

Massive Galaxy Evolution in the *Spitzer*/IRAC Shallow Cluster Survey

M. Brodwin (JPL/Caltech)
Massive Galaxies over Cosmic Time II
November 3, 2006

Collaborators

Core Cluster Search Team:

M. Brodwin (JPL/Caltech)
P. R. Eisenhardt (JPL/Caltech)
A. H. Gonzalez (U. Florida)
S. A. Stanford (UC Davis)
D. Stern (JPL/Caltech)

Surveys	Data	PI(s)
IRAC Shallow Survey	Imaging: 3.6/4.5/5.8/8.0 μ m	P. R. Eisenhardt (JPL/Caltech)
NOAO Deep Wide-Field Survey (NDWFS)	Imaging: Deep B _w /R/I/K	A. Dey (NOAO) B. T. Jannuzi (NOAO)
FLAMINGOS Extragalactic Survey (FLAMEX)	Imaging: Deep J/K _s	A. H. Gonzalez (U. Florida)
AGN and Galaxy Evolution Survey (AGES)	Spectroscopy: 20,000 optical spectra	D. Eisenstein (Arizona) C. S. Kochanek (Ohio State) B. T. Jannuzi (NOAO) & S. S. Murray (CfA)

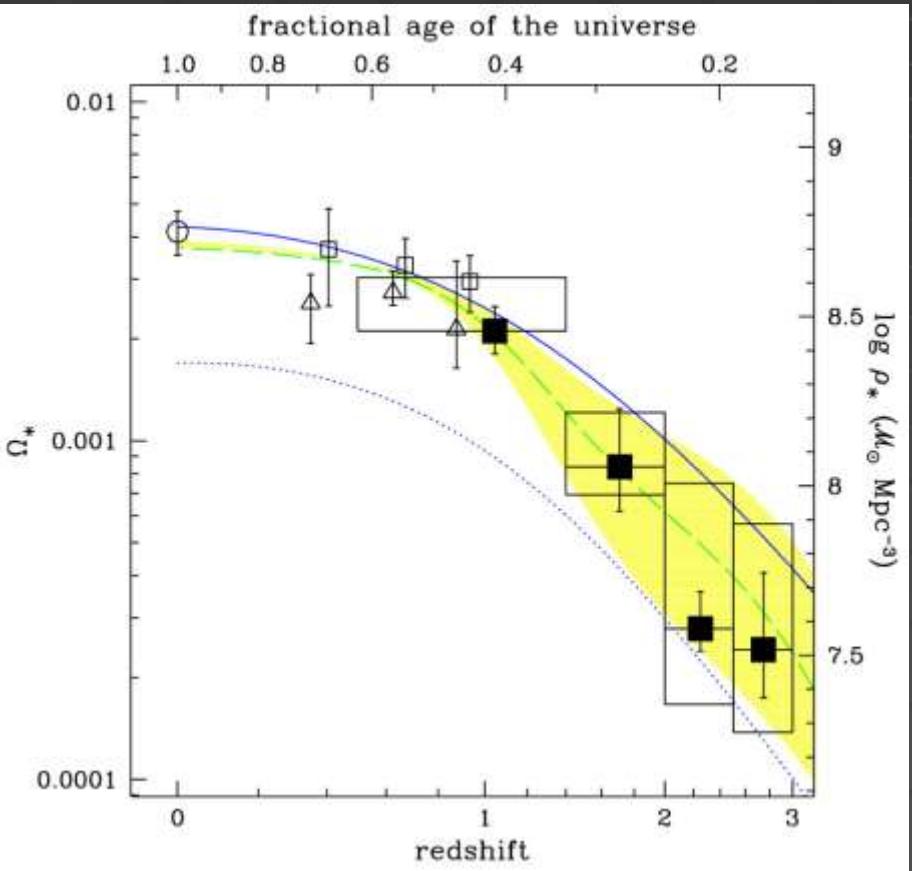


Operators

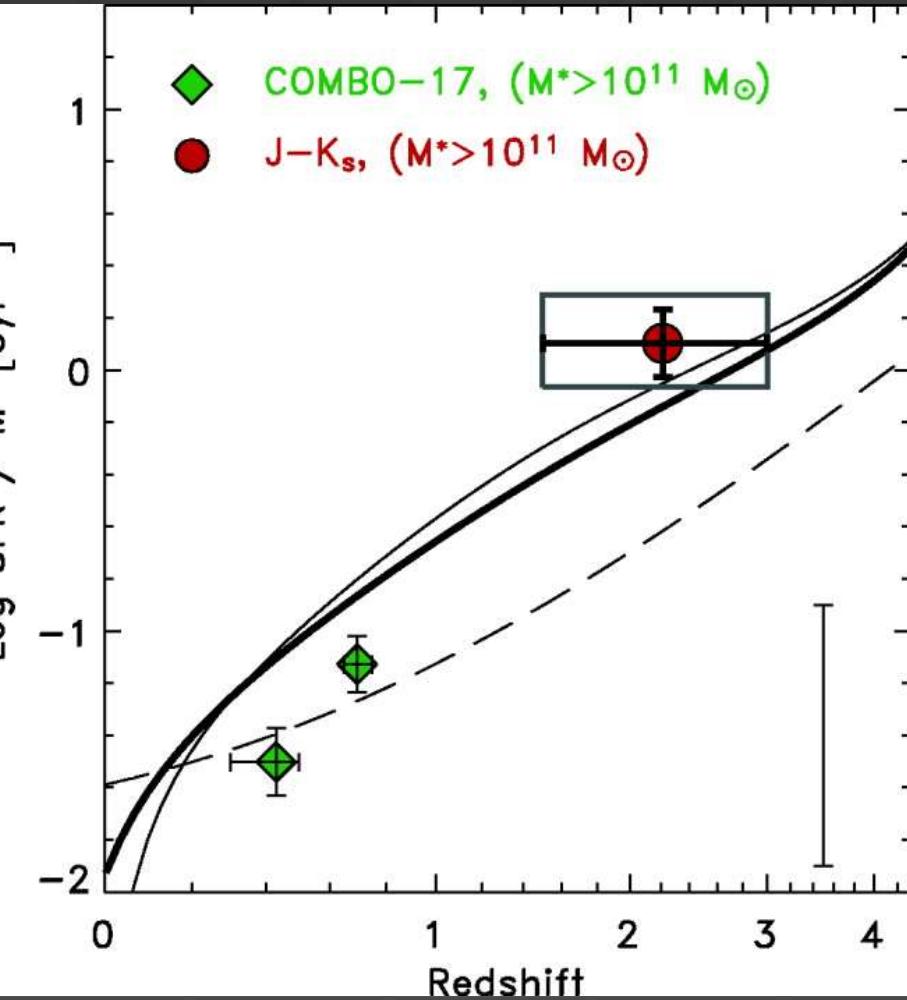
- M. Brodwin (JPL/Caltech)
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Mass Assembly in Massive Galaxies

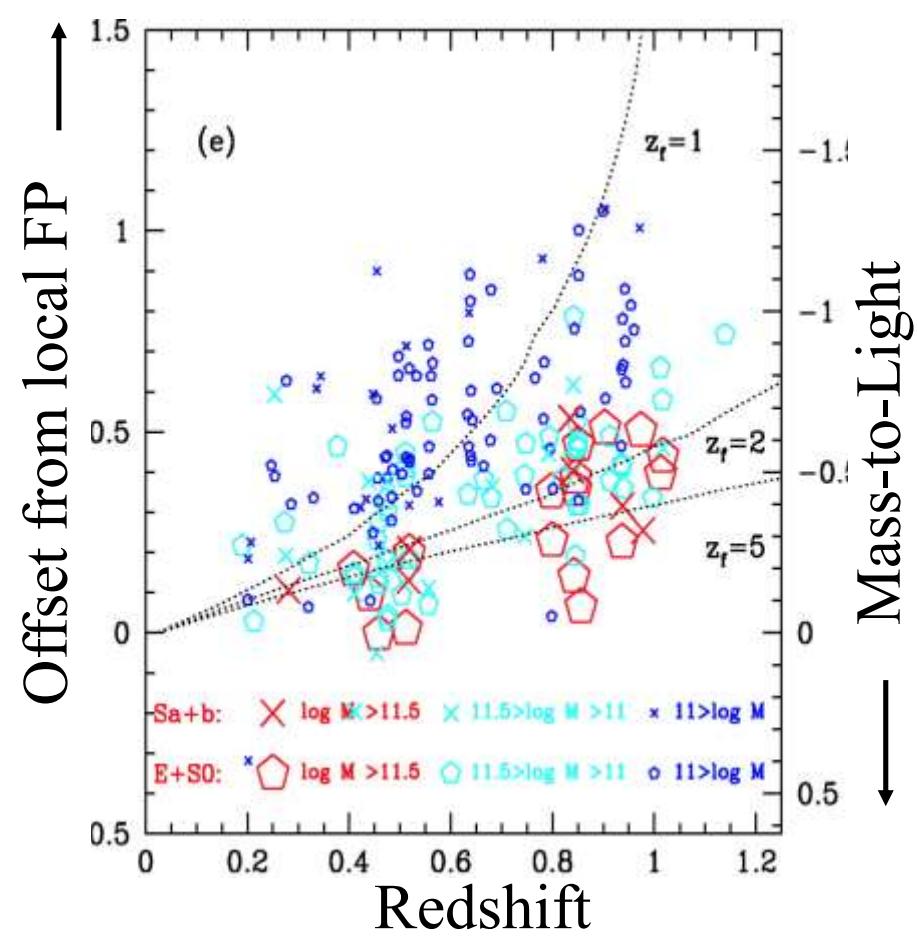
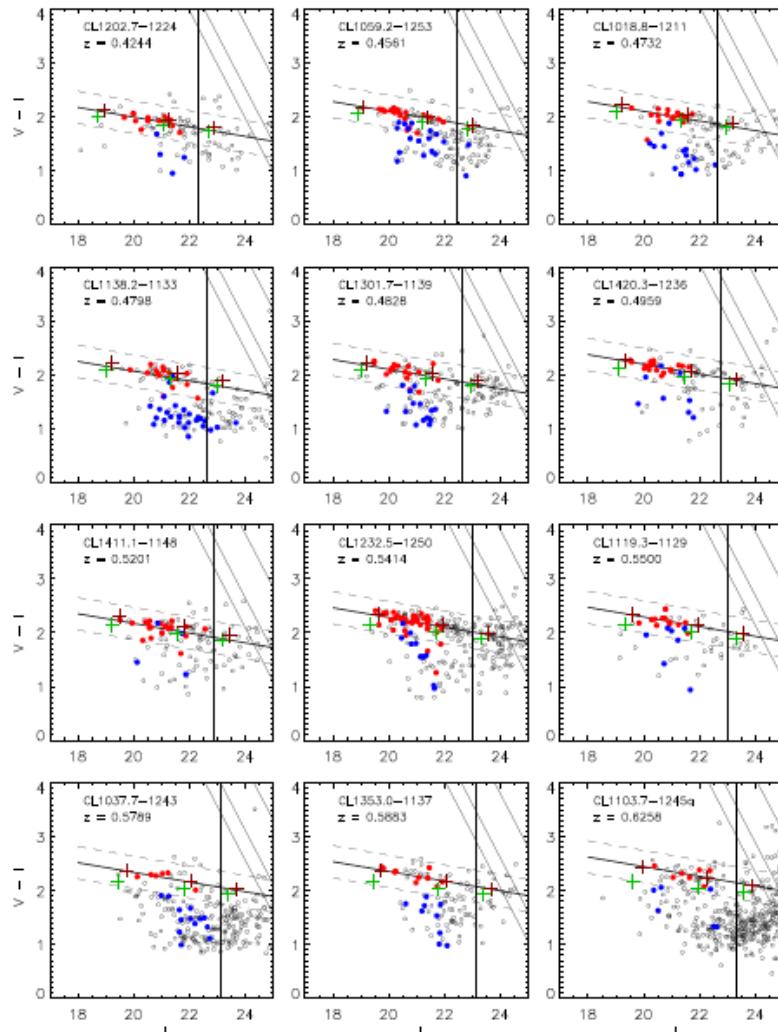


Dickinson *et al.* (2003)



Papovich *et al.* (2006)

Origin of Stars in Massive Galaxies



Treu et al (2005)

Stanford, Eisenhardt & Dickinson (1998)
De Lucia et al (2004), vd & vdm (astro-ph/0609587)

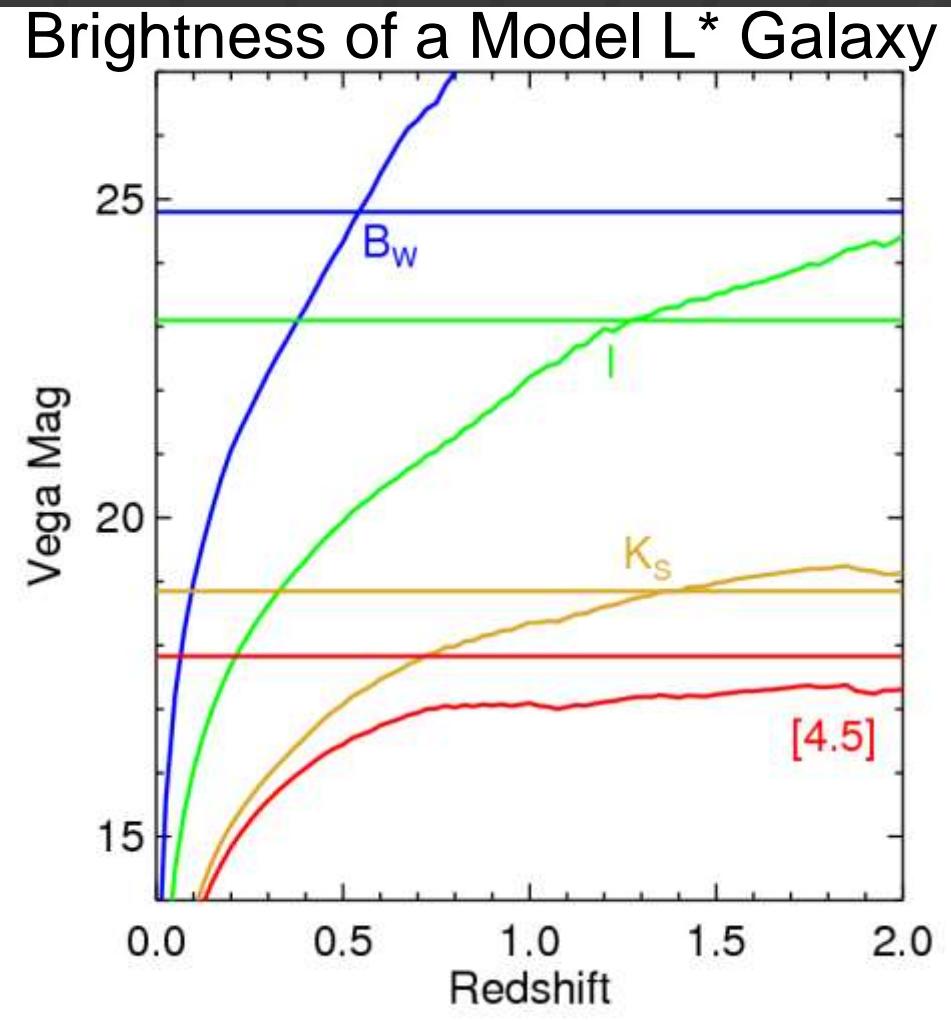
Massive Galaxies in Clusters at $1 < z < 2$

Questions:

1. What are the formation redshifts of massive galaxies in rich environments, from low-mass groups to rich clusters?
 - When were the stars formed?
 - When were the galaxies assembled?
2. What is the contribution of LIRGs/ULIRGs to the stellar mass budget? What is the AGN fraction?
3. When are the red-sequence, morphology-density relation and Hubble sequence established?

The Spitzer Advantage

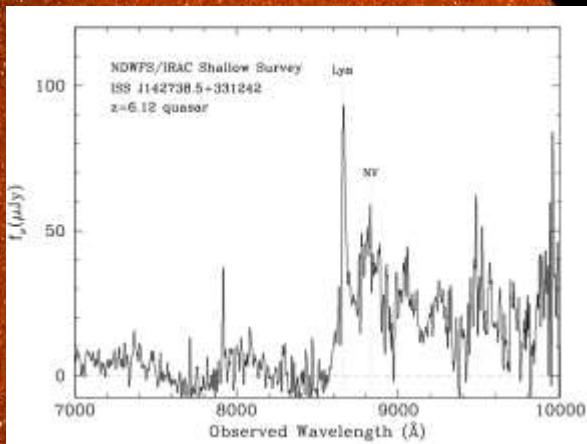
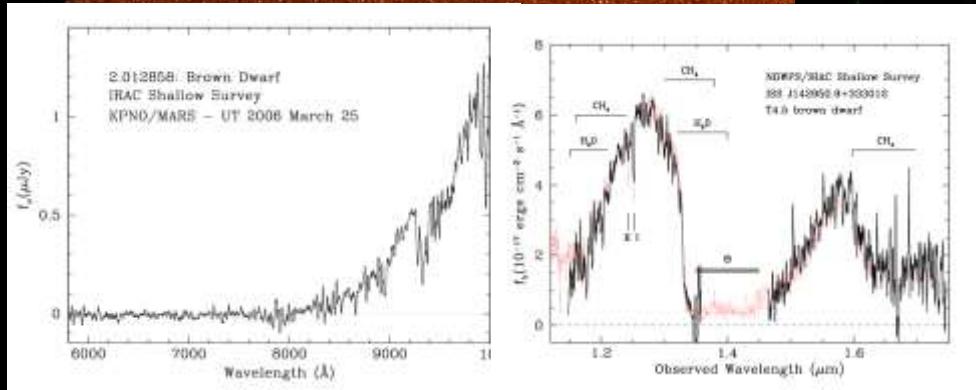
- Bruzual & Charlot model
 - 0.1 Gyr Burst, $z_f = 3$
 - $H_0 = 70$; $\Omega_M = 0.3$; $\Omega_\Lambda = 0.7$
- Red galaxies quickly fade in optical due to strong K-correction
- Near-IR better; hard to get deep, large areas
- Mid-IR best, with flat sensitivity at $0.7 < z < 2+$. Wide-field mapping efficient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



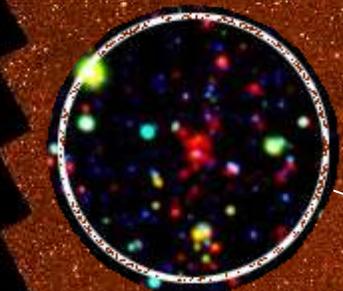
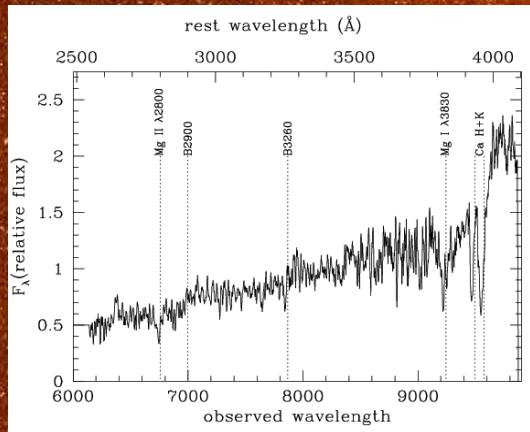
3.5 degrees

$z = 6.1$ Quasar
Stern et al 2006
submitted

Field T4.5 Brown Dwarf
Stern et al 2006
submitted



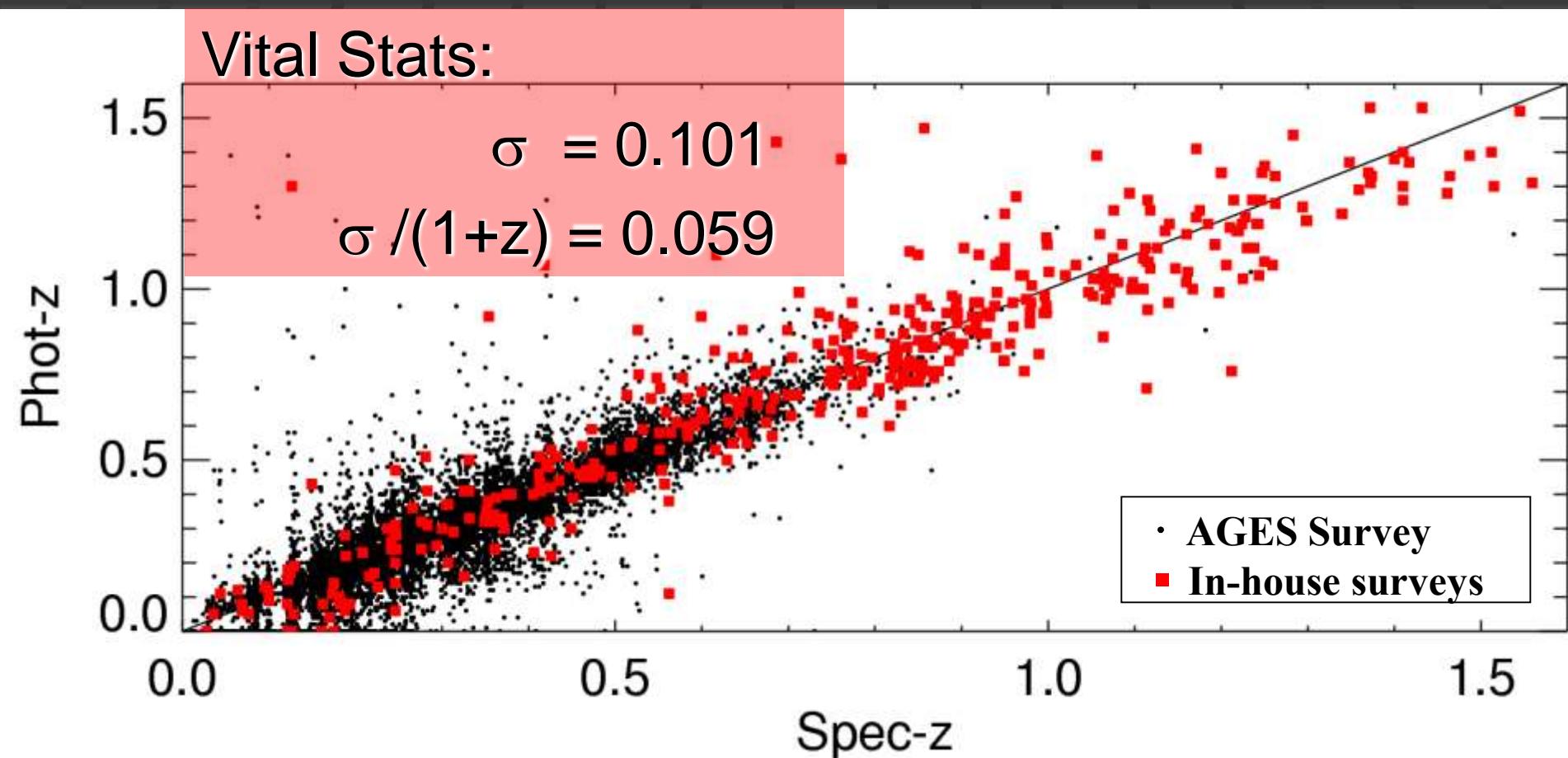
$z = 1.41$
Galaxy Cluster
Stanford et al 2005
ApJ 634 L129



Spitzer/IRAC Shallow Survey
4.5 μm image
8.5 sq degrees
3 x 30 sec/position
Eisenhardt et al 2004 ApJS 154, 54

N
E

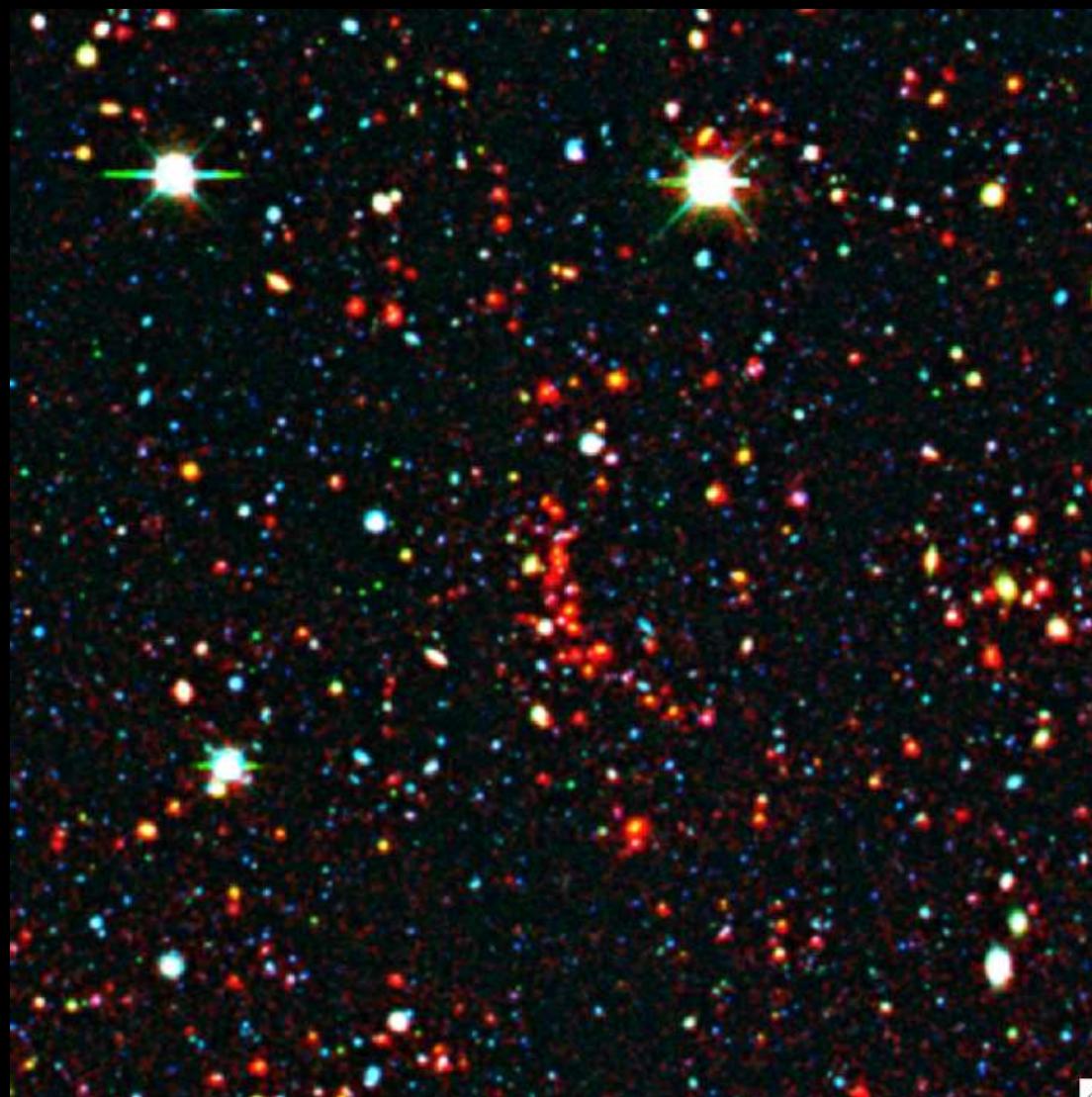
Photometric Redshifts



Optical
Alone



Optical
+
Mid-IR



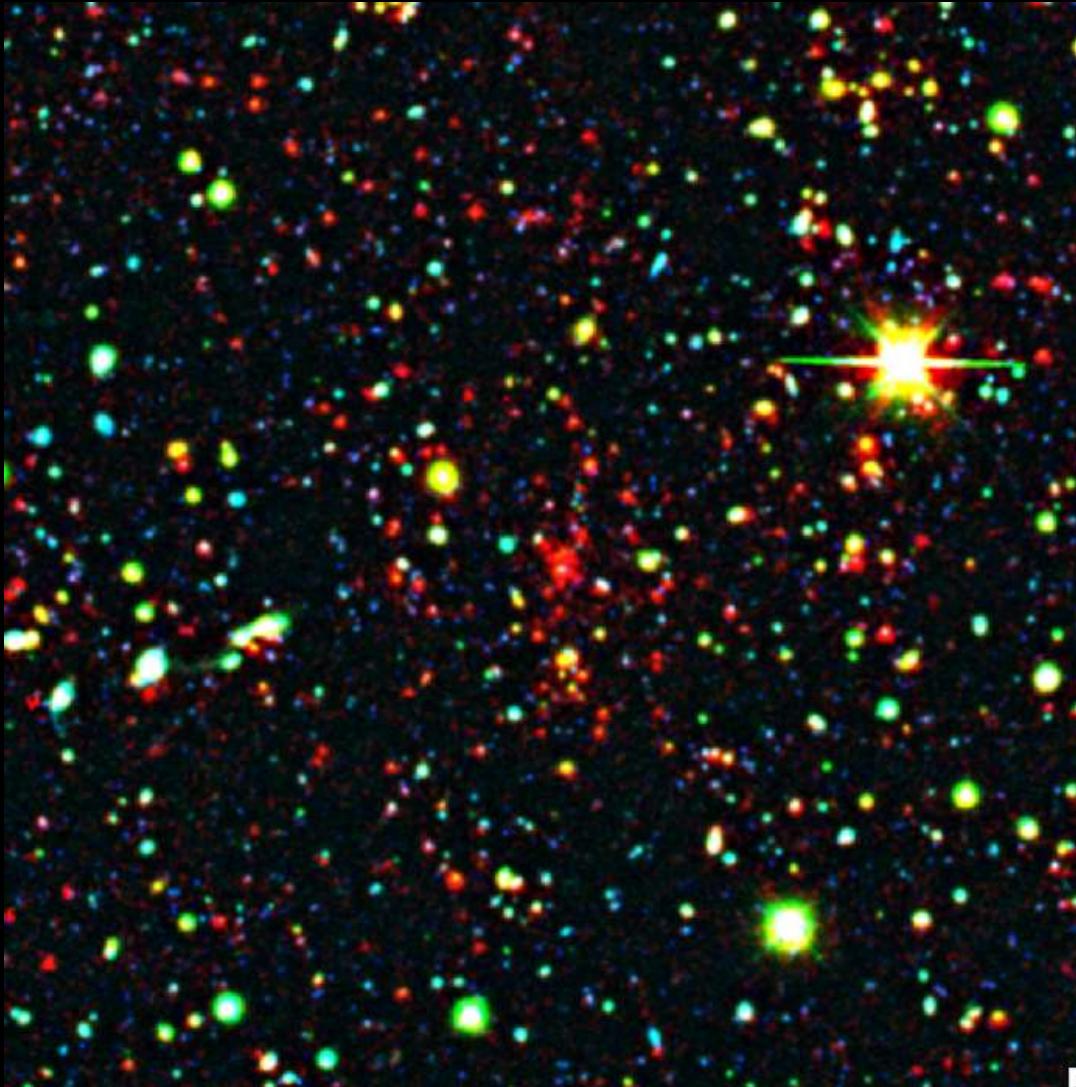
$\langle z \rangle = 1.24$

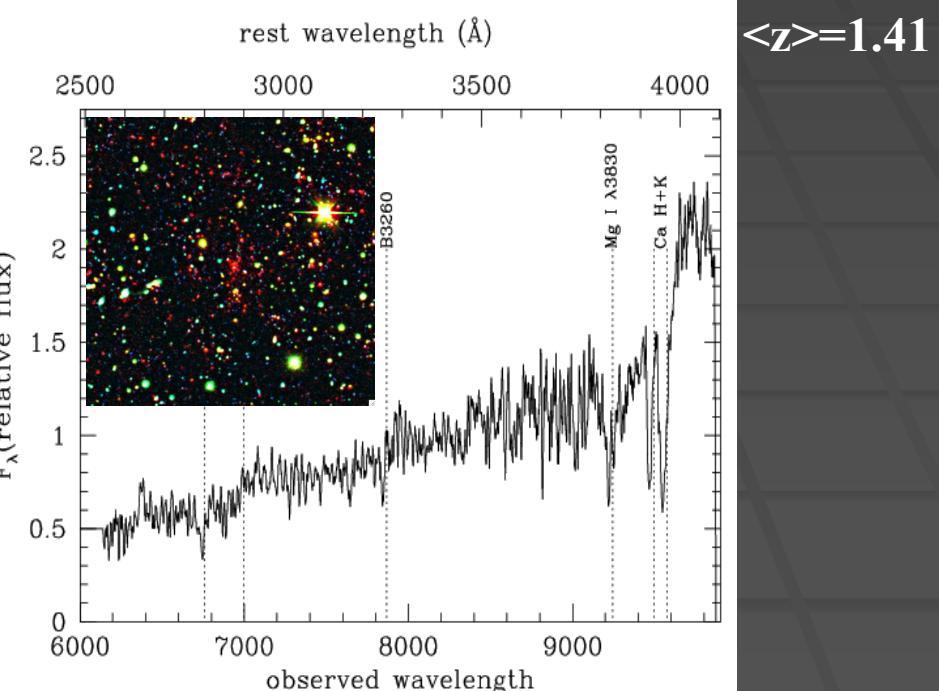
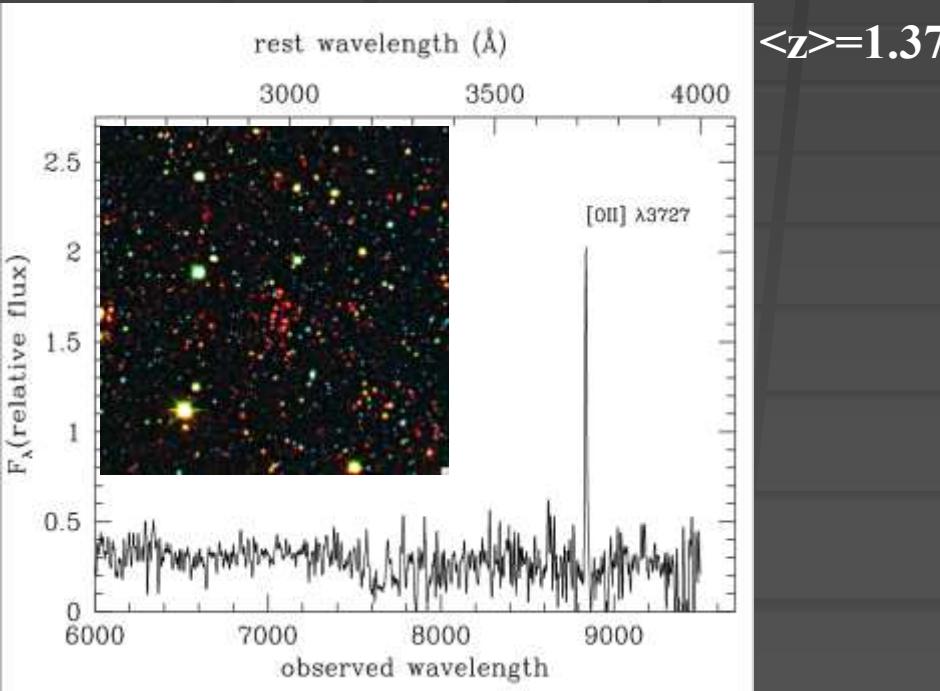
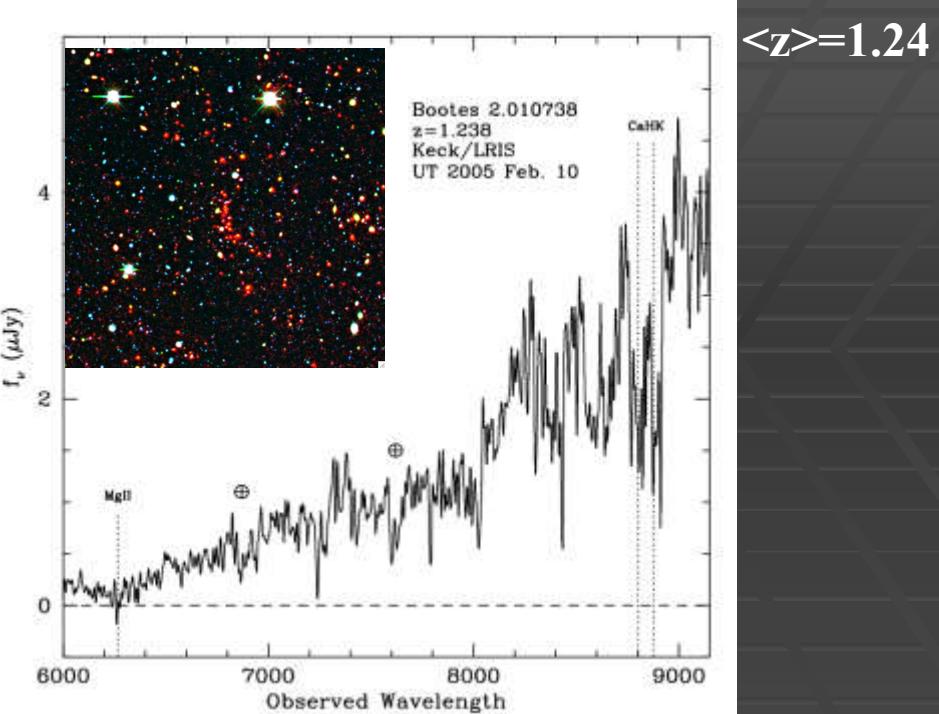
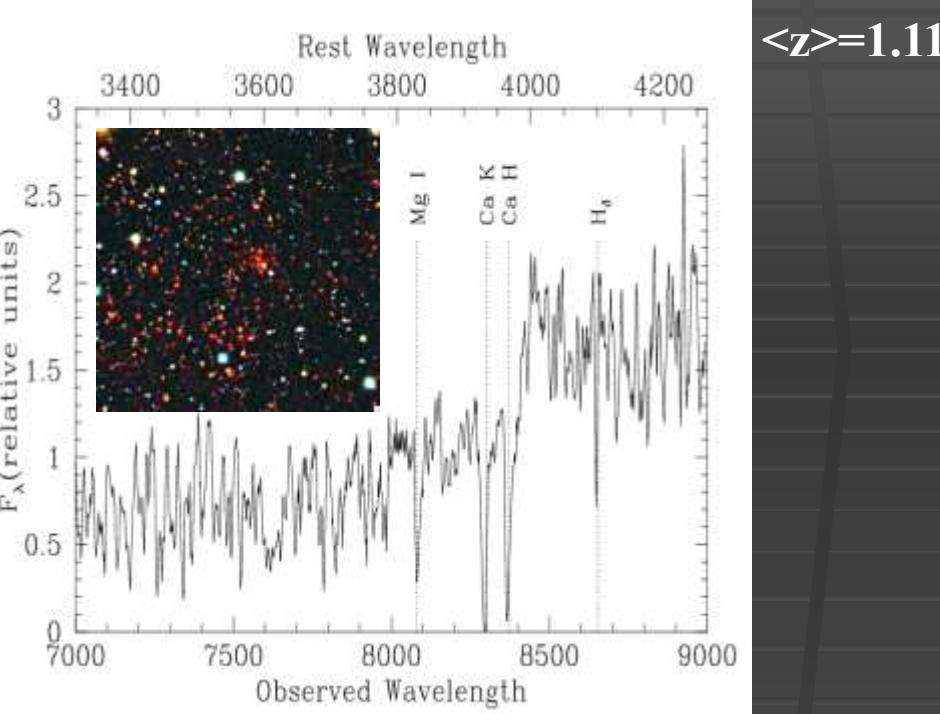
Optical
Alone



Stanford, Eisenhardt, Brodwin et al. 2005 (ApJ, 634, 129L)

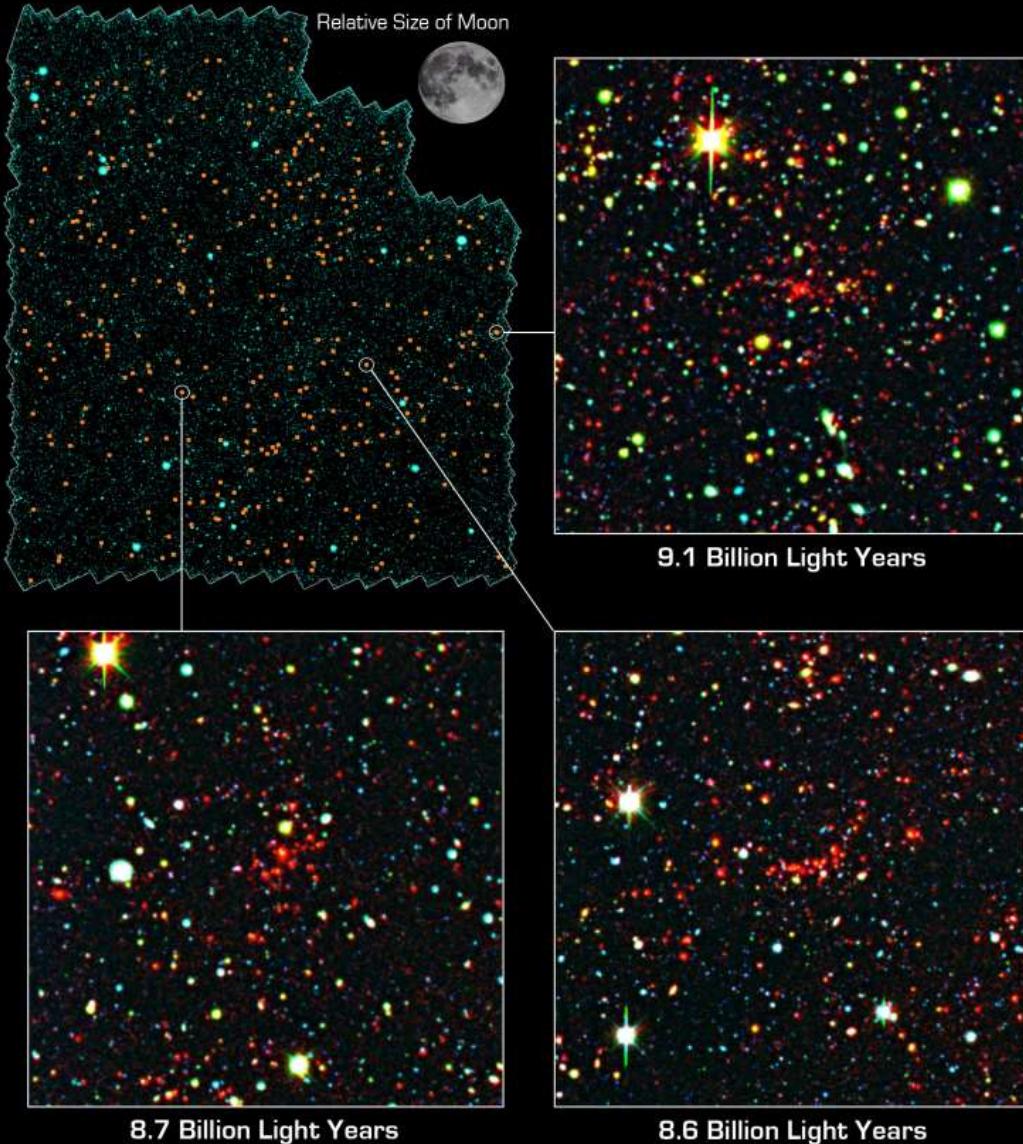
Optical
+
Mid-IR



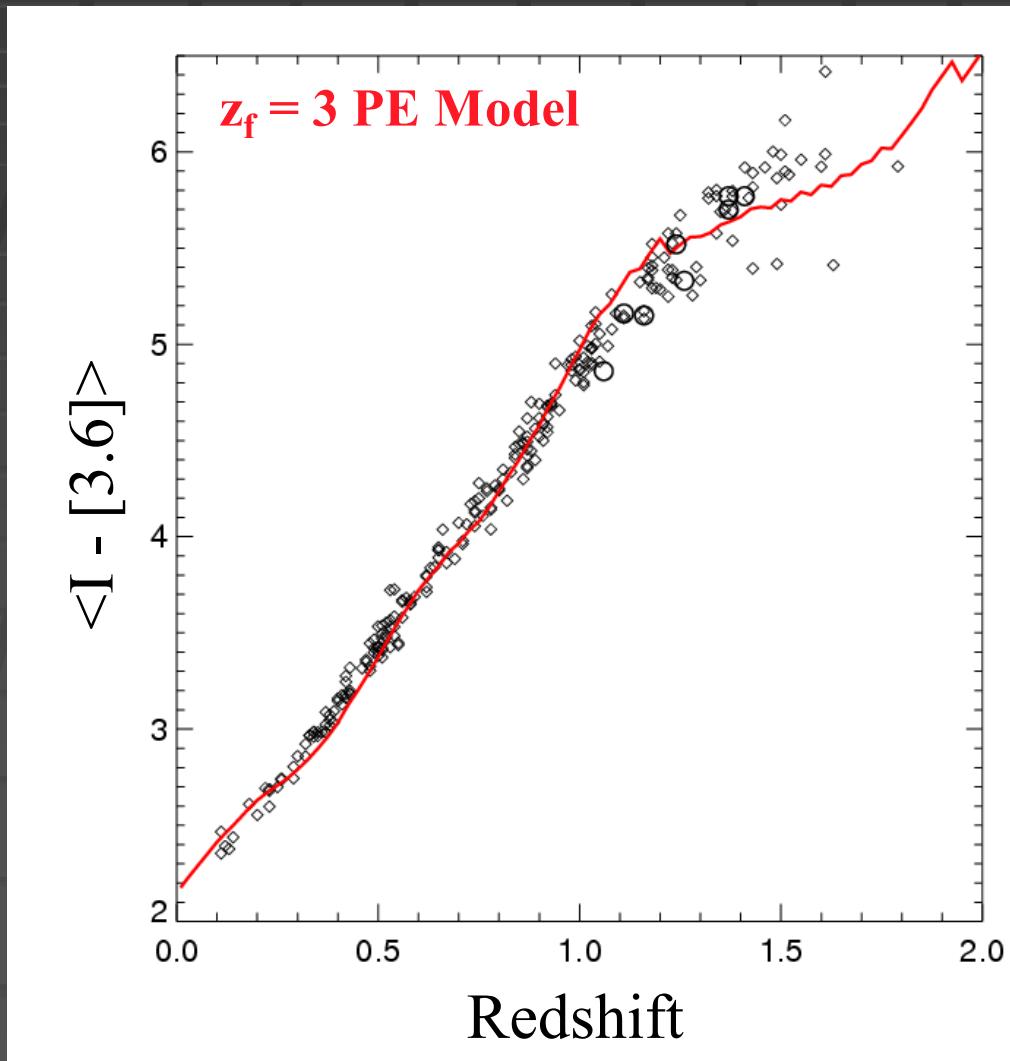


292 @ $0 < z < 2$

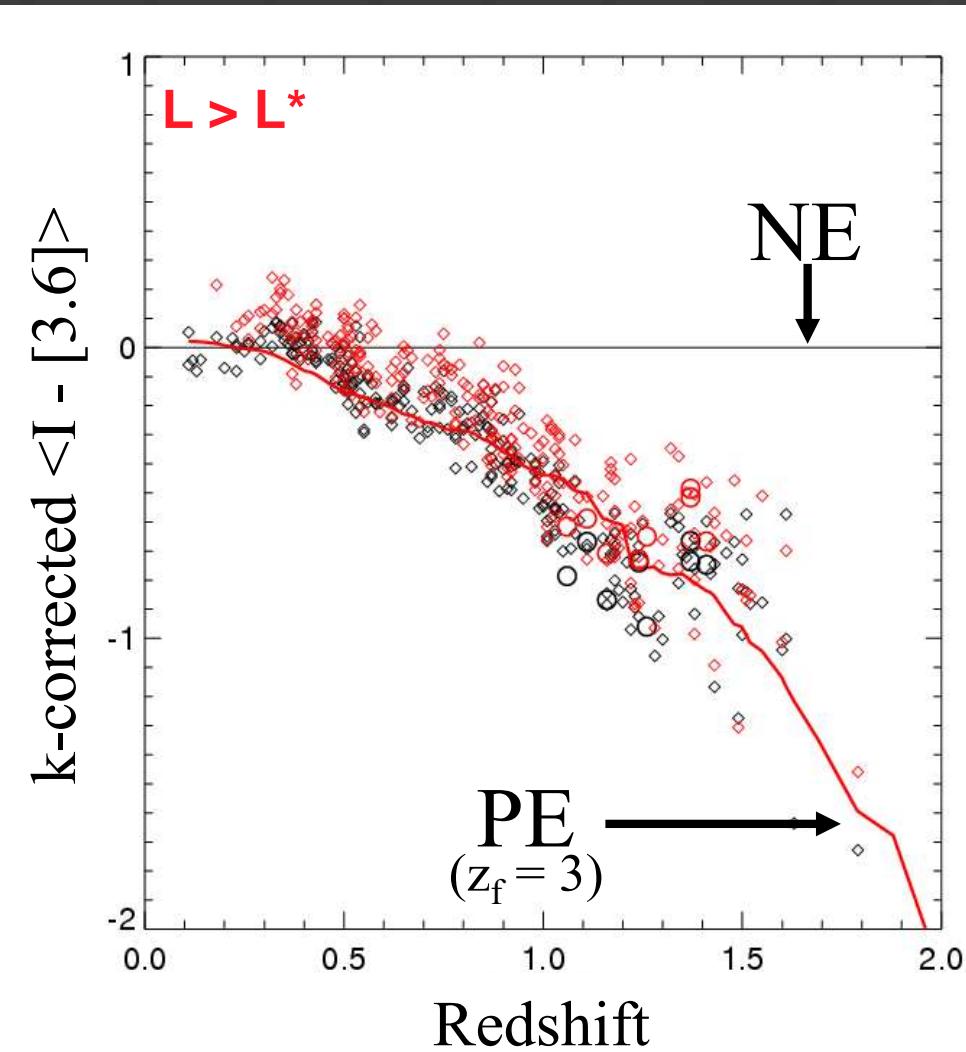
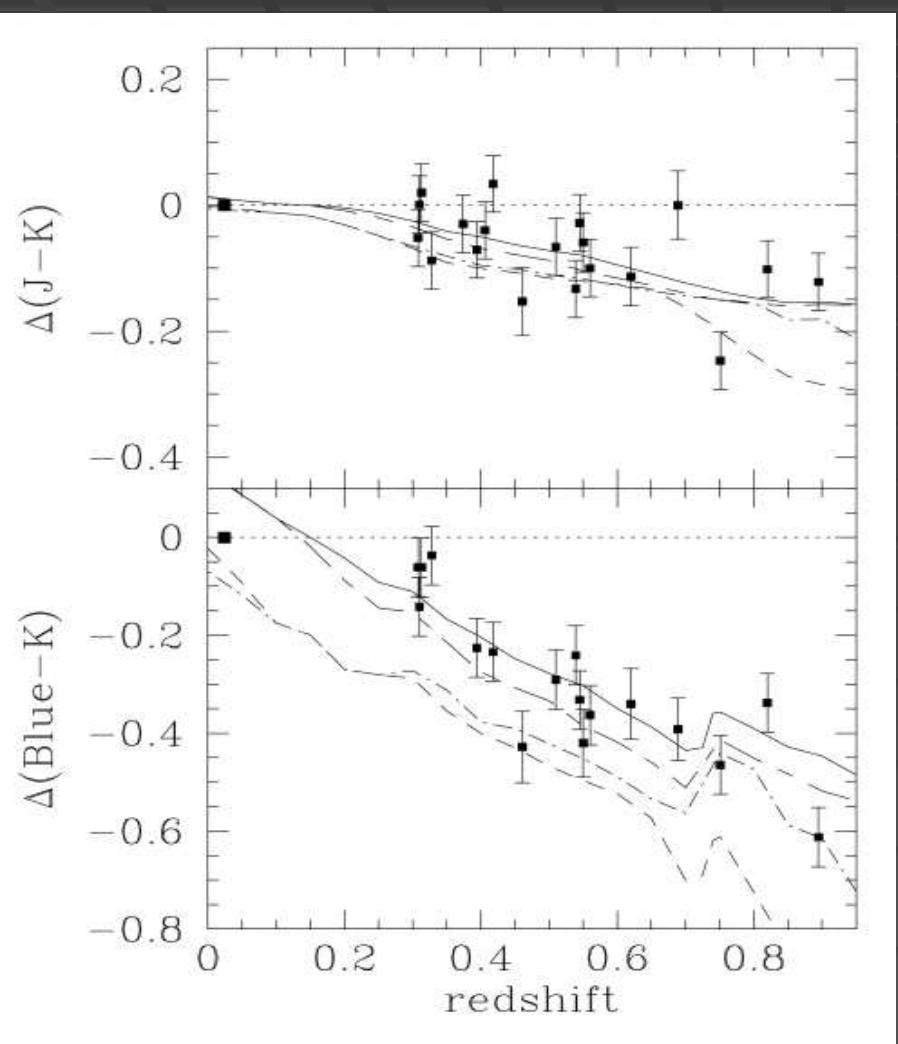
93 @ $z > 1$



Color Evolution of Galaxy Clusters over $0 < z < 1.5$



Relative to No Evolution

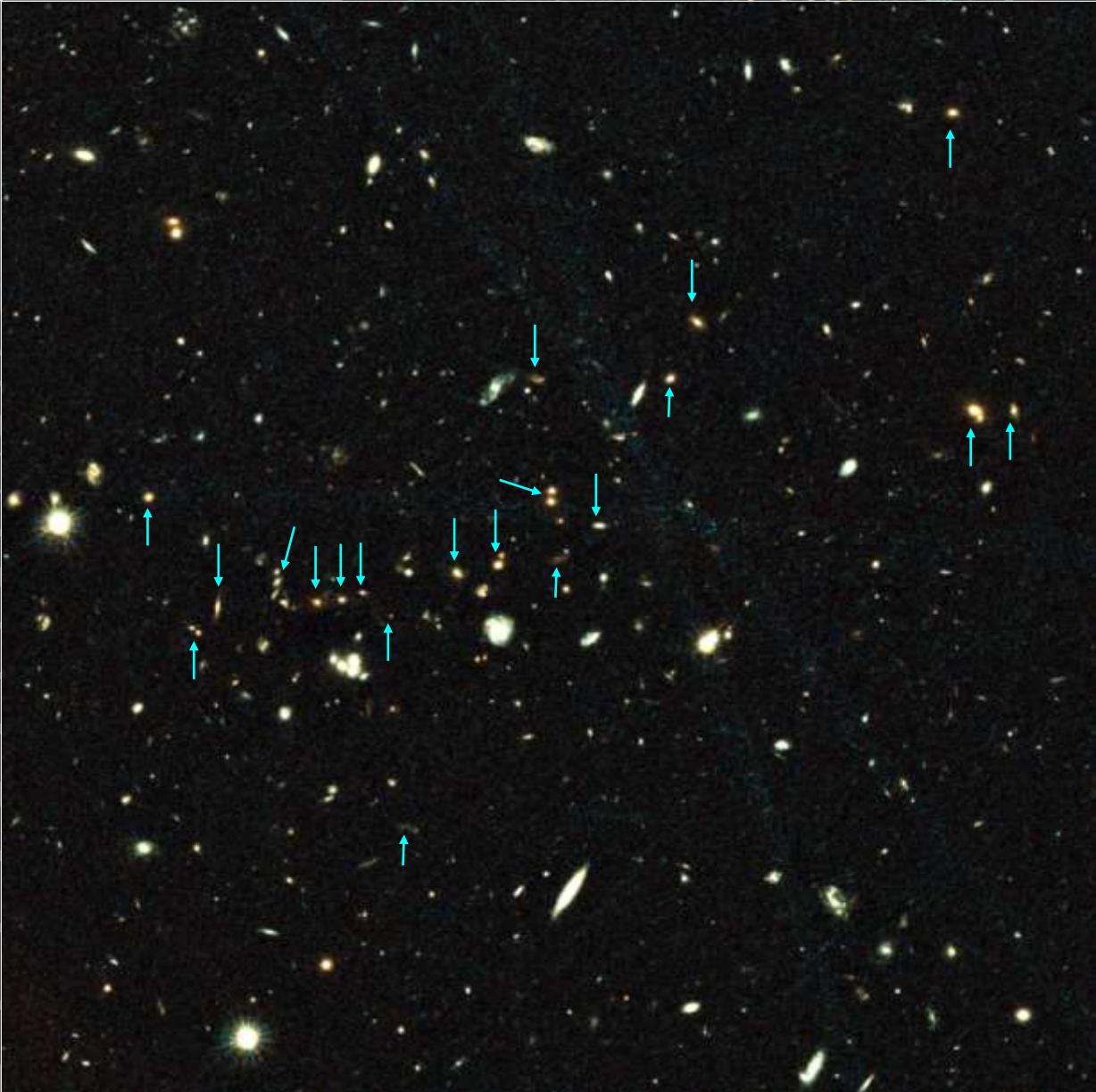


Stanford, Eisenhardt & Dickinson (1998)

Eisenhardt, Brodwin et al. in prep

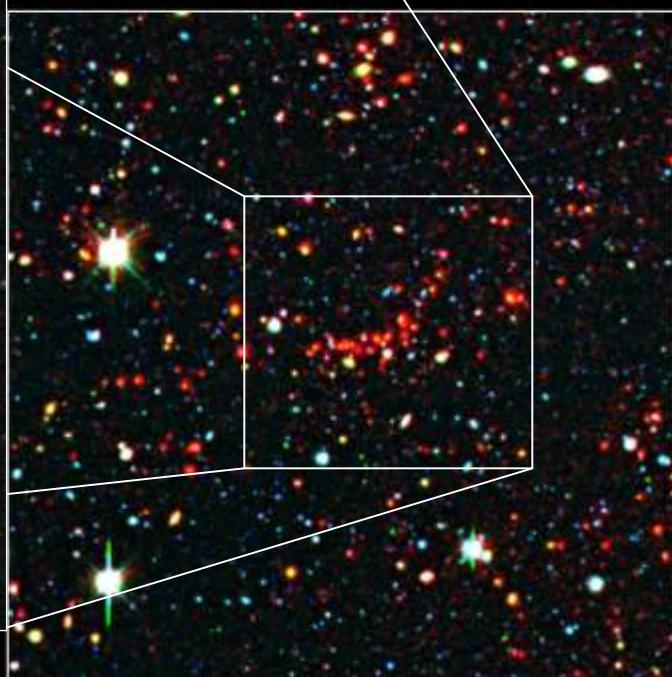
Uber Follow-up

- Data in Hand
 - Cycle 14 *HST*/ACS data for 8 $z>1$ clusters from SNe program (PI: Perlmutter).
- Allocated Time in Spring 2007
 - GO-3 *Spitzer*/IRAC+MIPS joint with *HST*/ACS in Cycle 15.
→ Deep IRAC, MIPS, and ACS imaging on 18 $z>1$ clusters
 - Cycle 15 *HST*/NICMOS on 5 $z>1.2$ clusters
- Proposals Spring 2007
 - Continuing Keck campaign
 - XMM imaging on 5 $z>1$ clusters
 - Palomar near-IR imaging for 13 non-NICMOS $z > 1$ ACS clusters
 - KNPO/MARS MOS to get velocity dispersions for 27 clusters at $0.4 < z < 1.2$



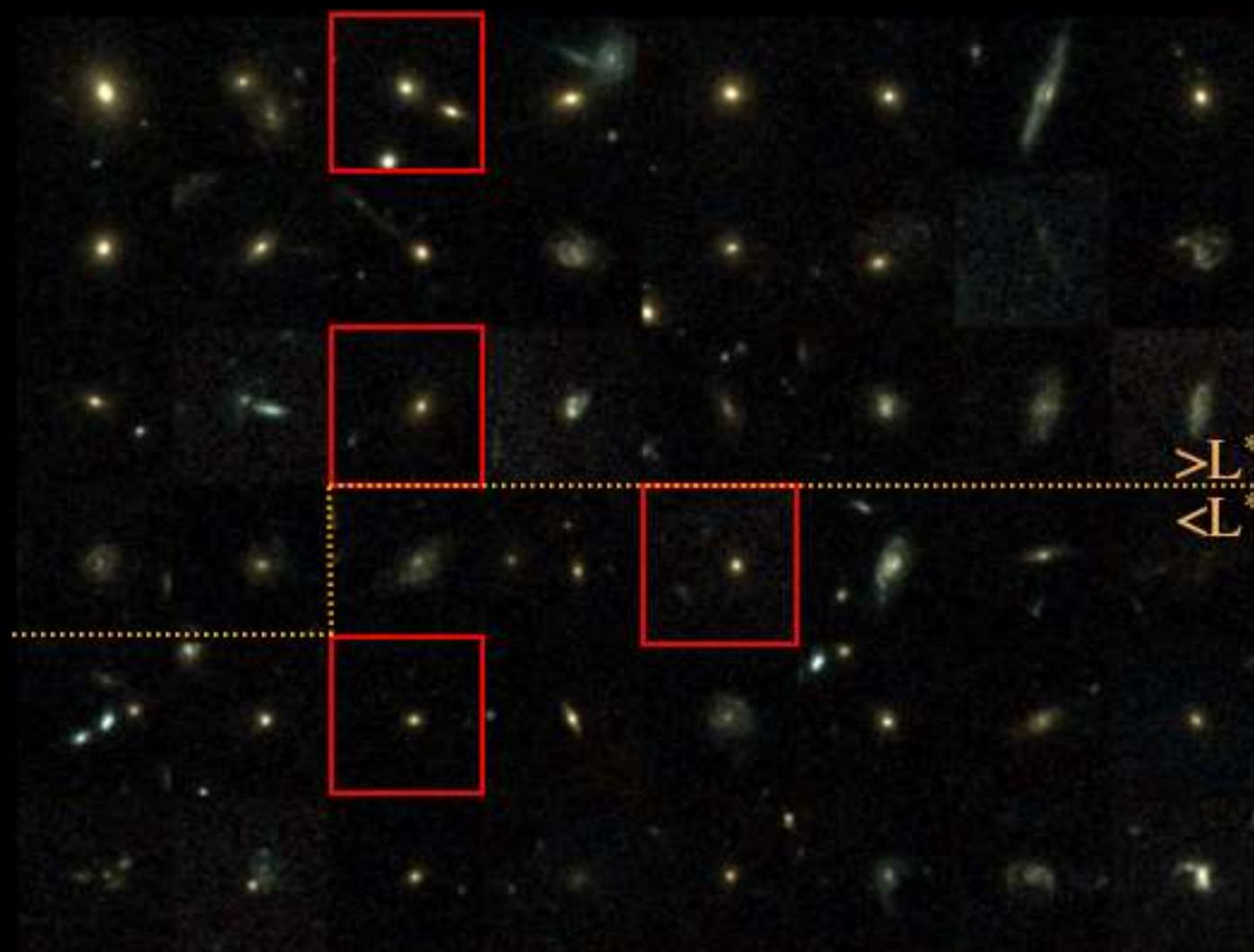
ACS (F850LP+F775W)

$z = 1.24$



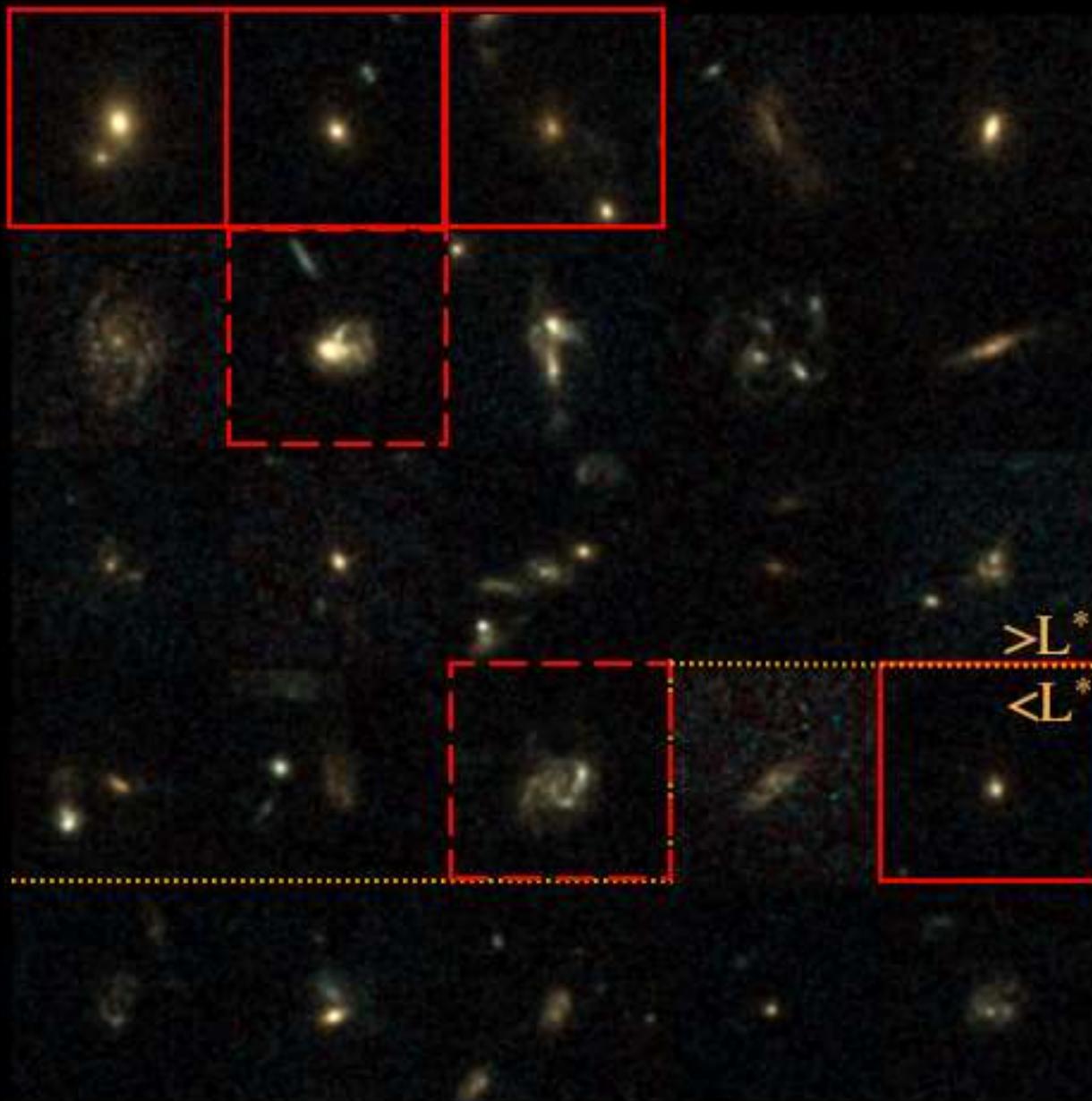
8.6 Billion Light Years

$\langle z=1.11 \rangle$



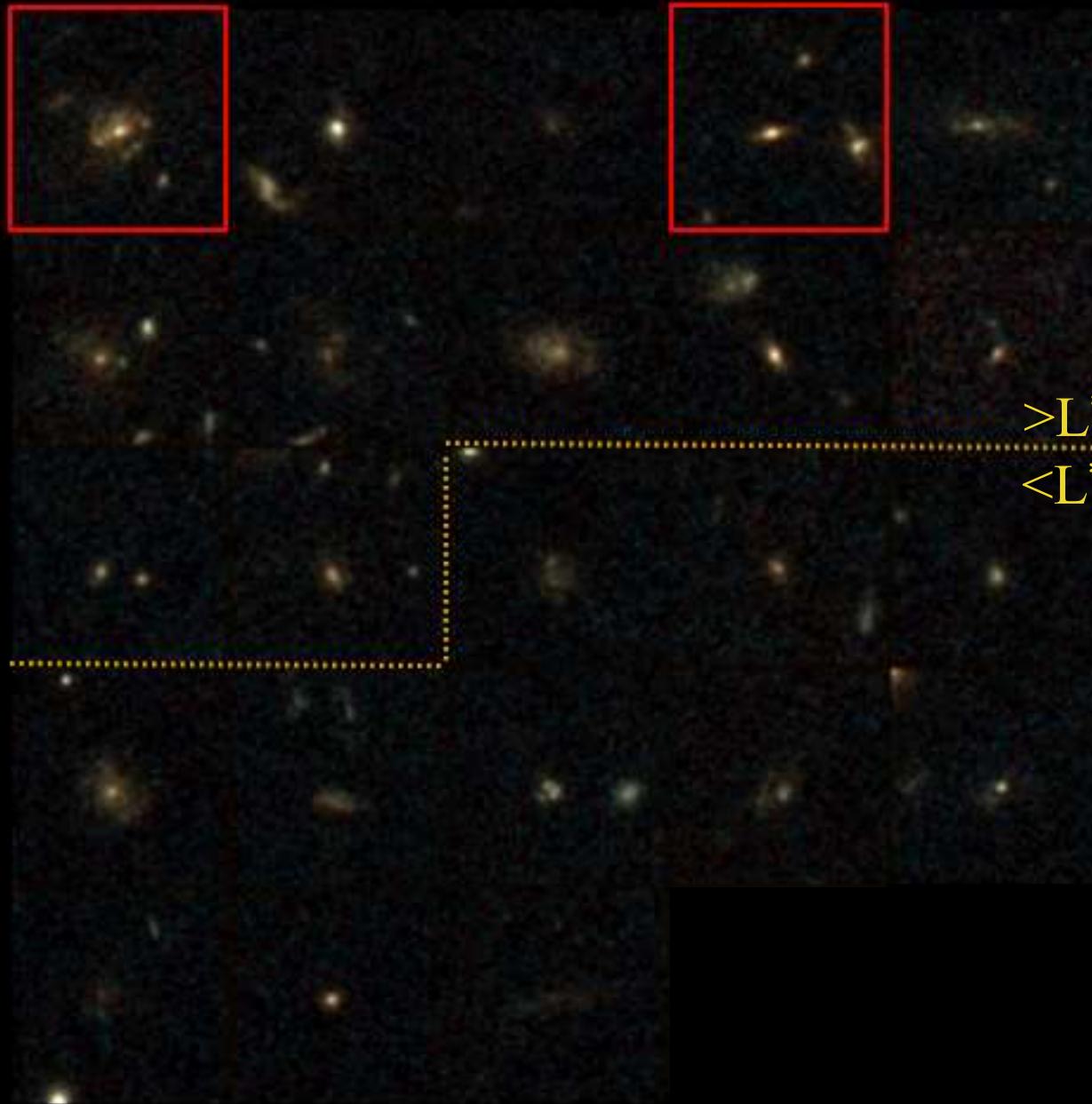
8 members: $\sigma = (920 \pm 230)$ km/s (Elston, Gonzalez et al. 2006)

$\langle z = 1.24 \rangle$

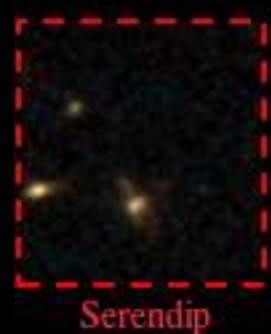


7 members: $\sigma \sim 600$ km/s; preliminary WL mass of $\sim 1\text{-}2 \times 10^{14}$ Msun

$\langle z=1.37 \rangle$

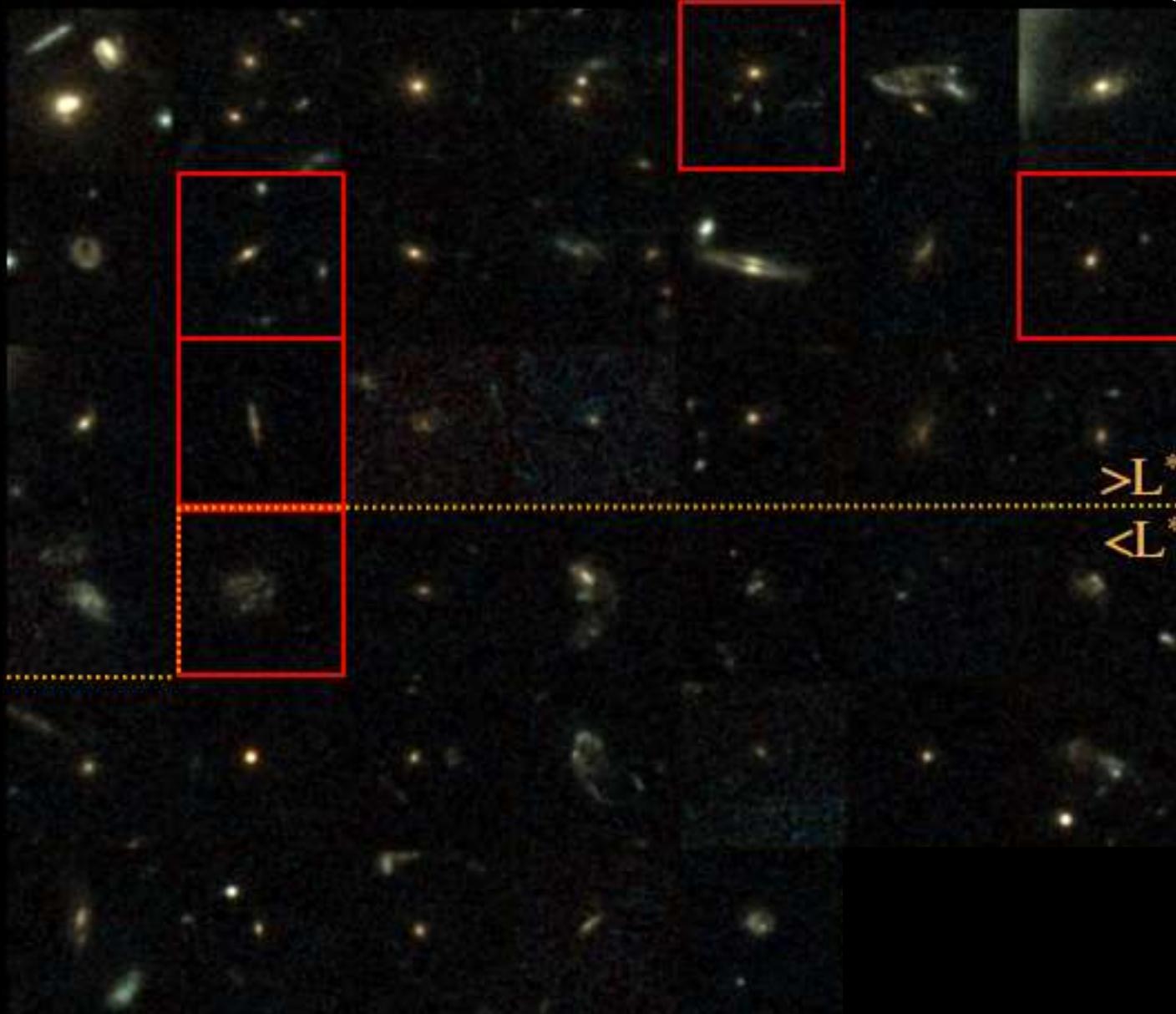


$>L^*$
 $<L^*$



5 members

$\langle z=1.41 \rangle$



6 members

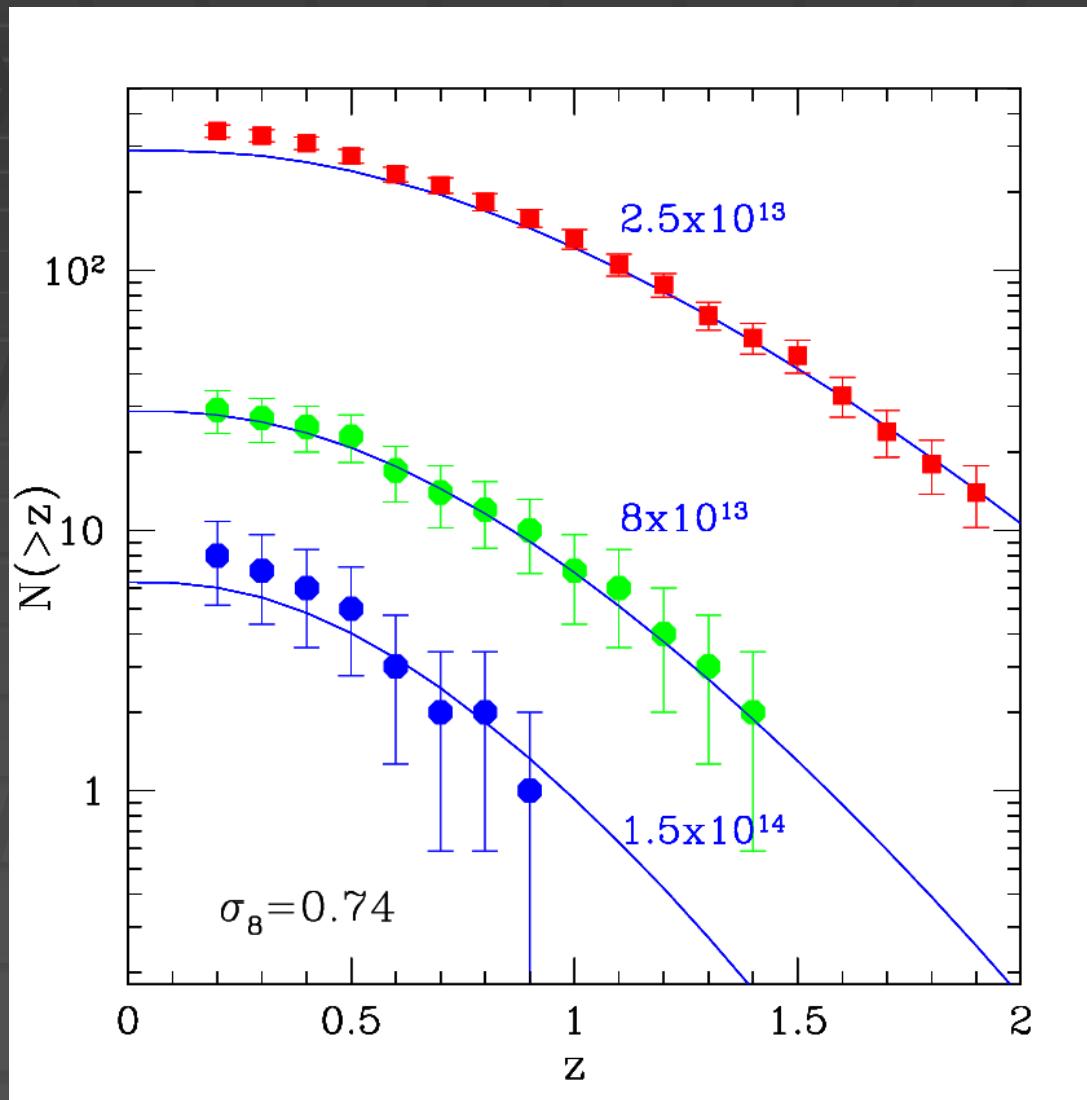
Next Steps

- Forthcoming deeper *Spitzer* and *HST* data will allow us to:
 - Observe the **mass assembly history** of massive cluster galaxies over 2/3 of the lifetime of the Universe.
 - Measure the evolution of the **merger rate** and the quantify the **dry merger fraction**
 - Probe the **Cluster/ULIRG connection** at the era of peak star formation
 - Compare WL and dynamical masses, calibrate $z>1$ mass-richness relation.

Summary

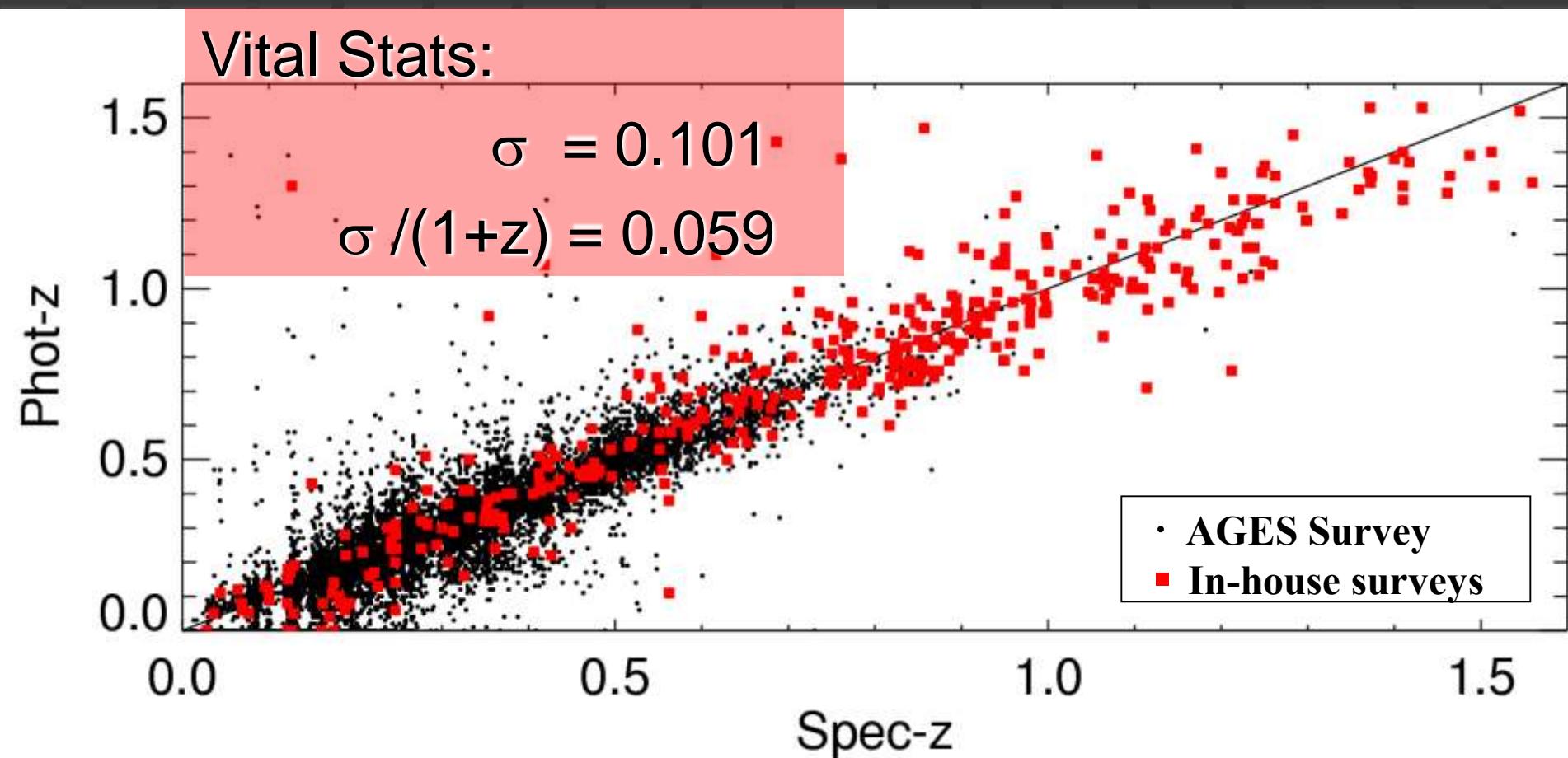
- Using a probabilistic multi- λ (0.4-5 μ m) photometric redshift technique, we have identified 300 new galaxy clusters and groups, of which almost 100 are at $z>1$, a 6-fold increase.
- To date 8 $z > 1$ clusters between $1.06 < z < 1.41$ have been spectroscopically confirmed with at least 5 members.
- Mean colors of clusters at $0 < z < 1.5$ are consistent with simple PE models with high formation redshifts ($z_f \sim 3$).
- Evidence of mass-metallicity relation in clusters at $z=1.5$
- Incidence of disturbed morphologies increases over the range $1.1 < z < 1.4$. Elliptical fraction appears to be decreasing as well. Quantitative results TBD.

Cluster “Masses”?



Thank you!

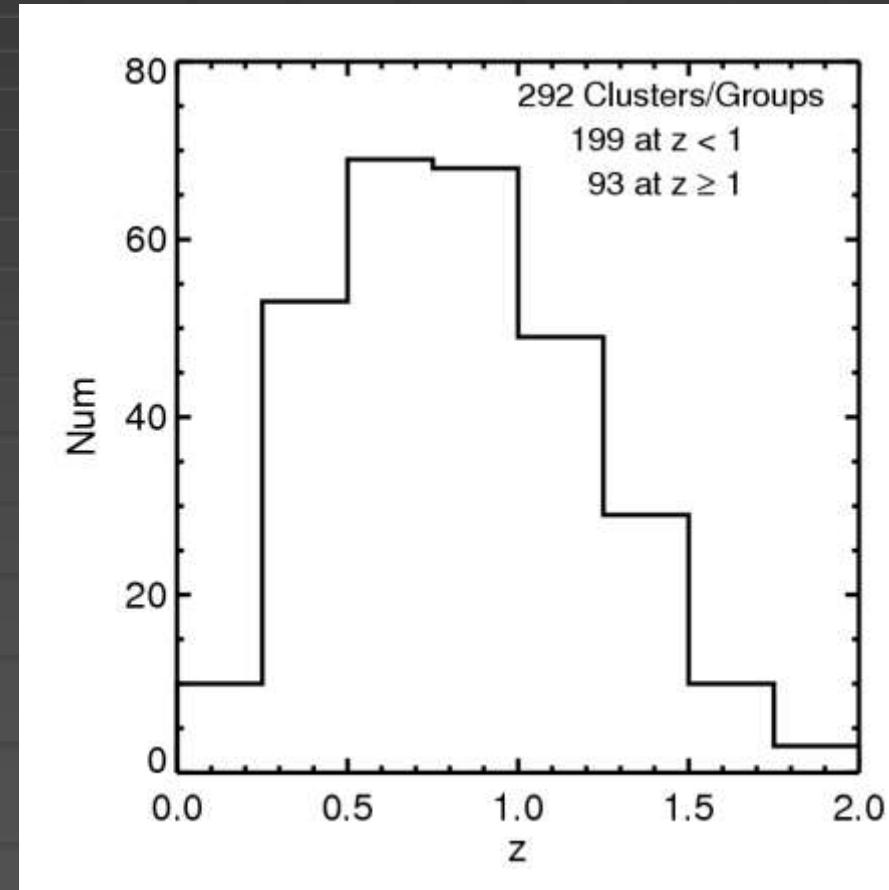
Photometric Redshifts



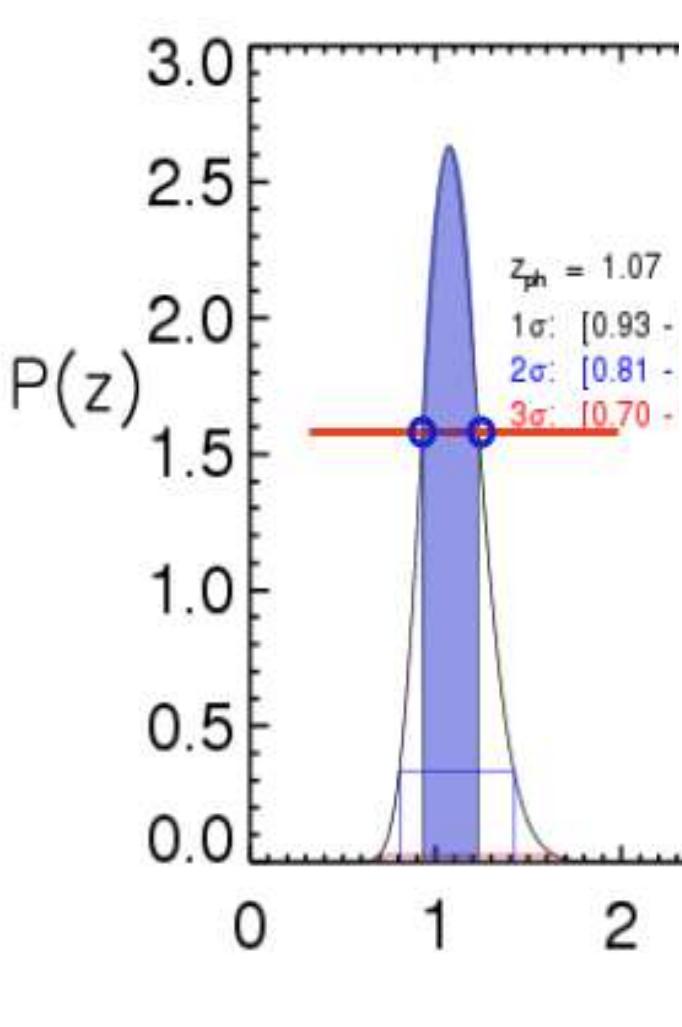
Galaxy Clusters at $0 < z < 2$ in the IRAC Shallow Cluster Survey (ISCS)

Results

- 292 candidate clusters and groups at $0 < z < 2$ over 8.5 deg² in Boötes.
- Of these 93 are at $z > 1$, a 6-fold increase over the number of confirmed high-z clusters in the literature.
- To date 8 confirmed at $z > 1$ ($1.06 < z < 1.41$).

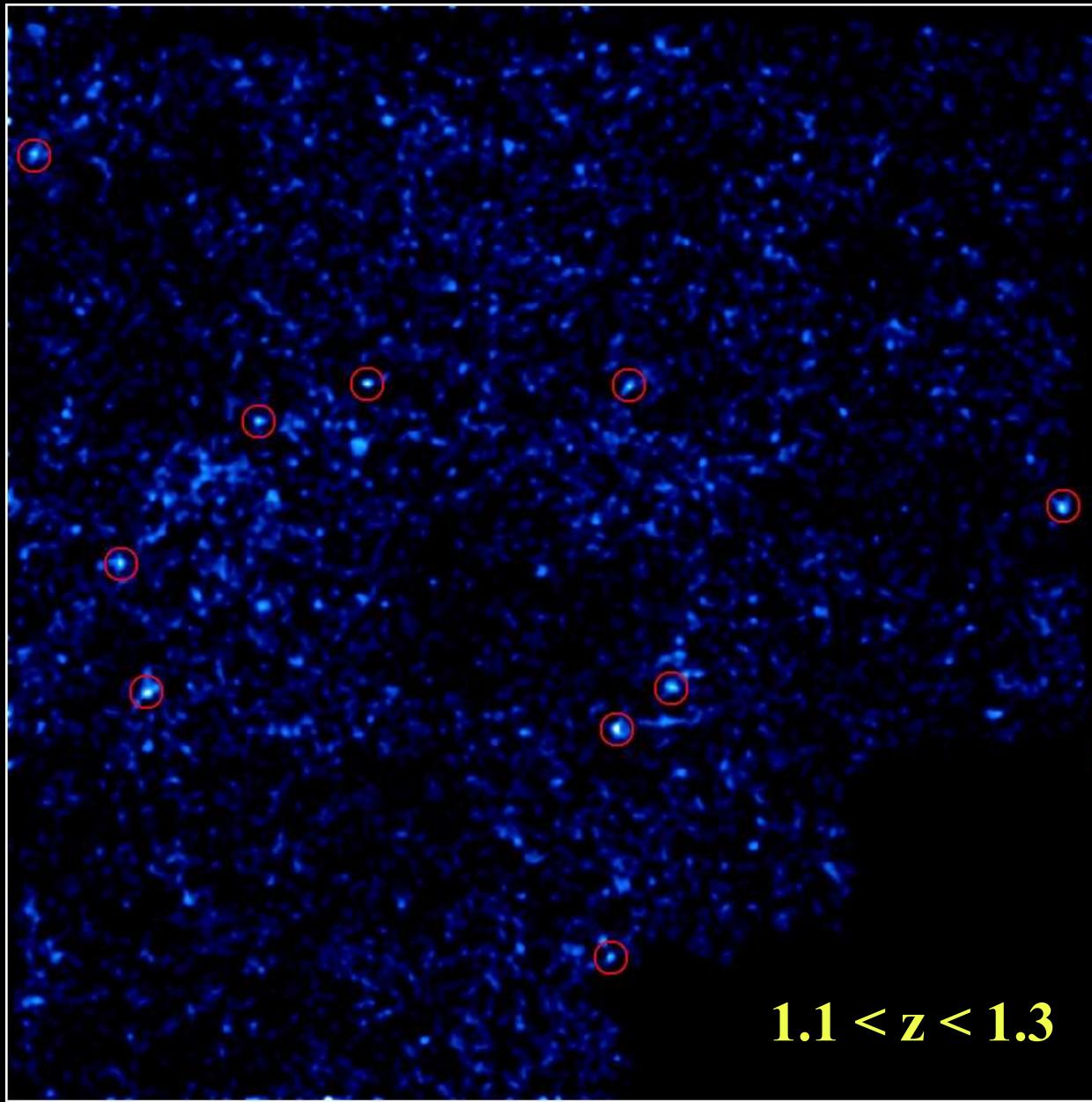


Redshift Probability Functions



Confidence Interval	Correct Within Confidence Interval	<i>Observed Fraction</i>	Gaussian Expectation
$\leq 1\sigma$	9722 / 13043	74.5%	68.3%
$\leq 2\sigma$	12335 / 13043	94.6%	95.4%
$\leq 3\sigma$	12848 / 13043	98.5%	99.7%
$> 3\sigma$	195 / 13043	1.5%	0.3%

Cluster Probability Density Map



Spectroscopic Confirmation

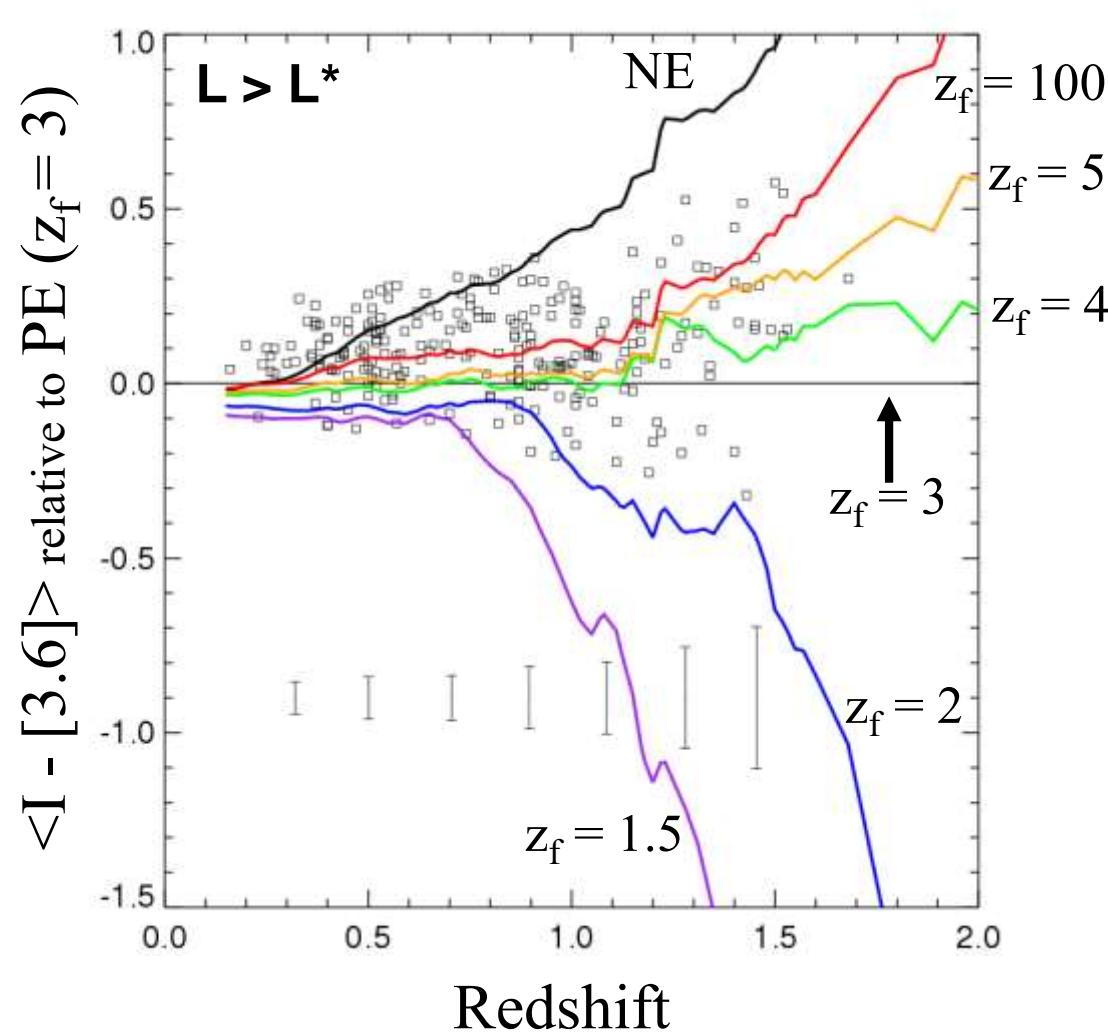
Keck 2005/2006

- Observed 10 clusters to date
- **8** confirmed with 5+ members within 2000 km/s in the rest-frame (approx $\Delta z \pm 0.015$)
- CI26 and CI79: Many objects with faint, red continua, no lines
- CI90: Evidence of projection. Line-of-sight structure at $z = 1.46$

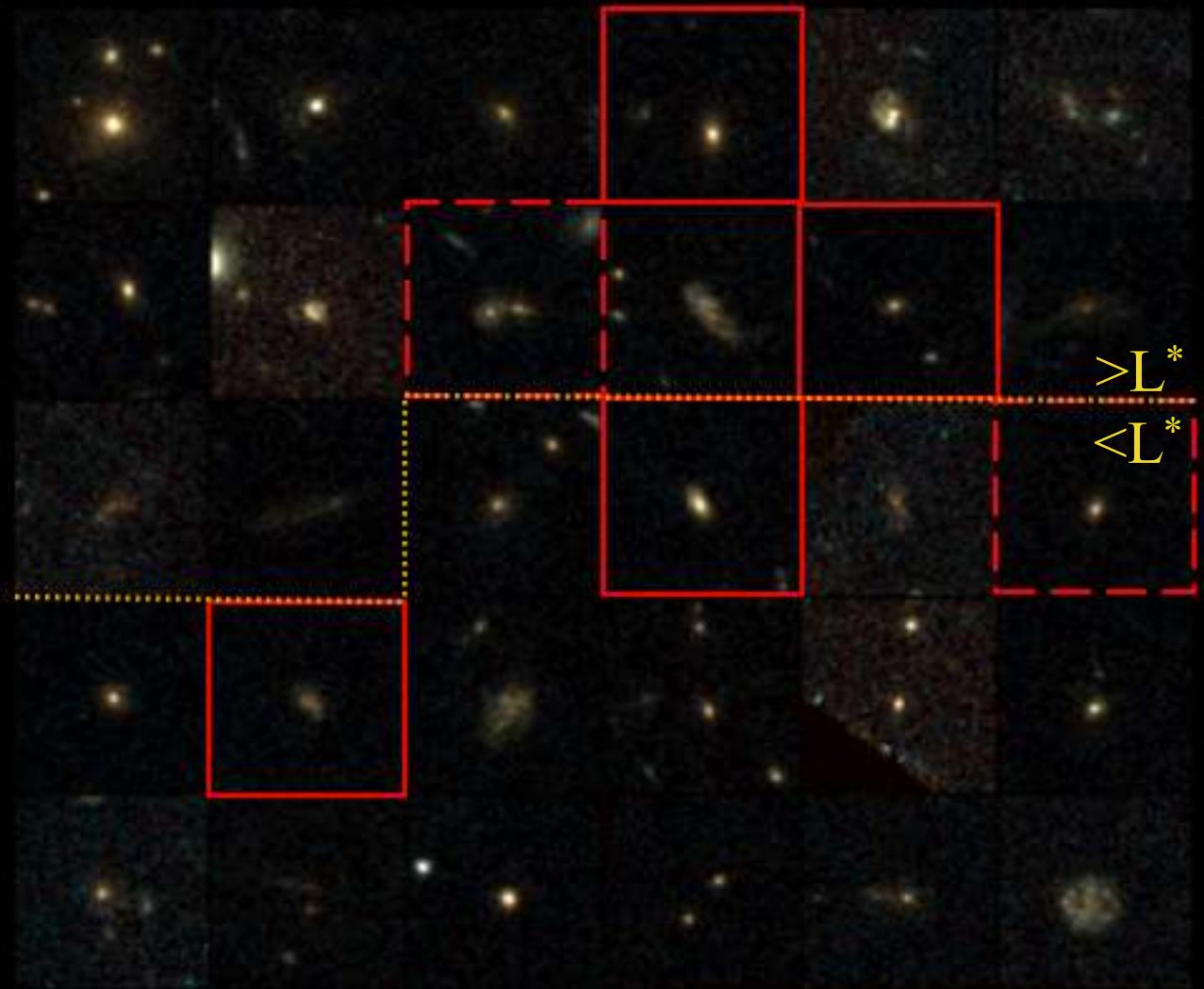
Subaru 2006 not yet reduced

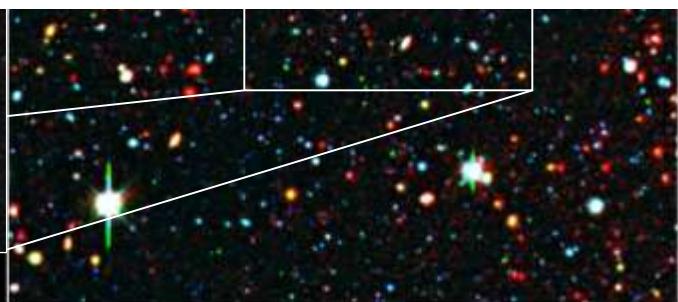
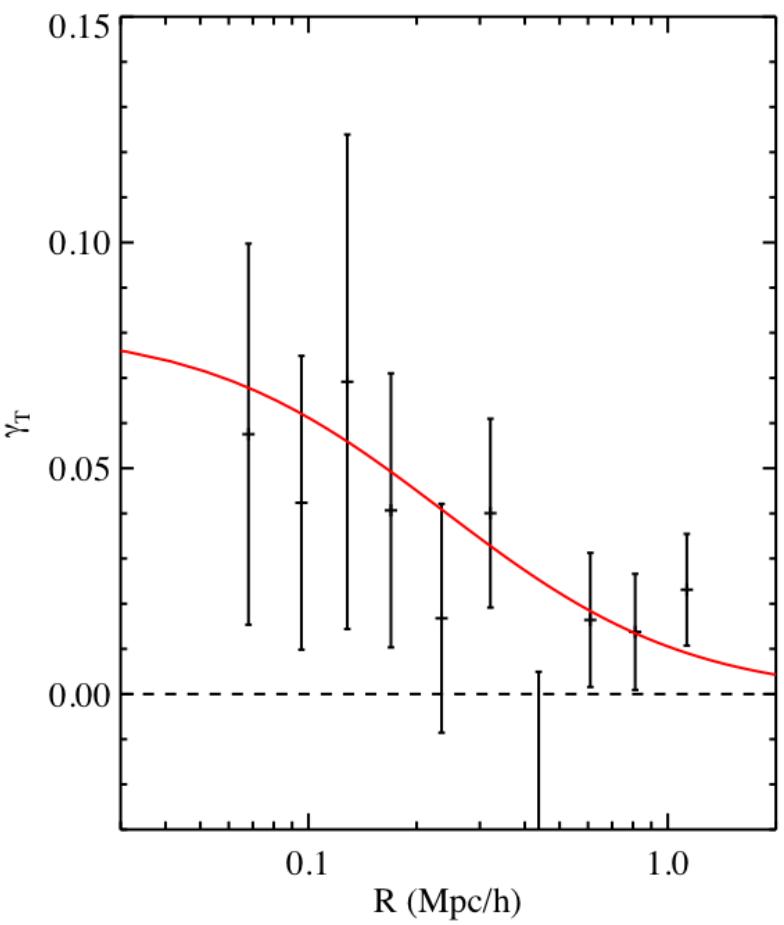
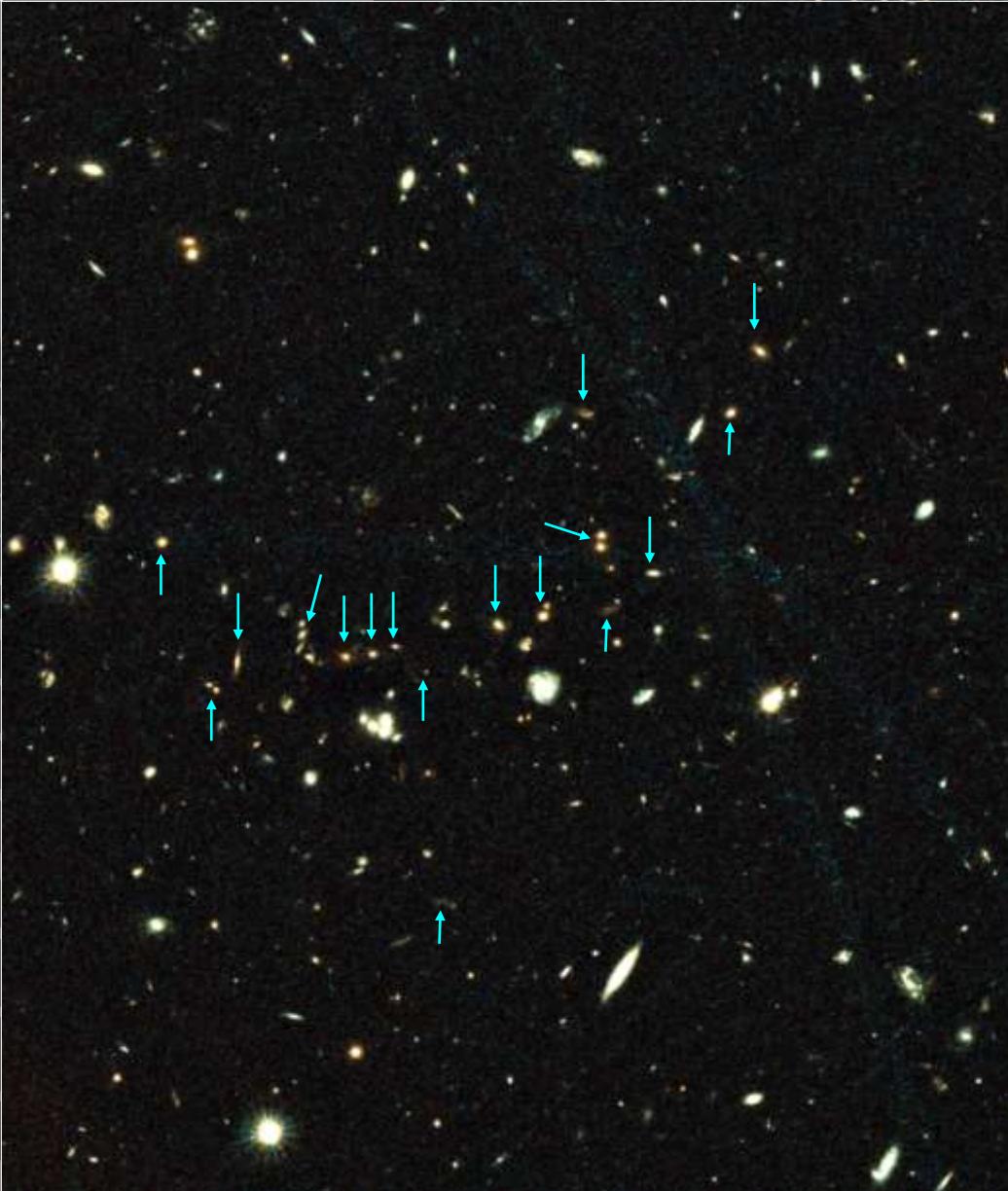
ID	Phot-z	<Spec-z>	#
39	1.00	1.06	7
13	1.09	1.11	8
15	1.11	1.16	5
283	1.18	1.24	7
27	1.17	1.26	7
90	1.36	1.37, 1.46	5, 4
23	1.38	1.37	5
21	1.34	1.41	6
29	1.25	-	-
79	1.41	-	-

Relative to $z_f = 3$ Model



$<z=1.26>$





8.6 Billion Light Years