The Red Sequence Cluster Surveys

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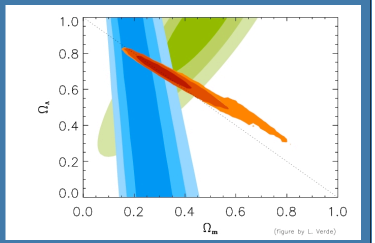
The New Cosmology

There is compelling evidence that the universe is accelerating its expansion: dark energy?

"… the nature of dark energy is probably the most vexing. It has been called the deepest mystery in physics, and its resolution is likely to greatly advance our understanding of matter, space and time."

Michael Turner, Chair
NAS Committee on Physics of the Universe

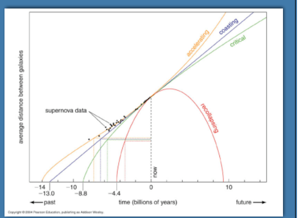


Constraining Dark Energy: w

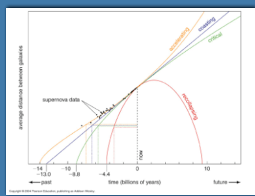
Equation of state:
W = P/ρ

Model here shows the currently favored model: dark energy acts as a cosmological constant or "vacuum energy":

W=-1, constant with time



- In reality, there is no current strong theoretical or observational constraint on w, which might vary from -1/3 to
  < -1 and could also change with time.
- Observations at high redshift (z=1 to 3, or about 7-10 billion years ago) provide the best leverage.



Approaches to the expansion of the universe at z=1-3

1.) More distant supernovae: currently difficult with existing observatories (e.g. Riess et al 2007).
Systematics with age, metallicity, dust extinction?
Possible future space missions?
(e.g., SNAP/ADEPT/DESTINY NASA/DOE 2015+)

2.) Baryon acoustic oscillations: features in the the galaxy power spectrum that can be used as standard rulers. Requires very large survey (e.g., LSST ?2013)

2.) Clusters of galaxies at z~1 or higher
Our topic today!!

Outline

Searches for distant clusters
The RCS Surveys: methodology
Cluster masses
RCS-2
Constraining Cosmological parameters
Strong lensing clusters

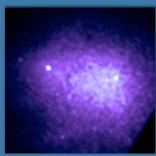
Galaxy Clusters

Largest gravitationally collapsed objects in the Universe:

10^{14-15} solar masses of dark matter

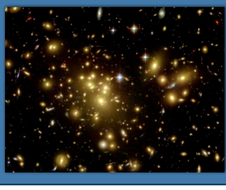
~10% of that in baryons, mostly gas shock-heated to 10^{7-8} K; visible in X-ray via thermal bremsstrahling

~1% of the total in stars in 100s-1000's of galaxies



Left: Coma Cluster: Chandra X-ray Observatory

Below: A1689, Hubble Space Telescope

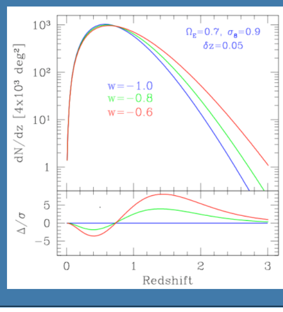


Galaxy Clusters and Cosmology

- Formation rate of massive clusters at z~2 to the present is very sensitive to the expansion rate of the Universe

Requires sample of ~ 10,000 clusters at

z ~ 1-1.5 for useful constraints

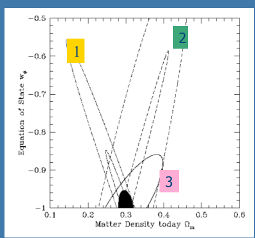


1: 200/400 SNe

2: WMAP/Planck

3: 1000 sq degree cluster survey to z=1.2, Tx > 5 keV

Needed: coverage to z~1, wide field, moderate masses



Levine, Schulz, & White, 2003

Searches for distant clusters

Difficulties: Massive clusters are RARE

(~1 per square degree)

Distant clusters are very faint in X-rays, requiring 10's of ksec for detection. Current X-ray telescopes are unable to provide ample coverage

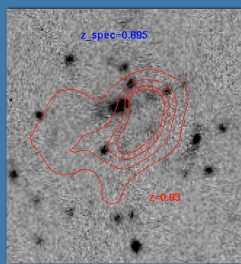
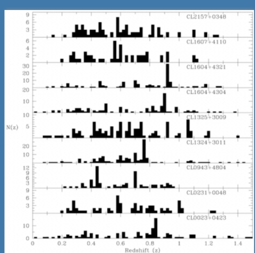


Image: 20 min exposure from CFHT 3.6m optical telescope
Contours: 5.5 hour exposure from Chandra X-ray Observatory

Optical surveys: bright cluster galaxies are visible in 10's of minutes, and large format detectors make wide surveys possible

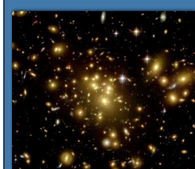
But, optical searches using galaxies suffer large contamination from foreground/background galaxies (different redshifts, unassociated with the cluster)



Postman et al., 1999

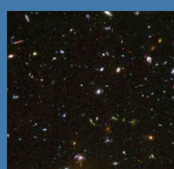
The Red-Sequence Method:

Galaxy clusters, even those at high redshift, always have a component of highly evolved red galaxies, which are relatively rare elsewhere in the Universe.



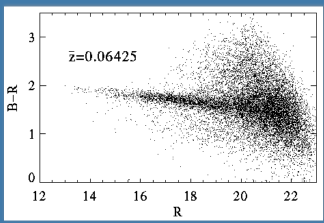
Cluster Abell 1689 (z=0.18 optical colors)

Cluster RCS 0439-2904 (z=0.93 IR colors)



Hubble Ultra-Deep Field (no cluster; optical colors)

The red sequence is an asymptotic end stage of stellar evolution. As stellar populations age, they reach this color in about 3 Gyr after their last episode of star formation. Cluster galaxies have had their star formation quenched (why??) and their cores are dominated by galaxies which lie on this sequence.



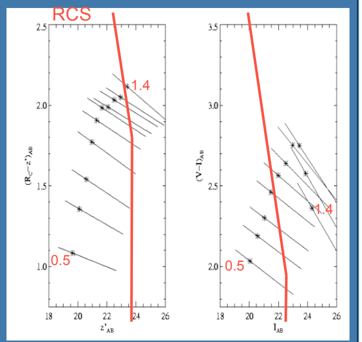
Composite of 30 low-redshift clusters, illustrating the compact color of the red sequence.

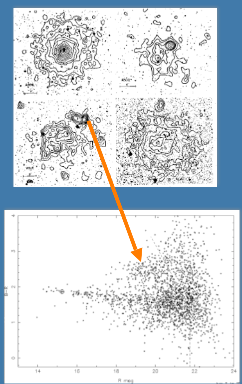
The red sequence shifts to redder observed colors with cluster redshift

R-z colors (left): good resolution from z~0.3 - 1.0

(samples the 4000A spectral break)

Extending to Z=2 requires IR colors (e.g. Muzzin et al. 2006)





Structures at different redshifts show different red sequences;

galaxies not in cluster create a broad "cloud" in color-mag.

The Red-Sequence Cluster Surveys

U. Toronto/CITA: H. Yee, D. Gilbank, I. Li, A. Muzzin, S. Majumdar
U. Chicago: M. Gladders
U. of Colorado: E. Ellingson, Y.S. Loh, J. Jones
U.Victoria: H. Hoekstra
MPIA-Heidelberg: K. Blindert
U. Virginia: A Hicks
P.U. Catolica, Chile: F. Barrientos, L. Infante
Taiwan (NCU.ASIAA): P. Hsieh, W. Ip, S.Y. Wang, T. Chieuh
McGill: T. Webb
MIT: M. Bautz

RCS-1 (Gladders & Yee 2005)

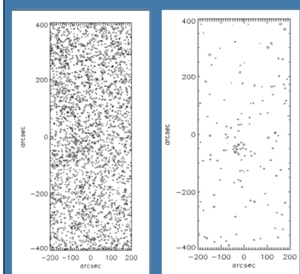
92 square degree survey, now completed at CFHT 3.6m and CTIO 4m using the CFHT-12K wide-field CCD mosaic camera
30 nights (including lost time)

R and z' filters, complete to R~24.8, z'~23.6
(t ~ 20 min each)

22 "patches" (typically 2.5 x 2.5 degrees) with a range of RA + Dec. Fields chosen to overlap with other widely studied fields; XMM and Chandra deep fields, PDCS fields, CNOC fields, etc.

Follow-up IR, optical multi-color imaging, spectroscopy, HST, Chandra and Spitzer observations of cluster samples

Significantly wider and somewhat shallower than other multi-color deep field surveys

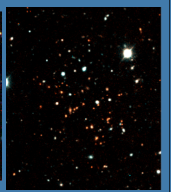


Cluster candidates are chosen via over-density in color-magnitude slices along the sequence.

Average galaxy surface densities are used for background subtraction and to derive 3.3- sigma detections as cluster candidates

Simulation: Abell 0 cluster at z=1.0 with and without color cut

Z=0.64 Z=0.87 Z=1.1

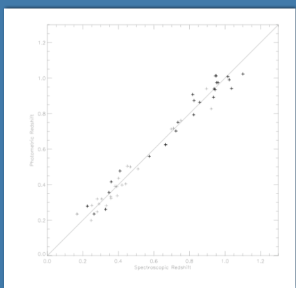


Context: only about a handful of massive (> 750 km/sec) clusters at z > 0.8 had been discovered prior to RCS. The RCS-1 sample contains ~50 such clusters.

Are these "real" clusters?

- Millennium simulations: contamination from excess of red large scale structures close to the cluster redshift (Cohn et al. 2007)
- Current simulations are not a sufficient match for quantitative predictions (cluster outskirts and groups are too red), but…
- Most likely <5% of the populations at z=0.4, <10% at z=1.0 have masses 50% or less than predicted optical overdensity in the red sequence

- For cosmology- once the clusters are found, we need their redshifts and masses
- Redshift calibration accurate to ~ 10% via the color of the red sequence



Photometric vs Spectroscopic redshifts for clusters

Cluster Masses

How to measure Dark Matter masses of 1000s of clusters?

Standard observables:
Velocity dispersion, X-ray temperature, weak lensing are all expensive or impossible to apply to the entire survey

Most powerful strategy is to use survey data to provide a calibrated mass proxy

Optical richness: Bgc

Galaxy-cluster covariance amplitude (e.g., Longair & Seldner 1978)

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

Corrected for foreground/background projection and normalized via the evolving luminosity function

Similar to total number of galaxies or total optical light in the cluster, but robust against variations in sampling radius and limiting magnitude

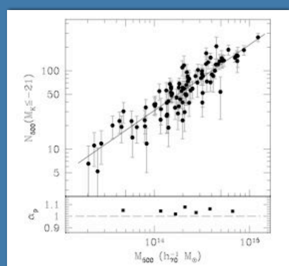
For RCS: measured within 0.5 Mpc of the cluster centroid, M*+2, assumed γ =1.77
Uses red sequence galaxies only

$$B_{gc} = N_{net} \frac{(3-\gamma) D^{\gamma-3} \theta^{\gamma-1}}{2 A_\theta I_\gamma \Psi\, [M(m_0, z)]}$$

Does richness correlate with cluster mass?

K-band luminosities would provide the most robust measurement-- stellar mass seems to correlate well at z~0 (Lin, Mohr &Stanford 2004)

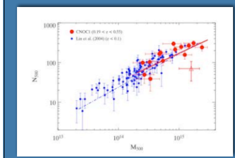
Will this change with observed wavelength, or with z…?



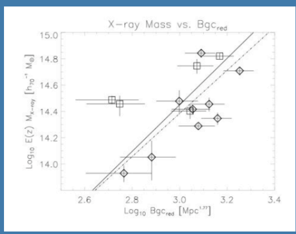
K-band galaxy counts
Masses from X-ray temperatures

Calibrations of optical Bgc at intermediate redshift (z ~ 0.3)

- CNOC sample; massive X-ray selected clusters at 0.2 < z < 0.6



K-band: Muzzin et al. 2007

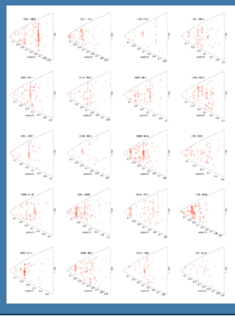


Optical, masses from resolved Tx profiles: Hicks et al. 2006

Mass estimates for RCS clusters- 3 ways to calibrate richness

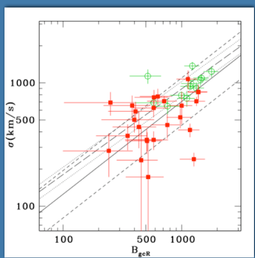
1.) Dynamical mass estimates

- Multi-object spectroscopy at z~0.3 (Blindert et al 2007)
- 37 clusters, includes both rich & poor systems, ~900 cluster redshifts in total (CFHT and Magellan)



Same general trend, though errorbars are significant

Outliers: about 5-10% of the sample are “blends” of less-massive groups close in redshift or embedded in sheet-like structures

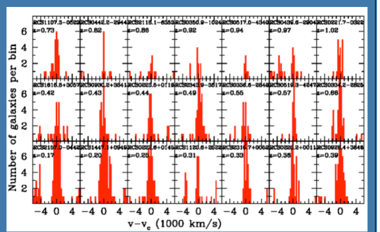


Blindert et al 2007
Green= CNOC Red = RCS sample

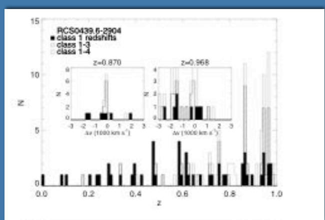
Spectroscopy at higher z

First results at z~1 from Gemini & VLT observations of 12 clusters

Velocity dispersions consistent with previous calibrations (but more data needed)

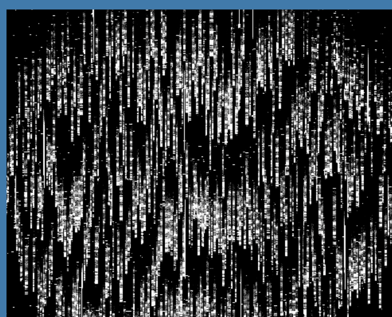


Gilbank et al. 2007

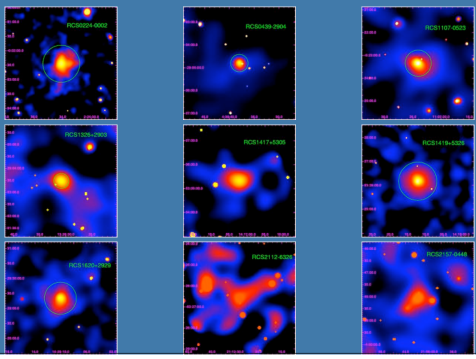


1/12 clusters at high-z is a blend of overlapping systems- still consistent with ~10% contamination

Ongoing observations of clusters with IMACS at Magellan- 500 galaxies at a time



2.) Chandra X-Ray Observations of RCS Clusters at z=0.6=1.3
20- 100 ksec exposures, 13/14 detected at 3-sigma+
Contamination by non-clusters is < 10%



This last one is 2.5-sigma

X-Ray Temperatures of RCS Clusters

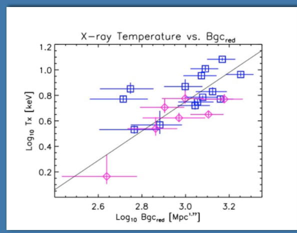
X-ray temperatures (Tx) provide an estimate of total cluster mass*

Pink Diamonds = 8 RCS clusters with enough signal to measure Tx

Blue squares: CNOC again

Excludes outlier identified via spectroscopy (see earlier)

(see however Rasia et al. 2006)



Hicks, et al. 2007

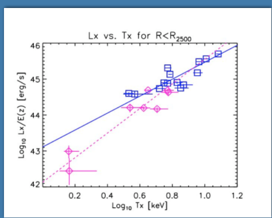
Lx-Tx relation for RCS clusters

X-ray luminosities may be slightly lower than for lower-z X-ray selected samples like CNOC (See also Lubin et al. 2002, Gilbank 2004, Donahue et al. 1999…) May also be generally true? (e.g., Ettori et al. 2004)

Note that since $\varepsilon_X \sim \rho^2$

Luminosities (and X-ray selected surveys) are sensitive to core gas distributions

Variation in baryon densities in cluster cores-- evidence for pre-heating, AGN, etc?

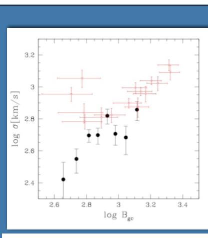


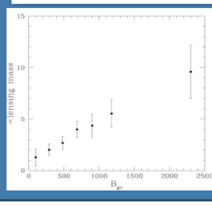
3.) Weak Gravitational Lensing:

Most likely the best calibrator for Bgc-- cylindrical mass with similar sensitivity to correlated structure

Composite of signal from abundant low-mass groups matches calibration from more massive clusters (Hoekstra et al 2003 (upper), in prep (lower))

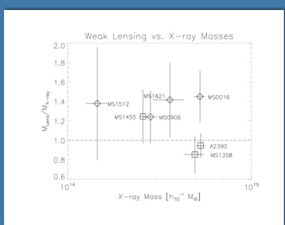
HST snapshot program of 50 clusters will continue calibration (data in hand- analysis underway)





Caution: weak lensing may also systematically over-estimate cluster "virial" mass by 30%

Statistical correction, check on cosmological constraints via simulations?



CNOC: Hicks et al. 2006;
X-ray and dynamical masses agree
See also Bardeau et al. 2007

Summary of Mass Calibrations

Cluster candidates are mostly actual clusters

Contamination is ~5-10% and as expected is mostly from structures similar in z to the cluster. Generally consistent with predictions from cosmological simulations (Cohn et al. 2007).

RCS clusters are consistent with previous mass-richness calibrations. Individual cluster masses will not be constrained better than ~30-70%, but large numbers of clusters will be available.

Secondary parameters (color dispersion, radial distribution, luminosity gap) may help tighten richness-mass relation

Cosmological constraints from RCS-1

From RCS-1, do we find the expected number of clusters predicted by the standard cosmology?

~934 clusters in 72 square degrees (Gladders et al. 2007), "self-calibrating" model of cluster number counts (Majumdar & Mohr 2003)

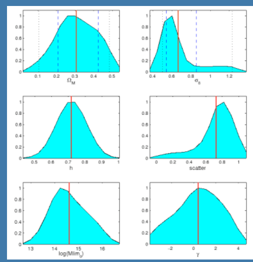
Ωm, σ_8,
+ 3 cluster parameters
linking richness to mass:
([A, α]=M_lim, γ, +scatter)
h (WMAP prior)
ns (WMAP prior)

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

Ωm = 0.31 +/- 0.10

σ_8 = 0.67 +/- 0.17

consistent with WMAP year 3 results:
Ωm = 0.24 - 0.27
σ_8 = 0.72 - 0.77



Mass calibrations from self-calibration (Majumdar & Mohr 2003)

log(A_{Bgc}) = 10.55 +/- 1.5	CNOC +RCS : 10.05 +/- 0.89
α = 1.64 +/- 0.7	CNOC+RCS: 1.58 +/- 0.27
γ = 0.40 +/- 2.5	CNOC+RCS -0.5 +/- 0.5)
scatter: 0.73+/-0.17	RCS: 0.65, Blindert et al. 2007)

RCS-1 is not missing or adding significant numbers of massive clusters.
Mass estimates are within expectations, though scatter in Bgc-mass calibration is large (could be improved??)

RCS-2

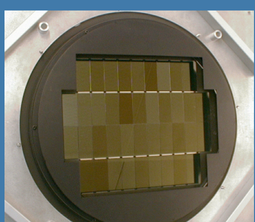
Underway: 1000 square degrees to z~1
Three filters: z' r' g' (SDSS)
exposure t: 6 8 4 min

5σ limits: 23.2 25.0 25.4 (AB magnitude)
Expected completeness/depth:
750 km/s (5 kev) clusters at z~1
Similar volume covered (in far less detail) as SDSS

CFHT Megacam
36 2k x 4.5k chips,
325M pixels, 750 MB/image
1 square degree FOV
0.18 "/pixel

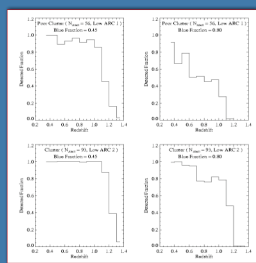
RCS2: ~600 square degrees in hand,
+ 170 from CFHT LS

Observations should be finished by end of 2007



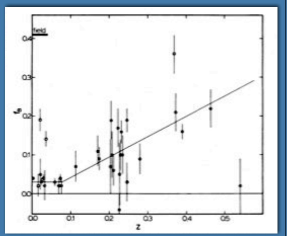
Galaxy Cluster Populations to z~1

From simulations
(Gladders, 2002, Cohn et al. 2007)
RCS method works well except for the poorest, bluest highest redshift clusters



Butcher-Oemler Effect

- From 1978, first handful of high redshift clusters known..
- Clusters at higher redshift appear to have a higher fraction of blue, star-forming galaxies
- Starbursts? Dusty starbursts?
- Role of infall of "field" galaxies?



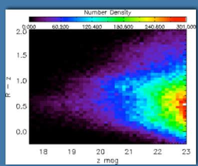
Butcher & Oemler 1984

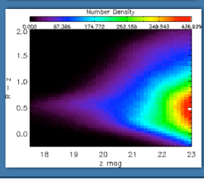
Complications over the years…

- Defining "red" and "blue" populations robustly across a redshift range
- Clusters have radial gradients in star formation rates-- more in outskirts (e.g. color-density relation)-- need scaling radius for comparisons
- Spectroscopic bias in identifying cluster members
- Inhomogeneous cluster samples
- The B/O Effect has grown and shrunk, depending on methodology (see Andreon 2005 for review)

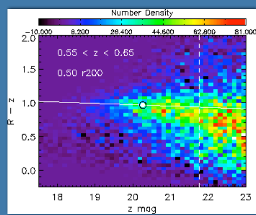
Composite color-magnitude diagrams

- Individual clusters (especially poor ones) provide relatively poor data
- Use composite of ~1000 clusters to estimate galaxy properties (z)

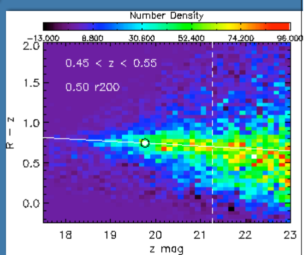




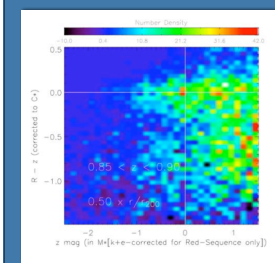
- Redshift from color of the red sequence
- Sampling radius scaled by $r_{200,}$ estimated by B_{gc}

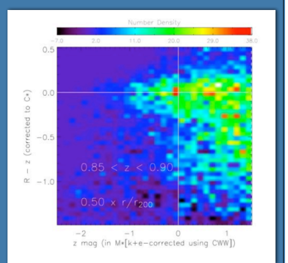


- Normalize the distribution in color to C* (color of CM diagram at z*) and slope of the red sequence
- Normalize magnitudes to observed z*
- Distribution is now relative to evolving Schechter function and red sequence color

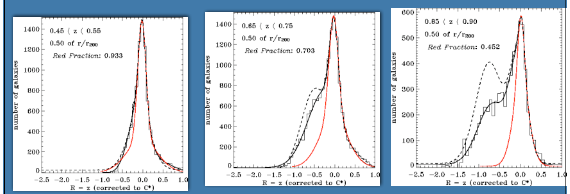


- Apply a color-dependent k-correction to correct for low-mass blue galaxies at higher redshifts





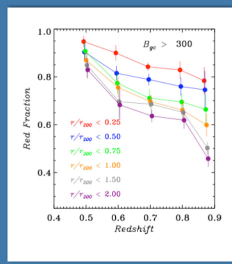
- Color bimodality is seen at all redshifts
- Fit red wing and subtract a symmetric red sequence (dominated by redshift error)



Butcher-Oemler Effect

There seems to be a moderate B-O effect in our sample-- slightly stronger in the cluster outskirts than in the cores-infall?

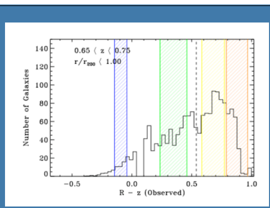
Cores of clusters are still quite red-- on average well above 50% red fraction where RCS technique struggled with poorest, highest-z systems

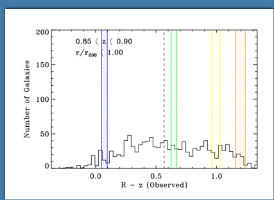


Colors of cluster blue galaxies

Colored bands are ~: 100 My starburst, Irr, Scd, Sab. Band widths are projection of the redshift range.

Median colors similar to normal field populations (Scd-Irr at similar redshifts; Bell et al. 2004), possible mild evolution to bluer colors from z=0.4-z=0.9



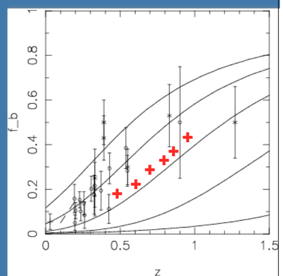


Is this what we'd expect?

Simple model of infall of field galaxies into clusters, with timescale for galaxies to turn from blue to red (model curves 0.5-2.5 Gyr, from flat to steep)

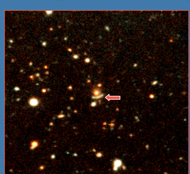
Timescale ~ 1.5 Gyr is quite rapid (similar to time needed just for stellar evolution). Galaxies are probably not as blue as field assumption-- "preprocessing" in groups before infall?

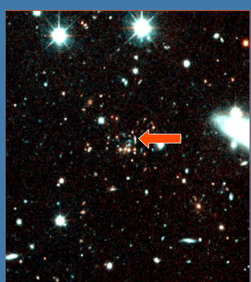
Requires better modeling of infalling population…



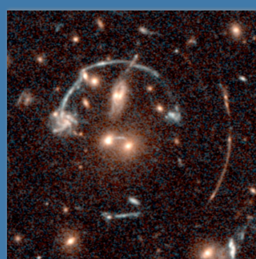
Black points- data from the literature
Red crosses: RCS. Note systematically
Fewer blue galaxies because of red
sequence modeling rather than a
straight color cut

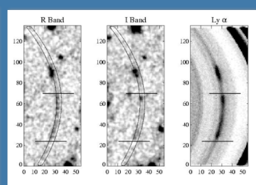
Strong Lensing in RCS Clusters





"The Beast:" cluster at z=0.78, multiple arcs to z=4.8

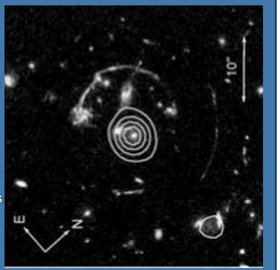




Tx=5.1 keV
Velocity dispersion ~ 900 km/sec
agree with masses from weak lensing
AND strong lensing (Hicks et al. 2007,
Swinbank et al. 2006)

Possible cosmological test?

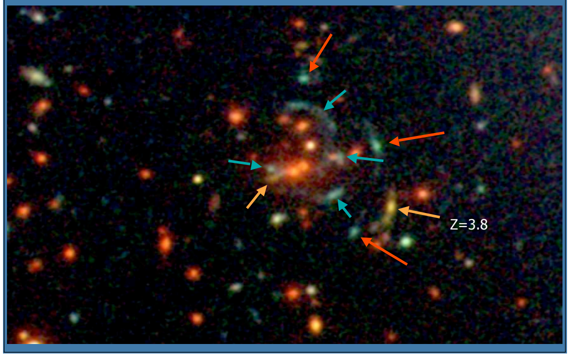
Lensing of many galaxies at different redshifts by a single lens allows a geometric solution their relative distances from the lens-- a new metric for cosmological distances with relative accuracy from z=1 to 5

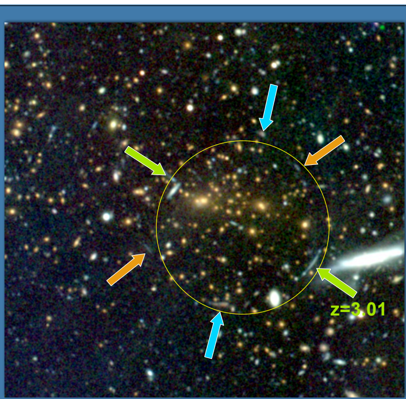


Requires redshifts of all lenses (tough for those at z=1-2 where there are few features visible at optical wavelengths), and a detailed mass map of the cluster core, constrained by X-ray observations

For "the beast" X-ray and lensing centroids are not perfectly aligned, suggesting a complex mass structure, which will complicate the analysis…

But the survey is large: another Multiple lensing cluster at z~1 (and we keep finding more….)





Z=0.70 cluster
From RCS2

3 separate arc Systems

49" radius
Makes this one of the most massive clusters Known

1400 km/sec Velocity dispersion

(Gladders et al. in prep)

Lensing clusters

- Incidence of lensing in RCS is higher than expected, at higher redshift and with lower cluster masses. Number of multiply lensed systems is particularly surprising (Gladders et al 2003)
- Lensing cross-sections enhanced by core substructure, baryons? A challenge for modelers… (Ho & White 2005, Rozo et al. 2006…)

Summary

Red-sequence optical surveys for clusters are inexpensive and efficient at discovering large samples of clusters at z~1 for cosmology, galaxy evolution and dark matter studies

RCS-1 results suggest that we are not missing large numbers of clusters; external checks suggest 5-10% contamination, mostly from structures of similar z

Cluster masses can be calibrated from overdensities of galaxies, though currently with large scatter. Weak lensing may be the best calibration, but (ongoing) multi-wavelength mass calibrations are also needed to check for systematics

- RCS clusters appear fairly normal in general: mass-richness, Lx-Tx, red/blue fractions.
- Lx may be systematically low, suggesting additional heating in cluster cores-- sample effects? Redshift?
- High incidence of spectacular lensing clusters may suggest that high-redshift clusters not chosen for their X-ray luminosity may have complex core structures
- RCS2 is coming…