Strong Lensing Clusters in the Red-sequence Cluster Surveys*

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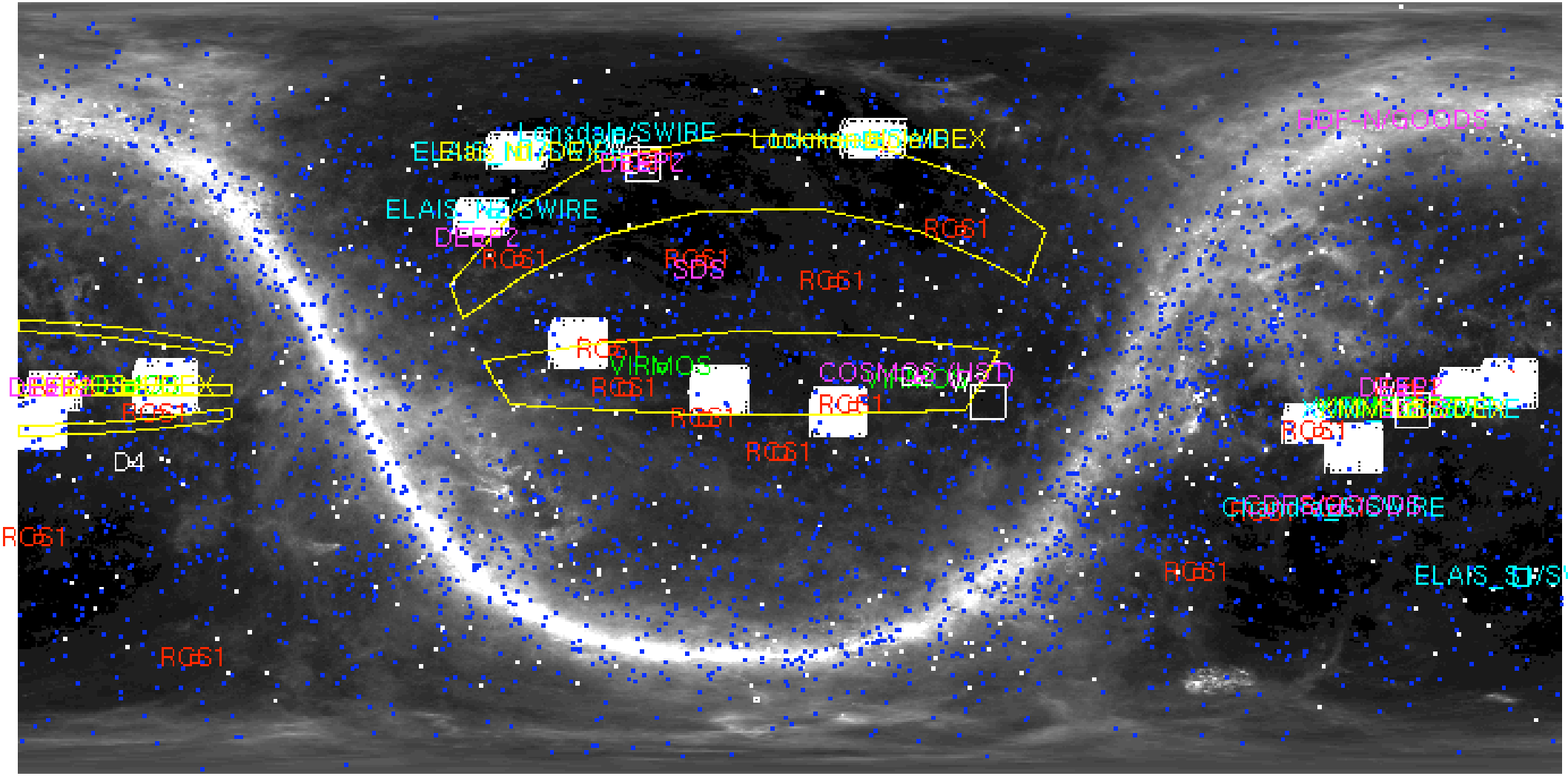
*http://www.rcs2.org

Surveys

- RCS-1 Gladders & Yee, 2005 ApJS, 157, 1
  - completed
  - 92 sq. deg. in R, z' bands (CFH12K, CTIO 4-m MOSAIC) to R~24.8 and z'~23.6
- RCS-2 Yee et al., astro-ph/0701839
  - on-going
  - 830 sq. degs. in g', r', z' with CFHT MegaCam (g~25.3, r~24.8, z~22.5, AB)
    - (+CFHTLS Wide = 1000 sq. deg.)

RCS-2



http://www.rcs2.org

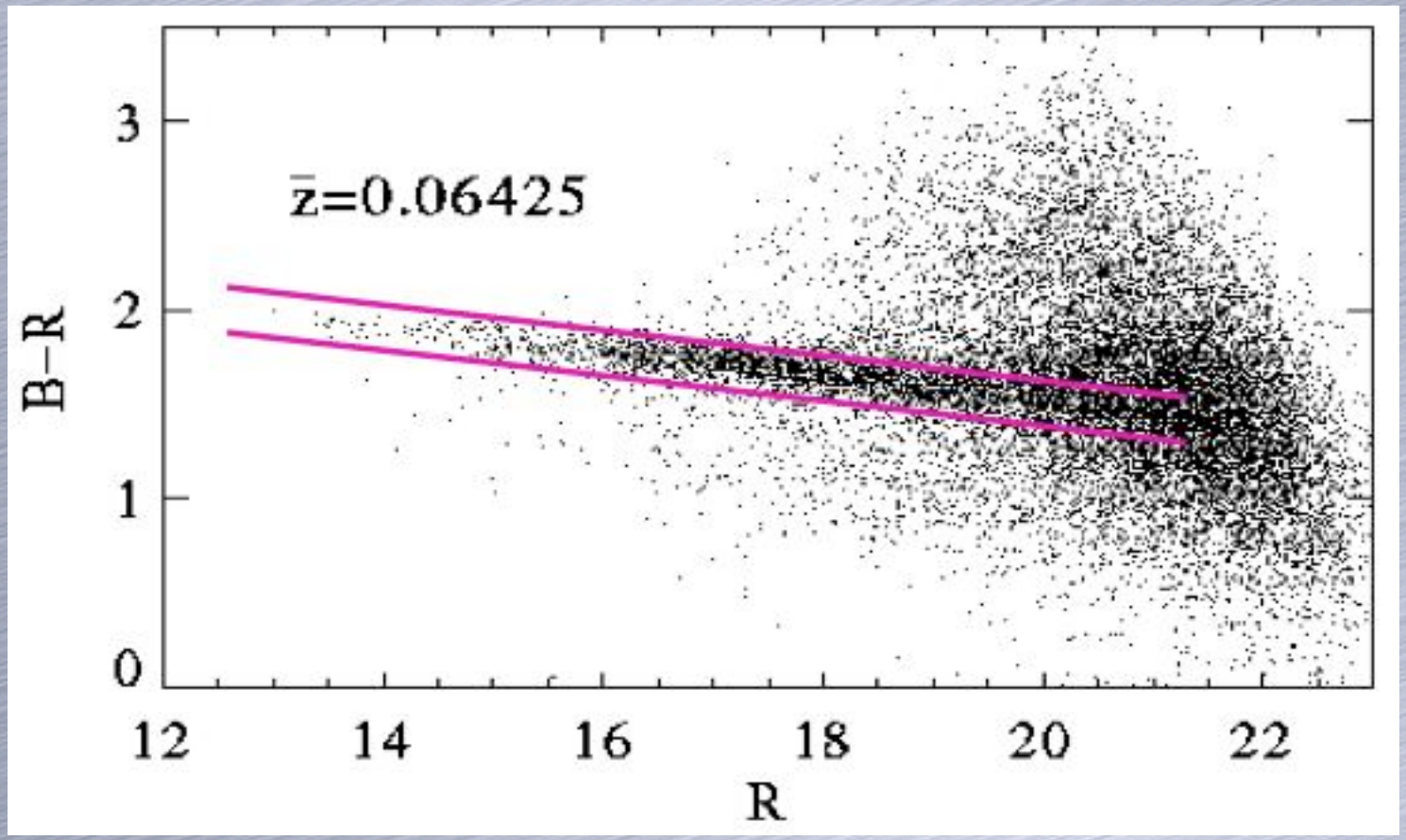
- 676 sq. deg imaged as of last week

Outline

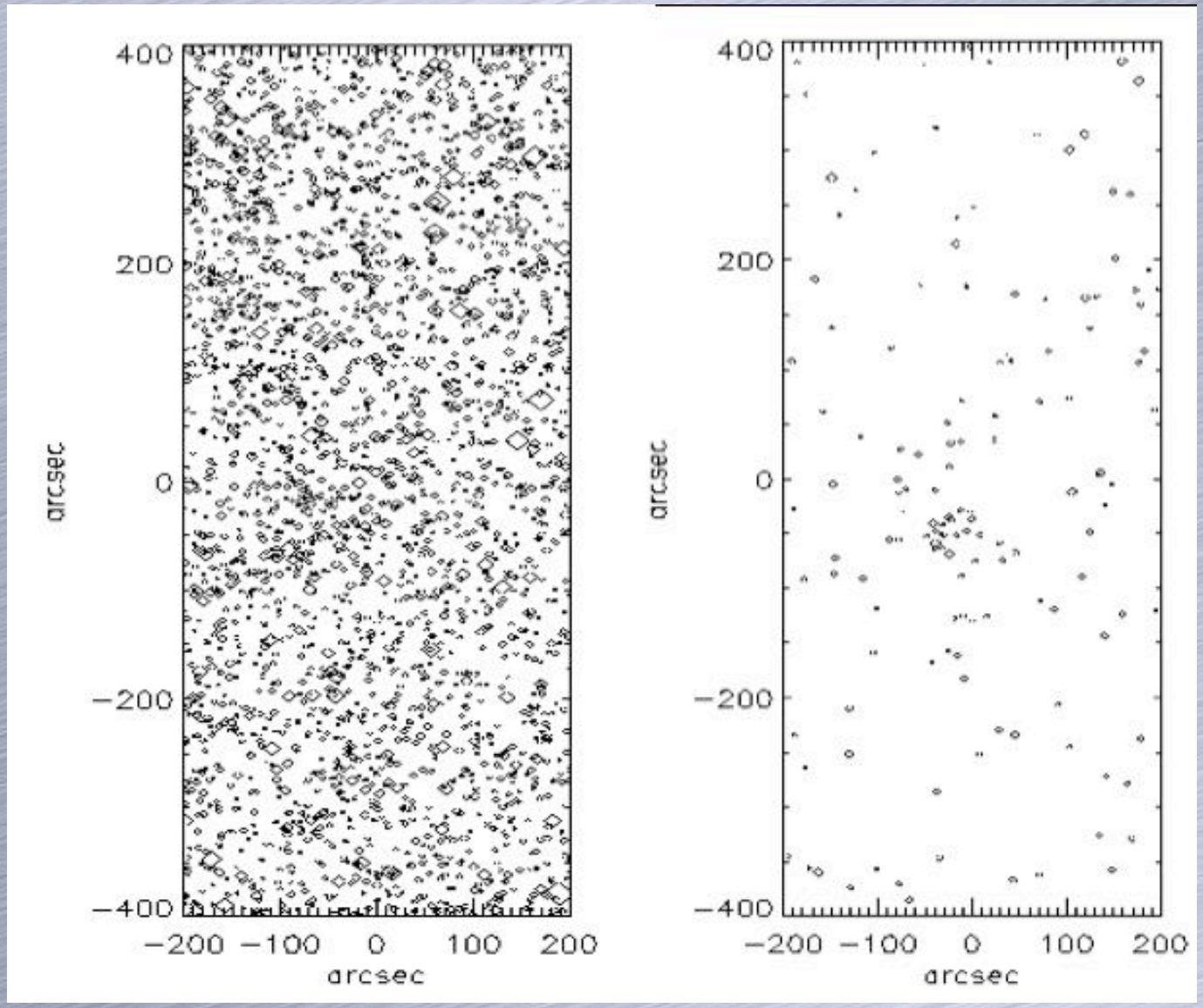
- Red-sequence selection method
  - Cluster finding
  - Arc finding
- Statistical samples
  - Redshift and mass distribution of lenses
- Individual lenses
  - Spectroscopic follow-up

Red-Sequence Cluster Finding

Gladders & Yee, 2000, AJ 120, 2148

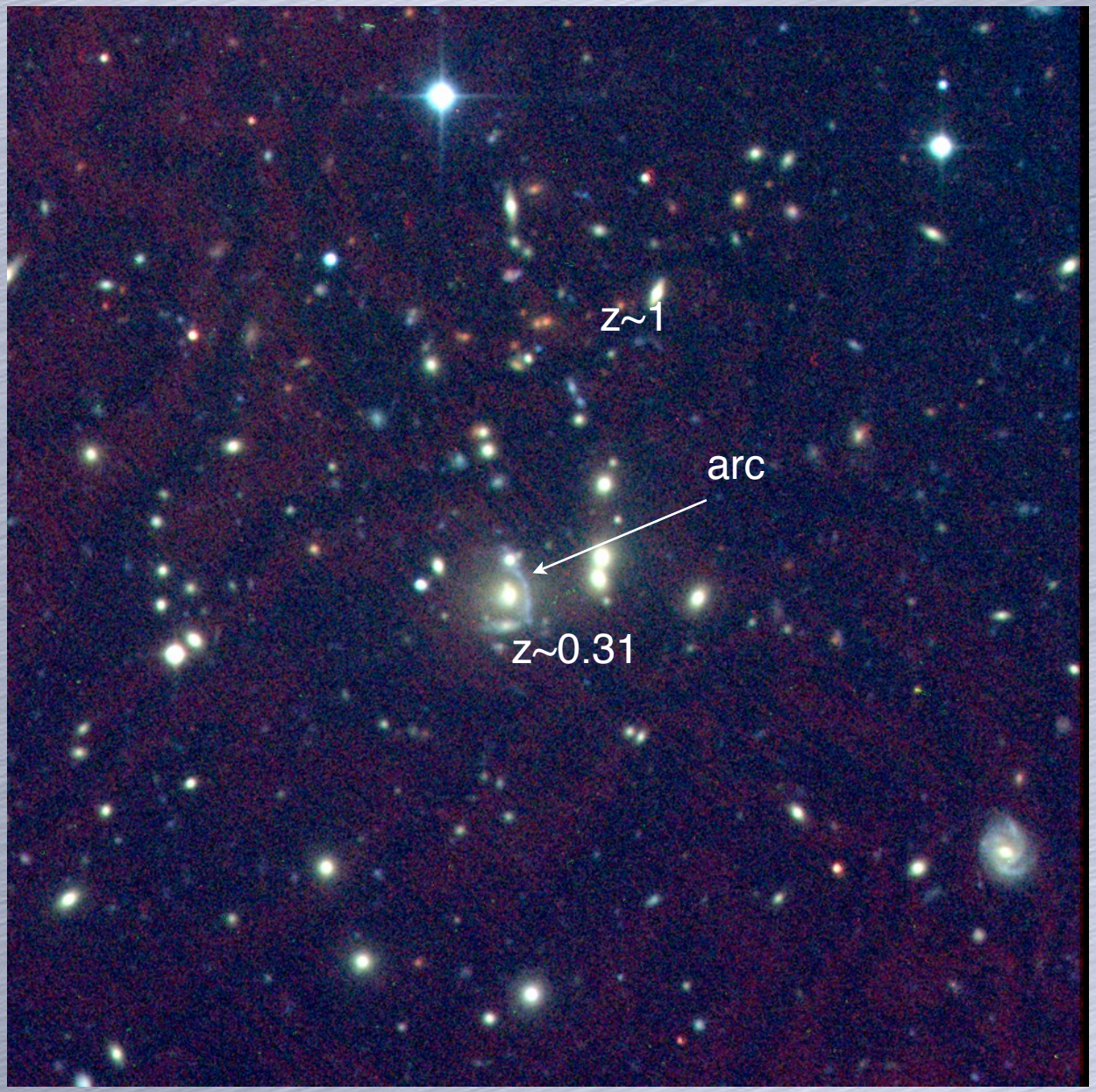


Red-Sequence Cluster Finding

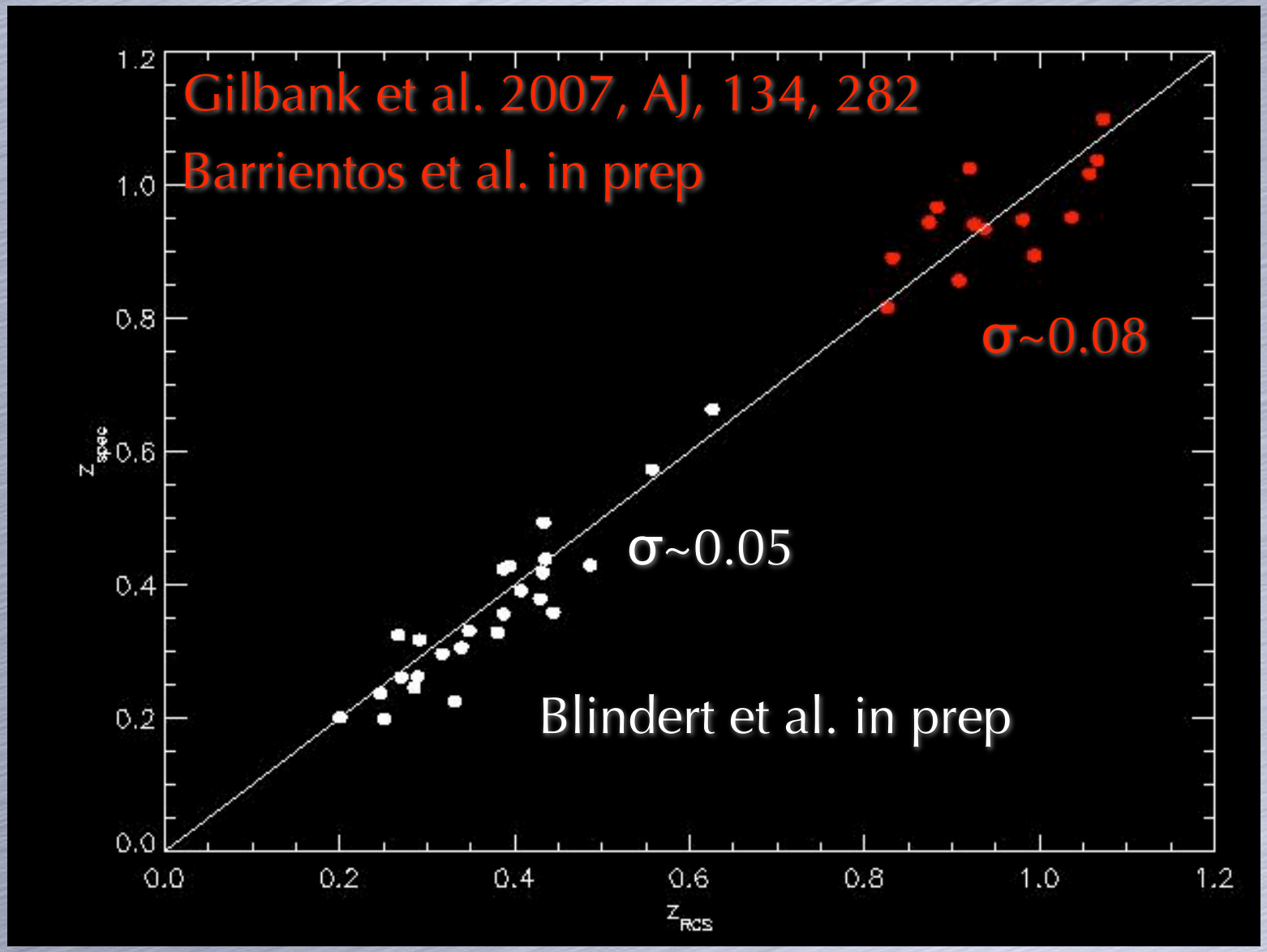


Magnitude limited

Magnitude limited with colour cuts


z~1
arc
z~0.31

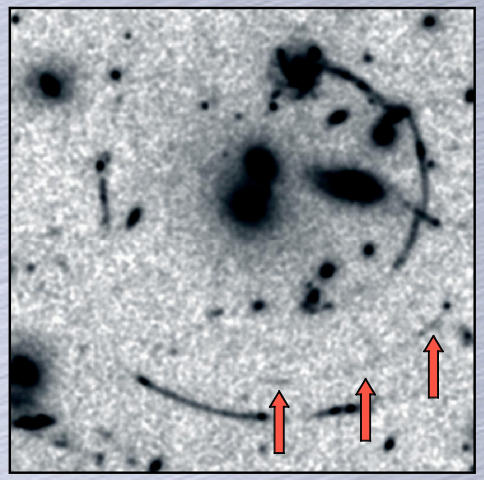
z_{RCS} VS z_{spec}



Statistics of lenses

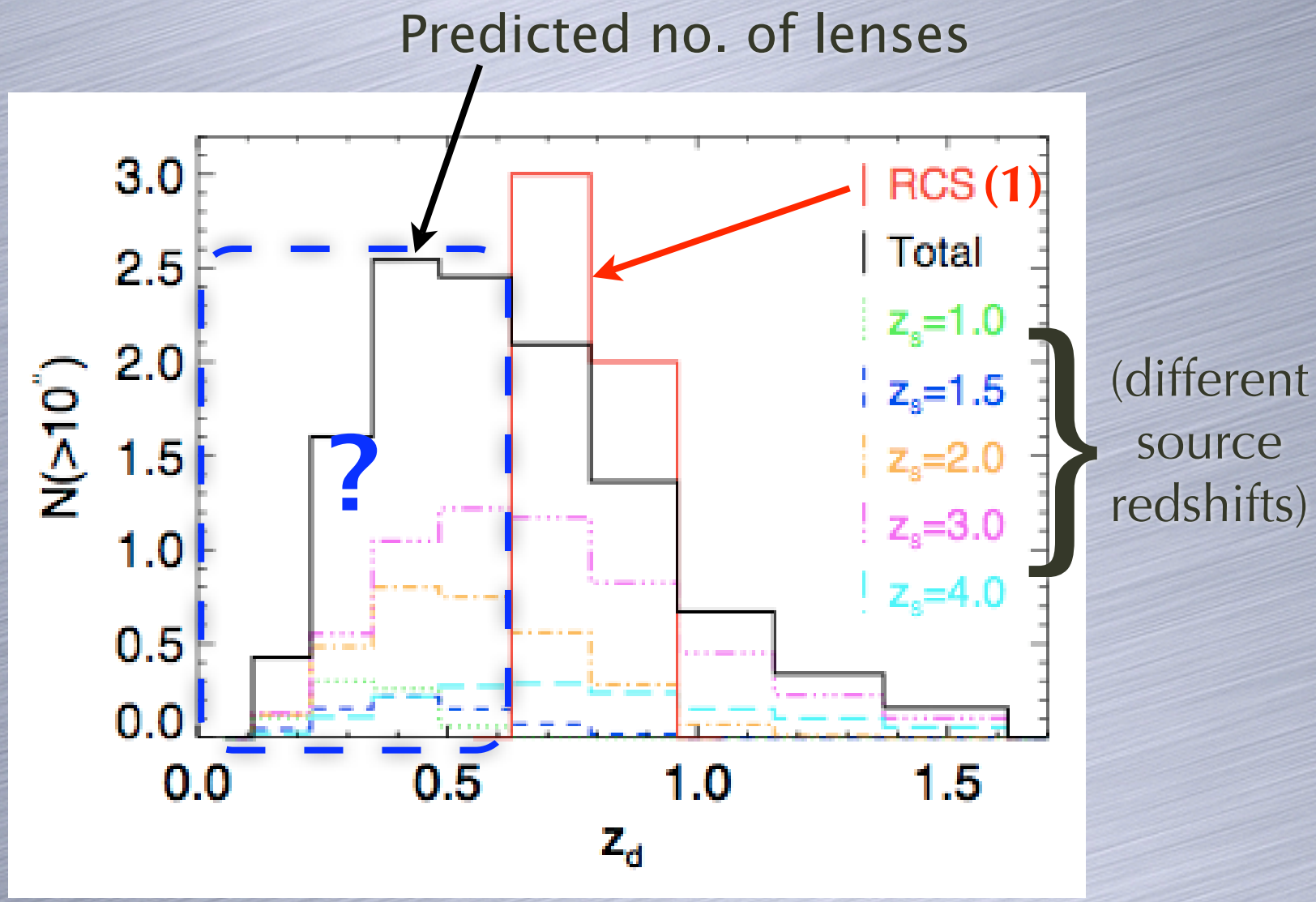
- Compare observations of statistical samples with ray-tracing through cosmological simulations, e.g.
  - Bartelmann et al. 1998,
  - Wabsganss et al. 2004,
  - Dalal et al. 2004,
  - Ho & White 2005,
  - .....

- Gladders et al. (2003) presented a sample of 5 (8) strong lenses from RCS-1 (~90 deg^2), μ_R<24 mag $arcsec^{-2}$
- Arcs found by visual inspection of cluster candidates in *R* images



HST image of a strong lensing cluster at z=0.77 discovered in RCS1. Multiple bright arcs are clearly seen. Arrows indicate a lensed z=4.88 galaxy (Gladders, Yee & Ellingson, 2002)

RCS-1 sample (5 lenses)



Hennawi et al. 2007

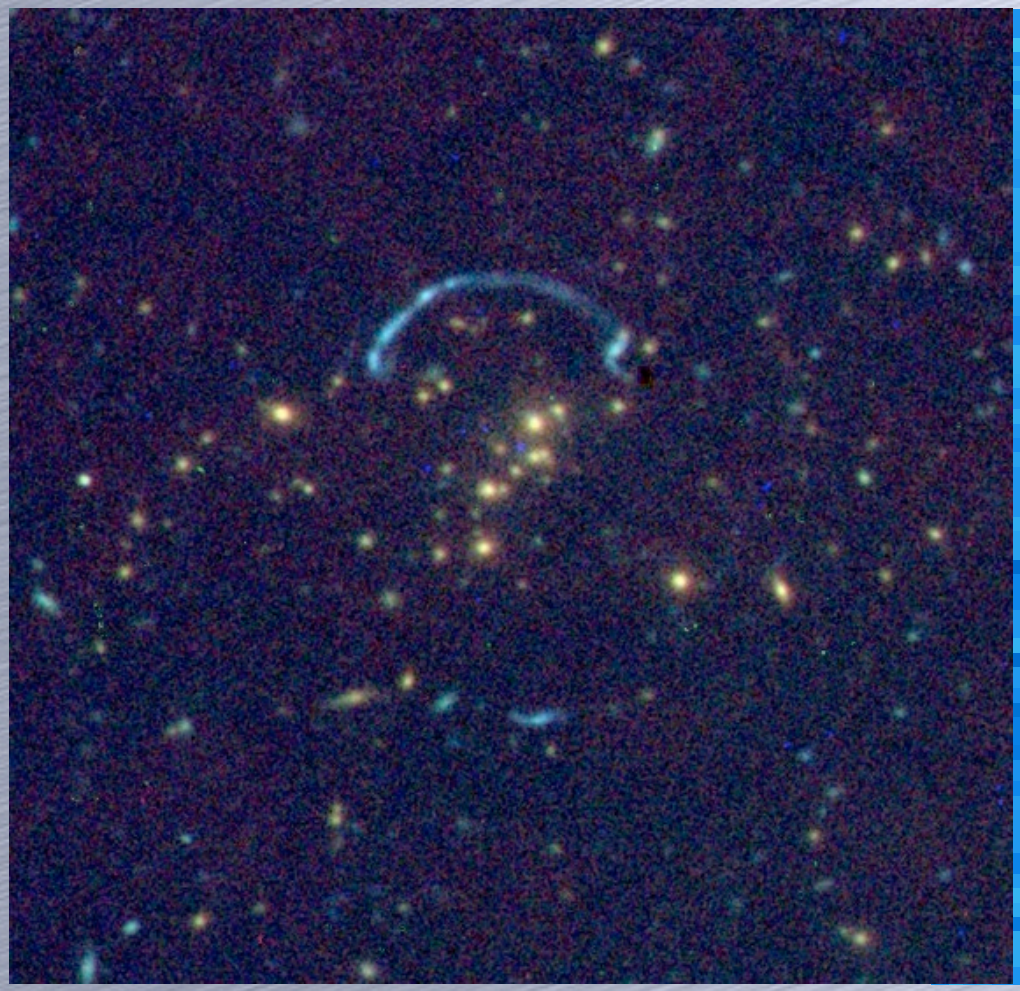
RCS-2

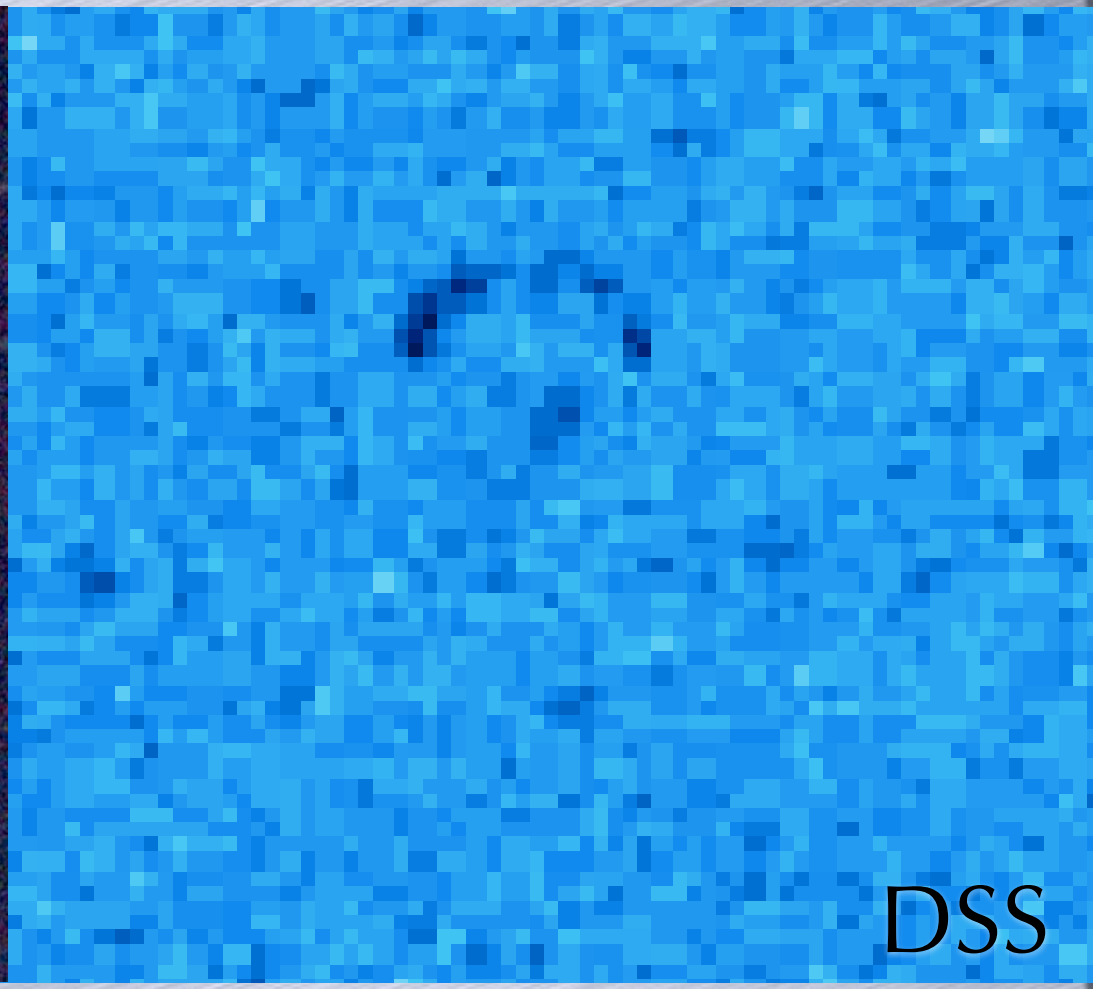
- 1000 deg^2 imaging survey in *g′*, *r′*, *z′*
- Relatively shallow! 4 mins, 8 mins, 6 mins on 4-m class telescope, but good seeing: ~0.6-0.8”
- Expect ~50-100 *high surface brightness*, strongly lensed arcs in full survey
- **Found 71 giant arcs in first 393 deg^2!**

RCS-2 Lens selection

- Most significant (>3.5σ) cluster candidates 0.1< z_{RCS} <0.9 visually inspected for arcs
  - ~6500 clusters from 393 sq. degs
  - Subsample of the ~20 000 lower significance (3.0-3.5σ) clusters visually inspected and no compelling arcs found
- Visual inspection performed independently and cross-checked

Example Strong Lensing Clusters



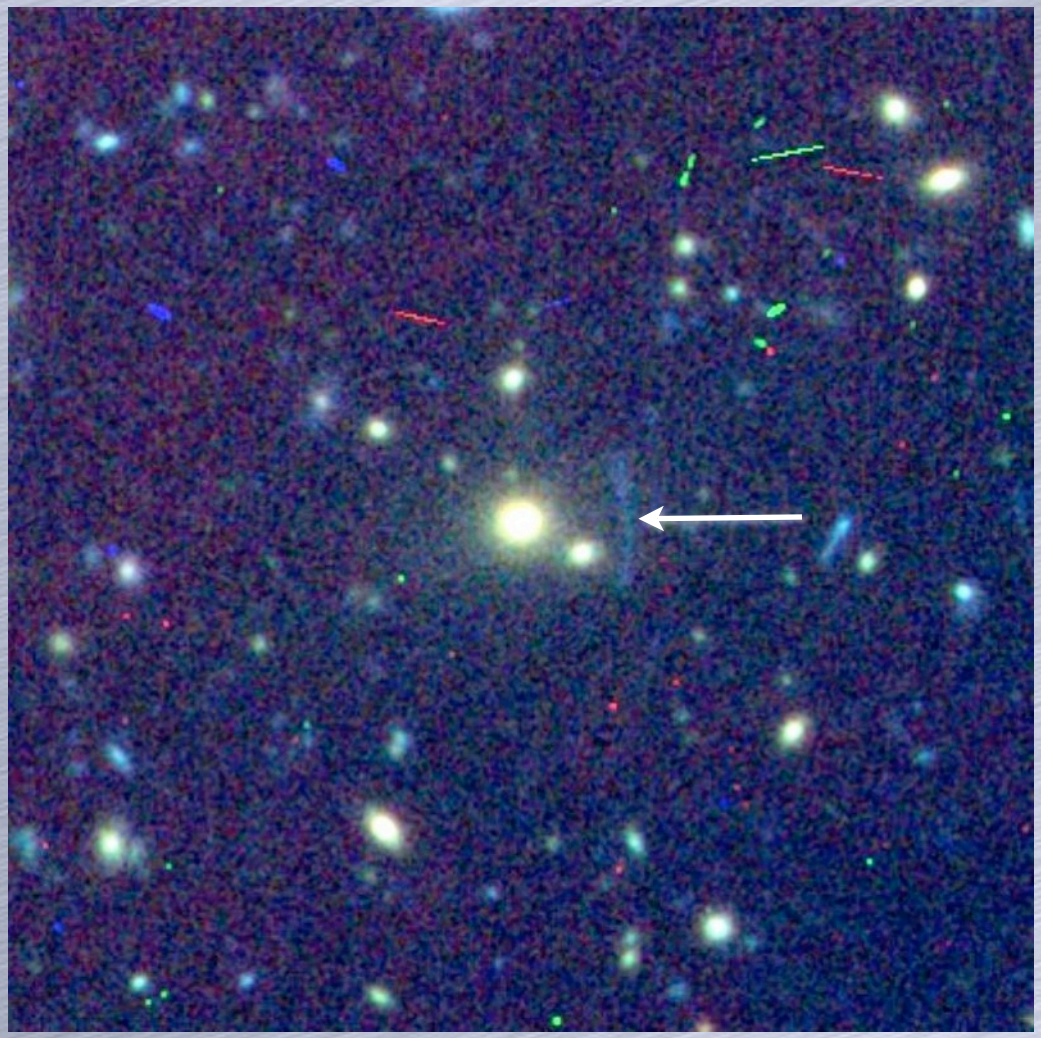


lensing cluster at z_{est}=0.59 with giant arc

Image from the RCS-2 *g′*, *r′*, *z′* survey data

More examples... giant arcs

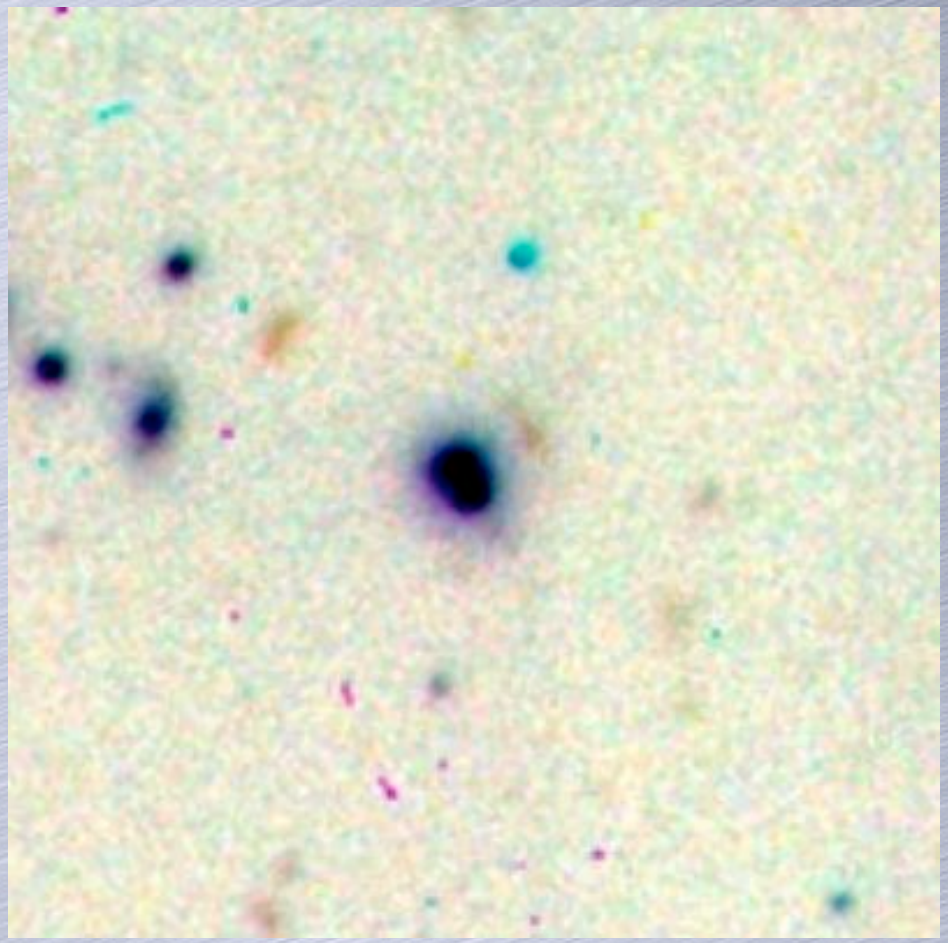
More examples... giant arcs



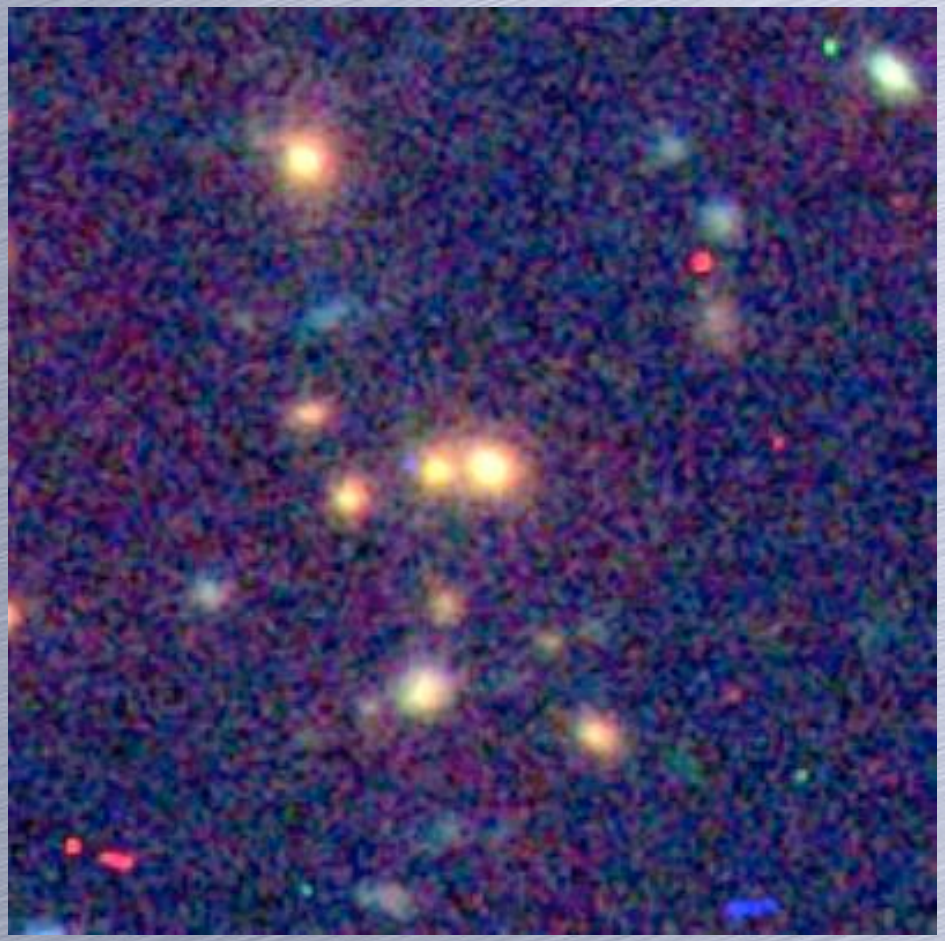
More examples... giant arcs

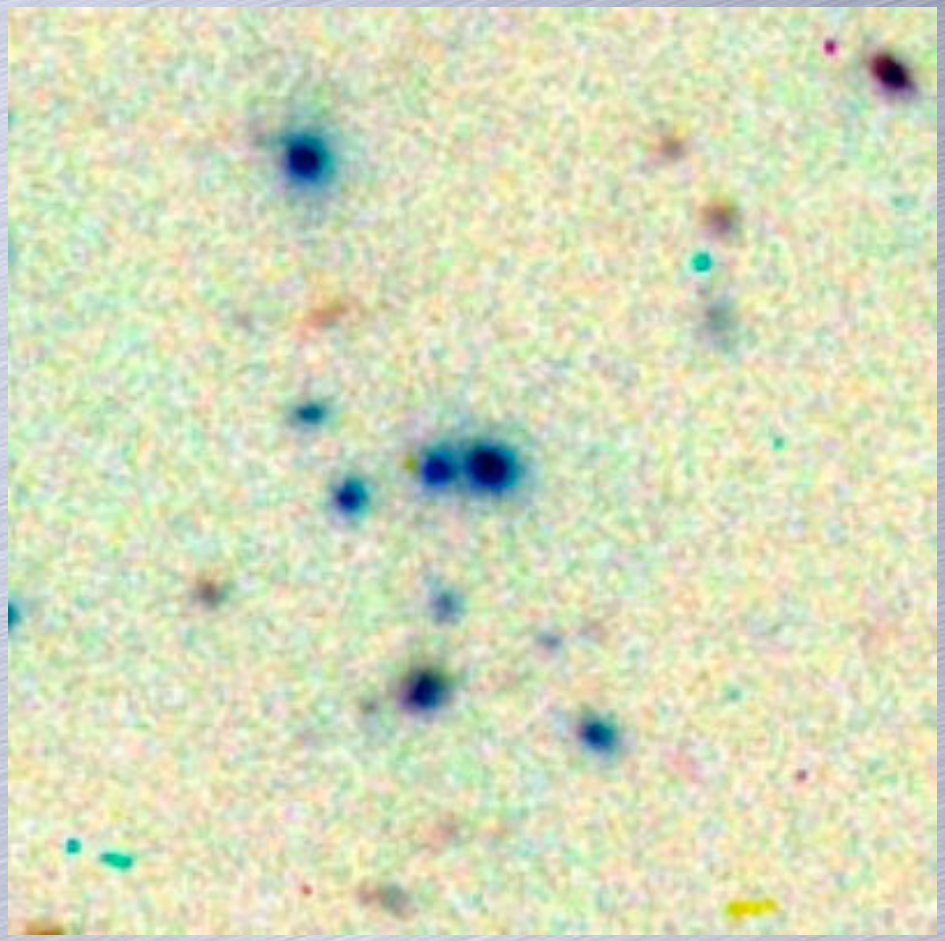
More examples... giant arcs

More examples... arclets

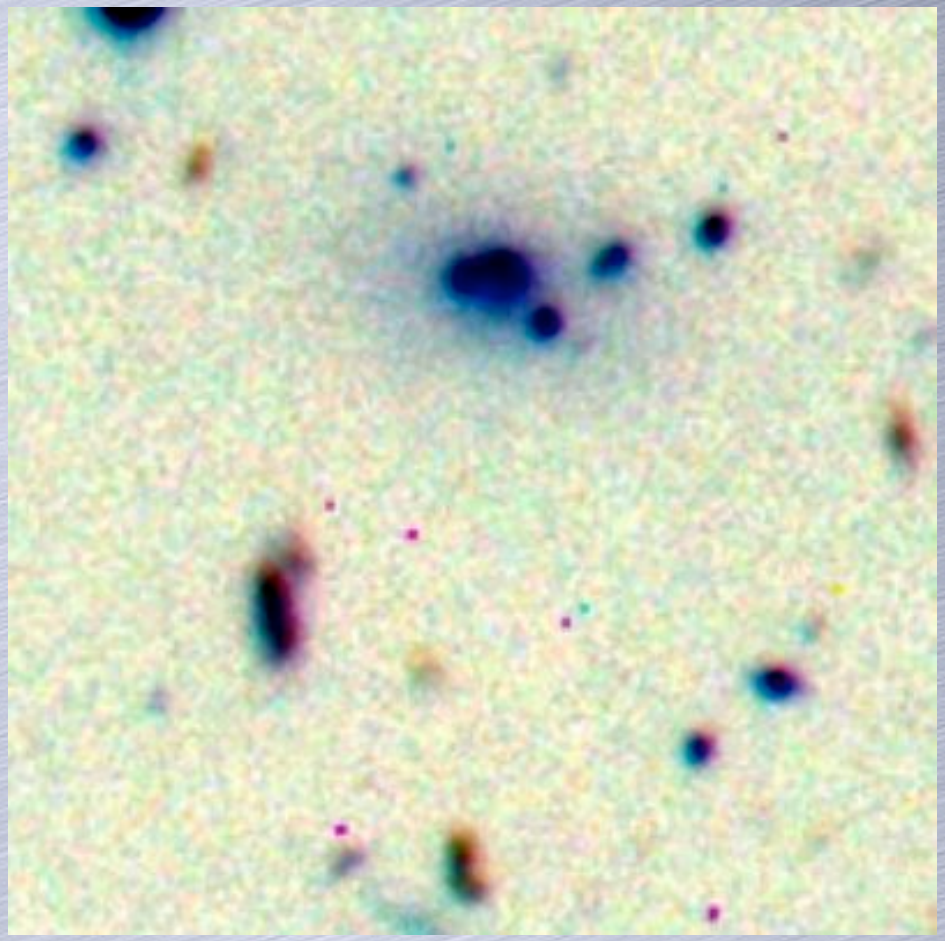


More examples... arclets

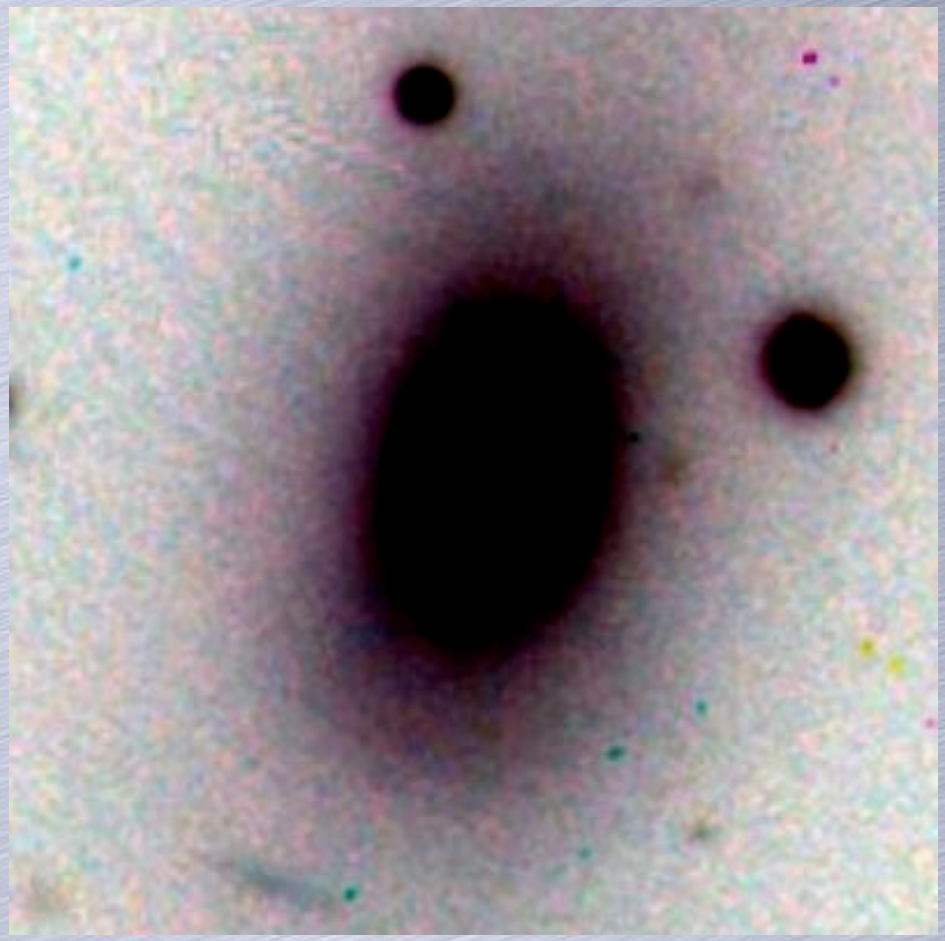




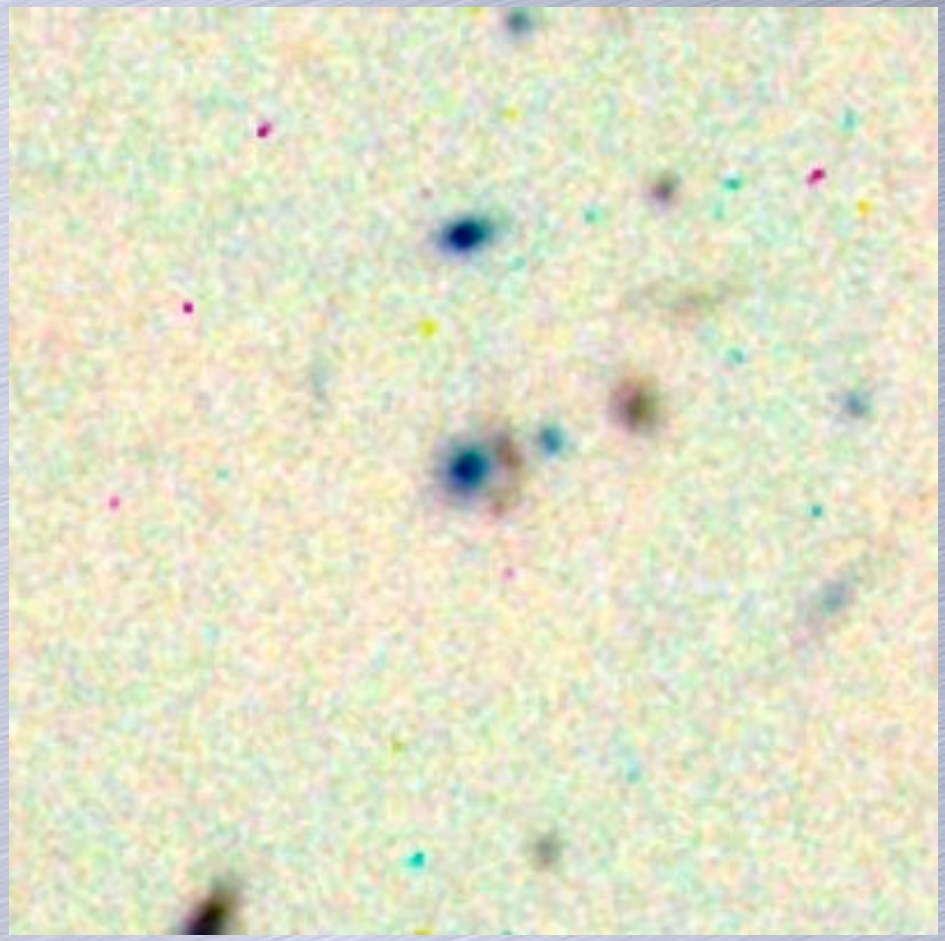
More examples... arclets



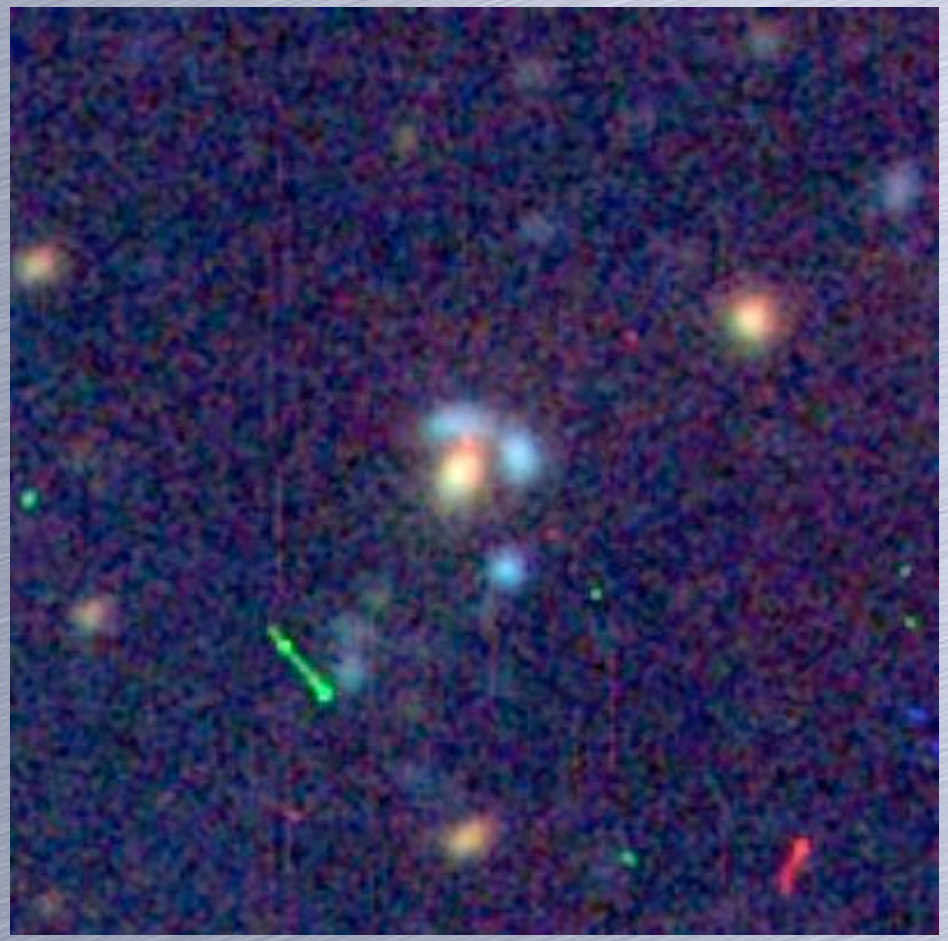
More examples... arclets

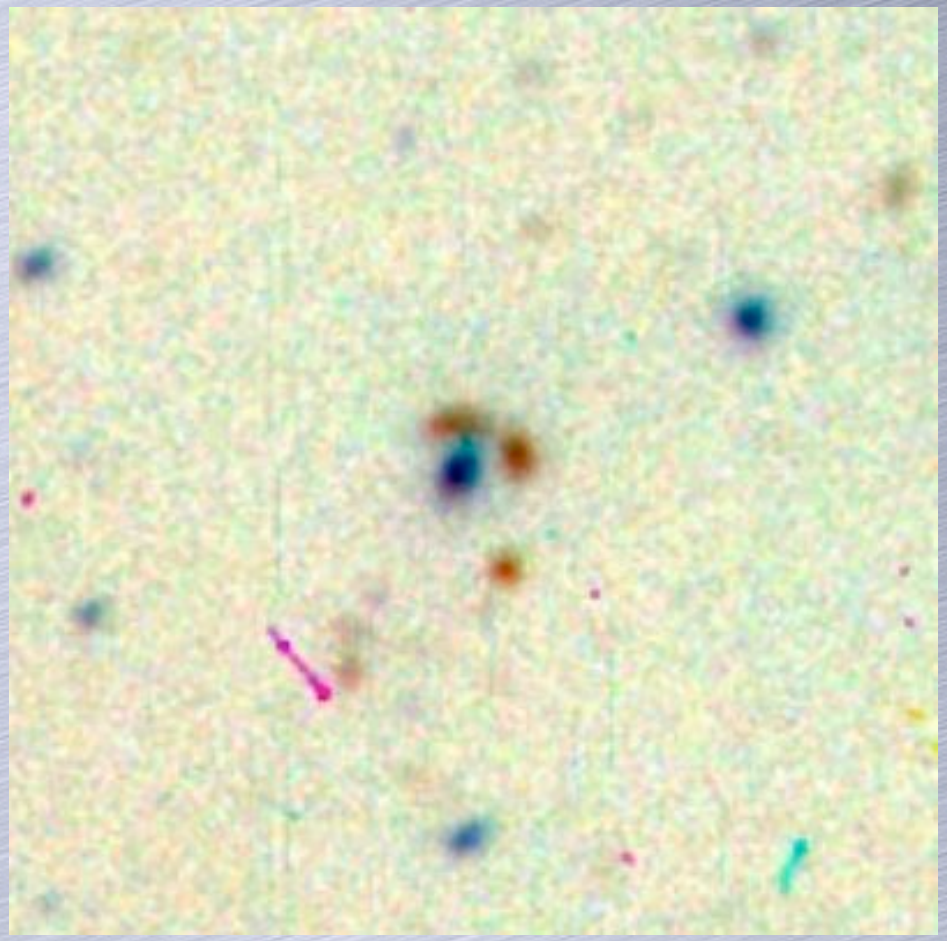


More examples...
lensing by individual cluster galaxies?

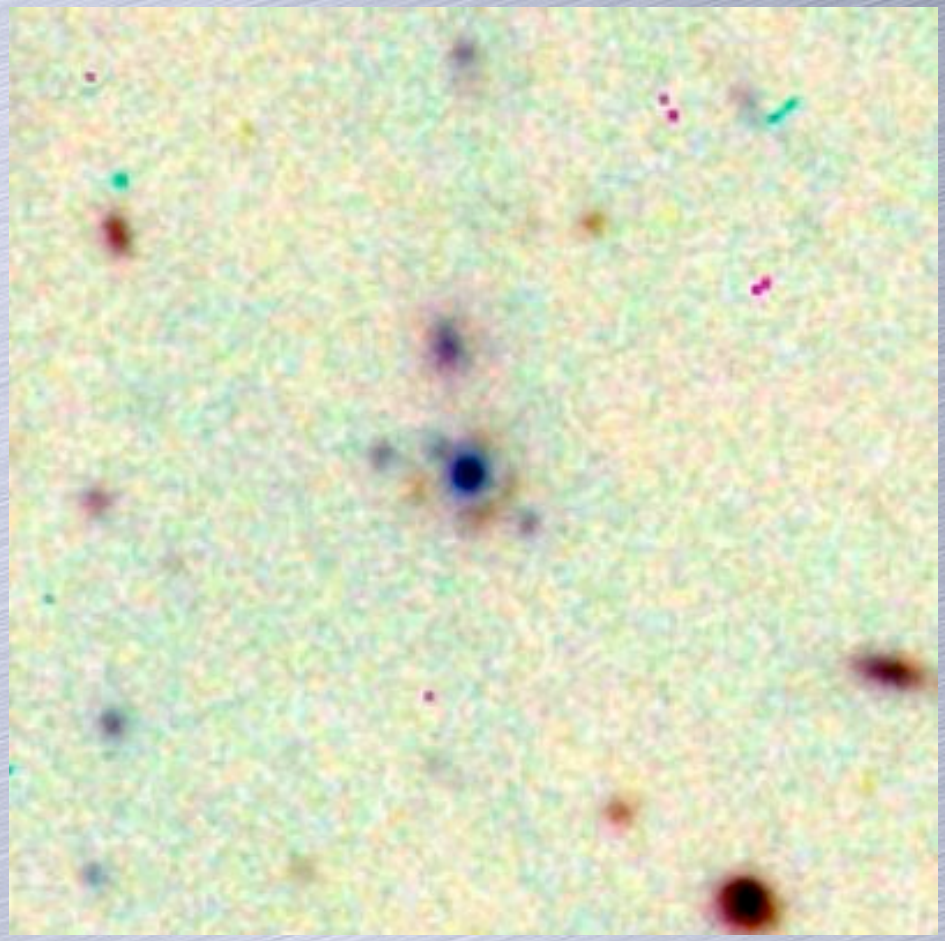


More examples...
lensing by individual cluster galaxies?

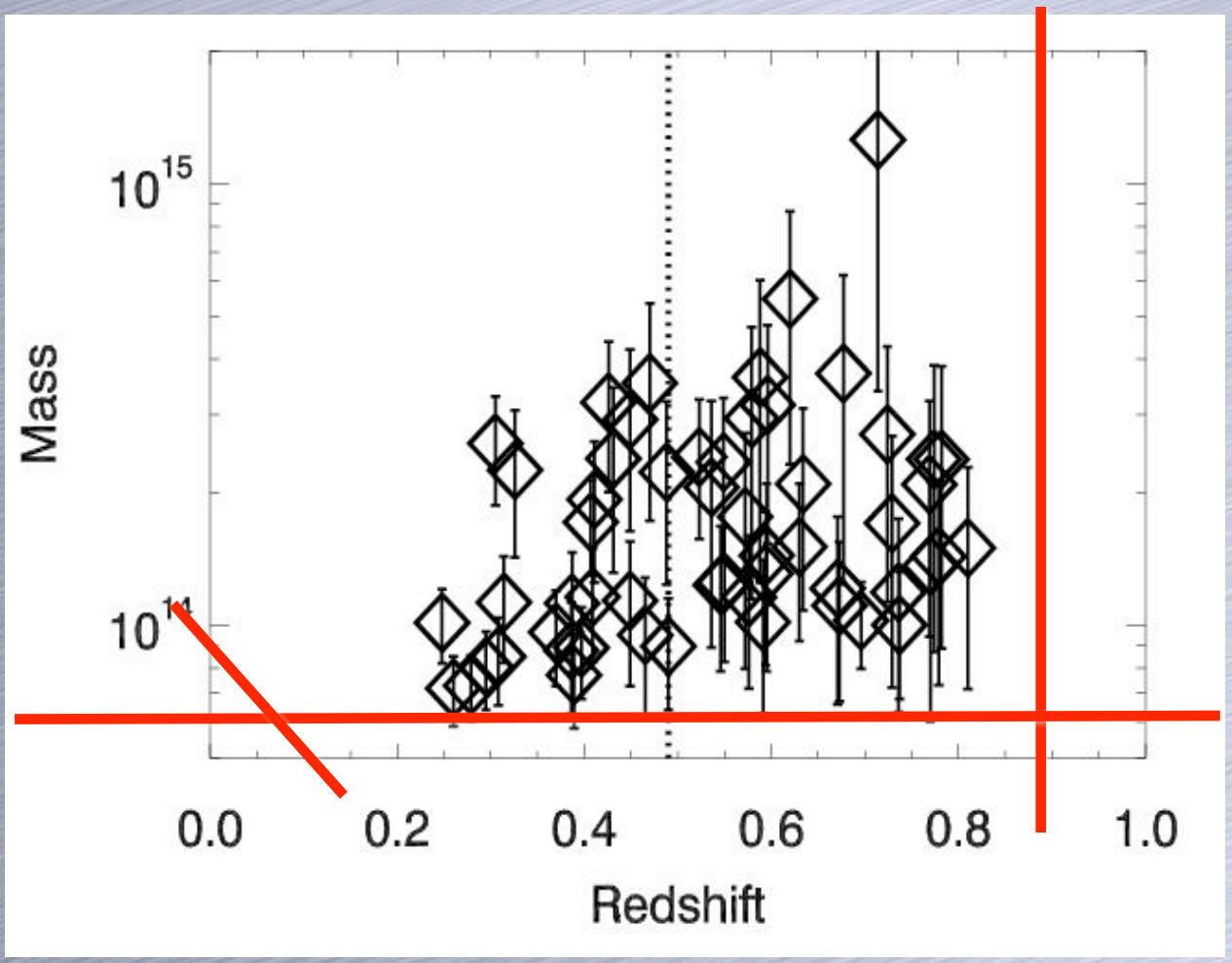




More examples...
lensing by individual cluster galaxies?

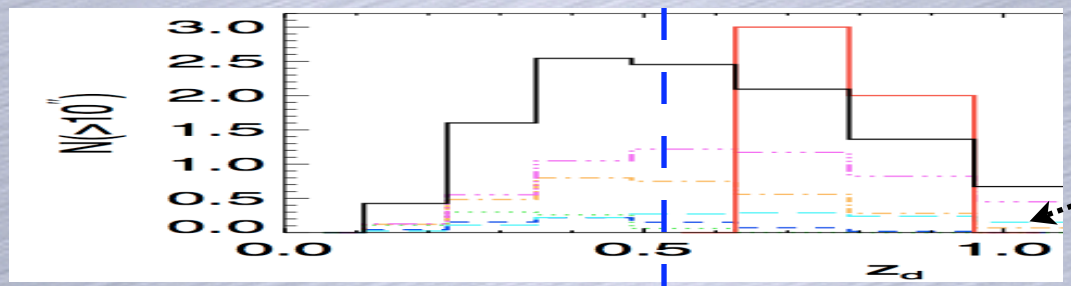


RCS-2 vs Model Predictions



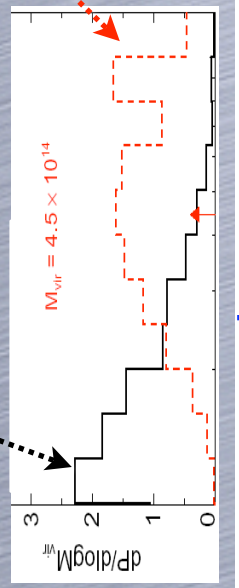
Mass calculated by assuming fitted circular radii equal to Einstein Radii for a SIS profile for all cluster lenses, and averaging over a random distribution of source redshifts.

RCS-2 vs Model Predictions

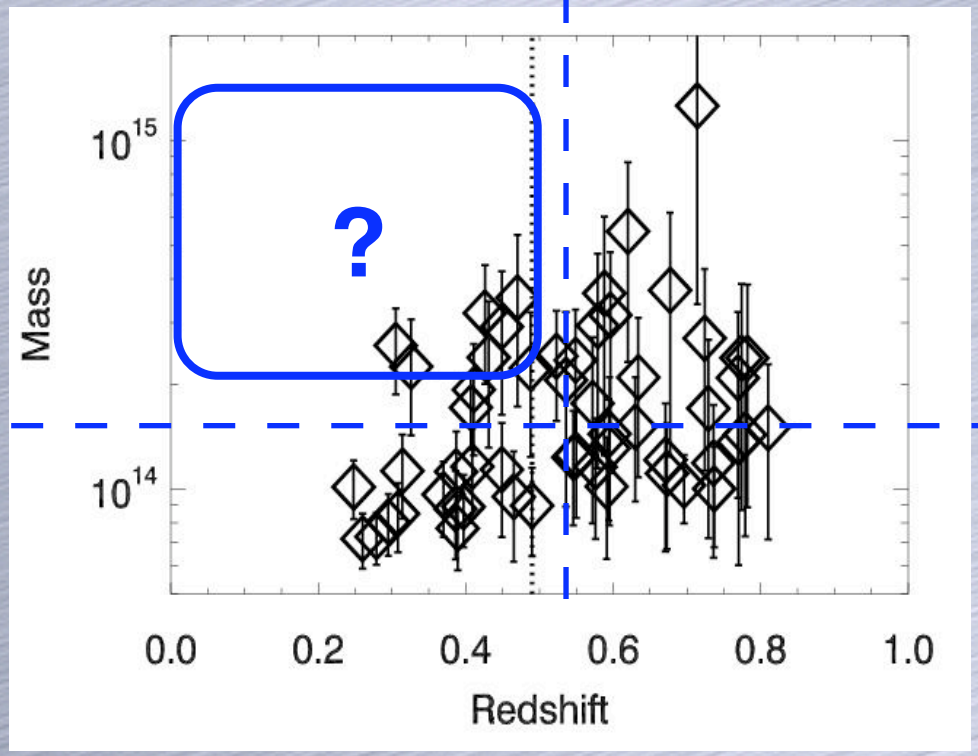


Hennawi et al. 2007 (RCS-1) prediction

lensing probability



mass function



Hennawi et al. 2007 (RCS-1) prediction

Numerical simulations predict high mass, low z, strong lensing clusters which we don't see!

RCS2 Lens statistics

Median azimuthal angle covered by giant arcs is 0.459 radians (or ~ 26 degrees, range is 10-60 degrees)

So our "giant arcs" are, in fact, reasonably giant

Median redshift = 0.549

Hennawi et al 2007 predict a median redshift of 0.49 for RCS-1 cluster lenses using simulations

Hennawi prediction is biased **high** for RCS-2 comparison: high σ_8 (0.95), deeper SB limit and redder filter

Hilbert et al (astro-ph/070380): low-z, high mass population of lenses predicted.

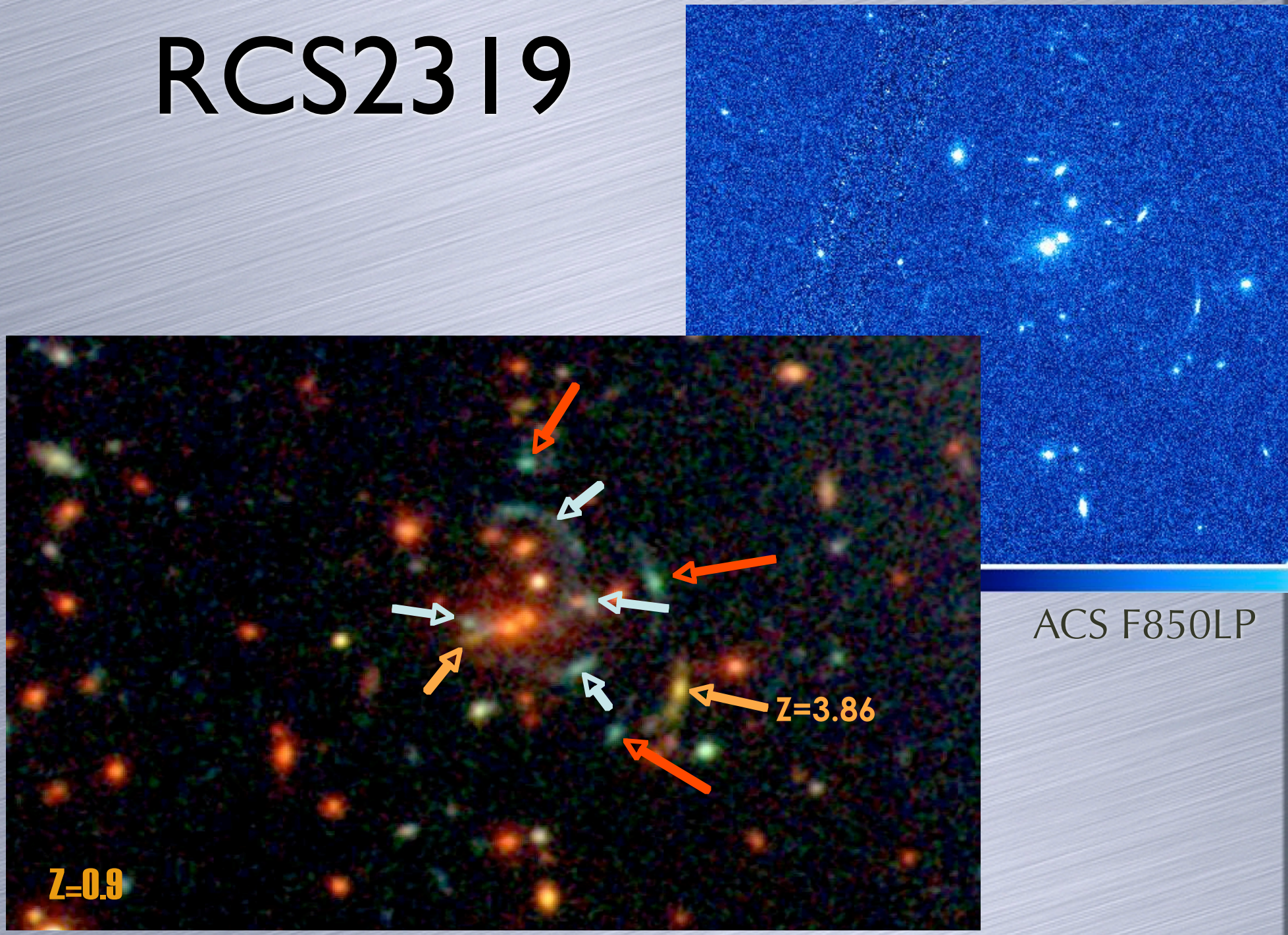
Results

- We see a large proportion of clusters displaying multiple arcs. The distribution of lensing cross-sections includes a small population with large cross-sections which dominate the lensing statistics. Recent modelling papers imply this is due to triaxiality and orientation effects (e.g. Ho & White 2004).
- The redshift distribution of lenses is skewed to high-z. This implies that mass alone is not responsible for promoting clusters as good lenses: something associated with cluster assembly enhances cross-sections and/or an effect at low-z reduces cross-sections.
- Clusters with arcs are not obviously the most massive systems. The expectation from modelling is a strong preference for the most massive systems to form the bulk of all arcs.

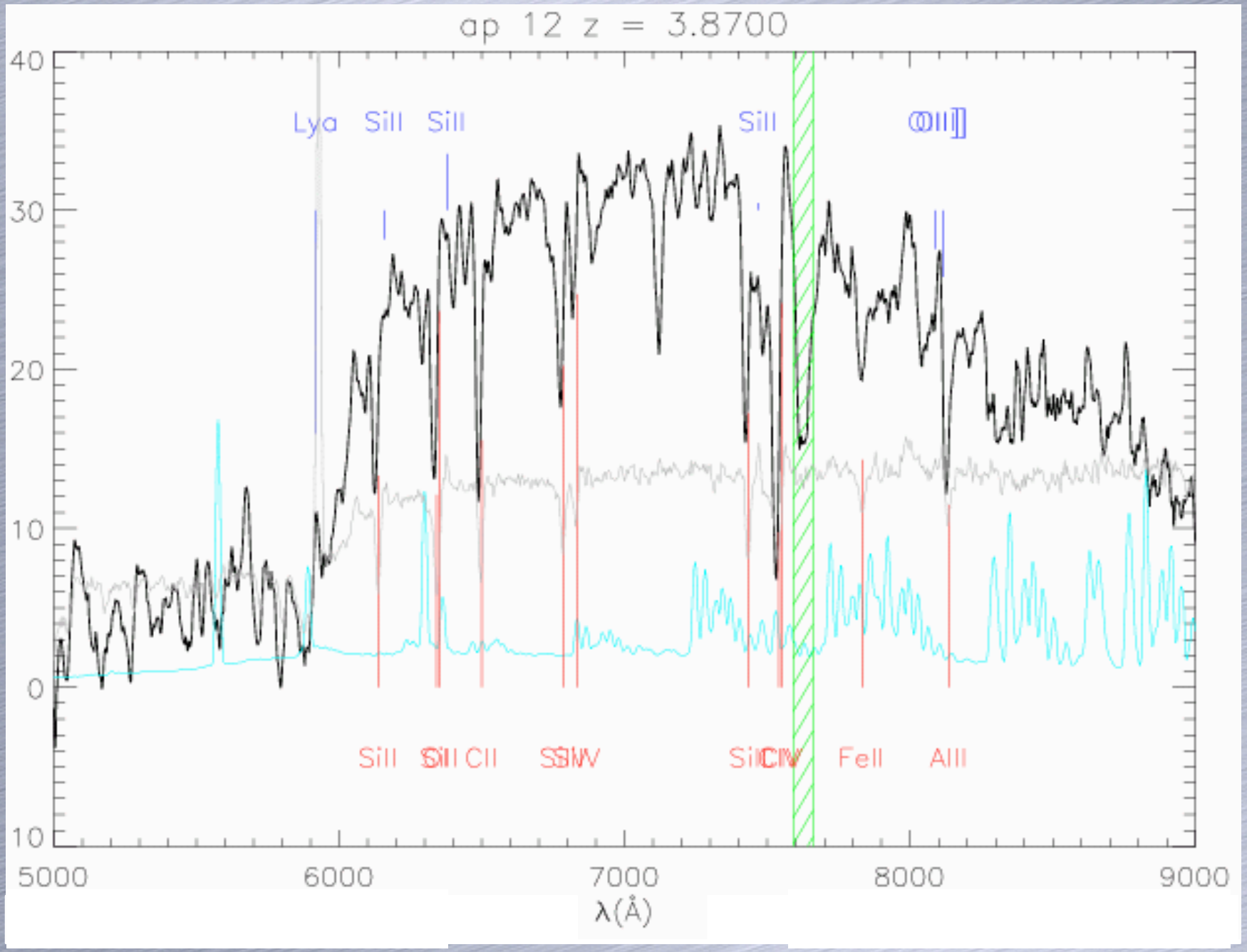
Spectroscopic follow-up of arcs

- Spectroscopic redshifts for only a few arcs around RCS clusters
  - RCS0224 (Gladders, Yee & Ellingson 2002)
  - RCS2319 (this talk)
  - +2 arcs from impressive RCS-2 clusters
- Beginning pilot programme on VLT for sample of RCS-2 clusters
  - 5 clusters

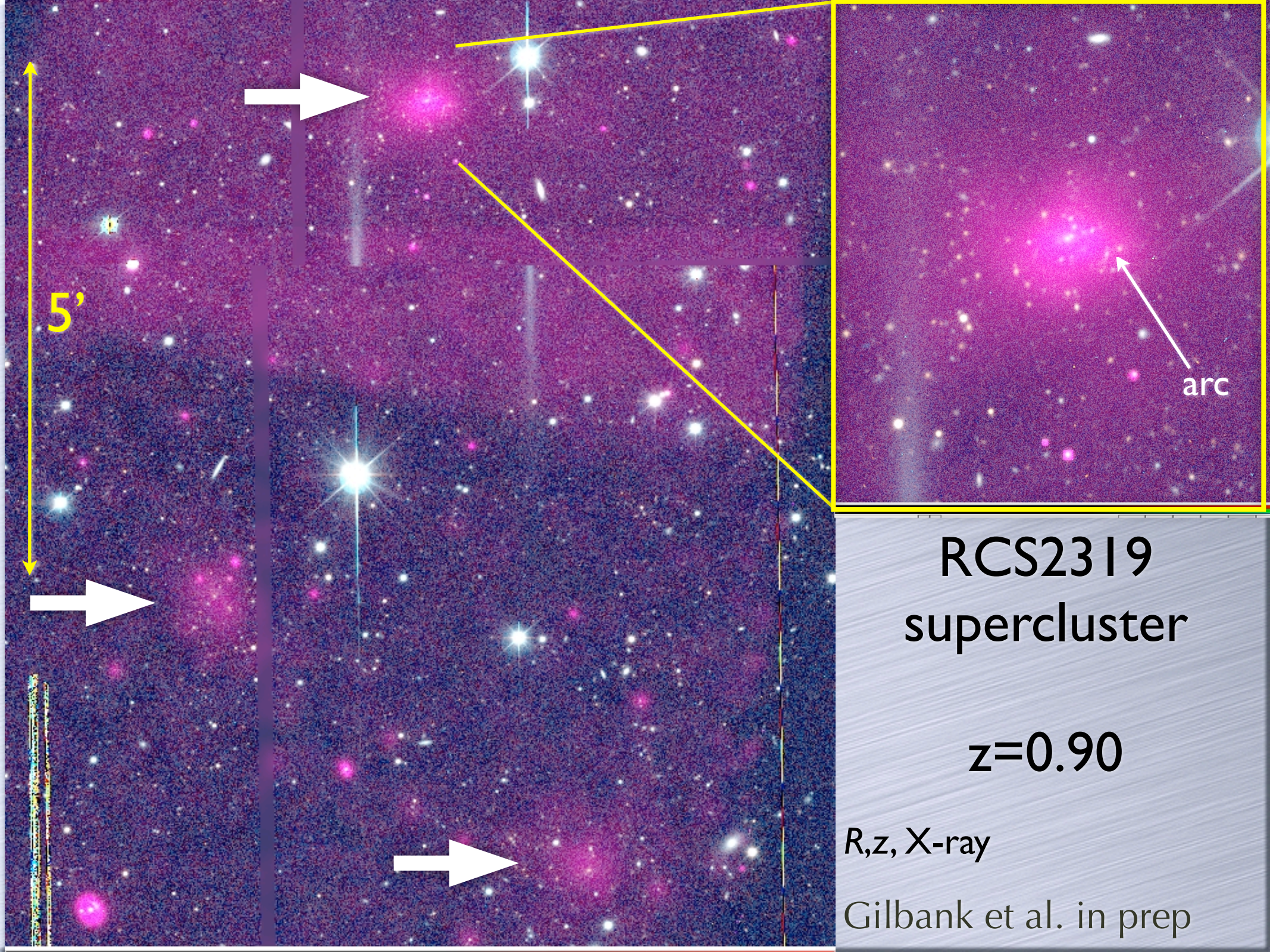
RCS2319



ACS F850LP



9 hours GMOS N&S



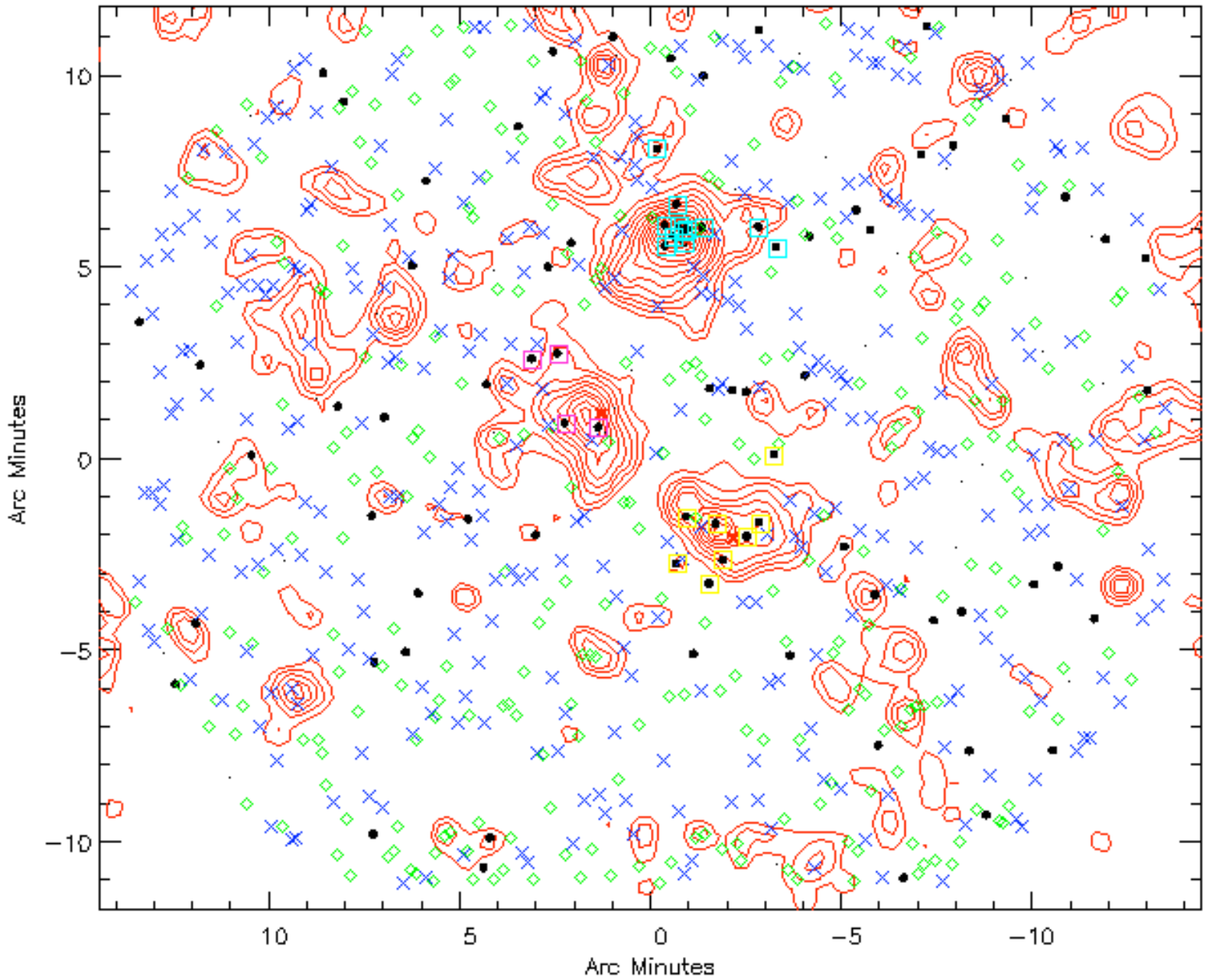
RCS2319 supercluster

z=0.90

R,z, X-ray

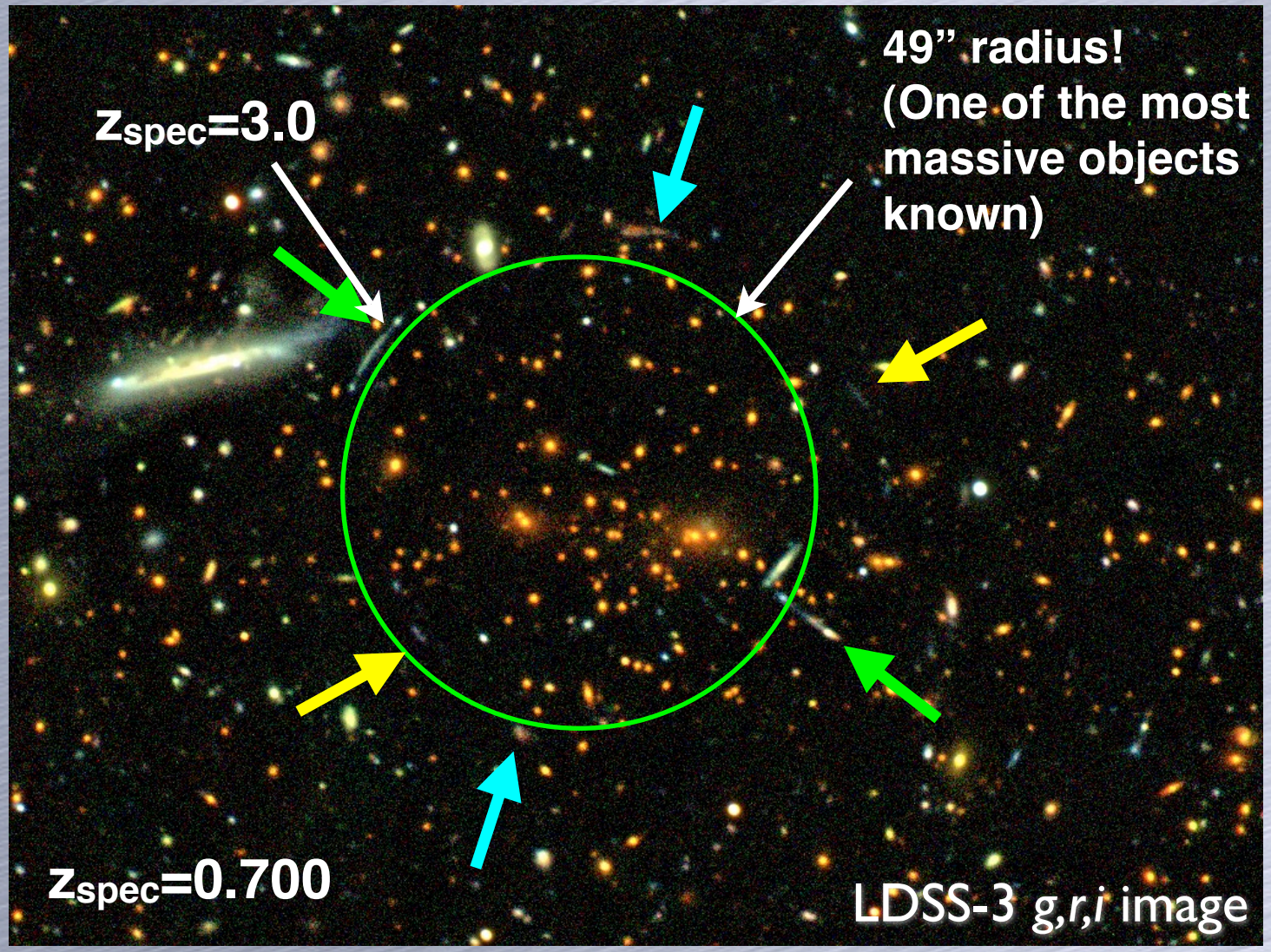
Gilbank et al. in prep

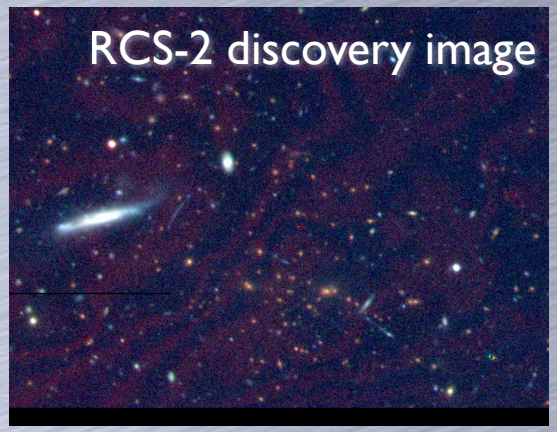
Red Galaxy Overdensity at z=0.9

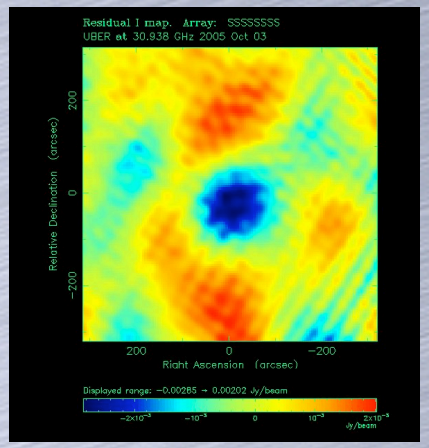


Richest cluster in RCS at any redshift!

RCS2-2327



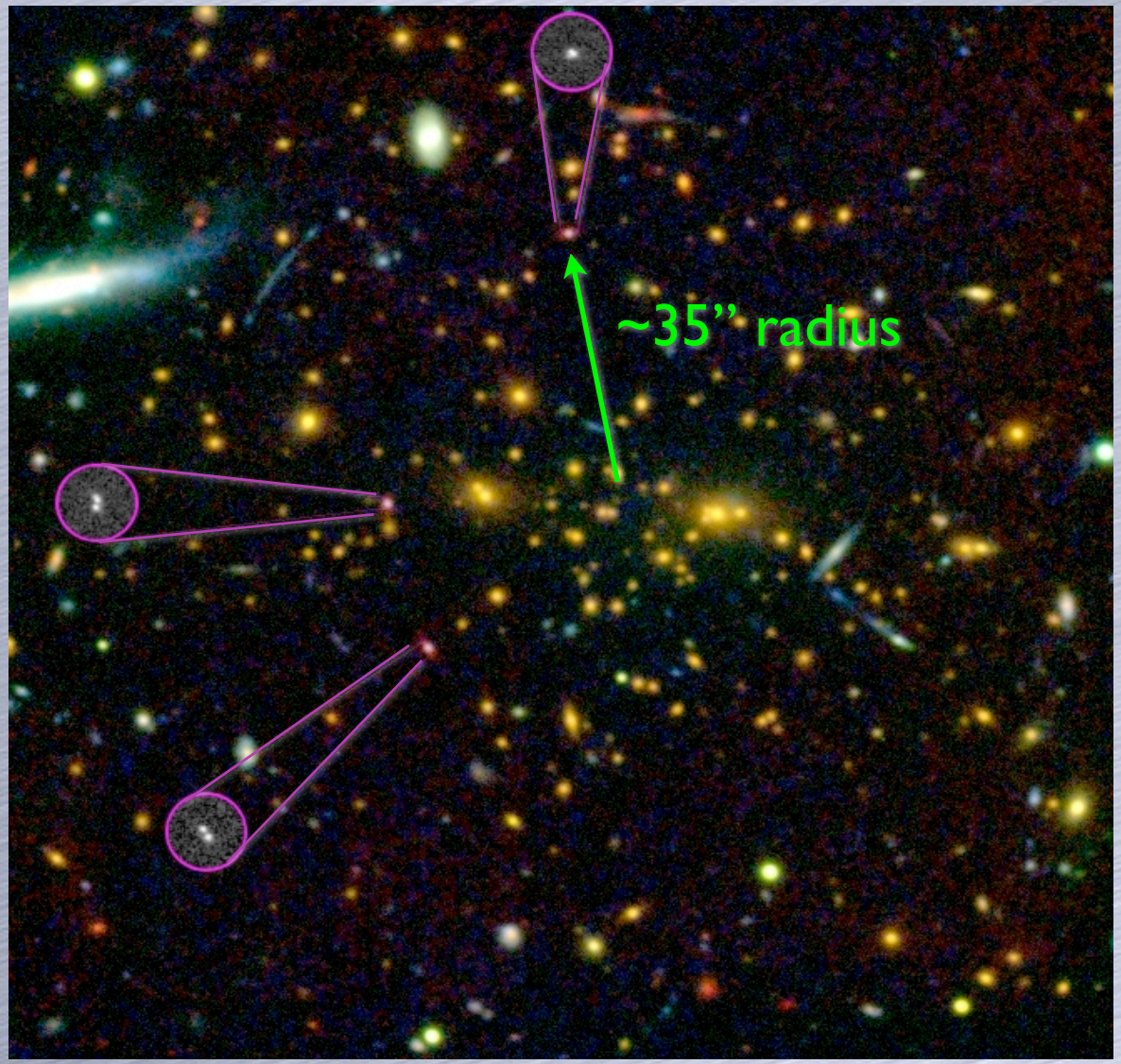




SZ observation from SZA (early reduction, dirty beam pattern, courtesy J. Carlstrom). The SZ decrement is comparable to CL0016 +16, a classic massive cluster at z=0.55.

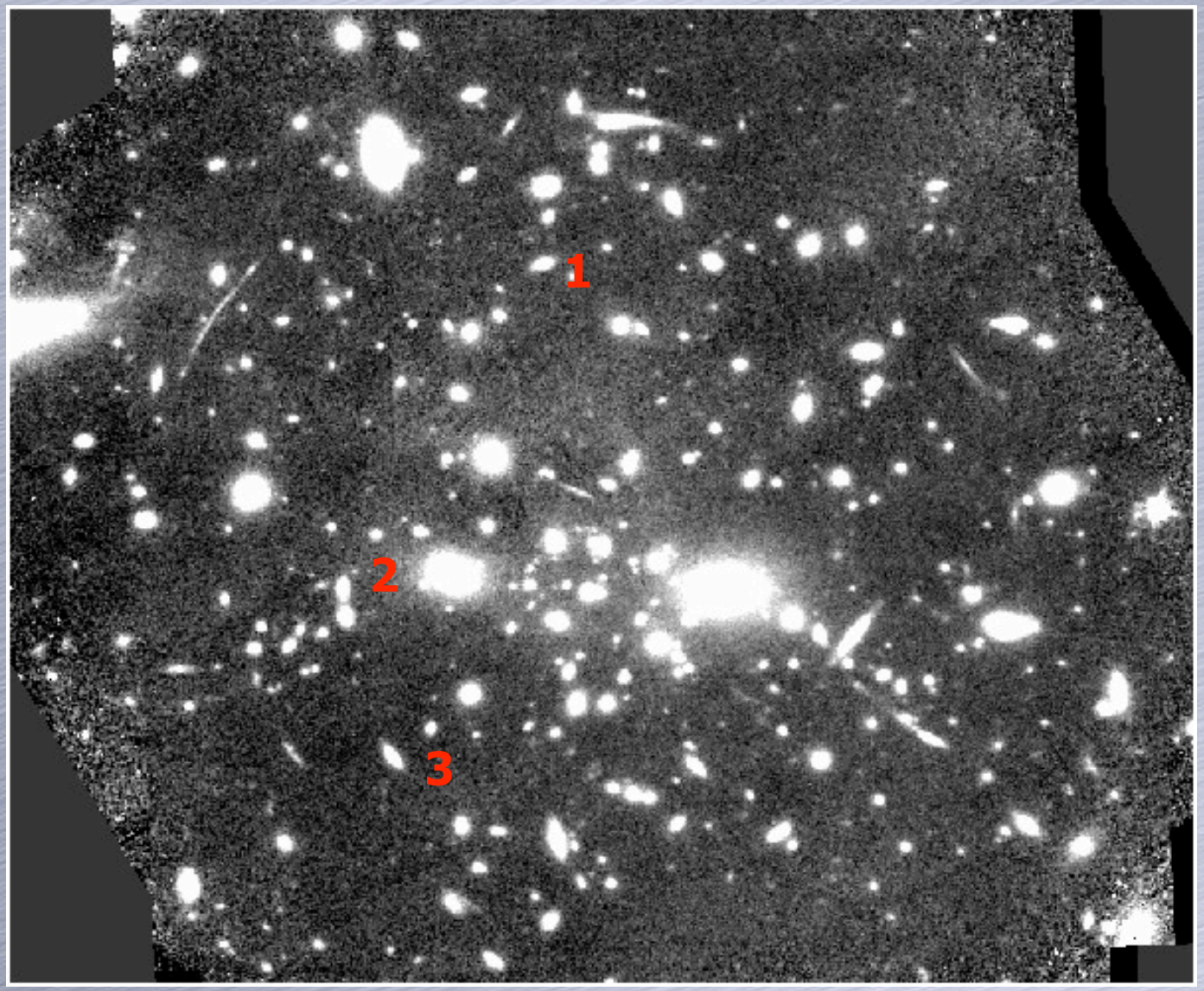
Weak lensing, SZ, X-ray and velocity dispersion mass estimates of this z=0.700 cluster all indicate a mass of 3–5 x 10^{15} $M_\odot$.

Strongly lensed binary quasar?



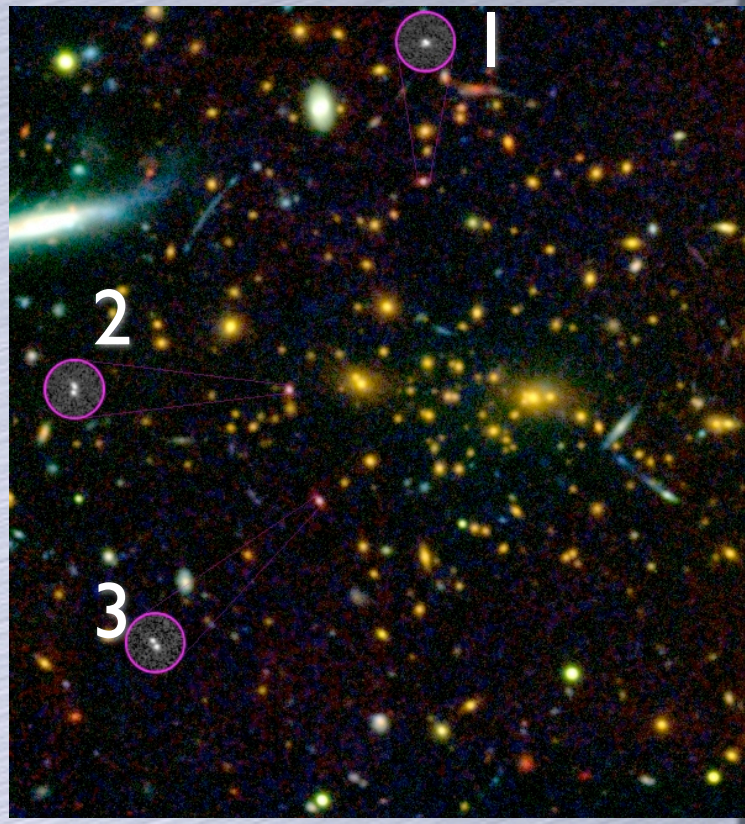
F435W, i, K

NICMOS F160W

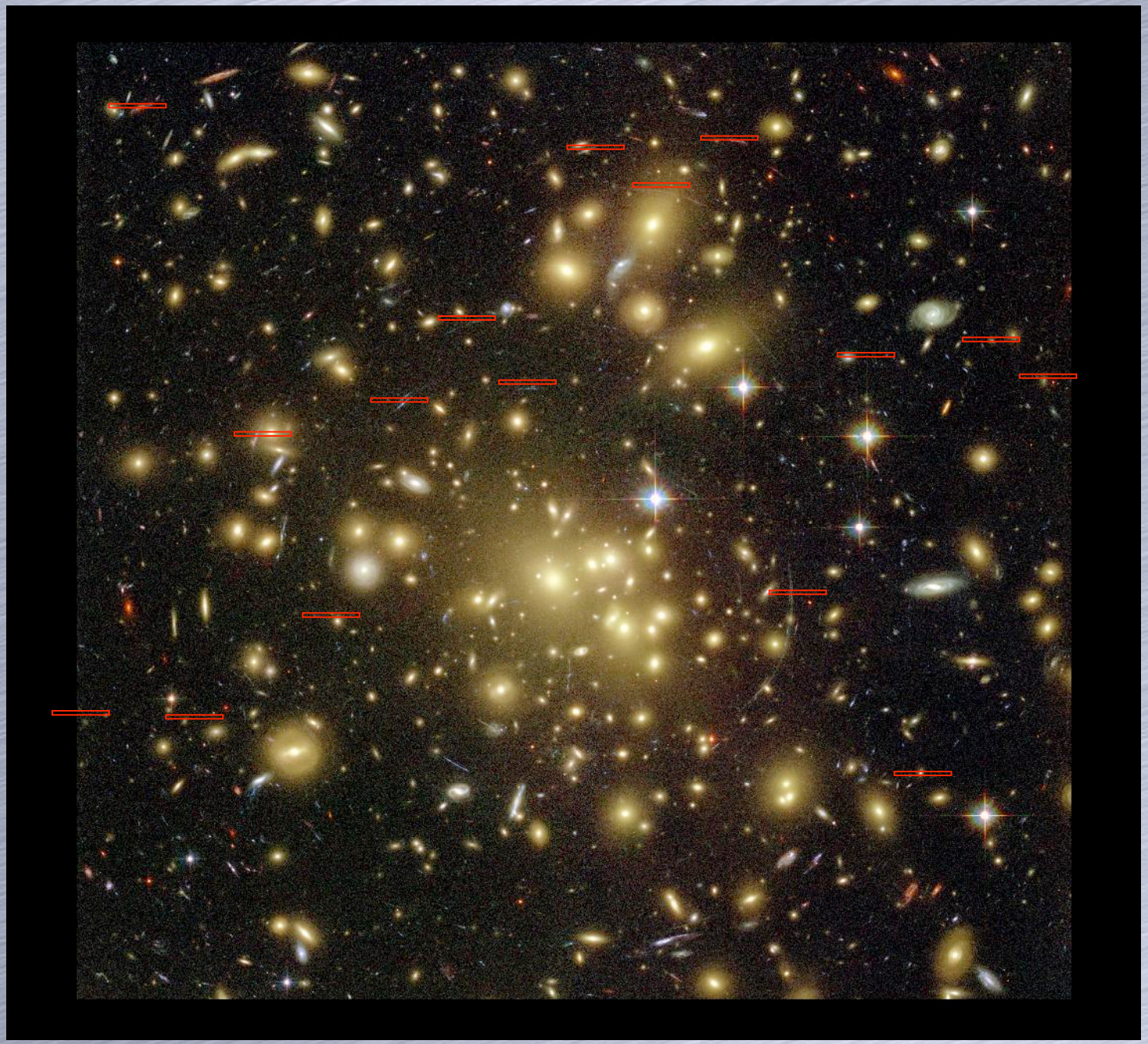


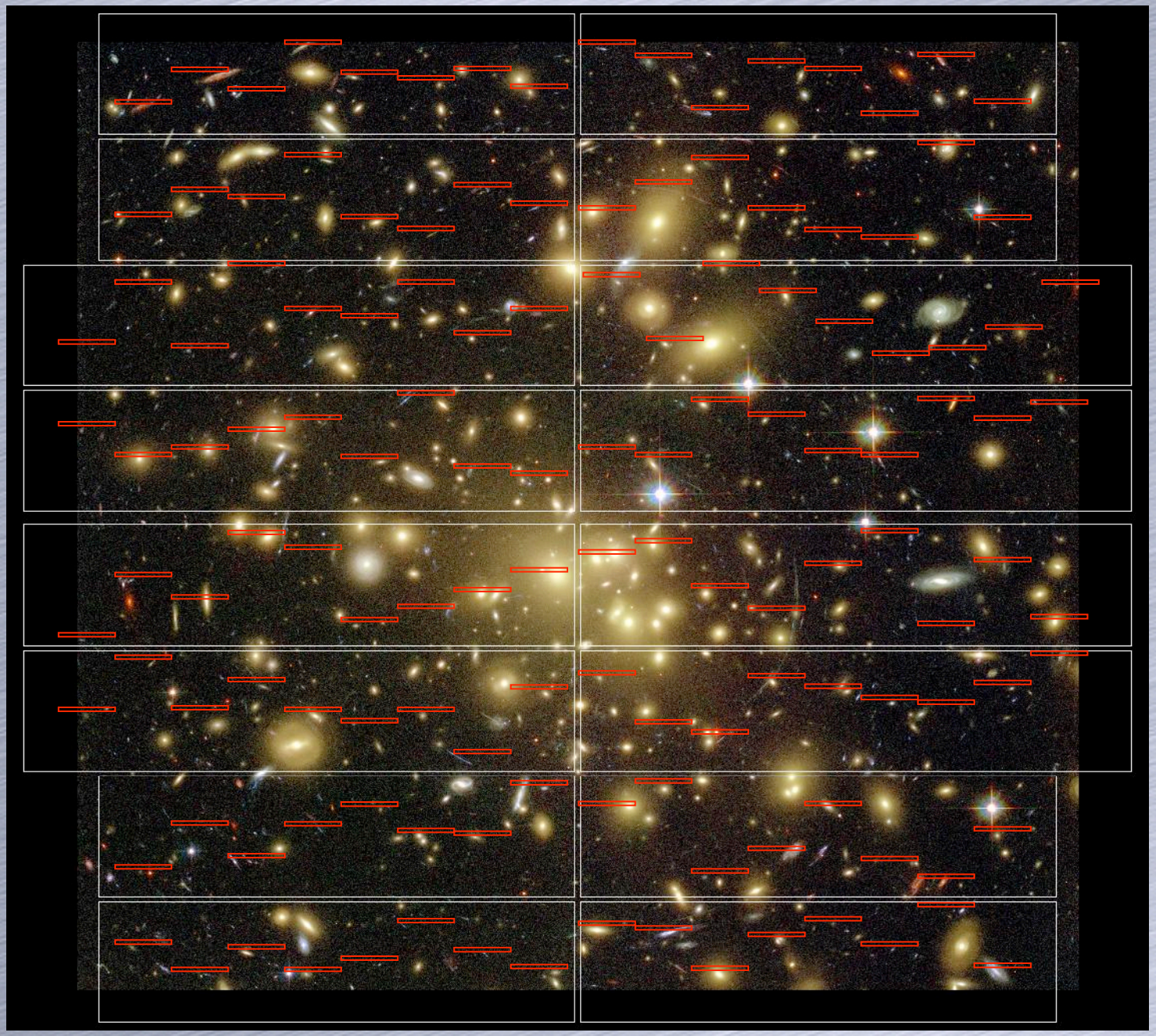
Photometry of Objects

	F435W	*g*	*r*	*i*	*K*
image 1	23.98	23.80	23.18	22.91	18.64
image 2	23.78	23.40	23.08	22.82	18.76
image 3	23.67	23.62	23.03	22.82	18.68



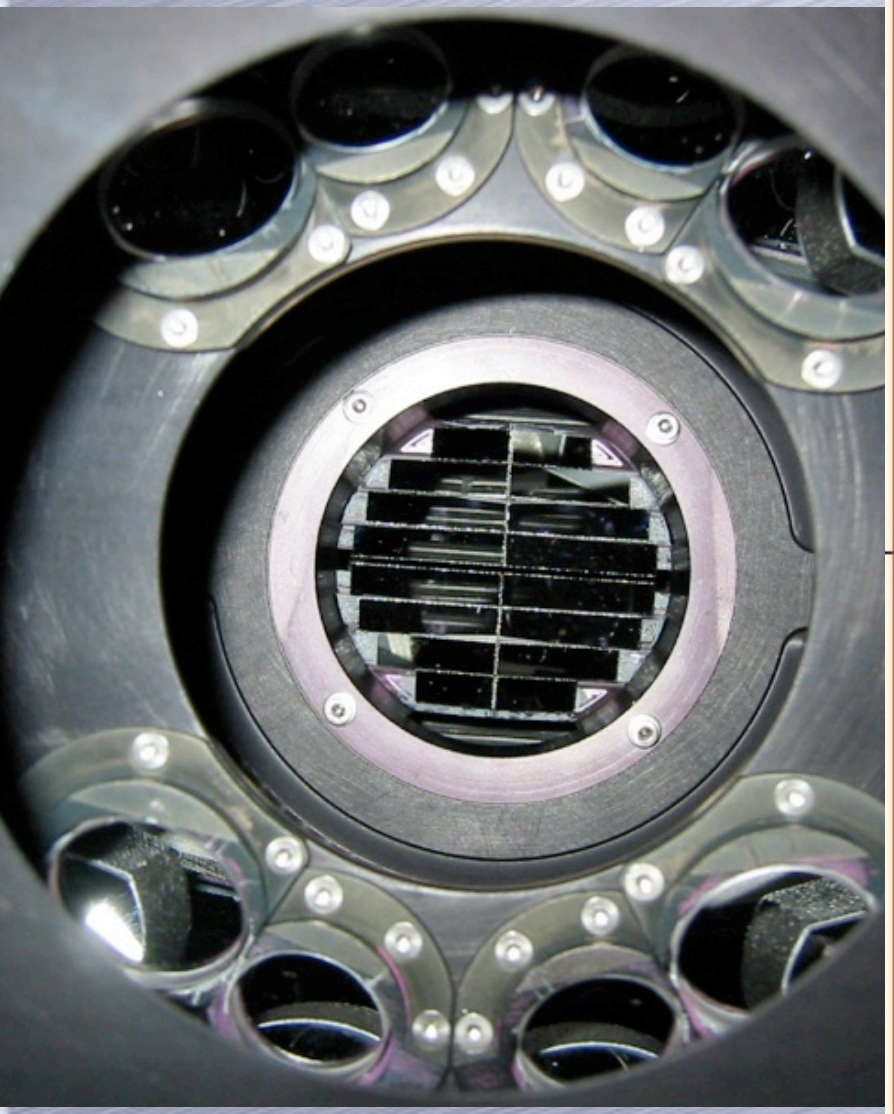
Optical colours consistent with moderate redshift quasar
(e.g., Szokoly et al. 2004).
NIR colours => early-type host galaxy

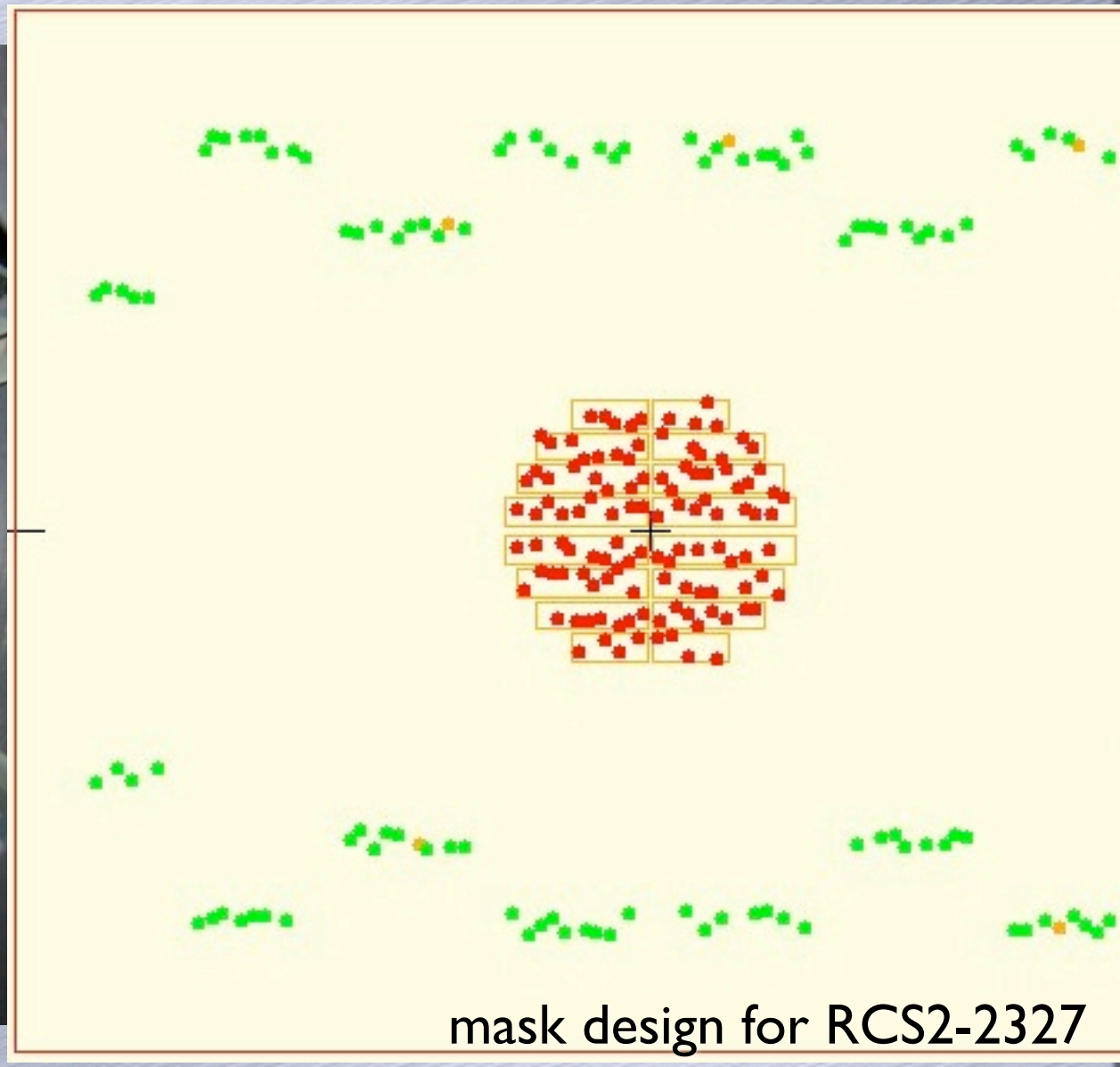




GISMO

Gladders Image-Slicing Multi-slit Option for IMACS





mask design for RCS2-2327

Summary

- RCS-2 (from ~400 sq. deg) has found 71 giant arcs + many more arclets
  - Deficit of low redshift, high mass clusters relative to predictions (supporting findings of RCS-1)
- Spectroscopy of modest samples of strong lenses underway
  - Interesting systems:
  - z=3.9 giant arc behind one member of z=0.9 supercluster
  - extremely massive cluster at z=0.70 (with possible multiply lensed quasar)