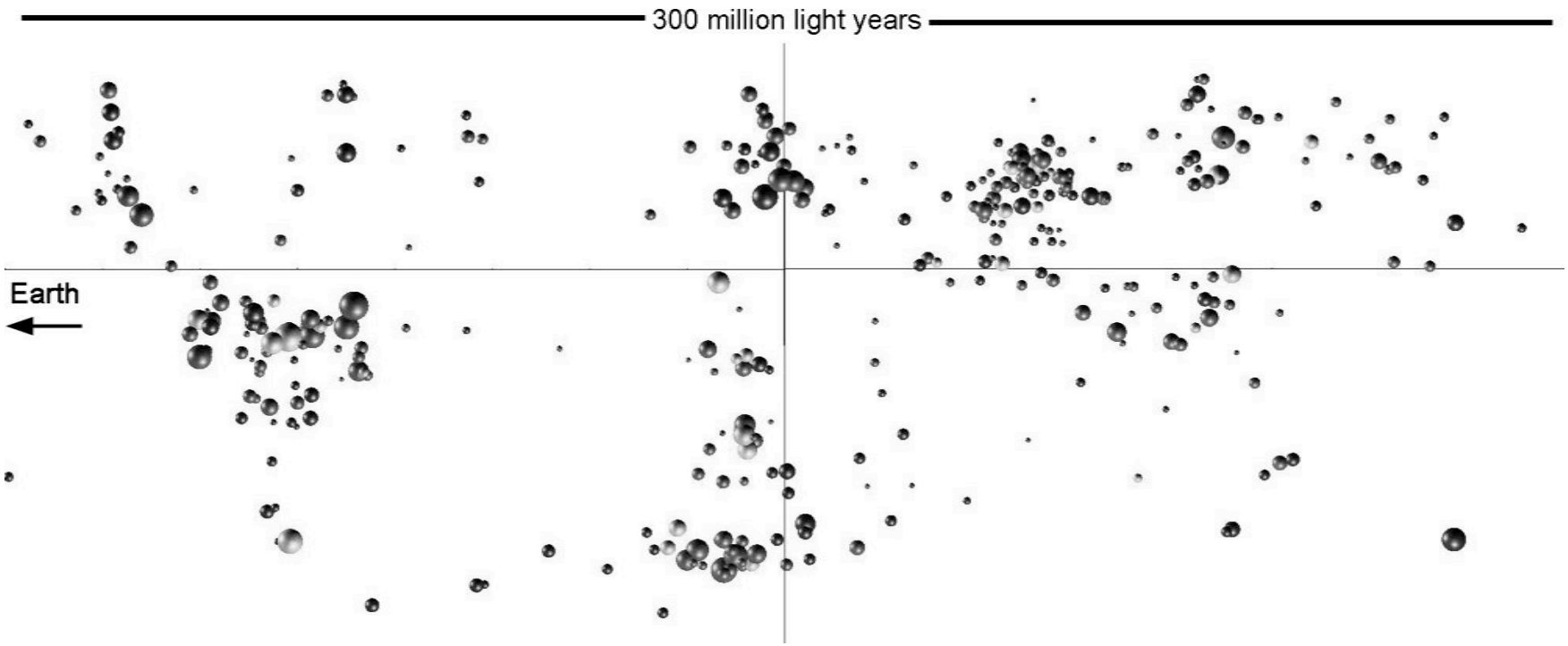
Understanding Cluster Formation and Galaxy Evolution … ORELSE

The Observations of Redshift Evolution in Large Scale Environments Survey



Lori Lubin (UC Davis)

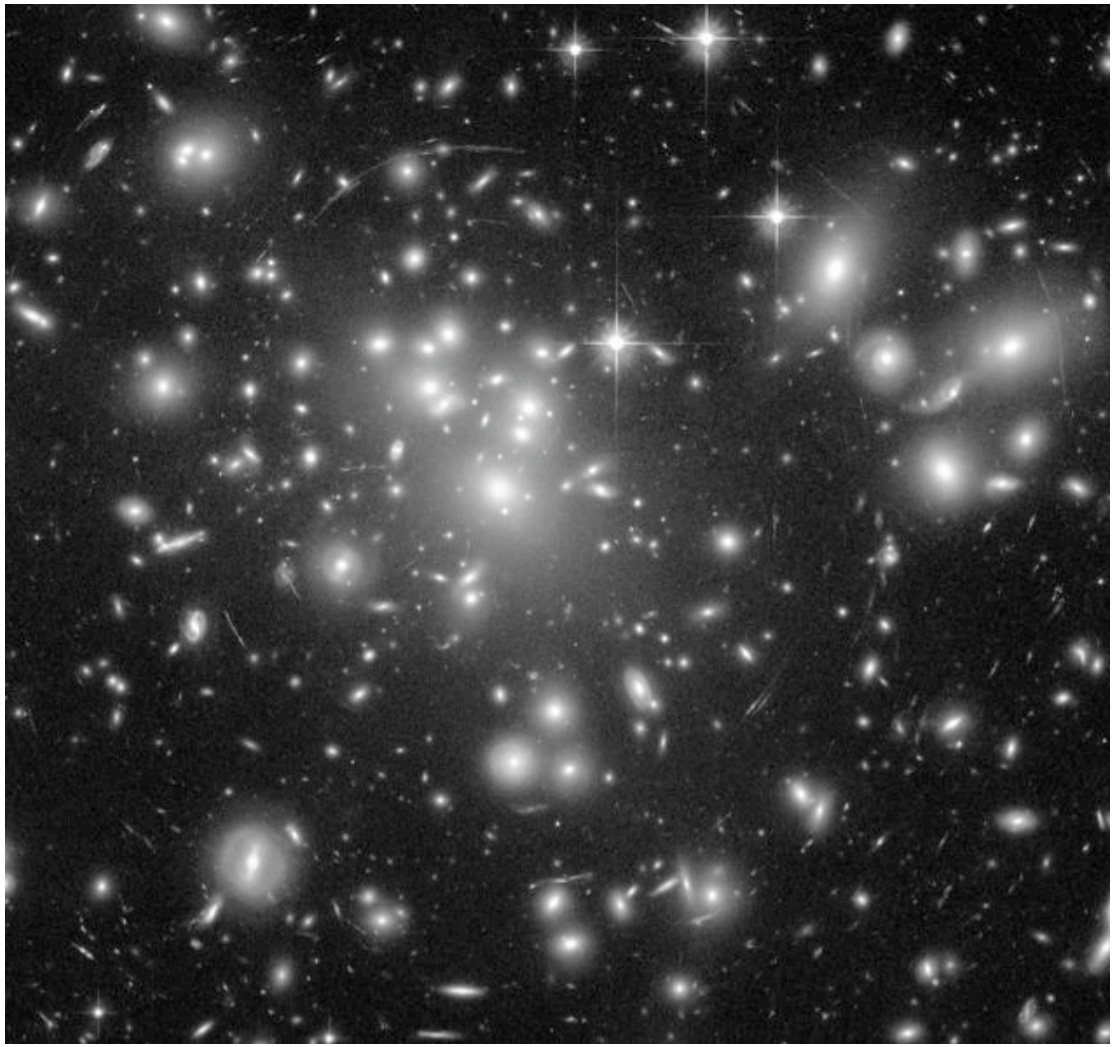
Brian Lemaux, Dale Kocevski, Roy Gal,
Gordon Squires, Chris Fassnacht, Neal Miller, Alice Shapley, Mark Lacy, and Jason Surace

Outline

- Cluster Background
- Galaxy Evolution Background
  - Red / Blue Divide
  - AGN Feedback
  - Motivation for Large Scales
- Survey Overview & Progress
- The Cl1604 Supercluster
  - 3D Structure
  - Galaxy population
  - Active Galaxies
- Other ORELSE Structures

Cluster Background

- Most massive, relaxed systems known in the Universe
- Ideal laboratory for studying a large population of galaxies
- Tracers of the largest structures in the Universe
- Easily detectable up to redshifts of z ~ 1.5
- As such, efficient tracer of galaxy evolution over this timescale



ACS Image of A1689 at z = 0.18

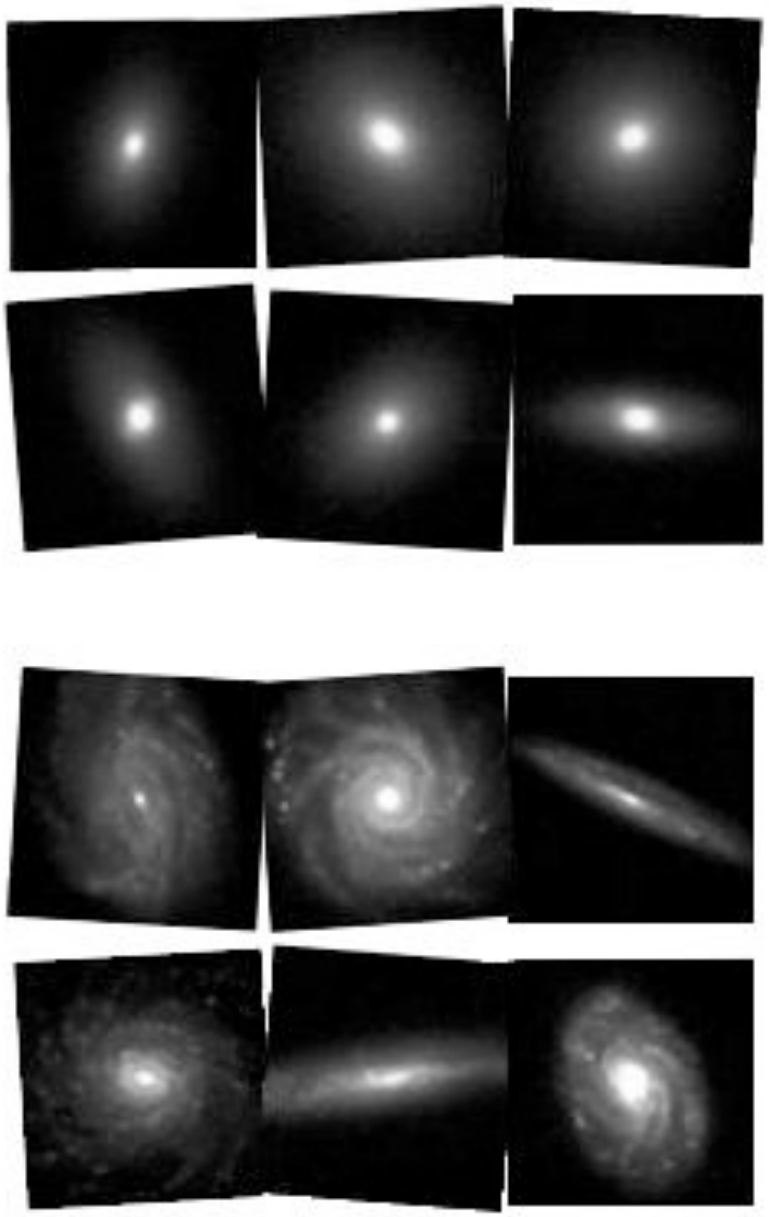
Galaxy Types

In the simplest terms, galaxies come in two basic types:

spheroid (early-type) or disk (late-type)

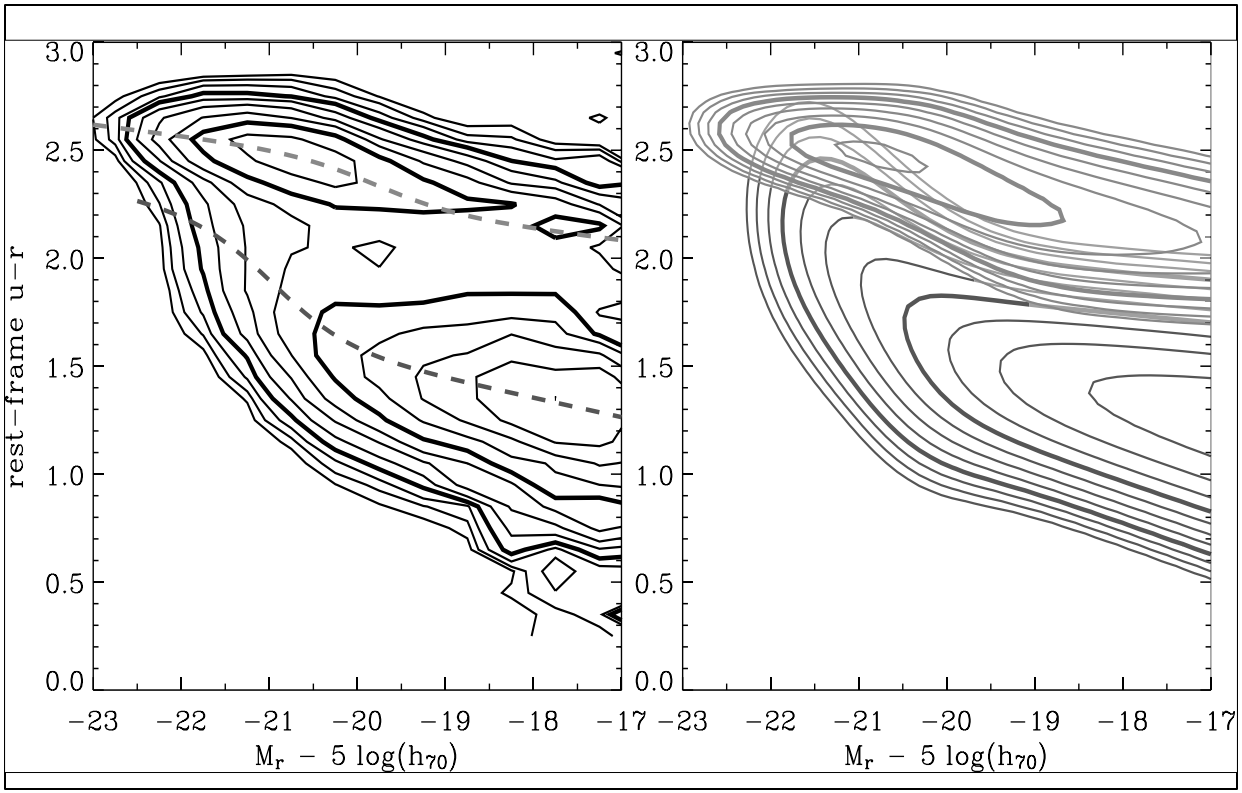
quiescent or star-forming

red or blue

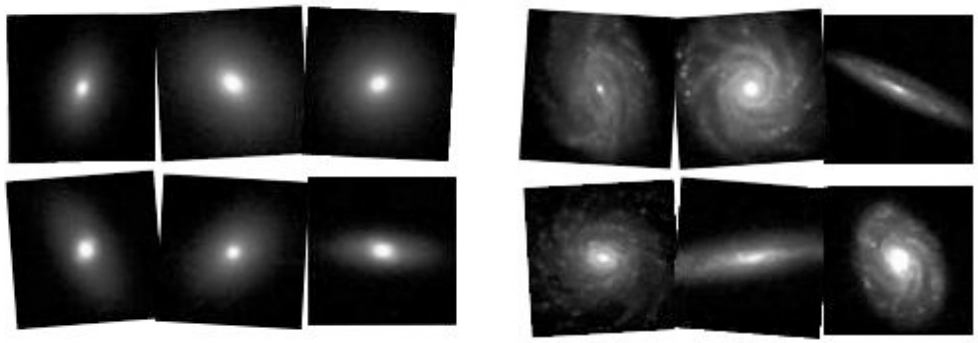


Global Properties at Low Redshift

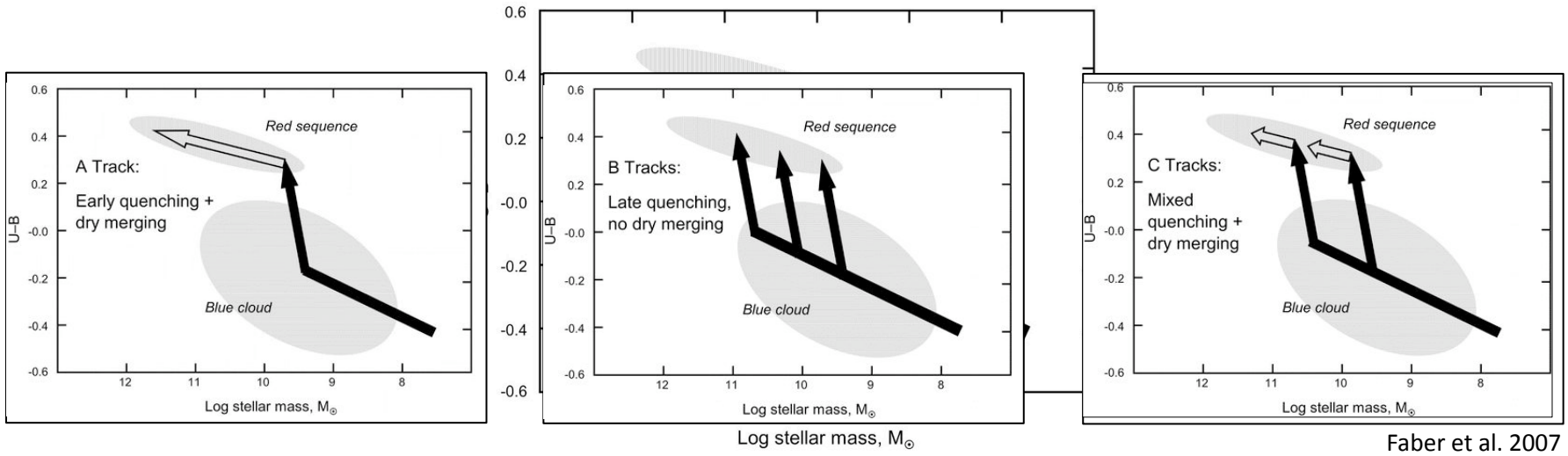
- Galaxy Colors Largely Bimodal
- Red Sequence: Red, quiescent, early-type systems
- Blue Cloud: Blue, star forming, late-type systems



Baldry et al. 2004



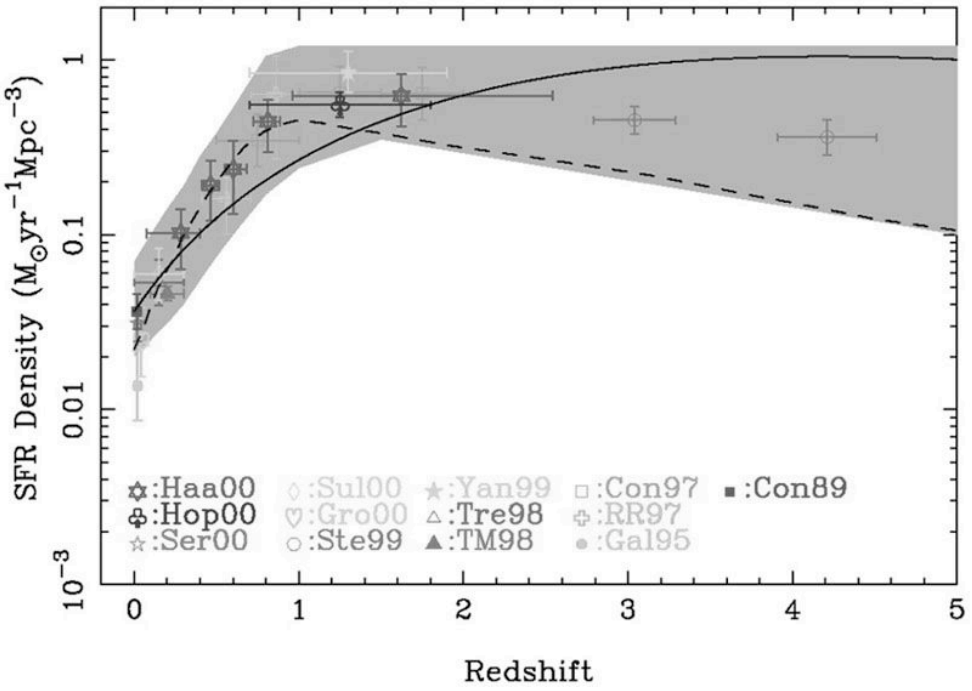
Evolution in the Blue / Red Divide



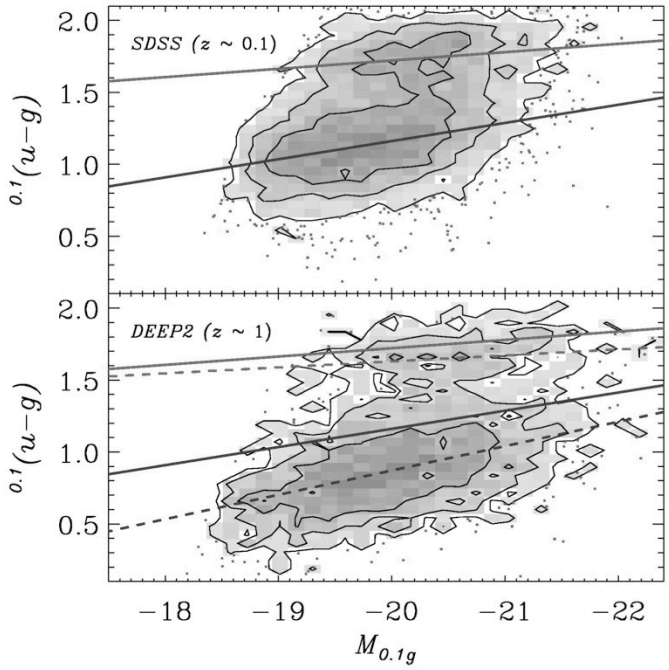
Faber et al. 2007

- Bimodality thought to be the result of evolutionary sequence.
- Following the termination of star formation galaxies quickly migrate from blue to red, leading to a sparsely populated “green valley”.
- Key question: what mechanisms are most responsible for quenching star formation and driving this evolution.
- Simple passive evolution of blue late-types can not explain high-mass end of red sequence.

Galaxy Evolution over the last 8 Gyrs



Hopkins et al. 2001



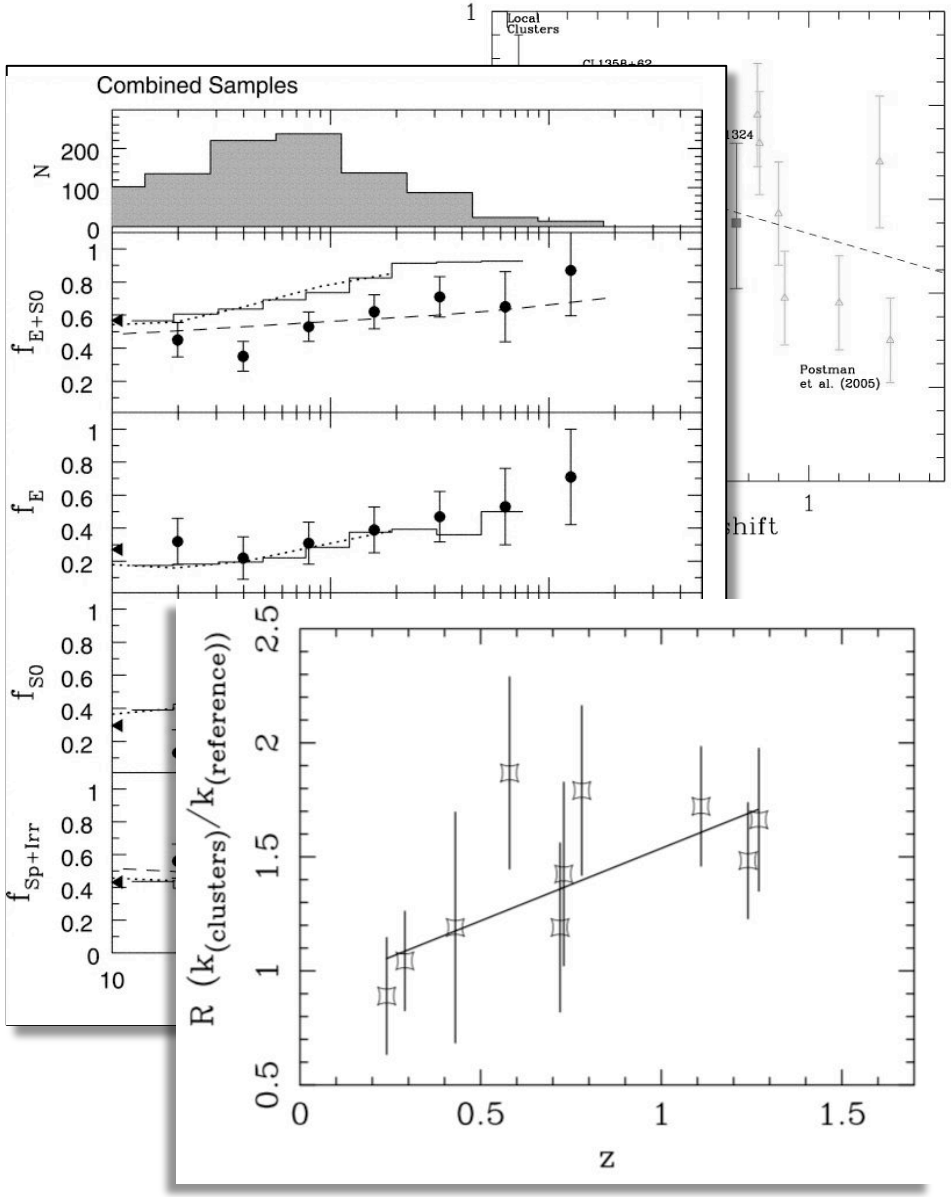
Blanton 2006

- Rapid decline in the cosmic star formation rate
- Increase in stellar mass on the red sequence

- Increase in the number density of red L* galaxies
- Presence of bright, blue galaxies in dense environments

Evolution of the Cluster Galaxy Population

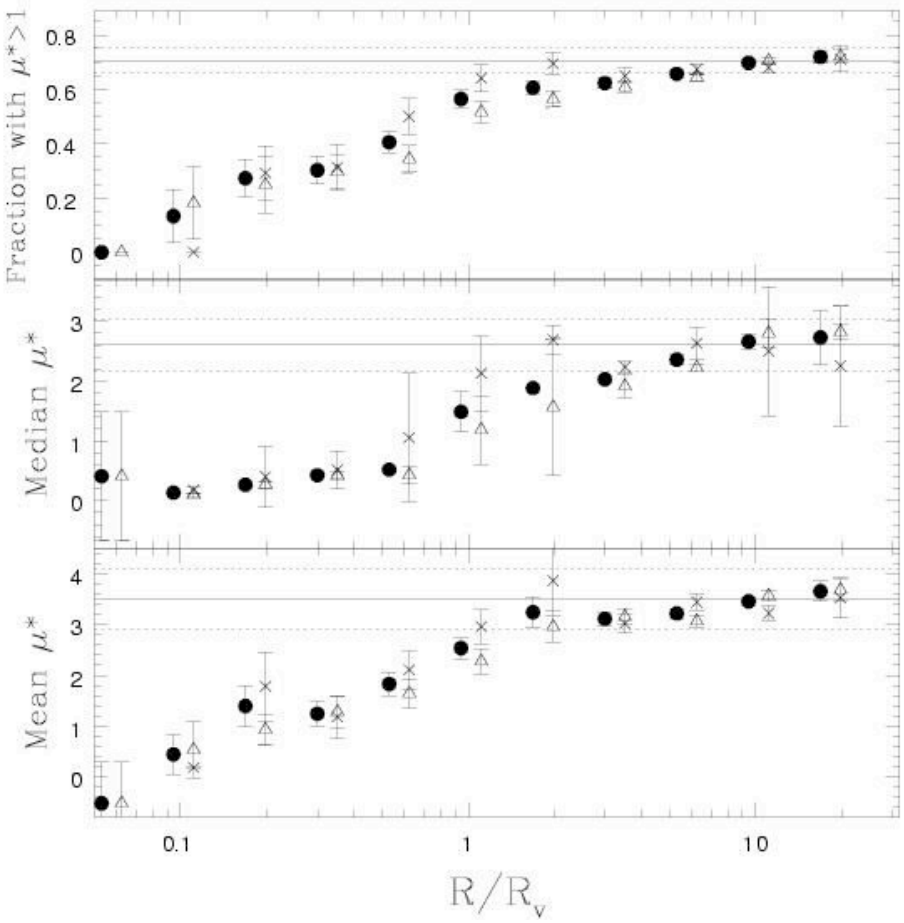
- Increase in fraction of blue, star-forming, late-type galaxies.
- Evolution in morphology-density relation and color-magnitude relationship.
- Increase in fraction of mergers and interactions
- Larger fraction of post-starburst “K+A” galaxies
- Increased overdensity of submm, radio, and X-ray sources



Lubin et al. 2002; Postman et al. 2005; Cappelluti et al. 2005

Effect of the Cluster Environment

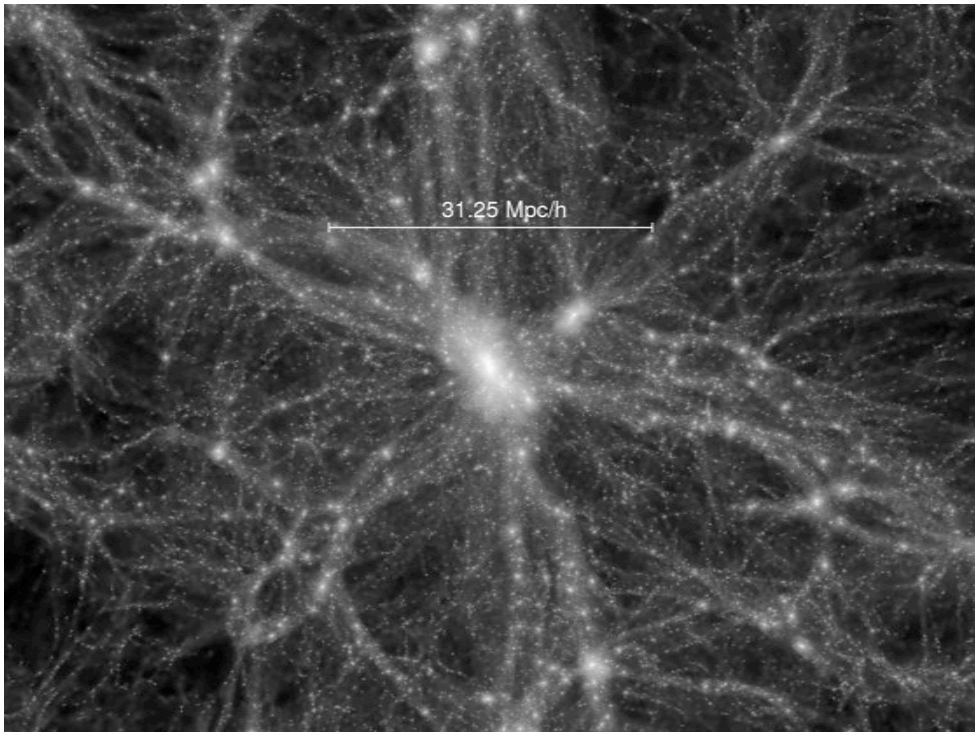
- Dense environments are generally hostile to star formation.
- Traditionally thought to be a result of galaxy interactions with the hot intracluster medium (ram pressure stripping).
- Reduced star-formation rates in intermediate-density regimes on the outskirts of clusters suggest other mechanisms important as well.



Lewis et al. 2002

Going to Large Scales

- Pre-processing: large-scale environment around clusters plays a pivotal role in driving galaxy evolution before galaxies reach the intracluster medium.
- Other key processes associated with low-density environments and cluster infall regions :
  - Harassment
  - Starvation
  - Interactions / Mergers
  - AGN Feedback



Millennium Simulation - Springel et al. 2005

AGN Feedback

- Semi-analytic models indicate merger induced starbursts not sufficient to reproduce observed properties of massive galaxies today, requiring an additional heating mechanism.
- Gravitational torques produced as a result of galaxy mergers funnel material to galaxy's nuclear region, leading to elevated accretion onto central black hole and enhanced star formation.
- If sufficiently energetic, AGN drives outflows that disrupt host and quench ongoing star formation (Quasar-mode feedback).
- AGN luminosity decreases as galaxy moves onto red sequence.
- Low level AGN emission prevents further star formation once system is on the red sequence (Radio-mode feedback).

V. Springel - MPE

Going to Large Scales

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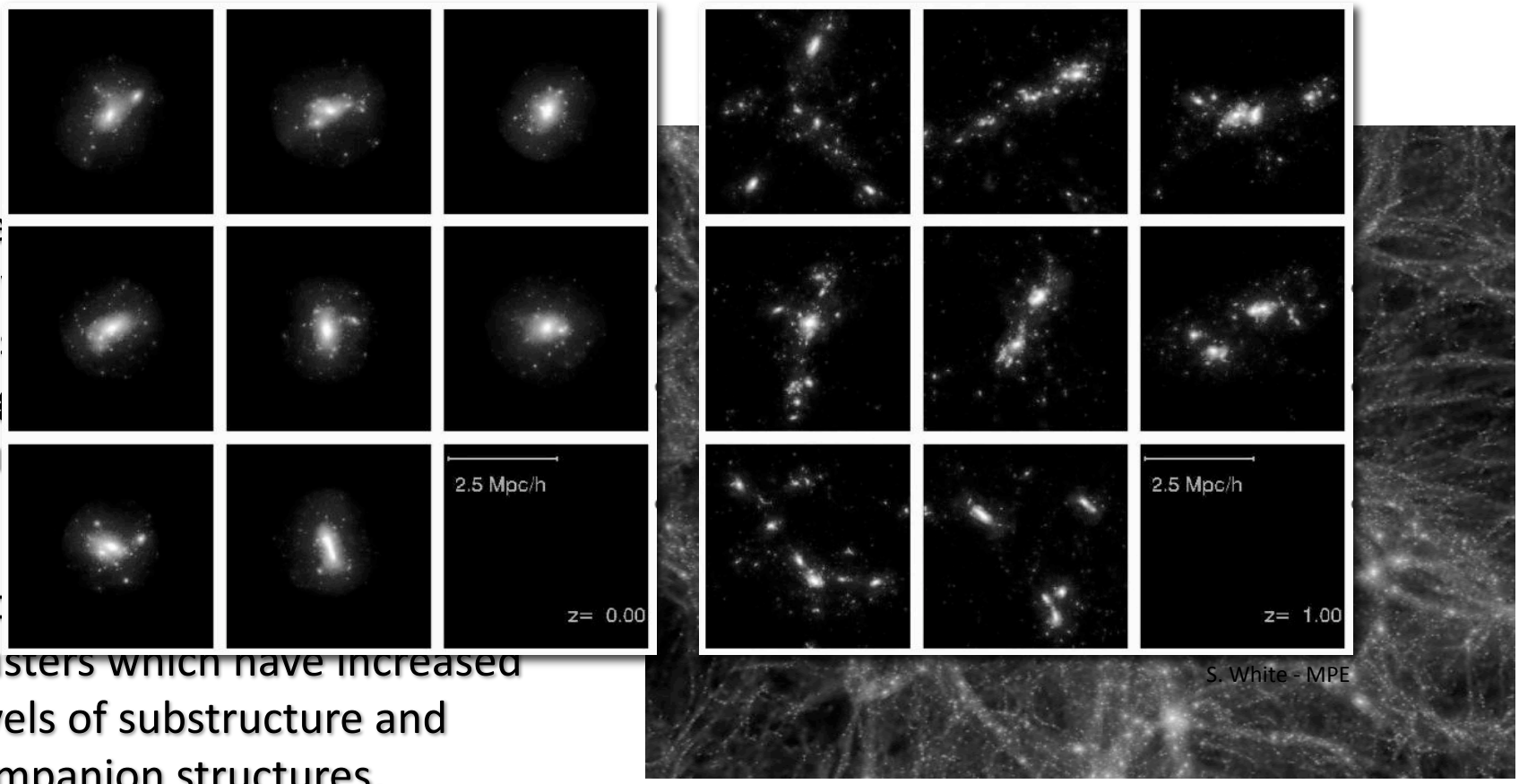
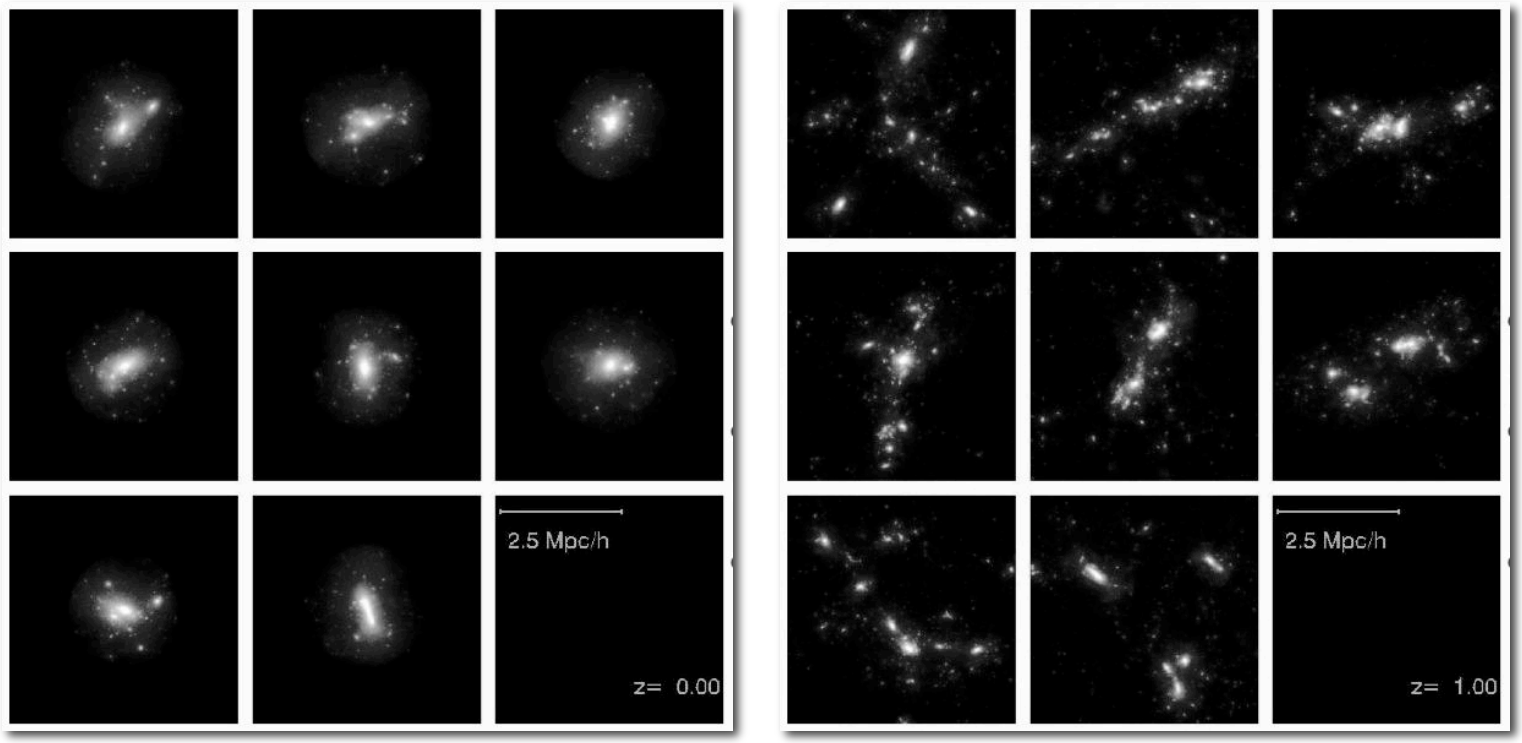
  clusters which have increased levels of substructure and companion structures.



Millennium Simulation - Springel et al. 2005

Going to Large Scales



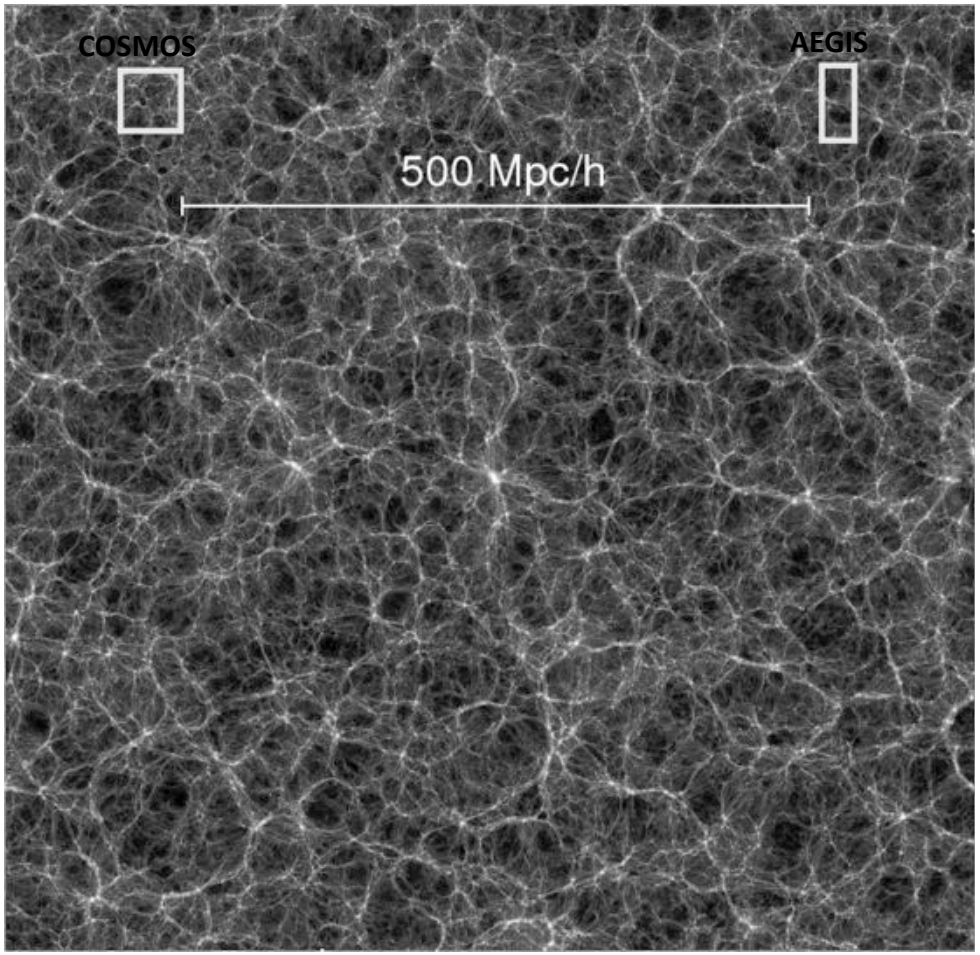
S. White - MPE

- Fraction of $M > 10^{14}\ M_{\odot}$ clusters with recent mergers increases with redshift.
- Hubble Volume Simulations indicate 50% of massive clusters at $z \approx 0.8$ are part of a supercluster (*two or more companion clusters of equal or greater mass within 100 co-moving Mpc*).
- Fraction of massive clusters with close companions of *group* size or greater is even larger.

Cohen et al. 2007, Metzler et al. 2008

Survey Strategy

- Search for LSS around 20 X-ray and optically selected clusters at 0.6 < z < 1.3 using deep, wide-field (30´) imaging in r´, i´, z´, J, K with:
  - LFC & WIRC - Palomar 5m
  - Suprime-Cam - Subaru 8m
  - WFCAM - UKIRT 4m
- High-resolution, multi-object spectroscopy with DEIMOS
- Multi-wavelength follow-up observations to study active galaxy population:
  - Optical - HST
  - X-ray - Chandra
  - Radio – VLA
  - MIR – Spitzer



Lubin et al. 2009

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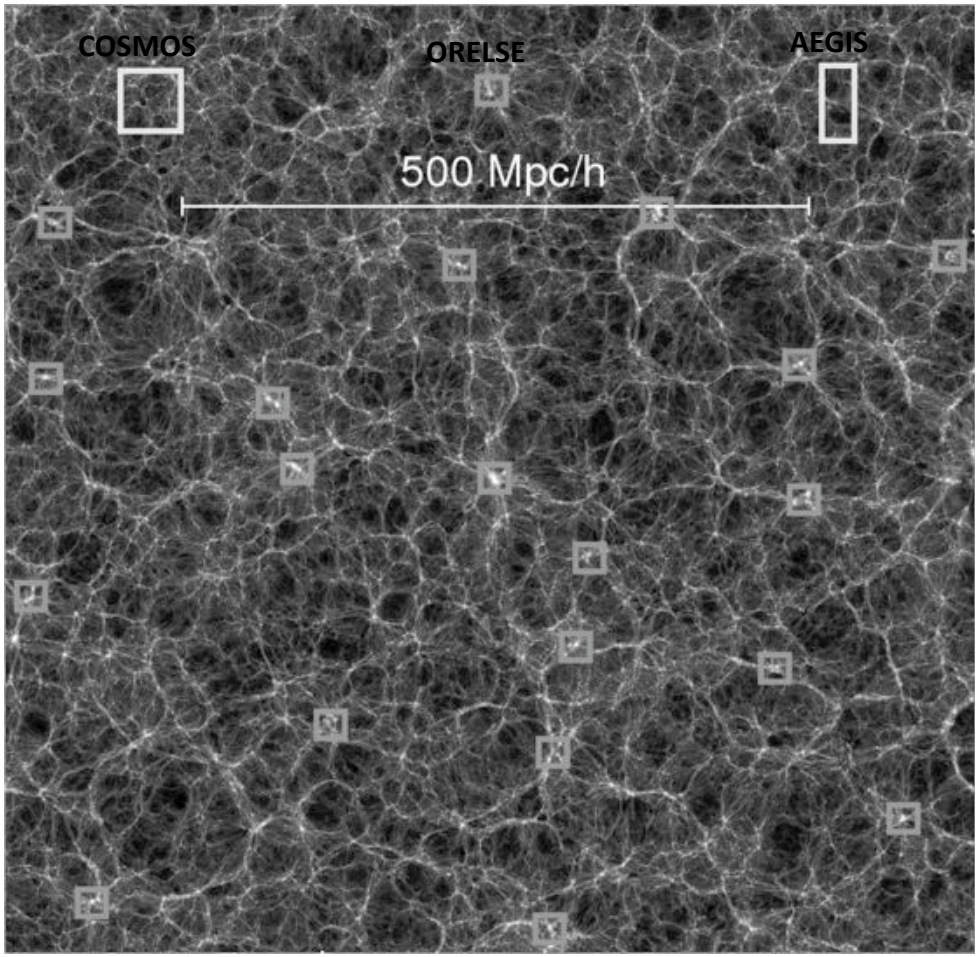
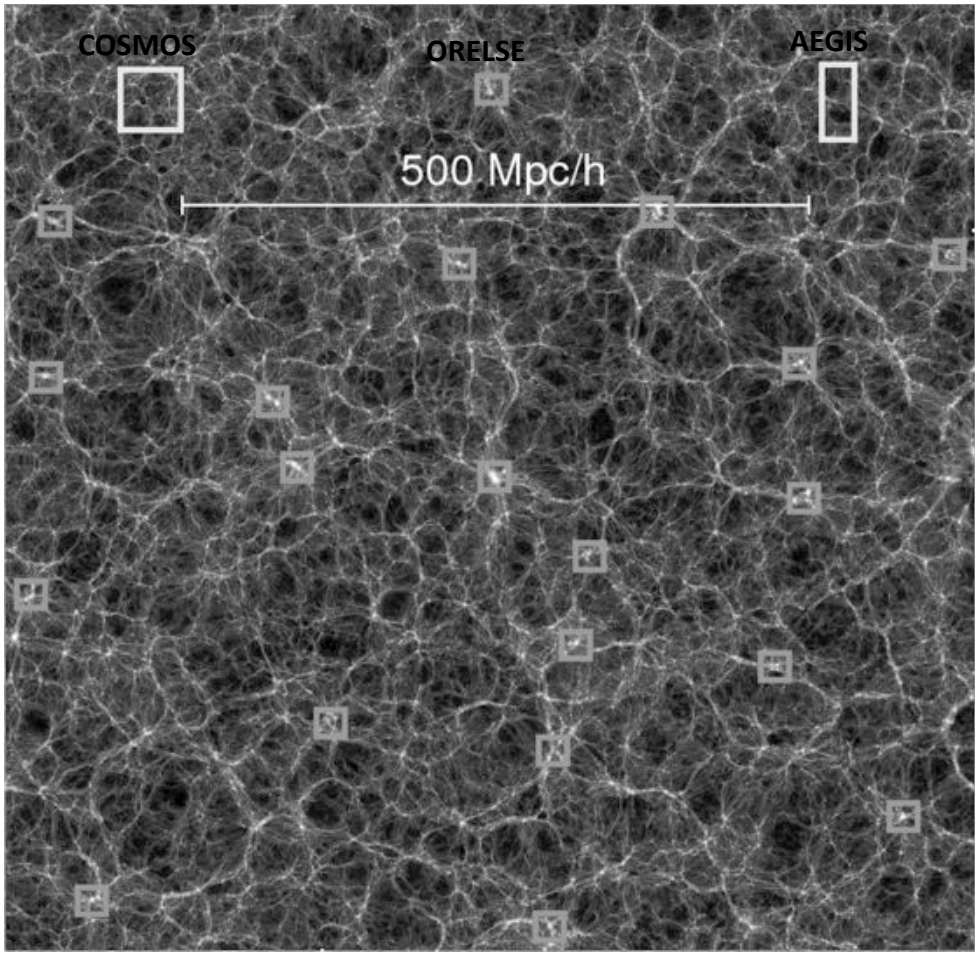


Lubin et al. 2009

Survey Progress

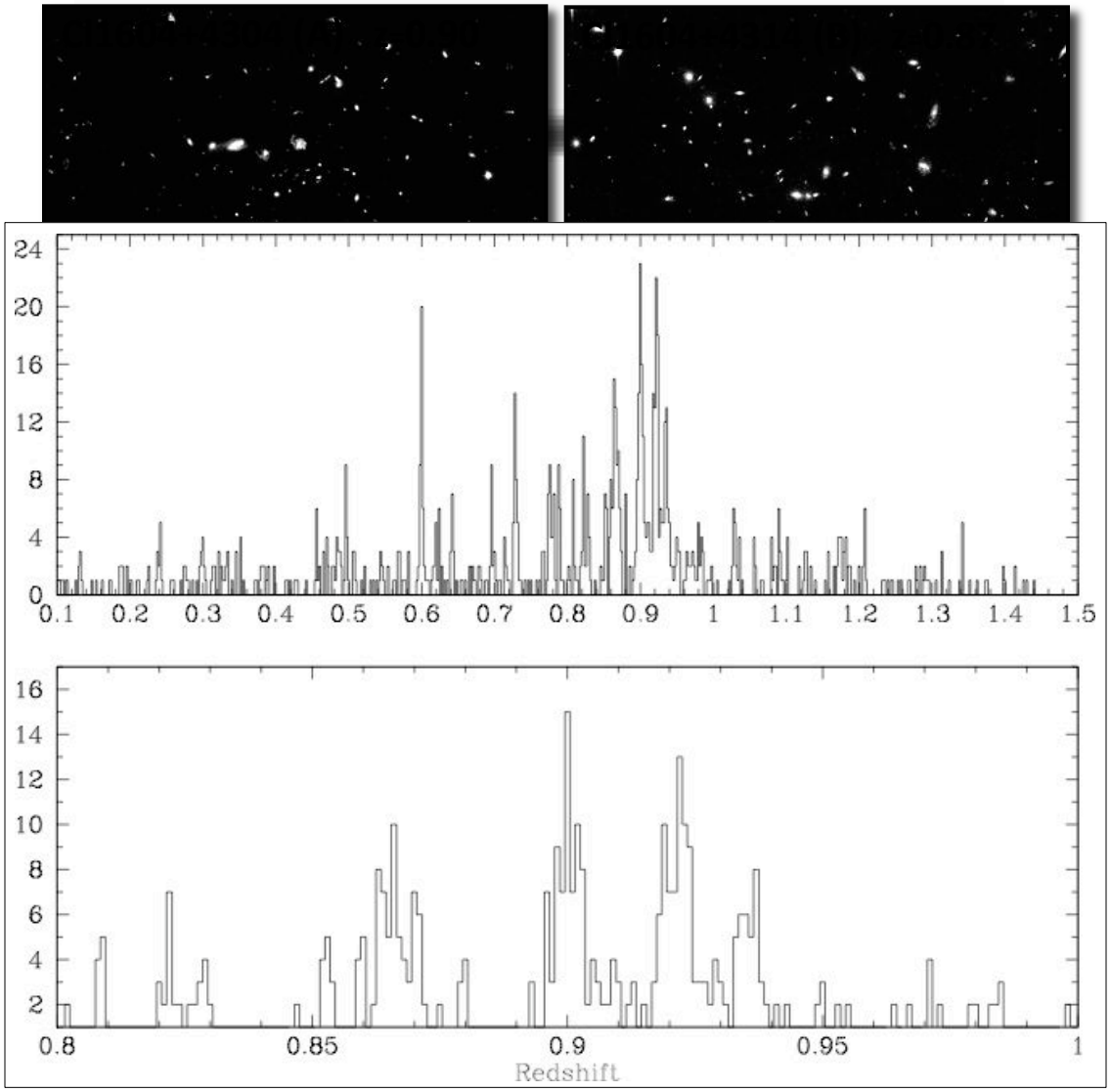
- Imaging survey of 5 square degrees in r´, i´, z´, J, K completed.
- Thus far confirmed:
  - Two large-scale superclusters
  - Two complex group mergers
  - Two isolated, X-ray luminous clusters
- Spectroscopic Follow-up:
  - 30 LRIS masks
  - 38 DEIMOS masks
  - Over 4000 redshifts so far



Lubin et al. 2009

The Cl1604 Supercluster

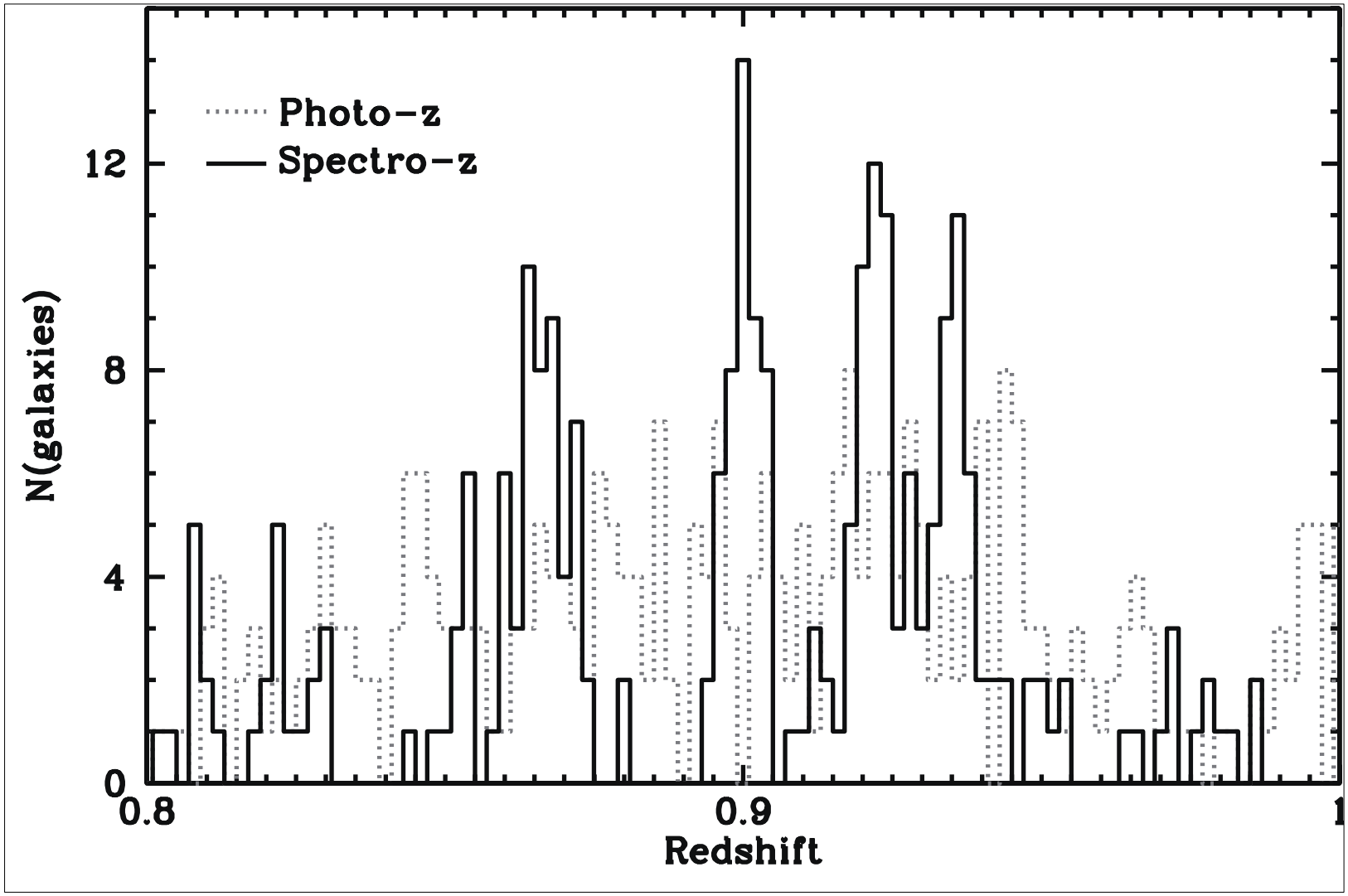
- 16h Supercluster (z=0.9):
  - 10 galaxy overdensities found in Palomar/LFC imaging
  - 4 spectroscopically confirmed clusters + 4 groups
  - Velocity dispersions range from 300-800 km/s
  - Structure size: 10 × 100 Mpc
- Follow-up Observations:
  - 1383 Redshifts obtained, 417 confirmed members
  - 17-pointing, 2-band ACS mosaic
  - 2 × 50 ksec Chandra observation
  - 35 hr VLA observation
  - 30 hr Spitzer observation



Red Galaxy Density Map

Gal et al. 2008

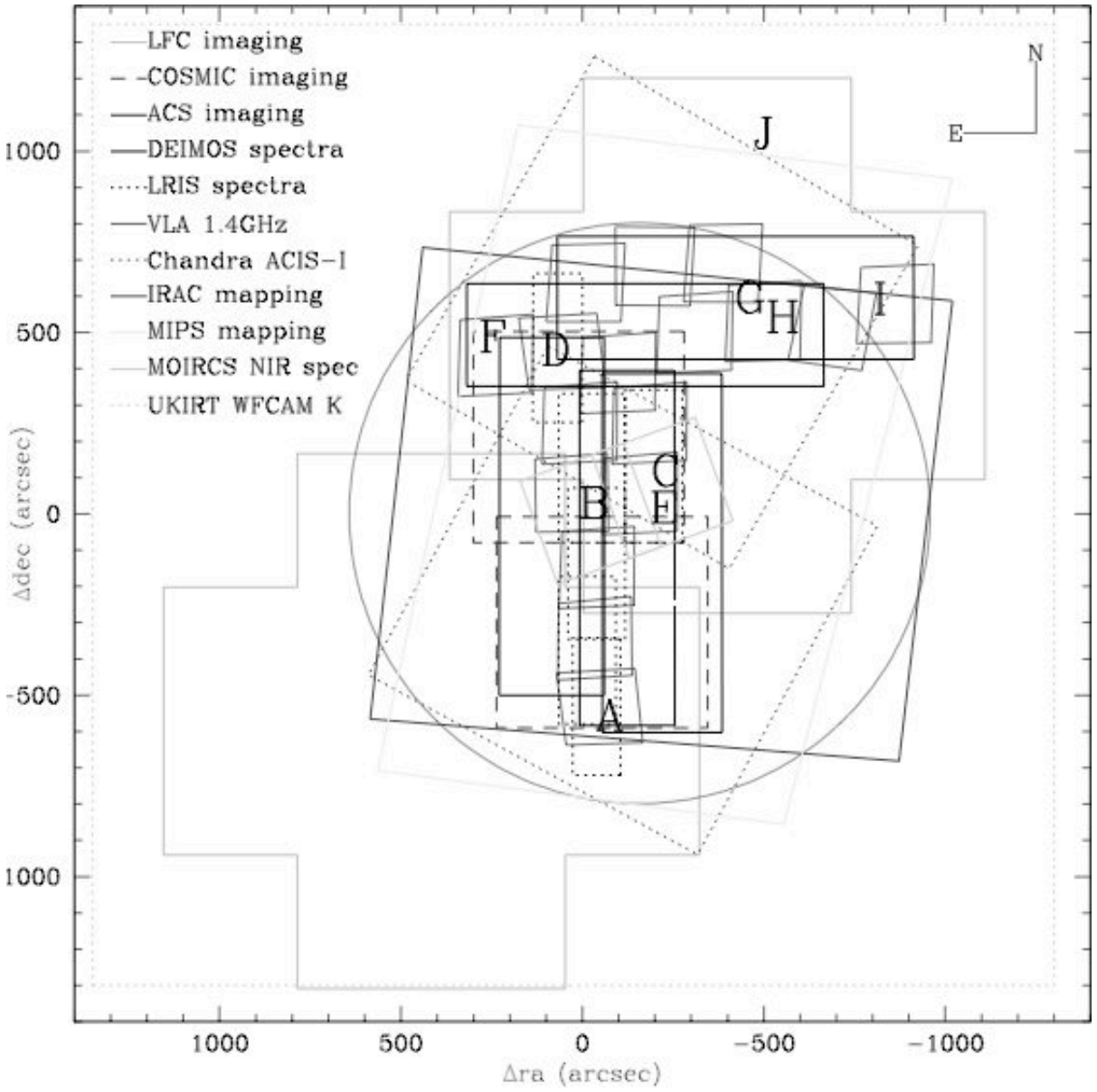
Importance of Spectroscopic Redshifts



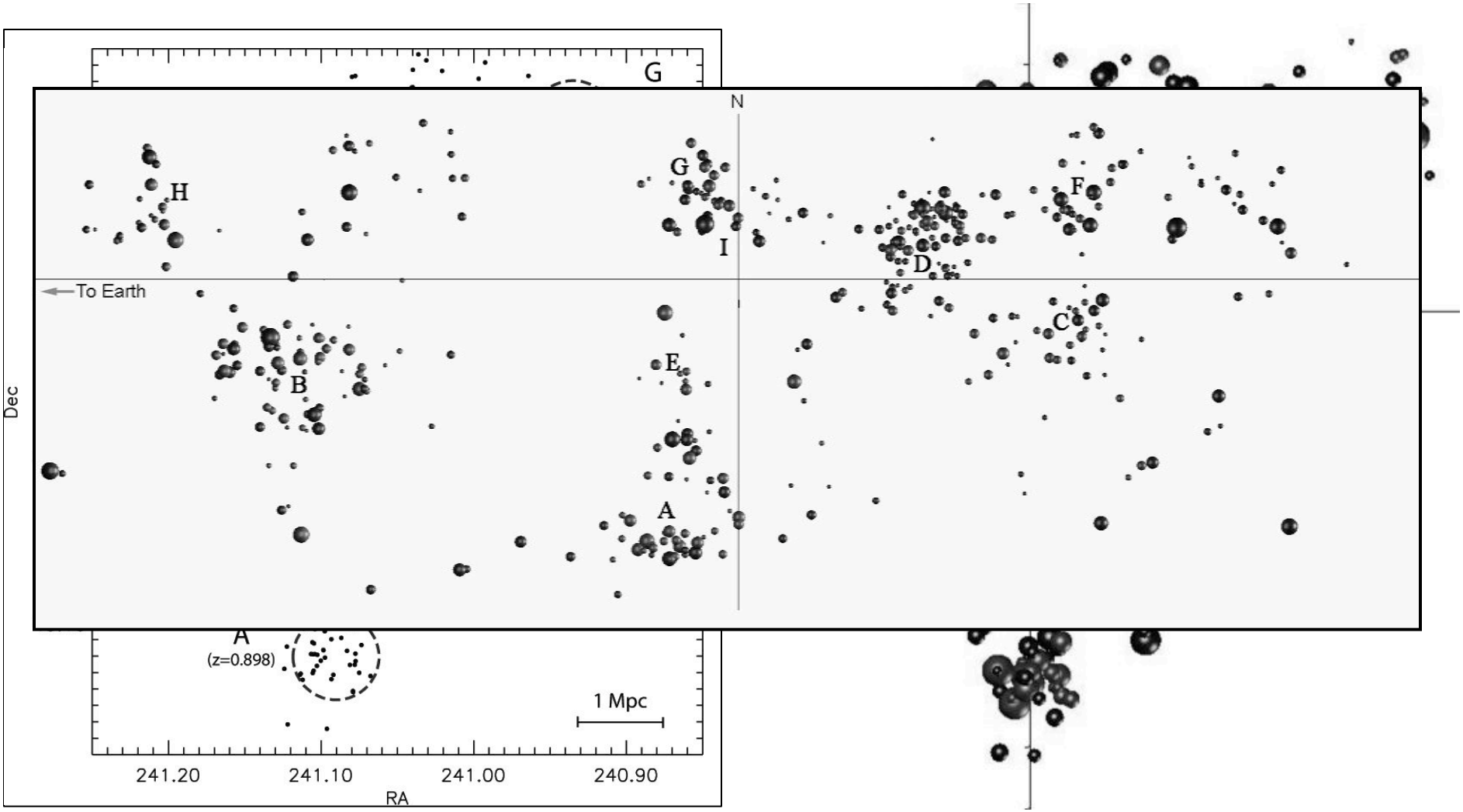
Gal et al. 2010

Photo-z from rizK+3.6 and 4.5 μm

The Multi-Wavelength Coverage

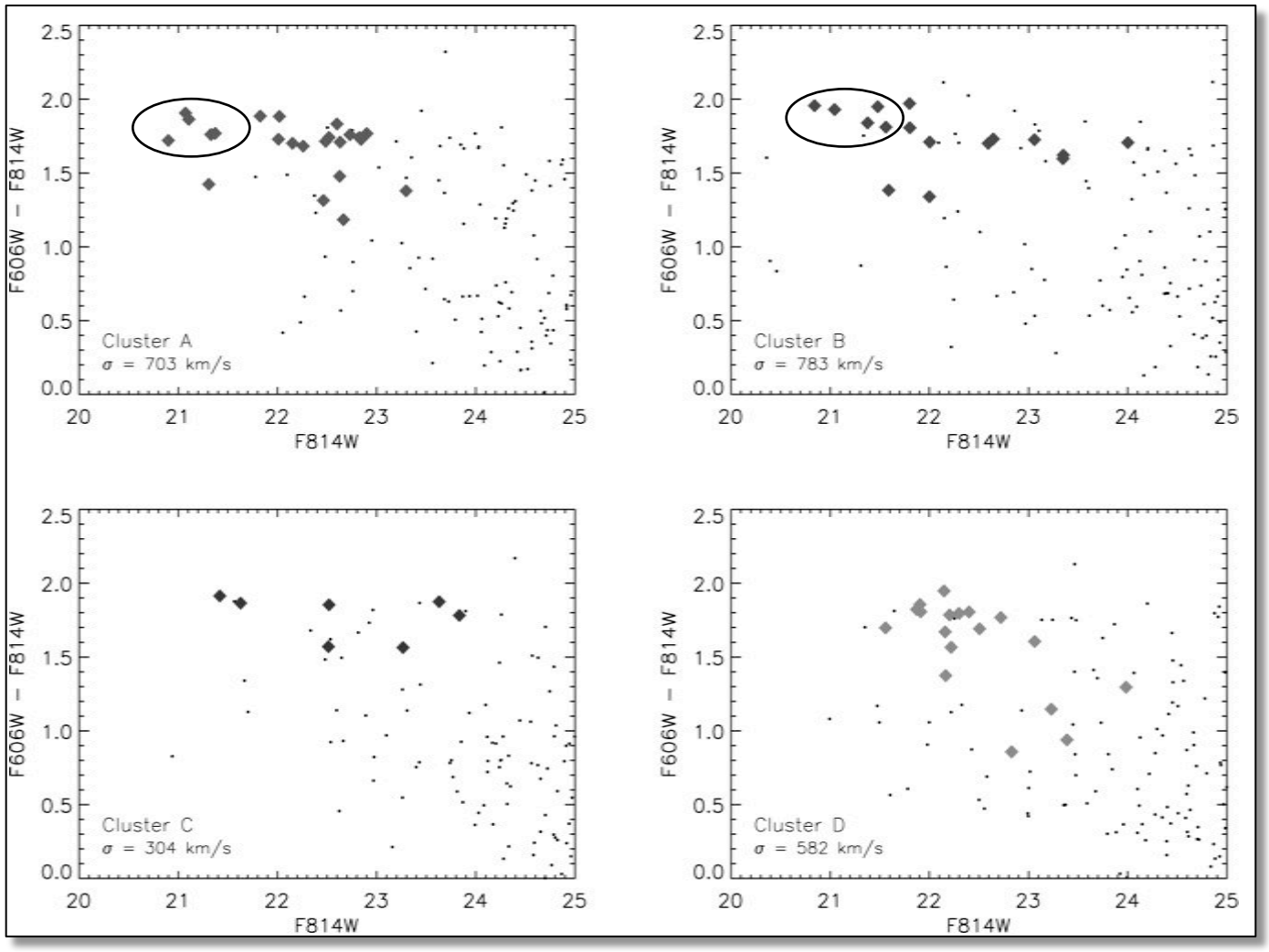


The Cl1604 Supercluster



Distribution of 417 Confirmed Members

Color-Magnitude Diagrams



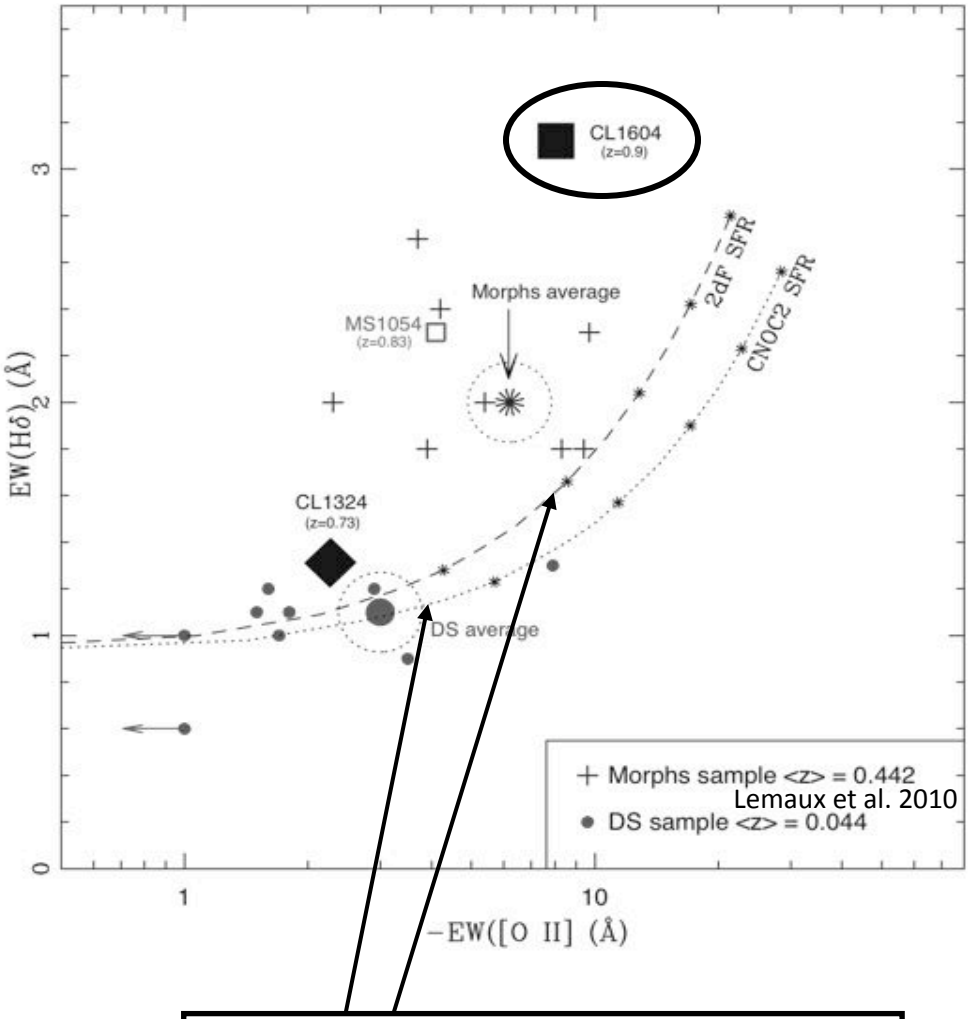
700-800 km/s

300-600 km/s

ACS (F814-F606W) versus F814W within 0.5 Mpc centered on each cluster

Spectroscopic Results

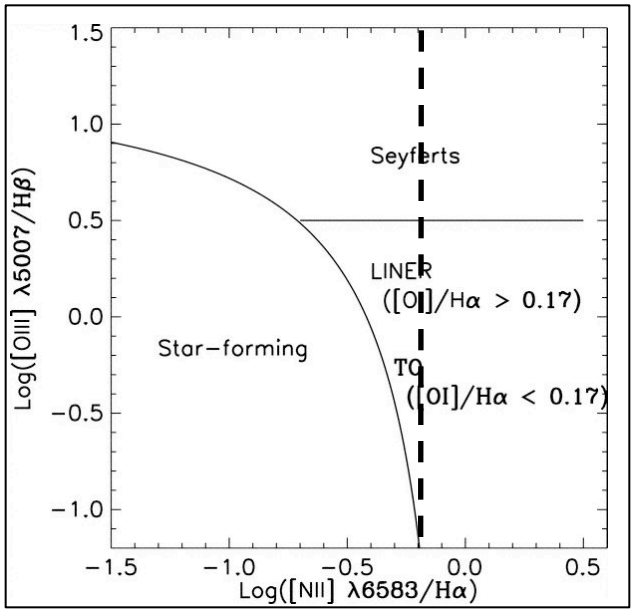
- 74% exhibit [OII] emission
- 11% K+A galaxies ([OII] > -5Å; Hδ > 5Å)
- Composite Spectrum :
  - Average equivalent width of [OII] = -8.0Å and Hδ = 3.1Å
  - Strong Hδ not consistent with simple increase in fraction of galaxies with normal star formation (see Dressler et al. 2004)
  - Implies larger fraction of post-starburst galaxies than local and moderate-redshift clusters



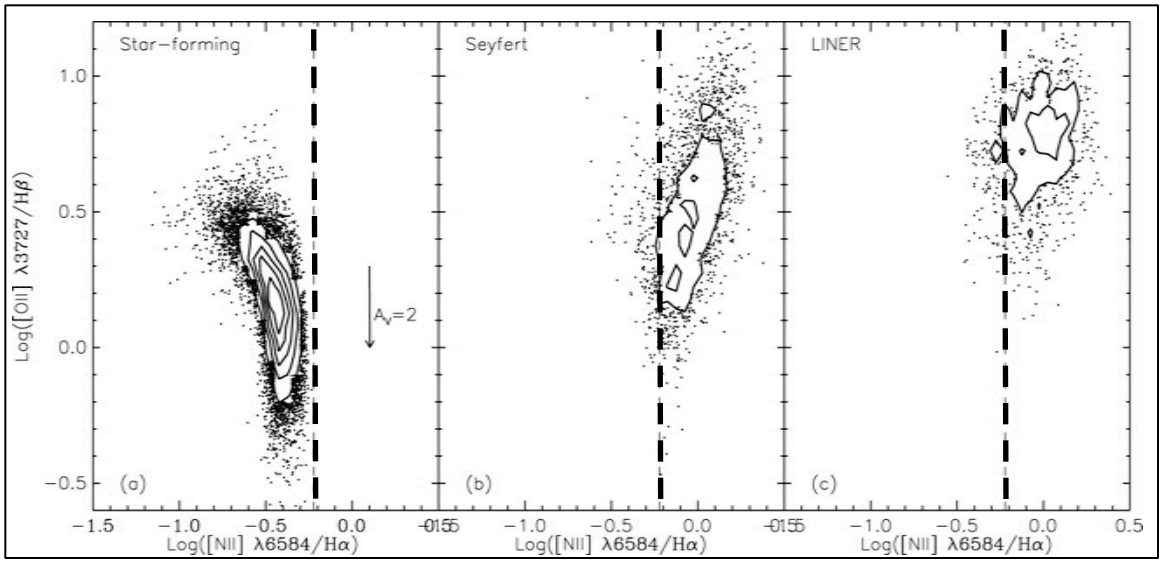
Different mix of passive galaxies and continuously SF galaxies

Spectroscopic Results

- Large fraction of post-starburst and red sequence members show [OII] emission lines:
  - Is [OII] from normal star formation or AGN activity?
  - How does this affect the "K+A" classification?
  - Effects on high-redshift surveys?



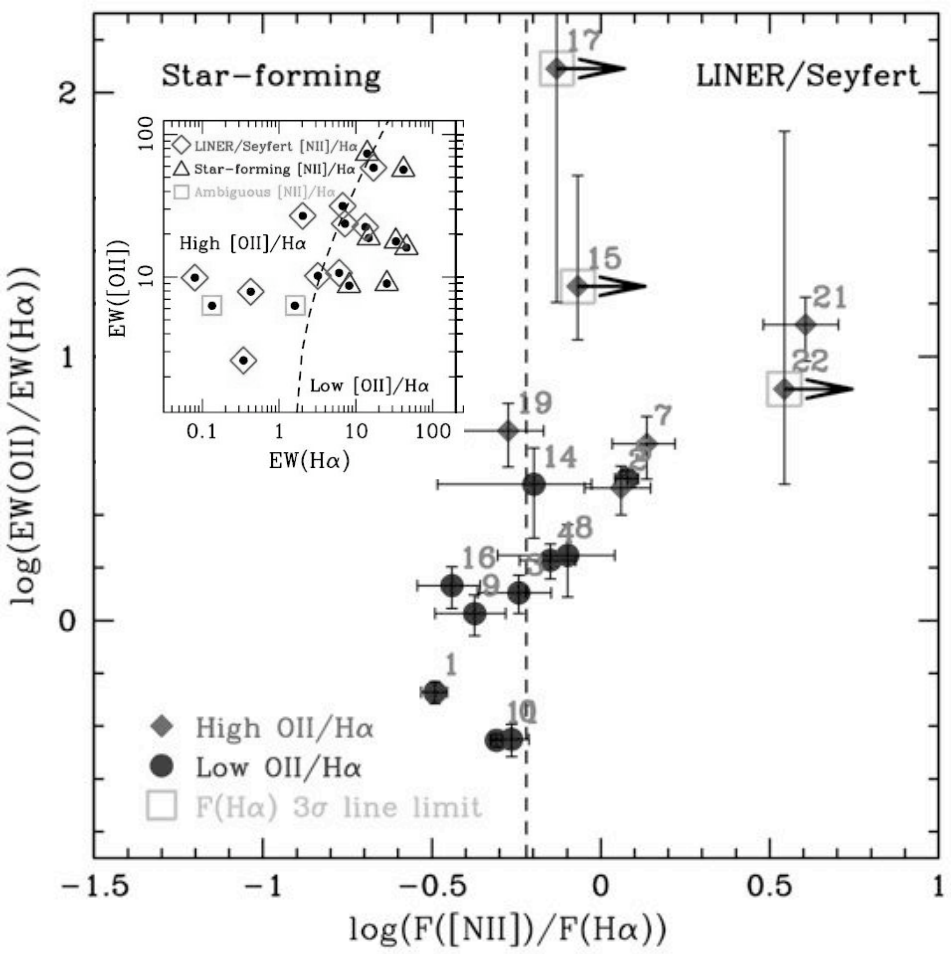
- Can use BPT diagrams to distinguish AGN from star-forming systems (Yan et al. 2006)



Yan et al. 2006; SDSS

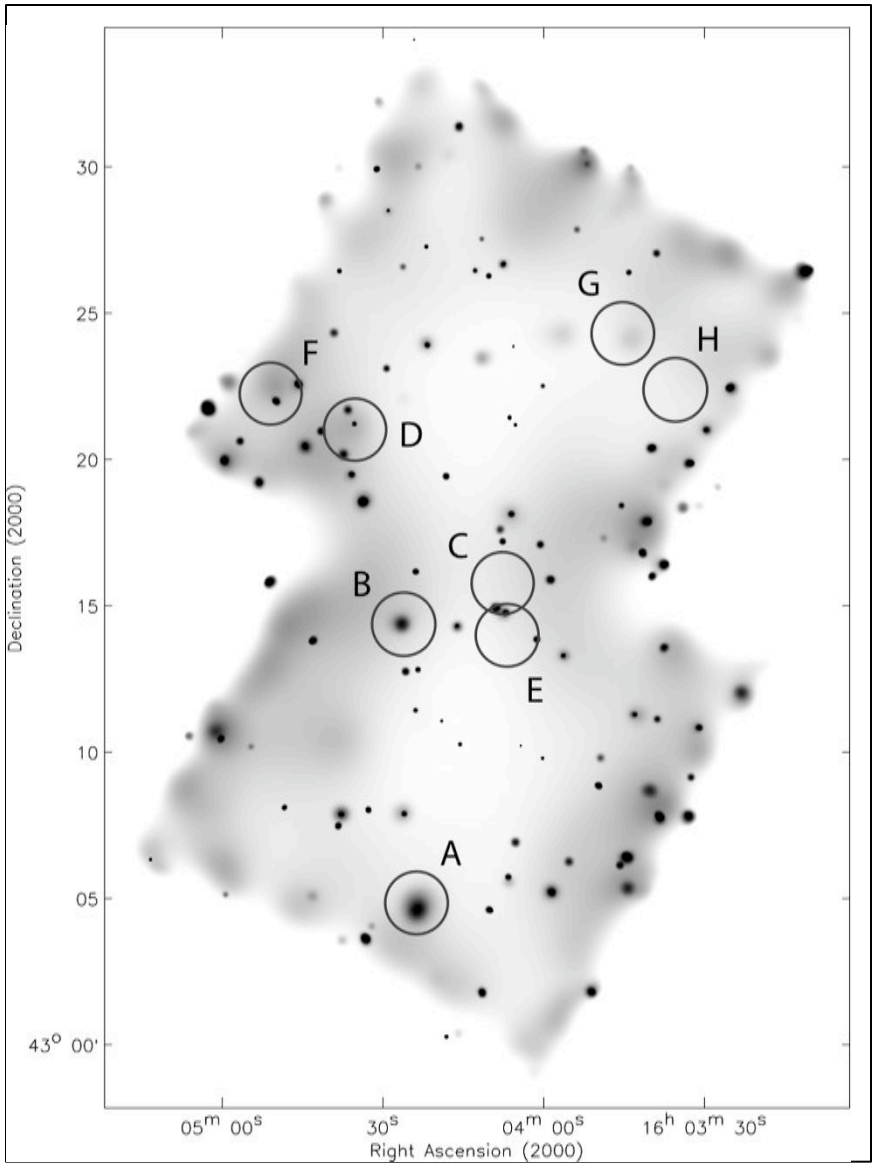
Spectroscopic Results

- Large fraction of post-starburst and red sequence members show [OII] emission lines.
- NIRSPEC observations of Hα and [NII] from 17 high-priority galaxies :
  - Emission in 10 of these due to LINER/Seyfert activity.
  - Almost all LINER/Seyfert lie on or near the red sequence and are bulge-dominated.
  - 20% of [OII] emission may be due to LINER/Seyfert activity.
  - [OII] is not an accurate tracer of star-formation in all cases – implications for high-redshift surveys that rely on [OII] alone.

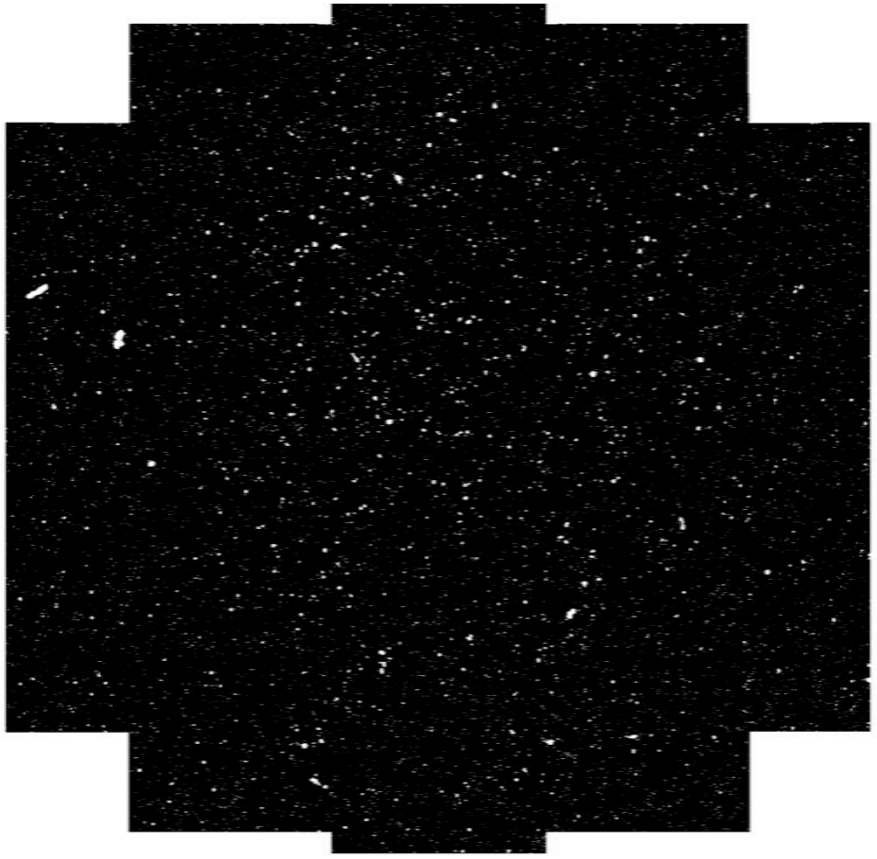


Lemaux et al. 2010

Overdensity of X-ray & Radio Sources



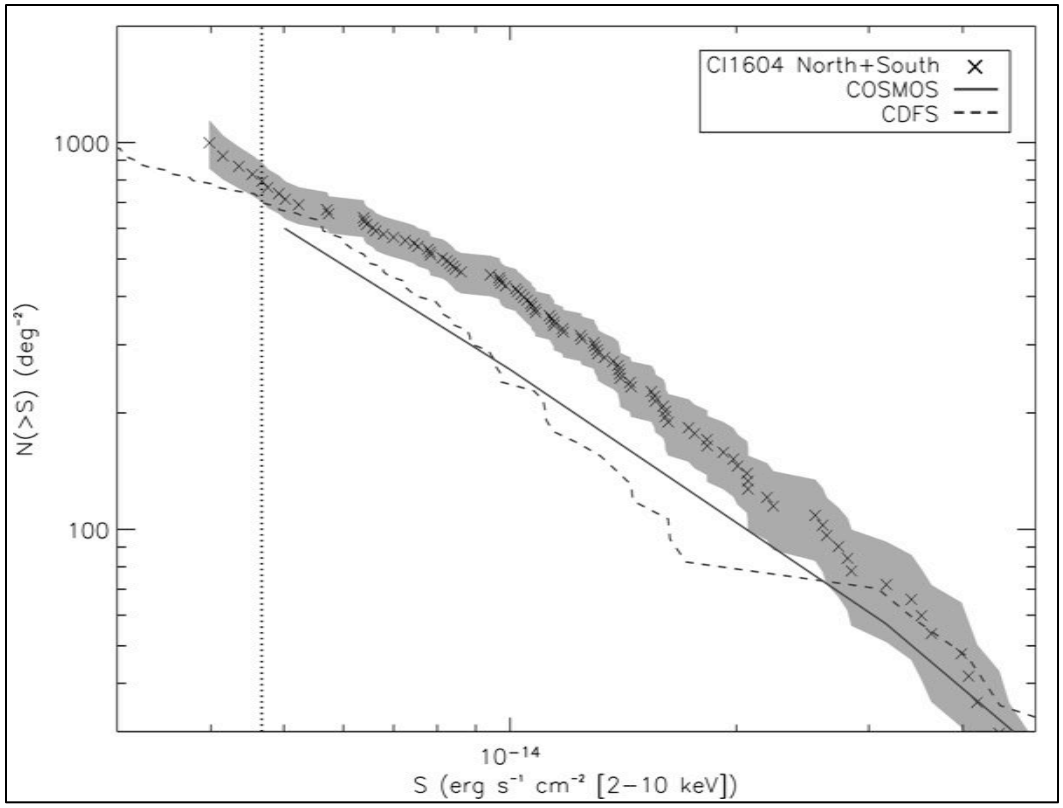
2 × 50 ksec Chandra ACIS-I observations



VLA B-Array 20-cm Image

Overdensity of X-ray Sources

- 2.5σ excess of hard band (2-10 keV) detected X-ray sources in an area covering two ACIS-I pointings (0.154 sq deg).
- No such excess observed in the soft band (0.5-2 keV).
- Source density is 1.47 times greater than a blank field.
- 161 sources detected, 112 matched to optical sources.
- 9 AGN found within the Supercluster with $L_X = 0.8\text{-}5 \times 10^{43}$ erg/s



Kocevski et al. 2009a

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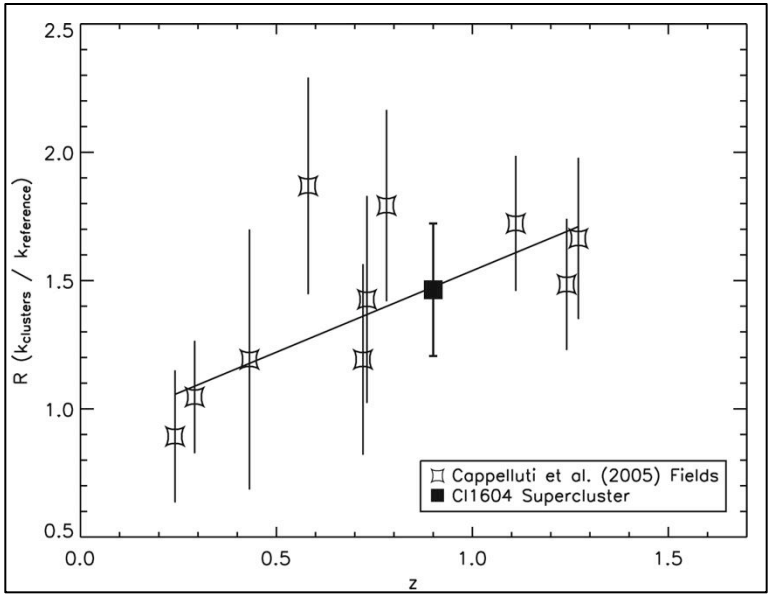
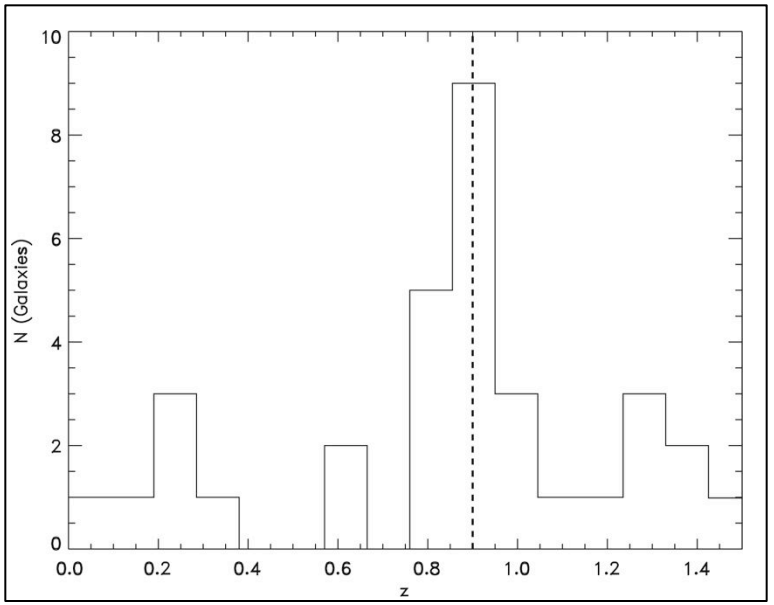
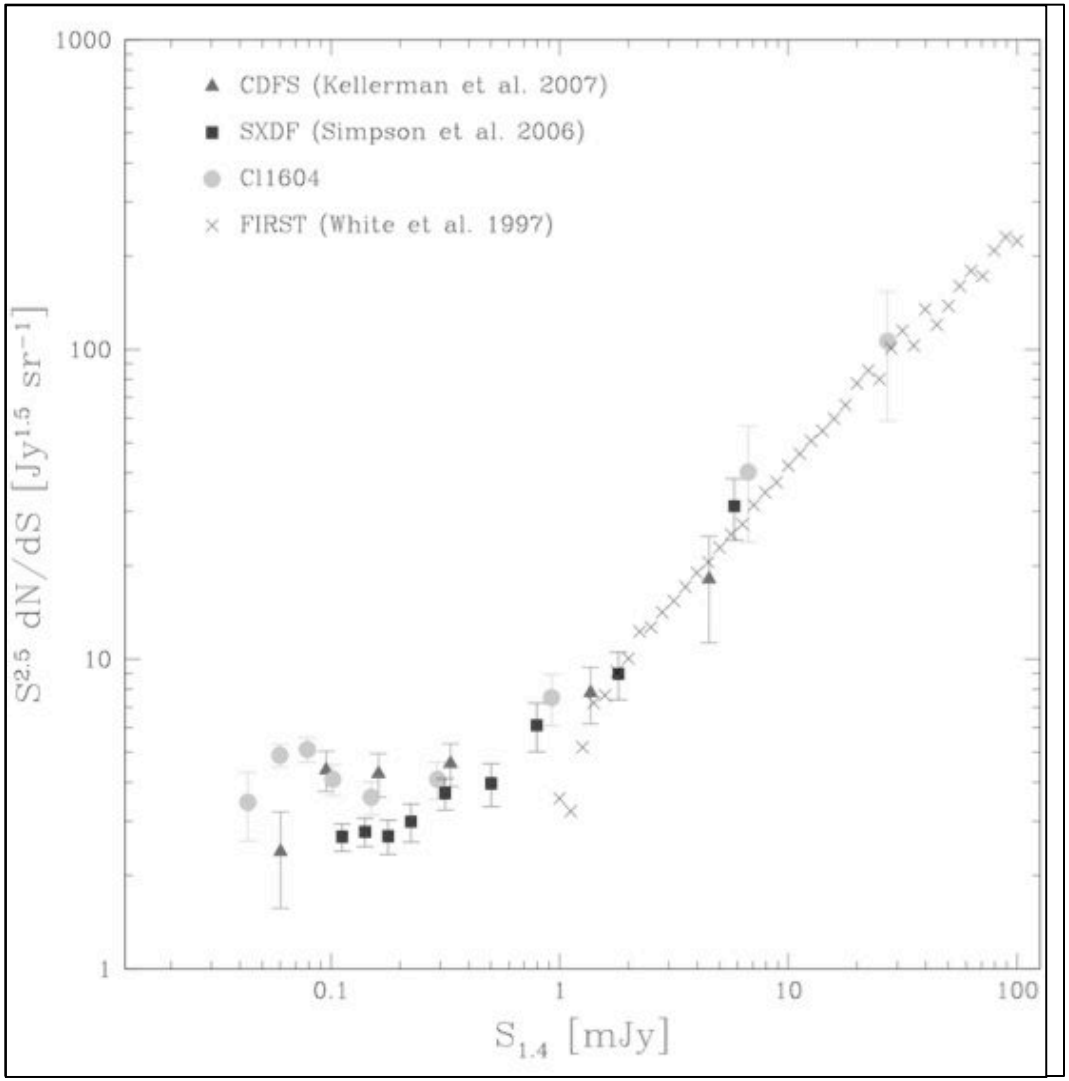


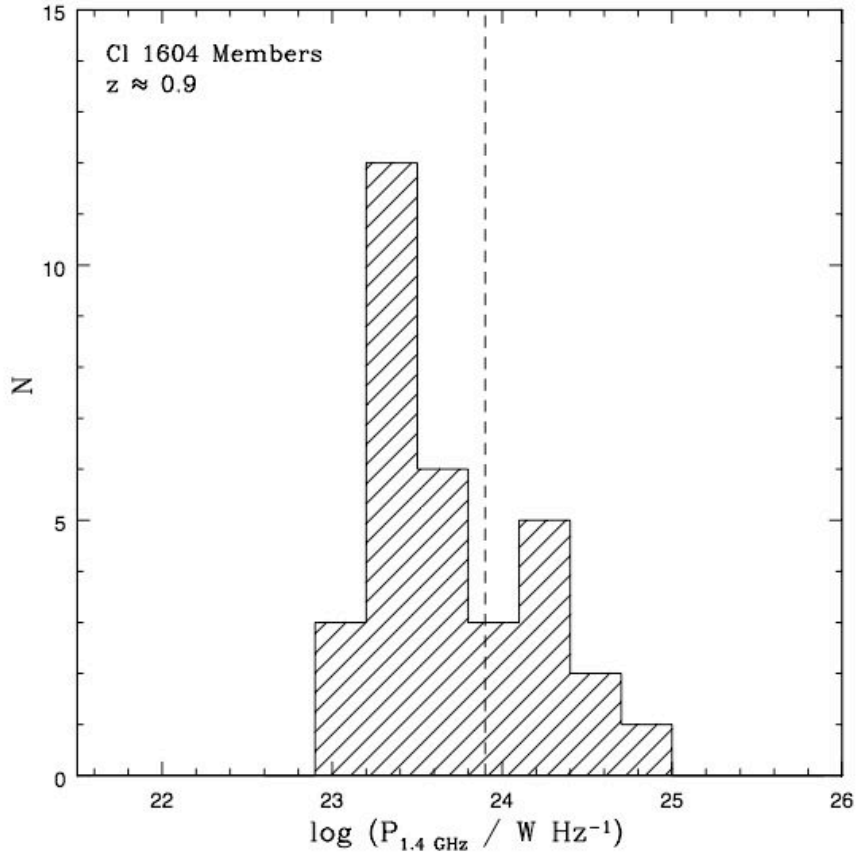


Overdensity of Radio Sources

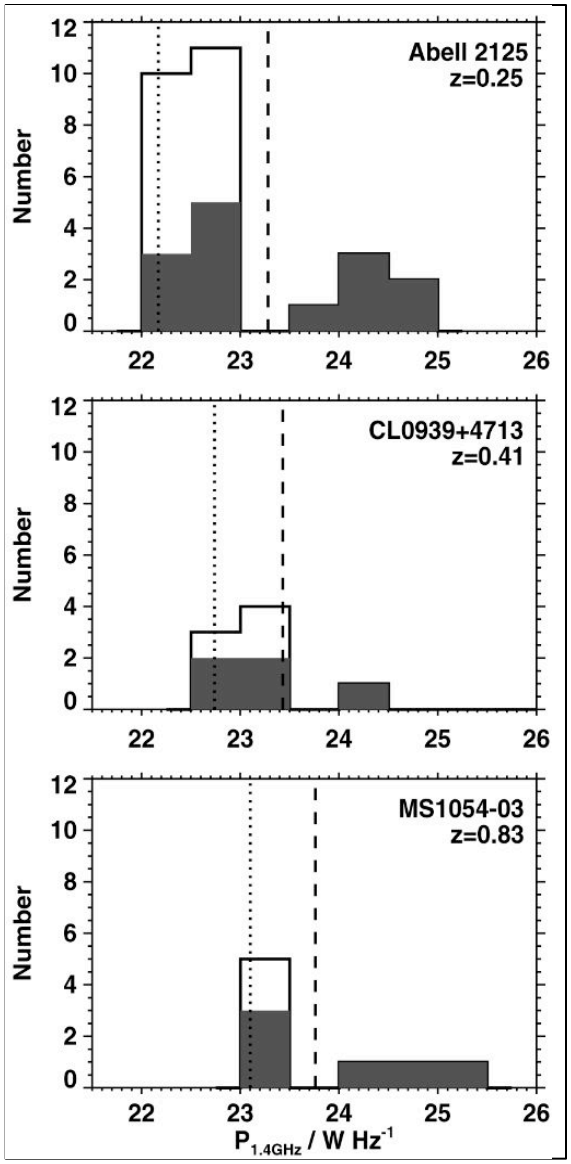


671 Radio sources detected, 101 with redshifts
32 supercluster members

Radio Flux Distribution



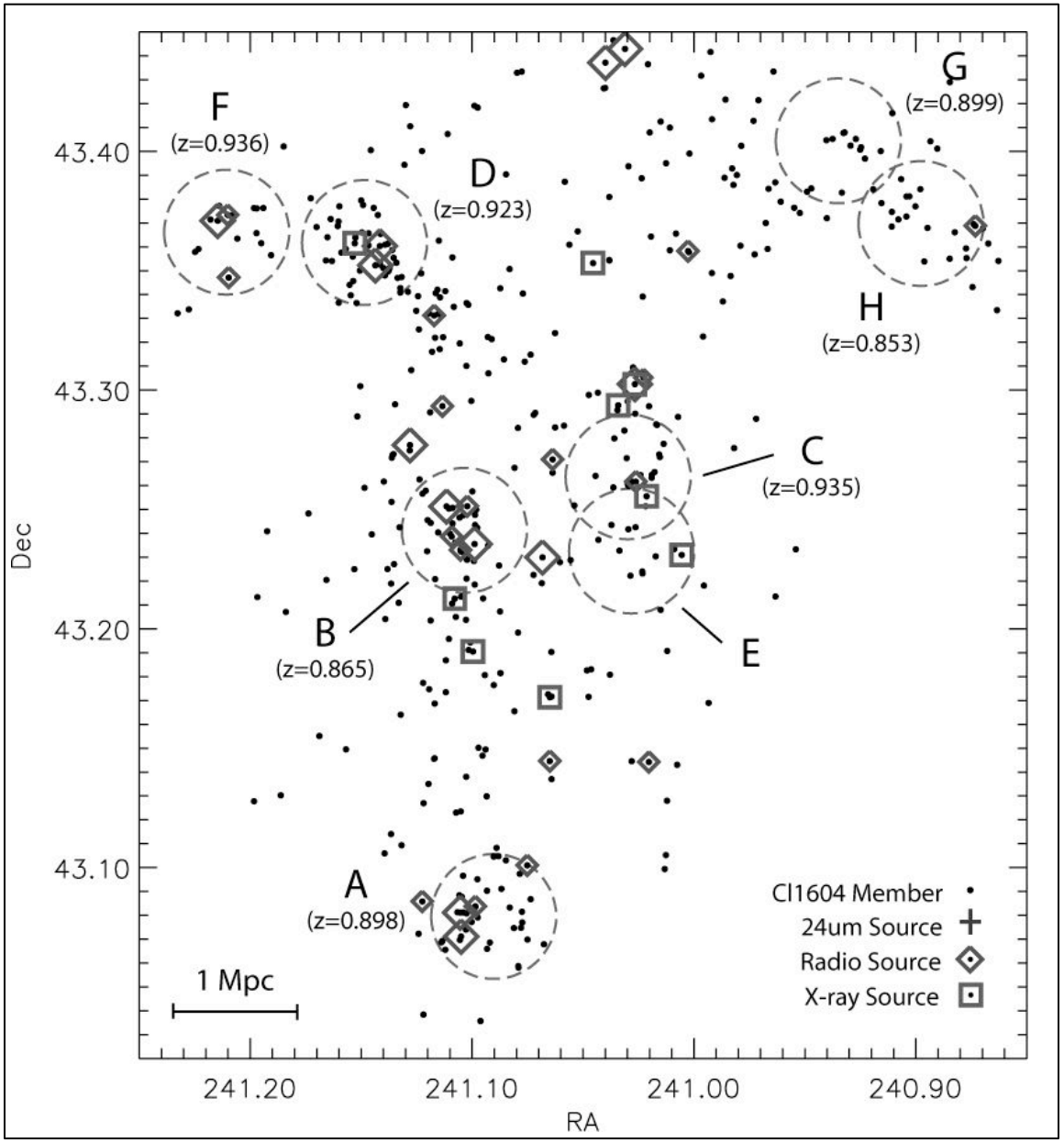
Lubin et al. 2010



Best et al. 2002

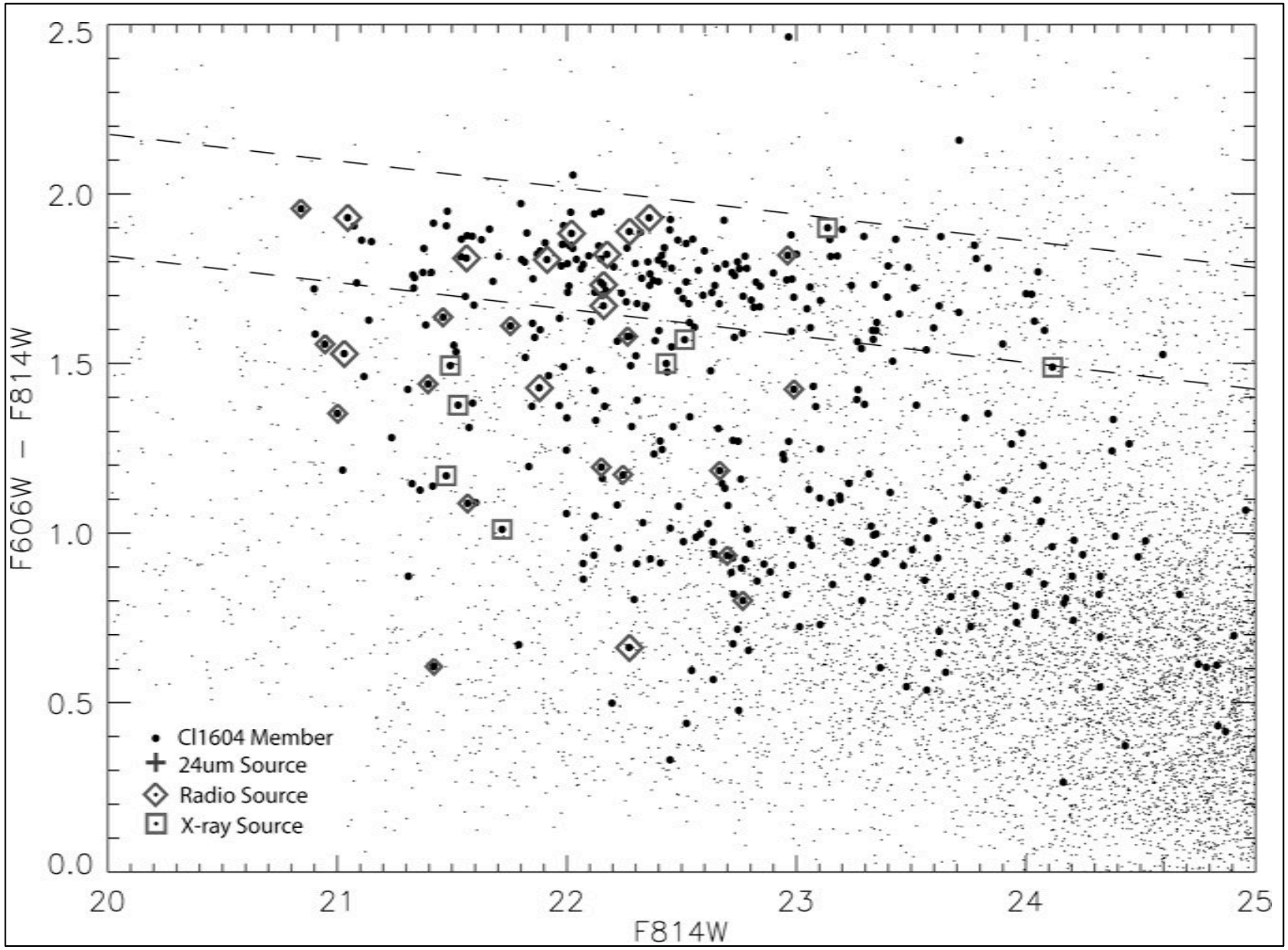
- Higher fraction of weaker radio sources, indicative of the supercluster's unrelaxed state
- Luminosity evolution, with the entire distribution shifter toward higher luminosities.

Active Galaxy Environments



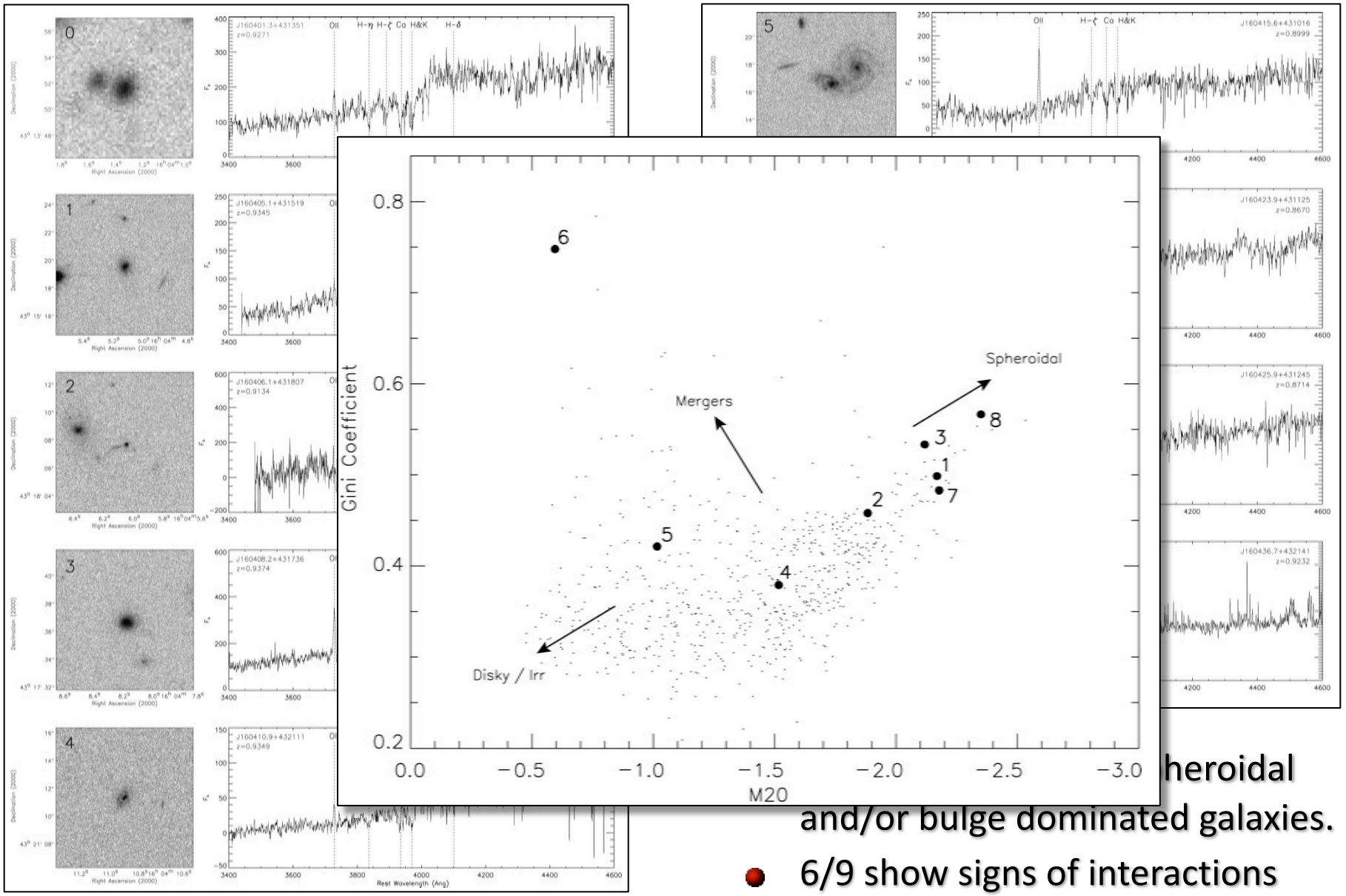
Kocevski et al. 2009b

Active Galaxy Colors



Kocevski et al. 2009b

X-ray AGN Morphologies

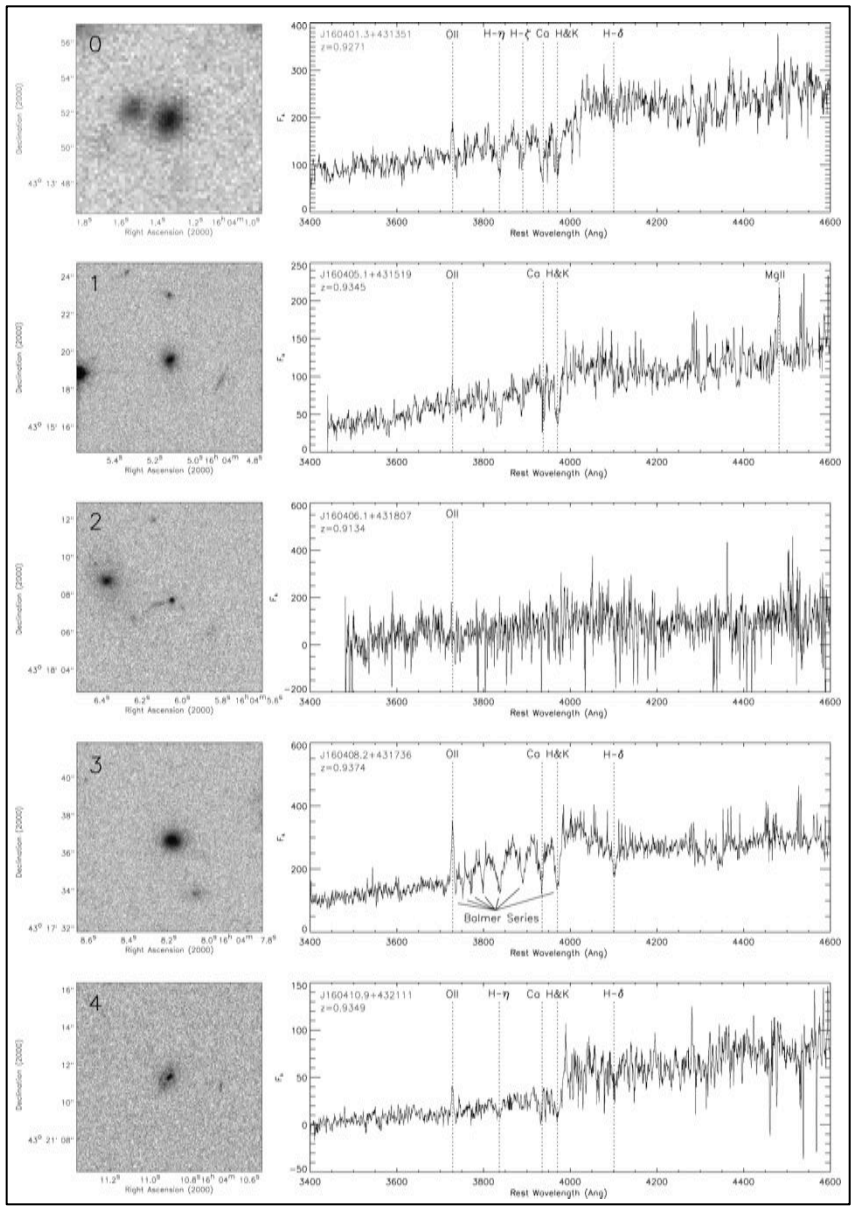


heroidal and/or bulge dominated galaxies.

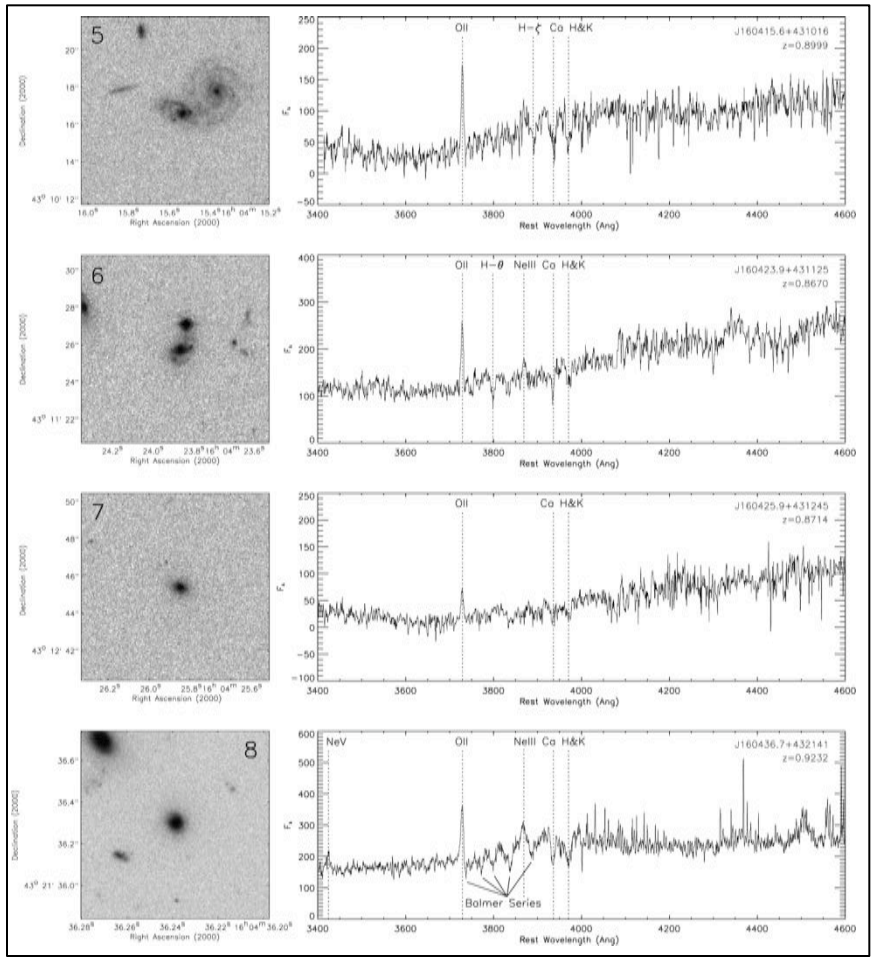
- 6/9 show signs of interactions

Kocevski et al. 2009b

X-ray AGN Spectral Properties

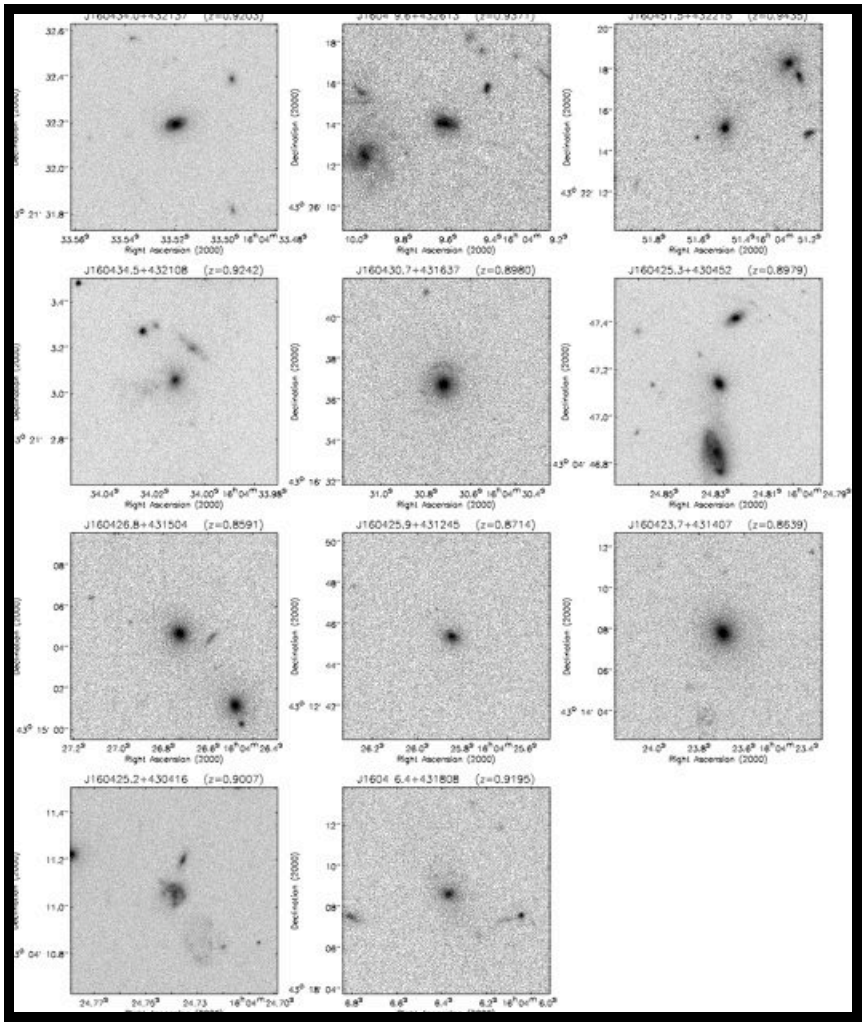


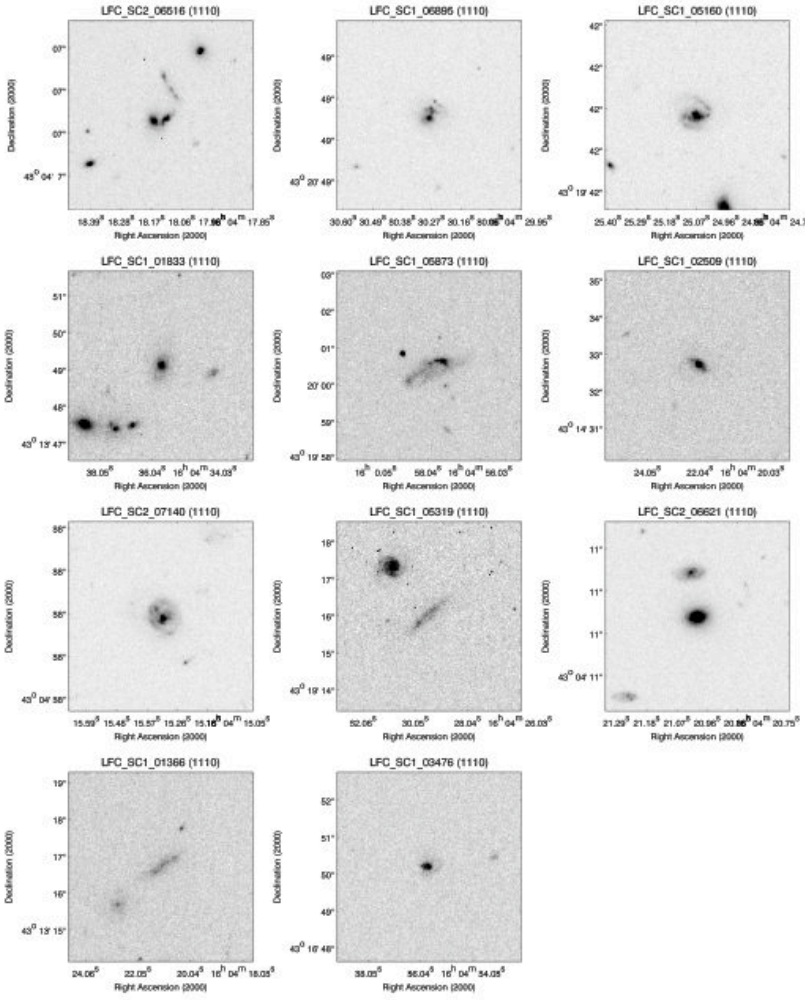
Kocevski et al. 2009b



- 4/9 show indications of post-starburst activity: strong H_δ absorption or Balmer series.
- Preliminary NIRSPEC observations suggest [OII] result of AGN.

Radio Source Morphologies



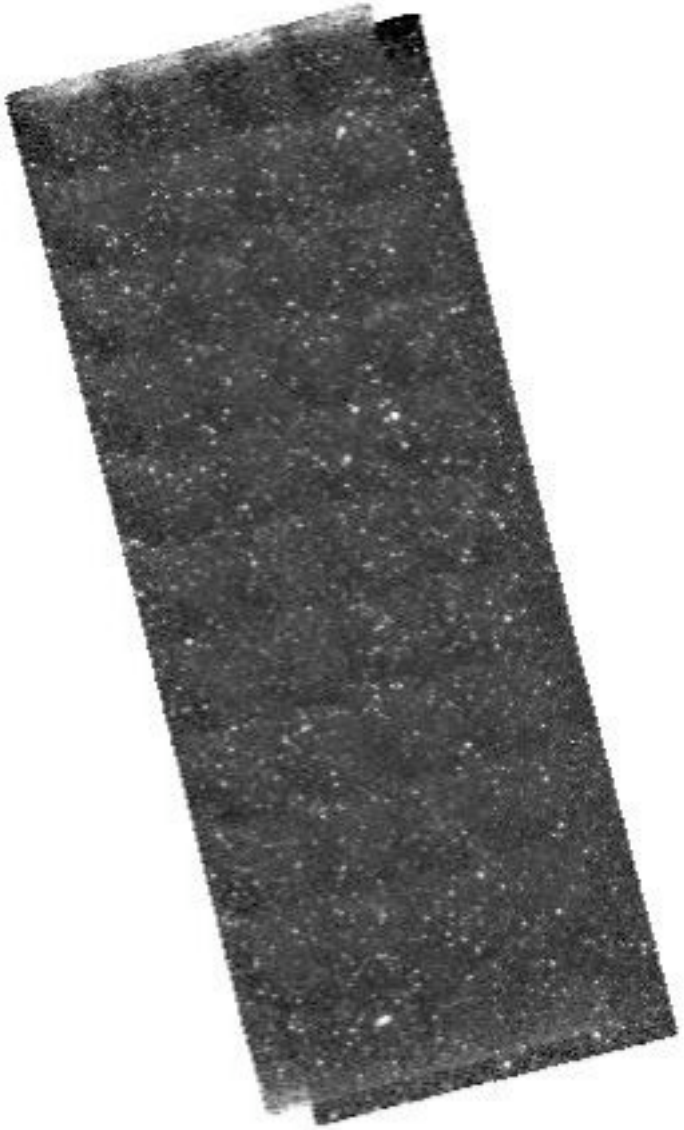


- **High L_{radio}**: spheroids, bulge-dominated or interactions, most show [OII] emission, lie on red sequence
- **Low L_{radio}**: mixture of morphological classes

Sorted by radio flux with □ > 150 μJy

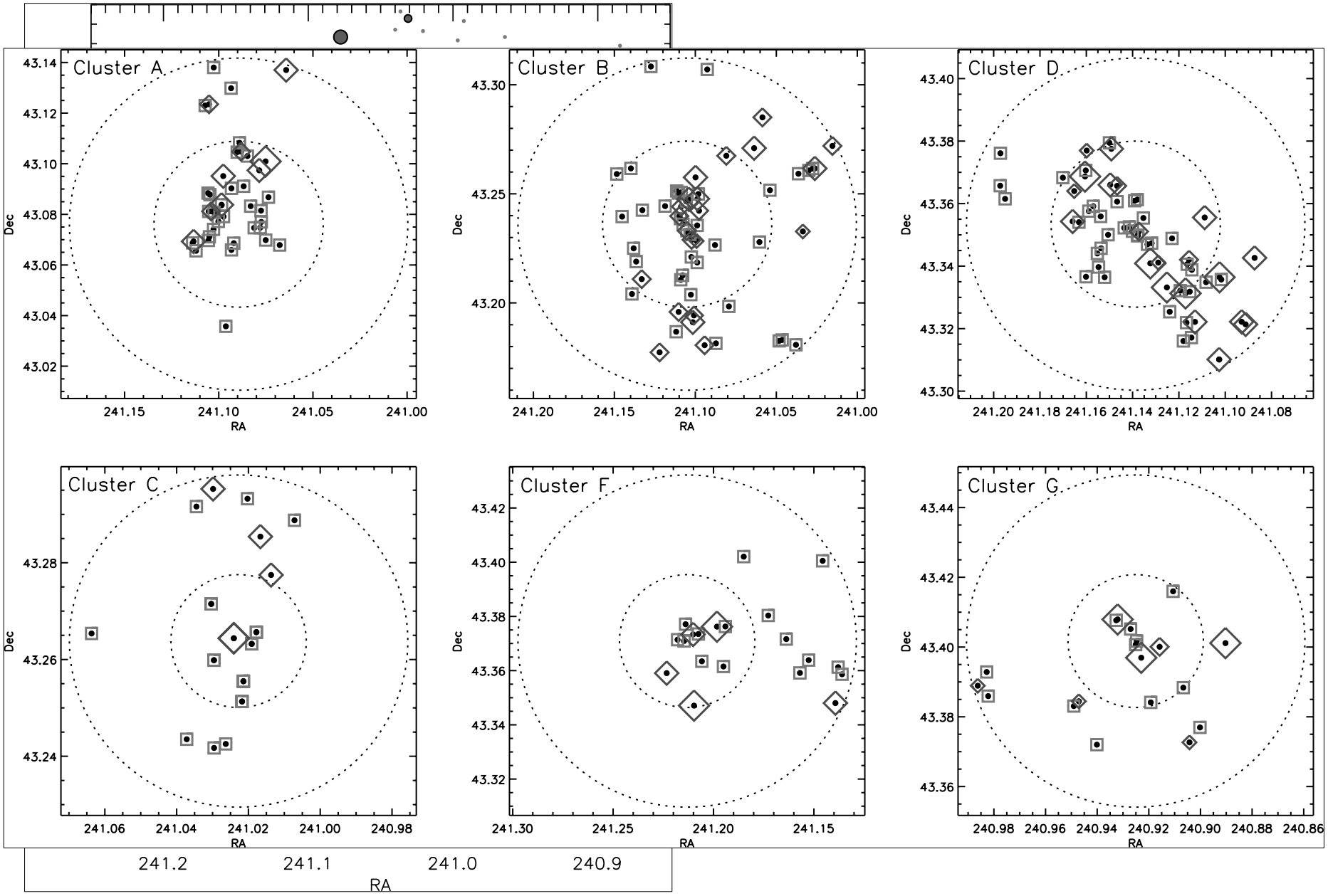
Mid-IR Observations

- 110 confirmed supercluster members with SFR ≥ 10 $M_{\odot}$/yr.
- 25% of the supercluster population is detected, a significant excess compared to the field and low redshift clusters.
- Most of these galaxies not associated with the main clusters but rather with infalling late-type galaxies in the cluster outskirts.



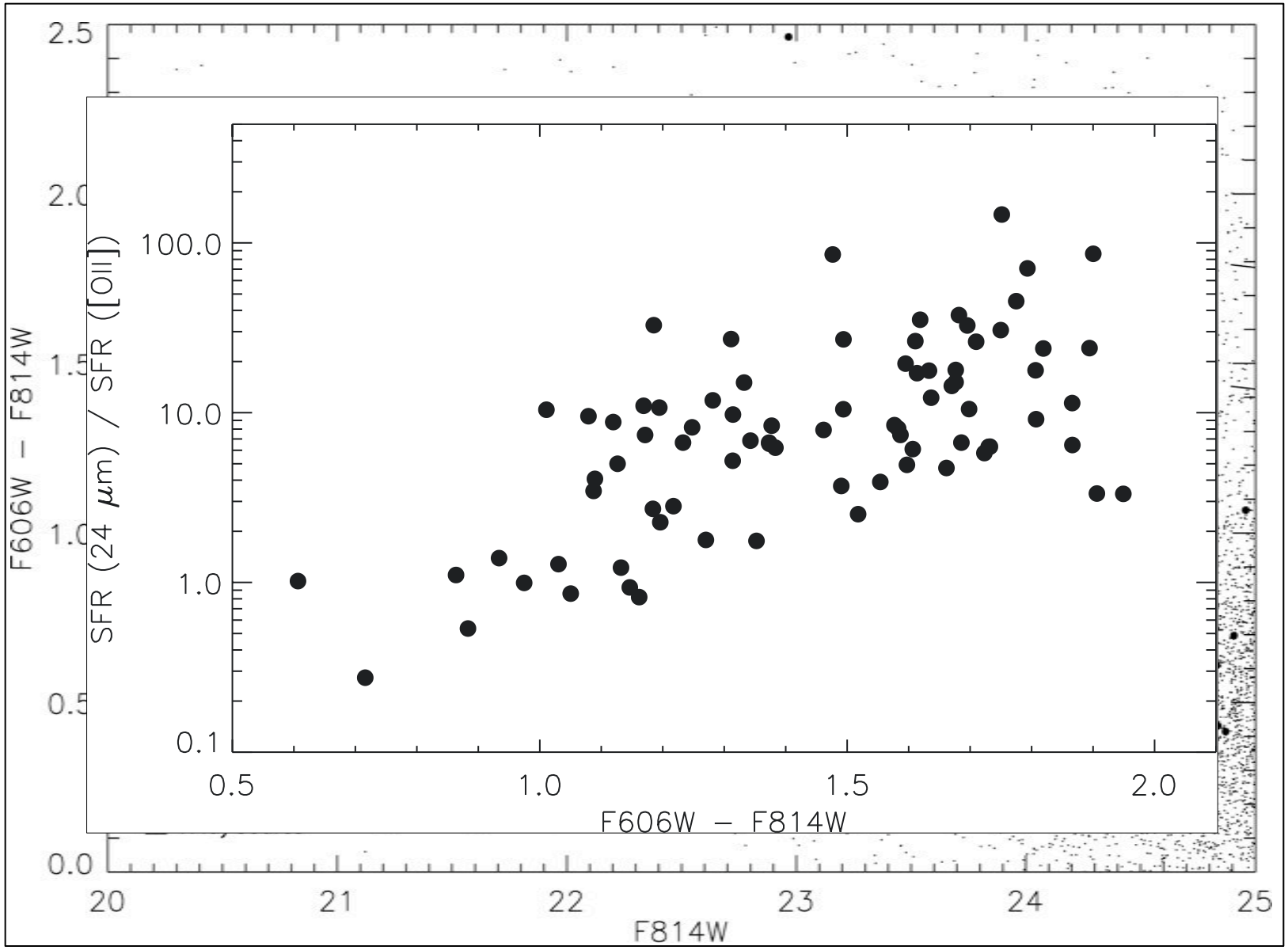
Spitzer MIPS 24 μm Scan

Distribution of 24 μm Bright Sources



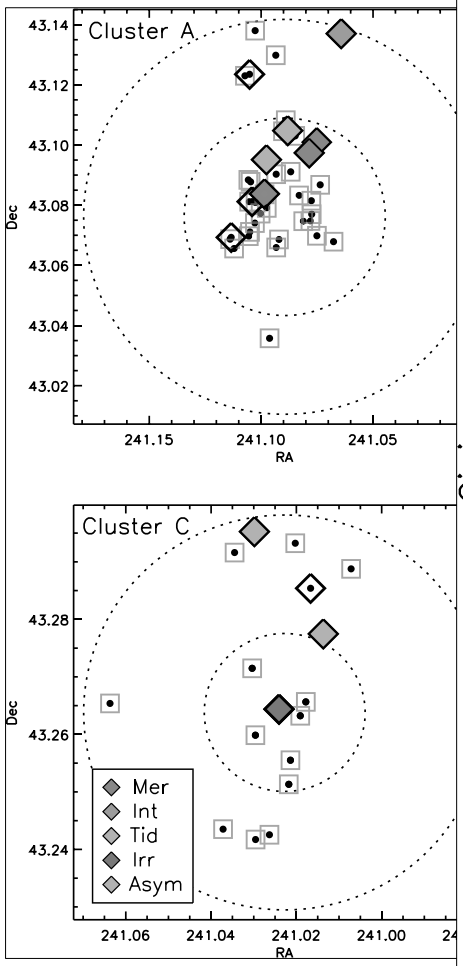
Kocevski et al. 2010

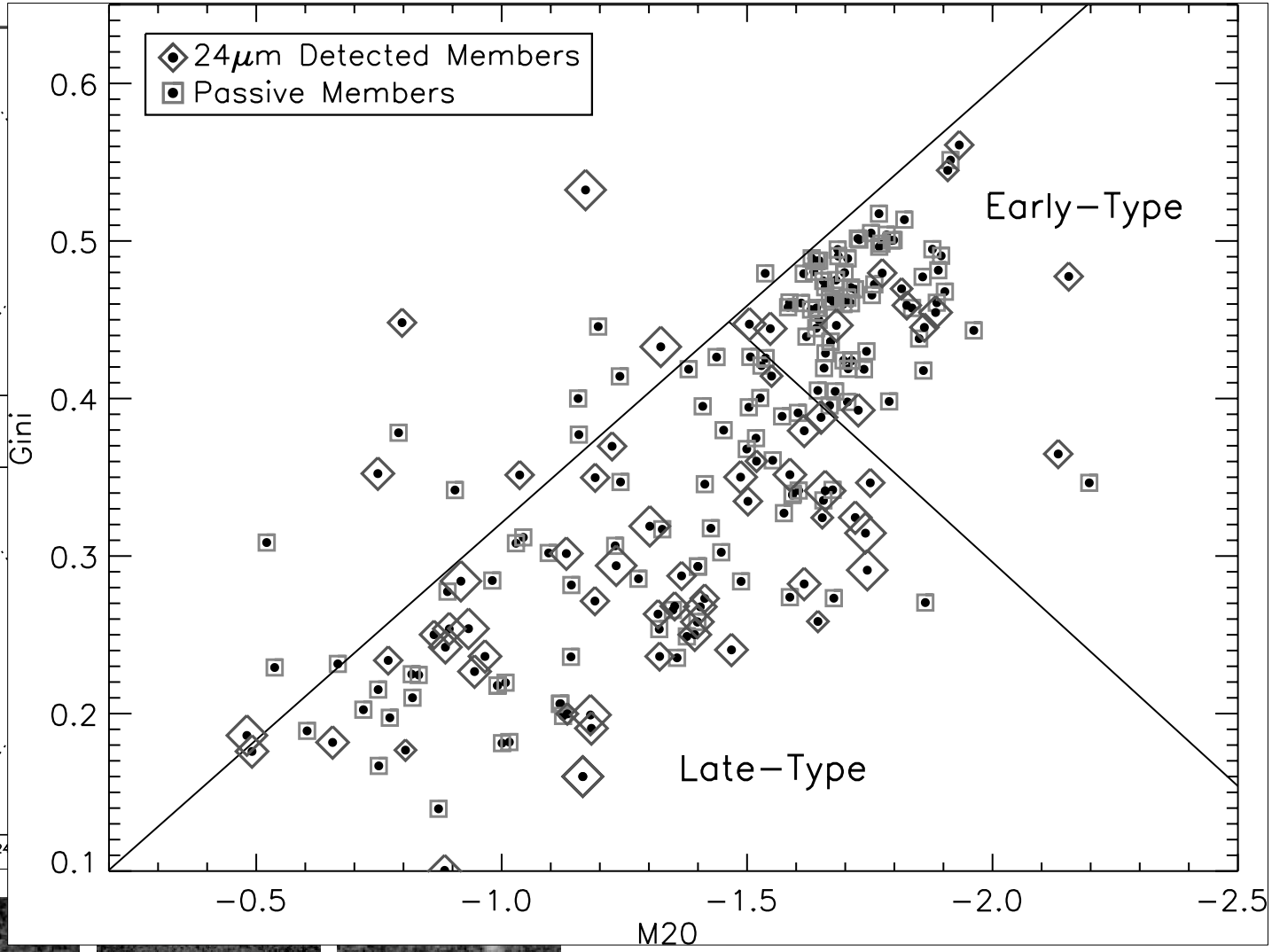
Colors of 24 μm Bright Sources

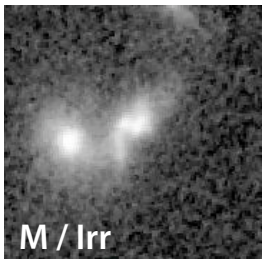


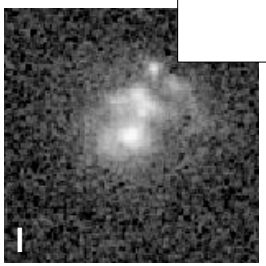
Kocevski et al. 2010

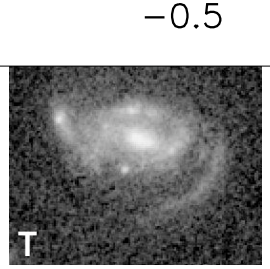
Morphologies of 24 μm Bright Sources

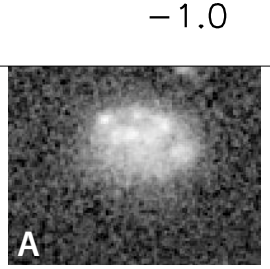










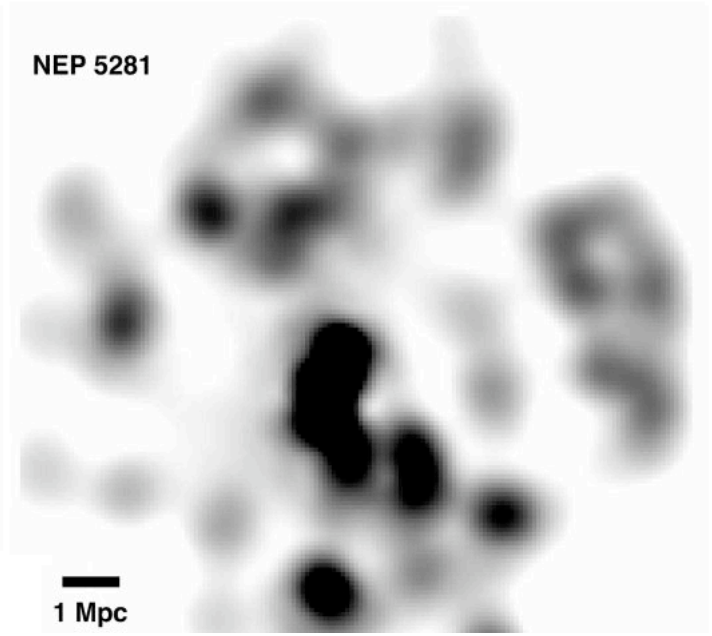


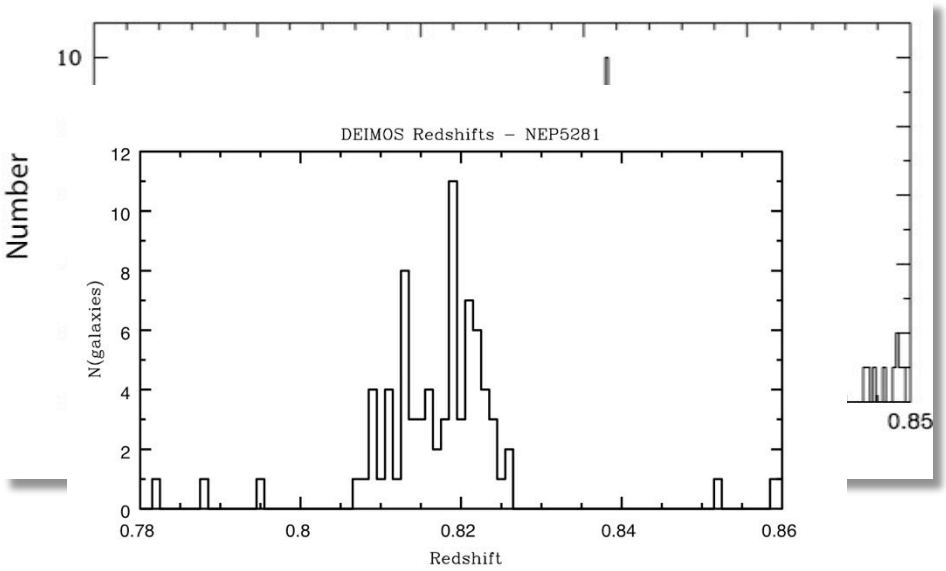
interactions in 24 μm bright group/cluster members within virial radii, compared to field

Kocevski et al. 2010

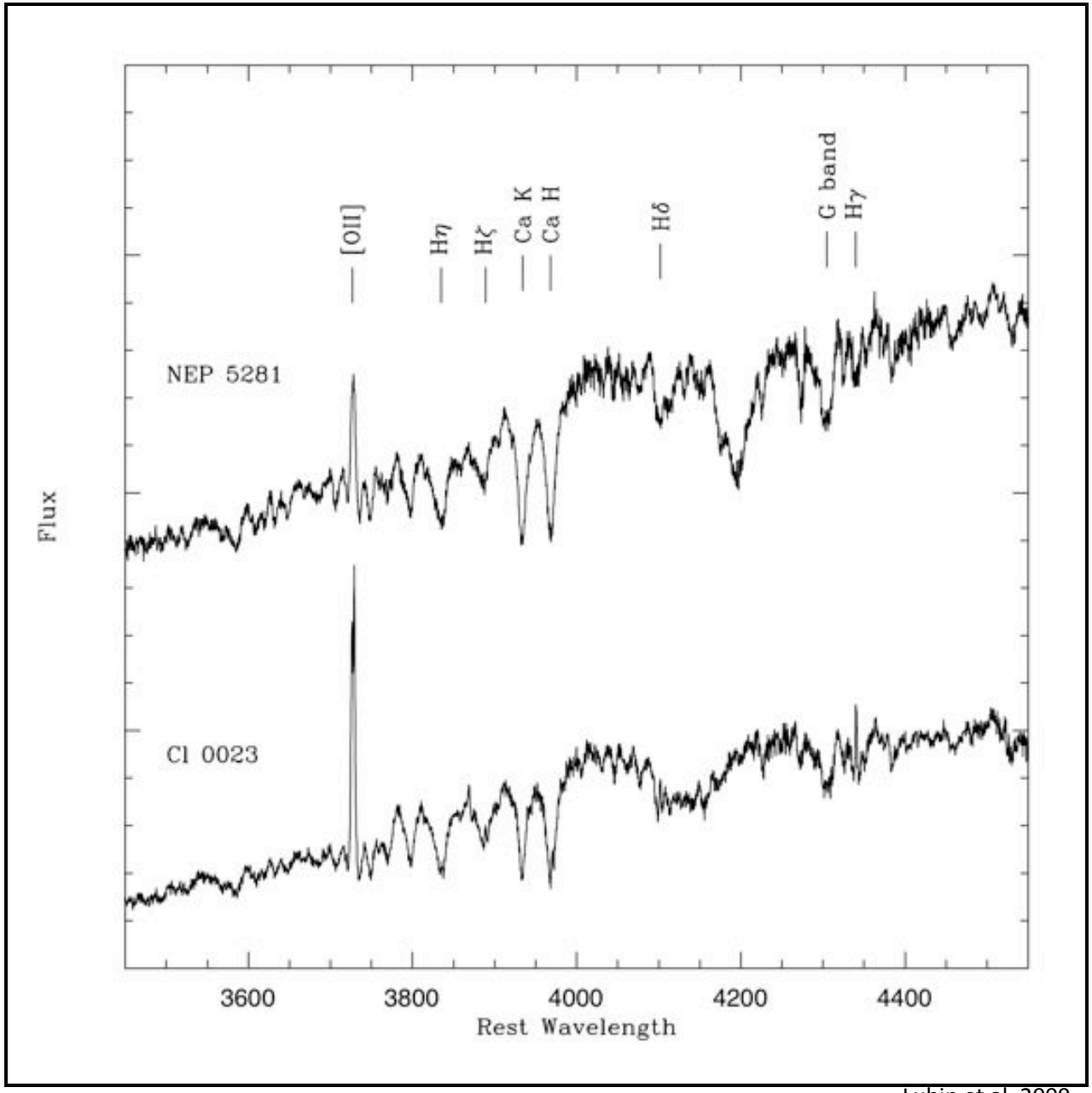
Other ORELSE Structures at z≈0.8

- 13h Supercluster (z=0.73):
  - 7 Clusters and Groups
  - Chandra observations complete,
    VLA observations pending,
    HST imaging to be proposed
  - 529 redshifts obtained
- 00h Merger System (z=0.84):
  - Merger of 4 small groups
  - Chandra, VLA observations complete
  - 321 redshifts Obtained
- NEP 5281 (z=0.82)
  - Isolated, X-ray selected cluster
  - Archival XMM observations
  - Chandra, VLA observations pending
  - 155 redshifts obtained



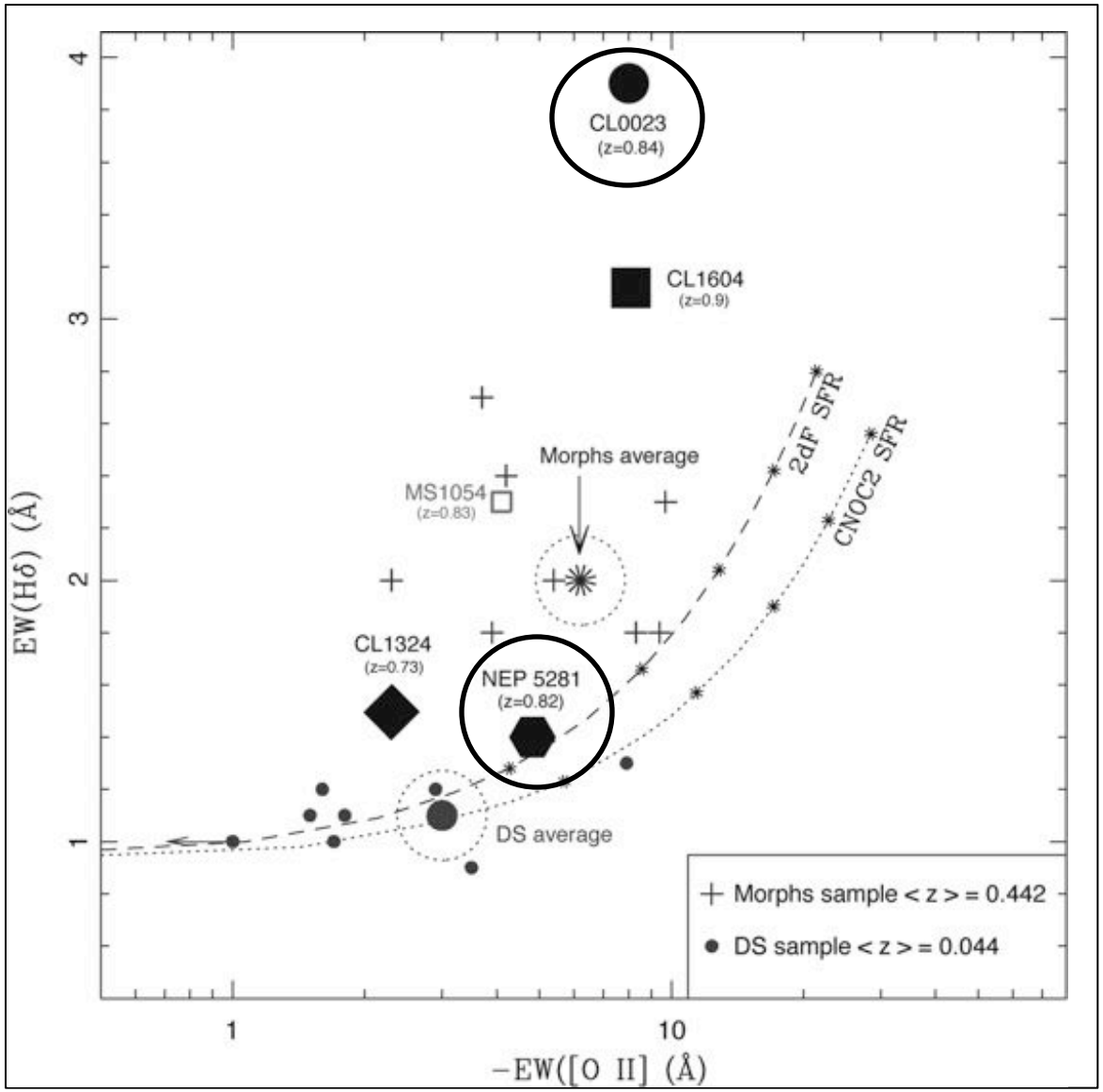


High (and low) levels of activity

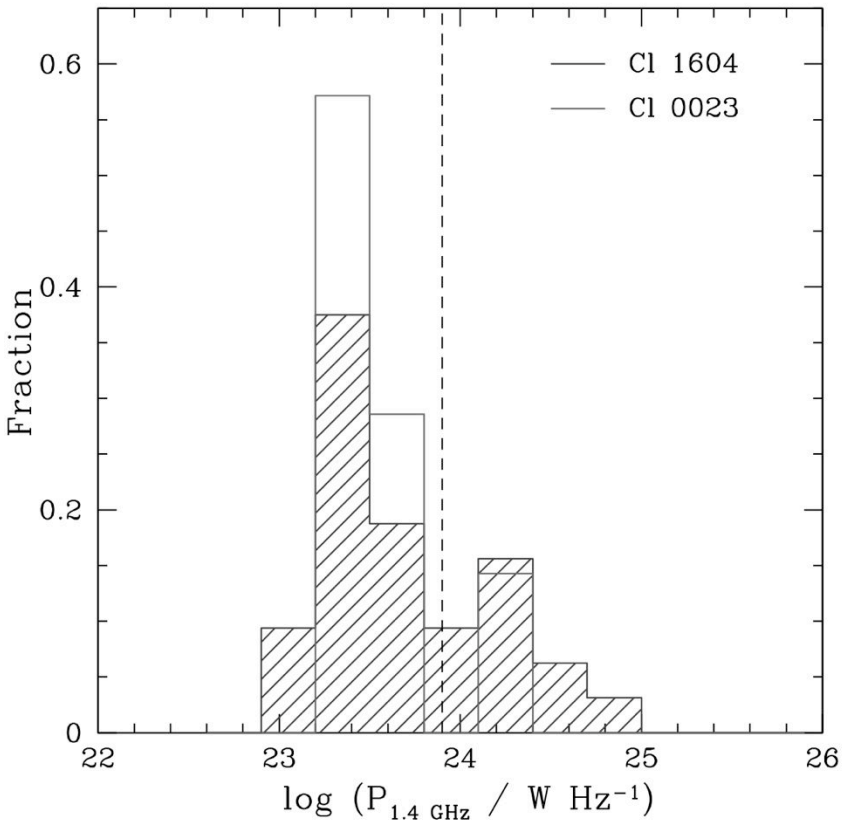


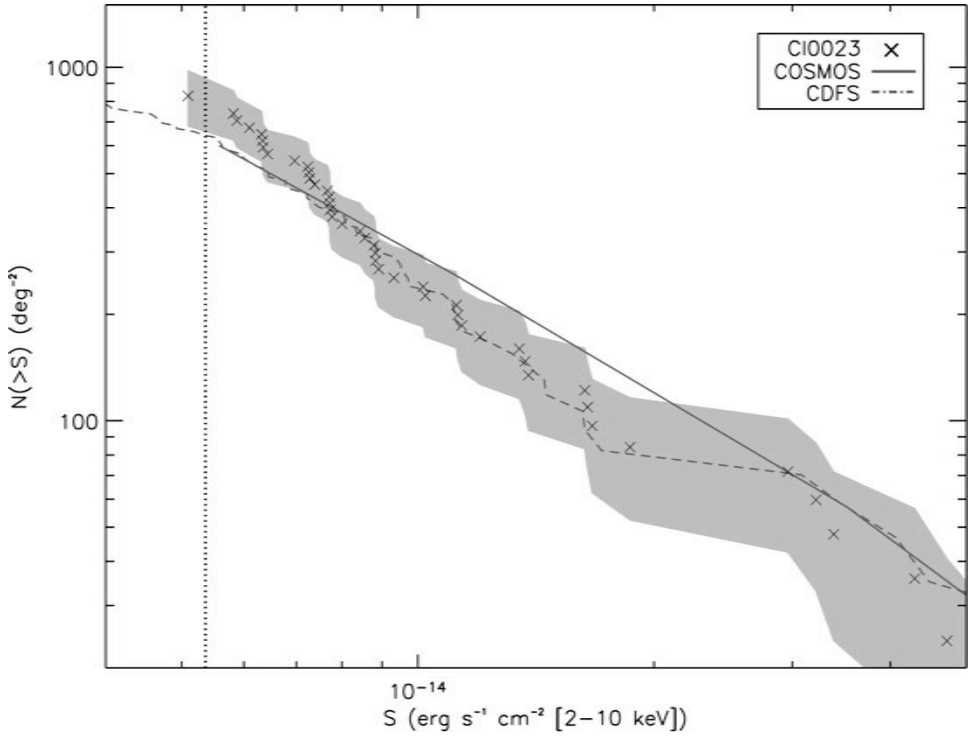
Lubin et al. 2009

High (and low) levels of activity



X-ray & Radio Properties of Cl 0023

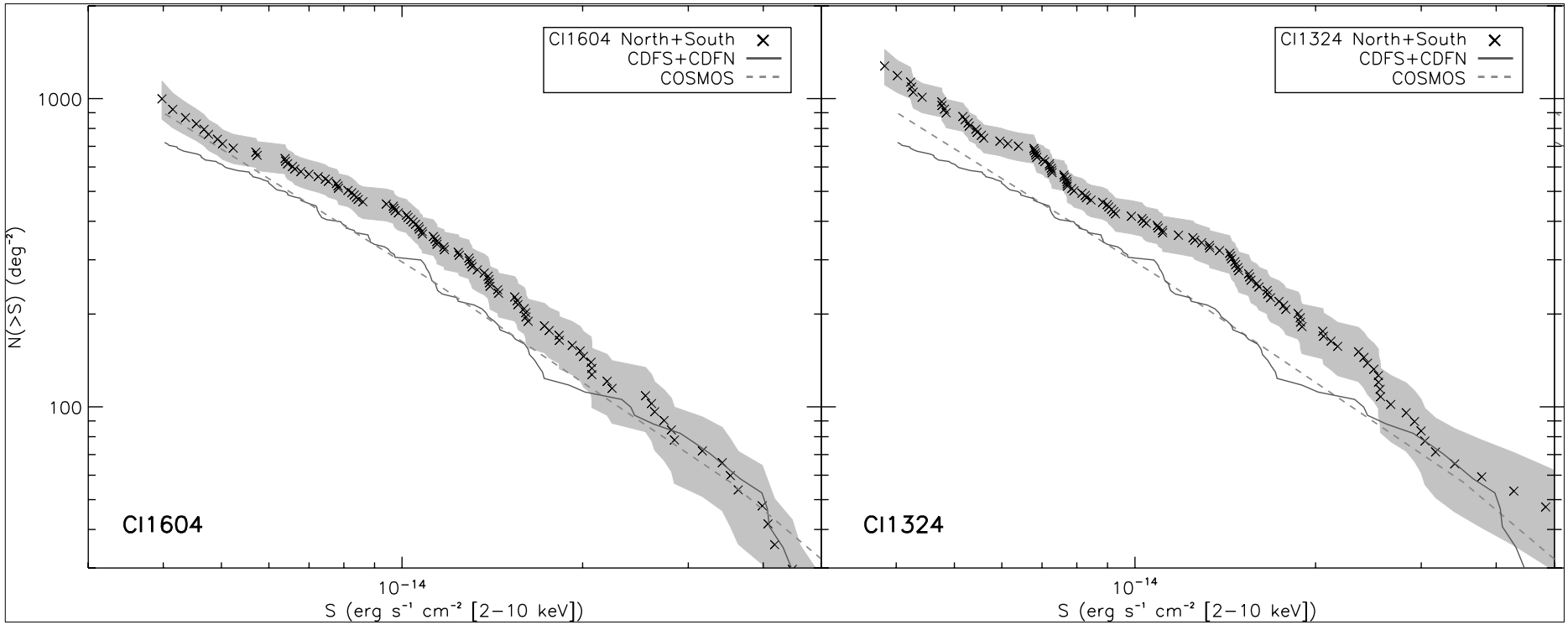




Kocevski et al. 2009c

- **Radio:** larger fraction of lower-luminosity (starburst) sources, consistent with dominant population of blue, star-forming galaxies
- **X-ray**: underdensity of X-ray sources, suggesting little AGN activity due to lack of bulge-dominated galaxies

Evolution of the Active Galaxy Population



- Substantially lower level of optical activity in the Cl 1324 supercluster.
- An overdensity of point sources also observed in this field, but with a larger excess at fainter fluxes.
- The six confirmed X-ray AGN all less luminous than those in the Cl 1604 supercluster, confirming luminosity evolution over this ~1 Gyr interval.

Summary (Part 1)

- The ORELSE survey is a systematic study of galaxy properties in the large-scale environments around 20 known clusters at z>0.6.
- The Cl1604 supercluster at z=0.9 is the largest structure confirmed at high redshift, containing eight groups/clusters, two of which are X-ray detected.
- Galaxy population in Cl1604 is optically active, with a significant fraction of [OII] due to LINER activity and overdensities of Radio, X-ray, and mid-IR sources.
- AGN host properties consistent with feedback scenarios:
  - X-ray AGN hosts found on the green valley, avoid dense environments.
  - Radio AGN located on the red sequence and in denser environments.
  - X-ray AGN and radio-loud galaxies are bulge dominated or interacting.
  - High fraction of X-ray AGN found in post-starburst hosts (45%).
- Large population of 24 μm bright (starburst) galaxies detected :
  - Located on bright blue end of blue cloud, consistent with late quenching scenarios.
  - Significant differences between group/cluster and field, implying environmental triggers.

Summary (Part 2)

- We have discovered another supercluster, a four-way group merger, and several isolated, X-ray luminous clusters, all showing strong variations with mass and epoch.
- Extensive optical and infrared spectroscopy, combined with multi-wavelength, observations, are providing details on the nature, environment, timescales, and physical processes of active galaxies.