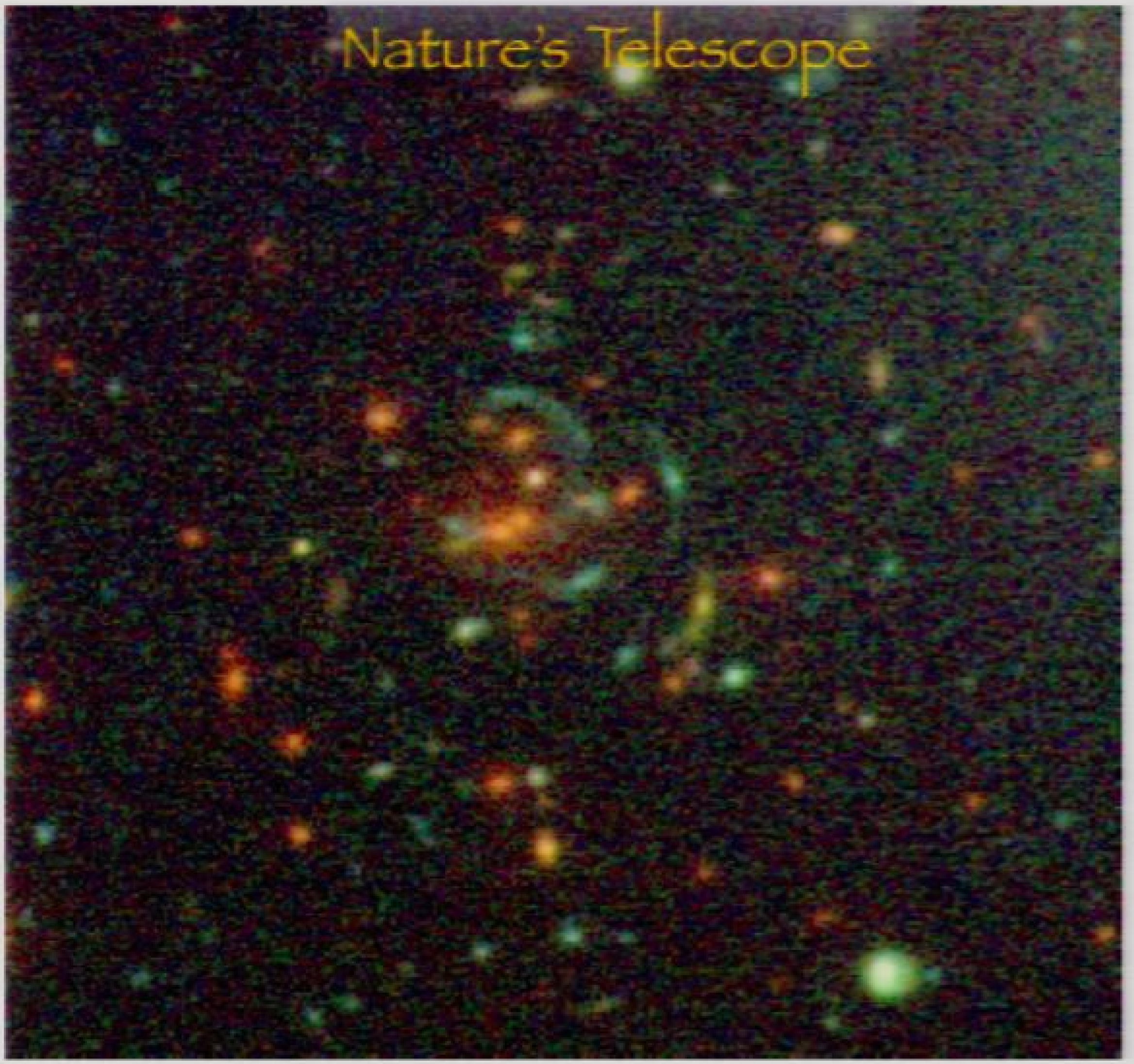
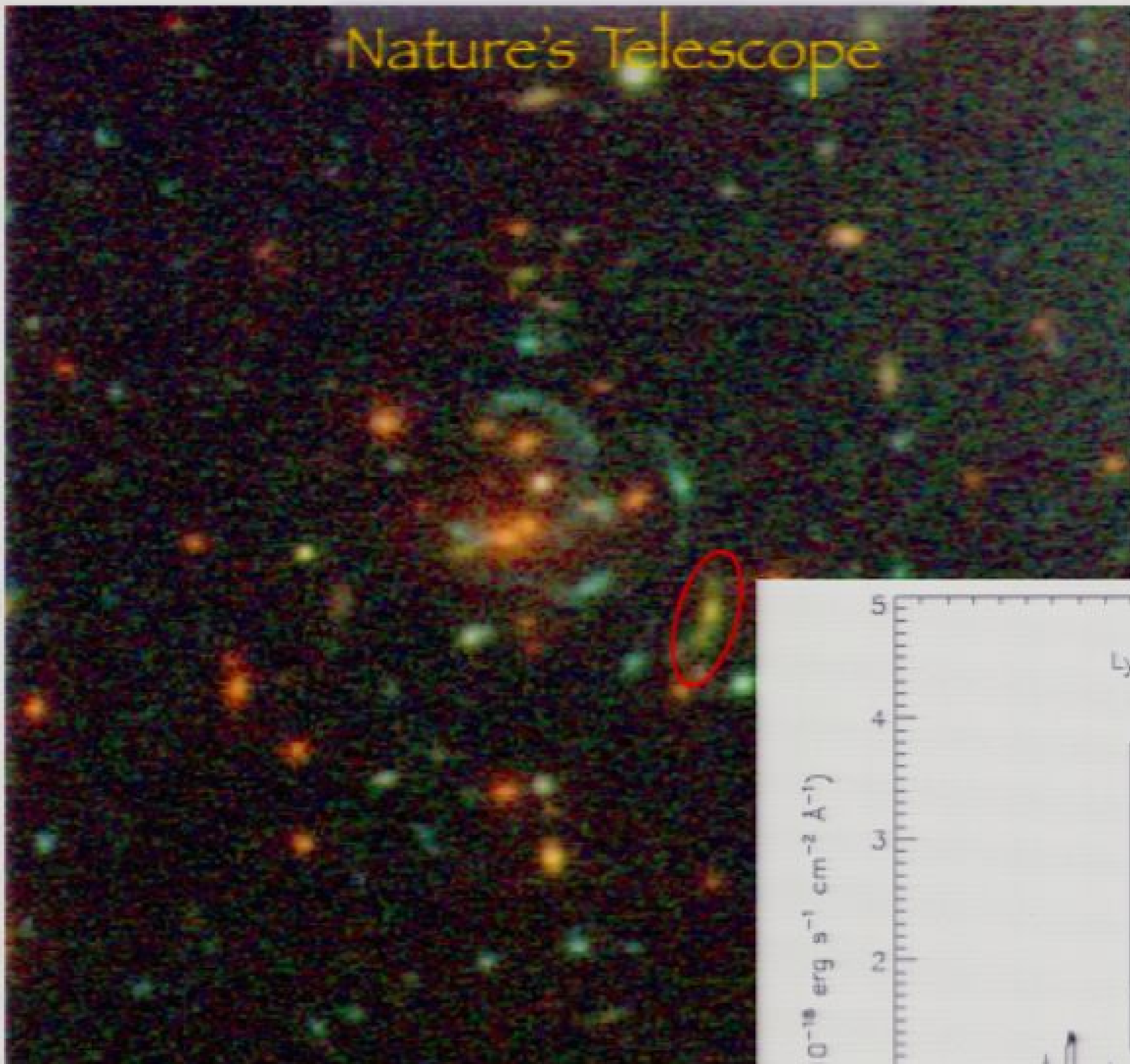
Galaxy lenses

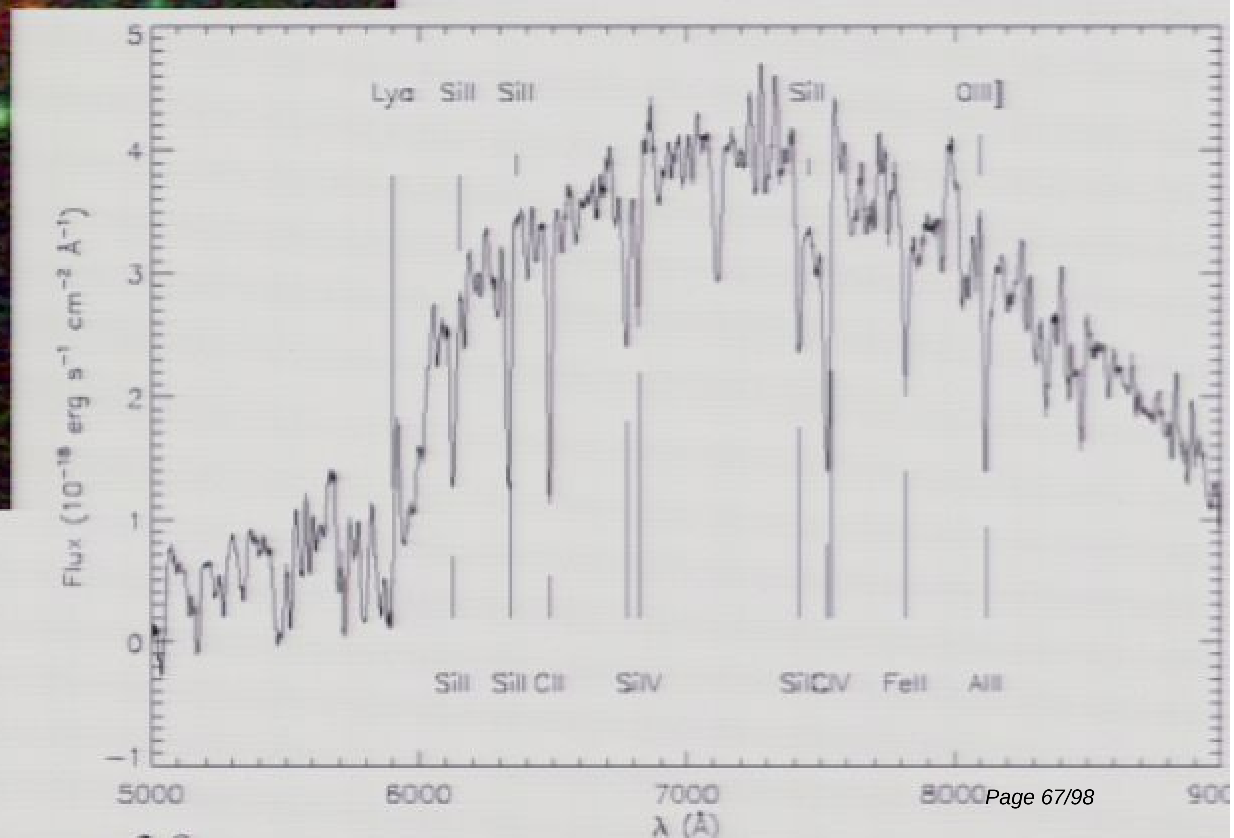




Gilbank et al. 2008 Ap.J

z=3.8

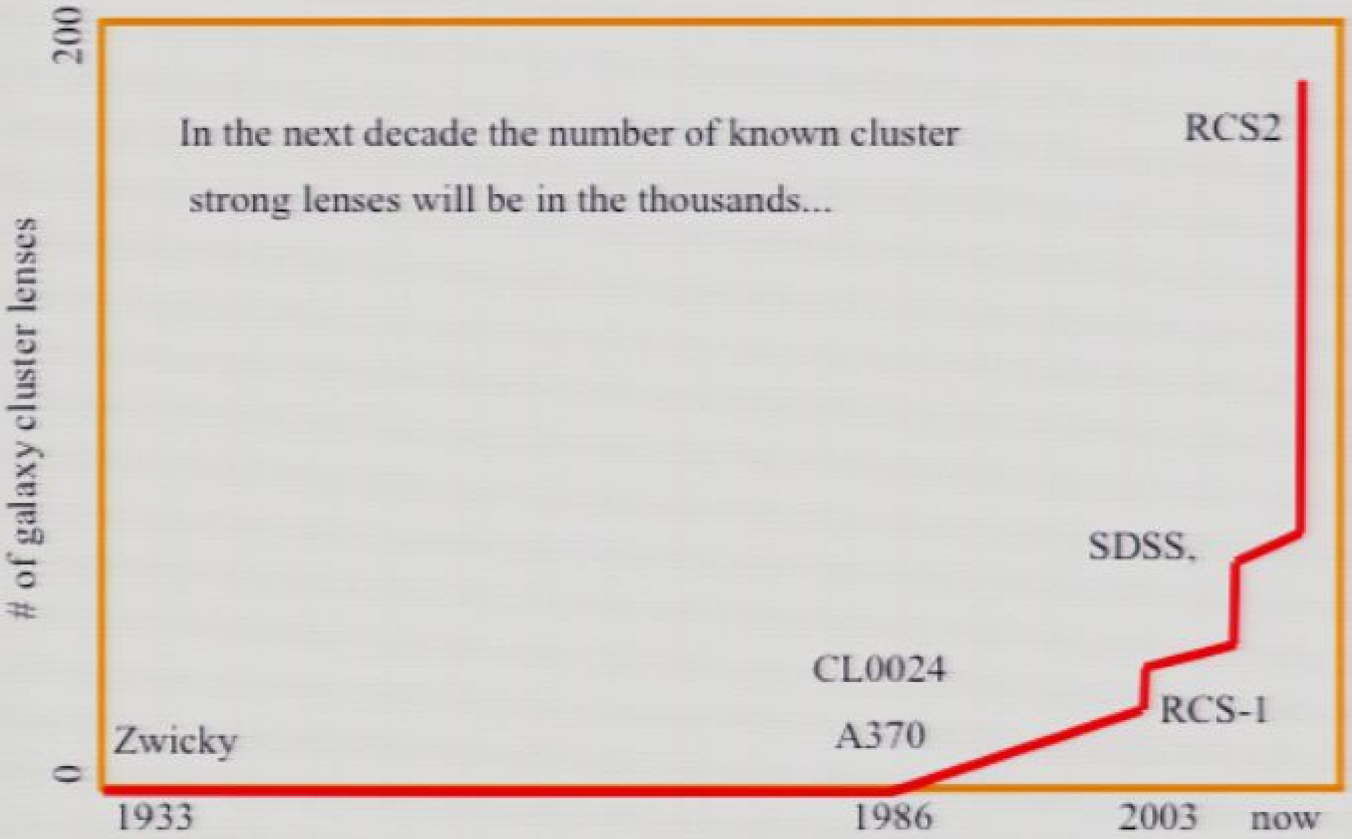




Gilbank et al. 2008 Ap.J

z=3.8

Cluster Strong Lenses, with "bright" arcs

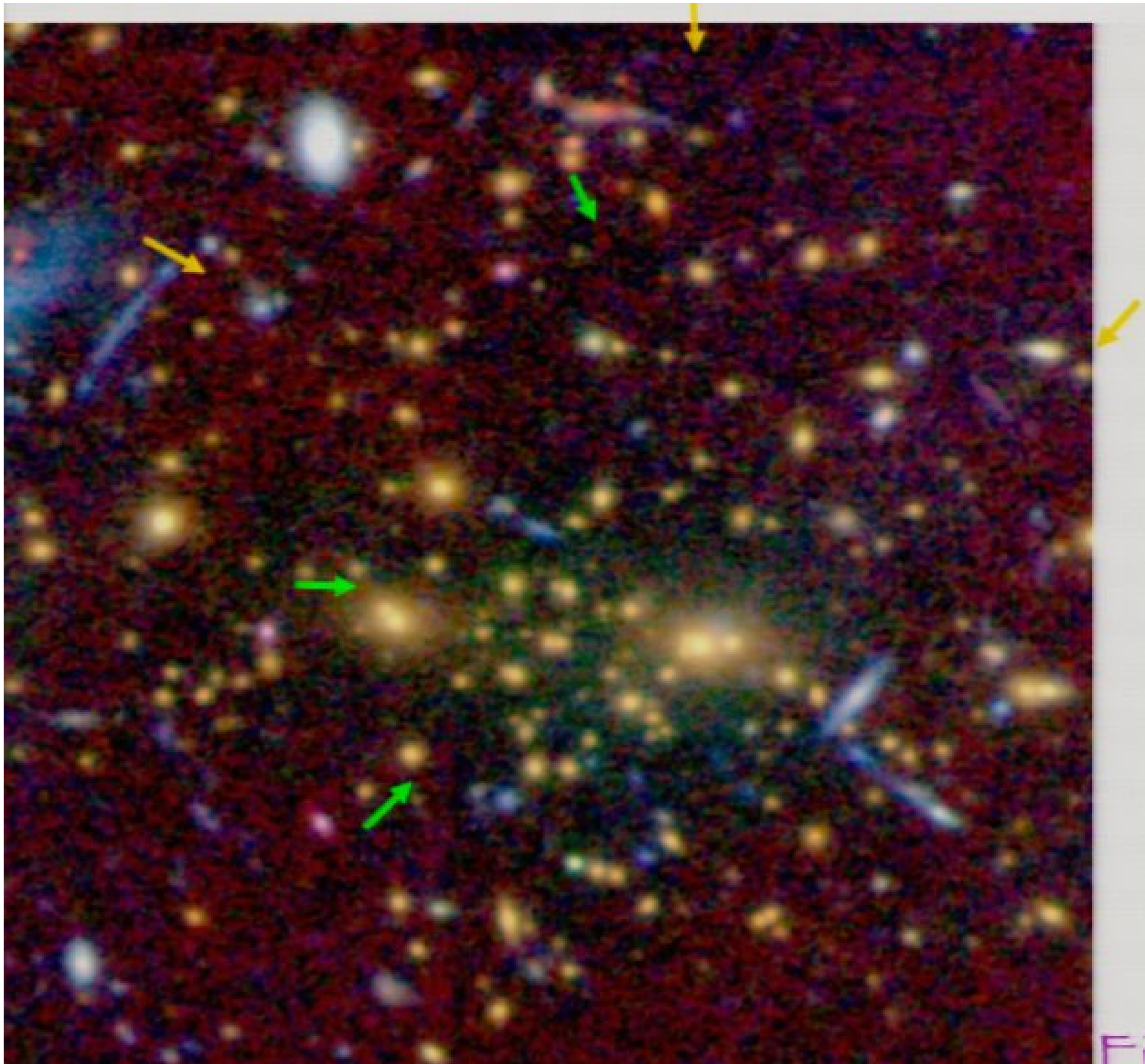


Similar Project in SDSS – here's recent color mosaic of some lenses (mostly SDSS, but pretty!)

Searching for RCS-2 Lensing Directly

- Search of 330 square degrees yields several hundred candidates
- Cutting on r_E>5" and l/w > 10, yields 27 distinct cluster lenses; (actual current number is ~40 including prior partial search results)
- Total expected number is ~75 cluster lenses under the strict criteria above;

* total number of lenses, including many at 1"-5" r_E, is in the hundreds

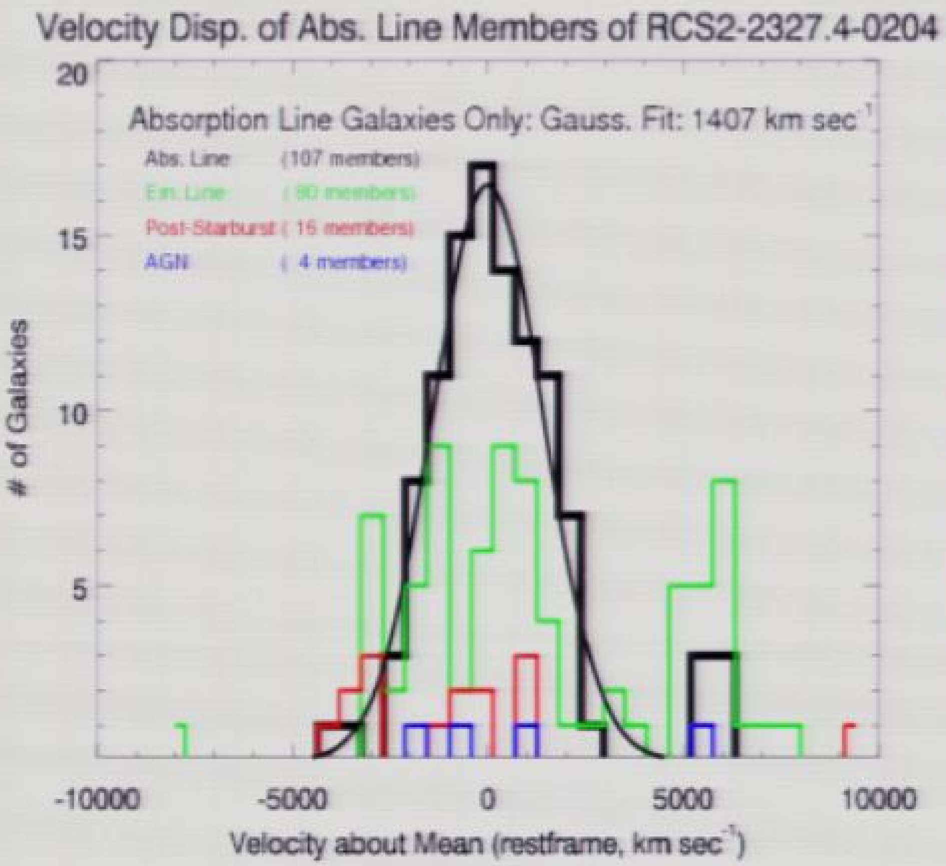


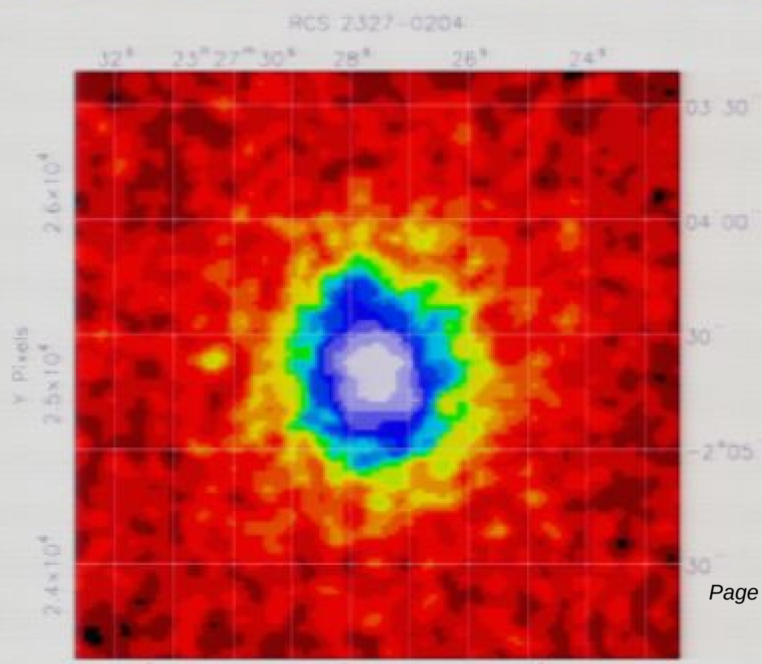
The most remarkable example:
massive clusters:
RCS2327

Einstein radius: 50"

Cluster Redshift: 0.6995

Source Redshift: 2.98

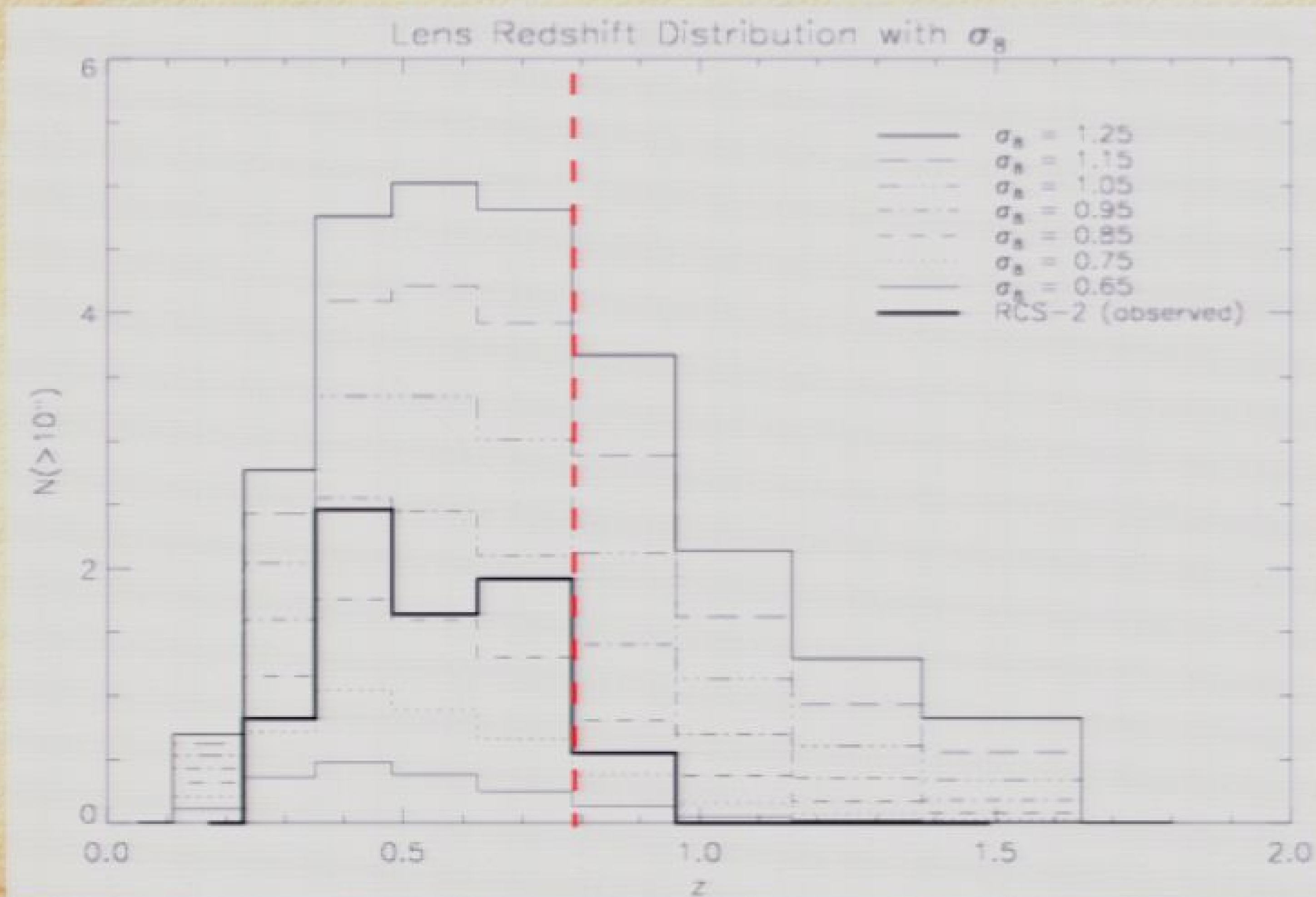




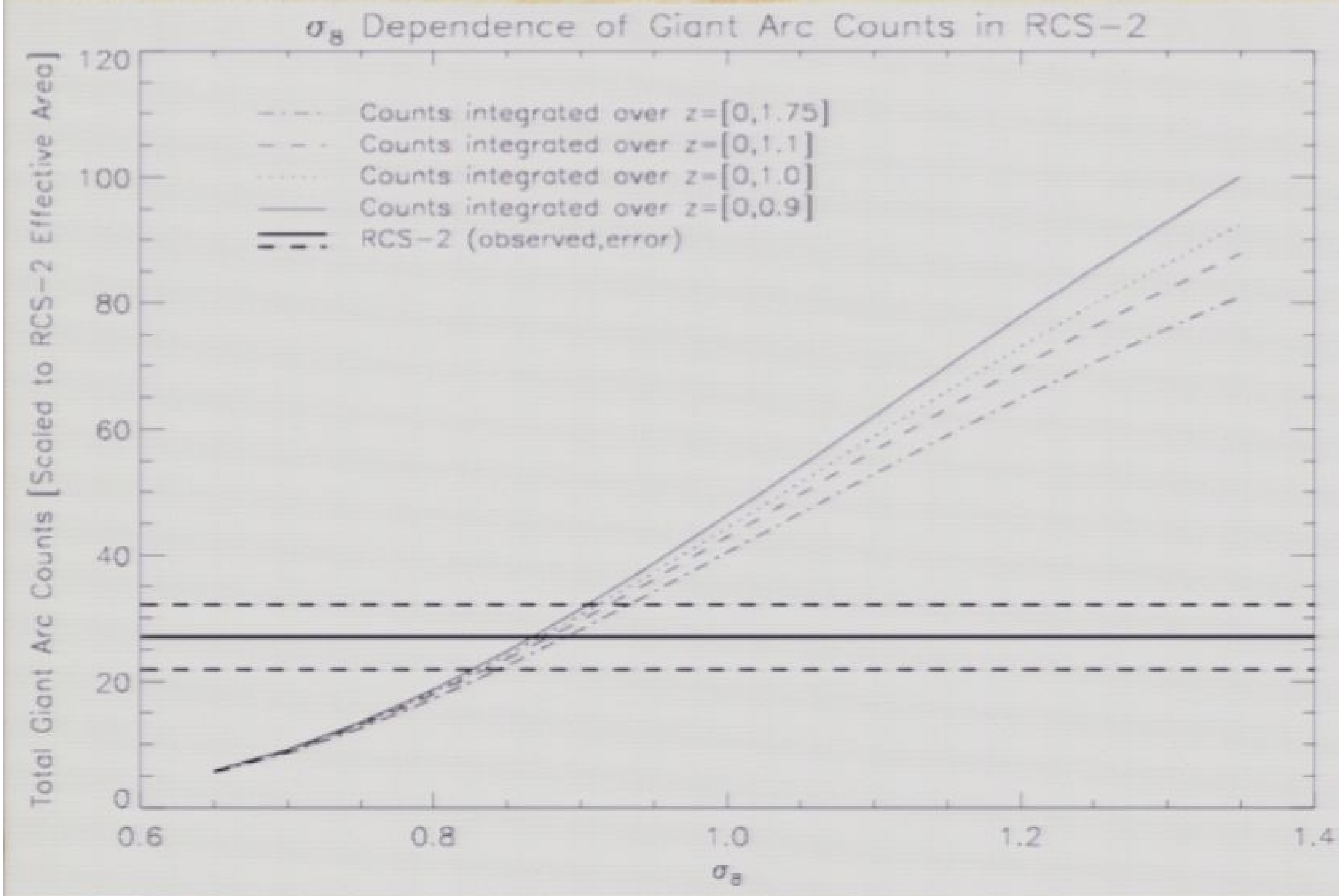
Velocity dispersion
1400 km/sec
Mvir~3x10^{15} Msun

Preliminary x-ray
temperature 9.5 keV

RCS-2 Arc Counts, Lens Redshift Distribution



(base on predictions from Hennawi et al. 2007)

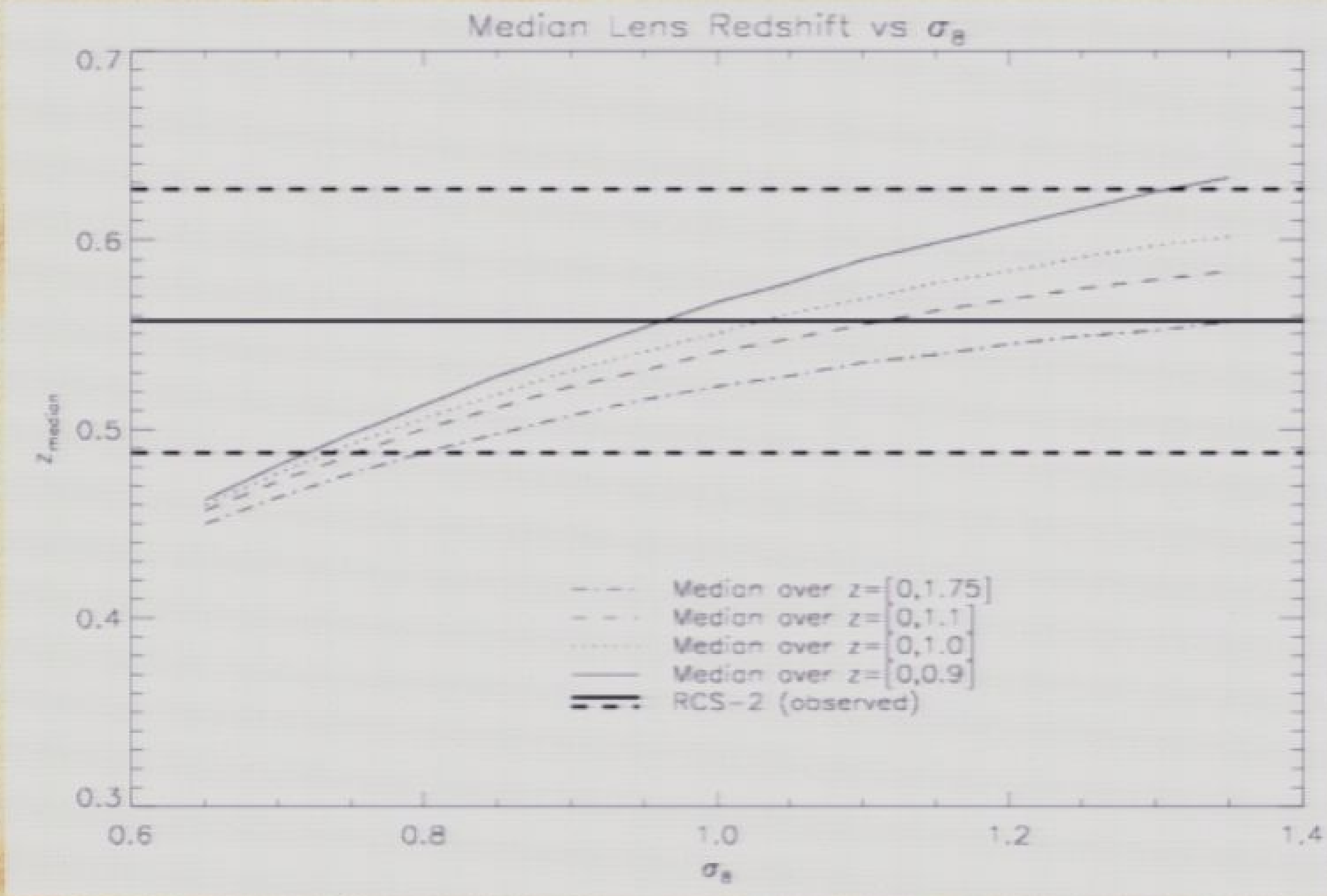


Caveats:

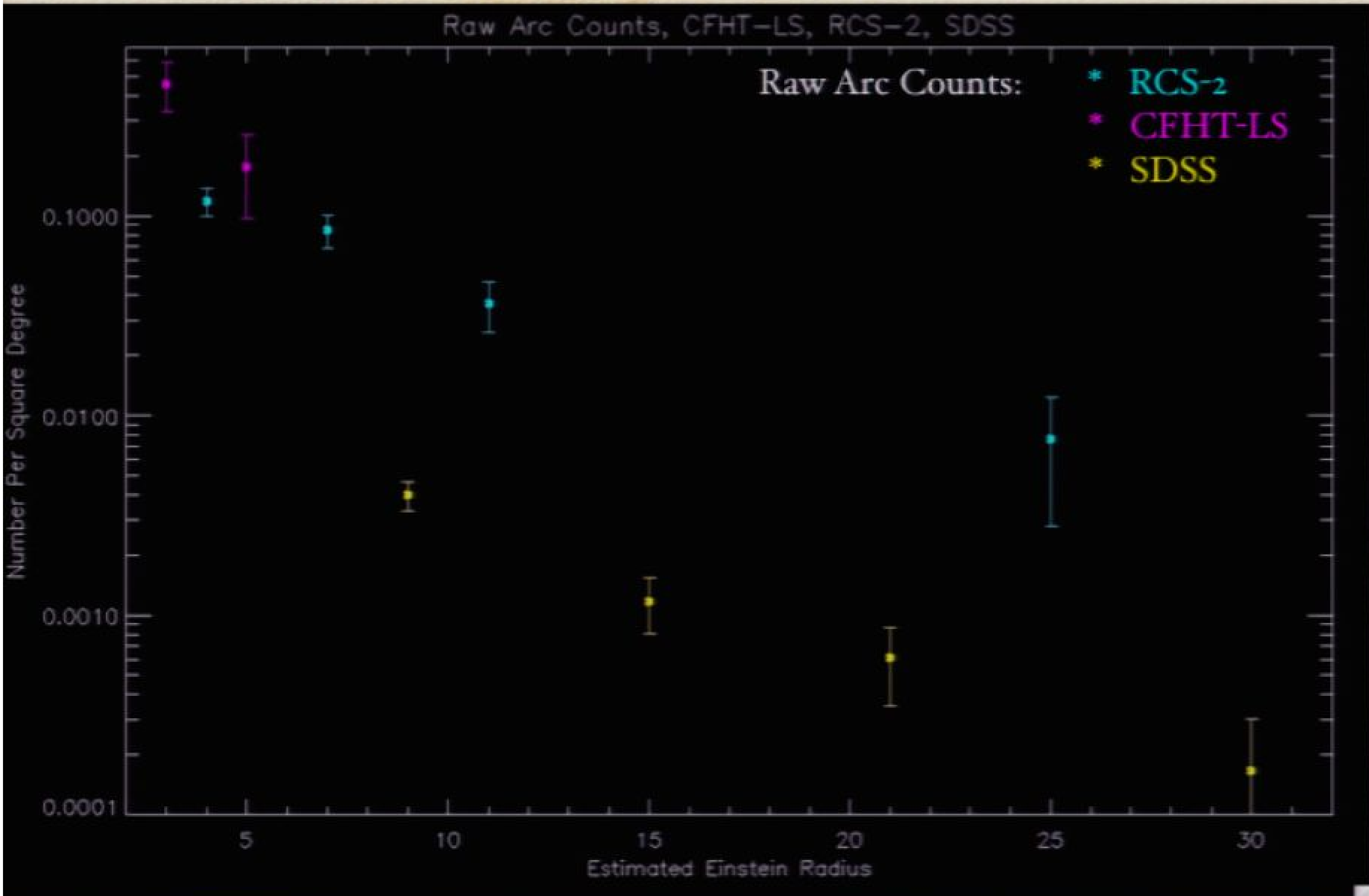
g-band versus r-band selection

surface brightness limits

However…


Median Lens Redshift vs σ_8
0.7
0.6
0.5
0.4
0.3
0.6
0.8
1.0
1.2
1.4
z_{median}
σ_8
Median over z=[0,1.75]
Median over z=[0,1.1]
Median over z=[0,1.0]
Median over z=[0,0.9]
RCS-2 (observed)

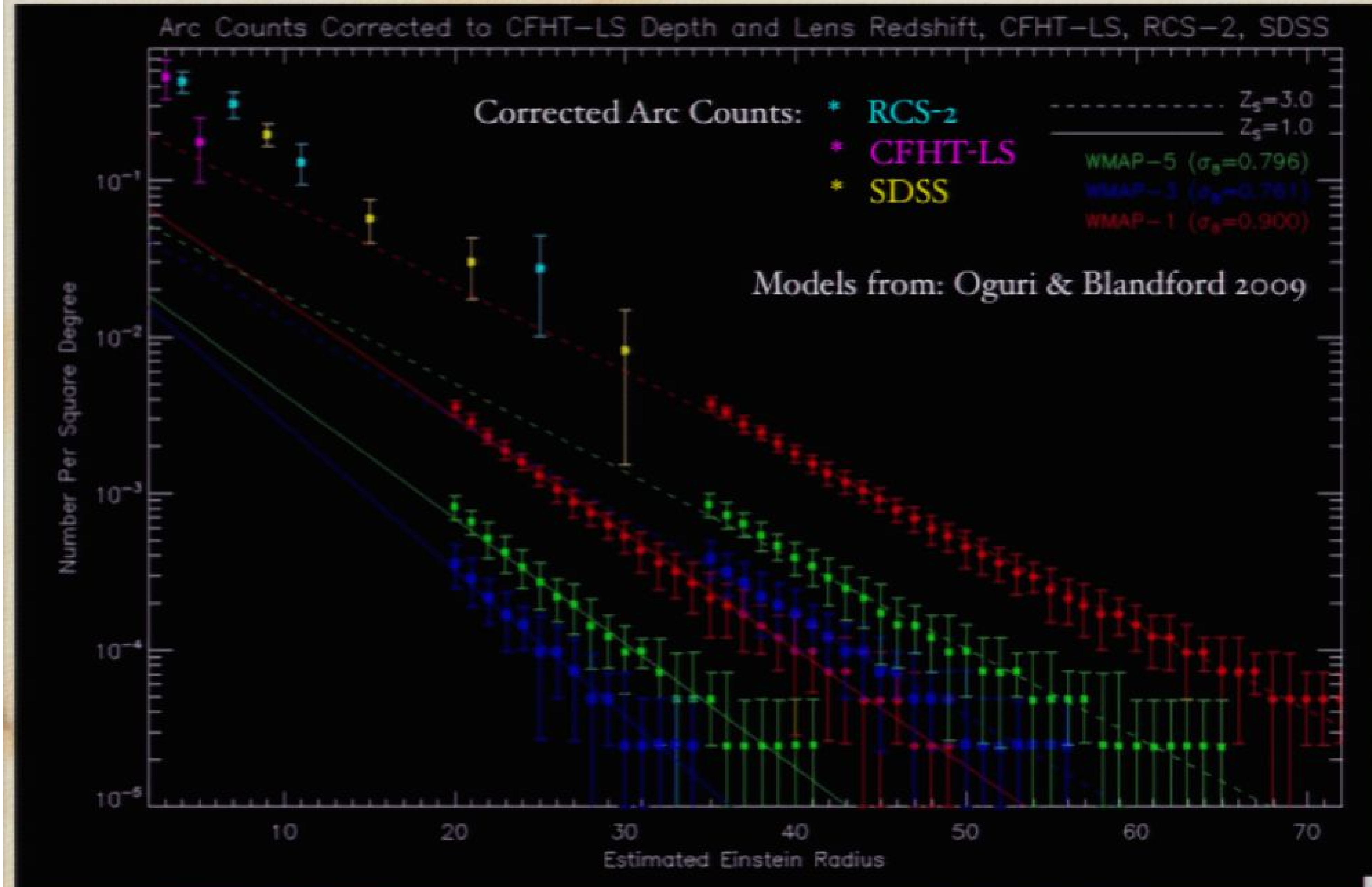
Statistics of Einstein radius



CFHT-LS: 28 sq deg, Cabanac et al 2007;

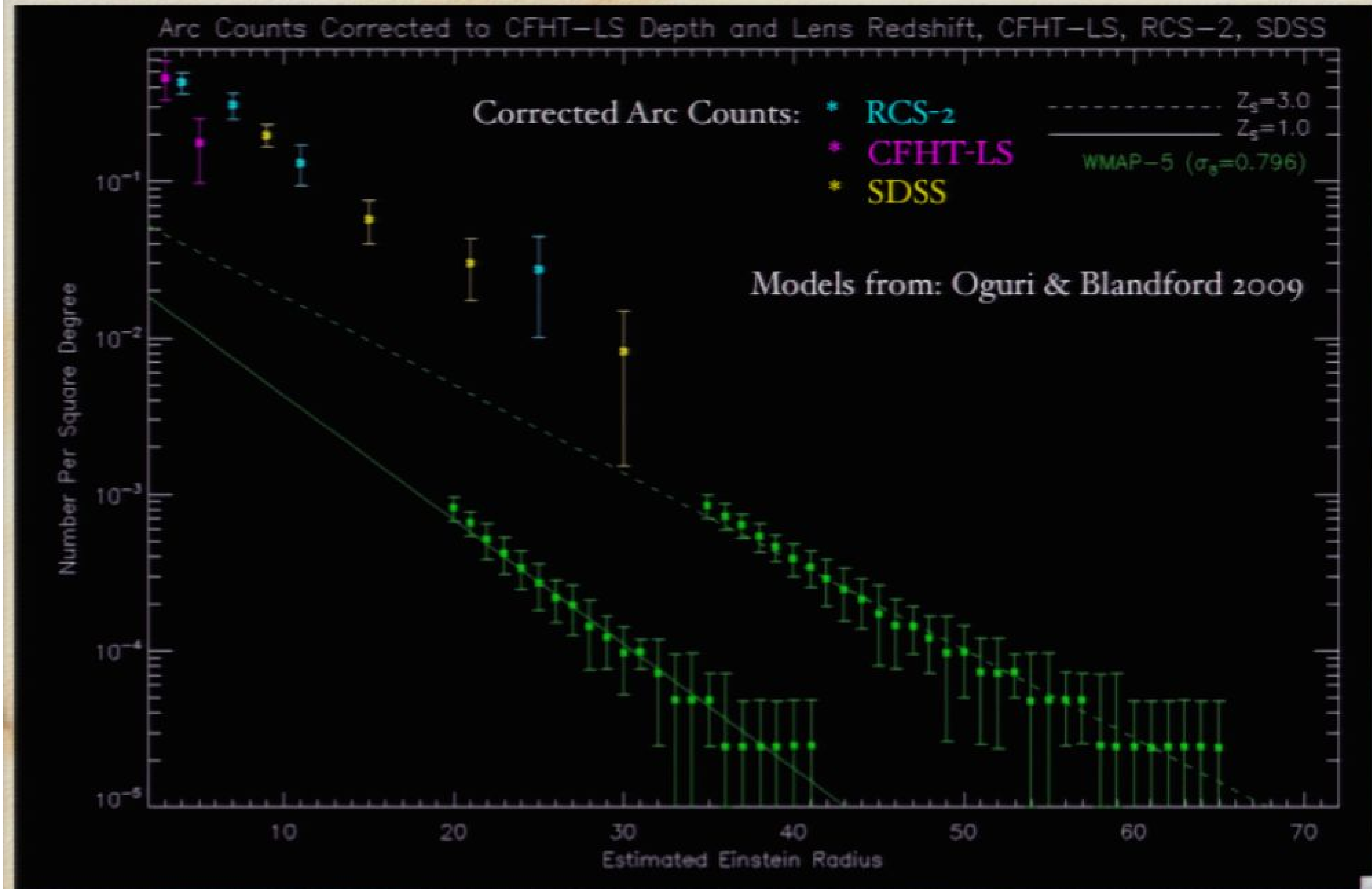
RCS2: 329 sq deg;

SDSS: ~9000 sq deg (direct search)



Note on source redshift: average z ~1.5 from those with spectro-z

u-band image: very few drop-outs (<5% with z>3)



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RCS-2 Cosmological Implications

• Total number of arcs is sensitive to cosmology, due to effects principally on total number of lenses, as well as concentration, sub-structure, etc.

• Current RCS-2 results are in decent agreement with relatively recent predictions for arc counts with redshift, and this comparison is NOT systematic dominated; generally a higher sigma-8 is preferred, **but**...

- similar results obtained by Fedeli et al. 2009 (astro-ph/0803.0656)

Follow-up: Cluster Masses

- Cluster dynamics being studied using GISMO as well as using ancillary slits in arc-targeted MOS observations at the VLT and Gemini telescopes

- Data are in hand for 28 systems; GISMO observations (21 clusters so far) yield 25-100 cluster members per mask;

- simple analysis confirms every system studied to date as a massive cluster: σ_V ranges from 600 -1300 km/sec

- SZA observations underway of the largest lenses – eventually targeting several dozen systems

The HST Cluster SN Survey

(PI: S. Perlmutter; paper I: Dawson K. et al, submitted to AJ

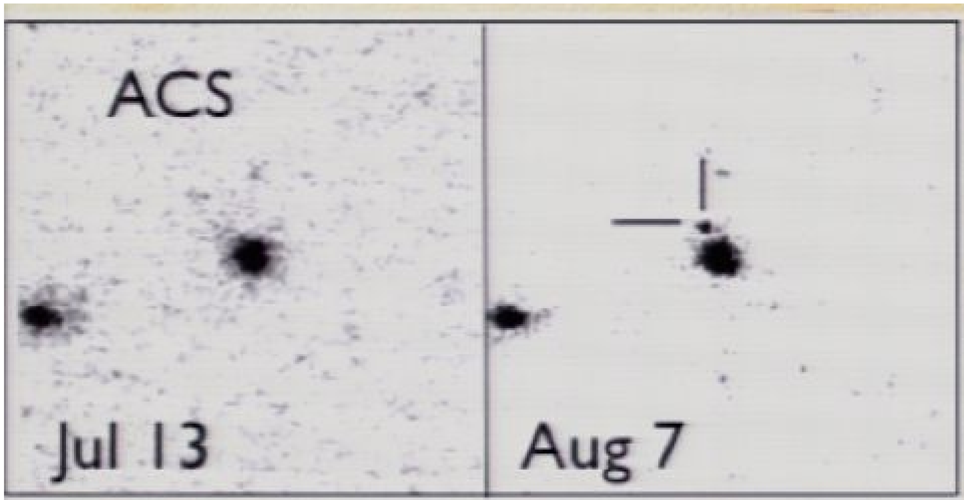
- a new strategy for high-z SNe:
  search in fields of z~1 clusters for SNe in E galaxies

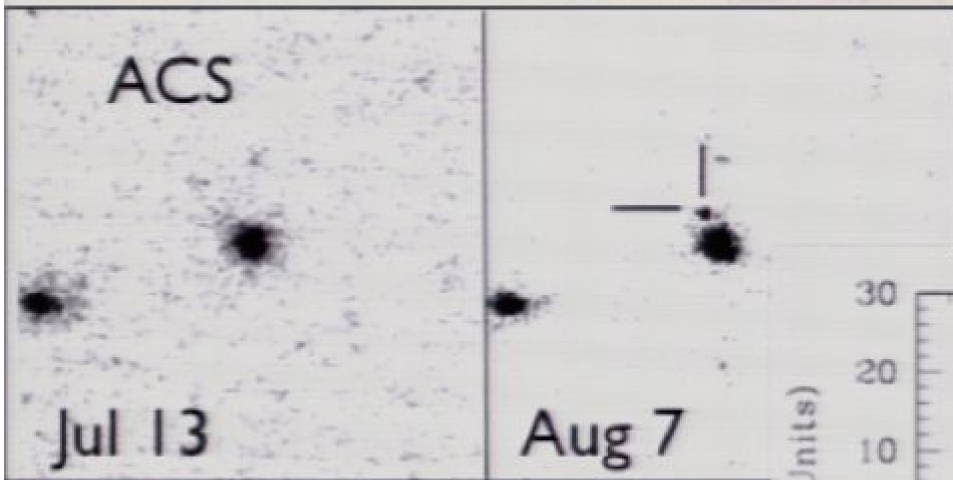
Advantages:

- significantly less dust in E, compared to Sp
- higher yield rate due to the presence of a cluster
- can target specific (high) redshift

- 219 orbits (188 ACS discovery, 31 Nicmos follow-up)

- 25 clusters, z~0.9 to 1.4; 10 clusters from the RCS


ACS
Jul 13
Aug 7


ACS
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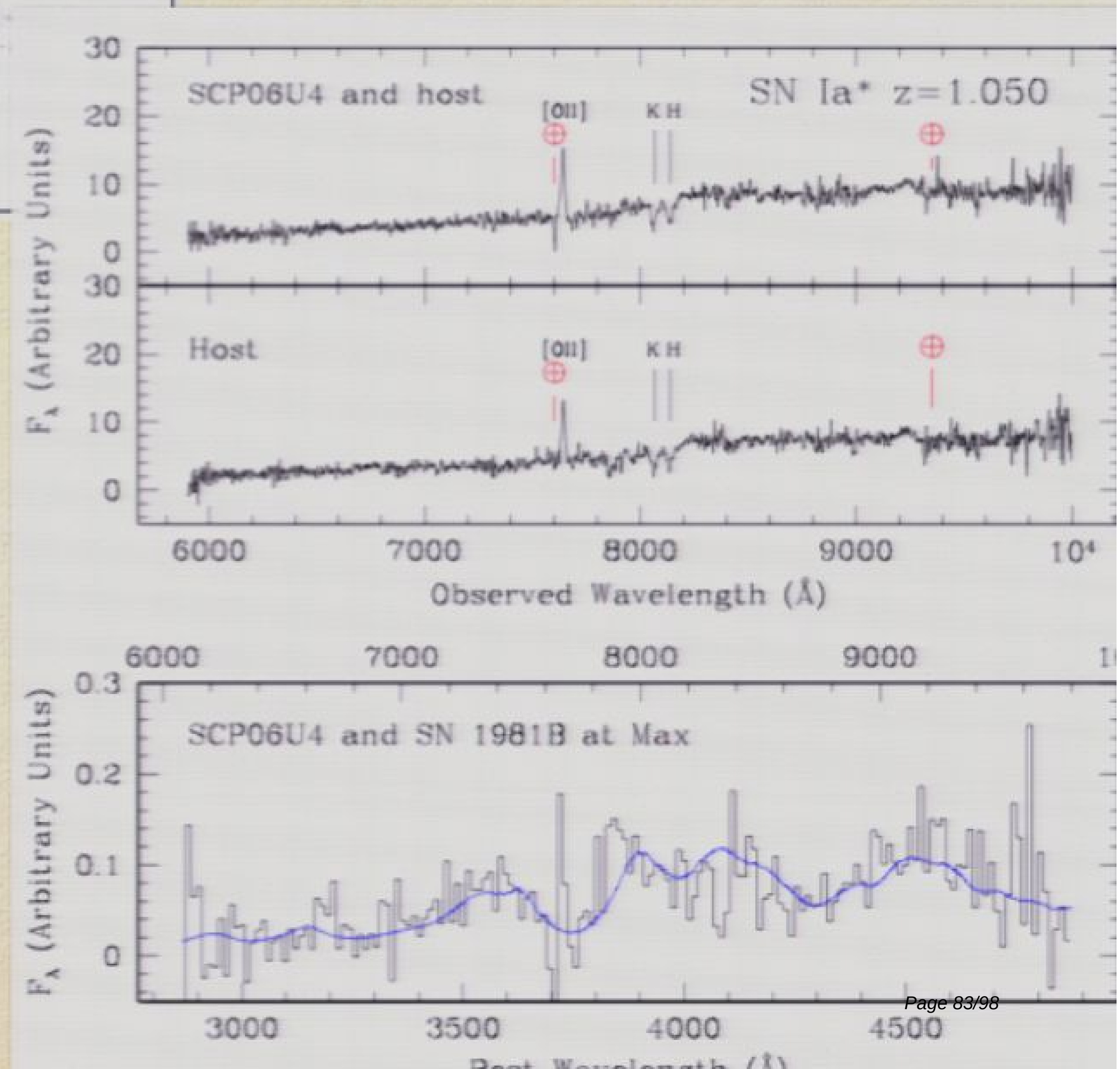
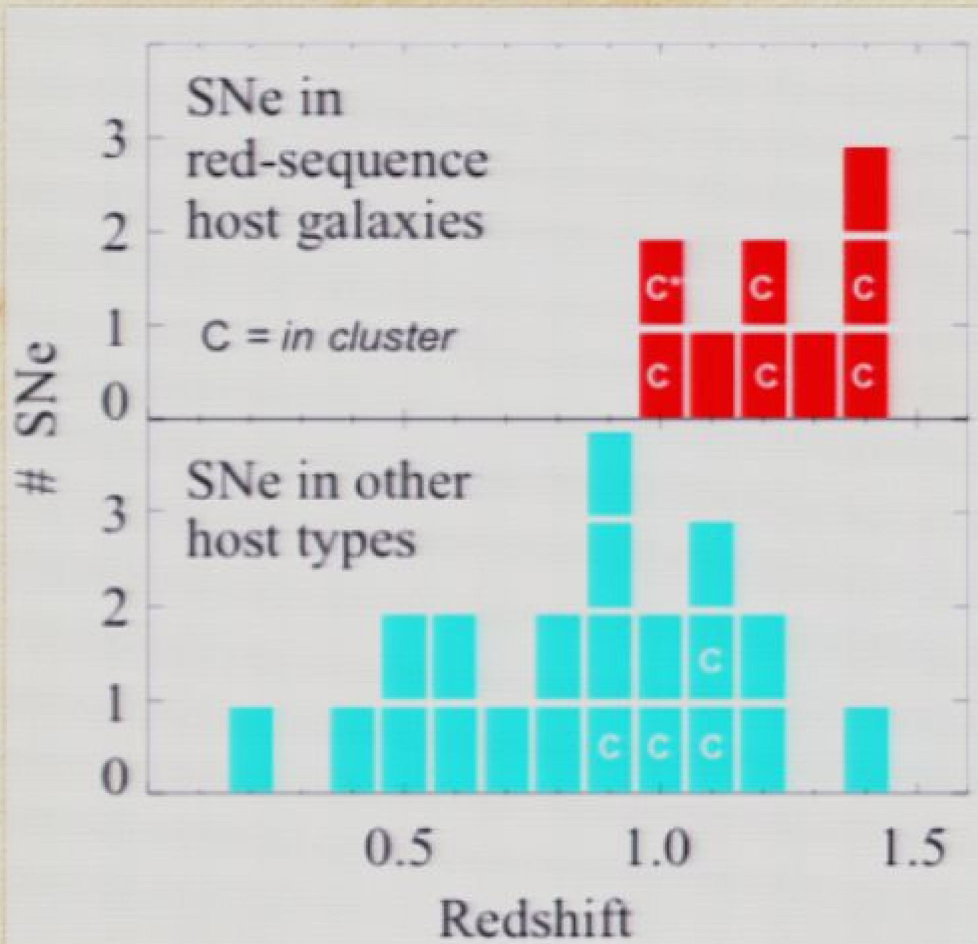
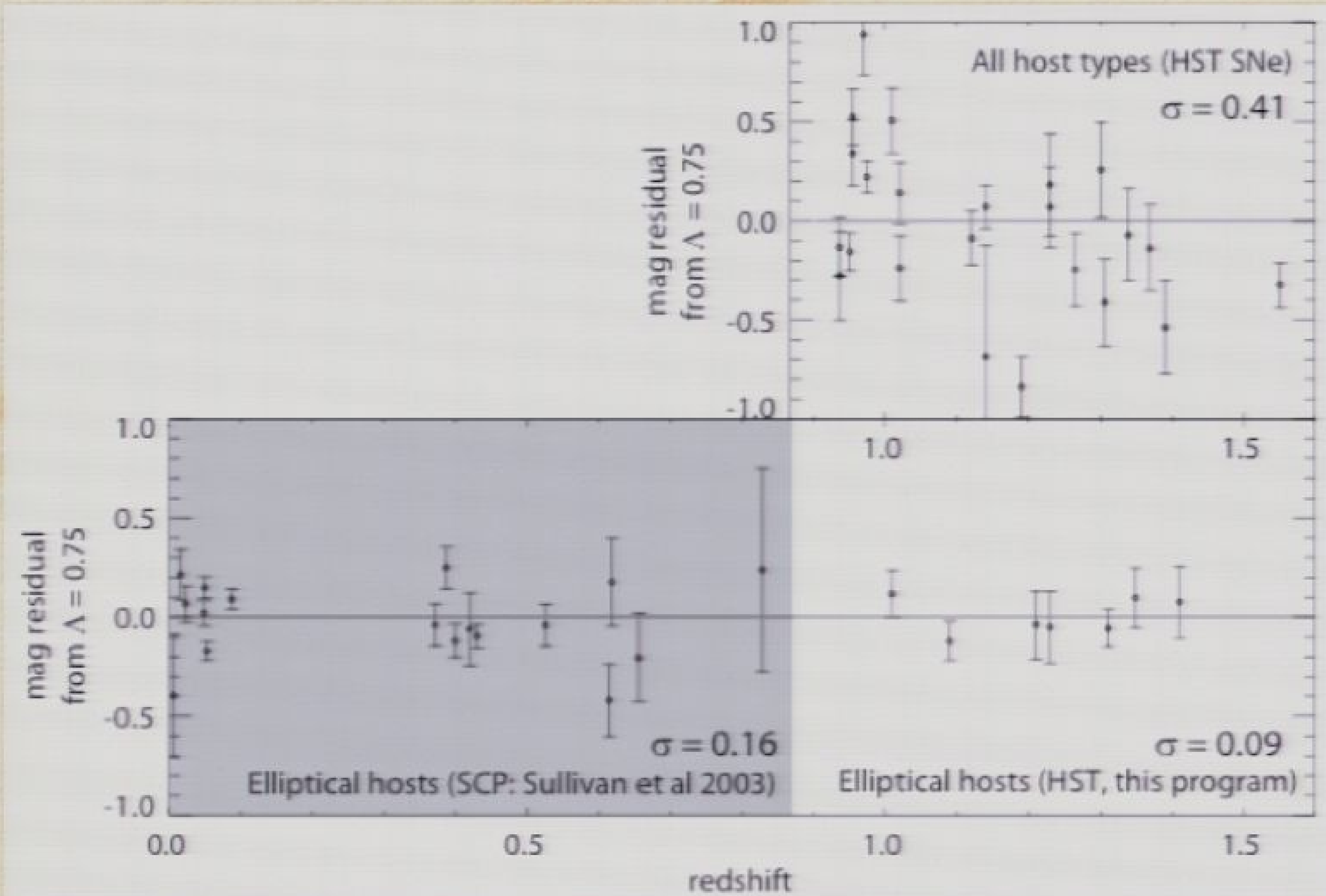

SCP06U4 and host
SN Ia* z=1.050
[OII]
K H
Host
F_λ (Arbitrary Units)
Observed Wavelength (Å)
6000
7000
8000
9000
10^4
SCP06U4 and SN 1981B at Max
3000
3500
4000
4500

Total of 37 SNe discovered



10 SNe in clusters
(out of 21 with z>0.9:
an increase of 90%)

6 out of 10 SNe in
ellipticals (an increase
of 150% in SNe in E's)

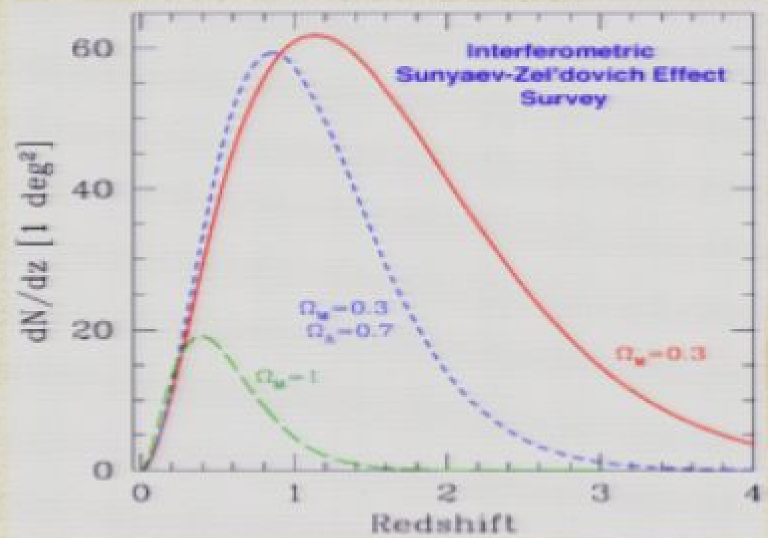


SNe in E's reduce dispersion by a factor of 4.
one SN in E is worth ~16 SNe in Sp!

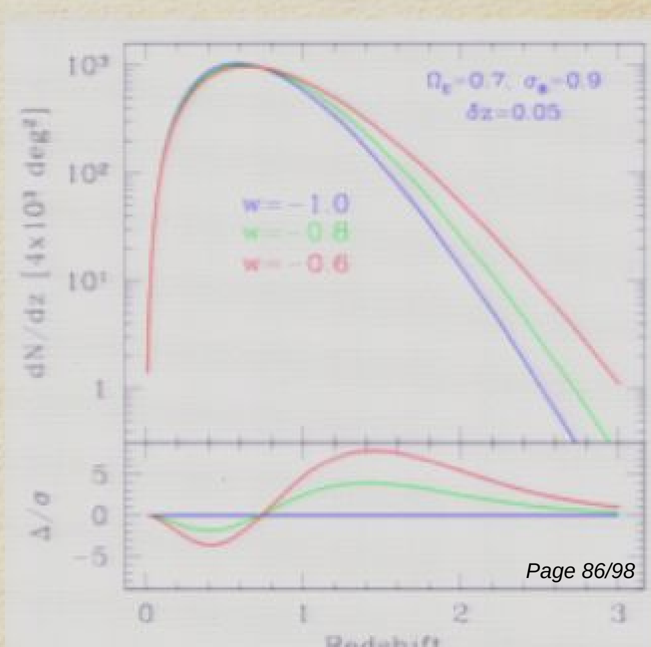
High-z clusters are valuable for SNe cosmology

The Search for z >1 Clusters

- better discrimination for cosmological parameters;
  BUT: many fewer clusters;
  very difficult to calibrate mass observables



- provide crucial target fields for SNe (especially in early-type galaxies) at z >1



- the RCS technique is optimized when the 2 filters straddle the 4000A break
- requires IR images for z>~1.1
  - the cluster redshift "desert": 1.3<z<2

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- requires IR images for z>~1.1
  - the cluster redshift "desert": 1.3<z<2

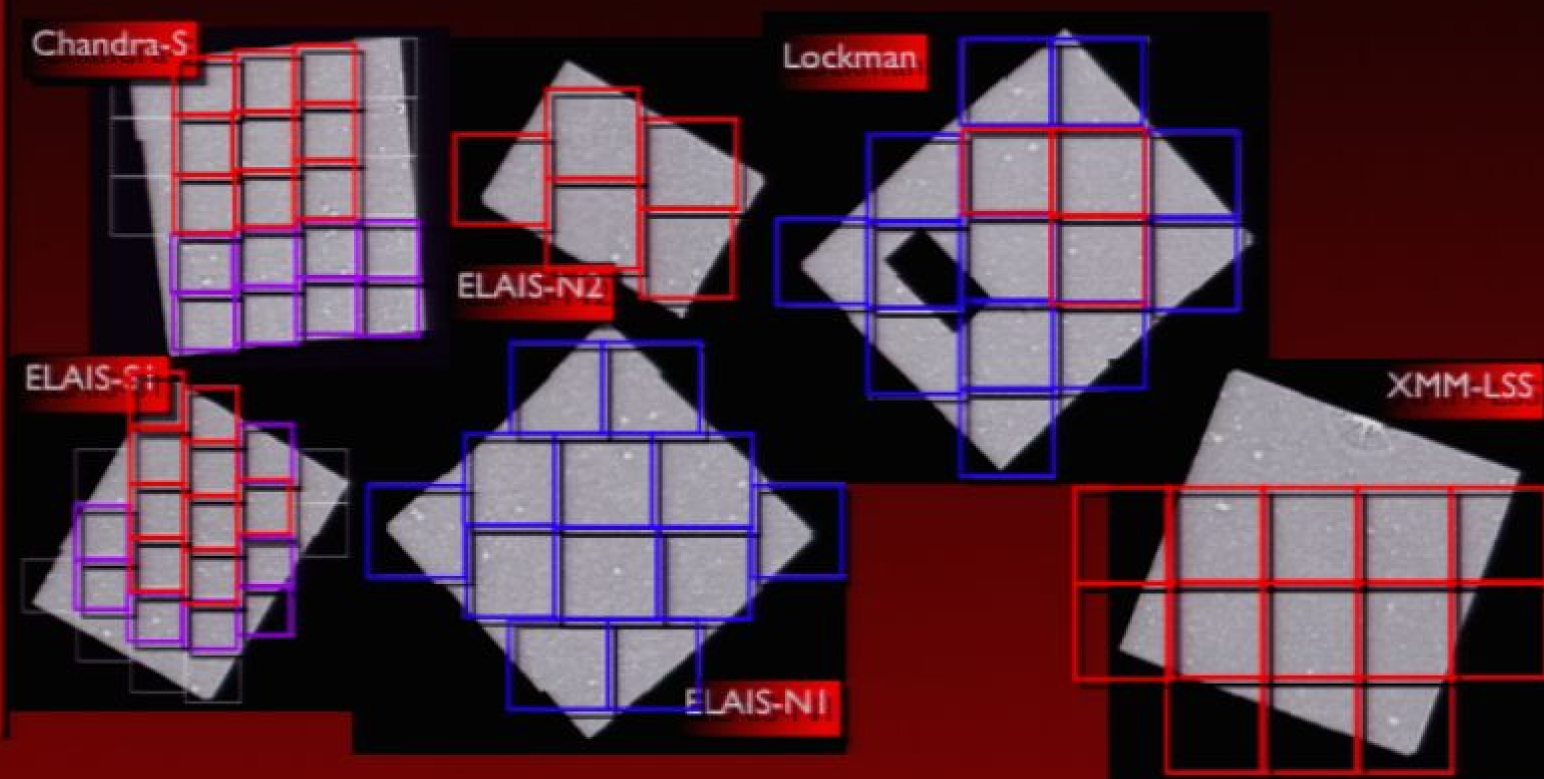
The SpARCS survey (Adam Muzzin, G. Wilson, Yee, +...)

(The Spitzer Adaptation of Red-Cluster Sequence)

- 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

- -- ~200 clusters with z>1;
  - currently a core sample of 10 being followed-up intensely with: MOS, multi-band imaging, X-ray....

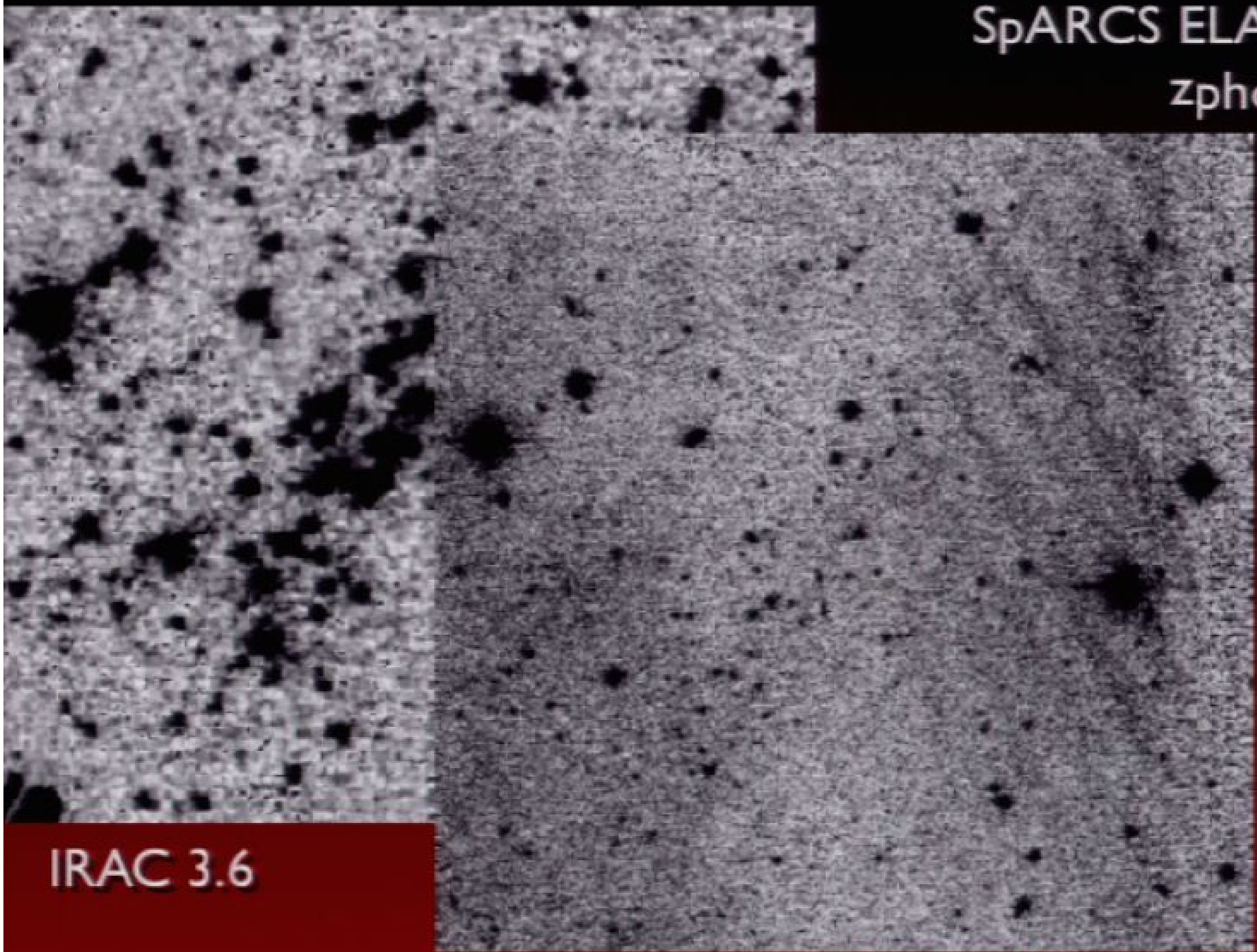
Final area: 42 deg^2

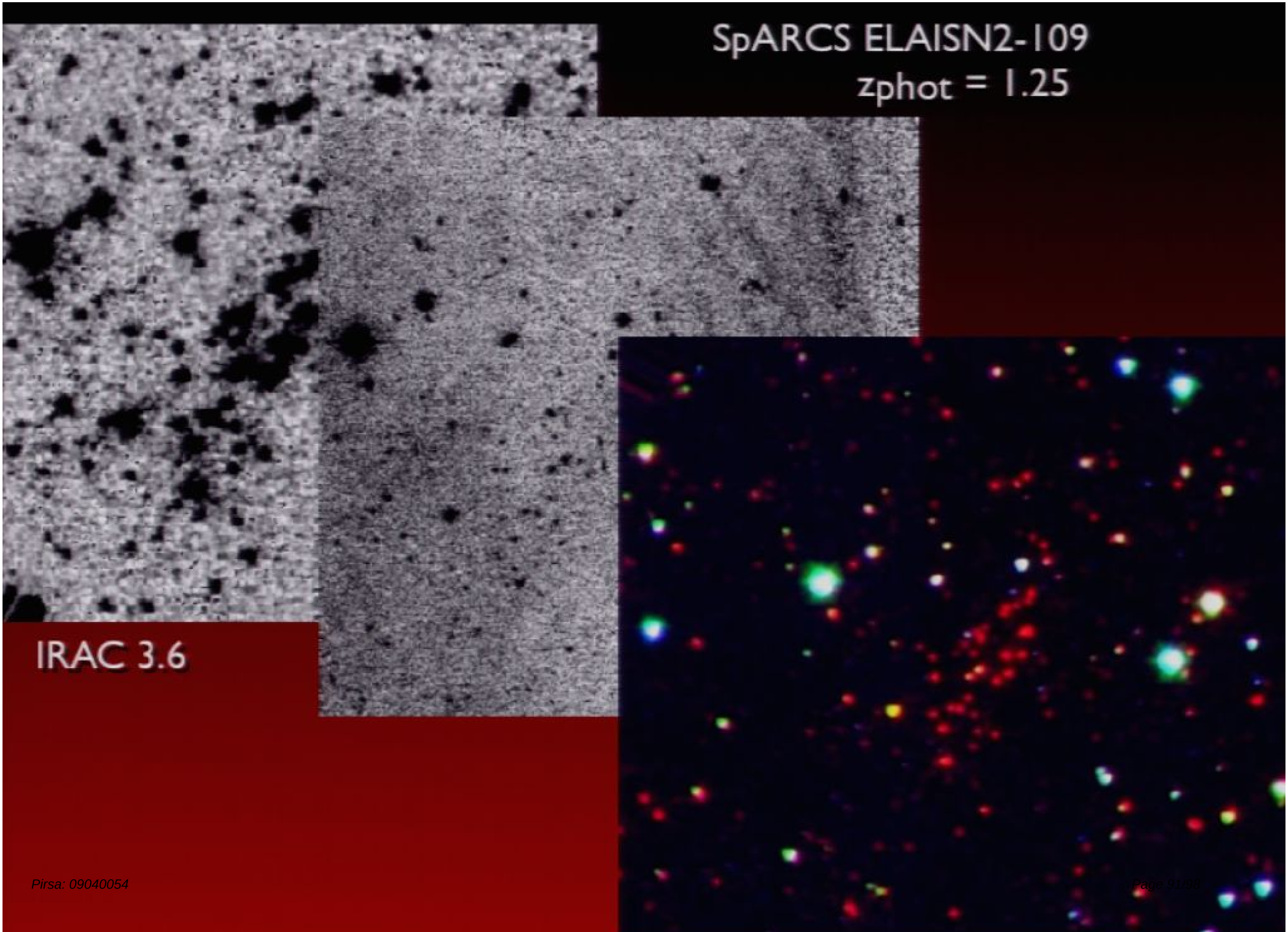


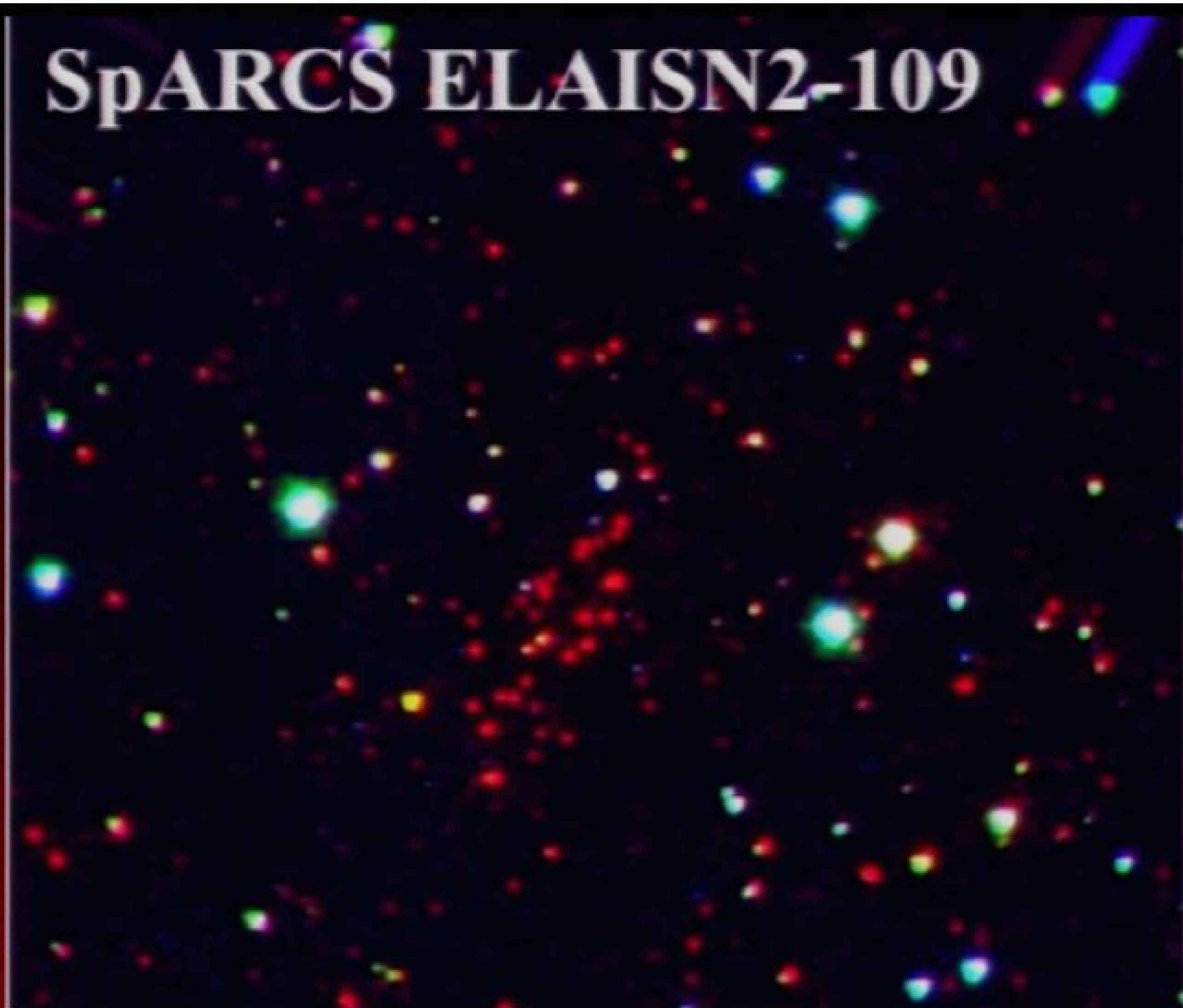
Muzzin, Wilson, Yee, et al, ApJ, in press, arXiv:0810.0005;
Wilson, Muzzin, Yee, et al. ApJ, in press, arXiv:0810.0036;

SpARCS ELAISN2-109

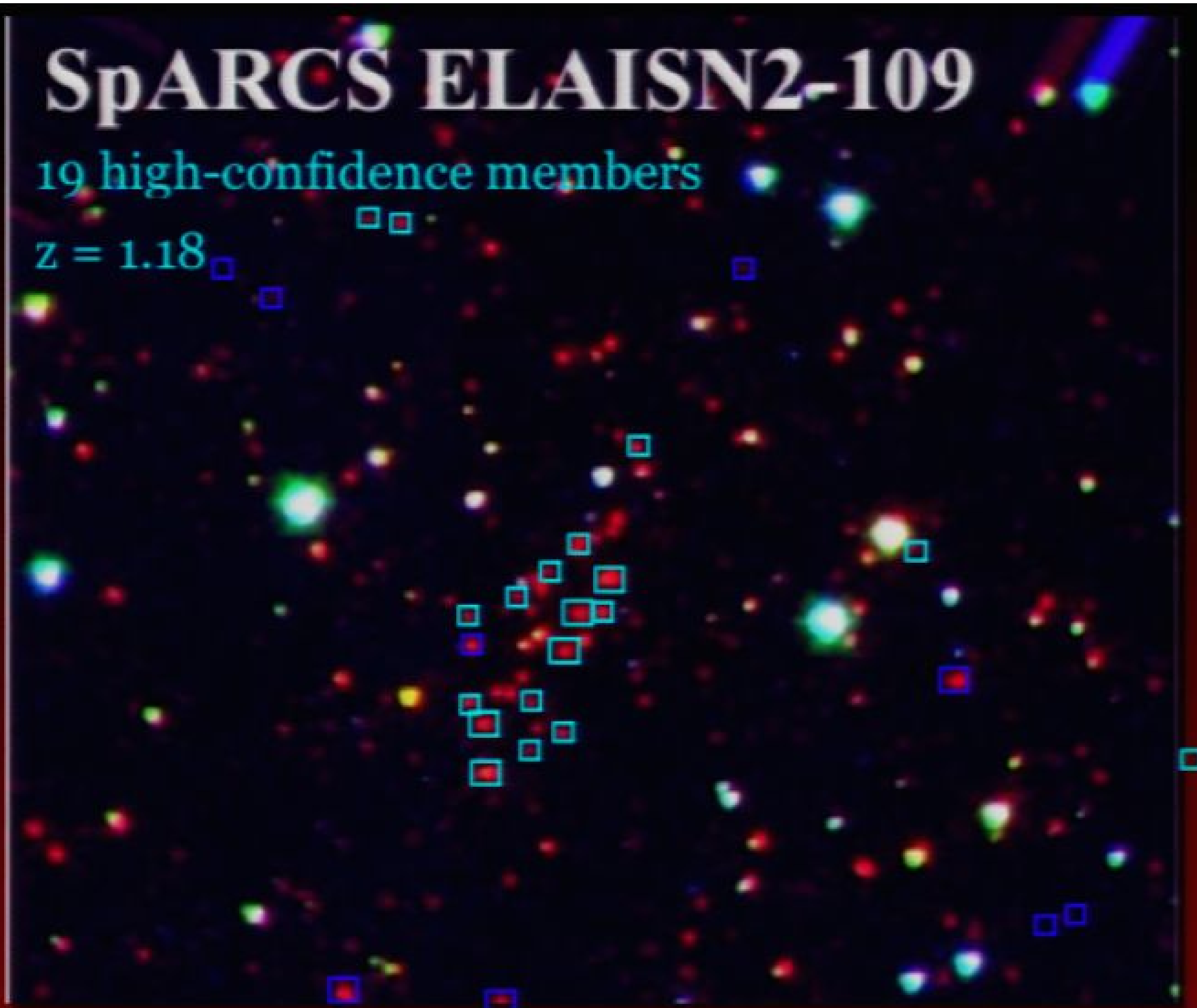
zphot = 1.25



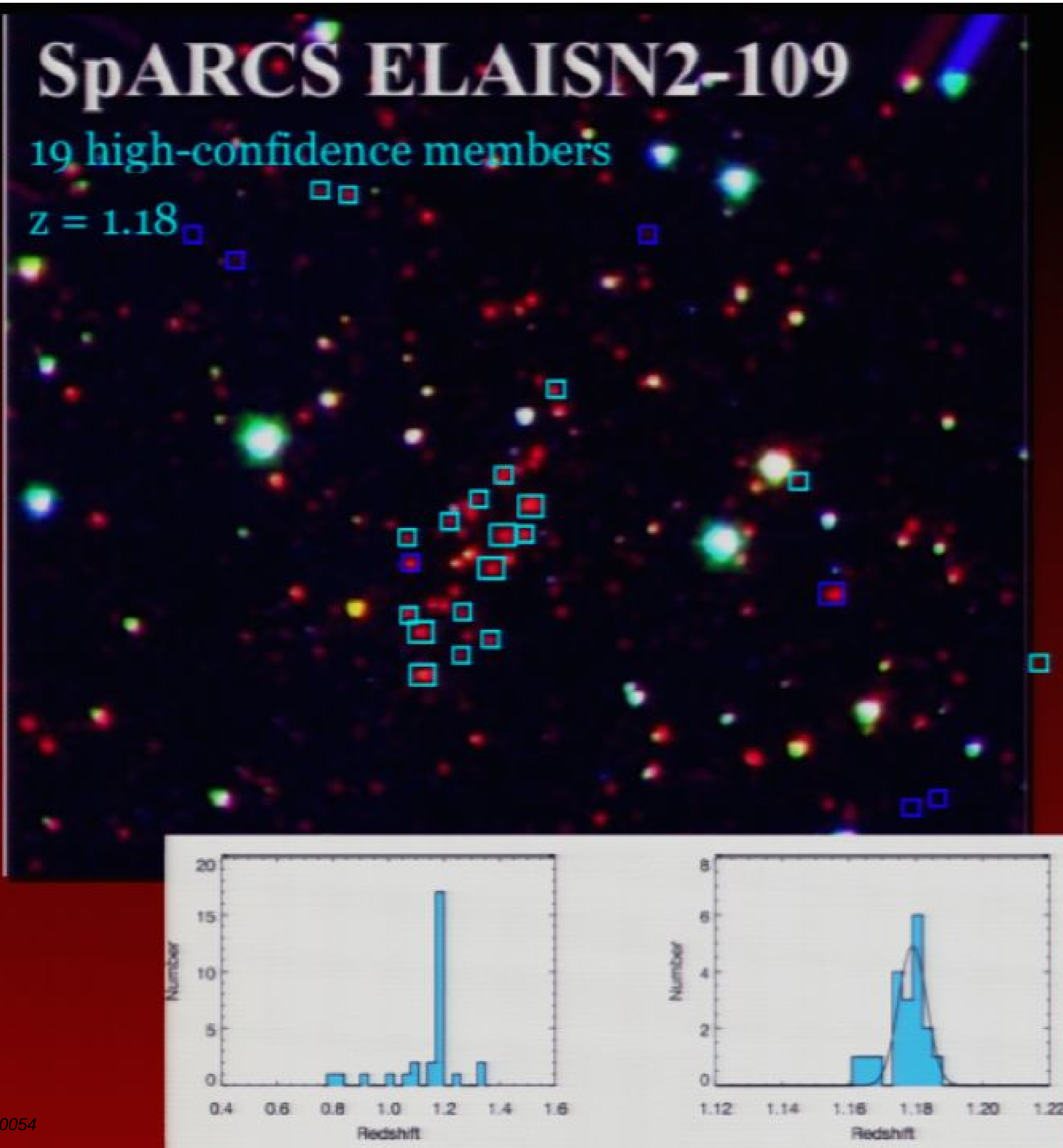

SpARCS ELAISN2-109
zphot = 1.25
IRAC 3.6

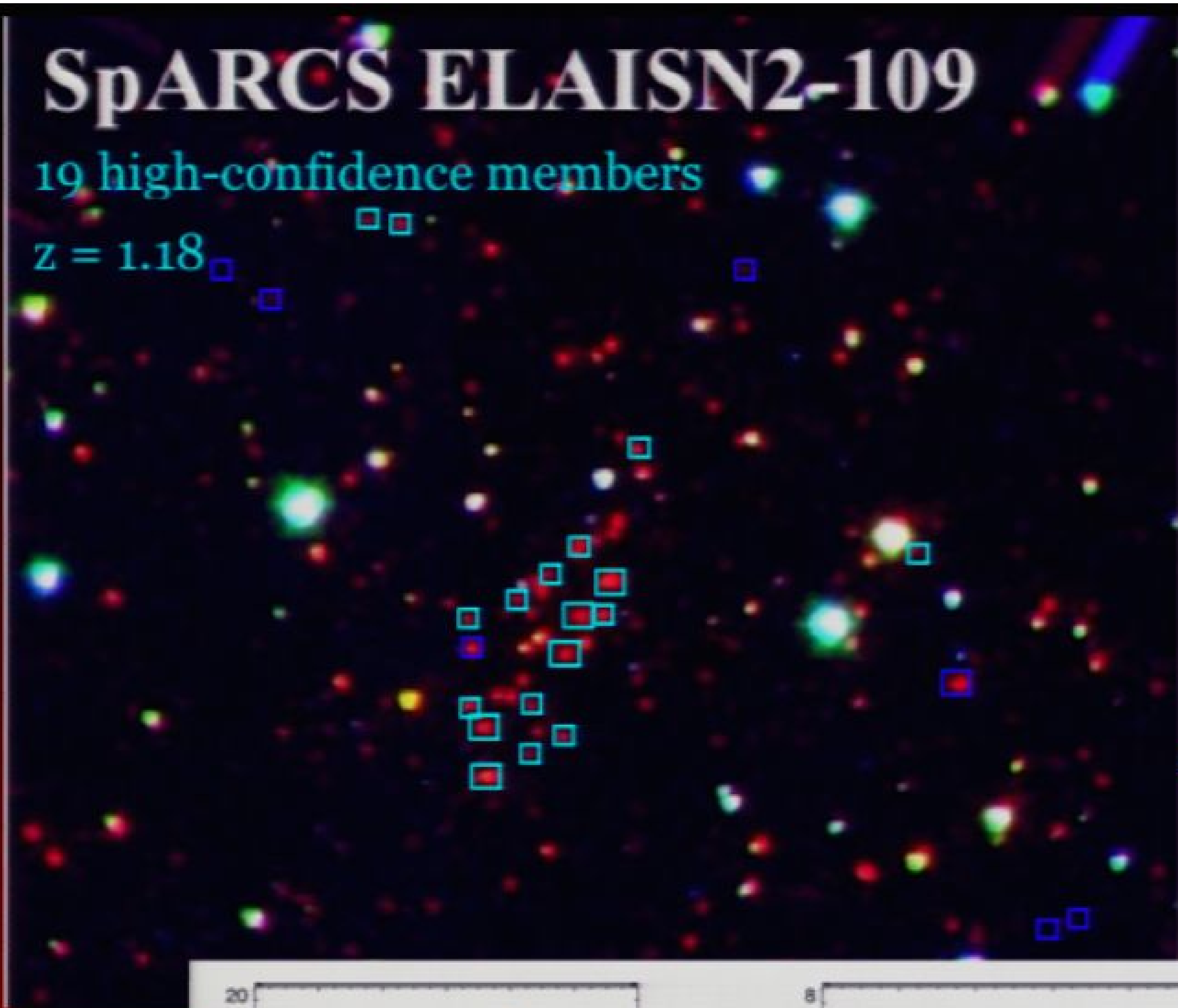


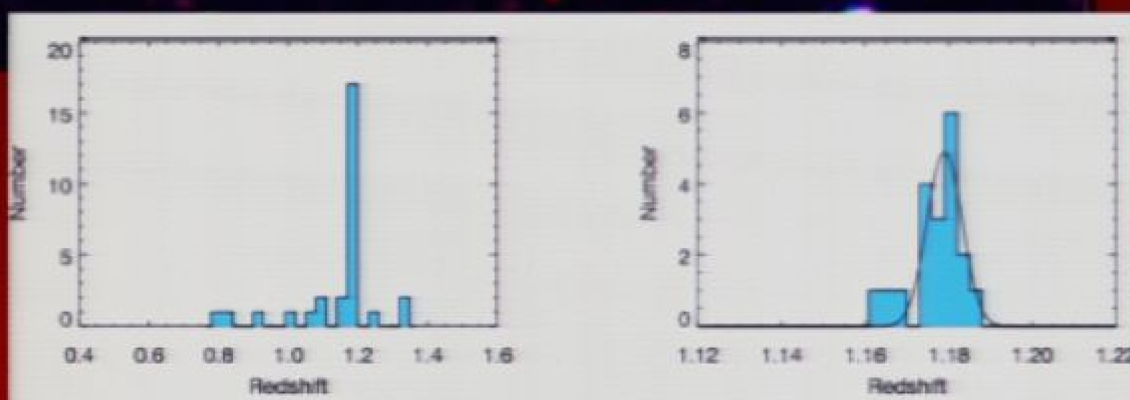
Gemini/GMOS N&S spectroscopy



Gemini/GMOS N&S spectroscopy


SpARCS ELAISN2-109
19 high-confidence members
z = 1.18
Number
Redshift
Number
Redshift

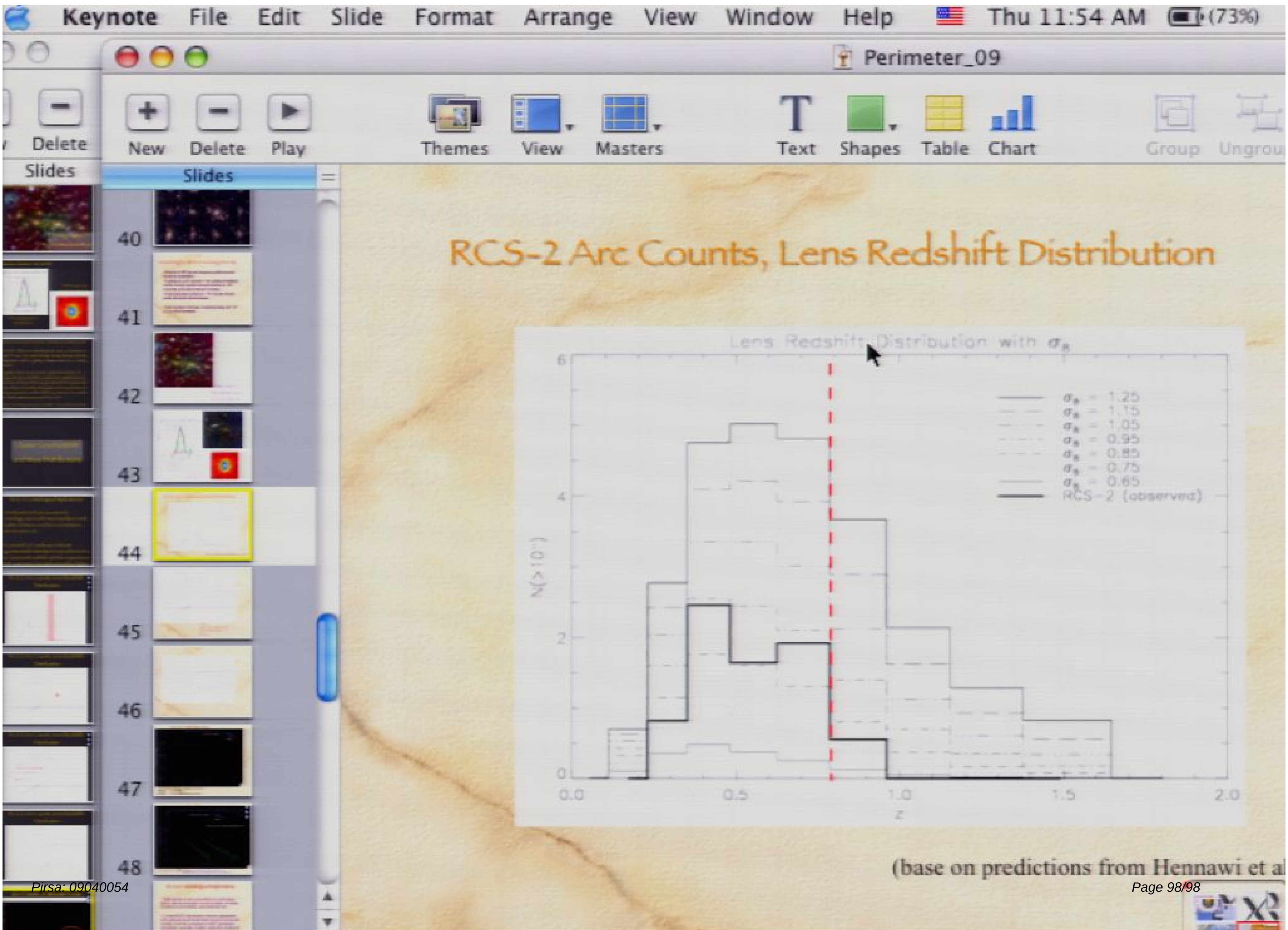




$z = 1.1796$
$\sigma = 700 \pm 200$ km/s

No Signal
VGA-1

[redacted]


Keynote File Edit Slide Format Arrange View Window Help
Thu 11:54 AM (73%)
Perimeter_09
New Delete Play Themes View Masters Text Shapes Table Chart Group
Slides
RCS-2 Arc Counts, Lens Redshift Distribution
Lens Redshift Distribution with σ8
σ8 = 1.25
σ8 = 1.15
σ8 = 1.05
σ8 = 0.95
σ8 = 0.85
σ8 = 0.75
σ8 = 0.65
RCS-2 (observed)
N(>10'')
z
(base on predictions from Hennawi et al