# Star Formation and Mass Assembly in High Redshift Galaxy Clusters

S. A. Stanford (UCD)

Berkeley

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# WISE

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## NASA MIDEX - Ned Wright, PI

- MIR imaging of the whole sky in 6 months
- passbands: 3.4, 4.6, 12, 22 microns
- Sensitivities: 75, 100, 1000, 5000 uJy

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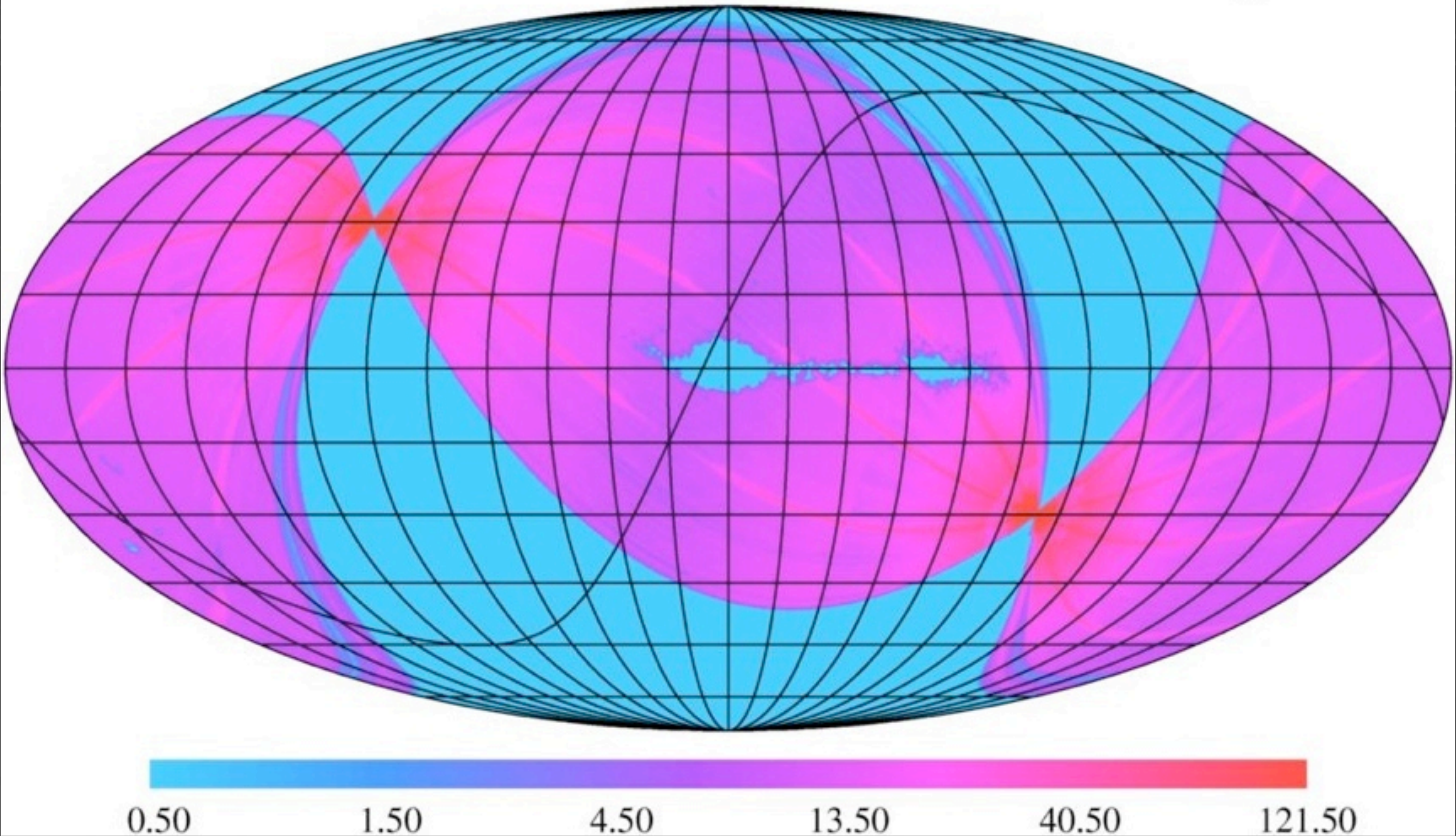
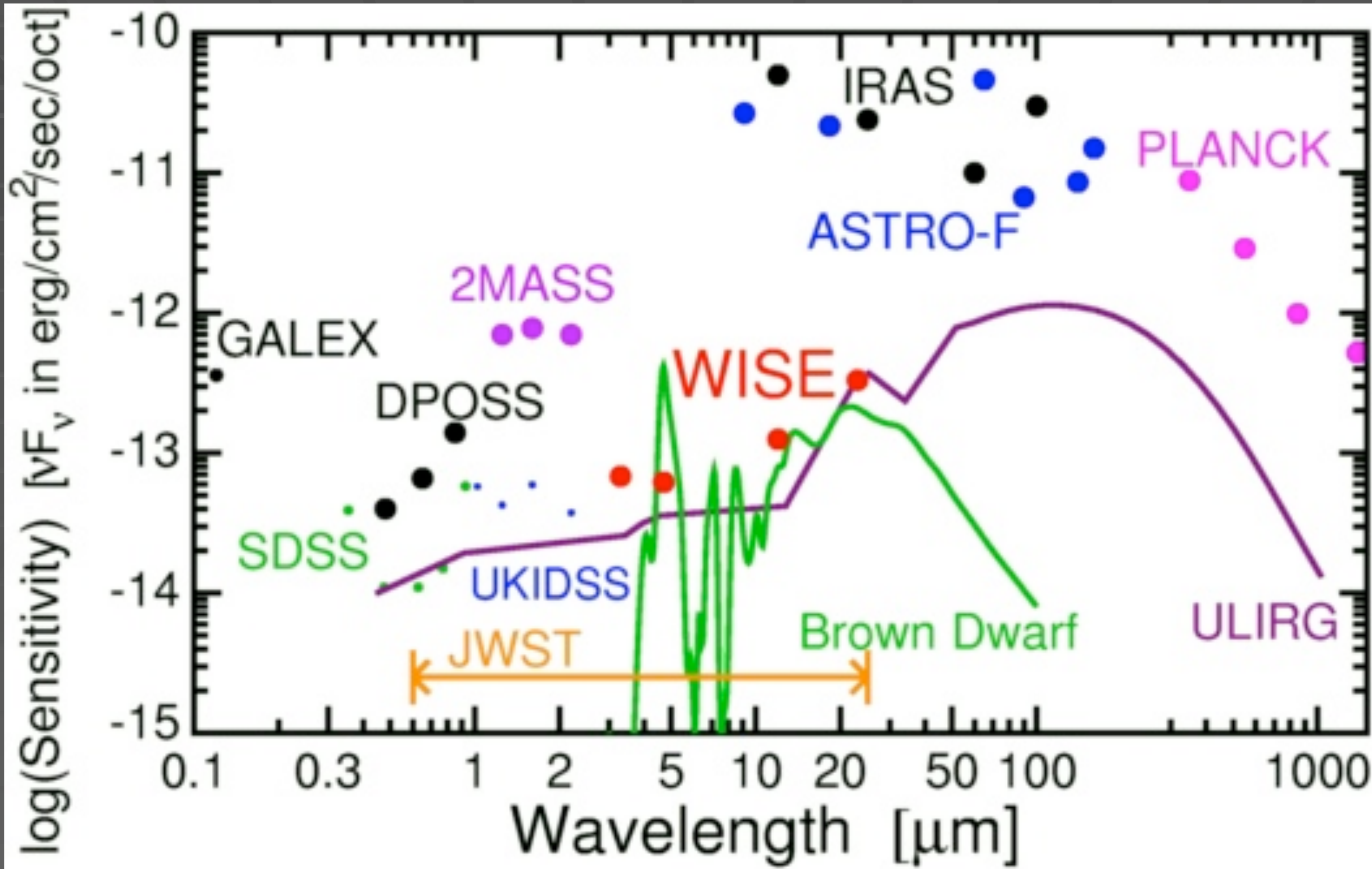
## Status

- Launched 12 December 2009
- Survey started in January 2010; finish in July 2010
- Cryogen expected to last until November 2010
- First data released planned for April 2011


05.22.2009

# 809443 frames thru 10-123.3; 63.1% to depth > 7





log(Sensitivity) [νF_ν in erg/cm²/sec/oct]
-10
-11
-12
-13
-14
-15
IRAS
PLANCK
ASTRO-F
2MASS
GALEX
WISE
DPOSS
SDSS
UKIDSS
Brown Dwarf
ULIRG
JWST
0.1
0.3
1
2
5
10
20
50
100
1000
Wavelength [μm]

# Outline

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Motivation - massive galaxy formation

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Discovery of High-z Clusters

- Why search in the infrared?
- The Bootes survey

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- The Bootes survey

Cluster Galaxy Evolution since z~1.5

- Stellar populations
- Stellar mass assembly history
- Star forming properties and extreme cases (AGN, DOGs, etc)

# Collaborators

| | |
|---|---|
| Peter Eisenhardt (JPL/Caltech) | PI of IRAC Shallow Survey |
| Anthony Gonzalez (U. Florida) | Cluster Detections |
| Mark Brodwin (CfA) | Photometric redshifts |
| Dan Stern (JPL/Caltech) | Optical spectroscopy |

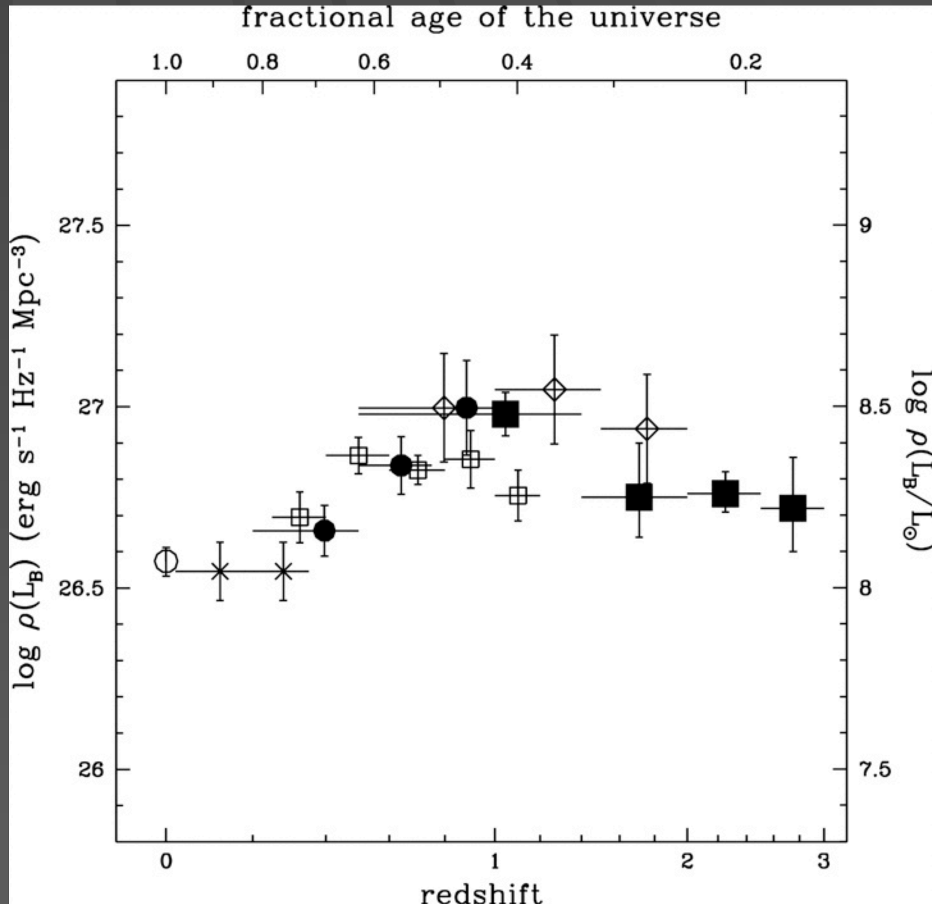
Lexi Moustakas, Conor Macone, Greg Zeimann, Arjun Dey, Buell Januzzi, Michael Brown, Audrey Galametz, Chris Kochanek, Kyle Dawson, Josh Myers, Christina Jones

# Origin of Massive Galaxies

SFR peaks at 1<z<2

Most of the stellar mass is created in this regime

Clusters contain lots of massive galaxies




*Dickinson et al*. (2003)

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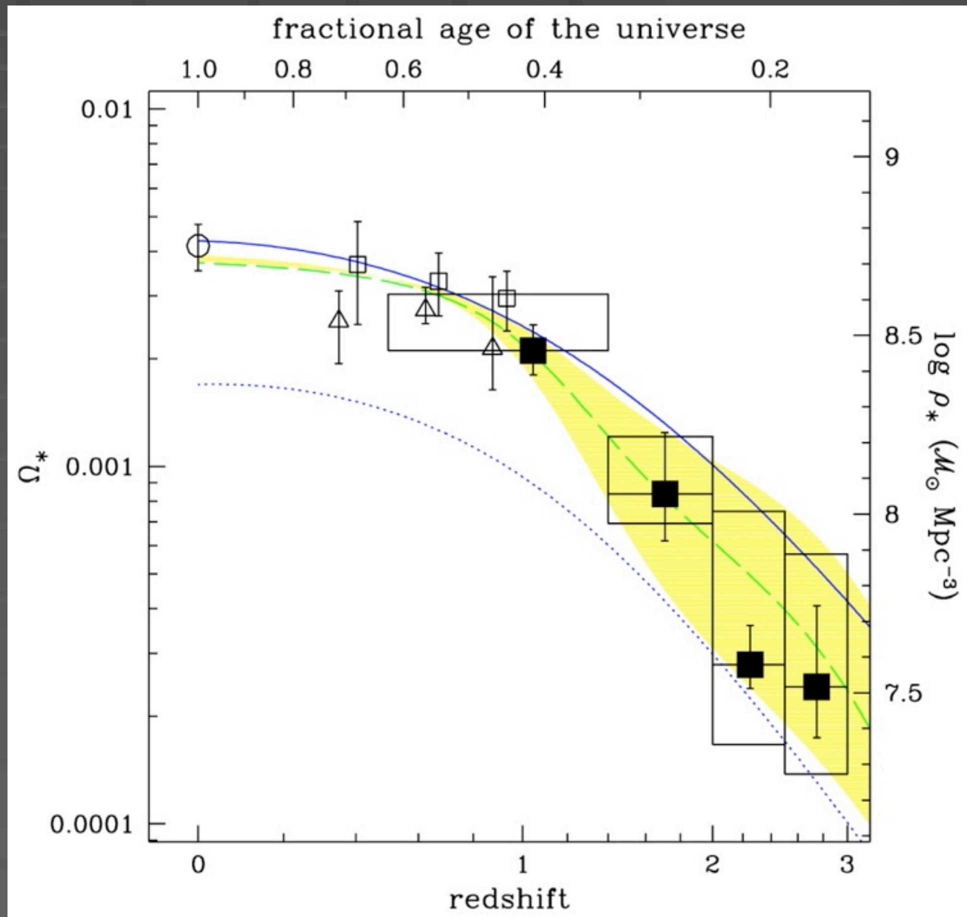
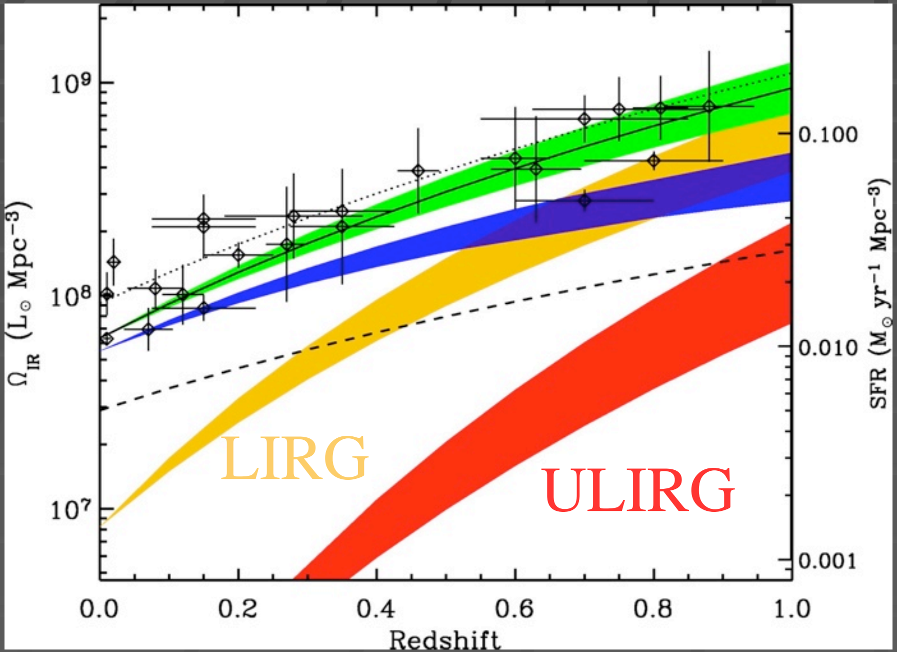
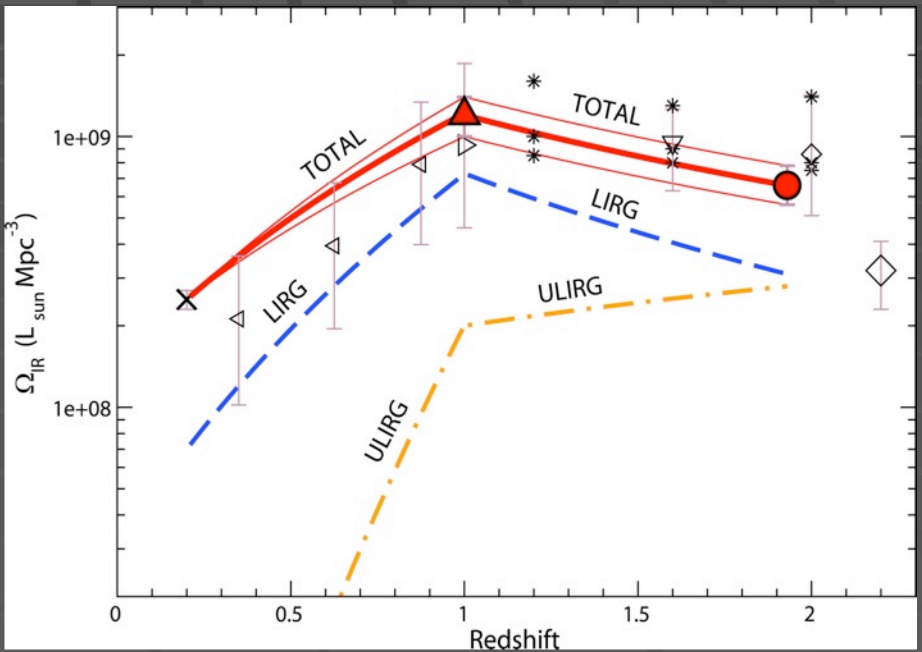



*Dickinson et al. (2003)*

# Origin of Massive Galaxies

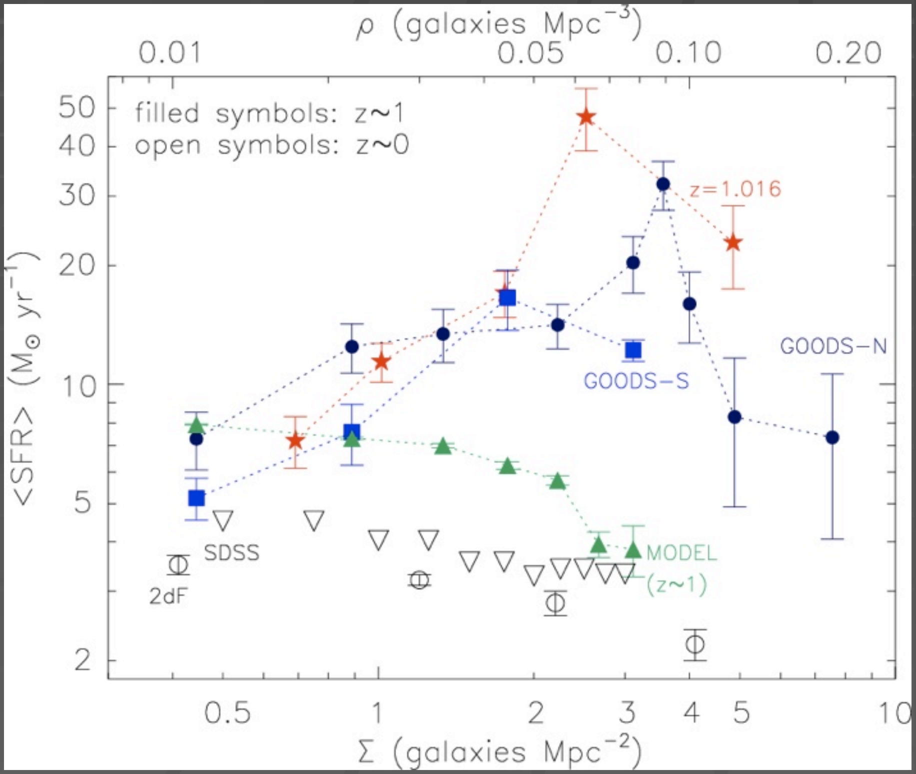



*Le Floc'h et al. (2005)*
*(see also Papovich et al. 2006)*

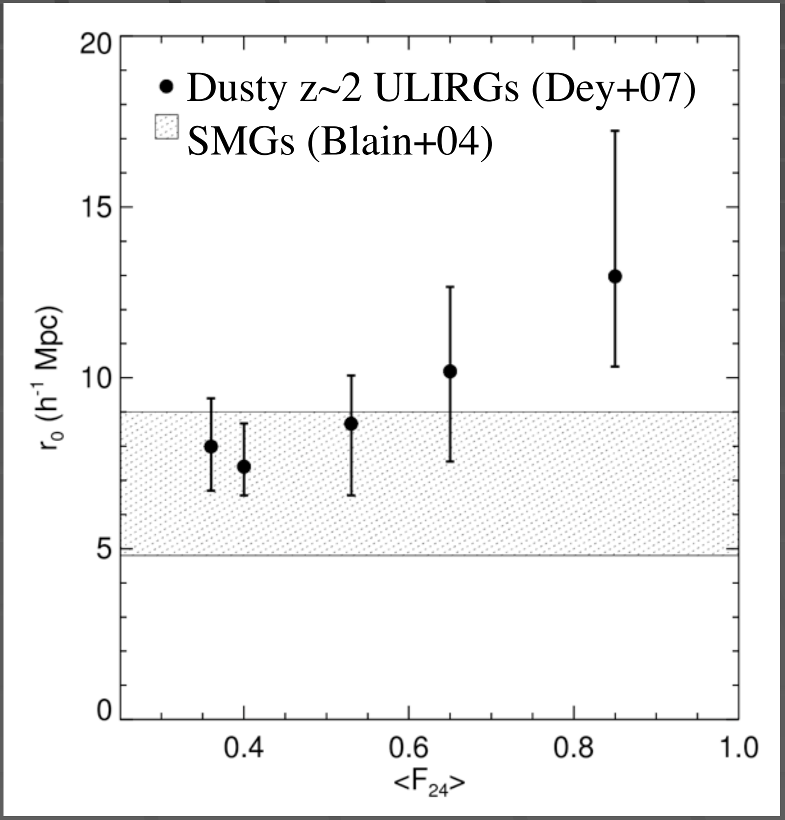
*Caputi et al. (2007)*

# Origin of Massive Galaxies: Effect of Environment




*Elbaz et al. (2007)*

*(see also Cooper et al. 2008; Muzzin et al. 2008)*




*Brodwin et al. (2008)*

*(see also Pope et al. 2008)*

# Why Study High-z Galaxy Clusters?

## Cosmology

- Measure parameters
- Probe the nature of dark energy

## Growth of Large Scale Structure

- Test numerical simulations, HOD modeling

## Clusters of *Galaxies*

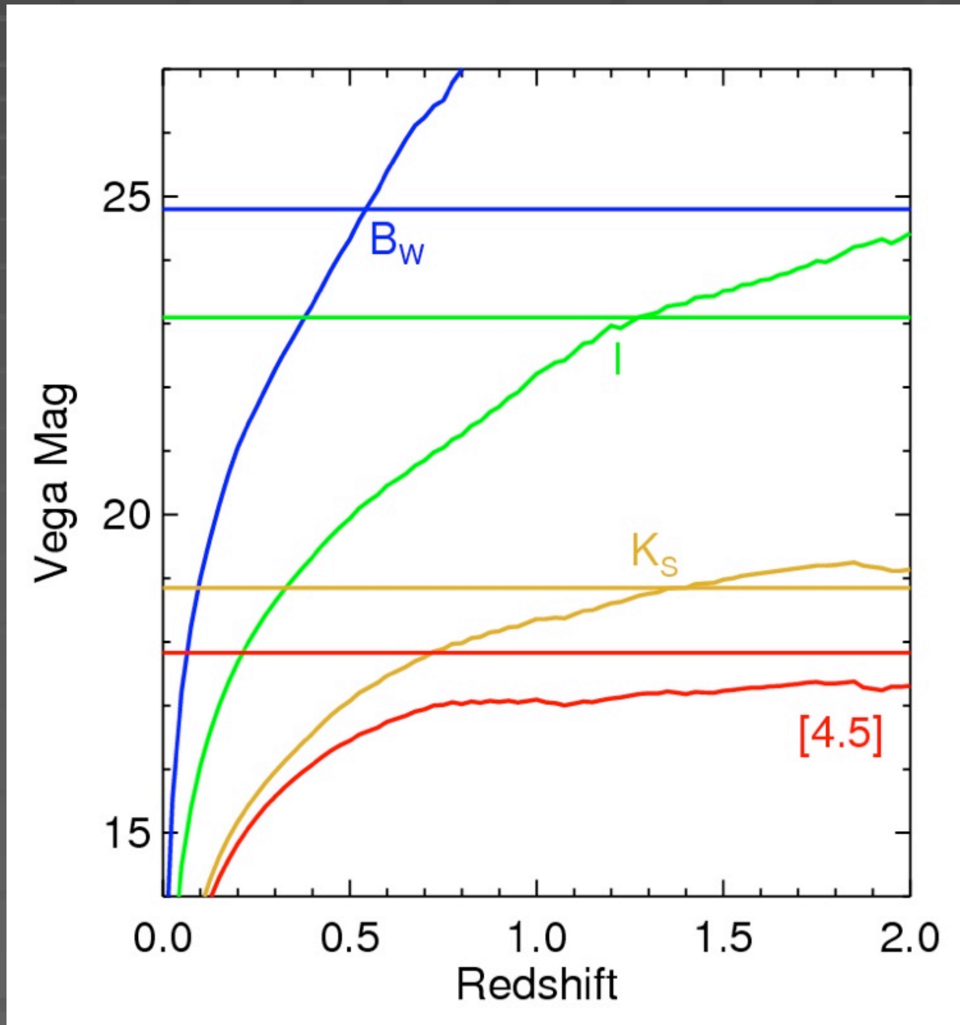
- Efficient probe of galaxy formation and evolution, particularly massive galaxies

# Why the IR?

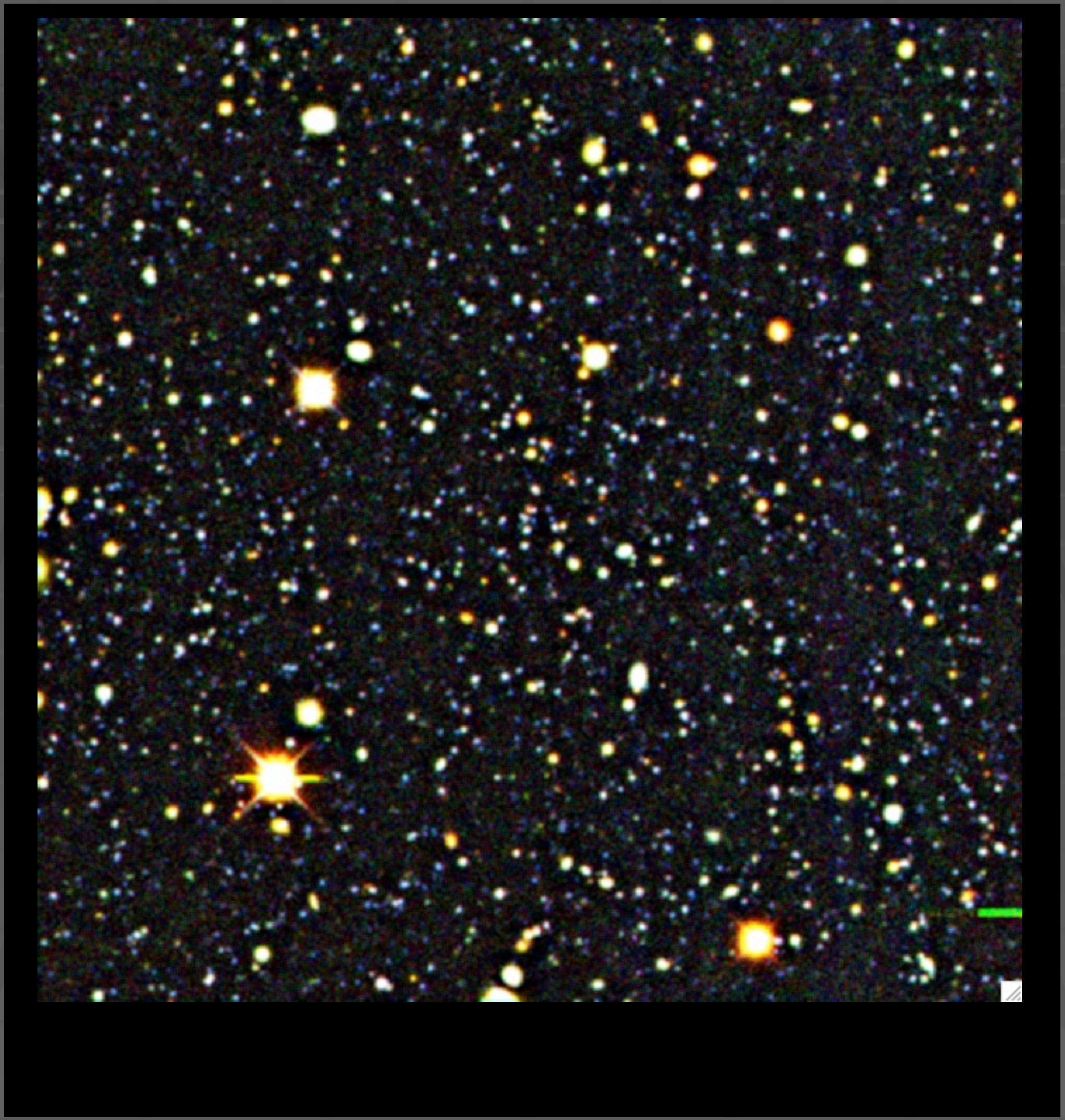
- Infrared selection detects all *massive* galaxies to high redshift
- Bulk of field galaxies avoided (they tend to be blue, low mass and low z)
  - ⇒ *Contamination* (e.g. “Projection”) minimized
  - ⇒ *Contrast* for real clusters increased

# NIR k-correction is your friend

- Bruzual & Charlot model
  - 0.1 Gyr Burst, $z_f = 3$
  - $H_0$=70; $\Omega_M = 0.3$; $\Omega_\Lambda = 0.7$
- Red galaxies quickly fade in optical due to strong K-correction
- Near-IR better; hard to get deep, large areas
- Mid-IR best, with flat sensitivity at 0.7 < z < 2+. Wide-field mapping surprisingly efficient with *Spitzer-IRAC*.



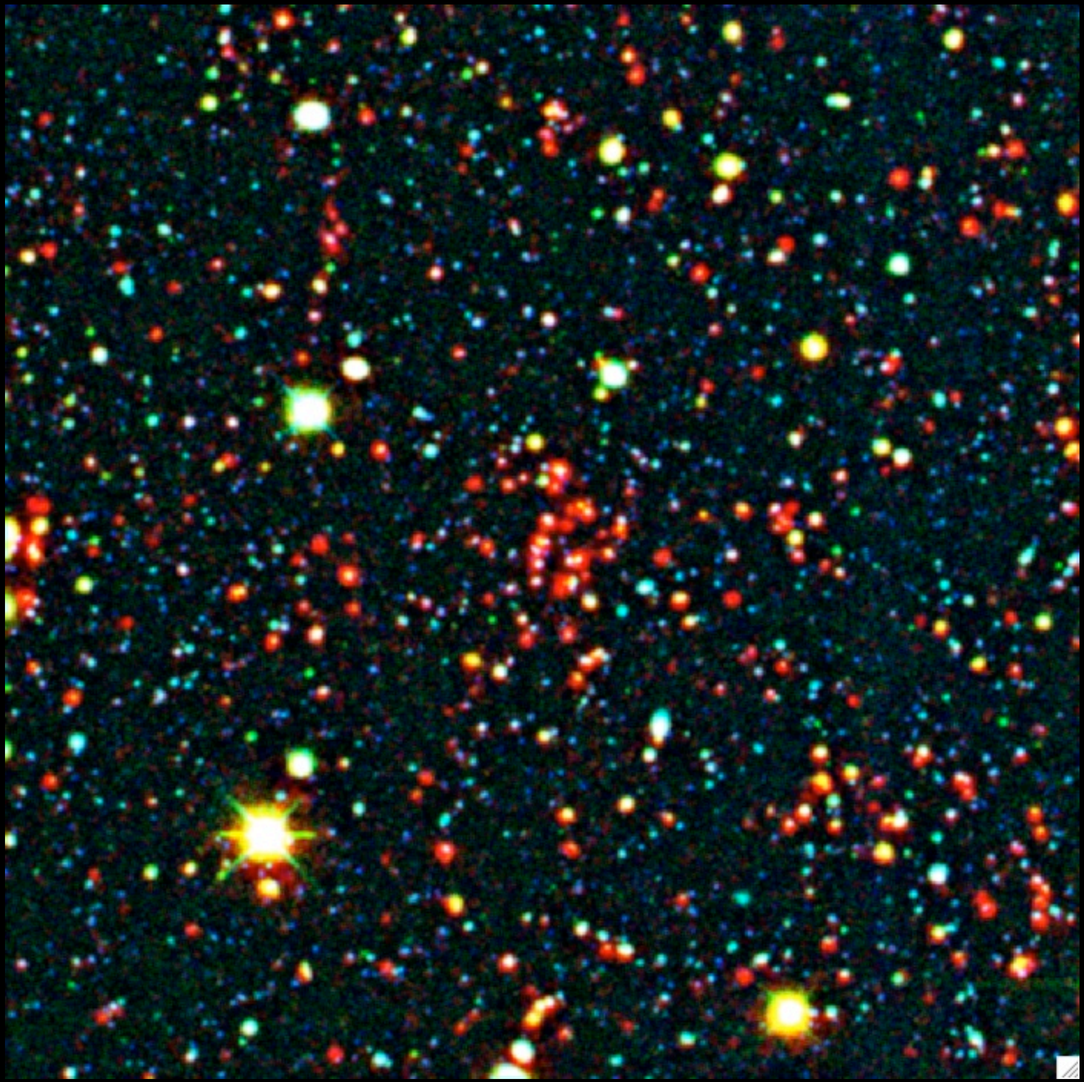
# NOAO Deep-Wide Field Survey



Optical
Alone

*Eisenhardt et al. (2008)*

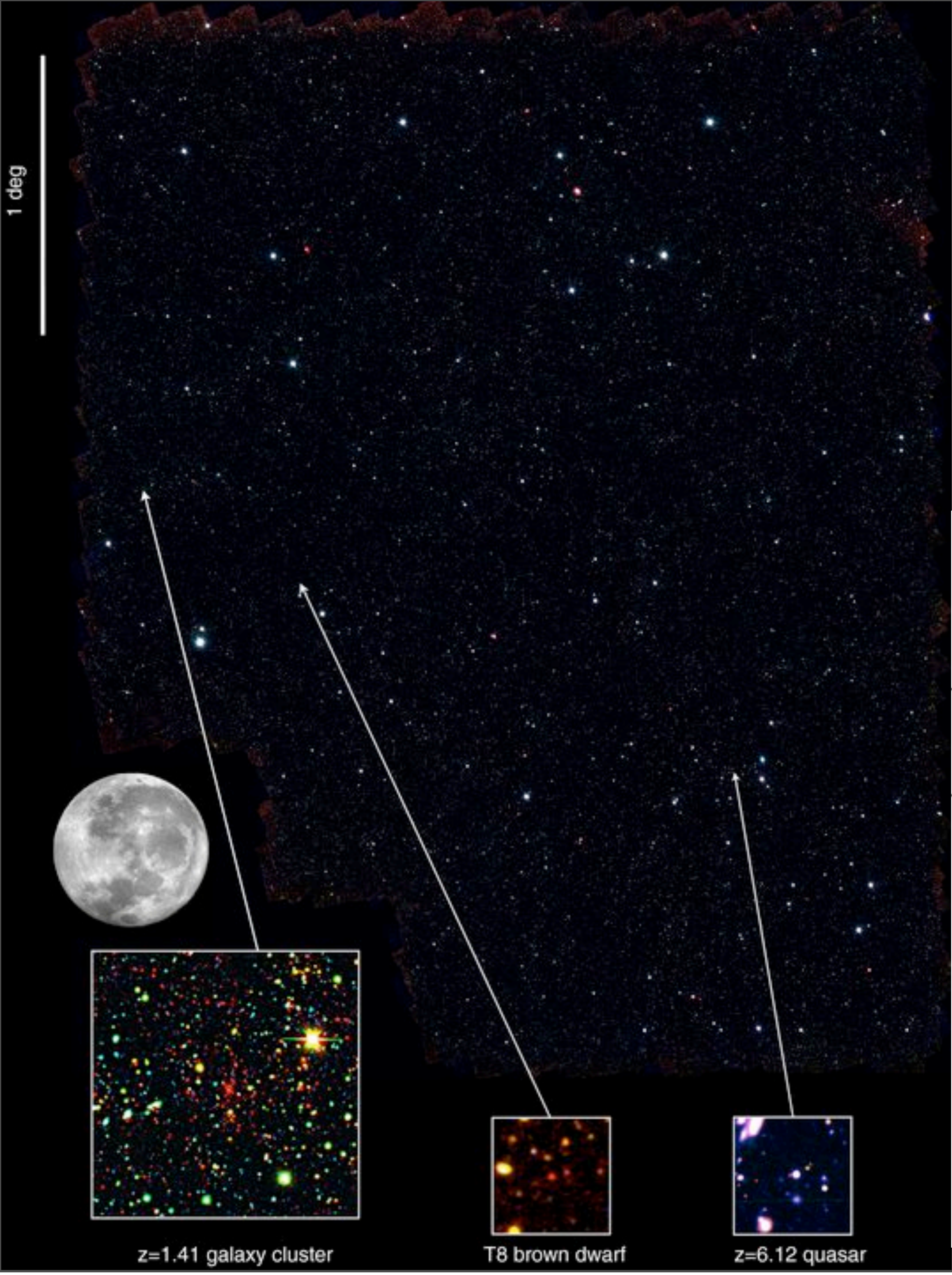
Optical
+
Mid-IR

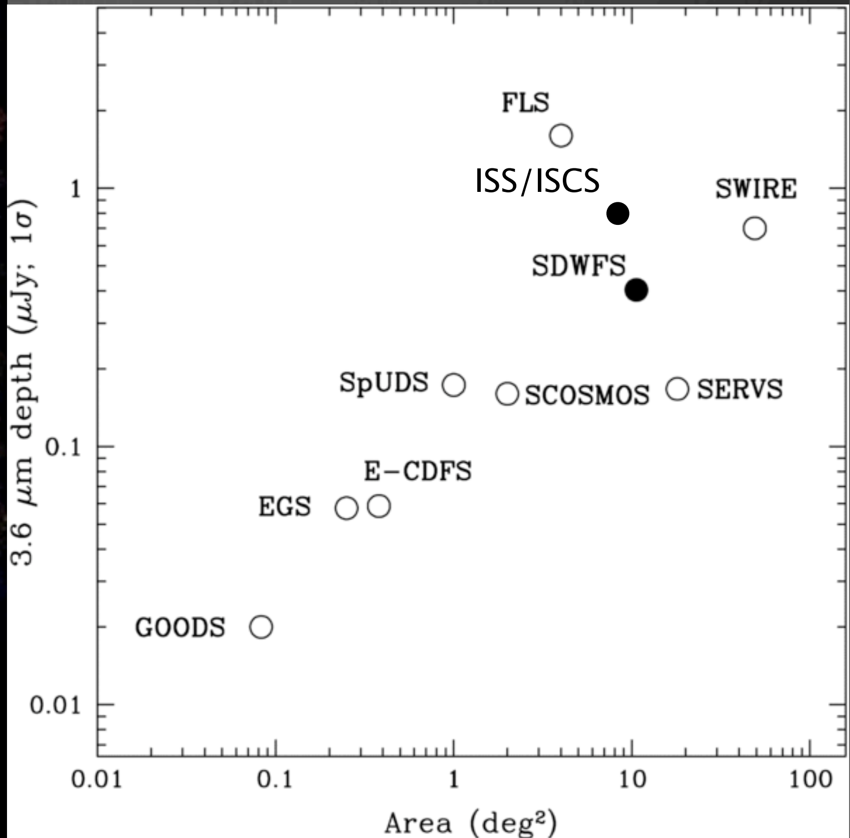


<z> = 1.37

# Spitzer Deep, Wide-Field Survey (SDWFS)

Ashby, Stern et al. (2009)

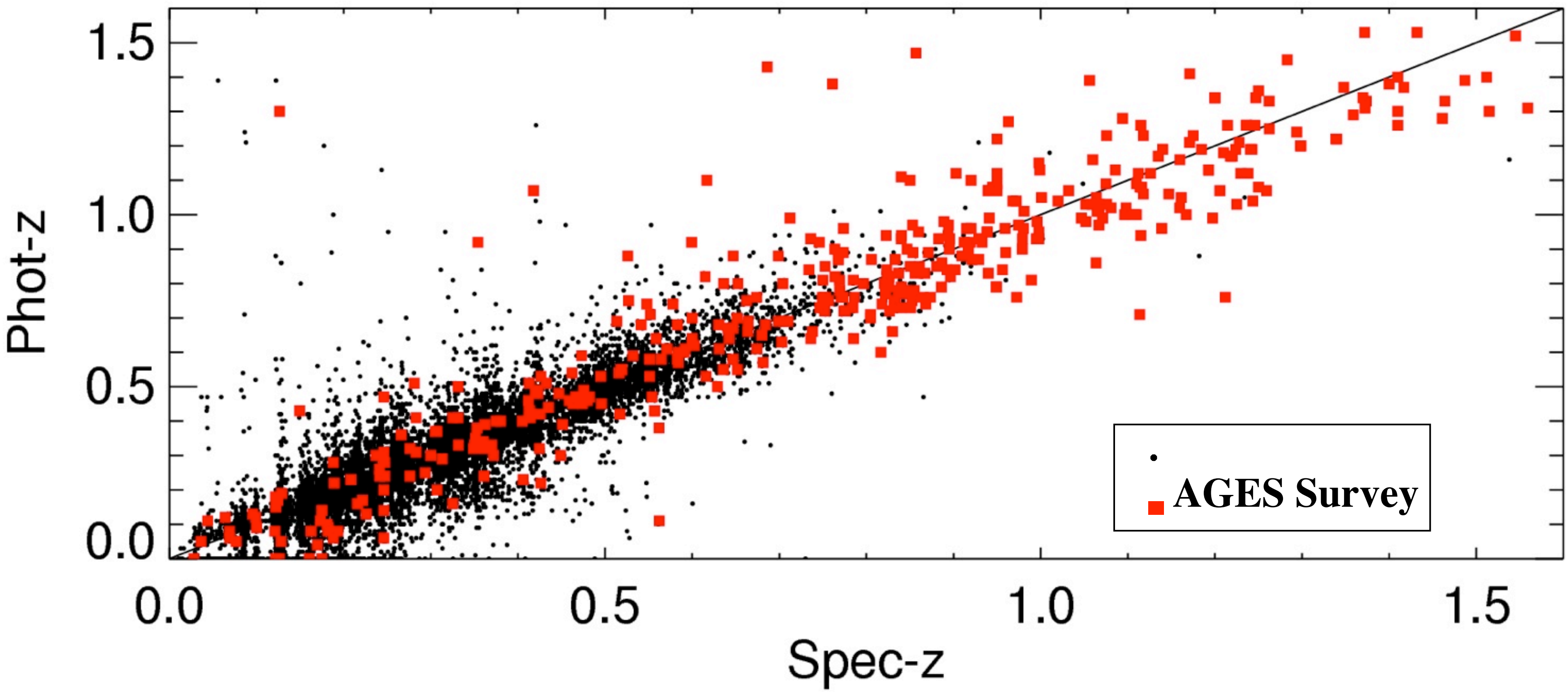


# Search Method

- Photometric Redshift Probability Functions, P(z), are generated for a flux-limited **4.5μm** sample, containing 200,000 galaxies over 8.5 $deg^2$, from NDWFS $B_wRI$ and *Spitzer*/IRAC [3.6][4.5] photometry.
- Wavelet detection algorithm, tuned to **~500 kpc** scales, is run on the 3D {α,δ,P(z)} catalog, resulting in cluster probability density maps, from which candidates are selected.
- Method is independent of the tightness, ***or even the presence***, of the cluster red-sequence.

# Photometric Redshifts



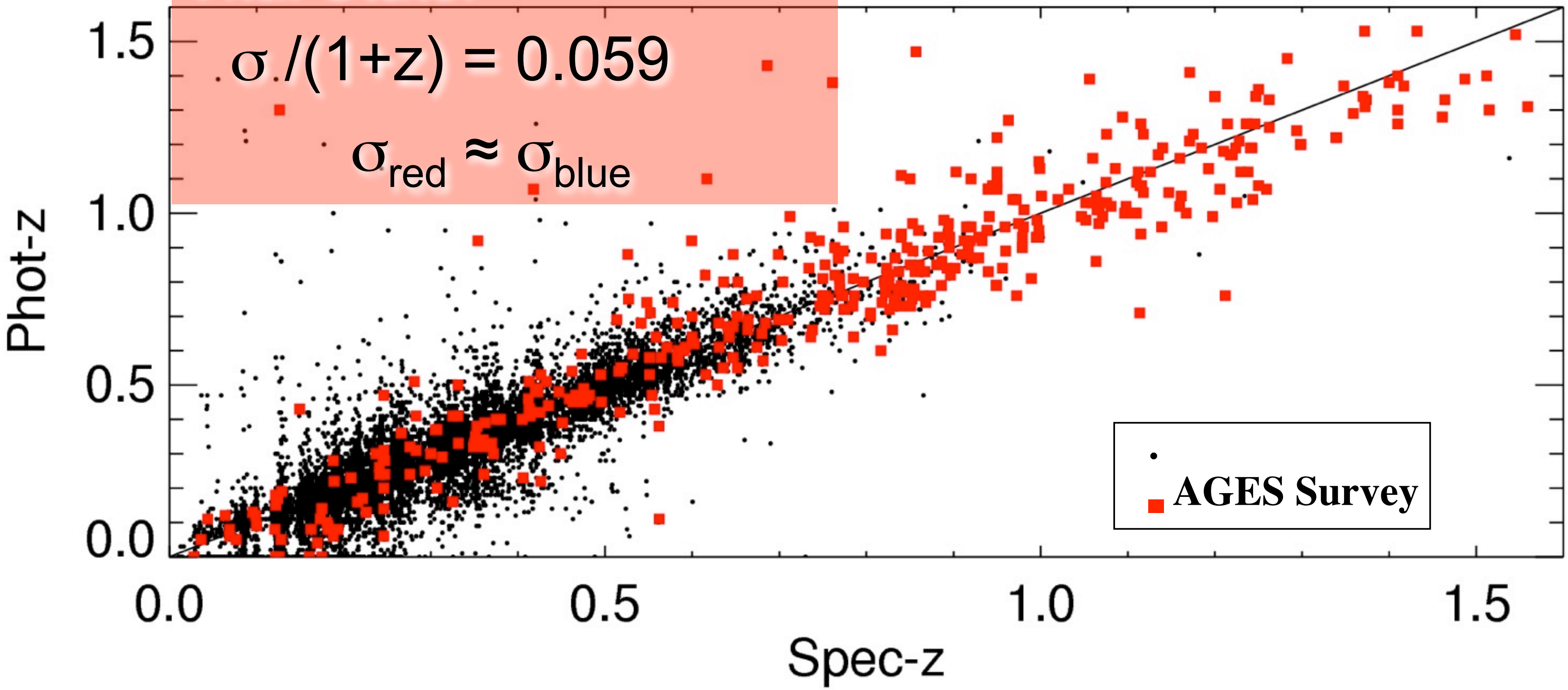

Brodwin et al. 2006 (ApJ, 651, 791)

# Photometric Redshifts

Vital Stats:

$\sigma/(1+z) = 0.059$

$\sigma_{red} \approx \sigma_{blue}$

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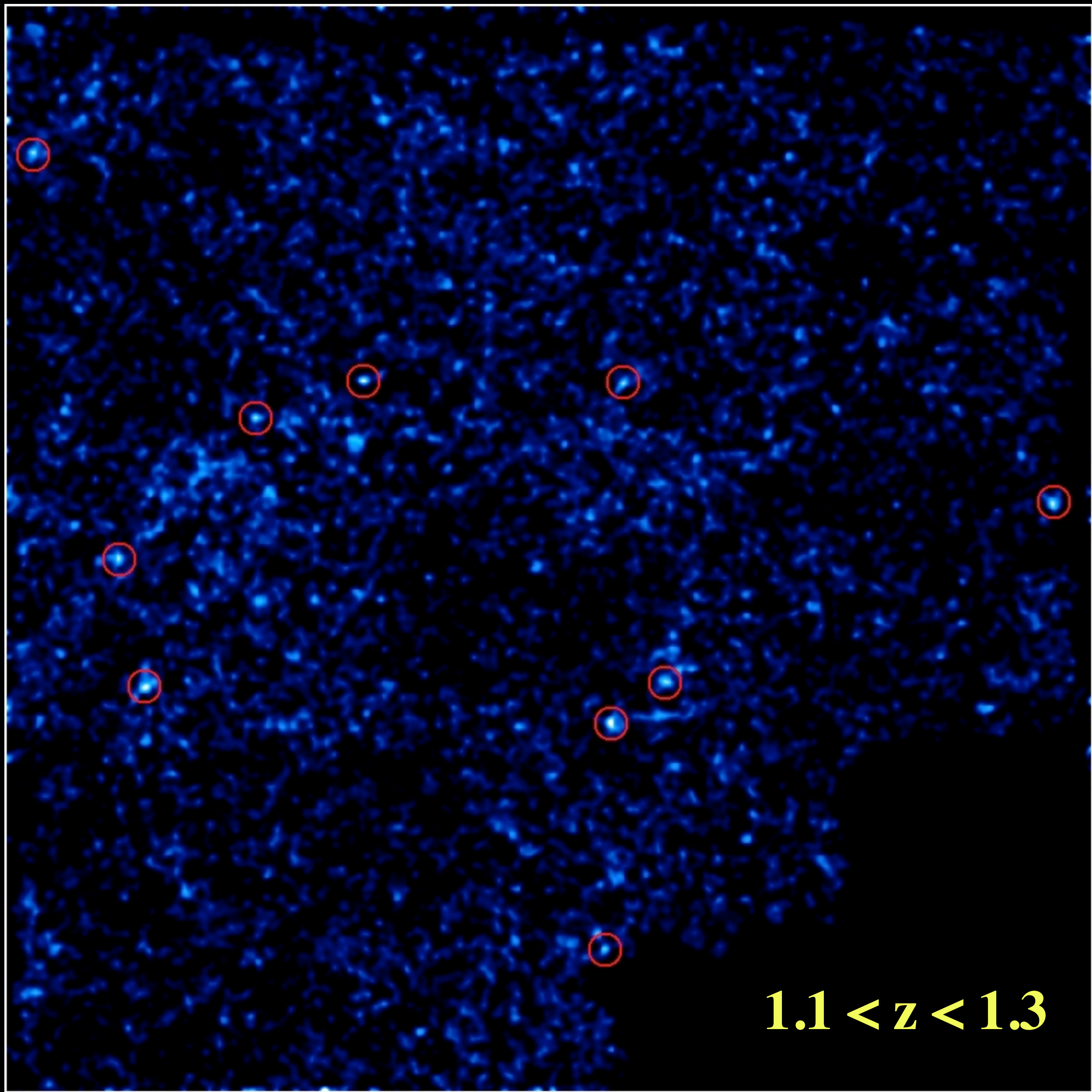
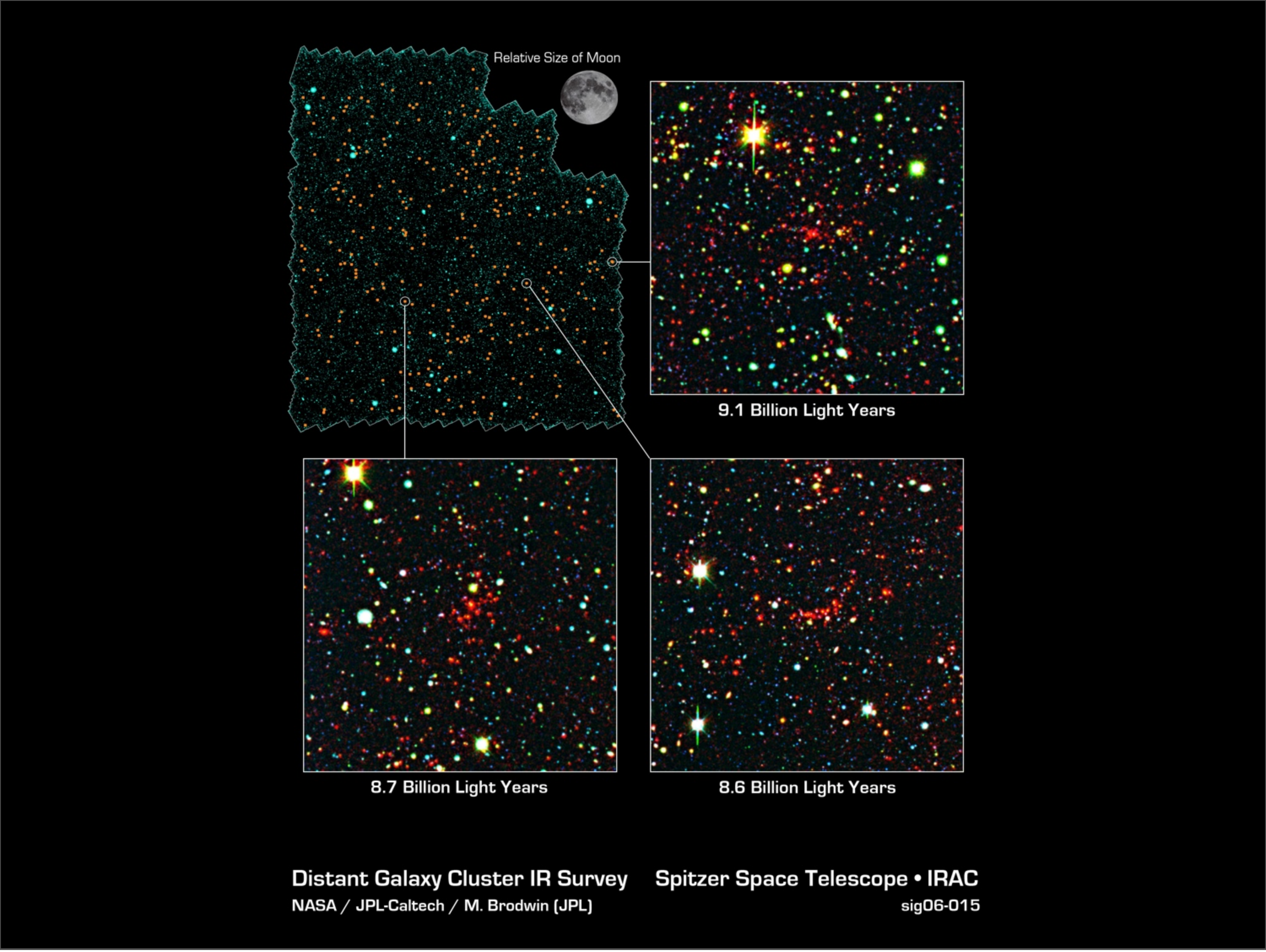
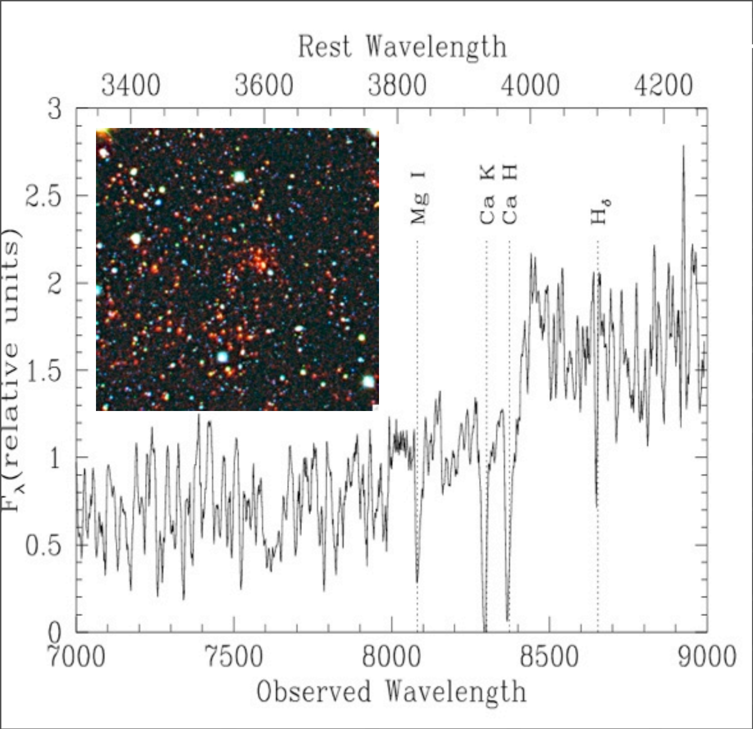
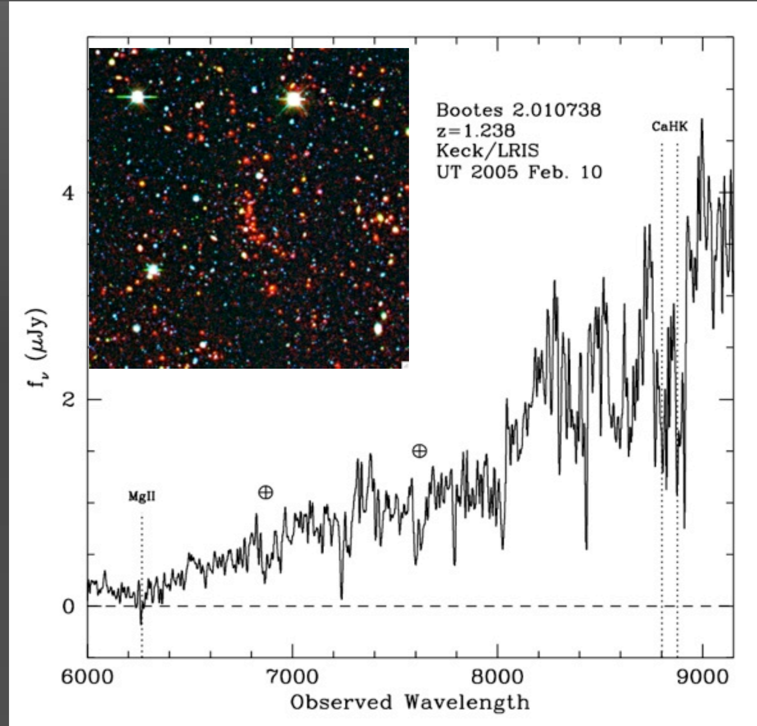
# Cluster Probability Density Map



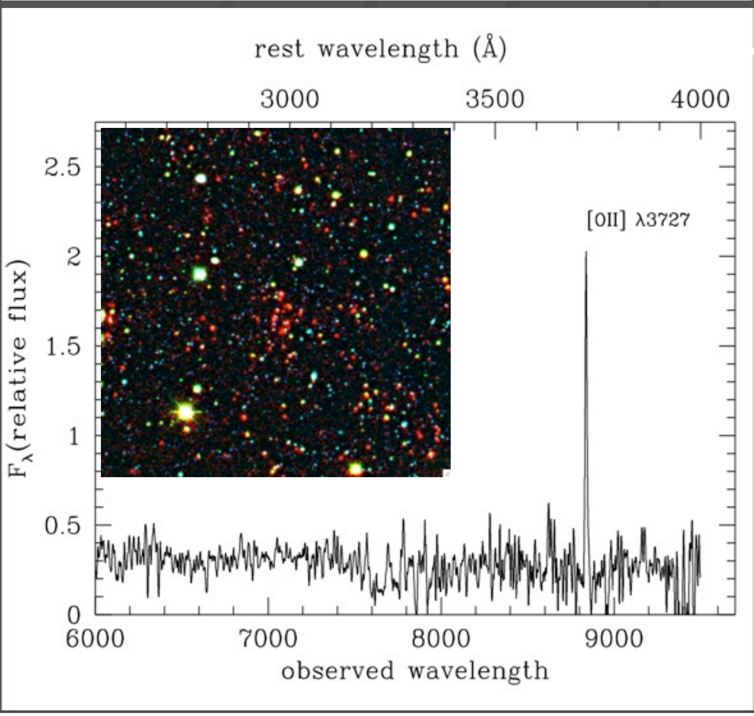

Relative Size of Moon
9.1 Billion Light Years
8.7 Billion Light Years
8.6 Billion Light Years
Distant Galaxy Cluster IR Survey
NASA / JPL-Caltech / M. Brodwin (JPL)
Spitzer Space Telescope • IRAC
sig06-015



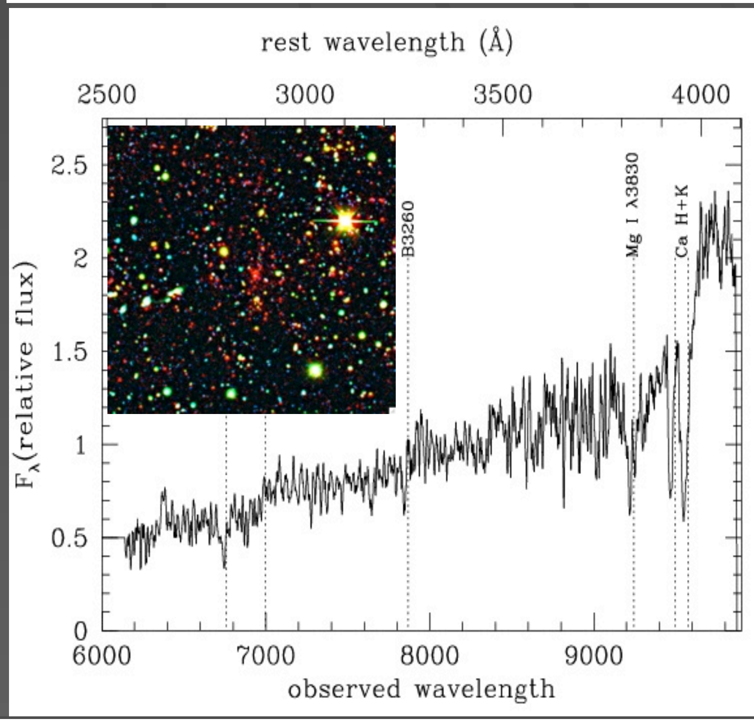

<z>=1.11




<z>=1.24




<z>=1.37




<z>=1.41

# Spectroscopic Confirmation

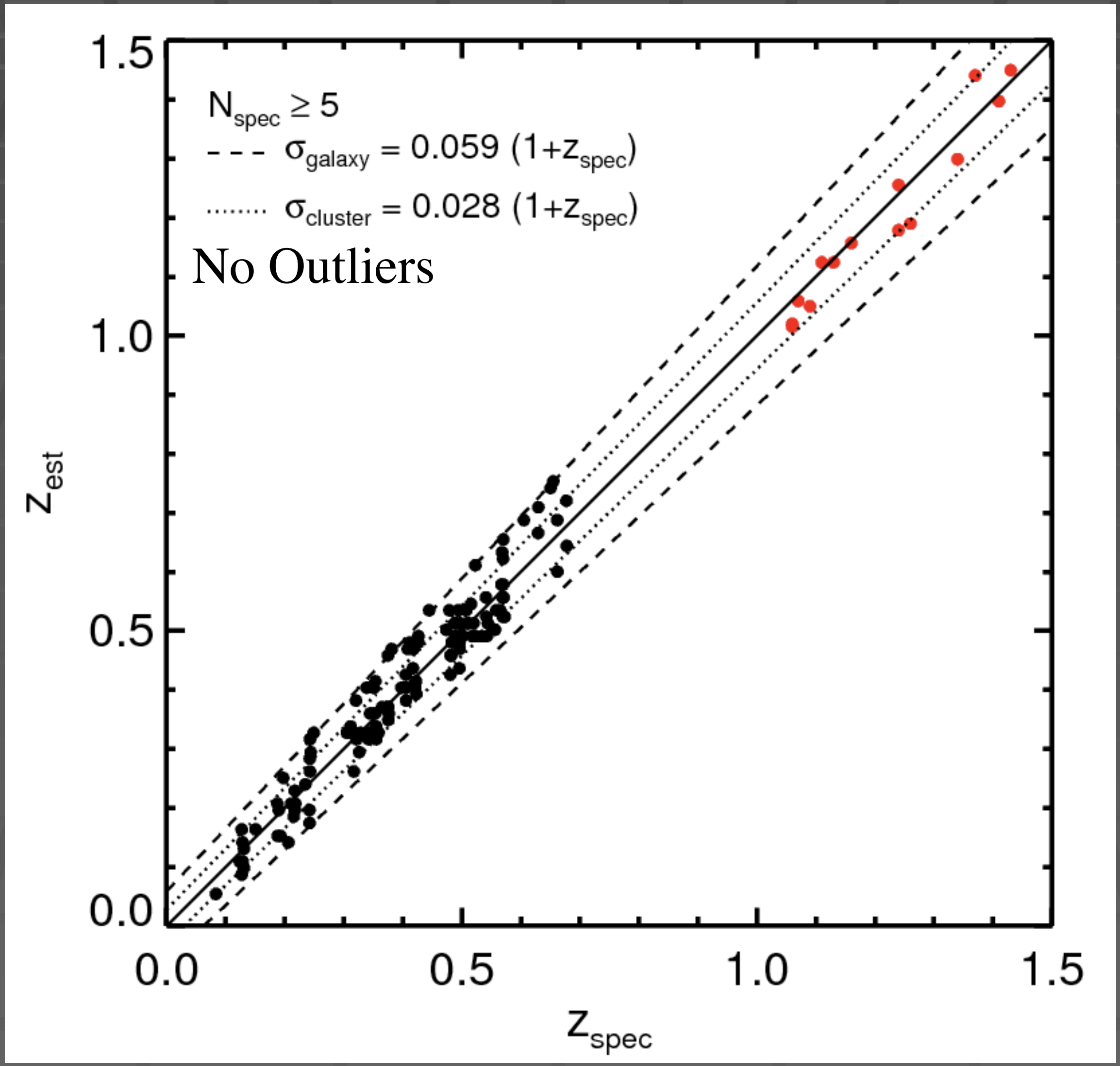
- Keck spectroscopy of z>1 candidates
- **16** confirmed with 5+ members within 2000 km/s in the rest-frame (approx $\Delta z \pm 0.015$)
- Remaining candidates need deeper data (many objects with faint, red continua)

Eisenhardt et al. 2008

* Not yet published

| ID | Phot-z | Spec-z | # |
|---|---|---|---|
| 51 | 1.02 | 1.06 | 7 |
| 152 | 1.02 | 1.06 | 6 |
| 123 | 1.05 | 1.09 | 6 |
| 19 | 1.06 | 1.07 | 20 |
| 17 | 1.12 | 1.11 | 24 |
| 34 | 1.12 | 1.13 | 8 |
| 14 | 1.16 | 1.16 | 5 |
| 50* | 1.18 | 1.24 | 5 |
| 342 | 1.26 | 1.24 | 11 |
| 30 | 1.19 | 1.26 | 9 |
| 29 | 1.30 | 1.34 | 10 |
| 25 | 1.44 | 1.37 | 5 |
| 22 | 1.40 | 1.41 | 10 |
| 206* | 1.45 | 1.43 | 5 |

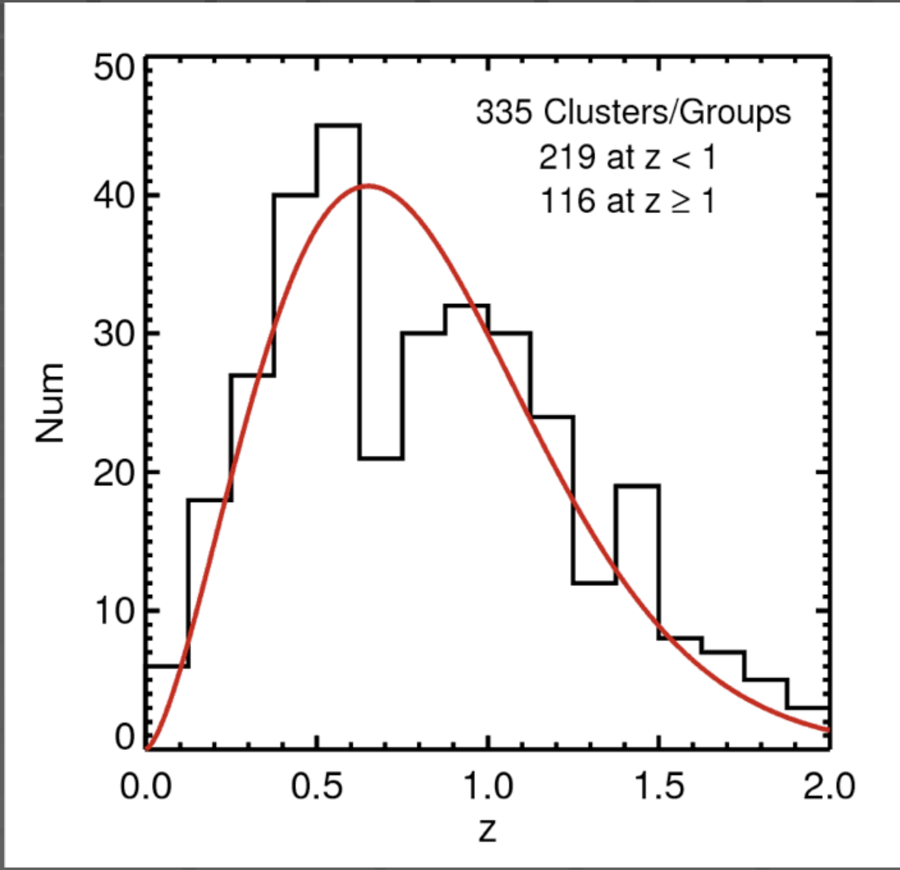
# Redshift Accuracy



# Redshift Distribution of Galaxy Clusters at 0 < z < 2

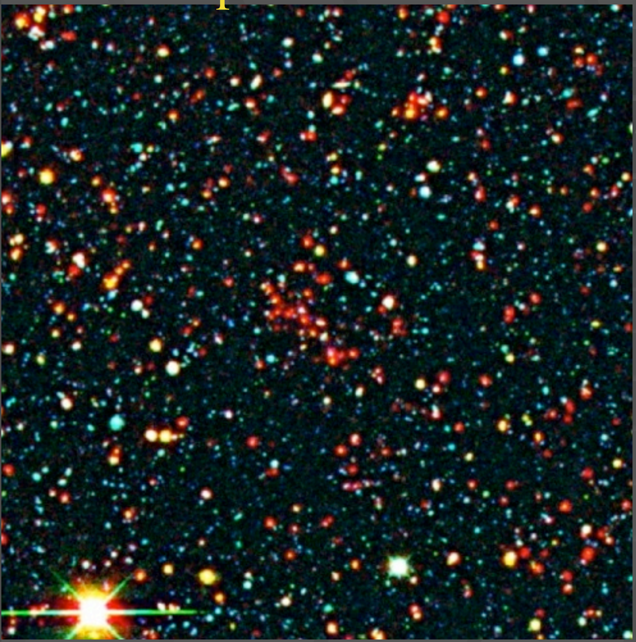
## Results

- 335 clusters and groups at 0 < z < 2 over 8 deg$^2$ in Boötes.
- Of these 116 are at z ≥ 1, a 5-fold increase over the number of confirmed high-z clusters in the literature.

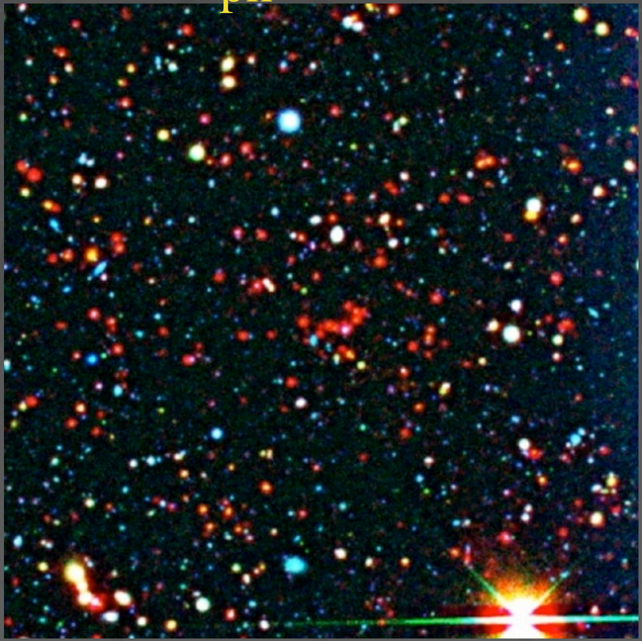


# SDWFS Candidates at 1.5 < z < 2.0

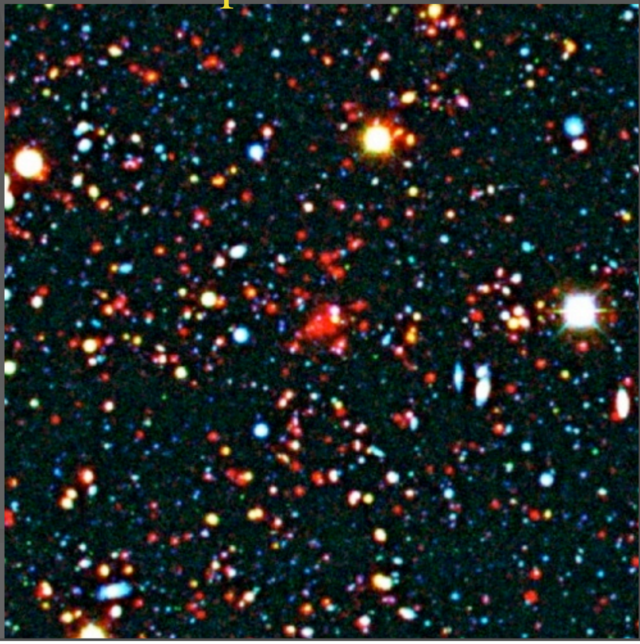
$z_{ph} \approx 1.5$



$z_{ph} \approx 1.8$



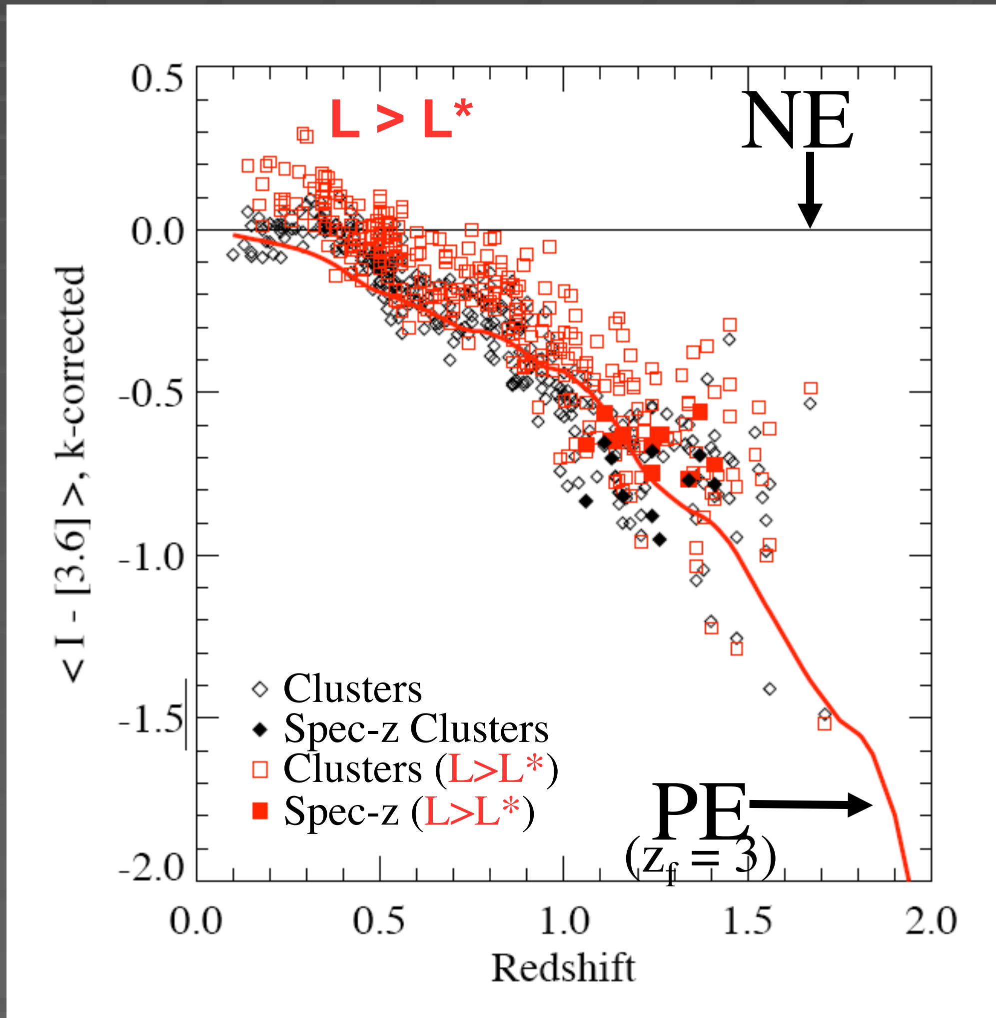
$z_{ph} \approx 1.9$



# Color Evolution of Galaxy Clusters over 0 < z < 1.7

- **Massive cluster galaxies redder/older**
  - Mass-Metallicity relation to z=1.5, and/or
  - Downsizing

- **Passive Evolution Model**
  - Bruzual & Charlot model
  - 0.1 Gyr Burst at $z_f = 3$, followed by simple passive evolution
  - $H_0=70$; $\Omega_M = 0.3$; $\Omega_\Lambda = 0.7$




Eisenhardt, Brodwin et al. 2008 (ApJ, 684, 905)

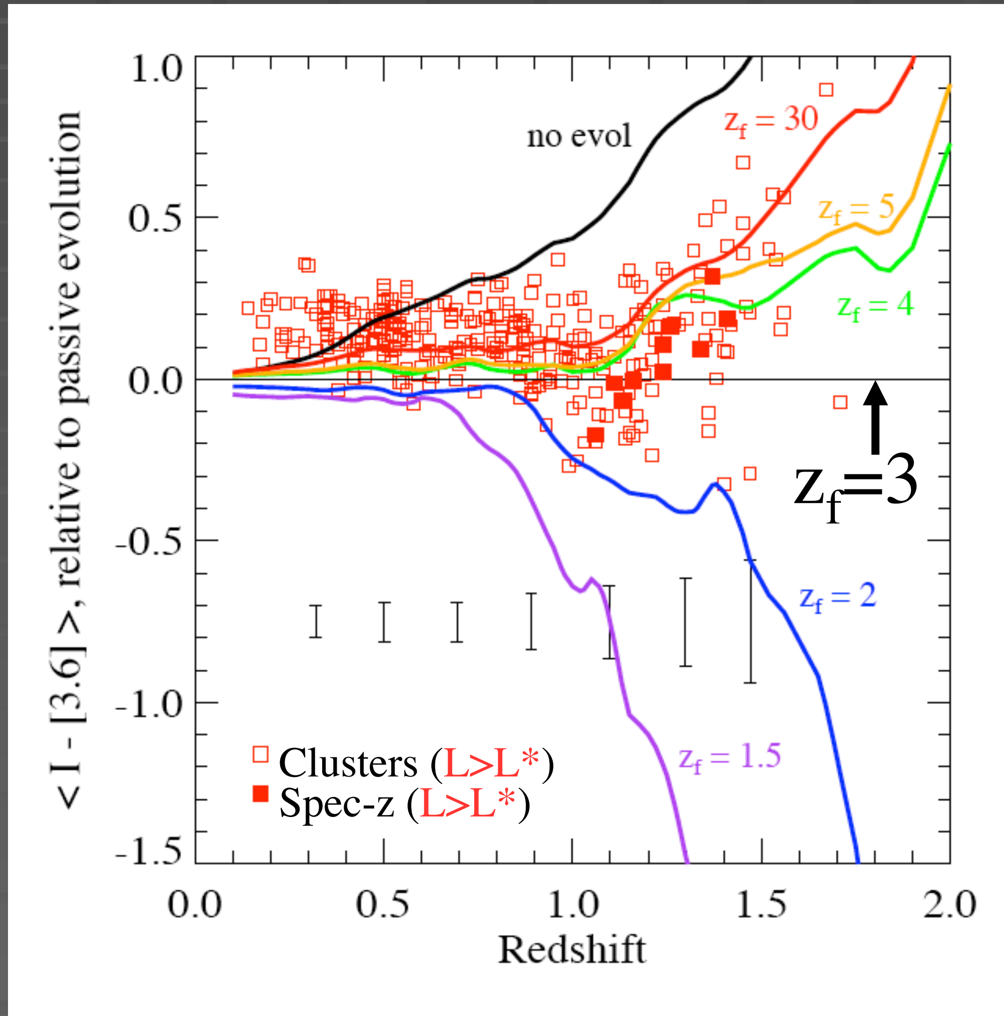
# Stellar Population Evolution

## Points

- Massive Cluster Galaxies (L>L*)

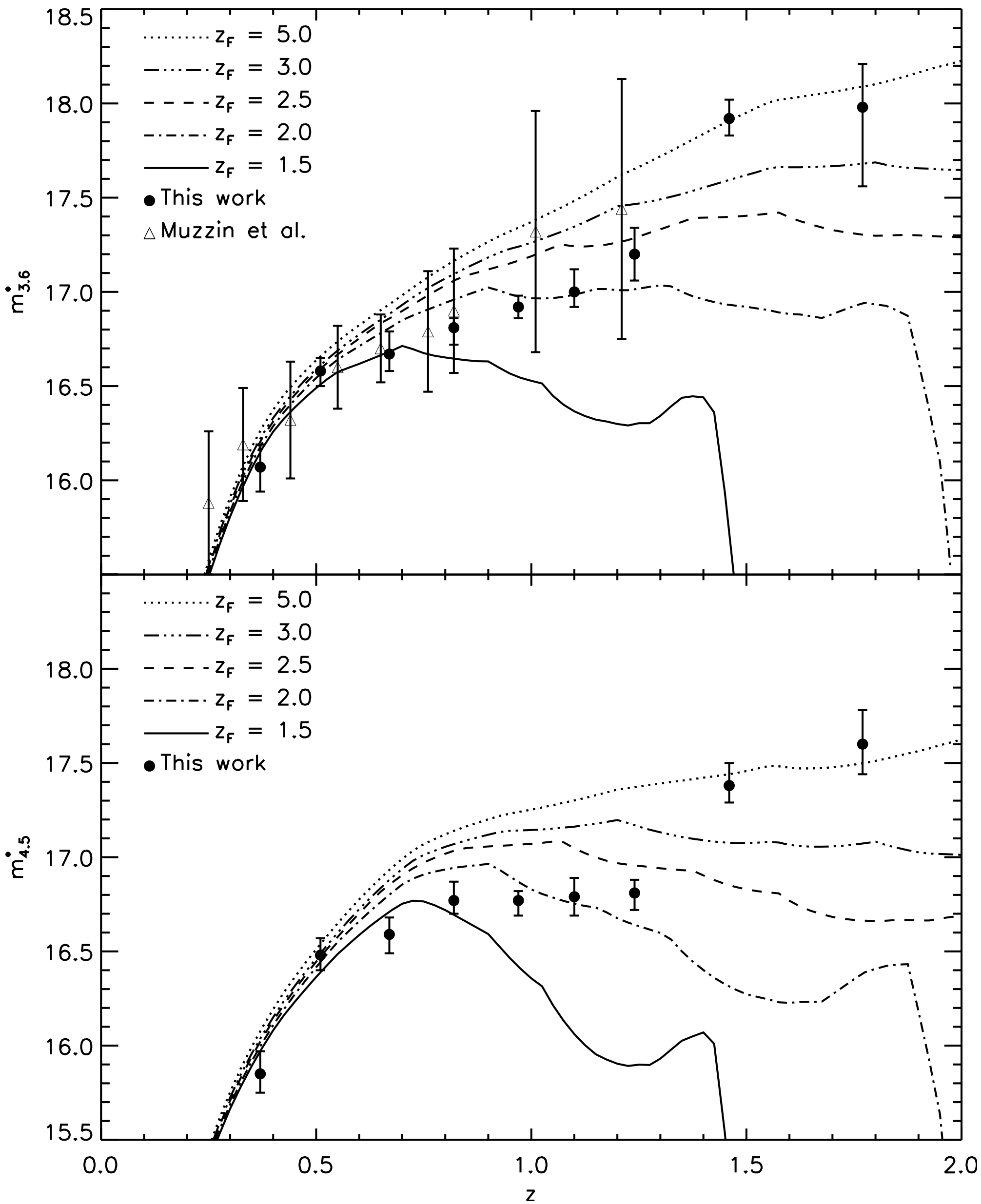
## PE Models

- Passive evolution after monolithic collapse at formation redshift: $z_f$ = [1.5, 2, 3, 4, 5, 30]

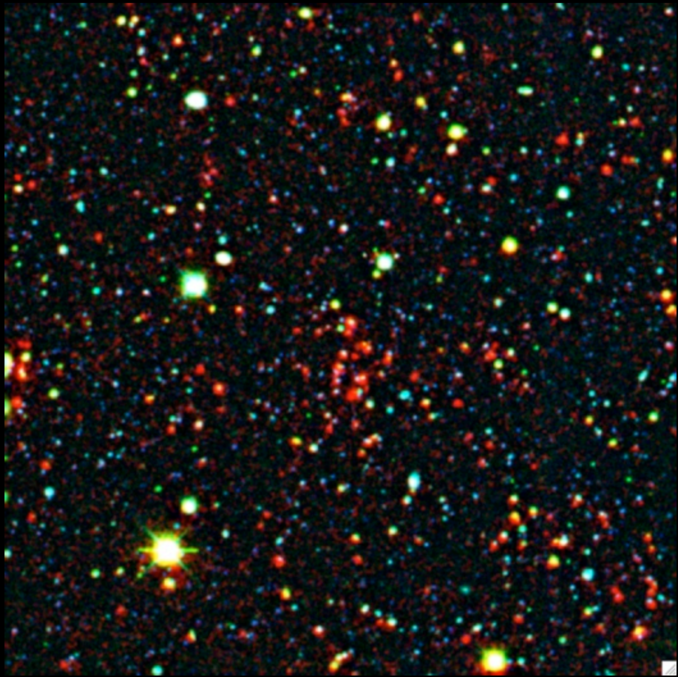



Eisenhardt, Brodwin et al. 2008 (ApJ, 684, 905)

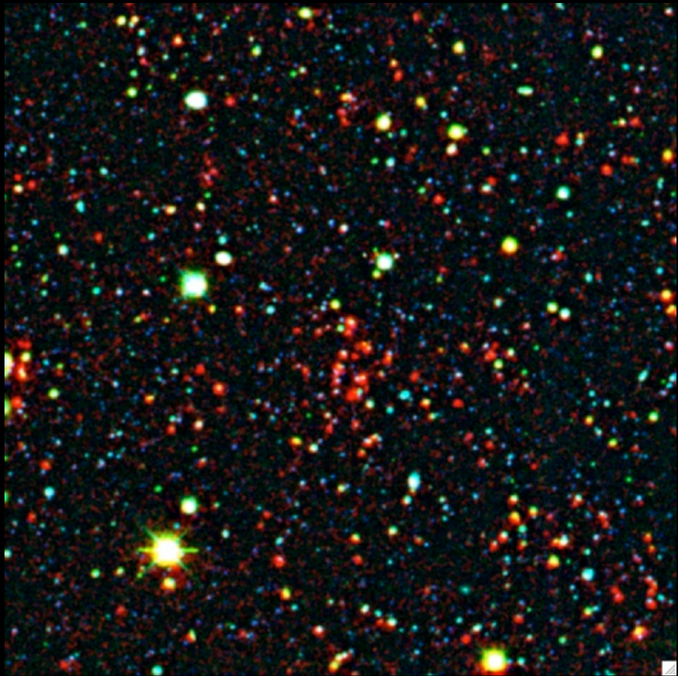
# Galaxy Mass Evolution?

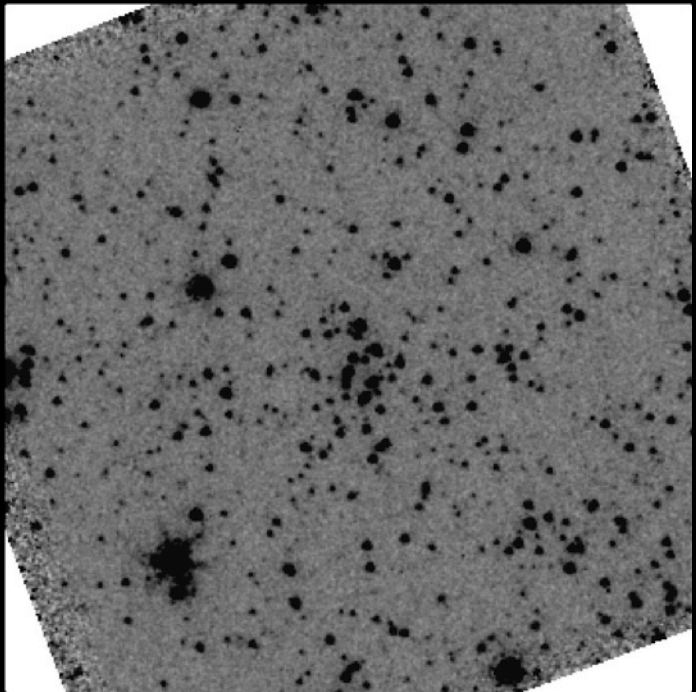


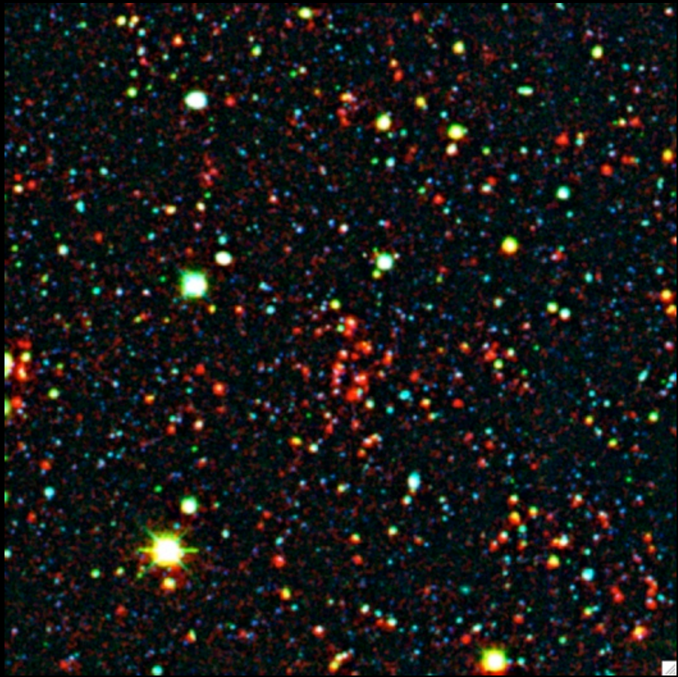

*ISCS; Mancone et al.*
*(ApJ, submitted)*



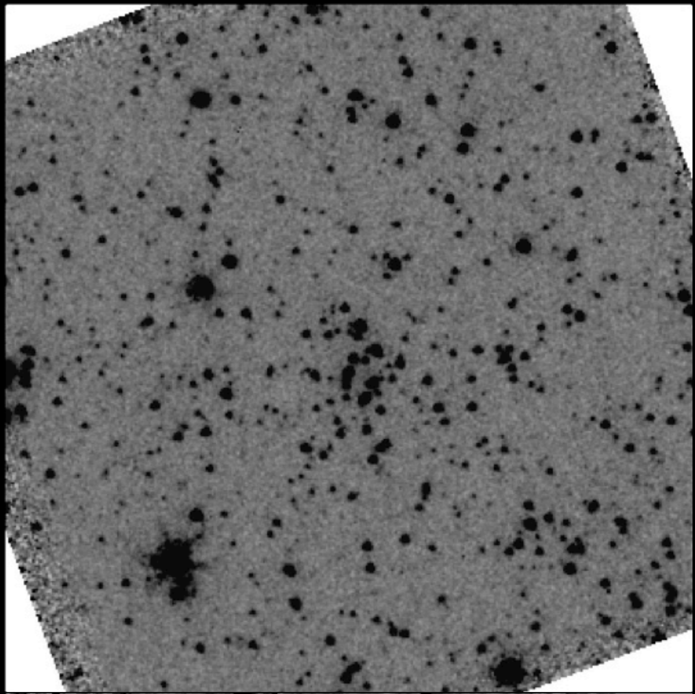
*z=1.37*


z=1.37

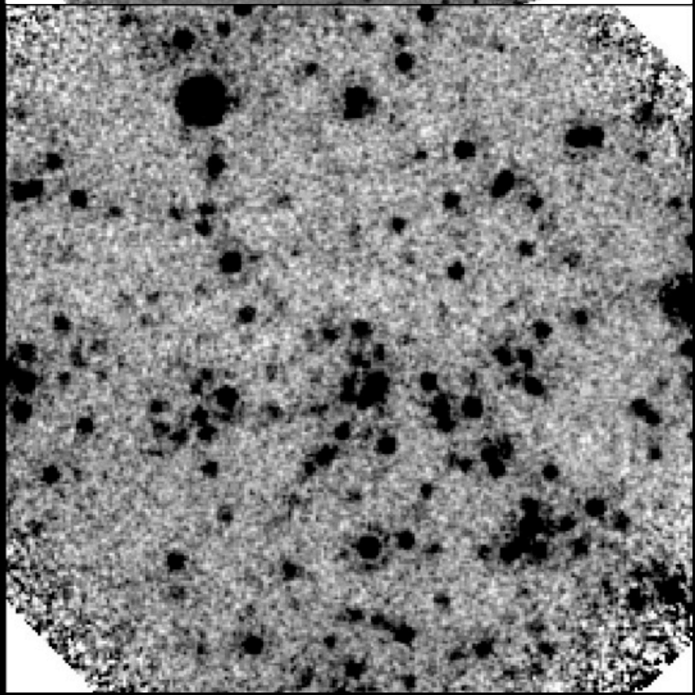

4.5μm



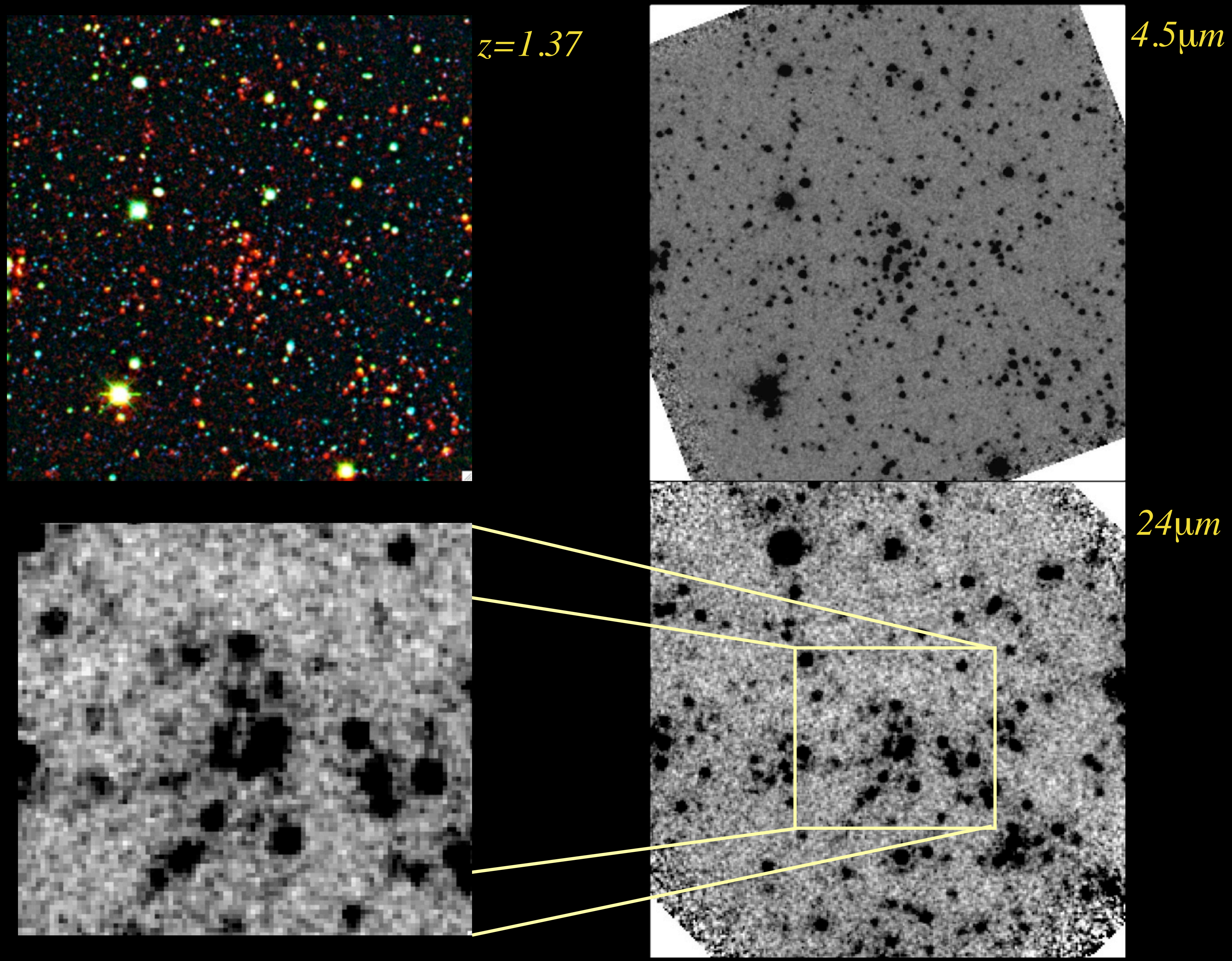
*z=1.37*



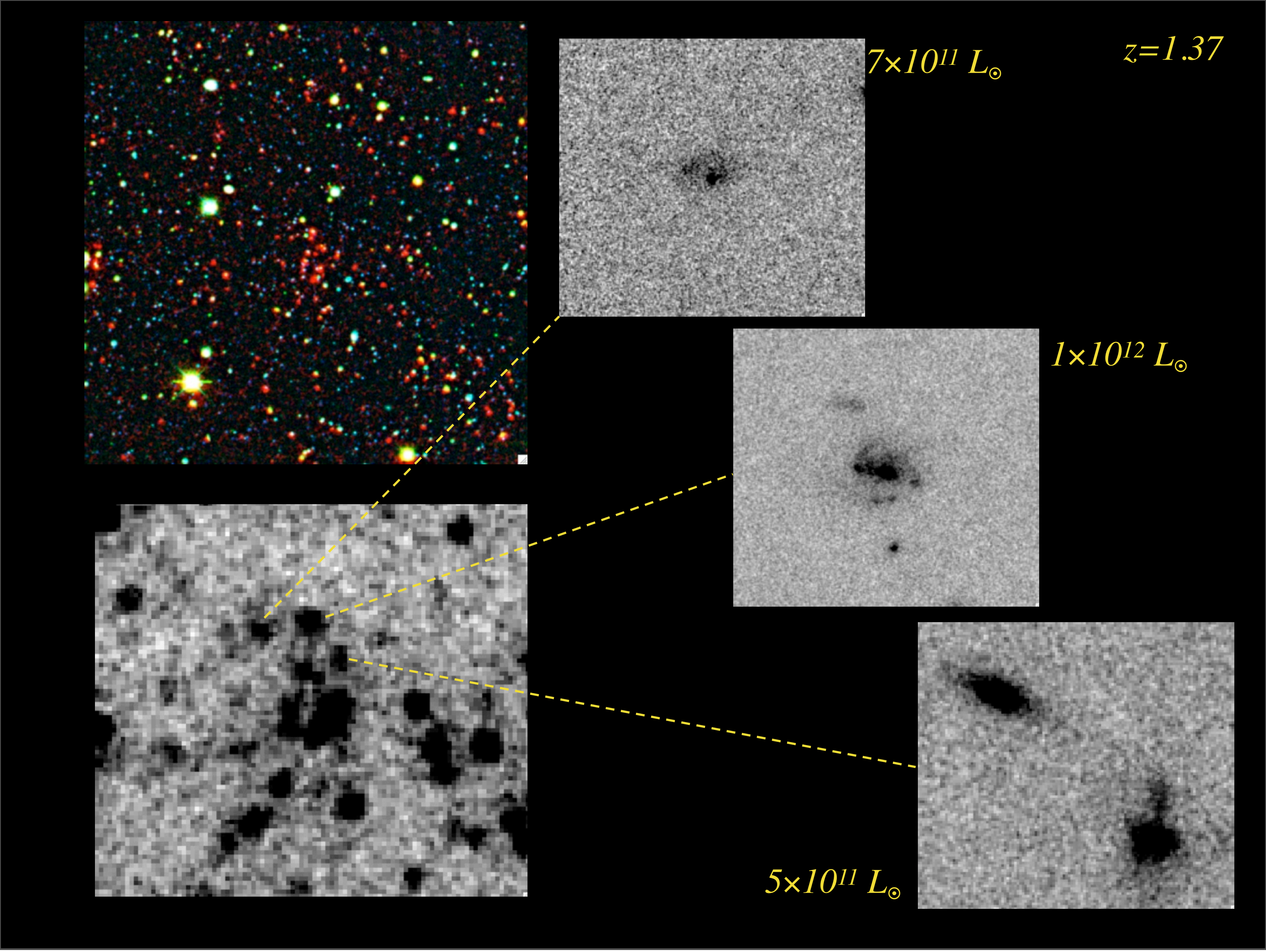
*4.5μm*



*24μm*



z=1.37
4.5μm
24μm

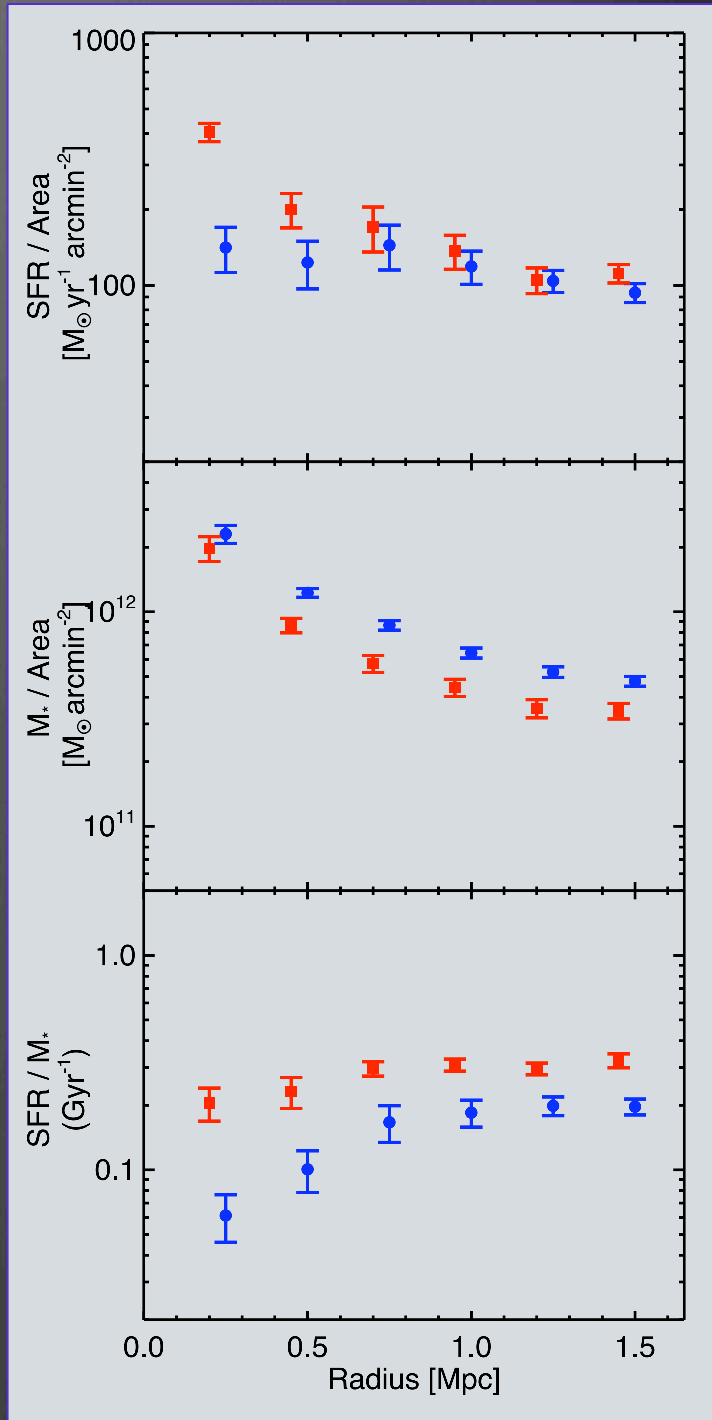

$7\times10^{11}\ L_\odot$
$z=1.37$
$1\times10^{12}\ L_\odot$
$5\times10^{11}\ L_\odot$

# High SFR in z>1 Clusters

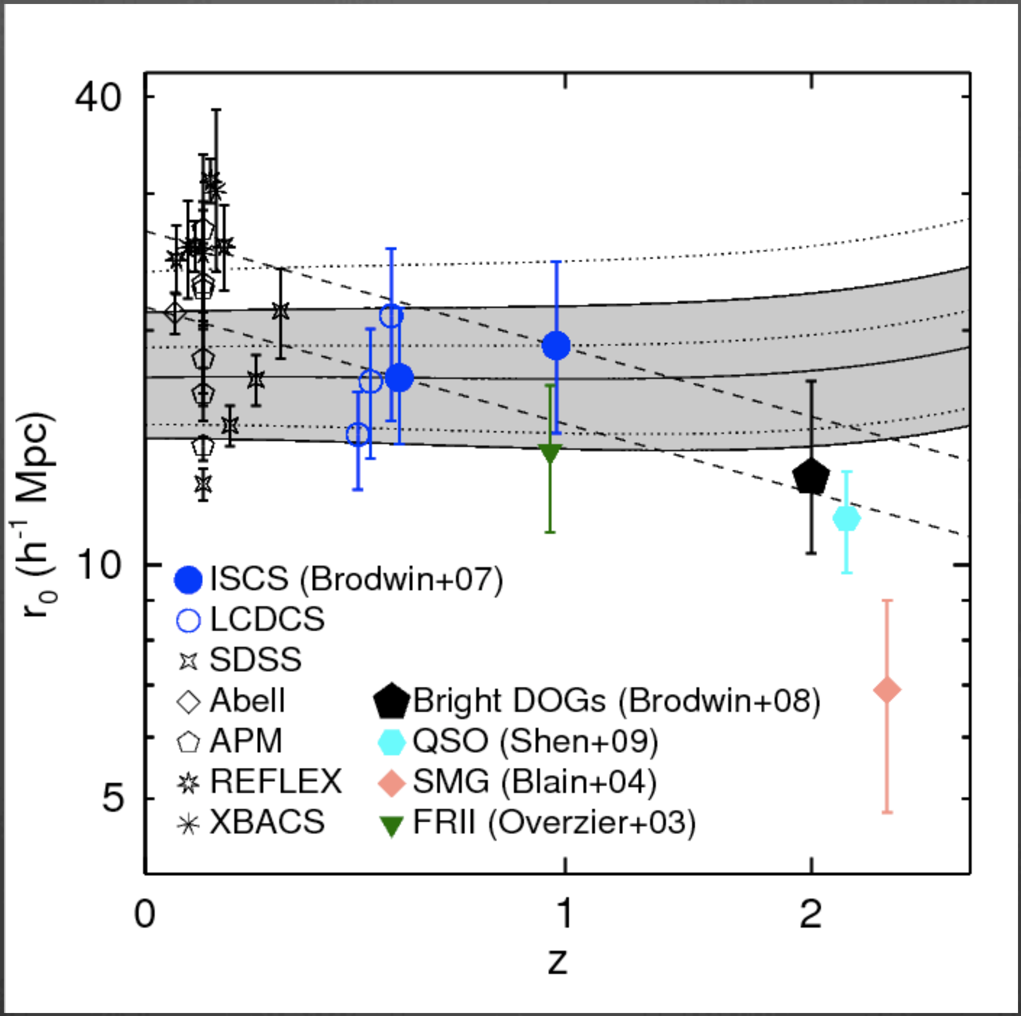
1.3 < z < 1.5
1.0 < z < 1.3

- SFR increases towards the cluster center in 15 1<z<1.5 clusters
- More extreme for z>1.3
- The specific SFR is roughly flat to decreasing

*Brodwin et al.*

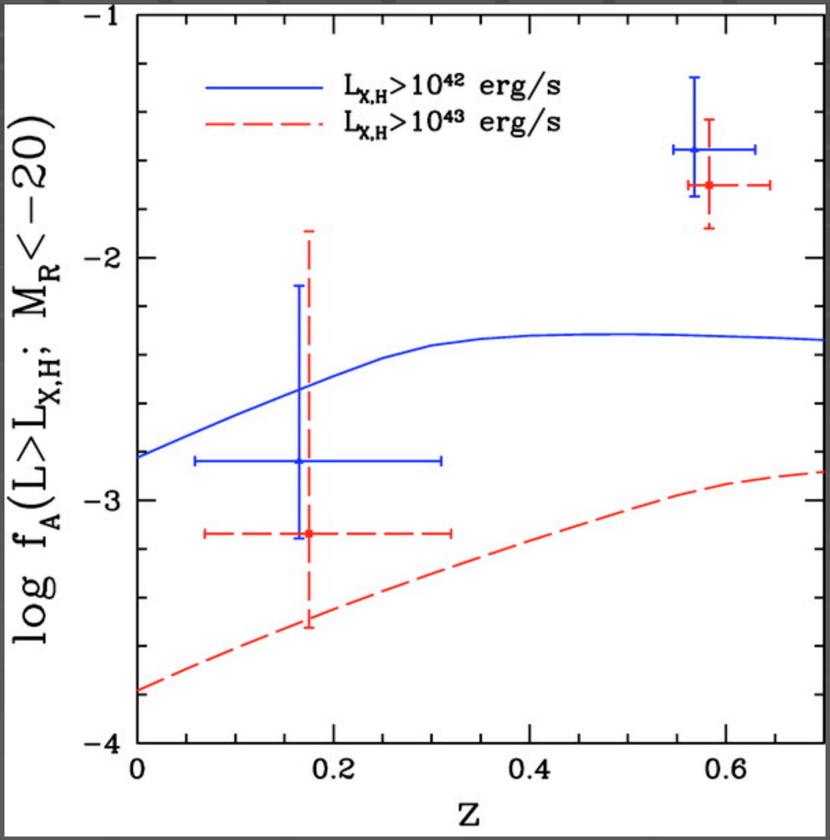


# Cluster/ ULIRG Connection?

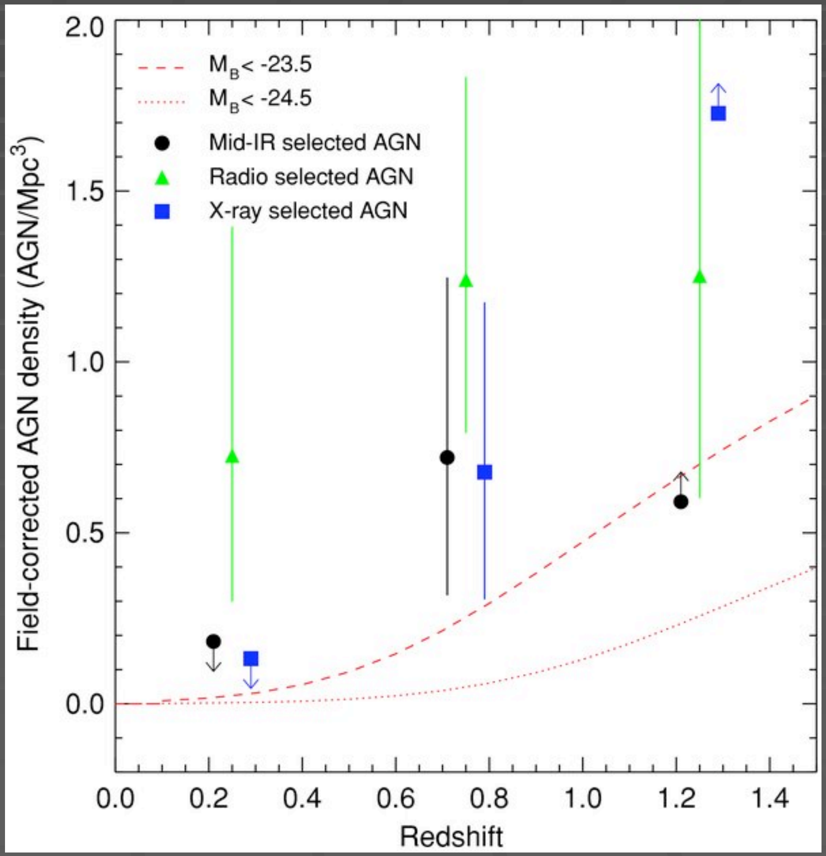



*ISCS; MB et al. (2007)*

# AGN Activity in Clusters




*Eastman et al. (2007)*




*ISCS; Galametz et al. (2009) from XBootes*

# Future Plans

- Combine new WFC3 NIR imaging with existing ACS data to make precise CMD
- Measure sizes of cluster members in WFC3 NIR imaging
- Measure SFR from WFC3 NIR grism spectroscopy
- Better determine incidence of AGN using moderate-depth Chandra ACIS data

# Summary & Conclusions

- We have identified 335 galaxy clusters and groups in the 8 $deg^2$ area of the NDWFS. To date 16 clusters between $1 < z < 1.5$ and 122 clusters at $z < 1$ have been confirmed. Cluster photometric redshift accuracy is $\sigma = 0.028\ (1+z)$. Clusters are effectively mass-selected.
- Mean colors of clusters at $0 < z < 1.5$ are consistent with simple Passive Evolution models with high formation redshifts ($z_f > 3$).
- Evidence of a mass-metallicity relation continuing to z~2
- Evolution in the LFs suggests mass assembly at $z > 1.4$ in the massive galaxy population of clusters.
- Evidence of ongoing massive SF in z>1 cluster cores, along with a strong radial dependence of AGN in z>1 clusters.